DESI – Year 1

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LHC Split Days, Hvar – Sept. 30, 2024

Dark Energy Spectroscopic Instrument

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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- **1. Baryonic Acoustic Oscillations (BAO)**
- **2. Overview of DESI**
- **3. Status of DESI – Year 1**
- **4. BAO with galaxies and quasars**

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Baryonic Acoustic Oscillations

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J. Peebles Nobel Prize in Physics 2019 Inaugural Lecture

Succes of ACDM

The Universe is described by:

- laws of physics
- ordinary matter standard model particles
- "dark matter" that interacts only through gravitation
- "dark energy" in the form of a cosmological constant
	- -> responsible for the accelerated expansion of the Universe first observed with SN1a – Nobel Prize 2011

BAO, a probe for Dark Energy

Acoustic propagation of an over-density

- Sound waves propagates through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination (z~1100) with a speed $\sim c/\sqrt{3}$ that depends on species densities
- Radius of the baryonic overdensity frozen at $r_d \sim 150$ cMpc (comoving).

BAO, a standard ruler

A special distance

- Galaxies form in the overdense regions.
- Small excess of galaxies at $r_d \sim 150$ cMpc away from other galaxies.
- **Measure this BAO "standard ruler" over cosmic history => Constrain the nature of Dark Energy**

Observation of baryonic acoustic peak

First observation

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs, <z> ~ 0.35 "Luminous Red Galaxies"

- **A 3D measurements**
- Position of acoustic peak
- **Transverse direction:**
- $\Delta\theta = r_d/(1+z)/D_A(z) = r_d/D_M(z)$
- \Rightarrow Sensitive to angular distance $D_A(z)$
- **Radial direction** (along the line of sight): $\Delta z = r_s \cdot H(z)/c$
- \Rightarrow Sensitive to Hubble parameter H(z).

Overview of DESI

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DESI Project

• **Scientific project**

- $-$ 3D map for 0 \leq z \leq 4
- Footprint \sim 14000 deg²
- International collaboration
- 72 institutions (46 non-US)
- \sim 900 members

• **Instrument**

10 spectrographs

- 4-m telescope at Kitt Peak (Arizona)
- Wide Field-of-View (~ 8 deg²)
- Multi-Object Spectrograph
	- Robotic positioner with **5000 fibers**
	- 10 spectrographs x 3 bands (blue, visible, red-NIR) \rightarrow 360-1020 nm

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 $0.0 < z < 0.4$

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Focal Plane – 5000 robotic fiber positioners

Configuration

- 10 petals in focal plane
- 500 fibers each (5000 total)
	- 10.4 mm pitch
	- 2 motors per positioner

Challenge

- Reposition the 5000 fibers in less than 2mns
- Position of each fiber better than 10 μ m

Ten spectrographs

Ten 3-channel spectrographs $\lambda = 360$ nm to 980 nm

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Rolling observations – Redshift factory

 \overline{z}

 -1

 -2

 -3 -0.5

 $W - 210$

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Status of DESI

-

Year One (Y1)

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DESI and DESI-II Timelines

- **DESI-I** is ~4 months ahead of schedule, DESI should finish in 2025
	- Analysis of Year 1 Dataset
	- Year 3 Dataset completed in April 2024
- \sim 2-year transition period with extension of the footprint and the passes
- **DESI-II** starts in 2028-2029

DESI Y1 footprint

- Grey area: DESI footprint over 5 years, \sim 14000 deg²
- On average 5 passes
- $-$ In Y1, only 1500 deg² with 5 passes

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DESI Y3 footprint

- In April 2024, Y3 dataset is completed and frozen
- $-$ ~70% of the final dataset (much more ELGs)
- $-$ In Y3, already 7300 deg² with 5 passes

DESI Y1 dataset

- $-$ Already biggest ever BAO dataset (both in $\mathsf{N}_{\mathsf{tracer}}$ and volume)
	- 5.7M discrete tracers (BG, LRG, ELG and QSO) cc inducts (DO, LNO, ELO ditu ω OO)
	- Effective cosmic volume V_{eff} = 18 Gpc³
- **3 times bigger than SDSS (20 years of data)**

resulting redshift catalogs used in this paper and will be released in DR1.

BAO with galaxies and quasars

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Methodology for DESI Y1

- **Blind analysis** to mitigate observer/confirmation biases (catalog-level blinding)
- **Unified BAO pipeline** applied to all (discrete) tracers/redshifts consistently
- Common modeling of BAO used for all tracers
- Reconstruction method applied to all tracers
- Analytic covariance matrices (validated with mocks)
- Extensive tests of systematics, done before unblinding
- Results given for **6 redshift bins** over 0.1<z<2.1

Density Field Reconstruction

Reconstruction

- BAO peak distorted by movements of tracers due to density field
- $-$ Estimation of the Zel'dovich (1st order) displacements from the observed field
- Reconstruction: correction of the displacements
- **Improve both precision and accuracy**

Systematics Error Budget

- Observational effects in data (**imaging**, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction
- Incomplete theory modelling
- Choice of fiducial cosmology
- Galaxy-halo (HOD) model uncertainties

Example of systematics: Imaging

- $-$ Non-homogeneity in target selection due variations of imaging catalogs (depth, dust contaminants,...) catalogs (depth, dust contamir ret selection due variations (↵*,*) to equal (0*.*88*,* 0*.*04), (0*.*7*,* 0*.*05), and (0*.*84*,* 0*.*04), \ldots \ldots \ldots \ldots \ldots \rm{ection} due variations of imaging \sim \mathcal{L}_{max} $f(\mathbf{a} \mathbf{b}, \dots)$ stable even when the BAO scales are very stable even when there was no mitigating and mitigating
- Regression methods developed to correct those effect $S₁$ Regression methods developed to correct those ef a machine-learning algorithm based on Random Forests available at 10 contect mose et even after density field reconstruction \mathbf{A} to correct the BAO is robust again, the BAO is robust again to reconstruc imaging systematics.
- **BAO almost insensitive to imaging effects** (RF). \pm to imaging effects \pm SELECTION

4.1. *Quasar Target Density*

 \blacksquare **IIIU** E. Burtin Slide 25 at most 0*.*27 (for the QSO \sim typically less than 0.2 on and is typically less than 0.2 on any of the measured modulate the density field obtained from the density field obtained from the LSS catalogs and thus the \sim

with and with an orientation $\mathcal{L}_{\mathcal{A}}$ for imaging systematics, the variation is found to be

Systematics Error Budget

- Observational effects in data (imaging, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction
- Incomplete theory modelling
- Choice of fiducial cosmology
- Galaxy-halo (HOD) model

No effect on BAO

Systematics Error Budget

- Observational effects in data (imaging, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction
- Incomplete theory modelling $\sigma_{theo} = 0.1\%$
- Choice of fiducial cosmology $\sigma_{fid} = 0.1\%$
- Galaxy-halo (HOD) model $\sigma_{HOD} = 0.2\%$

All systematics much smaller than statistical errors $\sigma_{total} = 1.05 \sigma_{stat}$

 $\sigma_{sys} = 0.25\%$

Negligible effect on BAO

Stability of the results

- Comparison with the baseline analysis for different configurations (with/without reconstruction, power-spectrum, without SGC, priors damping parameters, broadband modeling and reconstructions)
- **Robust results**

DESI Year 1: BGS

- $-$ **Friedman equation for a flat Universe** Fit - Friedman equation for a flat Universe $H(z) \equiv H_0 \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}$
- Limitation due the cosmic variance (small part of the visible Universe)

(*D*

DESI Year 1: BGS + LRG

0.0 1 DC: Moin tracer in CDCC pro $-$ LRG: Main tracer in SDSS, precise measurement

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DESI Year 1: BGS + LRG + ELG

0*.*0 0*.*5 1*.*0 1*.*5 2*.*0 2*.*5 – ELG: Main tracer in DESI, precise measurement, but redshift *z* only a small fraction was observed in DESI Y1

DESI Year 1: BGS + LRG + ELG + QSO

0*.*0 0*.*5 1*.*0 1*.*5 2*.*0 2*.*5 $-$ QSO: huge volume but small density (shot noise limitation)

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DESI Year 1: BGS + LRG + ELG + QSO + Ly- α

- $-$ Different dependence as a function of redshift $(\Omega_{\rm m},\Gamma_{\rm d})$
	- Break the degeneracy without knowing r_d

DESI Year 1 - Hubble diagram

- ~6 million discrete tracers
- $-0.1 < z < 2.1$
- $-$ 3 times bigger than SDSS
	- $-$ Measureme*pt* with Ly-α forest of QSOs at higher redshift JSI
	- $\sqrt{ }$ Total precision on BAO: 0.52%
	- $-$ Consistent with Λ CDM
	- Agreement with Planck: 1. 9σ
	- **BAO** -very low systematics 1*.*0
	- Cosmological constraints
		- ⇒Next talk by Dragan Huterer Redshift *z*

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Additional Slides

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Evolution of density perturbations

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Comparison DESI/SDSS 0*.*95 1*.*00 (*D*M*/r*d)*/*(*D*M*/r*d)DESI fid

- $-$ 2.5 σ to 3.0 σ discrepancy depending on the correlations between the two samples bins, while the di↵erent panels show results for *D^V /r*d, *DM/r*d, and *DH/r*d. In each group, the leftmost point is the published BOSS/eBOSS result. The second point from the left uses the published 1*.*00 p_{C} is the results of the results of r_{C} and r_{C} re 15. Hubble diagram of the Barantino diagram of the BAD diagram of the unbetween \mathbf{r} and the unbetween \mathbf{r} (*D*M*/D*H)*/*(*D*M*/D*H)DESI fid apport<u>anty on the correlations from</u> $\frac{1}{2}$, with $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$ Survey (DES Y6, [160]), as labelled. From top to bottom, the panels show *D*M*/r*d, *D*H*/r*d, *D*V*/r*^d and *D*M*/D*H, all relative to the respective quantities evaluated in the DESI fiducial cosmology described in
- Same redshift for the overlap catalog scheme here. The fiducial cosmology used to normalize the distance scales on the *y*-axis is the DESI Section 1. For 6dFGS, WiggleZ and some redshift bins of SDSS and DESI, only *D*V*/r*^d measurements were possible due to the low signal-to-noise ratio, so the third panel. In the third panel. In the third panel For the DESI and SDSS redshift bins where both *D*M*/r*^d and *D*H*/r*^d were measured, results for *D*V*/r*^d
- SDSS measurements identical when we use DESI pipeline fiducial cosmology used in this paper. qtical when we use DESI nineline $\frac{1}{2}$ and $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ survey the Dark Energy energy (SDS), and the Dark Energy energy (SDS), and the Dark Energy (SDS), and the Dark Energy energy (SDS), and the Dark Energy energy energy energ and *D*M*/D*^H in the third and fourth panels are displayed with open markers to indicate the repetition nfical when we use DESI pineline applied to the e↵ective redshifts of the SDSS results at *z*e↵ = 0*.*51 and 0*.*70 to avoid overlap and

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Main science at DESI

• **Baryonic Acoustic Oscillations (BAO)**

- $\sigma(BAO)$ ~0.2 % for 0.0<z<1.1
- $\sigma(BAO)$ ~0.3% for 1.1<z<1.9
- $\sigma(BAO)$ ~0.5% for 1.9 < z < 3.5
- SDSS(BOSS+eBOSS) few % measurements

• **Redshift Space Distorsion (RSD)**

- Multiple few % measurements over wide redshift range (z<2)
- ~10x better compared to SDSS
- **Neutrino masses**
	- $\sigma(\Sigma m_v) \sim 20$ meV
	- Current limit : $\Sigma m_v \sim 100$ meV, @ 95 CL
- Non-Gaussianity (f_{NL})
	- $\sigma(f_{NL})$ ~4 with k dependence of bias
	- As precise as Planck with a different technique

anisotropic BAO ring in the power spectrum, the right panel plots the two-dimensional power-spectrum divided by the best-fit smooth component. The wiggles

Baryonic Acoustic Oscillations (BAO)

• **BAO distance**

- Non-uniform distribution of galaxies, they form in overdense shells about 100 Mpc.h⁻¹ in radius.
- Excess in the correlation function at $~100$ Mpc.h⁻¹

\Rightarrow Standard Ruler

• **3D measurement**

- Position of acoustic peak
- **Transverse direction:**
	- \Rightarrow Sensitive to angular distance D_A(z)
- **Radial direction** (along the line of sight):
	- \Rightarrow Sensitive to Hubble parameter H(z)

Redshift Space Distorsion (RSD)

• **RSD origins**

- Acceleration toward overdense regions
- Flattening in radial direction from real space to redshift space (over tens Mpc)
- Allow us to measure action of gravity (10- 40 Mpc) at cosmological distance (Gpc)

BOSS Collaboration *Alam et al. (2016)*

Sight, Shown for the NGC only in the NGC only in the RGC only in the CSplit Days, Sept. 30, 2024 Slide 41 E. Burtin $\frac{1}{2}$ $\frac{1}{2}$ best-fit model. The anisotropy of the anisotropy of the anisotropy of R effects a combination of R effects a combination of R separately constrain *DM*(*z*)*/rd*, *H*(*z*)*rd*, and *f*8. The BAO ring can be seen in two dimensions on the correlation function plot. To more clearly show the