REPORT TO THE IN2P3 SCIENTIFIC COUNCIL

A large spectroscopic survey for Baryon Acoustic Oscillations: The DESI project

Report based on an earlier contribution from Julien Guy.

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Abstract

Baryon Acoustic Oscillations (BAO) are a major probe of the Dark Energy science, with low systematic uncertainties, and important complementarity with Type Ia Supernovae (SNeIa) for the measurement of the expansion history of the Universe. Massive spectroscopic surveys optimized for BAO can also measure the growth rate of structures with the redshift space distortions (RSD). This measure provides an independent test of General Relativity on cosmological scales, and helps constrain alternative theories of gravitation designed to explain the recent acceleration of expansion.

Massive spectroscopic and large imaging surveys are complementary to constrain Dark Energy. SNeIa, weak lensing, BAO and RSD provide different constraints on cosmological parameters. The combination of all the probes brings much more information that the sum of the projected constraints of each individual one. Also, the combination permits to mitigate the systematic uncertainties of each probe.

In2p3 groups have been involved for many years in the BOSS and projects and are pursuing their effort in the DESI survey, which is currently starting taking data. DESI is a large stage IV Dark Energy project aiming at measuring BAO and RSD with various targets (Luminous Red Galaxies, Emission Line Galaxies, quasars and Lyman-α forests) over a 14,000 square degree footprint. Observations are conducted on the 4-m diameter Mayall Telescope at Kitt Peak National Observatory, Arizona. The survey is about to start after being delayed by a few month by the COVID-19 crisis. DESI will be close to ten times as precise as the previous generation survey eBOSS at an effective redshift of $z \sim 1.3$, with a combined precision on the radial and longitudinal BAO scale of 0.3% and 0.5% respectively. At $z \geq 2.1$, with the Lyman-α forest auto-correlation, the integrated precision on the radial and longitudinal BAO scale is expected to be of 0.8% and 0.7%. DESI will bring an important complementarity to the Euclid BAO survey.

We present in this document the legacy of the SDSS BOSS and eBOSS projects and existing In2p3 contributions to the DESI project. In terms of financial cost, the participation to DESI is a relatively modest implication with a high expected scientific return. Continuing to participate in ground-based projects such as DESI is essential for In2p3 laboratories to maintain a high-level expertise on the BAO and RSD probes. This expertise will be needed to maximize the impact of In2p3 in the analysis of the future Rubin Observatory/LSST and Euclid surveys.

Contents

1 Introduction

The present document aims at presenting the current status of the DESI survey and the activity of the IN2P3 members involved in this project.

Being a probe of the expansion history, baryon acoustic oscillations (BAO) are a natural complement and extension of the Type Ia supernova (SNeIa) Hubble diagram at high redshifts. BAO have low systematic uncertainties making them very appealing if a sufficient statistical precision can be reached. This will be the case with the DESI spectroscopic survey that will be competitive and very complementary to the large programs Rubin Observatory/LSST and Euclid for constraining cosmological parameters describing the expansion history and growth rate of structures, the two main observables of Dark Energy. The DESI project will start its science data taking early 2021[1], *i.e.*, before Euclid and the Rubin Observatory/LSST, and important results are expected after the first year of observation. The preparation of the analyses started about 5 years ago and is still underway. It capitalizes on the BOSS and eBOSS collaborations experience. Members of IN2P3 involved in these two experiments are naturally pursuing their activity in DESI.

2 Scientific context

2.1 Baryon acoustic oscillations as a cosmological probe

Plasma sound waves that propagate in the early universe are frozen at recombination when matter and radiation decouple. They leave an imprint in the correlation function (or power spectrum) of the cosmic microwave background (CMB), which is an image of the universe at recombination. An excess of correlation is found at a comoving separation that can be accurately predicted from the energy density content of the early universe: it corresponds to the distance covered by the sound waves before recombination. This physical process is called baryon acoustic oscillations (BAO), and the preferred comoving separation, the sound horizon r_s.

BAO can also be found in large galaxy redshift catalogs (Figure 1, left) and quasars Lyman-α forests (Figure 1, right) that trace the matter density field at later times. The BAO scale detected in the angular correlation function of matter density tracers is a measurement of the angular diameter distance $D_A(z)$ at the redshifts of the tracers in units of r_s. Measuring it along the line of sight using the source redshifts gives the expansion rate $H(z)$ at the redshifts of the sources (in units of $1/r_s$). Combining CMB and BAO data in the framework of a given cosmological model gives an estimate of r_s and the constraints on $D_A(z)$ and $H(z)$ allow us to measure the expansion of the universe at late times and estimate for instance the cosmological constant or the Dark Energy equation of state parameter w.

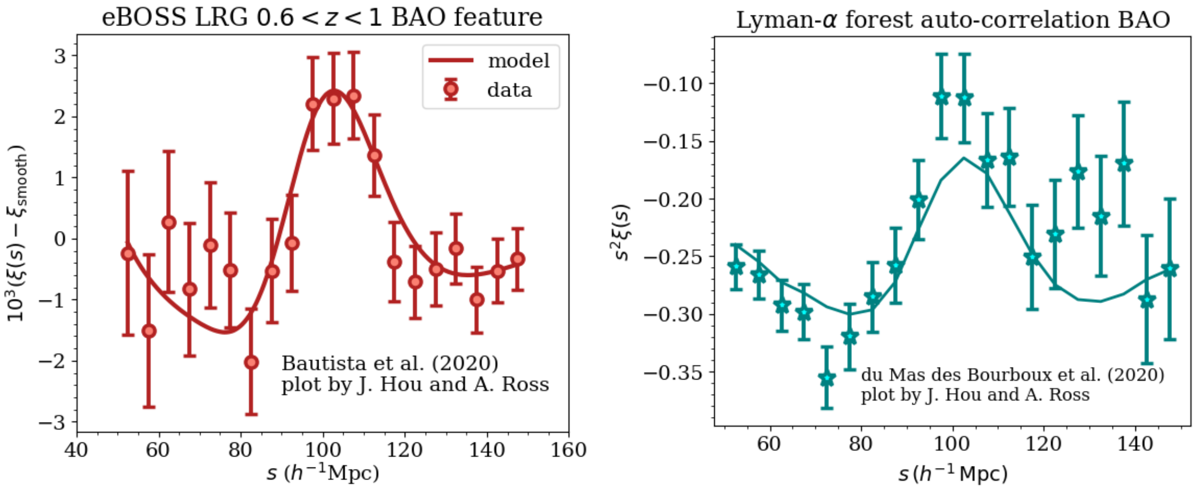

Figure 1: *BAO measurements from SDSS-eBOSS.* Left*: isotropic signal for LRG eBOSS sample at an effective redshift* $z = 0.7$ *[7].* Right*: combination of radial and transverse clustering measurements for the Lyman-*α *auto-correlation function measurement at an effective redshift* $z = 2.33$ *[17]*

Among the various tracers, Lyman-α forests open a new high redshift window for the measurement of the expansion rate. Each neutral hydrogen cloud at redshift z intersecting the line of sight of a background quasar leaves an absorption line in the quasar spectrum at a wavelength of $(1 + z) \times 121$ nm corresponding to the

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[1] With about 6/8 months delay due to the Covid-19 crisis that implied the shut-down of the Mayall telescope on which the DESI instrument is installed as early as March 16th, 2020.

Lyman-α atomic transition. The accumulation of such absorptions in a quasar spectrum at various redshifts is called a Lyman-α forest. It can be measured from the ground at wavelength $\gtrsim 350$ nm, corresponding to a minimal quasar redshift $z \gtrsim 1.9$. Whereas neither ground-based nor space-borne spectroscopic surveys are providing a sufficient density of high redshifts sources to measure the BAO scale at $z > 2$, this difficulty is overcome with the Lyman-α forests that do not require an equivalent statistics, as each quasar allows a pencil beam mapping of the neutral hydrogen along its line of sight. This has been demonstrated by the BOSS and eBOSS experiments where the BAO peak has been detected and measured in the correlation of Lyman-α forests at an effective redshift of 2.33 (Figure 1, right).

2.2 Strengths of the BAO probe

The BAO cosmological probe is complementary to SNeIa. Indeed, BAO measure absolute distances when combined with CMB, whereas supernovae only measure relative distances as a function of z. This allows for instance an independent estimate of the Hubble parameter H_0 (the inverse distance ladder) that can be compared with traditional measurements using the usual distance ladder [5]. In terms of statistical precision, whereas BAO cannot compete with SNe Ia at low redshifts because of the limited volume in a redshift shell (the so-called cosmic variance), they become more precise at $z \gtrsim 1$.

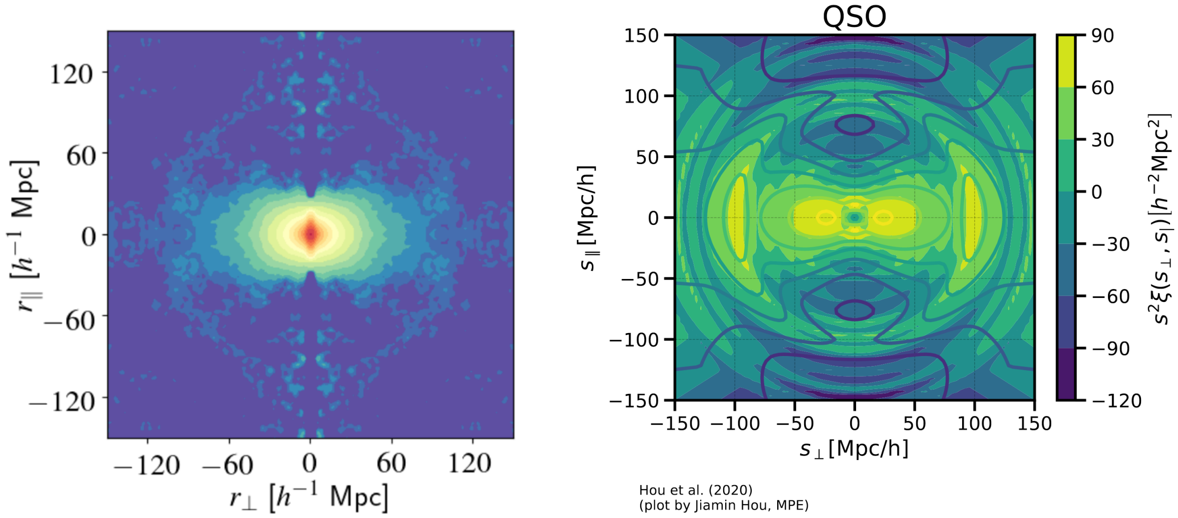
Another strength of BAO over other probes is that it is affected by low systematices uncertainties:

1. First, the measurement of a peak in the angular and redshift correlation function has very mild instrumental and data reduction systematic uncertainties. Even though important corrections are performed in the analysis process, for all target classes, they all impact the broad-band part of the correlation function and not its shape that would affect the BAO peak position, which is very stable to better than 1% in position. Moreover, the small shifts in the peak position can be modeled and corrected, leaving even smaller systematic uncertainties.

2. Secondly, the BAO peak is generated in the early universe where density contrasts are such that computations at the first order of perturbation give predictions at a sub-percent precision for the position of the peak. Higher order effects, due to the growth of structures at later times affect the shape of the peak. They are well quantified for galaxies, leading to a correction of 0.3%. The situation for Lyman-α forests is even more favorable as this tracer is in less dense regions.

2.3 Redshift space distorsion

Redshift space distorsions (RSD) refer to anisotropies observed in redshift surveys and induced by peculiar motions of tracers (Figure 2). Since coherent motions of galaxies are driven by gravity, RSD give us constraints on the growth rate of structures, $f(z)$. Measuring this growth rate is a test of General Relativity (GR) on cosmological scales, and permits to validate or rule out alternative theories of gravitation that could mimic the expansion history of ΛCDM, and hence be indistinguishable from the standard model of cosmology when constrained only by supernovae and BAO.



Hou et al. (2020)
(plot by Jiamin Hou, MPE)

Figure 2: Left: *anisotropic two-point correlation function of* eBOSS *LRG+CMASS galaxies at* $0.6 < z < 1$ *[7].* Right: *the 2D correlation function measured from the SDSS-eBOSS DR16 quasar sample [22].*

Besides the action of gravity shaping galaxy coherent motions, two other effects give rise to an apparent anisotropic clustering in redshift space. The first is the so-called Alcock-Paczynski test. Cosmological models that differ in their prediction for the expansion history will have different predictions for the transverse and longitudinal coordinate separation of a pair of galaxies given its observed angular and redshift separation. A model inconsistent with the true expansion history will lead to an apparent anisotropy in the correlation function.

A second effect is due to the dispersion of velocities of galaxies in dark matter halos at small scales that induce an apparent elongation of galaxy clusters along the light of sight (the so-called finger of god effect). This signal is difficult to model and leads to potential systematic uncertainties in the measurement of the growth rate and the Alcock-Paczynski test from the redshift space distortions.

2.4 Other science from large spectroscopic surveys

Recently, other probes have also shown to be promising objects for extracting cosmological parametres. Cosmic voids are excellent examples. These objects are defined as underdense regions of the Universe, surrounded by long filaments, walls and clusters of matter, that account for about 80 per cent of the total volume of the observable Universe. Several studies suggest that cosmic voids not only represent a key constituent of the cosmic mass distribution, but could also be one of the cleanest probes to test dark energy scenarios or modified gravity models. A very promising way to quantify deviations from GR is to measure the RSD in the cross-correlation of galaxies and void centres. Given their intrinsic low-density environment, voids are only weakly affected by complicated non-linear gravitational effects, and RSD modelling in the linear regime around cosmic voids provides a strong tool to extract the growth rate of structure.

Beyond BAO and RSD, massive redshift surveys also offer a very broad range of other scientific studies of interest for cosmology, particle physics, and the physics of the early universe. Measuring the matter power spectrum with galaxy catalogs, Lyman-α forest data and cosmic voids permits to test aspects of the standard cosmological model beyond the expansion and growth of structures, e.g., neutrino masses or inflation scenarios.

Finally, statistics beyond the two-point correlation function (or power spectrum) could help constrain the physics of the early universe.

3 The BOSS and eBOSS legacy

3.1 Data and BAO scale measurement

The Baryon Oscillation Spectroscopic Survey (BOSS [12]) and its extended version (eBOSS [13]), respectively during the SDSS phase-III and SDSS phase-IV, were conducted on the 2.5 m Sloan Telescope at Apache Point Observatory, New Mexico. The focal plane was equipped with an aluminum plate on which are plugged 1000 fibers dispatched to two spectrographs with 2 arms each. The spectrographs have a moderate resolution ($R \sim 2000$) which is sufficient to identify and measure the redshifts of targets at the required precision for a large scale structure survey. The design with two arms provides a good efficiency over a broad wavelength range from 360 nm to 1 μm.

Between 2008 and 2014, BOSS has collected optical spectra for over 1.5 million targets, distributed across a footprint of nearly 10,000 square degrees. The objects observed by BOSS are mainly Luminous Red Galaxies between $0.2 < z < 0.75$, and BOSS demonstrated for the first time that BAO correlations can also be seen using high redshift quasars and their Lyman-α forests as mass tracers. The BOSS DR12 [1] measurements achieve 1% precision measurements of the cosmological distance scale for redshifts $z < 0.75$ [2] and 2% precision measurements at $z = 2.33$ [6, 16]. BOSS showed that the BAO feature exists in the distribution of galaxies to greater than 10σ significance [2].

eBOSS began full operations in July 2014 and obtained spectroscopic observations of large-scale structure by targeting four distinct samples. eBOSS was completed on March 1st, 2019 and released its final Data Release (DR16) in July 2020. eBOSS extends the BOSS analysis using galaxies as direct tracers of the density field to measure BAO and RSD to higher redshifts, and increases the number of quasars used for Lyman-α forest studies. The four samples targeted by eBOSS correspond to Luminous Red Galaxy (LRGs) between $0.6 < z < 1.0$, Emission Line Galaxy (ELGs) between $0.6 <$ z < 1.1, Quasar clustering sample (QSO) covering the intermediate redshift range $0.8 < z < 2.2$ and high redshift quasars at $z > 2.1$ used through the Lyman-α forest. Along with the SDSS-I and -II, BOSS, and eBOSS spectroscopic surveys provide galaxy and quasar samples out to redshifts $z < 3.5$. The precision obtained of the expansion history measurements is 0.70% at redshifts $z < 1$ and 1.19% at redshifts $z > 1$, while the aggregate precision of the growth measurements is 4.77% over the redshift interval $0 < z < 1.5$ [3]. With this coverage and sensitivity, the SDSS experiment was unparalleled in its ability to explore models of dark energy.

3.2 eBOSS cosmological results

The SDSS BAO measurements cover 11 Gyr of cosmic expansion history. They allow to measure curvature, dark energy, neutrino mass, and the local Hubble expansion rate, while RSD measurements allow us to explore the impact of structure growth measurements on the cosmological model. When combining the results of SDSS BAO and RSD, Planck CMB, SNeIa, and DES weak lensing and clustering measurements, all multiple-parameter extensions remain consistent with a ΛCDM model. Regardless of cosmological model, the precision on Ω_Λ (the cosmological constant density parameter) and H_0 remains at roughly 1%. The dark energy constraints lead to an equation of state of $w_p = -1.020 \pm 0.032$ at a pivot redshift $z_p = 0.29$. The inverse distance ladder measurement under this model yields $H_0 = 68.20 \pm 0.81$ km s^{-1} Mpc^{-1}, remaining in tension with several direct determination methods [3].

3.3 Contribution of IN2P3 to the eBOSS project

The science developped at IN2P3 within the eBOSS collaboration is the Lyman-α forest auto-correlation analysis, the cross-correlation of Lyman-α forests with quasar density, and the quasar density auto-correlation (LPNHE), as well as the galaxy density auto-correlation and the use of cosmic voids as a probe of gravity (CPPM).

3.3.1 Lyman-α science

The first detection of the Lyman-α signal in the SDSS data [8, 15] was perfomed by a team at APC. The measurement of the Lyman-α auto-correlation function in the data release eBOSS DR14 has been entirely driven by LPNHE [14], improving over a similar analysis led by APC and LPNHE on the BOSS DR12 data [6]. The ouput of this work is a measure of the expansion rate at a few percents at $z = 2.33$. The LPNHE team was then strongly involved in the final analysis of the eBOSS DR16 data [17].

3.3.2 Cosmic Voids

With nearly one million galaxies measured redshifts in BOSS and eBOSS, the number of cosmic voids is of the order of a few thousand, depending of the void finding algorithm. CPPM researchers performed an RSD analysis around cosmic voids using data samples from the eBOSS DR16 [4]. Prior to the final DR16 analysis, the signature of RSD around voids was already performed using BOSS DR12 data [20, 19, 10] and the first two years of data from eBOSS Data Release 14 (DR14) in [21]. Results are very promising, and the large amount of data provided by next generation surveys such as DESI will dramatically reduce statistical errors.

3.3.3 Galaxy clustering and cross-correlation with weak lensing

CPPM researchers collaborate with some members of the Laboratoire d'Astrophysique de Marseille (INSU/LAM) and participate through a joint PhD thesis in the galaxy clustering analyses undertaken on eBOSS DR16 LGRs [7, 18]. In addition, they have been involved in a combined galaxy clustering and galaxy-galaxy lensing analysis using shape catalogues from CFHTLenS and CFHT-Stripe 82, and spectroscopic redshifts from the BOSS DR12 sample. The so-called probe of gravity was estimated as $E_G = 0.43 \pm 0.10$ [23], in agreement with ΛCDM-GR predictions of $E_G = 0.40$ [26].

4 DESI

4.1 Overview

The Dark Energy Spectroscopic Instrument (DESI) is a DOE Stage IV Dark Energy project aiming at measuring BAO and redshift space distortions with a sample of 10 million bright galaxies at $z < 0.5$ (BGS), LRGs (4 millions), ELGs (17 millions), quasars (1.7 millions) and Lyman-α (0.7 million) over a 14,000 square degree footprint. It is very similar to BOSS/eBOSS in its concept, but with a considerably increased statistics thanks to major improvements in the instrument system. Observations will be conducted on the 4-m diameter Mayall Telescope at Kitt Peak, Arizona. The focal plane is equiped with a 5000 robotically-actuated fiber system feeding 10 spectrographs located in a temperature-controled room. Each spectrograph receiving 500 fibers is composed of three arms/cameras which optics and CCD are optimised for blue, red and near infra-red wavelengths. The design maximizes the throughput over the wavelength range accessible with CCDs from the ground. The wavelength resolution is tuned for the identification of the two lines of the [OII] doublet, which is a crucial requirement to identify and measure the redshifts of faint ELGs.

After a delay due to the shutdown of the Mayall telescope during the Covid-19 crisis, the science survey will start at the beginning of 2021. The survey planning is optimized for early science results, with a first pass on the whole sky during the first year. Subsequent years will be dedicated to the re-observation of most targets, with additional targets that could not be allocated a fiber in the previous passes. With this strategy, significant cosmological results are expected after the first year of data taking.

4.2 Scientific goals

The expected precision on the BAO scale in independent redshift bins are reproduced from the DESI Technical Design report (TDR) in Figure 3 for the isotropic BAO scale (combined radial and transverse measurements). DESI will be a major experiment for the measurement of the expansion history, comparable to Planck for the CMB temperature anisotropies. As an example, DESI will be close to ten times as precise as eBOSS at an effective redshift of $z \sim 1.3$ (when integrating the combined ELG, LRG and quasar forecast over the redshift range probed by the main survey), with a combined precision on the radial and longitudinal BAO scale of 0.3% and 0.5% respectively. At $z > 2.1$, with the Lyman-α forest auto-correlation, the integrated precision on the radial and longitudinal BAO scale is expected to be of 0.8% and 0.7%. It is very likely that those statistical predictions will not be dominated by systematic errors. In addition to providing constraints on Dark Energy, DESI will provide new measurements that can constrain theories of modified gravity and inflation, and that will measure the sum of neutrino masses.

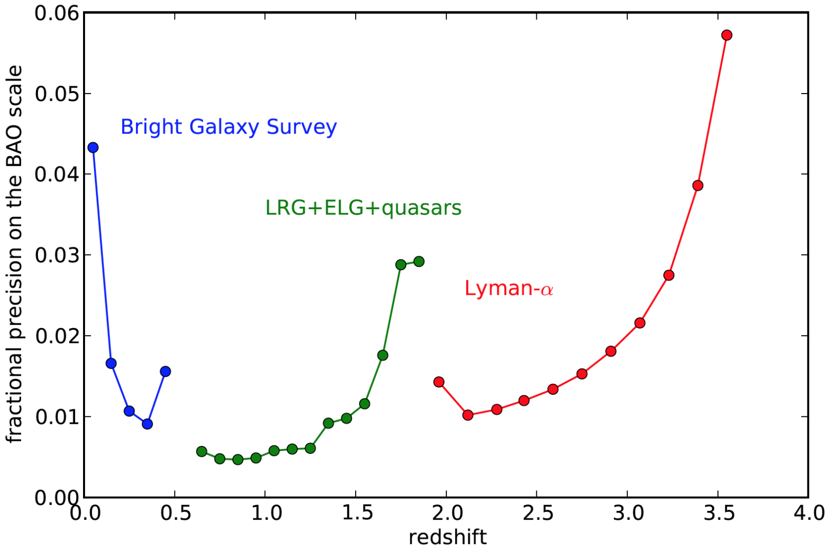


Figure 3: *Fractional precision on the isotropic BAO scale in independent redshift bins (from the DESI Technical Design Report)*

4.3 Current status of the experiment

After 6 months of shutdown due to the Covid-19 crisis, the commissioning at Kitt Peak has started again mid-September 2020. The re-commissioning plan covers the time period from regaining access to the instrument to the start of survey validation (SV). Some commissioning tasks will extend into SV and are expected to be performed during bright time. The early re-commissioning tasks cover restarting the instrument, validation of the fault monitor system and check out of new software and hardware components. This is followed by a group of tasks designed to calibrate DESI components: spectrographs, Guide Focus & Alignment systems and focal plane (positioners). We expect to return on focal plane by the end of October 2020 and we will check the focal plane metrology and update the instrument settings. Spectrographs are expected to be ready by mid-November.

SV is expected to start in December if there is no further delay in the schedule and the last group of tasks will be performed during SV when time permits (for example during bright time).

4.4 French contributions to DESI

Over the past five years, French institutes and teams have provided important contributions to the DESI project.

- CEA/IRFU has provided the cryostats for the 30 cameras (3 cameras for 10 spectrographs).

- An Aix-Marseille University (AMU) consortium, composed of the CPPM, LAM and OHP laboratories, has negociated a staff effort to the development of the DESI spectrographs. The ten DESI spectrographs have been developed, assembled and integrated by Winlight, a PACA company based in Pertuis (84) and reknowned for its high quality optics. The AMU consortium was responsible for the integration of spectrographs and for their scientific validation. The deployment of the ten spectrographs was completed in the beginning 2020.

- LPNHE has been involved in the software development of the spectroscopic pipeline, and has participated to the preparation of the spectrograph tests with software development and the construction of an optical device to calibrate the throughput of the spectrographs. This effort has led to a signed agreement with DESI to allow the participation of reseachers. 10 permanent researchers are linked to this effort, and 4 are at IN2P3.

4.5 IN2P3 participation to DESI

4.5.1 IN2P3 members involved in DESI

The DESI Collaboration has more than 600 total members from almost 80 institutions from 13 countries around the world. The IN2P3 members involved in DESI belong to two laboratories (CPPM and LPNHE) and include 5 permanent researchers (among which one Professor Emeritus), 1 research ingineer, 2 postdocs and 5 PhD students (see Annex 1). Each member has privileged access to DESI private data before it becomes public with Data Releases. Each DESI participant can sponsor up to 2 postdocs and an unlimited number of PhD students.

4.5.2 Software contribution

IN2P3 participants are involved in the Lyman-α forest and galaxy clustering working groups and the general purpose simulations in relation to the data pipeline. LPNHE researchers have contributed to the development of the DESI redshift fitting code and the production of redshfit catalogs from mock galaxy catalogs. They have also made substantial contributions to the software required for Lyman-α studies. These latter contributions are focused on two key elements of the analysis.

1. The first element is the quasar identification. Quasars targets need to be confirmed after the first pass in order to boost the purity in the susequent passes. This identification will be made automatically by combining the results of three different codes, RedRock, SQUEzE and QuasarNet, with different approaches. LPNHE researchers have contributed to RedRock, have developed QuasarNet, have adapted the code SQUEzE to be able to run with DESI data, and are working on establishing the combination strategy [24, 25, 9].

2. The second element is the main analysis code for BAO measurements using the Lyman-α forest. The eBOSS Collaboration developed the code PICCA as the main tool for this analysis. PICCA will also be used in DESI, but substantial changes are required to adapt it to DESI. These changes are coordinated by the PICCA task force, led by LPNHE researchers.

4.5.3 Integration and tests of DESI spectrographs

The ten DESI spectrographs have been built and tested in France at the main site of Winlight Systems, in Pertuis. The spectrographs qualification tests were under the responsability of a team of AMU led by P.-E. Blanc and S. Perruchot, in collaboration with the LPNHE team: J. Guy was in charge of the analysis of the spectrograph CCD frames and the corresponding pipeline, while L. Le Guillou was responsible of the spectrographs throughput measurements. The throughput measurement had been previously identified as a critical test, as a too low throughput could severely reduce the DESI performances.

For the throughput measurement, the LPNHE team has designed, tested and built an optico-mechanical device which allows to calibrate the absolute flux injected in the spectrograph at the exit of the fibers, and then, by comparison with the integrated light flux measurement on the CCD sensors of the 3 spectrograph arms, estimate the optical throughput of each spectrograph arm at several wavelengths.

This device has been installed on the AMU optical bench at Winlight in late 2016 ; it has been used for the prototype spectrograph EM#1, for which the LPNHE team found a very low throughput on the blue (B) and near-infrared arms (NIR). This low throughput was due to a wrong mounting (upside-down) of the corresponding Volume Phase Holographic Gratings (VPHG) of these two spectrograph arms, sending the -1 order instead of the optimized +1 order to the corresponding CCD sensors. This mistake was quickly fixed, and a later measurement with the same device confirmed that this problem was solved (Figure 5). During 2018 and 2019, the LPNHE team measured the throughput of the ten spectrographs (SM01 to SM10) with the same device.

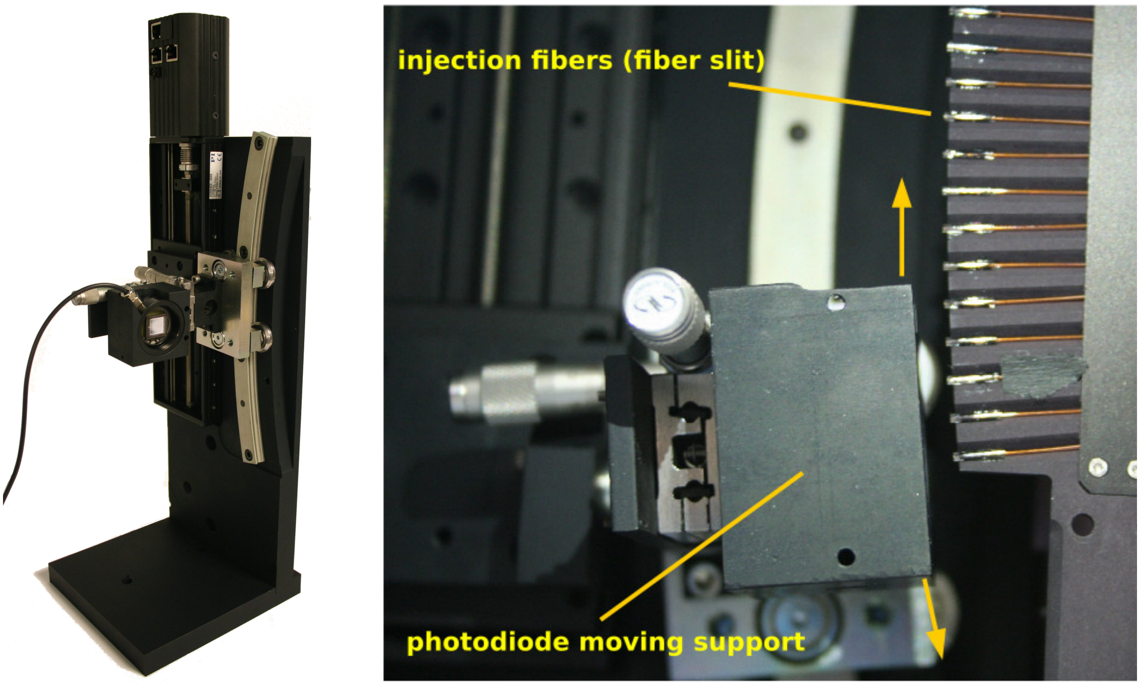


Figure 4: *The LPNHE device built to measure the DESI spectrograph throughput. It has been used for the prototype spectrograph EM#1/SM#1, and allowed the LPNHE team to detect a mistake in the way the Volume Phase Holographic Gratings were mounted on two of the three arms of the prototype spectrograph.*

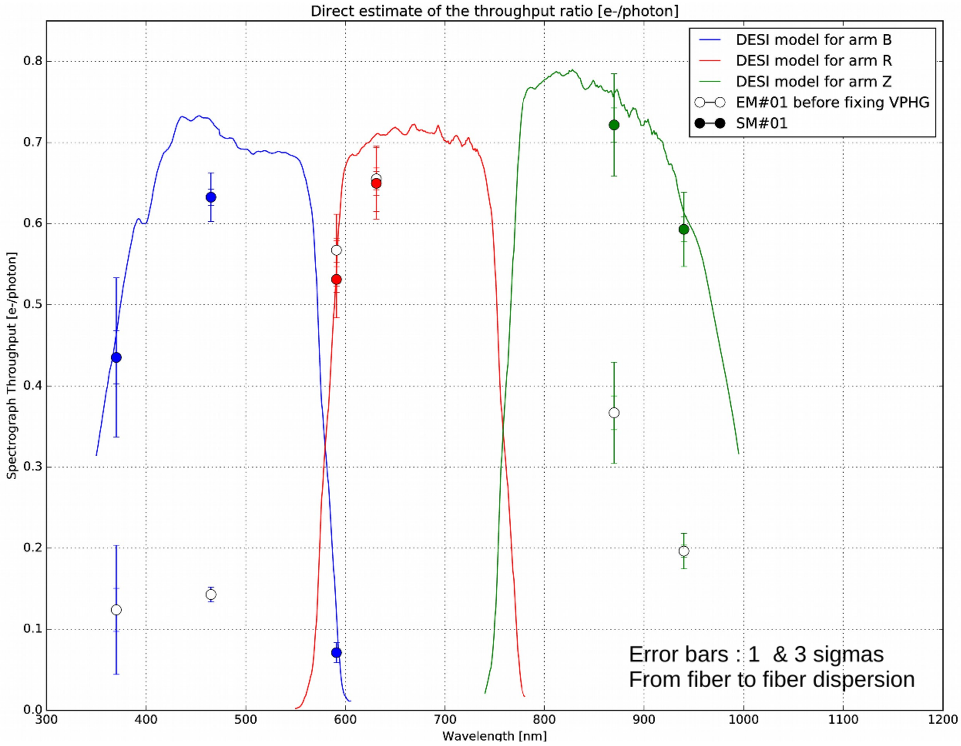


Figure 5: *the LPNHE estimate of the throughput of the EM#1 / SM#1 spectrograph, before (white dots) and after (full dots) the VPHG mounting has been fixed on the blue and near infrared arms. A comparison with the throughput prediction from the spectrograph optical model is also shown (lines).*

4.5.4 DESI calibration system on the Mayall telescope

The LPNHE DESI team was in charge of designing, building, testing, installing and commissioning the main DESI calibration system. It has been delivered in 2018 and 2019, and installed in 2019 at Kitt Peak, on the Mayall telescope. It consists of 4 identical calibrated illumination racks, attached on the upper ring of the

Mayall telescope, pointing towards a Permaflex Lambertian screen of a diameter of 4 m, attached to the Mayall dome. These devices allow to inject light into the 5000 DESI fibers with a well known spectrum and intensity. We provided the Permaflex screen, and we designed and built the 4 illumination racks.

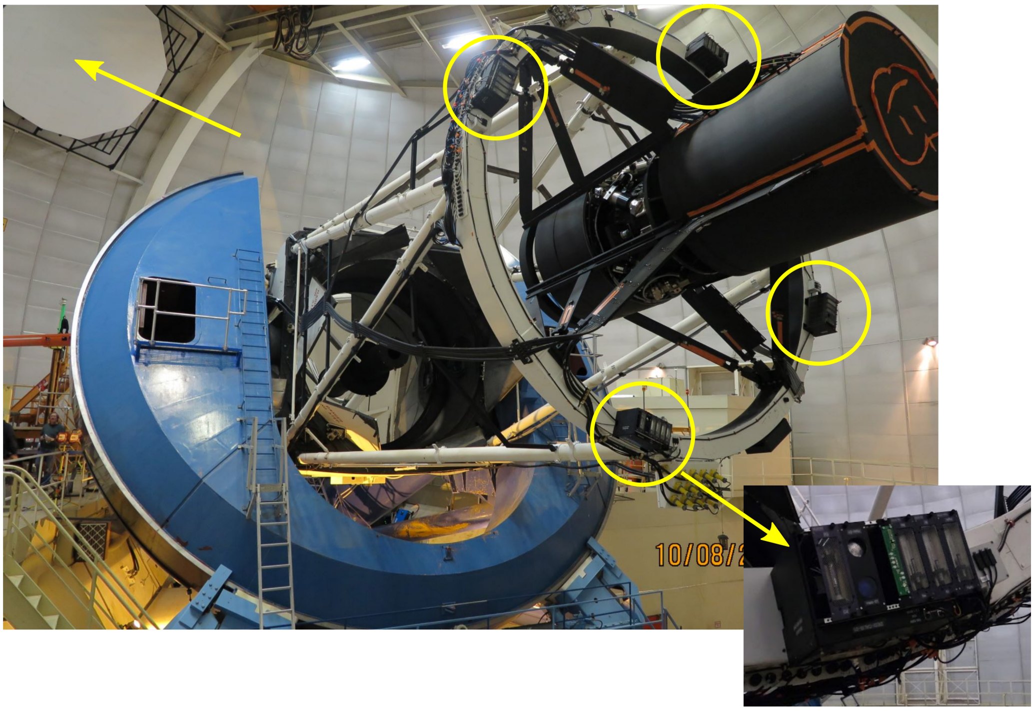


Figure 6: *The Mayall telescope with the DESI calibration system provided by LPNHE: the 4 illumination racks installed on the upper ring, and the Lambertian white screen attached to the dome.*

Each illumination rack contains an optimized combination of arc lamps (Xe, Kr, Cd, HgNe, Ar) to perform the wavelength calibration of the ten DESI spectrographs (this is done every night, just before the sky observations). They also contain continuum sources: halogen lamps and an home-made white lamp combining 60 tunable LEDs covering the whole DESI range (350–1000 nm). These continuum sources are used to estimate the relative throughput of each of the 5000 DESI fibers, which is critical to be able to properly subtract the sky background from the target spectra, especially for low S/N targets.

For their contribution to the building of DESI (for the spectrographs and the calibration system), Julien Guy, Sonia Karkar and Laurent Le Guillou from LPNHE have been awarded the status of *DESI builders*, which allow them to request authorship on any DESI publications.

4.5.5 Preparation of galaxy & Lyman-α analyses

After eBOSS, LPNHE continues its implications in the analyses of the Lyman-α forests with DESI in order to measure the BAO. CEA/Irfu has developed mock catalogues that generate quasar spectra with several properties such as the continuum, noise, presence of metals and high column density systems in order to mimic the data the most accurately possible. LPNHE is involved in the testing and analysis of these mocks to identify and mitigate the systematics that affect the measurement of the BAO feature in the signal.

LPNHE is also developing a new activity in galaxy clustering with a significant contribution to the Bright Galaxy Survey (BGS) with Pauline Zarrouk (who recently joined the laboratory) being the co-chair of this working group from September 2019 to October 2020. Contributions include the design of the target selection pipeline [27] for this sample (done before arrival at LPNHE) and the characterisation of the clustering properties of the BGS targets. These properties include the angular clustering of the BGS targets, its comparison with a power-law fitting at small scales in order to measure the slope and clustering scale which can be used to tune mocks for BGS. Eventually, cross-correlation with external spectroscopic datasets is also studied in order to extract information about the redshift distribution of the BGS targets without using any photometric information.

Eventually, LPNHE will also contribute to the standard BAO and RSD analyses with this sample of low-redshift galaxies, together with other non-standard analyses in order to extract information from the non-linear regime where the RSD effect is dominant and improve the measurement of the growth of structure and thus the constraints on General Relativity and alternative models of gravity. Two projects led by LPNHE using

DESI year-1 BGS data have already been announced within the DESI collaboration, one to develop a multi-tracer technique [28] in order to reduce cosmic variance in the BGS sample and get more precise constraints on the cosmological parameters; and another to explore the small-scale clustering of galaxies using a recently developed model of RSD [11]. Moreover, Pauline Zarrouk is now the co-convenor of Key Project 5 that consists in coordinating the Full-Shape analyses of the DESI Y1 data for all tracers (from BGS to quasars) in order to constrain the cosmological parameters.

4.5.6 Preparation of void analyses

CPPM researchers are strongly involved in void analysis and plan to pursue their activity on the constraint of the linear growth rate of structure using the RSD patterns around voids. This work will benefit of the massive DESI data, which will provide an unprecedented lever arm over the redshift range $0 < z < 2$.

Moreover, CPPM researchers are particularly interested in a joint analysis between different cosmological probes. A PhD student is starting his thesis on a complementary way to investigate tests of gravity by the measurement of the weak gravitational lensing around voids. Indeed, the measurement of weak gravitational lensing probes matter inhomogeneities in the Universe through the deflections of the light of background sources. Although the weak lensing measurements are widely performed to map matter overdensities, it has been suggested that they should be affected by underdensities in the matter distribution as well. This project has been announced within the DESI Collaboration.

4.5.7 Contribution to the survey validation

LPNHE and CPPM researchers have contributed to the visual inspection effort of Survey Validation data, both for galaxies and quasars. This effort is essential to construct truth tables of objects that will later be used to validate the automatic classification for quasars.

On the galaxy side, efforts are focused on assessing the required signal-to-noise ratio of the BGS spectra in order to get the desired redshift completeness and efficiency. On the one hand, the SV data will be compared to spectral simulations developed by LBNL and the survey strategy will be adjusted accordingly and on the other hand, it will be compared to the results obtained in Zarrouk et al (*in prep*), in particular those about the angular clustering and redshift distribution.

5 Conclusion

Baryon Acoustic Oscillations are a major probe of the Dark Energy science, with low systematic uncertainties, and important complementary with SNeIa for the measurement of the expansion history (absolute distance measurement, measurement of the instantaneous expansion rate, extension of the SNeIa Hubble diagram to higher redshifts). Maybe more importantly, BAO in the Lyman-α forests are the only means today to test the ΛCDM scenario in a redshift range where the expansion is largely dominated by the matter density and not the puzzling Dark Energy. Massive spectroscopic surveys optimized for BAO can also measure the growth rate of structures with the redshift space distortions. This provides an independent test of General Relativity on cosmological scales, and helps constrain alternative theories of gravitation designed to explain the recent acceleration of expansion.

There are obvious complementarities between large imaging surveys and massive spectroscopic surveys optimized for BAO. Among those, the most important one is related to the Dark Energy science. Supernovae, weak lensing, BAO and RSD provide different constraints on cosmological parameters, and the combination of all the probes, in a multi-parameter space, brings much more information that the sum of the projected constraints of each individual one. Also, being in essence very different observables, the combination permits to mitigate the systematic uncertainties of each probe.

IN2P3 groups have been involved for many years in the BOSS and eBOSS projects and are pursuing their effort in the DESI project, which is about to start taking science data. They have a good scientific visibility in the Lyman-α forests, galaxy clustering and void analyses. We have presented the recent and current IN2P3 contribution to DESI, which involves developments in two laboratories (CPPM and LPNHE). In terms of technical manpower and financial cost, the participation is a relatively modest implication.

The BAO activity presented in this report is very rich and has been evolving for the past 15 years and will continue to mature up to the start of Euclid and Rubin Observatory/LSST. It is of main importance that the IN2P3 teams be involved in the development of the analyzes in this domain by continuing their effort in DESI. This will allow them to be ready and prepared for the Euclid and Rubin Observatory/LSST science challenges with the same and unique objective, understanding the nature of Dark Energy.

6 Annex 1: DESI list of IN2P3 participating members

1. CPPM (AMU - RPG):
    - S. Escoffier (DR), member of the DESI Meetings Committee (2018-2020)
    - M.-C. Cousinou (PR Emeritus)
    - A. Secroun (IR)
    - P. Ntelis (PostDoc) until end of 2020
    - M. Aubert (PhD) (2017-2020)
    - R. Paviot (PhD) (2018-2021)
    - R. Boschetti (PhD) (2020-2023)
2. LPNHE:
    - C. Balland (PR Sorbonne Université)
    - P. Zarrouk (CR; from 2020)
    - L. Le Guillou (MCF Sorbonne Université)
    - I. Perez-Rafòls (PostDoc) until end of 2021
    - J. Stermer (PhD) (2018-2021)
    - T. Tan (PhD) (2020-2023)
3. Former members
    - N. Busca (CR, LPNHE, left end of 2018)
    - S. Karkar (IR, LPNHE, left mid 2019)
    - A. Ealet (DR, CPPM, left 2019)
    - A. Hawken (PostDoc, CPPM, left end of 2019)

7 Annex 2: list of SDSS-related and DESI publications involving IN2P3 participants

1. "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Galaxy Surveys at the Apache Point observatory", S. Alam et al. (eBOSS Collaboration) (2020), arXiv:2007.08991

2. "The Completed SDSS-IV Extended Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations with Lyα Forests, H. du Mas des Bourboux et al. (eBOSS Collaboration) (2020), ApJ, 901, 153

3. "The Completed SDSS-IV Extended Baryon Oscillation Spectroscopic Survey: Growth rate of structure measurement from cosmic voids", M. Aubert et al., (2020), arXiv:2007.09013

4. "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: geometry and growth from the anisotropic void-galaxy correlation function in the luminous red galaxy sample between redshifts 0.6 and 1", S. Nadathur et al. (2020), arXiv:2008.06060

5. "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: measurement of the BAO and growth rate of structure of the luminous red galaxy sample from the anisotropic correlation function between redshifts 0.6 and 1", J. Bautista, R. Paviot et al., accepted in MNRAS (2020), arXiv:2007.08993

6. "The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: measurement of the BAO and growth rate of structure of the luminous red galaxy sample from the anisotropic power spectrum between redshifts 0.6 and 1.0", H. Gil-Marin, J. Bautista, R. Paviot et al., Month. Not. Royal Astron. Soc. 498 (2020) 2492., arXiv:2007.08994

7. "Large-scale Structure Catalogs for Cosmological Analysis of the completed extended Baryon Oscillation Spectroscopic Survey", A.J. Ross et al., (2020), arXiv:2007.09000

8. "Constraints on the growth of structure around cosmic voids in eBOSS DR14", A. Hawken, M. Aubert et al., JCAP 06 (2020) 012, arXiv:1909.04394

9. "Spectroscopic QUasar Extractor and redshift (z) Estimator SQUEZE - I. Methodology", I. Perez-Ràfols et al. MNRAS, 496, 493 (2020)
10. "Spectroscopic QUasar extractor and redshift (z) estimator SQUEZE - II. Universality of the results", I. Perez-Ràfols et al. MNRAS, 496, 494 (2020)
11. “The Sixteenth Data Release of the Sloan Digital Sky Surveys: First Release from the APOGEE-2 Southern Survey and Full Release of eBOSS Spectra”, R. Ahumada et al. (SDSS-IV Collaboration), APJS 249 (2020) 3., arXiv:1912.02905 [astro-ph.GA]
12. “The Fifteenth Data Release of the Sloan Digital Sky Surveys: First Release of MaNGA Derived Quantities, Data Visualization Tools and Stellar Library”, D.S. Aguado et al. (SDSS Collaboration), Astrophys. J. Suppl. S. 240 (2019) 23, arXiv:1812.02759 [astro-ph.IM]
13. "Baryon acoustic oscillations from the cross-correlation of Lyα absorption and quasars in eBOSS DR14", M. Blomqvist et al. A&A, 629, 86 (2019)
14. "Baryon acoustic oscillations at $z = 2.34$ from the correlations of Lyα absorption in eBOSS DR14", de Sainte Agathe et al. A&A, 629, 85 (2019)
15. "The Extended Baryon Oscillation Spectroscopic Survey: Measuring the Cross-correlation between the Mg II Flux Transmission Field and Quasars and Galaxies at $z = 0.59$", H. du Mas des Bourboux et al., ApJ, 878, 47 (2019)
16. Overview of the DESI Legacy Imaging Surveys, A. Dey, et al. AJ, 157, 168 (2019)
17. “Testing gravity and dark energy with galaxy-galaxy lensing and redshift-space distortions using CFHT-Stripe 82, CFHTLenS and BOSS CMASS datasets”, E. Jullo et al., Astron. Astrophys. 627 (2019) A137, arXiv:1903.07160 [astro-ph.CO]
18. “Multivariate analysis of cosmic void characteristics”, M.-C Cousinou et al., Astron. Comp. 27 (2019) 53., arXiv:1805.07181 [astro-ph.CO]
19. "QuasarNET: Human-level spectral classification and redshifting with Deep Neural Networks", N. Busca & C. Balland, (2018) arXiv:1808.09955
20. “The scale of cosmic homogeneity as a standard ruler”, P. Ntelis et al., JCAP 1812 (2018) 14, arXiv:1810.09362 [astro-ph.CO]
21. “The Fourteenth Data Release of the Sloan Digital Sky Survey: First Spectroscopic Data from the extended Baryon Oscillation Sky Survey and from the second phase of the Apache Point Observatory Galactic Evolution Experiment”, B. Abolfathi et al. (SDSS Collaboration), Astrophys. J. Suppl. 235 (2018) 42, arXiv:1707.09322 [astro-ph.GA]
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24. “The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample”, S. Alam et al. (BOSS Collaboration), Month. Not. Royal Astron. Soc. 470 (2017) 2617., (arXiv:1607.03155 [astro-ph.CO])
25. “Multipole analysis of redshift-space distortions around cosmic voids”, N. Hamaus, M.-C. Cousinou et al., JCAP 1707 (2017) 014., (arXiv:1705.05328 [astro-ph.CO])
26. "Exploring cosmic homogeneity with the BOSS DR12 galaxy sample", P. Ntelis et al., JCAP 06 (2017) 019., arXiv:1702.02159 [astro-ph.CO]
27. “Constraints on cosmology and gravity from the dynamics of voids”, N. Hamaus, A. Pisani et al., Phys. Rev. Lett. 117 (2016) 091302. (arXiv:1602.01784 [astro-ph.CO])
28. “The SDSS-IV eBOSS emission-line galaxy pilot survey”, J. Comparat et al. (eBOSS Collaboration), Astron. Astrophys. 592 (2016) A121.

29. “Jackknife resampling technique on mocks: an alternative method for covariance matrix estimation”, S. Escoffier et al., arXiv:1606.00233 [astro-ph.CO] (2016)

30. “The SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Overview and Early Data”, K. Dawson et al. (eBOSS Collaboration), Astron. J. 151 (2016) 44., (arXiv:1508.04473 [astro-ph.CO])

31. "The DESI Experiment Part I: Science,Targeting, and Survey Design", A. Aghamousa et al. (2016) DESI Collaboration

32. "The DESI Experiment Part II: Instrument Design", A. Aghamousa et al. (2016) DESI Collaboration

33. “The Eleventh and Twelfth Data Releases of the Sloan Digital Sky Survey: Final Data from SDSS-III”, S. Alam et al. (SDSS Collaboration), Astrophys. J. Suppl. S. 219 (2015) 12.

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36. “The Tenth Data Release of the Sloan Digital Sky Survey: First Spectroscopic Data from the SDSS-III Apache Point Observatory Galactic Evolution Experiment”, C. P. Ahn et al. (SDSS Collaboration), Astrophys. J. Suppl. S. 211 (2014) 17.

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