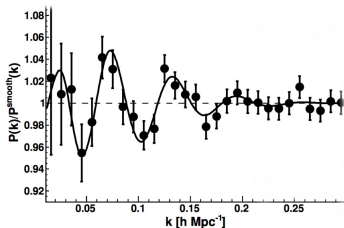
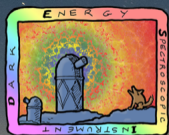


# Cosmology with the Dark Energy Spectroscopic Instrument (DESI)

Florian Beutler on behalf of the DESI collaboration



Royal Society University Research Fellow



# DARK ENERGY SPECTROSCOPIC INSTRUMENT

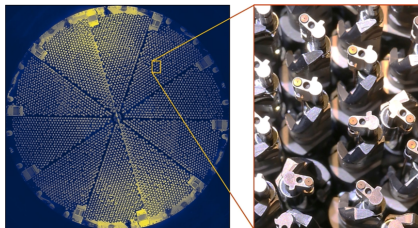
U.S. Department of Energy Office of Science



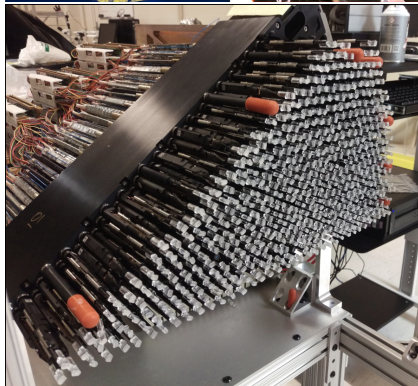
Thanks to our sponsors and  
72 Participating Institutions!

# The DESI galaxy survey

- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/redshifts per pointing
- 13.6 million flux-limited sample of galaxies at  $z < 0.4$  (BGS)
- 23.7 million color-selected galaxies at  $0.4 < z < 1.5$  (LRGs & ELGs)
- 2.8 million Quasars at  $z > 0.8$
- Ly- $\alpha$  forest at  $2 < z < 3.5$

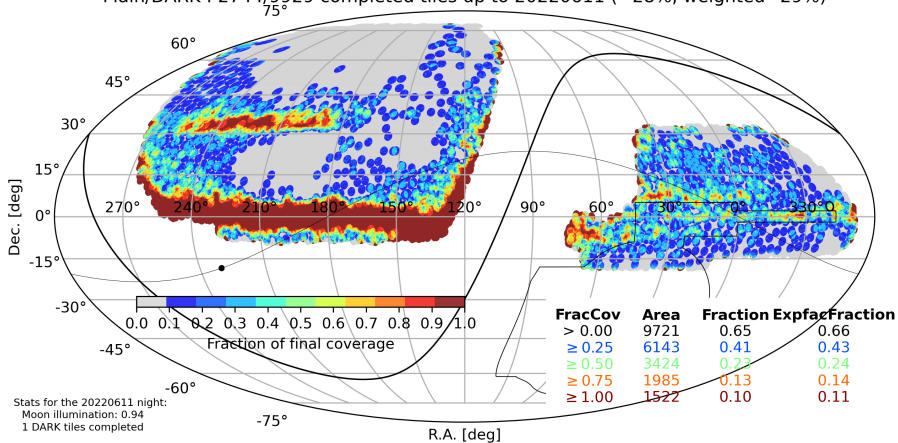


4m Mayall at Kitt Peak, Arizona. Twin to the Blanco, CTIO



# DESI 2025: Data Release 1

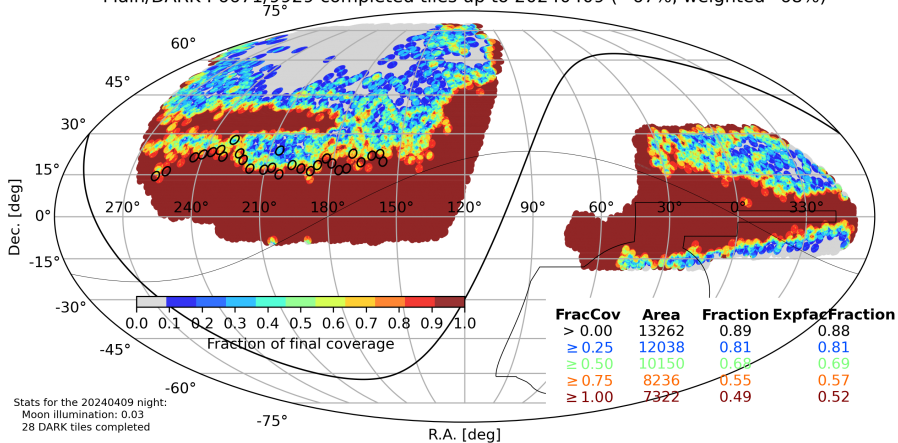
Main/DARK : 2744/9929 completed tiles up to 20220611 (=28%, weighted=29%)



- 5.7 million unique redshifts

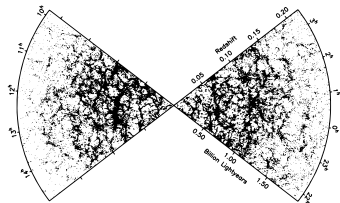
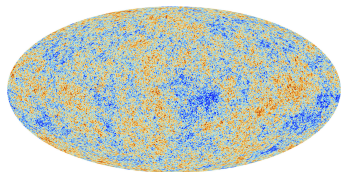
# DESI 2025: Data Release 2

Main/DARK : 6671/9929 completed tiles up to 20240409 (=67%, weighted=68%)



- 14 million unique redshifts

# What is a galaxy redshift survey?

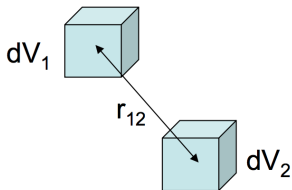


- 1 Measure the position of galaxies (RA, DEC + redshift).
- 2 The CMB tells us the initial conditions for today's distribution of matter.
- 3 How the initial density fluctuations in the CMB evolved from redshift 1100 to today depends on  $\Omega_m$ ,  $\Omega_\Lambda$ ,  $H_0$  etc.

# From a point distribution to a power spectrum

- Overdensity-field:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$



- Two-point function:

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x} + \mathbf{r})\delta(\mathbf{x}) \rangle \begin{cases} \text{isotropy} \\ = \\ \xi(r) \\ \text{anisotropy} \\ = \\ \xi_\ell(r) = \int_{-1}^1 d\mu \xi(r, \mu) \mathcal{L}_\ell(\mu) \end{cases}$$

- ...and in Fourier-space:

$$P_\ell(k) = 4\pi(-i)^\ell \int r^2 dr \xi_\ell(r) j_\ell(kr)$$

# From a point distribution to a bispectrum

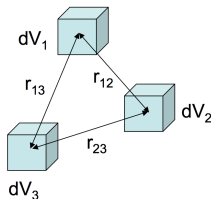
- Overdensity-field:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

- Three-point function:

$$\xi(\mathbf{r}_1, \mathbf{r}_2) = \langle \delta(\mathbf{x} + \mathbf{r}_1) \delta(\mathbf{x} + \mathbf{r}_2) \delta(\mathbf{x}) \rangle \begin{cases} \text{isotropy} = & \xi_L(r_1, r_2) \\ \text{anisotropy} = & \xi_{\ell_1 \ell_2 L}(r_1, r_2) \end{cases}$$

homogeneity

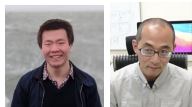


- ...and in Fourier-space:

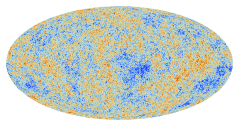
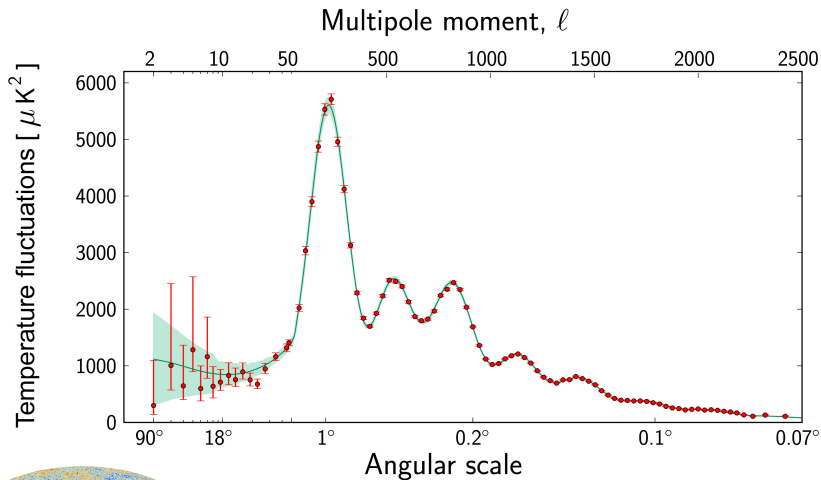
$$B_{\ell_1 \ell_2 L}(k_1, k_2) = (4\pi)^2 (-i)^{\ell_1 + \ell_2} \int r_1^2 dr_1 \int r_2^2 dr_2 \xi_{\ell_1 \ell_2 L}(r_1, r_2) j_{\ell_1}(k_1 r_1) j_{\ell_2}(k_2 r_2)$$

→ **Triumvirate**, Wang et al. (2024)

<https://triumvirate.readthedocs.io/en/latest/>

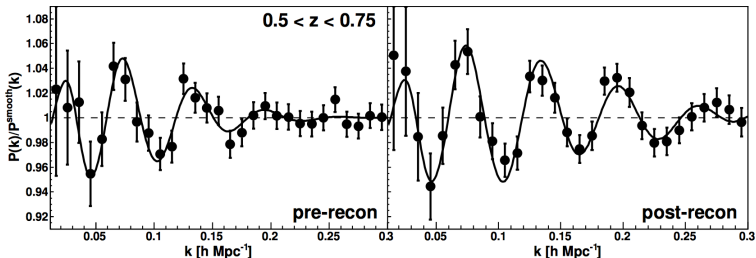


# What are Baryon Acoustic Oscillations?



Planck collaboration

# What Baryon Acoustic Oscillations constrain



- BAO are the most robust observable we can extract from LSS
- The observables are

$$\frac{D_M(z)}{r_d} = \int_0^z \frac{cdz'}{r_d H(z')}$$

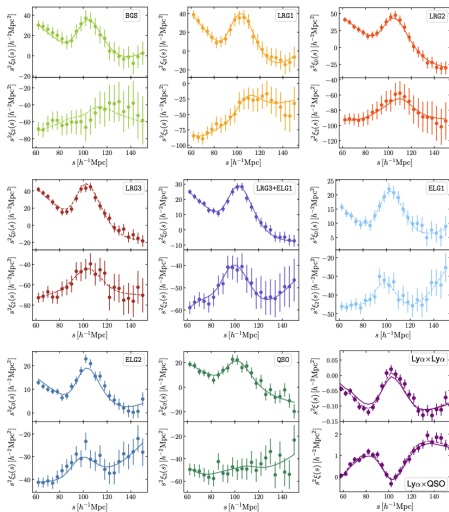
$$\frac{D_H(z)}{r_d} = \frac{c}{H(z)r_d} = c \left[ H_0 r_d \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)} \right]^{-1}$$

- We require a calibration of the ruler to constrain  $H_0$

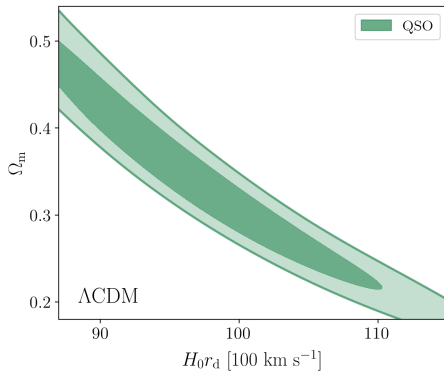
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz = 147.05 \text{ Mpc} \times \left( \frac{\omega_b}{0.02236} \right)^{-0.13} \left( \frac{\omega_{bc}}{0.1432} \right)^{-0.23} \left( \frac{N_{\text{eff}}}{3.04} \right)^{-0.1}$$

# DESI 2025: Measurements (5.6 - 14.7 $\sigma$ )

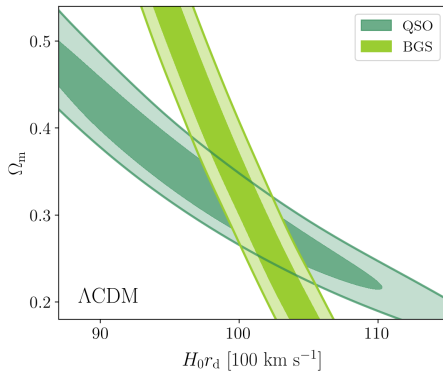
$$D_V(z) = [zD_M^2(z)D_H(z)]^{1/3}$$



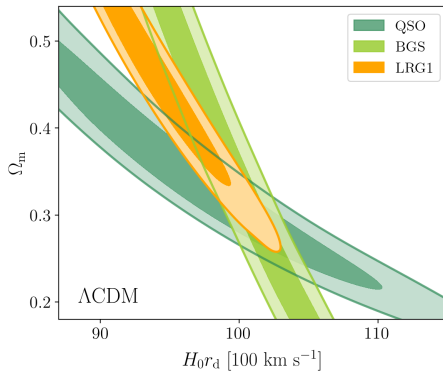
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



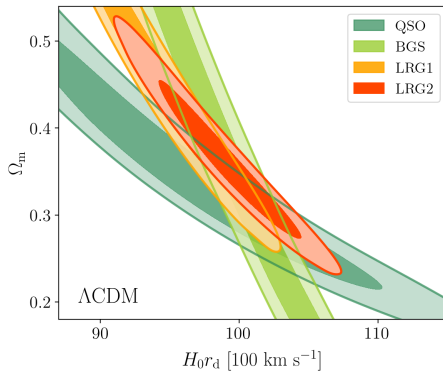
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



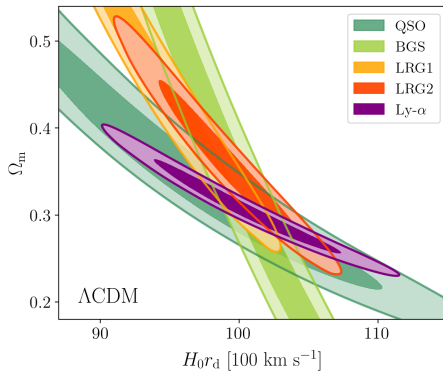
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



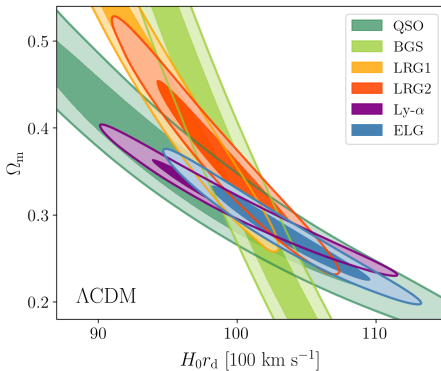
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



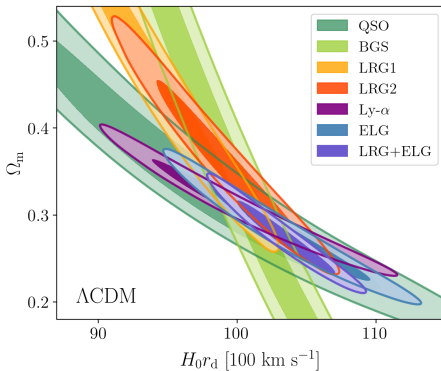
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



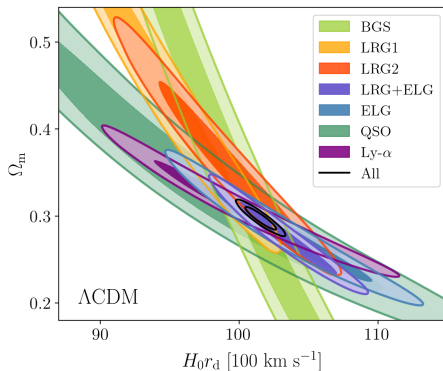
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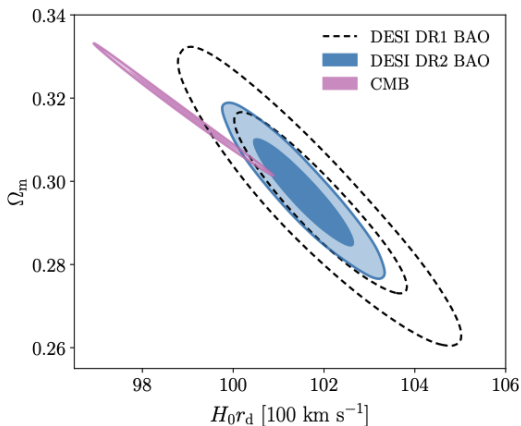
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



$$\Omega_m = 0.2975 \pm 0.0086 \quad (2.9\%)$$

$$H_0 r_d = 101.54 \pm 0.73 \times 10^2 \text{ km s}^{-1} \quad (0.72\%)$$

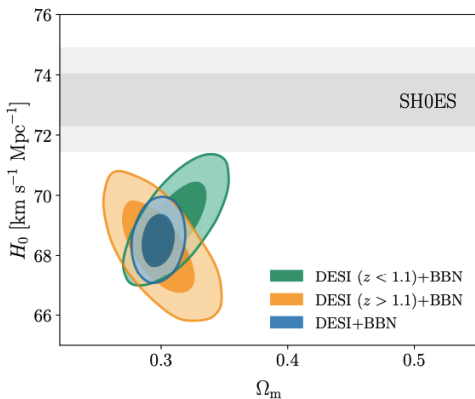
$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1 - \Omega_m)}$$



→  $2.3\sigma$  tension between DESI and the CMB ( $2\sigma$  with the recent ACT release).

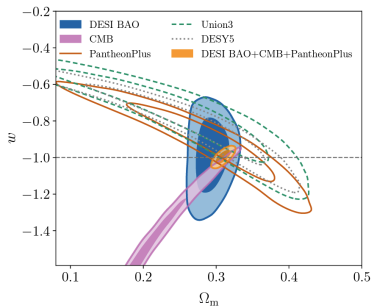
\*CMB = Planck [simall, Commander (for  $\ell < 30$ ) and CamSpec (for  $\ell \geq 30$ )] TTTEEE + (Planck PR4 + ACT DR6) CMB lensing

# DESI 2025: Hubble tension



- DESI + BBN gives a 0.8% constraint on  $H_0$   
( $68.51 \pm 0.58 \text{ km s}^{-1} \text{ Mpc}^{-1}$ )
- Planck has a 0.74% constraint ( $67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ )
- $4.5\sigma$  tension with SH0ES (no CMB involved!)

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega)}}$$



$$\left. \begin{aligned} \Omega_m &= 0.2969 \pm 0.0089 \\ \omega &= -0.916 \pm 0.078 \end{aligned} \right\}$$

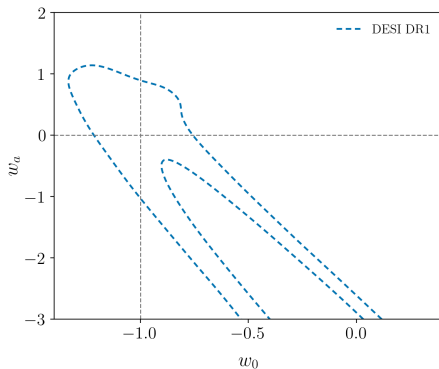
DESI

$$\left. \begin{aligned} \Omega_m &= 0.3098 \pm 0.0050 \\ \omega &= -0.971 \pm 0.021 \end{aligned} \right\}$$

DESI + CMB + DESY5

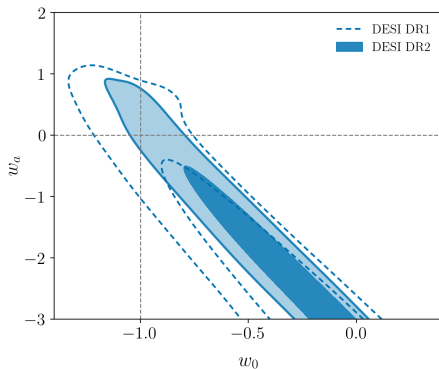
# DESI 2025: $\omega_0\omega_a$ CDM with $\omega(z) = \omega_0 + \omega_a\frac{z}{1+z}$

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)} e^{-3\omega_a\frac{z}{1+z}}}$$



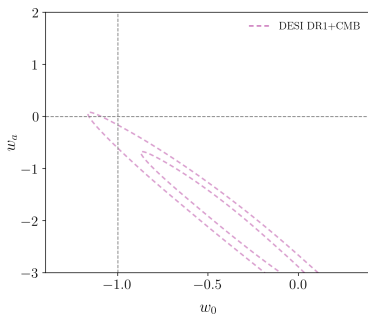
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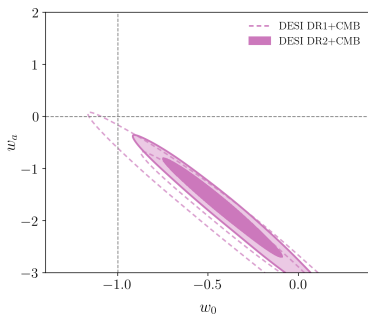
$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)} e^{-3\omega_a\frac{z}{1+z}}}$$



- DESI + CMB has a  $3.1\sigma$  preference for evolving DE



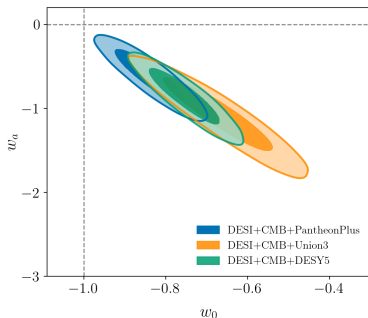
$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)} e^{-3\omega_a\frac{z}{1+z}}}$$



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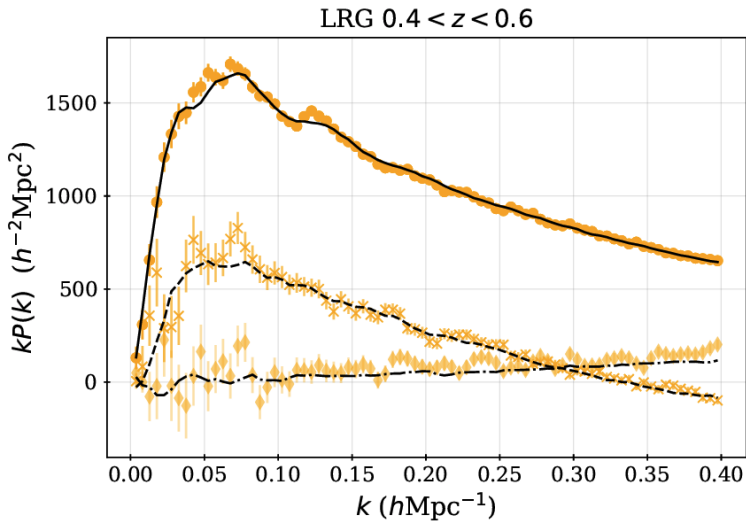


$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)} e^{-3\omega_a \frac{z}{1+z}}}$$

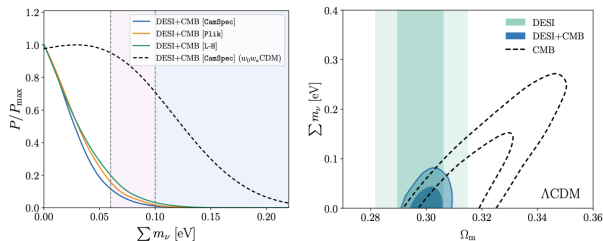


- DESI + CMB has a  $3.1\sigma$  preference for evolving DE
- Increases to between  $2.8$  and  $4.2\sigma$  when including SN datasets
- The  $4.2\sigma$  (DESY5) has recently been revised to  $3.2\sigma$  (Popovic et al. 2026)
- With the CPL parametrization  $H_0$  is getting smaller (not bigger)

# DESI 2025: Full-shape constraints from DR1



# DESI 2025: Constraining the neutrino mass



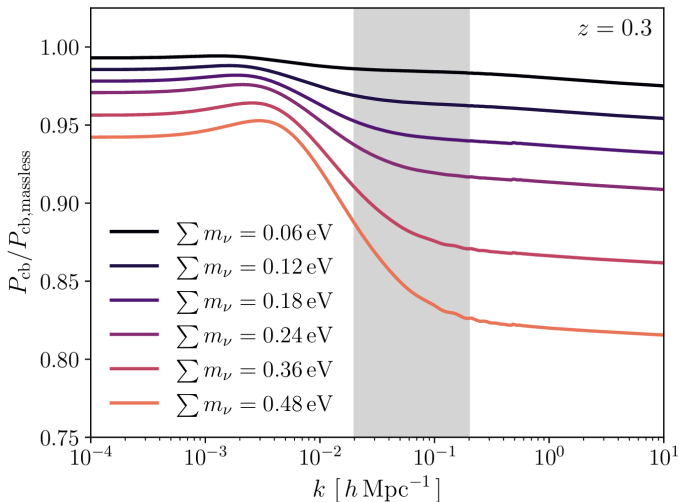
$$|\Delta m_{31}^2| \approx 2.56 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 \approx 7.37 \times 10^{-5} \text{ eV}^2$$

$$0.059 \text{ eV} \lesssim \text{CMB} \left( \Lambda\text{CDM} + \sum m_\nu \right) + \text{DESI} < 0.064 \text{ eV} \text{ (95\%)}$$

- Neutrino mass hierarchy  $\begin{cases} m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3} \rightarrow \min(\sum m_\nu) \approx 0.059 \text{ eV} \\ m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2} \rightarrow \min(\sum m_\nu) \approx 0.1 \text{ eV} \end{cases}$
- KATRIN:  $m_{\bar{\nu}_e} < 0.8 \text{ eV}$  (90%)
- Prior dependence:  $\sum m_\nu > 0.059 \text{ eV} \rightarrow \sum m_\nu < 0.112 \text{ eV}$  (95%)
- $\omega_0 \omega_a \text{CDM}$  (DESI+CMB+DESY5):  $\sum m_\nu < 0.129 \text{ eV}$  (95%)

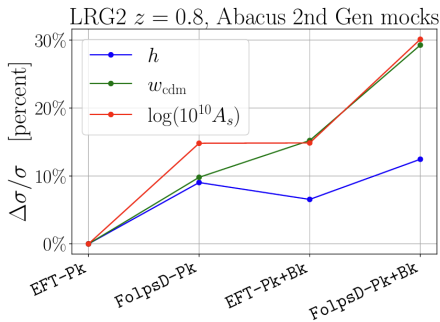
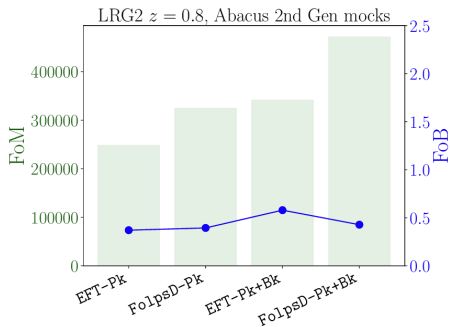
# Constraints from free streaming



DESI DR1 (FS+BAO) + BBN +  $n_s$  :  $\sum m_\nu < 0.3 \text{ eV}$  (95%)

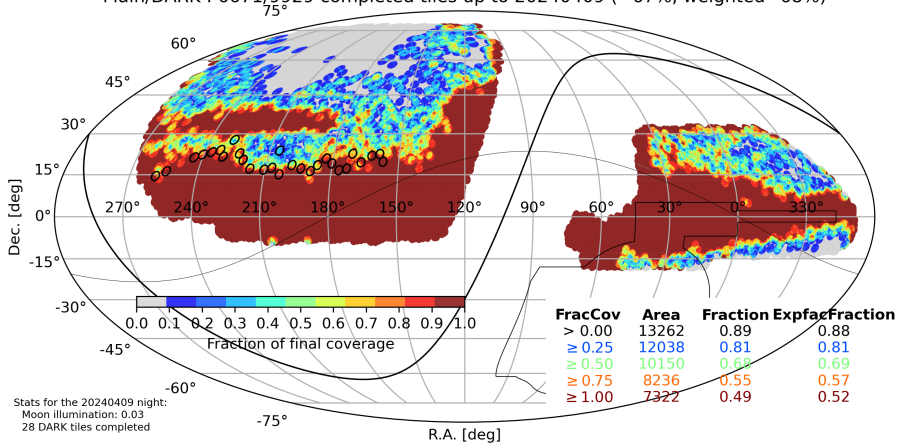
# Outlook

- We are currently running a mock challenge for the DR2 full-shape analysis
- Within DESI we produced much better mock datasets for DR2 to tests our models and derive covariance matrices
- Unblinding is this month and papers are to be published in Sep.

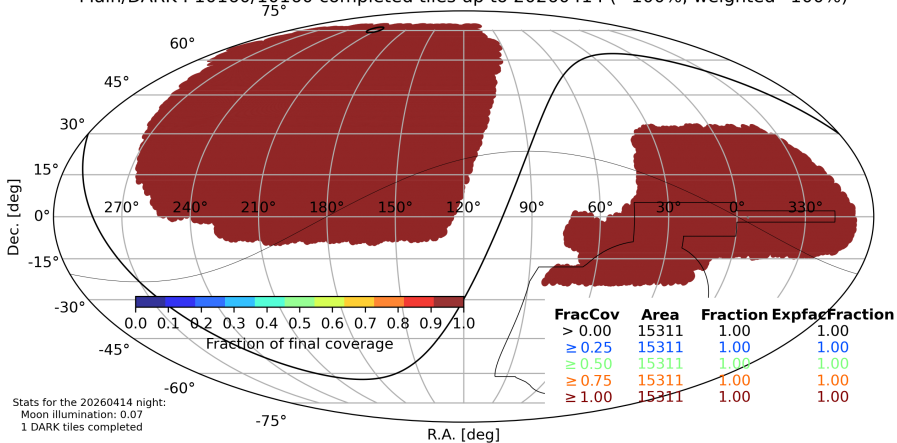


Bansal et al. (2026), see also Eggemeier et al. (2025)

Main/DARK : 6671/9929 completed tiles up to 20240409 (=67%, weighted=68%)



Main/DARK : 10160/10160 completed tiles up to 20260414 (=100%, weighted=100%)



# Summary

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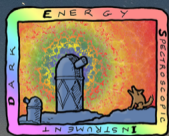
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- 5 More to come! Y5 observing are all done now! A 2.5-year extension has already started (extending the footprint and increasing completeness), which will keep DESI busy till 2028. DESI-II proposal for a further 5 years



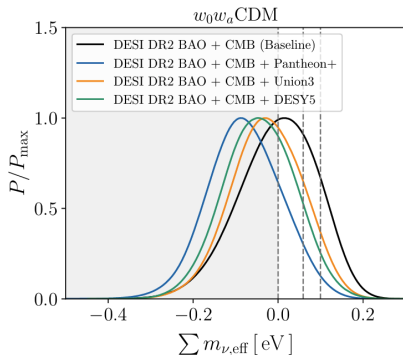
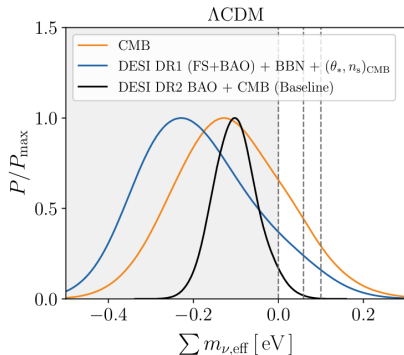
# DARK ENERGY SPECTROSCOPIC INSTRUMENT

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# Relaxing the priors



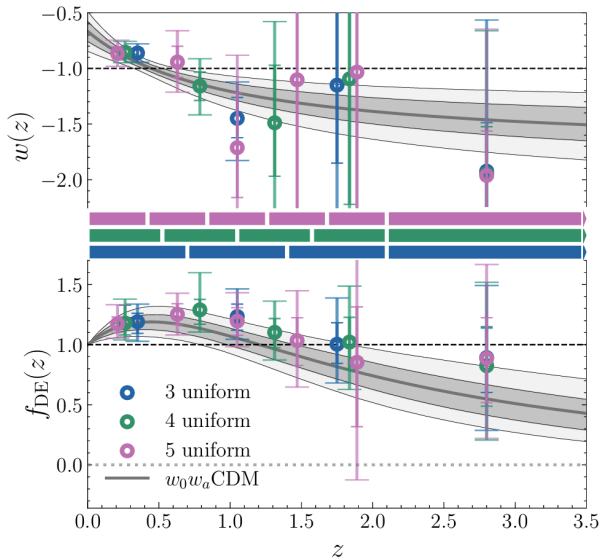
$$\text{DESI DR2 BAO + CMB} : \sum m_{\nu, \text{eff}} = -0.101^{+0.047}_{-0.056} \text{ eV (68\%)}$$

$$\text{CMB alone} : \sum m_{\nu, \text{eff}} = -0.11^{+0.12}_{-0.14} \text{ eV (68\%)}$$

# Systematic error budget

Tracer	Parameter	Theory (%)	HOD (%)	Fiducial (%)	Total (%)
BGS	$\alpha_{\text{iso}}$	0.1	No detection	0.1	0.141
LRG1	$\alpha_{\text{iso}}$	0.1	No detection	0.1	0.141
	$\alpha_{\text{AP}}$	0.2	0.19	0.18	0.329
LRG2	$\alpha_{\text{iso}}$	0.1	No detection	0.1	0.141
	$\alpha_{\text{AP}}$	0.2	0.19	0.18	0.329
LRG3	$\alpha_{\text{iso}}$	0.1	0.17	0.1	0.221
	$\alpha_{\text{AP}}$	0.2	0.19	0.18	0.329
LRG3+ELG1	$\alpha_{\text{iso}}$	0.1	0.17	0.1	0.221
	$\alpha_{\text{AP}}$	0.2	0.19	0.18	0.329
ELG1	$\alpha_{\text{iso}}$	0.1	0.17	0.1	0.221
	$\alpha_{\text{AP}}$	0.2	No detection	0.1	0.224
ELG2	$\alpha_{\text{iso}}$	0.1	0.17	0.1	0.221
	$\alpha_{\text{AP}}$	0.2	No detection	0.1	0.224
QSO	$\alpha_{\text{iso}}$	0.1	0.17	0.1	0.221
	$\alpha_{\text{AP}}$	0.2	0.19	0.18	0.329

# Alternative dynamical DE parametrisations

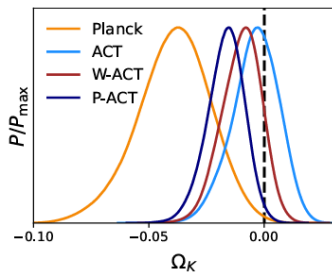
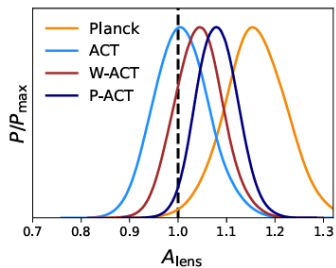


# Pros vs. Cons (relative to the DESI+CMB case)

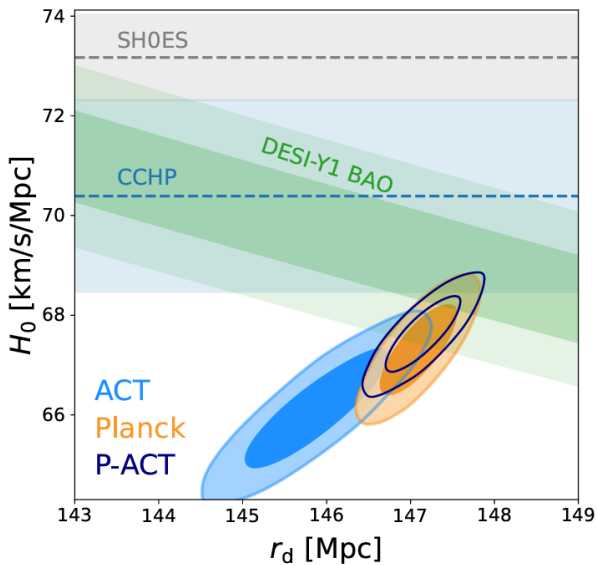
$\omega_0\omega_a$ does resolve the tension in the $\Omega_m - H_0 r_d$ plane between the DESI and the CMB		✓
Adding the most widely used SN dataset to date (Pantheon) reduces the significance from DESI+CMB	$-0.3\sigma$	✗
Adding the latest SN dataset (DESY5) increases the significance from DESI+CMB	$+1.1\sigma$	✓
Adding new CMB data from ACT TT and TE does reduce the significance from DESI+CMB	$-0.1\sigma$	✗
$\omega_0\omega_a$ does alleviate the growing tension between cosmological data and the lower limit of the sum of the neutrino mass eigenstates		✓
After adding SN, the neutrino mass eigenstates peak again below the terrestrial lower bound (with a much lower significance compared to the $> 3\sigma$ significance in $\Lambda$ CDM)		✗
The preference for phantom crossing does not allow a straightforward extension over $\Lambda$ (weak theoretical support)		✗
$\omega_0\omega_a$ does not solve the Hubble tension ( $H_0^{\text{DESI+CMB}} = 63.6^{+1.6}_{-2.1}$ km/s/Mpc)		✗
There is evidence even when excluding the CMB (DESI+DESY3(3x2pt)+DESY5)		✓
The SN datasets strongly depend on the low redshift SN which (basically) all SN datasets have in common		✗
The DESI+CMB evidence persists even with the CMB reduced to the distance priors ( $\theta^*, \omega_b, \omega_{bc}$ ) $\rightarrow$ CMB anomalies aren't driving this		✓
The evidence has grown from DESI DR1 to DESI DR2 (has it grown enough given the statistical improvement?)	$+0.4\sigma$	✓
Including the DESI full-shape information (in the case of DESI DR1) reduced the preference (using DESI+CMB+DESY5)	$-0.1\sigma$	✗

Table:

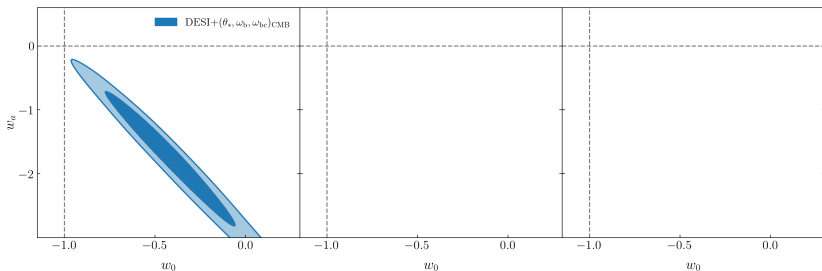
# Planck vs ACT 2025



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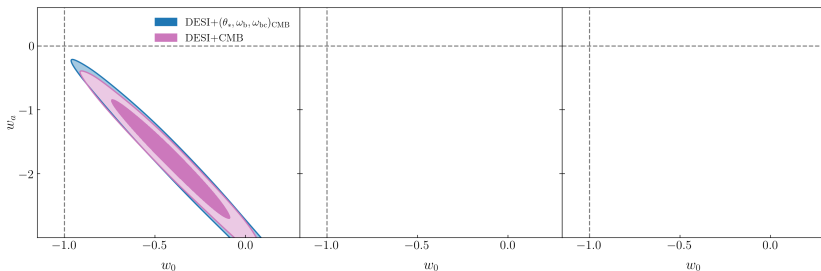
# More details



- Combining DESI with early-Universe CMB priors on  $(\theta^*, \omega_b, \omega_{bc})$  shows preference for evolving dark energy at the  $2.4\sigma$  level ( $3.1\sigma$  for the full CMB).



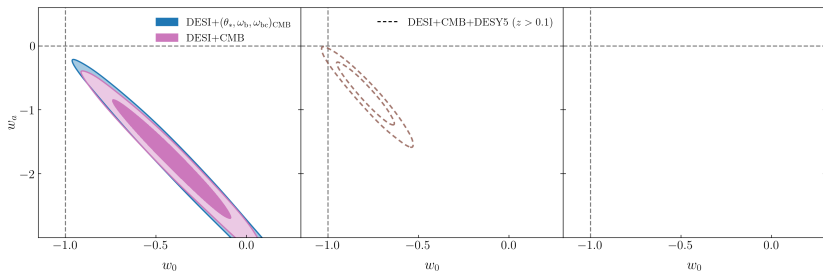
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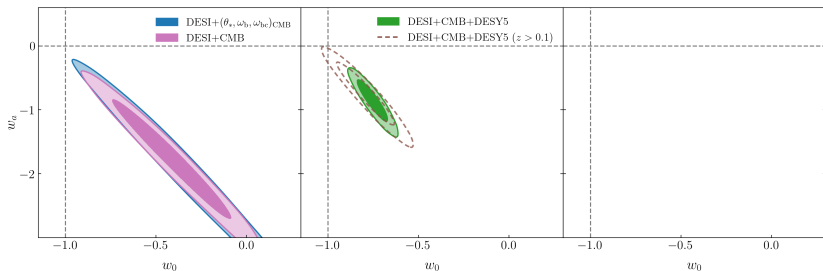


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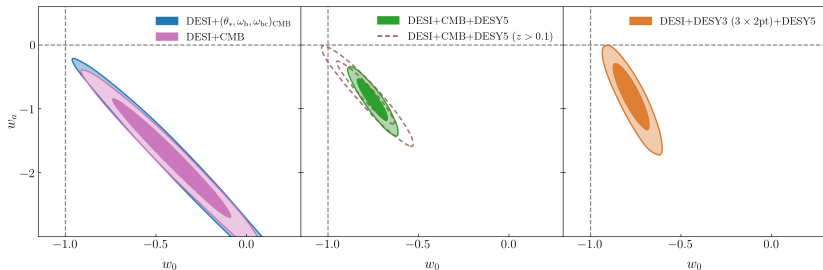
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- Excluding  $z < 0.1$  SNe reduces the statistical significance, but the best-fit values for  $\omega_0\omega_a$  remain far from  $\Lambda$ CDM  $\rightarrow 2.4\sigma$ .
-

# More details



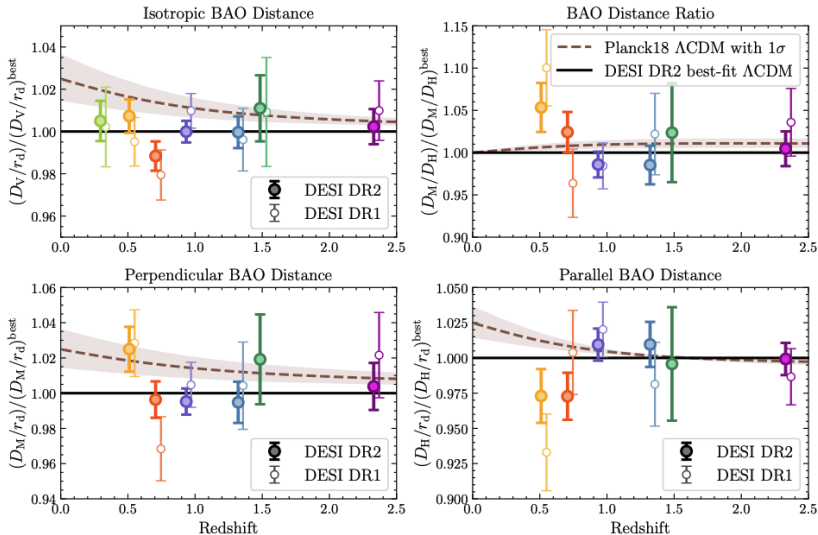
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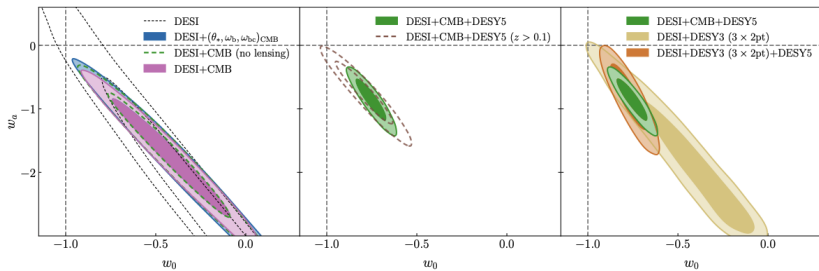


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- Excluding  $z < 0.1$  SNe reduces the statistical significance, but the best-fit values for  $\omega_0\omega_a$  remain far from  $\Lambda$ CDM  $\rightarrow 2.4\sigma$ .
- Replacing the CMB with DESY3  $3 \times 2$ pt (weak lensing), we obtain a constraint coming entirely from low-redshift cosmological probes (BAO, weak lensing, SNe)  $\rightarrow 3.3\sigma$ .

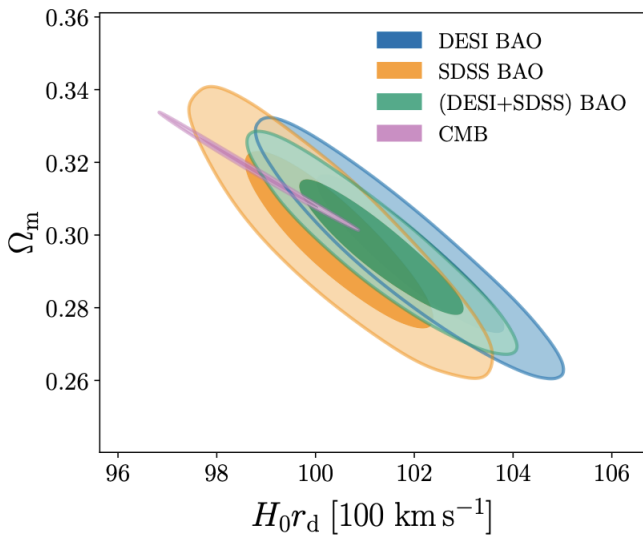
# Comparison of DR1 and DR2



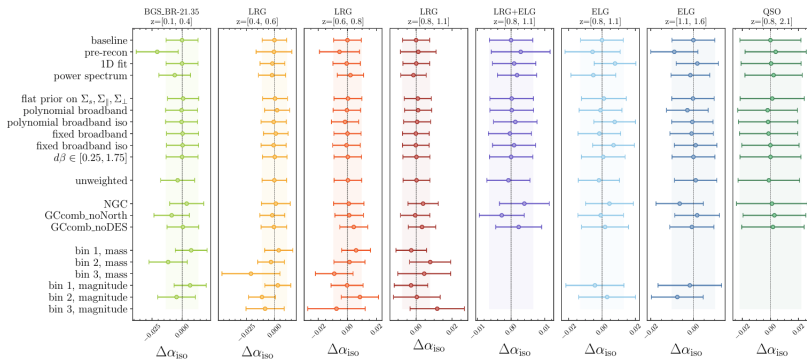
# Dataset combinations details



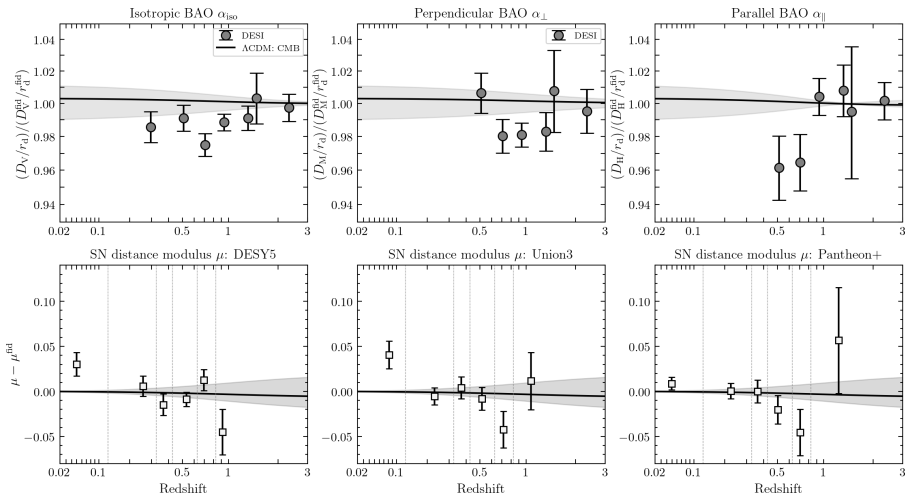
# Comparison: SDSS vs. DESI DR1



# DESI DR2 systematics tests

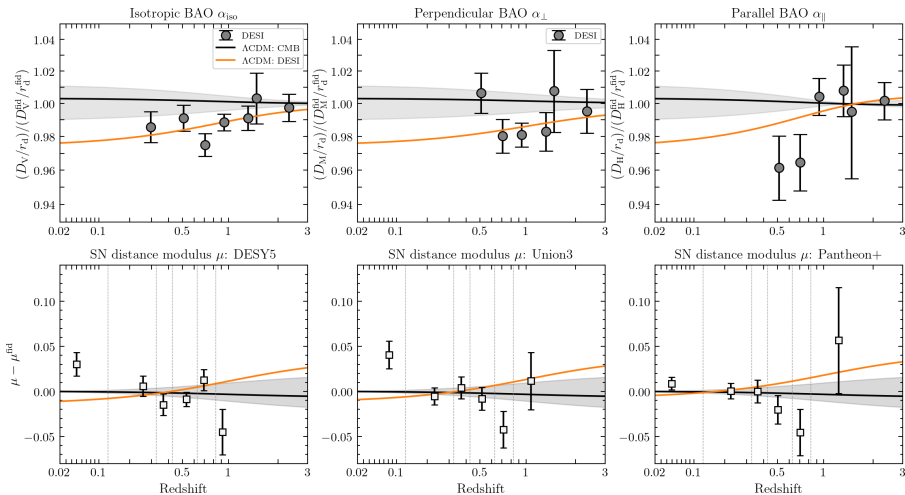


# Where is the tension?



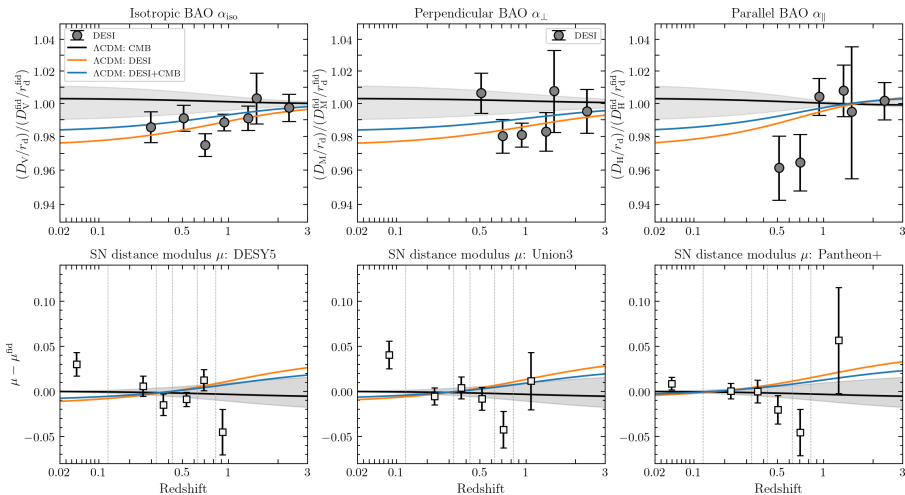
$$\Omega_m^{\text{CMB}} = 0.3169 \pm 0.0065$$

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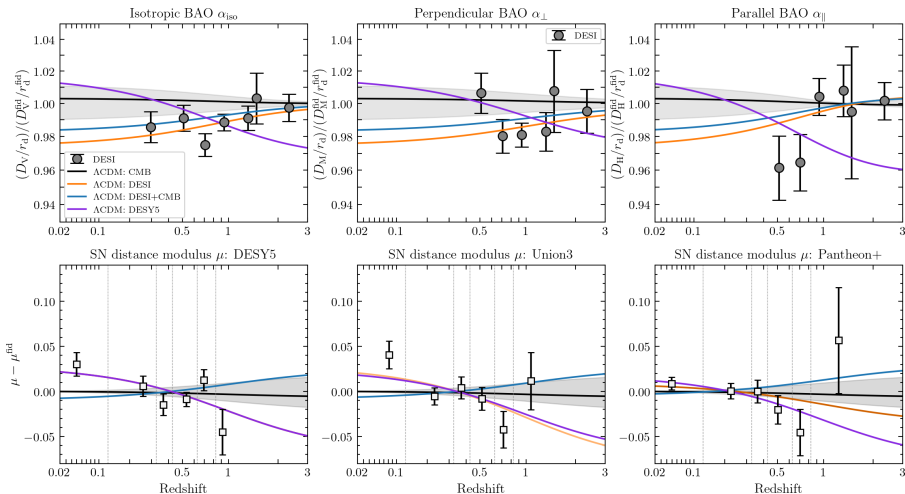
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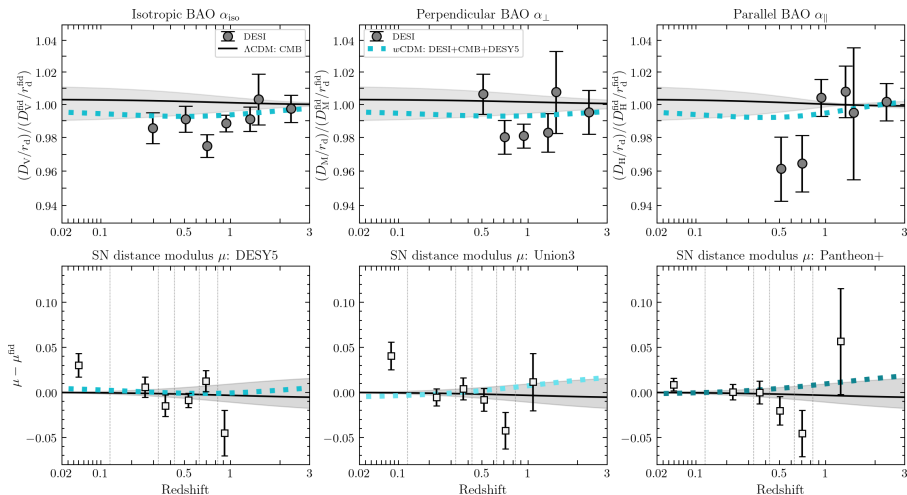
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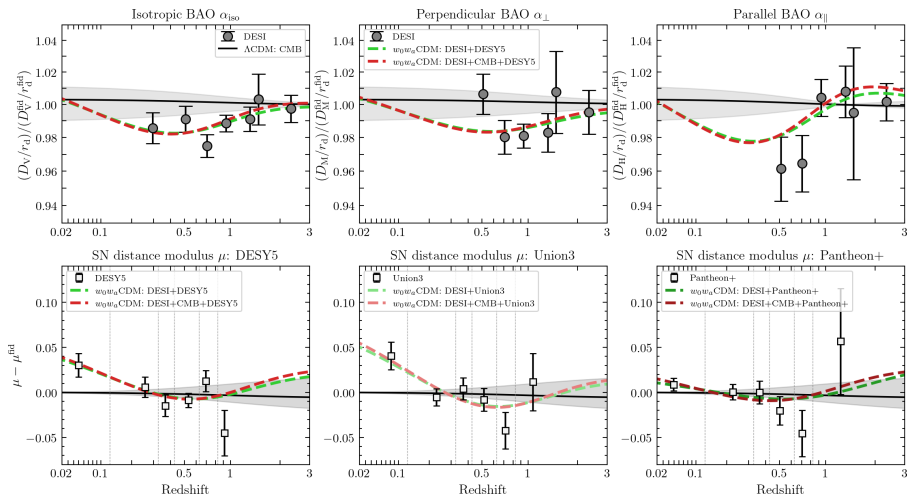
$$\Omega_m^{\text{CMB}} = 0.3169 \pm 0.0065 \quad \Omega_m^{\text{DESI}} = 0.2975 \pm 0.0086 \quad \Omega_m^{\text{DESY5}} = 0.351 \pm 0.017$$

# Where is the tension?



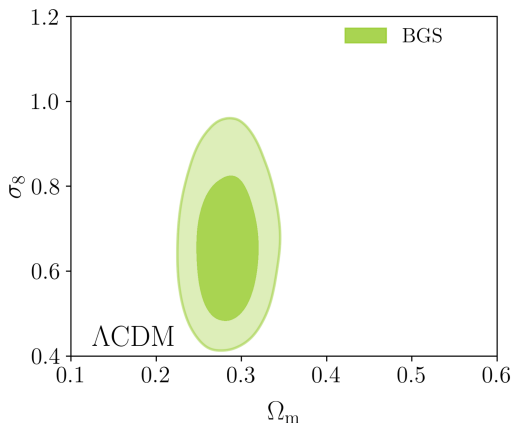
→  $\omega$ CDM does not have enough freedom to fit BAO, CMB and SN simultaneously.

# Where is the tension?



→  $\omega_0\omega_a$ CDM has enough flexibility to fit simultaneously all three datasets.

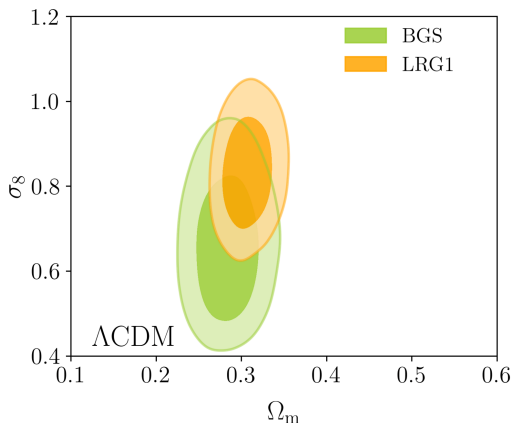
# DESI 2025: Full-shape constraints from DR1



$$\sigma_8^2(z) = \frac{1}{2\pi^2} \int_0^\infty k^2 P_{\text{lin}}(k, z) W^2(k 8 h^{-1} \text{ Mpc}) dk$$

$$W(x) = \frac{3(\sin x - x \cos x)}{x^3}$$

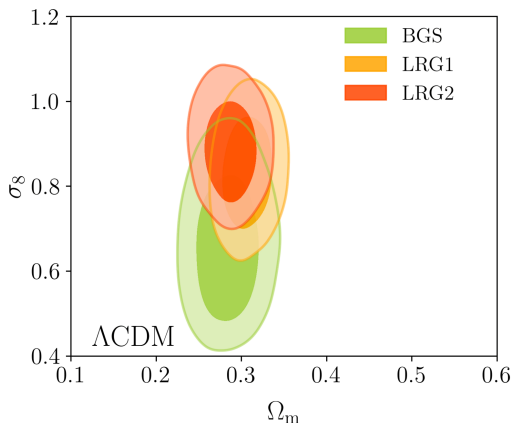
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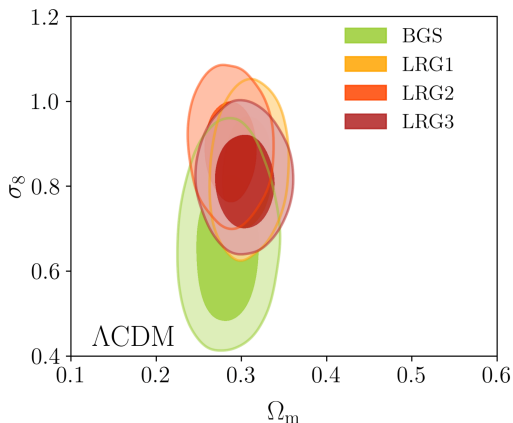
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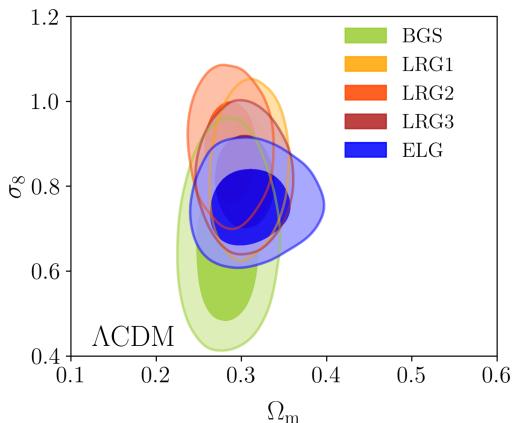
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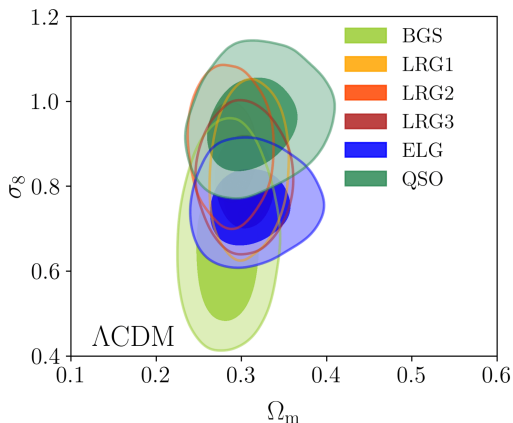
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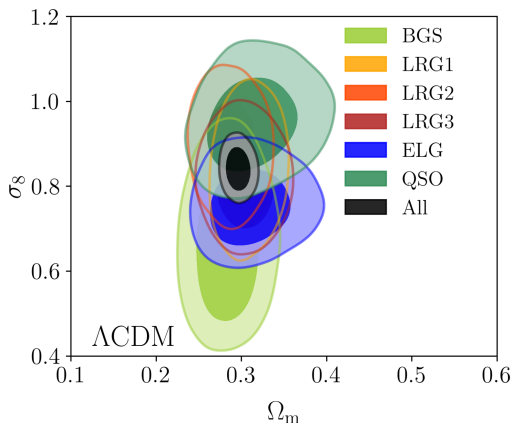
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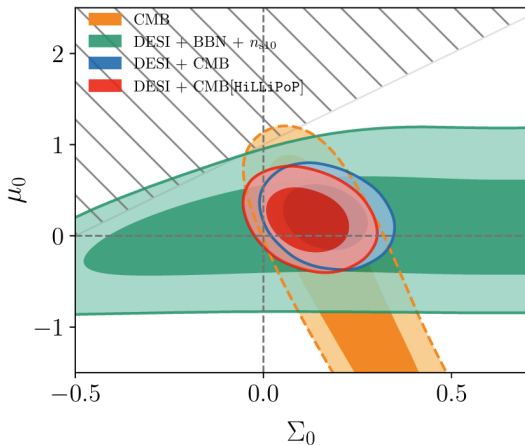
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# DESI 2025: Constraints on MG



$$k^2\Psi = -4\pi Ga^2\mu(a,k)\Sigma_i\rho_i\Delta_i, \quad \mu(a) = 1 + \mu_0 \frac{\Omega_{DE}(a)}{\Omega_\Lambda} \quad (CDM)$$

$$k^2(\Phi + \Psi) = -8\pi Ga^2\Sigma(a,k)\Sigma_i\rho_i\Delta_i, \quad \Sigma(a) = 1 + \Sigma_0 \frac{\Omega_{DE}(a)}{\Omega_\Lambda} \quad (light)$$