

Cosmology from three years of DESI (DR2)

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IJCLab Seminar, Orsay, June 16 2025



Dark Energy Spectroscopic Instrument

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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Introduction

-

Baryonic Acoustic Oscillations (BAO)



Context in Cosmology: Λ CDM

Λ CDM

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

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

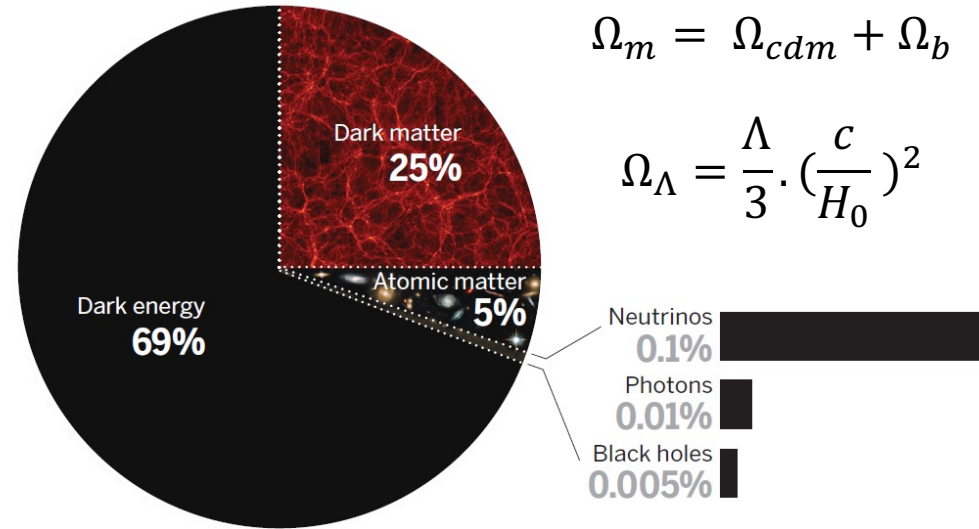
Extensions of Λ CDM

- Equation of state of Dark Energy

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

- Time evolving Dark Energy

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



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

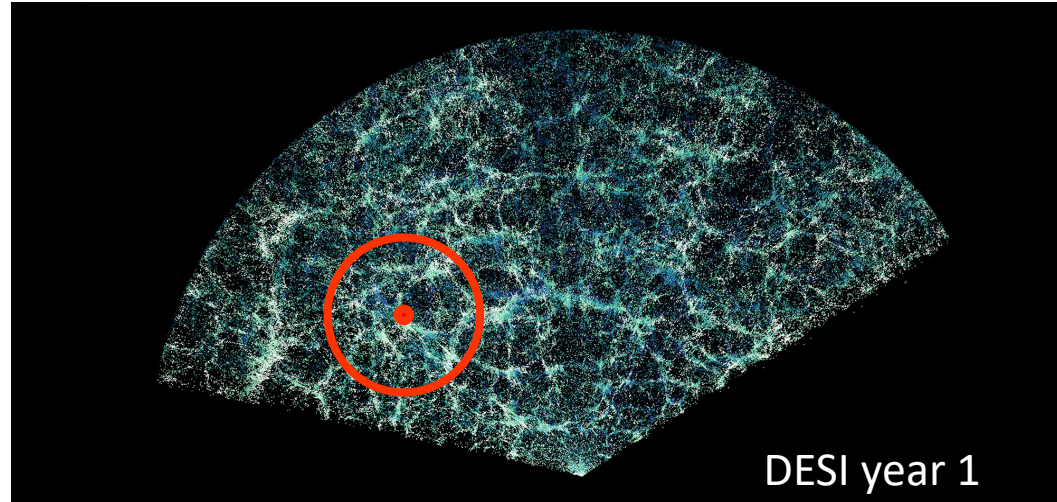
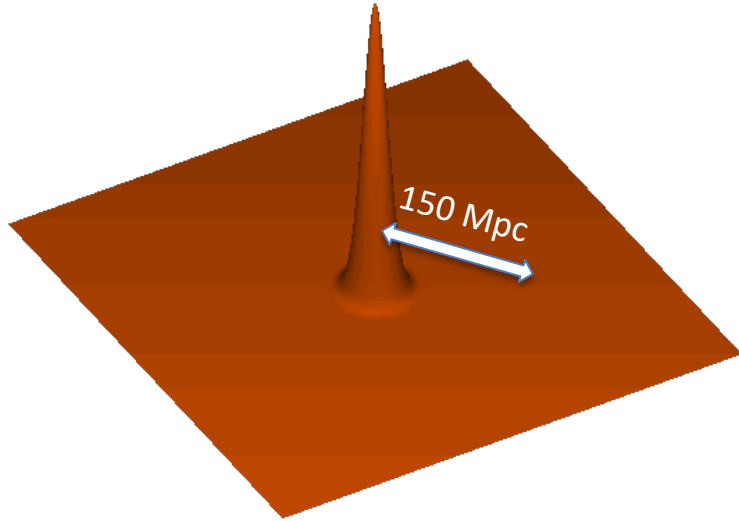
$$\Omega_\Lambda = \frac{\Lambda}{3} \cdot \left(\frac{c}{H_0}\right)^2$$

Open questions

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



BAO, a standard ruler

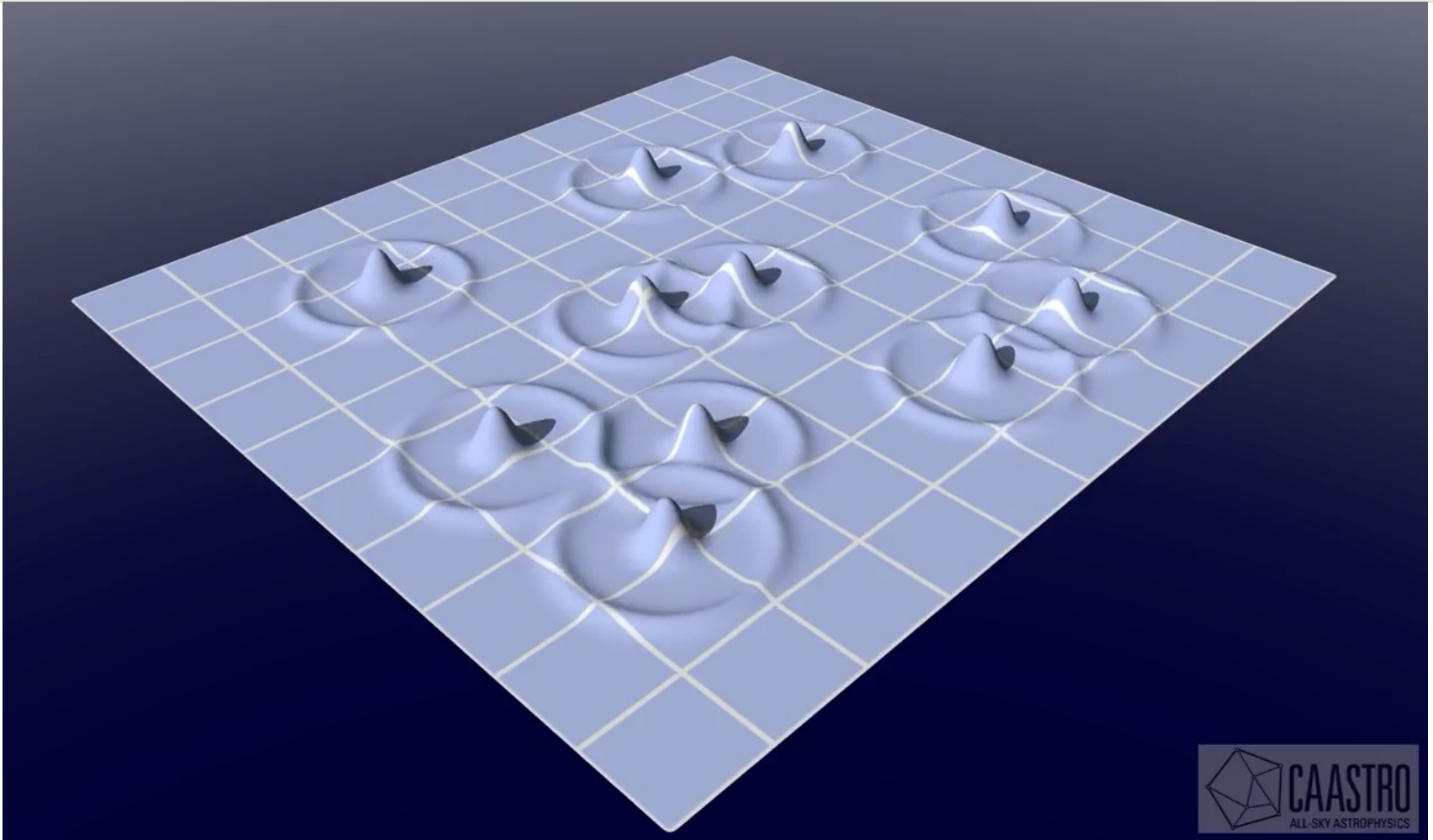


A special distance

- Sound waves propagate through relativistic plasma (baryons, electrons, photons) with a speed $\sim c/\sqrt{3}$
- They freeze at recombination ($z \sim 1100$ 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**



BAO: Correlation function



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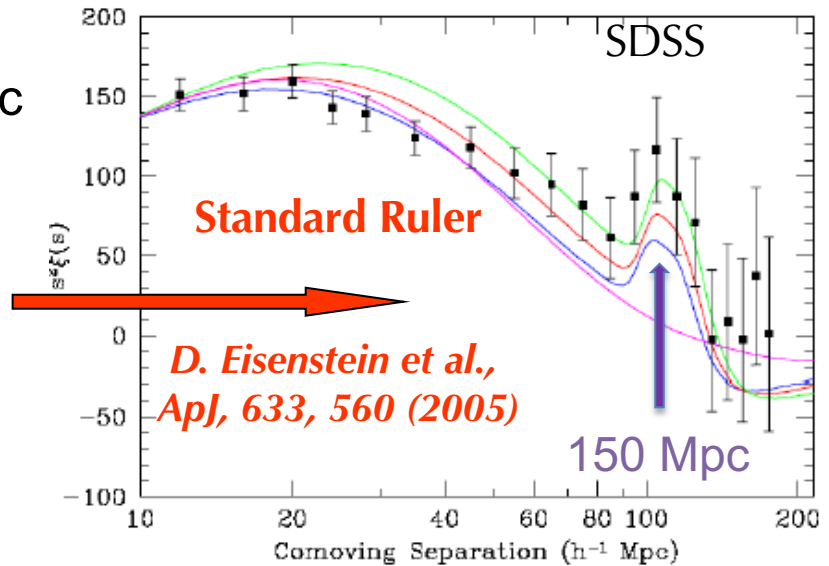
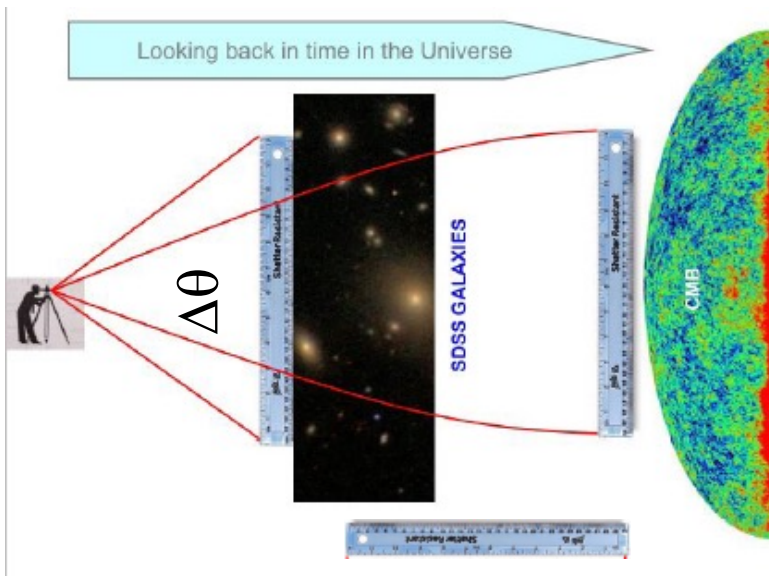
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Observation of baryonic acoustic peak

First observation

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~ 150 Mpc
- SDSS: $\sim 50\,000$ LRGs, $\langle z \rangle \sim 0.35$
“Luminous Red Galaxies”



A 3D measurements

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

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

⇒ Sensitive to Hubble parameter $H(z)$.

- **Transverse direction:**

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

⇒ Sensitive to angular distance $D_A(z)$

⇒ $\sim \int 1/H(z)$



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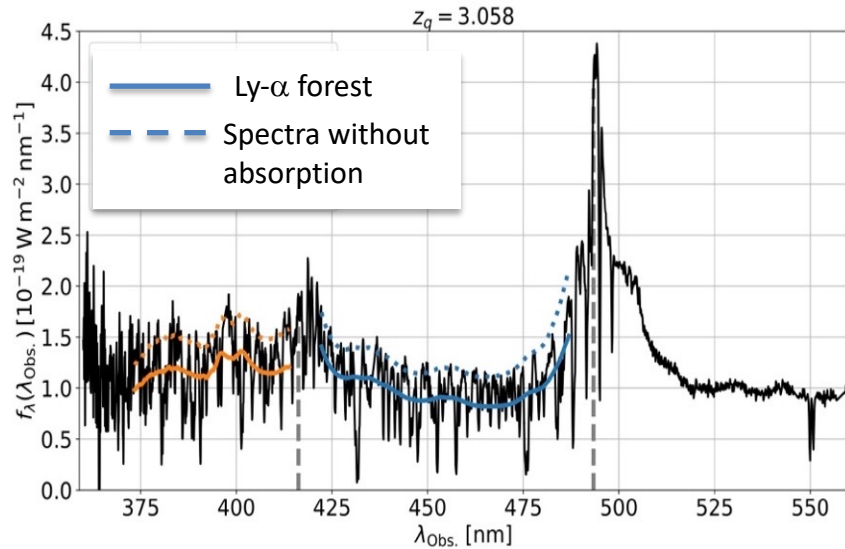
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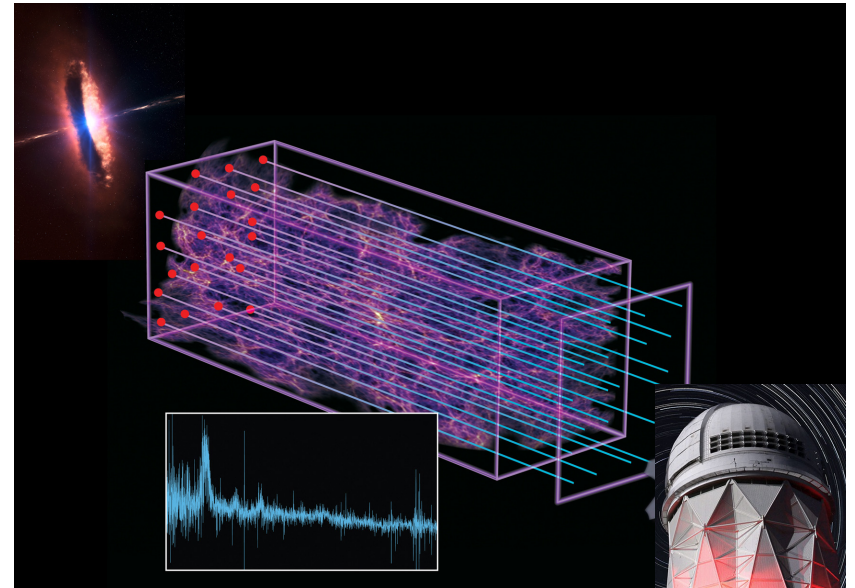
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Another Tracer of Matter: Ly- α forest of quasars



- 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



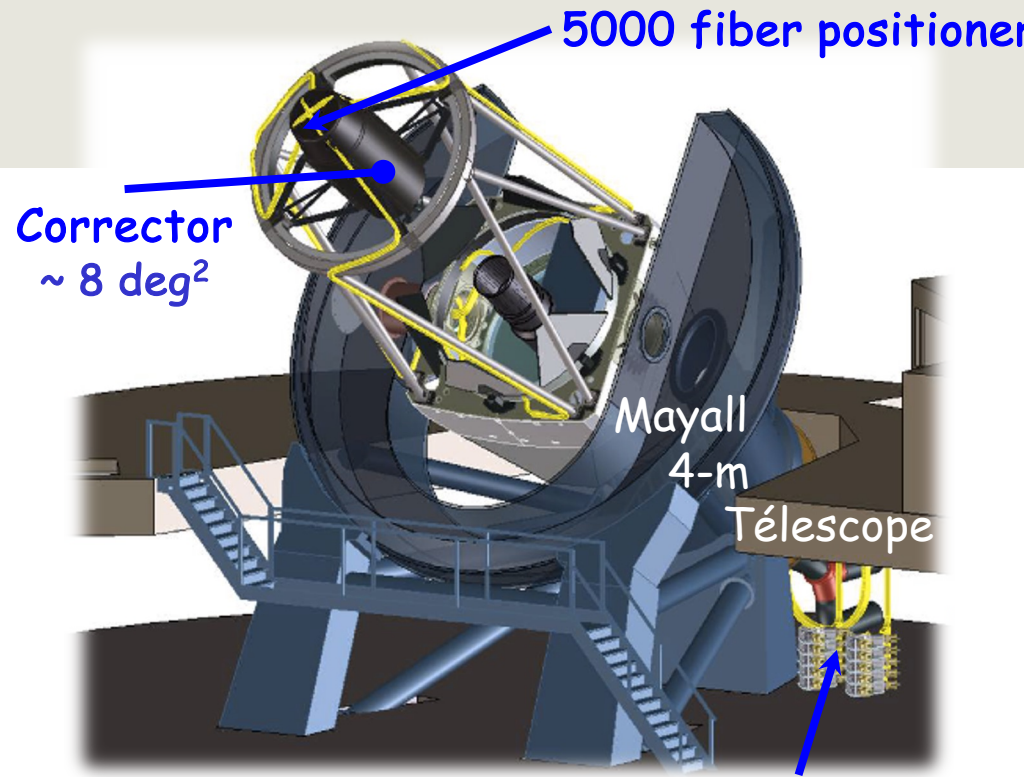
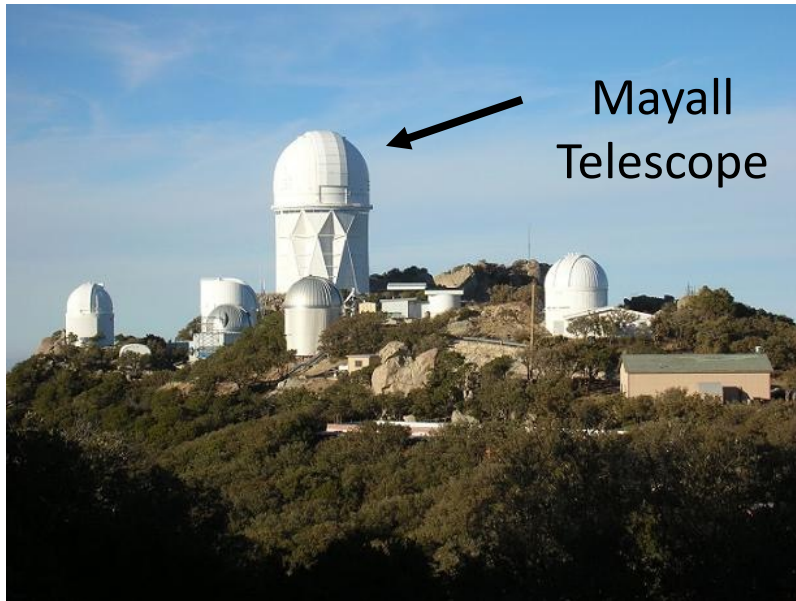
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DESI Project

- **Scientific project**

- 3D map for $0 < z < 4$
- Footprint $\sim 14000 \text{ deg}^2$ (1/3 sky)
- International collaboration
- 72 institutions (46 non-US)
- ~ 900 members



10 spectrographs

- **Instrument**

- 4-m telescope at Kitt Peak (Arizona)
- Wide FoV ($\sim 8 \text{ deg}^2$)
- Robotic positioner with 5000 fibers
- 10 spectrographs x 3 bands (blue, visible, red-NIR) $\rightarrow 360\text{-}1020 \text{ nm}$



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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

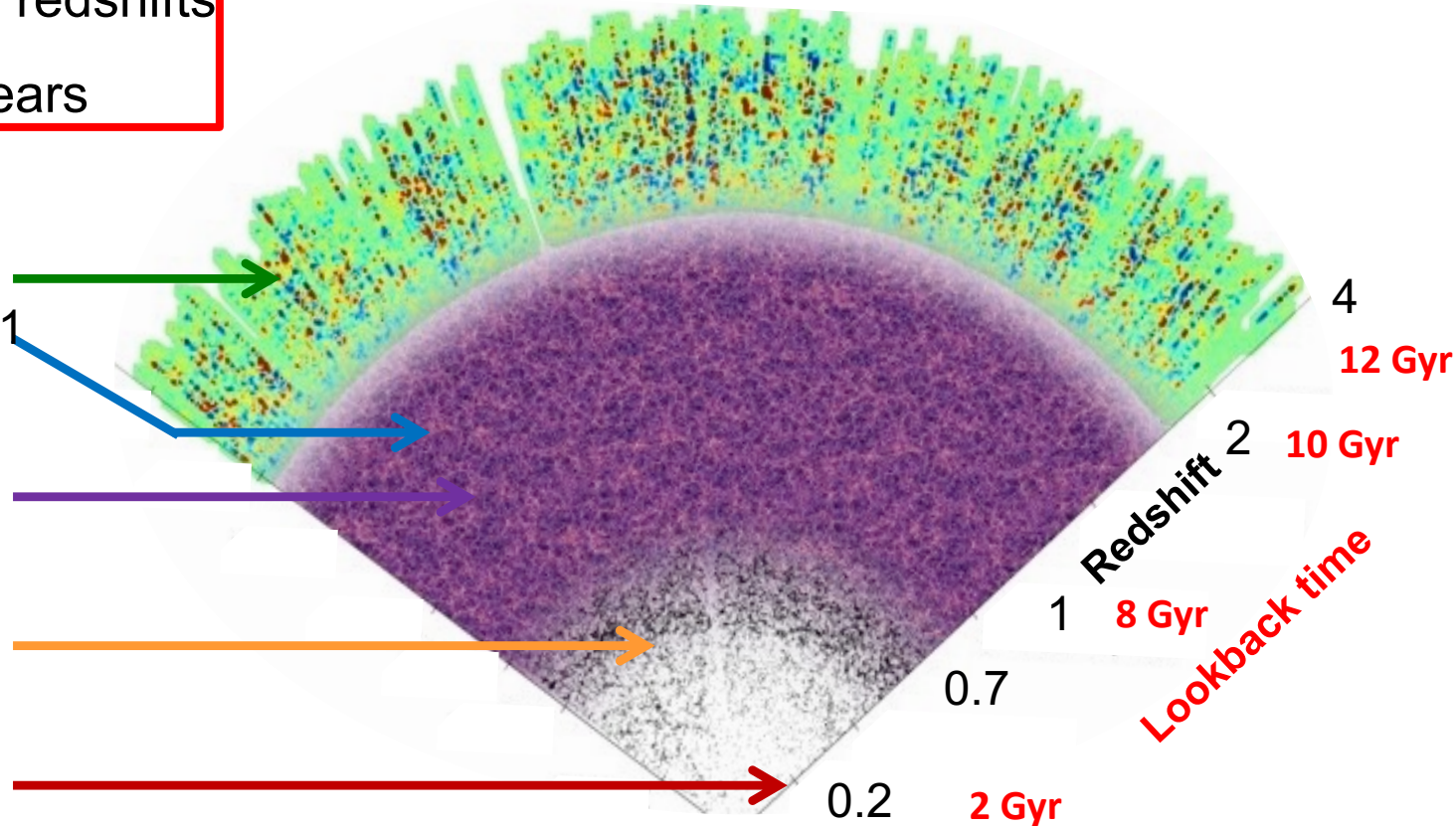
$0.6 < z < 1.6$

8 million LRGs

$0.4 < z < 1.0$

**13.5 million
Brightest galaxies**

$0.0 < z < 0.4$



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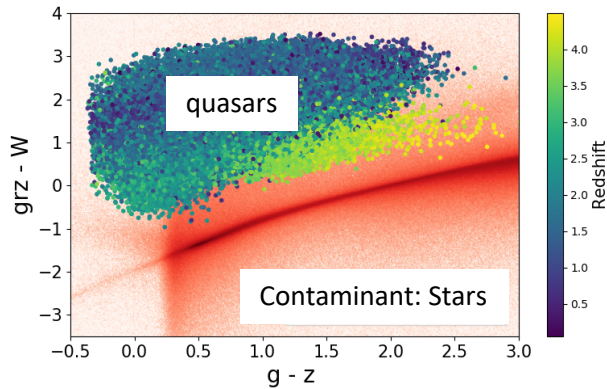
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Rolling observations – Redshift factory

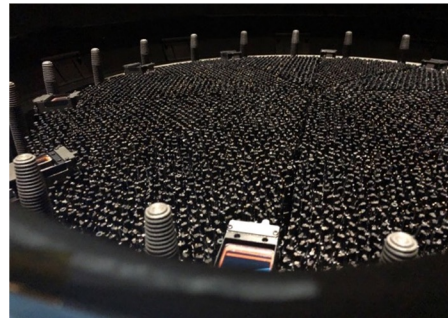
Target Selection



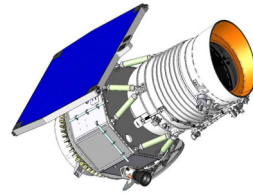
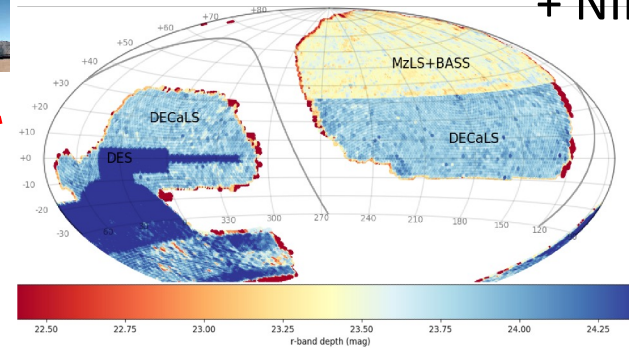
↓ Observation...



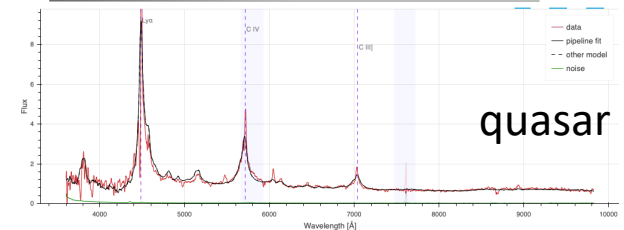
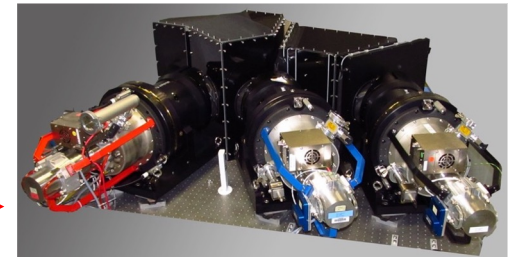
...of 5000 objects
every ~20mins...



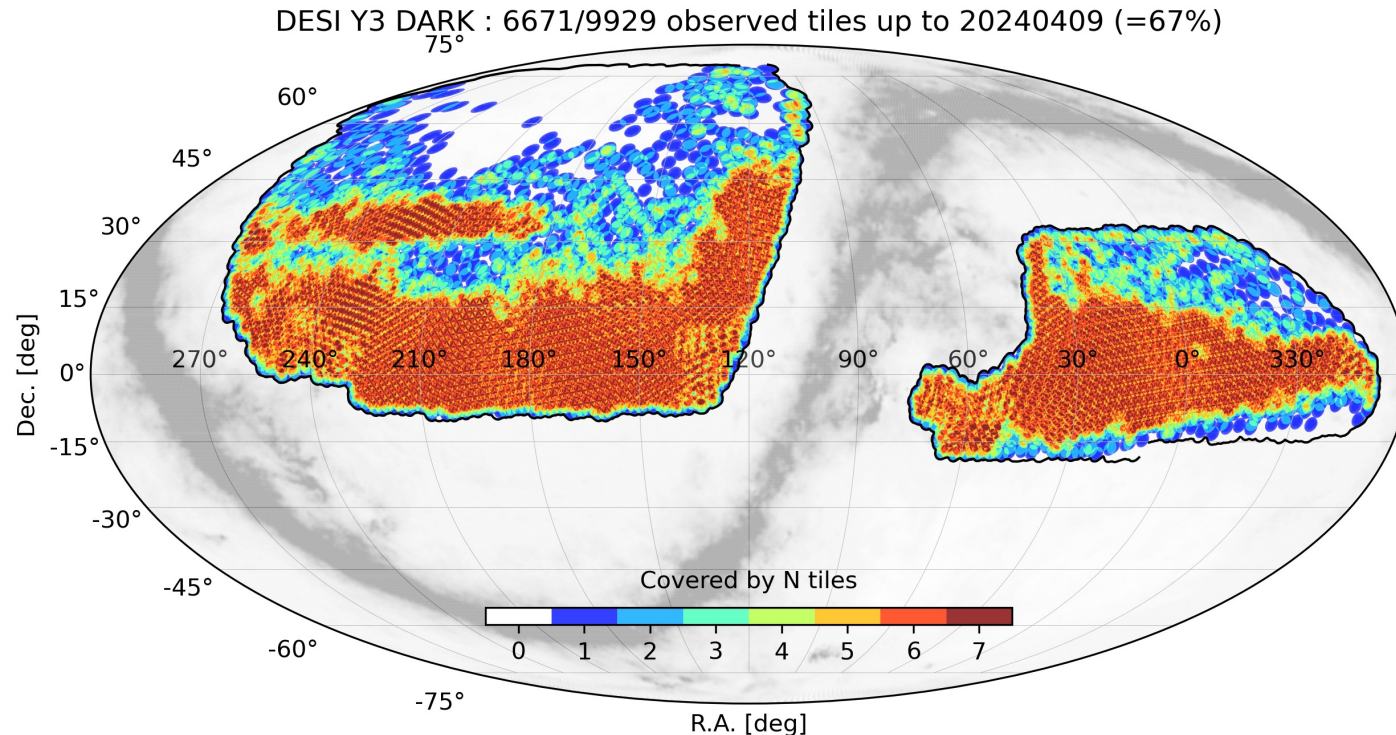
Imaging Surveys: optical grz bands
+ NIR with WISE



...and measure their redshift



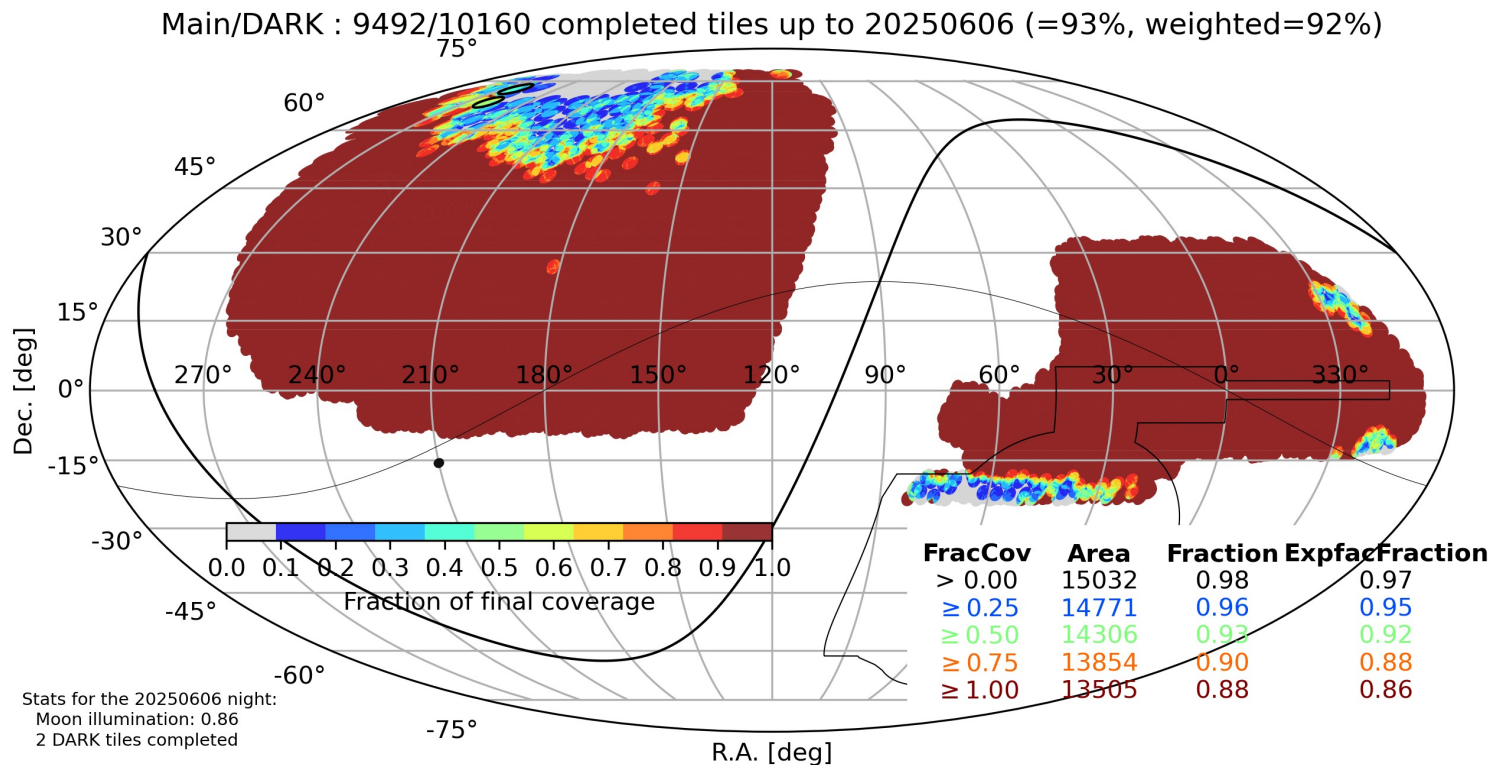
DESI DR2 footprint



- DESI footprint over 5 years $\sim 14000 \text{ deg}^2$
- DR2 (3 years) $\sim 70\%$ 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



- **~95% is already done**
 - **DESI** is ~6 months ahead of schedule
- ⇒ DESI should finish in Nov. 2025 (DR3)

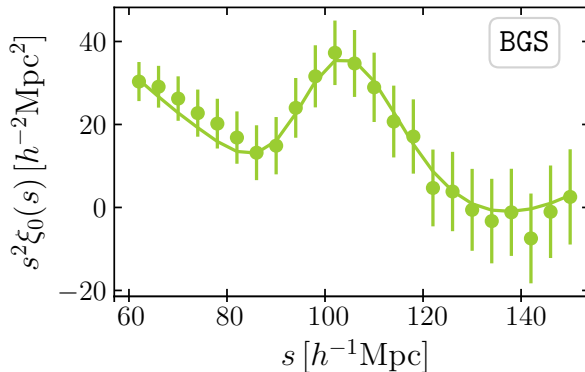


BAO Measurements



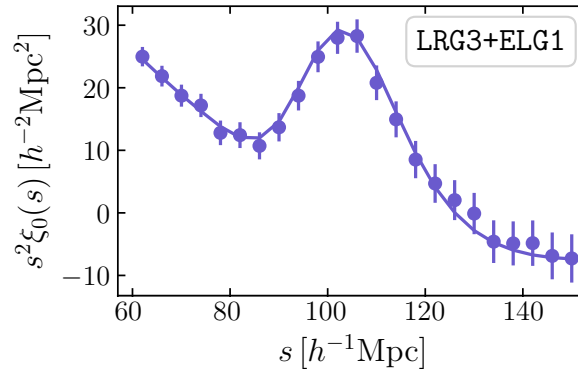
Results: a few examples

BGS $z=0.30$



Precision: 0.93%

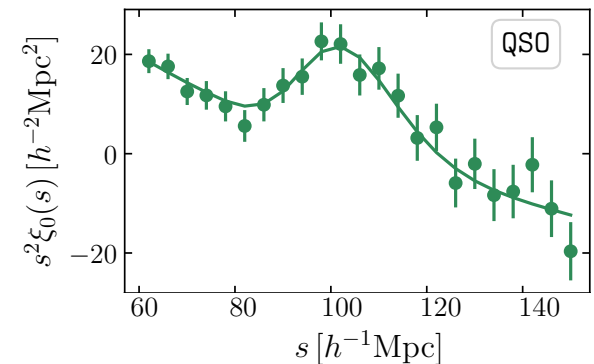
LRG3+ELG1 $z=0.93$



Significance: 14.7 σ

Precision: 0.45%

QSO $z=1.48$



Significance: 5.6 σ

Precision: 1.5%

– Dilation compared to a fiducial cosmology

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



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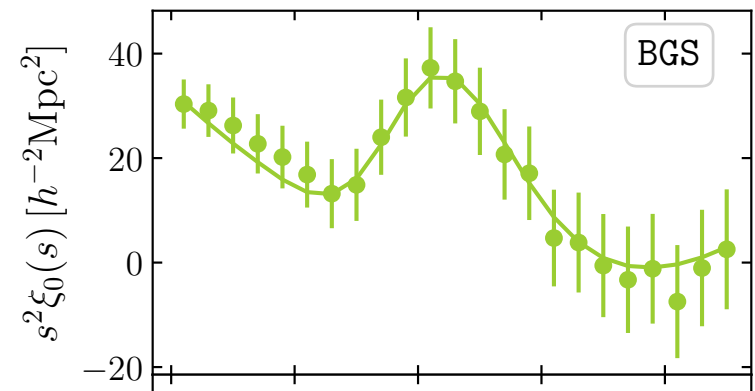
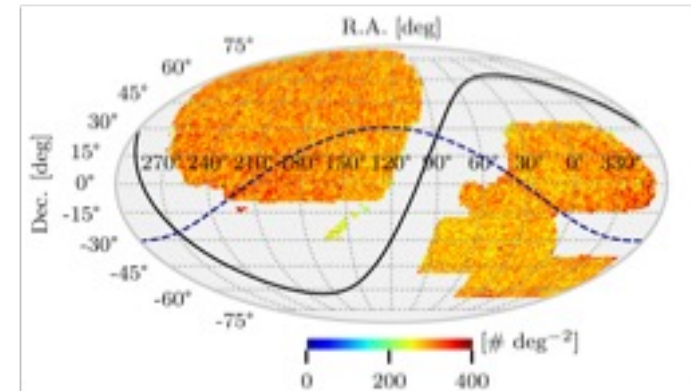
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Systematics Error Budget

- 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

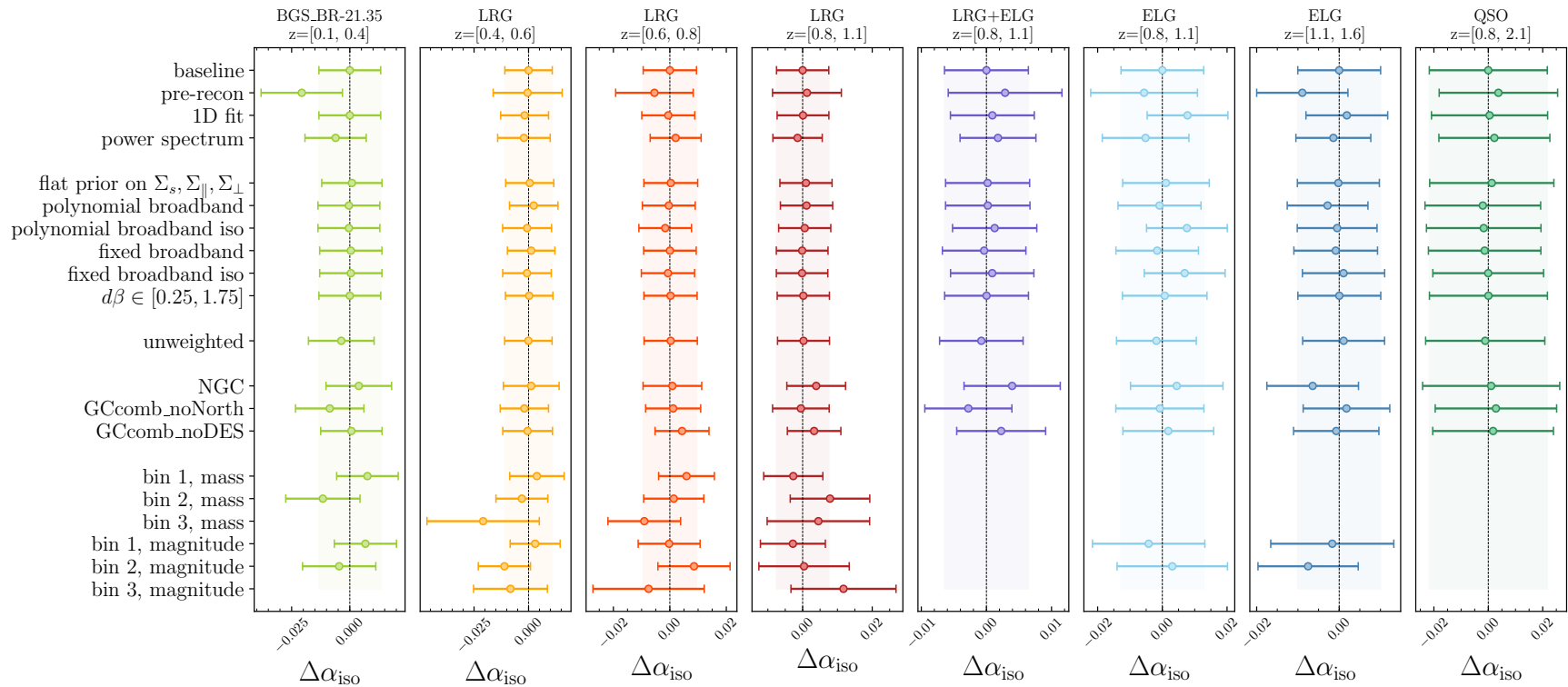
- Observational effects in data (imaging, fiber assignment,...)
 - Reconstruction algorithm
 - Covariance matrix construction
- No effect on BAO**
- Incomplete theory modelling $\sigma_{theo} = 0.1\%$
 - Choice of fiducial cosmology $\sigma_{fid} = 0.1\%$
 - Galaxy-halo (HOD) model $\sigma_{HOD} = 0 - 0.17\%$ (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



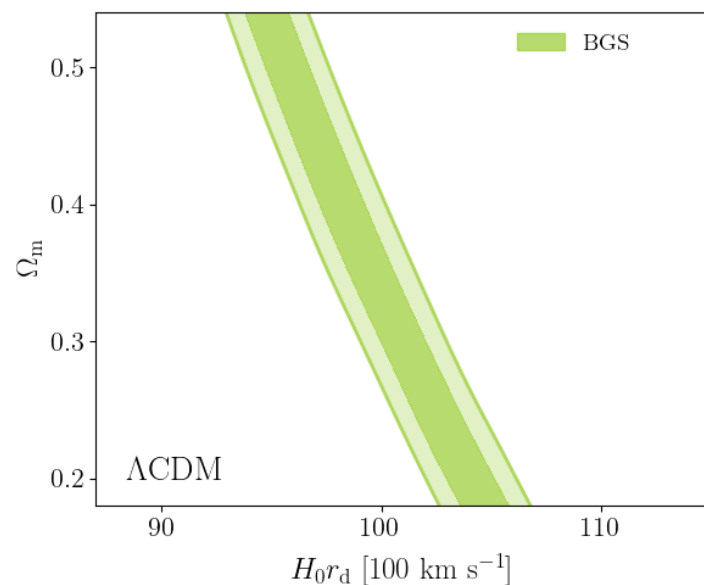
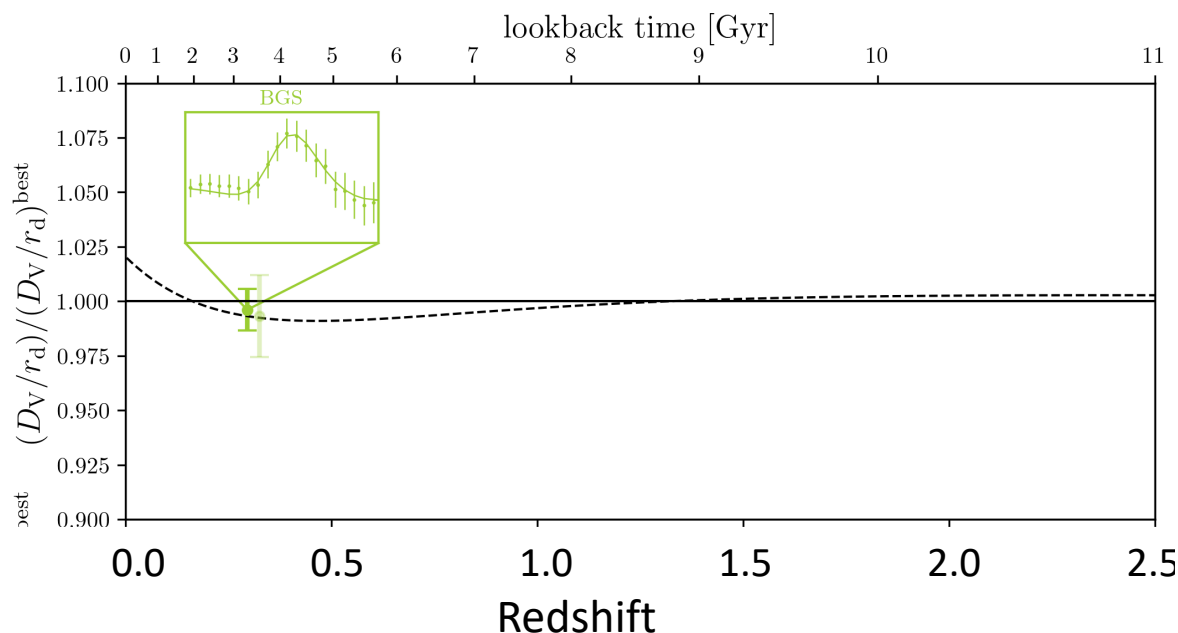
- Comparison with the baseline analysis for different configurations (with/without reconstruction, power-spectrum, broadband modeling priors damping parameters, imaging weights, footprint, mag mass)
- **Extremely stable results**



DESI DR2: BGS

$$\alpha_{\perp} = \frac{D_M}{r_d} \frac{r_d^{\text{fid}}}{D_M^{\text{fid}}} \quad \alpha_{\parallel} = \frac{H^{\text{fid}} r_d^{\text{fid}}}{H r_d} \quad \alpha_{\text{iso}} = (\alpha_{\perp}^2 \alpha_{\parallel})^{1/3}$$

In Λ CDM, the α parameters depend on $H_0 r_d$ and Ω_m



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



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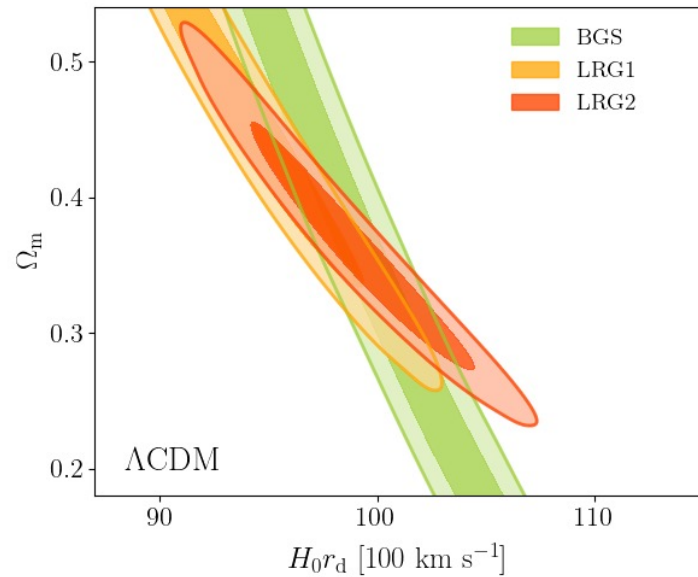
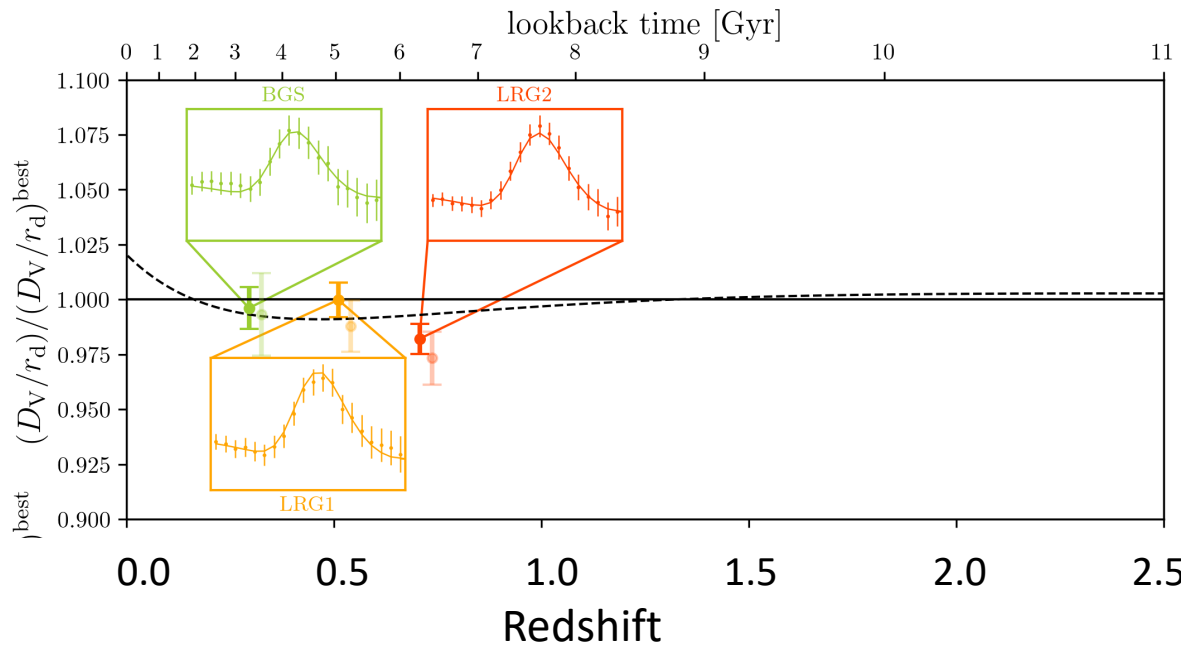
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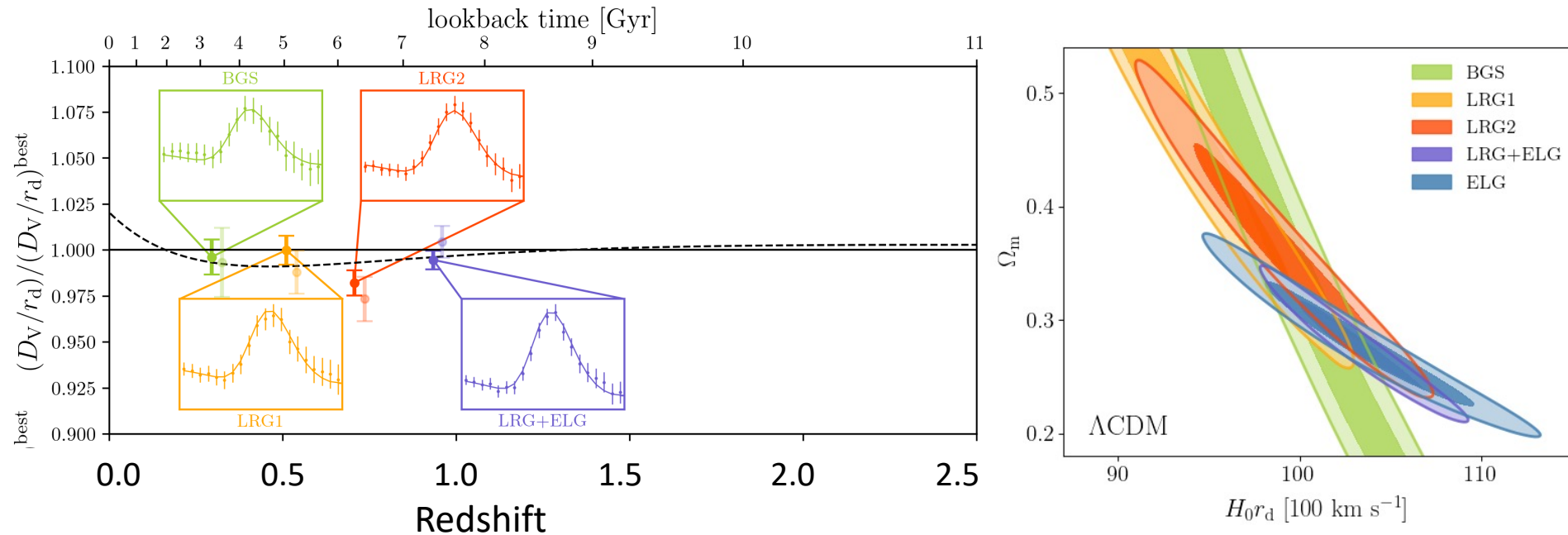
DESI DR2: BGS + LRG



- 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



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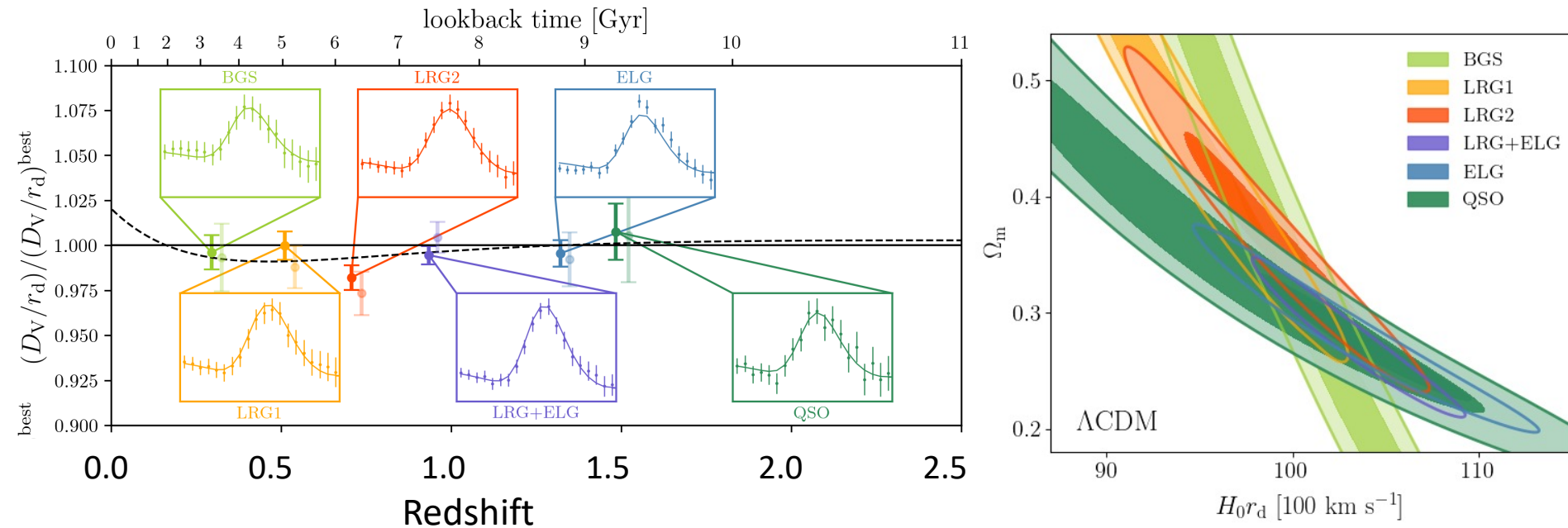
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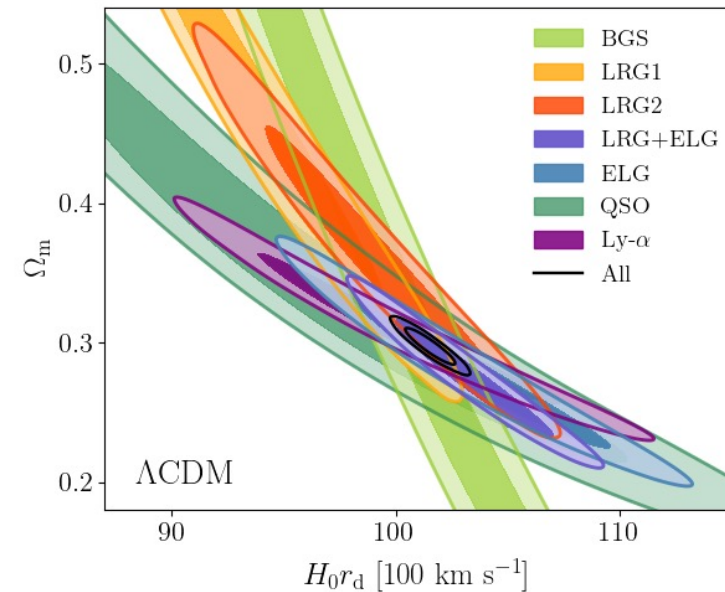
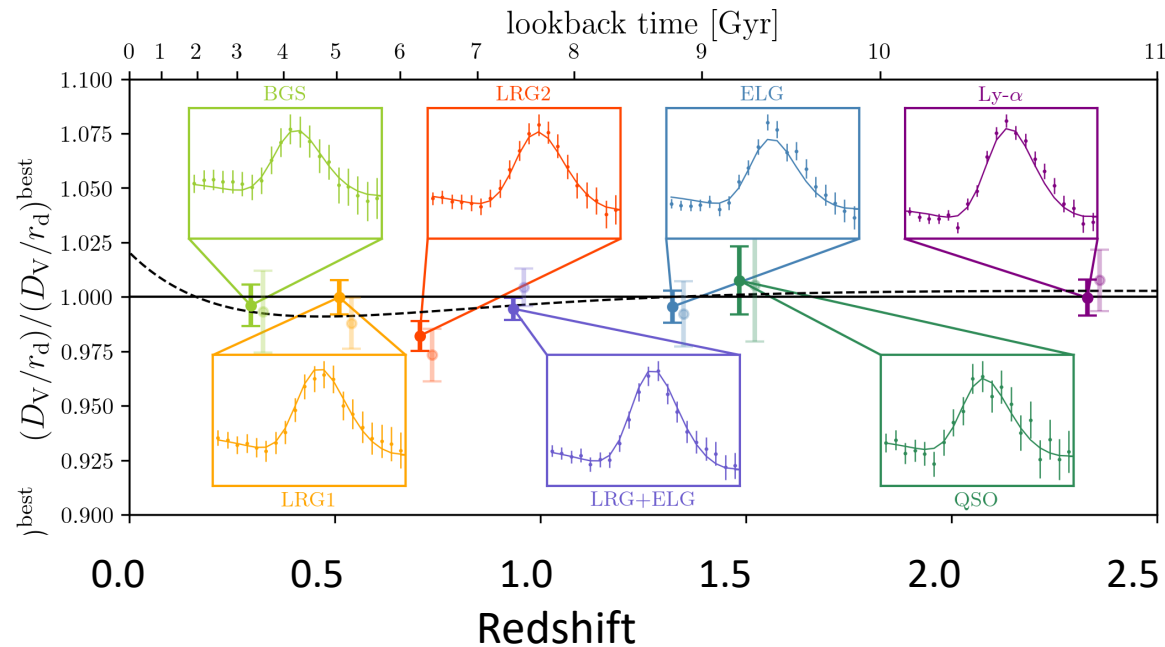
DESI DR2: BGS + LRG + ELG + QSO



- 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



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Cosmological Interpretation



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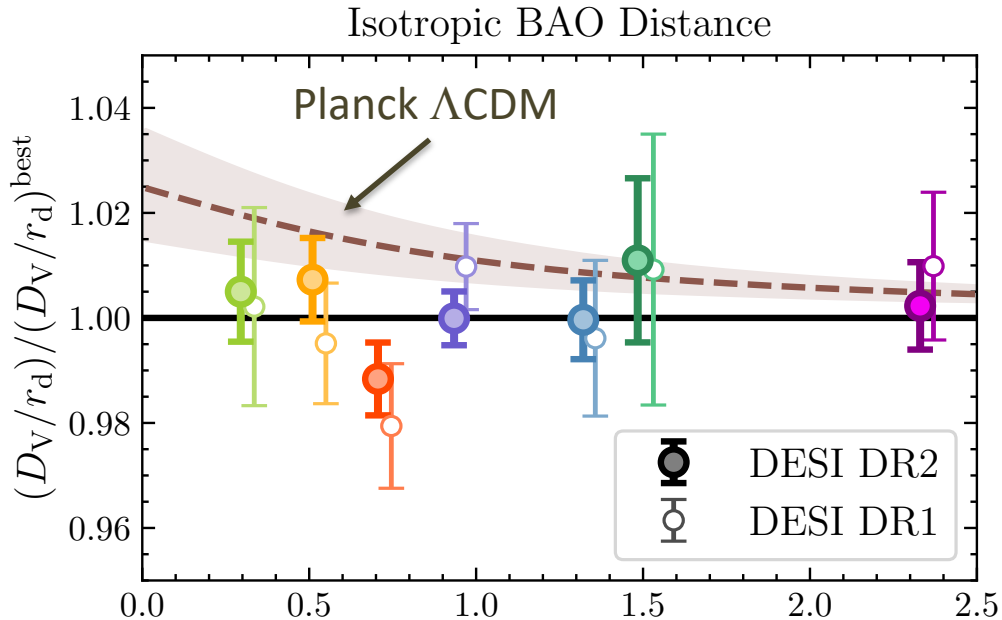
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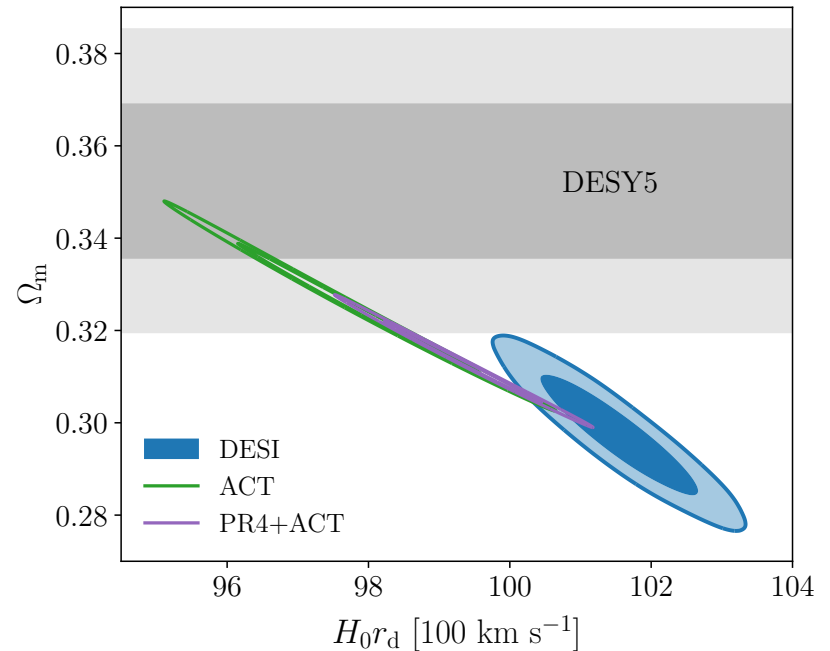
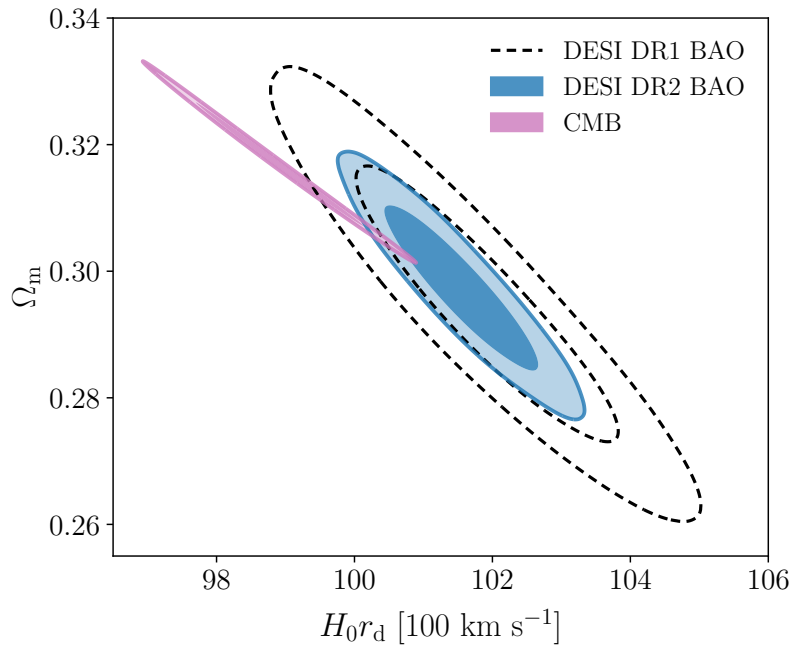
DESI - Hubble diagram



- ~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 $z \sim 2.3$: precision on BAO 0.7%
- **Excellent agreement** between DESI DR1 and DR2
- Consistent with Λ CDM but **small tension with Planck Λ CDM : 2.3σ**



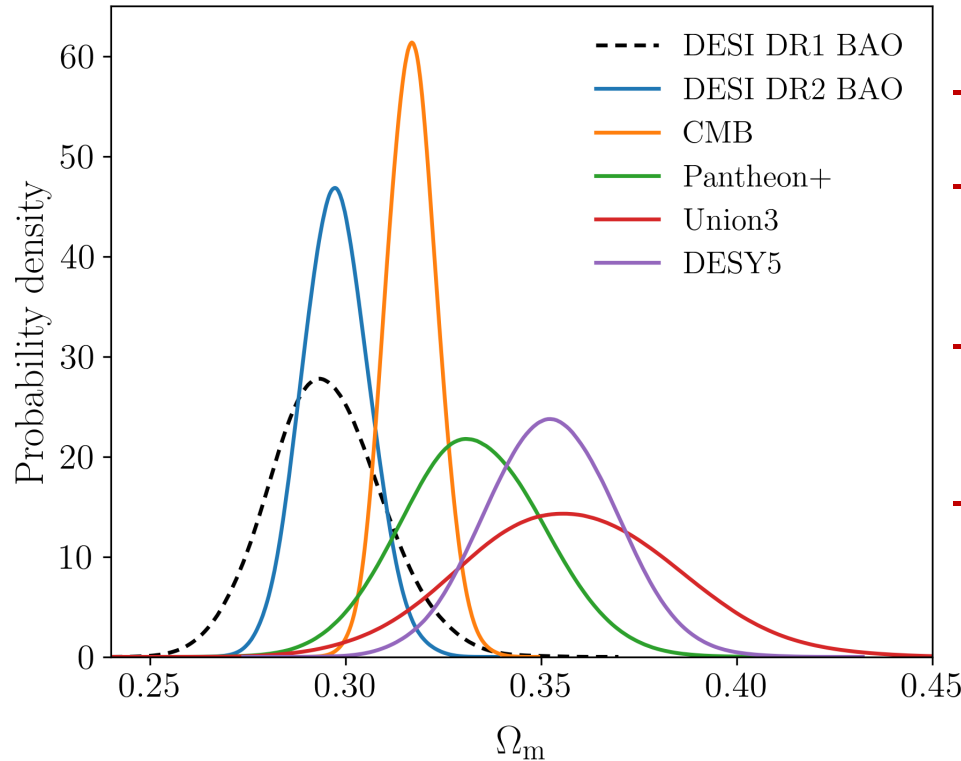
$\Omega_m - H_0 r_d$ Comparison CMB/BAO



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



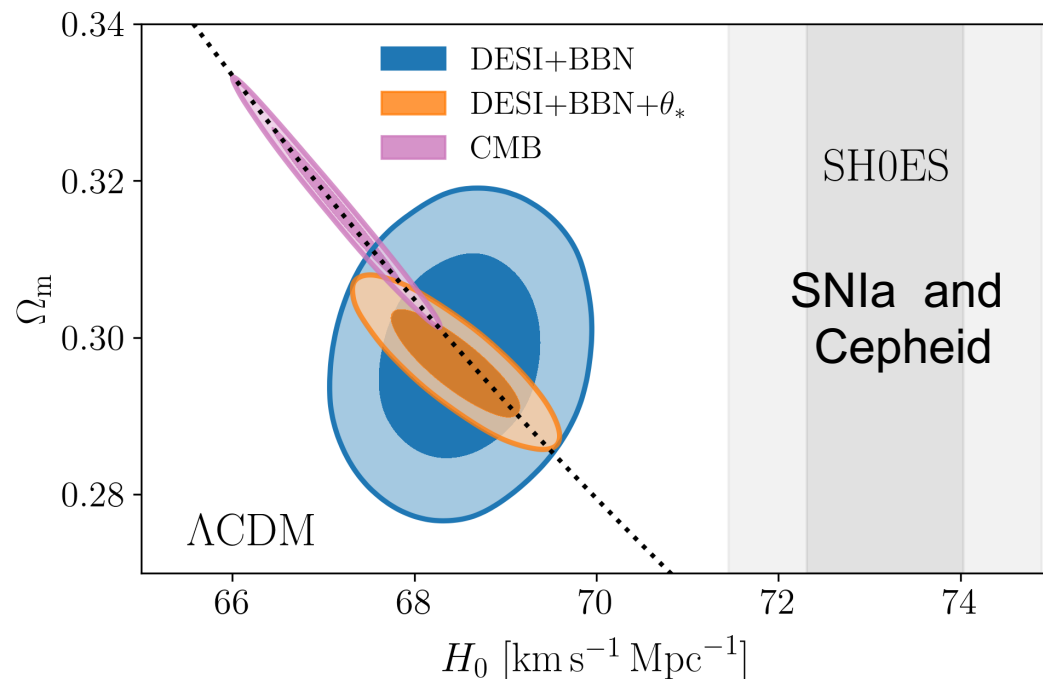
Ω_m - Tensions in Λ CDM



- 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 Λ CDM



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

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

θ_* : CMB angular scale

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



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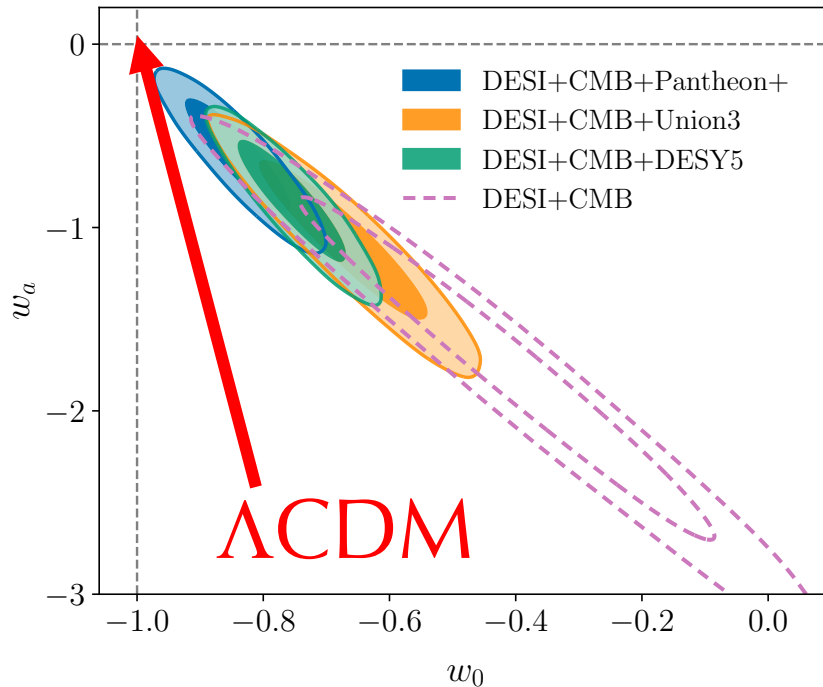
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Beyond Λ CDM: Dark Energy - Equation of State



Extensions of Λ CDM

- Equation of state of Dark Energy

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

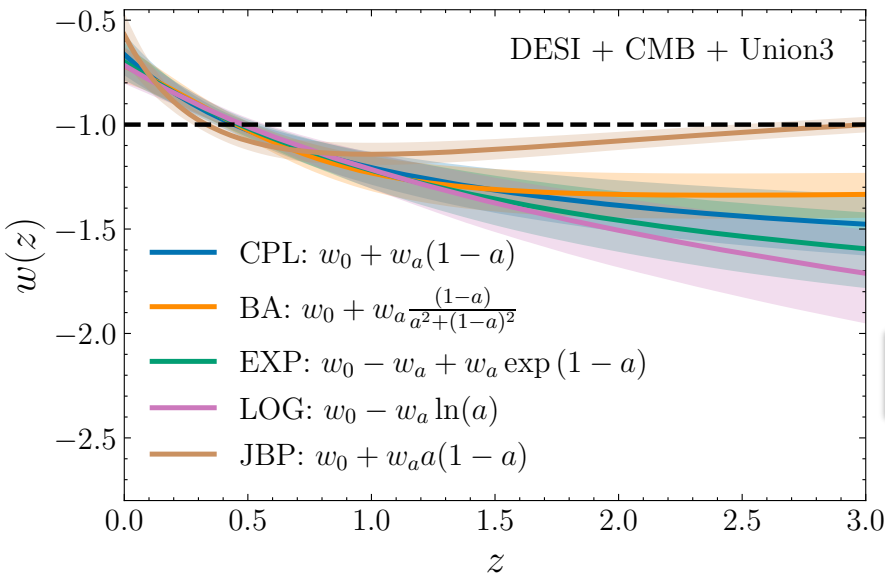
- Time evolving Dark Energy

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

- For Λ CDM, 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



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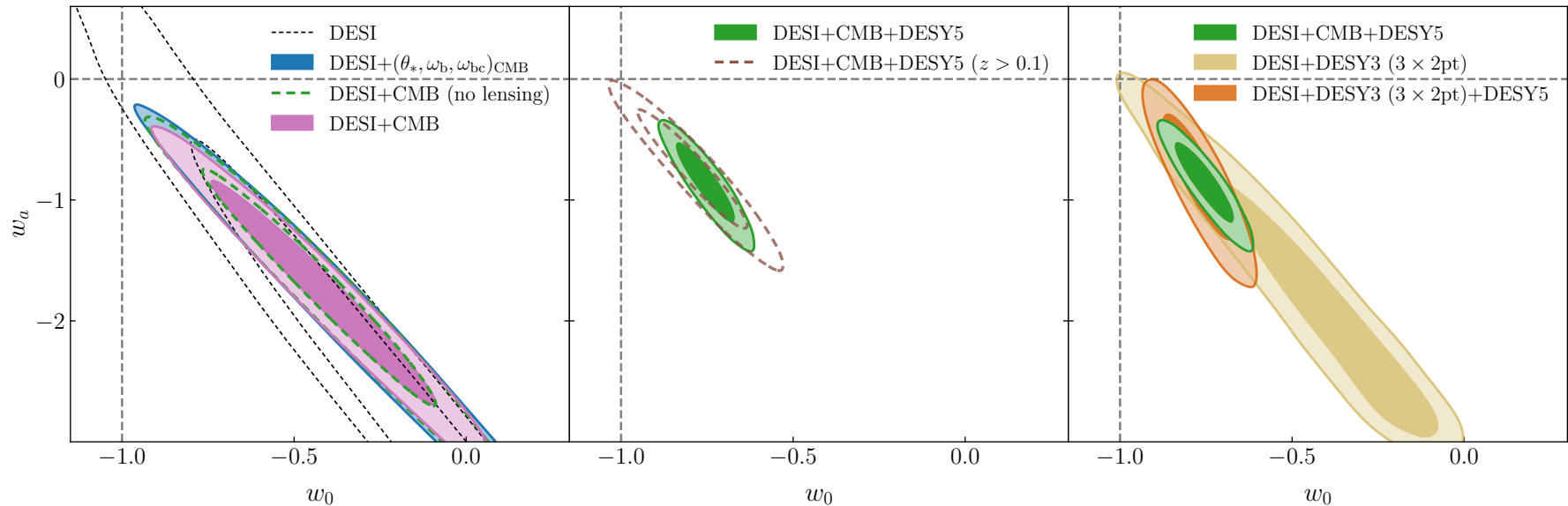
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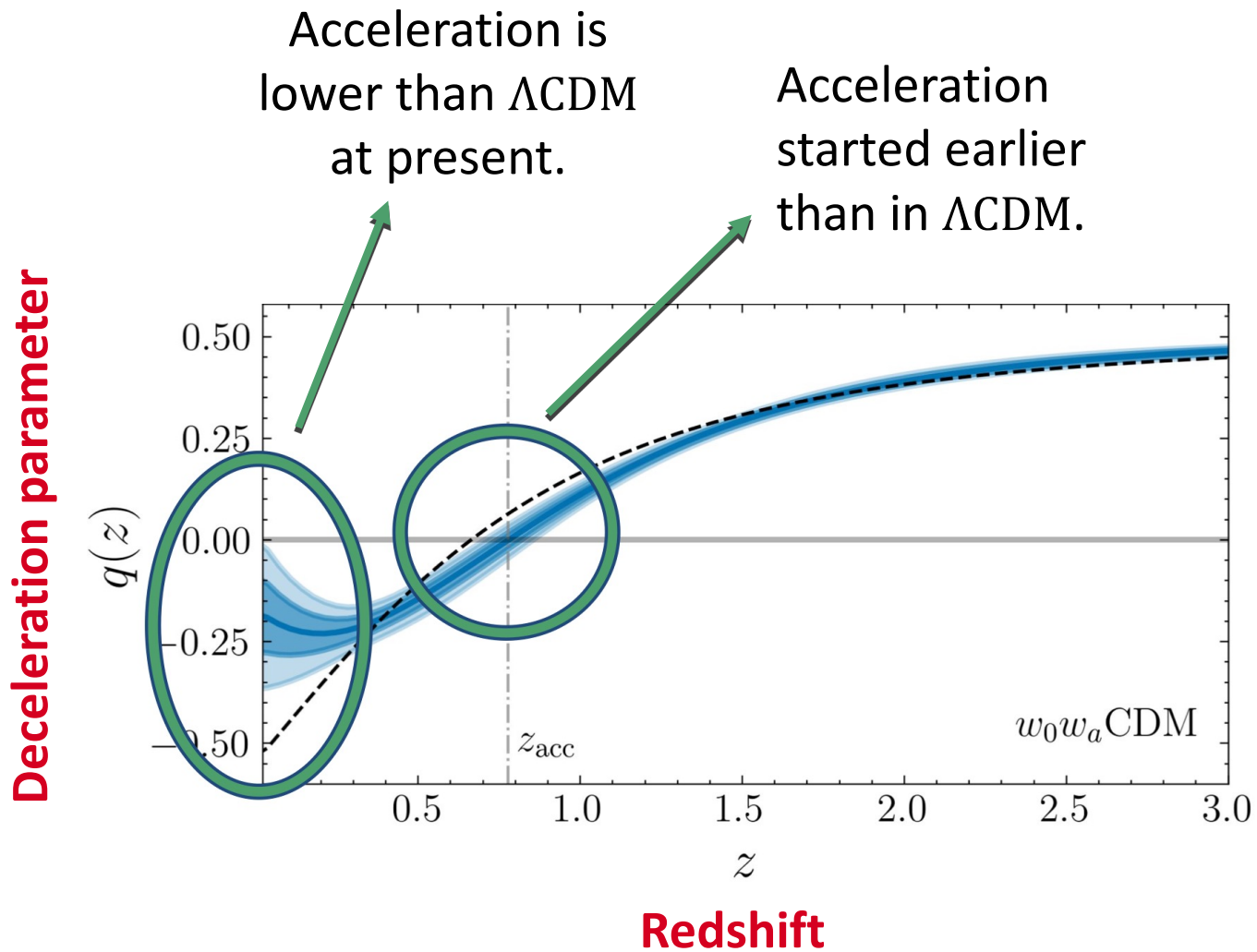
Dynamical Dark Energy – Robustness



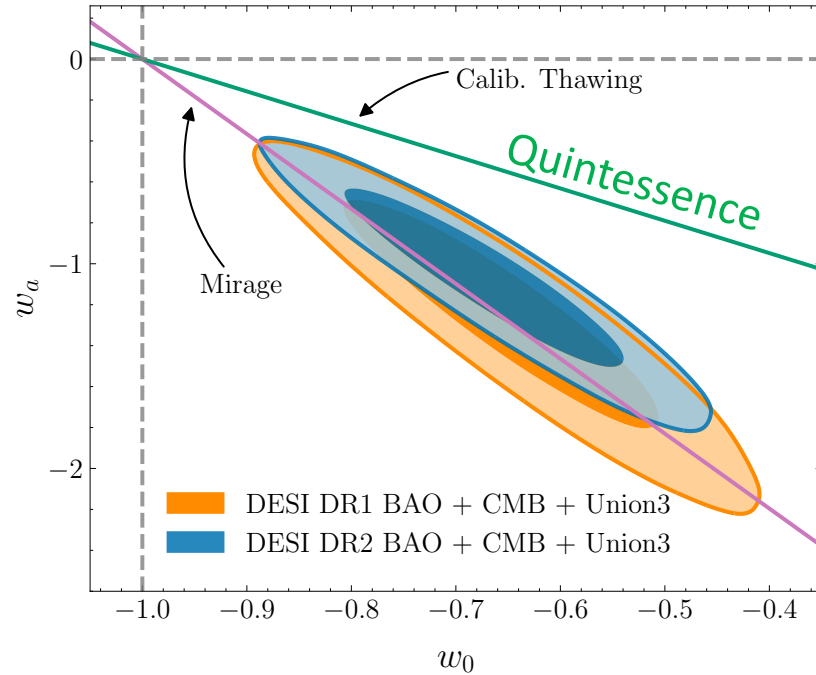
- Combining with early-Universe prior on $(\theta_*, \omega_b, \omega_{bc})$ from CMB shows preference for evolving DE.
- Excluding $z < 0.1$ SNIa reduces the tension but the best fit is far for Λ CDM
- Replacing CMB with DES 3x2pt continues to show a preference for evolving DE



Dynamical Dark Energy



Dynamical Dark Energy – Models

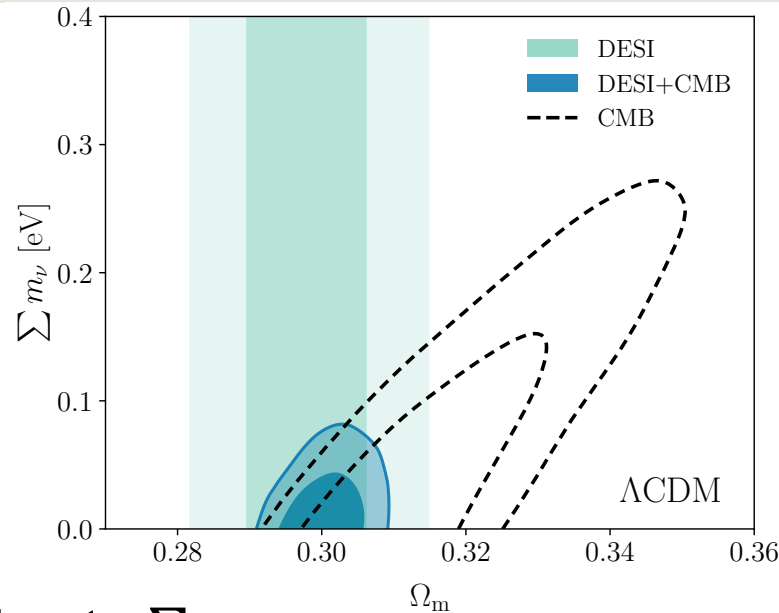


DE classes	DESI+CMB: +PantheonPlus	+Union3	+DESY5
	$\Delta\text{DIC} (\Delta\chi^2)$		
Thaw. (Cal.)	+0.4 (−1.6)	−0.6 (−2.5)	−5.8 (−7.1)
Thaw. (Alg.)	−1.0 (−2.9)	−4.6 (−6.9)	−10.1 (−13.2)
Emergent	+2.1 (−0.05)	+1.8 (−0.1)	+0.2 (−1.5)
Mirage	−9.1 (−10.5)	−13.8 (−16.2)	−18.7 (−20.7)
$w_0 w_a$	−6.8 (−10.7)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

- Mirage Dark Energy is preferred to Thawing (Quintessence) models
- “Mirage” models mimic ΛCDM and $\langle w \rangle \sim -1$ whereas there is a real time evolving Dark Energy



Sum of neutrino masses - Bayesian



- CMB is sensitive to Σm_μ
- BAO measures Ω_m and breaks the degeneracies

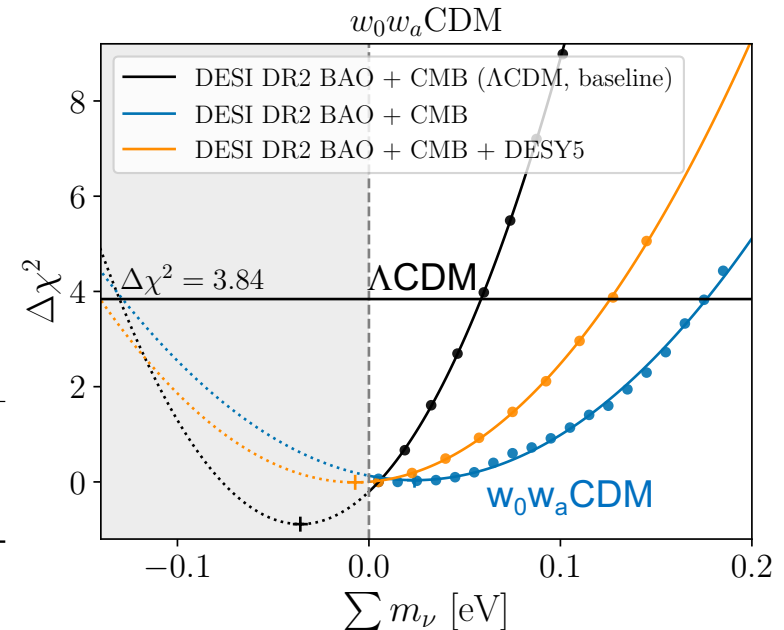
Limits at 95% CL:

- For Λ CDM with CMB alone: $\Sigma m_\nu < 210 \text{ meV}$
- For Λ CDM with CMB + DESI: $\Sigma m_\nu < 64 \text{ meV}$
- For $w_0 w_a$ CDM with CMB + DESI + SN: $\Sigma m_\nu < 130 \text{ meV}$



Sum of neutrino masses - Frequentist

Model/Dataset	μ_0 [eV]	σ [eV]	95% CL [eV]
Λ 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
w_0w_a CDM + $\sum m_\nu$			
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 $\sigma \sim 40$ meV with Λ CDM
- Because of the tension on Ω_m the limits artificially are too stringent

Limits at 95% CL with Feldman-Cousins:

- For Λ CDM with CMB + DESI: $\Sigma m_\nu < 53 \text{ meV}$
- For w_0w_a CDM with CMB + DESI + SN $\Sigma m_\nu < 126 \text{ meV}$



Conclusions



Summary: Results from DESI BAO DR2

– BAO results with DR2

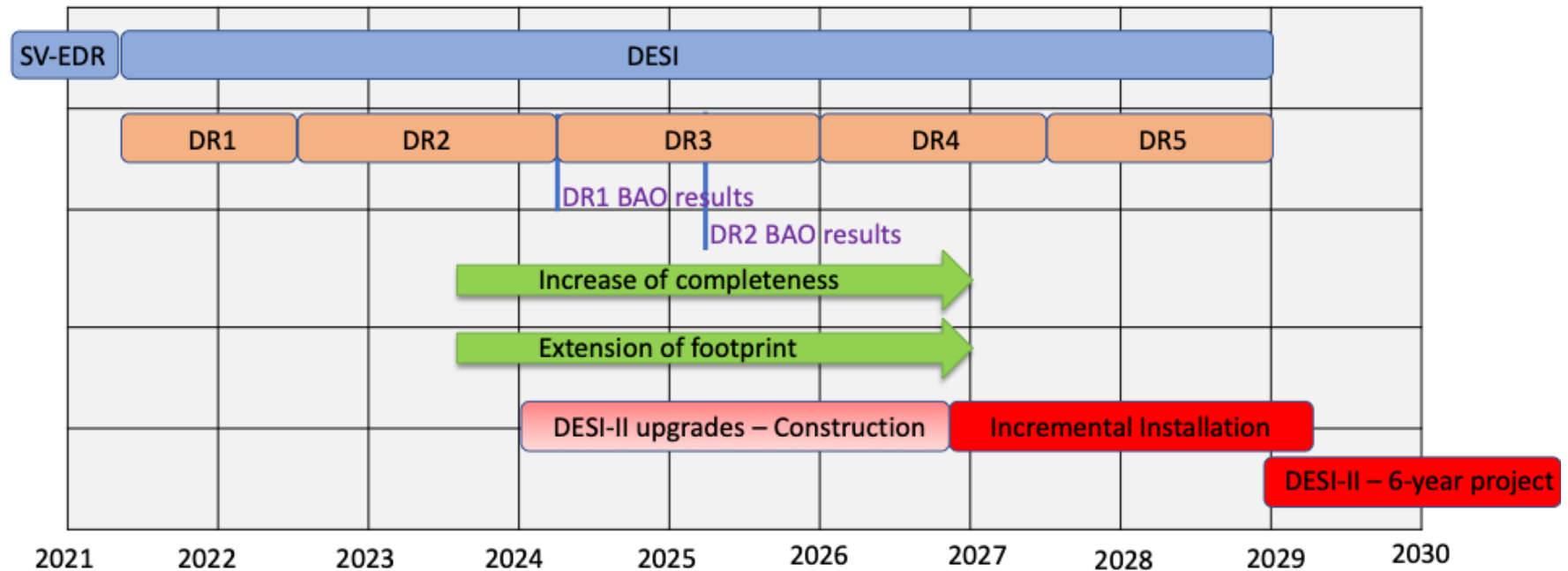
- With three years (DR2), DESI provides the most precise measurement of BAO over $0 < z < 3.5$
- DR2 results confirm DR1 results
- In Λ CDM, DESI is in slight tension with CMB ($\sim 2\sigma$) and DESI prefers lower Ω_m
- Stronger indications of time-varying Dark Energy equation of state with DR2, especially when SNIa are added
 $\Rightarrow$ **a 2.8σ to 4.2σ effect, not 5σ yet!**

– What next?

- BAO: Full dataset for DESI in 2026 (+ 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



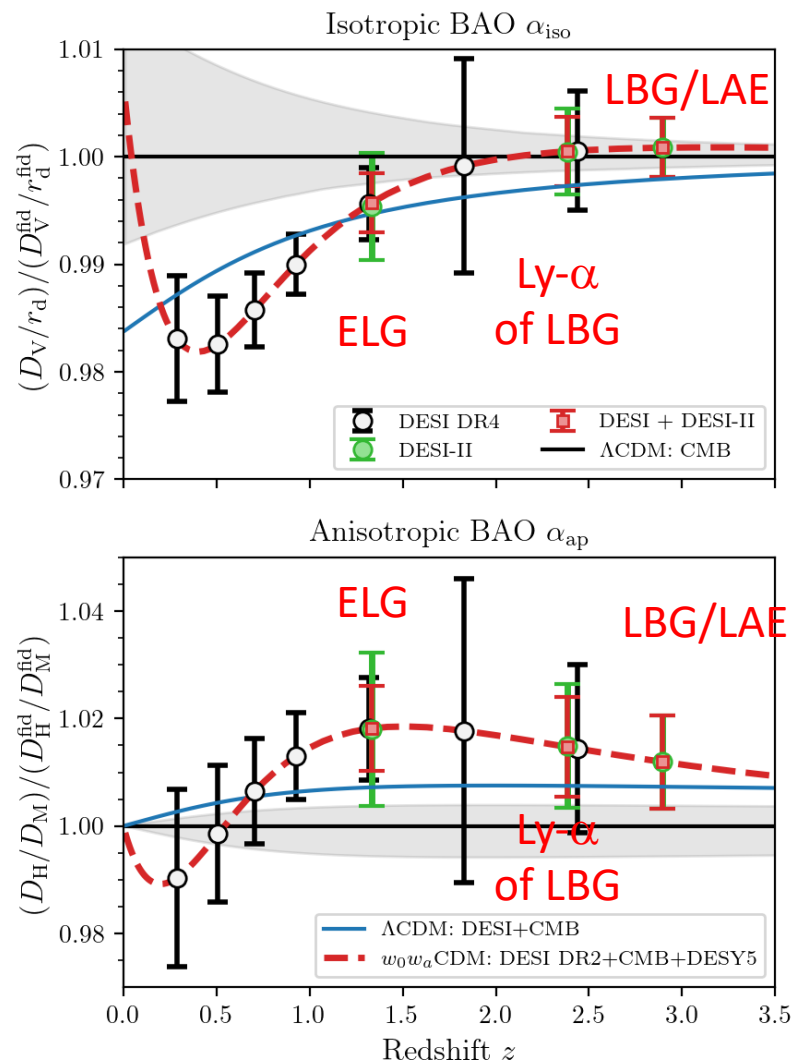
DESI and DESI-II Timelines



- **DESI** (DR1-DR3) should finish in Nov. 2025
- 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



DESI and DESI-II DE program



- **DESI (DR1-DR3)** is focused on the studies of DE
- **DESI (DR4) :**
 - Extension of footprint
 - Denser in DE region
- **DESI-II:**
 - higher-density at low- z
 - high- z programs

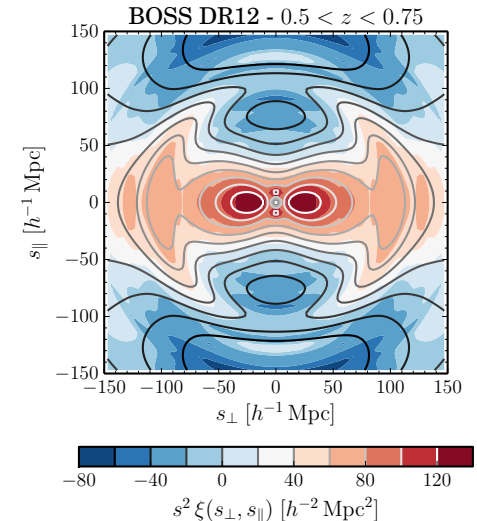
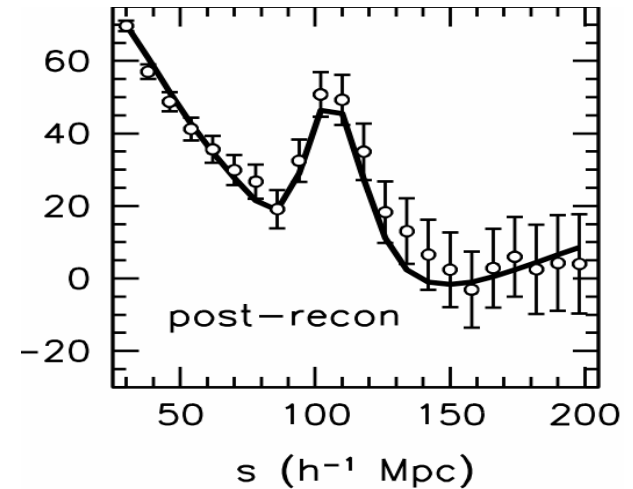


Additional Slides

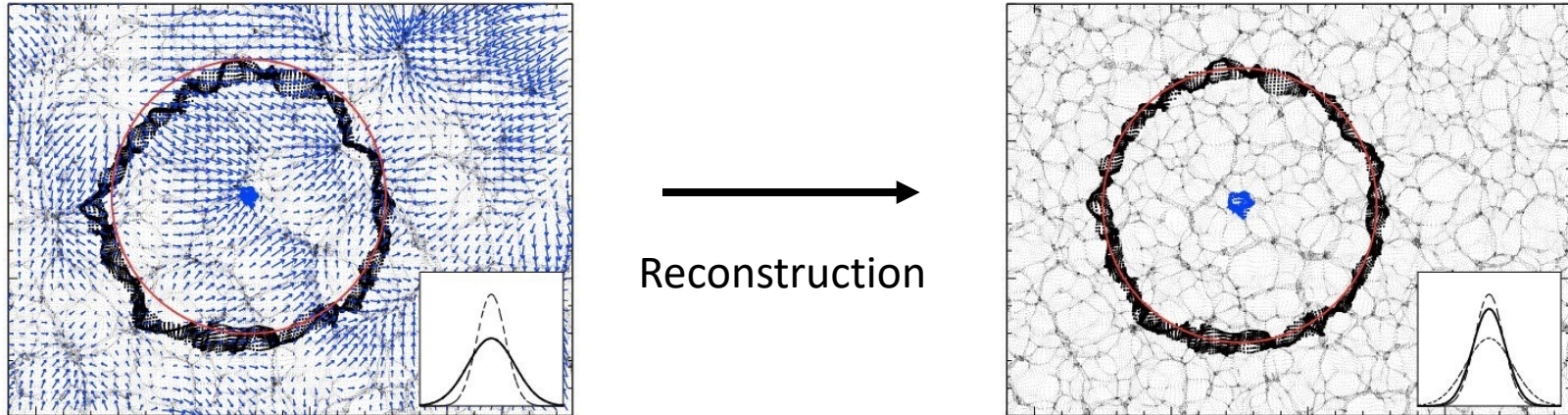


Main science at DESI

- **Baryonic Acoustic Oscillations (BAO)**
 - $\sigma(\text{BAO}) \sim 0.2\%$ for $0.0 < z < 1.1$
 - $\sigma(\text{BAO}) \sim 0.3\%$ for $1.1 < z < 1.9$
 - $\sigma(\text{BAO}) \sim 0.5\%$ for $1.9 < z < 3.5$
 - SDSS(BOSS+eBOSS) few % measurements
- **Redshift Space Distortion (RSD)**
 - Multiple few % measurements over wide redshift range ($z < 2$)
 - $\sim 10\times$ better compared to SDSS
- **Neutrino masses**
 - $\sigma(\Sigma m_\nu) \sim 20$ meV
 - Current limit : $\Sigma m_\nu < \sim 100$ meV, @ 95 CL
- **Non-Gaussianity (f_{NL})**
 - $\sigma(f_{\text{NL}}) \sim 4$ with k dependence of bias
 - As precise as Planck with a different technique



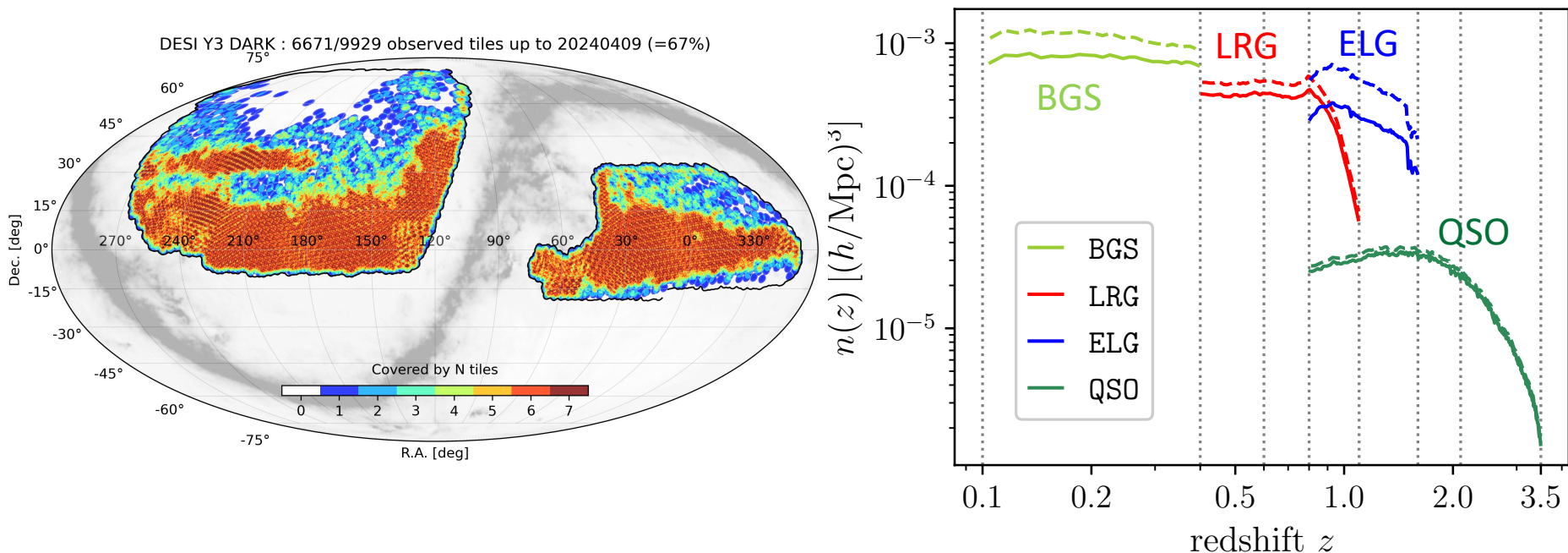
Density Field Reconstruction



- 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**



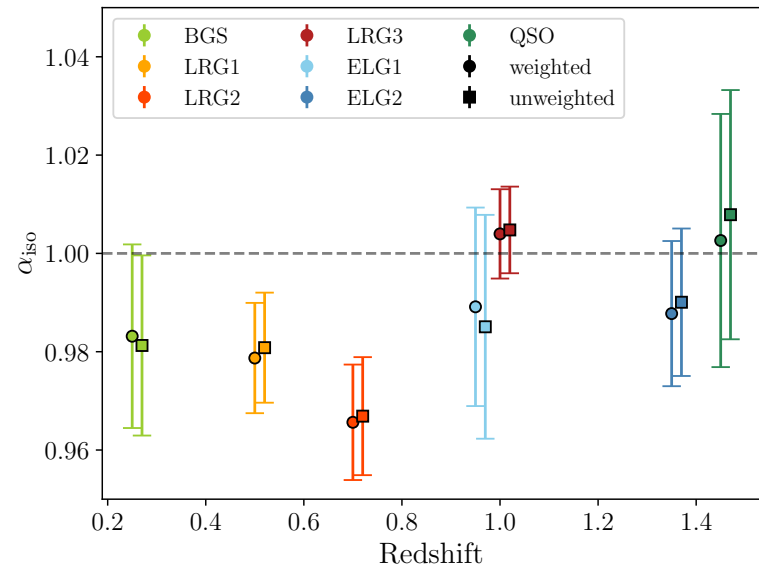
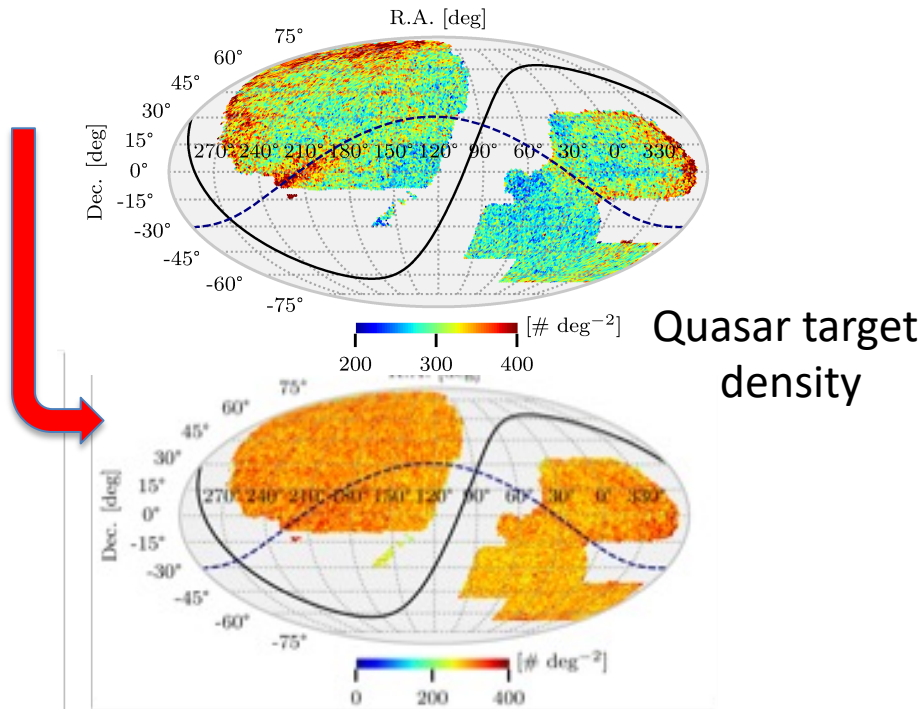
DESI DR2 dataset



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



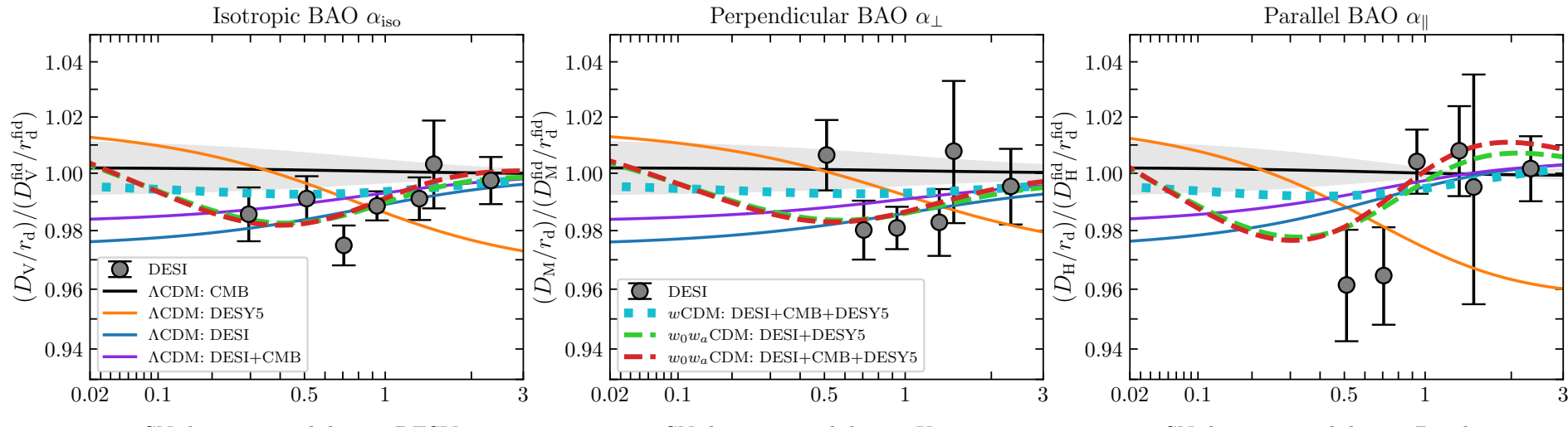
Example of systematics: Imaging



- 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**



Dark Energy – Hubble Diagram



- Combining DESI+CMB+SN: 2.8σ to 4.2σ effect depending on the SN sample
- Better agreement with w_0w_a CDM model



Dark Energy – Significance

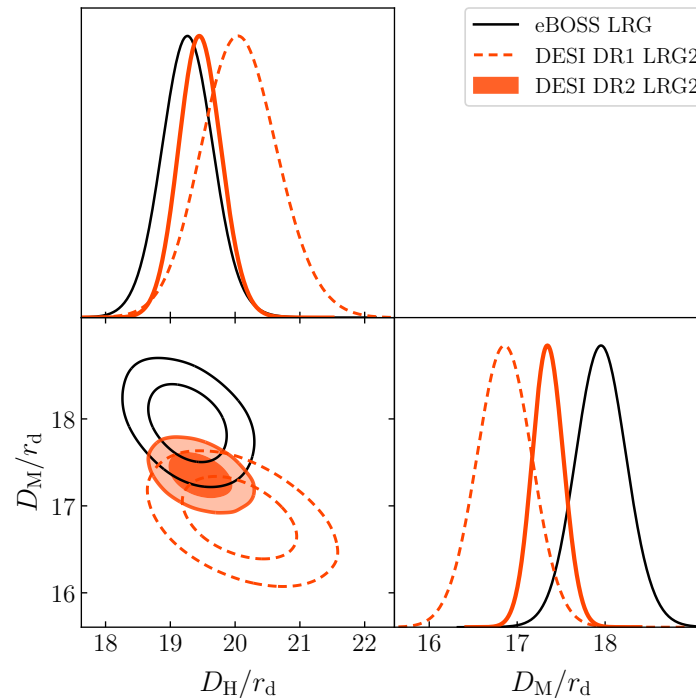
Datasets	$\Delta\chi^2_{\text{MAP}}$	Significance	$\Delta(\text{DIC})$
DESI	-4.7	1.7σ	-0.8
DESI+ $(\theta_*, \omega_b, \omega_{bc})_{\text{CMB}}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 ($3\times 2\text{pt}$)	-7.3	2.2σ	-2.8
DESI+DESY3 ($3\times 2\text{pt}$)+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



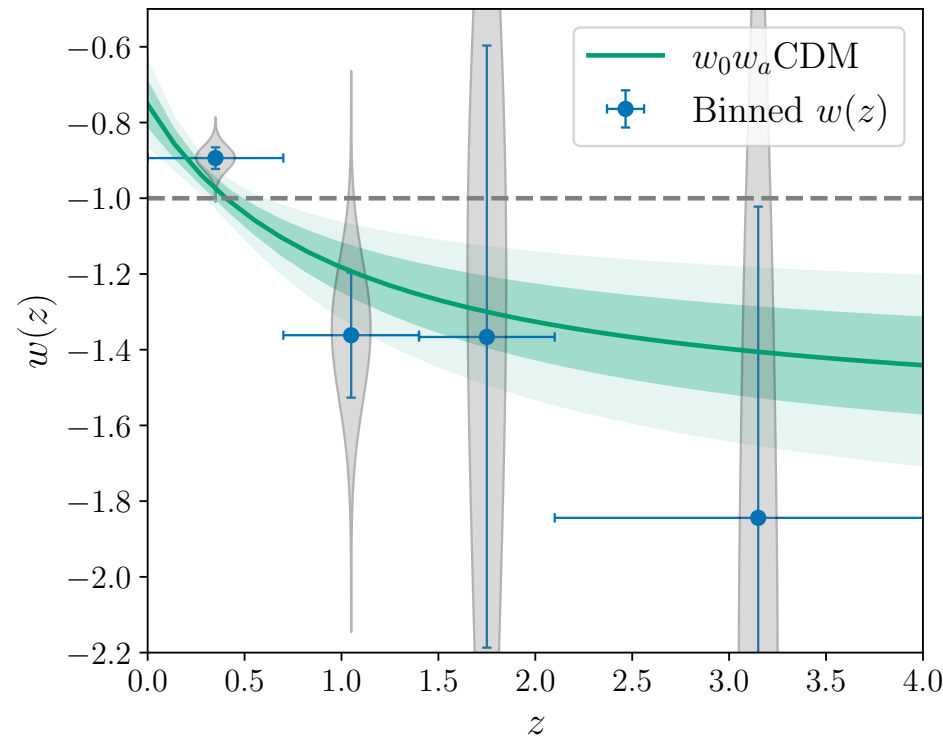
Comparison DESI/SDSS at $z \sim 0.7$



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



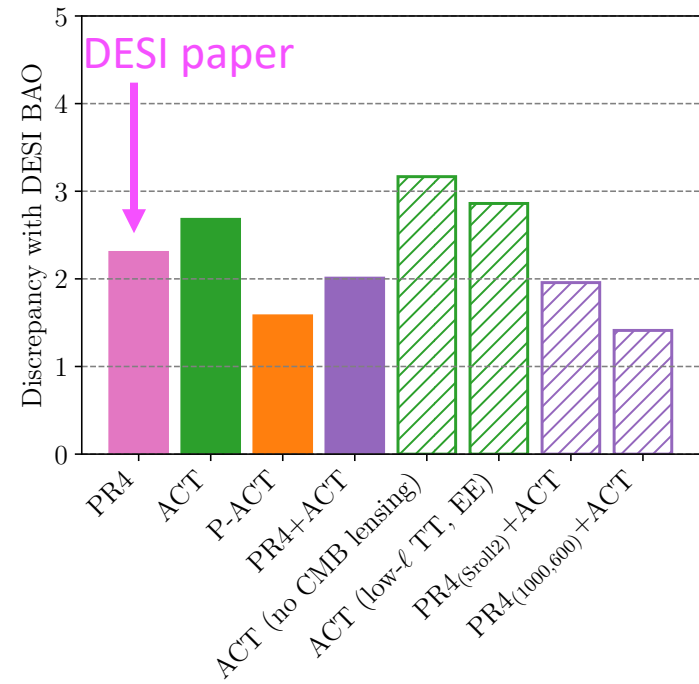
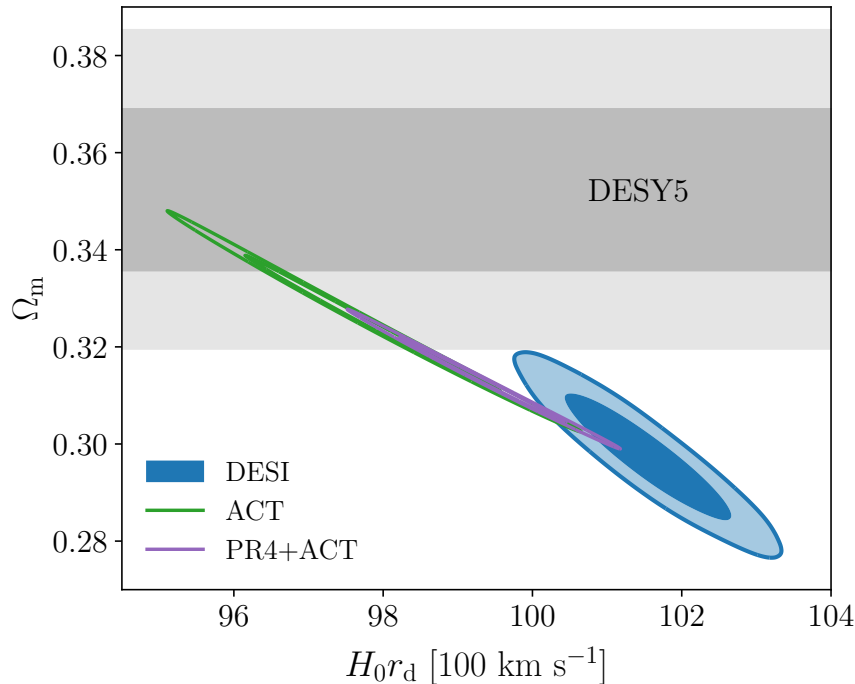
Phantom Crossing



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



Comparison DESI/ACT



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



Comparison DESI/ACT

3. CMB standalone likelihoods (including CMB lensing)	
low- ℓ TT	<i>Planck</i> 2018 PR3 low- ℓ Commander likelihood for TT in the range $2 \leq \ell < 30$ [37, 38].
low- ℓ EE SimA11	<i>Planck</i> 2018 PR3 low- ℓ SimA11 likelihood for EE in the range $2 \leq \ell < 30$ [37, 38].
low- ℓ EE SRo112	Alternative low- ℓ likelihood for EE based on the SRo112 code in the range $2 \leq \ell < 30$ [39].
high- ℓ PR3	<i>Planck</i> 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	<i>Planck</i> PR4 high- ℓ temperature and polarization likelihood using NPIPE maps. The high- ℓ TT, TE, EE spectra from <i>Planck</i> 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 <i>Planck</i> 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 <i>Planck</i> [21, 43].
4. Main CMB combinations	
ACT	low- ℓ EE SRo112 + ACT DR6 + CMB lensing
P-ACT	low- ℓ TT + low- ℓ EE SRo112 + high- ℓ PR3 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
PR4+ACT	low- ℓ TT + low- ℓ EE SimA11 + high- ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing
	→ ACT+DESI paper - Baseline
	ACT paper
5. Additional CMB combinations studied	
ACT (no CMB lensing)	low- ℓ EE SRo112 + ACT DR6 (same as ACT base in [31])
ACT (low- ℓ TT, EE)	low- ℓ TT + low- ℓ EE SimA11 + ACT DR6 + CMB lensing
PR4	low- ℓ TT + low- ℓ EE SimA11 + high- ℓ PR4 + CMB lensing (same as baseline CMB in [16])
PR4 _(1000,600) +ACT	low- ℓ TT + low- ℓ EE SimA11 + high- ℓ PR4 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
PR4 _(SRo112) +ACT	low- ℓ TT + low- ℓ EE SRo112 + high- ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing
	→ DESI paper

– Several comparisons were tested

