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FOR ALL-SKY ASTROPHYSICS

Reader’s Digest

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Publication stories about current CAASTRO research

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Cover image by Dr Marcin Sokolowski (ICRAR – Curtin University)

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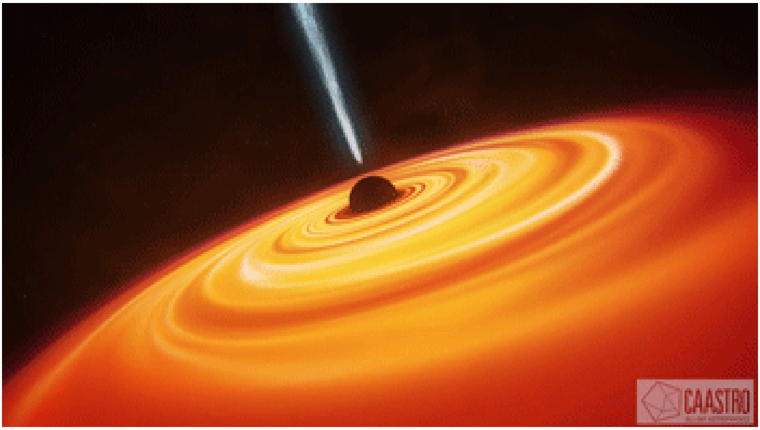
Bright Active Galactic Nuclei cause high velocity ionised wind

At the centre of most (if not all) galaxies lies a supermassive black hole. In most cases, as in our own galaxy, it is dormant. This means that it is not currently accreting matter. However, in some galaxies it is active: it is accreting matter and, as a result, radiating an enormous amount of energy across the electromagnetic spectrum. These so-called active galactic nuclei (AGN) likely play an important role in the lifetime of galaxies due to the close observed correlations between the mass of supermassive black holes and their galaxy's central bulge of stars. Such correlations suggest that they evolve and grow together.



A process called feedback is often invoked as the mechanism behind this correlation. AGN feedback is a broad term for all the effects that the presence of an accreting black hole will have on its host galaxy. In order to better understand feedback, and hence galaxy evolution, CAASTRO PhD student Rebecca McElroy (University of Sydney) and her colleagues selected an extreme sample of 17 local ($z < 0.11$) highly luminous type II AGN ($\log(L_{[\mathrm{O\ III}]}$/L_Sun) > 8.7) with very high accretion rates where the effects of feedback should be most pronounced. They used the Anglo-Australian Telescope’s AAOmega spectrograph to observe these galaxies by integral field spectroscopy (IFS) – a technique that allows for hundreds of spectra to be taken across the spatial projection of a galaxy at once. At the median redshift of the sample they covered a field of view of 915 square kiloparsec and were able to record the kinematics and emission in different regions of the galaxy – both near and far from the AGN.

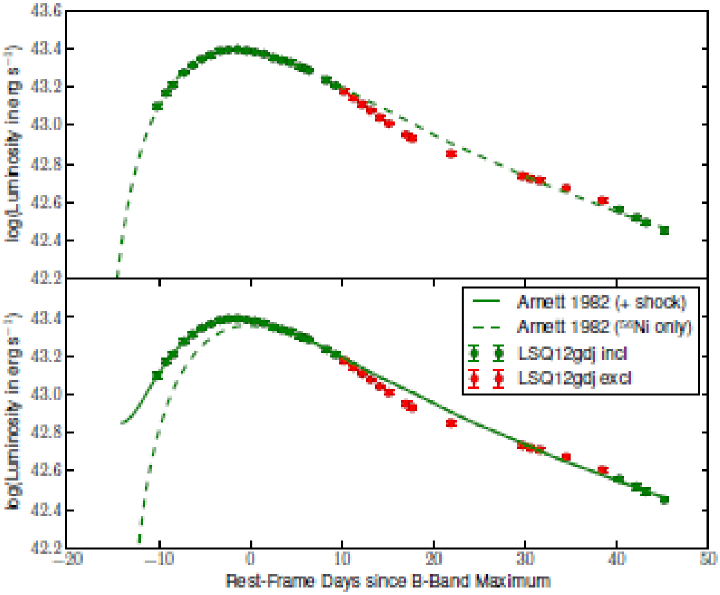
By fitting the emission lines present in the spectra across each galaxy the researchers were able to find signatures of outflows coming from the AGN in all 17 galaxies observed. These outflows were distinguished by their high velocity, velocity dispersion, and ionisation. In the majority of galaxies there was also evidence of shocks produced as the outflows pass through the surrounding gas. The research team could rule out radio jets as the cause for the outflows and concluded that the outflows come from these high luminosity AGN and are directly impacting the surrounding Interstellar Medium within the galaxies.

Publication details:

Rebecca McElroy, Scott Croom et al. in the Monthly Notices of the Royal Astronomical Society (2015): “*IFU observations of luminous type II AGN - I. Evidence for ubiquitous winds*”

Clues to origin of luminous supernovae may lie in ultraviolet

The widespread use of type Ia supernovae (SNe Ia) in cosmology, as one of the farthest rungs in the extragalactic distance ladder and as tools to study dark energy, depends on the accuracy with which their luminosity can be measured. The classic luminosity calibration relations used in cosmological studies apply only to SNe Ia with “normal” spectra. However, wide-field supernova searches (including CAASTRO's SkyMapper survey) are now revealing the true observational diversity of SNe Ia, uncovering a rare, ultraluminous subclass of SNe Ia which do not obey the calibration relations.



ANU-based CAASTRO Associate Investigator Dr Richard Scalzo's previous work on this subclass provides strong evidence that their ejected masses exceed the Chandrasekhar limiting mass for white dwarfs, justifying the commonly used label “super-Chandra”. Since all type Ia supernovae are believed to be explosions of white dwarfs, super-Chandra SNe Ia provide challenges to our understanding of white dwarf physics and stellar evolution. Super-Chandra SNe Ia are not only very luminous, but very blue – suggesting strong ultraviolet (UV) emission, which could arise from a shock driven by the supernova ejecta into a cloud of material surrounding the progenitor. Such clouds are also predicted by models of white dwarf mergers, and could explain the high luminosities of super-Chandra SNe Ia.

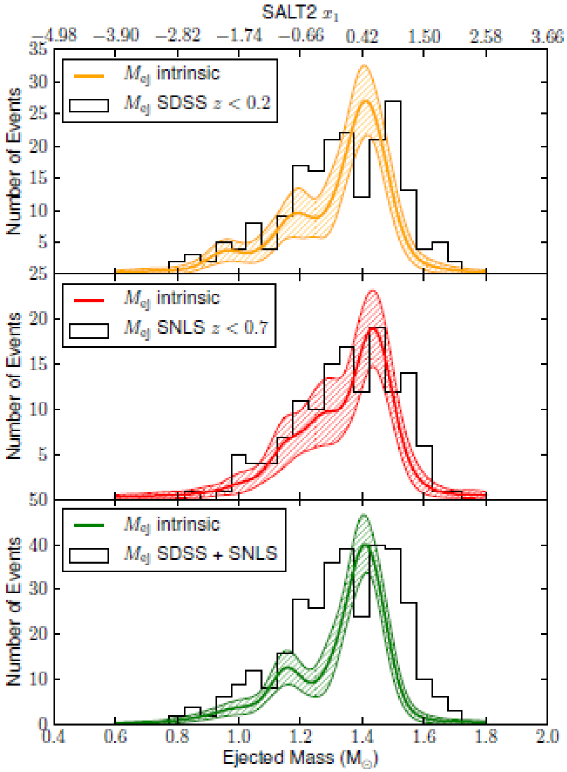
With a spectrum resembling other super-Chandra SNe Ia, LSQ12gdj was discovered just a few days after explosion – making it an excellent test case to search for UV emission from shocks. Dr Scalzo, the ANU group, and their European and American collaborators observed LSQ12gdj with the *Swift* space telescope as well as ground-based optical telescopes. Early in its evolution, over a quarter of LSQ12gdj's luminosity was emitted at UV wavelengths visible only to *Swift* (compared with 5 – 10% for normal SNe Ia). However, no more than 10% of LSQ12gdj's peak luminosity is likely to come from shocks, so any material surrounding the progenitor must be very compact. When all this is taken into account, LSQ12gdj's appearance is consistent with a Chandrasekhar-mass progenitor – showing that UV observations are crucial to understand these events fully.

Publication details:

Richard Scalzo, Michael Childress, Brad Tucker, Fang Yuan, Brian Schmidt et al. in the Monthly Notices of the Royal Astronomical Society (2014): "*Early ultraviolet emission in the Type Ia supernova LSQ12gdj: No evidence for ongoing shock interaction*"

At least a quarter of supernovae eject sub-Chandrasekhar masses

Despite their ongoing use as tools for cosmology, type Ia supernovae (SNe Ia) are still not fully understood physically. In the classic scenario, a white dwarf and a larger star orbit each other, with the white dwarf gradually accreting material from its companion until reaching the Chandrasekhar limiting mass (1.4 times the mass of our Sun) when it is expected to become unstable and explode. This scenario is now being actively challenged, due to tight observational limits on signatures of the accretion process (such as X-ray emission from host galaxies or hydrogen lines in SN Ia spectra) and to the low predicted rate of Chandrasekhar-mass explosions. Alternative models, such as white dwarf mergers or collisions, may eject different amounts of material.



Previous observational work by CAASTRO Associate Investigator Dr Richard Scalzo (ANU) has shown that for "normal" SNe Ia used to study the cosmological dark energy, ejected mass correlates strongly with rate of luminosity decline after peak. It also confirms that the mass of radioactive nickel-56 synthesised in the explosion correlates with the peak luminosity. The relation between decline rate and luminosity, used to calibrate SNe Ia as "standard candles" in cosmology, may thus reflect an underlying relation between ejected mass and nickel mass, giving a clue to the explosion mechanism.

In a recent paper with CAASTRO co-authors Dr Ashley Ruiter (ANU) and Dr Stuart Sim (Queens University Belfast), Dr Scalzo has exploited these relations to measure the detailed distribution of ejected masses for a sample of over 300 type Ia supernovae used in cosmological analyses. While the distribution has a sharp peak at the Chandrasekhar mass, it also shows a long tail towards lower masses and very few (< 2%) high-mass events. This picture shows for the first time that both Chandrasekhar-mass and sub-Chandrasekhar-mass explosions occur at significant rates. While white dwarf mergers or detonations of low-mass white dwarfs could explain some of the distribution's tail, some events with inferred sub-Chandrasekhar ejected masses are fainter than predicted in these scenarios – suggesting that these models need revision to explain the SN Ia calibration relation.

Publication details:

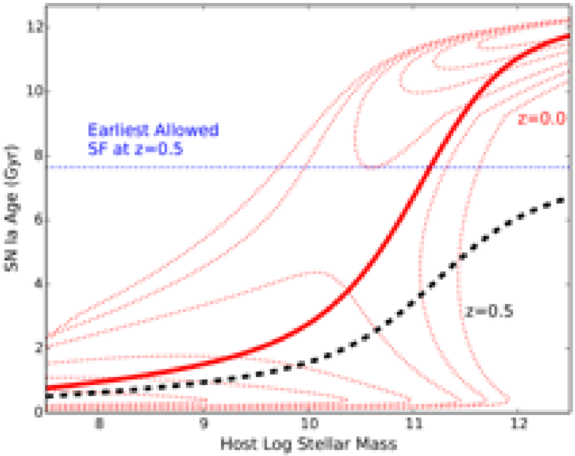
Richard Scalzo, Ashley Ruiter and Stuart Sim in the Monthly Notices of the Royal Astronomical Society (2014): “*The ejected mass distribution of Type Ia supernovae: a significant rate of non-Chandrasekhar-mass progenitors*”

Why supernovae are brighter in old massive galaxies

Type Ia supernovae (SNe Ia) are critical tools for measuring the contents of our Universe, but recent studies found their cosmological brightness showed a bias with respect to the environment in which they are found: SNe Ia in massive, old, metal-rich galaxies are slightly more luminous than their counterparts in less massive galaxies. This bias hinders efforts to precisely quantify the nature of Dark Energy, and its origin has been a subject of debate for several years. A new study by CAASTRO researchers Dr Michael Childress and Dr Christian Wolf with Harvard colleague Dr Jabran Zahid shows that this bias can be naturally explained by the ages of the stellar systems that explode as SNe Ia, but more importantly that this effect evolves dramatically over cosmic time.

SNe Ia are universally believed to originate from white dwarf stars which reach a critical instability as a consequence of interaction with a binary companion star. These binary systems come in a variety of configurations which result in a distribution of “delay times” between birth of the binary system and final triggering of the SN explosion. Thus SNe Ia have an intrinsic “delay time distribution” (DTD) which is set by the initial distribution of binary system properties, and this DTD is equivalent to the rate of SNe Ia as a function of time following a single instantaneous burst of star formation.

The ages of systems which explode as SNe Ia are influenced not only by this DTD but also by the star formation history (SFH) of the galaxy in which the SNe are born. In this new study, the authors develop a sequence of galaxy evolution models based on observations from large galaxy surveys. These models define the mean SFH for galaxies as a function of their current stellar mass for any epoch of cosmic history. With these at hand, they then derive



the age distribution of systems exploding as SNe Ia for a galaxy of any chosen mass at any epoch of cosmic time.

The results of this calculation show a dramatic change in the age of SNe Ia as a function of their host galaxy mass – one that closely resembles the trend of cosmological SN Ia luminosity bias with host galaxy mass. More importantly, the team found that this trend evolves with cosmic time, indicating that the SN Ia "host bias" is likely to evolve in a way currently not accounted for by supernova cosmology surveys. This work exhibits the power of theoretical galaxy evolution models for explaining systematic behaviours in supernova cosmology data, and provides key tools for correctly quantifying the nature of Dark Energy.

Publication Details:

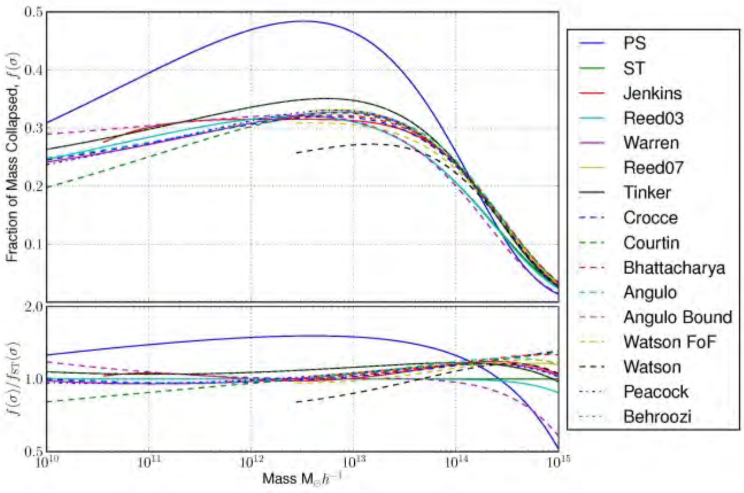
Michael Childress, Christian Wolf et al. in the Monthly Notices of the Royal Astronomical Society (2014): "*Ages of Type Ia Supernova Over Cosmic Time*"

HMFcalc: An online tool for calculating halo mass functions

The halo mass function describes the abundance of collapsed dark matter objects of a given mass and can be used in observational tests to constrain cosmological parameters and in theoretical models to predict galaxy clustering and even basic galaxy properties. As one of the basic measures of dark matter, it is a quantity which is frequently required across a broad spectrum of theoretical and observational fields.

Given its ubiquity, it is perhaps surprising that until now, no standard software has been developed which calculates this function in a robust manner. This results in many researchers “re-inventing the wheel” which is prone to human error and damages reproducibility.

In their 2013 paper, CAASTRO PhD student Steven Murray and Associate Investigator Prof Chris Power, together with Dr Aaron Robotham (all at ICRAR – University of Western Australia), present a new code, aimed at filling this crucial gap. The code, called hmf, is written in the popular Python language, and is well tested, well documented, numerically efficient, robust and easily extendible. Furthermore, to enhance ease-of-use across the broad user spectrum, they implemented a web-application interface to the code called HMFcalc at hmf.icrar.org, so any researcher is merely a few clicks away from a mass function.



The paper also presents some toy applications using the code, develops the theoretical background of the HMF, includes a “cheatsheet" table of HMF fits found in the literature, and includes examples of how to extend and customise the code.

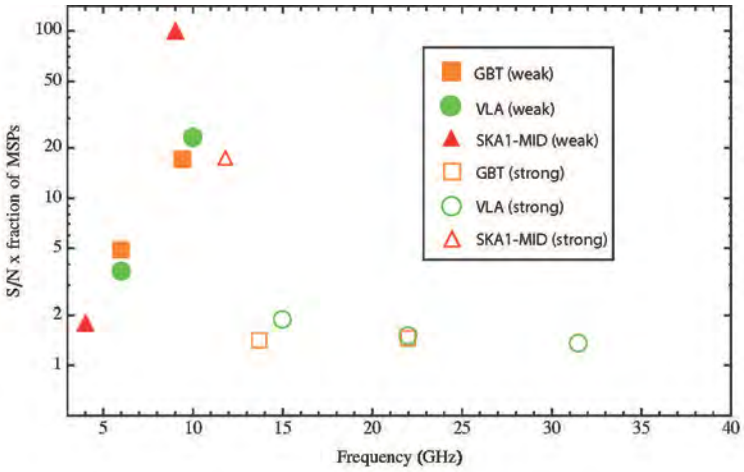
Publication Details:

Steven Murray, Chris Power et al. in Astronomy & Computing (2013): "*HMFcalc: An online tool for calculating dark matter halo mass functions*"

Where are all the pulsars at the Galactic Centre?

As stable, regularly pulsing rotators, pulsars are superb instruments for testing theories of gravity. An important test of General Relativity is the behaviour of bodies in extremely strong gravitational fields. The detection of a pulsar in the gravitational field of a black hole therefore potentially constitutes an exceptional test of theories of gravity in the strong field regime.

Astronomers have long sought to find pulsar-black hole binary systems by conducting large surveys of the Galactic pulsar population. But there is another way to find such systems: find a supermassive black hole and then search for orbiting pulsars. For this reason, the region immediately surrounding the four million solar mass black hole at the Galactic Centre, Sgr A* has been the site for a number of deep pulsar surveys over the past several decades. Yet, despite these searches, none of these searches has uncovered a single regular pulsar.



Where are all the pulsars at the Galactic Centre? In their current paper, CAASTRO Associate Investigator Dr Jean-Pierre Macquart (ICRAR – Curtin University) and colleague A/Prof Nissim Kanekar (National Centre for Radio Astrophysics, Pune / India) argue that the high stellar density in the central parsec around the Galactic Centre is likely to result in a pulsar population dominated by millisecond pulsars (MSPs). Earlier pulsar searches have been largely insensitive to such an MSP population, accounting for the lack of pulsar detections. We estimate the best search frequency for such an MSP population, taking into account new information on the scattering environment towards Sgr A* provided by the recently-detected magnetar near the Galactic

Centre. The optimal search frequency is near 8 GHz for pulsars with periods 1 – 20ms, assuming that the pulsars have a luminosity distribution similar to those in the rest of the Milky Way. We find that 10-30 hour integrations with the Green Bank Telescope or the Very Large Array would be sufficient to detect MSPs at the Galactic Centre.

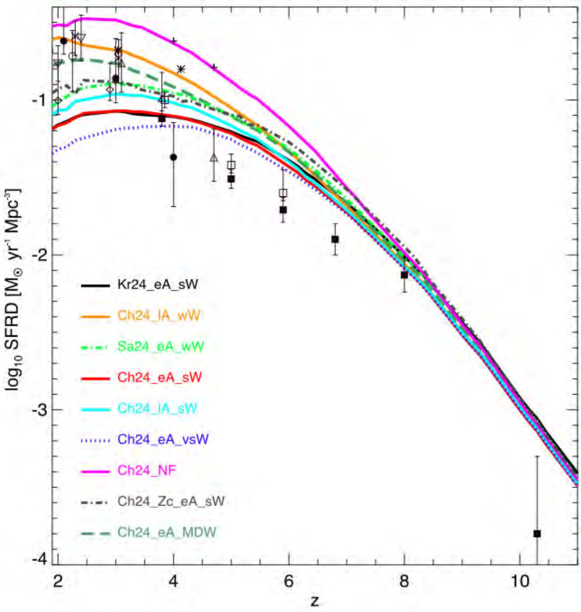
Interestingly, observations of the Galactic Centre at X-ray and GeV energies have, just within the last few months, independently suggested evidence for such an MSP population (Perez et al. 2015, O’Leary et al. 2015).

<u>Publication details:</u>

Jean-Pierre Macquart et al. in the Astrophysical Journal (2015): “*On Detecting Millisecond Pulsars at the Galactic Center*”

Old, gas-rich galaxies likely had early star formation boom

The most massive stars (with masses up to a hundred times the mass of our sun) explode as supernovae at the end of their life and release huge amounts of energy and material into their neighbourhoods. These phenomena are so energetic that they can alter the rate of star formation and impact the chemical composition of galaxies since heavy elements are synthesised in the interior of stars via nuclear fusion reactions. Astronomical observations suggest that many supernova explosions adding up can halt the formation of new stars and expel enriched gas out of galaxies. Indirect observations seem also to suggest that a supermassive black hole resides at the centre of virtually all galaxies. We still do not know how these objects formed but we believe that their masses are greater than 1 million solar masses and the energy emitted by gas falling into them could produce outflows at even higher velocity than the supernova driven outflows (thousands of km/s).



In a recent University of Melbourne led paper, Dr Edoardo Tescari and colleagues present the first results of the CAASTRO supported AustraliaN GADGET-3 early Universe Simulations project, or ANGUS for short. The team ran numerical simulations of the Universe in its early stages (up to 13 billion years ago) to study formation and evolution of galaxies and how they interact with their environment. They focused in particular on the so called “feedback” effects associated with the formation of stars and supermassive black holes at the centre of galaxies.

Including the effects of both, supernovae and supermassive black holes, their simulations tested different configurations of feedback (early/late and weak/strong). The researchers found that efficient feedback at early times is needed to reproduce new observations of the global amount of star formation in the “young” Universe. They propose the following theoretical scenario to explain their results: galaxies that formed 13 billion years ago contained a lot of gas that was quickly converted into many stars. The back-reaction of the star formation processes (i.e. feedback) has since suppressed subsequent star formation especially in low mass galaxies.

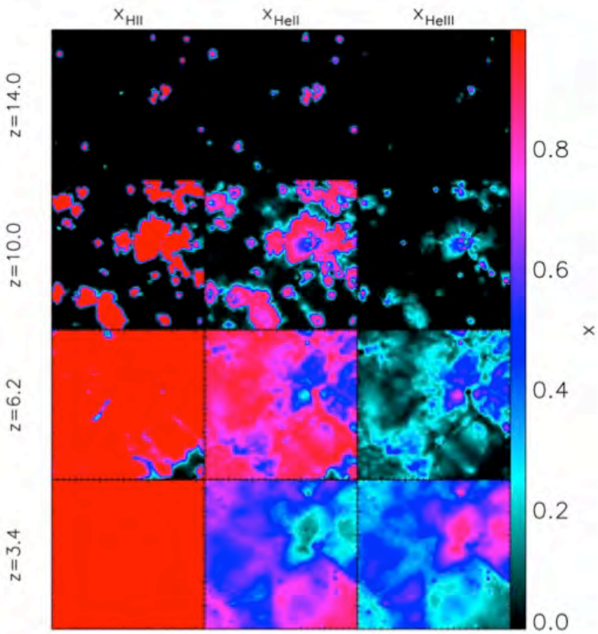
<u>Publication details:</u>

Edoardo Tescari, Antonios Katsianis, Stuart Wyithe et al. in the Monthly Notices of the Royal Astronomical Society (2014): “*Simulated star formation rate functions at z ~ 4 – 7, and the role of feedback in high-z galaxies*”

First estimates of ionised Helium clumping factors

Estimating the Intergalactic Medium (IGM) ionisation level of a region needs proper treatment of the reionisation process for a large representative volume of the Universe. The clumping factor, a parameter which accounts for the effect of recombinations in unresolved, small-scale structures, aids in achieving the required accuracy for the reionisation history even in simulations with low spatial resolution. Helium, along with Hydrogen, plays an important role in determining the temperature and ionisation structure of the IGM during reionisation, yet there exists no estimate of the Helium clumping factors.

Former CAASTRO postdoctoral fellow Dr Akila Jeeson-Daniel at the University of Melbourne, together with international colleagues Dr Benedetta Ciardi (Max Planck Institute for Astrophysics, Garching) and Dr Luca Graziani (INAF Osservatorio Astronomico di Roma, Rome) published a paper estimating the redshift evolution of ionised Hydrogen and Helium clumping factors for the first time. They used a suite of small high resolution CRASH radiative transfer simulations of box sizes 2.2 – 8.8 h^{-1} Mpc (comoving) and grid sizes 32^3 – 128^3 to estimate clumping factors exploring different definitions using IGM density thresholds (gas overdensities < 100), minimum ionisation level thresholds (x_i = 0.1, 0.5, 0.9) and using temperature dependent recombination rates.



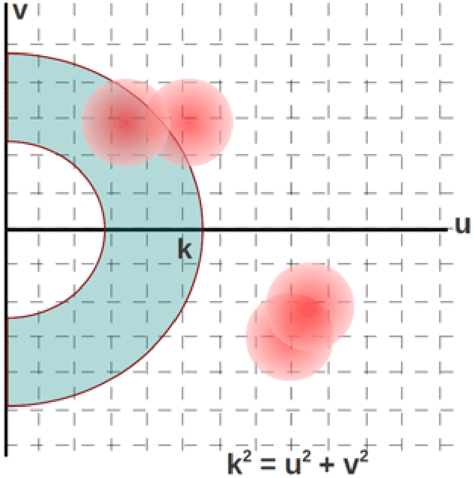
In their simulations, Hydrogen reionisation was completed by $z \sim 6$ while the Helium reionisation process extends to lower redshifts $z \sim 3$. As the ionised gas around sources increases in volume, the clumping factor increases. Clumping factors of HII, HeII and HeIII mostly have values in the range 1.5 – 4, similar to that of the total gas. The clumping factors of HeIII mostly have higher values compared to HeII due to the highly spatially inhomogeneous distribution really close to the ionising sources. HeII clumping factors show much higher values towards low redshifts ($z < 5$) when larger volumes of HeII around sources get converted to HeIII. It was found that the mean dimensionless density of the simulation volume plays a role in the determination of clumping factors. In most cases, clumping factors show a positive correlation with the mean dimensionless density, except for HeII during the later stages of reionisation when it significantly starts converting to HeIII. These estimates of clumping factors would prove very useful to improve the accuracy of future reionisation simulations.

Publication details:

Akila Jeeson-Daniel et al. in the Monthly Notices of the Royal Astronomical Society (2014): “*Clumping factors of HII, HeII and HeIII*”

Drift scans yield lower uncertainty in EoR observations with MWA

The Epoch of Reionisation (EoR) marks a period in the first billion years of the Universe when the first stars, galaxies and black holes produced light and changed the nature of the Intergalactic Medium, the gas between the galaxies. In this period, neutral hydrogen gas between galaxies was ionised by the radiation from these stars, shifting the Universe from a dark and neutral place, to one that more closely resembles the Universe we observe locally. The initial conditions of the Universe, and the evolution of the growth of the first structures, are imprinted in the neutral hydrogen gas, and we can probe the evolution of this early period by measuring emission from hydrogen gas. This can be achieved using low-frequency radio telescopes, such as the Murchison Widefield Array (MWA), which can detect the redshifted emission line from the neutral hydrogen nucleus and trace the gas in exquisite detail. The signal is exceptionally weak compared with the measurement noise of our experiments and contamination by other, substantially brighter, astrophysical sources (e.g. radio galaxies and Galactic emission), making this a challenging experiment to undertake and requiring 1000s of hours of data. At this point, no detection of this signal has been made, but there are many teams and instruments pursuing this goal.



The relative weakness of the signal, relative to other signals and noise, demands a careful analysis of the design of the experiment to maximise information available for science. In her recent paper, CAASTRO Associate Investigator Dr Cathryn Trott (ICRAR – Curtin University) studied the trade-offs for estimation of the high redshift hydrogen signal by observing the sky in different modes. The primary comparison made was “tracked scans”, whereby the instrument concentrates on a small region of sky, and drift scans, where a larger area of sky is measured but with less time per region. These modes yield a different balance of reducing the measurement noise efficiently and of reducing the “sample variance” – an error which reflects that having more measurements of a quantity leads to a more precise measurement. She found that both of these modes produce comparable results, but drift scans showed an added advantage in providing an instrument that is more easily calibrated. This work demonstrated that current and future instruments should consider drift scan modes for performing EoR experiments.

Publication details:

Cathryn Trott in the Publications of the Astronomical Society of Australia (2014): “*Comparison of observing modes for statistical estimation of the 21 cm signal from the Epoch of Reionisation*”

Paving the way to the detection of the global EoR with BIGHORNS

The Epoch of Reionisation (EoR) is the time in the early Universe when the first stars and galaxies formed and re-ionised the neutral hydrogen. Indirect information about the EoR has been obtained from the Cosmic Microwave Background and spectra of distant quasars. However, the pinnacle of information about the physical parameters of the EoR is encoded in the 21cm line (1420 MHz) from neutral hydrogen that got redshifted into the low radio frequency range 200-50 MHz, for redshifts of $6 < z < 30$. Multiple on-going projects ranging from interferometer arrays to single antenna experiments try to identify the elusive faint signal (in the order of milliKelvins) among the bright foregrounds (order of hundreds of Kelvins) and instrumental effects.

A team of CAASTRO researchers at ICRAR – Curtin University, led by Dr Marcin Sokolowski and Dr Randall Wayth, developed a portable, single antenna system called BIGHORNS – Broadband Instrument for Global Hydrogen Reionisation Signal – in order to detect the signature of the EoR in the sky-averaged radio spectrum, the so-called global EoR. For testing, the instrument was deployed in several remote and radio-quiet locations of Western Australia, and low radio frequency interference data were collected. The sky data in conjunction with many hours of laboratory test data allowed the team to develop a data analysis pipeline, to establish calibration procedures and to identify multiple instrumental effects which all resulted in further improvements to the system. Calibration of the signal from a single

antenna down to milliKelvin precision as required for the detection of the global EoR is an extremely challenging task. However, the BIGHORNS team – equipped with valuable expertise and experience, as well as their new conical log spiral antenna, deployed at the CSIRO Murchison Radio-astronomy Observatory – is now hoping to push the boundaries and to get closer to detecting the global EoR signature.

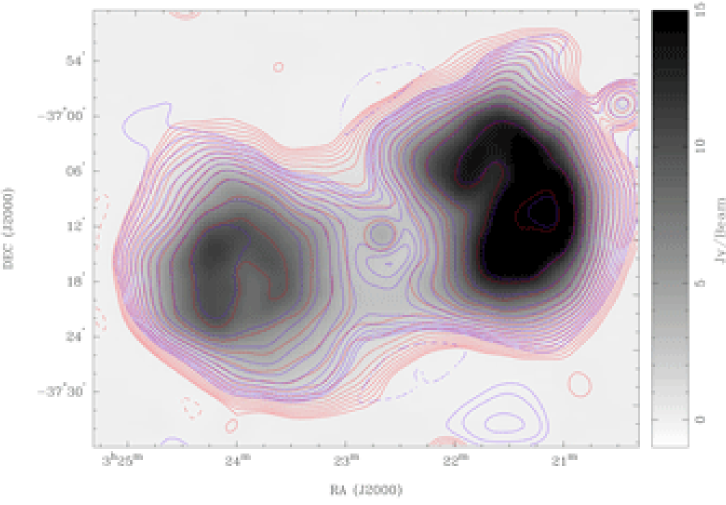
Publication details:

Marcin Sokolowski, Steven Tremblay, Randall Wayth, Steven Tingay et al. in the Publications of the Astronomical Society of Australia (2015): "*BIGHORNS – Broadband Instrument for Global HydrOgen ReioNisation Signal*"

What is producing the gamma-rays from the radio galaxy Fornax A?

Radio galaxies are distant objects that emit tremendous amounts of energy, allowing astronomers – such as CAASTRO postdoctoral fellow Dr Benjamin McKinley (University of Melbourne) and colleagues – to study them across the vast expanses of the Universe. Named so because they are easiest to observe in the radio part of the electromagnetic spectrum, radio galaxies such as Fornax A actually emit across a broad range of wavelengths, from microwaves to X-rays and gamma-rays. By combining data from a number of different astronomical instruments, Dr McKinley and team have studied the spectral properties of Fornax A to try and understand something that is still unknown: what mechanism is producing the high-energy gamma-rays that we observe?

The radio waves that we observe from galaxies such as Fornax A are produced by electrons being accelerated to close to the speed of light and spiralling around in the magnetic field of the galaxy. In a phenomenon that is extremely difficult to observe here on Earth, gamma-rays are generated when these high-speed electrons collide with low-energy background photons. The collisions boost the energy of the photons, producing the gamma-rays that we observe, or so it was thought. However, when you run the numbers, the observations do not match the theory: there just are not enough gamma-rays resulting from this process, known as inverse-Compton scattering, to account for the observed signal.



The researchers investigated an alternative mechanism for the generation of gamma-rays in Fornax A and found that including this new process in their modelling gave a much better fit to the data. They found that most of the gamma-rays are likely the result of collisions between protons, rather than between electrons and photons. The particles produced when protons collide decay into gamma-rays and this process, likely to occur frequently in the relatively thin and dense filaments of Fornax A's radio lobes, can account for the observed high-energy emission.

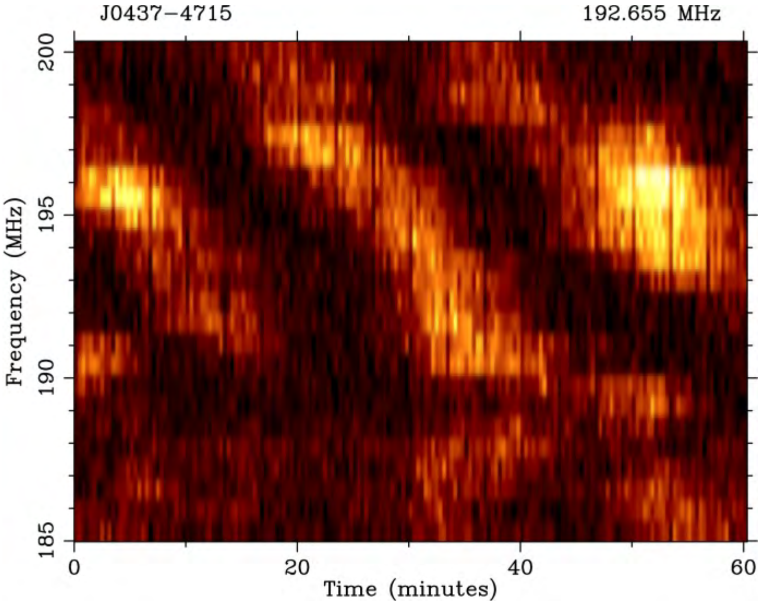
Publication details:

Benjamin McKinley et al. in the Monthly Notices of the Royal Astronomical Society (2014): "*Modelling the Spectral Energy Distribution of Fornax A: Leptonic and Hadronic Production of High Energy Emission in the Radio Lobes*"

Twinkling of the nearest and brightest millisecond pulsar

Originally conceived as an imaging telescope, the Murchison Widefield Array (MWA) has now been equipped with a high time resolution data recorder to enable time domain science applications such as pulsars and fast radio bursts. By taking advantage of this new capability, CAASTRO Associate Investigator Dr Ramesh Bhat led the first pulsar science project with the MWA. The team's observation of the milisecond pulsar J0437-4715 enabled them to study the pulsars's twinkling (i.e. scintillation), leading to new insights into the location of turbulent interstellar plasma that is causing it.

Discovered in 1993 by the 64-metre CSIRO Parkes radio telescope, this nearest and brightest millisecond pulsar spins at an astonishing rate of 174 times per second and is located at a distance of about 500 light years (150 parsec). It is an extremely important object for high-precision timing applications such as pulsar timing array experiments that aim to detect nanoHertz (light-year wavelength) gravitational waves and high-precision pulsar polarimetry and astrometry. The MWA observations enabled the lowest-frequency scintillation studies ever made of this top-ranked timing-array pulsar, revealing the observational signatures that arise from diffractive and refractive scintillation effects caused as pulsar signals travel through the interstellar medium.



A radio analogue of stellar twinkling, interstellar scintillation is a powerful tool that enables us to glean a wealth of information relating to the microstructure of turbulent interstellar plasma. In pulsar observations, it can manifest as rapid and deep modulations of pulse intensity in time and frequency and can be used to determine the location and distribution of interstellar plasma along the pulsar's line of sight. Their analysis suggests much of the plasma that is causing scintillation of the pulsar is located at a distance of ~80 – 120 parsec from the Sun, in stark disagreement with a recent claim that the screen is closer (~10 parsec). Their inferred location also matches well with the predicted distance to the edge of the Local Hot Bubble – a large, tenuous, X-ray emitting cavity that envelopes the Solar neighbourhood, and extends out to ~10 – 50 parsec in the Galactic plane and ~100 – 300 parsec perpendicular to the plane.

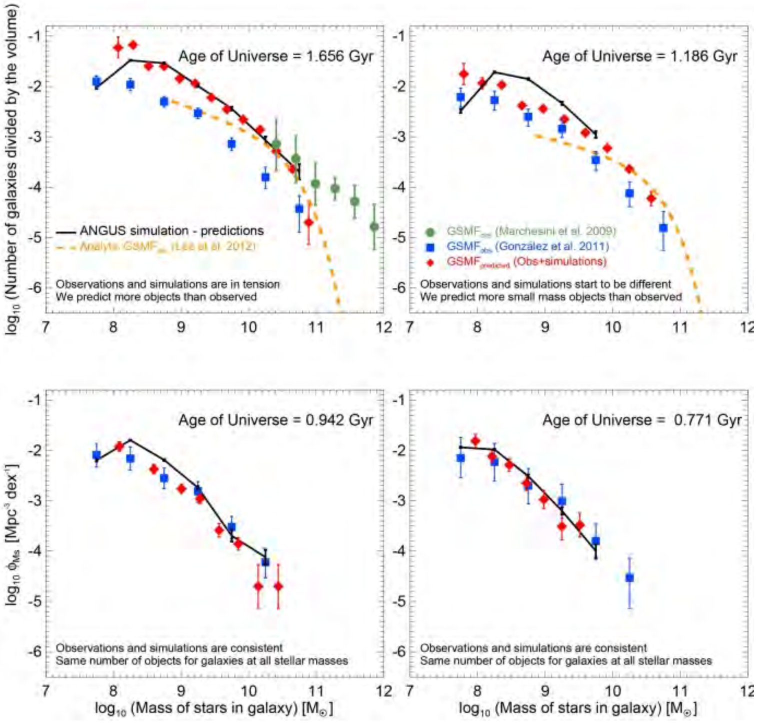
This early science from commissioning observations vividly demonstrates the MWA's potential for pulsar astronomy. A major boost in sensitivity is imminent with the implementation of a tied-array beam mode that coherently combines the tile powers to reach the full array sensitivity. Dr Bhat and his team will then undertake a low-frequency census of pulsars in the southern hemisphere including millisecond pulsars that are part of pulsar timing arrays (PTAs). Routine observations of such pulsars are particularly valuable for tracking interstellar space weather along their lines of sight, offering the potential of increasing the detection sensitivity of PTAs to gravitational waves.

Publication details:

Ramesh Bhat, Stephen Ord, Steven Tremblay, Steven Tingay et al. in the Astrophysical Journal – Letters (2014): "*The low-frequency characteristics of PSR J0437-4715 observed with the Murchison Widefield Array*"

ANGUS sees more faint and small galaxies in the early Universe

The seemingly peaceful night sky can make us forget how wild a place the Cosmos actually is. Supernovae, for instance, are the explosions of massive stars that end their lives violently. They are so energetic that they can affect the fate of their entire host galaxy. They impact on the chemical composition of their environment by expelling heavy elements that had been created inside stars when they were still young and bright. Supernovae hence alter the rate at which new stars form, and sometimes they can suppress star formation and even destroy their host altogether. Worse still, supermassive black holes greater than 1 billion solar masses accrete the surrounding matter in their host galaxy, grow ever larger with time and turn into the most luminous and energetic persistent sources of radiation in the Universe. The fate of the host galaxy changes in their presence.



In a recent work, CAASTRO PhD student Antonios Katsianis and his supervisors Dr Edoardo Tescari and Prof Stuart Wyithe at the University of Melbourne present the second paper of a series which reports on the numerical results of the CAASTRO-supported AustraliaN GADGET-3 early Universe Simulations project, or

ANGUS for short. The team used a set of cosmological simulations that focused on the early stages of the Universe to study the mass of stars inside galaxies and how these can change due to supernova explosions and supermassive black holes. While they found that there was a good agreement between numerical results and observations, they also note that their simulations produced more faint objects than real observations do.

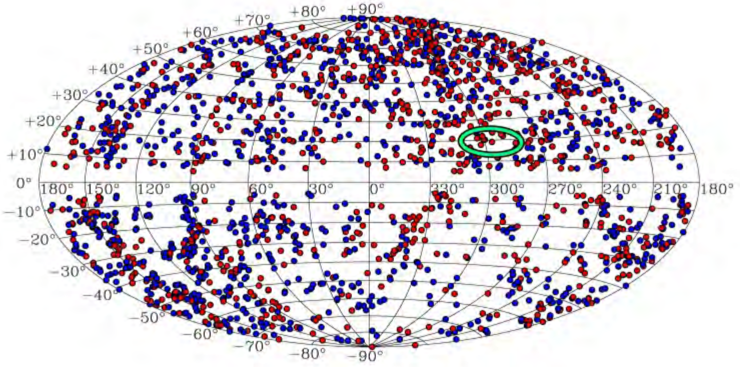
The authors therefore predict that future deep surveys with advanced instrumentation will find a large population of faint galaxies with low stellar masses. In addition, they demonstrated that observations possibly underestimated the masses of the observed objects due to false methodology. Recent observations of the young Universe obtained from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey support the predictions of the ANGUS project and report results consistent with the models presented here.

Publication details:

Antonios Katsianis, Edoardo Tescari, Stuart Wyithe in the Monthly Notices of the Royal Astronomical Society (2015): "*The stellar mass function and star formation rate-stellar mass relation of galaxies at z ~ 4 – 7*"

2MASS Tully-Fisher Survey maps the mass of the local Universe

In the expanding Universe, measurements of a source's redshift refer to its relative velocity away from the observer, known as Hubble's law, and its distance. Those galaxy redshifts that have been found to deviate from Hubble's law are known as "peculiar velocities": they are induced by the gravitational attraction of all surrounding matter. Peculiar velocities thus provide a tool to trace the overall matter density field and detect all gravitating matter, both visible and dark. They can be measured using redshift-independent distance indicators ("standard candles"), including Type Ia Supernovae, the Tully-Fisher relation of spiral galaxies and the Fundamental Plane relation of elliptical galaxies.



The 2MASS Tully-Fisher Survey (2MTF) is an all-sky Tully-Fisher survey aiming to measure the redshift-independent distances of nearby bright spiral galaxies. To provide a uniform sky-coverage, the 2MTF team (including CAASTRO members Dr Tao Hong, Dr Chris Springob and Prof Lister Staveley-Smith at ICRAR – University of Western Australia) used the Green Bank Telescope and the Parkes radio telescope to make new high-accuracy HI 21-cm line observations of galaxies in the Northern and Southern hemisphere, respectively. Combining these data with the ALFALFA survey data and archived HI data, 2MTF provides uniform sky coverage down to low Galactic latitudes of up to 5º.

The bulk flow is the dipole component of the peculiar velocity field which traces the matter over-densities outside the survey region. In past measurements of the bulk flow in the local Universe, astronomers have largely agreed on the direction of the flow, but disagree on its amplitude. Some research showed a large bulk flow velocity which cannot be explained by the standard cosmological model, Lambda

Cold Dark Matter (ΛCDM). Dr Hong and his colleagues measured the bulk flow of the local Universe at three different depths using the 2MTF sample and found that the bulk flow velocity is consistent with the ΛCDM model at the 1σ level.

Publication details:

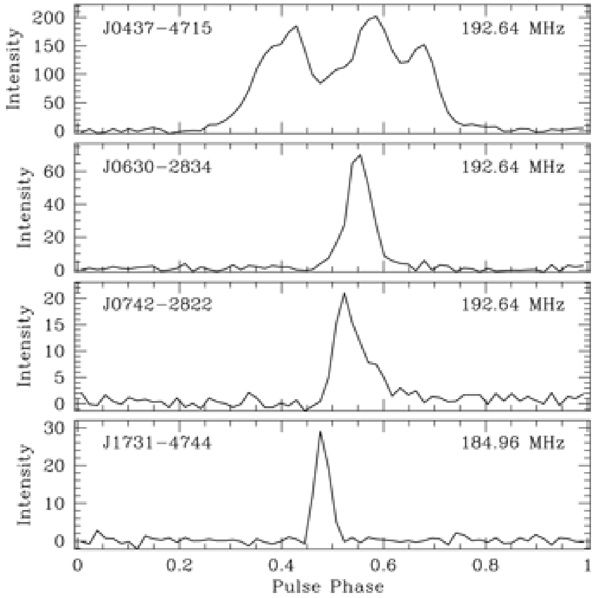
Tao Hong, Lister Staveley-Smith et al. in the Monthly Notices of the Royal Astronomical Society (2013): "*2MTF II. New Parkes 21-cm observations of 303 southern galaxies*"

Tao Hong, Christopher Springob et al. in the Monthly Notices of the Royal Astronomical Society (2014): "*2MTF IV. A bulk flow measurement of the local Universe*"

New capability: high-time resolution recording added to the MWA

Some objects in the Universe happen so quickly that we need our telescopes to work on a high-time resolution (less than one second). Such data let us answer questions within high impact research areas such as pulsar emission and the recently detected, possibly extragalactic, bursts of radio emission called fast radio bursts (FRBs).

The original design of the Murchison Widefield Array (MWA) – the low-frequency precursor instrument to the Square Kilometre Array (SKA) in Western Australia – lacked the ability to access these data since it was devised purely as an imaging radio interferometer. In their recent paper, CAASTRO researchers Dr Steven Tremblay, Dr Stephen Ord, Dr Ramesh Bhat, Prof Steven Tingay, as well as other CAASTRO members, describe how high-time resolution recording capabilities have recently been added to the MWA. Their system can record the 100 microsecond and 10 kHz resolution voltage data from the MWA. The team was able to implement an off-the-shelf solution to add this capability to the MWA's software correlator.



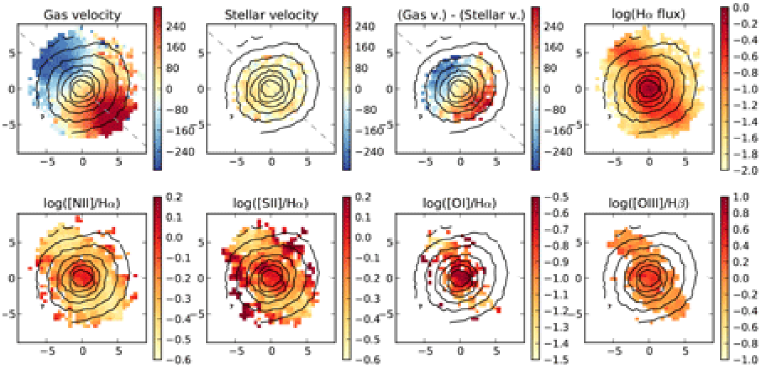
Pulsar observations were critical in the commissioning of this new system. The spin periods of the assorted pulsars, ranging from 5.75 to 3754 milliseconds, were used in the evaluation, as well as other characteristics. Since the signal from each pulsar travels through a different amount of ionised interstellar medium on its journey to Earth, each experiences a different amount of dispersive delay across the observed band. Being able to compensate for this and recover the pulsed signal is another assessment of the system's performance. This new system paves the way forward for southern hemisphere low-frequency high-time resolution radio science.

Publication details:

Steven Tremblay, Stephen Ord, Ramesh Bhat, Steven Tingay et al. in the Publications of the Astronomical Society of Australia (2015): "*The High Time and Frequency Resolution Capabilities of the Murchison Widefield Array*"

SAMI observes shifty black holes as loners, not pairs

After two galaxies merge, their two supermassive black holes will fall to the centre of the merged galaxy, orbit each other in a binary system, and finally coalesce into a single black hole. It has been suggested that galaxies near the end of this process could be spotted thanks to the orbital motions of the black holes. In particular, if one of the black holes is accreting material, and consequently is lit up as an active galactic nucleus (AGN), its orbit with the other black hole means that the light it emits will be slightly blueshifted or redshifted relative to its host galaxy. However, there are other ways this shift can be produced, so more information is needed to know if a shifted, or offset, AGN is in a binary orbit or not.



Two galaxies with offset AGN were recently observed as part of the SAMI Galaxy Survey. The survey obtains spatially resolved spectroscopy for each galaxy, giving a highly detailed picture of the stars and ionised gas. This allowed the SAMI team, led by CAASTRO Affiliate Dr James Allen (University of Sydney), to get a much better understanding of the histories of these galaxies than had previously been possible. Each is an interesting object in its own right, but in both cases the evidence points to other explanations for the offset AGN, not a binary orbit. The first galaxy appears to have undergone a merger with a smaller galaxy, about 100 million years ago. The gas that was brought in by the smaller progenitor has not yet settled down into a stable configuration, but is moving through the galaxy with a very different velocity to the stars, causing the observed shift. In the other case, the AGN is powering an outflow of gas pointed towards us, and the shift is simply due to observing this outflow. The fact that no evidence was found for either of these galaxies containing binary supermassive black hole systems suggests that offset AGN may not, after all, be an efficient way of finding such systems.

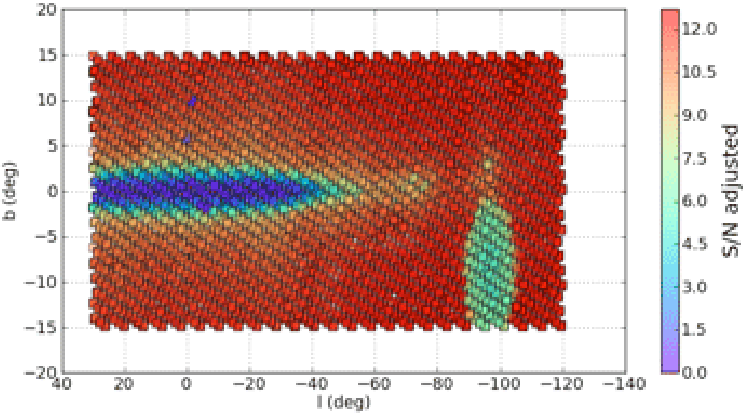
Publication details:

James Allen, Adam Schaefer, Nicholas Scott, Lisa Fogarty et al. in the Monthly Notices of the Royal Astronomical Society (2015): “*The SAMI Galaxy Survey: Unveiling the nature of kinematically offset active galactic nuclei*”

Absence of fast radio bursts at intermediate Galactic latitude

The majority of the enigmatic bright pulses called fast radio bursts (FRBs) have been found at high Galactic latitudes. The bursts are thought to originate in distant Galaxies, and the sparser interstellar medium at high latitudes might make them easier to detect. But the total FRB rate over the entire sky is estimated at 10,000 FRBs per day, meaning that bursts should also be relatively common at lower Galactic latitudes. A CAASTRO team led by Swinburne PhD student Emily Petroff searched for FRBs in a newly completed survey around the Galactic plane: the High Time Resolution Universe (HTRU) survey.

Although four FRBs had been reported from the HTRU survey at high latitudes (Thornton et al. 2013), no FRBs were found in the intermediate latitude survey. The non-detection came as a surprise since the intermediate latitude survey spent double the time on sky of the Thornton study, and between 3 and 10 FRBs were predicted to be discovered in the data. This result provided the first evidence that FRBs are preferentially found at higher latitudes, out of the Galactic plane, a finding that has since been confirmed through analysis of other surveys.



It is still unknown as to what could be causing this anisotropy. A first hypothesis put forward by the authors was that FRBs traveling through the larger amount of ionised material in the Galactic plane might be obscured or scattered out as they travel though the interstellar medium. However, modelling of strong Galactic effects on simulated pulses only showed obscuration for 20% of the total survey pointings, not enough to explain the absence of detections. Even if strong scattering effects were in play the team’s result is inconsistent with an isotropic distribution of FRBs at the 99% confidence level given the current FRB rate.

Ultimately this work makes a Galactic progenitor for FRBs unlikely as a Galactic population would preferentially occur in the plane, not the halo. Only a handful of FRBs are currently published in the literature and more sources are needed to fully understand the true FRB rate and the sky distribution of sources.

Publication details:

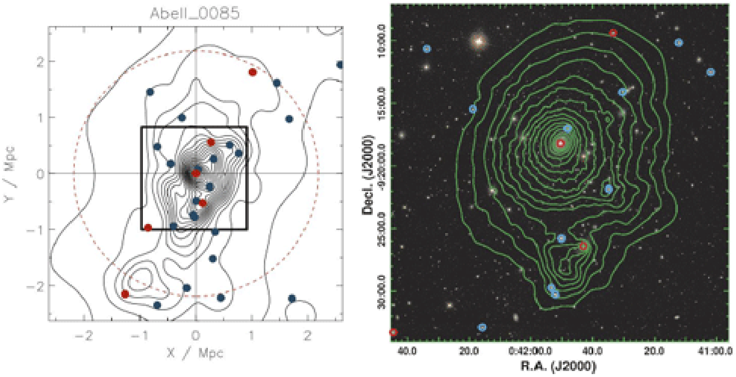
Emily Petroff, Willem van Straten, Simon Johnston, Matthew Bailes, Ewan Barr et al. in the Astrophysical Journal – Letters (2014): "*An absence of fast radio bursts at intermediate galactic latitudes*"

Slow rotating galaxies join clusters late and migrate to centre

Previous surveys have shown that early-type galaxies (ETGs), traditionally thought of as dispersion-dominated systems, show strong rotation in ~80% of cases. This led to a new kinematic classification of ETGs into fast rotators (strong rotation signature; FRs) and slow rotators (no sign of rotation; SRs). Due to their drastically different dynamics, these two families must have very different formation histories.

Earlier, it was also found that SRs are almost absent in the field, with the fraction of SRs in the ETG population increasing only in the densest environment. This is now known as the kinematic morphology-density relation and has been seen in other clusters. However, only four clusters had been examined for this effect until CAASTRO researcher Dr Lisa Fogarty (University of Sydney) and her SAMI Pilot Survey team set out to examine the kinematic morphology-density relation of three further clusters.

The SAMI Pilot Survey observed 106 galaxies in the clusters Abell 85, Abell 168 and Abell 2399. The team extracted stellar kinematics for the 80 ETGs in the sample and classified them as FRs or SRs based on their stellar angular momentum.



For two of those clusters, the researchers observed the expected trend of an increasing fraction of SRs in the densest region of the cluster – the cluster centre. But in one of the clusters (Abell 2399), this was not the case. Also contrary to most other studies, their survey found that neither of the brightest cluster galaxies in this cluster is a slow rotator. In the other two clusters, Abell 85 and Abell 2399, the team saw SRs on the outskirts of the cluster, hinting that these SRs are already fully formed as they fall into the cluster environment for the first time.

The formation mechanism for SRs therefore seems to not only occur in clusters but also in many other environments. Dr Fogarty and her team suggest a mechanism by which SRs first form in groups, then these groups grow to form clusters or join existing galaxy clusters. The SRs could then eventually migrate to the densest parts of the cluster, possibly through dynamical friction.

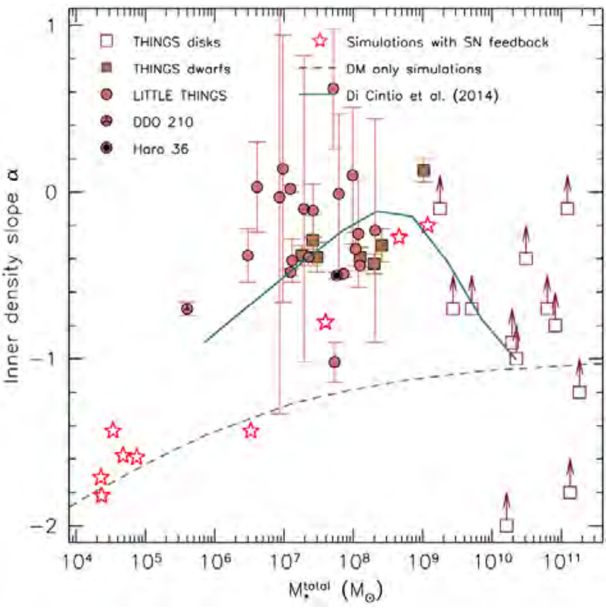
Publication details:

Lisa Fogarty, Nicholas Scott et al. in the Monthly Notices of the Royal Astronomical Society (2014): "*The SAMI Pilot Survey: The Kinematic Morphology-Density Relation in Abell 85, Abell 168 and Abell 2399*"

Dark matter halo of dwarf galaxies shaped by supernova feedback

The Cold Dark Matter (CDM) model has proven very successful, however there exists a long standing problem of ubiquitous “cusps” of dark matter halos, i.e. the dark matter distribution sharply increases to a high value at a central point. Significant improvements in the understanding of detailed physical processes of dark and luminous matter on galactic scales have been achieved by observational data from several galaxy surveys in tandem with advances in cosmological hydrodynamic simulations. These have only been tested in a small number of field galaxies though, owing to the lack of high-quality multi-wavelength data and of standardised analysis tools. In order to provide robust observational constraints to dark matter models, we need to extend the investigation to a larger number of galaxies in a more systematic and consistent manner.

In a new publication, CAASTRO researcher Dr Se-Heon Oh (ICRAR – University of Western Australia) and colleagues present high-resolution (20 – 300 pc) mass models of 26 dwarf galaxies and discuss the dark matter distributions near their centres, as part of the LITTLE THINGS survey. This is a high-resolution (~6" angular; < 2.6 km/s velocity resolution) HI 21cm survey of nearby (< 11 megaparsec) gas-rich dwarf galaxies undertaken with the NRAO Very Large Array (VLA) in the northern sky. In their publication, the team quantified the degree of the central dark matter concentration of the sample galaxies by measuring the logarithmic inner slopes of their dark matter density profiles. The mean value of the inner slopes (-0.32) indicates a mass distribution with a sizeable constant density-core



towards the centres of the galaxies. Comparing these observations with latest Lambda CDM simulations of galaxies where realistic baryonic feedback is included, the dark matter cusps of the halos in both samples can effectively be accounted for by supernova driven gas outflows.

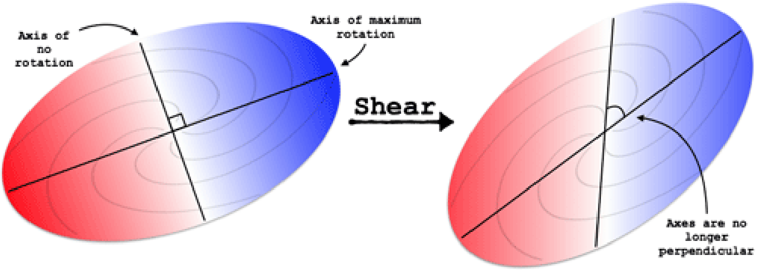
Some LITTLE THINGS sample galaxies, however, such as DDO 210, DDO 101 and Haro 29, have relatively steeper inner density slopes. According to the latest hydrodynamic simulations, SN feedback in low mass dwarf galaxies of less than 106 solar masses is not sufficient to disrupt the central cusps, largely due to low star formation efficiencies in these systems. Dr Oh and his team have submitted a Gemini observing proposal for spectroscopy of DDO 210’s inner dark matter halo density profile where simulations have predicted primordial CDM cusps to have survived. This will be a fundamental test for the presence or absence of a signature of the central cusp in low mass halos, and whatever the outcome, will inform the debate on the formation process of low-mass galaxies in particular, as well as provide a crucial test to the LCDM.

Publication details:

Se-Heon Oh et al. in the Astronomical Journal (2014): “*High-resolution mass models of dwarf galaxies from LITTLE THINGS*”

New trick uses velocity maps to measure weak lensing directly

Despite dark matter dominating the Universe with 84% of the mass compared to 16% of baryonic matter, it is non-interacting and cannot be measured directly. There are techniques to measure the fraction of the two types of matter but weak gravitational lensing is the only tool available to measure the spatial distribution of dark matter relative to its baryonic counterpart in galaxies, clusters and other structures. Understanding the matter distribution in galaxies is vital for constraining our models of cosmology and for forming a complete picture of galaxy formation and evolution. Current weak lensing techniques require hundreds of galaxies for a single weak lensing measurement, they are insensitive to the shape of the dark matter halo and they are useless for analyses that require individual, direct measurements of the weak lensing distortion, called "shear".



Our PhD student Catherine de Burgh-Day and her three CAASTRO co-authors from the University of Melbourne and the Australian Astronomical Observatory (AAO) have now developed a technique to directly measure the shear around galaxies with individual measurements: Direct Shear Mapping (DSM). DSM uses velocity maps to measure shear. A velocity map shows the velocity of each part of a galaxy relative to the motion of the centre of the galaxy (which in the galaxy's frame or reference is stationary). DSM is based on the assumption that a galaxy's velocity map is symmetrical about the axis of no rotation (i.e. the axis about which the galaxy is rotating) and the axis of maximal rotation. The distortions imposed by weak lensing destroy these symmetries. DSM uses a Markov-Chain-Monte-Carlo Maximum-Likelihood method to fit for the shear in the velocity maps of spiral and elliptical galaxies by attempting to restore symmetries. The researchers find that in simulated data DSM can measure shears to with an error of +\-0.01, and have obtained observational data for the first DSM measurement.

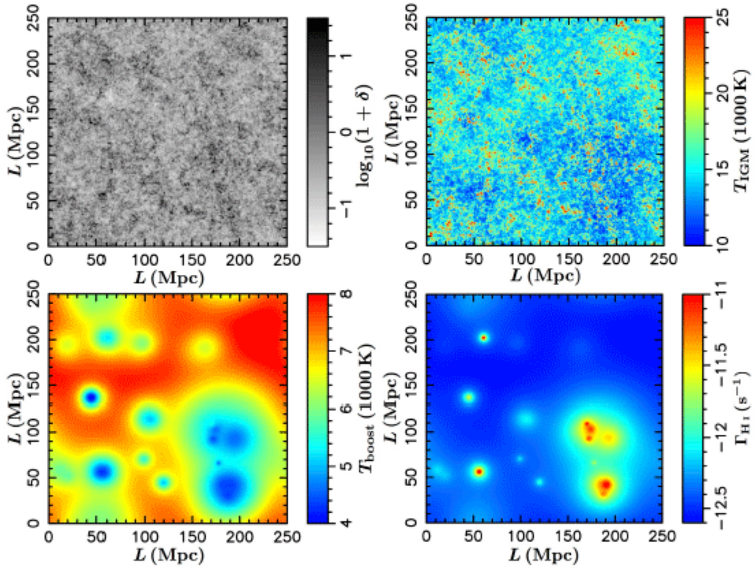
DSM is the first weak lensing technique which measures shear directly. This opens up exciting new possibilities for studying dark matter, with the ability to make direct measurements that are not possible with traditional weak lensing methods. For example, the team is currently working on a sample of simulated DSM measurements in a galaxy population to measure the scatter in the stellar mass-halo mass relation. With multiple DSM measurements around a single galaxy, it will be possible to measure not just the mass of the galaxy’s dark matter halo, but also the shape. This has previously only been possible with stacked weak lensing measurements.

Publication details:

Catherine de Burgh-Day, Edward Taylor, Rachel Webster, Andrew Hopkins in the Monthly Notices of the Royal Astronomical Society (2015): “*Direct Shear Mapping – a new weak lensing tool*”

Impact of IGM temperature fluctuations on large-scale clustering

In 2014, the measurements of the clustering properties from large-scale structures at high redshift by the Baryon Oscillation Spectroscopic Survey (BOSS) solidified our current understanding of the accelerated expansion of the Universe. The wealth and quality of BOSS data further allows for detailed studies of the intergalactic medium (IGM; i.e. diffuse gas between galaxies). By measuring the absorption of light by neutral hydrogen gas in the IGM in the spectra of over 100,000 bright background sources – known as quasars – it is possible to deduce the location and, through detailed modelling, the amount of neutral hydrogen along the line-of-sight. From this, global properties of the IGM, namely its temperature, as well as the intensity of ionising background radiation from star-forming galaxies and quasars, can be calculated. This is an important factor in the evolution of the Universe because helium reionisation at redshift z ~ 3 was driven by radiation from quasars. Due to the sparsity of these sources, along with the energy spectrum of ionising radiation, this process can produce spatial fluctuations in the IGM temperature of more than 10,000 K. These fluctuations impact on the individual absorption properties which could in turn affect the interpretation on these important clustering measurements.



As part of his PhD project at the University of Melbourne, ex-CAASTRO student Dr Bradley Greig (now in Pisa, Italy) and his supervisors used detailed semi-analytical simulations developed to investigate the impact of these temperature fluctuations on the clustering properties. These large-volume simulations employ a simple, physically motivated model for helium reionisation from which the researchers could construct synthetic quasar absorption spectra drawn through the IGM, mimicking observational programmes such as BOSS. This approach had the advantage of efficiently achieving a larger dynamic range than in computationally expensive, fully numerical simulations.

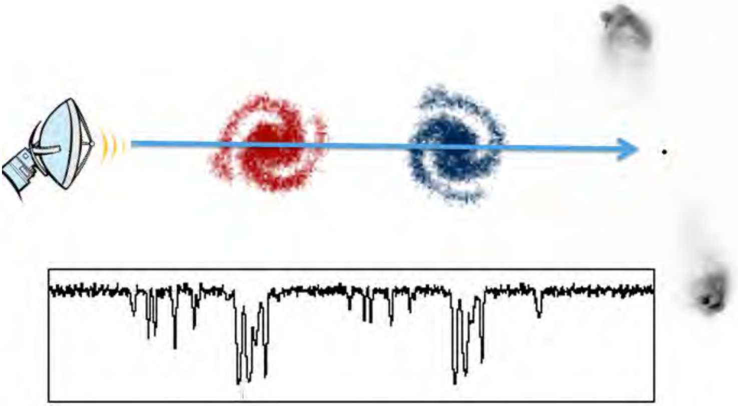
They found that these temperature fluctuations could cause a 20 – 30% increase in the amplitude of the clustering measurements. While this increase does not affect the precision cosmology inferred from clustering, it has important consequences for recovering information regarding the IGM properties. The team concluded that any attempt to infer information on the IGM temperature or strength of the ionising background from the BOSS data must include detailed forward modelling of the IGM temperature fluctuations from helium reionisation and the quasars responsible.

<u>Publication details:</u>

Bradley Greig, James Bolton and Stuart Wyithe in the Monthly Notices of the Royal Astronomical Society (2015): “*The impact of temperature fluctuations on the large-scale clustering of the Ly-alpha forest*”

Cosmic magnetic fields in ancient galaxies surprisingly strong

Magnetic fields influence the physics of exploding stars, galaxies, and even the cosmic large-scale structure. One of the most central questions is how they reached their current strength. It is believed that the amplification of galactic magnets happens through the so-called “dynamo effect”. The simplest version of this theory predicts that magnetic field strengths in galaxies should be continually evolving and should be much weaker in the cosmic past. Observational tests of the dynamo model could therefore hold the key to answering basic questions of fundamental physics during the history of the Universe.



Testing the dynamo model has been a long-standing problem because normal galaxies are very faint and mostly invisible to radio astronomers. CAASTRO Affiliate Dr Jamie Farnes at the University of Sydney (now at Radboud University in the Netherlands) and colleagues, however, used a novel “line-of-sight” technique to put the model to the test. This technique combines optical and radio data from bright quasars in the distant Universe. The optical data from over 35,000 sources served to determine the magnesium absorption lines in the spectra of sources, caused by the light passing through a foreground intervening galaxy. Sources with more magnesium lines, and hence more galaxies along the line-of-sight, should have larger magnetic fields. The radio data from over 25,000 polarised background sources allowed for measuring the magnetic field along the entire line-of-sight with measurements of their spectral index and rotation measure.

For their resulting sample of 599 sources, the researchers found – somewhat unexpectedly – that their flat spectrum sub-sample was correlated to the rotation measure at 1.4GHz. Having eliminated all potentially confounding factors in the data, the team concluded that magnetic fields seem to be the same strength 7 billion years ago as they are today. This result argues strongly that the simplest form of dynamo model cannot be operating, and that more exotic, fast-acting dynamos must be at play throughout the Universe. For example, some dynamo models argue that all the magnetic field amplification occurred early in a galaxy's history, and has now plateaued – in essence these dynamos "lived-fast and died-young". CAASTRO continues to have an involvement in this research with follow-up studies using the Very Large Array in the US.

Publication details:

Jamie Farnes, Shane O'Sullivan et al. in the Astrophysical Journal (2014): "*Faraday Rotation from Magnesium II Absorbers towards Polarized Background Radio Sources*"