Cosmology from three years of DESI (DR2)

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Dark Energy Spectroscopic Instrument

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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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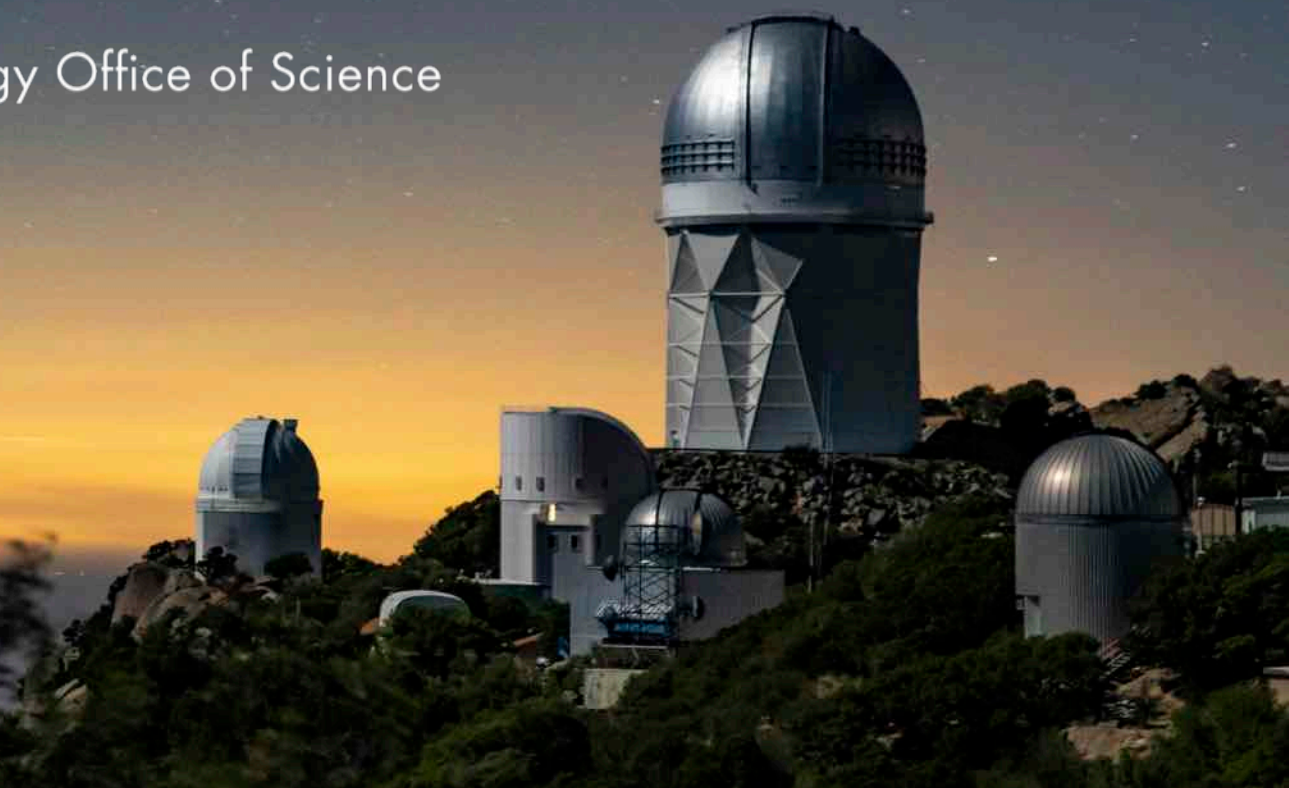

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Baryonic Acoustic Oscillations (BAO)

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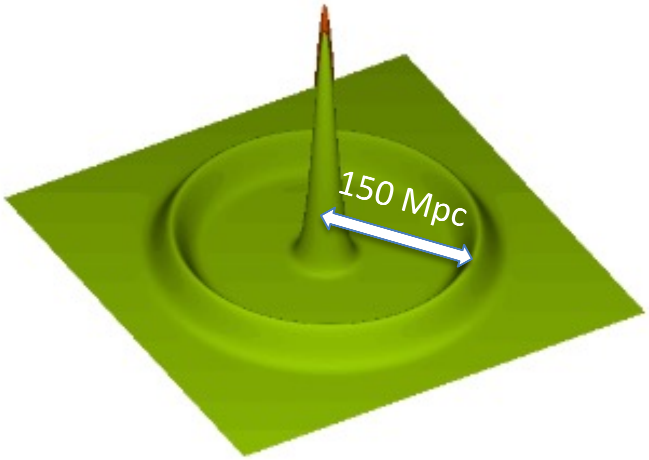
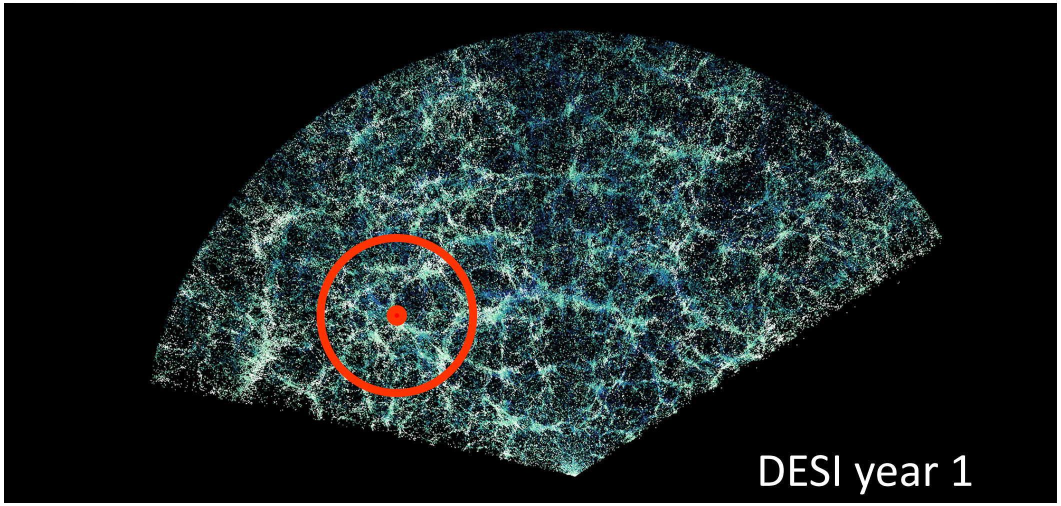
Dark Energy Spectroscopic Instrument (DESI)

BAO, a standard ruler





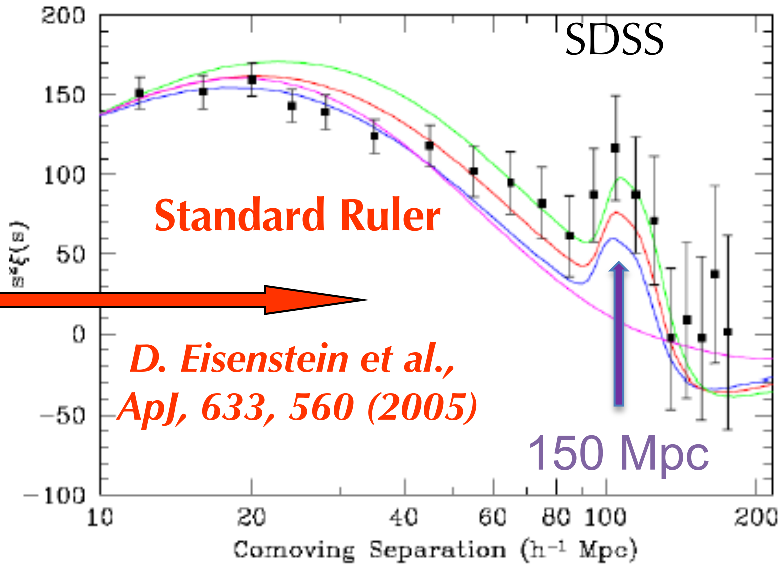
A special distance

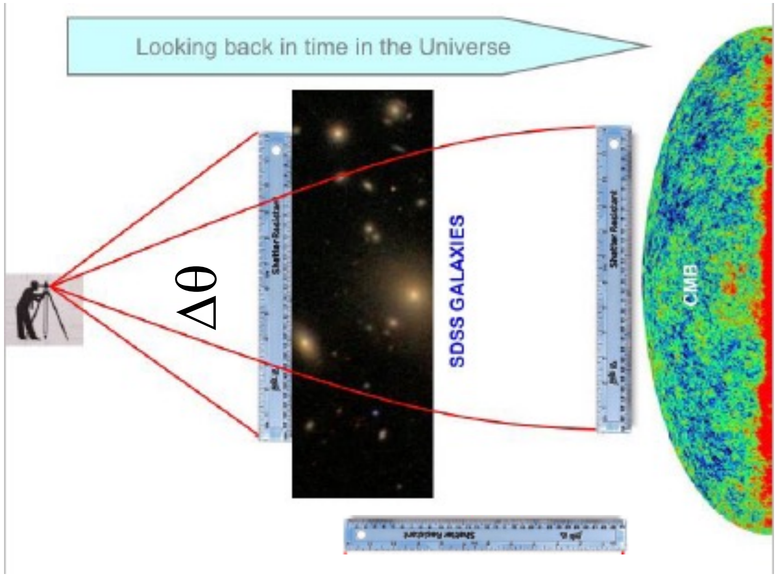
- Sound waves propagate through relativistic plasma (baryons, electrons, photons) with a speed $\sim c/\sqrt{3}$
- They freeze at recombination (z~1100 i.e 380,000 years)
- Galaxies form in the overdense shells about $r_d \sim$ 150 Mpc in radius from initial overdensities.
- $\Rightarrow$ Standard Ruler: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

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

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

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

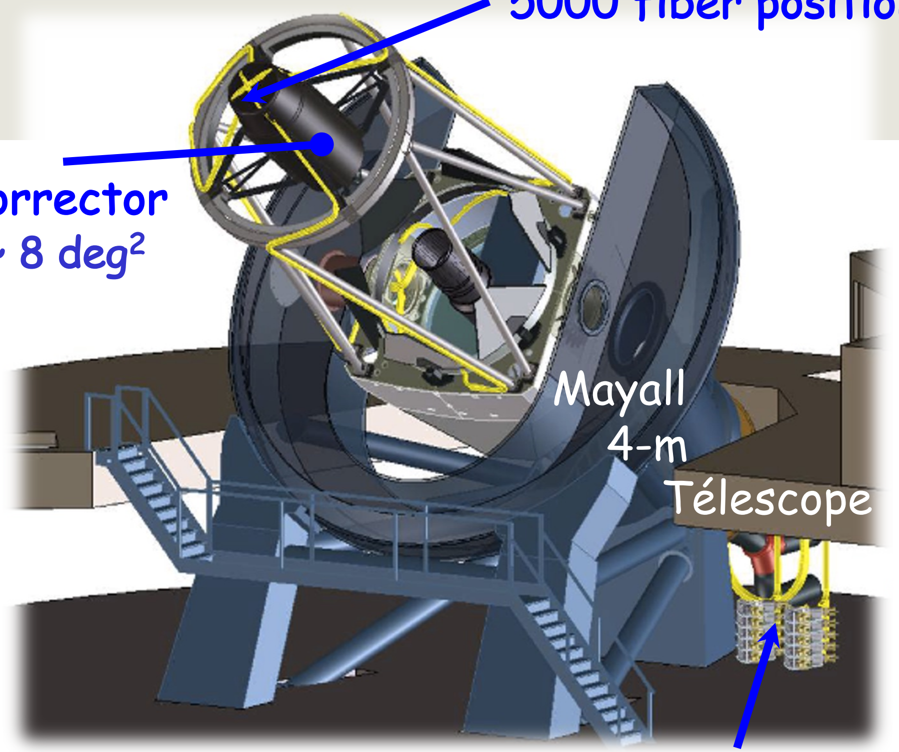
- **Transverse direction:**

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

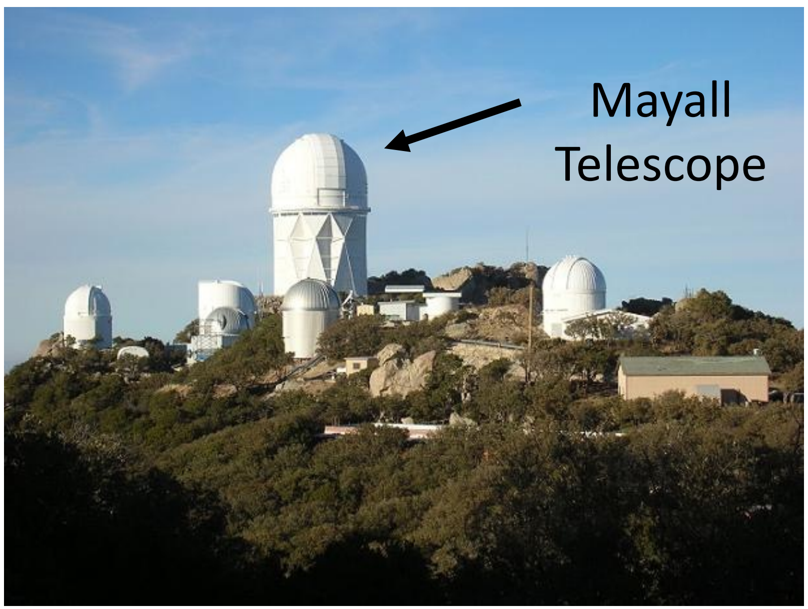
$\Rightarrow$ Sensitive to angular distance $D_A(z)$

$\Rightarrow \sim \int 1/H(z)$

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

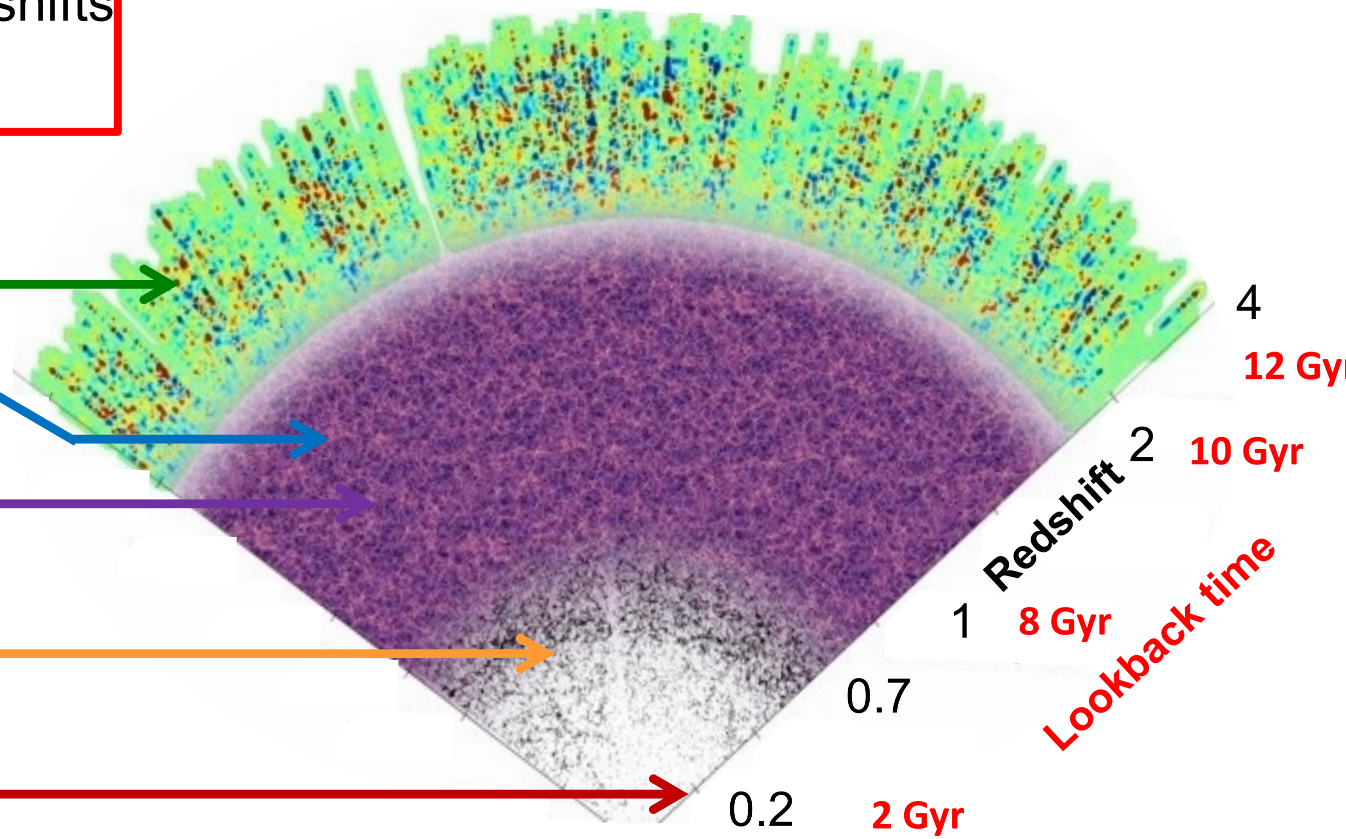
$0.6 < z < 1.6$

8 million LRGs

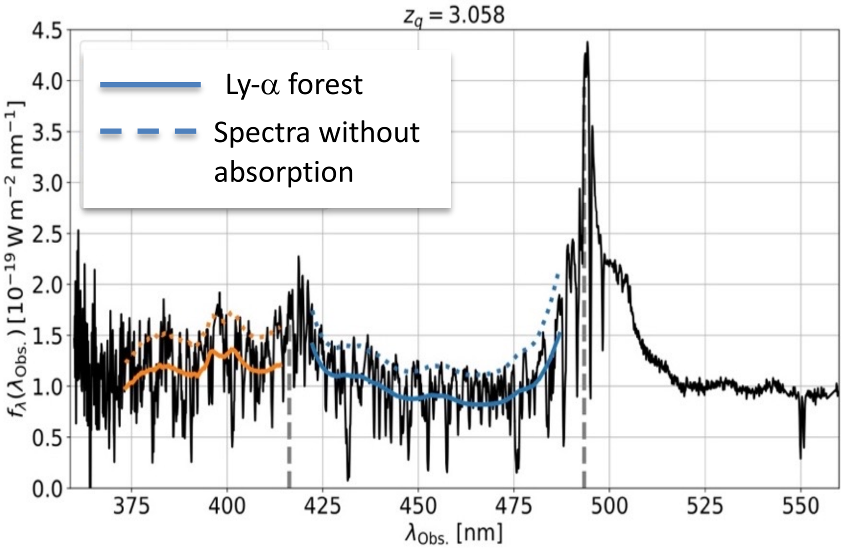
$0.4 < z < 1.0$

13.5 million
Brightest galaxies

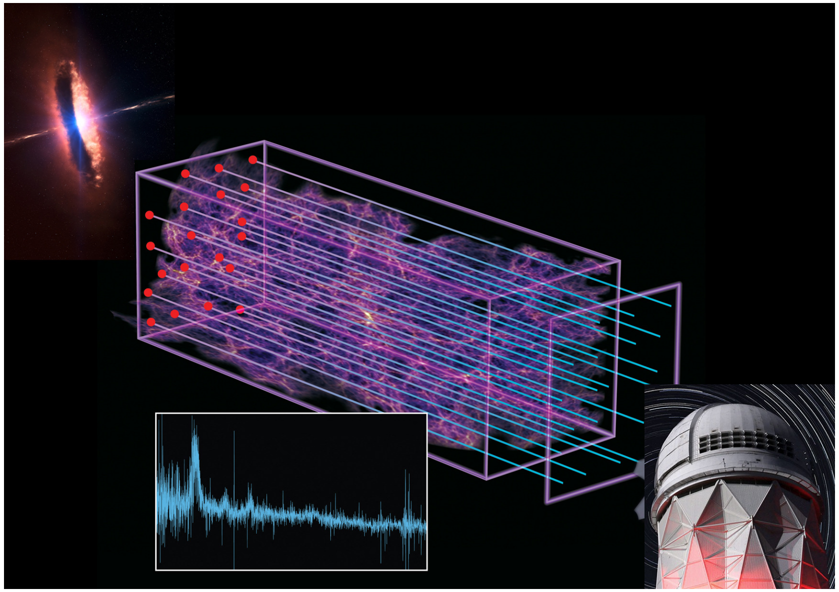
$0.0 < z < 0.4$



Another Tracer of Matter: Ly-α forest of quasars

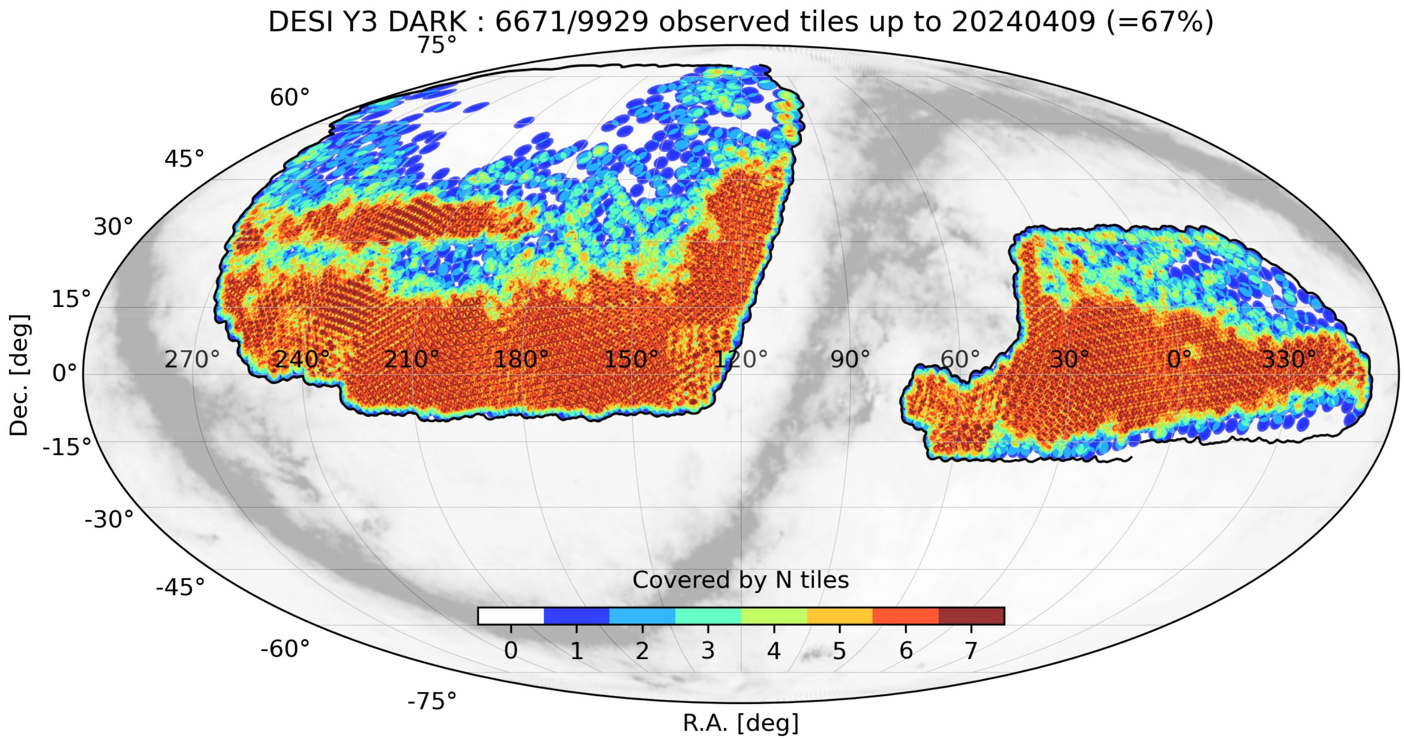


- For z>2, no discrete tracer (galaxy) observable with DESI
- Use Ly-α forests of quasars (2.0<z<3.5)
- HI absorption in intergalactic medium (IGM) along the line of sight of quasars



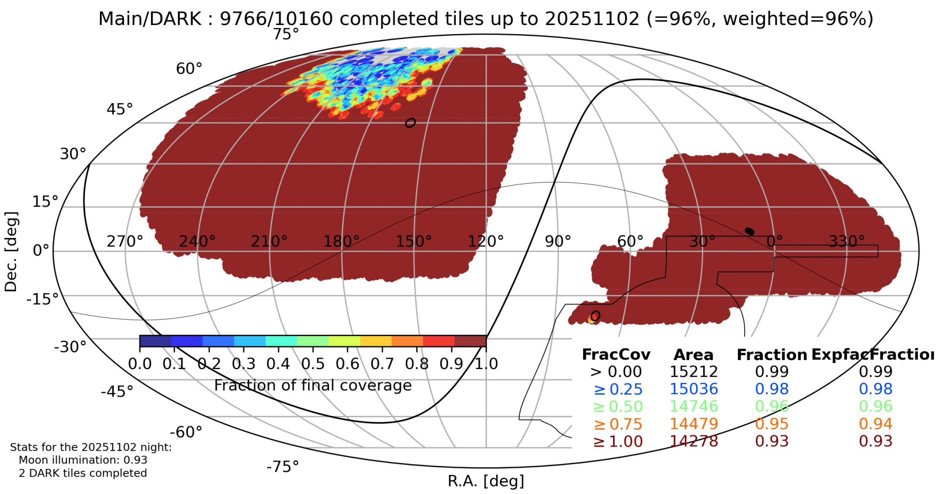
- We expect low density gas (IGM) to follow the dark matter density
- Compute correlation function between HI 'clouds'
- Measure the location of BAO

DESI DR2 footprint

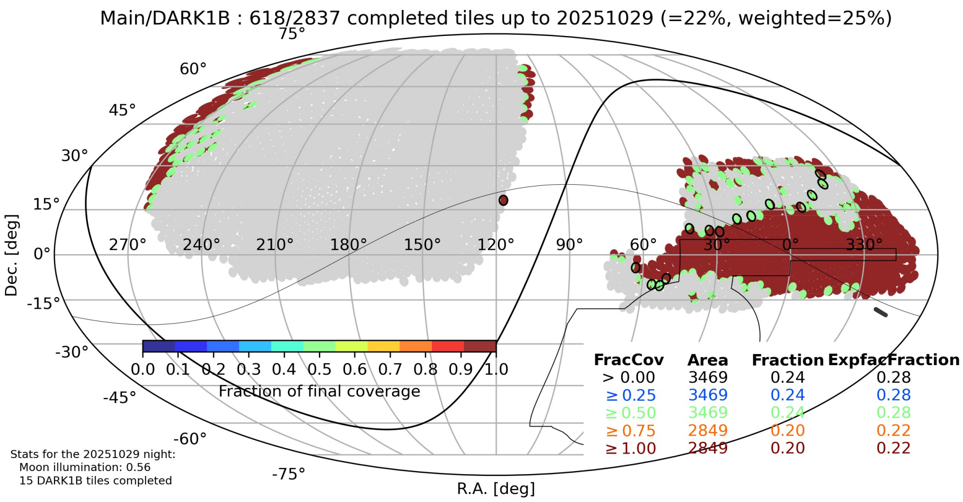


- DESI footprint over 5 years ~14000 deg^2
- DR2 (3 years) ~70% of final footprint
- Increase of V_{eff} by a 2.3 factor from DR1 to DR2
- 14.3M discrete tracers (galaxies and quasars), 800k Ly-α forests

Status of DESI observations



DESI-I footprint



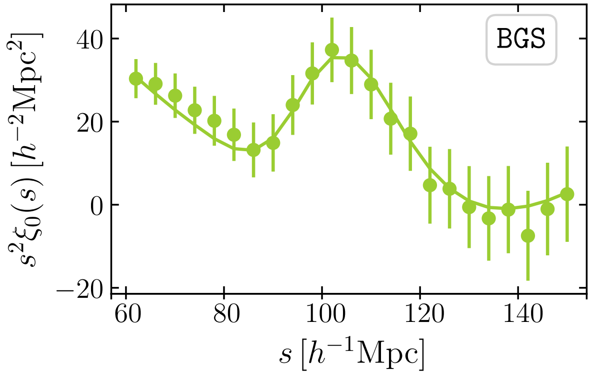
DESI-I additional passes

- **DESI-I ~96% is already done**
- Two additional passes over DESI-I footprint (already started)
- Extension of the footprint to the South (14000 deg^2 → 17000 deg^2) will start by the end of 2026

BAO Measurements

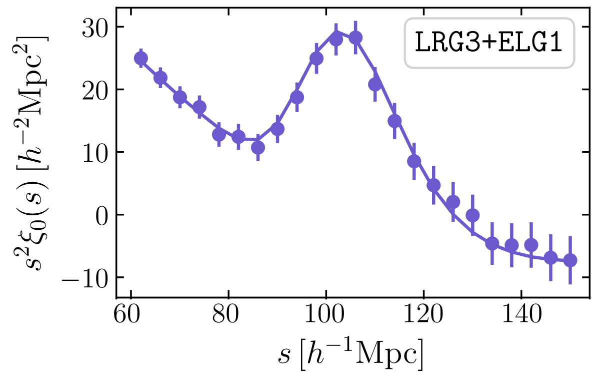
Results: a few examples

BGS z=0.30



Precision: 0.93%

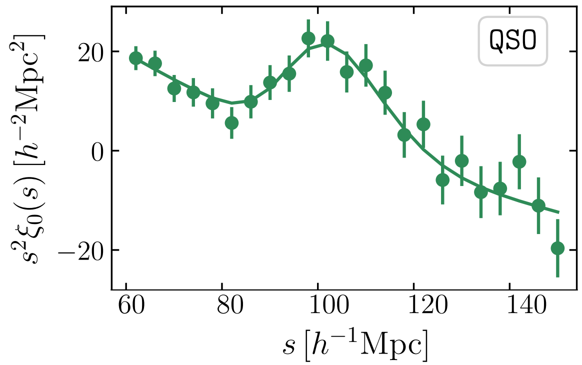
LRG3+ELG1 z=0.93



Significance: 14.7σ

Precision: 0.45%

QSO z=1.48



Significance: 5.6σ

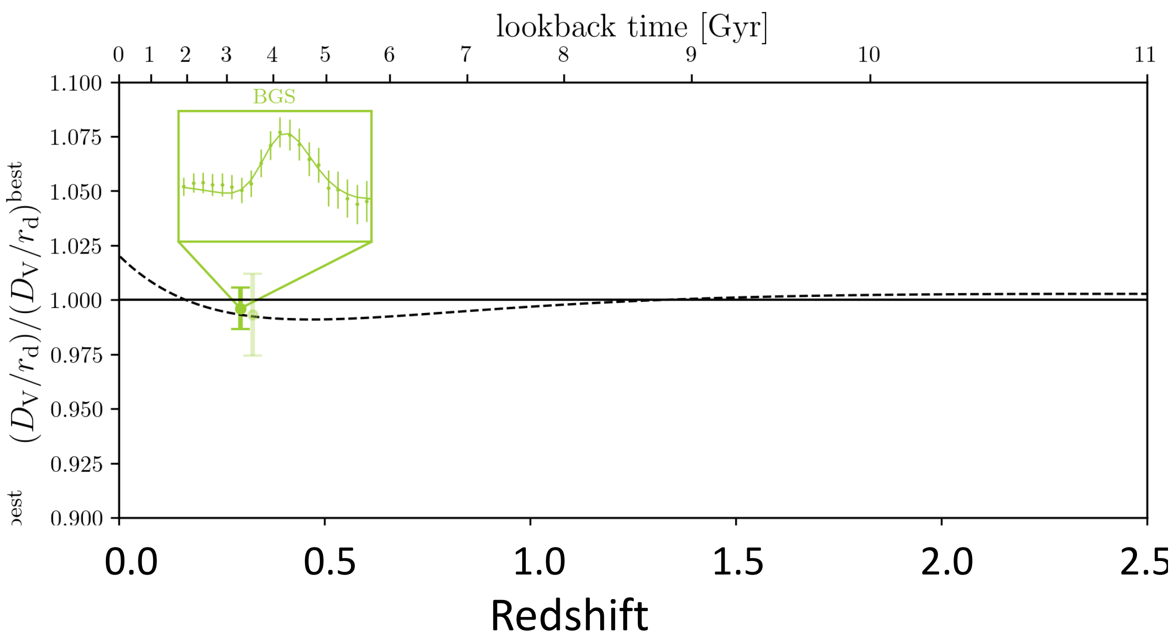
Precision: 1.5%

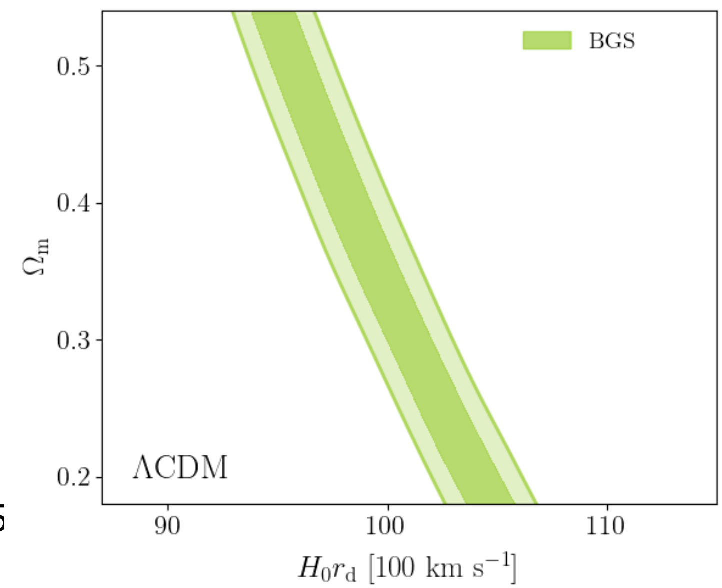
- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\mathrm{iso}} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest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

DESI DR2: BGS

$$\alpha_\perp = \frac{D_M}{r_d}\frac{r_d^{\rm fid}}{D_M^{\rm fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_d} \qquad \alpha_{\rm iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$$

In ΛCDM, the α parameters depend on $\mathbf{H_0 r_d}$ and $\mathbf{\Omega_m}$

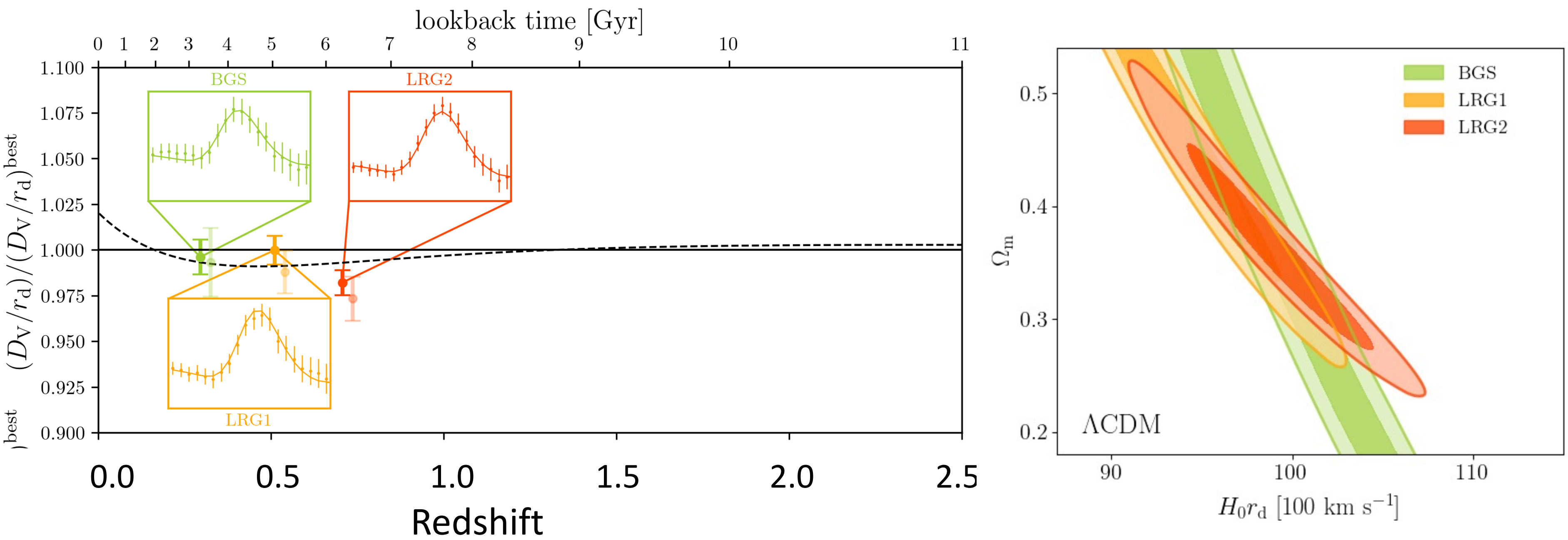




– Friedman equation for ΛCDM $H(z) \equiv H_0\sqrt{\Omega_m\,(1+z)^3 + (1-\Omega_m\,)}$

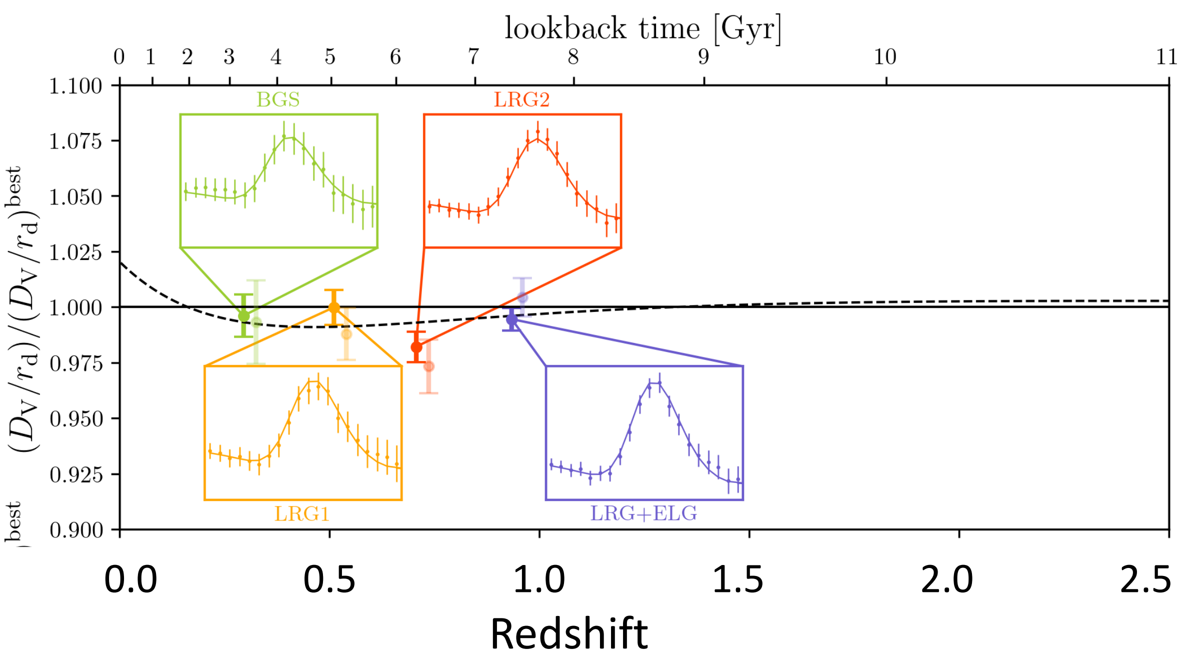
– Limitation due the cosmic variance (small part of the visible Universe)

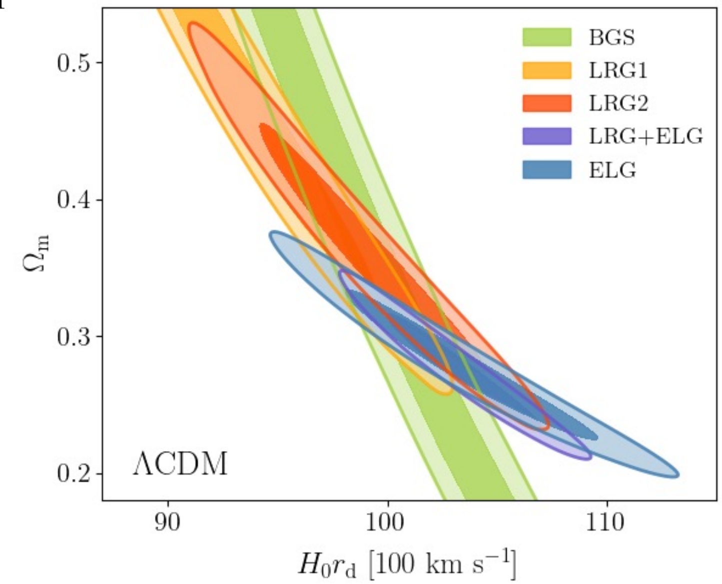
DESI DR2: BGS + LRG



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

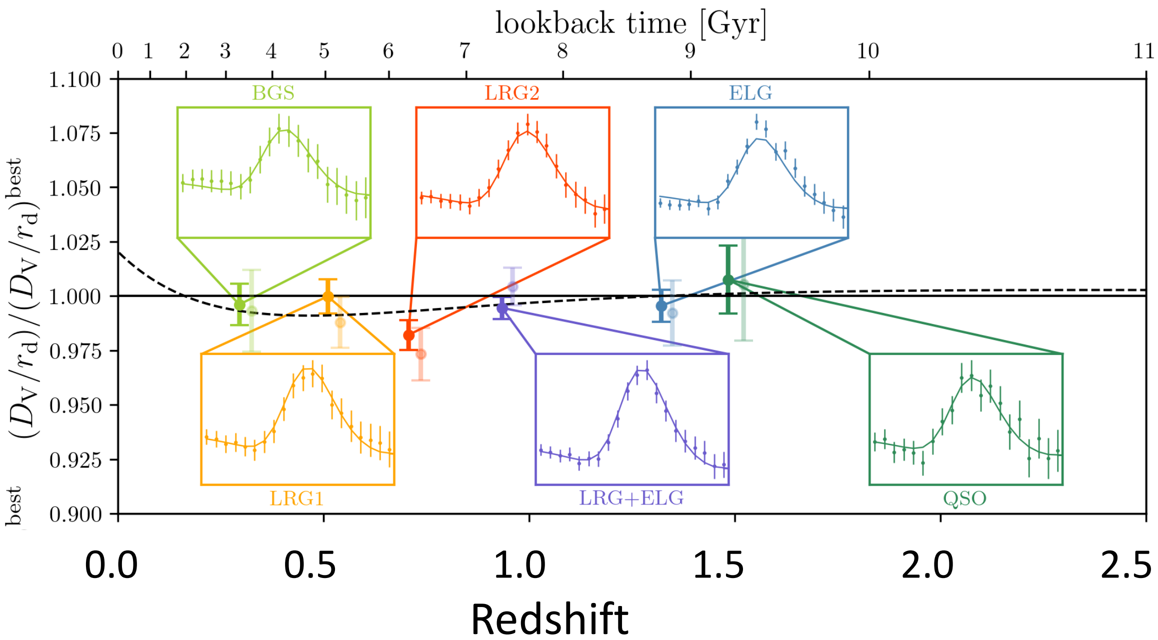
DESI DR2: BGS + LRG + ELG

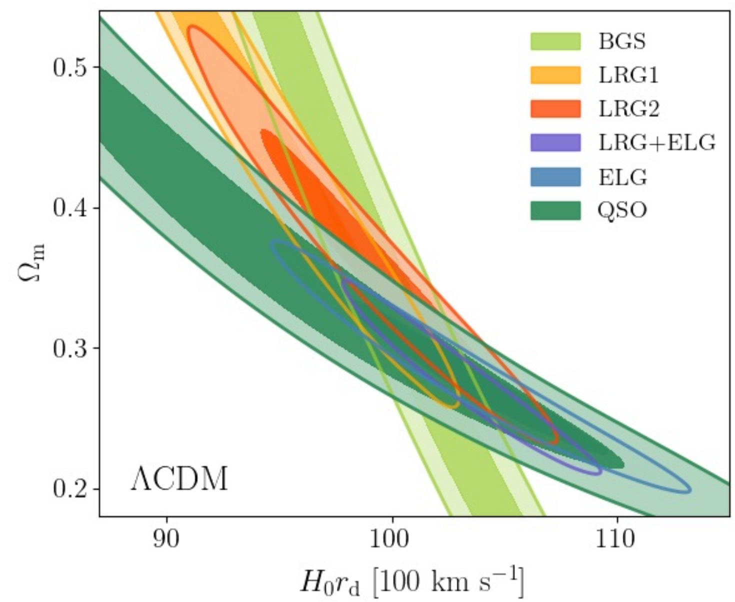




- ELG: Main tracer in DESI, precise measurement
- x 2.7 with DR2 compared to DR1

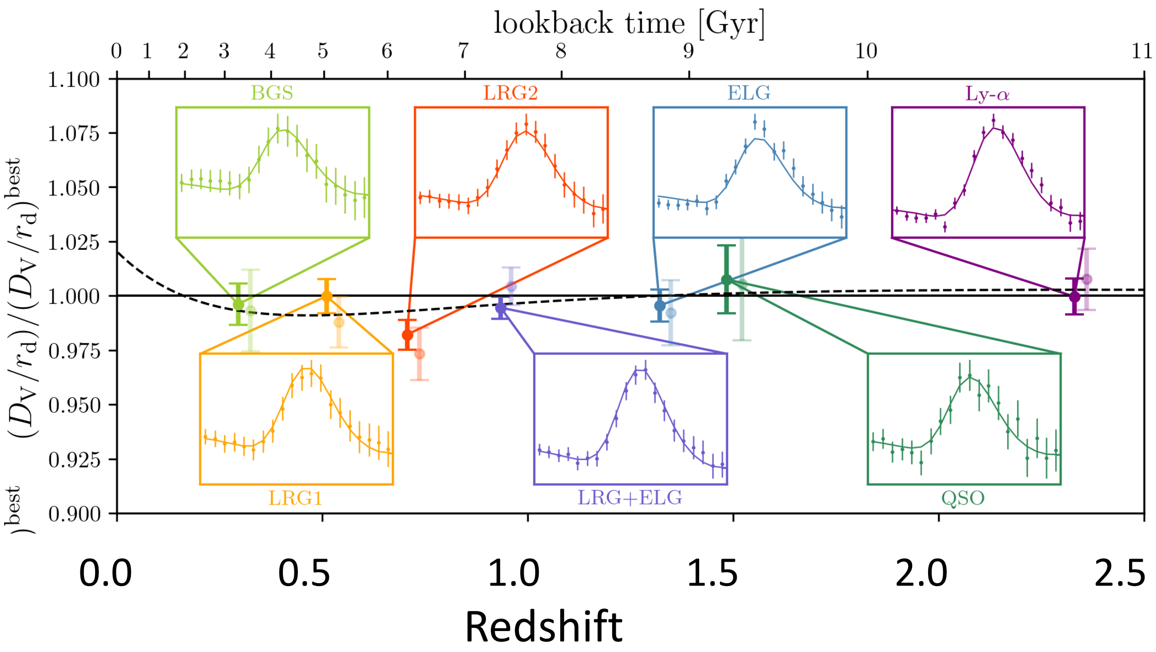
DESI DR2: BGS + LRG + ELG + QSO

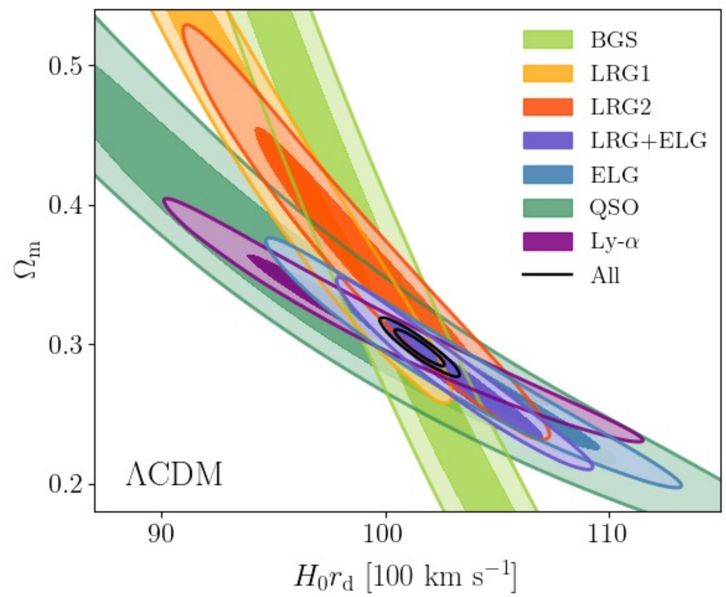




– QSO: huge volume but small density (shot noise limitation)

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

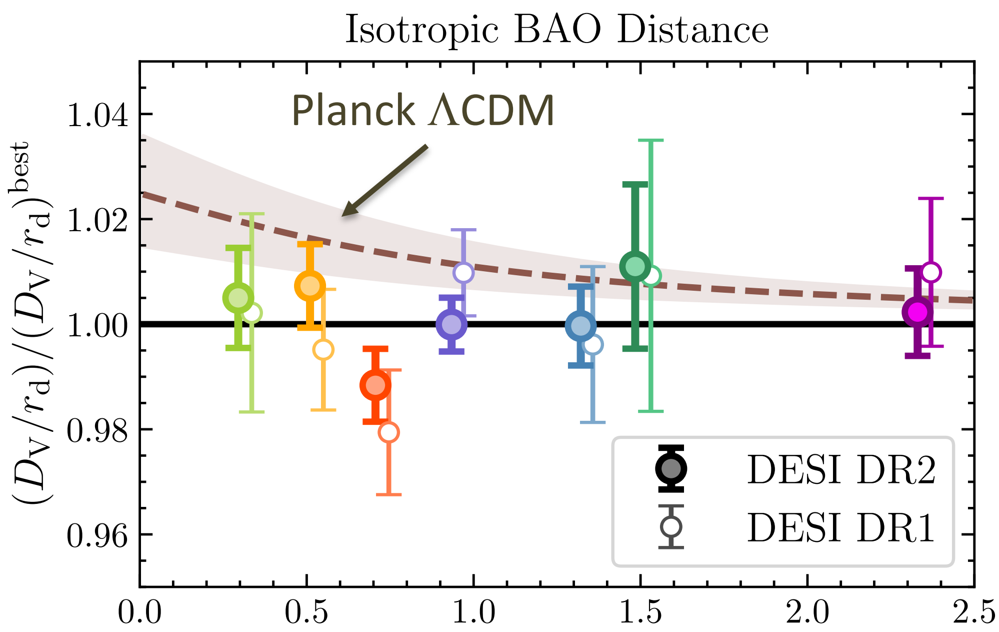




- Different dependence as a function of redshift (Ω_m, $H_0.r_d$)
- **Break the degeneracy without knowing r_d**

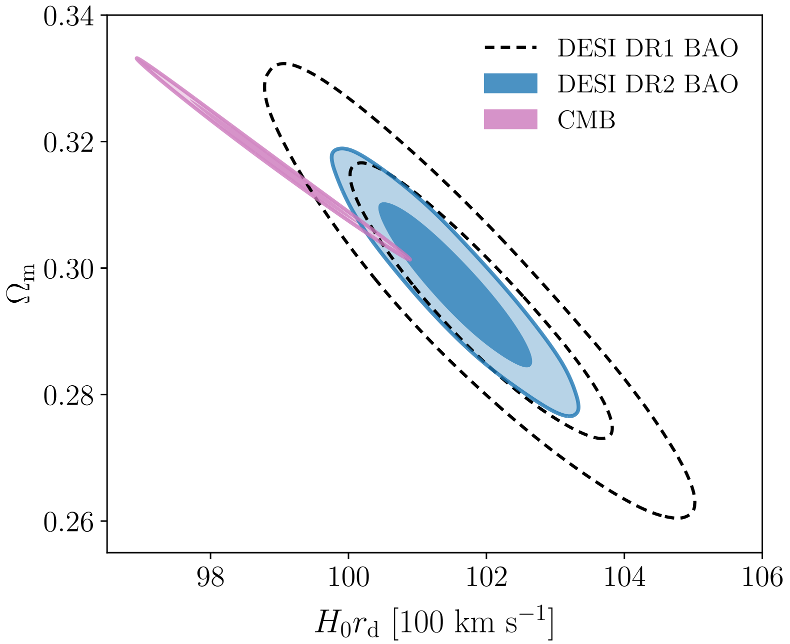
Cosmological Interpretation

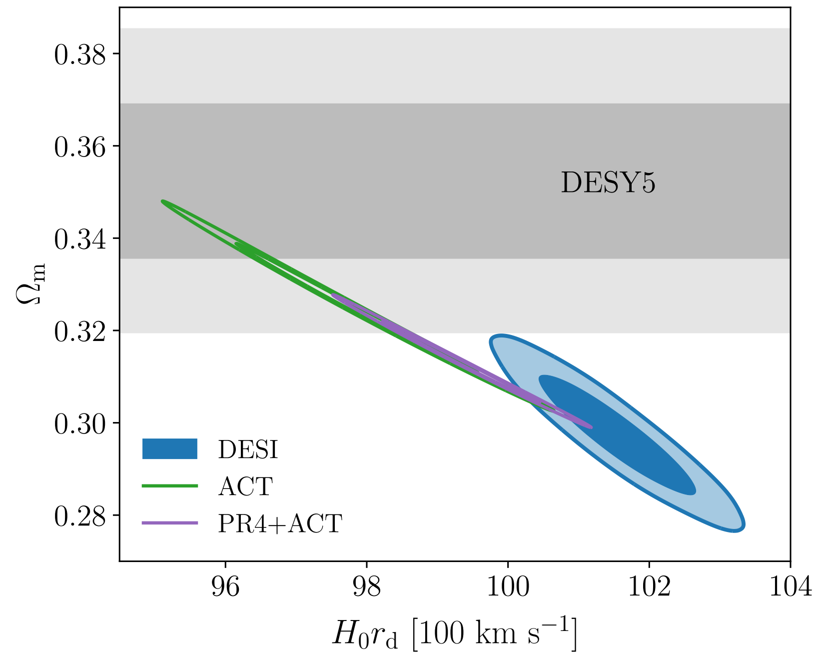
DESI - Hubble diagram



- ~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 **tension with Planck ΛCDM : 2.3σ**

Ω_m – $H_0 r_d$ Comparison ACT/BAO

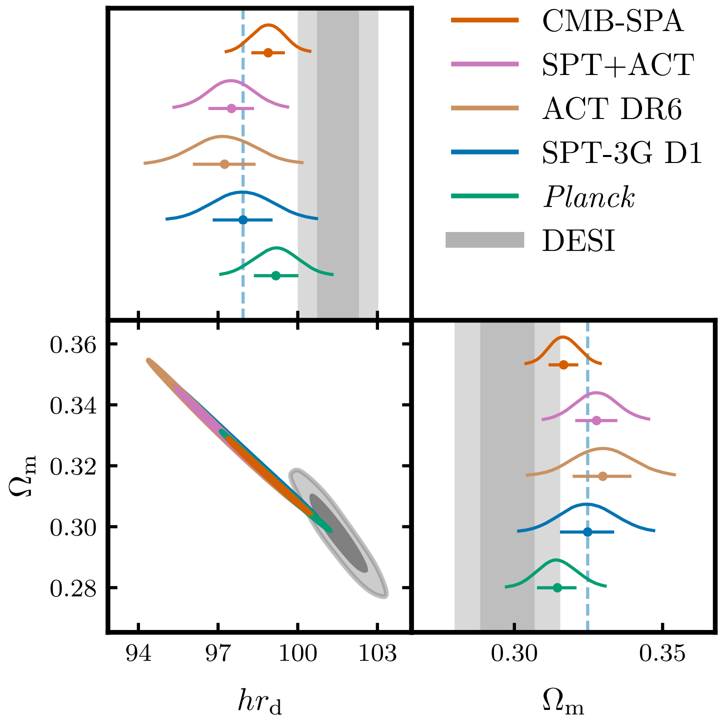




ACT+DESI (DESI Paper), arXiv:2504.18464

- Consistent results DR1/DR2
- 2.3σ discrepancy between CMB (PR4) and DESI
- 2.0σ discrepancy between CMB (PR4+ACT) and DESI
- 2.7σ discrepancy between CMB (ACT-alone) and DESI

Tension between CMB and BAO?

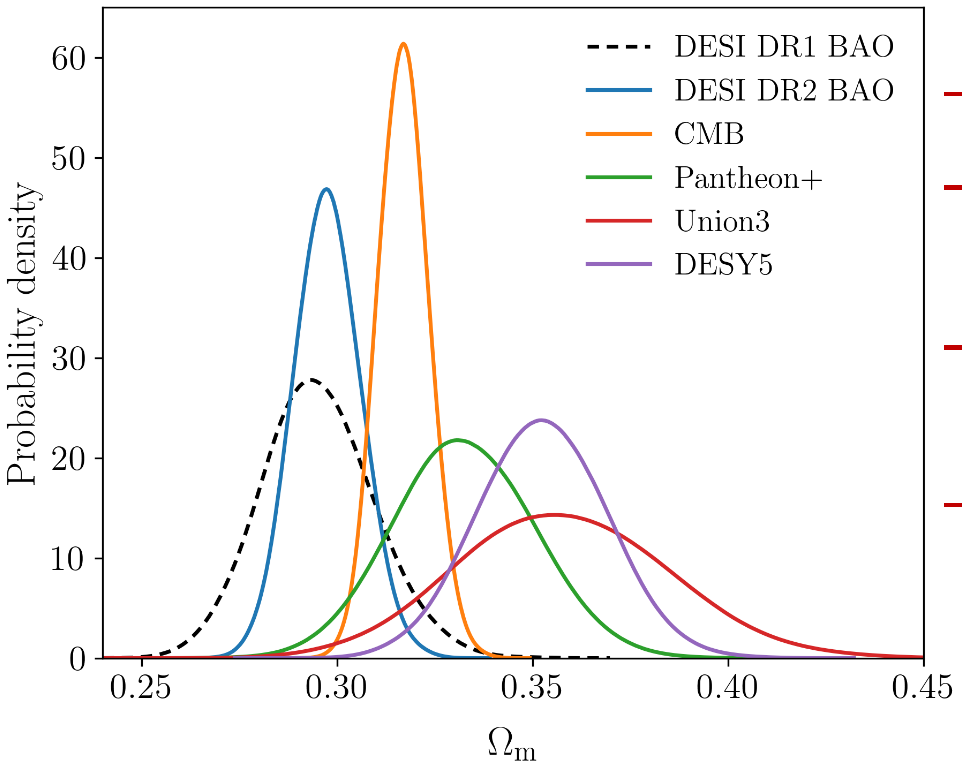


	$100\,\Omega_m$	hr_d [Mpc]	Distance to DESI
CMB-SPA	31.66 ± 0.50	98.89 ± 0.63	$2.8\,\sigma$
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	$3.7\,\sigma$
SPT+*Planck*	31.89 ± 0.54	98.63 ± 0.67	$3.0\,\sigma$
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	$3.1\,\sigma$
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	$2.5\,\sigma$
Planck	31.45 ± 0.67	99.18 ± 0.84	$2.0\,\sigma$
DESI	29.76 ± 0.87	101.52 ± 0.73	

SPT-3G, arXiv:2506.20707

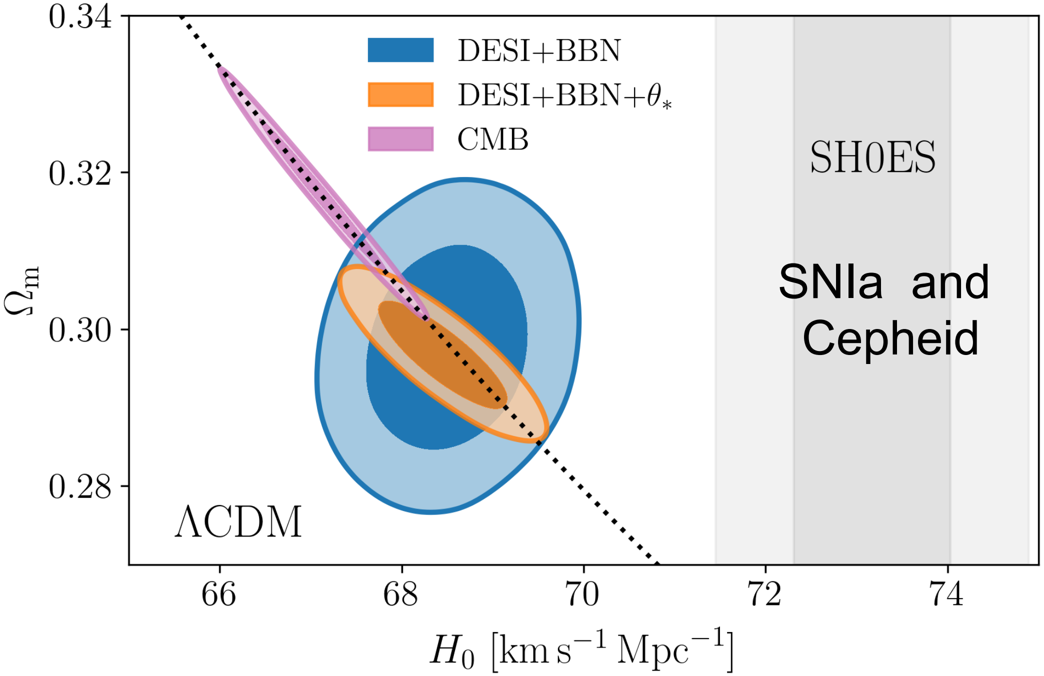
- SPT-3G is consistent results with ACT and DESI papers
- Discrepancy from 2.0σ to **3.7σ** between CMB and DESI
- **2.8σ** discrepancy between CMB (Planck+ACT+SPT) and DESI

Ω_m - Tensions in ΛCDM – BAO, CMB and SNIa



- Consistent results DR1/DR2
- Comparable precision on Ω_m for DESI and CMB
- 2.3σ discrepancy between CMB and DESI
- Discrepancies with SNIa samples
  - Pantheon+: 1.7σ
  - Union3: 2.1σ
  - DESY5: 2.9σ

Hubble constant in ΛCDM



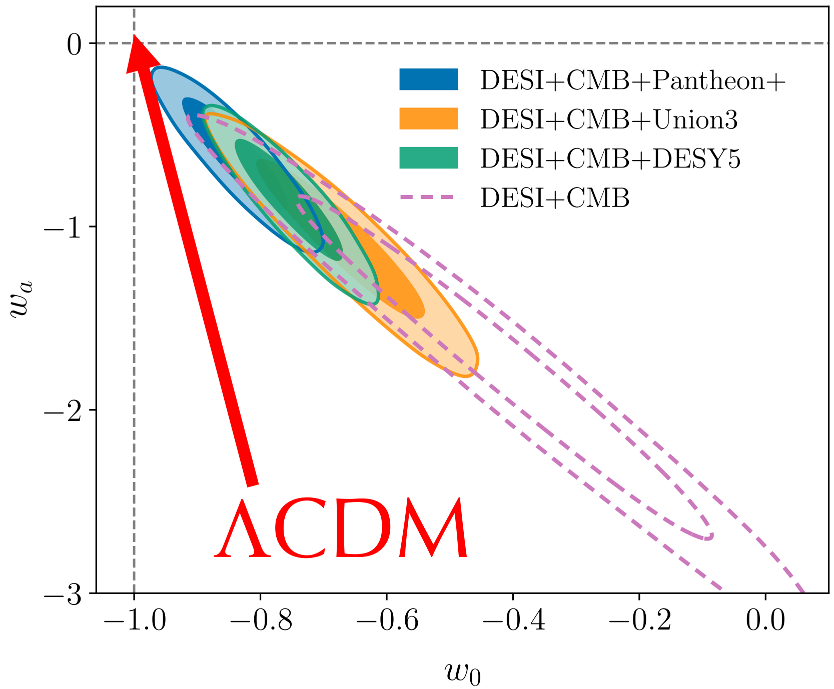
$$\underbrace{H_0 = (68.51 \pm 0.58)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\mathrm{DESI+BBN}}$$

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

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



Extensions of ΛCDM

- Equation of state of Dark Energy

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

- Time evolving Dark Energy

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

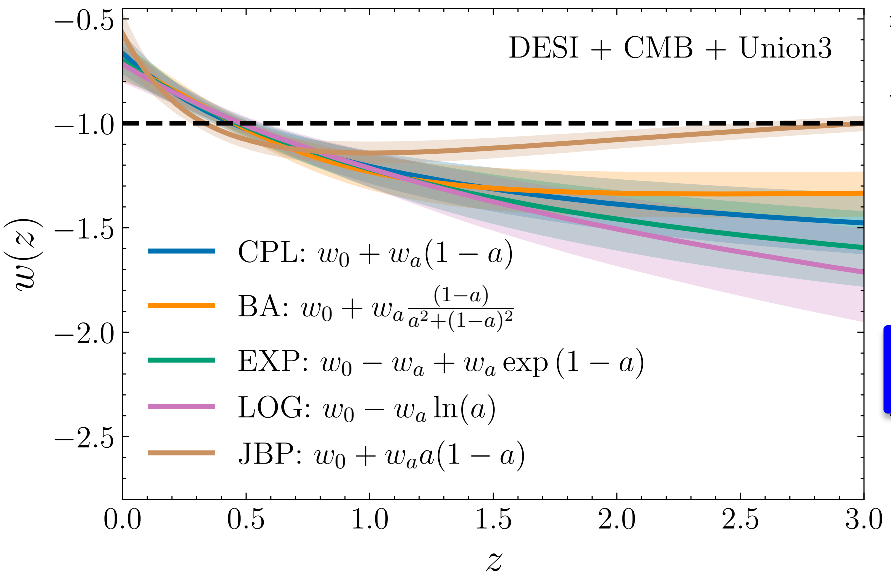
– For ΛCDM, we expect w=-1, i.e. w_0=-1 and w_a=0

– Combining DESI+CMB: **3.1σ effect**

– Combining DESI+CMB+SN: **2.8σ to 4.2σ** effect depending on the SN sample

– **Stronger Indications of dynamical dark energy with DR2**

Dynamical Dark Energy – Parametrization

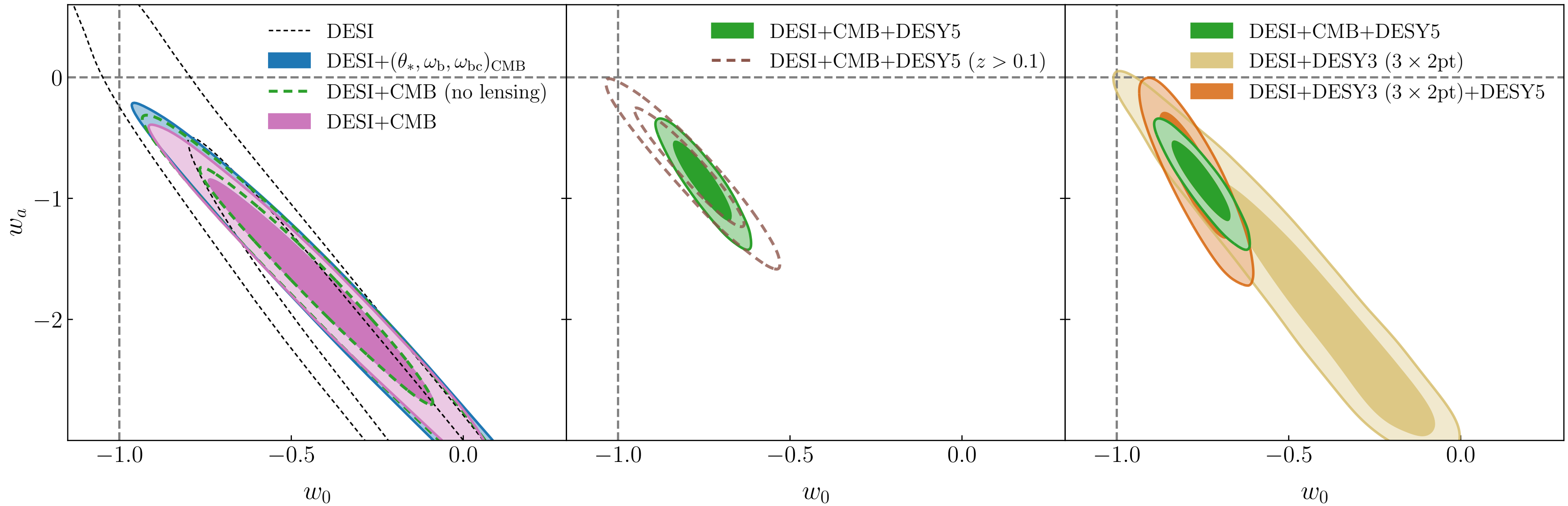


Param.	Functional Form	$\Delta\chi^2$
BA	$w_0 + w_a \frac{1-a}{a^2+(1-a)^2}$	-17.3
EXP	$(w_0 - w_a) + w_a \exp(1-a)$	-17.5
LOG	$w_0 - w_a \ln a$	-17.6
JBP	$w_0 + w_a\, a(1-a)$	-13.6
CPL	$w_0 + w_a(1-a)$	-17.4

CMB + DESI + SN(Union3)

– Significance does not depend on parametrizations

Dynamical Dark Energy – Robustness

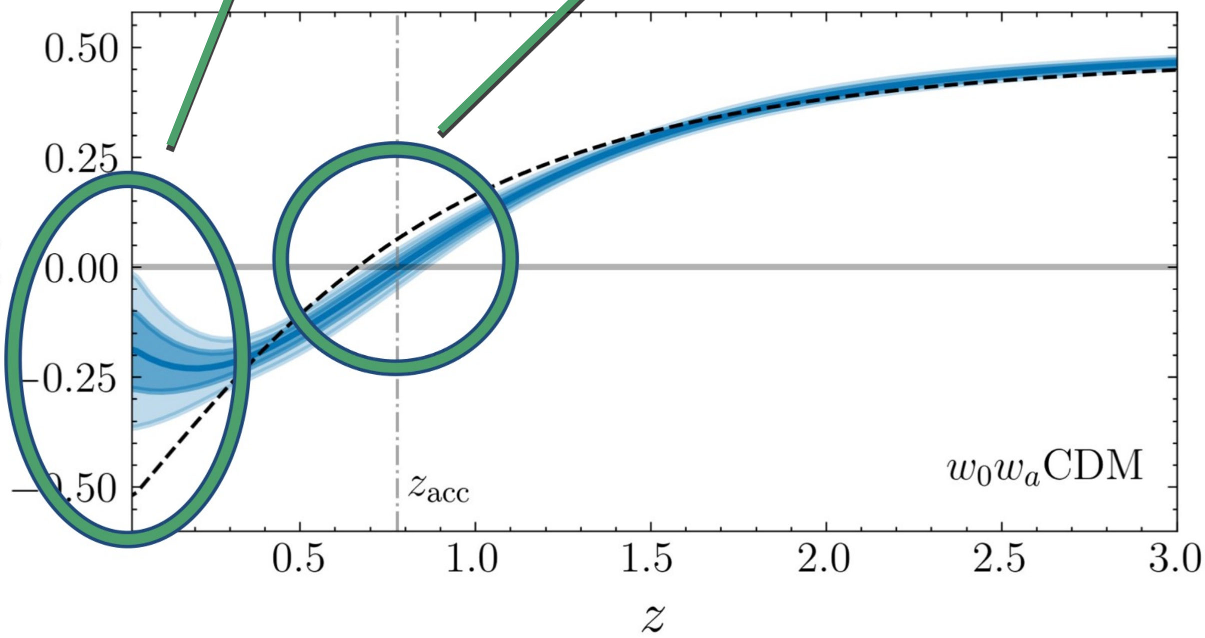


- Combining with early-Universe prior on $(\theta_*, \omega_b, \omega_{bc})$ from CMB shows preference for evolving DE.
- Excluding z<0.1 SNIa reduces the tension but the best fit is far for ΛCDM
- Replacing CMB with DES 3x2pt continues to show a preference for evolving DE

Dynamical Dark Energy

Acceleration is lower than ΛCDM at present.

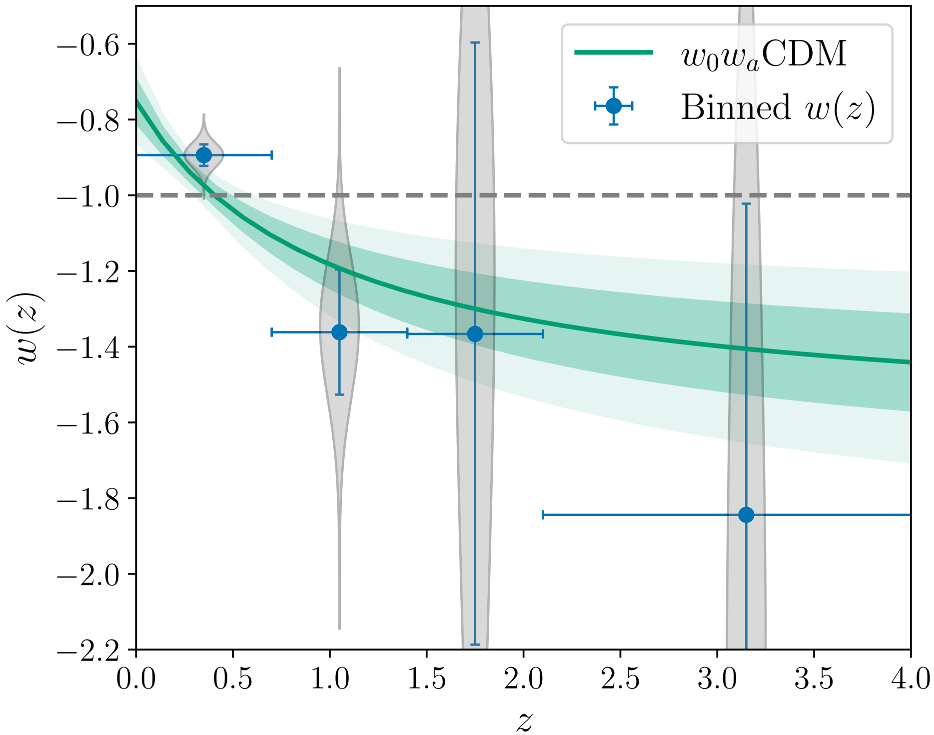
Acceleration started earlier than in ΛCDM.



Deceleration parameter

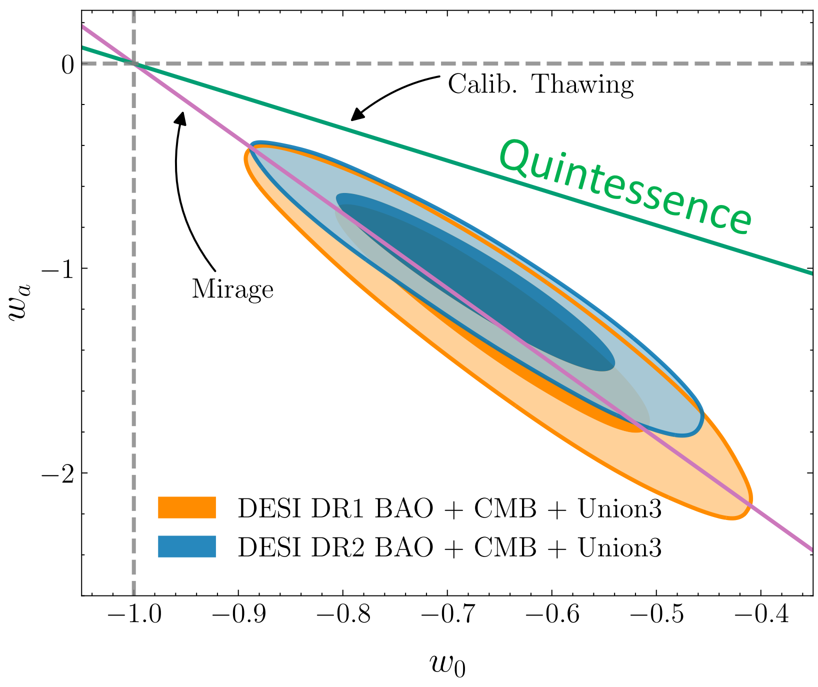
Redshift

Phantom Crossing



- w<-1 (phantom regime), possible with multiple fields…
- Phantom crossing at z~0.4
- Binned approach (blue dots) consistent with CPL parametrization

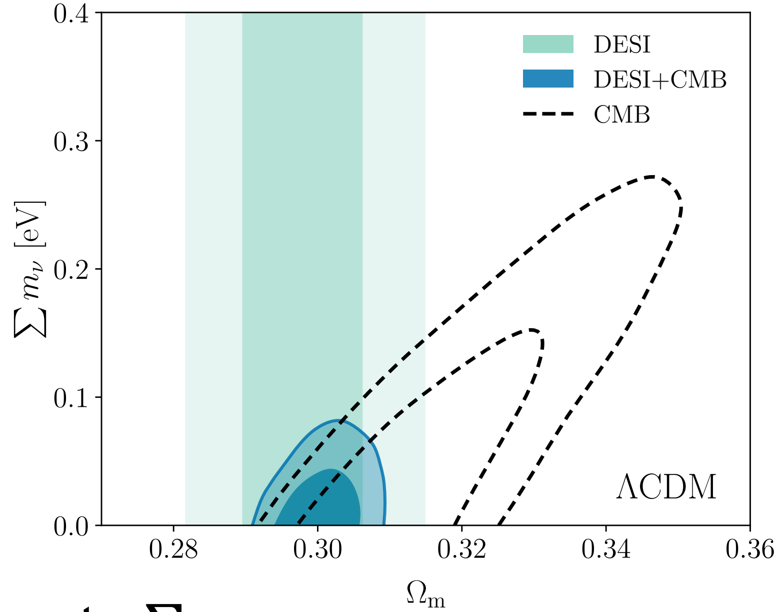
Dynamical Dark Energy – Models



DESI+CMB:	+PantheonPlus	+Union3	+DESY5
DE classes		ΔDIC ($\Delta\chi^2$)	
Thaw. (Cal.)	+0.4 (−1.6)	−0.6 (−2.5)	−5.8 (−7.1)
Thaw. (Alg.)	−1.0 (−2.9)	−4.6 (−6.9)	−10.1 (−13.2)
Emergent	+2.1 (−0.05)	+1.8 (−0.1)	+0.2 (−1.5)
Mirage	−9.1 (−10.5)	−13.8 (−16.2)	−18.7 (−20.7)
$w_0 w_a$	−6.8 (−10.7)	−13.5 (−17.4)	−17.2 (−21.0)

- Mirage Dark Energy is preferred to Thawing (Quintessence) models
- "Mirage" models mimic ΛCDM and <w> ~ -1 whereas there is a real time evolving Dark Energy

Sum of neutrino masses - Bayesian



– CMB is sensitive to $\sum m_\mu$

– BAO measures Ω_m and breaks the degeneracies

Limits at 95% CL:

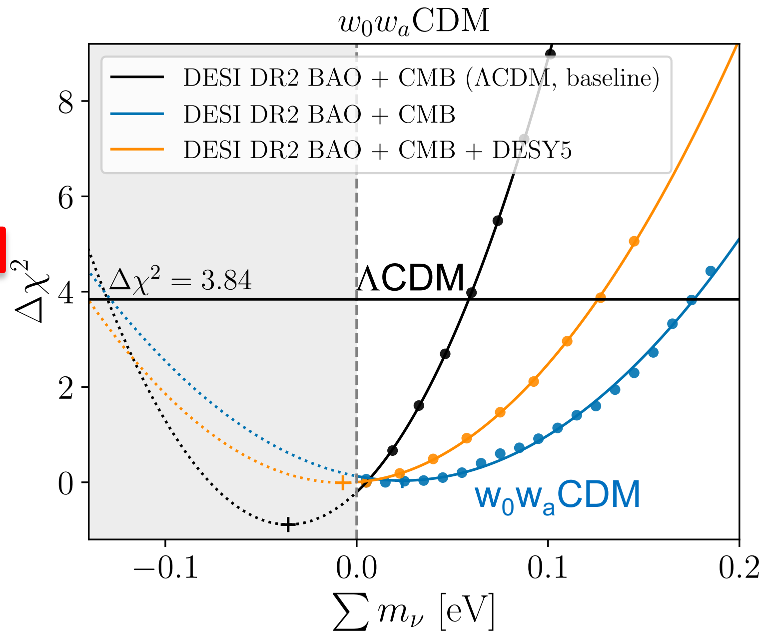
– For ΛCDM with CMB alone: $\Sigma m_\nu < 210\ meV$

– For ΛCDM with CMB + DESI: $\Sigma m_\nu < 64\ meV$

– For w_0w_aCDM with CMB + DESI + SN $\Sigma m_\nu < 130\ meV$

Sum of neutrino masses - Frequentist

Model/Dataset	μ_0 [eV]	σ [eV]	95% CL [eV]
$\mathbf{\Lambda CDM+\sum m_\nu}$			
DESI DR2 BAO+CMB (CamSpec)	-0.036	0.043	< 0.053
DESI DR1 BAO+CMB (CamSpec)	-0.048	0.054	< 0.063
DESI DR1 BAO+CMB-nl (CamSpec)	-0.068	0.067	< 0.074
$\mathbf{w_0w_aCDM+\sum m_\nu}$			
DESI DR2 BAO+CMB	0.024	0.078	< 0.177
DESI DR2 BAO+CMB+DESY5	-0.007	0.068	< 0.126



- Our "real" sensitivity on $\sum m_\nu$ is σ ~ 40 meV with ΛCDM
- Because of the tension on Ω_m the limits artificially are too stringent

Limits at 95% CL with Feldman-Cousins:

- For ΛCDM with CMB + DESI: $\Sigma m_\nu < 53\ meV$
- For w_0w_aCDM with CMB + DESI + SN $\Sigma m_\nu < 126\ meV$

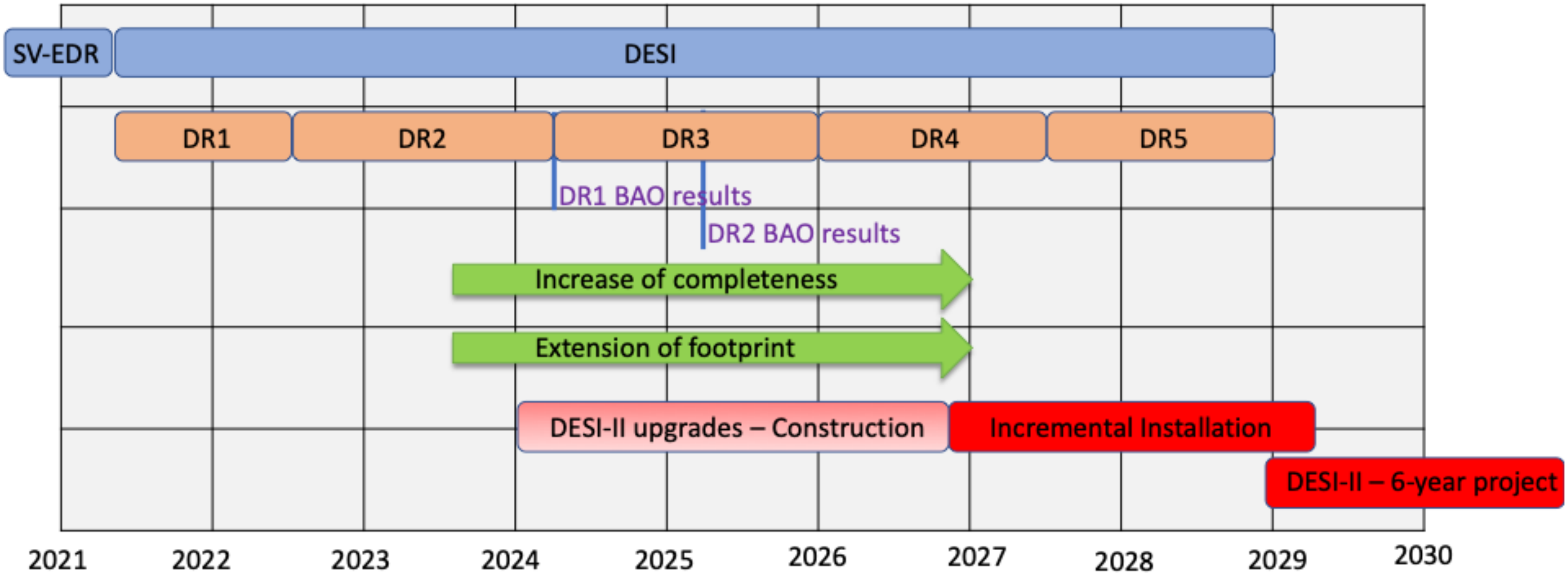
Conclusions

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 tension with CMB (~2.8σ) and DESI prefers lower Ω_m
  - Stronger indications of time-varying Dark Energy equation of state with DR2, especially when SNIa are added

    $\Rightarrow$ **a 2.8σ to 4.2σ effect, not 5σ yet!**
- **What next?**
  - BAO: Full dataset for DESI in early 2027 (+ Full shape analysis)
  - SNIa: ZTF and LSST homogeneous sample at z<0.1
  - CMB: ACT, SPT and in the long term SO and CMB-S4

DESI and DESI-II Timelines

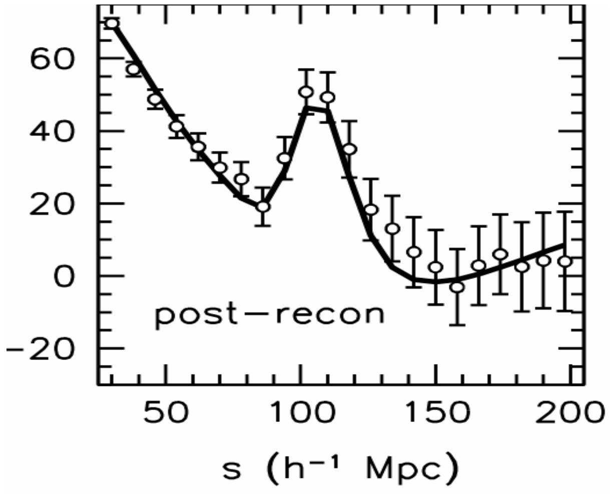


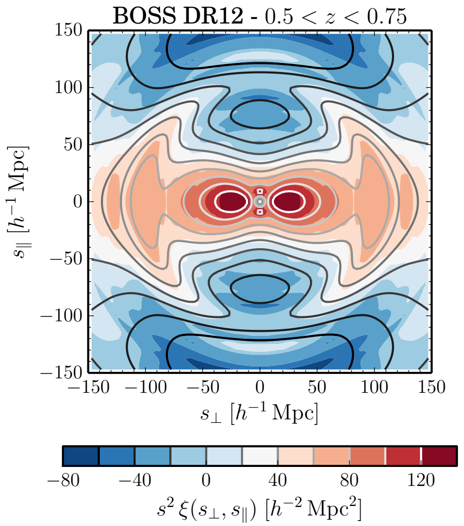
- **DESI** (DR1-DR3) should finish in March 2026, even earlier.
- Continuation of DESI (DR4-DR5) to end of 2028 with an extension of the footprint and an increase of the completeness
- **DESI-II (2029):** Dark Matter, high-density and high-z programs

Additional Slides

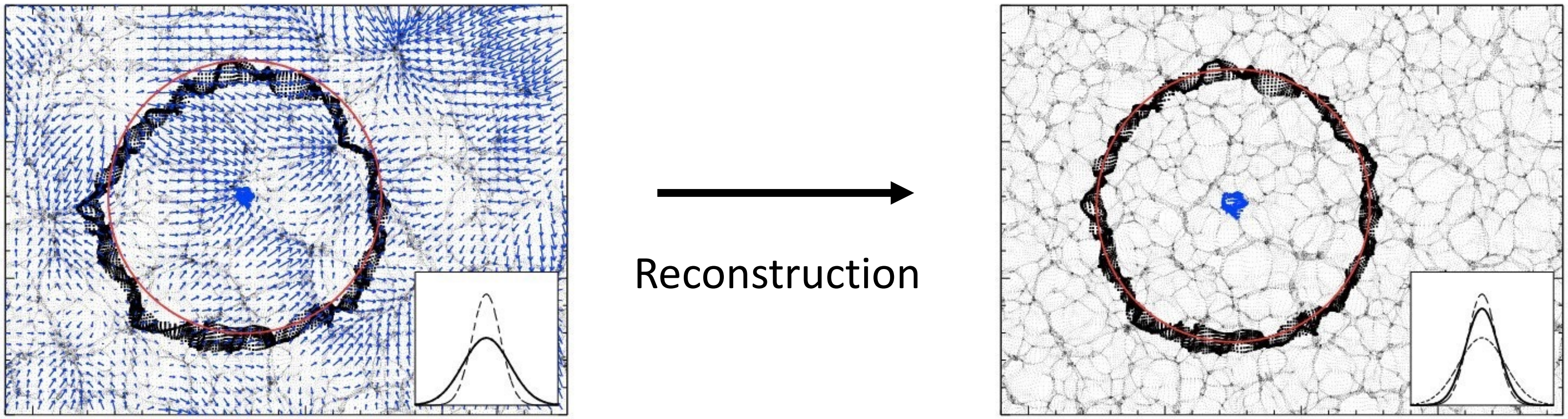
Main science with DESI-I

- **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



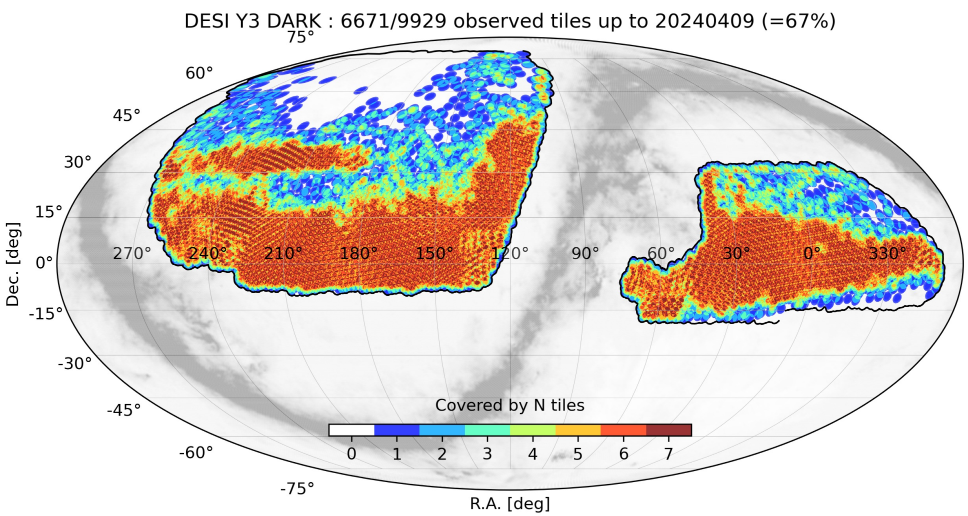


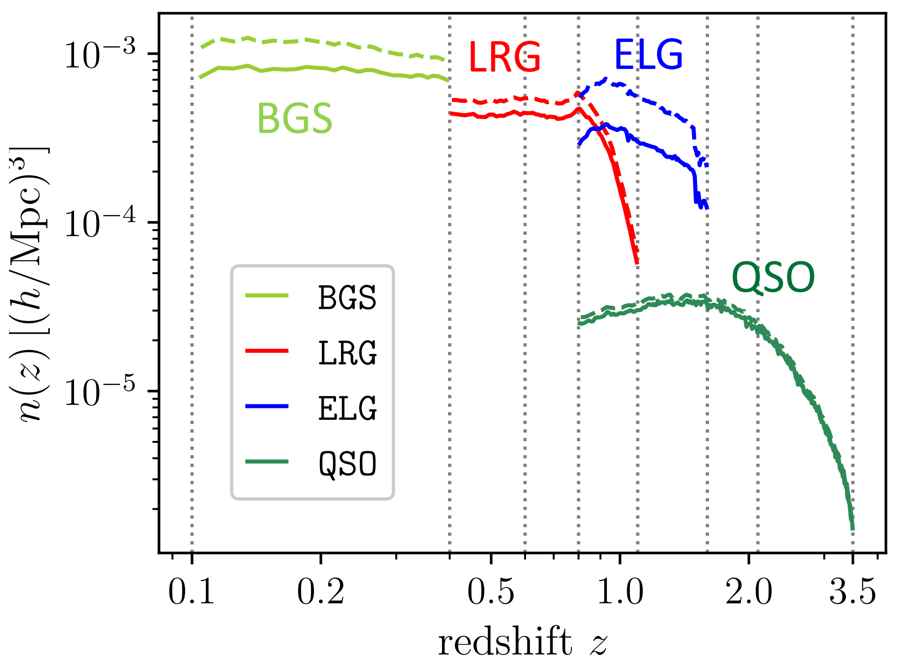
Density Field Reconstruction



- 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**

DESI DR2 dataset

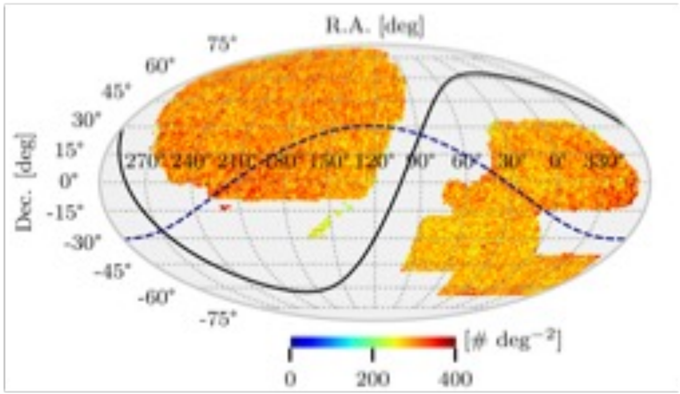




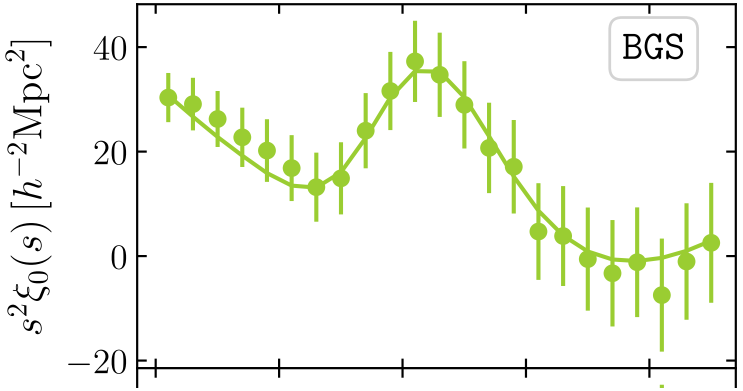
- Biggest ever BAO dataset (both in N_{tracer} and volume)
  - 14.3 M discrete tracers (BG, LRG, ELG and QSO)
  - Effective cosmic volume V_{eff}= 42 Gpc^3
  - Increase of V_{eff} by a 2.3 factor from DR1 to DR2

Systematics Error Budget

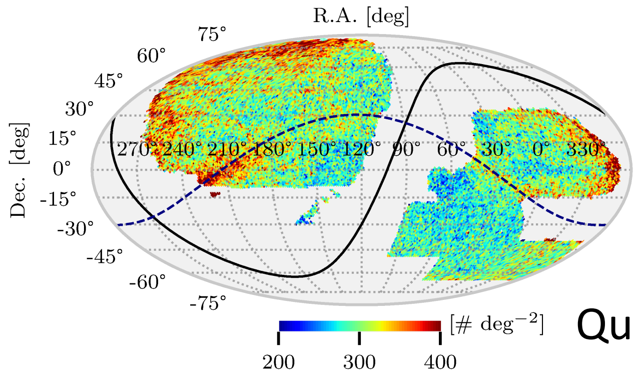
– Observational effects in data (imaging, fiber assignment,…)
– Reconstruction algorithm
– Covariance matrix construction



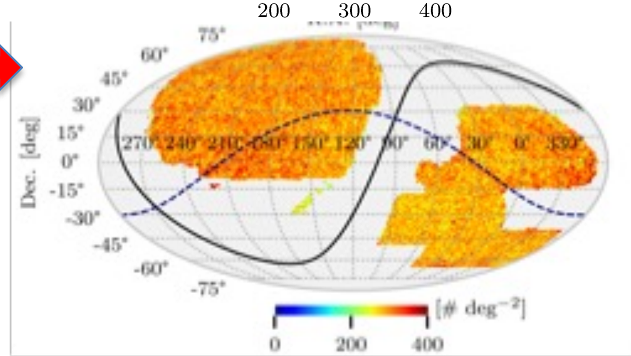
– Incomplete theory modelling
– Choice of fiducial cosmology
– Galaxy-halo (HOD) model uncertainties

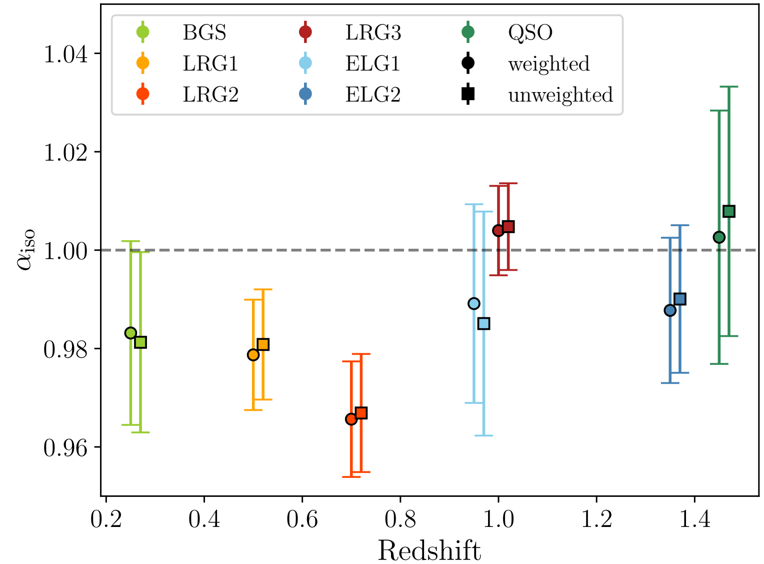


Example of systematics: Imaging



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**

Systematics Error Budget

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

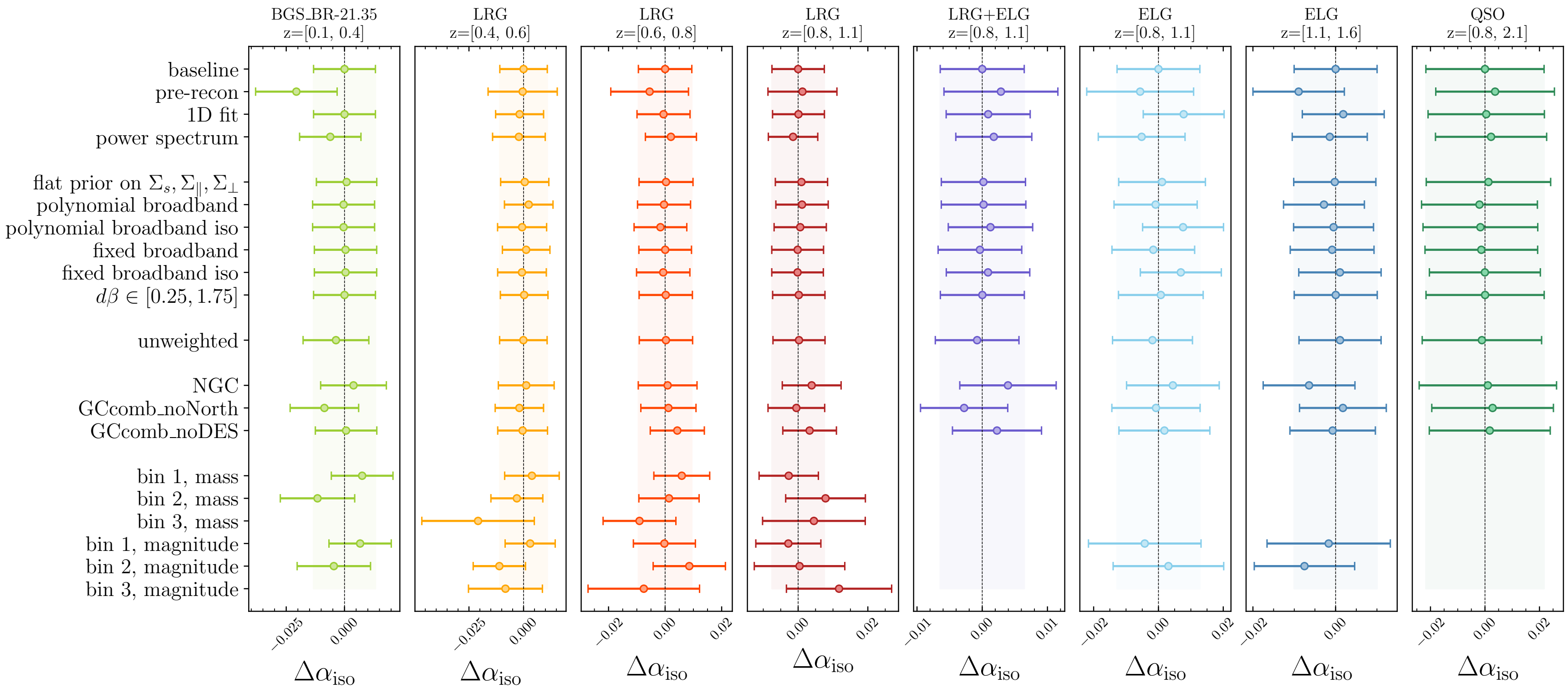
No effect on BAO

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

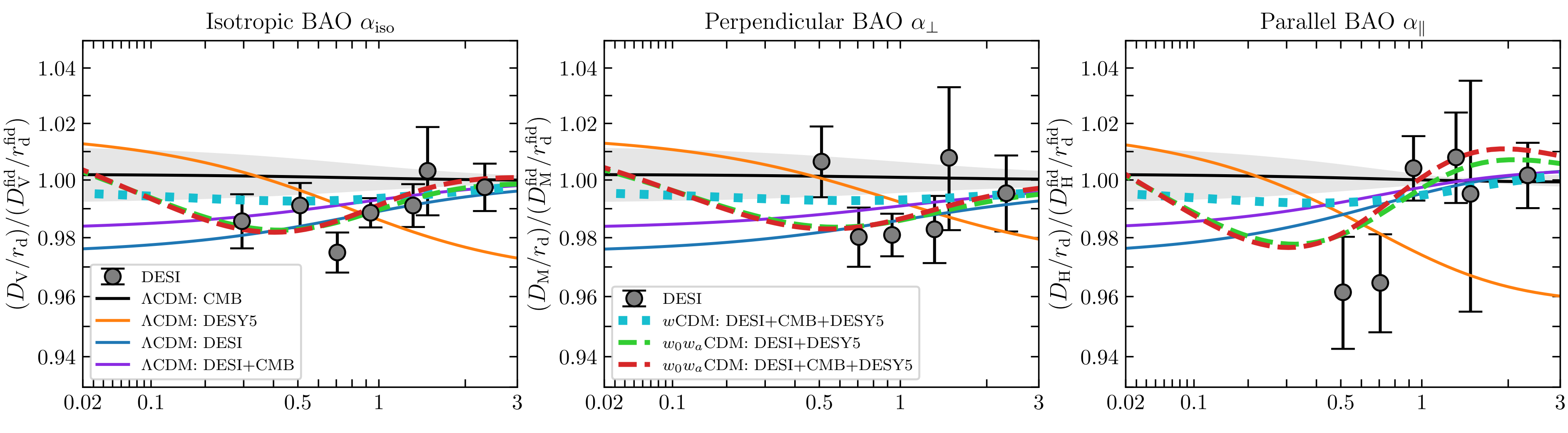
Stability of the results



– 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**

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

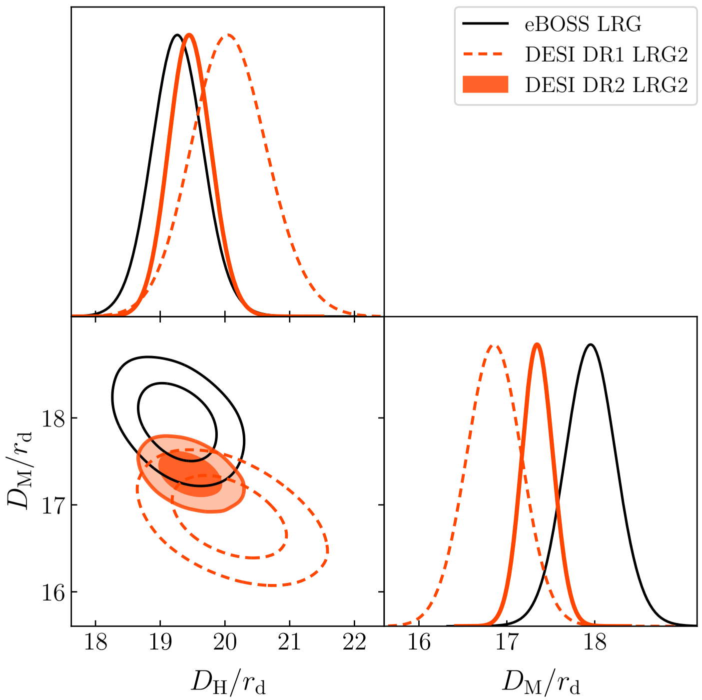
Dark Energy – Significance

Datasets	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_b, \omega_{bc})_{\rm CMB}$	-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)

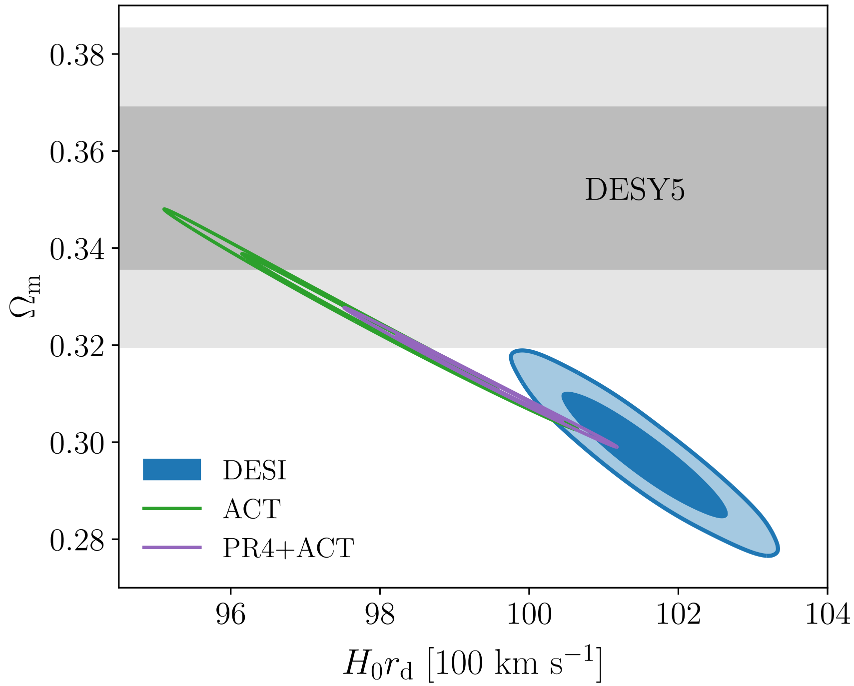
Three SNIa sample

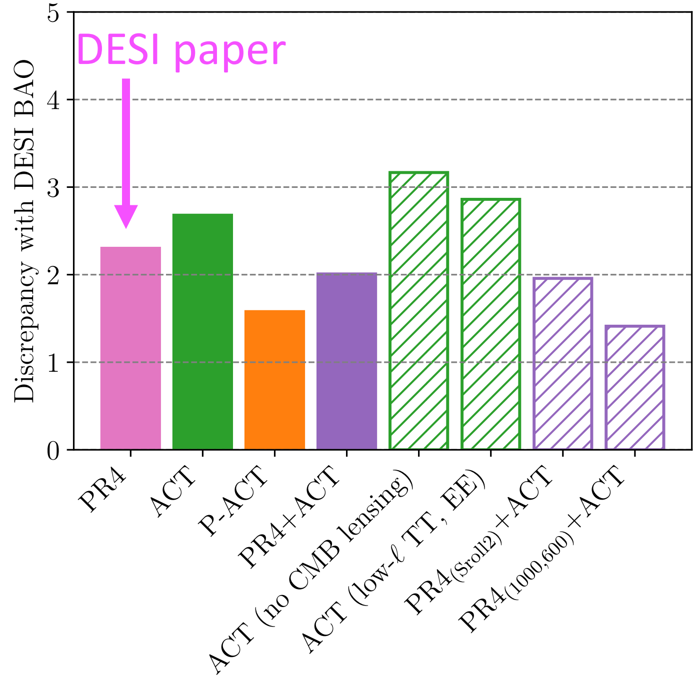
Comparison DESI/SDSS at z~0.7



- 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

Comparison DESI/ACT





ACT+DESI (DESI Paper), arXiv:2504.18464

- 2.3σ discrepancy with CMB (DESI paper)
- Adding ACT to PR4 2.3σ → 2.0σ
- Adding recent ACT results, it varies from 1.4σ to 3.2σ

Comparison DESI/ACT

3. CMB standalone likelihoods (including CMB lensing)	
low-ℓ TT	*Planck* 2018 PR3 low-ℓ `Commander` likelihood for TT in the range $2 \leq \ell < 30$ [37, 38].
low-ℓ EE `SimAll`	*Planck* 2018 PR3 low-ℓ `SimAll` likelihood for EE in the range $2 \leq \ell < 30$ [37, 38].
low-ℓ EE `SRoll2`	Alternative low-ℓ likelihood for EE based on the `SRoll2` code in the range $2 \leq \ell < 30$ [39].
high-ℓ PR3	*Planck* PR3 `Plik_lite` likelihood for the high-ℓ CMB TT, TE, EE spectra from $\ell = 30$ up to $\ell = 2500$ [37, 38].
high-ℓ PR4	*Planck* PR4 high-ℓ temperature and polarization likelihood using `NPIPE` maps. The high-ℓ TT, TE, EE spectra from *Planck* extends from $\ell = 30$ up to $\ell = 2500$ [40, 41].
ACT DR6	Power spectra from the anisotropies in the temperature and polarization CMB maps from the 6th data release of the Atacama Cosmology Telescope. The CMB power spectra extends from $\ell = 600$ up to $\ell = 8500$ [31].
CMB lensing	Combination of the CMB lensing measurements from the reconstruction of the CMB lensing potential using *Planck* PR4 `NPIPE` maps [42], and the CMB lensing measurements from the ACT Data Release 6 (DR6), which consists of five seasons of CMB temperature and polarization observations, with 67% of sky fraction overlap with *Planck* [21, 43].
4. Main CMB combinations	
ACT	low-ℓ EE `SRoll2` + ACT DR6 + CMB lensing
P-ACT	low-ℓ TT + low-ℓ EE `SRoll2` + high-ℓ PR3 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
PR4+ACT	low-ℓ TT + low-ℓ EE `SimAll` + high-ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing
5. Additional CMB combinations studied	
ACT (no CMB lensing)	low-ℓ EE `SRoll2` + ACT DR6 (same as ACT base in [31])
ACT (low-ℓ TT, EE)	low-ℓ TT + low-ℓ EE `SimAll` + ACT DR6 + CMB lensing
PR4	low-ℓ TT + low-ℓ EE `SimAll` + high-ℓ PR4 + CMB lensing (same as baseline CMB in [16])
$\text{PR4}_{(1000,600)}$+ACT	low-ℓ TT + low-ℓ EE `SimAll` + high-ℓ PR4 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
$\text{PR4}_{(\text{SRoll2})}$+ACT	low-ℓ TT + low-ℓ EE `SRoll2` + high-ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing

ACT paper (ACT, P-ACT)

→ ACT+DESI paper - Baseline (PR4+ACT)

→ DESI paper (PR4)

ACT+DESI (DESI Paper), arXiv:2504.18464

– Several comparisons were tested