Galaxies and Cosmology

Report of Working Group 1.1 of the Australian Astronomy Decadal Plan 2026-2035

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Executive summary

This report summarizes the key research themes expected to be important internationally and within the Australian community over the next decade. It is informed by five white papers on various topics written by working group members (available in Appendices A-E of this document) and various town hall meetings used to gain broader input from the Australian community. Together with the key science themes, we identify the critical capabilities that the community requires to carry out this research program.

Australian astronomy has had many successes over the last decade. Australian led programs at optical wavelengths have carefully characterized the internal structure of galaxies and the large-scale structures they sit within. Using internationally leading facilities, including the European Southern Observatory (ESO) and the James Webb Space Telescope (JWST), Australians have helped to reveal the nature of galaxies in the distant Universe. New radio telescopes have started major surveys of continuum sources and neutral hydrogen and pushed to deeper limits in the epoch of reionization. New cosmological measurements have placed tighter constraints on the contents of our Universe and uncovered significant problems within the standard model of cosmology. Theoretical research has developed new models of galaxy and star formation, adding more of the complex physics needed to understand the Universe around us, and to reconcile new multi-wavelength and multi-messenger observations. The above work provides the foundation for next steps to be taken in the coming decade.

WG 1.1 has identified four key science areas that will be the focus of efforts in the coming decade:

1. What regulates the star formation process from parsec to gigaparsec scales?
2. Understanding galactic ecosystems: what are the internal and external processes that shape galaxies and their surroundings?
3. What is the physical nature of galaxies and the intergalactic medium during the Epoch of Reionization and Cosmic Dawn?
4. The Universe as an experiment: searching for new particles and new physics.

Carrying out research addressing the above topics will require state-of-the-art capabilities. The suite of observational capabilities needed is broad, with a particular focus on optical/IR, radio

and mm wavelengths. At optical and infrared wavelengths, Australia will need continued access to 8m-class telescopes and then 30m-class telescopes when they come online during the next decade. 8m class access is currently provided through the ESO strategic partnership, but no 8m access is assured beyond 2027. For 30m-class telescopes, Australia is currently a partner in the Giant Magellan Telescope (GMT), but only at the level of ~5% and there continues to be uncertainty on GMT construction. The Atacama Large Millimeter/sub-millimeter Array (ALMA) is a unique facility for studies at mm wavelengths, and access to ALMA would be a major advantage. Continued access to the Australian SKA Pathfinder (ASKAP) and the Murchison Widefield Array (MWA), and the Square Kilometre Array (SKA) when it comes online in the next 5 years, will be enabling for a broad range of science. Australian collaborations have access to several other key facilities (e.g. the Vera Rubin Observatory, VRO; the 4-metre Multi-Object Spectroscopic Telescope, 4MOST; LIGO-Virgo-KAGRA; the Cherenkov Telescope Array Observatory, CTAO) and these should continue. Several unique facilities are international and space-based (e.g. The Hubble Space Telescope, HST; JWST; Euclid; Roman), these are open access or will quickly make data public. The Anglo-Australian Telescope (AAT) should be supported to complete the current large surveys. While it will not become operational in the next decade, engagement with and leadership within a next generation 8-10m class wide field spectroscopy survey telescope will help set up the community beyond the coming decade. The most important capabilities that are currently uncertain or unavailable are (not in priority order): i) access to 8m class telescopes; ii) access to 30m class telescopes; iii) access to ALMA.

The Australian community has long had an important leadership role in internationally competitive observational programs across wavelengths (e.g. large programs using the ESO Very Large Telescope (VLT); wide-field radio surveys using ASKAP and multiple generations of spectroscopic surveys on the AAT). Much of this is driven by technological instrumentation capabilities, and it is important that Australia's ability to build world-leading instrumentation continues to be supported. Historically, Australia has not focussed significantly on space astronomy, but the next decade will require space to be an important part of what we do (with JWST, Euclid, Roman etc). Engagement with space astronomy should be supported, for example through programs to provide and process data, help with application processes and allow for the development of space technology and instrumentation. In this regard, it is critical to advocate for the inclusion of science, including space astronomy, as one of the priorities of the Commonwealth Civil Space Strategy and for associated funding for science missions managed by the Australian Space Agency.

Australians have built strong collaborations (both nationally and internationally). These should be encouraged and grown to face the next generation of astrophysical problems. Building links between observational astrophysicists and theoreticians will be important to undertake world leading work. Links to the physics communities, in particular with regard to dark matter and gravitational waves, should be expanded. Increased investment in high performance computing (HPC) for simulations and next-generation data processing (e.g. from the SKA) is an important part of both theoretical and observational research having larger impact.

The largest risk across the next decade is the potential loss of access to front rank optical and infrared telescopes when the ESO strategic partnership comes to an end. Full membership of ESO would provide all the science capabilities that are currently uncertain or unavailable. Loss of access will severely reduce science productivity, as well as limit opportunities for return on investment via instrumentation and technology. A second risk is around the investment Australia currently has in the GMT. The future of GMT is uncertain, awaiting funding decisions in the US, and even with a positive outcome, GMT is not likely to be operating before 2035. The ESO Extremely Large Telescope (ELT) will likely be operating at least 5 years before GMT. A third risk is that as astronomy projects become larger in scope, they are continuing to become more international and operate for longer, often 5–10 years, or more. It will be important that Australia continues to be able to provide real and unique value to international consortia (e.g. via technology development and science leadership) and can provide stable funding streams for such projects.

1 Progress in the last decade, 2016-2025

The last 10 years have seen new discoveries and deeper understanding across a broad range of topics. Below, we discuss the key areas of progress globally, but also focus on how Australian work has contributed to this. We discuss these under five key science questions that the last decadal plan highlighted.

1.1 How did the first stars and galaxies transform the Universe?

Progress in this area has been along two broad themes, the first has focussed on detection of neutral hydrogen in the early Universe at radio frequencies. The second has been on characterizing galaxies at the earliest epochs.

Over the last decade, world leading low-frequency interferometers MWA (Australia), the Hydrogen Epoch of Reionization Array (HERA, South Africa) and the Low Frequency Array (LOFAR, Europe) have acquired sufficient data to in principle make measurements of fluctuations in rest-frame 21cm emission from neutral hydrogen during the epoch of reionization (EoR), at $z\sim6$-10. The major challenge in this field is to account for systematic effects so that a statistical detection of the EoR can be made. Teams have been consistently improving limits, pushing down towards the theoretically expected signal. Australians have also developed new simulations of the high-redshift Universe to better understand reionization. The last 5 years have also seen lower frequency (50-120MHz) telescopes looking to probe cosmic dawn ($z\sim12$-25). In tandem, development has started on systems that could in the future be deployed on the far side of the moon, away from the Earth's ionosphere and radio frequency interference. Detection of the redshifted 21cm signal from $z>6$ remains a priority goal for the MWA and upcoming SKA.

Global 21cm signal experiments have been a new development in the last decade, aiming to measure the average signal of reionization across the whole sky. In 2018, the EDGES project (observing in Western Australia and led by a US team) published a global detection, but other experiments have not been able to reproduce the result. There are many global 21cm experiments currently being developed, including in Australia at the MWA site.

Prior to the launch of JWST, deep fields imaged in the optical and near-infrared provided detections of galaxies at z>6. Some projects have made use of gravitational lensing by galaxy clusters to more easily detect and characterize these distant galaxies. A number of these programs were led or had significant involvement from the Australian community (e.g. BoRG, ZFORGE). Follow-up observations of small numbers of candidate high-z galaxies required deep near-infrared spectroscopy on 8m telescopes or at mm wavelengths with ALMA. Discovery of a large amount of dust in some of these galaxies is one of a number of puzzles yet to be answered, as most dust in the local Universe is produced by the late stage evolution of low mass stars that have not had time to evolve at early epochs.

Although only operational since 2022, JWST has completely transformed our understanding of galaxy formation at the earliest epochs, through imaging and spectroscopy in the near- and mid-infrared. Imaging has provided numerous photometrically selected candidate galaxies at z>10, and JWST spectroscopy has been able to confirm many of these. Spectroscopy has also been able to characterize the nature of the earliest galaxies, exploring early metal enrichment and star formation history. Australians have engaged significantly with JWST, leading 10 successful proposals and being co-investigators on another 186 (JWST cycles 1-3; note that not all of these are focussed on early Universe science). It is also noteworthy that JWST is heavily oversubscribed, by factors of 4:1, 7:1 and 9:1 in cycles 1, 2 and 3 respectively.

ALMA has also been revolutionary for the study of the most distant galaxies. Dust continuum, molecular (e.g. CO) and ionized gas (e.g. [CII]) emission have allowed the detailed study of galaxies in the early Universe. This seems to be showing that dynamically cold disks are more common in the early Universe than expected from simulations. This, as well as JWST imaging, is building a picture of galaxy disks often being in place at high redshift.

1.2 What is the nature of dark matter and dark energy?

Understanding the Universe, its composition and the physical laws that govern it, is a challenge that has attracted significant effort from Australian astrophysicists in the last decade.

The first results from the Planck satellite came out at the beginning of the decade. While these results ushered in a new era of precision on cosmological constraints from the early Universe, they also exposed the signs of tension in the LCDM model between (1) the current expansion rate inferred from the distance ladder (the Hubble tension) and (2) the amount of structure (the S8 tension), especially when the CMB data is combined with baryon acoustic oscillation (BAO) measurements. Over the decade, these tensions have persisted and have shown up in multiple experiments, while slowly increasing in significance as the observational uncertainties have improved. There has been significant interest in and development of alternative observational probes to seek competitive constraints on the Hubble constant independent of the distance ladder, such as gravitational wave sirens. The observations underpinning these tensions have come from large international collaborations, to which Australian astronomers are contributing for key science areas. The tensions have also sparked a wide-ranging zoo of hypotheses, from theorists in Australia and around the world, for how the dark sector might be modified to explain the observations, though as yet none have clearly solved the tension.

Beyond the Hubble and S8 tensions, there are a number of lower significance hints in data about physics beyond the standard cosmological model. While none has exceeded 5 sigma significance (unlike the Hubble tension), these may be the first signs of needing a more complicated dark sector than a cosmological constant and cold dark matter. Of special note is the aligned preference of recent SNe Ia results from the Dark Energy Survey (DES) and BAO results from the Dark Energy Spectroscopic Instrument (DESI) (Australians are part of the DES and DESI teams) for a time-varying dark energy equation of state when combined with CMB power spectra and lensing measurements from Planck and ACT experiments. All three of these observations are expected to see significant improvements in the coming decade, with more data coming for DESI, VRO about to begin for SNe (with spectra from 4MOST), and Simons Observatory beginning for CMB. Australia has helped build VRO and 4MOST, and Australian astronomers are deeply involved in the DESI and Simons Observatory collaborations. The combination of SNe, BAO and CMB currently prefers a time-varying dark energy equation of state at 3.9 sigma, raising the extremely exciting prospect that we are close to having conclusive evidence that dark energy is not a cosmological constant.

There has been substantial work in Australia on theory and phenomenology, both to elucidate more precisely the predictions of models for dark matter and dark energy in advance of next decade’s experiments and to see if reasonable models can be constructed to explain the observational tensions that have shown up already. This work has also extended to improving simulations, with advances to increase simulated volumes, to add more accurate descriptions of physics as well as considering models of dark energy and dark matter beyond LCDM, and to incorporate observational effects to more accurately compare theory to data.

Despite not yet knowing the nature of dark matter particles, improved constraints have been made in this area. Gamma-ray facilities like Fermi-LAT and HESS are testing a range of particle models (e.g. WIMPS), paving the way for the next generation facilities. There has also been progress on the ground, working towards direct detection of dark matter candidates, an area that has built linkages between the Australian astronomical and physics communities. Over this decade, these efforts have advanced new limits on axions using axion haloscopes like the ORGAN experiment in Perth. Construction has been completed on a new underground laboratory in Victoria to house the SABRE experiment, seeking to provide an independent confirmation of the reported detection by DAMA. Much of this direct dark matter detection work in Australia has been driven by the ARC Centre of Excellence for Dark Matter Particle Physics.

1.3 How do galaxies form and evolve across cosmic time?

Understanding galaxy formation is a multiscale, multiphase challenge and has been a significant focus across the Australian community from both theoretical and observational perspectives.

Galaxy formation simulations globally have seen consortia run simulation suites each using tens to a few hundreds of millions of CPU hours. These have led to substantial improvements in matching simulated data to observations, but there remains a gap in scales, with all cosmological simulations needing to provide sub-grid prescriptions for physics below their resolution limit. While there has been progress on closing this gap, it remains significant and will not be bridged any time soon.

Australian theory developments have proceeded in a number of directions, including development of new semi-analytical galaxy formation models (including separate models that focus on cosmological galaxy formation and on how the first galaxies impact reionization); detailed modelling of feedback, including AGN jets; new approaches to modelling the multiphase ISM; studies of discreteness and resolution that clearly expose the limitations of simulations; and code development that enables more direct comparison between observations and simulations. Over the last decade, stronger connections have been made between theorists and observers, leading to more rigorous approaches to testing galaxy formation models. Note that more discussion of theory is contained in the report by WG 1.4.

Australians have continued to be leaders in extragalactic research across the last decade. Much of this leadership has been through observational programs such as GAMA, SAMI and the new Hector Survey (all using the Anglo-Australian Telescope), as well surveys at radio wavelengths (e.g. GLEAM using MWA). Combining both integral field spectroscopy (IFS) and highly multiplexed single fibre observations has been critical to connecting internal galaxy properties to their large scale environments; for example, detecting galaxy spin alignment with large-scale structure and understanding the relationship between structural change and star formation. A combination of structural decomposition and multiband photometry has enabled an inventory of bulges and disks in the local Universe.

In the last decade new observational programs have also started to push out to higher redshift both with single fibres (e.g. DEVILS using the AAT) and IFS (e.g. MAGPI using MUSE on the VLT). These projects are starting to help us understand the details of transitions that happen in the galaxy population between z~0 and 1. At the same time, instruments like MUSE have enabled higher resolution studies of nearby galaxies (e.g. GECKOS and MAUVE surveys), and these data sets will continue to be exploited into the next decade. Higher resolution observational studies have also started to bridge the gap between extragalactic research and properties of our own Milky Way.

ASKAP's main surveys (e.g. WALLABY and EMU) are in full operation, starting in 2022. Much work prior to this at radio frequencies over the last decade has focussed on building spectral line data sets to understand the nature of the cold ISM in galaxies, largely based on integrated quantities. ALMA has also revolutionized the studies of molecular gas in galaxies, although Australians have not been able to lead major programs due to a lack of direct access.

Understanding feedback from stars and AGN continues to be a major focus for both theory and observation. Simulation work is attempting to get closer to observations of radio emitting jets from super-massive black holes that are ubiquitous in wide field radio continuum surveys. Studies connecting radio and gamma-ray emission have been valuable to help understand the non-thermal emission of AGN. Studies in the optical and infrared continue to examine the evolution and impact of luminous active galactic nuclei.

Recent JWST observations have opened a new window on galaxies at high redshift. Spectroscopy is now identifying 1000s of galaxies in this epoch, and imaging has surprised us by showing that many disk galaxies have spiral arms and bars that appear similar to those in the local Universe. Understanding why this is the case will be an important question going forward.

1.4 How do stars and planets form?

While some of this topic is outside the scope of WG 1.1 (and is covered by WG 1.2), star formation is undoubtedly central to galaxy formation. The environment and physical state of a galaxy can strongly influence star formation. Integral field spectroscopy in the infrared (e.g. the KMOS instrument on VLT) has demonstrated that gas ionized by star formation at high redshift is more turbulent than in local galaxies. The same picture is also seen in molecular gas, (e.g. from ALMA), but the dispersion in molecular gas is lower.

Australian led theoretical research has helped us to better understand how molecular gas collapses to form stars, and in particular the roles of turbulence, magnetic fields, dust, metallicity and cosmic rays. Another focus has also been on how feedback processes (e.g. outflows, radiation pressure) modulate star formation. This work has led to a deeper understanding of star formation efficiency and the origin of the turbulence and magnetic fields in star forming galaxies.

Large statistical samples of galaxies from Australian-led surveys (e.g. GAMA and DEVILS), coupled to multi-band imaging data, have allowed spectral energy distribution (SED) analysis to characterize star formation histories. This has also allowed improved measurements of the cosmic star formation history. An important enabling technology for this work is Australian software tools (MAGPHYS, ProFound, ProFit etc) that have been made publicly available. Large integral field surveys in the local Universe (e.g. the Australian led SAMI Galaxy Survey) allow a spatially resolved view of star formation in galaxies on ~1 kpc scales. Star formation in galaxies at higher resolution has been explored by numerous studies using integral field spectrographs such as MUSE on the VLT.

1.5 How are elements produced by stars and recycled through galaxies?

The understanding of metal production has progressed substantially in the last decade. We now have a largely complete inventory of metals, probed via absorption lines, solving the so-called “missing metals problem”.

Metals are thought to get into the circumgalactic and intergalactic medium (CGM and IGM) through outflows driven by energy injection from star formation and/or accreting super-massive black holes. In the last decade, outflows have been identified at high redshift through ionized gas (e.g. using KMOS on VLT). Characterizing cooler gas outflows is harder, even though most of the gas is expected to be in this phase. ALMA is making breakthroughs here, detecting cool outflows. JWST has also been breaking ground in this field, detecting outflows in neutral gas absorption from sodium. JWST spectroscopy has also revealed very early nitrogen enrichment in the first galaxies, possibly requiring exotic mechanisms such as pair-instability supernovae or hypernovae. Despite this, large questions remain concerning feedback and outflows, including detailed energy injection mechanisms and how and when baryons cycle back into galaxies.

Australian-led programs collaborating with Subaru Hyper Suprime-Cam (e.g., SHIZUKA) and analysis of other multi-year, deep imaging surveys (CFHT and DECam) and Australian Keck spectroscopic programs have detected and confirmed core-collapse and super-luminous supernovae at $z > 2$, along with pair-instability supernova candidates. This work has lent insight into the star formation rate, chemical enrichment and element ratios in early galaxies, along with galaxy outflows and impact on reionisation, and have trail blazed new methods to detect these events to $z \sim 10$ and higher with NASA Roman and JWST.

Fast Radio Bursts (FRBs) have solved the missing baryons problem, using the Macquart relation between redshift and dispersion measure to estimate the density of baryons in the intergalactic medium. Key to this is associating FRBs with optical galaxies to obtain redshifts, which has been made possible with the current access to the 8m VLT (e.g. the FURBY large program using MUSE). The presence and structure of gas containing these missing baryons are now being revealed in the cosmic web, and around galaxy clusters and groups, through Faraday rotation measurements generated by embedded magnetic fields. These measurements are enabled by Australian-led radio polarization surveys such as POSSUM on the ASKAP radio telescope, as well as by LOFAR.

2 Questions for the new decade

The four questions below capture the key science themes that will be critical in the coming decade. For each, we discuss potential issues and the resources required to address the questions. At the end of each subsection, we list the key capabilities and supporting capabilities to enable the science.

2.1 What regulates the star formation process from parsec to gigaparsec scales?

Understanding how and when stars form is central to a physical theory of galaxy formation. The challenge is that star formation is inherently a multiscale problem, with the direct formation of stars happening on very small scales (sub-parsec), while star formation rates are modulated by structures within galaxies (e.g. on kiloparsec scales) and by their large-scale environment (on megaparsec and greater scales). Star formation involves multiple phases. Hot ionized gas can cool to atomic gas, and then, when sufficiently dense and cool, also form molecular clouds.

These molecular clouds are the locations of star formation. When hot young stars form, they ionize surrounding gas to form HII regions. The stars themselves emit light mostly in the ultraviolet, optical and near-infrared wavelengths, which is also where ionized gas is most readily visible via emission lines. Atomic gas can be seen at radio wavelengths via the HI 21cm line, and molecular gas is most easily seen at mm wavelengths (e.g. through CO).

The next decade has the potential to provide a much more complete picture of star formation, if we can overcome the multiscale and multiphase challenges through theory and observation. Progress will come through combining atomic gas 21cm radio data (from ASKAP and then SKA-mid) with molecular gas (from ALMA, and beyond the next decade with next generation telescopes such as the proposed single dish Atacama Large Aperture Submillimeter Telescope, AtLAST) and optical data (particularly integral field spectroscopy from 8m class telescopes, and then 30m class telescopes later in the decade). Major programs led by Australians (particularly using ESO/VLT facilities) will connect these phases of star formation at the sub-kpc scale, as will deep narrowband imaging (with the Keck Wide-Field Imager, KWFI) of the Milky Way and nearby galaxies. On larger scales, a deeper understanding of environmental modulation of star formation will be afforded by a combination of deep, highly complete spectroscopic redshift surveys (e.g. from 4MOST), that will provide the most rich, multidimensional, measure of environment, and large multiplexed integral field surveys of local galaxies (AAT/Hector). Beyond the end of the decade, deeper probes of galaxy environment will be possible with a 10-12m class wide field spectroscopic survey telescope, such as ESO's proposed Wide Field Spectroscopic Telescope (WST).

A key issue is to understand why we see higher turbulence in ionized gas in high redshift galaxies, and how this maps to the stellar populations we see around us today. Turbulence has mostly been measured in relatively high mass, distant galaxies to date, but next generation facilities on 30m-class telescopes will be able to push down to lower mass galaxies, where feedback from star formation is expected to be much more significant. With the largest apertures and adaptive optics, we will be able to make high quality measurements of stellar kinematics to directly couple the motion of gas and stars in the high redshift Universe. Expanded data sets at mm wavelengths will also be crucial to characterize molecular gas, using ALMA (including upgrades). JWST will be central to understanding star formation at the highest redshifts, looking at questions such as how massive galaxies quench early.

A paradigm shift that will be possible in the next decade is the ability to resolve individual stars within galaxies beyond the Local Group. This is important as almost all analysis of galaxies is currently based on data that cannot resolve individual stars. Resolving individual stars allows the measurement of colour-magnitude diagrams to directly see the stellar populations with much less degeneracy in the derived physical properties. This is particularly vital for passive early type galaxies that are expected to have had very different star formation histories to our own Milky Way. The Australian built adaptive optics fed MAVIS on the VLT will have sufficient resolution to image external galaxy stellar populations. Integral field spectroscopy on 30m class telescopes (ELT/HARMONI and later GMT/GMTIFS) will have sufficient sensitivity to also obtain spectra of individual stars beyond the Local Group.

A key theoretical approach in this area is to continue to expand the complexity of simulations of star formation, so we can more fully understand the roles of turbulence, magnetic fields, cosmic rays and other processes. Australia has a strong track record in this area that needs to continue to be supported with new code development and major allocations of supercomputer time. A core long term aim is to increase the scale of these simulations to bring them closer to the cosmological-scale simulations used to examine galaxy evolution. Fully connecting to experimental results will require continued effort to improve how we map simulation results to multiphase observations.

Key capabilities: 8m and 30m class telescopes, ALMA, ASKAP, SKA-mid, JWST, multiscale and multiphase high-resolution simulations.

Supporting capabilities: AAT, 4MOST

Key new capabilities beyond the decade: WST/MSE, GMT, AtLAST

2.2 Understanding galactic ecosystems: what are the internal and external processes that shape galaxies and their surroundings?

We are now very far from thinking of galaxies as “island universes” that evolve as separate entities. Galaxies sit in a complex web of large-scale structure. Their growth and evolution are dependent on gas flowing in and out of them, fuelling star formation and supermassive black holes, and distributing heavy elements into the intergalactic medium (IGM). Interactions and mergers between galaxies shape the distribution of both gas and stars. The coming decade promises exciting progress in this field, from a number of directions.

Characterizing structure within galaxies is central to understanding this question. Major progress can be made in at least two different directions. The first is through kinematic measurements across multiple wavelengths from the optical and IR (stars and ionized gas with 4m and 8m class telescopes), to the mm (molecular gas with ALMA) and cm (atomic gas with ASKAP and SKA-mid). Bringing these measurements together, for example, AAT/Hector stellar and ionized gas kinematics and ASKAP 21cm HI will be important. The AAT Hector survey will be completed in the first half of the decade, along with the first generation of ASKAP surveys. For detailed studies in the local Universe and pushing to higher redshift, 8m and 30m integral field spectroscopy will be crucial, as will JWST at the earliest epochs. Access to 8m and 30m facilities will be crucial if Australia is to maintain its leadership in this area, building on current leadership of major programs using VLT/MUSE such as MAGPI, GECKOS, MAUVE and FURBY.

The second area that will lead to major progress in understanding galaxy structure is wide-field high resolution imaging in the optical/IR from space based telescopes, such as Euclid and

Roman. With HST-like imaging over a large fraction of the sky, our ability to structurally decompose galaxies will be massively enhanced. JWST is already changing our view of galaxies in the early Universe, with many more disks (including spiral arms and bars) being found than previously expected, and it will continue to be at the forefront of high redshift studies into the foreseeable future. VRO will also provide deep ground-based imaging across most of the Southern Hemisphere that will be powerful for structural analysis of galaxies, including in combination with space-based data from Euclid and Roman. VRO imaging will also be used to estimate photometric redshifts.

Crucial to understanding galactic ecosystems is a rich and detailed measurement of galactic environments. This has to go beyond just statistical measurements of local over-density, and include a multi-parameter assessments of environment, such as halo mass, location of galaxies within filaments and sheets, the classification of galaxies as centrals or satellites, and measurements of intra-cluster and intra-group gas in X-rays (e.g. eROSITA and in the future next generation facilities such as Athena) and via Faraday rotation in the radio band (e.g. the POSSUM survey on ASKAP). Below z=1, the 4MOST facility with the Australian led 4HS and WAVES surveys will provide these measurements, while at earlier epochs slitless spectroscopy from space (Euclid and Roman) as well as infrared spectroscopy from the ground (using instruments such as MOONS on the VLT) will be required. Another aspect of environment is tracing light from stars stripped off galaxies during mergers and interactions. These are visible as streams, shells and faint intra-cluster light. VRO will provide a powerful new window onto the low-surface-brightness Universe to characterize the light at and beyond the edges of galaxies.

Feeding and feedback remains central to our understanding of galaxy formation. Theoretical galaxy formation models need feedback from both star formation and AGN to form galaxies that look like those we see around us, but we still lack details in many areas. Solving feedback is a highly nonlinear problem involving a range of gas phases and scales. From a theoretical point of view, we need to close the gap between small-scale idealized simulations and larger-scale cosmological simulations. The latter incorporate sub-grid models to emulate processes below their resolution limit. To inform theory, detailed multiphase observations are needed. Again, this drives a requirement for observations in the optical/IR (stars and ionized gas), sub-mm (molecular gas) and radio (atomic gas). Non-thermal emission can effectively be probed at radio (ASKAP and SKA continuum) and gamma-ray (CTAO) wavelengths. These observations need to drive in two different directions. First, they need to probe high spatial resolution to understand the detailed physical coupling between phases. Second, they need to also push to higher redshift, as some feedback processes are extremely rare or non-existent in the local Universe. Key facilities will be integral field spectroscopy on 8 and 30m telescope (including VLT/MAVIS), ALMA, ASKAP/SKA-mid and JWST. Similar resources are needed to better understand the flow of gas into and through galaxies.

Stars produce heavy elements and feedback distributes them through galaxies and into the circumgalactic medium (CGM) and intergalactic medium (IGM). The low density of CGM and IGM gas means that it is often hard to detect it directly in emission, so observations based on absorption are often used. Powerful new tools to do this have recently become available, with

Fast Radio Bursts (FRBs) providing a probe of the previously “missing baryons” in the IGM. Additionally, Faraday rotation measure (RM) grids, where RMs are measured towards background radio sources back-illuminate magnetized gas in the foreground, offer a complementary approach by mapping the magnetic fields in these diffuse regions, further revealing their extent and structure. Following up on large samples of FRBs and utilizing these rotation measure grids will be central to this work in the next decade. Other absorption studies, using HI in the radio, have become more effective with wide field of view radio telescopes (e.g. ASKAP). Deep high resolution spectroscopy in the optical and IR will continue to be a powerful technique to push absorption studies to high redshift with the largest telescopes (8m and 30m). However, the development of the Australian-led Keck Wide-Field Imager and its extreme blue/UV sensitivity over wide fields will enable direct detection and mapping of CGM and IGM gas in emission. This can be done with narrowband imaging to detect faint diffuse Lyman alpha emission. Combining these data with those via absorption will form a more complete picture of the CGM and IGM. These observations have to be made in tandem with improved theory to understand the phase-space distributions of gas and dark matter in and around galaxies.

The dynamical impacts of magnetic fields in galaxies have been widely appreciated, yet it has proven challenging to observationally characterize the strength and structure of these fields. Over the coming decade, we can expect significant advancements in this area, with crucial data in radio polarization being delivered by the Australian-led POSSUM survey of ASKAP. Moreover, numerical simulations at all scales—from local patches of galaxies to galaxy-scale and cosmological-scale—are now regularly including magnetic fields to study their impact on galactic dynamics and the broader cosmic ecosystem. Importantly, magnetic fields play a critical, yet poorly understood, role in the dynamics of the circumgalactic medium (CGM), intergalactic medium (IGM), and gas within galaxy groups and clusters. Radio polarization surveys like POSSUM are beginning to probe the presence and structure of these magnetic fields, shedding light on their influence beyond galaxies. It will be vital for Australia to maintain its leading position in magnetism research with the SKA-mid and SKA-low telescopes, complemented by state-of-the-art numerical simulations. Only by jointly considering magnetic structures (from radio polarization observations and magneto-hydrodynamic simulations) alongside their gaseous (from HI, CO, IR, and optical) and stellar (from IR and optical) counterparts can we fully comprehend the astrophysical processes that shape galaxies and the larger cosmic web.

Key capabilities: 8m and 30m telescopes, AAT (till 2030), ALMA, ASKAP, SKA-mid, 4MOST, Euclid, Roman, JWST, multiscale and multiphase simulations.

Supporting capabilities: SKA-low, eROSITA, VRO, CTAO

Key new capabilities beyond the decade: WST/MSE, GMT, Athena, AtLAST

2.3 What is the physical nature of galaxies and the IGM during the EoR and Cosmic Dawn?

In the next decade, studying the epoch of reionization (EoR, z=6-10) and Cosmic Dawn (CD, z=10-30) will offer exciting opportunities for new discoveries. Progress will focus on two key areas: (1) direct detection and exploration of reionization by observing the intergalactic medium (IGM) using the HI 21cm signal and ionized gas in the UV; and (2) characterizing the first galaxies formed in this epoch, building on discoveries from JWST.

Building on MWA, SKA-low will be the key facility for direct EoR detection and imaging in the next decade. The high angular resolution, excellent surface brightness sensitivity and high sensitivity afforded by SKA-low will give us the best chance of improving on systematic limits that currently inhibit us from detecting the EoR in 21cm HI. Detection and exploration of the first billion years with 21cm and SKA-Low is one of its highest priority science goals. In the lead-up to SKA-Low full operations, the upgraded MWA will continue to be Australia’s front line telescope, alongside activity from SKA-Low Array Assembly 2 onwards. A powerful complement to SKA mapping neutral gas at this epoch is very deep wide-field optical mapping of ionized gas using the Australian-led Keck Wide-Field Imager that is sensitive to the extremely faint Lyman continuum flux, as well as other ionized gas in emission. MWA, ASKAP, Euclid and Roman can be used to detect radio-loud quasars within the EoR. These quasars have the potential to allow absorption detection of the EoR. Another opportunity exists to detect helium reionization that occurs at a lower redshift (z~3), by measuring the 8.66GHz transition of HeII, using SKA-mid. An alternative route to helium reionization is via fast radio bursts as probes, if they can be found in sufficient numbers at around z~4. This should be possible with SKA. Efficient and reliable HPC will become increasingly important for 21cm EoR data sets as SKA-low becomes operational.

The first observations with JWST have led to many questions about the galaxy population during the EoR and cosmic dawn. These include: understanding the nature of ultra-faint galaxies and their role in reionization; is there a higher density of AGN than previously thought? How, in detail, does early nucleosynthesis happen? How is dust built up during the EoR, particularly before AGB stars are dominant? Is there a consistent picture for massive z~10 galaxies? JWST will remain unique in the next decade for its ability to probe this early epoch. However, alternative probes of star formation may come from the detection of individual super-luminous SNe and gamma-ray bursts in the EoR epoch (for example from deep surveys such as Euclid Deep). While JWST is open access, it will be important that Australian astronomers can effectively compete for time. ALMA is the second facility crucial for probing galaxies in the EoR epoch. ALMA can directly see dust emission as well as various atomic, molecular and ionized lines. This also allows spatially resolved kinematics, which is important for understanding the structure of galaxies at these epochs. Development of upgrades to ALMA may provide opportunities for Australian industry, given the expertise in receiver technology held by CSIRO.

Ground based facilities that push into the infrared with high spatial resolution and high sensitivity will also be able to characterize galaxies during the EoR. Infrared imaging and integral field spectroscopy from instruments like MICADO and HARMONI on the ELT will be world leading in this area, with sensitivity comparable to JWST, but with higher spatial resolution, thanks to adaptive optics. 8m class telescopes will also be able to contribute, particularly with adaptive optics.

Although not directly probing the EoR, targeting galaxies at z~3-5 should help us to understand features of reionization by detecting galaxies producing escaping ionizing Lyman continuum radiation. This work must be done at redshifts z~3-5 because the Universe is opaque to Lyman continuum flux at z>5 and the Earth's atmosphere prevents study below z~3. Understanding the mechanisms behind the escaping flux and connecting other galactic properties observable at z > 6 to the escape fraction is needed in order to progress this field. To be observed from Earth, Lyman continuum flux requires rare, transparent sight lines and appears extremely faint, requiring very sensitive, wide field instruments. Useful tools here will be wide field imaging, including extremely deep u-band (e.g., the Australian led Keck Wide Field Imager), infrared (e.g., Roman) and narrow and wide field spectroscopy (e.g., VLT, Keck, WST, MSE).

Key capabilities: JWST, MWA, SKA-low, ALMA, 30m telescopes, 8m telescopes.

HPC capabilities: large-scale HPC and storage; use of AusSRC and SRC network

Supporting capabilities: ATCA, ASKAP, Euclid, Roman, SKA-mid, Line intensity mapping facilities

Key new capabilities beyond the decade: GMT, far-side of moon radio facilities

2.4 The Universe as an experiment: searching for new particles and new physics

The Universe provides the ultimate experiment for addressing many fundamental issues in physics. These issues include the nature of dark matter, the properties of neutrinos, the driving force behind cosmic acceleration, understanding whether general relativity is a good description of our Universe, and the role and nature of cosmic inflation. The last decade has seen a growing connection between fundamental particle physics and cosmology. The coming decade should lead to furthering this connection and has the potential to provide breakthroughs in addressing fundamental questions.

Dark matter is fundamental to our understanding of galaxies, with dark matter dominating gravitational collapse. Dark matter haloes form, and baryons collapse within them to form galaxies. The main challenge is that we don't know what dark matter is actually made of. Dark matter particles could be weakly interacting massive particles (WIMPs), light axions or other exotic particles. The Cherenkov Telescope Array Observatory (CTAO), of which Australia is a member, will be operational in the next decade and be an order of magnitude more sensitive to gamma rays than previous telescopes. This will enable exploration of dark matter candidates, such as searches for annihilation signatures of WIMPs and tests for axion oscillations with gamma rays from distant active galactic nuclei. Improved constraints are expected from various laboratory-based direct detection experiments (including in Australia), but will not be directly discussed here. However, improving links between the astronomy and physics communities is to be encouraged, aided by ARC Centre of Excellence for Dark Matter Particle Physics and the joint chapter of the Astronomical Society of Australia (ASA) and the Australian Institute of Physics (AIP): the Group for Astroparticle Physics.

There are various other astrophysical routes to constraining the nature of dark matter. One example is from deep and complete galaxy surveys, such as WAVES and 4HS with 4MOST that allow the construction of halo mass functions. The halo mass functions should allow tests of whether dark matter is "warm", as the warm dark matter removes structure on small scales. Another route to this question is via velocity functions using HI data from ASKAP and then SKA-mid.

While neutrinos cannot make up the majority of dark matter, they do have a noticeable effect on the formation of structure, inducing a suppression of structure below the neutrino free-streaming scale, that depends on the neutrino mass. Thus, measurements of large-scale structure allow estimates of neutrino masses and forecasts combining upcoming CMB and LSS experiments predict that by the end of the decade we will be able to detect the neutrino mass at $> 3\sigma$ for the minimum mass allowed by neutrino oscillations.

We have an accurate estimate of the current dark energy density, and know that it looks approximately like a cosmological constant. However, we are still some way from understanding its nature. There are intriguing tensions in current observations, such as the Hubble tension between local measurements of the Hubble parameter and values estimated from large-scale structure and the CMB. A second tension is the so-called S8 tension, related to the normalization of the power spectrum. Recently, DES and early DESI results have hinted at dark energy not being a cosmological constant, but having an evolving equation of state. We may be at the cusp of breaking the Lambda CDM paradigm and forcing a replacement or expansion of our current cosmological model, leading to new physics.

Experimental results in the next decade will be driven by large international programs, most of which have Australian involvement. From the ground optical imaging (VRO) and spectroscopic (DESI, 4MOST) programs are ongoing or about to start, with the number of spectroscopic redshifts increasing by an order of magnitude. SKA will measure large-scale structure using HI intensity mapping up to $z \sim 5.5$ (SKA-mid and SKA-low). These optical and radio measurements will be able to test for primordial non-Gaussianity and so give us a view of the early inflationary phase of the Universe. These large-scale structure measurements will also place tighter constraints on dark energy, dark matter and the neutrino sector. Sampling the large scale structure of the Universe using different tracers will be important to reduce systematic biases that can impact tracers in different ways. Combining methods, such as BAO and redshift space distortion, is also vital. Australia has some unique aspects of leadership here, particularly using peculiar velocities in the local Universe to estimate growth of structure (e.g. ASKAP/WALLABY, 4MOST/4HS).

Several space based projects will operate in the coming decade, including Euclid, Roman and SPHEReX. Australians will have access to these, as the data will be quickly made public. Modest investments to facilitate access to this and other large international data sets would be valuable.

The discovery of gravitational waves in the past decade has opened up a valuable new window for cosmology. Gravitational wave events caused by the merger of compact bodies (BHs or NSs) can act as "standard sirens" allowing an estimate of distance and hence expansion rate that is independent of the cosmic distance ladder. Key to this will be follow-up of the next generation of GW sources to characterize them and measure redshifts, likely needing 8m class telescopes. There are also alternative routes to using GWs for cosmology via "dark sirens", without a direct redshift measurements of the host galaxy. These approaches include cross-correlation with galaxy catalogues, breaking the distance-redshift degeneracy through tidal interactions of the binary or dark sirens, where the degeneracy is broken through understanding the underlying system's mass distributions (so-called spectral sirens). Complete and deep spectroscopic galaxy redshift surveys will be a valuable resource for GW cosmology. Beyond the next decade, Australia should engage with next generation gravitational wave observatories such as the Cosmic Explorer, Einstein Telescope or a Southern Hemisphere GW observatory hosted in Australia.

Various CMB projects will be making higher precision measurements in the coming decade (e.g. Simons Observatory, SO; South Pole Telescope, SPT). The CMB measurements are especially important for learning about the neutrino sector, searches for new particles, and the inflationary epoch. These are again international projects, not led by Australia, but opportunity for Australian involvement would be valuable, possibly by individual researcher buy-ins.

Further increases in precision will be made through next generation facilities across all wavelengths that will be planned and designed through this decade for operations in future decades. Examples of proposed experiments for the next decade include ESO/WST or MSE (neither yet fully funded). It will be crucial to support instrumentation development work through this decade for future facilities in key science areas, in recognition that instrumentation work this decade will enable Australian science leadership in the next decade. Maintaining meaningful leadership in the next generation of facilities will be important to Australia's future astronomers.

The ability for Australian researchers to fully engage in these long term projects (5-10 years) is critical to be at the forefront of cosmology research. This can be in tension with the often short term cycle of ARC grant schemes. Routes that provide reliable long term funding would be particularly valuable here.

Key capabilities: 4MOST, DESI, SKA-mid, SKA-low, Euclid, Roman, SPHEReX, VRO, LIGO-Virgo-KAGRA, CMB SPT/SO, CTAO.

Supporting capabilities: 8m telescopes, ASKAP

Key new capabilities beyond the decade: WST/MSE, CMB-S4, Cosmic Explorer and/or Einstein Telescope, LISA

3 Strengths in the community

The Australian community has considerable strengths in the fields of extragalactic astronomy and cosmology. This is demonstrated by leadership across a range of key programs in the last decade, such as GAMA, SAMI, OzDES, DEVILS and Hector with Australian facilities. Australia is leading a number of ASKAP surveys, such as WALLABY, EMU, POSSUM, DINGO and FLASH. Australian's also have leadership in HI observations of the EoR with MWA. In the last few years, Australia has been highly effective at exploiting the strategic agreement with ESO, leading the large programs MAGPI, GECKOS, MAUVE and FURBY with MUSE/VLT. Australian leadership is set to continue in various areas through leadership of international programs, particularly the WAVES and 4HS 4MOST surveys.

An important aspect of the leadership within Australia is how the development of instrumentation technology works with and enables major science programs. For example, the AESOP fibre positioner for 4MOST; the SAMI and Hector instruments on the AAT and of course, development of the ASKAP and MWA telescopes. Into the future, instruments such as MAVIS/VLT and Keck Wide-Field Imager give the opportunity for ongoing leadership. Likewise, Australia has significant leadership in radio instrumentation, through development of ASKAP and MWA, leading towards SKA.

Over the last decade, the ARC Centres of Excellence (CoE) program has enabled effective support of many of the major science projects listed above, with CAASTRO, ASTRO3D, OzGRAV and OzGRAV2. A crucial aspect of support from CoEs has been consistent funding across programs that have lifetimes of 5+ years.

The Australian community plays an important role in the international GW community, not only working as part of the LIGO-Virgo-KAGRA collaboration, but also delivering key technologies for current and future upgrading stages of LIGO, e.g., squeezed light, coatings of the optics, thermal compensation systems, experimental prototypes, etc. Australia is also strong in terms of GW data analysis, search techniques, astrophysical inference, etc, including cosmological analyses of gravitational-wave sources that will become relevant in the coming five years as the number of observations explodes because of the improved sensitivity of the instruments.

Australia has also managed to gain leadership in JWST programs, thanks to the telescope's open skies policy and significant expertise in relevant areas. Buy-ins to various projects have enabled engagement with international programs such as VRO and DESI for a subset of the community. Australia’s engagement in the CTAO enables influence and potential leadership roles in its various Key Science Programmes tackling cosmological challenges.

A broad Australian strength is the strong international links. Essentially all the major programs listed above have significant international collaboration. The title of the last decadal plan was “Australia in the era of global astronomy”. This has truly come to fruition, but will take effort to maintain as an increasingly high fraction of key projects become global in nature.

The theory community is one area where strong international collaboration is vital, as on-shore facilities do not have processing resources to carry out large-scale simulations that are competitive globally. The Australian theory community has been successful through developing world-leading experts in high-resolution (zoom and idealized) simulations of small-scale processes (star formation, turbulence, magnetic fields, cosmic rays, mixing, jets, radio galaxies, etc), as well as in cosmological simulations of galaxy formation.

4 Areas in need of development

As projects become larger in scale, they take longer and need long term support to function effectively. This includes both astronomers and other experts such as programmers, engineers and data scientists. ARC CoEs have provided some of this support, but without CoE funding, projects can often struggle to keep experts in place for the full length of the project. This has been made more challenging by the reduced success rate for ARC DPs, so a sustainable increase in DP funding would be of great benefit.

HPC is an increasingly important requirement for both theory/simulations and data processing. While there have been specific developments to aid processing from ASKAP, particularly the Pawsey Supercomputing Centre, the availability of adequate HPC has continued to significantly delay ASKAP and MWA processing. This challenge will only become greater with the operation of SKA. The Australian SKA Regional Centre (AusSRC), as Australia’s component of the global SKA SRC network, is funded until SKA full operation for pipeline development. There will need to be additional HPC available to support the processing and storage of radio data through the SRC.

International scale simulations of galaxy formation and evolution need tens to hundreds of millions of CPU hours to be competitive. The previous astronomy decadal plan listed a goal of large-scale computing equivalent to roughly one-third of a machine in the “top 100” list of (publicly known) world supercomputers. Current resourcing is well short of this goal, and this should remain a goal in the coming decade. Another approach would be the development of a world leading novel code that can address key current problems by incorporating missing physics in galaxy formation and evolution.

5 Opportunities

The next decade holds rich opportunities, with major new facilities coming online that will profoundly change our understanding of the Universe. The first 30m class telescope, ESO's ELT, is planned to have first light in 2028. SKA-mid and SKA-low are planned to be completed in 2029. VRO will start operations in 2025, as will the 4MOST spectroscopic surveys. Full operations of CTAO are expected from 2029/30, but some of its Key Science Projects will commence earlier as the array is completed.

As well as major telescopes/facilities, the next decade promises a suite of new instrumentation on existing telescopes, for example MAVIS, MOONS and BlueMUSE on VLT; ULTIMATE on Subaru; and the Wide-Field Imager on Keck. This instrumentation will provide a range of unique capabilities. It is worth noting that as instrumentation becomes more complex, different observatories provide different capabilities, and so careful consideration of the alignment of facilities with the Australian community is important. Instrumentation teams usually obtain guaranteed time to carry out major early programs, giving them a scientific advantage in exploitation of new capabilities.

One particular instrumentation capability likely to be powerful in the next decade is adaptive optics, reaching close to the diffraction limit on 30m class telescopes. This will enable a range of science cases, from exploration of resolved stellar populations in nearby galaxies to characterizing the first star clustering in the early Universe.

The sensitivity and resolution of SKA and ALMA will mean that much progress will be made in our understanding of multiphase gas. SKA in particular will resolve atomic HI outside the local Universe. Upgrade paths to ALMA will make this link even more powerful (and may have a role for Australia technology). In addition, for both facilities, the polarimetric capabilities will reveal the magnetic structures in and around galaxies.

In many cases, combining SKA with other wavelengths will be vital. One example (of many) is the use of FRBs to probe the intergalactic medium. While detected by radio telescopes, optical/IR facilities (in particular spectroscopy on 8m class telescopes) will be required to obtain redshifts and characterize FRB hosts.

Next generation GW measurements (e.g. upgraded LIGO-Virgo-KAGRA) also promise a new view of the Universe, for example, as "standard sirens" for cosmology. Again, this requires optical/IR spectroscopy to confirm redshifts, yet another example of the need for multi-wavelength and multi-messenger facilities. Australian involvement in LIGO-Virgo-KAGRA and related research is vital.

The open access or fast public release of data from space missions (e.g. JWST, Euclid, Roman) provides an excellent resource for Australians, and means that Australian astronomers will increasingly be working with data from space.

Development of major spectroscopic survey telescopes with 8-10m apertures are currently underway (e.g. WST by ESO; MSE by the CFHT consortium). These projects are currently in the concept study phase, but will provide game-changing facilities beyond the current decadal plan. Australian engagement in development of these during the coming decade will enable leadership.

Developments over the next decade will lead to an expansion of Australian research focussed on particle astrophysics. This includes direct dark matter detection experiments (e.g. driven by the ARC Centre of Excellence for Dark Matter Physics), as well as neutrino observatories such as IceCube and KM3Net which both have Australian involvement. Continuing to build connections between the strong Australian astrophysics and particle physics communities would be valuable.

Since the last decadal plan, Australia has taken the positive step of creating a national space agency. Currently, this focuses on growing the commercial space industry. While astronomy projects can be framed in the context of industry growth (e.g., the recently launched SpIRIT mission for high energy astrophysics), space agency support for scientific space missions would align the Australian Space Agency to its international peers and offer the astrophysics and planetary science community the opportunity to sustainably establish and maintain space instrumentation national capabilities.

6 Threats

The governance of optical astronomy has changed significantly in the last decade. As part of the agreement for the strategic partnership with ESO, the AAT became operated by a consortium of Universities and the instrumentation capability moved to Macquarie University to form part of the Astralis consortium (Macquarie, ANU, Sydney) as Australia's national optical/IR instrumentation capability. Effectively, there is no longer an Australian national optical observatory. To a some extent, ESO can fulfil this role, although ESO does not replace local instrument and technology capabilities. The current agreement with ESO ends in 2028, leaving a critical gap if full membership of ESO does not happen. As can be seen in the sections above, access to the large facilities operated by ESO is central to much of the science to be done in the next decade.

Without membership of an international observatory, such as ESO, Australia will also be shut out of cutting-edge instrumentation development. Not only does this bring direct investment back into the country, it generally leads to Australian astronomers being at the forefront of science exploitation of new facilities (e.g. through guaranteed time for the instrument team). Extragalactic astronomy is often driven by the largest apertures or new technology, given the need to observe increasingly distant, smaller, fainter sources to understand the evolution of the Universe. Not being connected to such facilities will severely limit Australia's ability to continue its high level of leadership in astronomy.

Not having sufficient HPC resources for next generation radio facilities and numerical simulations is seen as a significant risk. The challenge currently with ASKAP and MWA will only get harder with larger facilities. Optical facilities, particularly VRO, will also be generating vast datasets (2.7Pb per release). Without significant investment in updating and enhancing national supercomputing facilities to international standards, addressing frontier questions in the field of astrophysics and cosmology using numerical simulations poses a significant risk. This also hinders our ability to completely reap the benefits of our strong observational research program. For example, by federating large data sets to carry out multi-wavelength analyses.

The next decade will see the first of the 30m class telescopes come online. They will drive discovery and Australia should be involved in this. We have current membership of the GMT consortium, but the timeline for this is uncertain, and is awaiting decisions in the US about funding. It seems unlikely that GMT will come online before the mid-2030s. The increased budget required for GMT will also reduce the effective Australian share, unless further funding is provided. In contrast, ESO’s ELT is under construction and will be completed within the next 5 years (planned first light is 2028). It will be the first and largest of the 30m class telescopes, and will likely drive much discovery in its first decade of operation. Australia currently has no access to ELT and so, without an agreement to join ESO beyond 2028, will miss out on the opportunity to engage and lead in the cutting edge ELT will produce.

Galaxy evolution in particular requires exploring galaxies across a wide wavelength range in multiple phases. Australia has excellent access to atomic gas observations (radio using ASKAP and SKA-mid) stars and ionized gas (optical/IR using 4 and 8m telescopes), but has limited access to molecular gas observations (sub-mm using ALMA).

As projects become more international, there is a danger that the benefits that Australia can bring will no longer be unique enough to add value and that funding streams are not stable enough to enable meaningful engagement over the 5-10+ year timescales that these projects operate. It will be important that technology leadership continues in tandem with science leadership to provide international consortia with meaningful value from Australian participation. Technology development also has the benefit of bringing funding back to Australia.

Access to the Anglo-Australian Telescope for the next 5 years will be valuable, but funding continues to be uncertain and at a level that is below that required to effectively operate. The lack of funding stability also limits any development of future uses and new instrumentation beyond the next 5 years.

In the next decade, SKA will be the world leading radio facility and Australia is a leading partner in this. However, this will impact the international competitiveness of national radio facilities (ATCA, Parkes, ASKAP) and will require a review of these facilities.

7 Mapping of questions to capabilities and facilities

Below is a mapping of how capabilities (specifically observational capabilities) map to the four main science topics that this report discusses. Dark shading is for a key capability, while lighter shading is for a supporting capability.

	Topics:				
Capabilities	Star formation	Galaxies	EoR	Cosmology	Comment
8m optical/IR	■	■	■	▒	Uncertain from 2028
30m optical/IR	■	■	■		ELT or later GMT
Anglo-Australian Telescope (AAT)	▒	■			Till 2030
Atacama Large Millimetre Array (ALMA)	■	■	■		Limited access currently
Australian SKA Pathfinder (ASKAP)	■	■	▒	▒	Australian Facility
Murchison Widefield Array (MWA)			■		Australian based international collaboration
Square Kilometre Array - mid (SKA-mid)	■	■	▒	■	International facility with Australia a major partner
Square Kilometre Array - low (SKA-low)			■	■	Australian based international collaboration
Australia Telescope Compact Array (ATCA)			▒		Australian Facility
4-metre Multi-Object Spectroscopic Telescope (4MOST)	▒	■		■	Australians in collaboration
Dark Energy Spectroscopic Instrument (DESI)				■	Australians in collaboration
James Webb Space Telescope (JWST)	■	■	■		Open access
Euclid		■	▒	■	
Roman		■	▒	■	
Vera Rubin Observatory (VRO)		▒		■	Australians in collaboration
Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx)				■	

	Topics:				
Capabilities	Star formation	Galaxies	EoR	Cosmology	Comment
LIGO-Virgo-KAGRA				■	Australians in collaboration
South Pole Telescope (SPT)				■	
Simmons Observatory (SO)				■	Australians in collaboration
Cherenkov Telescope Array Observatory (CTAO)		▒		■	Australians in collaboration

8 Working group members

Members listed in bold below have specific leadership roles within the group.

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8 Glossary

Abbreviation/Name	Description (inc links)
4MOST	4-metre Multi-Object Spectroscopic Telescope https://www.eso.org/sci/facilities/develop/instruments/4MOST.html
AAT	Anglo-Australian Telescope https://aat.anu.edu.au/
ALMA	Atacama Large Millimeter/sub-millimeter Array https://www.almaobservatory.org/
ASKAP	Australian SKA Pathfinder https://www.atnf.csiro.au/projects/askap/index.html
ATHENA	Advanced Telescope for High ENergy Astrophysics https://www.the-athena-x-ray-observatory.eu/en
AtLAST	Atacama Large Aperture Submillimeter Telescope https://www.atlast.uio.no/
AusSRC	Australian SKA Regional Centre https://aussrc.org/
Cosmic explorer	Next generation gravitational wave observatory https://cosmicexplorer.org/
DES	Dark Energy Survey https://www.darkenergysurvey.org/
DESI	Dark Energy Spectroscopic Instrument https://www.desi.lbl.gov/
Euclid	Wide field optical/IR imaging and spectroscopy https://www.euclid-ec.org/
Einstein telescope	Next generation gravitational wave observatory https://www.et-gw.eu/
ELT	ESO's Extremely Large Telescope https://elt.eso.org/
CTAO	Cherenkov Telescope Array Observatory https://www.ctao.org/
eROSITA	extended ROentgen Survey with an Imaging Telescope Array https://www.mpe.mpg.de/eROSITA
ESO	European Southern Observatory https://www.eso.org/
GMT	Giant Magellan Telescope https://giantmagellan.org/
GMTIFS	Giant Magellan Telescope Integral Field Spectrograph https://rsaa.anu.edu.au/research/research-projects/giant-magellan-telescope-integral-field-spectrograph-gmtifs

HARMONI	High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph https://elt.eso.org/instrument/HARMONI/
HERA	Hydrogren Epoch of Reionization Array https://www.sarao.ac.za/science/hera/
HPC	High Performance Computing
HST	Hubble Space Telescope https://www.stsci.edu/hst
IceCube	https://icecube.wisc.edu/
JWST	James Webb Space Telescope https://www.stsci.edu/jwst
KWFI	Keck Wide Field Imager https://kwfi.swin.edu.au/
KM3Net	Cubic Kilometre Neutrino Telescope https://www.km3net.org/
LIGO-Virgo-KAGRA	Combined gravitational wave network of Laser Interferometer Gravitational-Wave Observatory (https://www.ligo.org/) Virgo Gravitational Wave Interferometer (https://www.virgo-gw.eu/) and Kamioka Gravitational Wave Detector (https://gwcenter.icrr.u-tokyo.ac.jp/en/)
LOFAR	Low Frequency Array https://www.astron.nl/telescopes/lofar/
MAVIS	MCAO-Assisted Visible Imager and Spectrograph https://www.eso.org/sci/facilities/develop/instruments/MAVIS.html
MOONS	Multi Object Optical and Near-infrared Spectrograph https://www.eso.org/sci/facilities/develop/instruments/MOONS.html
MSE	MaunaKea Spectroscopic Explorer https://mse.cfht.hawaii.edu/
MUSE	Multi-Unit Spectroscopic Explorer https://www.eso.org/sci/facilities/develop/instruments/muse.html
MWA	Murchison Widefield Array https://www.mwatelescope.org/
Roman	Nancy Grace Roman Space Telescope https://roman.gsfc.nasa.gov/
SKA	Square Kilometre Array https://www.skao.int
SO	Simons Observatory https://simonsobservatory.org/
SPHEReX	Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer https://www.jpl.nasa.gov/missions/spherex

VLT	ESO’s Very Large Telescope https://www.eso.org/public/teles-instr/paranal-observatory/vlt/
VRO	Vera Rubin Observatory https://www.vro.org/
WST	Wide-field Spectroscopic Telescope https://www.wstelescope.com/

A Appendix - Cosmology white paper

To be added (current version in latex, so will be added as PDF).

Cosmology sub working group white paper

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1 Science questions for the next decade

1.1 Particle cosmology: What can we learn about the fundamental components of matter from the Universe?

Recent years have seen a convergence between the fields of cosmology and particle physics, with some of the most significant open questions in particle physics connecting to astrophysical observations. These questions include the nature of dark matter, understanding the neutrino sector and origin of neutrino masses, the matter-antimatter asymmetry, inflaton physics in the early Universe, and searches for new physics (such as cosmic birefringence or evolution of fundamental constants) or new particles.

Science questions that are within the reach of the next decade include

1. *What is dark matter?* We should expect continuing improvements on tests of the dark matter particle mass and cross-sections.
2. *What are the neutrino masses? Are there sterile neutrinos?* We can also hope to understand the origin of neutrinos masses and to determine the neutrino hierarchy.
3. *Can we find evidence of new particles or new physics?* Cosmological observations over the next decade will test a number of theoretical models.

Cosmological observations require the existence of "dark matter", something that behaves gravitationally like matter but has a very low interaction cross-section. Dark matter has not yet been directly detected or identified in ground-based laboratories. There are a wide array of proposed dark matter candidates: from weakly interacting massive particles (WIMPs) to ultra light axions, to other exotic and relic particles (e.g.

Arcadi et al., 2018; Marsh, 2016). There may be multiple distinct particles, each accounting for a portion of the dark matter density.

The question of the nature of dark matter is being simultaneously pursued with astrophysical observations and laboratory experiments. Thus dark matter research has driven cross-disciplinary collaborations between astronomers and physicists, such as the ARC Centre of Excellence for Dark Matter Particle Physics and the joint chapter the ASA and AIP: the Group for Astroparticle Physics. Australia's lab-based experiments include Stawell Underground Physics Laboratory in Victoria (searching for WIMPs) and haloscopes (searchig for axions). In the next decade, we should expect further progress in astrophysical constraints on how 'warm' dark matter is through the number density and matter profiles of haloes; on annihilation or decay cross-sections through searches for the energy that would be released; and potential interactions between ordinary matter and the dark sector. Realising this potential will demand work on simulations to recognise any signature of dark matter properties in the observations. Learning about dark matter is being pursued across the entire EM spectrum, from radio with SKA to gamma rays.

The 2015 Nobel Prize was awarded for the discovery of neutrino oscillations and demonstration that neutrinos have mass (Fukuda et al., 1998). However, we do not yet understand why neutrinos have mass, nor do we know their masses. Cosmological observations are sensitive to the sum of the neutrino masses through neutrinos' effects on the CMB and large-scale structure (LSS) (Lesgourgues & Pastor, 2006). Massive neutrinos induce a scale-dependent suppression of structure growth below the neutrino free-streaming scale. The magnitude of the suppression is proportional to the neutrino energy density, or sum of the neutrino masses, and also depends on redshift. Over the last decade, we have made significant progress in modelling the effect of neutrinos on large-scale structure and improving observational limits on neutrino masses. In the next decade, we expect a combination of CMB and LSS to yield the tightest constraints on the neutrino masses. Forecasts combining upcoming CMB and LSS experiments predict we will be able to detect neutrino mass at $> 3\sigma$ for the minimum mass allowed by neutrino oscillations by the end of the decade.

Any light particles in thermal equilibrium during the "Hot Big Bang" phase of the Universe will change the relativistic energy density, and thus expansion rate, of the Universe. The contribution to the relativistic energy density is normally parameterized by the a change in N_{eff} the effective number of neutrino species. The minimum shift is $\Delta N_{eff} = 0.027$ for a scalar (spin-0) particle thermally decoupling before any other Standard Model particle. Particles with non-zero spin or that decouple later will introduce larger changes in N_{eff}. Thus cosmological observations offer the tantalizing possibility of probing for the existence of extra light relics, even ones out of reach of ground-based particle accelerators. Changes to the relativistic energy density shift the positions of the BAO peaks, and also change damping tail of the CMB power spectrum. Both CMB and BAO observations are expected to yield comparable constraints on N_{eff} in the next decade. The CMB, but not BAO, constraints are degenerate with Helium abundance if BBN consistency is relaxed. A combination of LSS and CMB is expected to yield the tightest constraints over the next decade. We do not expect to explore the entire discovery space, i.e. to be able to detect the minimum $\Delta N_{eff} = 0.027$, in this decade. The combination of CMB + LSS experiments (Simons Observatory and DESI) is forecast to reach $\sigma(N_{eff}) \simeq 0.04$ (Ferraro et al., 2022).

More broadly, the next decade promises a plethora of opportunities to test our understanding of physics and search for physics beyond the Standard Model. Amongst the possibilities is the search for axions, which is a world-wide pursuit that has Australian scientists leading efforts to detect axions in both cosmological surveys and in-lab haloscopes. Australia can also leverage its deep involvement in GW physics to search for GW polarisations beyond the two allowed in GR. As a final example, Australia is a leader in astronomical searches for variations in the fundamental constants of nature, especially the fine-structure constant, alpha – effectively the strength of electromagnetism. Indeed, Australia's partnership in ESO has provided a limit of just 1 part-per-million over half the Universe's history with the new ESPRESSO spectrograph on the ESO's VLT (Murphy et al., 2022). These and other searches for new physics may be perceived as "high risk", but they can often be performed with data collected for other science targets, and offer access to entirely different realms of parameter space where we might expect departures from the Standard Model. The discovery of any of the above effects would also be revolutionary, offering a long-sought-after path forward for a deeper understanding of physics.

1.2 Understanding the accelerating expansion of the Universe: What is the nature of dark energy?

Cosmological observations have provided proof that the expansion of the Universe has begun to accelerate. The physical explanation of the acceleration is still unclear, and we use "dark energy" as an umbrella term for the as-yet-unknown explanation. The simplest version of dark energy would be a unchanging cosmological constant, however dark energy may also be evolving, or it could be a manifestation that GR is not an accurate model for gravity. Other proposed solutions include a break down in current assumptions about cosmology, such as breaking homogeneity.

In the next decade, new observations will target the following key questions about dark energy:

1. *Is dark energy consistent with a cosmological constant or is there evidence for its evolution?* Many theories to explain the accelerating expansion predict that dark energy is not exactly a cosmological constant, and recent data show a mild $2.6\,\sigma$ hint towards evolving dark energy (DESI Collaboration et al., 2024). If the current signal is real instead of a statistical fluctuation, cosmological surveys should reveal definitive evidence for deviations from a cosmological constant by the end of the decade.

2. *Is General Relativity an accurate description of gravity on cosmological distance scales?* Measurements of structure growth and light propagation are expected to put tighter constraints on possible departures from GR.

Over the last decade, we have witnessed continued progress towards more precise constraints on dark energy and gravity. While a simple cosmological constant remains consistent with most observations, there are interesting points of tension with some observations, such as the Hubble tension and hints of evidence for dynamical dark energy. The Hubble tension shows disagreement between local observations of the expansion of the universe (distance ladder) and the Hubble constant inferred from high redshift-dependent probes, such as CMB and BAO (even thought the BAO is measured at $z < 2$, the encoded scale depends on the sound horizon at the drag epoch, $z \approx 1060$). In addition, combining measurements by DES and more recently by DESI with CMB data show ($2.6\,\sigma$) hints of dynamical dark energy (DESI Collaboration et al., 2024). This is a clear indication that dark energy sector can be more rich than a simple cosmological constant. The next decade will bring more observational probes, independent from redshift distance ladder such a Gravitational Waves (standard sirens), FRBs, QSOs (standardisable candles), gravitational lensing, and first attempts to constrain the redshift drift, as well as observations of the Epoch of Reionisation that probes young universe (as opposed to early and late) and could possible reflect some signatures of dynamical dark energy.

The next decade is expected bring a collaborative effort into developing the science of dark energy and gravity, that is similar to the one observed in astroprticle cosmology. While it is unknown if in the next decade we uncover the true nature of dark energy, it is very likely that data from cosmological surveys will allow us to disentangle dark energy from modified gravity, and either confirm GR or identify signatures of departure from Einsteinian gravity. Over the next decade, measurements of the growth rate will improve from the current level (∼10% accuracy) to approach 1% accuracy, using redshift-space distortions and direct galaxy peculiar velocities. The data will also test if the motion of galaxies is governed by the same gravitational potential as bending of light via the lensing mechanism. These tests will be used to detect potential departure from GR. We note that while any $f(R)$ extension of gravity can be unequivocally represented as a scalar field theory (i.e. equivalence between dark energy modelled as a scalar filed and extension for gravity), this is not the only possible extension of GR. Other possible extension that include extra fields (eg. vector or tensor fields), extra dimensions, or even extension beyond Riemannian geometry (i.e. models with torsion or nonmetricity) provide unique signatures (e.g. broken distance duality) that are not present in GR and cannot be explained away with evolving dark energy.

To answer questions about the nature of dark energy and gravity, collaborative efforts involving multiple facilities across the gamut of cosmological observables will be required. These include existing facilities: ASKAP, DESI, Euclid, Simons Observatory, and LVK (LIGO-Virgo-KAGRA); and facilities under construction: SKA, LSST, 4MOST, CMB-S4, and GMT/ELT. Australia also needs to be an active leader in the design, planning and eventual construction of successors to these experiments such as ESO's proposed next-generation spectroscopic survey WST to lay the foundation for the next decade. All of this will need to be accompanied by commensurate advancement in numerical simulations, which heavily relies on access to HPC.

1.3 Testing the "Standard model of Cosmology" ΛCDM

The ΛCDM model is the standard cosmological model that is based on an homogeneous and isotropic solution of the Einstein equations. The expansion of the universe is governed by the Friedmann equations with dominant components being: the cosmological constant Λ and the cold dark matter (CDM). Other components such as baryons, radiation, and neutrions, are subdominant today but played essential role in the early universe. The cosmic structures observed in the cosmological surveys are seeded by primordial perturbations sourced during cosmic inflation. Any change of these building blocks have a potential of invalidating the ΛCDM model. The science question that are within the reach of the next decade is

1. *Is ΛCDM a correct model of our universe?* Are the current tensions (such as the $> 5\,\sigma$ Hubble tension) observed with the ΛCDM model the first signs we need to change the model, or can they be explained within the ΛCDM framework?
2. *What is the explanation for the Hubble tension?* The Hubble tension could either be due to unaccounted systematics, or in the alternative indication that one (or some) of the building blocks of the ΛCDM model have to be changed, either in relation to the late epoch and its evolution, or in relation to the very early era (pre-CMB).
3. *Are the Universe's initial conditions consistent with a nearly scale invariant Gaussian power spectrum of scalar perturbations?* Detecting non-Gaussianity or departures from a simple power law would yield clues about the inflationary epoch.

A major challenge to the ΛCDM model today is the $> 5\,\sigma$ tension between estimates of the Hubble constant between CMB, BAO and distance-ladder measurements (Valentino et al., 2021). In the next decade, standard sirens (GW), and FRBs will provide independent measurements of the expansion rate that may heighten or resolve the Hubble tension. If the Hubble tension is solidified, this will be an indication that either the Friedmann equations sourced only by Λ and CDM are insufficient to correctly describe the evolution of the universe, or in the alternative that our understanding of properties of the early universe is incomplete. There are also other lower significance tensions within the ΛCDM model such as the roughly $3\,\sigma$ tension in S8 between the CMB and BAO and direct probes of the low-redshift matter distribution including cosmic shear, galaxy cluster abundances or RSD. An exciting prospect for the next decade is the possibility that we might witness a transition (similar to the one that occurred 20-30 years ago) to a new standard cosmological model.

Over the next decade, we can expect large improvements in sensitivity for tests of the initial conditions of the Universe, such as searches for primordial non-Gaussianity, deviations from a simple power-law spectrum, or non-scalar modes. Measuring the properties of the primordial perturbations is crucial as they are our only window into physics of inflation. Generic slow-roll models of inflation predict a nearly Gaussian, nearly scale invariant power spectrum of scalar perturbations, along with a potentially detectable spectrum of tensor perturbations. It is possible we will be able to detect these tensor perturbations in the CMB in the next decade, while GW observatories can test alternatives to slow-roll models that predict much bluer spectra of inflationary GWs. Other alternatives, such as multi-field inflation models, predict much higher and detectable levels of primordial non-Gaussianity, while features in the effective inflaton potential can produce features in the primordial spectrum. Deviations from Gaussianity manifest in the form of non-trivial higher-order correlations of cosmic fields, e.g., in their bi- or trispectrum. Non-Gaussianity can be probed with observables covering a large range of redshifts, from the local large scale structure (z$\sim$O(1)) which is accessible through optical and radio galaxy surveys as well as weak gravitational lensing, through to 21 cm observations (z $\sim$ O(10)) all the way to the CMB at redshift $z \sim 1000$. Precisely determining the Universe's initial conditions represents a unique opportunity to open a window to the inflationary era in the first moments of our Universe, and thus learn more about the physics at energies up to the GUT scale – far beyond the reach of laboratory experiments.

2 Key Data

2.1 Advances in simulations, methods and theory

Achieving precision cosmology and the full scientific potential of the rich suite of new instruments being built for the next decade depends crucially on our ability to compare observations to the predictions of models, i.e work on simulations, methods and theory. As sample sizes grow larger and statistical uncertainties shrink, both the accuracy and precision of current simulations and theoretical predictions will continue to be tested. The need to to keep up with the rapid expansion in current and planned survey volumes has driven rapid growth in the size of simulations. The need to more accurately account for ever smaller effects as observational errors have shrunk has also driven a continual push for the simulations to include more physics and model the physics more accurately. Simulations are critical to efforts to understand instrumental and astrophysical systematics in observational constraints, and are the foundation for all the science of the new observatories. We also require continued development of statistical techniques, suitable to the growing data volumes. Finally, maintaining and building upon Australia's existing capacity in theoretical research underpins our ability to use future observations to test alternate universes with modified laws of gravity and/or nontrivial dark sector physics (dark matter interactions, evolving dark energy, etc).

2.2 Optical surveys: Imaging and Spectroscopic

Large area optical surveys are expected to play a key role in tests of cosmology over the next decade. These include both imaging (LSST, Ivezić et al. (2019)) and spectroscopic (DESI, DESI Collaboration et al. (2016); 4MOST on ESO's Vista telescope, de Jong et al. (2019)) surveys. We expect this decade to see transformational, order-of-magnitude improvements in both areas. On the spectroscopic side, BOSS (2015) determined the redshifts of $\sim 10^6$ galaxies which will advance with DESI and 4MOST to more than 10^7 galaxies. Proposed successors (e.g. MegaMapper, (Blanc et al., 2022) or ESO's Wide-field Spectroscopic Telescope, (Bacon et al., 2024)) are targeting another factor of 10 improvement in mapping speed. On the imaging side, the LSST survey of 18,000 deg^2 of sky is expected to begin in the first half of 2025 and continue for the following 10 years. Australian scientists are playing leading roles across all of these surveys.

The LSST survey on the Vera Rubin Observatory will address key questions in §2 through multiple probes. To list a few, LSST's galaxy sample will allow a better understanding of the inflationary epoch by improving measurements of the primordial power spectrum and limits on primordial non-Gaussiantiy; LSST's galaxy cluster sample will strengthen constraints on the interaction cross-sections of dark matter; the numerous supernovae expected from LSST will better study the equation of state of dark energy; and measurements of the ISW effect using LSST and CMB data can test more exotic models in which dark energy can cluster. The imaging and spectroscopic surveys are tightly coupled: the LSST survey is critical to target selection for the spectroscopic surveys, while wide-field spectroscopy is essential for fully extracting information from the LSST survey.

The baryon acoustic oscillation and redshift-space distortion measurements from spectroscopic surveys are important cosmological probes. In fact, BAO measurements are central to one of the major current tensions in the ΛCDM model – the conflicting measurements of the Hubble constant between the CMB+BAO and the distance ladder + SNe. SNe may also be combined BAO measurements in an inverse distance ladder technique to recover competitive constraints on the Hubble constant without the CMB. These data will constrain the Universe's expansion rate history to $z \simeq 3.5$, and substantially shrink uncertainties on the dark energy equation of state and sum of neutrino masses. Combining the spectroscopic surveys with other surveys also enable new tests. For example, the combination of RSD and CMB lensing can test GR by independently measuring the two relativistic gravitational potentials. Further tests of gravity on different scales can be drawn from RSD measurements and using a combination of spectroscopic redshifts and CMB data to measure how quickly nearby massive haloes are falling towards one another. Spectroscopic redshifts are also crucial to the science of other surveys. DESI and 4MOST are the key spectroscopic surveys for science results in this decade, and Australia will have access to 4MOST due to its instrumental contributions. It is also important to prepare for the next decade of science (and maintain Australia's significant capabilities in optical spectroscopy and instrumentation) by investing in the planning, design and construction of at least one of their successors, such as MegaMapper or ESO's Wide-field Spectroscopic Telescope.

The Australian-led 4MOST WAVES and 4HS surveys on the ESO Vista telescope will allow us to map the dark matter distribution across half the sky and its evolution over half the age of the Universe. Dark Matter maps can be constructed by identifying bound haloes and using their velocity dispersions to quantify the dark matter mass. Almost 50% of dark matter is expected to be in haloes of milky way mass and above, with significant evolution predicted at $z < 1$. Together the 4MOST WAVES and 4HS surveys will identify several hundred thousand dark matter haloes from superclusters to diffuse groups, allowing for the reconstruction of the halo mass function and its evolution. The surveys will tests dark matter models over several orders of halo mass ($10^{12} M_\odot$ to $10^{16} M_\odot$).

2.3 Radio surveys: SKA and precursors

Australia is an international leader in radio astronomy. Australia hosts precursors to the SKA, ASKAP and MWA, which are already collecting science data. Excitingly, the next 10 years will see the beginning of the next-generation radio observatory, SKA. SKA-Low is situated within Western Australia and is expected to enter science verification around the start of the decadal period. Full science observations will begin soon thereafter.

Fast radio bursts (FRBs), when localised, offer an independent path to measuring the local expansion rate and resolving the Hubble tension (James et al., 2022). ASKAP has already contributed significantly in the FRB domain, and the number of FRBs from ASKAP and SKA is expected to skyrocket over the next decade.

These radio experiments will increase the sensitivity of pulsar timing searches for gravitational waves at longer wavelengths than accessible from ground-based interferometry. Among other science questions, pulsar gravitational wave astronomy will test a range of alternative models of gravity, through the impact on the orbital dynamics of binary pulsar systems.

SKA will enable measurements of RSD and the BAO features using HI intensity mapping (Square Kilometre Array Cosmology Science Working Group et al., 2020). The SKA-Mid surveys will measure BAO out to a redshift of 3, while SKA-Low surveys will cover the redshift range $3 < z < 5.5$. As in the optical surveys, these measurements will map out Universe's late-time expansion history, testing the simple cosmological constant explanation of dark energy and testing models of gravity. This survey will also test models for the first moments of the Universe, such a multi-field inflation models that predict significant primordial non-Gaussianity by placing new limits on primordial non-Gaussianity. Finally, gravitational lensing of the HI intensity mapping signal will reconstruction of the gravitational potential field across the $\sim$5000 deg^2 survey, which in turn will test our models for structure growth and related parameters like the sum of the neutrino masses.

2.4 CMB surveys

Observations of the cosmic microwave background provide detailed knowledge of conditions in the early Universe, while also strengthening late-time tests of cosmology by establishing the initial conditions from which the present-day Universe has evolved.

The coming decade will bring a series of major international CMB surveys covering increasing sky fractions to ever lower noise levels. In temporal order, we will see results from the South Pole Telescope (25% of the sky; Prabhu et al. (2024)); the Simons Observatory (50% of the sky, observations are funded to run from 2025 - 2033; Ade et al. (2019)); and the CMB-S4 experiment (70% of the sky, observations are planned for 2032-2042; Abazajian et al. (2016)). The first two of these have been funded for construction and operations; CMB-S4 is still in the design phase. The CMB-S4 experiment was ranked as the #2 priority by the US astrophysics decadal process, and #1 by the equivalent US particle physics process, the P5 report. However, uncertainty in the project timeline and scope has risen with the recent NSF decision not to allow new construction at the South Pole. Given the 10-year survey length and planned start in 2032, the majority of the scientific results from CMB-S4 should be expected to occur in the next decadal period. However, Australian participation in the project during the design and construction phase will be important for laying the groundwork for the next decade's science. Involvement in CMB-S4 is expected require a buy-in per faculty member similar to LSST.

These experiments will dramatically improve measurements of the CMB power spectra and lensing spectra (and thus cosmological inferences). The four major cosmology science targets are: (1) neutrino physics and potential light relics; (2) inflationary physics especially through searches for inflationary GWs; (3) testing the nature of dark matter, specifically for heavy WIMPs and ultralight axions; and (4) testing dark energy and modified gravity models, through measurements of the cosmic expansion history, galaxy cluster abundances and cosmic velocity field. The resulting mm-wave maps from Simons Observatory and CMB-S4 will have nearly complete overlap with other major surveys sited in Chile, such as LSST or 4MOST (as well as planned future surveys like ESO's Wide-field Spectroscopic Telescope), and enable a rich range of multi-wavelength studies. CMB data also complements the other surveys; for instance CMB lensing data roughly doubles the dark energy figure of merit for the Raman space Telescope (Wenzl et al., 2022).

2.5 GW astronomy

Gravitational wave astronomy will enter an exciting epoch during the next decade as we enjoy the fruits of the successful LIGO-Virgo-KAGRA experiments and prepare for the next generation of GW observatories such as the Cosmic Explorer or Einstein Telescope. There is also the potential for Australia to host a gravitational detector such as NEMO. Australia has played a significant role in technology development to LIGO, and the importance of these technology development work will grow in the lead up to Cosmic Explorer. The construction of Cosmic Explorer is planned for the second half of this decade, though science observations will likely wait till the next decade.

GW astronomy opens new tests of the nature of dark matter (e.g. Bertone et al., 2020), and can also constrain potential explanations for the accelerating expansion of the Universe involving modifications to general relativity (e.g. Ezquiaga & Zumalacárregui, 2018). GW observations provide unique tests of gravity. For instance, GWs could have up to six polarizations of which only two are predicted under GR – any detection of the other polarization states would demand a change to our understanding of gravity. Finally, as the number of GW sirens grows, they will enable independent measurements of the cosmic expansion rate that may resolve the current tension in measurements of the Hubble constant (e.g. Feeney et al., 2019).

2.6 Gamma Ray Observatories

Over the coming decade, the next-generation TeV gamma-ray facility, CTA, will allow new searches for new physics and particles. By looking for potential gamma ray signatures of dark matter annihilation, CTA can be used to provide some of the strongest tests of WIMP dark matter models, pushing below the fundamental 'thermal relic' levels. Gamma-rays are also a highly fruitful way to probe for light dark matter particles such as axions from distant AGN and GRBs. TeV gamma-rays may 'oscillate' to/from axion states so that such emission can avoid absorption effects on the extragalactic IR and optical fields. Beyond dark matter, gamma rays are also ideal probes cosmic 'relics', such as monopoles, quark nuggets, or primordial black holes.

The absorption of TeV gamma rays by extragalactic background light leads to characteristic cutoffs in TeV gamma-ray spectra from distant sources. The shape of the cutoff is a proxy for distance and hence gamma-ray spectral shapes can be used to form an independent test of the Universe's expansion rate (e.g. Domínguez et al., 2024) that might help discover the cause of the Hubble tension problem.

2.7 Cosmology from Space

The next decade will bring the launch of several satellites that are expected to make major contributions to cosmology. These include Euclid (ESA, launched in 2023, 15,000 deg^2; Euclid Collaboration et al. (2024)), SPHEReX (NASA, planned launch 2025, all-sky; Crill et al. (2020)), and the Roman Space Telescope (NASA, planned launch 2027, 200 sqdeg). The data from these surveys will be publicly available immediately for the NASA missions and after a short period for ESA. These data will complement the ground-based observations, and enrich our studies of cosmology of this decade.

3 Opportunities and Risks

3.1 International nature

Seeking answers to contemporary questions in cosmology requires engagement with international enterprises, most of which are located outside of Australia and many of which involve large international collaborations. The international nature of the effort comes with benefits as well as risks. On the positive side, partnering in large international facilities allows access to a much wider pool of instruments, HPC resources, and people, thereby enabling more ambitious scientific programs to answer foundational questions about the nature of the Universe. Australian-only experiments would necessarily be more constrained and limited in scope. By joining these international programs, Australian astronomers stay at the cutting edge of cosmological research world-wide. International programs also enrich the training of research higher degree students, raise the international visibility of Australia and make it easier to recruit top scientists to Australia.

On the risk ledger, internationalization raises two important issues. First, there is a risk of losing local capabilities and becoming over-specialised. This risk is enhanced by the world-wide trend towards fewer but larger instruments. The ability to maintain diverse local capabilities is limited by the low and intermittent nature of funding. The combination can make it harder to maintain the continuous stream of funded projects necessary to hold onto experimental capacity. A second question was raised in several variations, namely what does maintaining Australian competitiveness mean in the context of these large international collaborations? Australian scientists can and are doing work that is both excellent and important, but individual contributions are unlikely to be fundamentally irreplaceable or unique within the international context. Risk management at the project level mandates backup options for any key requirement. Another variation on this question was how to value prospective contributions. There are potentially transformational questions in cosmology, such as the nature of dark matter or dark energy, that generate tremendous interest across the interested public as well scientists; there are also more specialised questions targeting smaller mysteries. How does one value a useful contribution (but one where another international partner would step forward if Australia stepped back) to a "big" question versus a truly essential contribution to a smaller question?

3.2 Funding stability and resources

The short-term nature of major funding schemes adds complexity to Australian participation and leadership in international experiments. Many of these experiments have planned lifetimes of a decade or longer (e.g. LSST plans to observe for 10 years, while future plans for successors to LIGO extend to $\sim$2050), and thus extend over multiple ARC grant cycles. Funding uncertainty, compounded by a shrinking funding pool in real terms, complicates sustaining Australian expertise in these areas and can also lead to the exodus of skilled scientists to countries with more funding.

3.3 Optical capabilities

Australia has great strength in galaxy surveys for cosmology, particularly in peculiar velocity surveys such as those that form parts of the WALLABY and 4MOST Hemisphere Survey science programs. Unfortunately, there is widespread agreement that Australian optical capabilities faced potentially severe risks, especially in the doomsday scenario where full ESO membership fails and the AAT closes. Such a scenario could set back optical astronomy in Australia by decades. Ensuring the continuation of national optical facilities at some level will be important to maintaining scientific capability. While the AAT is not directly competitive with the international surveys, targeted followup observations on the AAT has been part of previous buy-in packages. For instance, part of Australia's buy-in to the Dark Energy Survey was the 6-year OzDES spectroscopic survey on AAT. In considering these risks, the major science questions in §2 are insulated from immediate, direct consequences. The key optical surveys for these questions are either not connected to ESO (e.g. LSST, Euclid, DESI), or, in the case of the 4MOST spectroscopic survey, would continue outside of ESO membership due to Australian hardware contributions to 4MOST. However in the 10+ year timescale, Australia's participation in the next generation of optical cosmological surveys, such as ESO's Wide-field Spectroscopy Telescope, is at risk.

3.4 Connections to other fields

There are strong connections between astrophysical probes of Beyond the Standard Model (BSM) physics with other fields of physics also searching for signs of BSM physics. For instance, the nature of dark matter is simultaneously being explored through cosmological surveys, direct dark matter experiments (including SABRE and haloscopes in Australia) and particle accelerators (with Australian involvement in LHC). The neutrino sector can be tested through neutrino experiments like IceCube or Hyper-Kamionkande (with Australian involvement in both), but also through the influence of the cosmological neutrino background on the evolution of the Universe and growth of structure. As noted in the theory white paper, Australia also has a strong and vibrant theoretical community working on BSM physics. There have been recent steps to bridge the fields like the GAP joint chapter between the AIP and ASA, or proposals for CoEs bridging the gap in dark matter, yet there is room to do better. Continuing to grow and expand connections between observational cosmology and these diverse communities would enrich the scientific impact of a wide sweep of Australian physics and astrophysics. Self-consistently combining what we learn from particle physics, astroparticle, and cosmology experiments will be critical to produce the strongest tests of the neutrino and dark sectors.

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B Appendix - Galaxy formation theory white paper

Galaxy formation, star formation, and the ISM

Panel: Aaron Ludlow (chair), Amit Seta, Aditi Vijayan, Stas Shabala, Chris Power, Danail Obreschkow

This document contributes to the 2026-2035 Decadal Plan White Papers for the *Theoretical Astrophysics* (WG1.4) and *Galaxies and Cosmology* (WG1.1) Working Groups. Our report includes feedback received from the Australian astronomy community prior to and after our Town Hall meeting (April 22, 2024).

Tasks:

1. Report on progress since the last Decadal Plan (DP) with reference to relevant questions identified there.
2. Identify the outstanding problems that the Australian community is well positioned to address in the next decade, 2026-2035.
3. Identify the current strengths that ensure the Australian community can address those problems; identify the skills or resources that must be developed.
4. Provide an inventory of the opportunities expected to arise over the next decade and the threats that may hinder our ability to take advantage of them.

Progress since the 2016-2025 Decadal Plan

The 2016—2025 DP identified a number of high-level science questions to be prioritized by its various working groups. Those relevant to WG1.1 and WG1.4 are:

1. What is the nature of dark matter (DM) and dark energy?
2. How did the first stars and galaxies transform the Universe?
3. How do galaxies form and evolve across cosmic time?
4. How do stars and planets form?

Additional theme-specific science questions or priorities were raised in various Appendices in the 2016-2025 DP. These include:

1. *Galaxy formation theory (Appendix 5, WG-1.1, 2016-2025 DP):*
    a. To maximize their utility, results from theoretical models should be archived and distributed through TAO (the Theoretical Astrophysical Observatory, part of the All-Sky Virtual Observatory).
    b. The development of exascale or GPU-enabled codes for modeling the ISM, star clusters, and feedback.
    c. Extensive comparisons between observations and numerical simulations, with emphasis on forward modeling simulation data into the observational space.
    d. Carrying out large scale cosmological magneto-hydrodynamical simulations with radiative transfer to model the formation of the first galaxies and reionization.
    e. Simulate realistic disk galaxies and outflows, which demands convergence of hydrodynamic simulations.
    f. Simulate galaxy formation in alternative DM models to search for observational clues to the nature of DM.

2. *Star Formation (Report of WG1.2; Section 4 and Appendix C, 2016-2025 DP):*
    a. How do stars form and evolve?
    b. Do high-mass stars form to core accretion or other processes?
    c. What is the origin of the stellar IMF?
    d. What are the other birth characteristics of stars?

The galaxy formation, star formation and ISM communities acknowledge that the questions highlighted in the 2016-2025 decadal plan are sufficiently broad as to remain relevant for the next decade, although progress has been made on each, which we detail below.

What is the nature of dark matter and dark energy?

Little progress has been made in addressing the DM or dark energy problems, although certain developments are worth highlighting. For example, the mass, redshift, and cosmology dependence of DM halo structural scaling relations are better quantified than ever and can be readily predicted from theory (Angel et al, 2016; Lopez-Cano et al 2022), yet on the level of individual halos complex cases remain. Although readily seen in simulated halos, the Milky Way (MW) is one observed example. Specifically, the S^5 Survey (using data collected by the AAT) has determined that the distortion of the MW's halo by the Large Magellanic Cloud is consistent with dynamical friction in a collisionless fluid, as expected in a cold or warm DM model (rather than alternative DM models; Lilleengen et al 2022).

Distinguishing between viable DM models will require careful comparison of observations to results from realistic high-resolution simulations that model both DM and baryonic fluids. Several groups have carried out DM-only cosmological simulations to study how halo properties are affected by the assumed DM model (e.g. Jibrail, Elahi, Lewis, 2020; Andermann et al 2019), or have incorporated DM annihilation radiation as a form of feedback to study its effects on the high-redshift 21 cm signal (e.g. List et al 2019, 2020; Iwanus et al 2017, 2019). Progress has also been made in simulating the Local Group in cold and alternative DM models to determine whether non-standard DM can help resolve tensions with LCDM.

Work at the University of Sydney (see papers by Ciaran O'Hare) have improved predictions for the DM detection rate in the MW halo and provided better constraints on the neutrino floor.

How do galaxies form and evolve across cosmic time?

Considerable progress in our understanding of how galaxies form and evolve was largely enabled by the community's efforts to develop: a) new galaxy formation models and codes; b) tools with which observational and theoretical results can be meaningfully compared; and c) our involvement in large-scale international simulation projects (e.g. EAGLE, Magneticum, TNG, Apostle).

Since 2015, three distinct semi-analytic models (SAMs) have been developed, including Meraxes (S. Mutch), Dark Sage (A. Stevens), and Shark (C. Lagos). They differ from competing codes: Meraxes, for example, includes a temporally and spatially coupled treatment of reionization; Dark SAGE resolves the radial structure of galactic disks. Each SAM has been run on Australian-led DM-only cosmological simulations (e.g. SURFs, WiggleZ, Tiamat) as well as runs carried out by international collaborators (TNG, Millennium, P-Millennium, etc). SAMs have also been used to place joint constraints on galaxy and radio jet populations, linking the observed AGN duty cycle to feedback (Raouf, Shabala, Croton et al.).

Newly developed environment-dependent analytic models have been used to interpret the feeding and feedback cycle in active galactic nuclei (AGN) within radio galaxies in SKA pathfinder surveys (Shabala, Turner), suggesting that the bulk of the low-redshift radio galaxies are likely powered by chaotic cold accretion. The CosmoDRAGoN Project (Power, Shabala, Yates-Jones et al.) — the first dedicated suite of AGN jet simulations in cosmological environments with forward modeling of radio continuum observables — has been used to make predictions for forthcoming SKA surveys. Progress has been made in modeling AGN jet feedback and the associated observational signatures (outflows, radio emission, etc) on galaxy scales (Bicknell, Mukherjee, Wagner).

In addition to SAMs and analytic models, various subgrid models for the muti-phase ISM have been developed which include dust and the breakdown of hydrogen into its neutral (including molecular) and ionized components. These models have been used to post-process existing hydrodynamical simulations (e.g. EAGLE and Ilustris; e.g. papers by C. Lagos, A. Stevens, A. Manuwal) or have been implemented in GPU-accelerated simulation codes (e.g. Bekki). But because the latter are computationally expensive, they have been limited to “zoomed” or idealized simulations of individual galaxies; large-scale cosmological simulations that simulate the cold, multi-phase ISM are uncommon, but are currently being developed. These runs have also taken deliberate steps to understand and mitigate discreteness-driven relaxation (C. Power) and heating (papers by A. Ludlow and M. Wilkinson) effects that have been shown to negatively impact the properties of simulated haloes and galaxies — a crucial step toward more realistic cosmological simulations of galaxy evolution..

The public release of large simulated data sets, including SAM-based mock light cones built with TAO and new code developed in Australia (e.g. Obreschkow), have allowed different theoretical models to be compared both with each other and with observations, a tactic that is now commonplace in Australian-led papers and an important part of observational surveys. This has also enabled “like-for-like” comparisons between simulations and observations that have helped identify systematics in observational data (e.g. K. Harborne’s SimSpin software; van den Sande et al 2019, etc).

The results above are based on crude models of galaxy formation that do not resolve the formation of individual stars, feedback from stars or AGN, or the enrichment of the ISM. Modeling these phenomena in cosmological simulations is currently not possible (and will likely remain impossible for at least the next decade), and high-resolution simulations or theoretical models of these small-scale processes are instead required. Since 2015, a number of such models and simulations have been developed, leading to an improved understanding of: a) mass-metallicity gradient relations (Krumholz et al 2018 and later works); b) how magnetic fields affect star formation and feedback-driven outflow rates in MW-mass galaxies (Wibking & Krumholz); c) how turbulence and magnetic fields depend on the phases of the interstellar medium (ISM; Seta & Federrath, 2022); d) how gravitational instabilities or feedback-driven energy injection lead to a more turbulent ISM in high-redshift galaxies (e.g. papers Krumholz and colleagues; Jiminez-Henrequez et al 2023); e) the origin and evolution of galactic magnetic fields (Seta et al 2020; Seta & Federrath, 2021); and f) better modeling of galactic outflows, mass and metal loading, and cosmic ray feedback in the multiphase ISM of galaxies (Krumholz et al 2020, Crocker et al 2020a,b; Vijayan et al 2024).

<u>How did the first stars and galaxies transform the Universe?</u>

Reionization and first stars/galaxies will be covered by other working groups, but the DRAGONS Project (The Dark-ages, Reionization And Galaxy-formation Observables Numerical Simulation Project; S. Wyithe) is worth highlighting. DRAGONS used the Australian-led MERAXES galaxy formation model and TIAMAT

DM-only simulation (G. Poole) to study early galaxy formation and includes a temporally and spatially coupled treatment of reionization.

How do stars and planets form?

Since 2015, Australian-led research has shed light on how stars form from molecular gas clouds and the regulating role of magnetic fields, dust, and cosmic rays. In particular, we now have a better understanding of a) the star formation efficiency in molecular clouds and its cloud-to-cloud variation (Zipeng et al, 2022); b) how metallicity drives the transition from the primordial to the present-day stellar initial mass function (IMF; Sharda & Krumholz, 2022); c) how the properties of turbulence affect the stellar IMF (Matthew & Federrath, 2021; Matthew et al, 2023); d) the statistics of magnetized turbulence in the ISM, and how the IMF and local star formation rate (SFR) depends on properties of clouds and magnetic fields (Sharda et al 2021, 2020; Krumholz & Federrath); e) how feedback-driven outflows, radiation pressure, and magnetic fields impact the formation of massive stars (Rosen & Krumholz, 2020). The impact of magnetic fields on the spectrum of dense, star-forming clumps has also been revealed by these simulations, and incorporating these findings into the next generation of cosmological simulations implies modeling dynamo, local turbulence, and CR heating. Some progress along these lines is being made by the astronomy group at the University of Sydney but is currently limited to zoom/idealized runs.

Outstanding problems for the 2026-2035 decade

Star formation and the interstellar medium

We now have a rudimentary understanding of how stars form from molecular clouds and the factors governing their lifetime and internal structure, but how turbulence and magnetic fields regulate SF, and how they contribute to chemical enrichment remain open questions.

During the next decade the CTA will target Galactic star-forming regions, star-forming galaxies, starbursts, and ultra-luminous galaxies, providing insight into the relation between high-energy particles and star formation. Observational data from the GMT (multi-object and integral-field spectrographs; with direct input from ANU, who are designing/building the GMTIFS) will constrain the chemical enrichment history of the MW and other nearby galaxies, the formation of first stars and galaxies, and the distribution of DM in nearby galaxies.

Questions for the next decade include:

1. What roles do turbulence, magnetic fields, and cosmic rays play in star formation on local and intra-galactic scales and in the evolution of galaxies more generally?
2. How is turbulence driven and how are magnetic fields amplified over cosmic time?
3. How are heavy elements created within stars and then distributed throughout the ISM and circum-galactic medium (CGM) of galaxies?
4. How are metals in the ISM lost or retained by galaxies as they evolve?

Answering these questions will require high-resolution simulations of star forming clouds and galaxies that include the effects of turbulence, magnetic fields, cosmic rays, thermal conduction, diffusion, etc.

Theoretical galaxy formation

The small-scale processes described above are rarely included in cosmological simulations, which lack the required mass and spatial resolution to model them. The next generation of cosmological and idealized simulations should aim to close this gap, or to develop physically-motivated sub-grid models that emulate these processes while simultaneously modeling the multi-phase structure of the cold ISM. As observations continue to improve in both quality and quantity, and to probe longer lookback times, more sophisticated galaxy formation models will be required to accommodate them.

Specific topics to be addressed in the coming decade are:

1. The development of realistic sub-grid models for non-thermal physics, including turbulence, magnetic fields, and cosmic rays.
2. Determine the phenomena that drive the baryon cycle in galaxies (e.g. inflows, outflows, mergers, accretion, star formation, feedback), and better understand the mutual feedback between supermassive black hole activity and star formation.
3. Establish whether current galaxy formation models can predict the properties of galaxies in the early universe and, if they cannot, determine what ingredients are missing.
4. Establish how the (phase-space) distributions of gas and DM in and around galaxies co-evolve and how they are affected by varying the DM model or sub-grid baryon physics. (This includes topics such as the kinematics of the CGM, intrahalo gas/stars, the diversity of rotation curves, role of DM substructure, etc.)
5. The development of cosmological simulations that specifically target HI surveys (e.g. WALLABY, DINGO, and future SKA-low surveys; where Australia has a unique observational advantage) is critical.
6. Underpinning all the above, appropriate forward modeling of simulation data to observational spaces should continue to be prioritized. This helps identify systematics in observational datasets and provides constraints on physical processes modeled using subgrid prescriptions. Specific areas for development include: galaxy stellar/gas dynamics, turbulence and magnetic fields, and interactions of AGN jets with their environments.
7. How can we reconcile and exploit new gravitational wave measurements with current models of star formation and galaxy evolution?

What strengths does the Australian community currently have that will ensure we can address those problems; what skills or resources need to be developed?

Existing strengths of the Australian Astronomy community

1. Australia has a strong background in observational astronomy (as evidenced by its leadership in world-class surveys; e.g., SAMI, GALAH, MAGPI, WALLABY, EMU, DINGO, POSSUM) which offers excellent opportunities for fruitful collaborations between Australian theorists and observers.
2. Australian theorists possess diverse expertise (cosmological and magneto-hydrodynamical simulations, analytic and semi-analytic modeling, software development, etc) which should enable collaboration on a broad range of fundamental questions.
3. The theory community maintains strong ties with leading international groups (Virgo, FIRE, Magneticum, BlueTides), allowing us to make important contributions to galaxy formation theory and to the development of the next-generation cosmological simulations, which typically require compute resources that are not readily available in Australia. This emphasizes the need to nurture our existing collaborations and to promote new ones.

4. Australia has world-leading experts in high-resolution (zoom and idealized) simulations of small-scale processes (star formation, turbulence, magnetic fields, cosmic rays, mixing, jets, radio galaxies, etc), as well as in cosmological simulations of galaxy formation. The community is thus well poised to advance our understanding of the multi-scale aspects of galaxy formation, but better connections between groups working on these extreme dynamic scales are needed.
5. There is a large community of Australian astroparticle physicists who are willing to collaborate with astronomers to better constrain the microphysics of the DM particle from its impact on galaxy properties. Developing these collaborations should be a priority.
6. There is a strong commitment by Universities to data intensive astronomy (although mainly aimed at the SKA) and technical support is available to teams and individual researchers through ADACS. Commitments to these programs should be reaffirmed and long-term/permanent software developer roles should be sought.
7. Reasonably good supercomputer access for small-scale projects through merit-based allocations on Gadi and Setonix (but compute-resourcing still falls short of what is required for internationally-competitive cosmological simulations).

Skills or resources that require development

1. Many important physical processes — e.g. molecular clouds, dust grains, radiative transfer, magnetic fields, cosmic rays and turbulence — can only be resolved in idealized or zoom simulations, and thus provide a biased representation of the galaxy population. Current cosmological simulations do not resolve these, and we lack the codes and/or sub-grid models needed to simulate them in cosmologically representative volumes.
2. Australian astronomers lead world-class radio and optical surveys to study star and galaxy formation across a broad range of wavelengths. Theoretical efforts to interpret this data are hampered by various assumptions and often provide limited insights into a small subset of the available data, leading to potential biases that must be quantified.
3. There is thus an increasing demand for instrument- or survey-specific tools to create mock observations from simulated datasets — this promises to maximize scientific returns from survey data and will allow for more meaningful comparisons between theory and observation. This is particularly true for HI and optical surveys, and for faint radio sources that will be observed this decade by the SKA-low.
4. In addition, there is a demand for theoretical tools that can be used to study diffuse gas, including through absorption (e.g. HI, FLASH) and Faraday rotation (e.g. ASKAP POSSUM, various FRB searches). This requires developing analytical and numerical models for absorption and Faraday Rotation in the presence of realistic background sources (AGN or FRBs).
5. As highlighted in the 2016-2025 DP, the compute resources available to Australian astronomers falls short of what is required to carry out ambitious, large-scale projects, including cosmological simulations of galaxy formation and MHD turbulence. Until a solution is found, support for international collaborations that can provide access to compute resources should be prioritized.
6. Australian theorists lack a “flagship” simulation code and as a result have not carried out a world-leading simulation project (e.g. Gadget-3, Swift, Arepo, StarForge). Theorists should identify the type of code that will offer the broadest long-term benefit to the Australian astronomy community and seek support for developing it.
7. Collaborations between groups with diverse expertise (i.e. those carrying out ISM+SF+MHD simulations, cosmological simulations, astro-particle physicists) remains weak, but there is a desire and willingness to improve this.

Identify opportunities that are expected to arise over the next decade and threats that may hinder our ability to take advantage of them?

Opportunities for the coming decade

The next decade will see continued improvements in the quality and quantity of survey data (e.g. ASKAP, MeerKAT, SKA, JWST, Euclid, Nancy Grace Roman Space Telescope, eROSITA, ATHENA) as well as from gravitational-wave observatories on the ground (2nd and 3rd generation interferometers) and in space (e.g. DECIGO, LISA, and pulsar timing experiments). Australia plays a key role in the SKA-Low, which will begin collecting data in the late 2020s. This instrument in particular will shine new light on 1) the distribution of cold gas in millions of $z<1$ galaxies; 2) the cycle of baryons from star forming regions to the ISM of the Milky Way; 3) the structure of magnetic fields from sub-galactic to cosmic scales; 4) the tomography of the neutral IGM in the early universe and when it became ionized. The wealth of data from these surveys will challenge current theories of galaxy formation, star formation and the ISM; and with these challenges will come opportunities for developing the next generation of theoretical models.

The large observational and theoretical datasets that will be collected in the coming decade will result in "big data" challenges; how do we efficiently analyze and disseminate these large datasets? Artificial intelligence and Exa-scale computing are fast-growing industries that may help address these challenges and Australia's supercomputing facilities should be encouraged to build their AI and exascale-computing capacities. This also offers excellent opportunities for industry engagement and co-funded PhDs (with, e.g. private or publicly owned supercomputer facilities, ADACS internships, etc).

The lingering challenge of dark matter will remain a hot topic in the coming decade and with it comes the opportunity for long-term collaborations between astronomers (both theorists and observers) and particle physicists. Establishing and nurturing these collaborations should be prioritized.

Threats that may hinder progress in theoretical astrophysics

Australia has a sizable community of observers who lead many large surveys, but the theory community remains comparatively small and under-resourced, despite a demand for increasingly sophisticated theoretical models. Theorists are also spread thin geographically, which inhibits collaboration. To ensure theoretical astrophysics in Australia remains internationally competitive, the community should seek support for the development of a dedicated center for theoretical astrophysics similar to, e.g, the Canadian Institute for Theoretical Astrophysics (CITA) in Toronto, the Institute for Computational Cosmology (ICC) in Durham, or The Kavli Institute for Astronomy and Astrophysics (KIAA) in Beijing.

Australia has a large body of domestic and international students who wish to undertake PhDs in astronomy but who cannot secure funding; this remains a poorly tapped resource. Those who do find funding and successfully complete their PhDs typically leave Australia to carry out postgraduate work. This is particularly true for theorists, whose pool of potential employers is quite small. The "Strategic Plan for Theoretical Astrophysics 2012—2015" prepared by ANITA flagged the possibility of establishing a national theory fellowship to attract world class theorists to Australia to help address this problem. This possibility was raised again by several members of the Australian astronomy community during discussions for the 2026—2035 DP.

An issue raised in the 2016—2025 DP — namely, that the demand for large supercomputer time allocations remains higher than available resources — will likely remain an issue in the next DP. As a result, the International community is leading the development of the next-generation of cosmological simulations while Australian researchers lack the resources needed to be competitive on all but a few well-chosen fronts. To remedy this, large compute time allocations must be made available to national collaborations (or made easier to obtain), or developing a large network of overseas collaborations must be seen as an asset. Some have suggested that applications for Discovery Projects and other sources of funding are judged too harshly according to whether they leverage Australian-based observing or HPC facilities, and this may hinder our ability to address the big questions likely to arise over the coming decade.

C Appendix - Local galaxies (z<1) white paper

WG 1.1 local galaxies (z~0-1)

Lead Authors: Luca Cortese, Katie Grasha, Jesse van de Sande

Contributions: Keith Bannister, Stefania Barsanti, Andrew Battisti, Jess Broderick, Luke Davies, Simon Driver, Ron Ekers, Deanne Fisher, Marcin Glowacki, Rebecca Davies, Clancy James

1. Report on progress since the last decadal plan

Galaxy evolution is studied through a combination of observational and theoretical approaches. Observationally, astronomers analyse the properties of galaxies at different cosmic epochs over a broad range of wavelengths (or energies). Comparison of galaxy properties (morphology, stellar populations, gas content, chemical composition, dynamics, etc) at cosmic epochs allows us to infer how galaxies formed and evolved over the last 13.8 billion years. Additionally, theoretical models and numerical simulations help to interpret these observations and provide a physically motivated framework underpinning galaxy evolution (e.g., star formation, gas accretion, mergers, feedback mechanisms, interactions with the intergalactic medium).

This is a sub-white paper of WG1.1 "Galaxies", focusing on the redshift range 0<z<1 (excluding the Milky Way) and hereafter referred to as “the Local Universe”. We start by reviewing the progress in the field since the last decadal plan. A lot has been achieved by the Australian community in the last ten years and we believe that the list below should include the most impactful discoveries made by the community (i.e. the most highly cited publications led by Australian astronomers according to NASA Astrophysics Database). We stress that the order of these topics is random and not indicative of priority or perceived impact.

Mapping the missing baryons in the Universe with Fast Radio Bursts

The discovery of Fast Radio Bursts (FRBs) is arguably one of the biggest and highest-impact breakthroughs from the past decade, representing the most intriguing and enigmatic phenomena in modern astrophysics. Initially discovered using single-dish radio telescopes like Murriyang (the 64-m Parkes Radio Telescope), FRBs appear as dispersed pulses of radio emission. This dispersion, where longer wavelengths arrive slightly later than shorter wavelengths, is due to the column of electrons between the burst source and the observer. For FRBs, this total column density is significantly higher than what is expected from the Milky Way alone. Given that the intergalactic medium is much sparser than the space within a galaxy, the implied distances to FRBs are substantial. FRBs have been confirmed to have host galaxies ranging from 2 Mpc distant to a redshift of 1, with yet others having a dispersion suggesting some may originate from sources with redshifts greater than 1.

While unknown in origin, they illuminate the space between galaxies to trace the free electrons that reside in this invisible Warm Hot Ionized Medium (WHIM). The discovery of FRBs has revolutionised this field of astrophysics to map the missing baryons in the Universe. Various astrophysical mechanisms have been proposed to explain their occurrence, including neutron star mergers, magnetars, black hole accretion, and cosmic strings, among others. Despite their unknown origins, the regular detection of extragalactic FRBs now provides for a detailed mapping of the gas distribution in the nearby universe and the best tool to trace what once were referred to as “the missing baryons”. At higher redshifts, they are proving to be potential cosmological probes to explore ionised gas throughout the cosmos.

A modern view of the Hubble Sequence

In the last decade, significant progress has been made to connect the underlying physical processes of the interconnected ecosystem of the baryonic structures of galaxies with their dark matter halos. The kinematics, baryonic, and gas content of galaxies serve as distinctive markers that link evolving galaxy populations over time, shedding light on the physical processes behind the build-up of present-day structures. These advancements are setting the stage for a deeper understanding of galaxy transformation beyond our Milky Way to extragalactic systems across the Hubble sequence.

The breakthrough in this area has been possible due to integral field spectroscopy (IFS) galaxy surveys. In Australia, the main player has arguably been the SAMI Galaxy Survey. The survey, observed with the Sydney-Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph mounted on the 4m AAT at Siding Spring Observatory, has been critical to refine our understanding of stellar and gas kinematics in galaxies, complementing 2D-based (or visual) morphology and providing a physical framework for understanding galaxy transformation. Indeed, it is now established that structural transformation is less important in quenching than previously thought. In addition, SAMI has been instrumental in demonstrating the alignment of galaxy spins with filaments, highlighting the importance of such alignments in understanding angular momentum accretion in galaxies. In the last couple of years, the MAGPI survey (the first Australian-led ESO Large Program) has been able to push these studies up to z~0.3. These Australian-led IFS studies are underpinning the co-evolution of morphology, and environment through combining environmental metrics with kinematic studies.

Improved modelling of star formation in disks, connection between gas flows, turbulence and star formation

Significant progress has been made also on the theoretical front. While this topic will be addressed in depth in another white paper, here we feel it important to flag the primary area where improvements to our theoretical understanding of galaxy formation have also informed observational studies. Specifically, Australian-led research has significantly advanced our theoretical understanding of resolved star formation, highlighting the regulatory roles of magnetic fields, dust, turbulence, and cosmic rays. We now have a deeper insight into the star formation efficiency within molecular clouds and variation between different clouds, and different scenarios proposed for the origin of turbulence in the gas have attracted a lot of attention from the observational community.

Moreover, significant progress has been made in the relationship between the initial mass function of newly born stars, the local star formation activity, and the properties of the birth clouds. It has also enhanced our knowledge of how turbulence and magnetic fields vary across different phases of the ISM, and contributed to improved modelling of galactic outflows, mass and metal loading, and cosmic ray feedback in the multiphase ISM of galaxies. Lastly, the role of cosmic rays in star formation has become more important, with clear progress requiring probing cosmic rays in galaxies via non-thermal radio, X-rays and gamma-ray observations.

Cold gas scaling relations across galaxy properties, setting the foundation for SKA (and precursor) studies

Despite the delays in the start of full survey mode with the Australian SKA Pathfinder Telescope (ASKAP), significant progress has been made in the past decade to transition studies of cold gas in galaxies from studies of individual objects or small samples, to large statistical investigations. This has slowly, but constantly, allowed spectral line studies in the radio to reach sample sizes and types of analysis that have been routinely achieved at other wavelengths in the last two decades.

Specifically, major effort has gone into using observations of the mass and distribution of the cold interstellar medium of galaxies, both in the atomic and molecular phase, into a framework of scaling relations providing a benchmark of how gas content varies with the internal and external properties of galaxies, as well as their redshift evolution. Most of the work in this area has been focused on global galaxy properties, and has also sparked the development of unique analysis techniques such as spectral stacking.

The advent of the Atacama Large Millimetre Array (ALMA) has also made it possible to revolutionise our view of cold gas (primarily molecular) in galaxies at parsec resolution. Unfortunately, as Australian astronomers do not have direct access to ALMA, our community has not been able to lead in this area. Nevertheless, Australia has contributed significantly to such efforts which have enabled detailed studies of the spatial distribution, kinematics, and properties of cold gas in galaxies to inform on the connection between gas dynamics and galaxy evolution. Mapping molecular-to-atomic gas mass ratio as a function of the galaxy environment, placing constraints on galaxy formation simulations and revealing intricate structures and kinematics within galactic disks. This has underscored the importance of resolving individual molecular clouds and assessing their properties in understanding the star formation process.

At the same time, understanding the intricate interplay between galaxy growth, star formation, supermassive black hole accretion, and the circumgalactic medium (CGM) has been a focal point and led to significant progress. Observations have started to allow us to unveil widespread outflows emanating from star-forming galaxies at low redshifts, yet questions persist regarding the fate of ejected material—whether it cycles back into galaxies, remains in the halo, or escapes into the intergalactic medium (IGM).

Getting closer to linking the Milky Way to other galaxies (GALAH's legacy)

Innovative technologies developed in the last decade, spearheaded by GALAH with the AAT at Siding Spring Observatory, have enabled the scaling up of star surveys in our Milky Way to unprecedented levels. The GALAH survey now encompasses a vast number of stars, facilitating detailed examination of chemical evolution from the early universe to the present day, leading to groundbreaking insights into the chemical enrichment and formation of the early Milky Way. Leveraging these data alongside cosmological simulations enables the identification of stellar remnants from galaxies that merged with the Milky Way, elucidating their role in shaping the components of galaxies. While the Milky Way is, technically, outside the focus of this white paper, we feel important to acknowledge it here as, in combination with existing local Universe surveys (e.g., SAMI), we are quickly approaching the scientific regime where it is possible to illuminate fundamental questions surrounding the growth of galaxies over cosmic time and the influence of Galactic and extragalactic stars and systems on the enrichment of chemical elements, applying techniques from GALAH survey to extragalactic systems.

Research leadership and code development

In the last decade, significant advancements in our understanding of galaxy evolution have been achieved, largely thanks to the Australian community's efforts in developing advanced tools and techniques for superior data analysis and processing. While these are not “scientific” achievements, they are now arguably critical for every scientific investigation. Moreover, our community has invested a significant number of resources in these areas and, as such, we feel it is important to recognise the major achievements here.

In code development, this includes large-scale semi-analytic models (SAMs), which have provided important constraints and predictions from AGN activity to galaxy evolution and predictions for the upcoming SKA; critical improvements in spectral energy distribution (SED) fitting, a powerful tool that integrates multi-wavelength data to compare their observed properties with theoretical models to provide a comprehensive picture of the physical and evolutionary properties of galaxies. This includes but is not limited to parameters such as stellar mass, age, temperature, metallicity, dust content, and star formation rate. Comparing observed SEDs with those predicted by different theoretical models enables comparisons to help validate or challenge existing theories about star formation and galaxy evolution.

Australia has also established itself as one of the leaders in the development of techniques to “mock” theoretical simulations, which ensure that comparisons between simulations and observations are “apples to apples”, allowing for observational and theoretical work to be meaningfully compared. Comparing simulated data with actual observations can better interpret observational results; simulations help in understanding the limitations and biases of observational techniques, such as selection effects and measurement uncertainties. In addition to assisting with interpreting data and understanding observational biases, simulations bridge the gap between theoretical predictions and empirical data, providing insights into the complex processes driving cosmic evolution. They help to elucidate the formation and growth of structures from the early universe to the present day.

Lastly, over the last decade, Australian-led research has maintained (and further grown) its ability to lead major observational surveys with ground-based facilities and release the data to the domestic and international community to maximise the scientific impact of their data. Enormous effort has gone into ensuring high-quality of public releases, and it is no surprise that some of the most highly cited papers of the last decade are data release papers. These include:

- Both the Galaxy And Mass Assembly (GAMA) and the Deep Extragalactic VIsible Legacy Survey (DEVILS) surveys, leveraging the Anglo-Australian Telescope at Siding Spring Observatory, utilise extensive multi-wavelength observations to investigate the properties of hundreds of thousands of galaxies across cosmic time. These surveys helped to unravel the complex interplay of galaxy formation and evolution, shedding light on the cosmic web's structure and the role of the environment in shaping galaxy properties.
- The SAMI (Sydney-AAO Multi-object Integral field spectrograph) Galaxy Survey: With spatially resolved spectroscopy of over 3000 galaxies, SAMI provides a detailed view of the internal structure and kinematics of galaxies.
- The GLEAM (GaLactic and Extragalactic All-sky MWA) Survey: Conducted with the Murchison Widefield Array (MWA), GLEAM has provided detailed radio images of the sky at multiple frequencies, covering the entire Southern Hemisphere. GLEAM has been crucial for studying radio galaxies, supernova remnants, and the cosmic web.
- The SkyMapper Southern Survey: Conducted with the SkyMapper telescope, this survey provides optical imaging of the entire Southern sky in multiple filters. It has been instrumental in discovering new celestial objects, such as supernovae and variable stars, and in mapping the distribution of stars and galaxies.

In addition, our community has been incredibly successful in securing leadership of surveys that either just started, or kick-off at the beginning of the next decade, providing a unique foundation to tackle the current big problems in the field. Among them:

- The major ASKAP surveys relevant for the local Universe: WALLABY, DINGO, EMU, FLASH, POSSUM and CRAFT.
- The redshift surveys with the ESO 4MOST facility. The vast majority of the dark time of 4MOST has been allocated to the Australian-led surveys WAVES and 4HS, putting Australia in the driving seat of scientific exploitation of 4MOST in the next decade.
- Similarly, the four Australian-led Large Programs on the VLT (MAGPI, MAUVE, GECKOS, and FURBY) focus on the redshift range on which this paper is focused and will reach their peak of scientific exploitation in the next decade.

2. Identify current big problems where progress can be made in the coming decade

The major advancements in the field described in the previous section have also contributed to a significant paradigm shift in the way we tackle the open questions in galaxy evolution in the "Local Universe", as real (or perceived) barriers between research areas, analysis techniques and facilities used have gradually disappeared.

Studies of nearby galaxies have reached such a level of detail that we can start comparing the local Volume with the Milky Way and look for analogs of our own Galaxy in the rest of the Universe. As such, the separation between Milky Way studies and extragalactic astronomy is quickly reducing and will keep "shrinking" in the upcoming decade. Similarly, kilo-parsec scale resolved studies of galaxies are becoming almost routine across the entire 0 to 1 redshift range, and sub-kiloparsec studies are no longer just limited to the Local Volume. The progress in ground- and space-based facilities has also allowed this field to become panchromatic by default and, specifically, to reveal the multi-phase complexity of galaxy evolution by tracing for the first time all the baryonic components (as well as dark matter) critical for galaxy evolution. As such, our community is moving away from labelling itself according to different parts of the electromagnetic spectrum. This is exemplified by the fact that, contrary to the previous Decadal Plan, working groups in this area have been divided according to science-based instead of technique-based criteria as done in the past.

This change in perspective also implies that we can no longer ignore that the question "*How galaxies form and evolve?*", particularly in the local Universe, is a multi-scale and multi-phase challenge, requiring a truly holistic approach to make significant progress in the next decade. For example, while the physical processes driving the formation of new stars naturally occur on the small scales of star-forming nebulae (parsec-scales), the properties of stellar nurseries dramatically depend on the past evolution of the entire galaxy (kilo parsec scale), as well as on the balance between different gas phases flowing in and out the disc coupled with the effect of feedback processes. In turn, this cycle is modulated by how galaxies move through the large-scale structure of the Universe and interact with each other and groups, clusters and filaments (the mega- and giga-parsec scales). The multi-scale and multi-phase aspect of galaxy evolution is arguably emerging as the primary challenge that our field will be facing in the next decade.

As such, while the overarching questions in this field remain practically the same as in previous decadal plans (e.g., "How galaxies form and evolve?", "Why do we see such a variety of morphologies and histories of star formation in galaxies?", etc.), this paradigm-shift offers the opportunity to re-frame most of these questions in order to highlight the promises of the upcoming decade and make this field clearly multi-scale and multi-phase.

The big problems for the next decade are thus divided below into four main big questions. It is important to stress that they are not ordered in terms of priority, as we believe that it is meaningless to assign priorities given that these are clearly not separate areas. They are all parts of the big puzzle of galaxy evolution and, inevitably, deeply interconnected.

What regulates the star formation process from parsec to giga-parsec scales?

Despite the tremendous progress made in the last decade, in particular, at sub-kiloparsec scales, we are still lacking a complete census of the star formation efficiency of individual molecular clouds across all environments. So far, despite the large number of individual clouds (1000s) already available for these types of studies, these are generally extracted from a relatively narrow range of galaxy types (i.e., massive star-forming disks). As such, expanding these studies to representative samples of merging galaxies, dwarf and early type systems, edge-on and cluster galaxies will be critical to reveal what are the physical drivers of star formation efficiency at this scale. At these scales, one of the crucial missing pieces has been atomic hydrogen. Being the dominant gas phase in the interstellar medium, it is needed for the formation of molecular clouds and star-forming regions, but its distribution at sub kiloparsec scale across galaxy properties is still unknown, as well as what are the physical mechanisms regulating its condensation into molecules.

At kiloparsec scales, we are lacking an accurate reconstruction of the current and past star formation and enrichment history of galaxies across the whole Hubble sequence and redshift, and the ability to link stellar properties to the various phases of the interstellar medium, as well as galaxy structure across the last ~8 billion years. The prospect of assembling a library of star formation histories at kiloparsec scales for hundreds of different regions within a galaxy, for thousands of different galaxies across space and time, and linking them with the status of other baryonic components, central supermassive black-hole properties and accretion rates, as well as dark matter, is particularly exciting. Moving to even larger scales, the fine details of the connection between star formation and large-scale environment are still eluding our community. It is no longer “*merger or no merger*”, “*cluster vs. field*”, or “*central vs. satellites*”. The complex topology of large structure and its constant evolution implies that we need to trace structures at all scales simultaneously, connecting galaxy-galaxy interactions, to group and cluster-related processes via the role of large-scale structure filaments and how galaxies move through them.

What drives the flow of matter in, out and through galaxies?

It is clearly established that galaxies are not isolated entities, but self-regulated systems governed by the balance between gas replenishment (via inflows from the intergalactic medium), consumption (via star formation) and ejection (outflows). Contrary to the study of the star formation process that has made tremendous progress in the last decades, we are still lacking a coherent, and physically motivated, picture on the replenishment and the ejection phases of matter in galaxies. Specifically, despite significant progress in the last decade, very little is known about the properties (distribution, temperature, density and kinematic) of the circumgalactic medium in galaxies and how they vary with galaxy morphology, mass, etc. The interface between the CGM and ISM is a particularly important, but challenging, topic as it hides key information on how galaxies get their gas. Is gas from the CGM directly feeding the disc from the outside-in, so that accretion is primarily happening in the outer parts of discs? Or does accretion take place throughout the disc, following a galactic fountain model? Theory suggests that both scenarios may be viable and their relative importance may change with redshift, but we are still missing significant observation constraints on this.

Whatever the mechanism responsible for how gas gets into the disc, we expect cold gas to flow through the disc, not only feeding star formation but also potentially regulating the level of turbulence in the interstellar medium. The last decade has seen an increased interest in understanding the balance between feedback and gas flows through the disc in regulating the kinematic state of the ISM, but no consensus has been reached due to the limitations of current data.

Moving to stellar populations, we know that not all stars in galaxies have been formed in situ, but a fraction has been formed in other galaxies and subsequently accreted via mergers. The balance between in-situ and ex-situ stars in terms of mass, age and metallicity and their dependence on galaxy properties, environment, as well as components within galaxies (e.g., bulge, thin and thick disk, bar), is an important missing piece in the galaxy evolution puzzle.

Equally important is to make progress on the physical processes driving matter outside galaxies, what is generally referred to as “feedback”. Feedback is arguably one of the key ingredients in our current theoretical picture of galaxy formation and evolution, but still the least constrained by observations. This is true for both AGN- and star formation-driven feedback and we have reached a stage where we can no longer ignore our ignorance of the physics driving these processes. In the next decade, it will be important to start clarifying how common outflows are, what are their typical mass, velocity, density and geometry, tracing multiple gas phases as well as tracing their metal enrichment.

Lastly, understanding the role of magnetic fields and cosmic rays in regulating the flow of matter in and out of galaxies is becoming increasingly critical from the theoretical point of view, but observational constraints are practically nonexistent at this stage.

How much matter is found outside galaxies and how is it distributed?

While understanding the formation and evolution of galaxies is the ultimate goal of extragalactic astronomy, we should not forget that most of the baryons in the Universe are outside galaxies. In the past, this was referred to as “the missing baryon problem”. The expectation has always been that the missing baryons were hiding in the intergalactic medium (IGM), and the advent of Fast Radio Bursts as a tool to measure the amount of baryons throughout the intergalactic medium has revolutionised this field and allowed the first reliable quantification of the total amount of baryons in the Universe. However, the number of Fast Radio Burst is still relatively small, meaning that we are very far from being able to reconstruct the 3D structure of baryonic matter in the Universe. Even if we focus on individual components, such as stars, atomic hydrogen and metals, it is still unknown what fraction of their mass lies inside galaxies and how much is “free-floating” in the IGM. We have no idea yet on the amount of intra-halo stars in galaxies and how this changes across space, time and galaxy properties. Similarly, the last decade has seen an increase in detection of free-floating atomic hydrogen clouds with little or no optical counterparts, but their abundance, origin and contribution to the global gas mass budget in the Universe is still unclear. The situation is even worse when it comes to the distribution of dark matter in the Universe. While in the last decade we have been able to improve our understanding of the distribution of dark matter halos in the cluster and big groups mass regime, tracing small groups and individual halos remains challenging. As these are the most abundant halos in the local Universe and critical for an accurate determination of the halo mass function, we need to push to lower halo masses to provide more credible constraints to model predictions of the dark matter distribution in the Universe, specifically outside galaxies.

How does dark matter affect the distribution of baryons (and vice versa) in and around galaxies?

The challenges and unknowns described in the previous question bring us back full circle to the symbiotic link between dark matter and baryonic components in regulating the structure of galaxies. On small scales, we haven't yet been able to assess what is the exact distribution of dark matter within galaxies, how this changes with galaxy properties, and whether feedback plays any role in it. This is exemplified by the so-called core-vs-cusp problem where we seem to see a discrepancy between the observed density profile of dark matter and those predicted by simulations. Is this an issue with the data, with our theoretical models, or both? In addition, reliable constraints on how the dark matter density profile varies as a function of redshift is still missing, as only recently we are starting to be able to measure dark matter density profiles across the entire $0<z<1$ redshift range, although not yet using the same techniques. At galaxy scales, the role of galaxy interactions and mergers to the distribution of baryonic and dark matter is still unclear. While it is now fully established that galaxy mergers have become less and less important from redshift 1 to 0, the exact quantification of the merger rate of galaxies as a function of mass has not yet been pinned down. This is particularly important to determine under which conditions ex-situ stars are important for a full understanding of galaxy evolution, and at which redshift in-situ growth by star formation becomes the dominant growth pathway for galaxies.

3. Identify capabilities that allow Australia to contribute to big problems and what we require to be competitive

A focus towards a multi-scale and multi-phase analysis of galaxies in the next decade will require new solutions for bringing together multi-wavelength facilities and terabyte or petabyte analysis capabilities and resources. Owing to the significant investments of the last decade, Australia already has guaranteed access to a range of facilities. This places us in an unparalleled position to confront the major challenges of the upcoming decade, provided we capitalise on these resources to their fullest extent. Most importantly, combining full ESO membership with the SKA will lead us to a watershed moment, where we can unravel the multi-scale and multi-phase physics of galaxies. This should arguably remain the top priority for the next decade.

Ground-Based Facilities

Multi-wavelength imaging and optical and (near-infrared) NIR spectroscopy will continue to play a fundamental role in observing the evolution of galaxies at all scales. Continued access to ground-based 4m and 8-10m class telescopes, at sites with excellent seeing conditions, will therefore remain crucial for both low-surface brightness, high-spatial-resolution, and spectroscopic follow-up.

The next decade will see Australian-led VLT-MUSE large programs come to maturity, capitalising on the ESO partnership investment. Where MAGPI traces the evolution of galaxies back in time, both GECKOS and MAUVE will have a unique impact on studying the multi-scale and multi-phase properties of galaxies by combining VLT/MUSE with ALMA and SKA precursors, and FURBY will push our understanding of host galaxies of FRBs. Australia's outstanding performance in leading large programs will likely continue until the end of the partnership agreement, especially when combined with the ASKAP surveys.

Connecting all scales will be made possible with VLT-MAVIS. Its spectacular angular resolution, down to 18 milliarcseconds, will allow us to resolve individual stars in nearby galaxies, and utilise the power of colour-magnitude diagrams as accurate probes to differentiate between different stellar population ages and metallicities, resolve the physics of ram-pressure stripping in local clusters, and resolve substructures in galaxies out to a redshift z=1. Besides diffraction-limited imaging, VLT-MAVIS will have a powerful IFS mode with multiple spatial scales, spanning the full optical wavelength range, with a spectral resolution from 5000-15,000. The instrument's exquisite image quality in the IFS mode will give Australian astronomy the capability to use all available optical diagnostics to measure the chemical and dynamical processes, from parsec to kpc-parsec scales that MAVIS will uniquely probe. Australia will have unique access to this ESO facility through significant Guaranteed Time Observations as part of building MAVIS.

Australia's leadership in 4MOST with the 4HS survey will yield a high-completeness spectroscopic sample of 6 million galaxies at $z<0.15$ across the full southern hemisphere. This survey will have an exceptional legacy value for determining the driving forces of the flow of matter in, out, and through galaxies. By simultaneously targeting much fainter and more distant galaxies (but over smaller fields), with 4MOST WAVES we will be able to measure the Universe's large-scale structures such as groups, filaments and voids, and their emergence and evolution during the past 7 billion years. On smaller scales, the WAVES spectroscopic survey will probe the size and mass distribution of galaxy groups and measure galaxy merger rates. Both the 4HS and WAVES surveys will be crucial in providing the environmental diagnostics, as well as pair and merger samples, required to link all of the galaxy studies to the larger-scale environment.

The advent of the Vera Rubin Observatory's survey (LSST) will greatly advance the availability of deep multi-band imaging (*u, g, r, i, z,* and *Y*) and transform our ability to investigate targets of interest found with other facilities (e.g. 4MOST, ASKAP). Over 10 years, LSST will observe the entire southern sky, on a weekly basis. All survey data combined will contain ~20 billion galaxies. With LSST, we will be able to understand the diffuse Universe and link the baryons with their haloes, through measurement of the intracluster or intra-halo light and low-surface brightness galaxies. While *immediate* data access for Australian scientists beyond 2028 is currently uncertain, all Rubin Observatory data is expected to become fully public after two years of observations. Furthermore, through a partnership with LCO and local facilities such as the Huntsman Telescope, Australia will have an amazing opportunity to pursue deep explorations of the low-surface-brightness Universe.

Over the last two decades, Australia has been a world leader in fibre-based single-object and multi-object IFS galaxy surveys. Even with more powerful multiplexed fibre instruments on the horizon, the AAT still has the capabilities to continue to deliver high-quality observations using 2dF, KOALA, and Hector. 2dF will remain competitive in the Southern Hemisphere for science that is not scheduled as part of the new surveys (e.g. 4MOST). KOALA can be utilised to fill a niche area in monolithic IFS follow-up, for wavelength ranges and spectral resolution that are not accessible to MUSE. Lastly, Hector is the only multi-object IFS instrument that has a spectral resolution high enough to determine the stellar kinematic properties of low-mass galaxies (log $M^*/M_\odot < 9$) and the outer regions of disk galaxies. The Hector Galaxy Survey is expected to observe a total sample of 15,000 and has the opportunity to connect galaxies across scales.

One of the most significant local prospects on the horizon for the next decade lies within the realm of the Square Kilometre Array project (SKA), with one of the two telescopes (SKA-low) located on Australian soil in Western Australia. The SKA will be the globe's largest and most adaptable radio telescope, poised to unravel some of the most profound mysteries in astrophysics. With SKA construction already started, and the first science verification data to be taken in 2027, the next decade will see exponential growth in our ability to probe the radio sky.

The first half of the next decade will also see a continued focus on taking advantage of the Australian SKA precursors. With the Australian SKA Pathfinder (ASKAP), there are several surveys focused on understanding the role of cold neutral hydrogen gas (HI), using the 21-cm line of neutral hydrogen in galaxy evolution (e.g. DINGO, WALLABY, FLASH). These surveys have now concluded their pilot programs and have begun observing in full-survey mode over the coming years, and will play a vital role in measuring the integrated and resolved HI gas content of galaxies deep into the Universe. Similarly, other ASKAP surveys (e.g. EMU, POSSUM, CRAFT, etc) will play a critical role in determining the cosmic history of star formation in galaxies, the role of magnetic fields, and the low-density material surrounding galaxies. Combining these surveys with large spectroscopic campaigns (e.g. GAMA, DEVILS, SAMI, Hector, 4MOST) will lead to a truly unique opportunity to develop a full multiphase picture of gas accretion and feedback processes from stars and black holes.

The MWA is the longest-running SKA precursor and has produced one of the largest catalogues with radio sources, including galaxies and their AGNs. Ongoing surveys such as GLEAM-X will continue to provide deeper and more detailed radio catalogues. Due to its success, the low-frequency SKA (SKA-Low) will be built at CSIRO’s Murchison Radio-astronomy Observatory in Western Australia, in the same area as the MWA. SKA-Low will operate at frequencies between 50 and 350 MHz and is scheduled to commence full science operations before 2030. Due to its larger number of antennae and longer baselines, SKA-Low will achieve a greater sensitivity and higher resolution than its precursors. SKI-Mid, to be located in the Karoo region of South Africa, will operate between 350 MHz and 14 GHz. Combined, SKA-Low and Mid will give the Australian community a powerful new tool to study the evolution of cold gas and WHIM in galaxies out to z~1.

Space-Based Facilities

Contrary to ground-based facilities, access to space-based observatories is possible due to the U.S. open skies policy, which guarantees any researcher (U.S. or international) equal and free access to U.S. federally funded telescopes. Space-telescope data will be used to provide a higher-resolution view needed for lensing studies, morphologies, structural decomposition, and the identification of merger systems.

The Hubble Space Telescope (HST) remains a powerful telescope that can obtain diffraction-limited imaging from UV to NIR. Despite its age, it continues to deliver excellent high-quality imaging at wavelengths inaccessible by other facilities. Within just two years of being operational, JWST has proven to be the next flagship observatory, revolutionising infrared astronomy. With its high-sensitivity and high-resolution imaging NIRCAM and MIRI instrument, as well as NIRSPEC spectroscopy, the detailed properties of galaxies can be traced back across time, we are seeing new objects that were too old, distant, or faint for HST. In nearby galaxies, JWST has given us a spectacular new view of star formation and outflows. At intermediate redshift, it has revealed a wealth of details in clusters, allowing us to probe the small-scale structure of lensed galaxies at high redshift.

The next decade will also see ESA's Euclid mission come to fruition. Euclid will also observe more than one-third of the extragalactic sky outside the Milky Way in the optical and NIR, with image quality at least four times sharper than ground-based sky facilities. Data will be released to the world in yearly data releases. Complementary to Euclid, NASA's Nancy Grace Roman Space Telescope, to be launched in 2027, will provide a high-resolution wide-field, 100 times larger than HST, in the visible and near-infrared. With an expected launch in 2025, SPHEREx will measure 40 narrow-band photometry from optical to mid-IR, for all sources in the entire sky brighter than magnitude 21, which will result in tens of millions of photometric galaxy redshifts. While operations of the space-based X-ray instrument eROSITA are currently suspended, the planned all-sky surveys would be transformational for detecting galaxy clusters and active galactic nuclei. The X-Ray Imaging and Spectroscopy Mission will also provide high-throughput imaging and high-resolution spectroscopy, with data to become publicly available after one year.

Connecting Theory and Observations

Simulations of galaxies play a crucial role in trying to test theoretical predictions of galaxy formation and evolution. However, the validity of simulation predictions becomes more powerful when compared to observations. While many different approaches for simulating galaxies exist, a crucial hurdle for next-generation simulations will be coming from subjecting them to observations that the simulations were not specifically calibrated to replicate. Observing galaxies in higher resolution, in different wavelengths, or deeper into the universe, will reveal more complex physics and more extreme objects, constantly pushing the simulations to the limit.

Australia has been successful in bringing together teams of theorists, simulators, and observers in the past, in pursuing the common goal of understanding how galaxies form and evolve. With a strong track record in comparing simulated mock galaxies with observational data, a continued effort in forward modelling simulated data tailored to ESO and ASKAP/SKA facilities will be crucial for being able to tackle the big problems and remain competitive on the astronomical world stage.

Meeting the Demands of Observational Surveys in the Next Decade

Access to Hyper Performing Computing and Cloud storage is no longer just a necessity for theoretical studies and large simulations but has become an integral part of observational surveys for data reduction and data analysis. Leading large observational surveys has highlighted new challenges for storing, reducing, accessing, and sharing data. Having access to HPC for computing is no longer enough, as observational surveys now require simultaneous computing power and storage reaching tens of terabytes of data. Conventional methods for running data reduction and analysis on “local” machines have become infeasible, limited by network speeds and storage access, as well as limited computing power.

Team-wide access to raw, reduced, and analysed data, furthermore requires access to a single-entry system that supports the needs of domestic and international astronomers. Having the data storage and computational abilities in one place will be essential. With increasingly large datasets, the traditional approach of using data reduction and analysis software also becomes inefficient. Only with the help of data and software engineers, e.g. through the ADACS and programs, can we make our data reduction and analysis software on HPCs more optimised for dealing with terabytes or petabytes of data.

Continued (and hopefully a significant increase in) nationwide storage, computational power, and support — such as through Pawsey, the Australian SKA regional centre, and DataCentral — will be essential for the success of large observational programs.

4. Identify opportunities that are expected to arise over the next decade, and what threats to our ability to take advantage of those opportunities?

Observing opportunities

Australia is uniquely positioned to address many of the big science questions outlined for the coming decade. Nonetheless, there are several opportunities that we should invest and capitalise on to avoid running the risk of losing leadership and our ability to set the next decade's scientific agenda.

The transition from the ESO partnership to becoming a full member will allow access to many more key facilities and strengthen our ability to lead large multi-wavelength observational campaigns. ESO's Extremely Large Telescope (ELT) will be the first of the thirty-metre class telescopes to come online. The ELT will have a suite of instruments uniquely aligned to the needs of the Australian community, both for high-resolution imaging (MICADO) and integral field spectroscopy (HARMONI). In parallel, further commitment to the development of the Giant Magellanic Telescope (GMT) will make Australia the only country with unique access to the two of world-leading telescopes of the next decade. The next generation of ELTs will enable stellar spectroscopy of individually resolved stars beyond M31 probing galaxies out to 5 Mpc, and semi-resolved out to 10Mpc.

Furthermore, access to the submillimetre-wavelength regime with ALMA will give Australia the ability to study the complete multi-phase ISM in galaxies. Australian astronomers have already an excellent track record in securing most of the "open skies" time with ALMA. However, this is a tiny fraction of the time offered by the observatory and our community is forbidden from leading any large program.

Full ESO membership would also facilitate Australia playing a key role in building the next generation of instruments and survey telescopes, in particular the Wide-Field Spectroscopic Telescope (WST) and BlueMUSE. Tailored to Australian needs and strengths, WST combines the power of multi- and large field-of-view spectroscopy in a facility with the ability to spectroscopically explore the entire Southern Sky in larger depth than ever before. Following in the footsteps of MUSE, ESO's most in-demand instrument, BlueMUSE will fill a niche parameter space by targeting bluer wavelengths and a larger field of view. BlueMUSE will enable new and unique science opportunities in extragalactic astronomy, beyond those possible with current instruments.

Australian extragalactic astronomers are doing exceptionally well at leading large surveys, utilising every available telescope (e.g. AAT, ASKAP, SKA, 4MOST, VLT) to deliver ground-breaking science. Without continued access to any of these facilities, Australia will lose its capability to lead and drive the direction of the scientific landscape in 2030 and beyond. Hence, securing full ESO membership will be of the utmost importance.

The next decade will also see the launch of the Nancy Grace Roman Space Telescope, an infrared wide field facility that will survey our galaxy and other nearby galaxies. On the ground, the CTA (Cherenkov Telescope Array) will be part of a new generation of ground-based gamma-ray instruments, whereas AtLAST – a 50-meter class single-dish – will observe the sub-millimetre and millimetre wavelengths.

All these new facilities come with a potential risk. Uncertain completion dates of telescopes and instruments may present a challenge for the community in securing ongoing funding. Delays with telescopes that are “too big to fail” (e.g. JWST) have had a major impact on funding the science programs with these facilities, while also impacting smaller facilities funded from the same budget. Facilities with strong Australian leadership, e.g. 4MOST, ASKAP, and SKA, have already experienced delays due to the complexity of instruments and have impacted the timeline for operational capabilities These projects drive technological advancements, create educational opportunities, and become the facilities available for the next generation of scientists. By successfully navigating the challenges, we can ensure these facilities reach their full potential, delivering insights into our understanding of the cosmos.

Computational opportunities

The next decade will see a near-exponential growth in observational data, increasing in both volume and resolution. However, there is a significant risk of progress being hindered by limited computational resources, including hardware, software, and expertise.

An analysis focusing on the multi-scale and multi-phase analysis of galaxies will require a revolutionary approach to storing, analysing, and accessing the terabyte or petabyte of data from multi-wavelength facilities. The current approach separating centres based on facilities or wavelengths is not scaleable or adapted for the data challenges of the next decade. An excellent example of such an approach is the Canadian Astronomy Data Centre or the IDIA in South Africa, which has a centralised cloud infrastructure enabling data-intensive astrophysical research for all types of surveys, facilities, and wavelength regimes. Without a significant investment in this area, not just in resources but also in approach and coordination, Australia is at risk of being of having our computational facilities become ineffectual for our community's needs,

Equally important, interpreting these increases in data rate and volume in the next decade will require a significant computational investment. Integrating expertise in computational physics to complement observational efforts has been a crucial objective over the past decade. With the recent success of more data-intensive, large-volume ESO programs, this integration has become even more essential today.
The recent focus on exploiting large international build simulations has been incredibly successful, but there may be room to lead more model development. Significant progress has already been made in providing the community with software that brings observational and simulation results closer together, but future progress may require more tailored simulations and increased theoretical effort. While the current size and computational resources may not be optimised for leading large-volume hydrodynamical simulations (e.g., EAGLE, IllustrisTNG, Magneticum), a stronger and more coordinated effort should be pursued to explore the most effective and impactful strategies.

Community

With an impressive list of observational and theoretical accomplishments, current efforts, and future goals, continued investment is required into a community with broad skill sets and expertise to utilise these opportunities. The experience gained in running large surveys in the previous decade has led to a rapid expansion in the number of successful Australian-led surveys. However, as the size of our community is limited, a large number of surveys has left the community spread thin resulting in a large overlap of members across multiple teams. This creates a critical issue for a community that is aspiring to expand its leadership in new areas (e.g., space) while maintaining major engagement in SKA surveys, 4MOST and hoping to secure (and exploit) full ESO membership. Either the level of funding available to support the community (from the number of PhD scholarships to continuing positions) receives a boost in the next decade, or we will be forced to significantly downgrade our goals. This particular field has experienced a golden 15-year period thanks to the support from two ARC Centres of Excellence. Now we are standing at the edge of the cliff, and it is imperative that our community finds a way to keep growing and remain competitive at an international level.

In addition to funding, a shift in how the community works would be beneficial. More coordination in sharing resources and developing team-wide applicable codes could avoid duplication of efforts and waste of resources. Related to this, while the current funding climate does not reward or encourage large science teams to develop community resources, perhaps a more data-science-focused centre could fulfil this role, similar to the role of ADACS, but on a larger scale. A growth in the number of software or focussed positions is also required if we want to take advantage of all the facilities we will have access to. To attract a larger number of talented domestic and international postdocs, an investment in longer-term postdocs could increase efficiency and short-term knowledge drain in projects.

D Appendix - Cosmic noon (z~1-6) white paper

2026-2035 Decadal Plan White Paper

WG 1.1: Galaxies and Cosmology - Cosmic noon

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Progress since the last Decadal Plan

Cosmic Reionization and Lyman-continuum emitting galaxies at z ~ 3-5 - Measuring the escape fraction of ionising radiation from galaxies as close as practically possible to the Epoch of Reionization as analogs of those at z > 6, has now produced a handful of excellent sources and many candidates from a variety of techniques (Cooke et al., 2014, Mestric et al., 2020, Prichard et al., 2022, Wang et al., 2023, Kerutt et al., 2024, Gupta et al., 2024). It has been found that measuring the escape fraction in individual galaxies produces an observational bias due to the stochastic nature of the absorbing foreground IGM (Bassett et al., 2019, 2021).

Lyman-alpha (Lya) emitters, blobs and cosmic web at 2 < z < 6 - Much progress on understanding these phenomena has been made with large-field IFUs like MUSE on the VLT and KCWI on Keck. The sensitivities of the IFUs have mapped Lya emitter evolution and further support previous detections of extended gaseous halos surrounding many distant star-forming galaxies (e.g., Steidel et al, 2011, Leclercq et al. 2017, Mukherjee et al., 2023). They have revealed ubiquitous Lya blob emission around all quasars and the cosmic web has started to be imaged in line emission.

Metal absorbers and the CGM – Metals via their detection in absorption-line systems at high (z > 3) and low (z ~ 0) redshift are now fully accounted for, solving the ‘missing metals problem’ (Macquart et al., 2020, Davies et al., 2023).

Galaxy outflows - Over the past decade, sensitive new instrumentation has propelled the study of outflows at cosmic noon from a focus on individual powerful outflows to galaxy population statistical studies. Large near-infrared galaxy surveys enabled the first census of ionised outflows at $1.5 < z < 4$ through [NII]+H-alpha emission (Foerster Schreiber & Wuyts 2020), revealing that star-formation-driven and AGN-driven outflows have distinct properties and that ionised outflows likely do not remove gas fast enough to quench star-formation. Cold gas outflows have been much harder to study. ALMA has revealed the presence of cool outflows at $z \sim 5$ through [CII] emission (e.g., Ginolfi et al. 2020) and OH(+) absorption (e.g., Spilker et al. 2018), although the prevalence of such outflows across the galaxy population is not well understood.

The launch of JWST has heralded a new era in the study of feedback because we are now able to routinely detect continuum emission from galaxies at cosmic noon, enabling us to measure galaxy star-formation histories and detect cool outflows through NaD absorption. Early studies suggest that AGN-driven neutral-atomic outflows are much stronger than their ionised counterparts and may be linked to rapid quenching of star-formation in massive galaxies (e.g. Belli et al. 2024, Davies et al. 2024).

Kinematics and star formation - Large near infrared spectroscopic surveys, particularly those making use of KMOS and SINFONI on VLT, led to significant advances in our understanding of the kinematics and spatial distribution of star-formation, ISM properties, and feedback across galaxies out to z~3 (see Forster Schreiber & Wuyts 2020). Spatially resolved ALMA [CII] observations provided the first insights into the kinematics and structure of typical star-forming galaxies at z~5, revealing that a large number of them are interacting and have very irregular structures compared to their lower redshift counterparts (e.g., Le Fevre et al. 2020).
Statistical samples have been built up from 3D-HST, MOSFIRE, KMOS, VIMOS across 'deep fields' that have produced large samples of IFU results show the evolution of disk fractions, TFR, angular momentum, dark matter fractions, MZR, and information on winds (Förster Schreiber & Wuyts 2020). ALMA+NOEMA have been used for measurements of molecular gas fractions for large samples of galaxies (e.g., Liu et al. 2019).

Cosmic Star Formation History and AGN History - Direct and forensic methods explored by GAMA+COSMOS+3D-HST and DEVILS.

Cosmic background - Leading measurements of the Cosmic Background and EBL (which peaks around z ~ 1-2) from UV to radio and significant roles in legacy programs to reanalyse the entire HST and JWST archives (SkySurf and DarkMAPS).

Cosmic noon supernovae and insight into galaxy formation - Using deep, wide-field surveys (e.g., CFHT Legacy Survey, DECam SN survey, Subaru HSC SSP/SHIZUKA), over ~100 core-collapse and superluminous supernovae have been detected at z ~ 2-4 over the last decade and a subset spectroscopically confirmed. These events have high utility for galaxy formation and evolution (outflows, IMF, cosmic star formation rates and chemical enrichment history, etc.), as background beacons to study host ISM, CGM, and intervening IGM in absorption, and probes of cosmic reionisation. They provide one of our only means to probe the z ~ 2-20 Universe using existing and upcoming facilities (8m-class wide-field imagers, Roman, JWST, ELTs). Their rates have been shown to be higher than expected and, as these events are predicted to have high-mass progenitor stars, suggests an evolution or environment effect resulting in a top-heavy stellar initial mass function. High redshift pair-instability supernova candidates have been detected, which provide insight into Pop III stars. Finally, a class of superluminous supernovae shows promise as a standardisable candle and, if confirmed, would provide a consistent means to measure the expansion rate of the Universe from z ~ 0-20.

Space Observatories - JWST is dominating the progress in galaxy evolution. Its NIRSpec and NIRISS IFU, multi-object, and wide-field slitless spectroscopy have been very useful for z ~ 1- 6 galaxy evolution, as they provide rest-frame optical emission lines that are widely used for ISM diagnostics. An expectation is that 2-3 JWST cycles will provide more galaxies with ‘robust’ measurements (i.e., with multiple emission lines for diagnostics) at this epoch than has been measured from 8-10m facilities and HST since they were built. For example, a large Cycle-1 pure-parallel WFSS program with JWST/NIRISS called PASSAGE has obtained ‘robust’ spectroscopy for ~1000 galaxies at cosmic noon (e.g., ~4x more than the MOSDEF program using Keck/MOSFIRE). There are similar JWST programs planned and targeted spectroscopic programs, such as JADES. The Euclid Space Telescope is starting a survey with NISP that will provide wide-field slitless spectroscopy across a large area of the sky and the NASA Roman Space Telescope will be launched between October 2026 and May 2027 that will provide deeper capabilities over wide fields.

Fast Radio Bursts - FRBs have been confirmed as incredibly bright transients that originate from galaxies at cosmological distances. Progress has been made in FRB research in confirming that FRBs directly measure the total line-of-sight ionised baryons and are our only direct means to probe the gas content of the Universe. Known FRB host galaxies have been identified up to z = 1, and modelling suggests that some currently detected FRBs originate at z ~ 2, enabling a probe of the peak cosmic star formation at cosmic noon and helium reionization.

Current problems to progress in the coming decade

1. What Processes Induce and Arrest Star Formation in Galaxies?

a. **Star formation across all stellar masses:** The environments at cosmic noon were markedly different from those observed in the present universe, and studying these differences is key to developing a comprehensive model of galaxy formation and evolution.To fully understand the baryon cycle and its impact on galaxy evolution, it is crucial to understand the mass and energy budget of galaxies across all stellar masses. While extensive research has focused on massive galaxies, low-mass galaxies have received less attention due to their intrinsic faintness and compactness. The next decade is ripe for making major advancements in extending our understanding of star formation across all stellar mass ranges. Major advancements can come from extending the scaling relations such as the Tully-Fisher Relation (TFR), Mass-Metallicity Relation (MZR), and Main Sequence (MS) to low mass star-forming galaxies. Large spectroscopic surveys on ground-based facilities such as MOONS or space-based facilities such as Euclid, Roman, JWST and WST in the coming decade will provide large statistical samples of galaxies at cosmic noon across all stellar mass ranges for such studies.

b. **Quenching of star-formation in low mass galaxies:** Outflows play a significant role in galaxy evolution by expelling gas and regulating star formation. Instruments like the Keck Cosmic Web Imager (KCWI) have made progress in studying nearby outflows, but there remain uncertainties about whether these processes operate similarly at cosmic noon, a period when galaxies were more gas-rich. Feedback from the AGNs dominate at high stellar masses. But feedback mechanisms, such as supernovae and stellar winds, are more dominant at low stellar masses, where our observations so far have been extremely lacking. The integral field spectrographs on 30m-class telescopes will have the sensitivity required to resolve the detailed structure and dynamics of low-mass galaxies, enabling in-depth studies of star formation and galactic winds. In addition, superluminous supernovae occur in low-mass galaxies and can completely arrest star formation in the smallest, while inducing star formation in more massive systems. As low-mass galaxies at high redshift are theorised to make a significant contribution to EoR, these events can challenge that assumption. 8m-class wide-field optical imagers, Roman, JWST, and ELTs are needed to measure their impact and progress this field.

c. **Early Quenching of Massive Galaxies:** Recent discoveries have identified massive quenched galaxies as early as redshift z~3 indicating that these galaxies underwent extremely rapid formation and subsequent quenching of star formation. Thus, the mechanisms responsible for halting star formation must be both highly efficient and effective over short timescales. AGN feedback has long been considered the primary driver behind the quenching of star formation in massive galaxies. However, the precise efficiency of AGN feedback in suppressing star formation and the exact timescales over which it operates remain areas of active research and debate. The advent of large spectroscopic facilities will allow us to conduct a full census of star formation quenching pathways at cosmic noon. Follow-up observations with sensitive instruments will provide insights into the physical conditions within galaxies, including the presence and impact of AGN activity, star formation rates, and the distribution of gas and dust.

2. What role does the cosmic web play in the formation and evolution of galaxies?

a. **Large Scale Structure:** Reconstructing the large scale structure is essential to understanding galaxy formation and evolution. Wide-field optical imagers (Rubin, HSC, Keck Wide-Field Imager) and infrared imagers (Euclid and Roman) can help map LSS significantly deeper and with high spatial resolution. New methods exist to select galaxies at cosmic noon by their spectroscopic properties using only broadband imaging, as well as their large scale environments, to compare with simulations. Wide-field spectroscopic facilities, like the 4m-class DESI nd 4MOST and the 10m-class Subaru PFS, WST and the Maunakea Spectroscopic Explorer, along with SphereX will make a step change, gathering 100s of millions of spectra.

b. **Accretion of gas:** Gas accretion is critical to the cosmic baryon cycle, particularly at cosmic noon. Quasar sightline observations detect extended HI gas around galaxies, suggesting significant direct accretion of gas at cosmic noon. However, identifying and studying gas accretion remains challenging due to the limited number of effective tracers. Despite these challenges, current instruments like the ALMA, MUSE are making headway.

   In the coming decade, deep IFU observations of MgII or Lyman-alpha emission lines will help detect inflows and outflows of gas. The upcoming MOS/IFU facilities, including the proposed WST, will excel in probing Mg II at cosmic noon, offering the necessary sensitivity to study gas inflows and outflows in detail. The Keck WFI will have the sensitivity to detect and map Lya, MgII, OVI and other gas in emission via its narrowband imaging for galaxies, their CGM and the IGM/ICM over Mpcs. Planned upgrades to ALMA will increase its sensitivity and

resolution, allowing for more detailed studies of gas accretion. Conducting large, multi-cycle surveys with ALMA is essential to map the inflow and outflow of gas across a diverse range of galaxies and environments. These surveys can significantly enhance our understanding of the mechanisms driving gas accretion.
SKA will provide new insights into the role of HI by offering direct observations of HI at the lower end of cosmic noon and absorption measurements at higher redshifts. This will help clarify how HI contributes to the gas accretion process and its significance during different cosmic epochs.

c. **Preprocessing and proto-cluster formation:** Galaxy clusters are the largest gravitationally bound structures in the universe, yet the timeline and mechanisms by which these colossal entities began to form and influence the evolution of their constituent galaxies remain largely unclear. To fully understand the preprocessing of galaxies, the formation of massive clusters, and the phenomenon of downsizing—where more massive galaxies form stars earlier and evolve faster than their less massive counterparts—extensive redshift surveys are essential. Highly multiplexed facilities in near-infrared such as MOONS, JWST-NIRSpec/NIRISS, Euclid, wide field imager on Suburu/ULTIMATE will significantly enhance our ability to gather large statistical samples necessary for studying galaxy environments at cosmic noon.

3. How was the Universe chemically enriched?

Chemical enrichment of the universe still remains a mystery. Cosmic noon is the period of extreme star-formation activity where presumably a bulk of metals would have been produced. Understanding how these metals were created and distributed from the first galaxies to those we observe in the local universe is a ripe area for research in the coming decade.

a. **MZR across cosmic time and stellar mass range:** The mass-metallicity relation (MZR) describes the correlation between a galaxy's stellar mass and its metal content. To study the MZR across different cosmic epochs and stellar masses, highly multiplexed near-infrared facilities such as MOONS (Multi-Object Optical and Near-infrared Spectrograph), JWST (James Webb Space Telescope) NIRSpec/NIRISS, and Euclid are indispensable. These instruments will gather large statistical samples of galaxies and target rest-optical emissions, enabling accurate estimates of metal content throughout cosmic history.

b. **New metallicity calibrators:** One of the major opportunities for the coming decade is the revision of existing metallicity calibrators. Current empirical and theoretical relations were developed using observations of low-redshift galaxies. However, these calibrators may not be applicable to galaxies in the early universe, which exhibit different internal conditions such as higher pressures and temperatures. Developing new calibrators suitable for these conditions is essential for accurate metallicity measurements at high redshifts.

c. **Building the enrichment ladder:** Moving beyond total metallicity measurements, the next decade will be about the relative abundances of various elements. For instance, observations have suggested variations in the nitrogen-to-oxygen ratio or alpha-elements at high redshifts due to the relative lack of Type Ia supernovae in the earlier epochs. Understanding these relative abundances will provide deeper insights into the nucleosynthetic processes and the chemical evolution of galaxies.

d. **CGM metal absorption and emission:** CGM is the interface region surrounding galaxies where much of the metal and baryon recycling occurs. At cosmic noon, quasar absorption line studies have provided extensive measurements of low and high ionisation species such as Mg II, C IV, and O VI etc. But we need to probe the spatial distribution and dynamics of various species across galaxy types to understand the detailed metal recycling processes in galaxies during this critical period.

4. What shapes the internal structures of galaxies?

One of the most compelling science drivers for next-generation telescopes, such as the Giant Magellan Telescope (GMT) and the James Webb Space Telescope (JWST), is the study of the formation and evolution of spiral galaxies like our Milky Way. According to current theoretical models, galaxies form inside out, initially assembling halos around compact, dense cores. In the past decade, some observations have suggested the presence of rotation-dominated disks as early as redshift z~9-10. However, the pathway from the irregular, clumpy galaxies observed at cosmic noon to the grand-design spirals like the Milky Way remains elusive. Understanding this transformation is critical for a complete picture of galaxy formation and evolution.

a. Thick-disk vs thin disk formation: Observations suggest that thick disks consist of relatively older stellar populations, and thus formed first and subsequent star formations formed thin disks. However we don’t know if older stellar populations puffed up over time due to tidal interactions, or early star formations formed by mergers which settled into more dispersion-dominated stellar disks.

b. Bulge: The central bulge of a galaxy is thought to form through mergers. However, the timing and specific processes involved in bulge formation are still areas of active research.

c. **Spiral Arms:** Instruments like ALMA and JWST's NIRCam are providing glimpses into the early formation of spiral structures. Sensitive Integral Field Unit (IFU) spectrographs on upcoming 30-metre-class telescopes will be able to determine whether early spiral galaxies are stable or transient features, and whether the spiral structure forms due to density waves caused by gravitational instabilities or tidal interactions.

Beyond observational facilities, HPC resources are crucial for conducting high-resolution simulations of Milky Way-type galaxies within a cosmological context. These simulations need to be of sufficient resolution to capture the detailed processes of galaxy formation and evolution, providing theoretical insights that complement observational data.

5. What were the sources of reionization?

Understanding the reionization of the universe and identifying the sources responsible for it remains a top priority for astrophysics in the coming decade.

a. **Large statistical sample of Lyman-continuum emitters:** JWST has provided us excellent measurements of the number density of galaxies well within the reionisation. Recent model of reionisation using the updated luminosity density of galaxies, predicts over-abundance of ionising photons, even without including the effect of AGNs. The escape fraction of ionising radiations still remains one of the biggest uncertainty in these models. the complex geometry of galaxies and the stochastic nature of the IGM sightlines probed by Lyman-continuum emitters, making it challenging to predict the escape fraction for galaxies at cosmic noon.

   Thus, we need to measure the escape fraction for large statistical samples of galaxies as close as practically possible to the EoR to correctly estimate the total ionisation budget of galaxies. A wide field u-band imager/IFU spectrograph or space-based UV imager is required to probe the ionsing radiations from a large sample of galaxies without relying on other properties for initial target selection.

b. **Connecting to observable at z>6:** At redshifts greater than 6, the neutral IGM prevents direct detection of Lyman-continuum radiation escaping from galaxies. Therefore, finding accurate proxies for the escape fraction is crucial for determining the total reionization budget. In the local universe, the O32 ratio and Lyman-alpha profiles correlate well with the escape fraction. However, these indicators are less effective at cosmic noon. New observations indicate MgII and UV emission lines such [CIV] that can be detected well into the reionisation as promising candidates.

c. **Helium reionisation:** When did Helium reionise? With a sufficient number of FRBs from redshifts around 4, which is expected from the Square Kilometre

Array (SKA), it will be possible to detect the epoch of helium reionization. This can be achieved through changes in the dispersion measure (DM) to redshift relation of FRBs, providing a direct probe of helium reionization.

6. What do high redshift transients inform us about galaxy formation?

a. **Core-collapse and superluminous supernovae at z ~ 2-20:** These events are highly luminous in the rest-frame UV and detectable with 8m-class optical telescopes. There has been photometric detection of over 100 events, with a subset spectroscopic confirmation, with multiple search and follow up programs in progress and planned. Superluminous supernovae are one of our only means to probe the early Universe and their host galaxies back to z ~ 20 with current facilities (8-10m-class telescopes, Roman, and JWST). These events have high utility for galaxy formation and evolution. For example, they provide a direct means to measure the stellar IMF in their host galaxies. They provide temporary beacons to study the intervening IGM and their host CGM and ISM. Their temporary nature enables a comparison analysis of star formation indicators in absorption with those in emission once the event fades. Their rate at high redshift helps galaxy outflow and star formation simulations, cosmic star formation and chemical enrichment history measurements. Superluminous supernovae provide a means to detect pair-instability supernovae and the deaths of the first stars that formed the first galaxies. Supernovae and gamma-ray bursts at z ~ 2-5 provide sightlines into galaxies at those redshifts to measure the fraction of Lyman continuum flux that is escaping from their host galaxies. In addition, the enormous energy these events produce and their long durations contribute to the EoR, as well.

b. **FRB production and their progenitors:** Understanding when the majority of FRBs are produced is a crucial question in astrophysics. Do FRBs peak in production during the period of peak star formation at redshifts z~1-3 or is there a significant delay? This question not only pertains to identifying the progenitors of FRBs but also to understanding how effectively we can use FRBs to probe the universe. Determining the peak in the production rate of FRB will provide insights into the lifecycle and environments of their progenitor systems, enhancing our ability to use FRBs as cosmological tools.

c. **Properties of FRB hosts:** Another important aspect of FRB research is studying the properties of their host galaxies, particularly the ionised gas content at redshifts greater than 1. For example, we have already identified a merging galaxy system at $z=1.01$ as an FRB host. As more such sources are discovered, we will be able to statistically analyse the ionised gas content in galaxies during cosmic noon. This analysis is vital for understanding the evolution of the universe's baryon budget.

Expected opportunities in the next decade

(and threats to our ability to capitalise those opportunities)

The next decade promises several exciting opportunities due to Australian involvement in international projects such as the Square Kilometre Array (SKA), Giant Magellan Telescope (GMT), and the Large Synoptic Survey Telescope (LSST) etc. These projects will provide unprecedented sensitivity and resolution for exploring galaxies at cosmic noon.

Ground-based Facilities

a. **Highly multiplexed optical and near-infrared facilities:** Instruments such as MOONS, WST, and Subaru/ULTIMATE will provide large samples of unresolved galaxies to study scaling relations and environmental effects at cosmic noon. By targeting a constellation of background galaxies, we will be able to perform 'tomography' on absorbing foreground gas to map the cosmic web in HI and metals. MAVIS will map Lyman-alpha emission at unprecedented spatial and spectral resolution, enabling deep investigations into gas accretion and outflows at cosmic noon.

b. **The Australian-led Wide-Field Imager (WFI) for Keck** - The Australian-led Wide-Field Imager (WFI) for Keck will offer extremely deep, wide-field (1 degree field of view) imaging and blue wavelength imaging, including narrowband filters to fill the significant gap left by the Subaru Hyper Suprime-Cam (HSC) and the Rubin Observatory. WFI will enable a wide array of cosmic noon scientific research, including (1) the only instrument capable (for decades) of detecting and mapping Lyman continuum emission from high redshift galaxies, as the emission is in the observed u-band, extremely faint (m ~ 28-30) and requires wide fields of view (degree) to detect the systems in rare transparent sightlines to Earth and to map against neutral gas mapped by SKA, (2) detection of faint circumgalactic medium (CGM) emission (e.g., Lya, OVI, MgII, etc) via extremely deep narrow-band imaging, (3) the faint end of the luminosity function and gravitationally lensed galaxies for the ELTs and JWST, and (4) transients, such as FRB host galaxies and counterparts with its added CMOS detectors.

WFI began development in 2019 and is a technical partnership led by Swinburne University and includes AAO-Macquarie, ANU-AITC, Caltech, the University of California, and Keck, with an expected on-sky date around 2028-2029. No other wide field, blue/UV optimized 8m-class or space-based imager is planned or feasible for the foreseeable future (decades) and WFI is the only 8m-class instrument in this category that will not be superseded by 30m-class telescopes. WFI will be accessible to Australian researchers via multiple avenues, including guaranteed time as part of the instrument for survey and independent Australian research projects, via Swinburne partnership time, NASA and NOIRLab access time, Australian purchased time, and collaborations with Keck community researchers.

c. **30m class telescopes:** The unprecedented sensitivity, spatial resolution, and spectral resolution of 30m-class telescopes will allow us to observe galaxies at cosmic noon with detail comparable to nearby galaxies. These observations will enable studies of the spatial correspondence between different gas phases and detailed measurements of ionised and neutral outflow rates, and thus constrain the multiphase mass budget. Access to 30m telescope time, particularly through instrument teams or Guaranteed Time Observations (GTO) programs, will be crucial for conducting groundbreaking spatially resolved surveys that will revolutionise our understanding of distant galaxies.

d. **ALMA:** ALMA will remain an outstanding instrument for studying gas and dust in galaxies at cosmic noon. Its higher spectral resolution compared to rest-optical facilities makes it ideal for studying detailed gas kinematics. Full ESO membership will give Australian astronomers access to ALMA, enabling Australia-led large, multi-cycle programs to map the inflow and outflow of gas across a diverse range of galaxies and environments.

Space-based facilities

The launch of JWST has revolutionised our ability to study rest-frame optical ionised gas emission lines in galaxies up to redshift z~6. This advancement allows us to consistently compare the properties of galaxies across a vast expanse of cosmic history for the first time.

The upcoming Euclid and Roman missions will further transform our understanding of the universe during cosmic noon. These missions will provide spectra for millions of galaxies within the redshift range $1 < z < 2$ (e.g., Bagley+20). While JWST will remain crucial for spectroscopic samples of galaxies at $z > 2$ and for obtaining high spectral resolution data when necessary, Euclid and Roman will fill in critical gaps by covering the lower redshift range with extensive datasets.

The public availability of these datasets significantly reduces the risk associated with large-scale astronomical research. However, a unique avenue for Australian astronomers could emerge from follow-up programs at other wavelengths. For instance, conducting observations with VLT or ALMA, particularly if Australia secures a partnership with the ESO, would enhance the scientific returns from these space missions. Such follow-up programs would provide complementary data, helping to build a more comprehensive picture of galaxy formation and evolution during cosmic noon.

Radio Facilities

SKA promises to be a groundbreaking project for scientific discovery, offering unprecedented insights into various cosmic phenomena. SKA will provide new insights into the role of neutral hydrogen (HI) by enabling direct observations of HI at the lower end of cosmic noon and absorption measurements at higher redshifts. This capability will help clarify how HI contributes to the gas accretion process and its significance during different cosmic epochs.

SKA has the potential to observe tens of thousands of FRBs and localise them with exceptional precision. It should be sensitive enough to detect FRBs out to redshift $z = 10$, if they existed at such early times. However, the implementation of FRB detection presents technical challenges. There is a risk that this aspect of the project might not be executed properly, and there is also a risk that other SKA collaborators might scoop this science if we are excluded from the technical developments.

To accurately identify FRB host galaxies at redshifts greater than 1, we require substantial access to deep optical imaging and spectroscopy with 8m-class telescopes, space-based observatories, and 30m-class telescopes. Securing this access will be challenging. It is already evident that 8m-class instruments do not always successfully identify FRB hosts at $z = 1$. Therefore, obtaining the necessary observational time on these powerful telescopes is crucial for advancing our understanding of FRBs and their environments.

HPC resource

Beyond observational facilities, high-performance computing (HPC) resources are crucial for conducting high-resolution simulations of Milky Way-type galaxies within a cosmological context. These simulations must achieve sufficient resolution to capture the detailed processes of galaxy formation and evolution, providing theoretical insights that complement observational data.

Increased computing power is also essential for running advanced radiative transfer modelling to understand how Lyman-continuum radiation escapes from galaxies. These models will help us interpret observational data and refine our understanding of the mechanisms behind Lyman-continuum escape, thereby enhancing our knowledge of the reionization process and the role of galaxies in it.

Risks

The involvement in international projects and access to cutting-edge facilities is essential for Australian astronomers to make significant advancements in the study of galaxies at cosmic noon. The combination of high-resolution observations, large statistical samples, and advanced instrumentation will provide unprecedented insights into the formation and evolution of galaxies, ultimately enhancing our understanding of the universe.

However, a significant threat to our ability to carry out ‘cosmic-noon’ science is the lack of access to either ELTs for detailed physical studies or large survey facilities for statistical studies. Australia has a 5% share in GMT through AAL, which provides some access to a 30m-class telescope. ESO membership would grant access to the ELT, significantly increasing our capacity to utilise this groundbreaking next generation of telescopes. The 4MOST project, being optical and on a 4m-class telescope, does not allow for significant progress in cosmic noon science.

The Wide-Field Spectroscopic Telescope (WST) presents an opportunity, but the infrared component has been deemed prohibitively expensive and is unlikely to be included. This limitation forces reliance on rest-frame UV observations to study galaxies at cosmic noon, which has proven to be biased and challenging for robust line detection.

Additionally, the limited workforce in Australia dedicated to studying the cosmic noon epoch poses a minor threat to exploiting these opportunities. There is a need for substantial investment in local infrastructure and expertise to sustain Australia's leadership in astronomy.

ASKAP is currently world-leading, but it risks becoming outdated. Upgrading ASKAP to be more sensitive with improved phased array feeds would allow it to remain relevant until the beginning of SKA science. There is a potential gap of approximately five years or more between ASKAP remaining relevant (post-2025) and the start of SKA operations (around 2030). Addressing this gap is crucial for maintaining Australia's competitive edge in radio astronomy.

The data flow though is vast and there are real risks to manage it and properly glean all available information. Large radio datasets have illustrated the inherent difficulties. We stand to be at risk in multiple wavelength regimes.

Capabilities that enable Australia to be competitive

Funding scheme to support access to competitive facilities: Conducting science on highly competitive facilities requires substantial additional funding for travel and personnel, after the proposal acceptance. Implementing a funding scheme linked to accepted proposals could be a pivotal launching pad and provide a competitive edge to Australian astronomers. This scheme will ensure Australian lead investigators have the necessary resources to capitalise on their access to top-tier facilities.

Access to JWST, Euclid, and Roman - The open-skies policy of the USA allows Australian astronomers competitive access to existing and upcoming space-based facilities, such as JWST and Roman and access to public surveys, including those from ESA Euclid. This policy ensures that Australian scientists can fully participate in and benefit from cutting-edge space missions, fostering international collaboration and enhancing the global impact of Australian astronomical research.

Access to an ELT - Australia has a 5% share in the billion-dollar Giant Magellan Telescope (GMT) through AAL, which provides access to a 30m-class telescope. Construction has started on the site and facility and all seven 8-metre mirrors are fabricated. The completion date and first light of the GMT are still unclear. The GMT first-light instruments, GMACS optical spectroscopy, GMTIFS IFU spectrograph and imager, and GMTNIRS infrared spectrograph will significantly progress cosmic noon science.

Access to SKA - Australia is a major partner on SKA.

Access to ESO - Full ESO membership will provide Australian astronomers access to the billion-dollar E-ELT, as well as ALMA and next-generation survey facilities on 8m-class telescopes such as MOONS. These facilities will be at the forefront of discovery for cosmic noon science in the next decade.

Access to a deep wide-field imager - All the facilities above are $1-8 billion dollar facilities, which is beyond Australia's capability to lead. However, the Australian-led Wide-Field Imager for Keck is less than ~1% the cost and is essential for the above facilities to achieve their main science aims. For example, NASA Roman needs m ~ 28-29 u- and g-band wide-field imaging for accurate photometric redshifts for its main weak-lensing, cosmic noon, and transient scientific goals. Roman can identify the morphology of galaxies emitting Lyman continuum flux and if there are lower redshift contaminants but it requires WFI to detect the Lyman continuum emission. The SKA will map neutral HI at high redshift and only WFI can map the ionised Universe at these epochs - and can do so with a similar field of view. SKA will also detect FRBs to z ~ 10 and WFI is the only 8m-class instrument with the sensitivity to identify their hosts. WFI will find the faint and rare lensed galaxies and other sources, including the low-mass galaxies at cosmic noon for JWST and the ELTs spectroscopic follow up. Finally, all existing deep, wide-field imagers are 12-22 years old now and/or are not sensitive in the blue, and no deep, wide-field imagers are planned for the future (decades) on Earth or in space.

Advanced instrumentation

Australia has been a leading force in building the next generation of astronomy instruments, significantly contributing to the advancement of astronomical research.

a. **MAVIS -** Australia is spearheading the construction of the Multi-conjugate Adaptive-optics Visible Imager-Spectrograph (MAVIS) with adaptive optics (AO), hosted by the VLT. MAVIS will provide spectral resolution at optical wavelengths comparable to near-infrared instruments on JWST and ELTs across a relatively large (30 arcsecond) science field. For the cosmic noon science, MAVIS will resolve Lyman-alpha emitters with exceptional spatial and spectral resolution, enabling a deeper understanding of gas inflows and outflows.

b. **Upgrades to radio facilities** - Upgrading ASKAP and MWA with more sensitive phased array feeds would allow it to remain competitive until the beginning of SKA science.

E Appendix - Epoch of reionization (z>6) white paper

WG 1.1 EoR (z>6) white paper

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Report on progress since the last decadal plan

Radio/21cm

In 2015-2016, radio interferometers seeking the redshifted 21cm signal from the IGM at z>6 were in their early full operations phases. Interferometers are sensitive to spatial brightness temperature fluctuations and can theoretically access the spatial fluctuation power spectrum, and direct imaging (tomography).

LOFAR, based in the Netherlands, the Murchison Widefield Array (MWA), based in Western Australia and operated by Curtin University, and the PAPER array, based in South Africa, were all publishing early science results. At that time, no telescope had acquired sufficient data volumes (observing time) to theoretically detect the cosmological hydrogen signal. These experiments primarily probe the Epoch of Reionisation (z=6-10, nu=130-200MHz), where the signal is expected to be in emission relative to the CMB, and the signal structure is dominated by the ionisation morphology.

In the Decadal Plan period, PAPER was decommissioned and replaced by the larger HERA array in South Africa, which is nearing construction completion but has been acquiring and publishing science data. Unlike LOFAR and MWA, which are general purpose low-frequency interferometers, HERA is designed to undertake this particular experiment, and is optimised for power spectrum estimation. LOFAR and MWA have both observed sufficient data to theoretically detect the 21cm signal in z=6-10. With a detection still eluding the research teams, the focus of the past ten years has turned to ensuring a clean signal chain, reducing and mitigating systematic effects, and improving analysis methodology to ensure no signal degradation.

In the past 5 years, lower frequency interferometers (z=12-25, nu=50-120MHz) have been probing the higher redshift universe, seeking details of the Cosmic Dawn and Epoch of X-ray Heating, where the signal expected to be in absorption against the CMB, and the spatial fluctuations are driven by spin temperature fluctuations induced by differences in density, and radiation field. There has been increasing interest in pursuing the detection of 21-cm fluctuations from Cosmic Dawn, and in earlier Dark Ages, with space missions that aim to deploy long-wavelength arrays on the far side of the Moon, where the Earth’s ionosphere and terrestrial man-made RFI are not impediments to detection. In previous years designs for systems, construction and deployment mechanisms relevant for far-side siting have progressed (for example, FARSIDE and FARVIEW); pathfinder missions are trialling the technologies and testing the environment (ROLSES, LuSEE-Night).

Global 21cm signal experiments have been a new development of the past ten years. Aiming to measure the global brightness temperature change of the 21cm line relative to the CMB, these experiments require low sensitivity, but exceptional calibration precision. Global EoR experiments are typically composed of single element systems (e.g., dipole or other antenna), which have all-sky fields-of-view. Unlike interferometers, where the antenna-based gain is averaged to zero via the cross-correlation of independent signal chains, single elements require precision instrumental understanding: of the spectral confusion arising from chromatic response to continuum sky and of additives from receiver and ground emissions. Over the previous decade, progress in precision performance of antennas and receivers with improvements in technology have reduced systematic errors to levels where some classes of models for reionisation, within standard cosmology, have been ruled out (Singh et al. 2017, 2018; Monsalve et al. 2019). Additionally, in 2018, Bowman et al reported the detection of a deep 21 cm absorption trough centred at 78 MHz, and identified the feature as that from the period of Ly-alpha coupling and X-ray heating from the first stars. The signal amplitude and spectral shape differed significantly from models of the evolution of the early Universe, and theorists have been led to explore new physics for Dark matter and new populations of radio sources towards finding a model that fits the data. Subsequently, the SARAS-3 experiment (Singh et al. 2022) failed to confirm the EDGES absorption trough, rejecting a cosmological origin for the signal with 95 percent confidence. Currently, the EDGES results are considered unverified in the literature.

There has been a proliferation of other single element global signal experiments since the EDGES report. In Australia, GINAN (McKay et al. 2023) is a CSIRO advancement in receiver technology that provides in-situ dynamic calibration of internal systematics and antenna response for single-element radiometers, and has had first light at Narrabri observatory using an SKA-Low antenna element; the SITARA system, on the MWA site (an MWA external instrument), advances detection of the global signal with a different technique - a short-spacing interferometer using the spectral leakage of global signal into small interferometer modes to trade signal for experimental design.

The final piece of major progress relates to efforts to identify high-redshift radio-loud QSOs that could be used as continuum sources for 21cm Forest. Akin to Ly-alpha Forest in the optical, but probing early reionisation, 21cm Forest seeks to detect absorption features toward the background continuum light that corresponds to cold, neutral gas along the line-of-sight. Earlier simulations showed that deep LOFAR and then SKA-Low observations could do this experiment, but it requires a bright radio source at z>8. Work out of Curtin has identified some potential z>7 candidates, with one confirmed at z~5.6, but confirmation of the redshifts of others is still a work in progress. A couple of weak, radio-loud sources (1.4-GHz flux ~ 1 mJy) have been identified with obscured AGN in the deep narrow surveys (i.e. a z~6.8 source in the COSMOS field and potentially one at z~7.7 in a JWST survey field). These results are important in showing that radio-loud AGN do exist within the EoR and that searching for radio-loud obscured AGN in the EoR is a fruitful technique. Very powerful SFGs (1000s Msun/yr) have also been detected at z>7, but are ~40x fainter than these radio-loud AGN at 1.4 GHz.

Broad properties of current telescopes are in Table 1, below.

NAME	LOCATION	TYPE	START DATE	FREQ/ REDSHIFT RANGE	SHORTEST/ LONGEST BASELINE	STATUS
Murchison Widefield Array (MWA)	Australia	Pseudorandom Interferometer -aperture array	2013	130-200MHz (some 70-90MHz); z=6-10 (17-19)	14m;3km	Operating; publishing limits
Low Frequency Array (LOFAR)	Netherlands	Pseudorandom Interferometer - aperture array	2010	120-240MHz (70-90MHz); z=5-12 (17-19)	100m;1000km	Operating; publishing limits
Hydrogen Epoch of Reionization Array (HERA)	South Africa	Redundant Interferometer - single elements	2018	50-250MHz; z=6-27	15m;800m	Operating; publishing limits
21CMA	China	Two-arm interferometer - aperture array	2007	50-200MHz; z=6-27	130m;8km	Closed
NenuFAR	France	Pseudorandom Interferometer - aperture array	2021	10-85MHz; z=18-30	20m;400m	Operating; early science
GMRT	India	Pseudorandom Interferometer - dish array	1995	150-1500MHz; z=0-7	500m;25km	Operating; mostly does post-reion signal
LEDA	USA	Pseudorandom Interferometer - aperture array	2012	40-90MHz; z=15-30	5m;200m	Operating; cosmic dawn experiment
EDGES	Australia	Single element global	2012	50-200MHz; z=6-27	N/A	Operating; upgrading
PRIZM	Marion Is	Single element global - 2 dipoles	2017	60-110MHz; z=14-25	N/A	Operating
GINAN	Australia	Single element global	2023	40-230 MHz; z=5-30	N/A	First Light
SITARA	Australia	2-element interferometer	2020	50-300MHz; z=5-27	2m	Currently unused
SARAS-3	India	Single element global	2019	50-200MHz; z=5-27	N/A	Operating; receiver upgrades
REACH	South Africa	Single element global	2022	50-170MHz	N/A	Operating; commissioning

The current observational constraints from 21cm interferometric measurements are found in Figure 1.

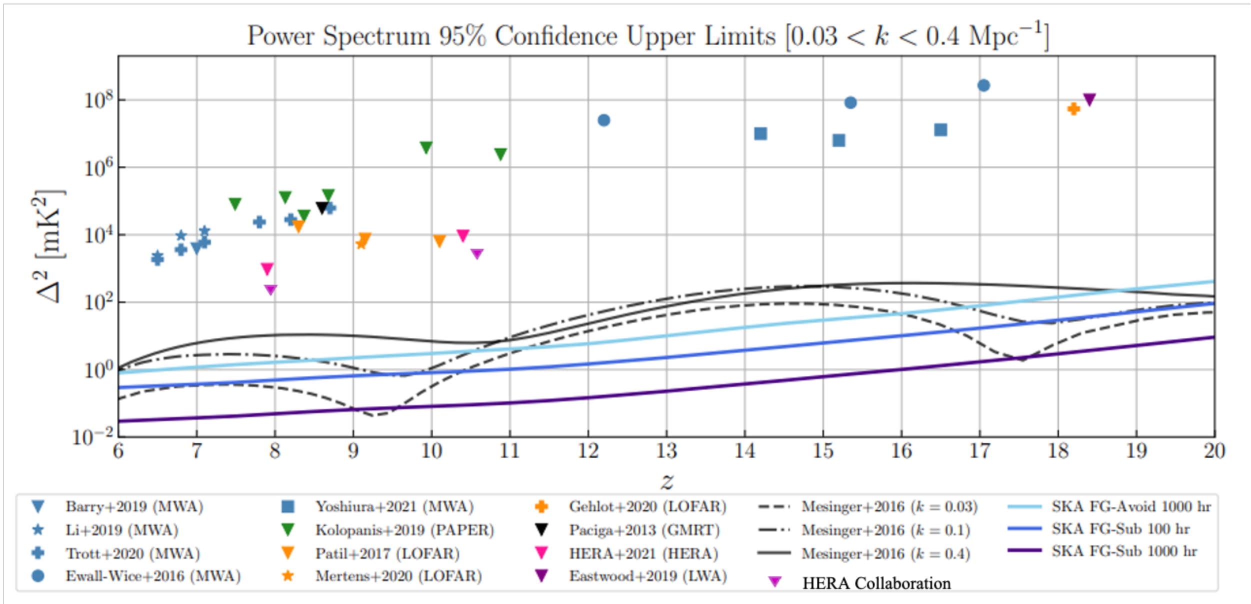

Figure 1: Current observational limits on the brightness temperature fluctuation power in the 21cm line from the IGM at z>6 (adapted from N. Barry et al.).

One of the largest advances in this field over the decade has been the work to understand the source of systematic errors in the data. Systematic-generated power has so far prevented interferometer experiments from reaching the expected signal level. The experiment requires a 10^9 dynamic range from the power in the foreground radio sky to the signal level, demanding precise and accurate treatment of the data. Any spectral contamination can mimic the 21cm signal. The primary areas of concern have been identified to be: (1) completeness of sky model for calibration, (2) spectral smoothness of calibration solutions, (3) separation of diffuse foregrounds and 21cm signal for calibration and foreground removal, (4) mutual coupling of signals leading to correlated noise, (5) low-level RFI; but there are other sources of systematic contamination that are particular to each experiment and analysis method.

Advancements made in the optical/NIR/Sub-mm regime

The previous decadal survey did not specifically address probing the EoR in the optical to sub-mm wavelength window. The Australian astronomy community working on this field has grown during the last decade, thus, this decadal survey is expected to consider the Australian outlook in this regime.

In the previous decade, ground and space-based facilities made significant advancements in probing properties of EoR galaxies. This white paper will briefly address the advancements made on characterizing EoR sources which refine our galaxy and chemical evolution models in the early Universe. Advancements made in cosmology are expected to be addressed by the cosmology W.G. XX.

With the launch of the James Webb Space Telescope (JWST) in 2021, our understanding of the EoR has completely transformed. Thus, we first briefly discuss EoR advancements in the pre-JWST era. Most EoR science in the pre-JWST era was driven by deep near-infrared (NIR) imaging/spectroscopic surveys and sub-mm observations of bright photometrically selected $z>6$ candidates. Surveys were carried out in blank fields and also in fields with massive foreground clusters to aid with reaching to fainter intrinsic magnitude limits by taking advantage of gravitational lensing.

In blank fields deep optical and NIR imaging surveys such as CANDELS (Grogin+11, Koekemoer+11), 3DHST (Momcheva+16), ZFOURGE (Straatman+16), UltraVISTA (McCracken+12) combined with deep IR imaging surveys such as GREATS (Stefanon+21) made significant advancements in identifying EoR candidates. Additionally, HST pure parallel surveys such as BoRG (Brightest of Reionizing Galaxies, Trenti+11) were also able to identify EoR candidates. These were complemented by cluster field surveys such as Hubble Frontier Fields (HFF, Lotz+17), Cluster Lensing AND Supernova survey with Hubble (CLASH, Postman+12), Grism Lens-Amplified Survey from Space (GLASS, Treu+15), Grism Lens-Amplified Survey from Space (RELICS, Coe+19). This was possible due multi-band photometric surveys being able to identify the overall shape of galaxy spectral energy distributions (SEDs) as shown by Figure 2. SED features such as the Lyman/Balmer breaks and strong emission lines when compared with model templates not only provide the redshift information of the sources but can also be used to study the ionizing conditions at the EoR.

With the significant number of photometric sources identified over these deep extragalactic fields, constraining early galaxy evolution was possible through studying the Ultra-Violet (UV) luminosity functions and mass functions (e.g. Bouwens+15, Finkelstein+12, Adams+15, Livermore+17). Advancements were made in understanding types of galaxies that drove reionization, canonical values required in ionizing production efficiencies and escape fraction of ionizing photons in EoR sources for a timely completion of reionization by $z\sim6$ (Robertson+15). Stellar mass and size growth in the early Universe was measured but with caveats of wavelength dependent limitations in exploring the rest frame rest-UV of the galaxies. See Stark+16 for a review.

Photometric sources identified by deep imaging surveys were followed up using ground based NIR spectrographs such as Keck/MOSFIRE and VLT/XSHOOTER to obtain spectroscopic confirmations. Access to 8-10m class telescopes was crucial to reach sufficient S/N limits for these faint emission lines within reasonable time limits. Thus, with significant time investments, rest-UV emission lines such as Ly-α, CIII] were utilized to confirm the redshifts of these sources (e.g. Mainali+18). The detection of rest-UV emission lines further hinted at the possibility of highly ionized conditions in these EoR sources.

Facilities such as ALMA, NOEMA were also efficient in obtaining the dust continuum, molecular emission lines (such as CO 6-5 and 7-6 transitions), and ionized gas (such as [CII]158µm, [OIII]88 µm) detections of EoR sources. Surveys such as Reionization Era Bright Emission Line Survey (REBELS, Bouwens+22) and

Mapping Obscuration to Reionization with ALMA (MORA, Casey+21) made advancements in spectroscopically confirming EoR sources and probing the rapid dust buildup in the early Universe. These results point to the necessity of having novel dust production mechanisms in the early universe to address the higher-than-expected amount of dust observed in the EoR; this cannot be explained through traditional dust production channels such as AGB stars because the Universe at z>6 is younger than 1 billion years required for AGB stars to be the dominant dust production mechanism. Enhanced dust production through supernovae and possibly WR stars are expected to drive the rapid dust buildup in the EoR Universe, however, there is no consensus on how the early Universe was so efficient in producing dust. See Hodge & Cunha 20 for a review.

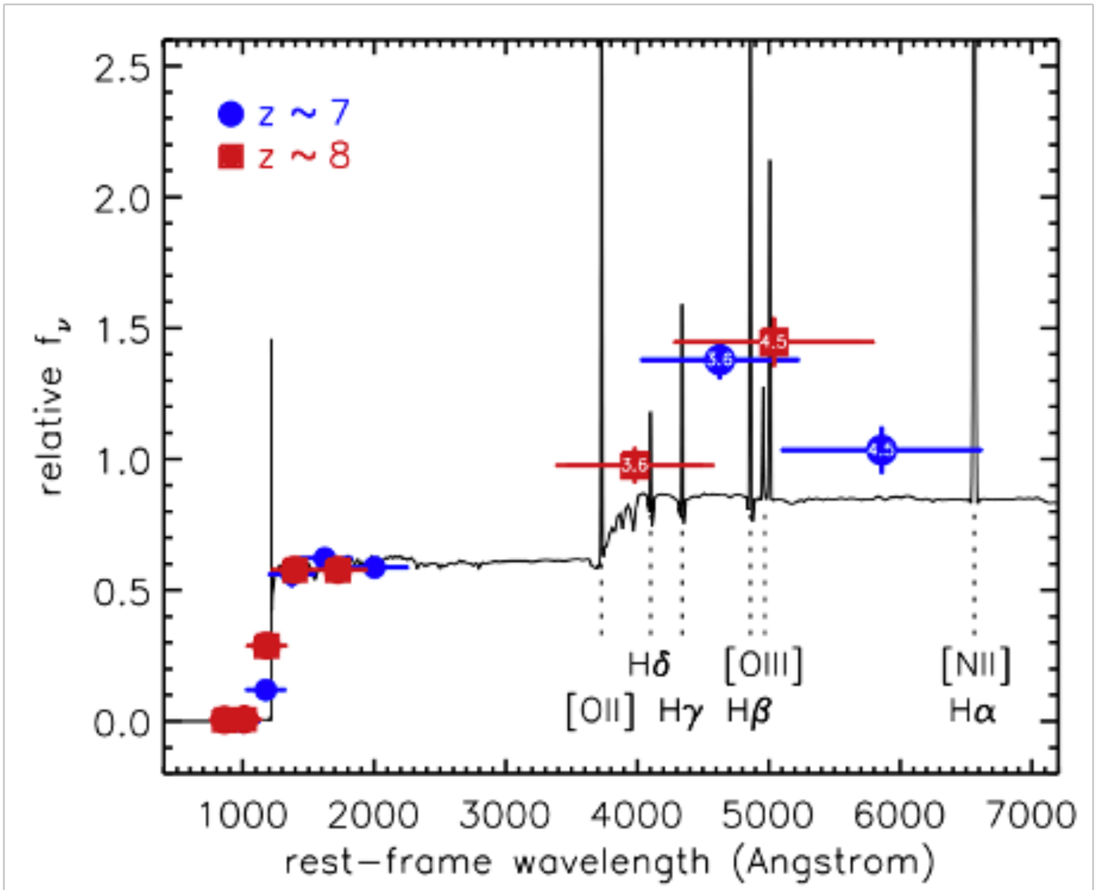

Figure 2: Demonstration of how multiband photometric data can be used to obtain redshift and emission line strengths of strong lines based on SED fitting techniques. Figure is from Labbe et al. 2013 ApJL 777:L19 and the caption is as follows: "Comparison of the average rest-frame SEDs of IRAC detected galaxies at z ∼ 7 and z ∼ 8 from the average HST/ACS, HST/WFC3, and Spitzer/IRAC fluxes. The IRAC [3.6] and [4.5] fluxes are indicated. The SEDs are in units of f v (arbitrary scaling). A young star forming stellar population model with emission lines is shown in black. The observed [3.6] − [4.5] colors at z ∼ 7 and z ∼ 8 are substantially different, despite the short time elapsed between these epochs (about 130 Myr). Combined, the rest-frame SEDs suggest a clear flux excess at ∼5000 Å, shifting from [3.6] at z ∼ 7 to [4.5] at z ∼ 8, likely due to a contribution from strong [O iii]4959, 5007 and Hβ emission lines."

In addition to spectroscopic confirmations, ALMA observations can also be utilized to study the kinematics of the gas of such sources. Such measurements provide crucial clues on the interaction between ionized and neutral gas in galaxies and inform us about the buildup of angular momentum in galaxy disks from the early Universe to form a picture of morphological evolution of galaxies at z>6. One such example of a galaxy at z=7.31 from Rowland+24 is shown by Figure 3, and this demonstrates that dynamically cold disks are more common in the early Universe than what is expected by cosmological simulations.

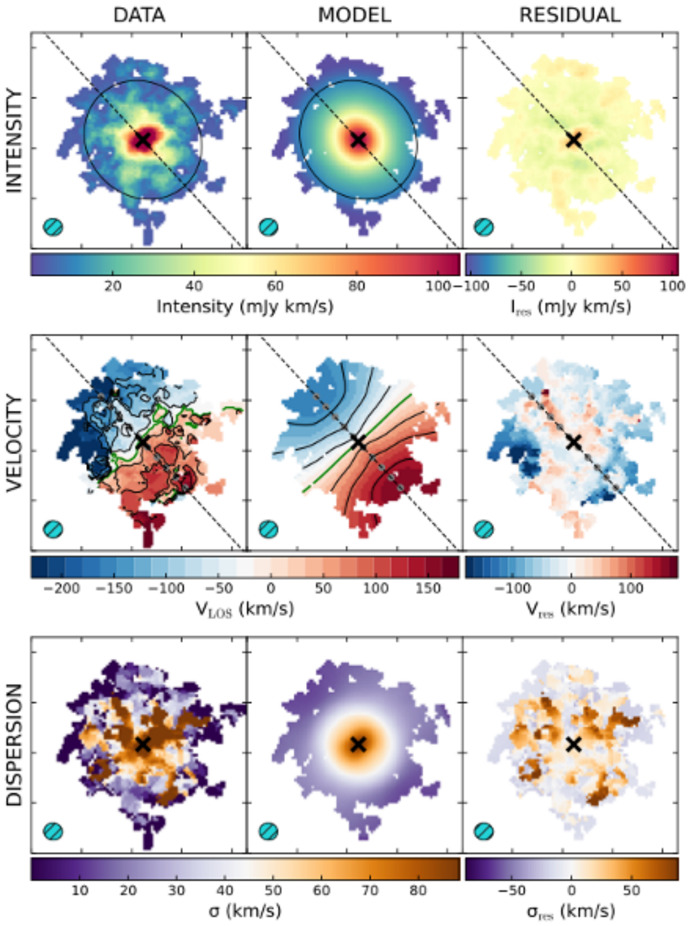

Figure 3: Kinematics of a z=7.31 galaxy obtained through ALMA [CII] line intensity mapping. Adapted from Rowland+24. The caption reads "3DBAROLO fitting for REBELS-25. Emission is masked at 2σRMS. The first column on the left shows the observed data, the middle column the model and the column on the right shows the residuals. The first row is for the intensity map, the second row for the velocity field map and the bottom row for the velocity dispersion map. In the first row, the black cross, ellipse and dashed line show the centre, radial extent and position angle of the 3DBAROLO model, respectively. In the second row, the grey dots give an indication of the separation of each ring along the velocity field (0.11"). In the velocity field map of the data and model, we also plot the iso-contours from -180 to 180 km s−1 in 45 km s−1 increments. In all maps, the beam size is indicated by the turquoise ellipse in the bottom left corner."

In addition to direct detections, reconstructing the z>6 SFHs utilizing z>3 quiescent populations also provided indirect constraints to galaxy evolution models in the EoR. Ground-based instruments such as Keck/MOSFIRE were instrumental to confirm the existence of quiescent galaxies at z>3 and their rapid formation histories that challenged our galaxy evolution models (e.g. Glazebrook+17, Schreiber+18, Valentino+20).

Near and mid-infrared imaging and spectroscopy through JWST opened a new window to probe the EoR in the last few years. The NIRCam instrument in JWST covers 0.6µm-5.3µm regime between 31-63mas/pixel resolution enabling high resolution deep imaging of the Universe. In the first two years of science operations, JWST imaging has targeted HST blank fields through surveys like Cosmic Evolution

Early Release Science Survey (CEERS, Finkelstein+22), Public Release IMaging for Extragalactic Research (PRIMER, PI Dunlop), and JWST Advanced Deep Extragalactic Survey (JADES, Eisenstein+23). This was further complemented by deep imaging over HST observed gravitational lensing cluster fields through surveys like GLASS-JWST (True+22) and UNCOVER (Bezanson+22). These surveys probed deeper and at redder wavelengths compared to what was possible with the HST to find fainter and earlier galaxies in the Universe. The advancements made in finding EoR candidates by the first extragalactic surveys conducted by JWST is shown by Figure 4. The complex morphology of the EoR candidates as visualized through multi-band JWST/NIRCam imaging is shown by Figure 5.

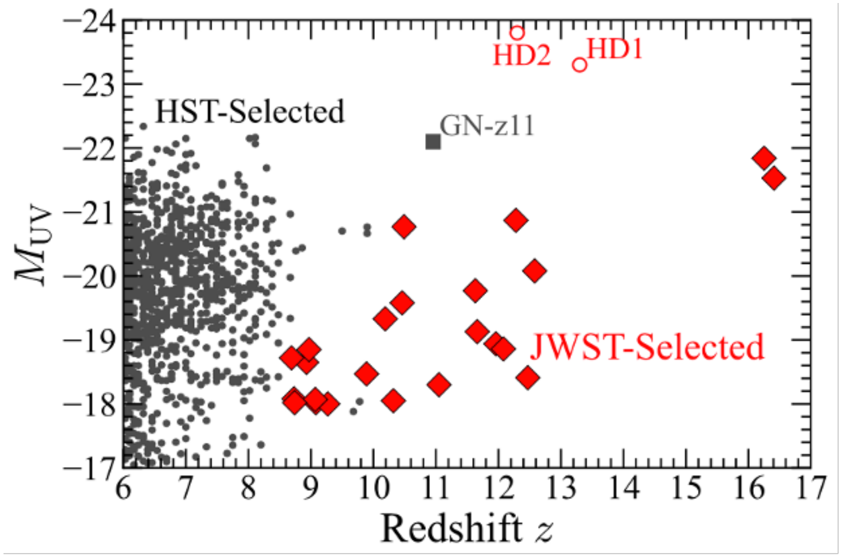

Figure 4: The transformation of EoR photometric candidates within the first year of JWST operations. Adapted from Harikane+23. The caption reads: "Absolute UV magnitude as a function of the redshift for galaxies at 6 < z < 16. The red diamonds represent our dropout galaxy candidates selected with the JWST images. The red open circles show HD1 and HD2 previously found by the combination of the images taken with Spitzer and ground-based telescopes (Harikane et al. 2022a). The gray square and circles denote GN-z11 (Oesch et al. 2016; Jiang et al. 2021) and dropout galaxies selected with deep HST images (Bouwens et al. 2015)."

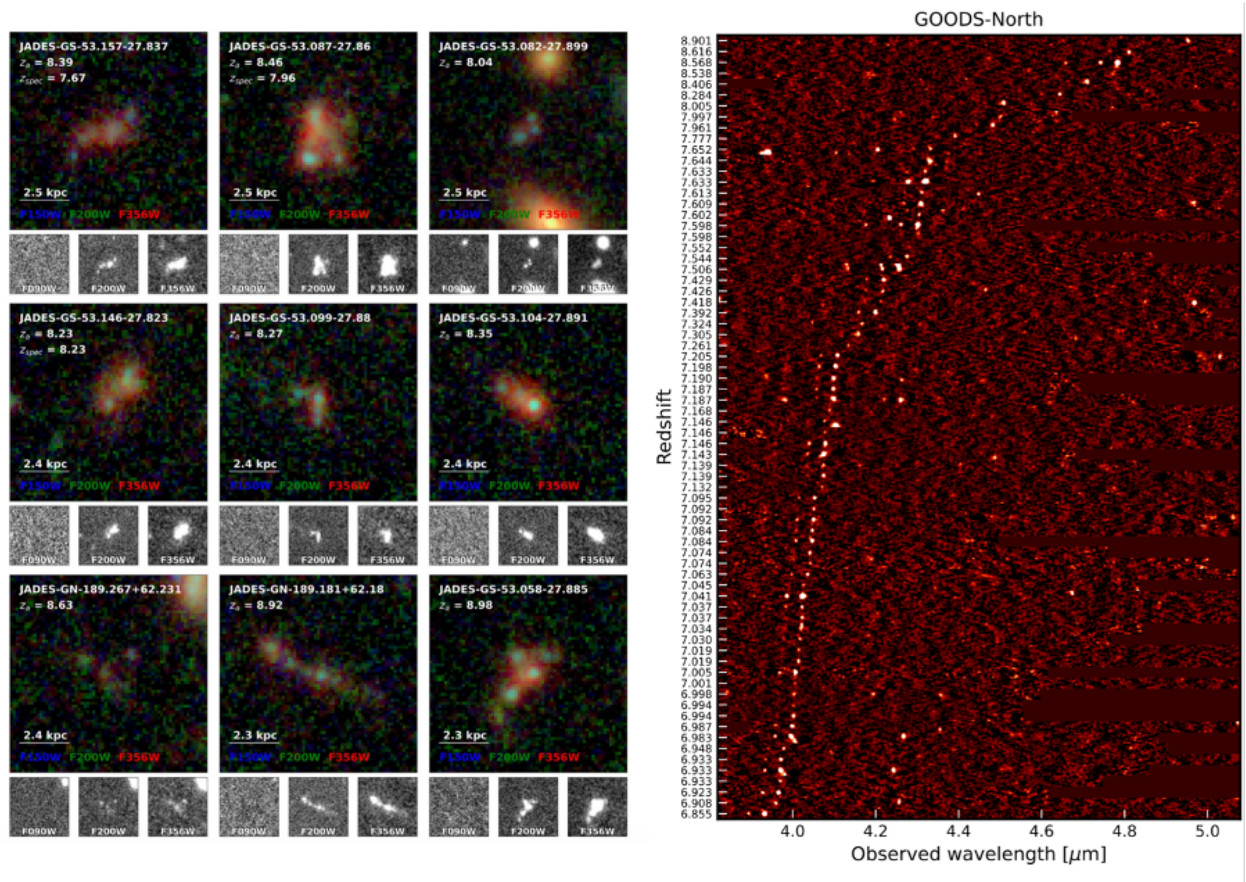

Figure 5: Left: RGB images of selected Eor galaxies discovered by JWST. Adapted from Hainline+24 and the caption reads "Color thumbnails for a selection of nine za = 8−9 resolved galaxies with multiple components. Each thumbnail is 2" on a side, and we include a size bar showing 0 5 for each object. The color image is composed of F356W, F200W, and F090W as red, green, and blue, respectively. We also show images in those filters for each object separately to demonstrate the dropout nature of these objects in the F090W filter." Right: A subset of EoR [OIII] emitters discovered by JWST NIRCam grism spectroscopy from the FRESCO survey. The figure is adapted from Meyer+24 and the caption reads "2D spectra of all the confirmed [OIII] emitters in FRESCO in GOODS-North, ordered by redshift. A strong overdensity of sources is present at GOODS-South 6.9 < z < 7.2. CO band heads contamination was masked in some extractions."

JWST NIRCam and NIRISS grism spectroscopy provides a unique opportunity to obtain imaging and spectroscopy of EoR sources in one go. While challenges lie in modelling contamination in sensitive grism spectroscopy enabled by JWST, surveys such as FRESCO have been efficiently able to probe the EoR through detection of strong optimal emission lines. A sample [OIII]λ5007 emitters detected by NIRCam grism spectroscopy is shown by Figure 5. NIRSpec multi object spectroscopy has also been an efficient tool in obtaining spectroscopic confirmations of the EoR candidates identified by the deep imaging surveys. The simultaneous coverage of the 0.6μm-5.3μm coverage of the NIRSpec grism observations combined with its multiplexing capability has resulted in spectroscopic confirmation of EoR sources leading to orders of magnitude of higher sources compared to what we had in the pre-JWST era. The medium and higher resolution gratings of NIRSpec have allowed detailed analysis of the properties of stars and gas in EoR galaxies and to explore the early chemical enrichment in the universe. Additionally, spectroscopy from JWST MIRI instrument of z>10 sources enable the study of rest-frame optical emission lines allowing direct comparison with galaxies seen at z~0 through surveys like SDSS and GAMA. In Figure 6 we show NIRSpec and MIRI spectroscopy of two of the brightest z>10 galaxies.

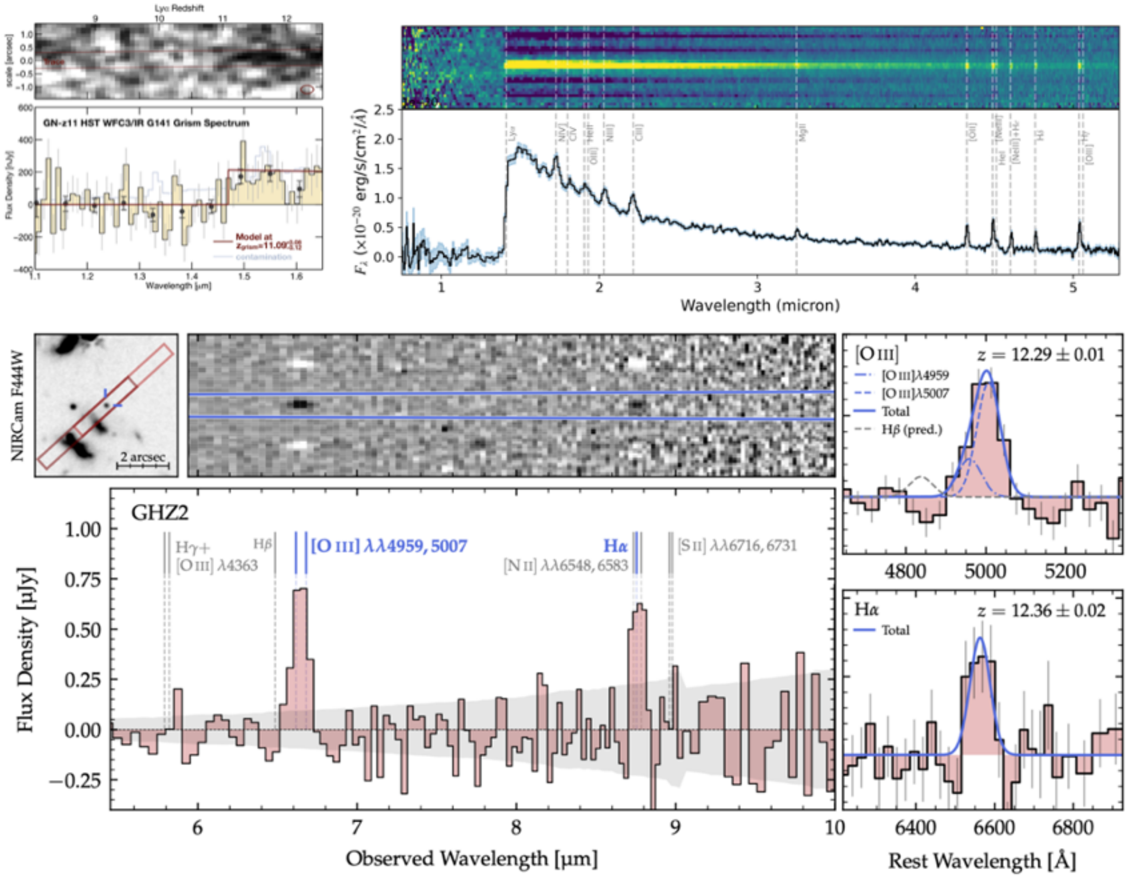

Figure 6: Spectroscopy of two ultra-bright galaxies in the EoR at z>10. The top left panel is adapted from Oesch+16 which shows the 2d and 1D HST Grism spectrum of GNz11, the highest redshift galaxy known in the pre-JWST era. The right panel shows the 2D and 1D JWST/NIRSpec prism spectrum of the same source presented by Bunker+23, which confirmed the redshift of the source to be at z=10.6. The lower panels show 2D and 1D spectrum of GHZ2, a galaxy at a redshift of 12.3 obtained using JWST MIRI. The rest-frame optical Ha and [OIII]5007 emission lines are zoomed into the right panels. The figure is adapted from Zavala+24 and the JWST/NIRSpec spectroscopy of the sources is presented in Castellano+24. We refer the readers to the original papers for caption to assist with brevity of this document.

In addition to the direct analysis of EoR sources, JWST NIRSpec spectroscopy enables detailed analysis of the star formation histories of z~3-6 massive and quiescent galaxies (Carnall+24, de Graaff+24, Glazebrook+24, Nanayakkara+24). Reconstructed SFHs of these galaxies show the efficient mass buildup of galaxies by z~10, providing a detailed view of galaxy evolution in the EoR. Detailed element abundance studies, specially through α-process elements can be utilized to study the rapid buildup of massive stars in the early Universe and to obtain constraints to reionization and other hierarchical galaxy assembly models.

While JWST has only been in operation for ~2 years by the time of this white paper, the discoveries made by JWST in EoR are far too many to be summarized. In this section we have thus only highlighted the redshift frontier that has opened with JWST which has allowed us to probe deeper into the EoR. In the next section, we briefly state some of the discoveries made by JWST that have resulted in further questions about our understanding of the early Universe.

Big Data, Computing, and High Performance Computing (HPC) Facilities

Funding for AusSRC for SKA and precursors; Pawsey/NCI including Astronomy Australia Limited funding of some National Computer Infrastructure resources has been crucial for SKA precursor science. JWST data analysis has also benefited through HPC facilities such as OzSTAR and Ngarrgu Tindebeek supercomputers.

Identify current big problems where progress can be made in the coming decade

Radio/21cm

Treating systematics remains the largest problem in 21cm cosmology at high redshift. With the MWA Phase III upgrade yielding a smoother signal chain and increased sensitivity, the MWA will continue to build improved sky models for calibration, and produce spectrally cleaner datasets. Early SKA array releases and the full operational SKA-Low array will further improve the calibration sky model, giving an advantage to MWA while the SKA EoR experimental pipelines get up and running.

Detection of Global 21-cm from cosmic dawn through reionization is key to informing the redshift domains to target for interferometer measurements of the 21-cm power spectrum, and also to provide the base level that informs when fluctuation power is in absorption or in emission. The coming decade is expected to see improvements on constraints already made on the parameter space that governs emergence of First Light from formation of first stars in ultra-faint galaxies, and the lowering of detection threshold with improvements in instrument design and algorithms for analysis may well eventuate in a genuine detection.

The areas where there is likely to be the most progress over the coming decade are, (1) improved sky model through MWA Phase III and early SKA; (2) RFI identification and excision with ML techniques; (3) cross-correlation of the 21cm signal with other tracers of the early Universe, alleviating foregrounds and yielding new science, (4) improved radiometer technologies with in-situ calibrations, (5) pathfinder missions to the lunar far side aimed at 21-cm detections from dark ages and cosmic dawn.

Specifically,

1. Incomplete sky model (depth and angular resolution) is one of the leading causes of systematics in EoR 21cm datasets. The MWA Phase III upgrade, followed by the SKA science-quality arrays (AA2, AA3, AA*) will produce increasingly deep and resolved sky models for data calibration.
2. RFI comes in many flavours, and we are increasingly seeing that different tools are good at finding different RFI. Low-level RFI, which may only be detected statistically, poses a large challenge to EoR experiments. There is currently significant investment of energy in this field, with MWA and early SKA data excellent datasets for using ML to find and excise RFI.
3. Foregrounds remain a large issue in EoR data due to the large (10^4-10^5) dynamic range of foreground to cosmological signal. One avenue to circumvent this is to cross-correlate 21cm with a tracer that has independent foregrounds. The next decade sees the start of operations of several widefield Line Intensity Mapping (LIM) experiments, probing CO, CII, OIII, Ly-a, which can be used for radio cross-correlation. The key move from pencil-beam observations to LIM wide-field observations allows a matching of angular scales for radio and LIM tracer observations.
4. Global 21-cm radiometer detection capability is currently limited by calibration systematics from internal receiver noise and from interactions of the EM sensor element with the ground, apart from chromaticity in the sky response function. Man-made RFI from terrestrial and satellite transmitters confuses any cosmological signal. Current investment in improved technologies for in-situ calibrations - of receiver, sensor and environment - and siting such accurate radiometers on the lunar far side, is the recognized pathway to discovery.

JWST also presents an interesting opportunity. Currently, JWST's small field-of-view makes comparison of radio and JWST data next to impossible. As more fields are observed, the scales become more comparable and work may be done on this when SKA-Low comes online and its arcsecond resolution can be put to good use.

21cm Forest potential work will likely get some attention as groups identify radio-loud QSOs at z>7 that could be observed with SKA-Low. With the existence of radio-loud AGN in the EoR confirmed, searches will continue for the rare, but most powerful AGN in the early Universe. However, follow-up remains challenging. JWST results are pointing to a large fraction of partially obscured AGN at high redshift, a subset of which must be radio-loud. How are such sources identified and then redshifts obtained?

Cosmological recombination lines (from the surface of last scattering) may also be in the grasp of telescopes in the coming decade.

Optical/NIR/Sub-mm regime

The wavelength and redshift frontier opened with JWST with other key sub-mm facilities has transformed our view of the galaxy and chemical evolution processes in the early Universe. The discoveries have reformed questions that we urgently need to answer in the EoR to fully utilize the current technological capabilities with limited lifetime.

In the reionization front, JWST has spectroscopically confirmed 100s of galaxies in the EoR. Multiple emission line detections have allowed detailed constraints on the ionizing conditions of EoR galaxies across the redshift spectrum from z=6 to z=12 within the first 2 years of operation. This, when combined with deep Sub-mm observations from ground-based facilities provide a multi-wavelength view from rest-frame UV-IR of the EoR mass and dust buildup.

Here we list some key questions in reionization physics, galaxy and chemical evolution that need addressing in the next decade.

- ★ JWST has discovered populations of ultra-faint galaxies in EoR (M_{UV}~-15 to -17) and that they produce ionizing photons ~ 4 times higher than what was expected (e.g. Atek+24, Simmonds+24). By taking advantage of magnification from gravitational lensing, 0.05L* galaxies at z~10 have been spectroscopically confirmed with multiple emission lines (e.g. Roberts-Borsani+23). The new discoveries point to reionization completing earlier by z~8 as opposed to z~6 as shown by Figure 7. Therefore, it is vitally important to constrain the parameters related to reionization including if and where the turnover of the UV luminosity function happens, and the number of ionizing photons produced and leaked by EoR galaxies across various physical and chemical properties. Obtaining (spatially resolved) higher resolution spectroscopy with NIRSpec and other ground based Adaptive Optics assisted 8m+ NIR facilities is crucial to map the neutral gas geometries of EoR galaxies through resonant emission lines such as Ly-α and MgIIλ2796λ2803. Open questions also remain about the possibility of efficiently obtaining emission line diagnostics to z>10 galaxies that are not ultra-luminous (e.g. sources that are intrinsically fainter than GNZ11 or GHZ2) with JWST (Hainline+24) and why galaxies with similar properties to GNZ11 have not been observed at z<10.

- ★ Gravitational lensing has enabled individual star-forming regions to be probed in the EoR (Adamo+24, Mowla+24). Initial results point to these sources to be extremely hot with low metallicities and top-heavy initial mass functions. Properties of these galaxies point towards them being proto-globular clusters. Understanding the intricate connections between the extreme stellar surface densities of these individual star-forming regions with extremely dense z>12 sources such as GHZ2 (Castellano+24) is necessary to form a spatially resolved picture of how the first stellar clusters and primordial galaxies formed and evolved.

- ★ JWST has discovered a new population of previously unseen galaxies at EoR. Dubbed “Little Red Dots”, these are red selected galaxies which are morphologically compact highly reddened sources (e.g. Labbe+22, Greene+24). The number of sources in EoR is 2-3 orders of magnitude higher than the bright quasar population (e.g. Kocevski+24). While the spectroscopy points towards AGN activity, constraints from X-ray detections are inconclusive (Ananna+24). Thus, various mechanisms are currently being developed to explain this galaxy population (Maiolino+24). The complexity of enhanced dust presence to leakage of ionizing photons makes it vitally important to determine the true abundance, nature, and formation mechanisms of this newly discovered population.

★ In a similar theme, the first galaxies observed at z>10 points towards highly ionizing conditions (e.g. Cameron+23). AGNs have been invoked to explain these ionizing conditions (e.g. Xu+24), thus, how the very first super massive black holes accrete material in super-Eddington rates to build up stellar mass and the effect it has on regulating star-formation of the first galaxies needs to be determined.

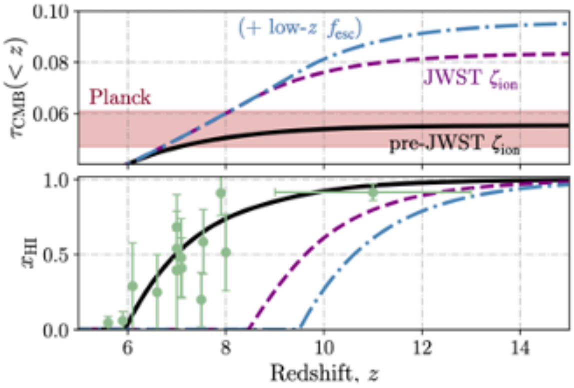

Figure 7: The abundance and ionizing properties of EoR galaxies point towards an early reionization. The figure adapted by Munoz+24 illustrates how the JWST results are in conflict with Plank and other pre-JWST results. This points to a need of refining our galaxy evolution properties and caution us on using calibrations developed using local analogues of high-z galaxies directly at the EoR. The caption reads: "The new JWST and low-z observations imply an earlier reionization, in tension with the CMB. Bottom: Evolution of the neutral fraction xHI as a function of redshift z for a pre-JWST model (black solid, with a cutoff at MUV = −13 and $f$esc = 0.2, following R15), for the same model but with a JWST-calibrated ξion (purple dashed, following Simmonds et al. 2024), and a model where in addition $f$esc is determined from low-$z$analogues (blue dot- dashed, using the fit in Chisholm et al. 2022). Green points show a collection of observational constraints from (McGreer et al. 2015; Greig et al. 2017, 2018; Sobacchi & Mesinger 2015; Mason et al. 2019; Whitler et al. 2019; Wang et al. 2020; Nakane et al. 2023). Top: CMB optical depth τCMB, where the red band is the measurement from Aghanim et al. (2020). The new galaxy observations give rise to far more ionizing photons, and at face value are in severe tension with CMB data."

★ In addition to determining physical processes on how the first AGN are formed, stellar population (including non-solar scaled models and variable IMF models), photoionization, and feedback models (e.g. Dekel+23) should be developed to include realistic conditions of EoR galaxies. It is vital to develop new diagnostics (e.g. emission line ratio diagnostics) to determine types of and relative contributions of different types of exotic stars, including variations of the initial mass function (e.g. Lacey+16), and AGN to the ionizing spectrum with consistent chemical evolution (e.g. Robotham+20).

★ EoR spectroscopy of galaxies point towards very early enrichment of nitrogen in the first galaxies (Cameron+23) and for a helium overabundance of galaxies in EoR (Yanagisawa+24). Effects such as primordial stellar nucleosynthesis, Wolf-Rayet stars, exotic supernovae mechanisms such as pair instability supernovae and hypernova have been proposed to alleviate the tensions between early chemical enrichment models and observations. Currently there is no consensus. Determining primordial nucleosynthesis is a crucial component in building up our view of the anthropic principle of evolution, thus, should be of highest priority to answer with the current technological capabilities.

- ★ How the universe efficiently built-up large quantities of dust in the EoR is a mystery. Main dust production mechanisms are tied to AGB stars, thus enhanced contributions to the dust mass through core collapse supernovae and rapid chemical enrichment (Hodge & Cunha 20) along with possible contributions from Wolf-Rayet stars might be necessary to model the dust masses of EoR galaxies. Complete IR analysis of EoR sources with sub-mm facilities obtaining ionized gas and multiple dust continuum detections is crucial to determine the nature of the dust and gas in EoR to constrain current models.

- ★ The star-formation histories of z~3-5 massive quiescent galaxies currently suggest the existence of 10^{10} M_{sol} massive galaxies at z~10 (Carnall+24, de Graaff 24, Glazebrook+24, Nanayakkara+24). There has been evidence for direct detection of such massive sources up to z~9 (Labbe+22). Currently, the mass buildup of such sources requires 100% of baryon to star conversion efficiencies (Carnall+24) and in some cases has shown also to be inconsistent with our current halo mass buildup constraints at z>10 (Glazebrook+24). Spectroscopic confirmations of the most massive sources at EoR, analysis of their stellar populations, along with SFH reconstruction of z~3-5 massive quiescent galaxies with considering consistent metallicity evolution are required to answer how the Universe efficiently built up the most massive galaxies extremely efficiently within ~500 Myrs of the Big Bang and their morphological evolution.
- ★ The buildup of spectroscopic samples of galaxies from cosmic noon to EoR through facilities such as Euclid, SphereX, Roman will enable the dark matter distributions and large scale structure to be mapped. Therefore, probing how the galaxy environment evolves and underpins galaxy evolution and how the universe evolved from density perturbations to sheets and walls, filaments and voids requires to be addressed to refine our cosmological models.

Big Data, Computing, and High Performance Computing (HPC) Facilities

The 21cm datasets are already large with current precursors, and this will only increase with SKA. With AusSRC funded, we have a good foundation for managing the data flows, but efficient and reliable HPC, large storage, significant GPU access, will become increasingly important to extract the science from the data.

Identify capabilities that allow Australia to contribute to big problems and what we require to be competitive

Radio/21cm

The largest opportunity presented in the coming decade is SKA. As the world's largest and most flexible radio telescope, SKA-Mid and SKA-Low will answer some of the biggest questions in astrophysics. For high-redshift 21cm science, SKA-Low is the principal instrument. Being located in Western Australia, we are perfectly placed to maximize our proximity to the telescope and data to take leadership in 21cm cosmology. SKA-Low's primary advantages over existing telescopes for exploring the early Universe are, (1) high surface brightness sensitivity in the array core for deep power spectrum and tomography, (2) very long baselines for building a highly complete and deep sky model for calibration, and then use of those baselines in the calibration and source subtraction steps of the analysis, (3) flexibility to change the field-of-view of the telescope and shape primary beams via the individually-digitized dipoles, (4) very wide instantaneous bandwidth for calibration lever arm.

Australia has clear observational expertise with MWA, HERA, and early SKA, as well as unique geographical location to do this experiment. Proximity to the MWA/SKA data lends a natural advantage to WA in particular, but for all of Australia through the fast AARNet network.

Curtin researchers are leading efforts to identify high-z radio-loud QSOs, and there is good potential for success in the next 3-5 years. These efforts are bolstered by access to MWA and ASKAP as two telescopes that form measurements critical to identify candidate sources.

Australia's expertise in hydrogen reionisation observation places it well for probing Helium reionization using the 8.66GHz line. Co-observation of 21cm and 3cm radiation can place constraints on the temperature of the IGM at $z=2.5$-4.5, but there are also opportunities for studying helium in the $z>6$ epoch. With early work with ATCA underway, SKA-Mid is a good instrument for this.

Australia has almost a century of experience in innovative radio telescope designs that have made breakthroughs in unravelling the radio universe. The most advanced radiometer designs with in-situ calibration capability have been developed in the last few years by Australian effort; this has been deployed to demonstrate wide-band spectral measurements of sky radio radiation across the cosmic dawn and reionization windows. Mated with purpose designed wideband achromatic antennas, and sited in radio quiet locations exclusively accessible in the interior of the continent, the advanced radiometers have the potential to lead the field of 21-cm global signal detection and constraining the physics of gas and galaxy evolution in the early Universe. Together with emerging opportunities for space programmes, this local expertise presents an opportunity to devise payloads for deploying the local technology on the far side.

Optical/NIR/Sub-mm regime

Australia has significant expertise in utilizing space based observatories such as HST and JWST in EoR science. Australian researchers have led large treasury programs contributing wealth of data to the community. The JWST Australian Data Centre (JADC) funded to the end of 2025 has provided training for ECRs on planning JWST proposals which are highly technical. In cycle 2, all ECR Australian PI JWST proposals were attendees of the JADC JWST training. Based on overall Cycle 1 and 2 JWST outcomes, Australian scientists have been exceptionally successful in obtaining competitive time from JWST compared to nations that are not a partner of JWST. Continued assistance for the Australian community in planning and preparing JWST (and other future space observatories) observations and data reduction assistance will be beneficial. It may also be beneficial to revisit the dedicated Australian Space Institute idea from 2020 mid term review white paper from Driver, Glazebrook, and Hopkins 2020.

Interferometric expertise of the Australian community is unparalleled. In addition to SKA, opportunities for EoR science lie in sub-mm interferometry. It is the only way to obtain rest-frame IR coverage of EoR, which forms a crucial wavelength window in analyzing the build up of metals in the early universe. As shown by Figure 8, ionized gas and dust continuum emission from galaxies can be obtained efficiently throughout the EoR utilizing facilities such as ALMA. Thus, Australia seeking dedicated access to such facilities is vital for EoR science and will be complementary to the capabilities of the SKA. Opportunities are also expected to arise in receiver upgrades for ALMA. ALMA 2030 (Carpenter+18) lists Origins of Galaxies as of highest priority for ALMA which requires upgrades to Intermediate and high frequencies to perform spectral surveys of fine structure lines in EoR. Quoting from the The ALMA Development Roadmap: “The Working Group proposes the following fundamental science drivers for ALMA developments over the next decade: Origins of Galaxies
Trace the cosmic evolution of key elements from the first galaxies ($z>10$) through the peak of star formation ($z=2–4$) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour” and “Intermediate frequencies can probe [CII] (158 μm) at $z=3.5-8.5$, [NII] (205 μm) at $z=2.4-6.3$, and [NII] (121 μm) at $z=4.8-11.3$. High frequencies trace [OIII] (52 μm) at $z=5.1-12.6$, [OIII] (88 μm) at $z=2.6-7.0$, and [OI] (63 μm) at $z=4.0-10.2$”.
Thus, future contracts to develop these capabilities will be mutually beneficial for industry engagements while developing capabilities to advance EoR science.

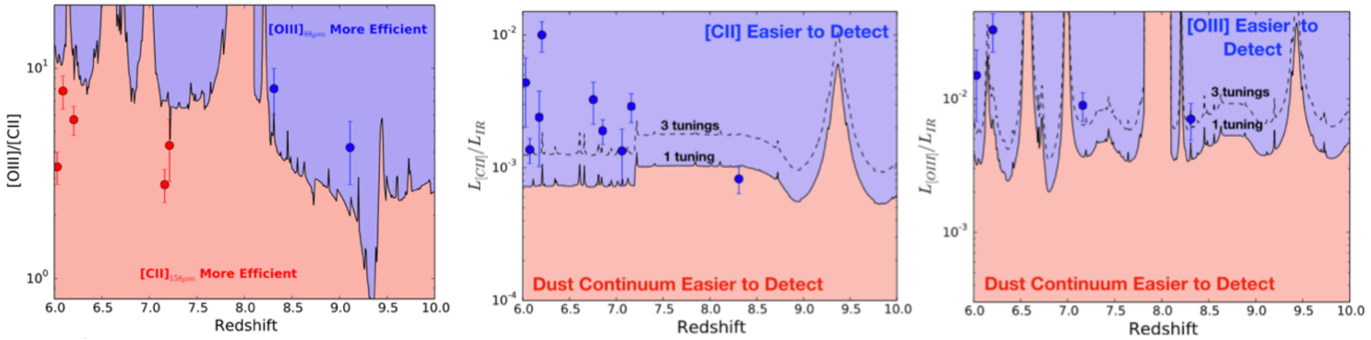

Figure 8: Adapted from Bouwens+20 demonstrates the strength of ALMA in obtained ionized gas and dust continuum constraints at EoR. Constraining the dust temperature via multiple detections is vital to determine the evolution of the dust properties with cosmic time and to constrain mechanisms that resulted in large quantities of dust within the 1st billion years of the Universe, time period before AGB stars are dominant.

Australia is a world leader in instrumentation. While NIR instrumentation poses significant technical challenges, the expertise within the community is well suited to develop new technological advancements in the field. ESO, Keck, and Subaru telescopes have ambitious Adaptive Optics projects expected to assist EoR science during the next decade. Australia should get involved where practically possible and early as possible in these projects to drive community interests and obtain best science returns for the Australian investments.

Theory

Australia's strengths in EoR simulations and Bayesian inference of 21cm results for astrophysical parameter estimation place us in an excellent position to capitalise on interpretation of early SKA results. Retaining strength in the theoretical cosmology community is key to ensuring this.

Computing/Big Data/HPC

The SKA z>6 science case will not be possible without a large amount of dedicated compute (GPU, CPU) and storage for retaining the averaged visibilities. Failure to be able to retain data, and undertake the data processing will leave Australia behind the rest of the world. With the data residing in WA, Australia has the easiest access and ability to be at the forefront of these key experiments, but this will not happen if we don't have the computing infrastructure needed.

The high performance computer infrastructure available to manage SKA can be used to support the design, execution, and analysis of space mission data. Especially in the era of Euclid and Roman, the data processing capabilities will become very important, thus the infrastructure can be used to enable local processing and peering (to SKA) of large data sets (Euclid, Roman). Additionally, data analysis via machine learning will be of utmost importance due to data volume, for which high performance computer infrastructure with novel GPUs will be crucial.

Identify opportunities that are expected to arise over the next decade, and what threatens our ability to take advantage of those opportunities?

SKA

SKA will be the largest opportunity in the radio for z>6. With a 14% share in the telescope, and proximity to SKA-Low, Australia is poised to reap large benefits from SKA. We need to ensure that we are prepared to take leadership positions in the Key Science Projects, and be ready to take and process data for the high-impact science. There is some risk to realizing the science due to the complexity of the telescope, with SKA-Low being composed of hundreds of thousands of independent elements. The flexibility of the telescope is also a potential source of delays, with new calibration and data analysis techniques needing to be developed and tested to undertake the big science programs.

The combination of Euclid with wide-area radio surveys will be very fruitful in finding future candidate radio-loud AGN within the EoR. The availability of ALMA and JWST (and possibly 30-m class telescopes) will be vital in confirming the redshifts of such sources. Combining 21cm Forest observations which probe HI density distributions directly along a specific line of sight with other EoR tracers over the same volume will provide even more stringent constraints on the EoR.

Space based astronomy

An emerging opportunity is for space-based astronomy, with an emerging national space industry pioneering niche technologies demonstrated by the private sector, and an Australian Space Agency that supports space activities and technologies that inspires Australians and supports space ties with international partners. The SpIRIT project (Trenti+21) has been successful in demonstrating the combined capabilities of science and industry sectors through government investments. Future opportunities arise by further refining the role of the Australian Space Agency to assist the research and industry sectors for scientific space missions. Additionally, astronomers could utilize the reach of the agency to bid for future NASA/ESA missions ranging from probe scale missions to great observatories. Technological advancements enabled through developing innovative UV integral field spectrographs for proposed missions such as HabEx in the next decade will assist broader scientific and industry collaborations in the space sector. Furthermore, redshifted 21-cm power spectrum at the longest wavelengths and also precision detection of Global 21-cm is best performed on the far side and translation of the ground based advance to lunar sites is a natural progression of the science that requires pathfinder endeavours in the coming decade.

Current JWST lifespan would extend well beyond the next decadal survey. The combined existence of several space observatories such as HST, JWST, EUCLID, Roman would provide a wealth of data that is suitable for exploring the EoR. The formation of the Australian Space Agency during the current decadal plan was welcome. Advocating a scientific remit for the agency through the decadal survey would provide key advantages for the Australian astronomy community. Grants tied to space observations would provide valuable contributions to graduate student and postdoc funding in Australia which is independent of the ARC. This extra source of funding dedicated to observational projects will be advantageous to furthen Australian astronomy science.

Access to sub-mm facilities

Australia currently has no dedicated/preferential access to sub-mm facilities. After space based NIR facilities, the most critical is constraining the rest-IR of EoR galaxies through large interferometric facilities such as ALMA. Additionally planned single dish facilities such as AtLAST will enable study the end of the EoR by reaching to z~7 in frobing the rest-IR (van Kampen+24).

Molecular line intensity mapping

The next decade will see a rapid increase in widefield line intensity mapping (LIM) telescopes and experiments, providing key insights into star formation tracers including CO, CII, OIII, and Ly-α. The opportunity to cross-correlate these lines with radio becomes a reality with the long baseline of SKA-Low matching the angular resolution of LIM experiments, and the widefield intensity mapping approach providing maps over a reasonable angular scale. Most LIM experiments are international, and collaborations will need to be formed to get data access. Early opportunities for this work rest with current MWA datasets.

Access to 8m-30m class telescopes

For EoR science, wavelengths beyond optical with adaptive optics is beneficial to complement what can be achieved with current and future planned space observatories. Upgrades to Keck AO through the Keck All Sky Precision Adaptive Optics (KAPA, P. Wizinowicha) project and new Keck instrumentation such as Liger (Wiley+21) and updates to Subaru instrumentation through the ULTIMATE project (Minowa+20) will benefit spatially resolved science in EoR in the NIR. MAVIS will cover Ly-α up to z~8 enabling spatially resolved science, but lack of coverage in NIR will limit EoR science. Future ESO VLT NIR instruments such as MOONS will be beneficial for redshift conformations. Opportunities also arise in obtaining redshift confirmations for EoR radio-loud AGNs discovered by the SKA by utilizing these NIR facilities.

Risks

Optical/NIR/Sub-mm

Lack of dedicated access to 8-30m class telescopes and sub-mm facilities for the community will have implications for fostering international collaborations to advance EoR science.

Australia currently has a limited partnership with ESO allowing access to the 8m class telescopes for the first ~2 years of the next decadal survey window. Swinburne University joined the Keck consortium in 2023 as a partner, getting dedicated access to ~20 nights per year on the 10m keck telescopes. The partnership is expected to run throughout most of the next decadal survey. However, the Swinburne agreement with Keck is institution specific, thus, after the expiry of the limited ESO agreement, most of the Australian community will lose direct access to 8-10m class facilities.

On the NIR 30m front, the highest risk is the Australian monetary investment for the Giant Magellan Telescope. If the project is not completed within the expected specifications, Australia will have no access to 30m class telescopes. ESO's E-ELT project, for which Australia is not a partner, is expected to be completed during the next decade. Diffraction limited spatially resolved analysis in the EoR will be the next frontier which will complement advances made by JWST, thus there is a possibility Australia will be left behind in EoR science if Australia lacks access to such projects.

On the sub-mm front, Australia currently lacks dedicated access to sub-mm facilities. This will under utilize the large knowledge base in Australia in higher wavelength science and limit opportunities for leading international collaborations which are crucial for EoR science given the nature of large observational time and multiwavelength requirements.