GALAXY AND MASS ASSEMBLY (GAMA)

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Introduction

The GAMA survey (Driver et al. 2008) commenced on 1 March 2008 using AAOmega to obtain 50k new galaxy redshifts and spectra over 21 clear nights, out of the 22 awarded. GAMA is the latest Large Observing Programme, which was allocated an initial 66 nights by AATAC over a three year period. This takes GAMA up to the point at which the UK involvement in the AAT finally stops. In a sentence, GAMA is a study of structures on kpc to Mpc scales and builds on the long-standing Anglo-Australian tradition of world class galaxy redshift surveys (APM, Autofib, LDSS, 2dFGRS, MGC, 6dFGS), but with an additional twist: GAMA is not a single facility programme but draws data from several telescopes and satellites (see Fig. 1) to produce a truly unique large area multi-wavelength survey. Substantial time has now been allocated for GAMA area follow-up on the VLT Survey Telescope (VST), the Visible and Infrared Survey Telescope (VISTA), the UK Infrared Telescope (UKIRT), and ESA's Herschel Space Telescope (Herschel). The GAMA Team also leads a pending time request for the NASA Galaxy Explorer Space Telescope (GALEX), and discussions are underway to adopt one or more of the GAMA regions for the Australian Square Kilometre Array Pathfinder (ASKAP) deep field(s).

A major GAMA contribution to the astronomical community will be the delivery of an International Virtual Observatory compliant database of ~250k galaxies at low redshift ($z < 0.5$) over ~250 deg^2 with medium-resolution (3–7 Ang) optical spectra, and UV, optical, near-IR, far-IR imaging, and with complementary line widths and continuum measurements at radio wavelengths. The basic rationale is that after nearly 80 years of galaxy studies we have not yet formed a clear picture of galaxy formation but recognize that galaxies are highly complex non-linear systems involving both distinct but interlinked components (nucleus, bulge, bar, disc etc.) and constituents (stars, dust, hot and cold gas) with strong environmental and mass dependencies. To create a plausible blueprint of the galaxy evolution process requires the construction of a comprehensive database (in terms of statistical size and wavelength coverage), which contains measurements of all of these facets, i.e. bulge-disc decompositions; stellar, gas, dust and dynamical masses; and spanning a range of environments and epochs. Fig. 2 shows how the GAMA survey compares in terms of depth and area to other past and ongoing studies. While not as wide as the SDSS nor as deep as the VVDS redshift surveys, it

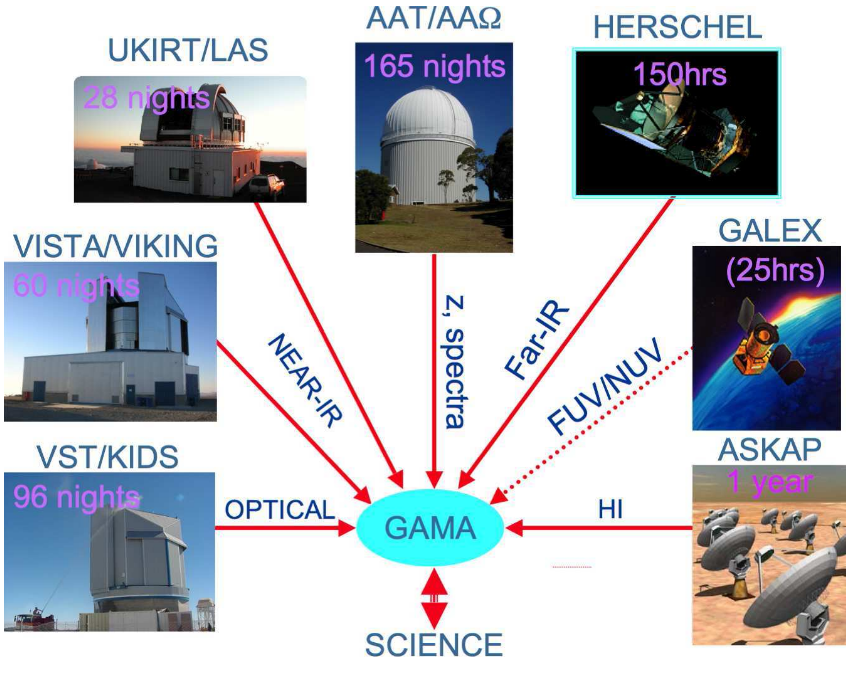

Figure 1: Facilities contributing to the final GAMA database, with approximate number of nights allocated to the GAMA regions indicated. All data flows shown with a solid line are guaranteed while those pending approval are shown with a dashed line. All UKIRT observations are now complete and undergoing analysis.

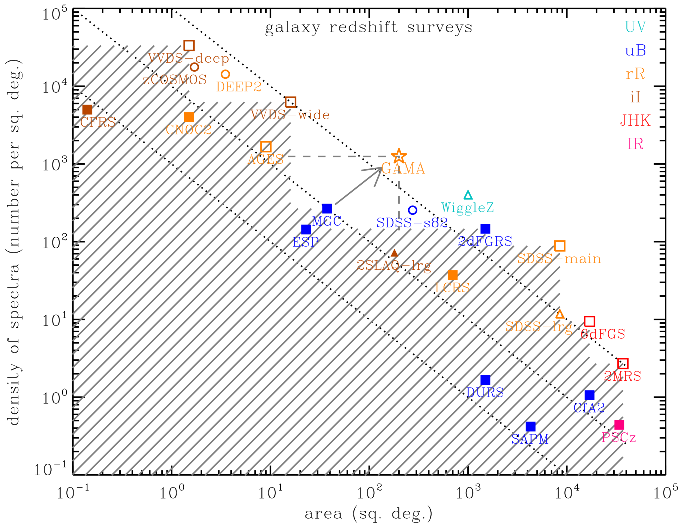

Figure 2: A comparison of past and ongoing major surveys indicating the tendency towards either very deep and very narrow surveys (e.g. VVDS) or very wide and very shallow surveys (e.g. SDSS). GAMA fills not so much a niche as a yawning chasm, and the AAT is the only facility worldwide currently capable of surveying this region of parameter space.

precisely fills the niche between the well sampled wide/shallow and narrow/deep domains. However, unlike SDSS and VVDS which rely mostly on unresolved global measurements of the stellar flux only, the GAMA focus is very much on resolved structural studies provided by e.g. bulge-disc decompositions, and on multi-wavelength coverage (UV through radio), enabling a coupled study of the stars, dust and gas. Fig. 3 shows the anticipated resolution (upper panel) and 5σ-point source detection (lower panel) limits for the final database. Overlaid on this figure is the NGC891 galaxy spectrum shifted to z=0.1 (based on Popescu et al. 2000). This shows that, for dust rich systems at least, GAMA will contain optical/near-IR resolved and fully wavelength sampled data enabling us to realize total SED fitting combined with optical and near-IR structural analysis.

In addition to the provision of a unique dataset for the generic study of galaxies and galaxy formation, the GAMA survey also contains a number of focused science experiments, which are less reliant on the auxiliary data and more directly aimed at providing robust constraints on the currently favoured structure and galaxy formation paradigm. In particular:

1. Measurement of the halo mass function via galaxy group velocity dispersions to directly test the predictions of various dark matter models, like CDM and WDM, down to Local Group masses.

2. Measurement of the dynamic, baryonic, HI and stellar mass functions to LMC masses and their dependence on redshift, environment, galaxy type and component, along with higher order relations, like mass-spin [M-λ].

3. Measurement of the recent merger and star formation rates as a function of galaxy type, mass and environment over a 4 Gyr baseline.

These three experiments are briefly discussed below followed by a summary of the year 1 data obtained in March/April 2008.

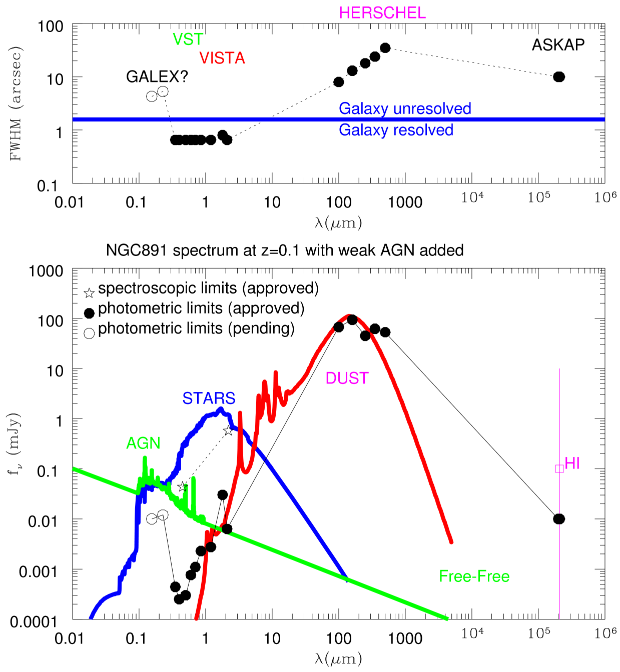

Figure 3: When the final GAMA database is assembled it will survey to the resolution (upper panel) and depths (lower panel) shown. Overlaid is the spectrum for NGC891 with a weak AGN added and shifted to z~0.1. GAMA should be able to simultaneously enable a combined analysis of the AGN, stars, dust and gas for a large fraction of the sample. The deeper objects may not be sampled in the far-IR although effort will be invested in obtaining deeper far-IR observations with Herschel in due course.

Testing the CDM model with the Halo Mass Function

Testing the popular Cold Dark Matter (CDM) paradigm in detail has proved extremely difficult, especially in the regime where baryon physics becomes important. Certainly on large scales (from a few to hundreds of Mpc) the theoretical model is very successful in reproducing the observed galaxy clustering for a wide variety of samples. On the other hand, on smaller sub-Mpc scales, clear evidence for success of the CDM model is much more sparse and certainly at first sight more open for debate: (i) apparent over-prediction of the density of small scale structures (the missing satellite problem); (ii) apparent inability to explain the relatively shallow inner rotation curves of galaxies (core-angular momentum problem); (iii) apparent inability to explain the similarities of fragile thin disc systems (angular momentum distribution problem). That these issues have not formed a knock-out blow for CDM is because there is great uncertainty in how to relate pure dark matter predictions to observations which strongly depend on baryon physics. Therefore it becomes increasingly important to be able to constrain the underlying structure formation model using a method that is only mildly sensitive to details of baryon physics, or ideally, insensitive to them.

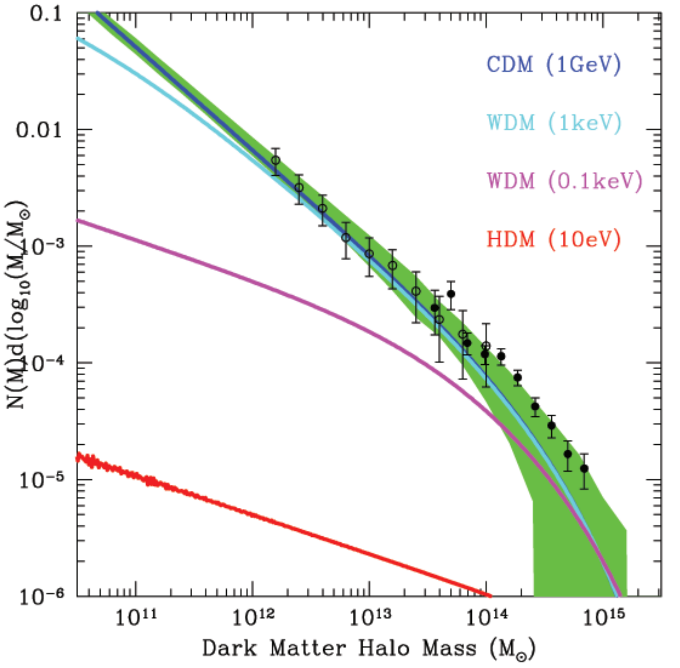

Figure 4: The halo mass function as predicted by Cold Dark Matter (CDM), Warm Dark Matter (WDM) and Hot Dark Matter (HDM). This is a clear-cut numerical prediction which depends only on the (known) CMB initial conditions and the (unknown) dark matter particle mass. The GAMA survey will sample initially the HMF through the measurement of halo masses via galaxy group velocity dispersions and latterly at lower mass limits through dynamical masses obtained directly via HI rotation curves. The open data points shown are a projection based on galaxy group velocity dispersion measurements only, while the solid points correspond to results from 2PIGG (Eke et al. 2006).

In current galaxy formation models, the galaxy velocity dispersion of a virialised cluster or group is believed to be a direct indicator of the dark matter halo mass in which it resides, as the system's dynamical mass is clearly dark matter dominated on those scales. Hence by surveying a sufficiently large volume one should, in principle, be able to empirically construct the halo mass function (HMF) using galaxy group velocity dispersion estimates. The HMF is precisely predicted from any dark matter model with no uncertainty due to baryon physics, so the HMF empirical measurement therefore constitutes a direct test of the underlying structure formation hypothesis. Fig. 4 shows the predicted HMF for three dark matter models (Cold, Warm, and Hot Dark Matter, i.e. CDM, WDM and HDM respectively) along with the current best constraints from the 2dFGRS (2PIGG; Eke et al. 2006), and the expected constraint from GAMA for the final 250 deg^2 survey. The advantage of GAMA over 2PIGG is the ability to probe to lower halo masses (deeper survey with higher spectral resolution), increase the number of detected group members (improved velocity dispersion uncertainty, hence mass determination), as well as overcome the fibre-collision selection bias by sampling each region of sky numerous times. AAOmega is the only facility available worldwide with which such a dataset can be obtained. We note that the data, if combined with ASKAP dynamical mass estimates at the very low mass end, should also be able to convincingly test WDM models and place an upper limit on the dark matter particle mass by extending the HMF to smaller masses than galaxy group based methods can probe.

Mass functions and galaxy feedback

A significant goal of many galaxy surveys, including 2dFGRS and SDSS, is to measure the galaxy luminosity function, primarily because it is considered to be the most basic quantity that characterises the sample as a whole, but also because it provides firm constraints on galaxy formation model predictions. To some extent the focus is now shifting towards constraining the mass functions instead: this is an attempt to empirically bypass some of the difficulties in accurately modelling baryonic physics in simulations.

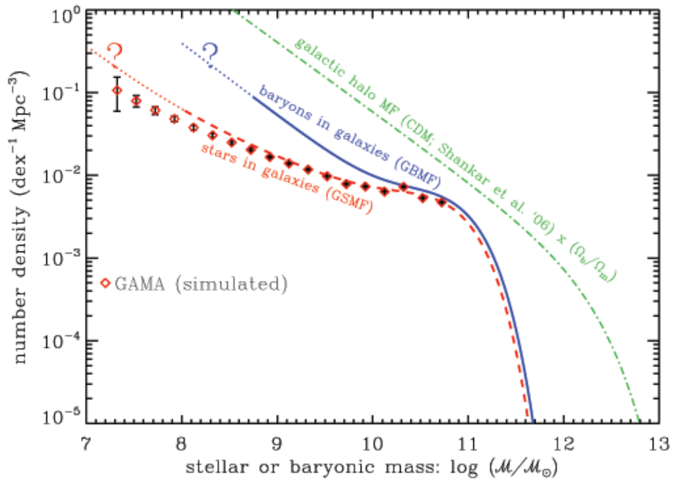

Figure 5: An illustration of three key mass functions: the galactic halo mass function (Shankar et al. 2006), the galaxy baryonic mass function (stars+HI), and the galaxy stellar mass function. GAMA will probe directly the HMF and GSMF, and indirectly the galactic halo mass function and the GBMF, the latter only in combination with ASKAP.

In particular the aim is now to measure the galaxy baryonic mass function (GBMF), and the galaxy stellar mass function (GSMF). These are of course related to the HMF via galaxy feedback, galaxy/star formation efficiency and the galaxy halo occupation distribution. The simplest scenario would be a unit halo occupation and constant dark matter-to-baryon-to-stellar mass ratios, in which case all mass functions exhibit the same shape but are offset only in mass. In reality the situation is much more complex, with mass-dependent halo occupations (i.e. the number of galaxies residing within the same halo depends on the halo mass) and with totally different shapes for the HMF and GSMF: steep low halo mass slope and sharp high mass cut off for the former, while the GSMF is close to flat for low stellar masses and presents an even sharper cut off at high stellar masses. This picture is best resolved if galaxy/star formation efficiency and galaxy feedback are strongly mass-dependent processes, as perhaps evidenced by the well known mass-metallicity relation. It has now been effectively argued into common perspective that high mass haloes are strongly dependent on AGN feedback to truncate their star formation, and low mass haloes are sensitive to SNe blowout, regulating their star formation. Together with appropriate halo occupation statistics, these add the required shape changes to go from the theoretically predicted HMF to the observed GSMF. Fig. 5 shows various mass functions: a galactic halo mass function (GHMF) with groups removed (Shankar et al. 2006), a suggested field GBMF based on a simple stellar-to-baryon conversion (Baldry et al. 2008), and a GSMF using SDSS very-low redshift data (flow corrected).

The relationships between the HMF, GHMF, GBMF and the GSMF curves precisely determine the levels of feedback and baryon retention required. Either these levels are plausible with our stellar and chemical evolution models, in which case CDM lives on, or they are not, in which case the CDM paradigm will require major revision. GAMA will probe directly the HMF and the GSMF, and indirectly the GHMF and the GBMF (with ASKAP). In due course data from VST, VISTA and Herschel will provide robust bulge-disc decompositions and individual dust estimates leading to improved stellar and baryonic mass estimates.

Galaxy assembly

The build-up of both dark matter haloes and the baryonic mass of galaxies through repeated mergers of smaller units is one of the principal modes of growth in CDM based galaxy formation models. For example, De Lucia et al. (2006) predicted that as much as 50% of halo mass has been accreted since z = 0.8. Observationally this process is constrained by measuring the galaxy merger rate and its redshift evolution, and comparing these estimates with theoretical predictions provides a fundamental test of the CDM paradigm. In recent years there have been numerous attempts to measure the galaxy merger rate both locally and at high redshift, yet no clear picture has emerged. Too much, too little and just the right amount of evolution have all been observed.

GAMA will improve on previous low-z studies in several ways: (i) The galaxy merger rate is measured either by finding galaxies in pairs that are close enough (on the sky and in redshift) so that they will merge in the near future, or by identifying recent merger remnants through their asymmetric light distribution. These methods require large scale spectroscopy that is highly complete for close pairs, which is difficult because of fibre placement restrictions, and high-resolution imaging, respectively. Existing large-scale surveys, such as the 2dFGRS and SDSS, essentially fail on both counts. In contrast, the high target density of GAMA will require 5–6 configurations per AAOmega pointing which will entirely eliminate any close pair bias in the spectroscopy. Hence, together with the high-resolution VST and VISTA imaging, GAMA will be ideally suited for studies of the galaxy merger rate; (ii) We expect GAMA to deliver a sample of 10^3 to 10^4 close pairs and merger remnants. Not only will this result in an order of magnitude refinement over previous measurements but it will also

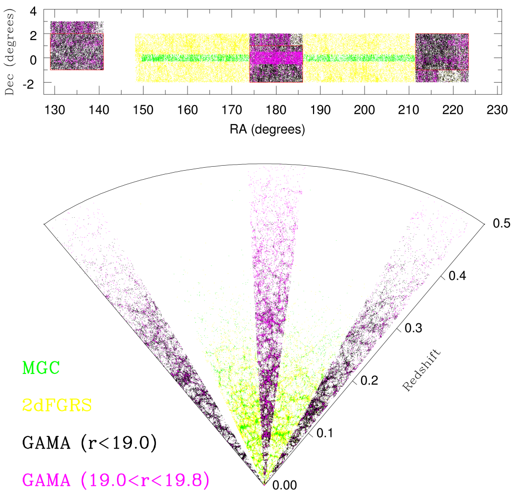

Figure 6: The areas surveyed by GAMA (upper panel) and the cone diagram (lower panel) showing the progression in depth (redshift) over previous AAT/2dF surveys (i.e., 2dFGRS and the MGC). All known redshifts (inc. GAMA) within the GAMA regions are shown as black ($r_{AB} < 19$) or magenta ($19 < r_{AB} < 19.8$) dots. Data for the 2dFGRS and MGC are shown as yellow or green dots respectively.

allow us to split the sample by environment, redshift, galaxy type, and recent evolution; (iii) The dependence of the major merger rate on mass, and the contribution of minor mergers to the growth of galaxies, is observationally unconstrained. The reason is that existing surveys lack the size and dynamic range in luminosity to probe these questions. With GAMA we will be able to measure the merger rate down to a mass ratio of 1:100.

First Light for GAMA-I

The GAMA survey is being conducted in two parts, mainly because of the politics involved in the UK's withdrawal from the AAO, but also to accommodate the tremendous science potential afforded by overlap with the ASKAP deep field (Johnston et al. 2007). The initial allocation of 66 nights (PI: Driver) represents 2/3 of the UK's remaining dark time and will enable us to survey 100k galaxies to limits of r_{AB}=19.4 and to K_{AB}=17 over 150 sq degrees in three distinct and equally sized chunks (necessary to maximise the RA baseline), and to a limit of r_{AB}=19.8 within the central 50 sq degree region. The three regions are all equatorial, 4 deg. wide, and centred at approximately 9h, 12h and 14.5h, as shown in the upper panel of Fig. 6, while the bottom panel shows the corresponding galaxy cone plot for that region of the sky. To complete the GAMA survey goals as specified above we will require a further comparable allocation (~250k galaxies over ~250 sq. degrees within three 12x7 degree regions).

The observing run for GAMA-I started on 1 March with a remarkable sequence of 21 clear and mostly trouble free nights, out of the 22 allocated split over two lunations. The setup used the 385R and 580V gratings with 55–75 min integrations, mostly limited by the AAOmega reconfiguration time. The targets for the input catalogue were derived from SDSS Data Release 6 (DR6), selected by SDSS Petrosian dust corrected r-band magnitude, and filtered to remove objects with fibre magnitudes fainter than r_{AB}=22 and erroneous detections identified by visual inspection. Several hundred objects identified as potentially spurious were visually inspected by up to three observers to ensure the input targets were real and that those eliminated were genuinely unattainable or erroneous. Guide stars and spectroscopic stellar standards (4 per field) were also derived from the SDSS DR6 catalogues.

In order to maximise the accuracy of our velocity dispersion measurements and close pair statistics we prioritised all close pair members, irrespective of their apparent magnitude. In addition, for our year 1 run we also prioritised a deep 1 deg wide strip of fainter ($r_{AB} < 19.8$) objects within the 12h region (G12) to enable early sampling of the completeness function (see Fig. 7), and to enable us to optimise exposures for the year 2 and 3 strategy (as well as to maximise the diversity of year 1 science). Apart from these exceptions the prioritisation was assigned based on magnitude (bright to faint).

In total we targeted 52557 galaxies (50% of the GAMA-I target list) with Petrosian magnitudes ranging from r_{AB} = 14 to 19.8 mag. From these targets we obtained credible redshifts for 97% and medium-to-low S/N spectra for the majority. These new redshifts and spectra complement those already known for this region of sky from the SDSS, 2dFGRS and MGC and results in a combined catalogue of 80k redshifts (see cone plot in bottom panel of Fig. 6). The main panel of Fig. 7 shows the incompleteness as a function of apparent magnitude and apparent surface brightness, showing only a minimal increase towards fainter magnitudes but a stronger bias with surface brightness. While relatively few targets exist at low surface brightness their significance depends on the volume surveyed and some 8m follow-up will be required for these few objects. Overall the performance was significantly better than expected.

One implication of the extraordinarily high redshift yield is that AAOmega is clearly capable of conducting a complete magnitude limited redshift survey to even fainter flux limits with a modest increase in exposure time (e.g. $r_{AB} < 20.5$ mag). This will be taken into consideration, along with any ASKAP design changes, when finalising the bid for GAMA-II. To highlight the potential in combining data from these two facilities we show, in Fig. 8, the GAMA redshift distributions for both the

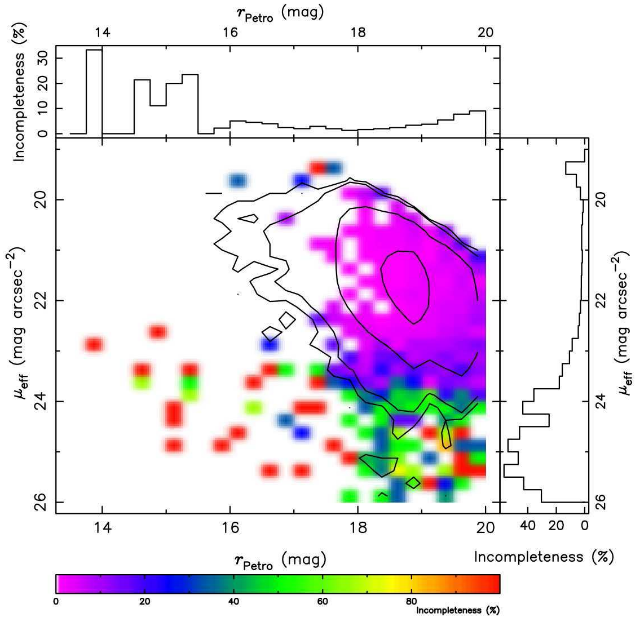

Figure 7: The target density (contours) and incompleteness (colours) of the GAMA year 1 survey in terms of the target Petrosian apparent magnitude and mean effective surface brightness. Contours are in density intervals of 5, 10, 100 and 1000 galaxies. The side panels show the collapsed incompleteness distributions, as a function of effective surface brightness (left) or apparent magnitude (top) only.

shallow (r_{AB}<19) and deep (r_{AB}< 19.8) regions compared to that projected for the ASKAP deep field. Clearly the compatibility in terms of sky area (GAMA chunk = 50 sq deg, ASKAP pointing = 36 sq. deg) and depth (Fig. 8) is striking and should herald an entirely new era in the study of galaxy evolution through the combined investigation of the stars, the gas, and their interplay.

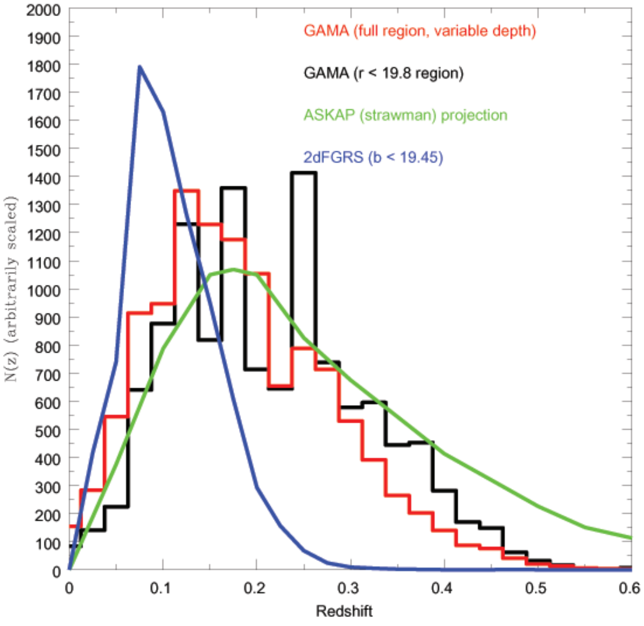

Figure 8: The redshift distribution for both the shallow (r_{AB}<19) and deep (r_{AB}< 19.8) GAMA regions compared to that projected for the ASKAP deep field and the one for the 2dFGRS over that same area. All distributions are arbitrarily rescaled.

Summary

The GAMA project has begun with data flows imminent from a number of international facilities (to be followed by the eventual incorporation of radio continuum and HI data from ASKAP). The survey will allow for a comprehensive study of structure on 1 kpc to 1 Mpc scales as well as the subdivision of the galaxy population into its distinct components (nuclei, bulges, bars and discs) and constituents (stars, gas and dust). Although the headline goals will take some years to complete, it is worth noting that from the year 1 data alone the GAMA Team is currently working on ~15 papers for publication in 2008/9.

Progress and data releases, with first data release forecast for Dec 2009, can be monitored via the GAMA website: http://www.eso.org/~jliske/gama/ and anyone interested in further details or collaborative projects should contact Simon Driver directly at spd3@st-and.ac.uk.

Finally we would like to especially thank all of the staff at the Anglo-Australian Observatory for their professionalism and dedication in bringing about the two-degree field facility, and the AAOmega upgrade, and making it such a leading instrument.

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