DESI DR2 Results

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Introduction

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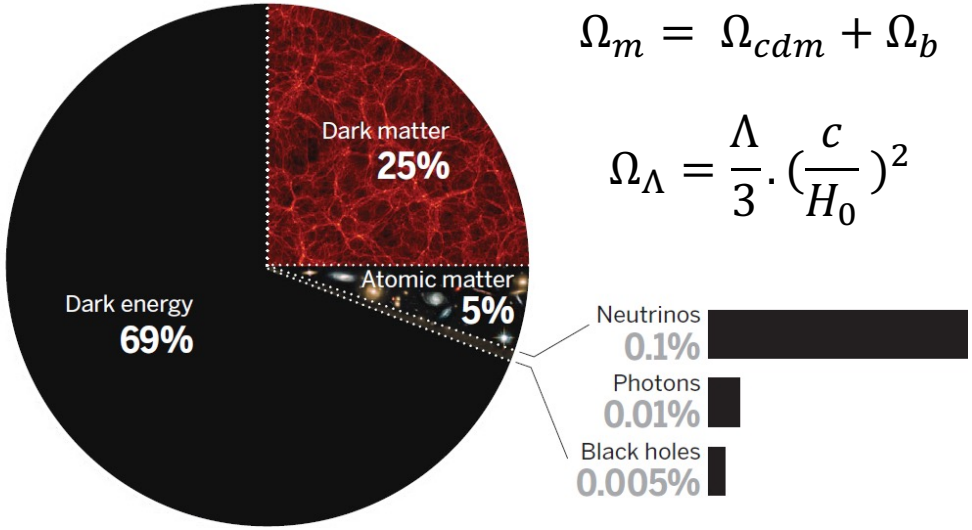
Baryonic Acoustic Oscillations (BAO)

Context in Cosmology: ΛCDM

ΛCDM

- "Standard Model" of cosmology
- General Relativity (GR)
- Cosmological constant (Λ)
- Flat Universe

$$\Omega_m + \Omega_\Lambda + \Omega_r = 1$$



$$\Omega_m = \Omega_{cdm} + \Omega_b$$

$$\Omega_\Lambda = \frac{\Lambda}{3} \cdot \left(\frac{c}{H_0}\right)^2$$

Extensions of ΛCDM

- Equation of state of Dark Energy

$$w(z) = \frac{p(z)}{\rho(z)}$$

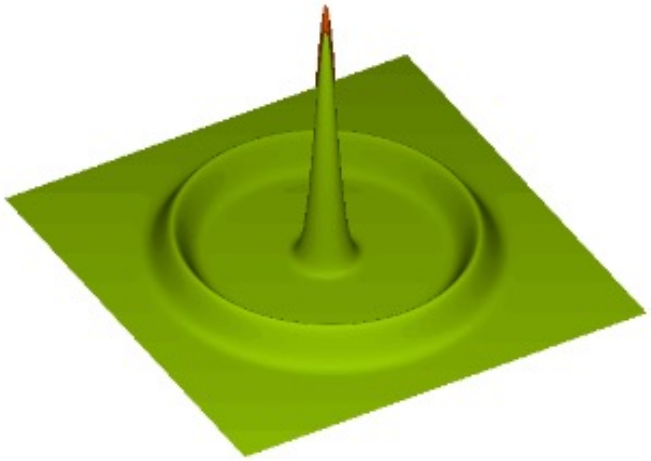
- Time evolving Dark Energy

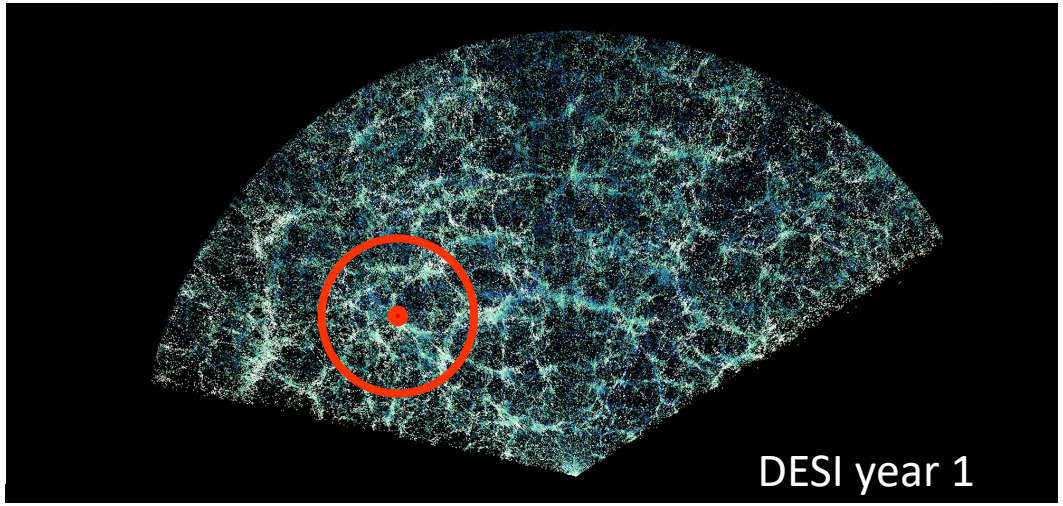
$$w(z) = w_0 + \frac{z}{1+z} w_a$$

Open questions

- H_0 tensions
- Time evolving DE ($w_0 w_a$CDM)

BAO, a standard ruler





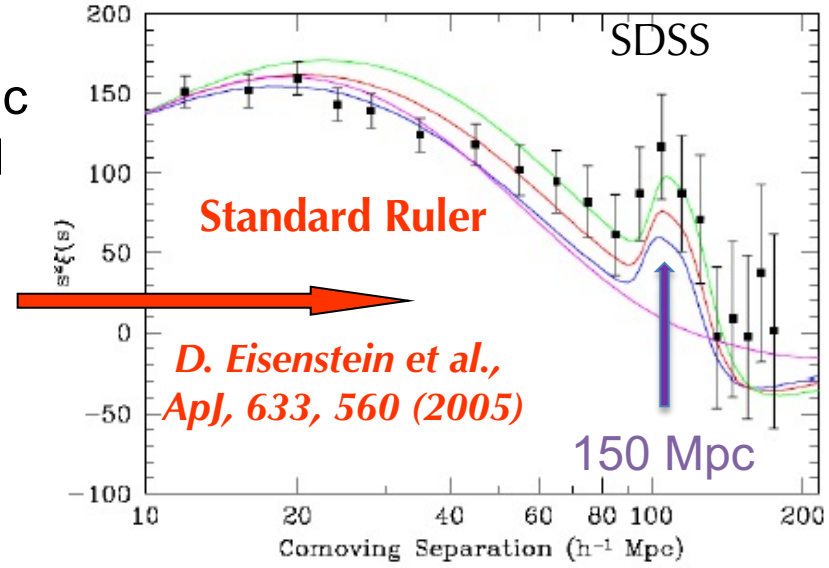
A special distance

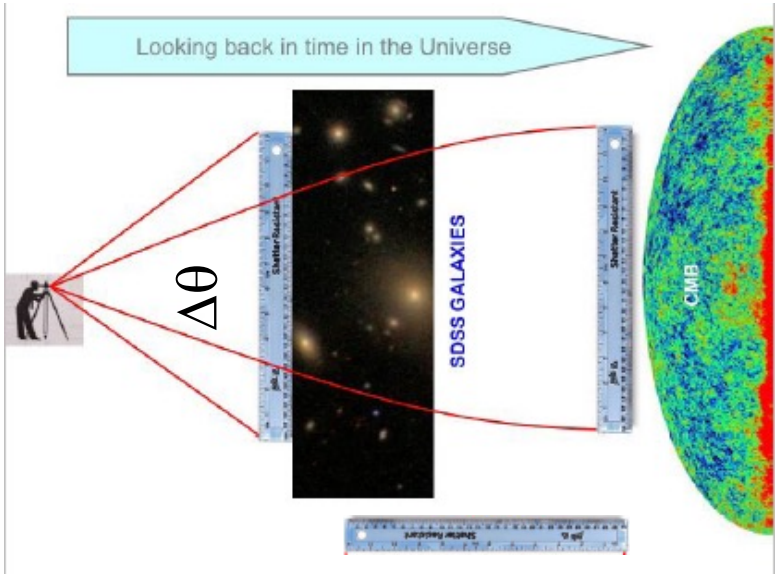
- Sound waves propagate through relativistic plasma (baryons, electrons, photons) with a speed $\sim c/\sqrt{3}$
- They freeze at recombination (z~1100 i.e 380,000 years)
- Galaxies form in the overdense shells about r_d ~ 150 Mpc in radius from initial overdensities.
- $\Rightarrow$ Standard Ruler: r_d ~ 150 Mpc in comoving distance

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:**

$\Delta\theta = r_d/(1+z)/D_A(z) = r_d/D_M(z)$

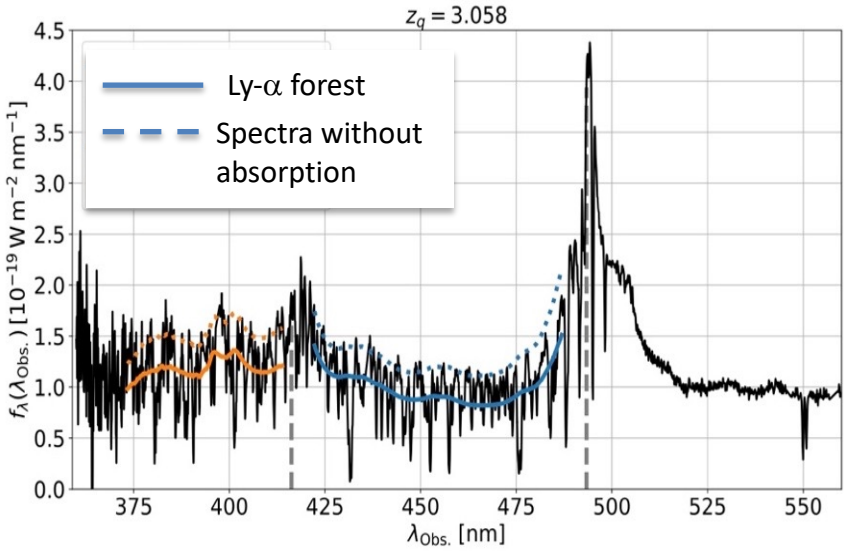
$\Rightarrow$ Sensitive to angular distance $D_A(z)$

- **Radial direction** (along the line of sight):

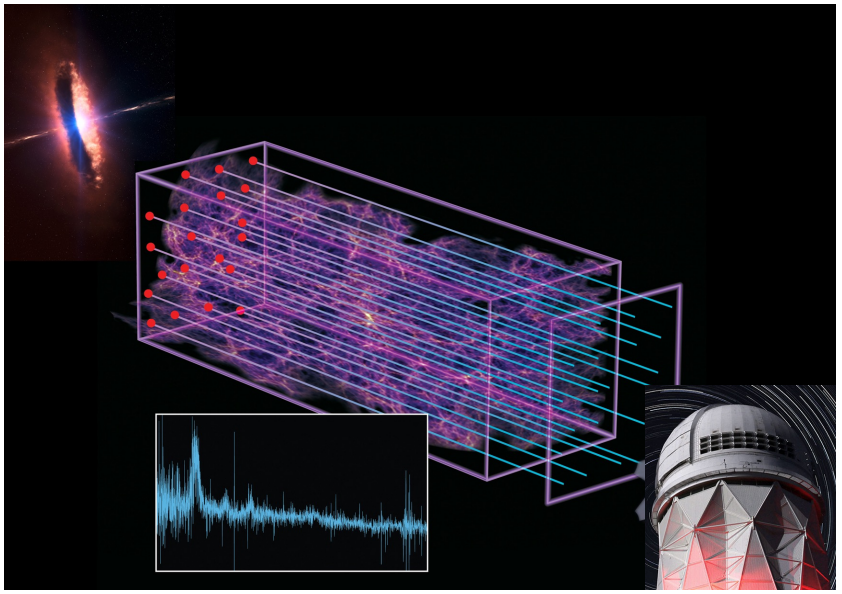
$\Delta z = r_d \cdot H(z)/c$

$\Rightarrow$ Sensitive to Hubble parameter H(z).

Another Tracer of Matter: Ly-α forest of quasars



- For z>2, no discrete tracer (galaxy) observable with DESI
- Use Ly-α forests of quasars (2.0<z<3.5)
- HI absorption in intergalactic medium (IGM) along the line of sight of quasars



- We expect low density gas (IGM) to follow the dark matter density
- Compute correlation function between HI ‘clouds’
- Measure the location of BAO

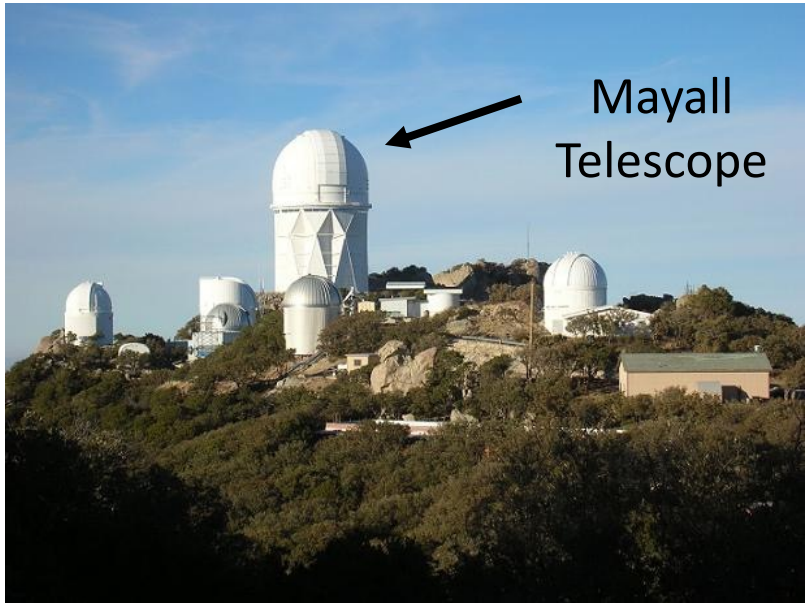
Dark Energy Spectroscopic Instrument

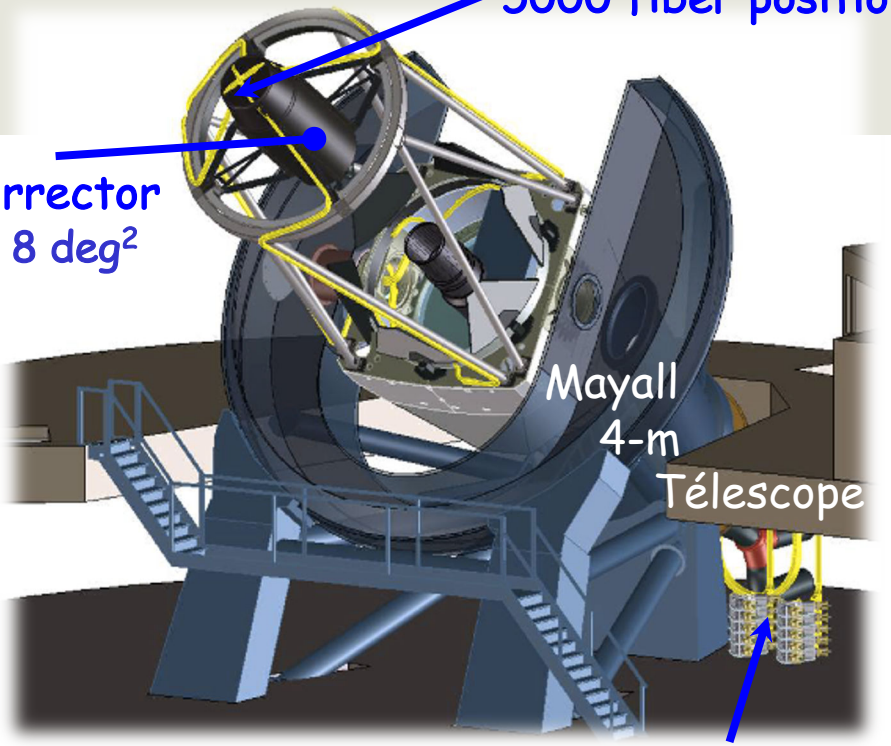
-

DESI

DESI Project

- **Scientific project**
  - 3D map for 0<z<4
  - Footprint ~14000 deg^2 (1/3 sky)
  - International collaboration
  - 72 institutions (46 non-US)
  - ~900 members





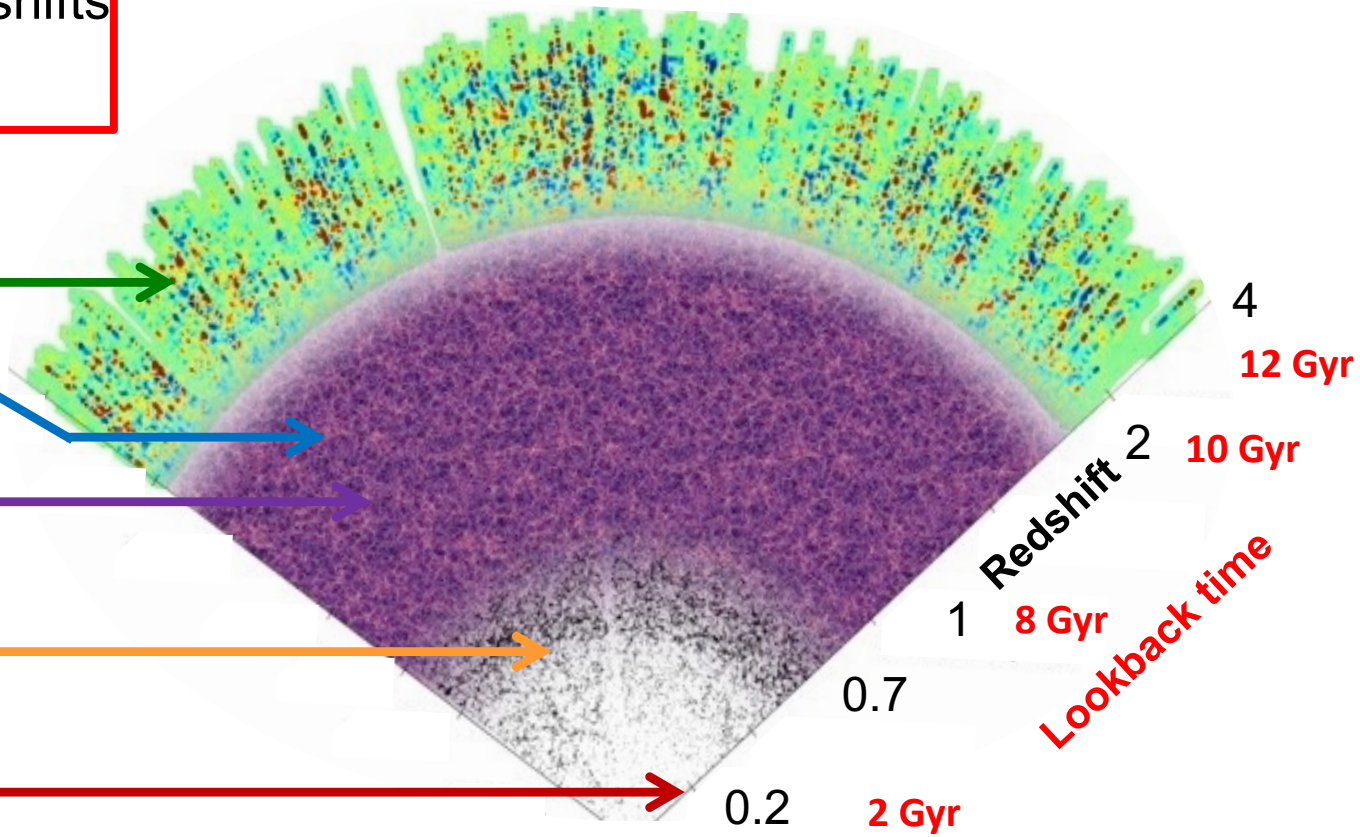
- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide FoV (~ 8 deg^2)
  - Robotic positioner with 5000 fibers
  - 10 spectrographs x 3 bands (blue, visible, red-NIR) →360-1020 nm

DESI tracers of the Matter

Five target classes

~40 million redshifts

in 5 years



3 million QSOs

Ly-α z > 2.1

Tracers 0.9 < z < 2.1

16 million ELGs

0.6 < z < 1.6

8 million LRGs

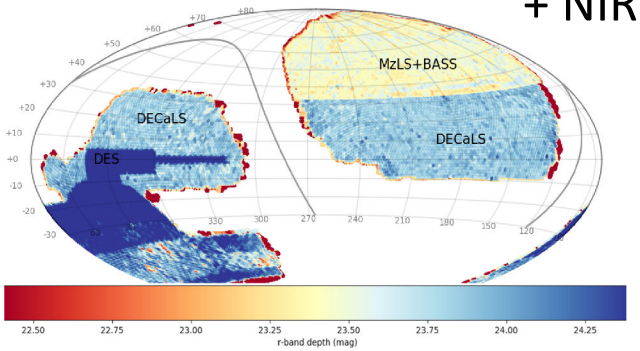
0.4 < z < 1.0

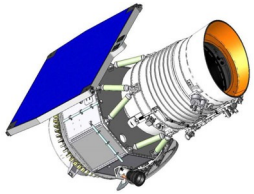
13.5 million Brightest galaxies

0.0 < z < 0.4

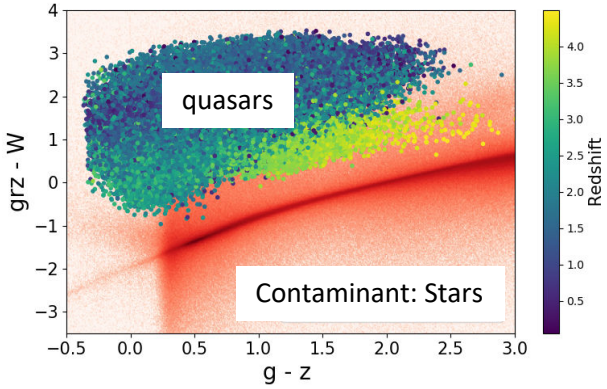
Rolling observations – Redshift factory

Imaging Surveys: optical grz bands
+ NIR with WISE



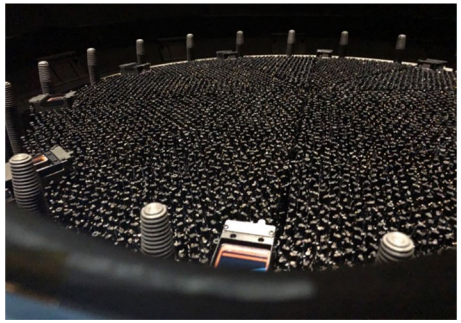


Target Selection

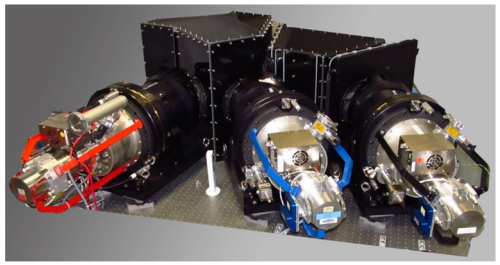


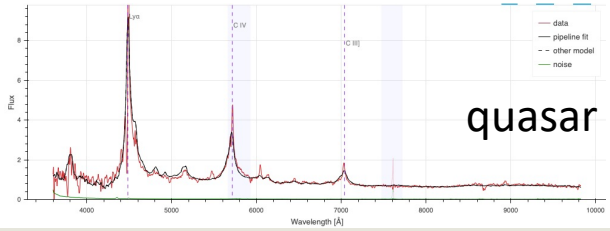
Observation…

…of 5000 objects
every ~20mins…

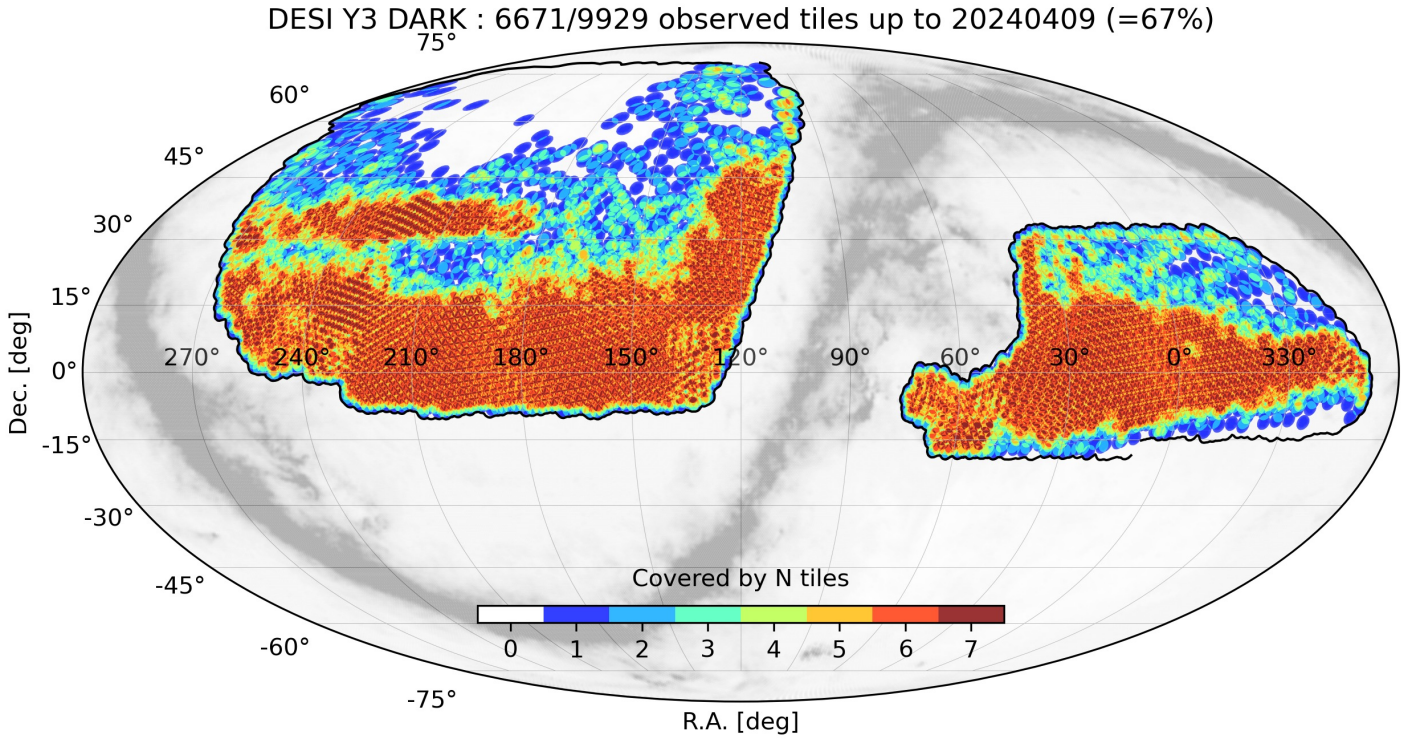


…and measure their redshift





DESI DR2 footprint

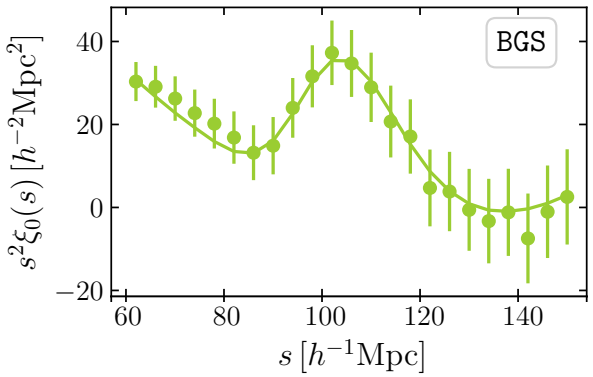


- DESI footprint over 5 years ~14000 deg^2
- DR2 ~70% of final footprint
- Increase of V_{eff} by a 2.3 factor from DR1 to DR2
- 14.3M discrete tracers (galaxies and quasars), 800k Ly-α forests

BAO Measurements

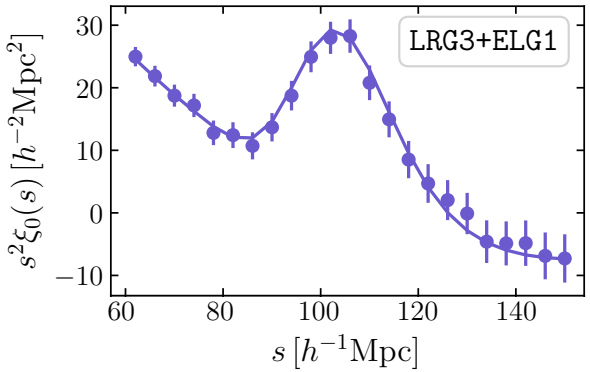
Results: a few examples

BGS z=0.30



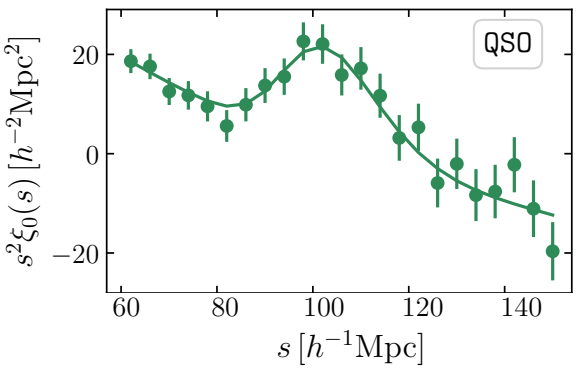
Precision: 0.93%

LRG3+ELG1 z=0.93



Significance: 14.7σ
Precision: 0.45%

QSO z=1.48



Significance: 5.6σ
Precision: 1.5%

- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\rm iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest significance. 5.6σ

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

Systematics Error Budget

- Observational effects in data (imaging, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction

No effect on BAO

- Incomplete theory modelling
- Choice of fiducial cosmology
- Galaxy-halo (HOD) model

Systematics Error Budget

- Observational effects in data (imaging, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction

No effect on BAO

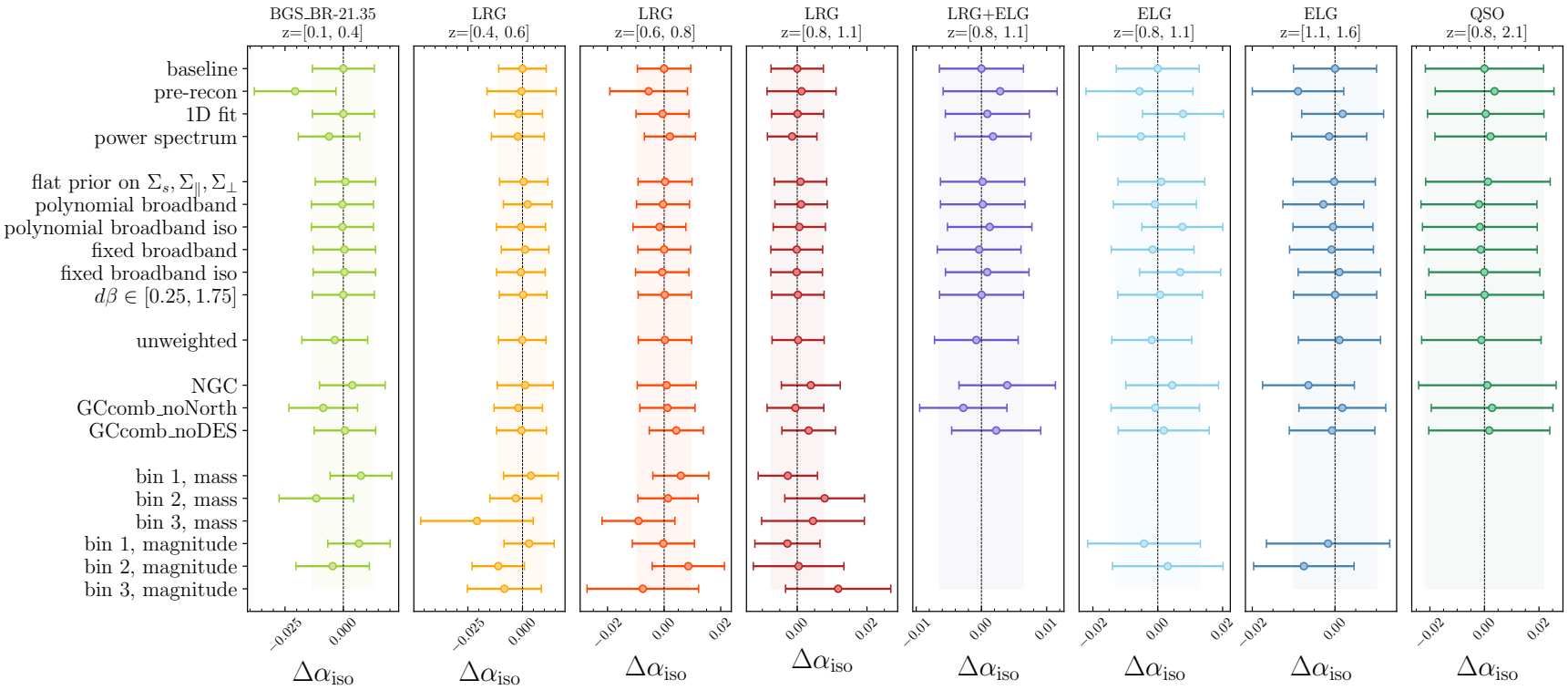
- Incomplete theory modelling $\boldsymbol{\sigma_{theo}} = 0.1\%$
- Choice of fiducial cosmology $\boldsymbol{\sigma_{fid}} = 0.1\%$
- Galaxy-halo (HOD) model $\boldsymbol{\sigma_{HOD}} = 0$ - 0.17% (depending on tracers)

$\sigma_{sys} < 0.22\%$

All systematics much smaller than statistical errors

$\boldsymbol{\sigma_{total} = 1.01\sigma_{stat.}}$ **(BGS)** - $\boldsymbol{\sigma_{total} = 1.09\sigma_{stat.}}$ **(LRG3+ELG1)**

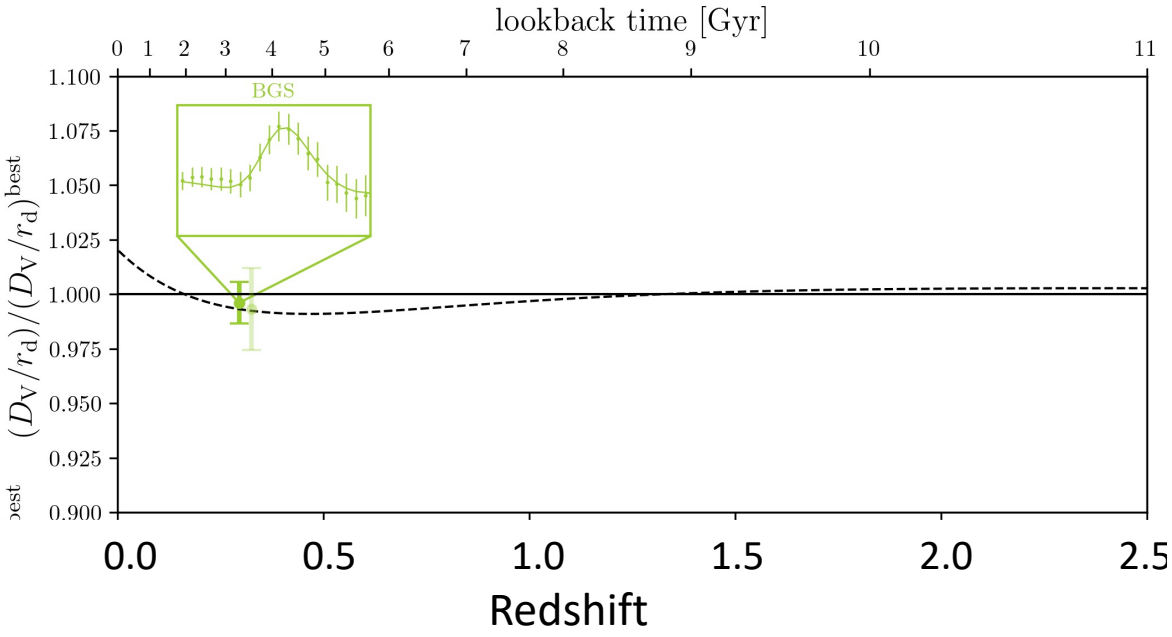
Stability of the results

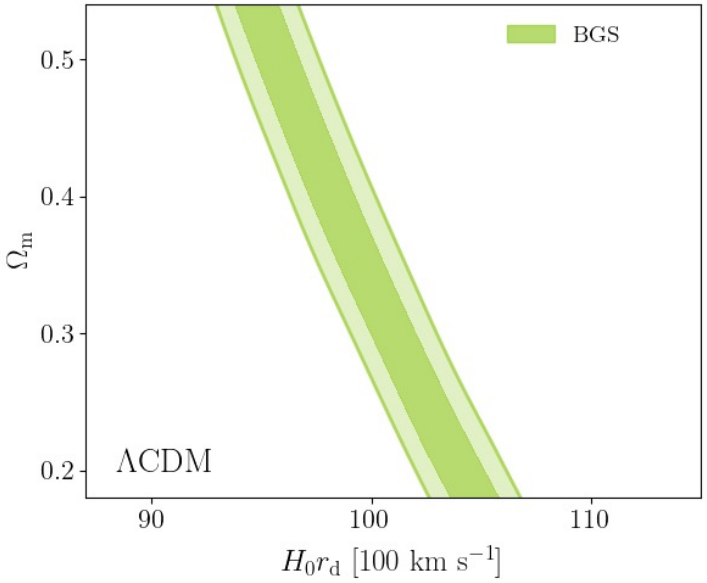


- Comparison with the baseline analysis for different configurations (with/without reconstruction, power-spectrum, broadband modeling priors damping parameters, imaging weights, footprint, mag mass)
- **Extremely stable results**

DESI DR2: BGS

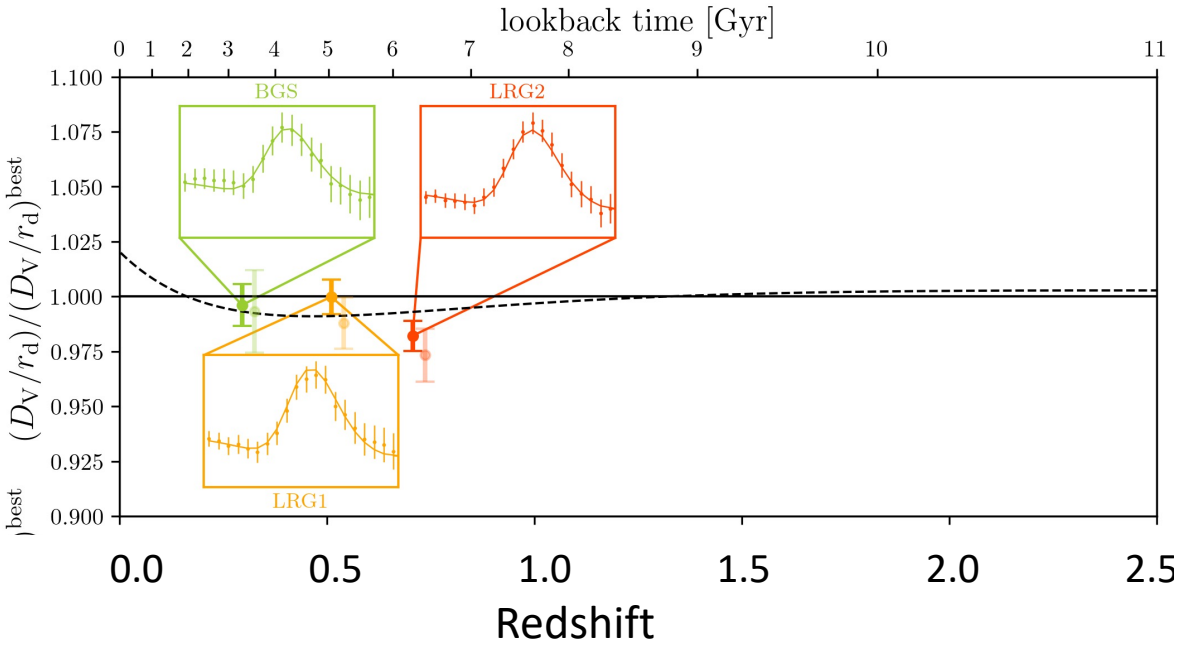
$$\alpha_\perp = \frac{D_\mathrm{M}}{r_\mathrm{d}} \frac{r_\mathrm{d}^\mathrm{fid}}{D_\mathrm{M}^\mathrm{fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_\mathrm{d}} \qquad \alpha_\mathrm{iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$$

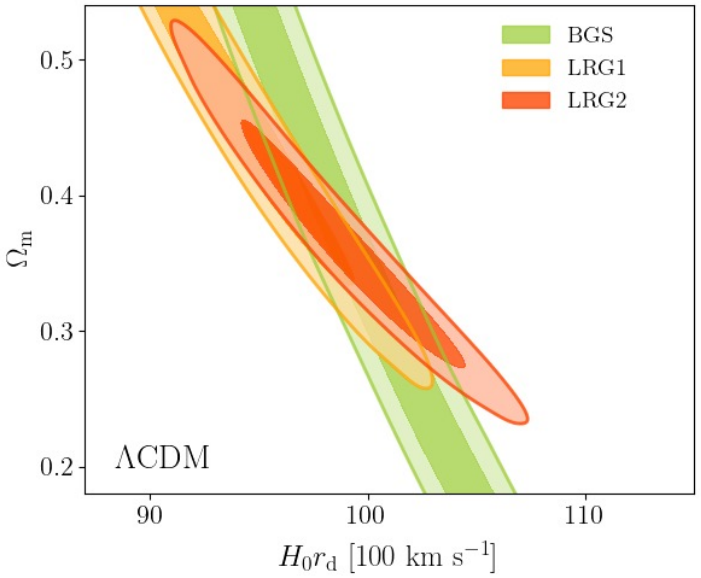




- Friedman equation for ΛCDM $H(z) \equiv H_0 \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}$
- Limitation due the cosmic variance (small part of the visible Universe)

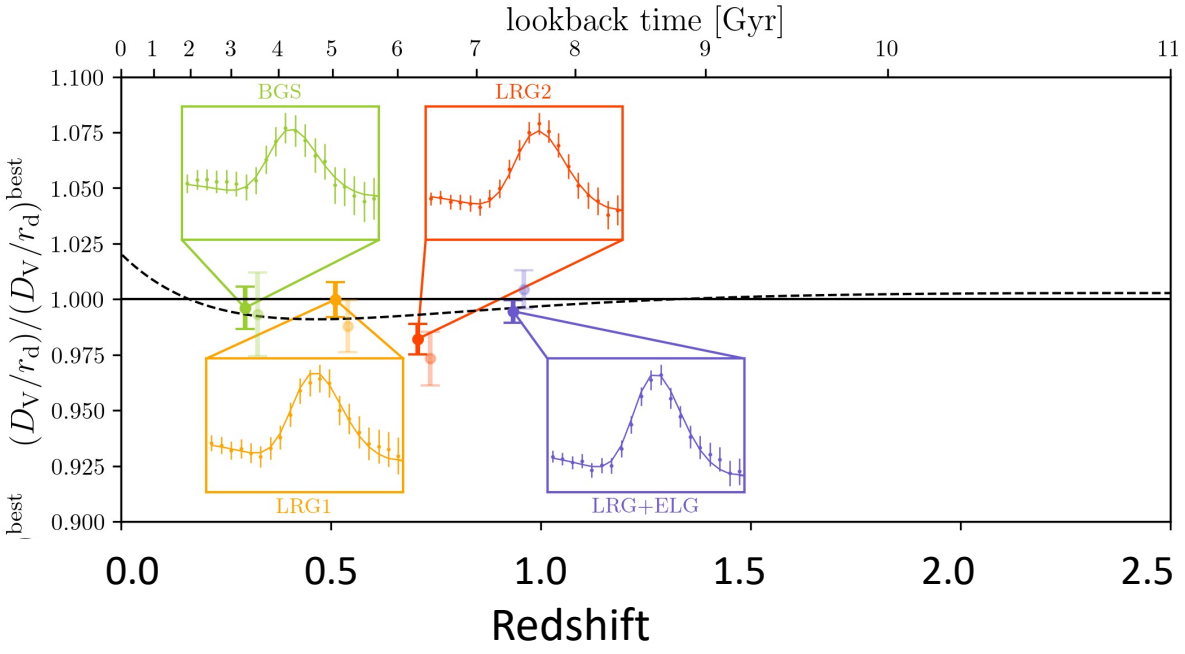
DESI DR2: BGS + LRG

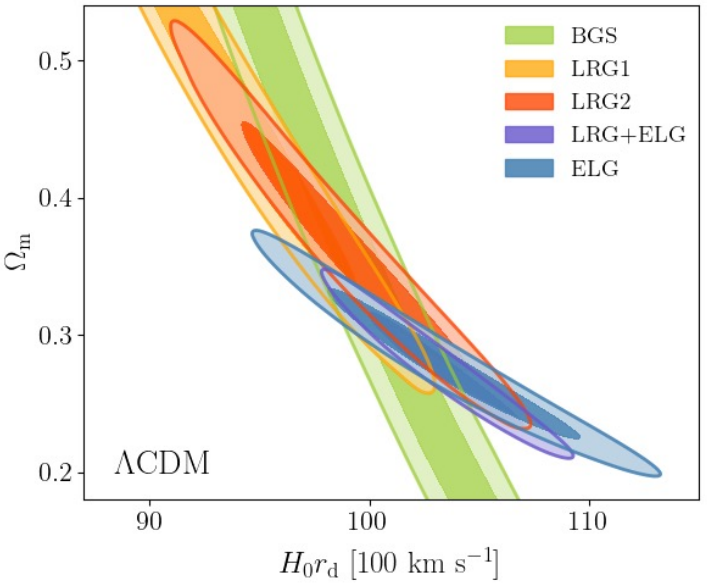




- LRG: Main tracer in SDSS, precise measurement in DESI

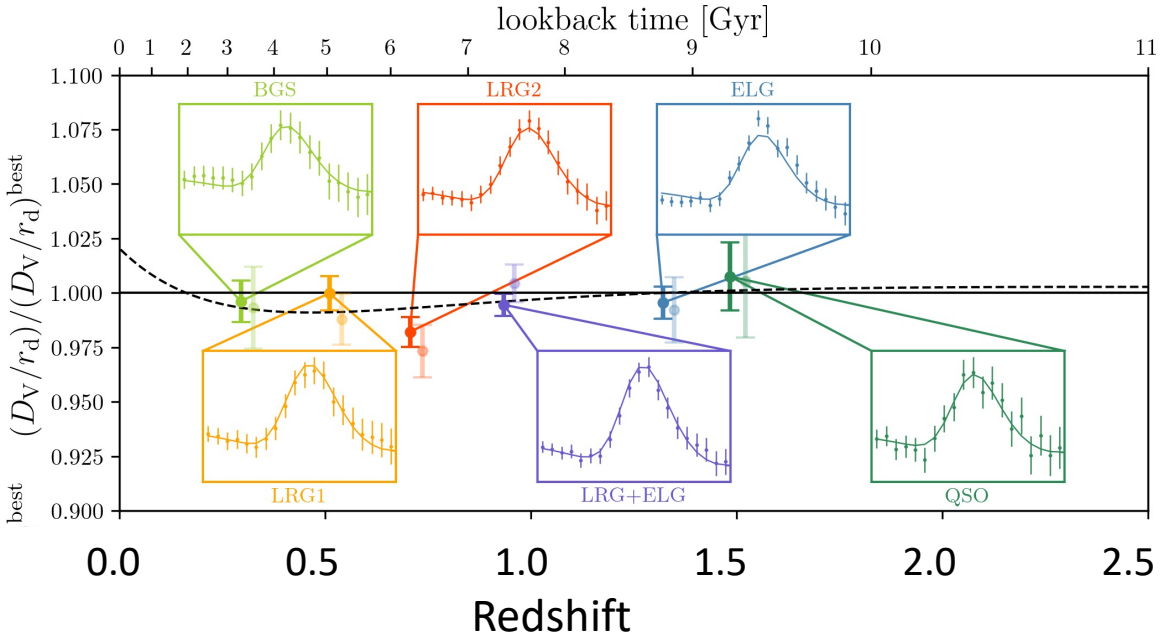
DESI DR2: BGS + LRG + ELG

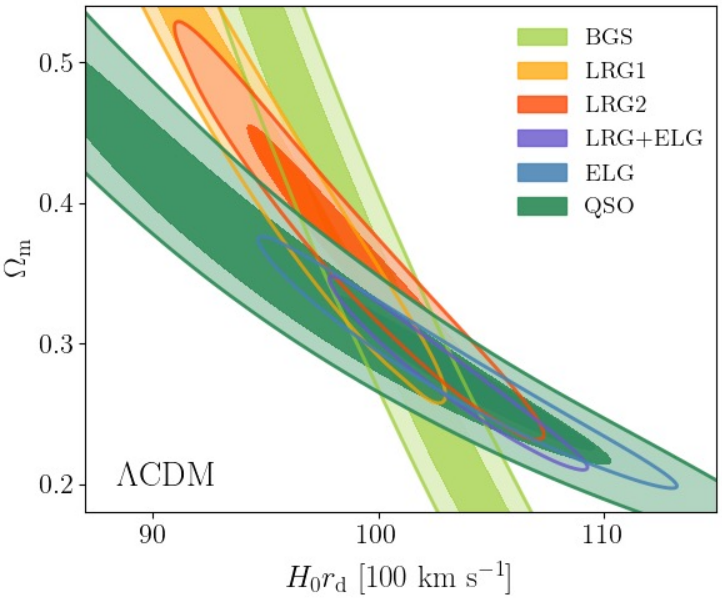




- ELG: Main tracer in DESI, precise measurement
- x 2.7 with DR2 compared to DR1

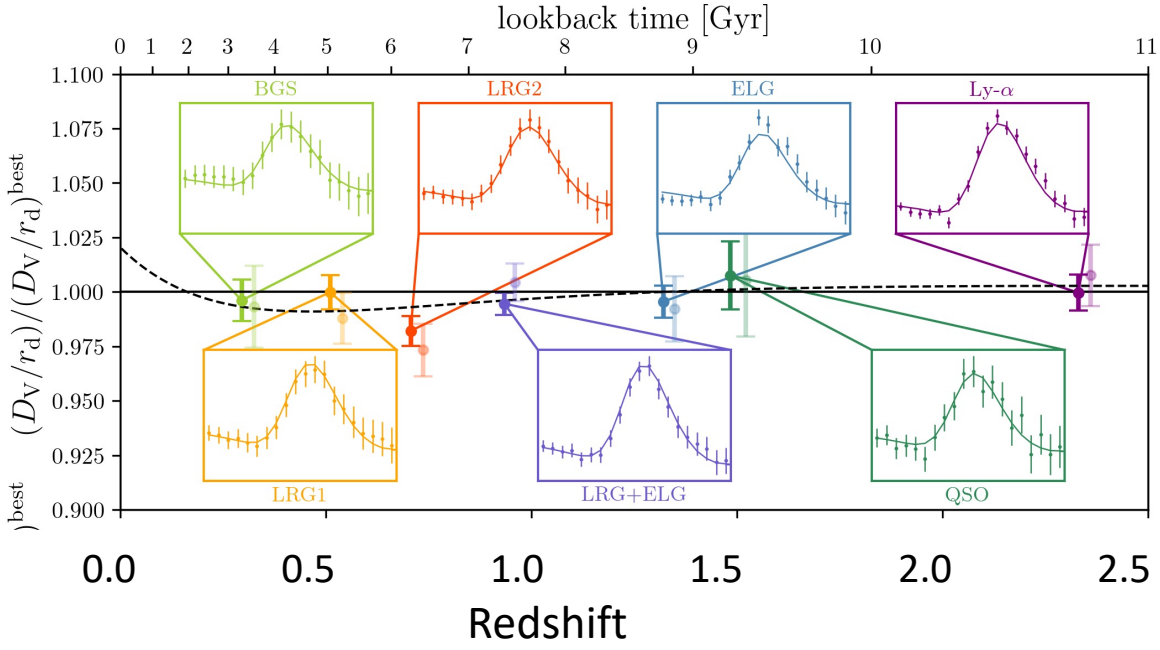
DESI DR2: BGS + LRG + ELG + QSO

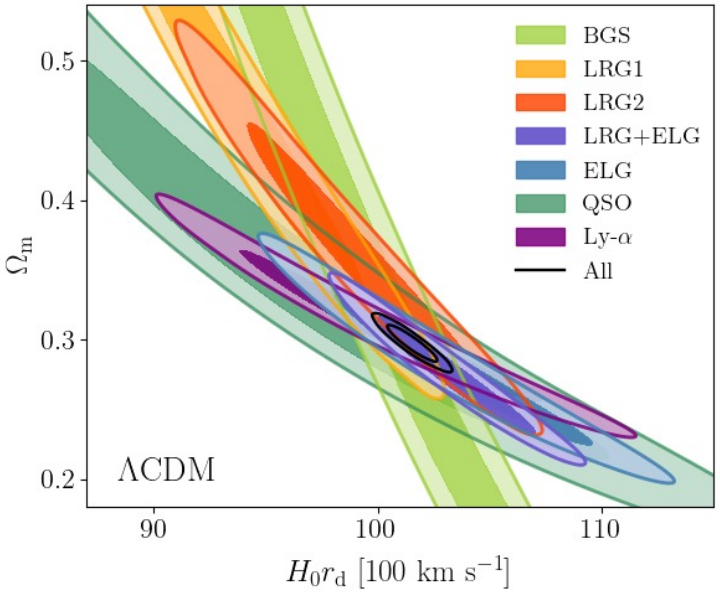




- QSO: huge volume but small density (shot noise limitation)

DESI DR2: BGS + LRG + ELG + QSO + Ly-α

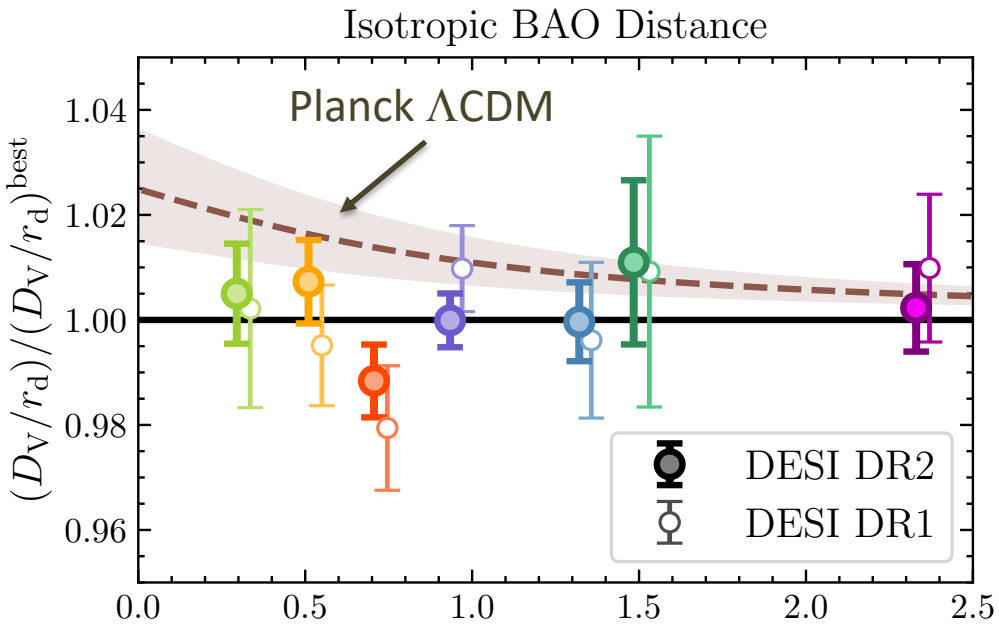




- Different dependence as a function of redshift (Ω_m,r_d)
- Break the degeneracy without knowing r_d

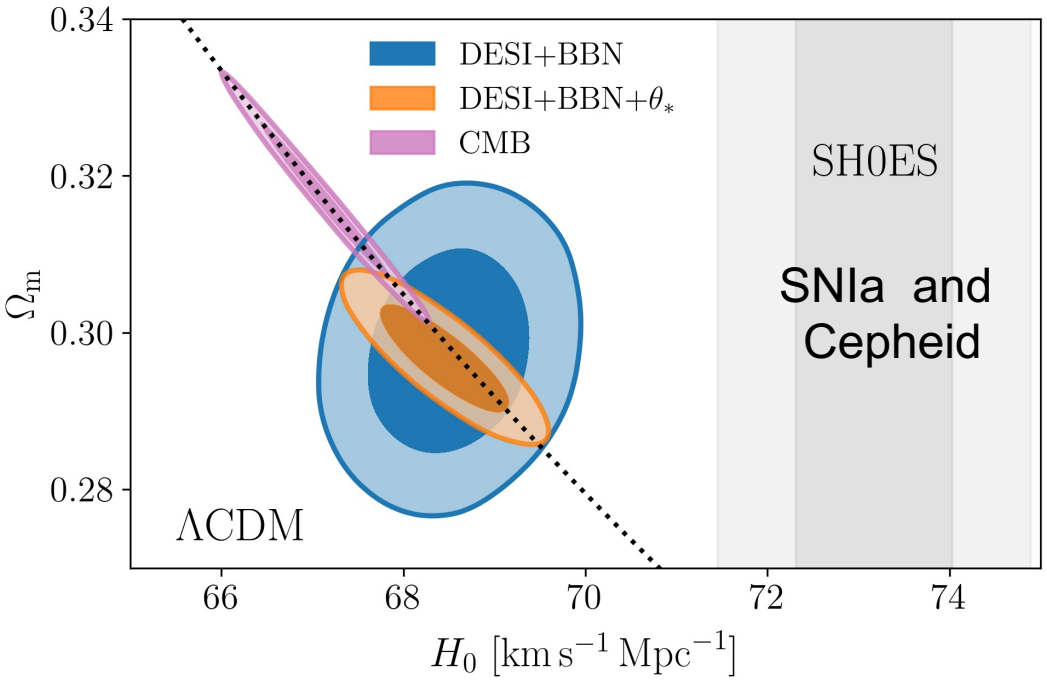
Cosmological Interpretation

DESI - Hubble diagram



- ~14M discrete tracers with 0.1<z<2.1 in 6 redshift bins
- Precision on BAO: from 1.5% (QSO) to 0.45% (LRG3+ELG1)
- With Ly-α forest of QSOs at z~2.3 : precision on BAO 0.7%
- Excellent agreement between DESI DR1 and DR2
- Consistent with ΛCDM but small tension with Planck ΛCDM : 2.3σ

Hubble constant in ΛCDM



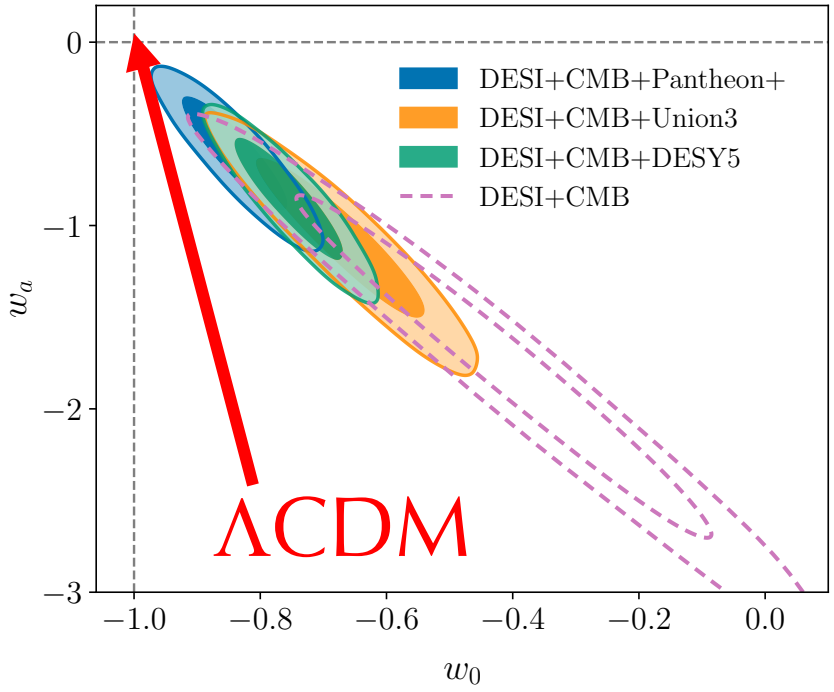
$$\underbrace{H_0 = (68.51 \pm 0.58)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\mathrm{DESI + BBN}}$$

$$\underbrace{H_0 = (68.45 \pm 0.47)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\mathrm{DESI} + \theta_* + \mathrm{BBN}}$$

θ_* : CMB angular scale

- **Main tension in cosmology**: 5σ discrepancy between CMB and late measurements (SNIa)
- Big Bang Nucleosynthesis (BBN) can be used to measure r_d
- DESI + BBN (without CMB), tension with SNIa (SH0ES): 4.5σ

Beyond ΛCDM: Dark Energy - Equation of State



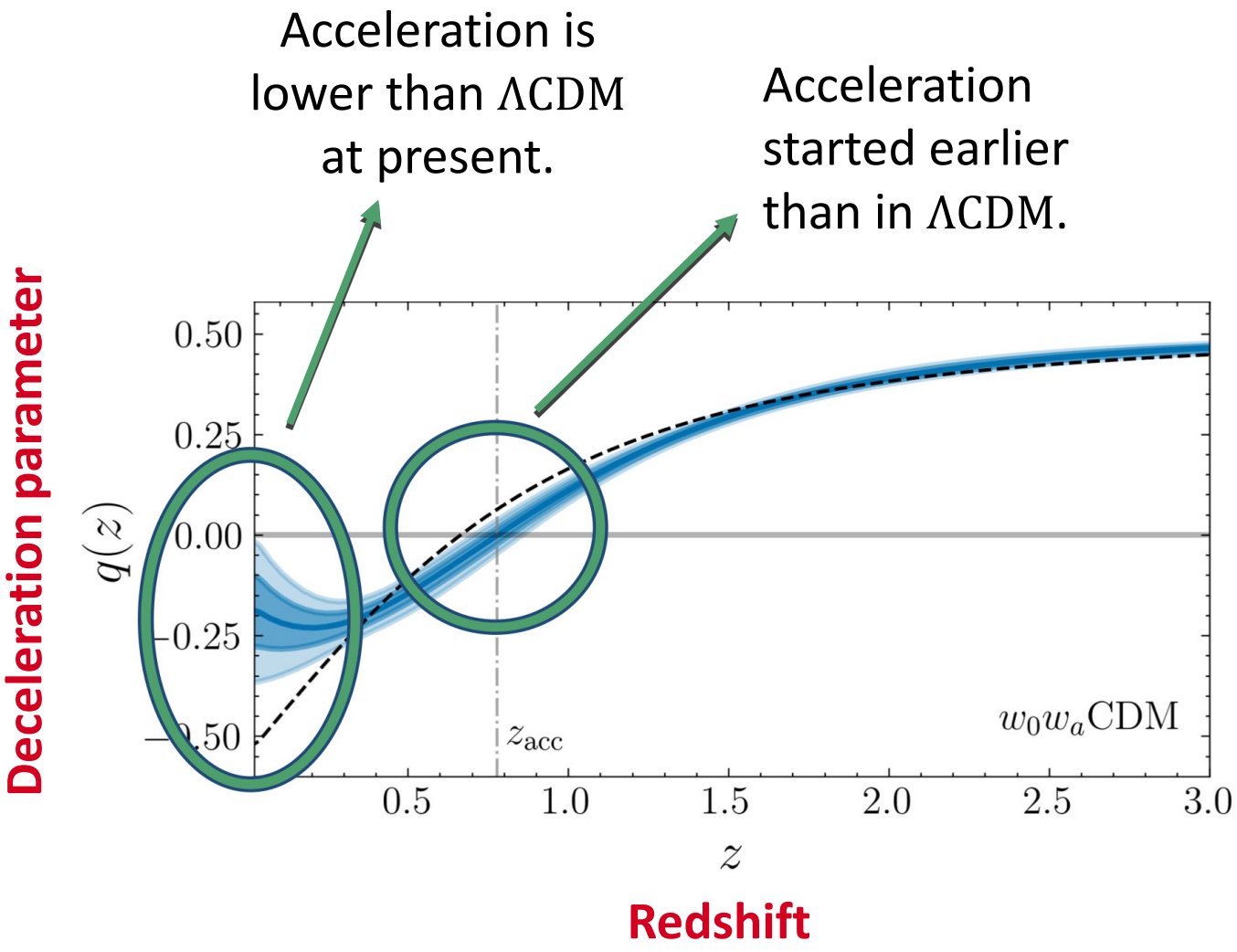
Dark Energy Equation of State

$$w(z) = \frac{p(z)}{\rho(z)}$$

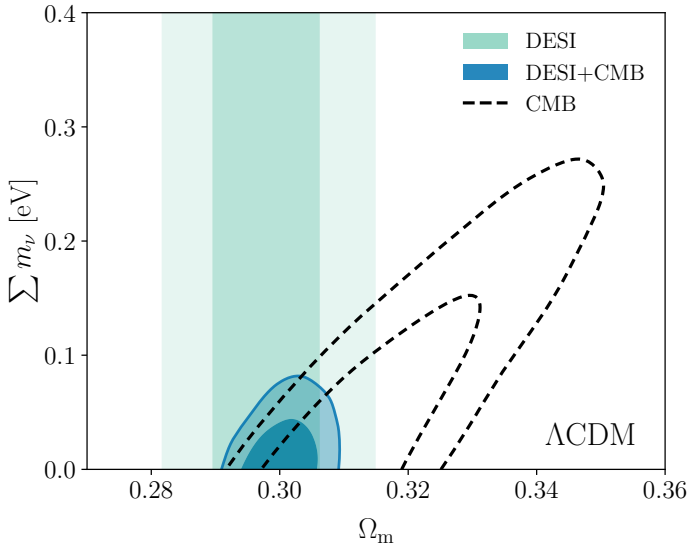
$$w(z) = w_0 + \frac{z}{1+z} w_a$$

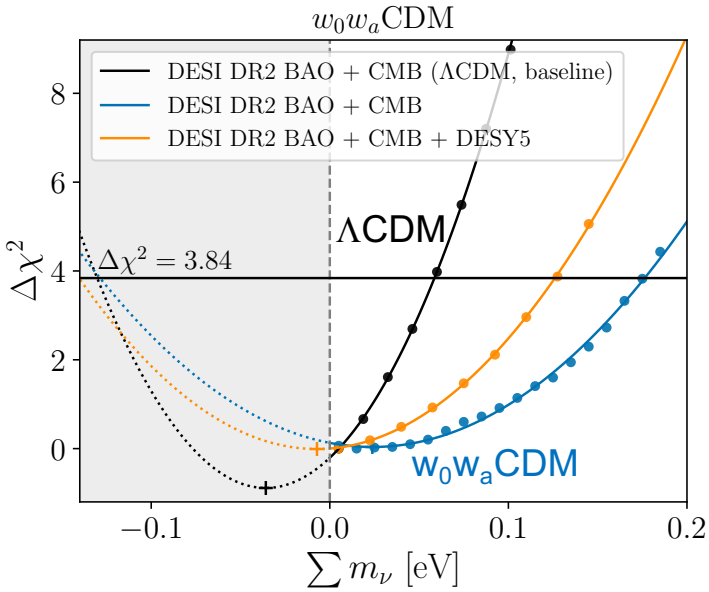
- For ΛCDM, we expect w=-1, i.e. w_0=-1 and w_a=0
- Combining DESI+CMB: 3.1σ effect
- Combining DESI+CMB+SN: 2.8σ to 4.2σ effect depending on the SN sample
- **Indications of dynamical dark energy with DESI?**

Dynamical Dark Energy



Sum of neutrino masses





- CMB is sensitive to $\sum m_\mu$
- BAO measures Ω_m and breaks the degeneracies

Limits at 95% CL:

- For ΛCDM with CMB alone: $\Sigma m_\nu < 210\ meV$
- For ΛCDM with CMB + DESI: $\Sigma m_\nu < 64\ meV$
- For w_0w_aCDM with CMB + DESI $\Sigma m_\nu < 130\ meV$

Summary: Results from DESI BAO DR2

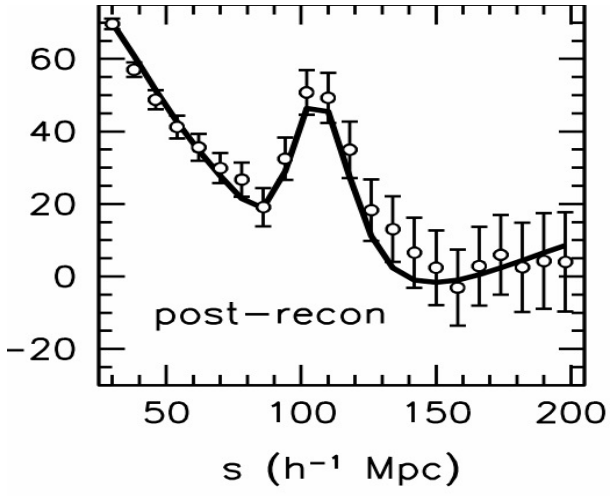
- **BAO results with DR2**
  - With three years (DR2), DESI provides the most precise measurement of BAO over 0<z<3.5
  - DR2 results confirm DR1 results
  - In ΛCDM, DESI is in slight tension with CMB (~2.3σ) and DESI prefers lower Ω_m
  - Indications of time-varying Dark Energy equation of state, especially when SNIa are added

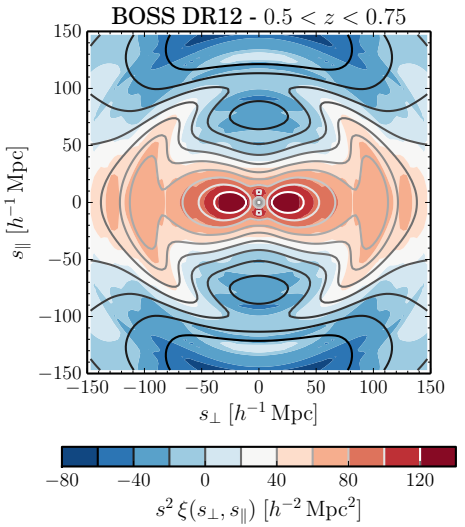
    $\Longrightarrow$ a 2.8σ to 4.2σ effect, not 5σ yet!
- **What next?**
  - BAO: Full dataset for DESI in 2026 (+ Full shape analysis)
  - SNIa: ZTF, homogeneous sample at z<0.1
  - CMB: ACT, SPT and in the long term SO and CMB-S4

Additional Slides

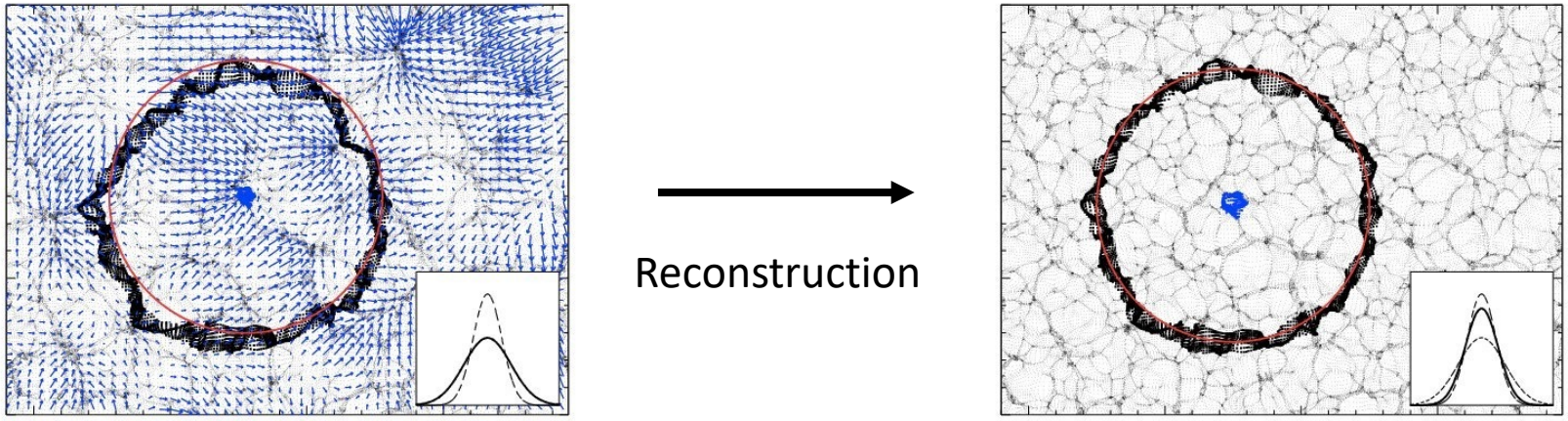
Main science at DESI

- **Baryonic Acoustic Oscillations (BAO)**
  - σ(BAO) ~0.2 % for 0.0<z<1.1
  - σ(BAO) ~0.3% for 1.1<z<1.9
  - σ(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**
  - $\sigma(\Sigma m_\nu)$ ~20 meV
  - Current limit : Σm_ν <~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



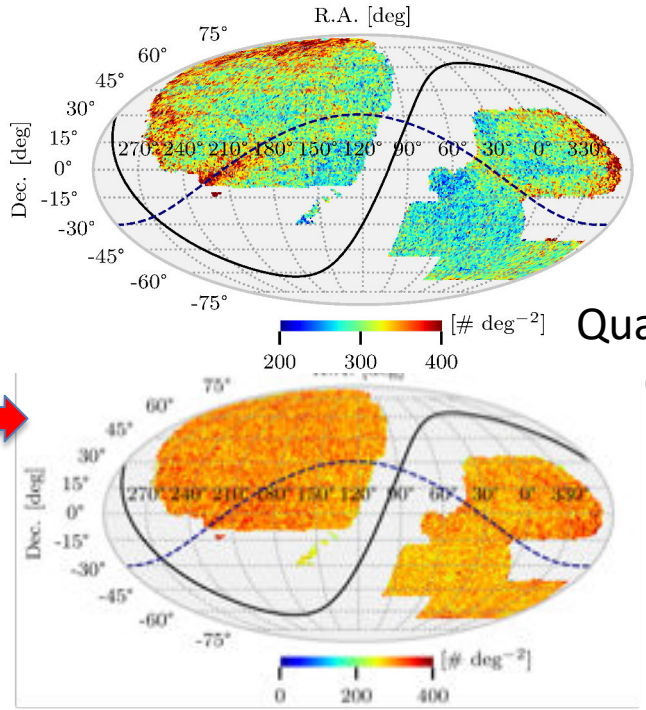


Density Field Reconstruction

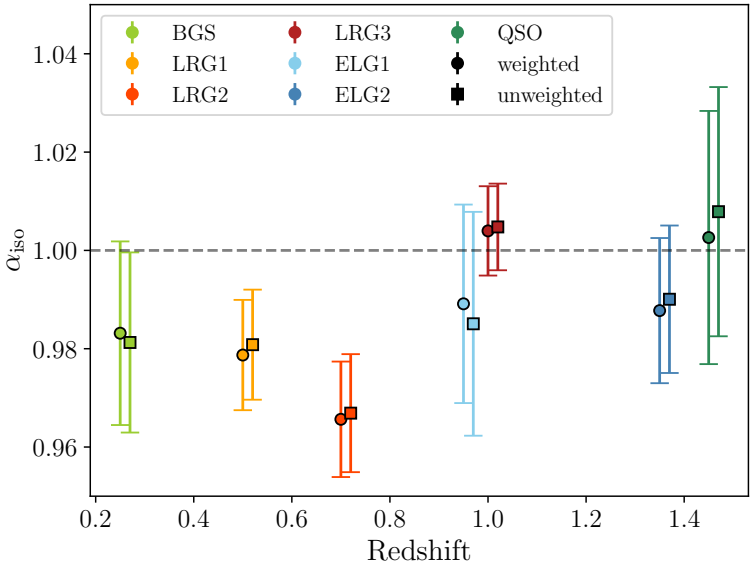


- BAO peak distorted by movements of tracers due to density field
- Estimation of the Zeldovich displacement from the observed field
- Reconstruction: correction of the displacements
- **Improve both precision and accuracy**

Example of systematics: Imaging

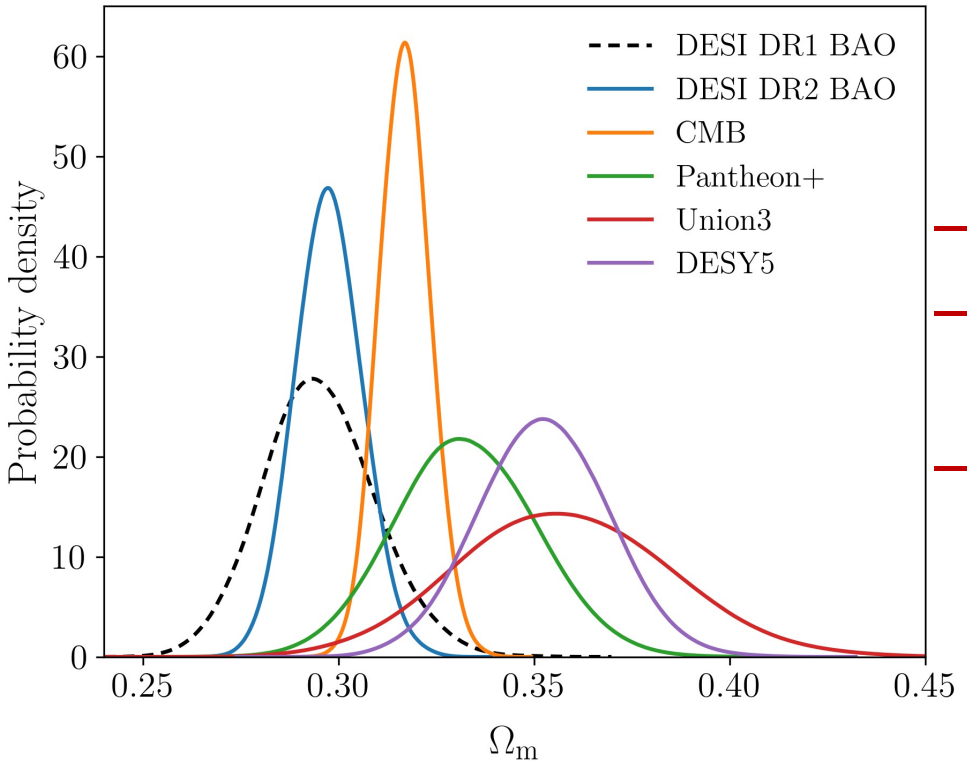


Quasar target density



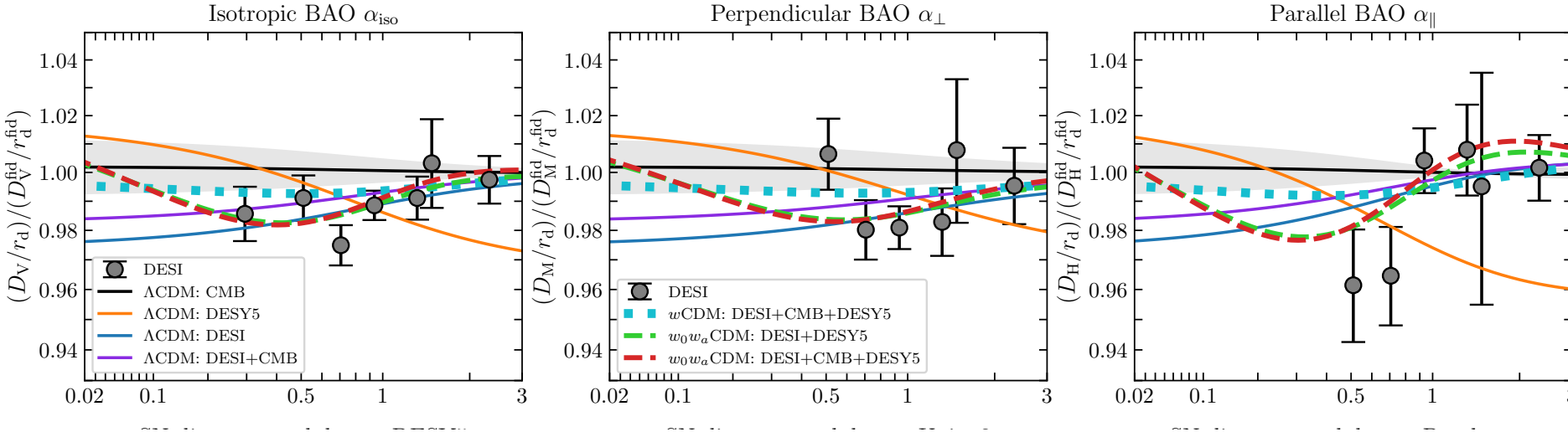
- Non-homogeneity in target selection due variations of imaging catalogs (depth, dust contaminants,…)
- Regression methods developed to correct those effect
- Same measurements of BAO with/without corrections
- **BAO almost insensitive to imaging effects**

Ω_m tensions in ΛCDM



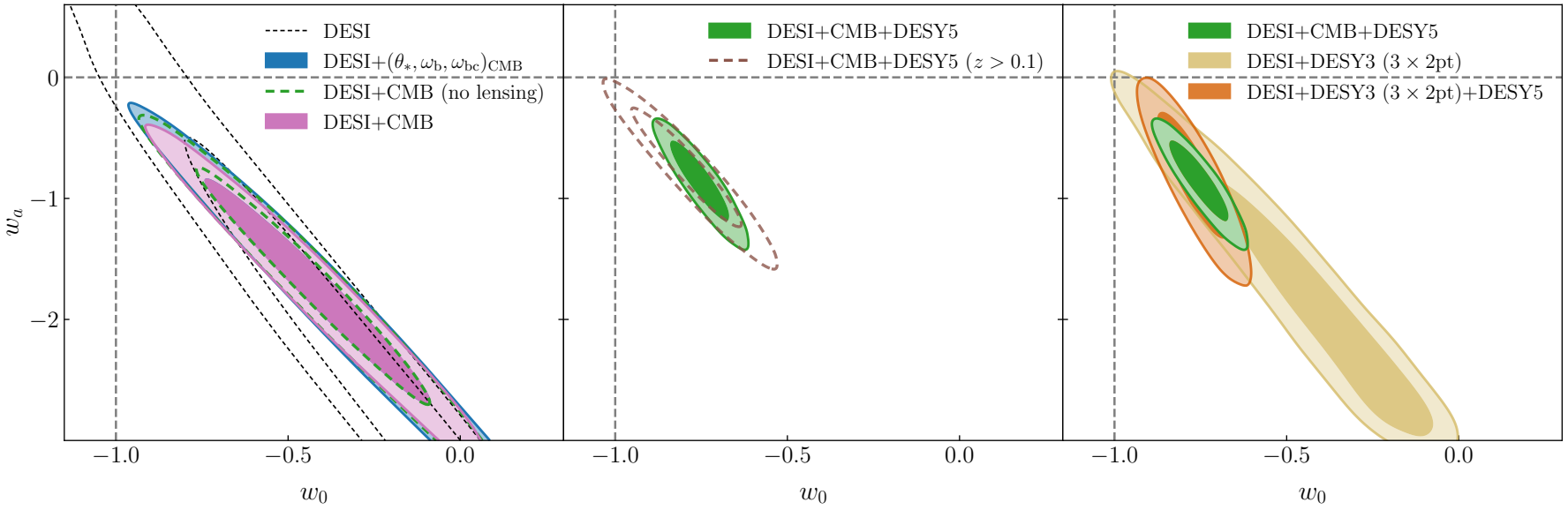
- Consistent result DR1/DR2
- 2.3σ discrepancy between CMB and DESI
- Discrepancies with SNIa samples
  - Pantheon+: 1.7σ
  - Union3: 2.1σ
  - DESY5: 2.9σ

Dark Energy – Hubble Diagram



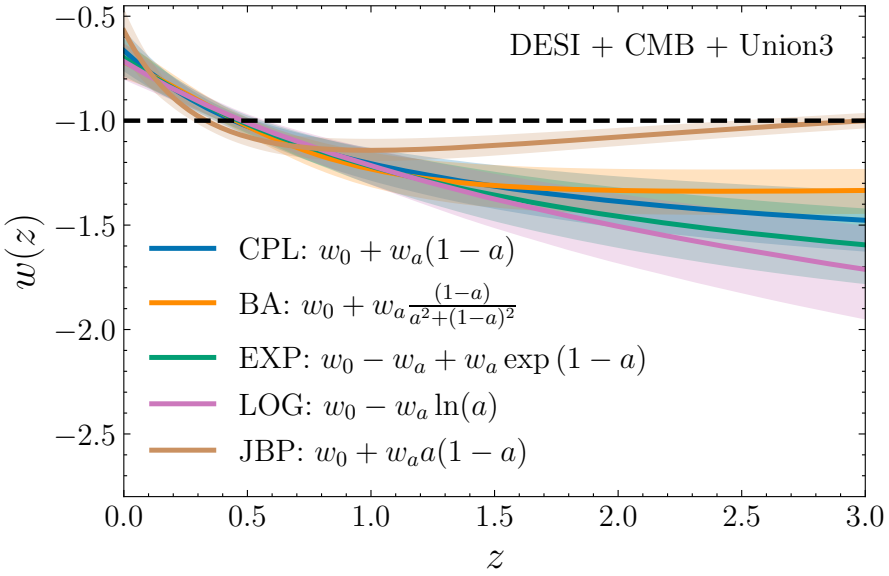
- Combining DESI+CMB+SN: 2.8σ to 4.2σ effect depending on the SN sample
- Better agreement with w_0w_aCDM model

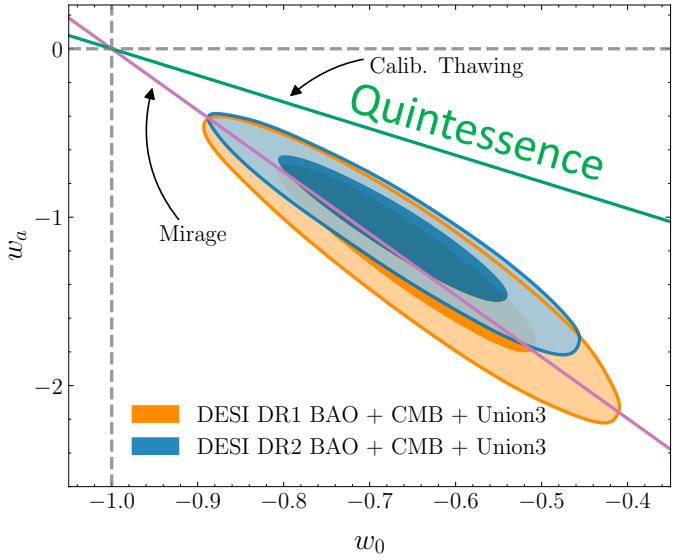
Dark Energy – Robustness



- Combining with early-Universe prior on (θ_*,ω_b,ω_{bc}) from CMB shows preference for evolving DE.
- Excluding z<0.1 SNIa reduces but the best fit is far for ΛCDM
- Replacing CMB with DES 3x2pt continues to show a preference for evolving DE

Dark Energy – Parametrization – Models





- Significance doesn't depend on parametrizations
- Mirage Dark Energy is preferred to Quintessence models

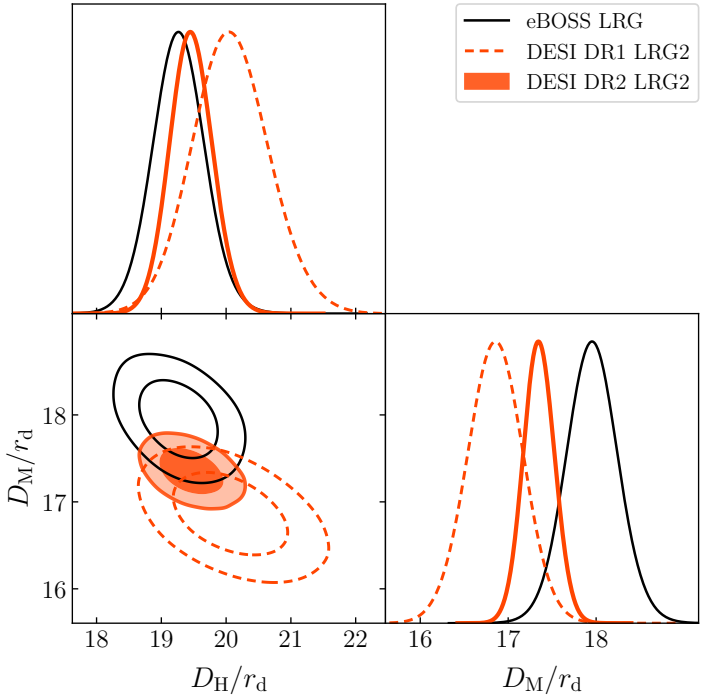
Dark Energy – Significance

Datasets	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_{\rm b}, \omega_{\rm bc})_{\rm CMB}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 (3×2pt)	-7.3	2.2σ	-2.8
DESI+DESY3 (3×2pt)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2

CMB (including lensing)

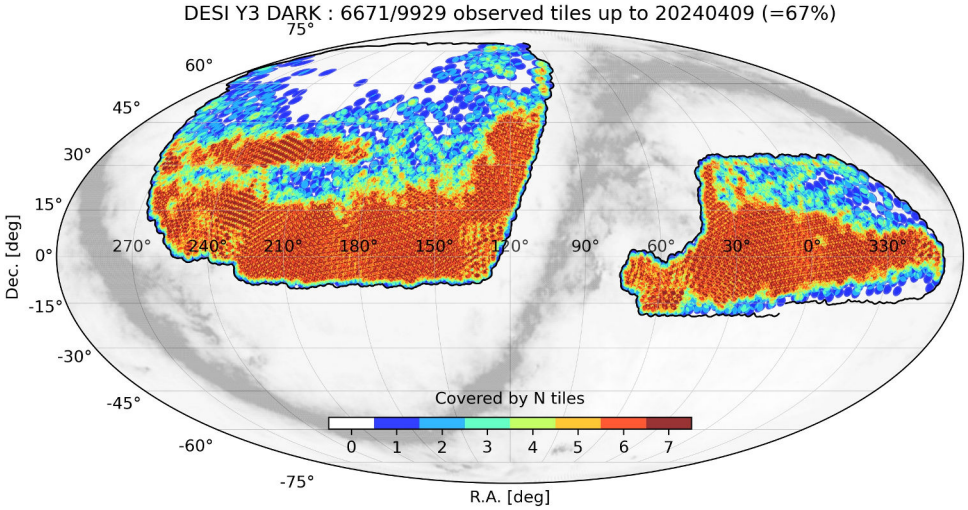
Three SNIa sample

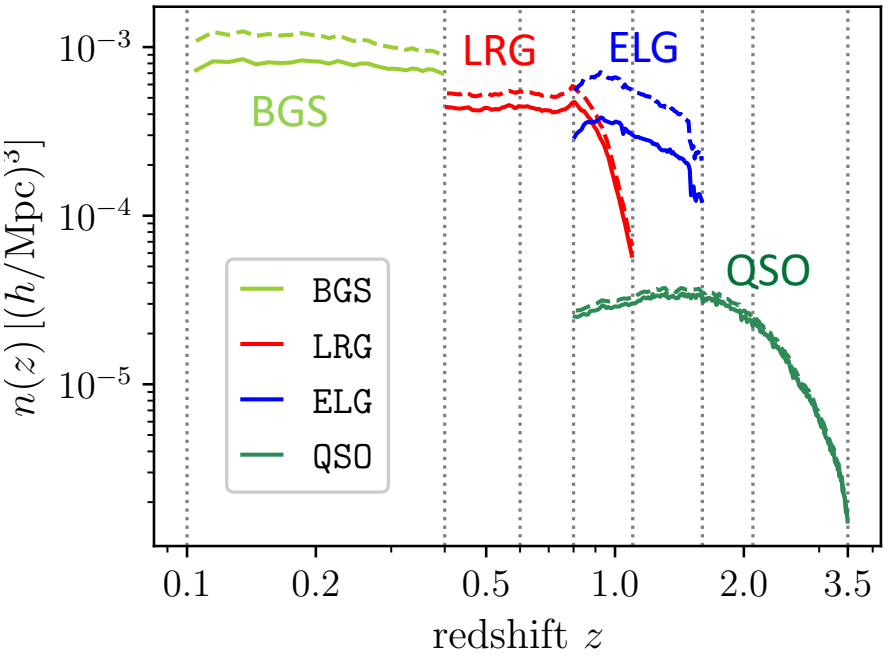
Comparison DESI/SDSS at z~0.7



- 1.5σ to 2.3σ discrepancy depending on the correlations between the two samples at z~0.7
- Much better agreement with DR1 than with DR2

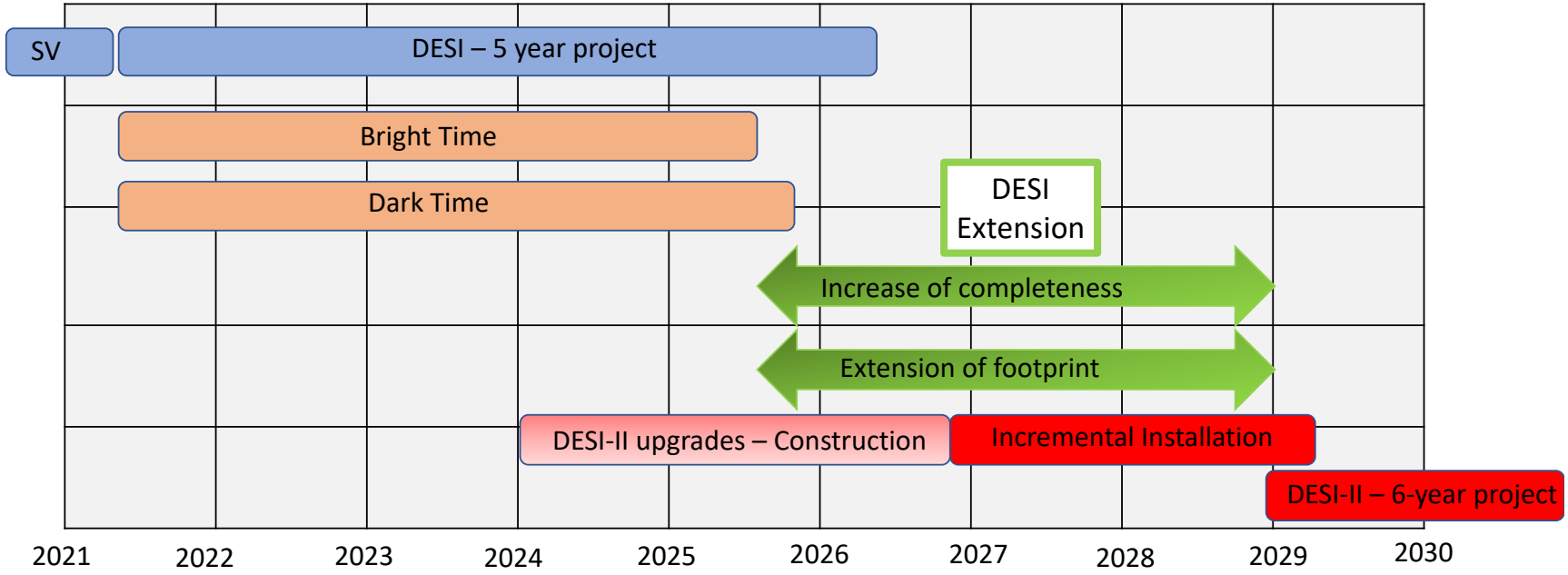
DESI DR2 dataset





- Biggest ever BAO dataset (both in N_{tracer} and volume)
  - 14.3 M discrete tracers (BG, LRG, ELG and QSO)
  - Effective cosmic volume V_{eff}= 42 Gpc^3
  - Increase of V_{eff} by a 2.3 factor from DR1 to DR2

DESI, DESI-ext and DESI-II Timelines



- **DESI** is ~6 months ahead of schedule,

  ⟹ DESI should finish in Nov. 2025
- **DESI Extension:** ~ 3.5 year transition period
- **DESI-II:** Dark Matter, high-density and high-z programs