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MSE VELOCITY SURVEY

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Abstract. A huge velocity survey based on the Maunakea Spectroscopic Explorer facility (MSE) is proposed, aiming at investigating the structure and dynamics of the cosmic web over 3π steradians up to ~ 1 Gpc and at unprecedented spatial resolution, its relationship with the galaxy formation process, and the bias between galaxies and dark matter during the last three billions years. The cross-correlation of velocity and density fields will further allow the probe any deviation from General Relativity by measuring the the linear-growth rate of cosmic structures at precision competitive with high-redshift spectroscopic redshift surveys.

Keywords: Survey, cosmology, large-scale structure of Universe, dark energy

1 MSE and MSEv

The Maunakea Spectroscopic Explorer (MSE)* is a proposed upgrade of the CFHT 3.6m optical telescope by a 10m-class dedicated multi-object spectroscopic wide-field facility, with completion expected in 2025. With three optical-NIR channels covering the wavelength range $370 - 1400$ nm, a multiplexing of 3200 fibers at spectral resolutions $R = 3000$ and 6500, and 1000 fibers at $R = 40000$, and further IFU capabilities expected for the second light, this instrument will be unique to tackle basic science questions ranging from stellar astrophysics, the physics of the Galaxy and Local Group, the galaxy evolution and clustering across cosmic time, to cosmology.

We propose to realize a velocity survey (MSEv) to measure the redshift of about 2 million of early- an late-type galaxies over 3/4 of the full sky apart from Milky Way and out to redshift $z \simeq 0.25$, and radial velocities of about half of them over $10,000 - 24,000$ square degrees. Both the Fundamental Plane (FP) and optical Tully-Fisher (TF) techniques will be employed, with galaxy number density and sampling similar to Cosmicflows-2 (CF-2; Tully et al. 2013). The redshift and sky coverage and the total number of MSE velocities is designed to supersede in terms of volume or number density the most recent velocity surveys, such as SFI++ (Springob et al. 2007), 6dFGSv (Springob et al. 2014), and CF-2, and the forthcoming *I*-band velocity survey TAIPAN (starting around mid-2016; Kuehn et al. 2013). MSEv will further provide the optical-NIR counterpart of the HI surveys ASKAP-WALLABY and WNSHS (Koribalski 2012; Johnston et al. 2008).

2 Science case

Low-redshift growth-rate of structures: dark energy and modified theories of gravity — Peculiar velocities provide a powerful tool to study the distribution of mass directly, without the complicated details of galaxy and star formation, e.g. by applying the *velocity-velocity comparison* (e.g. Kaiser et al. 1991). Focusing on the joint analysis of angle-averaged auto- and cross-power spectra of the density and velocity fields, a preliminary Fisher matrix analysis following Koda et al. (2014) indicates that a minimal MSEv covering $10,000\,\mathrm{deg}^2$ and with a number density of $n_{\rm gal} = 0.003\,h^3\mathrm{Mpc}^{-3}$ (i.e. $\sim 10^6$ galaxies with $z < 0.25$, for which both redshift and distances are measured) will constraint the ratio $\beta = f/b$, between the linear growth-rate and the bias of the tracers, and the amplitude of matter fluctuations, σ_8, at the level of $\delta\beta/\beta = 0.065$ (0.036) and $\delta\sigma_8/\sigma_8 = 0.060$ (0.032) out to redshift $z < 0.1$ (0.2); see Fig. 1. Because of the small volume, these errors increase by a factor $\sim 1.5 - 2.3$ if measuring only the density power spectrum (i.e. redshift space distortions, RSD). Instead, similar precisions to the MSEv joint velocity-density analysis are expected by future spectroscopic redshift surveys at high-redshift such as PFS-SuMIRe, DESI and Euclid, though probing the growth-rate in a more challenging regime.

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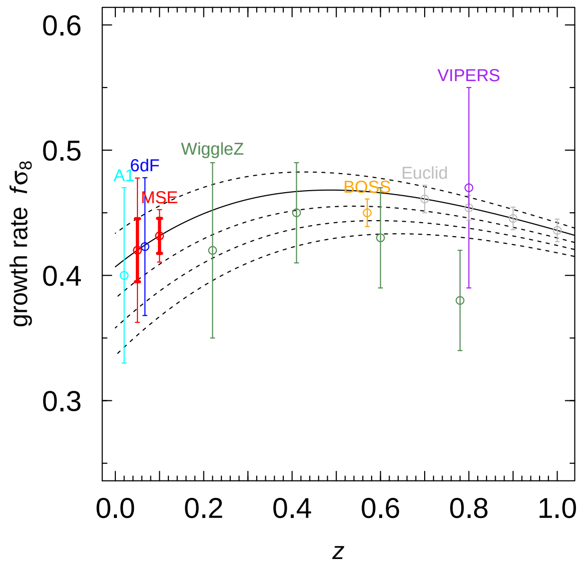

Fig. 1. Fisher matrix 1σ constraints on the linear growth rate $f \approx \Omega_{\rm m}^{\gamma}$ around the fiducial ΛCDM cosmology (solid line, $\gamma = 0.55$; dotted lines are separated by $\delta\gamma = 0.05$, increasing downward), for the minimal MSEv ($10,000\,{\rm deg}^2$, $n_{\rm gal} = 0.003\ h^3{\rm Mpc}^{-3}$). Thick (thin) error bars for the MSEv constraints account for density-velocity cross-correlation (density-only, i.e. RSD, with same number density) up to redshift $z = 0.05$ and $z = 0.1$.

MSEv will allow also a powerful application of the *luminosity fluctuation method* (Feix Nusser & Branchini 2015), which promises to be a powerful test of the current cosmological paradigm. Successfully applied to the velocities reconstructed from $\sim 10^5$ galaxies from the SDSS-DR7, this technique will tremendously benefit of the $\sim 10^6$ MSE peculiar velocities.

From local dynamics to galaxy formation — The low-redshift spacetime symmetries are not evident. The kinematics probed over the huge MSEv volume, which largely encompasses the homogeneity scale (Hogg et al. 2005), will assess the cosmological bulk flow probing its consistency with CMB dipole out to 800 Mpc and allow the test of subtle issues like the backreaction conjecture (Buchert 2008).

MSEv will enable the kinematical classification of the cosmic-web components resolving cosmic structures down to $\lesssim 0.1h^{-1}$Mpc (Hoffman et al. 2012), providing much more details than similar classification algorithms based on density field (see Forero-Romero et al. 2009, and references therein). Moreover, exploiting the high-resolution spectroscopic capabilities of MSE, the knowledge of the velocity-web will provide a unique basis to investigate the tidal torque theory, the alignment of the galaxy spin to the cosmic-web filaments, and the segregation of galaxies and halos with respect to their environment and dynamics.

3 Feasibility study (phase-1)

Spectroscopic and photometric requirements — Both early- and late-type galaxies will be surveyed up to magnitude $i_{\rm AB} < 24.5$, to obtain the redshift and equivalent-width of the principal absorption and emission lines (NaD, Mg b, [CaII]; H_α, [OIII], [OII], etc.). The spectra of early-type galaxies should be measured at the same resolution as TAIPAN, i.e. $\sim 70\,{\rm km\ s}^{-1}$ rest-frame, while those of late-type galaxies at resolution $< 30\,{\rm km\ s}^{-1}$. By comparison with spectra by Keck-II/DEIMOS (Newman et al. 2013) and MMT/Red Channel Spectrograph (Franx 1993), such accuracy can be achieved by exposures of 3,600 s with the mid-resolution MSE channel; see Fig. 2. Besides, accurate photometry (~ 0.1 mag) is needed for pre-imaging (target selection) and measurement of distances, e.g. provided by Pan-STARRS, CFIS, and Euclid, and by LSST and DES for Dec < 30 deg.

Instrumental setup: mini-IFUs — We propose to assess the kinematic of galaxies by fibre-fed mini-IFUs, a technology especially suited to probe the velocity curve of fast rotators but expected to improve the measurement of velocity dispersion of slow rotators and early-type galaxies as well (Krajnović et al. 2011). Each mini-IFU could consist in linear 5- or 7-fibre bundles to simulate long-slits, which nevertheless require alignment to the

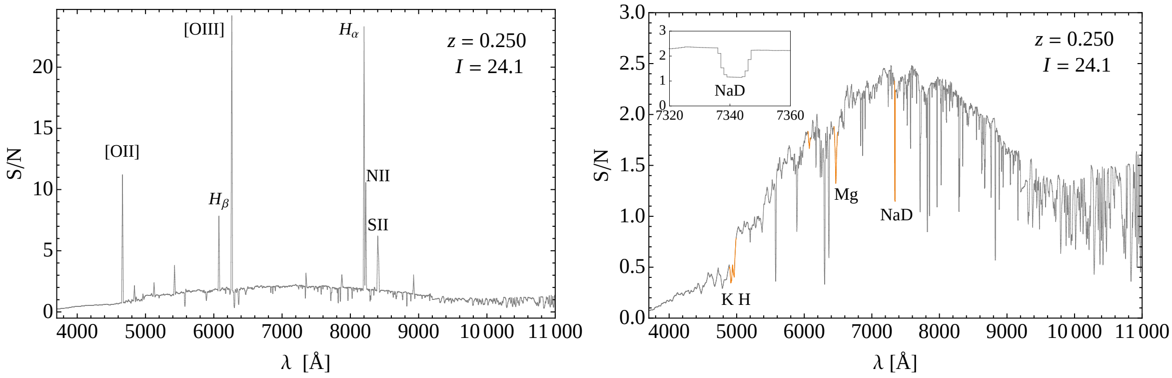

Fig. 2. Synthetic spectra computed with the MSE exposure time calculator (3,600 s exposure-time, mid-resolution). **Left:** elliptical galaxy, centered on the NaD absorption line. **Right:** spiral galaxy, centered on H_α and [OIII] lines.

kinematical axis. A better option would be provided by MaNGA-like close-packed hexagonal mini-IFUs (Drory et al. 2015), each one consisting of 19- or 37-fibre bundles, which do not require any alignment while assuring an optimal measurement of the velocity dispersion. Single fibres of diameter 1.1”-1.5” would guerantee sufficient angular resolution of typical L^*-galaxies out to redshift $z = 0.25$. Using hexagonal mini-IFUs and 4,000 fibres per field-of-view as in the current MSE setup, one obtains $70 - 140$ galaxies per square-degree and $1.7 - 3.7$ millions of L^*-galaxies over $24,000\,\mathrm{deg}^2$ out to $z = 0.25$ at the required number density. A ten-times larger number density of sources with the same field-of-view would likely require a different integral-field technology.

Open issues — i) The typical error on the distance of single galaxies from TF and FP methods is of order 15-20%, improvements on currently devised grouping techniques are needed to assess peculiar velocities down to few-hundreds km s^{-1} at $z \simeq 0.25$. *ii)* The MSE IFU capability, including mini-IFUs, and the observational strategy (bimodal for MSEv) are under discussion in accordance with other MSE projects.

4 Conclusions

MSEv has been recognized as high-value proposal by the MSE Science Executive. The MSE project is entering the phase-2 study.

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