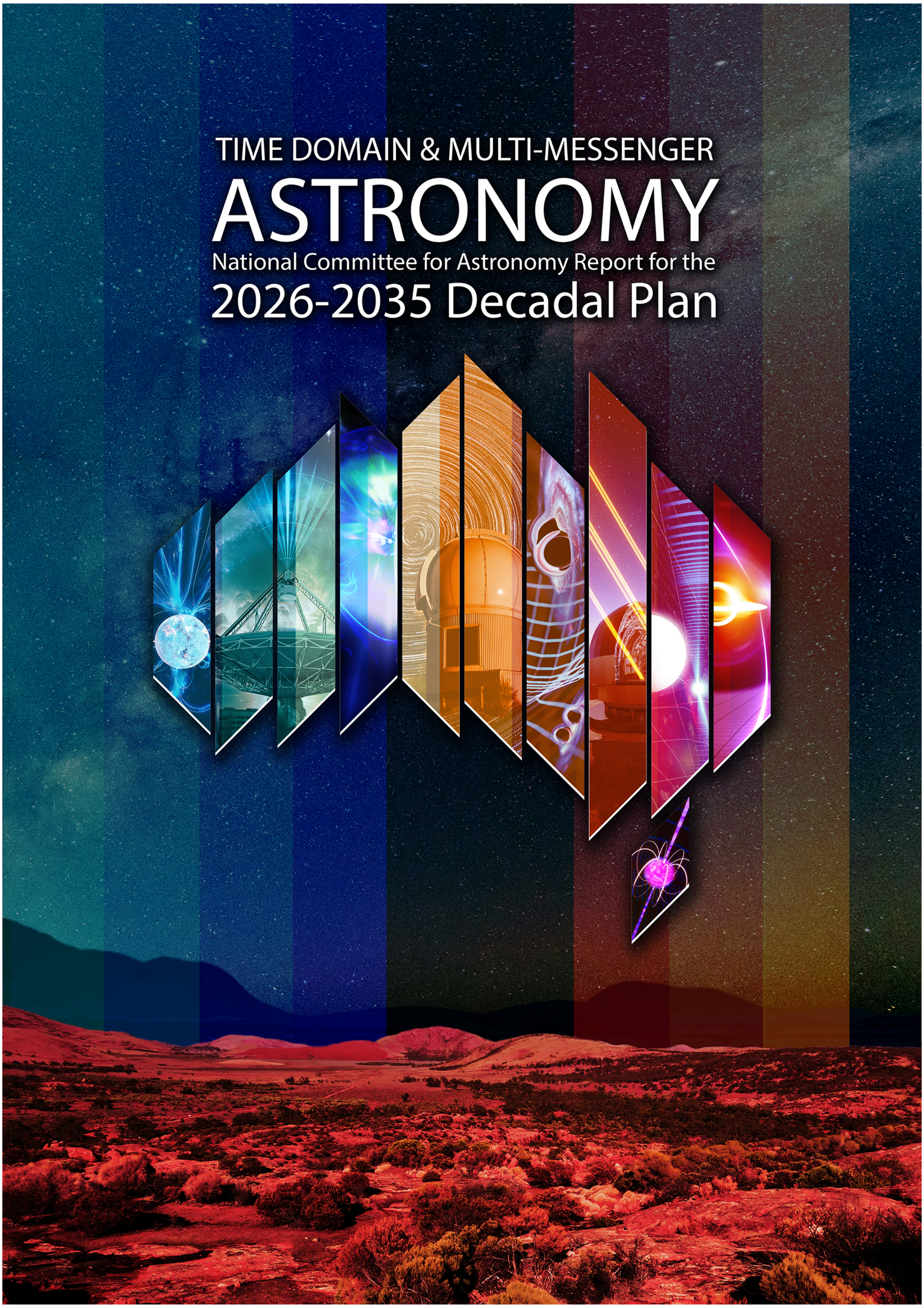
TIME DOMAIN & MULTI-MESSENGER
ASTRONOMY
National Committee for Astronomy Report for the
2026-2035 Decadal Plan

Time Domain & Multi-Messenger Astronomy

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1 Executive Summary

Time-domain and multi-messenger astronomy is the study of how the sky changes on timescales of milliseconds to years using a variety of messengers: from optical light to radio waves to ripples in the fabric of spacetime (gravitational waves). This interdisciplinary topic is the connective tissue of astronomy, linking together the broad communities of optical, radio, gravitational-wave, particle/high-energy, and theoretical astrophysics. These fields have seen enormous growth over the past decade, from the discovery of gravitational waves, to the explosion of fast radio burst science, to the discovery of astronomical transients that were previously unknown. Some of the most significant astronomical discoveries of the last decade fall within the domain of time-domain & multi-messenger astronomy—and the next decade is likely to see an explosion in the discoveries of these fields as we move into a new era of large-scale, multi-messenger surveys and the advent of new capabilities.

We identify four key questions for the coming decade (see Section 4):

1. *How do stars die?* This question highlights what we can learn when we observe the final cataclysmic moments of a star's life and the remnants they leave behind.

2. *What is the role of black holes in the Universe?* This question highlights the importance of black holes at all mass scales: driving galaxy evolution, generating gravitational waves, and ripping apart stars.

3. *What do astronomical transients teach us about the Universe?* This question highlights how transients can be used as cosmological probes, e.g., to measure cosmic expansion and the baryon content of the Universe.

4. *What is the nature of matter at extreme densities?* Our final question emphasises the importance of neutron stars as the progenitors of kilonovae, as sources for fast radio bursts and gravitational waves, and as laboratories for nuclear physics.

These key questions motivate significant investment in the following infrastructure priorities (see Section 5):

1. Becoming a full member of the **European Southern Observatory** (ESO).

2. Continued support for the **Square kilometre Array** (SKA) and SKA pathfinder facilities.

3. Support for Australian contributions to a global network of **next-generation gravitational-wave observatories**.

We also highlight the importance of:

4. Ongoing support of facilities in Australia and the critical role these facilities will play over the next decade due to Australia's unique and strategic geographical location.

5. Ongoing support for the Vera C. Rubin Observatory.[1]

6. Access to the Giant Magellan Telescope (GMT).

7. Support for dedicated astronomical computing infrastructure, e.g., Ngarru Tindebeek/OzStar, SKA data processing, the Gravitational-Wave Data Centre, etc.

[1]Rubin was formerly known as the Large Synoptic Survey Telescope (LSST).

2 Capabilities

Over the past 20 years, an extraordinary variety of new phenomena has been revealed through time-domain and multi-messenger astronomy. Key discoveries include gravitational waves from merging compact objects [1, 2], fast radio bursts [3], and ultra-long period radio transients [4] to name just a few. Looking towards the next decade, we foresee that time-domain and multi-messenger astronomy's golden age will further develop and grow, due in part to new observatories that will detect orders of magnitude more transient sources than current facilities, and due in part to new multi-messenger facilities that can detect transient sources using gravitational waves, gamma-rays and neutrinos. Here we review the current state of Australian capabilities in this space.

2.1 Domestic Observatories

2.1.1 Radio

Australia has led the world in the discovery of new transient radio sources with recent discoveries including fast radio bursts and ultra-long period transients. This has been enabled by telescopes such as Murriyang (Parkes) and the Murchison Widefield Array (MWA) with their wide fields of view and flexible detection systems. The Australian Square Kilometre Pathfinder (ASKAP)'s field of view has also proved game-changing, with the Commensal Real-time ASKAP Fast Transients (CRAFT) and Variables And Slow Transients (VAST) survey science projects. Australian facilities such as the Australia Telescope Compact Array (ATCA) and the Long Baseline Array (LBA) have also played important roles in follow-up observations of time-variable sources, from gravitational wave (GW) events to gamma-ray bursts (GRBs) and tidal disruption events. Recent updates to the CRAFT Coherent (CRACO) system on ASKAP, CyroPAF (Cryogenic Phased Array Feed) and the ultra-wide bandwidth low (UWL) receiver on Parkes, Phase 2 for the MWA, and the Broadband Integrated GPU Correlator for ATCA (BIGCAT), keep these facilities world class. International demand for these facilities, which offer unique capabilities in the Southern Hemisphere has also facilitated Australian access to the extended Roentgen Survey with an Imaging Telescope Array (eROSITA) on-board the Russian–German Spectrum-Roentgen-Gamma (satellite) mission, which observes the sky at X-ray wavelengths.

Australia also plays a foundational role in nanohertz frequency gravitational wave astronomy. The first major pulsar timing array (PTA) experiment, the Parkes PTA (PPTA), was established using Murriyang in 2004. The data set provided by the PPTA provides some of the highest quality legacy data, and access to Southern Hemisphere millisecond pulsars inaccessible by major northern hemisphere PTA experiments. Australian pulsar timing was a major player in the recent detection of nanohertz gravitational waves [5].

2.1.2 Optical

Australia's well established optical facilities play a key role in discovering and monitoring time variable sources. Time on these facilities is increasingly being sought by astronomers from all over the world, largely due to Australia's unique and strategically important geographical location. Australia fills in a gap in longitude that cannot be easily covered elsewhere and demand for these facilities will sky-rocket once the Legacy Survey of Space and Time (LSST) at the Rubin Observatory starts collecting data in 2025.

Australia is home to Siding Spring Observatory (SSO), the largest optical astronomical observatory in Australia. SSO hosts a dozen facilities run by national and international consortia. Several of the facilities at SSO have been specifically built or recently upgraded to study astronomical sources in the time domain. These include the now fully robotic ANU 2.3 m telescope and GOTO-South, which is used to search for the optical counterparts to gravitational wave events. In the near future, new facilities[2] with a focus on the time domain will be installed at SSO. These include additional LCO[3] telescopes at SSO, which all Australian astronomers have access to, and DREAMS, a new wide field imager that will survey the entire southern sky every few nights in the near infrared. The SSO Transient Factory, which links several telescopes at SSO into a system to automatically discover and follow-up transient sources without human intervention, will be deployed in 2025. SkyMapper, which just finished its Southern Sky Survey, is currently being used for transient discovery and follow-up, but can be used for regular monitoring of variable sources over a very broad range of time scales.

Other observatories in Australia contribute to time-domain science and are currently going through upgrades to improve their capability for rapid response time-domain astronomy. These include Mt Kent Observatory (QLD), Greenhill Observatory (Tasmania), and the Zadko Observatory (WA).

2.1.3 Gravitational waves

The Australian community develops some of the key infrastructure for the Laser Interferometer Gravitational-wave Observatory (LIGO). Laboratories at ANU are used to develop squeezed light sources and for testing the coatings of LIGO optics. The University of Adelaide hosts labs that are used to develop Hartmann wavefront sensors and to test thermal compensation systems. The University of Western Australia hosts an 80 m interferometer, which is used as a prototype for experimenting with new technologies.

2.1.4 Gamma and X-ray nano-satellites

Australia has also recently developed its first space telescope: the SpIRIT (Space Industry Responsive Intelligent Thermal) nano-satellite. Launched into orbit on the 1st December 2023, and developed with funding from the Australian Space Agency in cooperation with the Italian Space Agency, the instrument successfully achieved first light with nominal in-orbit performance. The SpIRIT satellite is expected to operate as part of the European HERMES constellation, that will be launched in 2025. The SpIRIT satellite will be one of seven satellites designed to detect transient high energy emission (2 keV to 2 MeV) and triangulate the source position from differential photon arrival time measurements. Expected discoveries include gamma-ray bursts at high redshift in the epoch of reionisation and counterparts of gravitational wave mergers [6, 7].

2.2 International observatories

2.2.1 The European Southern Observatory

The European Southern Observatory (ESO) runs the La Silla and Paranal Observatories and jointly runs ALMA, all of which are located in northern Chile. Paranal is home to the ESO Very Large Telescope (VLT) and the Visible and Infrared Survey Telescope for

[2]The AAT is more limited in its capacity to follow sources in the time domain as it is classically scheduled and there are insufficient resources to support a rapid response observing mode. Automating the AAT would require significant investment.

[3]Las Cumbres Observatory

Astronomy (VISTA). Australian astronomers are heavily invested in future surveys using VISTA. Staring in 2025, the 4-metre Multi-Object Spectroscopic Telescope (4MOST) survey, which uses an Australian-built fibre positioner, will conduct a series of spectroscopic surveys of the southern sky on VISTA. The Time-Domain Extragalactic Survey (TiDES) survey in 4MOST will obtain spectra of over 50,000 transients during the 5 years it will run [8]. Located nearby and currently under construction are the ESO Extremely Large Telescope (ELT) and the southern site of the Cherenkov Telescope Array Observatory (CTAO).

As part of an agreement between ESO and the Australian Government, Australian astronomers have the same level of access to ESO facilities at La Silla and Paranal as full ESO member countries. This agreement comes to an end in 2027. Access to these facilities beyond 2027 and to the ESO ELT will only occur if Australia joins ESO as a full member. ESO facilities provide Australian astronomers with access to some of the most powerful and diverse range of optical and infrared instruments currently available anywhere.

The ESO VLT hosts twelve main instruments (plus several more in the inteferomertic lab). These instruments (in particular FORS2) have proven critical to identifying and characterising FRB host galaxies and measuring their redshifts, driven by the Fast and Unbiased FRB host galaxY (FURBY) survey [9], led by the CRAFT Collaboration. MUSE and X-Shooter are other instruments on the VLT that are regularly requested by Australian astronomers to follow-up a wide range of science.

Rapid followup of interesting transients is crucial if we are to unlock some of the most pressing questions in this field. ESO led the world in implementing target of opportunity (ToO) and rapid response mode (RRM) observations, which allow transients to be observed within minutes of their discovery. ESO queue-based observing system allows monitoring of variable sources.

2.2.2 Laser Interferometer Gravitational-wave Observatory (LIGO)

The Australian gravitational-wave community has access to data from LIGO via membership in the LIGO Scientific Collaboration. Historically, LIGO membership has been funded through LIEF grants. The LIGO facilities—based in the USA—are the most sensitive gravitational-wave observatories in the world. At the time of writing, LIGO has detected ≈ 208 gravitational-wave transients. Access to this data is essential for Australian involvement in gravitational-wave astronomy. Australia contributes important technology to LIGO; see 2.1.3. The Australian community are active members in LIGO commissioning through the LIGO Fellows program.[4]

2.2.3 International radio partners

Most international radio facilities have open-skies policies, and regularly provide time to Australian astronomers to perform follow-up observations of time-variable sources. These include the Very Large Array in New Mexico (VLA), the Giant Metrewave Radio Telescope (GMRT) in India, the Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, the Radio Telescope Effelsburg in Germany, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China, and the Square Kilometre Array (SKA) precursor, MeerKAT, in South Africa.

Australia leads (and designed the infrastructure for) the MeerKAT large science project MeerTIME [10], which is a pulsar timing array experiment able to observe 80 pulsars to

[4] https://dcc.ligo.org/public/0116/M1400336/002/LSCfellowsProgram_160413_public.pdf

higher precision than the 30 PPTA pulsars. Australia is also involved in the TRANsients and Pulsars (MeerTRAP) project on MeerKAT, which detects FRBs [11], ULPs [12], and other transients.

2.2.4 The Vera C. Rubin Observatory

Formerly known as the Legacy Survey of Space and Time (LSST), Rubin will revolutionize time-domain astronomy by imaging the entire southern sky every night for a decade to unprecedented depths. Australian involvement in Rubin is currently funded through a LIEF grant that will end in 2027. Australian astronomers participate in Rubin through several science collaborations, such as the Dark Energy (DESC), Transient and Variable Stars (TVS) and the AGN Science Collaborations. Additionally, seven Rubin community brokers worldwide will select the most promising detections from the millions discovered every night and connect them in real-time to researchers and observing facilities for follow-up. Australia is leading and has a strong membership in the Fink broker Collaboration[5] that will enable Australian-led science and follow-up.

2.2.5 High-energy instrumentation

At the highest energy wavelengths, Australian researchers are part of the international Cherenkov Telescope Array Observatory (CTAO), which is constructing TeV gamma-ray observatories on La Palma, Spain, and at Paranal, Chile. Australian astronomers are also members of the High Energy Sterescopic System (H.E.S.S.; TeV gamma-ray instrument in Namibia), Pierre Auger (cosmic ray) Observatory in Argentina, and several neutrino observatories including IceCube (USA, at the South Pole), KM3NeT (Europe), and Hyper-Kamiokande (Japan). Australian researchers have also taken advantage of the Fermi Gamma-ray Space Telescope to obtain information about the GeV gamma-ray emission of sources, which can only be obtained from space.

X-rays also provide an important insights into a wide range of phenomena associated with transients, ranging from nucleosynthesis yields, shock physics, probes of circumstellar medium, jet physics, to accretion. Australia currently has a partnership with eROSITA (extended Roentgen Survey with an Imaging Telescope Array) that has performed the first imaging all-sky survey in the X-ray range up to 10 keV [e.g., 13], while many Australian researchers use a wide range of X-ray satellites to perform their science. This includes the Chandra X-ray satellite, XMM-Newton mission, Neutron Star Interior Composition ExploreR (NICER), the X-Ray Telescope (XRT) onboard the Neil Gehrels Swift Observatory, the X-ray Imaging and Spectroscopy Mission (XRISM), which observes in the soft X-ray band (up to $\sim$ 10 keV), and the Nuclear Spectroscopic Telescope Array (NuSTAR) and Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory that observe in hard X-rays up to $\sim$ 150 keV.

2.2.6 Optical/IR/UV resources

Australian researchers are intimately involved in and are heavy users of a wide range of internationally lead ground-based and space-based instrumentation that cover the IR/optical to UV wavelengths. Australia is currently a partner with the Giant Magellan Telescope (GMT), which is a next generation optical/infrared telescope, that is currently under construction at the Las Campanas Observatory in Chile.

[5] https://fink-broker.org/

Beyond these, Australia researchers either lead or are involved with projects that use space-based IR to UV instruments such as the James Webb Space Telescope (JWST), the Hubble Space Telescope (HST), the soon to be launched Nancy Grace Roman Space Telescope, and the Transiting Exoplanet Survey Satellite (TESS). Beyond ESO and Rubin, there are many other ground-based IR to optical resources that Australian researchers are taking advantage of. For photometry, this includes the All-Sky Automated Survey for Supernovae [ASAS-SN: 14], the Asteroid Terrestrial-impact Last Alert System [ATLAS: 15, 16], the Zwicky Transient Facility [ZTF: 17], Pan-STARRs [e.g., 18], GOTO [19], the distributed network of 25 telescopes of the Las Cumbres Observatory, the Korean Microlensing Telescope Network, the 1 to 2-metre class telescopes at the South African Astronomical Observatory, and the Dark Energy Camera (DECam) on the 4-metre Blanco Telescope. While for spectroscopy, key resources include Gemini, the South African Large Telescope (SALT), the Nordic Optical Telescope, NASA Infrared Telescope Facility, Keck, among others.

2.3 High Performance Computing

High-throughput and high-performance computing is essential for analysing data in time-domain and multi-messenger astronomy. The Ngarru Tindebeek/OzSTAR supercomputing cluster, maintained by Astronomy Data and Computing Services (ADACS), provides critical computing support for the entire Australian astronomical community. Computing support for ASKAP is provided by Pawsey and CSIRO, which assists in ASKAP data management. The Australian SKA Regional Centre (AusSRC) has recently been formed to service the needs of the SKA project, in particular SKA-Low. Meanwhile, the Gravitational-Wave Data Centre (operated by ADACS) supports gravitational-wave software development and data access.

3 Highlights from Last Decade

3.1 Gravitational Waves

The last decade saw gravitational waves become a new and exciting window on the Universe, with the detection of gravitational waves from a binary black hole by the LIGO Scientific Collaboration and Virgo Collaboration. This discovery simultaneously confirmed the existence of gravitational waves and provided the first detection of a binary black hole system while launching the era of gravitational wave astronomy. Not long after this initial discovery, LIGO and Virgo detected GW170817—gravitational waves from a coalescing pair of neutron stars. This system produced light across the whole electromagnetic spectrum. The detection of a coincident gravitational-wave event, gamma-ray burst and kilonova became one of the most intensely studied astronomical events in history. The Australian gravitational-wave community played an important role in these discoveries, developing instrumentation for LIGO, developing data analysis pipelines, and leading LIGO Collaboration papers. Of the more than 70 telescopes monitoring this source, 15 were directed by Australians, and 9 were on Australian soil [20].

Since then, the global network of laser interferometers have detected over 200 gravitational-wave events associated with the merger of a black hole or neutron star, firmly establishing the field of gravitational wave astronomy. These discoveries have allowed us to study the nature of gamma-ray bursts and kilonovae, probe shock physics in extreme environments, provide independent constraints on the Hubble expansion, provide an opportunity to place the most precise constraints on the speed of gravity, while shedding light on the origin of heavy elements. It is clear that this continually expanding catalogue of gravitational-wave transients will provide significant insight into a wide range of physics from understanding matter at extreme densities to probing the fate of massive stars.

As the sensitivity of current gravitational-wave observatories improves, their ability to detect gravitational-wave events to larger distances and from different types of sources will further revolutionise the field.[6] Since the last decadal survey, Australia has contributed to the upgrade of Advanced LIGO: a new facility called A+ via commissioning and people power (supported through ARC LIEF grants). During this time, Australian leadership in gravitational-wave astronomy has grown significantly thanks to a pair of ARC Centres of Excellence: OzGrav 1 and OzGrav 2.

Meanwhile, the groundwork is being laid for Australian participation in the next-generation of gravitational-wave observatories. The Australian Gravitational-Wave Observatory Project has been founded to consider various options ranging from the construction of a gravitational-wave observatory in Australia [21, 22], to the contribution of key hardware to the American-led Cosmic Explorer observatory. The NCRIS-supported Gravitational-Wave Data Centre (GWDC) provides the infrastructure and the national data and computing support for Australian gravitational wave researchers to analyse gravitational-wave data. Ongoing computing support will be key to sustain Australia's gravitational-wave science capabilities.

3.2 Fast Radio Bursts and ULPs

Fast radio bursts (FRBs), first discovered using facilities in Australia, are radio transient events, with dispersion measures (DMs) greater than expected for Galactic sources [23]. For years, only a handful were known. However, with the development of observatories like the Canadian Hydrogen Intensity Mapping Experiment (CHIME), FRB science exploded. Observations with the Parkes radio telescope, UTMOST, and initial science observations by the CRAFT Collaboration on ASKAP first confirmed that FRB DMs obeyed a dispersion-fluence relationship, expected from cosmological transients [24]. The ASKAP and CRAFT facilities then localised the first non-repeating FRB to a galaxy at redshift $z = 0.32$ [25]. The Macquart relation (named in honour of the late Australian astronomer, J.-P. Macquart) was used to solve the missing baryon problem by confirming that the total ionised gas distribution in the $z < 1$ Universe is consistent with CMB cosmology [26]. This science was enabled by ASKAP's wide field of view, high angular resolution, and dedicated FRB detection system; combined with follow-up optical observations with 8 m class telescopes. Simultaneously, international efforts to detect FRBs have taken off, led by CHIME [27], MeerKAT [11], FAST [28], and DSA-2000 [29]. Approximately 1000 distinct FRBs have been published to date, of which ≈ 60 have identified host galaxies.

While we have learned a tremendous amount about FRBs, new questions have emerged [30]. Radio astronomers are searching for the progenitors of FRBs in order to elucidate the physics of their emission. They are also investigating whether all FRBs repeat eventually, or if some are truly once-off events, for example, from binary neutron star mergers? Last, they seek to know how FRBs are linked to Galactic sources such as the so-called Galactic FRB from magnetar SGR 1935+2154 [31].

[6] Gravitational-wave sources do not follow the familiar inverse square law well known to electromagnetic astronomy. Rather, gravitational-wave strain falls like the inverse distance to the source. Thus, even modest improvements in detector sensitivity can lead to significant increases in the observed spacetime volume.

Fast radio bursts are increasingly used to study the distribution of ionised gas in the Universe. They provide a unique way to probe highly diffuse ionised gas which is otherwise inaccessible to other techniques. For example, FRBs have been used to constrain the halo gas content of our Milky Way [32], to observe galaxies intersecting the FRB line of sight [33], and to measure FRB host galaxies out to $z > 1$ [34], which inform on galactic feedback processes. They can also can be used to measure cosmological parameters, which could prove useful resolving the Hubble tension [35]. Future observations of FRBs have also been proposed to study the epoch of Helium reionisation at $3 \lesssim z \lesssim 4$ [36].

In 2022, a new class of radio transients was detected by the Murchison Widefield Array [4]. So-called ultra-long period (ULP) transients are Galactic sources with periods from tens of minutes to hours—far longer than the known pulsar population, which extends only to $\approx 1\,\text{min}$ periodicity. Only a handful of such sources are now known. As well as the MWA, the VAST Collaboration on ASKAP, and the new CRACO detection system of CRAFT have detected ULP transients while a handful more have been detected by international instruments. The nature of these sources is uncertain: are they neutron stars/magnetars, despite spin-down rates well below the so-called death line [37]? Or are they white dwarfs, despite their emission properties resembling that of neutron stars? How many such sources are there? What is their frequency dependence and luminosity distributions? The science of ULPs is just beginning.

3.3 Dark Energy

Unlocking the mystery of dark energy is one of the key goals of the current Decadal Plan. Until recently, the ΛCDM model, in which the dark energy equation-of-state parameter w is exactly -1, had survived the enormous improvement in constraints achieved since the original discovery of the accelerating universe in the 1990's [38, 39]. However, recent results from the Dark Energy Survey (DES) and the Dark Energy Spectroscopic Instrument (DESI) put the ΛCDM model under pressure [40, 41]. A model in which w varies with time is now favoured by the data. If verified, this would suggest that cosmological acceleration is driven by something more complicated than a cosmological constant.

Both surveys had key involvement from Australian researchers. In particular, DES obtained redshifts of supernova host galaxies with the 2dF+AAOmega spectrograph on the AAT in a companion survey called OzDES [42]. These redshifts were crucial to the limits set by DES. It is an excellent example of how an in-kind contribution from Australia (in this case AAT time and human resources to run OzDES) can lead to participation in a much larger international project. The DES collaboration has published over 300 papers to date and pioneered new analysis methods adaptable to the next decade.

3.4 Other notable discoveries

The last decade has also seen many other key discoveries in the transient and multi-messenger space. The first source of high-energy astrophysical neutrinos, the blazar TXS 0506+056, was identified by the IceCube Collaboration [43]. An excess of high-energy neutrinos from our Galaxy has also been detected, although the source have not yet been identified [44]. The Pierre Auger Collaboration confirmed the extragalactic origin of at least some ultra-high-energy cosmic rays, though their source remains elusive [45]. Meanwhile, the High Energy Stereoscopic System (H.E.S.S.) has completed a Galactic Plane Survey [46], identifying 78 TeV gamma-ray sources. Australian researchers make key contributions to all three collaborations. Both H.E.S.S. and the Large High Altitude Air Shower Observatory have found evidence to support the idea that the Galactic Centre accelerates protons to PeV energies and above [47, 48].

The last decade has also revealed that gamma-ray bursts (GRBs) are sources of TeV gamma ray emission [49, 50], with seven TeV-emitting GRBs now known [51]. The paradigm of two GRB populations—short GRBs from compact object mergers, long GRBs from the collapse of massive stars—has been challenged, with observations of peculiar long [52] and short [53], bursts of each class, respectively.

The number of tidal disruption events has grown from < 10 [e.g., 54] to > 100, through dedicated optical surveys [e.g. 55–57], and a similarly large increase in the number of radio-detected tidal disruption events [58, 59]. This has yielded discoveries of new phenomena, such as repeating flares that could indicate a partial tidal disruption event [60–62], long-lived accretion disks [63], and rapid radio brightening $\sim 3.5\,\mathrm{yr}$ post-discovery [64]. The Australia Telescope Compact Array have played a key role in many GRB and tidal disruption event discoveries, e.g., [65], and [66], along with papers cited above.

The search for fast transients, with timescales of milliseconds to hours, is an area that has seen considerable growth over the past decade with Australian-led programs such as the Deeper Wider Faster program [67]. Very luminous supernovae at very high redshifts is another area that has seen considerable growth over the past decade. These kinds of supernovae are very rare in the local universe as they generally prefer lower metallicity environments. Potentially, they can be used to measure the expansion history of the universe over a redshift interval that is not accessible to type Ia supernovae [68].

4 Key Questions

In this section we highlight key scientific questions for the coming decade, highlighting how they connect different areas in astronomy, and noting the facilities required to address these questions.

4.1 How do stars die?

At the end of their lives, massive stars explode in various forms of supernovae and/or gamma-ray bursts—events so energetic that some can momentarily outshine the rest of the Universe. Over the coming decade, observations of stellar explosions will provide crucial insights into not only the origin of the heavier elements not formed in the cores of stars (so-called r-process elements), but also the progenitors and their environments which result in these explosions. They will help us to understand the central engines powering gamma-ray bursts and the properties of a number of supernovae, and the dynamics leading up to supernova explosions. Furthermore, both gamma-ray bursts, supernovae and supernova remnants have been proposed as sites of for the acceleration of high-energy particles. Thus, cosmic rays, neutrinos, and TeV gamma-rays are important probes of these cosmic accelerators.

The "afterlife" of stars is also an emerging priority in astronomy for the next decade. At the end of their lives, most massive stars leave behind a compact object such as a neutron star or a black hole, in addition to a supernova remnant. Some of these compact objects go on to merge with each other, producing gravitational waves, which next-generation observatories will be able to detect out to incredible distances, redshifts of $z = 12$ for typical binary neutron stars and $z = 37$ for some binary black holes [69].[7] The gravitational-wave signals

[7]These horizon distances are calculated for $1.4M_{\odot} + 1.4M_{\odot}$ binary neutron stars and $30M_{\odot} + 30M_{\odot}$ binary black holes respectively.

from stellar remnants provide a unique way of reconstructing the life and death of massive stars. Tracking how the properties of stellar remnants evolves with redshift provides insights into diverse topics from the most extreme supernovae to the environments of early star formation.

Rare, extreme supernovae such as super-luminous supernovae or hydrogen and helium poor supernovae are expected to be much more common in the very distant universe. Measuring their rates will inform us of the impact these extremely energetic events have on the production and distribution of metals in young galaxies at high redshifts.

Lower-mass stars, meanwhile, end their lives as white dwarfs. White dwarfs have emerged as a promising laboratory for extreme densities and magnetic fields, while the thermonuclear explosion of a white dwarf leads to a Type Ia supernova explosion. These white dwarfs may be responsible for the recently discovered, enigmatic long-period radio transients [4], while the resulting explosions have important implications for a wide range of physics.

- Summary: stellar explosions and stellar remnants are critical to our understanding of stars: how they explode, and where in the Universe they form.
- Key sub-fields: optical astronomy, radio astronomy, gravitational-wave astronomy, high-energy astronomy, theory.
- Connections to other working groups: #1.1 Cosmology, #1.2 Stars, # 1.4 Theory.

4.2 What is the role of black holes in the Universe?

When the history of astronomy is written, the present day may well be remembered as "the black hole era." The past decade saw the first detection of binary black holes via the observation of gravitational waves [1], the first image of a black hole's event horizon using very long baseline interferometry (VLBI) [70, 71], the discovery of the first unambiguous optical periodicity from an AGN [60, 61] and just this year Australian researchers observed the fastest-growing black hole [72]. These breakthroughs have set the stage for a hugely productive decade in black hole science.

The coming decade is likely to see the creation of the next-generation gravitational-wave observatories, which can see *every binary black hole merger in the entire Universe.* By measuring these millions of binary mergers, astronomers will gain insights into topics as varied as star formation, binary evolution, supernovae physics, and the evolution of metallicity over cosmic time. Meanwhile, recent evidence for a stochastic background from supermassive black holes [73–76]—enabled by precision pulsar timing—has opened up a new front in gravitational-wave astronomy, allowing us to probe galaxy mergers and the evolution of supermassive black holes. Recent results from the SKA precursor MeerKAT telescope suggest that the next generation of radio telescopes have the potential to transform this field [77].

Black holes are also important for their role in electromagnetic astronomy. They power jets in the cores of active galaxies, visible in both optical and radio. They shape the environment of galaxies through feedback, regulating star formation, redistributing gas, and affecting the galaxy size [78]. These jets have been proposed as sites of ultra-high-energy particle acceleration, producing the first known extragalactic source of high-energy neutrinos [43]. Meanwhile, stars that wander too close to a supermassive black hole are pulled apart in tidal disruption events, which produce optical signatures through to gamma rays. Tidal disruption events will enable us to probe the demography of supermassive black holes, to study accretion, and the formation of jets [79].

Over the coming decade, black holes will increasingly be the tool of choice for precision tests of general relativity in the ultra-relativistic regime. From VLBI imaging of the black hole event horizon to tests of the no hair theorem with gravitational waves, black holes arguably provide our best chance of finding new gravitational physics.

- Summary: black holes are key to understanding the evolution of galaxies and their central environments; they will produce $\mathcal{O}(10^6)$ gravitational-wave signals in next-generation observatories + persistent signals in pulsar timing arrays; they are a powerful new tool for testing general relativity.
- Key subfields: optical astronomy, radio astronomy, gravitational-wave astronomy, high-energy astronomy, theory;
- Connections to other working groups: #1.1 Cosmology, #1.2 Stars, #1.4 Theory.

4.3 What do astronomical transients teach us about the Universe?

Transient and multi-messenger phenomena allow us to not only understand the individual properties of the phenomena themselves, but can also be used as powerful probes with significant impact in nearly all areas of astrophysics. One of the most well known examples of transients used as tools is the use of Type Ia supernovae as "standard candles" to trace the expansion of the universe [e.g., 40]. From these observations (in combination with other distance indicators), we find that the current expansion rate of the Universe as measured by the Hubble constant (H_0) differs from that measured from the Cosmic Microwave Background (although note the more recent study by [e.g., 80]). While there have been many attempts to address this "Hubble tension," it is clear that new methods are required to understand the true evolution of the Universe. At higher redshifts, recent analyses have shown evidence for dark energy evolving with cosmic time [40, 41]. Over the coming decade, data from the Vera C. Rubin Observatory and 4MOST will be used to test this result. However, with more and more gravitational waves being discovered each day, they have the potential to solve the Hubble tension, with e.g., [81] forecasting a $\sim$1-2% measurement of H_0 using gravitational waves over the next decade.

Discovering electromagnetic counterparts associated with gravitational-wave sources, especially those that involve the coalescence of a neutron star with either another neutron star or a black hole, also provide an opportunity to understand how elements are created and how these are distributed within the universe. The most famous example is the kilonova associated with the binary neutron star merger GW170817 [82, 83], which allowed us to use multi-wavelength and multi-messenger constraints on the origin of the heaviest elements in the periodic table (r-process nucleosynthesis) [e.g., 84]. As more and more of these events are discovered using both gravitational-wave detectors and ground-based or space-based instrumentation, these discoveries will provide insight into the life, death and properties (such as nucleosynthesis yields and masses) of stars across the Universe, which are complementary to the studies and constraints obtained from analysing supernova and supernova remnants in the local universe [e.g., 85].

Beyond gravitational waves, the discovery of transients at high redshifts ($z > 1$) is currently a relatively unexplored, but exciting field of research that will only continue to grow as the James Webb Space Telescope (JWST) covers more of the sky, Rubin starts and the Keck Wide Field Imager (KWFI) becomes available. Until recently, only a $\sim$ 30 supernovae had been discovered using the Hubble Space Telescope (HST) [86–88], but due to depth and spatial resolution of JWST, the number of non AGN transients at high redshift has dramatically increased to over 100 [89, 90] and will only continue to increase with time. As we go to higher redshifts, dark energy will have less of an impact on the expansion rate, assuming a dark-matter dominated Universe. As such, any change in the brightness of e.g., Type Ia SN detected at these distances would then be intrinsic to the SN themselves and thus provide a handle on systematics [e.g., 91]. While SN at high redshifts allow also allow us to probe how the observation properties (such as nucleosysnethesis yields, and mass loss rates) and rates of different SN populations evolve with redshift, and understand how, e.g., metallicity of a host galaxy influences the types of explosions that we observe [e.g., 92].

Fast radio bursts (FRBs) which are intense, millisecond bursts of radio emission [23, 93], are another phenomena that has evolved from a curiosity to a potentially revolutionary tool for probing the structure of the Universe. Due to their intensity, one can detect FRBs up to $z = 1$ and beyond [34]. The light from these events can be scattered and even lensed by material during the journey to Earth, which can be used to map the distribution of matter in front of the burst [see review by e.g., 94]. As a result, FRBs allow us to estimate the electron density along the line of sight, as they provide an estimate of the integrated electron column density between the source and the observer. This can be combined with an independent distance measure (i.e., host galaxy redshift). With a large number of these well-localised events, FRBs have the potential to, not only allow one to measure all ionised material in the local Universe [95], but also to provide an independent constraint on cosmological parameters such as H_0 [35]. They can also constrain galactic feedback by measuring halo gas in galaxies at all scales [96, 97].

As we move into the next decade with the Vera C. Rubin Observatory taking its first light observations in 2025, with the increase sensitivity of Advanced LIGO and with SKA turning on, it is clear that these and other facilities will continue to yield increasing numbers of well localised detections of SN, gravitational waves and FRBs and other transients, which combined with multi-wavelength and multi-messenger observations will be pivotal to understanding the evolution of the Universe over a wide redshift range.

- Summary: a wide range of transient phenomena are powerful tools for probing the history, nature and properties of the Universe.
- Key subfields: optical/IR astronomy, radio astronomy, gravitational-wave astronomy, high-energy astronomy, theory;
- Connections to other working groups: #1.1 Cosmology, #1.2 Stars, #1.4 Theory.

4.4 What is the nature of matter at extreme densities?

Neutron stars, which are formed during the final stages of a massive star's life, are among some of the densest objects in the Universe, and as such, are unique natural laboratories for studying a wide range of phenomena. Their extreme densities, temperatures and magnetic fields, make them ideal laboratories to study nuclear matter and electromagnetic fields under unique conditions that are completely inaccessible here on Earth. From electromagnetic observations of pulsars and fast radio bursts, we have been able to constrain the neutron-star equation of state (EOS) [98], probe properties of the neutron star crust [99], and study their magnetospheres [100]. Gravitational waves allow us to probe deep within the neutron star, probing the neutron star equation of state via tidal effects. This approach provides complementary constraints compared to those obtained from electromagnetic observations

[101]. Furthermore, as ground-based gravitational-wave instrumentation become more sensitive, the tidal signal in merging binary neutron stars will enable redshift measurements without the need for host galaxy identification [102].

Due to their extreme nature, and the fact that they also are formed in the violent end of a massive stars life, neutron stars provide opportunities to understand accretion and particle acceleration under extreme conditions. Some neutron stars are pulsars: rapidly rotating objects with extreme magnetic fields. Pulsars can produce regular pulses of radiation that can be measured through timing in radio and other wavelengths. Pulsar timing of individual neutron stars can be used to precisely determine the properties of binary system and to test general relativity. Large-scale timing surveys of dozens of pulsars also provide constraints on the gravitational wave background [103]. When the magnetic fields of these neutron stars become extreme, these magnetars can emit outbursts, which can disrupt the surface of the neutron star and exhibit strong and luminous outbursts that can last for a few millisecond to many months. These extremely magnetised neutron stars are likely the progenitors of FRBs [e.g., 31] and may play a key role in the evolution of light curves of supernova-related transients such as long and short duration γ-ray bursts [e.g., 104] and super-luminous supernovae [e.g., see review by 105].

- Summary: neutron stars provide the opportunity to place constraints on the fundamental properties of matter under extreme conditions. They can be used to probe the gravitational wave background, the equation of state of matter and also explain a wide range of transient phenomena such a FRBs and SNe that are discovered using SKA, SKA-precursor, gravitational-wave instrumentation and optical/IR facilities.

- Key subfields: optical astronomy, radio astronomy, gravitational-wave astronomy, high-energy astronomy, theory;

- Connections to other working groups: #1.1 Cosmology, #1.2 Stars, #1.4 Theory.

5 Infrastructure Priorities

5.1 Tier-One Priorities

5.1.1 Full ESO Membership

When an interesting astronomical object is identified, it will be (in a significant number of cases) too faint for spectroscopic follow-up with all but the largest telescopes. In the case of transients, time may be of the essence. One therefore needs access to suitably equipped large facilities that can be rapidly scheduled to follow-up these targets. In the optical, the four 8 m telescopes at the European Southern Observatory (ESO) can be rescheduled at very short notice and can be on source within a couple of minutes of an alert being received. The telescopes are equipped with state-of-the-art instrumentation covering a broad range of wavelengths and spectral resolutions, thus allowing a range of studies. For example, access to 8 m class time is essential for FRB host galaxy identification and follow-up. Access to the one or more of the 30 m-class telescopes that will likely be operational in the next decade is needed if Australian astronomers are going to continue being the leaders in this exciting field. Access to the 39 m ESO Extremely Large Telescope (ELT) will only be possible if Australia become a full ESO member.

5.1.2 Continued support for the SKA and SKA pathfinders

The Square Kilometre Array Observatory (SKAO) is a 11-country Intergovernmental Organisation building two radio telescopes, SKA-Mid in South Africa and SKA-Low in Australia. Construction has already begun on SKA1, with first science operations expected by 2029. As a member state of the SKAO, Australia has already committed to the construction and support of the SKA project. This will provide Australia with unprecedented sensitivity to both Galactic and extragalactic sources. Pulsar, FRBs, and image-plane transient surveys are planned to be SKA key science projects; as an SKA partner and host for SKA-low, Australia will have full access to this data. Membership of the SKAO remains a high priority to enable a new era of radio transient discovery. Until full SKA science begins, SKA precursors ASKAP and the MWA will continue to be critical transient-finding systems. Even in the SKA era, these two instruments will have wider fields of view than their SKA counterparts and so will be complementary to SKA. Furthermore, radio transient discovery has been driven not just by the raw capabilities of telescopes instruments, but by their back-end data-processing capabilities. We expect opportunities to arise to upgrade these instruments, significantly improving their capabilities.

5.1.3 Support for Australian contributions to a global network of next-generation gravitational-wave observatories

Cosmic Explorer and the Einstein Telescope are proposed gravitational-wave observatories. Using improved length-sensing technology, and employing longer interferometer arms, these next-generation observatories will measure gravitational-wave strains ten times lower than current observatories. As a result, they will see the vast majority of merging compact binaries in the Universe. With a wider observing band, they will detect merging binary neutron stars up to 90 min before merger, providing early warnings to electromagnetic astronomers. Conceptual designs are underway, with the US National Science Foundation providing $9M US for the current round of studies. Over the past two decades, Australia has earned a reputation for excellence in gravitational-wave astronomy enabled in large part from our contributions to LIGO instrumentation. It is therefore essential that Australia continues its leadership in gravitational-wave astronomy by playing a significant role in the forthcoming network of next-generation gravitational-wave observatories. Whether contributing a key subsystem to Cosmic Explorer, or hosting a gravitational-wave observatory on Australian soil, the next decade will be Australia's opportunity to define an influential role for itself in the next era of gravitational-wave astronomy.

5.2 Tier-Two Priorities

5.2.1 Continued support for existing national facilities

Australian-based facilities will continue to play an important role in discovering and following up new transients, thanks to our geographical location and the decades of investment made in national and university-run facilities based in Australia. Early and regular follow-up of transients and their host galaxies is crucial. For anything more than one or two pointings, this can only practically be done using facilities that are automated such as the ANU 2.3 m or with facilities that scan the entire sky (e.g. MWA, DREAMS). The scientific return of these instruments is amplified if there are automatic data reduction pipelines that can provide processed data within minutes of the data being taken as this enables time-critical decisions on follow-up with other facilities anywhere in the world to be made. We support efforts to automate existing facilities in Australia and to develop automated end-to-end observing pipelines, from discovery to follow-up.

Larger telescopes, such as the AAT at Siding Spring Observatory have contributed to several significant studies over the last decade, such as recent evidence for thawing dark energy using 2dF, and discovering exoplanets through the precise and regular spectroscopic monitoring of stars. While the AAT is not robotic, it is, along with 4MOST on the ESO VISTA telescope, *one of only two* 4 m class telescopes in the Southern Hemisphere that can obtain spectra of hundreds of objects at once. However, 4MOST[8] is restricted to observing targets that are defined before the surveys starts. *The AAT will not be restricted in this way* and will be more able to follow targets that are new. Crucially, it is the *only* 4 m telescope in the Southern Hemisphere that can observe after the sun has risen in Chile, providing spectroscopic follow-up of transients discovered there. Funding to continue operating the AAT until the end of the LSST survey (2035) is recommended. This will ensure that the AAT will play a significant role in following and monitoring sources into the next decade.

The Parkes radio telescope—now equipped with two new receiver suites, the ultra-wideband low receiver (UWL) and the Cryogenically-cooled Phased Array Feed (CryoPAF) —and the Australia Telescope Compact Array play critical roles in the follow-up of transient sources, from FRBs to GRBs, gravitational waves to tidal disruption events. These instruments should continue to be supported to enable characterisation of transients.

5.2.2 Access to Vera C. Rubin data

Discovering events worthy of follow-up first requires wide-field surveys with sufficient cadence. In the optical, the Legacy Survey of Space and Time (LSST) at the Rubin Observatory will have first light in 2025 and will, for the next decade, image the entire southern sky with a cadence of several days. Australia provides in-kind contributions (primarily 3 FTE of software effort per year working on Rubin projects plus a data centre). In exchange, 47 named PIs from 14 Australian institutions (plus four junior associates each) get immediate access to the annual LSST data releases at the same time as their US and Chilean colleagues. Currently funding is available for three years starting from 1 July 2024. The program is intended to run through to 2036. Funding to continue this level of access is needed. It is estimated that Rubin will produce 10 million transient alerts per night. It is not possible for humans to sift through such a large number of transients. Instead, machine learning algorithms and filtering techniques need to be developed and implemented via Rubin Community brokers with access to the transient data in real-time (e.g., the Australian led Fink broker [106]). Building the capacity to develop and deploy these algorithms will be essential if we are to remain competitive in this field and not waste valuable observing time on ground-based and space-based facilities.

5.2.3 Continued support for GMT

The 25 m Giant Magellan Telescope (GMT) is one of two extremely large telescopes located in the Southern Hemisphere that will become operational during the coming decade, the other one being ESO's ELT. The two telescopes have very different designs leading to very different capabilities—capabilities that Australian astronomers are well equipped to exploit. AAL and the ANU are founding members of the GMTO Corporation[9] and Australian institutes are

[8] Targets will defined at the end of this year, in advance of the survey starting in mid-2025.

[9] The GMTO Corporation is an international consortium of research institutions currently representing seven countries from Australia, Brazil, Chile, Israel, South Korea, Taiwan, and the United States.

helping to build two of the five science instruments—MANIFEST and GMTIFS—as well as the laser guide star system. Much as WiFeS on ANU 2.3 m telescope is used to follow bright transients, Australian astronomers will use GMTIFS to follow transients soon after they explode, when they are fainter and out of reach of smaller telescopes.

5.2.4 Dedicated computing infrastructure

The computational needs of the transient and multi-messenger community are significant. In the radio regime, the detection of image-plane transients requires near real-time processing of large data volumes. For example, FRB detection requires dedicated real-time detection hardware. However, searches of archival data have proven invaluable for studying transients over periods of up to 30 years. Similarly, for fast transients, near real-time compression, transfer, processing and analysis of large amounts of data is needed. The techniques developed to meet these needs are translatable to industry. These needs are met by several key facilities: Ngarru Tindebeek/OzStar, Pawsey, the Gravitational Wave Data Centre (GWDC) and in the near future, the SKA Science Data Centre. We support the continued funding of these centres to enable the full exploitation of transient science. Reliable funding for the GWDC would constitute an important Australian contribution to LIGO.

5.2.5 LIGO

The two LIGO detectors, one located at Hanford, Washington and the other in Livingston, Louisiana, are expected to remain the preeminent gravitational-wave discovery machines in the stellar mass range over the next decade. Over the course of the 2025–2035 period, LIGO will undergo a series of upgrades: from Advanced LIGO A+ to A# (c. 2029). These upgrades will improve LIGO's strain sensitivity, leading to orders-of-magnitude increases in event rate. Australia plays a significant role in LIGO with 124 scientists formally members of the LIGO Scientific Collaboration. As members of the LIGO Scientific Collaboration, Australian scientists gain access to proprietary LIGO data and have the opportunity to lead Collaboration papers, many of which earn over 1000 citations. Australian membership in LIGO is currently supported through LIEF grants. A more sustainable longterm solution is recommended.

5.2.6 CTA

The Cherenkov Telescope Array Observatory (CTAO) is constructing two next-generation imaging atmospheric Cherenkov (TeV gamma-ray) telescopes: CTA-North in La Palma, Spain, and CTA-South in Paranal, Chile. Fully funded, first light for one CTA telescope arrays has already been achieved, with full science operations expected to commence by 2030. These telescopes will target both Galactic and extragalactic sites of particle acceleration, search for the annihilation signatures of dark matter, and follow-up transients such as gamma-ray bursts. The CTA-Australia Consortium consists of seven institutes, with 25 non-student members. CTA membership will provide Australian astronomers access to key science projects, which represent about 40% of the observing time over the first 10 years of full operations; and allow Australians to lead guest observing time proposals, representing another 40% of observing time.

5.2.7 KWFI

The Keck Wide Field Imager (KWFI), a joint Australian-US project (with Australian leadership) to equip one of the Keck Telescopes with a wide field imager of unparalleled UV sensitivity, will see first light in 2029. Swinburne astronomers has access to 20 nights per year for the next 9 years on the Keck telescopes with an expectation that the access will continue. Enabling all Australian-based astronomers to access this facility is desirable. The level of access depends on the level of federal funding. Each night on the Keck telescope costs approximately 150,000 AUD.

6 Summary

The coming decade holds tremendous promise for time-domain and multi-messenger astronomy. Consider astronomical transients such as fast radio bursts and gravitational waves from merging binaries. When the last Decadal Plan was crafted, fast radio bursts were only a new discovery with only a handful found and gravitational waves had not been detected. However, multi-messenger observations of the binary merging neutron star GW170817 and the association of FRBs to sources in distant galaxies, were two of the scientific highlights of the last decade.

In the coming decade, the Square Kilometre Array (SKA) will detect thousands of FRBs every year, the Vera V. Rubin Observatory (VRO) and the Roman Space Telescope will find millions of transient phenomena to unprecedented depths, while next-generation gravitational-wave observatories will detect $\mathcal{O}(10^6)$ binary mergers out to the edge of the visible Universe. Thus the new decade will be marked by the maturation of astronomy with gravitational waves and fast radio bursts. Meanwhile, the recent discovery of long-period radio transients with the Murchison Widefield Array [e.g., 4] demonstrates the truth of an old cliché: when a new window is opened on the Universe, discoveries follow. Sustained support for the SKA and its precursors, along with funding to support Australian participation in next-generation gravitational-wave observatories, as well as support for both local and international optical resources such as those at ESO, Rubin, the GMT and instrumentation at Siding Springs Observatory, is *essential* to maintain momentum in these areas.

With appropriate support, the Australian community can expect to be key players/leaders in the breakthroughs expected in the science intimately connected to time-domain and multi-messenger astronomy. Here we identify the key scientific questions of the next decade that Australian researchers seek to answer; the community will:

- Probe the death and afterlife of stars to understand how they lived and died, which will transform our understanding of stellar and binary evolution; revealing the processes that power some of nature's most dramatic explosions throughout cosmic time.

- Play a lead role in black hole astrophysics: understanding the role of supermassive black holes in the evolution of the Universe, testing Einstein's theory of general relativity, and observing $\mathcal{O}(10^6)$ gravitational-wave signals from some of the first black holes.

- Use supernovae standard candles and gravitational-wave standard sirens to measure the evolution of the Universe over cosmic time with unparalleled precision; probing the distribution of baryonic matter with FRBs.

- Use the extreme environments of neutron stars to infer the existence of new states of matter, to understand their extreme magnetic fields, to probe the mechanism behind pulsar emission, fast radio bursts.

A recurring theme in these questions is the necessity of *multi-messenger* astronomy: measurements with optical/IR/UV, radio, gravitational waves, and high-energy particles coming together to yield a new understanding of the Universe. We emphasise the connections between time-domain astronomy, cosmology (working group #1.1), stars (working group #1.2), and theory (working group #1.4). We look forward to an exciting new decade of synergy across astronomical observatories and multifaceted science.

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