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The 4MOST Hemisphere Survey of the Nearby Universe (4HS)

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The 4MOST Hemisphere Survey (4HS) will obtain uniform spectroscopy and redshifts for approximately six million galaxies over $\sim 2\pi$ steradians, and with high and unbiased completeness for $z < 0.15$. 4HS aims to 1) complete the map of mass and motion in the Local Volume, 2) map the influence of environment on galaxy evolution through overwhelming statistics, and 3) define the local ($z < 0.15$) galaxy reference sample for the era of LSST, Euclid, and ASKAP/MeerKAT/SKA. The result is a dataset with exceptional and long-lasting legacy value.

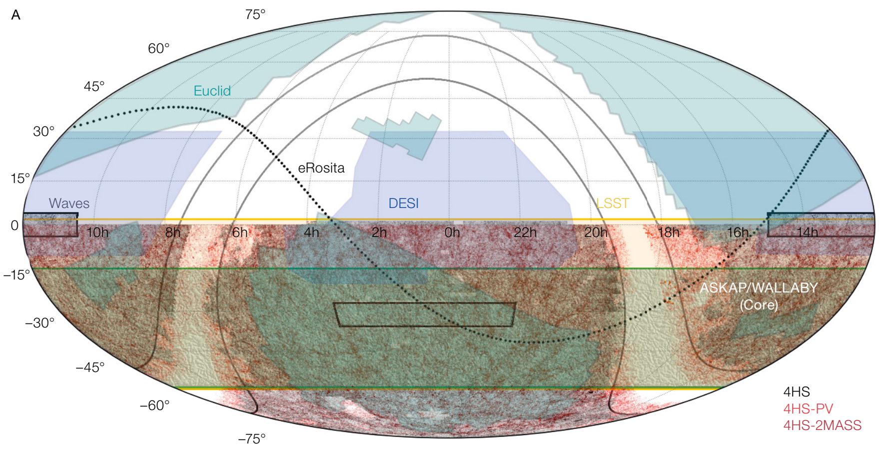
Scientific context

Census-class surveys of the low-*z* galaxy population are central to the study of galaxy formation and evolution in at least three ways. First, empirical mappings of demographic distributions and scaling relations at $z \sim 0$ are vital in the calibration and/or validation of numerical simulations and theoretical models. Second, local samples provide the essential $t \sim 0$ reference point to anchor evolutionary studies over higher redshifts. Third, statistically representative samples are critical as control groups for studies of interesting or unusual classes or populations, for example group and cluster populations, radio- or HI-selected samples, transient hosts, etc.

The last decades have shown how low-*z* science is driven by — or can be limited by — the availability of spectroscopic redshifts and high-quality multiwavelength imaging over wide areas. Imagine a Universe in which we have eRosita, LSST, VISTA-VHS, Euclid, Roman, WISE, SKA, and LIGO/LISA, but where low-*z* science in the south is limited to 6dFGS (Colless et al., 2001; $K_{AB} < 14.5$), WAVES ($\sim$ 1000 deg^2; Driver et al., 2019) and/or the margins of DESI-BGS (Hahn et al., 2022).

In this context, the 4MOST Hemisphere Survey (4HS) addresses an urgent need for uniform, wide-area, local-Universe spectroscopy in the southern hemisphere, to support low-*z* science with flagship European and global facilities. Accordingly, 4HS is designed to provide the best possible description of the low-*z* galaxy population in the southern Universe, with particular emphasis on science activities that absolutely require spectroscopy and/or spectroscopic (as opposed to photometric) redshifts.

In particular, 4HS takes full advantage of the unique capabilities of the 4MOST facility and consortium structure to achieve high and unbiased spectroscopic completeness for low-*z* galaxies over the widest possible area. Sharing the focal plane enables 4HS to efficiently obtain high completeness, and stellar partners enable us to press into the historic Zone



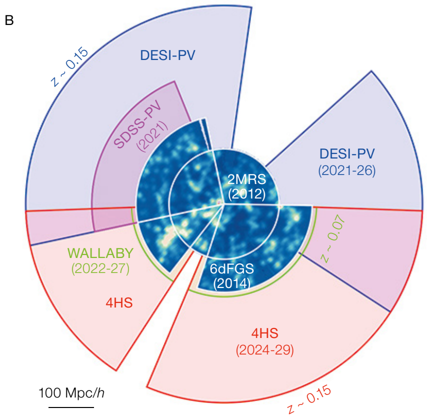


Figure 1. A: 4HS in the context of wide-field surveys, including ASKAP-WALLABY, VRO-LSST, and Euclid. The points show our preliminary input catalogue, based on a reanalysis of archival VISTA imaging. The main, PV, and 2MASS XSC sub-surveys are shown in black, red, and dark red, respectively. Note how 4MOST enables us to operate efficiently even deep into the historic Zone of Avoidance for PV science. B: 4HS in the context of major PV cosmology surveys. We stress that having overlapping samples is critical for controlling systematics between different surveys/teams. On its own, 4HS will be the largest southern PV experiment by a factor of about 10 in volume, and about 50 in the number of galaxies, and the largest globally by ~ 30% in area and a factor of two in number. Together with DESI-PV, 4HS will complete the map of the cosmic density and velocity fields in the Local Volume.

of Avoidance. (Equally, 4HS supports stellar halo science around the Galactic caps and the Sagittarius stream.) As well as extending samples and areas for other participating extragalactic surveys, shared observing costs for common targets means that 4HS carries efficiency dividends within the 4MOST consortium amounting to ~ 25–30%.

Specific scientific goals

The key science goals for 4HS are set out below.

Map the mass, motion, and gravitational growth of structure in the southern Universe

4HS will measure velocity dispersions to enable distance and peculiar velocity (PV) determinations from the Fundamental Plane (FP) for up to ~ 650 000 early-type galaxies at $z < 0.12$. (The soft limit of $z \sim 0.12$ represents the limit of where the uncertainties in FP-derived distances, which scale with redshift, begin to blow up.) The unique contribution of 4HS will be to map the cosmic velocity field to distances of ~ 500 Mpc, covering virtually the full southern extent of the Local Volume, and including the most massive cosmological structures (i.e., Laniakea, Shapley, Vela, etc.) that are found in the south. When combined with the cosmological density field (as traced by galaxy positions), this provides a snapshot of the cosmic web in formation via gravitational collapse. 4HS will map the late-time (< 3 Gyr) evolution of the growth rate of structure through 5–10% precision measurements of the parameter combination $f(z),\sigma_8$ which is composed of the cosmological growth rate and mass clustering parameters, in each of six independent redshift bins over the interval $0 < z < 0.3$. The relation between the cosmic density and velocity fields also represents a direct measurement of gravitation on the largest scales (>> 10 Mpc): when combined with Planck data, 4HS will provide a ~ 5% measurement of the gravitational growth index, γ, to directly test general relativity and modified/alternative theories of gravity.

Map the demographic trends across the $z < 0.15$ galaxy population as a function of local and large-scale environment

That galaxy populations vary with environment is well established (for example, the morphology-density relation, group/cluster conformity, etc.), but the challenge remains to disentangle the mechanisms and effects that produce the observed trends. This multidimensional problem will only be resolved with overwhelming statistics. With high and unbiased completeness for a large statistical sample of $z < 0.15$ galaxies, 4HS will deliver the comprehensive suite of environment metrics (for example, local density, halo mass, situation with respect to group/void/filament/node, etc.) that is needed to advance the field. Further, 4HS will identify > 60 000 galaxy groups, including ~ 30 000 in the low-to-intermediate mass range (10^{11}–10^{13} $M_\odot$; multiplicities in the range 1–10) where group and galaxy properties seem to be most sensitive to the relative strengths of interacting processes (for example, Davies et al., 2019). Thus 4HS is designed to provide a solid empirical basis to describe exactly how environment influences galaxy properties, in order to challenge and constrain the next generations of hydrodynamical simulations, and so to resolve the environmental processes/effects that most influence galaxy formation and evolution.

Establish the benchmark local galaxy reference sample for the next generation of wide-area surveys and large/high-resolution simulations

With an increase in statistical power of about seven over the Sloan Digital Sky Survey and about 65 over the Galaxy And Mass Assembly (GAMA) survey, 4HS will establish the definitive benchmark sample of galaxies at $z < 0.15$, including ~ 400 000 galaxies in the $8.5 < \log M_* < 9.5$ dwarf regime, all the way up to the very rarest and most massive galaxies. Relative to DESI-BGS, the southern advantage gives

4HS access to areas covered by LSST, ALMA, and ASKAP/MeerKAT/SKA, plus extensive overlap with eRosita, and with Euclid in the South Galactic Cap, to add to existing data from all of GALEX, VISTA-VHS, and WISE. Following the successful model of GAMA (Driver et al., 2022), and together with 4MOST partners including WAVES and CHANCES, 4HS is the keystone galaxy redshift survey necessary to establish a truly transformational laboratory for empirical studies of galaxy formation and evolution with comprehensive, panchromatic vision across the entire baryon cycle.

Target selection and survey area

The 4HS input catalogue is derived from a reanalysis of *JK* imaging from the VISTA Hemisphere Survey (VHS) plus several other programmes to fill gaps as far as possible. For target characterisation (for example, masses, star formation rates, etc.), we currently include optical imaging from Pan-STARRS1 where available (Dec > –30°). We plan to extend to infrared imaging from WISE in the next year, and then to LSST optical and Euclid infrared imaging as they become available. Our photometric pipeline is built around the Scarlet deblender (Melchior et al., 2018) to obtain robust and signal-to-noise (S/N)-optimised extended source photometry. We are committed to releasing this new photometry as a public resource before the start of 4MOST survey operations.

The main 4HS sample is selected as $J_{AB} < 18$ and $(J-K) < 0.45$ (foreground corrected; AB), with a notional mean target density of ~ 325 deg^{-2}. *J*-band selection is a nearly optimal basis for pre-selecting stellar-mass-limited samples: 4HS is volume limited for log $M_* > 9.3/10.0/10.3$ and $z < 0.05/0.10/0.15$. As a means to pre-select $z < 0.15$ galaxies with near total completeness, our simple $(J-K)$ colour selection is maximally transparent, and is only marginally less efficient than a photometric *z* selection. For star/galaxy separation, we use a combination of both colour and resolved-ness in the VISTA imaging, with the opportunity to include information from Gaia. To cover the widest possible area, the main survey footprint is defined as the area where $E(B-V) < 0.3$ in the Planck dust map; including the two WAVES-Wide fields this gives a total area of ~ 18 000 deg^2.

Our observing strategy is to obtain approximately uniform spectroscopic depth for all targets, equivalent to ~ 18 minutes integration in nominally grey conditions. This strategy guarantees > 98% redshift success per observation for our $z < 0.15$ targets. Further, we expect S/N $\gtrsim$ 12 for a high fraction (> 80%) of log $M_* > 10$ early-type galaxies at $z \lesssim 0.12$ to enable the velocity dispersion measurements that underpin our PV cosmology aims. Having roughly uniform spectral data quality brings other significant science benefits: for example, easy-to-characterise sensitivity limits for emission-line science (star formation rates, metallicities, emission-line diagnostics, etc.), and additional science opportunities using high-S/N subsets of the data (beyond our key PV cosmology science goals, including Galactic/Magellanic dust attenuation, etc.).

For PV cosmology, more than completeness, the object is to span the largest possible area/volume. To this end, we define a PV subsample as $J_{AB} < 16.5$ and $0 < (J-K) < 0.3$ (~ 65 deg^{-2}), which extends beyond the footprint of the main survey to $E(B-V) < 1.5$, for a total of ~ 19 890 deg^{-2}. Our goal with this sub-survey is to capture those early-type galaxies at $z < 0.12$ for which we can obtain useful velocity dispersion measurements. As a means of pre-selecting suitable FP targets from the main sample, this selection is ~ 60–65% complete and ~ 30–35% reliable. In contrast to the main sample, the *J*-magnitude selection for this sub-survey is applied to magnitudes as observed (i.e., without foreground correction), to focus on targets where we can get sufficient S/N for a velocity dispersion measurement to $\lesssim$ 0.1 dex. We anticipate this sub-survey will provide about an additional 30 000 useful PV measurements over and above the main sample, extending our area/volume for PV science by ~ 10%.

Further, we include the 2MASS Extended Source Catalogue (Jarrett et al., 2000) as a supplemental sample to push to very low Galactic latitudes towards the Galactic anticentre, through the Magellanic Clouds, and wherever there are gaps in the VISTA imaging.

Figure 1a shows a preliminary 4HS input catalogue in the context of other current and future wide-area surveys. We also emphasise 1) the strong synergies between 4HS and each of VRO-LSST, Euclid, and ASKAP-WALLABY, 2) the complementarity of 4HS in the south with DESI-BGS in the north, and 3) the lasting legacy value of uniform and highly complete spectroscopic redshifts across the hemisphere.

As a near-infrared-selected spectroscopic redshift survey of the southern hemisphere, 4HS is more than three magnitudes deeper than 6dFGS for a factor of > 50 increase in target density and number of redshifts. In combination with high-quality optical-to-infrared photometry from LSST, Roman, Euclid, VISTA, and WISE — plus eRosita X-ray and ultimately ASKAP/MeerKAT/SKA radio data — 4HS can equally be viewed as providing GAMA-like depth and panchromatic coverage over > 60 times the area, to establish an incredible legacy dataset.

As a PV cosmology survey, 4HS expands the current state of the art (for example, Qin et al., 2018; Kourkchi et al., 2022; Howlett et al., 2022) by factors of > 60 and > 10 in number and volume, respectively (see Figure 1b). More importantly than 'factor of' comparisons, in combination with DESI in the north, and with complementary data from ASKAP-WALLABY at lower redshifts, 4HS will complete the map of gravitational mass and motion in Local Volume.

Acknowledgements

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References

Colless, M. et al. 2001, MNRAS, 328, 1039
Davies, L. J. M. et al. 2019, MNRAS, 483, 5444
Driver, S. P. et al. 2022, MNRAS, 513, 439
Driver, S. P. et al. 2019, The Messenger, 175, 46
Hahn, C. et al. 2022, arXiv:2208.08512
Howlett C. et al. 2022, MNRAS, 515, 953
Jarrett T. H. et al. 2000, AJ, 119, 2498
Kourkchi, E. et al. 2022, MNRAS, 511, 6160
Qin, F. et al. 2018, MNRAS, 477, 5150
Melchior, P. et al. 2018, Astronomy & Computing, 24, 129