Large spectroscopic surveys for Baryon Acoustic Oscillations: the eBOSS and DESI projects

Report to the IN2P3 scientific council

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Summary

Baryon Acoustic Oscillations are a major probe of the Dark Energy science, with low systematic uncertainties, and important complementary with Supernovae Ia for the measurement of the expansion history (absolute distance measurement, measurement of the instantaneous expansion rate, extension of the Hubble diagram to much higher redshifts with the Lyman-α forests). Massive spectroscopic surveys optimized for BAO can also measure the growth rate of structures with the redshift space distortions (RSD). This provides an independent test of general relativity on cosmological scales, and help constrain alternative theories of gravitation designed to explain the recent acceleration of expansion.

There are obvious complementarity between large imaging surveys and massive spectroscopic surveys optimized for BAO (measurement of the host galaxies redshifts of photometrically identified SNe, calibration of photometric redshifts, both being mandatory for the physical interpretation of the Supernova Hubble diagram and the weak lensing power spectrum). Supernovae, 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 project and are pursuing their effort in the eBOSS survey, which is currently taking data. The same groups are participating to the preparation of the upcoming DESI survey.

DESI is a large Dark Energy project aiming at measuring BAO and redshift space distortions with LRG, ELG, quasars and Lyman-α over a 14,000 square degree footprint. Observations will be conducted on the 4-m diameter Mayall Telescope at Kitt Peak, Arizona. The survey will begin in 2019. DESI will be close to ten times as precise as 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 $z > 2.1$, with the Lyman-α forest auto-correlation, the integrated precision is 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 existing IN2P3 contributions to this project and a path to reinforce them. It involves software and hardware developments in three laboratories. In terms of technical manpower and financial cost, the participation to eBOSS and DESI is a relatively modest implication with a high expected scientific return. Participating to the ground-based projects eBOSS and 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 LSST and Euclid surveys.

An important outcome of this scientific council would thus be an evaluation of this proposal: an IN2P3 participation to the DESI project, and a moderate support to the on-going eBOSS activities.

Contents

1 Introduction

This document is part of a larger review on Dark Energy science at IN2P3. We report here on the potential of the baryon acoustic oscillations (BAO) and redshift space distortions (RSD) probes and focus on two projects with existing IN2P3 activities, eBOSS (for extended Baryon Oscillations Spectroscopic Survey) and DESI (for Dark Energy Spectroscopic Instrument). We discuss those activities in the context of a participation of IN2P3 to LSST and Euclid. The intention is first to demonstrate that BAO and RSD will be key to the Dark Energy science in the coming years, and second, that DESI is a promising and advanced project for this observable, that complements the Euclid BAO survey at both lower and higher redshifts.

Being a probe of the expansion history, BAO are a natural complement and extension of the Supernova Ia 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 LSST and Euclid for constraining cosmological parameters related to the expansion history and growth rate of structures, the two main observables of Dark Energy. The DESI survey will start at the end of 2019, before Euclid and LSST, and important results are expected after the first year of observation. We present in this document current and possible development of activities at IN2P3 for the project construction phase. Because in the coming four years (2016-2019), it is desirable to develop the BAO and RSD analysis techniques with existing data sets, the IN2P3 groups involved in DESI are also participating to the eBOSS project, which is currently taking data.

We give a brief overview of the probes, the key physics questions they address, emphasize their complementarity with Type Ia supernovae and weak lensing, discuss their systematic uncertainties and summarize the results obtained with the existing projects in §2. We then present the eBOSS and DESI projects in §3 and §4, focusing on the scope of the activities being pursued at IN2P3. We then conclude in §5.

2 Scientific context

2.1 Baryon acoustic oscillations as a cosmological probe

2.1.1 Physical process

Plasma sound waves that propagate in the early universe are frozen at recombination when matter and radiation decouple. This is imprinted 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 wave before recombination. This physical process is called baryon acoustic oscillations (BAO), and the preferred comoving separation the sound horizon (or r_s). BAO can also be found in large galaxy redshift catalogs (see Figure 1) and quasars Lyman-α forests (see Figure 2) that trace the matter density field at later times (or lower redshift). 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.

2.1.2 BAO in the Lyman-α forests

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 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 (because the atmospheric and instrumental UV cutoff) corresponding to a minimal quasar redshift $z \gtrsim 1.9$.

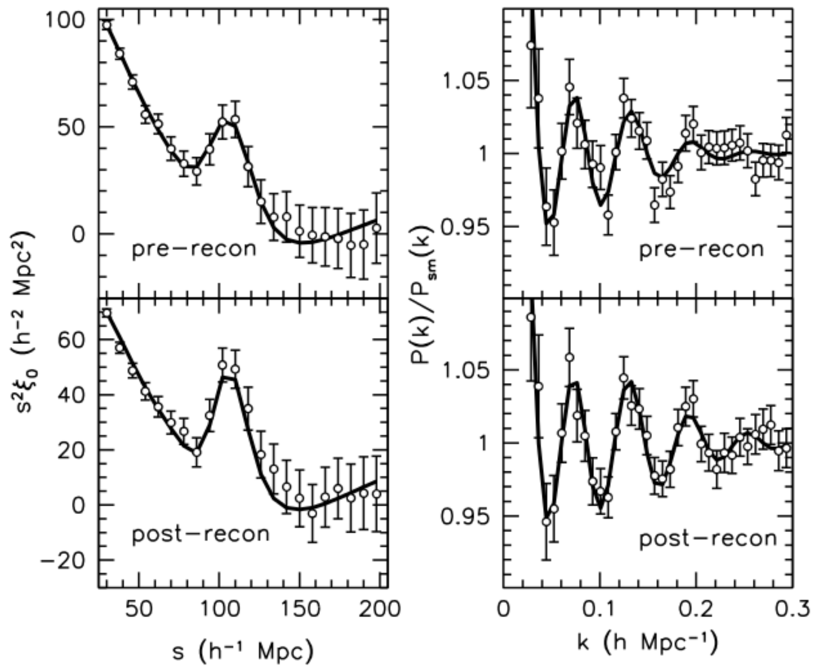

Figure 1: BOSS DR11 CMASS (at $z \simeq 0.57$) clustering measurements (black circles) with $\xi(s)$ shown in the left panels and $P(k)$ in the right panels. The top panels show the measurements prior to reconstruction and the bottom panels show the measurements after reconstruction. This figure is extracted from Anderson et al. (2014).

Lyman-α forests open a new high redshift window for the measurement of the expansion rate. Whereas neither ground-based and space-borne spectroscopic surveys are providing a sufficient density of high redshifts sources[1] 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 experiment where the BAO peak has been detected and measured in the correlation of Lyman-α forests at an effective redshift of 2.3 (see see Figure 2 and Section 2.4).

2.1.3 Complementarity with Supernovae Ia

The BAO cosmological probe is complementary to Supernovae Ia (SNe Ia). Qualitatively, 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 that can be compared with traditional measurements using the distance ladder (Aubourg et al. (2014)). Also, the direct measurement of $H(z)$ breaks degeneracies when combined with distances (which are integrals of $1/H(z)$). In terms of statistical precision, whereas BAO cannot compete with SNe Ia at low redshifts because of the cosmic variance (limited volume in a redshift shell), they become more precise at redshifts greater than one. This is demonstrated with the Lyman-α forest BAO measurement at an effective average redshift $z \sim 2.4$ in Delubac et al. (2015). This will also be the case with the measurement of the quasar clustering in eBOSS (Dawson et al. (2015)), and in the mid-term with DESI with Emission Line Galaxies (ELG), quasars, and Lyman-α forests.

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[1] Spectroscopic surveys are intrinsically limited at high redshift, because of the brightness and transmission of the atmosphere in the near infra-red for ground-based surveys, and schematically because of the possible collection area (mirror size) for space missions, making it impossible to obtain a sufficient density of bright enough sources at high-z.

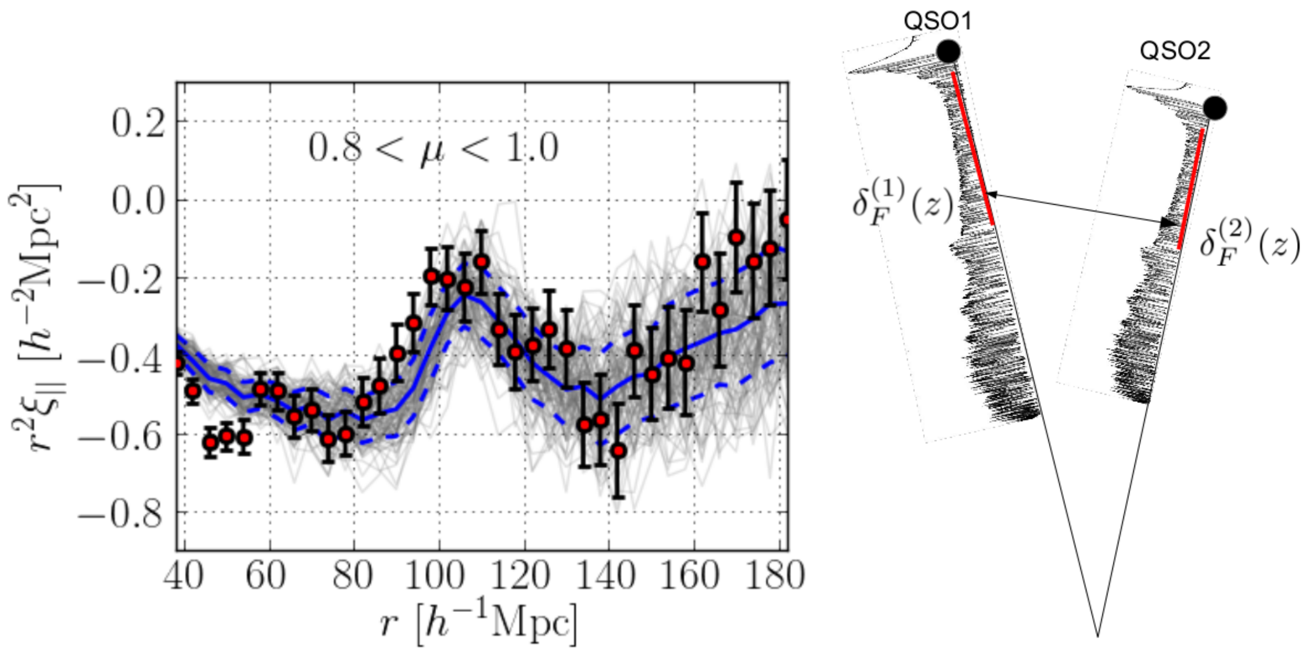

Figure 2: Left : BOSS DR11 Lyman-α forest correlation function (line of sight angular wedge, red points with error bars) at $z \simeq 2.3$. The gray curves represent the simulations and the blue curve their average for the fiducial cosmology. This figure is extracted from Delubac et al. (2015). Right: A sketch of the measurement principle.

2.1.4 BAO have low systematic uncertainties

First, the measurement of a peak in the angular and redshift correlation function has very mild instrumental and data reduction systematic uncertainties. This is striking for the galaxy clustering measurement of BOSS (see for instance Ross et al. (2012)). The variations of the targeting[2] efficiency on the sky (due to variations of atmospheric transparency, image quality, sky brightness during the imaging observations) imprint a spurious large scale signal in the galaxy correlation function. Those variations of efficiency are corrected for by reweighting the galaxy catalog entries. However, the resulting BAO scale measurement is hardly modified by those important corrections as they modify the broad-band part of the correlation function and not its shape at scales that would affect the peak position. For Lyman-α forests, the source of systematics is different but the conclusion is qualitatively the same. Sources of correlated noise are introduced in the spectroscopic observations and data reduction and result in a spurious broad-band contribution to the measured Lyman-α correlation function. This has been studied and will be published soon, and we reach the same conclusion that instrumental and data reduction artifacts induce negligible shifts ($\lesssim 1\%$) on the BAO measurement given the current precision. They can also be corrected, leaving even smaller systematic uncertainties.

Second, 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 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 the tracer (flux decrements due to the presence of neutral hydrogen over-densities) has a much lower bias than galaxies (i.e. in less dense regions).

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[2] The targeting is the selection process of spectroscopic targets from imaging catalogs. It is based on a set of cuts on the magnitudes and colors of galaxies designed to optimize the yield, purity and redshift distribution of the selection.

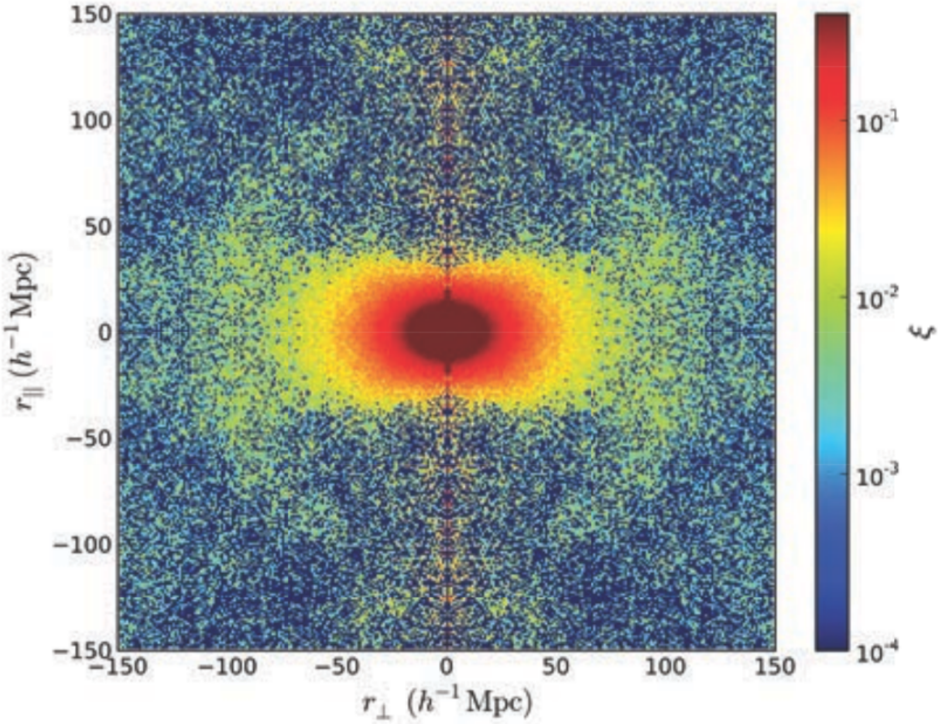

Figure 3: The two-dimensional correlation function of the BOSS DR11 CMASS galaxies, measured perpendicular (x-axis) and parallel (y-axis) to the line of sight. The BAO ring, distorted by redshift space distortions is clearly visible, as is the characteristic squashing of the correlation function on large scales. We also see the Finger of god effect at $r_\perp \sim 0$ and $|r_\parallel| \sim 20$ Mpc.h^{-1}.

2.2 Redshift space distortions

2.2.1 Measuring the growth rate of structures

Despite the fact that the galaxy clustering is statistically isotropic, we observe an increased density contrast along the line of sight in redshift surveys at intermediate scales ($\sim$ 40 Mpc, see Figure 3). This is due to the Doppler effect induced by the coherent peculiar velocities of galaxies that tend to fall in gravitational potentials. Because the divergence of the peculiar velocity field is directly related to the time derivative of the density contrasts through conservation of mass, the so-called Redshift Space Distortions (RSD) give us constraints on the growth rate of structures. Measuring this growth rate is a test of General Relativity 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.

2.2.2 Alcock-Paczynski test

Two other effects give rise to an apparent anisotropic clustering in redshift space. The first is the so-called Alcock-Paczynski (AP) 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 ($D_A(\bar{z})\Delta\theta$ and $\Delta z/H(\bar{z})$) . A model inconsistent with the true expansion history will lead to an apparent anisotropy in the correlation function. The Alcock-Paczynski test is hence constraining the product $D_A(z) \times H(z)$. BAO also constrain this parameter combination, but the AP measurement in the context of RSD is based on the 2D broad-band shape of the correlation function at smaller scales than BAO, resulting in a nearly independent (or statistically uncorrelated) observable.

2.2.3 Fingers of god effect

The 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. This signal is striking in the correlation function. It is however difficult to model and leads to potential systematic uncertainties in the measurement of the growth rate and AP test from the redshift space distortions.

2.2.4 Systematic uncertainties

The Fingers of god is an obvious manifestation of non-linear effects that need to be modeled when trying to interpret the galaxy clustering signal at small scales. Enter in the analysis the ability to model accurately the population of galaxies in dark matter halos that are themselves defined by the method used to select them in dark matter simulations. This is a domain of active research, with many approaches, N-body and/or hydrodynamical simulations, perturbative developments, or more empirical methods. For the measurement of growth rate, we hence expect some serious competition with the direct measurement of the amplitude of matter power spectrum with time from weak lensing. RSD however come for free in massive redshift surveys optimized for BAO, and we do not know yet the final systematics of weak lensing surveys.

2.3 Other science from large spectroscopic surveys

Whereas BAO can be arguably considered a primary science goal, with RSD as a bonus, 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 and Lyman-α forest data permits to test other aspects of the standard cosmological model (beyond the expansion and growth of structures) : neutrino masses, warm dark matter scenarios, inflation scenarios (with a measurement of the primordial power spectrum, power law index n_s and its possible deviation from a pure power-law). Other tracers such as large cosmological voids could also provide interesting insights. Finally, statistics beyond the two-point correlation function (or power spectrum) could help constrain the physics of the early universe.

2.4 BOSS results

The Baryon Oscillation Spectroscopic Survey (BOSS) was conducted on the SDSS 2.5 m telescope at Apache Point, New Mexico. The focal plane is 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 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.

The goal of BOSS was to target 1.35 million massive and passive galaxies (hereafter LRG for Luminous Red Galaxies) in a redshift range $0.2 < z < 0.7$ over a footprint of 10 000 square degrees. Targets were selected using the SDSS photometry with selection cuts designed to select preferentially galaxies in two sub-samples centered at $z \sim 0.3$ and $z \sim 0.6$ (labeled LOWZ and CMASS respectively). Along with the galaxy sample, 160 000 quasars were targeted for Lyman-α studies and quasars science.

In 2014, the BOSS collaboration has published their cosmology analysis of about 90% of the data (data release DR11). The LRG BAO analysis is described in Anderson et al. (2014). A precision on the (isotropic) BAO scale of 2% and 1% was obtained for the LOWZ and CMASS sample respectively (see also Figure 1). The results were found to be consistent with the best fit ΛCDM cosmological parameters derived from Planck and SNe results. The DR11 Lyman-α BAO analysis was published in Delubac et al. (2015) (see also Figure 2). The combination of the Lyman-α auto-correlation and Lyman-α - QSO density cross-correlation lead to precision of the (isotropic) BAO scale of 1.4%. Interestingly this result is in a $2.5 - \sigma$ tension with the best fit ΛCDM model from Planck, BOSS galaxy BAO, and SNe Ia.

The final BOSS data set (DR12) was published and made public in 2015, Alam et al. (2015). It is only a 10% increase over DR11. BAO analysis for both for the galaxy and Lyman-α samples are still going on.

The Lyman-α analysis is lead by a French group with researchers from APC, CEA and LPNHE. Important systematics studies were conducted and the Lyman-α paper is in preparation.

BOSS results confirm the potential of BAO, with measurements at a precision of 1% today. The constraints at high redshift (> 2) brought by the Lyman-α forests are very promising, as they test the standard model ΛCDM in a redshift region unexplored with other probes (Supernovae, lensing, or BAO from the galaxy clustering).

The BOSS collaboration has also published several analysis of the redshift space distortions. The statistical precision increases with the minimum scale included in the analysis, as the cost of higher systematic uncertainties. Samushia et al. (2014) and Beutler et al. (2014) measure the product of growth rate and the amplitude of density contrasts at a precision of 10% at $z \simeq 0.57$ with two different analyzes. A much more aggressive approach, modeling the Fingers of god, results in a statistical precision of 2.5% on the same quantity (Reid et al. (2014)). All three methods give slightly different results but are statistically compatible. The latter gives a result in a $2-\sigma$ tension with Planck when assuming ΛCDM.

2.5 Summary

BAO are a major probe of the Dark Energy science, their potential has been proven with BOSS. Upcoming massive redshift surveys will considerably increase the statistics. Measuring the BAO scale in large galaxy redshift surveys and in the Lyman-α forest of distant quasars is a mean to push forward the measurement of the expansion history of the universe pioneered with supernovae. At $z \lesssim 0.8$, BAO are complementary to SNe. However one of the most exciting aspect of BAO is to extend the Hubble diagram to higher redshifts, and measure accurately the expansion in the deceleration era, when the content of the Universe in terms of energy density is dominated by cold dark matter in the standard scenario.

Redshift Space Distortions can be measured in the same redshift surveys. They offer a mean to disentangle various scenarios of modified gravity that would otherwise be indistinguishable from ΛCDM. Large redshift surveys also open a broad spectrum of other possible contributions to test further the puzzling standard model of cosmology.

In this context, IN2P3 groups (from APC, CPPM, and LPNHE) have been involved in the BOSS project, and are continuing this effort in eBOSS. The same groups also have implications or are interested to develop activities on DESI. We review those activities in the next sections. For a sake of completness, we also note the interest of IPNL and APC researchers to two projects with narrower scientific goals : LORCA, focusing on low redshift ($z < 0.2$), and WEAVE, focusing on Lyman-α . These projects do not request, at present, support from IN2P3. LORCA (see Comparat et al. (2015)) will reach a statistical precision of 4%. Its goal is to study in detail the impact of the non-linear motions of galaxies on the measurement of BAO. WEAVE is a wide-field survey facility for the 4.2-meter William Heschel Telescope[3], equipped with a 1000 fiber positioner system. Running between 2017-2022, WEAVE will dedicate 120 fibers per field to observe the spectrum of candidate high-redshift quasars (60 quasar targets per square degree) over a 10,000 deg^2 footprint.

3 eBOSS

3.1 Project and collaboration

eBOSS, for extended Baryon Oscillation Spectroscopic Survey, is the continuation of the BOSS project. It uses the same instrument and data analysis pipeline (though with implemented and foreseen improvements). eBOSS was initiated by the BOSS French Participation Group whose members have been very actively involved in preparatory studies showing that the target selections of ELGs and QSOs are feasible. This has greatly facilitated the acceptance of eBOSS by the Apache Point Observatory Research Consortium. Several pilot programs have been performed to validate both the target selection and the observation strategies

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[3] WEAVE web site: `http://www.ing.iac.es/weave/index.html`

proposed by the FPG, and most of the FPG members were signatories of the eBOSS proposal in 2011, that was accepted in 2012. The survey has started mid-2014.

It is a six year project aiming at pushing to higher redshift the BAO measurement with galaxy redshift catalogs and increasing the statistics of high-z quasars for the Lyman-α analysis of BOSS. The survey design and target catalogs are described in Dawson et al. (2015). The targets are 250,000 LRG[4] at a median redshift of 0.72, 195,000 ELG[5] at $z \sim 0.87$, and 500,000 quasars[6] in the range $0.9 < z < 2.2$. The expected precisions of the measured BAO scale for those samples in the transverse and radial directions are $(1.2\%, 2.1\%)$, $(3.1\%, 4.1\%)$ and $(2.8\%, 4.2\%)$ for LRG, ELG and quasars respectively. At $z > 2.1$, where quasars Lyman-α forests can be observed at wavelength greater than 360 nm with the spectrographs, 60,000 new quasars will be observed and 60,000 quasars from BOSS reobserved to increase the signal to noise ratio. This will allow a statistical improvement of 40% when compared to BOSS.

The eBOSS survey is the cosmology survey component of the SDSS-IV program. SDSS is funded by the Alfred P. Sloan Foundation, the participating institutions, the NFS (U.S. National Science Foundation) and DOE (U.S. Department of Energy). eBOSS is a large international collaboration with a majority of U.S. institutions. The French members are organized in a French Participation Group (FPG) in order to reduce the participation costs. The FPG is composed today of 20 physicists and post-docs from IN2P3 (APC, CPPM, LPNHE), INSU (IAP, LAM) and CEA (IRFU).

3.2 Scientific goals

The novel scientific aspect of eBOSS with respect to BOSS is the measurement of the BAO with emission line galaxies and quasars. With quasars at a median redshift of 1.5, eBOSS will probe the cosmological model in the deceleration era, as Lyman-α , but in a different redshift range and with different systematic uncertainties (a galaxy redshift catalog instead of flux decrements, a highly biased matter tracer). In terms of science, the French Participation Group is focused on quasar and galaxy clustering, as well as Lyman-α forests analysis.

For the galaxy clustering, the aim is to provide percent-level distance measurements with BAO in the redshift range $0.6 < z < 2$, when cosmic expansion transitioned from deceleration to acceleration. Indeed the eBOSS project will create the largest volume 3D map of the Universe ever made, addressing fundamental questions in unexplored redshift regimes, critically in the $1 < z < 2.2$ redshift range which has never been probed at comparable accuracy. In addition to BAO distance measurements, eBOSS will provide new tests of GR on cosmological scales through redshift-space distortions (RSD), new tests for non-Gaussianity in the primordial density field, and new constraints on the summed mass of all neutrino species.

The goal of the participation of IN2P3 to the eBOSS project is also to prepare cosmological measurements before the start of future large spectroscopic surveys like DESI and Euclid. An important task concerns the modeling of data and the estimate of potential systematic uncertainties. eBOSS will also lay the groundwork for the target selection and analysis techniques envisioned for DESI (ELG and Lya). eBOSS will also be a laboratory to test and validate data reduction algorithms developed for future projects.

The eBOSS collaboration has a very important overlap with the DESI collaboration. It is obvious that the science analyzes of DESI will be developed much more efficiently with eBOSS data rather than with DESI simulations (though simulations are also important to test the specifies and capabilities of DESI).

3.3 Activities at IN2P3

The science topic developed at IN2P3 is the Lyman-α forest auto-correlation analysis, the cross-correlation of Lyman-α forests with quasar density, and the quasar density auto-correlation (APC, LPNHE), as well as

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[4] LRG: Luminous Red galaxies, i.e. massive and passive galaxies. Those are the brightest galaxies, they are highly biased tracers of the matter density field. LRG were the primary targets of BOSS.

[5] ELG: Emission Line Galaxies are star forming galaxies with bright emission lines (O-II, O-III, H-α, H-β) that are easier to detect in noisy spectra compared to passive galaxies which only present a continuum emission.

[6] Quasars, or QSO for quasi-stellar objects, are the most luminous objects in the visible wavelength. They display broad emission lines that are emitted from the central region of massive galaxies, presumably in the vicinity of massive black holes. Quasars have a much lower density than other targets, but they can be used to probe huge volumes of the Universe at high redshifts thanks to their luminosity.

the galaxy density auto-correlation and the use of cosmic voids (CPPM).

The Lyman-α forest BAO probe is "young": The signal was detected for the first time in 2013 (Busca et al. (2013)), and this work was led by the French team (as the second paper based on 90% of the data, Delubac et al. (2015)). We are now finalizing the BOSS analysis and are still finding significant improvements: accurate modeling of the distortions of the correlation function induced by the continuum fit, modeling and marginalization of the contamination signal coming from other atomic transitions in the Lyman-α -forest, detailed modeling of spurious correlations introduced by the measurement and analysis method (mainly from the sky signal modeling and spectro-photometric calibration). Many more improvements are expected with eBOSS. In addition to the gain from statistics (40% on uncertainties), we hence expect a very significant improvement of the precision of the measurement, testing for the first time ΛCDM at $z \sim 2.4$ at 1%.

The IN2P3 team is also involved in the galaxy clustering on BOSS and eBOSS data. These activities concern the multipole analysis for the extraction of BAO, RSD and AP informations. One part is focused on a joint analysis between galaxy clustering (BAO,RSD) and weak lensing (WL) taking advantage of both imaging and spectroscopic surveys. The goal when combining RSD and WL is to pinpoint possible deviations between measurements and predictions with general relativity. A preliminary work has focused on overlap regions between the BOSS survey and the CFHTLS fields, and will be extent to the eBOSS survey. This includes generation of simulated lightcones and estimate of covariance matrices. Another way to get precise constraints on dark energy is the use of cosmic voids that are emerging as a novel and innovative probe of both cosmology and astrophysics.

Another activity is focused on improving the data reduction pipeline. eBOSS is using the same instrument as BOSS but is targeting fainter objects. In consequence, whereas BOSS was not limited by the signal to noise ratio of the spectra, this is not the case anymore for eBOSS, and the redshift efficiency is much more sensitive to the observational conditions. It must be optimized and calibrated accurately to minimize the impact of its variations on the sky for the clustering analysis. This involves developments in many areas of the pipeline, and provides an ideal test case for DESI, both for the improvements of the algorithms and the evaluation of the impact of various artifacts induced by the data reduction technique.

3.4 Financial resources

The funding of the participation of the FPG comes from various sources (LABEX, ANR, PNCG, ILP, INSU, IN2P3). Funding from IN2P3 to IN2P3 laboratories is not the most important resource but is mandatory for this activity. IN2P3 support is needed for the participation costs, in order to maintain a minimal number of two researchers (staff physicists and post-docs) working on the project per laboratory. It is one of the objective of this report to the scientific council to emphasize this point, if the development of BAO activities at IN2P3 is seen as desirable for a coherent effort on Dark Energy, and if contributions to on-going redshift surveys are encouraged.

4 DESI

4.1 Project and collaboration

The Dark Energy Spectroscopic Instrument (DESI) is a DOE Stage IV Dark Energy project aiming at measuring BAO and redshift space distortions with LRG (4 millions), ELG (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 will be 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 wavelength. 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 O-II doublet, which is a crutial requirement to identify and measure the redshifts of faint ELGs.

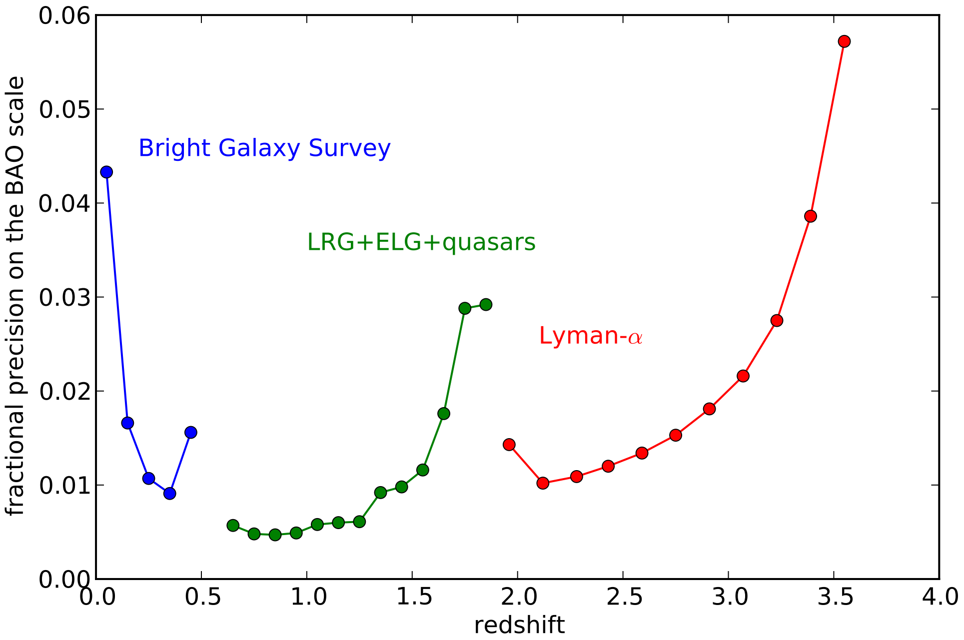

Figure 4: Fractional precision on the isotropic BAO scale in *independent* redshift bins (from Table 2.3, 2.5 and 2.7 of the DESI Technical Design Report)

DESI passed the DOE CD-2 review in July, 2015. The budget profile was signed by DOE in September (total budget of $56M), the construction schedule updated, with an expected first light mid-2019. The CD-3 review is schedule for May 2016. After few month of commissioning the science survey will start at the end of 2019. 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, before LSST and Euclid.

4.2 Scientific goals

DESI will achieve a Dark Energy Task Force Figure of Merit (FoM)[7] of 169 from BAO alone (galaxy and Lyman-α combined). This number is however quite biased toward surveys efficient at low-redshift where Dark Energy has an important weight, so it is not very favorable for BAO projects. More interesting are the expected precision on the BAO scale in independent redshift bins given in Table 2.3, 2.5 and 2.7 of the DESI Technical Design Report (TDR)[8]. The results from those tables are reproduced in Figure 4 for the isotropic BAO scale (combined radial and transverse measurements). DESI will be a major experiment for the measurement of the expansion history, in analogy with 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 is on the radial and longitudinal BAO scale is expected to be of 0.8% and 0.7% (compared to 5% and 3% today with BOSS). It is very likely that those statistical predictions will not be dominated by systematic errors.

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[7] The FoM of Dark Energy has been designed to quantify the constraining power of upcoming surveys. It is approximately the inverse of the product of the uncertainties of the mean and time derivative of the Dark Energy equation of state parameter $(\sigma(w_p)\sigma(w_a))^{-1}$ (arranged in the form of uncorrelated quantities), see Albrecht et al. (2009).

[8] DESI TDR `http://desi.lbl.gov/tdr`

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.

4.3 Current activities in France and IN2P3

There are already important contributions to the DESI project in France.

CEA/IRFU is providing the cryostats for the 30 cameras (3 cameras for 10 spectrographs).

An AMU consortium (Aix-Marseille University), composed of the CPPM, LAM and OHP laboratories, has negociated a staff effort to the development of the DESI spectrographs. The ten DESI spectrographs are developed, assembled and integrated by WINLIGHT, a PACA company based in Pertuis (84) and famous for its high quality optics. The AMU consortium is responsible for the integration of spectrographs and for their scientific validation. The first DESI spectrographs (out of 10), referred to as the 'prototype', will be assemble this winter and tests are scheduled to start in March 2016.

LPNHE is contributing to the software development of the spectroscopic pipeline, and is participating 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 lead 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.

4.4 Contributions to the project construction and infrastructure at IN2P3

We list here the current contributions to the project and propositions to increase our participation. APC is also interested to participate to those activities. They are an in kind contribution to the project and help reduce the funding effort. The agreement with the DESI project will be formalized to take this into account.

4.4.1 Software contribution

LPNHE is involved in many aspects of the development of the DESI spectroscopic pipeline. This includes the modeling of the spectrograph PSF (including the trace location and wavelength calibration), the optimal extraction code, the subsequent calibration steps (fiber flat-fielding, sky subtraction, photometric calibration), and the redshift fitting code (two researchers are contributing to this effort). This work is fully integrated with the DESI project software team, as part of the project Data System WBS (work breakdown structure), it follows a well defined development plan managed at LBNL. This contribution to the project is giving an important visibility to the team. The quality of the data reduction will be key to the success of the project. The main challenge is to be able to model and subtract the sky emission with high accuracy, so that it does not become a dominant factor for the redshift efficiency of faint ELGs (constrained by a requirement on the rate of catastrophic failures).

4.4.2 Integration and tests of DESI spectrographs

CPPM is participating the tests of the DESI spectrograph within the AMU consortium. The scientific verification encompasses many technical activities, such as installing the calibration unit, electronic and software implementation, data archival and data packs. A very strong collaboration between Winlight and the AMU consortium is necessary and has been developed, knowing that all tests will take place within Winlight premises. The tests comprise: focus adjustment, wavelength solution, thermal performance and straylight analysis (second order contamination, cross-talk between fibers, ghosts and scattering). For the purpose of the spectrograph validation, AMU has been developing a dedicated optical test bench and analysis tools, both of which may be useful for further testing during calibration at Mayall. CPPMs specific responsibility is that of the CCD cameras, including the participation to the test plan definition and the implementation of CCDs images analysis tools.

LPNHE will help with dedicated software development in addition to the tools that are already part of the DESI Data System responsibilities (preprocessing of raw CCD images, trace locations and wavelength calibration in tests conditions). The key aspect of those tests is to validate the stability of the cameras optics with repeated measurements in varying conditions. An unstable PSF (Point Spread Function) would degrade the performances of the sky modeling and subtraction, as it is foreseen to calibrate it only once per night.

4.4.3 DESI calibration system on the Mayall telescope

The contribution of IN2P3 to the project can be increased with the responsability of developing, building and maintaining the on-site calibration system. The currently planed design is minimal and basically reproduces the one of BOSS/eBOSS. This calibration system is composed of an array of lamps on the upper ring of the telescope structure shining a diffusing screen attached to the dome of the telescope. The lamps that are considered are halogen lamps for a continuum illumination, and Hg-Cd and He-Ar spectral line lamps for the wavelength calibration. The images obtained with this system are used to calibrate the trace locations, wavelength (wavelength as a function of CCD pixel coordinates), and fiber flat-field (relative calibration of the various fiber responses). There is room for improvements in terms of wavelength coverage, stability, homogeneity. The homogeneity of the illumination of the screen determines the quality of the fiber flat fielding which is key for the subtraction of the sky emission. The LPNHE group, which developed an expertise on this subject with the DICE project,could bring important improvements to this system. The cost of this calibration system is evaluated to be of $150k by the project.

4.5 Science preparation and expertise at IN2P3

The collaboration has organized the work with a "Science Readiness Plan" which describes the tasks that need to be done for the imaging, target selection, survey strategy, data pipelines, simulations, and a large series of tasks specific to each working group. In this frame, the IN2P3 participants are currently engaged in the Lyman-α forest working group and galaxy clustering working group tasks and the general purpose simulations in link with the data pipeline. Contributions will of course increase if new members join the team.

Building on the experience from BOSS, the APC intends to keep its high visibility within the Lyman-α cosmology working group. The goal of sub-percent precision requires a deep understanding of the analysis methods which can only be achieved with thousands of full end-to-end simulations. Generating the volume of Lyman-α data expected for DESI is in itself a challenging task (current methods are able to simulate only fractions of BOSS). We will continue improving the statistical analysis of Lyman-α data by actively contributing to the simulations production chain, from the creation of simulated data themselves to the final cosmological analysis. Our close interactions with LPNHE will allow us to follow the understanding of the calibration systematics effects. These effects will be included in the simulations in order to assess their impact on the final cosmological results. This will also provide feedback to the pipeline team. Other important systematic uncertainties are astrophysical in origin, related to how good our understanding of the intergalactic medium is. Within BOSS, we have closely collaborated with researchers in LAM (Mat Pieri and collaborators) who are experts in IGM physics in order to make simulations more astrophysically rich. This collaboration will carry on directly to DESI.

On the galaxy side, CPPM intends to strengthen the visibility of the IN2P3 groups on the galaxy clustering by exploiting the full information of the galaxy correlation function applied on ELG and LRG, in particular RSD and AP informations, as well as to test deviations from General Relativity using combination with lensing.

5 Conclusion

Baryon Acoustic Oscillations are a major probe of the Dark Energy science, with low systematic uncertainties, and important complementary with Supernovae Ia for the measurement of the expansion history (absolute distance measurement, measurement of the instantaneous expansion rate, extension of the Supernova Hubble diagram to higher redshifts). Maybe more importantly, BAO in the Lyman-α forests are the only mean 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 (RSD). This provides an independent test of general relativity on cosmological scales, and help 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 are the measurement of the host galaxies redshifts of photometrically identified SNe, and the calibration of photometric redshifts. Both are mandatory for the physical interpretation of the Supernova Hubble diagram and the weak lensing power spectrum. In that sense, LSST needs massive redshift surveys such as DESI.

The most important complementarity is however 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 invoved for many years in the BOSS project and are pursuing their effort in the eBOSS survey, which is currenlty taking data. They have a good scientific visibility both in the Lyman-α forests and galaxy clustering analyzes. It is of major importance for them, to continue eBOSS and to have the opportunity to prepare the upcoming DESI survey.

In many ways, DESI is a good preparation to Euclid, but it also brings an important complementary to the Euclid BAO program. It is probing BAO in a larger redshift range, encompassing that of Euclid both at lower and higher z (with Lyman-α forests). This will allow a synergy and a combination of information that will help our understanding of the evolution of the Universe.

We have presented a path to an IN2P3 contribution to this project which involves software and hardware developments in three laboratories. In terms of technical manpower and financial cost, the participation to eBOSS and DESI is a relatively modest implication. It would not drain significantly the resources dedicated to the existing efforts pursued by IN2P3 on Dark Energy. It is on the contrary desirable that the IN2P3 groups participating to the construction efforts on LSST and Euclid have part of their activities dedicated to on-going surveys to prepare the science, train PhD students, and allow the recruitment of post-docs that would help develop the scientific expertise.

The BAO activity presented in this report is a very rich and evolving domain since 2006 and will continue to mature up to the start of Euclid and LSST. It is of main importance that the IN2P3 teams follow in detail the development of the analyzes in this domain by participating to the ground based projects eBOSS and DESI. This will allow them to be ready and prepared for the Euclid and LSST science challenges with the same and unique objective, understanding the nature of Dark Energy.

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