Future ground-based redshift galaxy surveys:

Dark energy spectroscopic instrument (DESI)
& Maunakea Spectroscopic explorer (MSE)

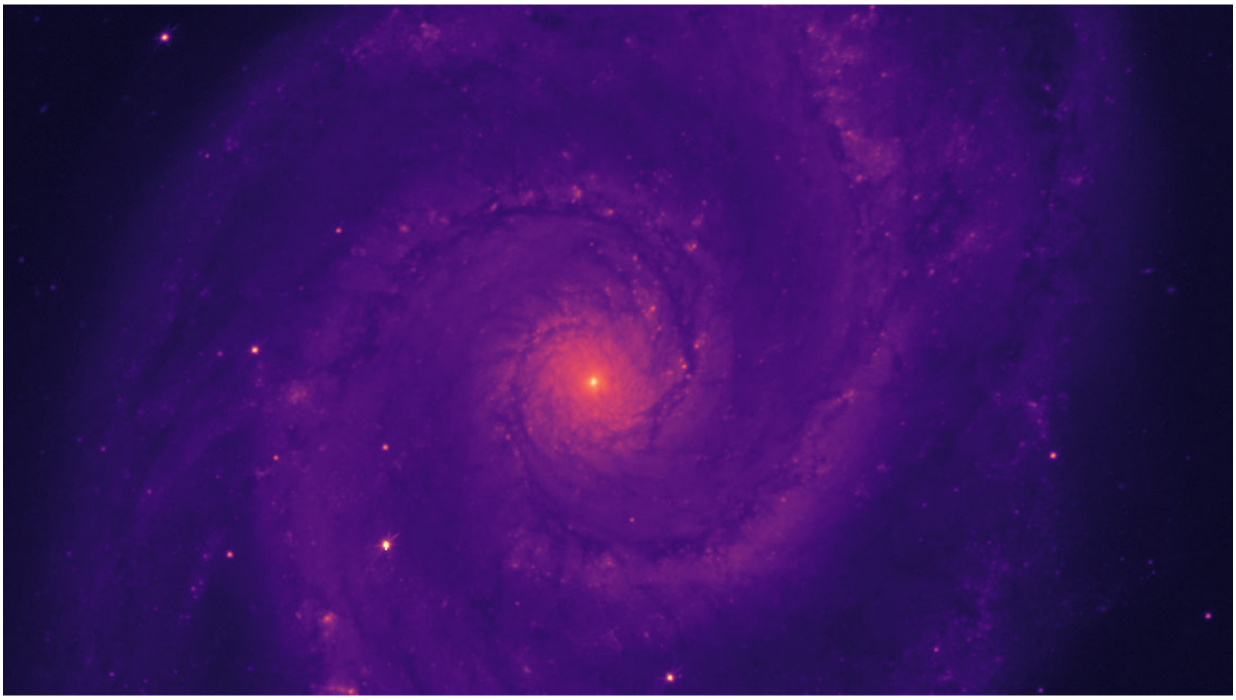
Principal author: Stéphanie Escoffier, CPPM, escoffier@cppm.in2p3.fr, 0491827664

Co-authors:

- Christophe Balland (LPNHE), Marie-Claude Cousinou (CPPM), Laurent Le Guillou (LPNHE), Pierros Ntelis (CPPM), Christophe Yeche (CEA IRFU)

Endorsers:

- Réza Ansari (LAL), Dominique Boutigny (LAPP), Yannick Copin (IP2I), Hélène Courtois (IP2I), William Gillard (CPPM), Adam Hawken (CPPM), Jérémy Neveu (LAL)



DESI "first light" image of the Whirlpool Galaxy, also known as Messier 51. This image was obtained the first night of observing with the DESI Commissioning Instrument on the Mayall Telescope at the Kitt Peak National Observatory in Tucson, Arizona; an r-band filter was used to capture the red light from the galaxy. (Credit: DESI Collaboration)

SCIENTIFIC CONTEXT

Observational cosmology has been leading for more than 20 years now to the discovery of one of the greatest puzzles of contemporary physics: the acceleration of the expansion of the Universe. Discovered in 1998 through the study of type Ia supernovae (Perlmutter et al. 1999; Riess et al. 1998), cosmic acceleration can be understood as a repulsive effect counteracting gravitational attraction, often depicted as an energy of unknown origin called dark energy. In this way, the Standard Model of cosmology describes the Universe as spatially flat and made up of 5% baryonic (ordinary) matter, 27% cold dark matter (CDM) and 68% dark energy (Λ), according to latest results from Planck (Planck VI et al. 2018). A fundamental question is therefore why the Universe is accelerating, and a way to address it is by understanding the nature of dark energy.

On the theoretical side major effort is being made, because the most basic definition of dark energy as a cosmological constant (Λ) incorporated in Einstein's equations raises a number of questions: is Λ a constant of integration? can Λ be linked to the vacuum energy of quantum physics? is dark energy evolving in time? Or is cosmic acceleration the signature of a modified gravity theory? Understanding the nature of dark energy is undoubtedly one of the most challenging aspects of modern cosmology.

On the observational side, the large-scale structure of the universe, as traced by galaxies in redshift surveys, has played a central role in establishing the modern cosmological model based on dark matter and dark energy. Amongst the most-notable spectroscopic surveys are the VIMOS Public Extragalactic Redshift Survey (VIPERS) (Guzzo et al. 2014), the WiggleZ Dark Energy Survey (Drinkwater et al. 2010), the Galaxy and Mass Assembly (GAMA) (Driver et al. 2011) and the 6dFGRS (Beutler et al. 2011). The largest redshift survey to date is the Sloan Digital Sky Survey (SDSS) (York et al. 2000), in particular the BOSS (Dawson et al. 2013) and the eBOSS (Dawson et al. 2016) surveys, which measured redshifts of nearly one million galaxies (Abolfathi et al. 2018).

A way to provide a test of General Relativity (GR) is to measure the linear growth rate f that quantifies how rapidly structure is being assembled in the Universe as a function of cosmic time. Since coherent motions of galaxies are driven by gravity, anisotropies observed in redshift surveys and induced by peculiar motions (Redshift Space Distortions called RSD) are used to constrain the quantity $f\sigma_8$, where σ_8 is the late-time fluctuation amplitude and f is parametrized as $f = \Omega_m^{\gamma}$, where Ω_m is the matter density and γ a free parameter. For ΛCDM, a value of γ=0.55 is expected, while a deviation from this value would indicate a modification of the equations of GR.

Upcoming massive galaxy redshift surveys such as DESI (Aghamousa et al. 2016a), Euclid (Amendola et al. 2018) and MSE (Percival et al. 2019) will place significant constraints on theories of modified gravity by joint measurement of RSD and Baryon Acoustic Oscillation (BAO) features in the clustering pattern of galaxies. In addition, galaxy surveys address many other science problems such as the summed neutrino particle mass or the level of primordial non-Gaussianity, a powerful tool to test inflation.

We focus in this document on ground-based instruments.

THE DESI SURVEY

OVERVIEW AND KEY SCIENCE GOALS

The **Dark Energy Spectroscopic Instrument (DESI)** is a ground-based dark energy experiment sited on the Kitt Peak National Observatory Mayall 4m telescope (Arizona, USA). DESI will conduct a five-year survey designed to cover 14,000 deg2 and to map the large-scale structure of the Universe at $0 < z < 3.5$ by measuring 37 million redshifts (Aghamousa et al. 2016a). DESI will perform stringent cosmological tests and will allow definitive tests of gravitational physics by constructing a unique redshift-space (3D) map of the large-scale structure of the Universe. Using the Ly-α forest technique, coverage will include early times when the expansion rate was decreasing.

DESI has been designed to address the fundamental question about the nature of the Universe through measurements of BAO as a standard ruler and through the study of the growth of structure with RSD. The survey is designed to measure the distance scale from BAO with 0.3% precision from $0 < z < 1.1$ and 0.4% precision from $1.1 < z < 1.9$. The gravitational growth measurements precision is expected to be < 1% at $0.5 < z < 1.4$ using RSD. The challenge is to distinguish between the different possible manifestations of dark energy, as illustrated in Figure 1.

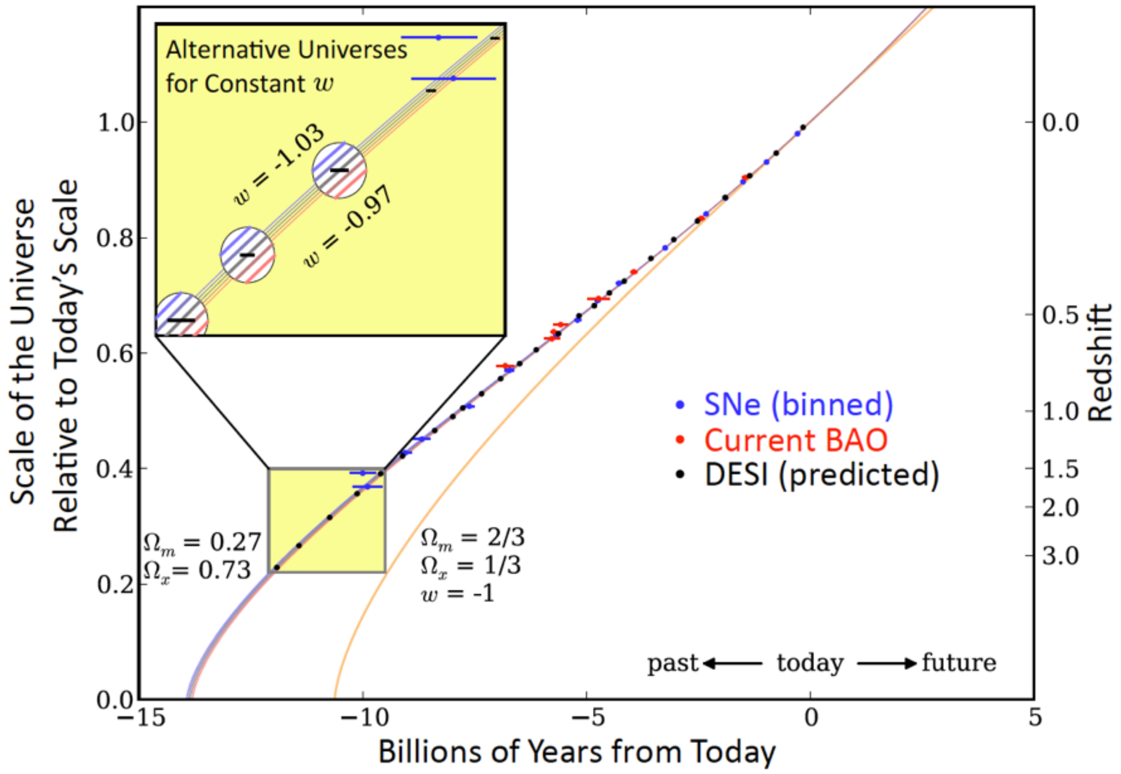


Figure 1: The expansion history of the Universe for different models of dark energy. The inset shows the spacing between five models with constant w ranging from -0.97 to -1.03, showing the exquisite precision required to distinguish these. Measurements from current supernovae are shown in blue; current BAO measurements from BOSS DR9, WiggleZ, and 6dF are shown in red; projections for DESI are shown in black.

DESI will also measure the sum of neutrino masses with an uncertainty of 0.020 eV, suficient to make the first direct detection of the sum of the neutrino masses at 3σ significance and rule out the inverted mass hierarchy at 99% CL, if the hierarchy is normal and the masses are minimal.

TECHNICAL OVERVIEW

The DESI instrument (Aghamousa et al. 2016b) is a robotically fiber-fed spectrograph capable of taking up to 5,000 simultaneous spectra in an 8 deg^2 focal plane feeding ten identical spectrographs, whose construction is under the responsibility of the French company "Winlight Optical Systems". A pair of dichroics in each spectrograph splits the light into three channels that together produce a continuous spectrum for each object from 360 nm to 980 nm, with a spectral resolution that ranges from 2000 in the UV to over 4000 in the red and IR.

The survey will make spectroscopic observations of four distinct classes of extragalactic sources. In dark and grey time, DESI will observe luminous red galaxies (LRGs), star-forming emission-line galaxies (ELGs) and quasars (QSOs). As shown in Table 1, over 7M LRGs will cover the redshift range $0.4 < z < 1$. The ELG sample is the largest set, 18M, covering $0.6 < z < 1.6$ and providing the majority of the distance scale precision. QSOs will be targeted both as direct tracers of the underlying dark matter distribution and, at higher redshifts, for the Ly-α forest absorption features in their spectra. In bright time, DESI will conduct a flux-limited survey of 10M brightest galaxies (BGs), with a median redshift around 0.2. DESI will provide at least an order of magnitude improvement over BOSS both in the comoving volume it probes and the number of galaxies it will map.

Table 1: Target categories in the DESI survey

Target	Number of objects	Redshift range
Luminous Red Galaxies (LRG)	7.7 million	z = 0.4-1.0 (dark time)
Emission Line Galaxies (ELG)	17.1 million	z = 0.6-1.6 (dark time)
Tracer QSOs	1.7 million	z < 2.1 (dark time)
Ly-α QSOs	0.7 million	z > 2.1 (dark time)
Bright Galaxies (BG)	9.9 million	z = 0.05-0.4 (bright time)

SCHEDULE

At the time of writing, DESI construction is nearly complete (fall 2019). The commissioning is starting in October 2019 till the end of February 2020. The collaboration will then conduct a 4-month Survey Validation program in spring 2020 and will begin the survey in summer 2020 for a five-year period.

ORGANIZATION AND PARTNERSHIP

The DESI Collaboration has more than 600 total members from almost 80 institutions from 13 countries around the world. DESI is being built by the DESI Collaboration with primary funding from the U.S. Department of Energy, and additional funding from other DESI Member Institutions (CEA, IN2P3 and INSU).

While the DESI instrument could continue to be usefully operated in the same configuration as the pre-2025 phase, there may be opportunities for augmentations. Notably, the spectrographs are modular and could be altered or replaced, subject to cost and space constraints, if the adopted science goals called for it.

THE MSE SURVEY

OVERVIEW AND KEY SCIENCE GOALS

The **Maunakea Spectroscopic Explorer (MSE**) is an end-to-end science platform for the design, execution and scientific exploitation of spectroscopic surveys. It will unveil the composition and dynamics of the faint Universe and impact nearly every field of astrophysics across all spatial scales, from individual stars to the largest scale structures in the Universe. The MSE project will transform the CFHT 3.6m optical telescope, atop Maunakea, on Hawaii's Big Island, into a 10m class dedicated multi-object spectroscopic facility, with an ability to simultaneously observe more than four thousand objects. The project is currently in its design phase, with full science operations nominally starting in 2027.

The MSE High-z Cosmology Survey (Percival et al. 2019) is designed to probe a large volume of the Universe with a galaxy density sufficient to measure the extremely-large-scale density fluctuations required to explore primordial non-Gaussianity and therefore inflation. A measurement of the level of non-Gaussianity as parameterized by the local parameter f_{NL} to a precision $\sigma(f_{NL})=1.8$ is expected.

Combining the MSE High-z Cosmology Survey data with data from a next generation CMB stage 4 experiment and existing DESI data will provide the first 5σ confirmation of the neutrino mass hierarchy from astronomical observations. Only combining the data from the MSE High-z Cosmology Survey together with Planck provides a 4σ neutrino mass measurement.

In addition, the Baryonic Acoustic Oscillations (BAO) observed within the sample will provide measurements of the distance-redshift relationship in six different redshift bins between z=1.6 and 4.0, each with an accuracy of ~0.6%. These high-redshift measurements will provide a probe of the Dark Matter dominated era and test exotic models where Dark Energy properties vary at high redshift. The simultaneous measurements of Redshift Space Distortions (RSD) at redshifts where Dark Energy has not yet become important directly constrain the amplitude of the fluctuations parameterized by σ_8, at a level ranging from 1.9% to 3.6% for the same redshift bins.

TECHNICAL OVERVIEW

The MSE telescope has an 11.25m aperture with a 1.5 square degree field of view that will be fully dedicated to multi-object spectroscopy. MSE is designed for transformative, high precision studies of faint astrophysical phenomena. 3249 fibers will feed spectrographs operating at low (*R* ~ 3000) and moderate (*R* ~ 6000) spectral resolution, and 1083 fibers will feed spectrographs operating at high (R ~ 20/40K) resolution. All spectrographs are available all the time. The entire optical window from 360–950 nm and the near-infrared J and H bands will be accessible at the lower resolutions, and windows in the optical range will be accessible at the highest resolution.

The survey will cover 10,000 deg^2, measuring redshifts for three classes of target objects: Emission Line Galaxies (ELGs), 5.4M galaxies, with $1.6<z<2.4$, Lyman Break Galaxies (LBGs), 7.0M galaxies, with $2.4<z<4.0$, and quasars $2.1<z<3.5$. The ELGs and LBGs will be used as direct tracers of the underlying density field, while the Ly-α forests in the quasar spectra will be used to probe structure along their lines of sight.

SCHEDULE

MSE has successfully completed the conceptual design and is starting the preliminary design phase, scheduled till the end of 2020. Following the end of preliminary design, the project will transition to the construction phase, including final design and fabrication work for each of the subsystems, followed in 2023 by the assembly, integration, testing and commissioning on Maunakea.

Two major milestones must first be achieved prior to the construction phase. First, land authorization for long-term continuation of astronomy on Maunakea, under which all Maunakea telescopes operate, must be renewed – a process that is underway now. Second, the MSE partnership must agree to fund and initiate the construction phase. The current schedule anticipates achieving both of these milestones by the end of 2022, leading to full science operations commencing in 2029.

ORGANIZATION AND PARTNERSHIP

The partnership model for MSE is designed to encourage partner communities to join by offering: the opportunity to design and lead major survey programs with MSE and access to data from all Legacy survey programs. During design and construction, there is an excellent opportunity for partners to contribute to the instrumentation program. Especially, in-kind contributions count toward partnership level.

The partners may be countries or communities, institutes or consortia of institutes, collaborations or participation groups. MSE currently counts 7 partners (Canada, France, Hawaii, Australia, China, India and Texas A&M) and two observers (NOAO and a consortium of institutions from the UK).

In addition to their contribution to the science cases, two French institutes, CNRS/INSU and more recently CEA/IRFU are involved in the design and the construction of six low and moderate resolution spectrographs. The design period would last two years, inducing strong interaction with the manufacturer of the DESI spectrographs, Winglight.

REFERENCES

Abolfathi, Bela et al. 2018. "The Fourteenth Data Release of the Sloan Digital Sky Survey: First Spectroscopic Data from the Extended Baryon Oscillation Spectroscopic Survey and from the Second Phase of the Apache Point Observatory Galactic Evolution Experiment." *The Astrophysical Journal Supplement Series* 235(2): 42.

Aghamousa, A. et al. 2016a. "The DESI Experiment Part I: Science, Targeting and Survey Design." arXiv:1611.00036 [astro-ph.IM].

———. 2016b. "The DESI Experiment Part II: Instrument Design." arXiv:1611.00037 [astro-ph.IM].

Amendola, Luca et al. 2018. "Cosmology and Fundamental Physics with the Euclid Satellite." *Living Reviews in Relativity* 21(1): 2.

Beutler, Florian et al. 2011. "The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant." *Monthly Notices of the Royal Astronomical Society* 416: 3017–32.

Dawson, K. S. et al. 2016. "The SDSS-IV Extended Baryon Oscillation Spectroscopic Survey: Overview and Early Data." *The Astronomical Journal* 151(2): 44.

Dawson, K.S. et al. 2013. "The Baryon Oscillation Spectroscopic Survey of SDSS-III." *Astron. J.* 145(1): 10.

Drinkwater, Michael J. et al. 2010. "The WiggleZ Dark Energy Survey: Survey Design and First Data Release." *Monthly Notices of the Royal Astronomical Society* 401(3): 1429.

Driver, S. P. et al. 2011. "Galaxy and Mass Assembly (GAMA): Survey Diagnostics and Core Data Release." *Mon.Not.Roy.Astron.Soc.* 413: 971.

Guzzo, L. et al. 2014. "The VIMOS Public Extragalactic Redshift Survey (VIPERS): An Unprecedented View of Galaxies and Large-Scale Structure at $0.5 < z < 1.2$." *Astron.Astrophys.* 566: A108.

Kollmeier, Juna A. et al. 2017. "SDSS-V: Pioneering Panoptic Spectroscopy." https://arxiv.org/abs/1711.03234v1 (August 5, 2019).

Percival, Will J. et al. 2019. "Cosmology with the MaunaKea Spectroscopic Explorer."

Perlmutter, S. et al. 1999. "Measurements of Ω and Λ from 42 High-Redshift Supernovae." *The Astrophysical Journal* 517(2): 565–86.

Pieri, M. M. et al. 2016. "WEAVE-QSO: A Massive Intergalactic Medium Survey for the William Herschel Telescope."

Planck VI et al. 2018. "Planck 2018 Results. VI. Cosmological Parameters."

Richard, Johan et al. 2019. "4MOST Consortium Survey 8: Cosmology Redshift Survey (CRS)." *Messenger* 175: 50.

Riess, Adam G. et al. 1998. "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant." *The Astronomical Journal* 116(3): 1009–38.

Tamura, Naoyuki et al. 2016. "Prime Focus Spectrograph (PFS) for the Subaru Telescope: Overview, Recent Progress, and Future Perspectives." *Proc.SPIE Int.Soc.Opt.Eng.* 9908: 99081M.

York, Donald G. et al. 2000. "The Sloan Digital Sky Survey: Technical Summary." *The Astronomical Journal* 120: 1579–87.