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The Wide Area VISTA Extra-galactic Survey (WAVES)

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Abstract The "Wide Area VISTA Extra-galactic Survey" (WAVES) is a 4MOST Consortium Design Reference Survey which will use the VISTA/4MOST facility to spectroscopically survey ~ 2 million galaxies to $r_{\rm AB} < 22$ mag. WAVES consists of two interlocking galaxy surveys ("WAVES-Deep" and "WAVES-Wide"), providing the next two steps beyond the highly successful 1M galaxy Sloan Digital Sky Survey and the 250k Galaxy And Mass Assembly survey. WAVES will enable an unprecedented study of the distribution and evolution of mass, energy, and structures extending from 1-kpc dwarf galaxies in the local void to the morphologies of 200-Mpc filaments at $z \sim 1$. A key aim of both surveys will be to compare comprehensive empirical observations of the spatial properties of galaxies, groups, and filaments, against state-of-the-art numerical simulations to distinguish between various Dark Matter models.

1 Introduction

Since the pioneering days of the 2dFGRS and SDSS, extra-galactic spectroscopic surveys have come in two flavours: those optimised for cosmology, and those opti-

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mised for galaxy evolution. The distinction is important. Cosmology surveys (e.g., WiggleZ, BOSS, DESI) use specific tracers to probe the underlying large scale structure. These surveys advance cosmology but provide a biased cross-section of the galaxy population. Conversely galaxy-evolution studies (e.g., MGC, GAMA, zCOSMOS, DEEP2, MOONS) uniformally sample the full galaxy population, but only cover modest areas. These samples are ideal for studying galaxy evolution and its interplay with environment, but lack the area coverage for cosmological studies. WAVES, in the era of dedicated cosmology experiments, represents the next step in galaxy evolution studies, bridging the gap between the very near ($z < 0.3$; SDSS, GAMA) and the very far ($z > 0.8$; MOONS, HST, JWST), as well as probing the intrinsically faint (low mass) and dim (low surface density) populations within the nearby Universe ($z < 0.2$).

The WAVES target catalogue will be based on the VST KiDS South subarcsecond optical imaging and is intended to complement Euclid, LSST, and the SKA. The key science drivers and initial survey concept design are outlined in the sections which follow. Here we briefly introduce the two WAVES components (Deep and Wide), outline the primary science motivations, and describe the preliminary design concept.

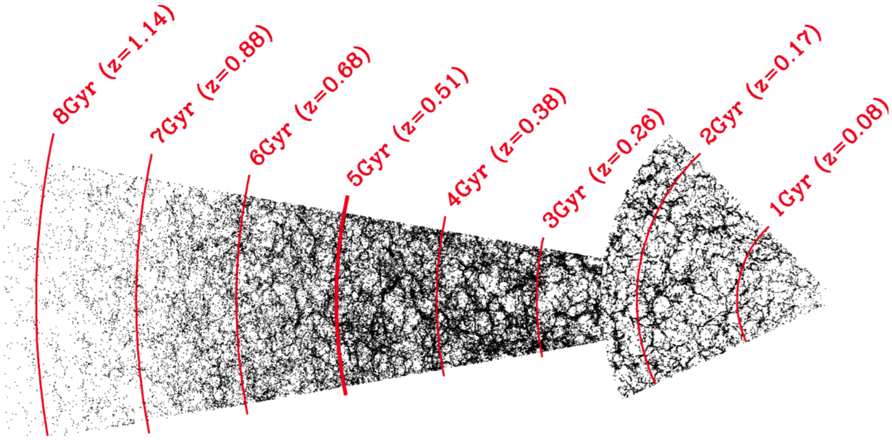

Fig. 1 A representation of the RA geometry of the WAVES survey (derived from the Theoretical Astrophysical Observatory), highlighting the complexity of structures that will be sampled.

WAVES-Deep will cover 100 sq. deg. to $r_{\rm AB} \sim 22$ mag and extend the power of SDSS and GAMA like population statistics out to $z \sim 0.7$, tracing the rarest structures even up to and slightly beyond $z \sim 1$. This ~ 1.2 million galaxy redshifts survey is key in providing the largest and most representative galaxy group and filament catalogue ever constructed.

WAVES-Wide will cover 750 sq. deg. to $r_{\rm AB} \sim 22$ mag with additional photo-z preselection ($z_{\rm photo} < 0.2$). This will target ~ 0.9 million galaxies allowing a detailed study of the occupancy of $\sim 10^{11}$–$10^{14}\mathrm{M}_\odot$ halos to a stellar mass limit of $10^7\mathrm{M}_\odot$, and providing a dwarf galaxy sample over a representative volume of $10^6\,\mathrm{Mpc}^3$.

2 WAVES Science Drivers

2.1 Ensemble of Milky-Way sized systems to test CDM

The nature of dark matter is one of the key questions in modern day cosmology. The currently favoured Cold Dark Matter model, ΛCDM, provides a good description of the large scale structure of the Universe (see Figs. 1 & 2). Comparison of robust model predictions with empirical galaxy clustering measurements on Mpc scales supports the Cold Dark Matter model for the growth of structure (e.g. [31]). On sub-Mpc scale, i.e. on galaxy and group scales, baryons and baryonic physics become critical: the kpc to Mpc range is the key scale over which Dark Matter halos virialize and merge, and baryons decouple, collapse and eventually form complex structures such as galaxies. In this regime, our theoretical understanding is less well-founded, in great part due to the immense complexity of the physics encountered.

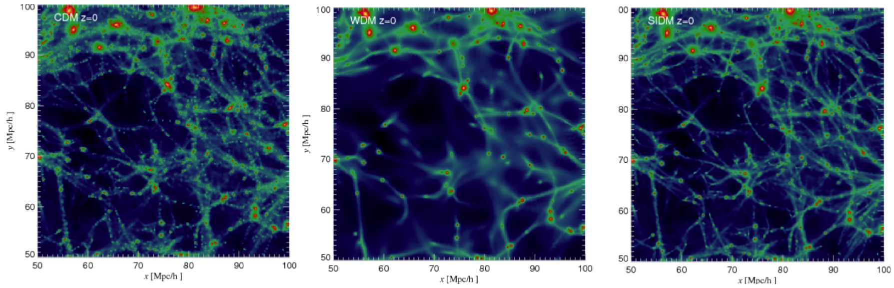

Fig. 2 Numerical simulations of the galaxy distribution at z=0 from (left-to-right) Cold, Warm, and Self-interacting dark matter. The images show the dark matter density within a cube of 50Mpc×50Mpc×5Mpc

Galaxy group samples are now able to probe down to a few $10^{12}\mathrm{M}_\odot$, with arguably the most complete being the "GAMA Galaxy Group Catalogue" ($\mathrm{G}^3\mathrm{C}$; [24]). Properties of low mass galaxy groups are limited by the intrinsic lack of survey depth. This explains why for $10^{12}\mathrm{M}_\odot$ systems ($\mathscr{M}_{h12}$ hereafter), only two really well studied examples exist: the Milky-Way and the Andromeda systems, both in our own neighbourhood. Galaxies in the Local Group are extensively used to probe in detail the Cold Dark Matter paradigm. They are often central to the strongest evidence against the standard Cold Dark Matter model, from "the missing satellite problem" (e.g.[20]) to "the too big too fail problem" (e.g.[6]). via "the co-planar location of satellite galaxies (e.g.[16]). Given that $\mathscr{M}_{h12}$ halos are the most important ones in terms of galaxy formation (with galaxy formation efficiency peaking just around that mass scale in all standard CDM model) and one of the more critical in terms of testing CDM, it is fundamental to ensure that this limited sample of well studied $\mathscr{M}_{h12}$ systems is representative. To create such statistical sample is a central goal of WAVES.

WAVES-Wide, which survey depth results in LMC like galaxies to be close to volume limited out to $z \sim 0.2$, is specifically designed to deliver a high fidelity group catalogue ($\sim$4k groups with 5 or more members) probing to the very lowest halo masses. This sample size should allow the intrinsic scatter in the sub-halo / stellar mass occupation statistics to be measured. WAVES-wide will result in a proper characterisation of $\mathscr{M}_{h12}$ groups, including assessing how representative our two best studied examples are.

2.2 *The low surface brightness and dwarf domains*

The study of the field dwarf galaxy population offers a unique testing ground for galaxy formation and the underlying physics. Cold dark matter (CDM) simulations predict that there are many more low-mass than high-mass halos remaining today ([20]). Observationally there appears to be a deficit with respect to this prediction; the observed galaxy stellar mass function is not as steep as the halo mass function. This could be in part because the mass of the dark matter particle is in the keV range (i.e., WDM), which suppresses power on dwarf galaxy scales ([4]). However, dwarf galaxy formation is also sensitive to the impact of the photo-ionizing background, supernovae feedback, and environmental effects ([2]). Disentangling the baryonic effects from any change in the power spectrum requires large statistically representative samples.

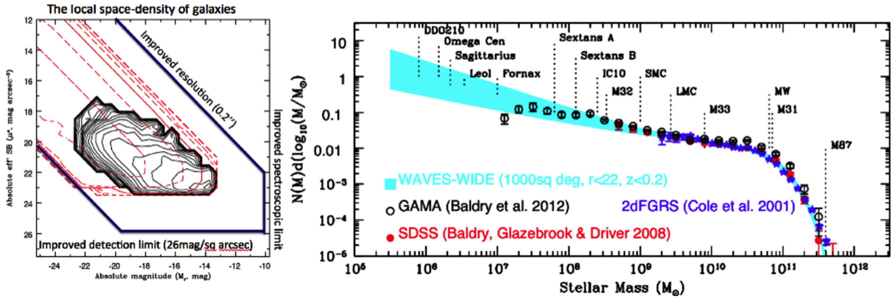

Fig. 3 (left) The space-density of galaxies in the luminosity-surface brightness plane (derived from GAMA). The logarithmic density contours in red show the current robust sampling region bounded by the selection limits of the Sloan Digital Sky Survey. WAVES will extend our census of the nearby galaxy population to the blue boundary due to the superb imaging quality and limiting surface brightness sensitivity of the VST KiDS data. (right) The improvement in the measurement of the stellar mass function possible with WAVES-Wide.

Local surveys such as the SDSS and follow-on campaigns such as GAMA are fundamentally limited by surface brightness sensitivity of the imaging data, and the reality of the luminosity-surface brightness relation ([7],[10]). Various studies including [3, 11, 1] clearly demonstrate that the SDSS becomes incomplete for systems with $\mu_e \geq 23.0$ mags/sq arcsec which become frequent below absolute magnitudes of $M_r = -18$ mag (Fig. 3 left). For this reason the low surface brightness and dwarf galaxy domains continue to remain uncharted territory for modern surveys. Only deep surveys of clusters (highly unrepresentative of the average Universe) have entered this dwarf galaxy low-SB regime. The first deep wide-area imaging survey capable of probing into this domain will be VST KiDS covering 750 sq. deg in the Southern and Northern Galactic Caps. WAVES will use the VST KiDS data as its input survey to provide targets to $r_{\rm AB} < 22$mag with $\mu_e < 26$ mag/sq arcsec allowing for the construction of a complete sample of galaxies to $M_r = -14$mag, i.e., 4mags deeper than SDSS (see the blue boundary in Fig. 3 left). The WAVES survey, $r_{\rm AB} < 22$, with high-completeness for low-SB galaxies would enable the galaxy stellar mass function to be measured accurately down to $10^6 {\rm M}_\odot$ (see Fig. 3 right).

2.3 The evolution of galaxy structure (with Euclid)

Studies of the mass-size relation of galaxies in the nearby ($z < 0.1$) and distant Universe ($z > 1$) show a $\times 5$ growth in galaxy sizes at fixed stellar mass (e.g., [28, 29]) and in number-density (e.g., [15]). This extraordinary result, confirmed by numerous groups (e.g., [5]), implies a dramatic physical change occurring in the galaxy population over the redshift range $0.2 - 1.0$. Possible explanations include dynamical relaxation, major mergers, minor mergers, and disc growth ([13]). However this result is only clearly established for high stellar mass systems (i.e., $> 10^{11} M_\odot$), found in extreme dense cluster environments. Whether this growth is endemic or confined to a specific mass or environment remains unclear. A deep spectroscopic survey with HST resolution imaging over a sustained area is needed to extend the measurements to fainter mass limits and to distinguish between the competing hypotheses. WAVES-Deep in combination with Euclid imaging (see Fig. 4 left), provides exactly the dataset required to study this extraordinary growth.

A key starting point will be to address whether the fundamental nature of galaxies is its bimodality (red v blue), or its evident duality (bulges plus discs). At very low redshift ($z < 0.1$) this issue is clear-cut with multi-component decomposition a routine part of the analysis toolkit. At high redshift ($z > 1.5$) the case is less clear as galaxies no-longer appear to adhere to the simple idea of bulge plus disc systems, but exhibit highly asymmetrical and irregular shapes. As such the language of high-redshift galaxy work is typically focused on turbulence, distortions, and the global colour (red v blue).

To date the largest contiguous survey by HST covers 1.8 sq deg (COSMOS). Euclid will transform this by imaging upto 8000sq degrees of sky at $0.2''$ resolution. Surveying this entire area spectroscopically is unrealistic, however WAVES-Deep

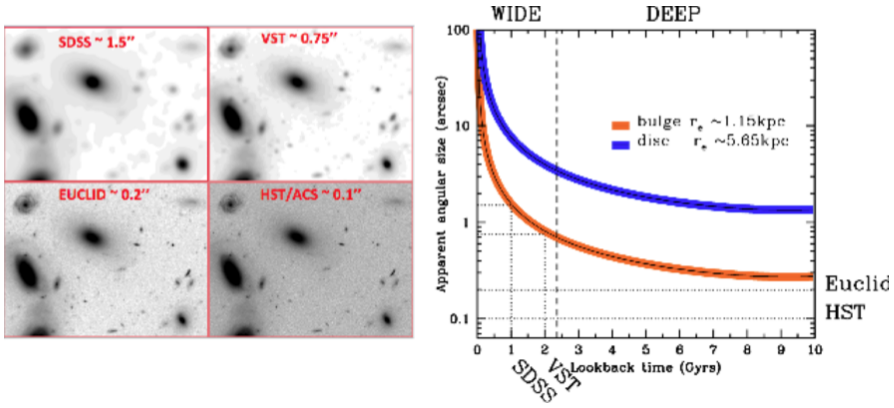

Fig. 4 Angular-size versus lookback time with the low-z limitations of the SDSS and VST shown. (right) Comparison of various imaging datasets, with median seeing as indicated.

will provide over 1-million galaxies in the range $0.2 < z < 0.8$ with imaging resolution sufficient to discern and measure bulge, bar, and disc components to 1kpc resolution (see Fig. 4 right). This will open the door for direct measurements of the mass and size evolution of the distinct structural components (bulges, bars, discs) within a sufficiently comprehensive survey to dissect trends by halo mass, star-formation rate or a multitude of other indicators. *If* tracing the duality of galaxies is critical for understanding galaxy formation, as we suspect ([13]), then WAVES-Deep/Euclid will provide more than an order of magnitude advancement over COSMOS/zCOSMOS, and in doing so firmly bridge the near and far Universe.

2.4 The evolving HI universe (with ASKAP/SKA)

The SKA and its pathfinders will allow, for the first time, a direct study of the HI content of galaxies and its role in galaxy evolution over cosmologically representative volumes and over significant cosmic time. Understanding the complicated interaction between the gas content of galaxies, their environments, and other major galactic constituents, remains a largely unsolved problem. In anticipation of the next generation of observational programs, current simulations of cosmic evolution now increasingly provide measures of gas content and its phase breakdown (atomic, molecular, ionized; e.g., [21, 22, 19]), and numerous models have been advanced for the fundamental physical processes that underly the observable gas scaling relations. These models must now be tested, and our observational understanding of evolution in the scaling relations improved to advance the field.

The advantages of alignment between HI and optical spectroscopic programs are many-fold: a comparison of gas content with high fidelity measures of environment and halo mass from optical spectroscopy, metrics that are imperfectly traced by HI galaxy redshifts alone due to the strongly anti-biased nature of this population; improved treatment of issues such as galaxy confusion, satellites, and multi-wavelength counterpart identification due to the comparatively higher spatial resolution of optical data; optically motivated source finding to increase the size of HI source catalogues; and the maximal exploitation of deep HI data through the application of statistical techniques, such as HI stacking, that increase the cosmic baseline over which evolutionary measurements of gas content can be made. Optical redshift catalogues further enable the properties of the gas-rich population to be directly compared to the general galaxy population as selected by tracers much more closely linked to stellar and halo mass.

While the current generation of optical redshift surveys are well-suited to the SKA pathfinders, such datasets are absent for SKA phase 1. In particular, SKA1-mid is expected to survey a 100sq deg region (i.e., comparable to WAVES-Deep) out to $z \sim 1$ and beyond. No such dataset currently exists, being too expensive in telescope time for current facilities, and a unique opportunity for VISTA that will be met by WAVES. Combined with data from SKA phase 1 and Euclid, Deep-WAVES will enable robust measurement of HI over half the history of the Universe, and unique measurements over cosmologically representative volumes of the complex interplay of gas content with other major galactic constituents.

2.5 A legacy resource

WAVES is designed as a legacy survey from which numerous science questions can be asked and numerous follow-on campaigns launched. For this reason the survey selection, crucial for establishing legacy value, is kept as simple as possible with only flux selection for WAVES-Deep and flux and photo-z selection for WAVES-Wide. More complex selection ultimately minimises the generic usefulness of a survey. For example the very specific selection algorithms of large cosmology programmes (e.g., BOSS) reduces the usability of such surveys for evolutionary studies of the galaxy population. There is also a direct opportunity to connect the WAVES survey to planned campaigns (Fig. 5) with Euclid — capable of providing $0.2''$ images over the entire WAVES region in optical and near-IR bands — SKA Phase I — capable of sampling HI to $z \sim 0.2$ over WAVES-Wide and to $z \sim 1.0$ over the WAVES-Deep region as well as the all-hemisphere/sky surveys to be conducted by LSST and eROSITA. Apart from fulfilling the science cases outlined above this presents a unique opportunity to combine a deep spectroscopic campaign with both Euclid, SKA Phase I, LSST and eROSITA to study the late-time assembly and evolution of galaxies over a broad mass and redshift baseline with robust stellar masses, gas masses, morphologies and structural decompositions.

Galaxy evolution is complex, and the current picture murky. Clarity will come from comprehensive studies based on the highest quality inputs combined with rigorous analysis such as that provided by the Sloan Digital Sky Survey ([30]) and Galaxy And Mass Assembly ([12]) teams. WAVES will game-change by extend-

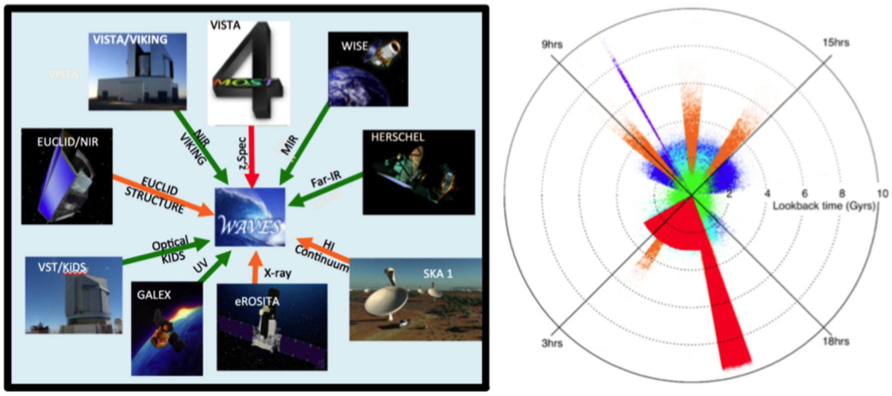

Fig. 5 (left) The facilities ultimately contributing to the WAVES survey. (right) a cylinder-plot showing the region of the Universe probes by WAVES compared to other notable surveys.

ing to flux limits 4 magnitudes fainter than SDSS locally, and outward in redshift ($z \sim 1.0$). The scale of each of the proposed surveys are SDSS-like in scale and the 1-million galaxy ball-park has proven crucial in establishing key trends such as the mass-metallicity relation ([27]) and other key measurements. In addition conducting a fully sampled contiguous survey provides the opportunity to construct a robust halo mass catalogue to explore the role and influence of the halo on galaxy evolution ([25]) as well as the intrinsic properties of halos themselves ([23]).

Hence with WAVES-Deep one can ask questions such as whether the stellar mass-size relation of spheroids and discs evolves in the same manner irrespective of halo mass, or how does the stellar-to-gas mass fraction vary over 4dex in stellar mass from rich clusters, to filaments, to voids. Perhaps most important of all but not discussed in detail here are the possibilities opened up by the $R \sim 5000$ mid-resolution spectrograph which will provide robust metalicity, age, dust and star-formation measurements (e.g., GANDALF; [26]) for the higher signal-to-noise subset (i.e., $r_{\rm AB} < 21$ mag and S/N/Å~ 20), of the WAVES galaxies. Finally we note that the proposed regions are or will be pre-surveyed by notable facilities including GALEX, VST (KiDs), VISTA (VIKING), WISE, and Herschel (Herschel-Atlas).

3 WAVES survey design

The survey scope is bounded by the likely capabilities of the VISTA/4MOST facility, the availability of suitable data to define a target catalogue, and consideration of available complementary datasets. Within these bounds the design is then driven by the science drivers which push towards a comprehensive (100—750 sq deg), contiguous, faint flux limited ($r_{\rm AB} < 22$ mag) survey. The tension between studying galaxy evolution over a broad timeline versus probing down to the faintest halo mass and halo occupation limits leads to a survey split into WAVES-Deep and WAVES-

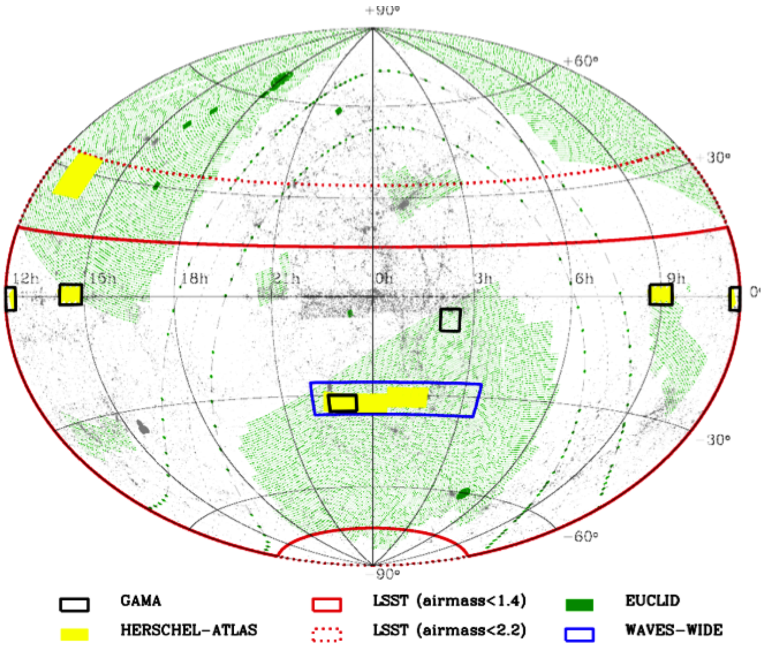

Fig. 6 An Aitoff projection showing the location on the sky of various surveys including GAMA, Herschel-Atlas, Euclid and WAVES-Wide.

Wide. For efficiency and legacy purposes these surveys are interleaved with identical initial target selection but with an additional photo-z selection applied to WAVES-Wide (derived from $ugriZYJHK$ VST/VISTA matched aperture photometry where $\Delta z/(1+z) \sim 0.03$ is realistic).

The final WAVES catalogue is expected to contain ~ 2 million galaxies, 140k groups, and 14k filaments from within the VST KiDS South footprint (see Fig. 6). This region of sky passes directly overhead at Paranal and would represent the first major spectroscopic campaign South of the Galactic equator since 2dFGRS over a decade ago.

Both WAVES surveys are designed to operate to the limiting sensitivity of the 4MOST facility, taken here as $r_{\rm AB} < 22$ mag for a 2hr (5×24min) integrations with the Mid-Res spectrograph ($R \sim 5000$, $\Delta\lambda 0.4 - 0.9\mu m$, S/N/Å$\sim 3$). All 1800 low-res fibres would be engaged, and the survey density (1000 and 9800 gals/sq.deg for WAVES-Wide and WAVES-Deep) is such that the WAVES-Wide footprint will be sampled only once while the WAVES-Deep footprint will be sampled $\sim 6\times$ (ideal for sampling the cores of dense groups). Pre-selection will consist solely of flux and colours consistent with galaxies for WAVES-Deep while WAVES-Wide will include an additional photo-z selected ($z < 0.2$) using $ugriZYJHK$ photometry provided by VST KiDs and VISTA VIKING.

4 Summary

As of November 2014 WAVES has been adopted as one of the eight key Design Reference Surveys for VISTA/4MOST and should commence circa 2021. The WAVES team remains committed to four overriding principles: (i) simplicity of survey design, (ii) high contiguous coverage, (iii) maximising the synergy with complementary facilities, and (iv) the professional release of high quality data products to the community. Updates on the progress of the project will be broadcast via the website: http://www.wave-survey.org/

We would like to finish by thanking the organisers for the invitation to participate in “The Universe of Digital Sky Surveys” meeting, our thanks in particular to Massimo Capaccioli for his vision and resolve in delivering VST (upon which WAVES builds), and the editors for kindly allowing us to exceed our page allocation in describing the WAVES concept.

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