Galaxy And Mass Assembly (GAMA)

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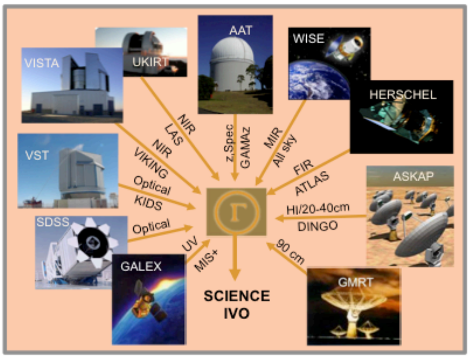

Figure 1: Facilities contributing to the GAMA database.

Abstract

The Galaxy And Mass Assembly (GAMA) redshift survey is the latest, in a long tradition of high-impact spectroscopic surveys, now underway on the 3.9m Anglo-Australian Telescope at Siding Spring Observatory. GAMA is engineered to map extragalactic structures on scales of 1kpc—1Mpc to a redshift of 0.1, and on scales of 10kpc—10Mpc to $z = 0.5$. This covers the size range of galaxy groups, pairs, bulges, bars and discs. The headline science is to conduct a number of tests of the currently favoured hierarchical structure formation paradigm, i.e., cold dark matter (CDM). The tests considered consist of robust measurements of: (1) the Dark Matter Halo Mass Function (as inferred from galaxy group velocity dispersions), (2) the baryonic processes, such as star-formation and galaxy formation efficiency (as derived from Galaxy Stellar Mass Functions), and (3) the evolution of galaxy merger rates over a 5 Gyr timespan (via galaxy close pairs and galaxy system asymmetries). Additionally, this data will form the central part of a new galaxy database, aimed at building a definitive blueprint of the nearby galaxy population and its recent evolution. The final GAMA database aims to contain ∼275,000 galaxies with multiwavelength coverage from coordinated observations with the latest international ground and space based facilities: GALEX, VST, VISTA, WISE, HERSCHEL, GMRT and ASKAP. Together these data will provide increased depth (over 2 magnitudes), doubled spatial resolution ($0.7''$), and significantly extended wavelength coverage (UV through Far-IR to radio) over the main SDSS spectroscopic survey for five ∼48 sq. deg. regions. Such a database will allow for combined studies of the stars, dust, gas and dark matter plus detailed investigations of the structural, chemical, and dynamical properties of all galaxy types, across all environments, and over a 5 billion year timeline.

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Moving towards a model of galaxy formation

Large international surveys, such as the 2-degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001, 2003) and the Sloan Digital Sky Survey (SDSS: York et al. 2000; SDSS DR6: Adelman-McCarthy et al. 2008) have transformed our understanding of large scale structure ($>$ 1Mpc) and have contributed directly towards the emergence of a concordance cosmological model (e.g., Spergel et al. 2003, 2007; Cole et al. 2005): a flat, Dark Energy dominated collisionless cold dark matter model (ΛCDM). It is the most successful hierarchical structure formation model capable of explaining the observed Universe on Mpc (and larger) scales. On smaller sub-Mpc scales (i.e., on the scales of clusters, groups and galaxies) our numerical understanding of the growth of structure is less well-founded and at kpc scales it breaks down almost entirely. It is on these scales (1 kpc – 1 Mpc) that dark matter haloes virialize and merge, and that baryons decouple (from the DM), collapse and eventually form the complex structures we call galaxies. The 1 kpc to 1 Mpc range is therefore *the* key scale over which the baryons and baryon physics become critical to our understanding of the structures we see. The complexity of the physics and the range of scales involved (atomic to cosmological) prevents full numerical modeling and this regime can only currently be investigated by phenomenological modeling guided and informed by direct empirical datasets (e.g., Baugh 2006). Advancements in the empirical datasets are required in two key areas: (a) improved spatial resolution as galaxy sizes, shapes and their structural components (e.g. bulges, bars, discs) are believed to contain a record of their (individual) formation histories; (b) increased wavelength coverage to trace all the galaxies' baryonic constituents (e.g. stars, dust and gas), also crucial to decode their formation history and their potential for continued evolution. GAMA is designed specifically to explore this key 1kpc-1Mpc regime, providing both spatial and full wavelength coverage in as comprehensive a manner as current technology allows.

Probing the cold dark matter paradigm

Although GAMA is envisaged as a generic galaxy survey we adopt a specific set of headline science goals, related to testing

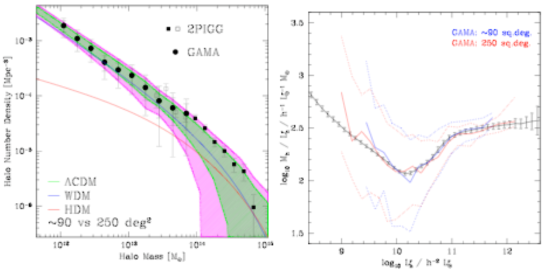

Figure 2: **Left:** The Dark Matter Halo Mass Function (HMF) derived analytically for several Dark Matter particle masses (lines as indicated) along with the prediction from the Millennium Simulation (green shading). Overlaid is the constraint on the HMF from the 2dFGRS 2PIGG catalogue (crosses) and our expected constraint from the final GAMA survey with G^3 (solid symbols). **Right:** Dynamical Mass-to-Light ratio for different galaxy group catalogues: 2PIGG (2dFGRS: Eke et al. 2004), G^3 (GAMA: a projection for the final survey), some predictions of some semi-analytic mock galaxy catalogues. **Both figures to be updated by Peder**

the CDM paradigm, which we use to define the survey parameters. These headline goals are:

1) measure the Dark Matter Halo Mass Function (HMF) and its evolution using galaxy group catalogues probing down to Local Group sized systems.
2) infer the required baryonic processes, i.e. star-formation efficiencies, shaping the Galaxy Stellar Mass Function (GSMF) over the last 5 Gyrs.
3) constrain the galaxy merger rates over 5 Gyrs via the observed number of close pairs and via structurally asymmetric systems.

The first of these tests is addressing a direct prediction of numerical simulations, the second engages with the phenomenological assumptions and the later is the basic mechanism for growth in the CDM paradigm. Below we describe in more detail the basis of these tests after first briefly reviewing the concepts inherent in the CDM paradigm.

Cold dark matter is believed to have formed in the very early history of the Universe (when the median ambient photon energy was >1Gev), to interact only via gravity, and to outweigh normal baryonic material today by a factor of $\sim 5.5 : 1$. Because of its earlier freeze-out time CDM starts to aggregate before the baryonic matter (i.e., prior to matter-radiation decoupling), and more efficiently (due to the lack of internal pressure), thereby embedding an underlying mass structure in the apparently uniform and smooth Cosmic Microwave Background (CMB) — giving rise to the spatial anisotropies detectable by CMB studies such as WMAP. Both the additional Dark Matter mass and the accelerated clustering are vital for producing the large scale structure we see today and, together with the CMB anisotropies (e.g., Spergel et al. 2007), constitutes the key successes of the CDM paradigm (e.g. Baugh et al. 2004). The more latent baryonic material is pulled along by the gravitational forces implied by the collapsing Dark Matter and is rapidly drawn into the Dark Matter cores (dissipating its additional potential energy though collisional radiation and through angular momentum transfer with the emerging Dark Matter halo). When sufficient gas densities are reached star-formation occurs (Kennicutt 1998) to form an observable galaxy (i.e., a self-gravitating Dark Matter halo containing gas and stars). In this scenario galaxies will act as test particles tracing the underlying Dark Matter distribution, like a lighthouse on the rocks. However due to the hierarchical build up of structure in the CDM paradigm the correspondence between galaxies and Dark Matter haloes is not necessarily a direct one-to-one match. Instead one must adopt a halo occupation distribution — a measure of the number of galaxies each Dark Matter halo contains (e.g. Berlind & Weinberg 2002). Typically massive Dark Matter haloes will contain several hundreds of galaxies, in a similar fashion to large galaxy clusters, and low mass haloes one or two bright galaxies with a handful of fainter ones. In both cases the motion of the bound galaxies within the halos are dictated by the DM halo mass: the larger the mass, the greater the motion. It is this motion, predicted by CDM, that we can measure.

Measuring the Halo Mass Function

To achieve our first science objective, measuring the Halo Mass Function, requires surveying and acquiring redshift information for a large contiguous volume and identifying the bound galaxy groups from which the group velocity dispersions can be measured and the Dark Matter halo masses inferred. In Fig. 2 (left) we show (coloured lines) the predicted Halo Mass Function determined analytically for a range of Dark Matter particle masses along with the current constraints from the 2dFGRS survey (2PIGG: Eke et al. 2004; crosses with errorbars). The shaded regions shows the expected range of Halo Mass Functions drawn from the Millennium simulation (Springel et al. 2005) for a random sample of 50 sq deg regions surveyed to a depth of $r_{\rm AB} < 19.4$ mag (pink) and a random sample of 250 sq deg regions surveyed to a depth of $r_{\rm AB} < 19.8$ mag (green). Overlaid are our expected measurements for the mean of these distributions with the larger errorbars corresponding to the smaller shallower survey. The figure demonstrates that not only is the experiment viable but there is also the potential to place some (weak) constraint on the Dark Matter particle mass to complement those derived from QSO absorption lines studies. Glossed over in the above description are a number of important subtleties which include the uncertainty in group membership, the efficiency of group finding algorithms, and the relation between galaxy group velocity dispersion and underlying halo mass. Some of these, in particular the complexity of group finding, are discussed further in Panel B. In practice these issues are dealt with by generating mock catalogues and simulating the observing processes by using the final spatial completeness maps and identical group finding algorithms. The mocks shown in Fig. 2 have been instrumental in defining our required minimum survey area to be 250 sq deg with a required survey depth of $r_{\mathrm{AB,Limit}}$ = 19.8 mag.

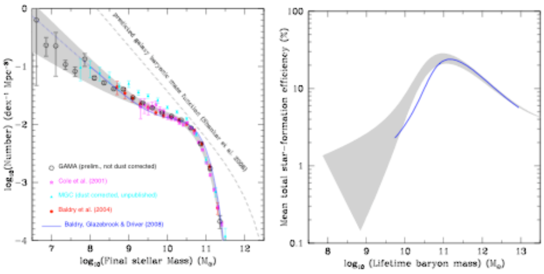

Figure 3: **Left:** The Galaxy Stellar Mass Function (GSMF) from various recent studies (2dFGRS, SDSS and MGC), including preliminary results from the first two years of GAMA observations (open circles). The grey shaded region shows the approximate error range from the current GAMA data. Also shown as a dashed line is the expected galaxy mass function from numerical simulation coupled with a basic halo occupation distribution model. **Right:** The grey shaded region is the star-formation efficiency which is required to match our observed galaxy stellar-mass function with the galaxy mass function. Star-formation efficiency is defined as the ratio of the final stellar mass to the sum of baryonic mass (i.e., the initial baryonic mass plus that accreted through mergers). The blue curve shows a previous estimate based on SDSS data from Baldry, Glazebrook & Driver (2008). The figure demonstrates that star-formation efficiency must drop to $\sim$ 1% in lower mass systems to reconcile observations with CDM theory.

Constraining the baryonic processes

Understanding the physical processes that cause the differences in shape between the Dark Matter Halo Mass Function and the Galaxy Stellar (or Baryonic) Mass functions is one of the key aims of galaxy formation. This fundamental study can be addressed in at least two ways in GAMA: (a) via the appropriate comparison of the galaxy group stellar (or baryonic) mass function and the HMF (as galaxy groups are the equivalents of the predicted DM haloes); (b) by assuming some Halo Occupation Distribution function for the galaxies and by comparing the inferred halo stellar mass function with the HMF. The former will be done with G^3, as shown in the right hand panel of Fig. 2, where for comparison purposes the dynamical mass-to-light ratio is presented (instead of the more physically motivated dynamical mass to baryon mass ratio). As evident from the increasingly large scatter for low luminosity groups, this G^3 based study will be largely limited by the capacity of G^3 to appropriately recover the dynamical mass of smaller galaxy groups with few members. These limitations can be overcome in the second approach by directly measuring the Galaxy Stellar Mass Function. Fig. 3 shows our current measurement of the GSMF using the 90000 redshifts obtained so far. Also shown for comparison are similar results from the SDSS, 2dFGRS and MGC surveys. We can see that in the field environment GAMA is already extending to significantly lower masses than these previous studies although one must be mindful of size and shape completeness biases towards lower stellar mass systems. Shown as a dashed line is the predicted galaxy baryonic mass function (Shankar et al. 2006) which is derived from the numerically predicted Halo Mass Function combined with a Halo Occupation Distribution — to populate each Halo with an appropriate distribution of galaxies. The shaded region and the short dashed line are directly connected through the star-formation efficiency (i.e., the fraction of baryon mass converted to stellar mass) and the resulting star-formation efficiency required to reconcile these distributions is shown in the right panel. At the moment our preliminary results suggest that in low mass haloes, $\sim$1% or less of the combined progenitor baryon mass is converted to stars, i.e. star-formation seems significantly less efficient in lower mass haloes (possibly due to SN heating or acceleration of the baryon-gas out of the halo at reionisation; e.g. Baldry, Glazebrook & Driver 2008). This raises the question as to where and in what form the remaining 99% of the baryons originally associated with low mass systems now resides. In due course we hope to answer this question directly though deep radio observations with the Australian Square Kilometer Array Pathfinder (ASKAP; Johnston et al. 2007) which will map the neutral HI component and its velocity profile out to redshift ~ 0.5. At this stage it is premature to draw too many conclusions, as proper treatments of the halo occupation distribution of galaxies, stellar mass measurement uncertainties, dust attenuation effects, surface brightness selection biases, and mass dependent completenesses have yet to be made. Fig. 3 simply illustrates the processes by which the star-formation efficiency can be effectively constrained and, in due course, it should be possible to determine its dependency not only on mass but on morphology, environment, and redshift. For this science high completeness in the spectroscopic survey is essential coupled with deep multicolour imaging to overcome surface brightness bias, enable reliable stellar mass measurements, and to enable accurate dust attenuation corrections.

Quantifying the merger rates

In our final test of CDM we explore the core mechanism underpinning CDM. Through its hierarchical nature, the CDM paradigm builds massive DM haloes through the merging of smaller ones. As most if not all haloes are expected to contain galaxies, the halo merger rate as predicted by CDM must match, to within some galaxy merging timescale, the evolution of the pair fraction (indicative of pre-mergers; Patton et al. 2002) and the incidence of highly asymmetric systems (indicative of post mergers; Conselice, Rajgor & Myers 2008). The greater the number of pairs and incidences of asymmetry the greater the amount of merging. These effects should scale both with environment and look-back time enabling a relatively sophisticated comparison with the halo merger trees within numerical simulations. However significant wiggle room exists in this test as the dynamical merger and asymmetry timescales for galaxies are poorly constrained by simulations. If timescales are fast then fewer pairs and less asymmetry are seen. Higher-resolution simulations of specific galaxy merger scenarioes (e.g., Khochfar & Burkert 2006) appear to suggest merger timescales and asymmetry timescales are both of the order ∼0.5-2Gyr, and so a significant number of dynamical pairs and highly asymmetric systems should be seen with the GAMA survey (several thousand in each case). Observationally it is therefore imperative that all potential close-pairs are well sampled and high signal-to-noise sub-arcsec imaging data obtained.

Table 1: Coordinates of the five GAMA fields

Field	RA(Deg.)	Dec(Deg.)	Area
G03†	33.75...43.25	$-30.0... - 36.0$	8×6
G09	129.0...141.0	$+3.0... - 1.0$	12×4
G12	174.0...186.0	$+2.0... - 2.0$	12×4
G15	211.5...223.5	$+2.0... - 2.0$	12×4
G23†	340.25...349.75	$-30.0... - 36.0$	8×6

† Time allocation for the southern fields pending.

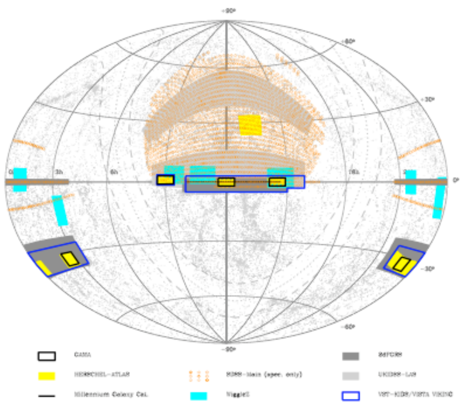

Figure 4: An Aitoff projection of the sky in equatorial coordinates centred at $12h, 0^o$ showing the location of key surveys which are currently in progress or about to commence. The five GAMA regions are shown as black rectangles which overlap a significant portion of the Herschel-Atlas survey (yellow regions).

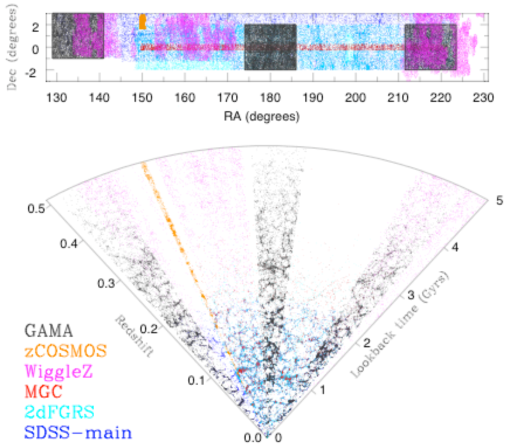

Figure 5: (main panel) A lookback time/redshift cone plot for a 2 deg wedge of sky ($-1^o < \delta < +1^o$) highlighting the current state of the GAMA survey (black data points). Overlain are data from the SDSS (blue), 2dFGRS (cyan), MGC (red), zCOSMOS (orange), and WiggleZ (magenta) surveys for the same chunk of sky (shown in the upper panel. GAMA is the only study which can reveal the evolution of the large structure since $z = 0.5$. Note the zCOSMOS has been relocated to lie within the 2 deg. wedge.

The GAMA spectroscopic survey

To achieve our headline science goals of measuring the Halo Mass Function and the efficiency with which galaxies form in different environments, the GAMA survey will eventually need to cover five ∼48 sq. deg. regions (see Table 1 and Fig. 4), including the on-going three equatorial fields and the two additional southern fields. The present allocation of 66 nights takes the GAMA survey up to the UK's withdrawl from the AAO in mid-2010 and will enable us to reach complete redshift coverage to limiting depths of $r_{AB} < 19.4$ in G09 and G15 and $r_{AB} < 19.8$ mag in G12, and $K_{AB} < 17.5$ over all three equatorial regions. To reach a uniform limiting depth of $r_{AB} < 19.8$ and $K_{AB} < 17.5$ in all five fields requires a further 99 nights.

The five GAMA regions were selected to overlap with the planned VST KIDS and VISTA VIKING ESO Public Surveys (vital for providing robust stellar masses and addressing surface brightness bias) and later adjusted to maximise overlap with the Herschel-ATLAS survey (vital for modeling the dust attenuation). At the heart of the redshift survey is the recently commissioned AAOmega spectrograph system (an upgrade of the original 2dF spectrographs; Sharp et al. 2006) and this is being used to deliver 5Å resolution spectra from 3700Å to 8800Å for all galaxy targets inside the GAMA regions to (eventual) flux limits of $r_{AB,\mathrm{Pet}} < 19.8$, $z_{AB,\mathrm{Model}} < 18.2$ and $K_{AB,\mathrm{Kron}} < 17.5$. GAMA will be ∼2 magnitudes deeper than the main SDSS galaxy redshift survey (York et al. 2000; Adelman-McCarthy et al. 2008) and ∼3 magnitudes deeper than the 6dF Galaxy Survey (6dFGS: Jones et al. 2009). Baldry et al. (2009) presents a complete description of the GAMA input catalogues, which are based on data from SDSS DR6 (Adelman-McCarthy et al. 2008) and UKIDSS-LAS **DR4** (Lawrence et al. 2007).

At these final depths GAMA is fully sampling a source density of ~1150 objects per sq. deg. over a sustained area of 240 sq. deg. which compares to limits of ~140 objects per sq. deg. for the 2dFGRS and ~90 objects per sq. deg. for SDSS. Fig. 5 shows the current redshift cone plot for the three equatorial regions which highlights the comprehensive sampling of the large scale structure out to $z = 0.5$ by GAMA. Also plotted are the current leading-edge wide area shallow surveys (i.e., SDSS, 2dFGRS, MGC), and one of the ongoing pencil beam surveys (i.e., zCOSMOS). This comparison effectively illustrates GAMA's niche embodied by the comprehensive mapping of galaxy structures over a 5 Gyr lookback time. While the shallow surveys cover insufficient depth the pencil beam surveys sample insufficient cross-section to unveil the largest structures at low to intermediate redshifts. At the moment GAMA is the only intermediate redshift survey in this regime. However plans are afoot in North America to extend the SDSS by converting the KPNO Mayall to a dedicated 4m spectroscopic facility (Schlegel et al. 2009) and in China via the LAMOST collaboration (Wang et al. 2009). When the GAMA spectroscopic survey is completed around 2012, the GAMA Team will have acquired ~275k spectra. As of May 2009, the survey is about one third of the way to this final target.

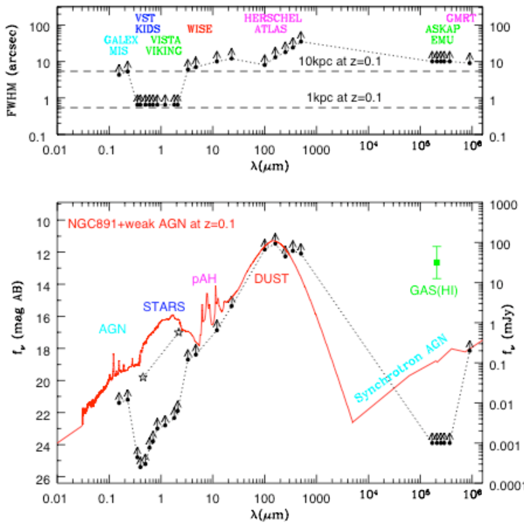

Figure 6: (lower main panel) 5σ point source detection limits and (upper) spatial resolutions for the facilities and surveys contributing to the final GAMA database. Overlaid on the main panel is the model spectrum of NGC891 (Popescu et al. 2000) redshifted to $z = 0.1$ and with a weak AGN added.

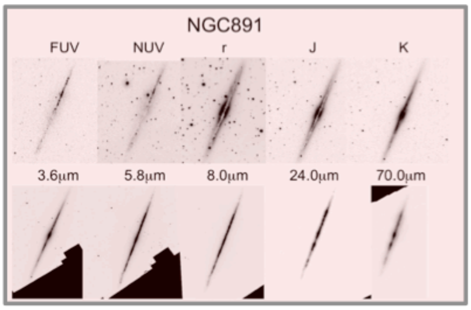

Figure 7: NGC891 as observed in far-UV (FUV), near-UV (NUV), optical (B), near-IR (J, K), Mid-IR (3.6-24.0 μm) and far-IR (70 μm) wavelengths (as indicated). One can see significant variations in the image as one moves from filters sensitive to active star-formation, young stars, old stars, dust and highlight the importance of acquiring multiwavelength data. All data has been downloaded from the NASA Extragalactic Database or provided by the relevant PI.

The broader multiwavelength GAMA survey

Although we have focused on the tests of CDM, GAMA is far more than just a galaxy redshift survey and contains quality spectra, from which detailed line analysis work can be conducted and combined with moderate to deep imaging data from UV through IR to radio wavelengths (see Fig. 6 and Table 2 for information of the sensitivities, resolutions, and timescales of the contributing facilities). Galaxies are complex systems with a life-cycle consisting of collisions, accretion, infalling cooling gas, active-galactic nuclei, star-formation, dynamical and chemical feedback, outflows and tidal interactions. The simplest description of a galaxy involves a significant number of components (nucleus, bulge, bar, disc, halo), and phases of matter (hot gas, cold gas, stars, dust and of course Dark Matter). A galaxy therefore looks significantly different depending upon the wavelength in which it is observed, as evidenced by Fig. 7 which shows NGC891 in multiple GAMA wavelengths. Not surprisingly a single simple model for galaxy formation has not emerged but rather an awareness of strong environmental influences combined with a collection of distinct physical processes which all interweave to shape the particular characteristics of each individual galaxy. Given this complexity we contend that a full picture of galaxy evolution will neither come from a detailed study of a single galaxy nor fine studies of small ad hoc samples. Rather one must first build a comprehensive and well defined database which fully samples the parameter space over which galaxies exist and which is capable of separating out the individual components (bulges, bars, discs etc) and constituents (stars, gas, dust etc).

This is precisely the broader aim of the GAMA team and builds on the notion that in the current era databases are now as important as facilities, as perhaps best exemplified by the Sloan Digital Sky Survey (SDSS; over 2000 papers with over 50000 citations in total; Strauss et al. 2008; Trimble et al. 2008). In fact when complete the GAMA project will be significantly larger in terms of data volume than the entire Sloan Digital Sky Survey (see Table 3 for a direct comparison of GAMA and SDSS survey parameters). However like all facilities the database is only as good as the instruments (in this case software instruments) and the manner in which the data is delivered. The four software instruments currently planned for the GAMA data are shown in **Panel C**.

Table 3: GAMA and SDSS survey parameters

Parameter	GAMA	SDSS
Galaxy redshifts	275k	700k
Sky coverage (sq. deg.)	250	$\sim$8000
Spec. res. (Å)	4.6	3.3
Spec. range (Å)	3700—8800	3900—9100
r limit (mag)	19.8	17.6
M^* z lim.	0.27	0.11
M^* volume (h^{-3}Mpc^3)	6.6×10^6	25.9×10^6
Imaging bands	21	5
Spatial res. ($''$)	0.5	1.5
λ range (μm)	0.15-10^6	0.3-0.9
Data volume	120Tb–1Pb	60 Tb

Engaging with the wider community

At the present time the study of galaxies is fragmented in a number of ways, mainly by wavelength (i.e., X-ray, optical, far-IR, sub-mm, radio) but also between those who study galaxies in exquisite detail (e.g., SINGS, THINGs etc), those who study the coarse statistical properties of the population as a whole (e.g., SDSS, 2dFGRS etc), and those who study specific (distant or rare) sub-samples (e.g., SCUBA sources, E+A, Ly-break dropouts etc). Often these sub-disciplines do not interact as closely as one might like and have evolved apart within their sub-disciplines. The GAMA database has the potential to reverse this trend by providing a comprehensive sample with detailed rather than coarse information, spanning (almost) all wavelengths (UV to radio) and utilising a multitude of advanced analysis techniques (e.g., bulge disc decomposition, spectral line analysis, spectral energy distribution modeling, and direct dynamical measurements). In due course, and with the advent of ALMA, JWST and SKA, the GAMA database has the potential to be extended out in redshift eventually resulting in a comprehensive homogeneous multiwavelength sampling of the entire galaxy population over the full timeline of the Universe. We therefore urge anyone considering a major survey programme to consider conducting their observtions within the GAMA regions.

For the moment the GAMA survey has only just begun with over 90k redshifts obtained in 43 nights of allocated time in the first two years of AAT observations, and with data concurrently being gathered by UKIRT, GALEX and GMRT. VISTA and Herschel observations should commence in the coming year followed by VST, WISE and eventually ASKAP. Assembling this amount of data presents a tremendous logistical challenge, not least of which is the fundamentally different physical origins of the detected radiation (starlight, gas excitation and dust emission). To complete the first stage outlined here will take approximately five years however the team is committed to issuing regular staged releases as and when complete subsets become available. Anyone wishing to become directly involved with the project or to start planning following on programmes is invited to contact the GAMA team via spd3@st-and.ac.uk.

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A Panel A: The UK bids farewell to the Anglo-Australian Observatory

On 1^{st} June 2010 the UK formally withdraws from the Anglo-Australian Observatory (AAO), ending a 43 year partnership between the UK and Australian Governments that led to the construction of the Anglo-Australian Telescope (AAT; first light April 1974), the operation of the UK Schmidt Telescope (UKST; since 1988), and the establishment of a world leading instrumentation group specialising in fibre positioners. Through these facilities, and associated instruments, comprehensive breakthroughs have been made in almost all branches of astronomy (exoplanets to cosmology). One statistic that is worth highlighting, however, is that the AAO is responsible for over $\sim$35% of all known redshifts ($\sim$2.0 million known of which $\sim$700k were measured by AAO facilities). The AAO's share of the redshift market is rapidly growing with the advent of AAOmega and the ongoing WiggleZ (Blake et al. 2007) and GAMA surveys (main article). In fact by the time of the UK's withdrawal the AAO's market share will have risen to over $\sim$40%. Table A lists some of the more recent AAO redshift surveys and the number of redshifts measured. However one slices or dices it the AAO has been a superb investment producing a remarkable science return. In a recent review of worldwide astronomical facilities (Trimble & Ceja 2008) the AAT is listed as the most successful 4m facility worldwide with more than double the citation rate of any other 4m class telescope. In comparison to all optical telescopes (terrestrial or otherwise), the AAT comes in at 5^{th} in terms of both productivity and impact (see Director's Message in the August 2008 AAO Newsletter).

The partnership between the UK and Australian governments began in 1967 following 10 years of heated dialogue (Lovell et al. 1985) with an agreement to start construction of the Anglo-Australian Telescope (AAT). Land was leased from the Mt Stromlo Observatory who already operated a number of telescopes at the Siding Spring site and construction of the AAT was completed in 1974 (Gascoigne, Proust & Robbins 1990). Since that time the AAT has seen a number of instruments come and go and is currently in the progress of building its next generation instrument (HERMES) which will conduct a unique survey of Galactic stars

Table 4: Redshift surveys from the Anglo-Australian Observatory

Survey	Dates	N.Objs
2dFGRS	1996-2001	227k
2QZ	1996-2001	28k
MGC	2002-2006	8k
LRG	2003-2006	16k
2SLAQ	2003-2006	3k
6dFGS	2003-2008	110k
UCD	2002-2006	16k
AUS	2006+	50k
WiggleZ	2007+	140k(200k)
GAMA	2008+	90k(250k)
Total	688k(910k)	

to unveil the sequence by which our home Galaxy assembled itself. In the meantime the WiggleZ and GAMA surveys are set to continue the AAO's world leading role in mapping the cosmos.

B Panel B: From a galaxy distribution to a (DM) Halo Mass

To obtain an estimate of the underlying Dark Matter Halo Mass Function from a galaxy redshift survey requires many critically important steps, as outlined here. Throughout the process, inherent assumptions will be necessary or model parameters determined, with each of them having to be tested on realistic mock galaxy catalogues to show that the method considered remains unbiased.

Our starting point is the GAMA galaxy distribution itself. Each galaxy comes with basic spatial properties (e.g., position on the sky (α,δ) and "distance" away from us or redshift, z) and some intrinsic properties, e.g., flux (r_{AB}, K_{AB}, ...). By appropriately selecting a galaxy sample for which the survey selection function can be characterized with high accuracy and good fidelity, the first part consists of converting the observed galaxy distribution into a collection of galaxy groups. The fundamental motivation is due to our theoretical assumption from the CDM paradigm that all galaxies reside in Dark Matter haloes and each galaxy group is uniquely identifiable with its own Dark Matter halo.

There is a vast amount of literature about finding groups from a discrete distribution of objects, with each leading to slightly different solutions. To test CDM it is therefore vital that we subject the real and mock data to the same group finding algorithm. In numerical simulations, dark matter haloes are most commonly defined using a standard friends-of-friends (FoF) algorithm, with one free parameter: the linking length b, whose value is usually $\sim$20% of the mean (Dark Matter) particle separation. Once the Dark Matter haloes are defined, all galaxies within them are defined as being bound to that halo.

At the heart of the problem lie two fundamental differences between Dark Matter haloes and galaxy groups: (a) the former can be roughly described as a continuous field, while the galaxies form a clearly discrete distribution, even if surveys like GAMA now provide a galaxy mean number density at least three times that of earlier surveys at similar redshifts; (b) the Dark Matter density field is accurately known in 3-D, while the galaxy density field is only precisely known in 2-D (i.e. in projection on the sky), with the third dimension being "measured" to several Mpc/h only, at least 5 times the average group size. These two issues are highlighted in Fig. 9, and it becomes clear from such a picture that the process one has to perform to go from a galaxy distribution in redshift space to a dark matter halo distribution are far from trivial and require several levels of tuning.

Once a galaxy group catalogue has been constructed, the dynamical mass estimate is straightforward and obtained by using some velocity dispersion estimator on the group members and some adopted scaling relation between velocity dispersion and halo mass. Like the fine tuning of the group catalogue, the relations between galaxy group velocity dispersion and dynamical mass are calibrated from realistic mock galaxy catalogues, for which we know both quantities.

C Panel C: The GAMA database

Currently we envisage that the broader GAMA data will be processed by four distinct pipelines which are briefly, consist of:

- **Structural analysis pipeline** — Based on GALFIT3 (Peng et al. 2002) all galaxies with $z < 0.1$ will be spatially modeled in 2D to determine the intensity and shape parameters of any central nucleus, pressure supported bulge, pseudo-bulge, bar, inner disk and outer (truncated) disc components in all optical/near-IR filters. For those systems with $z > 0.1$ a single elliptical-Sérsic profile will be measured (Graham & Driver 2005) sufficient for separating concentrated and diffuse systems and measuring ellipticity/inclinations. Central super massive black hole masses can then be predicted from both the bulge Sérsic index and bulge luminosity in optical and near-IR wavebands (e.g., Vika et al. 2009). In addition concentration, asymmetry, and smoothness (Conselice 2003) along with Gini coefficient and M20 measurements to enable classification by the ZEST+ code developed by the zCOSMOS team.
- **Spectral analysis pipeline** — All spectra will be flux calibrated using inhouse software and then processed by a modified version of GANDALF (Sarzi et al. 2006; Schawinski et al. 2007) to isolate the absorption and emission components. Measurements of the emission line equivalent widths will provide information on the ionisation state of the gas, and hence star-formation rate, AGN activity, gas metallicites and kinematics. Measurements of the absorption line indices provide information on the stellar population properties and hence star-formation histories, ages, metallicites, element abundances and velocity dispersion. See Fig. 10 for target lines.

- **Spectral energy modeling pipeline** — For those systems with detections in the far-IR the total Spectral Energy Distribution (SED) from UV to far-IR will be used to derive the intrinsic distributions of stellar emissivity and dust on an object-by-object basis using self-consistent SED model of Popescu et al. (2000). The model incorporates three distinct components (thin dust disk, thick dust disc and a clumpy component). This will provide measurements of dust opacity, temperature, mass, SFR and SFH. For those systems without far-IR coverage, corrections for the optical light can be estimated using statistical methods calibrated on the far-IR sample, taking into account similar morphology and environment.
- **Mass measurement pipeline** — Based initially on velocity dispersion measurements from GANDALF combined with effective radius measurements, and later on HI rotation measurement (via ASKAP), dynamical mass estimates will be determined along with stellar, HI, and baryonic mass measurements. SMBH and dust masses will be provided by the structural and SED pipelines.

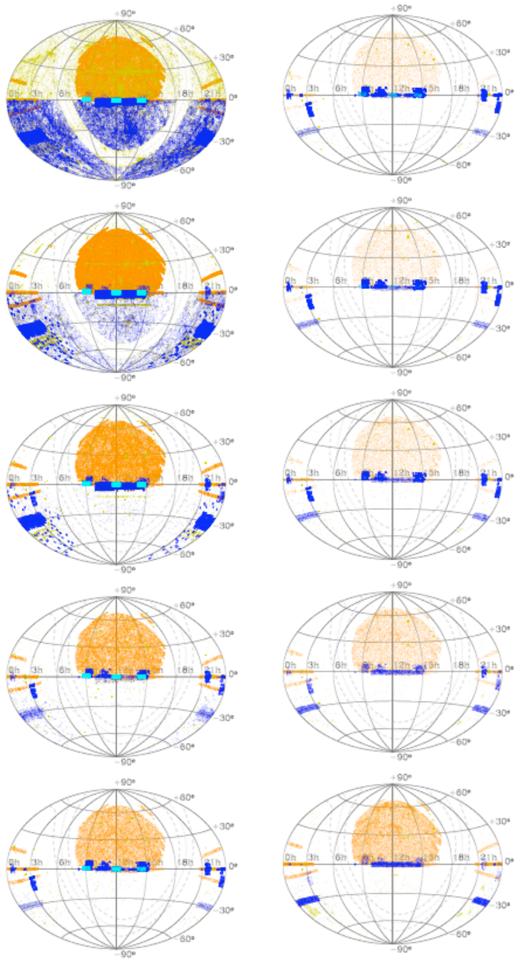

Figure 8: The distribution of all known redshifts on the sky (i.e., galaxies & QSO) in intervals of 1Gyr in lookback time from top left (0−1Gyr, $0.0 < z < 0.077$) to bottom right (8−9Gyr; $1.07 < z < 1.38$). Data obtained by: the Anglo-Australian Observatory (blue; 2dfGRS, TQZ, 6dfGS, MGC, 2SLAQ) except for GAMA (cyan); the Sloan Digital Sky Collaboration (orange); and other sources (gold; CfA ZCAT, ESP, LCRS, zCOSMOS, VVDS, DEEP2).

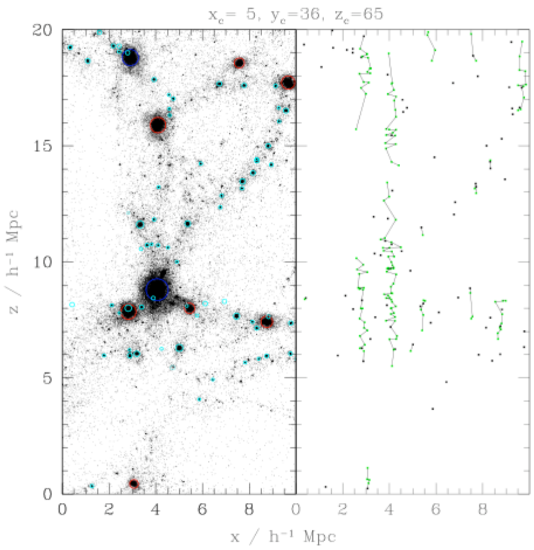

Figure 9: **Left panel** a 4Mpc thick slices through the Millennium Simulation showing the dark matter particles and bound groups. The group mass range is indicated by the colour circles (magenta, $> 10^{14}\mathrm{M}_{\odot}$; blue, $10^{13}\mathrm{M}_{\odot} - 10^{14}\mathrm{M}_{\odot}$; red, $10^{13}\mathrm{M}_{\odot} - 10^{14}\mathrm{M}_{\odot}$; cyan, $< 10^{12}\mathrm{M}_{\odot}$). **Right panel** the same volume as left but showing the galaxy distribution in redshift space (i.e., with the additional velocity components due to the group velocity dispersion added). Dominant group galaxies are shown in black and other group members in green and connected with lines. The figure illustrates the complexity involved in recovering the group associations and masses from the galaxy distribution observed in redshift space. NB: These plots have adopted a Halo Occupation Distribution which matches the 2dFGRS luminosity dependent galaxy clustering.

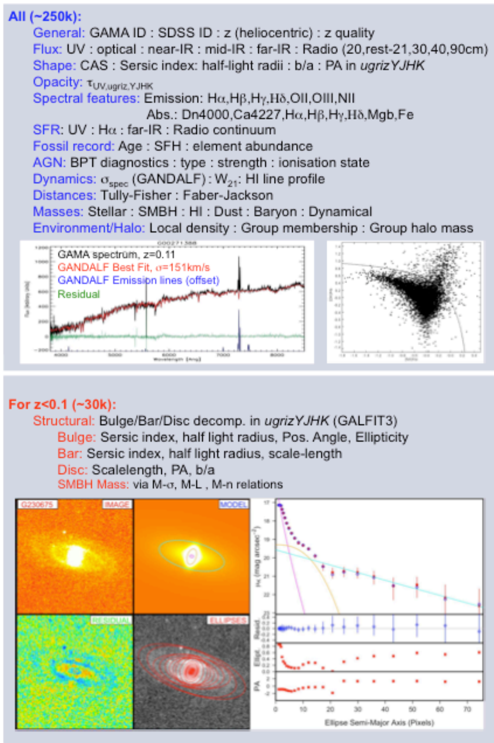

Figure 10: An overview of the information which will be extracted for GAMA galaxies. The upper panel shows the spectral information which we will extract for the entire dataset while the lower panel shows the structural information we will extract from the $z < 0.1$ data. The galaxy shown in the lower panel is representative of the final data quality for a luminous spiral galaxy at $z = 0.05$ where the bulge, bar and disc can be readily separated.

Table 2: Facilities contributing to the GAMA database, all time is guaranteed unless otherwise indicated.

Survey	PI	Wavelength	Time on GAMA	Obs. Period
AAT-GAMAz	S.Driver	Optical Spectra	66+99† nights	2008—2012
UKIRT-LAS	S.Warren	Near-IR imaging	28 nights	2008-2009
VISTA-VIKING	W.Sutherland	Near-IR imaging	60 nights	2009-2010
HERSCHEL-ATLAS	S.Eales	Far-IR imaging	150 hours	2009-2010
GALEX-GAMA/MIS	R.Tuffs/C.Popescu	UV Imaging	50 hours	2009
WISE-All Sky	E.Wright	Mid-IR imaging	100 hours (public)	2009-2010
GMRT-HATLAS	M.Jarvis	Radio continuum	110 hours	2009-2010
VST-KIDS	K.Kuijken	Optical Imaging	96 nights	2009-2010
ASKAP-DINGO/EMU	M.Meyer/R.Norris	Radio Line/Continuum	1 year (pending)	2012+
All				2012-2015

† Requires time allocation beyond mid-2010.