ASTRO 3D

STRATEGIC PLAN
2021-2024

UNLOCKING THE UNIVERSE
INSPIRING THE FUTURE

Australian Government
Australian Research Council

ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions

Our Collaborating Universities:

Our Partner Institutions:

OVERVIEW

The ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D) is a $40m Research Centre of Excellence funded over seven years by the Australian Research Council (ARC) and supported by nine collaborating Australian universities - the Australian National University (ANU), Curtin University, Macquarie University, Monash University, Swinburne University of Technology, University of Western Australia, University of Sydney, University of Melbourne, and the University of New South Wales – as well as two national partners – CSIRO and the National Computational Infrastructure – and six international partners – the California Institute of Technology, University of Oxford, University of Toronto, University of Washington, the Netherlands Institute for Radio Astronomy (ASTRON), and the Chinese Academy of Sciences.

OUR VISION

To unlock the mysteries of the Universe using innovative 3D technology, while sharing the excitement and wonder of astronomy to inspire the broader community.

OUR MISSION

- ✓ To propel Australia to the forefront of astronomical research by combining Australia's radio, optical and theoretical expertise to understand the origins of our Universe and the galaxies within it.
- ✓ To train future Australian astronomers to lead breakthrough science on the next generation of telescopes.
- ✓ To share our discoveries and passion for research with the broadest possible audience and inspire the scientists of the future.

OUR STRATEGIC GOALS

1. Transform our understanding of the Universe and how we got here

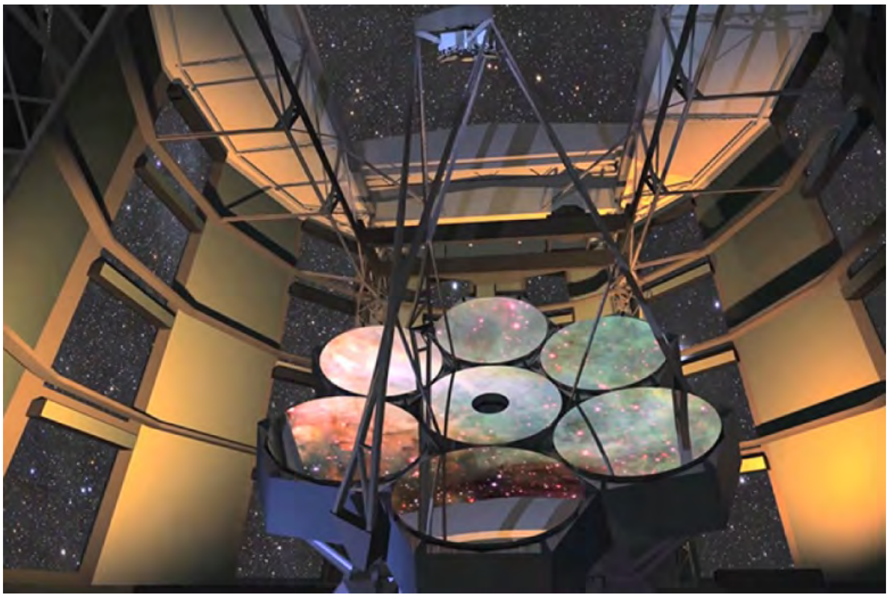
- ✓ We will conduct ground breaking new 3-dimensional surveys alongside an observationally-driven theory program with dedicated telescope and supercomputing facilities
- ✓ We will develop new data intensive astronomy infrastructure to analyse the Petabytes of data that will ensue from the Square Kilometre Array.
- ✓ We will translate this research into high impact publications with broad and far-reaching international dissemination of our results, through our unified and cohesive scientific collaborations and our efficient administrative structure.
- ✓ **Build and maintain the infrastructure, skills and expertise required to maximise Australia's investment in the new era of mega-scale optical and radio telescopes** Through our research programs, skills workshops, mentoring, leadership and succession planning, we will train young Australian scientists to drive the future world-leading programs on the next generation of telescopes
- ✓ Through the long-term investment and continuity that ASTRO 3D provides, we will ensure that the Federal government's investment in the Square Kilometre Array and Giant Magellan telescopes is realised.

2. Inspire, train and mentor the next generation of diverse Australian scientific leaders

- ✓ We will inspire students to study science, technology, engineering and mathematics (STEM) through new teacher education programs and our ambitious nation-wide public outreach campaigns.

3. Provide young Australian scientists with transferrable skills for the modern workforce

- ✓ We will train the new generation of young Australian astrophysicists in transferrable skills including data intensive science, providing a broad range of career options outside astrophysics, including market analysis, population statistics, medical science, bioinformatics, genomics, and commercial sector data analytics.



The Giant Magellan Telescope will be one member of the next class of giant ground-based telescopes that promises to revolutionize our view and understanding of the universe. It will be constructed in the Las Campanas Observatory in Chile. Commissioning of the telescope is scheduled to begin in 2022. The GMT will have a resolving power 10 times greater than the Hubble Space Telescope.

The GMT project is the work of a distinguished international consortium of leading universities and science institutions, including Australia and the ANU.

OUR SCIENCE GOALS

The elements transform the way stars are born and how they evolve, how they explode and die, and how they assemble into galaxies. Australia is currently leading research in this field using different experimental and theoretical approaches, targeting different wavelength ranges, and different ages and size scales of the Universe. In ASTRO 3D, these areas coalesce under the common goal of understanding the origins of the elements of the periodic table and how they built into the galaxies around us. Our science goals are:

1. The Origin of Matter and the Periodic Table

- ✓ To use state of the art 8-10m telescopes to track the chemical elements in the first stars and within galaxies across cosmic time.
- ✓ To measure the elements in the first stars and their descendants, discovered with the ANU SkyMapper telescope.
- ✓ To map the elements in the earliest galaxies via metal absorption lines viewed through the spectra of background quasars.
- ✓ To track the growth of the chemical elements and matter using spectroscopy and integral field technology that creates 3-dimensional data cubes, to bridge the epoch of reionisation to the present day.
- ✓ To use gravitational lensing, as proposed by Einstein, where the massive gravity of nearby clusters of galaxies magnifies the light of faint background galaxies 10-50x, creating nature's largest telescopes, to probe the most distant galaxies.
- ✓ To combine integral field technology on the Anglo-Australian Telescope, the European Southern Observatory and other international 8-10m telescopes with 3D data from the Australian Square Kilometre Array Pathfinder (ASKAP) in Western Australia.

- ✓ To use ASKAP to survey three-quarters of the entire sky with unprecedented resolution and depth in neutral Hydrogen, mapping the distribution of gas and dark matter in over 600,000 galaxies through a series of dedicated surveys.
- ✓ To measure the distribution of mass and angular momentum in the nearby Universe during the first two years of this Centre using the new wide-field instrument, SAMI. With the next generation SAMI (called HECTOR), we will survey an unparalleled 15,000 galaxies across a contiguous volume of the southern sky, revealing how galaxies are distributed across space, their dynamic motions, and how these fundamental properties affect the accumulation of the chemical elements in galaxies.
- ✓ To compare the observed growth of the elements and matter in spiral galaxies with the archaeological history of our Milky Way for the first time.

The junction of these traditionally separate research areas, alongside theoretical modelling on Australia's most powerful supercomputers, stands to transform our understanding of the chemical Universe. The culmination of this theme will be the first comprehensive picture of the build-up of the chemical elements and matter in the Universe, from the scale of galaxy superclusters to star-forming regions within individual galaxies.

The European Southern Observatory (ESO) Very Large Telescope (VLT) in Chile. Australia has a strategic partnership with ESO, providing Australian astronomers with world-class optical telescope access. These telescopes are a core component of many ASTRO 3D surveys and projects.

2. The Origin of the Ionised Universe

During the infancy of the Universe, a watershed event dramatically changed the Universe from neutral and dark to being almost completely ionised. This period is when the very first structures in the Universe formed and is intricately linked to fundamental cosmology. Despite its pivotal role, the Epoch of Reionisation is one of the least understood phases in the history of the Universe. ASTRO 3D is uniquely poised to measure and characterise the beginning and end of reionisation, the sources of reionisation, and the conditions at the Epoch of Reionisation. Our goals in understanding the ionised Universe are:

- ✓ To employ the Murchison Widefield Array (MWA) in WA to detect the structure created by the first ionising sources in the Universe using the power spectrum of neutral Hydrogen.
- ✓ To measure when the reionisation of the Universe occurred and how long this important process lasted.
- ✓ To investigate the conditions under which these first stars in the Universe were born with the European Southern Observatory and other 8-10m telescopes.
- ✓ To track the ionising radiation in galaxies over the past 12 billion years using luminous emission-lines in galaxy spectra created by atoms in gas clouds that are ionised and excited by young, hot stars, massive shock fronts from galactic-scale winds, or supermassive black holes in the centres of galaxies and will bridge the gap between the first galaxies and the local Universe.

3. Genesis Theoretical Simulations

Large scale supercomputer models of galaxy formation are providing an ever-increasingly detailed theoretical framework for interpreting observations. Within Genesis, our goals are:

- ✓ To channel Australian observational and theoretical expertise into new state-of-the-art cosmological simulations of galaxy formation and evolution that are directly constrained by our observations across cosmic time.
- ✓ To track the birth, growth and ultimate fate of galaxies from the earliest epoch of galaxy assembly, through the Epoch of Reionisation to the present day and simulate the first stars, early Universe chemical enrichment, proto-galaxy formation, reionisation, galaxy growth through star formation and mergers, the build-up of angular momentum from the scales of galaxy clusters to star-forming regions within galaxies, the emergence and evolution of large-scale massive structures in the Universe, and the evolution of the material between galaxies.
- ✓ To combine advanced physical galaxy modelling techniques with realistic 3D radiative transfer models to produce tailored theoretical models to create synthetic multi-wavelength datasets that can be used to interpret the observations from our major 3D surveys directly. The models will incorporate "zoom-in" re-simulations that will track the growth of targeted galaxies within the simulation in exquisite detail, allowing us to model the local galaxy population and the imprint of galactic history in the chemistry and structure of the galaxy population to compare directly with our 3D observations.

FUNDING

The Australian Research Council has provided $30.3M over seven years to fund the Centre to reach its strategic and scientific goals. With the addition of our three new nodes, UNSW, Macquarie and Monash university, $9.5m in cash has been committed by the nine collaborating universities. In-kind support is significant, totalling $143M. The contributions of the individual institutions, including our new node universities, are detailed below.

	CASH $	**IN-KIND $**
Australian Research Council	**30,300,000**	**-**
COLLABORATING UNIVERSITIES		
Australian National University	2,876,001	13,192,953
Curtin University	965,335	685,885
Macquarie University	589,573	3,580,908
Monash University	245,000	1,541,771
Swinburne University of Technology	1,261,885	10,637,241
University of Melbourne	1,319,980	2,680,003
University of New South Wales	195,640	6,544,026
University of Sydney	1,290,776	6,982,788
University of Western Australia	1,251,607	1,996,260
	9,995,797	**47,841,836**
NATIONAL PARTNERS		
CSIRO	-	49,828,906
National Computational Infrastructure	-	2,368,800
		52,197,706
INTERNATIONAL PARTNERS		
California Institute of Technology	-	1,447,390
University of Oxford	-	525,000
University of Toronto	-	903,994
University of Washington	-	11,765,895
Netherlands Institute for Radio Astronomy	-	817,600
Chinese Academy of Sciences	-	15,960,000
	-	**31,419,879**
TOTAL	**40,295,797**	**131,459,420**

GOVERNANCE AND ORGANISATIONAL STRUCTURE

We have established a collaborative and cohesive structure (shown on following page) that focuses on the effective and efficient delivery of the Centre's Strategic Goals and meeting our Key Performance Indicators.

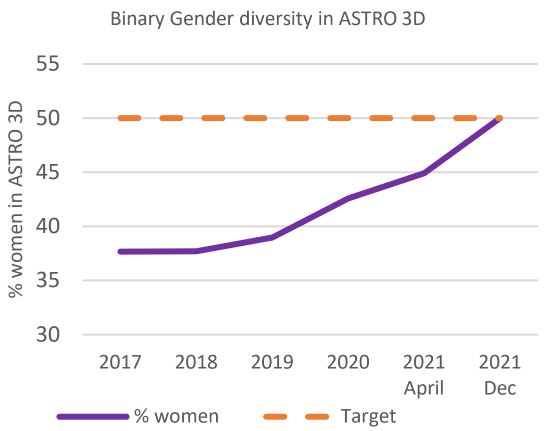
In the first half of the Centre, the Centre administration (led through the Australian National University and supported by administration staff at our large nodes) has set up efficient processes and tools for membership management, KPI reporting, financial expenditure reporting, and budgeting utilising Smartsheets. We also deliver professional support for event management (both in-person and virtually). We ensure equitable funding processes for travel, science visitors, workshops and conferences, and carer's funding. We run professional development and transferrable skills workshops for all our members. The preparation of Annual Reports is a smooth process and is done entirely in-house. We also provide support for the Advisory Board and our Committees.

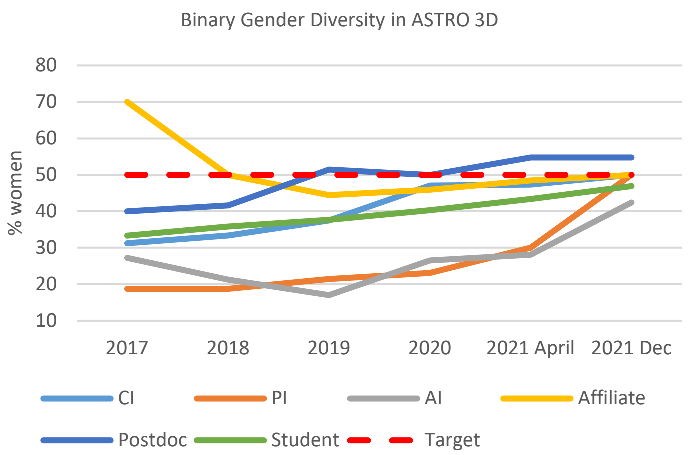
The second half of the Centre will focus on continual improvement of Smartsheets processes, incorporating the latest workflow and data reporting updates. We continue to utilise feedback on our significant events (Annual Retreats and Science Meetings) and our training and mentoring programs to be efficient and effective in using those funds.

The continued impact of COVID-19 on our ability to travel will mean that the funding allocated to researcher travel, visitor programs, carer's funding may be reallocated to programs that connect our researchers to the international astronomical community (for example, support for attendance of virtual conferences), that bring a diverse range of international students to Australia (through international PhD scholarships targeting students from minorities) and programs that help promote our research to a broad audience (for example, our Virtual Reality Program and the STARS regional telescopes in schools program).

We will continue to provide professional research skills training and transferrable skills training for our researchers and professional staff. We are investigating a wide range of courses, both safe in-person and virtual/dual delivery modes, including innovation and research impact, maker skills, start-up entrepreneurial skills, advanced coding and big data skills. Our highly successful writing retreats and telescope proposal writing workshops will continue. Our ECRs are further supported by targeted training on developing practical supervision skills, grant writing, and job applications in academia and industry.

To reach our diversity goals (50% women at all levels by end of 2021), we will continue our Leadership workshops for all staff and our Women's Leadership training. Our Diversity workshops will continue to explore intersectionality and include training and awareness around disability, indigenous and cultural diversity. Our diversity international PhD scholarships will increase the proportion of female students in the Centre. We are engaging our international partners to provide a gender balanced set of Partner Investigators for the second half of the Centre, to begin in 2021.

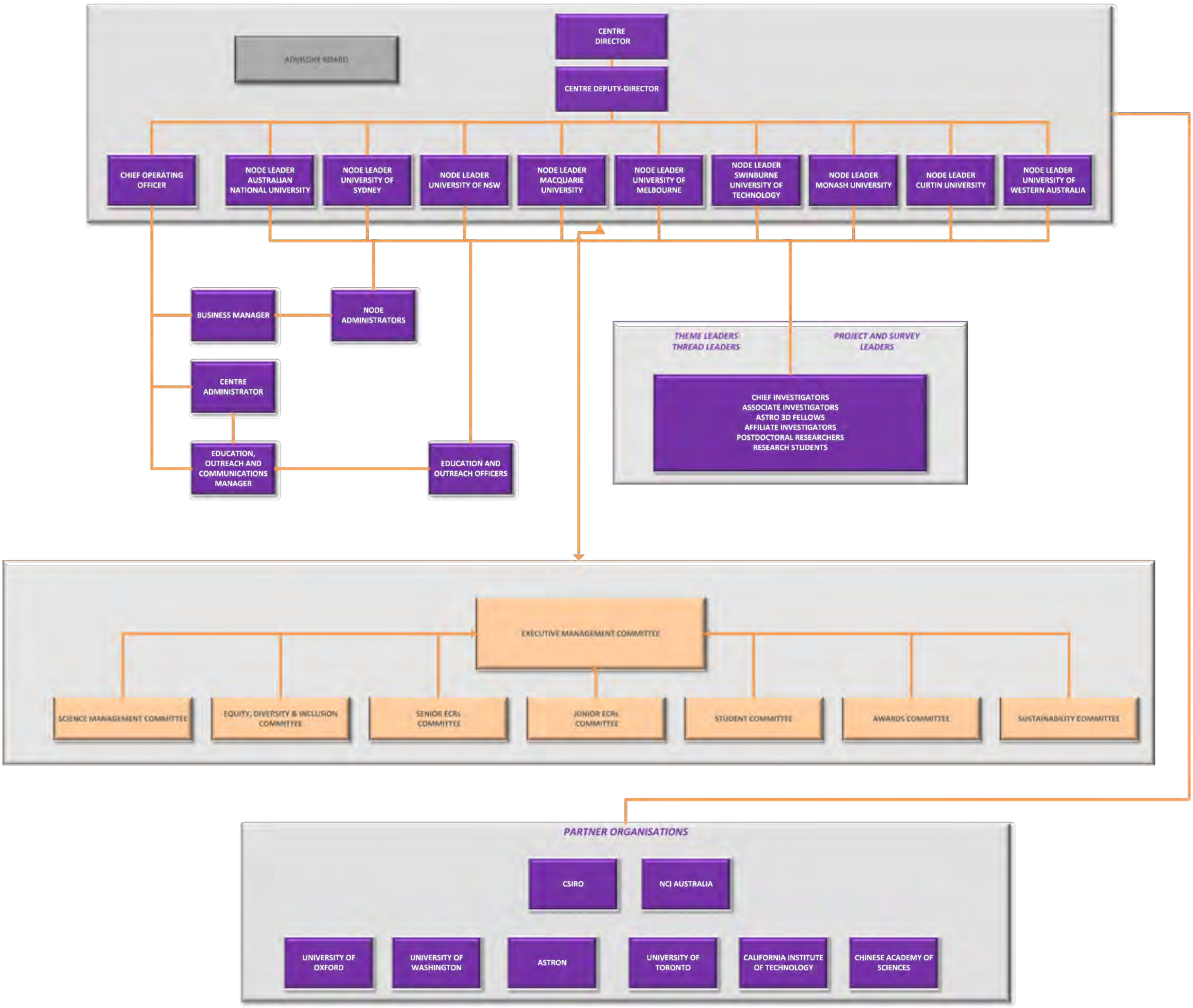




The total binary gender diversity in ASTRO 3D (left) and binary gender diversity at each researcher level (right) compared with our 50% women target (dashed lines). 'Women' refers all ASTRO 3D people who identify as women, and 'men' refers to all ASTRO 3D people who identify as men. The 2021 Dec data are our predictions based on confirmed new postdoctoral researcher position acceptances, confirmed incoming domestic and international students, new international partner organisations (University of Hertfordshire and University of Texas, Austin) to be added in 2021, and new international collaborators to be added in 2021, both based on our partnership plan.

Our Advisory Board will continue to meet annually (in person or virtually) to provide support and advice to the Director and the Executive Management Committee on the effectiveness of the Centre in reaching its scientific, technical, and education/outreach goals, and ensuring the Centre is known as a world-leading scientific research body. The Board identifies opportunities for international collaboration and innovation and provides feedback on the international competitiveness of the Centre. The Board advises the Centre in its training of the next generation of scientists to develop and deliver public education and outreach programs and the strategic planning and management of the Centre. The Board further identifies opportunities for collaboration and engagement with industry and government.

The management structure will continue to be supported by several active internal Committees that provide advice in specific areas of focus for the Centre, as shown below.

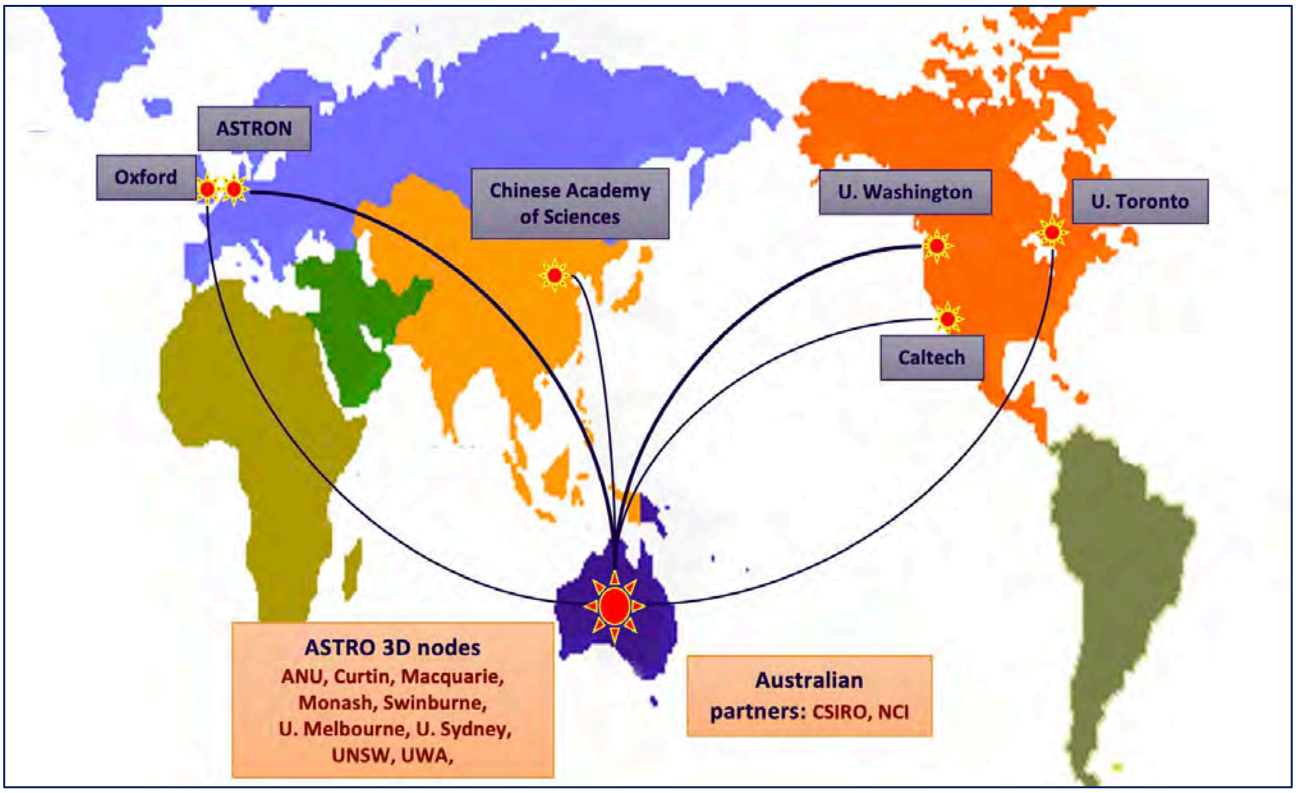


ASTRO 3D Centre Structure. Our committees report to the Executive Management Committee, chaired by Director Lisa Kewley. The Executive Management Committee manages the Centre recruitment, operations, budget, science, education and training programs. The Science Management Committee, chaired by Deputy Director Stuart Wyithe, oversees the progress of the science surveys and projects and provides advice to the Executive Management Committee on progress, risks and new opportunities. The Centre Advisory Board, chaired by Prof. Tim de Zeeuw, oversees all aspects of the Centre, and provides feedback annually to the Director and Deputy Director.

SCIENTIFIC RESOURCES

Organisation

ASTRO 3D consists of 250 researchers, management, education/outreach, and administrative staff across 9 Australian nodes, 2 Australian partner organisations, and 6 international partners.



Scientists

The Centre concentrates leading Australian astrophysicists, Directors of Australia's major observatories and supercomputing centres with a tremendous number of Australia's future scientific leaders. Our team currently includes nine Fellows of the Australian Academy of Science, two ARC Laureate Fellows, ten ARC Future Fellows, and four Discovery Early Career Award (DECRA) postdoctoral researchers. Our investigators spend a substantial fraction of their time on Centre Science and leadership (0.5 FTE on average for CIs and 0.3 FTE on average for PI/AIs). This large and focused effort is ensuring that the Centre science goals are reached on schedule. Our large team of Associate and Affiliate Investigators profoundly strengthens the Centre, providing an exceptional range of expertise and support. The expertise of our investigators comprehensively encompasses theory and observation, optical to radio, and data intensive astronomy. The majority of these investigators contribute to more than project or survey, helping cement the linkages and collaborations across the Centre.

Collaboration

The collaborative nature of ASTRO 3D is nurtured through the following key initiatives, which we will continue during the second half of ASTRO 3D.

- ✓ We have a dedicated "Collaboration Leader" to drive collaboration across projects and surveys within nodes, across nodes, and with our international partners.
- ✓ Busy weeks and writing workshops - the multiple nodes and international partners involved in each survey and project attend regular (in-person or virtual) busy weeks where concentrated collaboration activity is conducted towards specific scientific and data analysis goals. Busy weeks are extraordinarily productive and build cohesiveness within the Centre programs. We hold cross-program busy weeks

during critical periods where surveys/projects require input from one another, such as Genesis-FLASH survey busy weeks. We have regular in-person and virtual publication writing workshops, including goal-setting, peer review, and focused quiet group writing sessions.

- ✓ One of the flagships of ASTRO 3D is our prestigious ASTRO 3D Fellowship Program, similar to the highly successful NASA Hubble and Carnegie-Princeton Fellowship programs in the US. Outstanding, highly motivated young researchers have been recruited from the domestic and international job market with priority for those who collaborate and/or reside at different nodes and partner organisations. These fellows will bridge gaps among institutions and add to the cohesiveness of the Centre. The ASTRO 3D fellow-led MAGPI collaboration is a highlight of our Fellowship program.
- ✓ Key Performance Indicators for the Centre include milestones for publications with multi-node affiliations, publications with cross-project co-authors and PhD student cross-node co-supervision.
- ✓ Cohesion is maintained across the entire Centre through two annual meetings of all Centre members; an annual Science Meeting and an annual Strategic Planning Retreat. These meetings promote the sharing of exciting new science results with the entire team, development and assessment of the mentoring and leadership training of early-career researchers, and build and expand cross-project collaborations.
- ✓ Investigators from all participating organisations have access to travel funding to promote cross-institution collaboration. Funding enables individual investigators or entire research groups to visit at the same time, allowing for direct collaboration across all levels from PhD students to senior faculty. The Centre Director, Deputy Director, Collaboration Leader, and Chief Operating Officer undertake regular node visits and updates to partner organisations to ensure that the Centre researchers are appropriately engaged in Centre activities and maintain cross-institution collaborations.
- ✓ Cohesion between theorists and observers is an important goal for the Centre, with theory embedded within the surveys and observational units through strategic postdoc hiring and active engagement of theorists with observers in every survey and project. The embedding of theory within experimental projects gives us a significant advantage over competing theory groups who traditionally work separately from observers to produce simulations over periods of years. Our observations directly confront the model predictions from multiple different angles, with fast feedback loops, yielding more realistic models and more robust model predictions for our future observations.

RESEARCH PROGRAMS 2021-2024

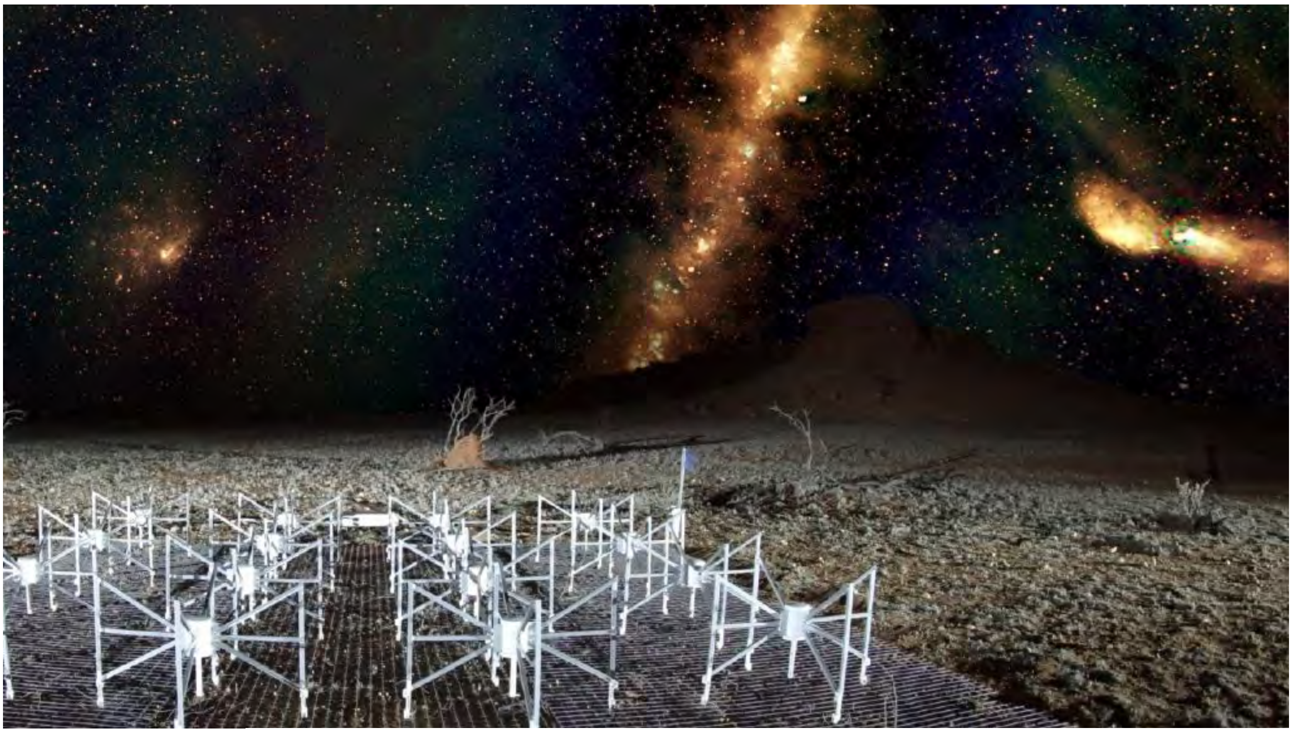
ASTRO 3D has been extremely successful in realising the Centre science goals for the first half of the Centre. This success provides the ideal platform to launch the next phase of our scientific program. This section provides an outline of our high-level plans and direction from 2021 – 2024.

1. The Murchison Widefield Array Epoch of Reionisation Survey

The MWA EoR **(**Murchison Widefield Array Epoch of Reionisation) survey is at the forefront of measurements of the universe at the Epoch of Reionisation (EoR). In 2019, ASTRO-3D published two papers describing the most stringent upper limits to the EoR power spectrum from tens of hours of 2013 and 2016 data, followed by the publication of 298 hours of data from all three observing fields and across all redshifts, including the deepest limits at z = 6.5 - 7.1 from 110 hours.

The MWA EoR program will continue to obtain, reduce and analyse observations with the MWA. With the forthcoming MWA Phase-III upgrade, the second half of ASTRO-3D will focus on developing diffuse emission models for calibration and signal subtraction and removing radio frequency interference from the MWA data.

ASTRO 3D MWA science bridges the gap between the current generation of radio telescopes and the Square Kilometre Array (SKA). Full science operations for the SKA is slated for 2029. ASTRO 3D MWA researchers are involved in developing the SKA EoR observing program and data analysis methods.



A "radio colour" view of the sky above a "tile" of the Murchison Widefield Array radio telescope, located in outback Western Australia.
Radio image: Natasha Hurley-Walker (ICRAR/Curtin) and the GLEAM Team

2. The First Stars

The First Stars in the Universe caused the Epoch of Reionisation. Our First Stars project aims to discover the first stars or their direct descendants in the Milky Way. We search for these candidates using images from the ANU SkyMapper telescope. We identify star candidates with extremely low levels of elemental abundances (called extremely metal-poor stars). We follow up the most promising targets with the European Southern Observatory Very Large Telescope and the Magellan Telescope in Chile. In the first half of ASTRO 3D, the First Stars program made considerable progress, with our team discovering the top three most metal-poor stars in the Universe.

In the second half of ASTRO 3D, the follow-up of SkyMapper extremely metal-poor star candidates will continue. We will use Gaia information to supplement spectral information on extremely metal-poor stars, and to derive a complete chrono-chemo-dynamical picture of stars in the early Galaxy.

3. The First Galaxies

The First Galaxies research program has discovered galaxies during the epoch of reionisation, and characterised their properties both through follow-up space and ground-based observations, as well as through theoretical and numerical modelling. The project's strategy for the second half of the Centre is to focus primarily on investigations into the detailed chemical and structural properties of first galaxies that were deferred due to the James Webb Space Telescope (JWST) launch delay. This observational analysis will be complemented by continued theoretical and numerical modelling of galaxy, star, black hole and gamma-ray burst formation at high-redshift.

ASTRO 3D members are co-investigators of the James Webb Space Telescope (JWST) GLASS Early Release Science program and the CEERS Early Release Science Program which will provide both imaging and spectroscopy of distant galaxies. ASTRO 3D members also collaborate on a JWST Guaranteed Time Observations program which will include medium-deep parallel fields with the JWST near-infrared camera, NIRCAM. These observations will be ideal to identify the earliest galaxies in the Universe ($8<z<14$). During the second half of the Centre, ASTRO 3D First Stars researchers will contributed to the development of observational and theoretical tools for these programs, and they will continue their development of the SkyHopper Cube Satellite. When JWST launches, the First Galaxies researchers will focus on forthcoming JWST data.

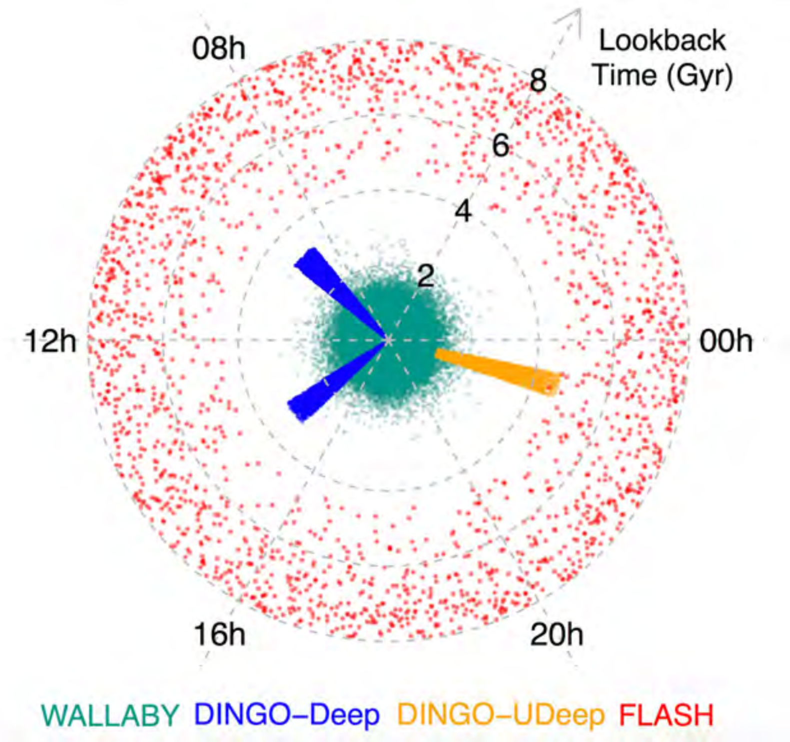
3. The Galaxy Evolution Program

The Galaxy Evolution Project aims to track mass assembly, chemical evolution and ionising radiation in galaxies across cosmic time from the First Galaxies to the galaxies discovered in the ASKAP and SAMI/HECTOR surveys. This project covers 12 billion years of cosmic time and is making rapid progress through a suite of large and complementary surveys. In the first half of ASTRO 3D, we developed the large ESO VLT MAGPI project to measure the kinematics and mass assembly of galaxies. We searched for distant gravitationally lensed galaxies in the Dark Energy Survey. Our all-sky follow-up of these targets (called AGEL) to measure their elemental abundances and kinematics on the ESO VLT in the south and Keck in the north is ongoing. With the addition of Deanne Fisher as a CI from Swinburne as part of our succession planning strategy, our Centre now includes a major survey to study the ionised gas in star-forming disks (called DUVET). This survey complements the existing large Galaxy Evolution surveys and provides much-needed observations on ionisation in distant galaxies. During the second half of the Centre we will complete these surveys and measure the elemental abundances, mass build-up and ionisation conditions in galaxies, bridging the first galaxies with the local Universe probed by SAMI/HECTOR.

Our galaxy evolution program also includes a theory program that is conducted in collaboration with the Genesis team. We are creating the world's most detailed 3D photoionisation models that will be used to analyse local and distant galaxies. We have created stellar tracks with realistic elemental abundance sets that will be used in stellar evolution synthesis and our 3D photoionisation models in the second half of the Centre to model the spectra from galaxies observed with the First Galaxies, AGELs, DUVET, and SAMI/HECTOR.

4. The ASKAP Surveys

The ASTRO 3D ASKAP Surveys project encompasses three closely-linked projects: WALLABY, DINGO and FLASH (see Figure, right). WALLABY aims to examine the HI properties and large-scale distribution of ~500,000 galaxies out to a redshift of 0.26 (equivalent to a look-back time of ~3 billion year) to study galaxy formation in the Local Group, the HI mass function and its variation with galaxy density, and physical processes governing the distribution and evolution of cool gas at low redshift. DINGO will analyse co-evolution of the stellar, baryonic, and dark matter content of galaxies, and will be the first comprehensive study of these components over the past 4 billion years of cosmic time. FLASH is a blind HI absorption-line survey that uses background radio continuum sources to identify and characterise foreground neutral hydrogen. FLASH science outcomes for the second half of the Centre are focused on both the neutral gas content of galaxies and the cosmic HI mass density in the redshift range 0.5 < z < 1.0, where the HI emission line is too weak to be detectable in individual galaxies. The ongoing observations will increase the total number of absorption line systems by an estimated two orders of magnitude, allowing us to study gas assembly in galaxies to unprecedented distances. All three surveys are important pathfinders for galaxies to target with the Square Kilometre Array.



All three surveys have made significant progress during the first half of the Centre. The ASKAP telescope is now operational in its full 36-antenna configuration, following a period of Early Science observations carried out in 2018-19 with an array of 12-18 dishes. From mid-2019, each of the three surveys was allocated 100 hours of 'Pilot Survey' time with the full 36-dish array, ahead of the formal start of the ASKAP surveys. The ongoing ASKAP-X upgrade will improve telescope reliability, and the 2021 Pawsey upgrade will allow survey teams to remove bottlenecks and accelerate survey progress.

Improvements in survey data products will follow from splitting of ASKAP observing bands to maintain bandwidth but avoid radio-frequency interference (RFI) near 1200 MHz from Earth-orbiting satellite transmissions.

The focus in the second half of ASTRO 3D includes shifting to multi-wavelength radio galaxy follow-up with the European Southern Observatory (ESO) Very Large Telescope (VLT) with the MUSE and DECAM instruments. These observations will enable the ASKAP survey teams to further strengthen links with the Genesis simulations team and with the SAMI/HECTOR team. The main ASKAP surveys and science goals will be completed in the second half of the Centre, including the analysis of the build-up of neutral hydrogen mass in galaxies from 8 billion years ago to the present day.

5. The SAMI and Hector Surveys

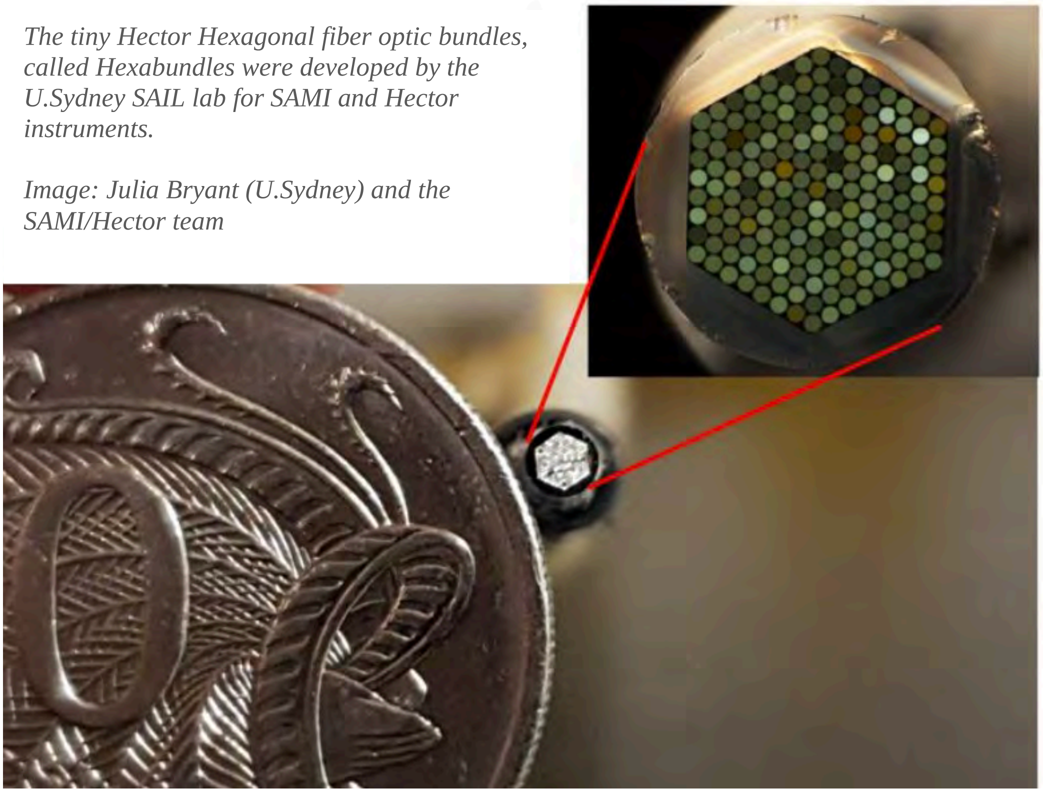
The observational aim of the SAMI Galaxy Survey project was to obtain 3D integral field spectroscopy for over 3000 galaxies to understand the physical role of environment in galaxy evolution, the interplay between gas flows and galaxy evolution and how the mass and angular momentum are built up in galaxies. The SAMI observing campaign has completed with full data release to the public. In the second half of ASTRO 3D, we will focus on exploiting the full data set from the SAMI survey for science, including stellar population gradients, connection to kinematics and star formation rates, and connection to higher redshift through the Galaxy Evolution programs.

We are developing the successor to the SAMI instrument, called Hector. Hector will have a larger number of hexabundles (see image below), with varying sizes and a new spectrograph with higher spectral resolution. As well as enabling a larger sample of galaxies, Hector opens up other unique windows not accessible to SAMI, including stellar dynamics of lower mass galaxies and detailed analysis of outflows at large radii in galaxies. Hector will employ the first new Hector spectrograph (blue and red arm) alongside the existing AAOmega spectrograph, with 21 new hexagonally-packed hexabundles with up to 169 fibre cores each. Hector has a combination of robotic and manual positioning, and offers significant science gains over SAMI with increases in survey speed, galaxy coverage to 2 effective radii for most galaxies and higher spectral resolution.

The instrument development for Hector is ongoing at the University of Sydney SAIL lab and the AAO-Macquarie lab. Hector is the next major dark-time instrument for the Anglo-Australian Telescope and commissioning is expected by mid-2021. For the second half of ASTRO 3D, we will conduct a large Hector survey of 15,000 galaxies, with 70% of galaxies imaged to 2 effective radii. This will be the only integral field spectroscopy survey sufficiently large to connect galaxy evolution and kinematics to large-scale-structure to explain the evolutionary history leading to the individuality of galaxies. Our Hector science will build on our SAMI science of stellar population gradients, connection to kinematics and star formation rates as well as dynamical bulge-disk separation. With the Hector survey, we will investigate how galaxies build up their mass and angular momentum, how star formation and nuclear activity are affected by environment, the role of feedback, and how the large-scale environment modulates galaxy growth through tidal torques and gas accretion.

The tiny Hector Hexagonal fiber optic bundles, called Hexabundles were developed by the U.Sydney SAIL lab for SAMI and Hector instruments.

Image: Julia Bryant (U.Sydney) and the SAMI/Hector team



6. The GALAH Survey

The GALAH ASTRO 3D survey aims to reconstruct the history of star formation, chemical enrichment, radial migration and minor mergers in the Milky Way using detailed and precise elemental abundance patterns, ages and kinematics of a million stars. ASTRO 3D has made excellent progress in Phase 1 of the survey on the Anglo-Australian Telescope (AAT), with the first half of the observing programme complete, and key scientific discoveries published based on high-quality data analysis. The GALAH Data Release 2 (DR2) led to 2000+ refereed papers in 2 years. Our recent GALAH Data Release 3 (DR3) in Nov 2020 – with increased precision in all parameters, and elemental abundances for 588,571 stars – will have an even greater impact. In the second half of ASTRO 3D, we will continue our GALAH survey on the AAT towards our target of 1 million stars. Following the release of the Gaia satellite DR3 data, the second half of ASTRO 3D will focus on combining GALAH data with Gaia DR3 to analyse the star formation, chemical and mass assembly history of the Milky Way. Once complete, we will compare the star formation, chemical, and mass assembly history of the Milky Way with the history of external galaxies across cosmic time traced from our First Galaxies, Galaxy Evolution, SAMI/Hector and ASKAP surveys.

7. The Genesis Simulations

The Genesis Simulations were developed to bridge all surveys and projects, providing star and galaxy formation and evolution models that spans the epoch of reionisation to the present day. During the first half of the Centre, our Genesis team has made progress in the areas of large cosmological N-body simulations, semi-analytical models, and hydrodynamical simulations. The team has strong collaborations with a number of projects and overseas teams including the Illustris and EAGLE teams. Following ASTRO-3Ds investment in the development of SWIFT, we can now run our ambitious 300 billion particle simulation with NCI, enabling the large volume simulations for needed for ASTRO 3D and galaxy survey and reionisation science.

During the second half of the Centre, we will leverage future opportunities with the EAGLE, Colibre, and Illustris collaborations. EAGLE-XL consists of an EAGLE galaxy formation prescription run in a Millennium volume, such that the statistics of galaxy groups and clusters is significantly improved. Complimenting this, Colibre focuses on a volume equivalent to the EAGLE high resolution run, but with enhanced resolution and improved models for the physics of the interstellar medium. The Illustris TNG offers cutting edge predictions of how the mass and chemical elements build across galaxies over time. Genesis and Galaxy Evolution team members are already embedded in the core EAGLE-XL, Illustris and Colibre teams and will utilise the next set of state-of-the-art galaxy formation simulations that will be available during the lifetime of ASTRO 3D.

8. Data Intensive Astronomy (DIA) Program

The ASTRO 3D flagship telescopes (AAT, ASKAP, MWA, SkyMapper) are collecting unprecedented volumes of multi-dimensional data sets, while the Genesis Simulations will produce prodigious amounts of theoretical data. These Peta-byte scale data sets require sophisticated data management and access mechanisms as well as new algorithms and visualisation tools to efficiently extract scientific information. Overcoming these "Big Data" problems is critical for scientific exploitation of the MWA, ASKAP, the future SKA, and other major international projects, like the US Large Synoptic Survey Telescope (LSST).

This program aims to meet the data processing and analysis needs for our surveys, provide a single common architecture for the direct comparison between our surveys and the *Genesis Simulations* and build the infrastructure to effectively analyse Petabytes of data in the lead-up to the Square Kilometre Array and other next generation telescopes. Our new node Macquarie University runs Astronomy Data Central (ADC), which provides important data curation and data servers for ASTRO 3D surveys. In the second half of the Centre, we will complete a new survey of the ASTRO 3D surveys/projects to determine the main outstanding data needs, and incorporate these needs into ADC. We will include the Genesis simulations into an expanded ADC, as well as additional surveys to provide background photometric data and value-added products (such as photometric and spectroscopic redshifts, stellar masses) for galaxies in the ASTRO 3D ASKAP surveys. We will leverage the ADC professional software engineering and project management resources and a new data intensive astronomy postdoctoral researcher at Macquarie to reach these goals.

EDUCATION AND OUTREACH

Telescopes in Schools

ASTRO 3D is expanding the highly successful *Telescopes in Schools* program to all node states. Initially run out of the University of Melbourne (where it is funded through a philanthropic foundation), the program is targeted at high school students in Years 7 to 9. We select high schools that have low entrance rates to university to encourage students to enter university to pursue careers in science. Telescopes in Schools provides the schools with a computerised telescope, training, astronomer support, and all the necessary gear to observe the night sky, image the objects in the night sky and conduct small research projects. These telescopes are large enough to view deep sky objects such as nebulae and far away galaxies or zoom in on a crater on the moon. Students engage with an astronomer about their research and then learn how to set up and drive the telescope to conduct their own research projects.

During the first half of the Centre, we continued the Victorian Telescopes in Schools program and expanded this program to Western Australia through the SPIRIT Telescope, in collaboration with ICRAR at the University of Western Australia. The SPIRIT in Schools program targets female students and students from lower socioeconomic backgrounds. Teachers are given the tools and support to help their students design, implement and complete an astronomy project over a school term using the SPIRIT remote internet telescope. This program will continue to attract students in rural, regional, and remote WA over the next three years.

In the second half of the Centre, we will expand Telescopes in Schools into NSW urban schools through our new node Macquarie University and the Macquarie Astronomical Observatory, and into NSW rural schools through our new STARS program.

Scientists Taking Astronomy to Regional Schools (STARS)

As an expansion of our Telescopes in Schools program, in 2021, we began the STARS program, which engages primary and secondary school students in rural, regional and remote locations including indigenous schools, through a series of visits by research scientists and PhD students in astronomy and astrophysics. Through external sponsorship, ASTRO 3D is providing an 8" Dobsonian telescope and accessories to each school. We support teachers and students by providing training and stargazing sessions as well as a range of technical information, curriculum resources, and student project ideas and instructions.

In late 2020, the Federal Government awarded ASTRO 3D an $85,000 Maker grant to implement the program until mid-2022. In late 2022 and 2023, ASTRO 3D will continue the STARS program visiting new regional and remote schools. We will also continue to develop supporting resources for teachers and students, which we will place on the ASTRO 3D website for easy access.

Our telescopes in schools program provides telescopes to underprivileged schools to encourage engagement and careers in science.

Virtual Reality Program

The ASTRO 3D Virtual Reality (VR) education program is an innovative, immersive program that aims to increase student engagement in and understand the complex astronomical science on the origin of the Universe. It highlights the parts of ASTRO 3D research that address key portions of the Year 10 Australian Curriculum for Science.

Our VR program is currently under development through our collaboration with the Deakin University Virtual Reality Laboratory. We will complete the VR program in the latter half of 2021 and will promote it extensively to schools with a dedicated launch. ASTRO 3D will initially set up 'lending libraries' of class sets of the Oculus Quest 2 headsets for schools to borrow to enable schools that do not have headsets of their own to participate. Schools that do have headsets will be able to purchase the program for ongoing use.

ASTRO 3D Education and Outreach Officers will train teachers to use the VR program through professional development workshops. Teachers will also have access to custom-made teaching and learning resources to complement the VR package, to be made available on the ASTRO 3D website.

Once the package is complete, we will source further grants and philanthropic funding to add activities to the VR and purchase more headsets to the lending library.

Work Experience programs

Work experience is the short-term placement (usually one week) of year 10-12 students with researchers. The aim of our work experience program is to provide insights into the work of astronomers. Students explore research interests by undertaking small astronomical projects under the supervision of a professional astronomer, attending presentations/scientific talks by ASTRO 3D astronomers, and learning how to align future school studies with potential career aspirations.

During the second half of the Centre, ASTRO 3D will continue to run three versions of the work experience program across the nodes. We will run face-to-face and virtual work experience programs multiple times per year, based on demand. The pilot of the Indigenous Work Experience program, currently being developed and scheduled for June 2021 at the Australian National University, will be evaluated on completion and is expected to be conducted by other nodes in 2022-2024.

ASTRO in the Classroom

ASTRO in the Classroom is a program targeting primary students in Years 3-6 and their teachers. Rather than going into classrooms, teachers overwhelmingly asked us to provide videos, providing them with more scheduling flexibility. In 2021, ASTRO 3D researchers will be filmed giving age-appropriate 10-15 minute presentations on topics that address the primary school Earth and space science curriculum. These presentations will form a suite of videos accessed on the ASTRO 3D website. Teachers will be able to use these videos at any time that suits their curriculum program. After their students watch the video, teachers can then book a live 'Q&Astronomer on Demand' session through ASTRO 3D or consult a bank of previously answered questions housed on the dedicated ASTRO in the Classroom website.

ASTRO 3D will launch the program in mid-2021. The library of videos will grow as more topics/presentations are recorded and based on requests. The ASTRO in the Classroom webpage will also include educational materials to support both the student and teacher in the classroom.

ASTRO 3D Depth Study and Teacher Professional Learning (PL) workshops

ASTRO 3D Education & Outreach will continue to run annual, 2-day Depth Study programs at Siding Spring Observatory for Year 12 NSW students. This program provides the 15 hours of proven investigative study that further develops one or more concepts found in the senior science curriculum.

A pilot teacher Professional Learning program will be trialled at Siding Spring in 2021, to run either annually or, if there is demand, biannually until mid-2024.

RESEARCH AND LEADERSHIP TRAINING PROGRAM

Centre-wide Mentoring Program

We will continue to deliver our mentoring circles program across the Centre. Mentoring circles have been shown to build a sense of collegiality, satisfaction, confidence and achievement across the Centre. We group early career researchers with a mentor in non-hierarchical, collaborative groups to address specific areas such as research, career paths, time management and work-life balance. We will continue to measure the success of our mentoring program through annual Mentoring circle surveys and through our Centre-wide climate surveys.

Professional Astronomical Skills Training Workshops

Astronomy students require a range of professional and personal skills to successfully conduct and lead research on the international stage. Capitalising on the existing experience of our team, we will continue to offer annual workshops in skills such as scientific writing, writing postdoctoral job applications, writing telescope proposals, writing ARC grant and DECRA applications, supervision skills, mentoring skills, professional presentations and time management skills to all students and early career researchers nationwide, both within and outside ASTRO 3D.

Transferrable Skills Program

The Australian Astronomy Decadal Plan identified a critical mismatch between supply and demand in Australian astronomy. Astrophysics PhD students typically finish their studies having gained substantial problem-solving and statistical skills, so we will impart them with a set of transferrable skills to provide highly skilled graduates for roles in the wider community.

Data intensive science is a rapid growth field. Training students to manage massive datasets opens an array of new career paths, including population statistics, medical science, bioinformatics, banking, media science, and genomics, yielding lasting benefits to the Australian community. We will continue to offer transferrable skills courses in managing large data sets, programming in languages in demand by industry, training in industry practices, and in the second half of the Centre, we will expand these offerings to include professional project management skills.

We measure the usefulness and success of our transferrable skills program through workshop surveys, Centre climate surveys, and by tracking the careers of former Centre participants. Providing highly skilled scientists with outstanding problem solving and data management experience for the Australian economy is a significant benefit of our transferrable skills program.

Leadership Program

In the era of mega-scale telescope facilities, astrophysics will shift from relatively small teams and networks (typically a few to a few tens of active researchers) to significantly larger teams and global networks of researchers. We will continue to provide leadership training and mentoring to our most promising young researchers to help them confidently and successfully transition from researcher to team leader. Our CI/PI team contains many of Australia's most talented scientific leaders. We will continue our Women's Leadership program to further improve the academic environment and advancement of women to senior levels.

In the second half of the Center, we will offer a workshop specifically aimed at developing the skills to work and lead in the mega-scale telescope environment, including developing a vision, effective team building, large project management, risk management, negotiation and conflict resolution, and time management. We will utilise our partner organisations AAO and CSIRO, as well as our university and industry partners to bring in experts from each of these areas.

The success of our leadership programs are measured through workshop exit surveys and by tracking the careers of participants throughout the course of the Centre.

Succession Planning

The next generation of telescopes, including the ESO Extremely Large Telescope (E-ELT), the Giant Magellan Telescope (GMT) and the Square Kilometre Array (SKA), come to fruition in the coming decade. Australia has invested over $500M in astronomical infrastructure so far to build these next-generation telescopes, and the Federal Government has committed $294M to build the Australian SKA as part of its National Innovation and Science Agenda. ASTRO 3D exploits current Australian telescope innovations to build the observational and theoretical leadership and the overall research capacity and the technical expertise required to build cutting-edge instrumentation and lead large international programs with these next-generation telescopes.

The benefits of the Centre extend far beyond its lifetime. Our Succession Planning program identifies future leaders in the Centre. Our mentoring program and leadership workshops aim to provide our future leaders with the confidence and skills required to conduct world-leading and internationally competitive research in the new global era of science. We also provide concrete career paths for ASTRO 3D researchers in astronomy.

We have incorporated succession planning into our Centre to ensure that there is a clear career progression for the best young researchers as well as a renewal of the scientific drive in the latter half of the Centre. We have recruited four women into ASTRO 3D continuing positions at three university nodes: U.Melbourne, UWA, and ANU. We are currently undertaking our final female-only continuing position hire at the University of Sydney.

In 2020-2021, we began our CI and Node Leader succession program with some of our senior CIs and Node Leaders rotating out of their positions to make way for junior researchers with leadership. At UWA, CI & UWA Node Leader Lister Staveley-Smith was succeeded by AI Barbara Catinella. At Swinburne, Node Leader Karl Glazebrook was succeeded by CI Emma Ryan-Weber, and Swinburne AI Deanne Fisher transitioned to a CI role. We have identified additional junior leaders who will to step into CI and Node Leader roles in the second half of the Centre at the ANU and the University of Sydney. Beyond ASTRO 3D, these new leaders and their teams will be ready to lead the large Australian programs on the next generation of telescopes.

Finally, one of the main impacts for Australia of the Centre is its broad national education and outreach program. Our education and outreach programs have been set up in partnership with node universities which will continue to operate these programs and host their associated web videos and materials beyond ASTRO 3D.