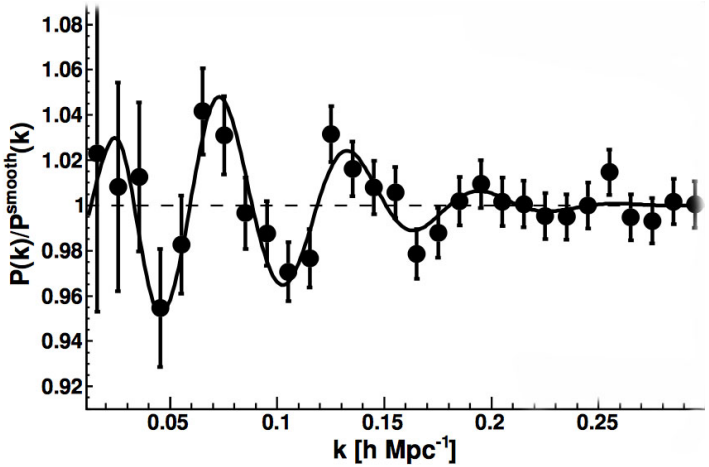
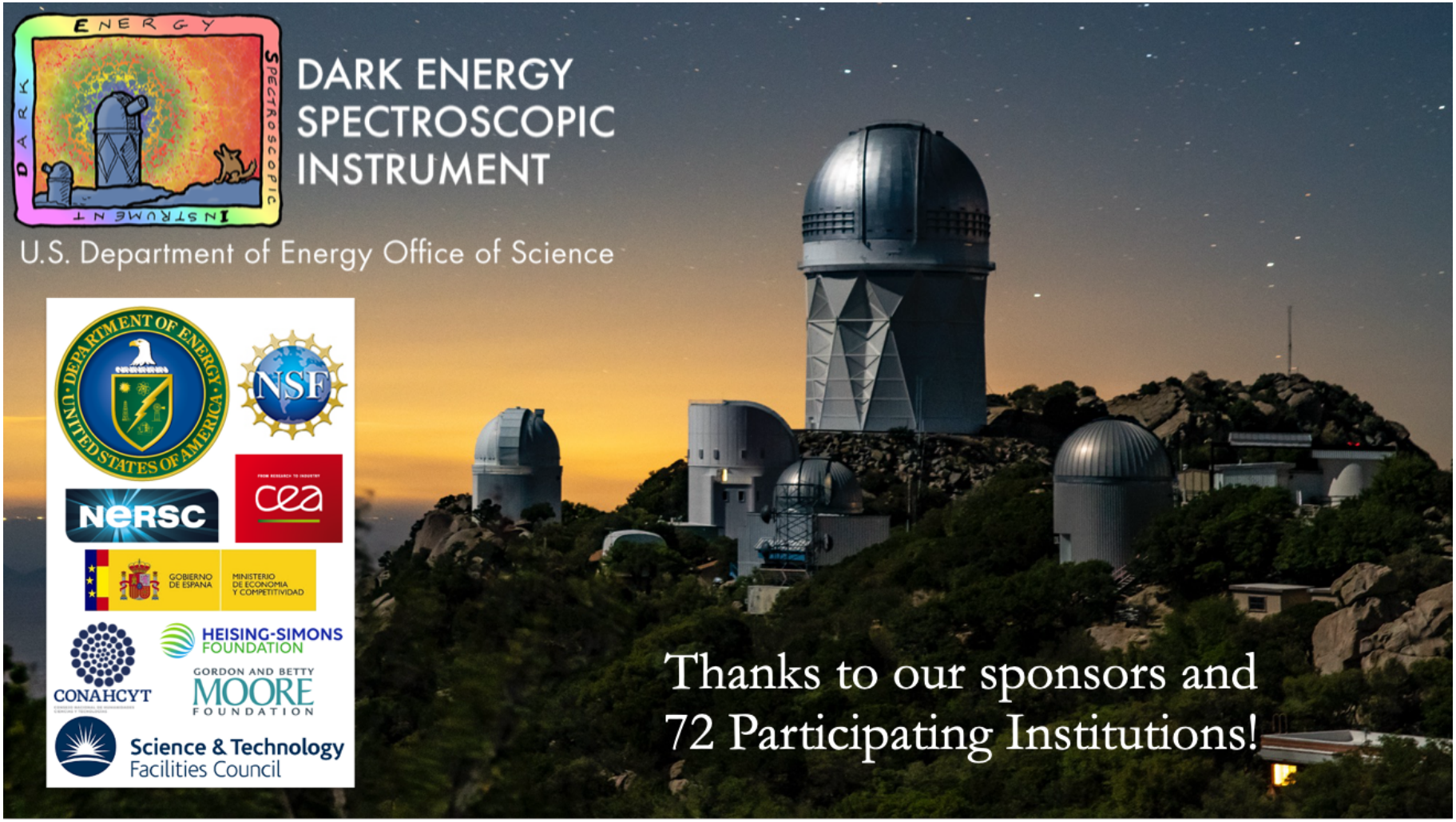
Cosmology with the Dark Energy Spectroscopic Instrument (DESI)

Florian Beutler on behalve of the DESI collaboration



Royal Society University Research Fellow


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
NERSC
cea
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
HEISING-SIMONS FOUNDATION
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GORDON AND BETTY MOORE FOUNDATION
Science & Technology Facilities Council
Thanks to our sponsors and
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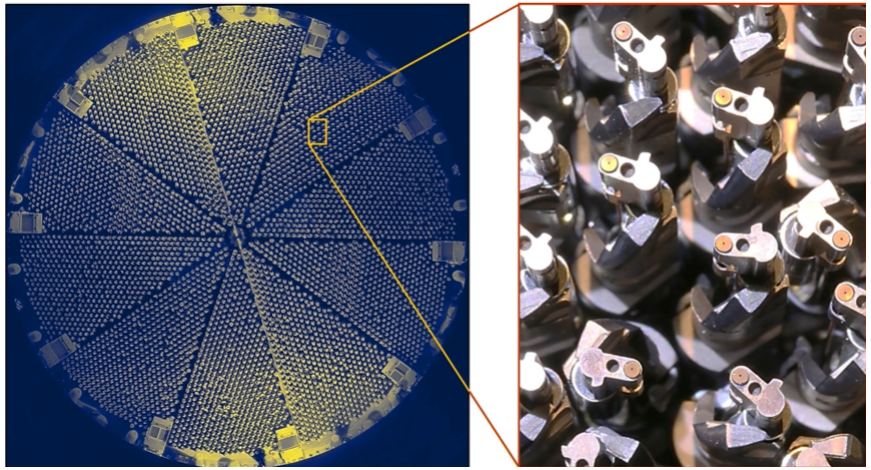
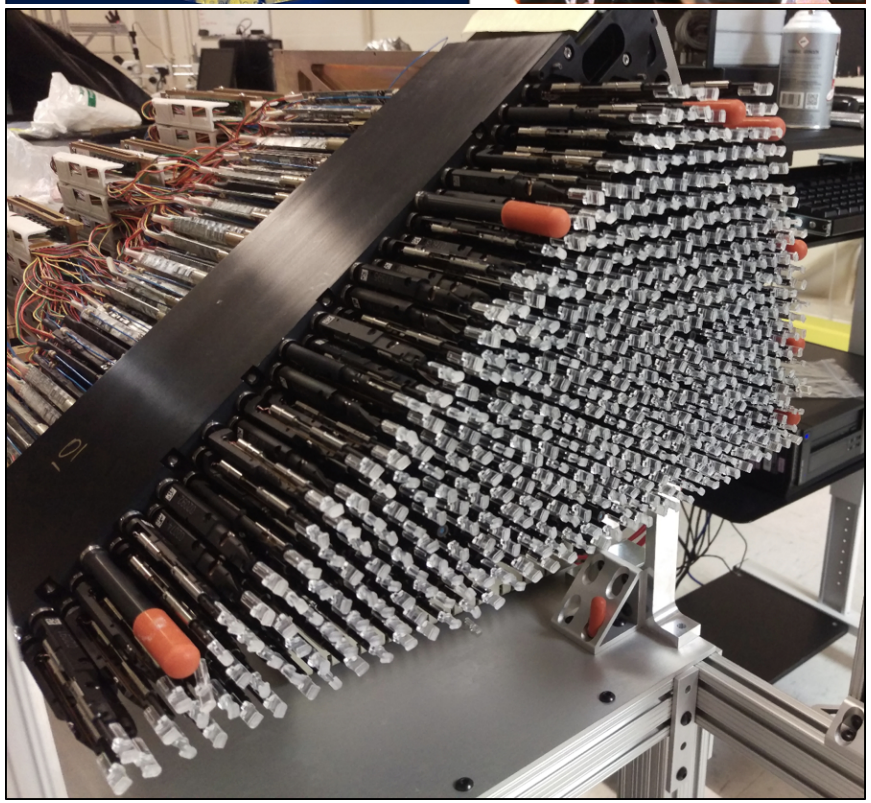
The DESI galaxy survey

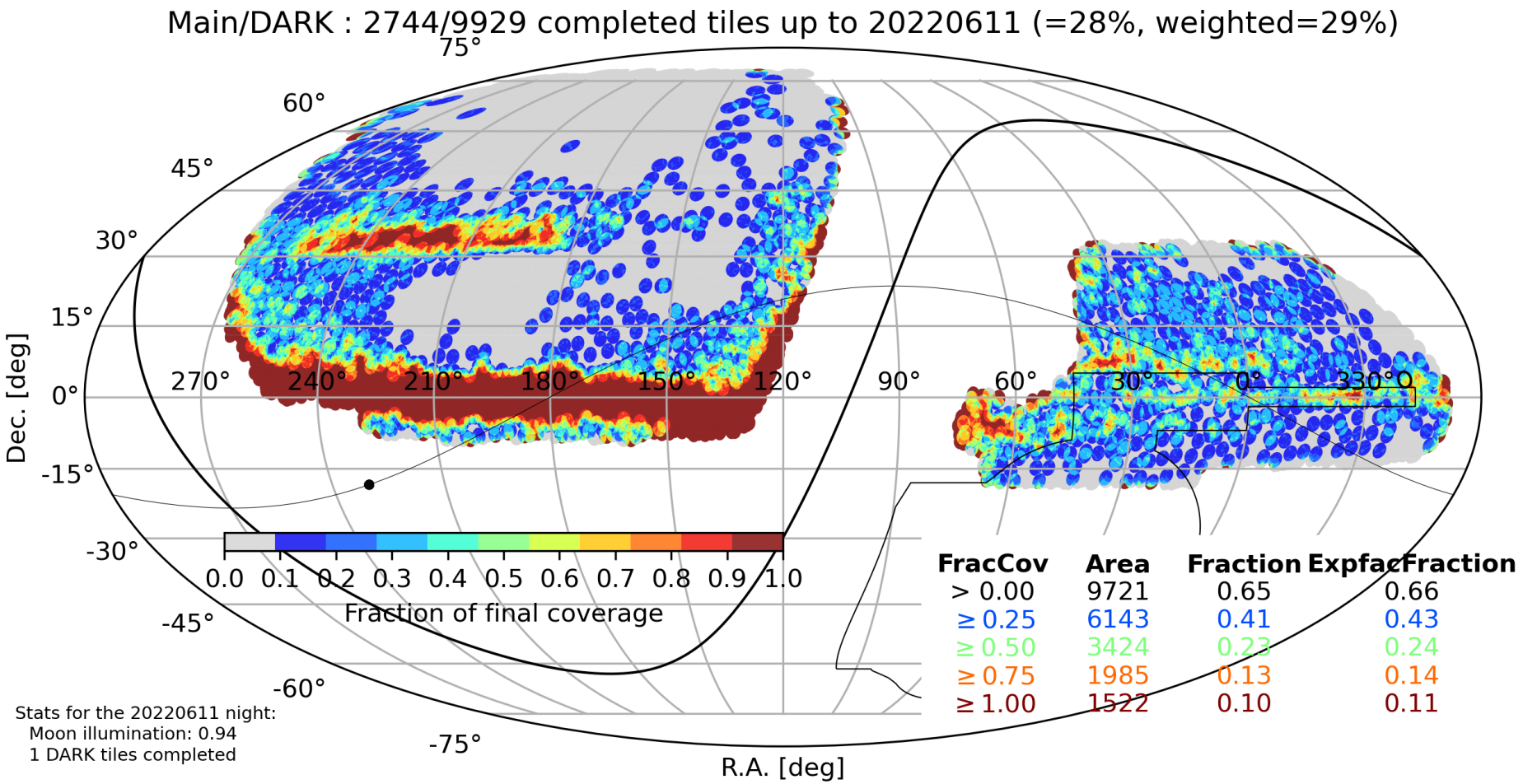
- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/redshifts per pointing
- 13.6 million flux-limited sample of galaxies at $z < 0.4$ (BGS)
- 23.7 million color-selected galaxies at $0.4 < z < 1.5$ (LRGs & ELGs)
- 2.8 million Quasars at $z > 0.8$
- Ly-α forest at $2 < z < 3.5$

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



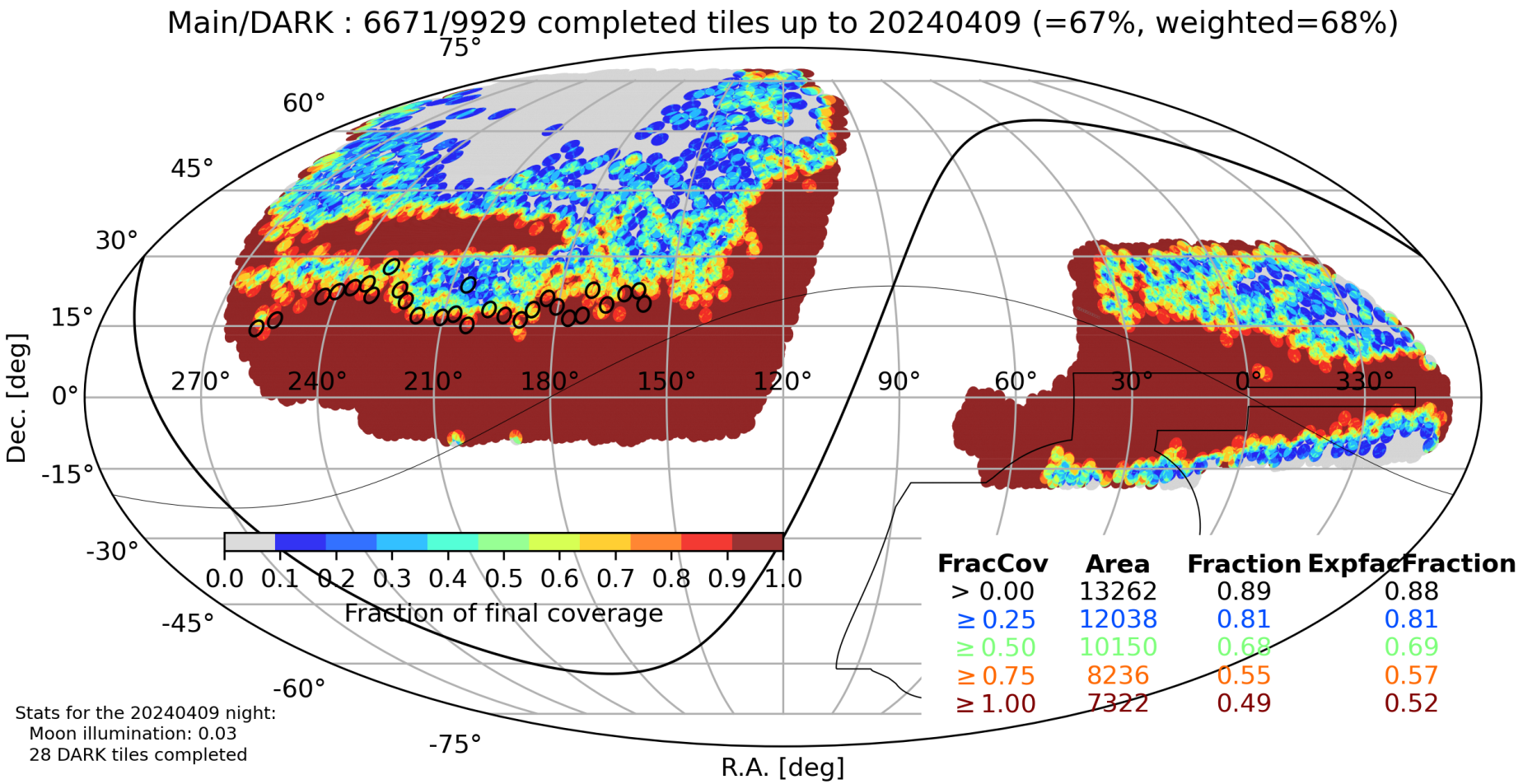


DESI 2025: Data Release 1



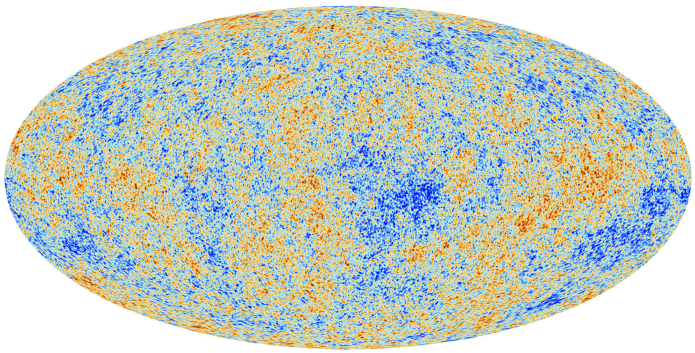
- 5.7 million unique redshifts

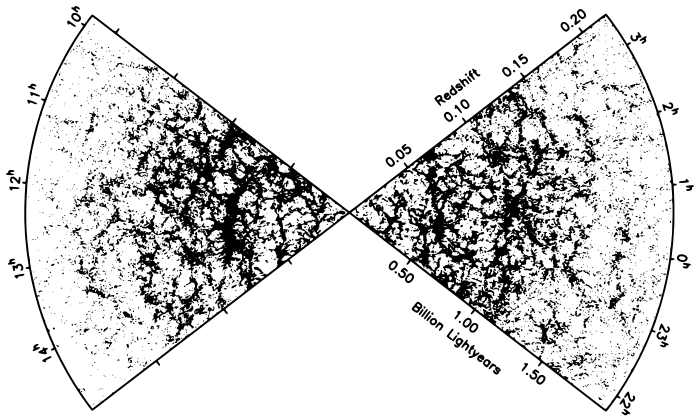
DESI 2025: Data Release 2



- 14 million unique redshifts

What is a galaxy redshift survey?



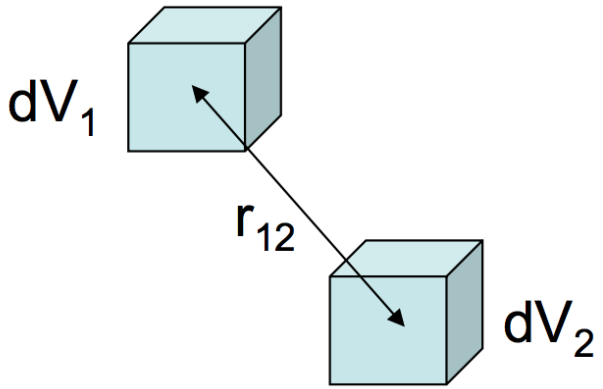


1. Measure the position of galaxies (RA, DEC + redshift).
2. The CMB tells us the initial conditions for today's distribution of matter.
3. How the initial density fluctuations in the CMB evolved from redshift 1100 to today depends on Ω_m, Ω_Λ, H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



- Two-point function:

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

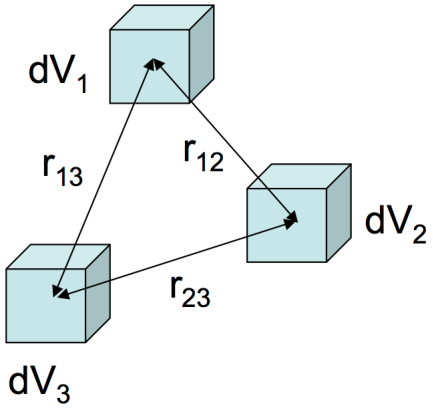
- ...and in Fourier-space:

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

From a point distribution to a bispectrum

- Overdensity-field:

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



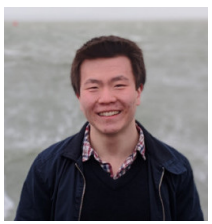
- Three-point function:

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

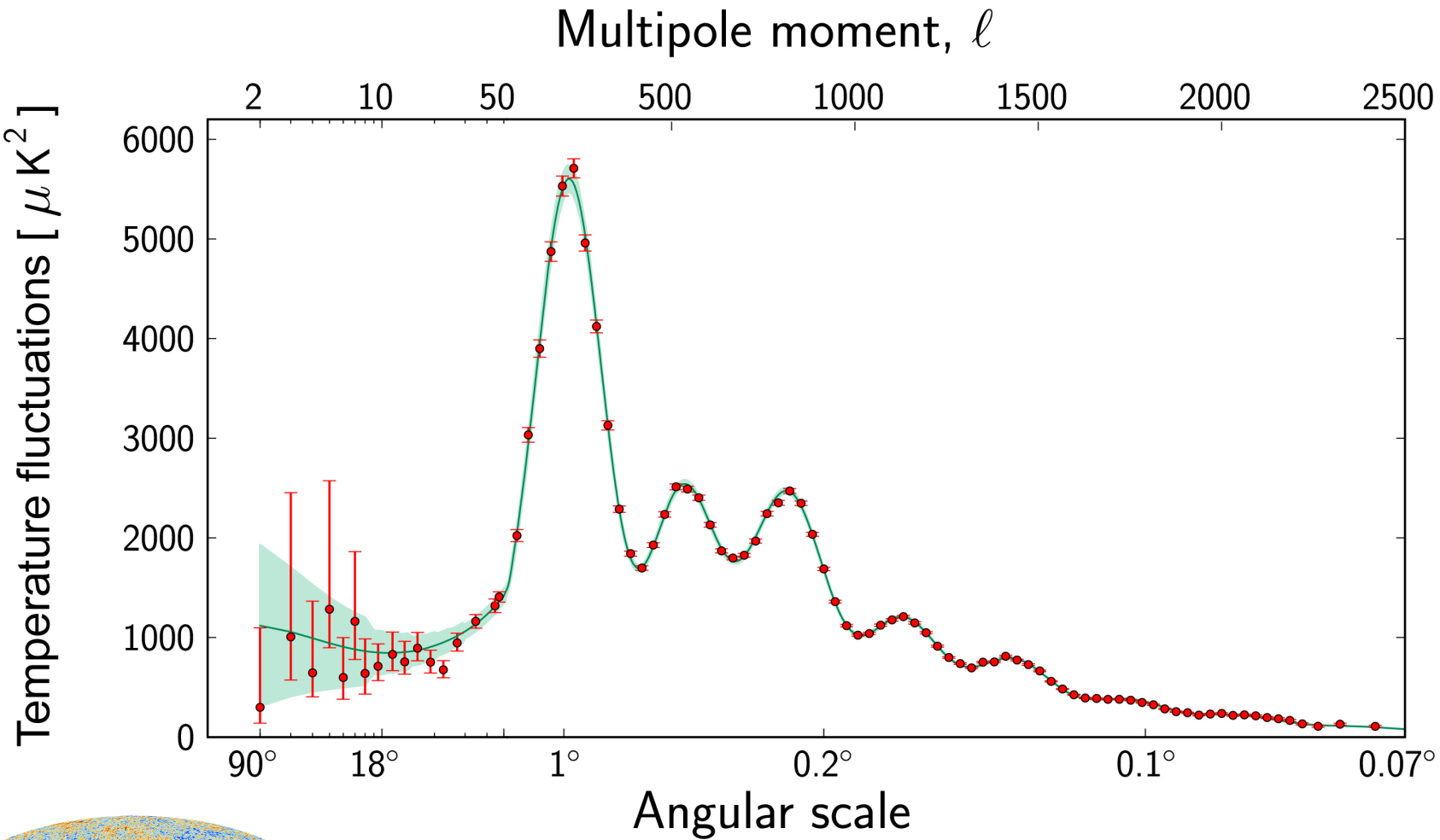
- ...and in Fourier-space:

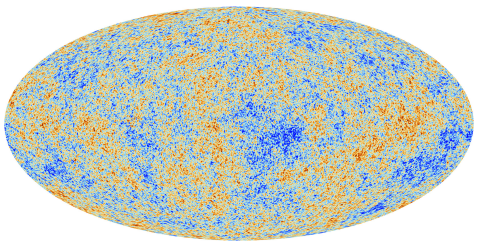
$$B_{\ell_1\ell_2 L}(k_1, k_2) = (4\pi)^2(-i)^{\ell_1+\ell_2} \int r_1^2 dr_1 \int r_2^2 dr_2 \xi_{\ell_1\ell_2 L}(r_1, r_2) j_{\ell_1}(k_1 r_1) j_{\ell_2}(k_2 r_2)$$

→ **Triumvirate**, Wang et al. (2024)
`https://triumvirate.readthedocs.io/en/latest/`



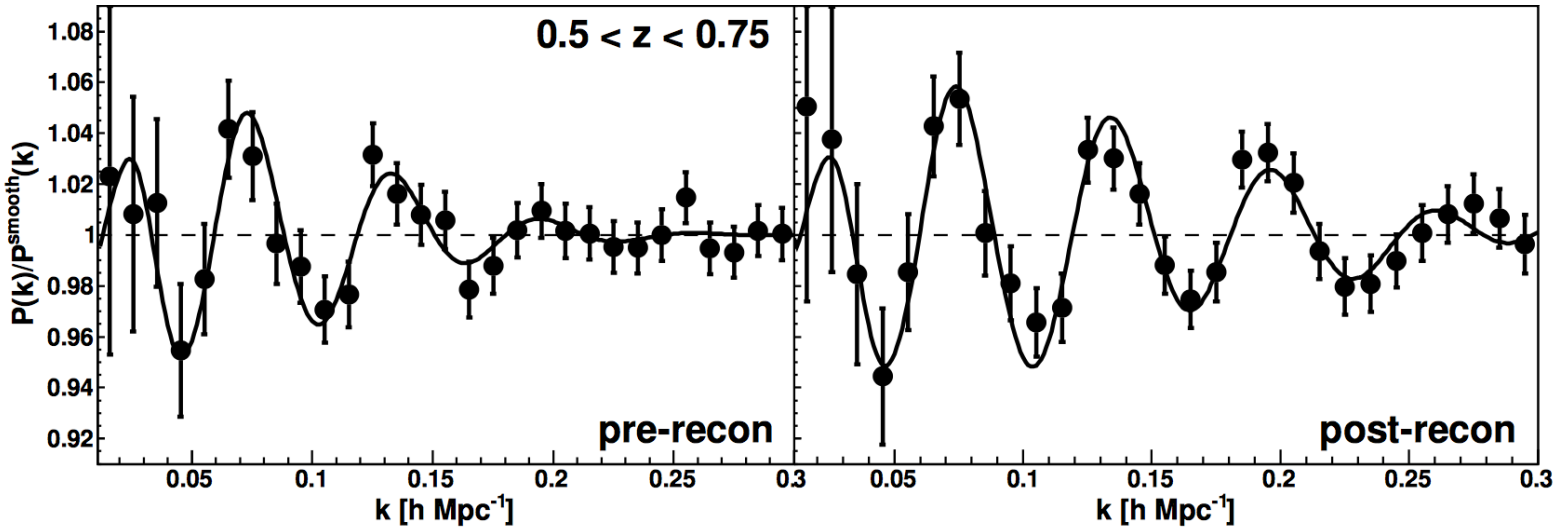

What are Baryon Acoustic Oscillations?





Planck collaboration

What Baryon Acoustic Oscillations constrain



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

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

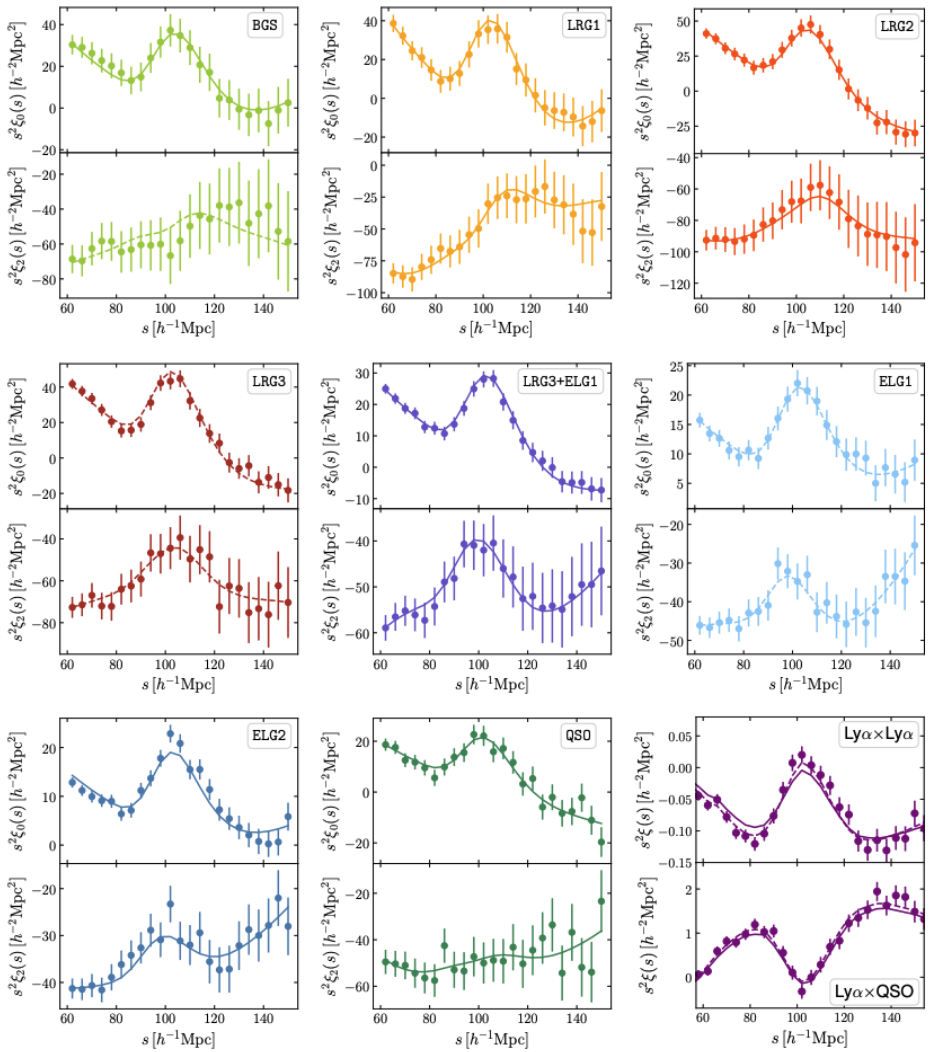
$$\frac{D_H(z)}{r_d} = \frac{c}{H(z) r_d} = c \left[H_0 r_d \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)} \right]^{-1}$$

- We require a calibration of the ruler to constrain H_0

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

DESI 2025: Measurements (5.6 - 14.7σ)

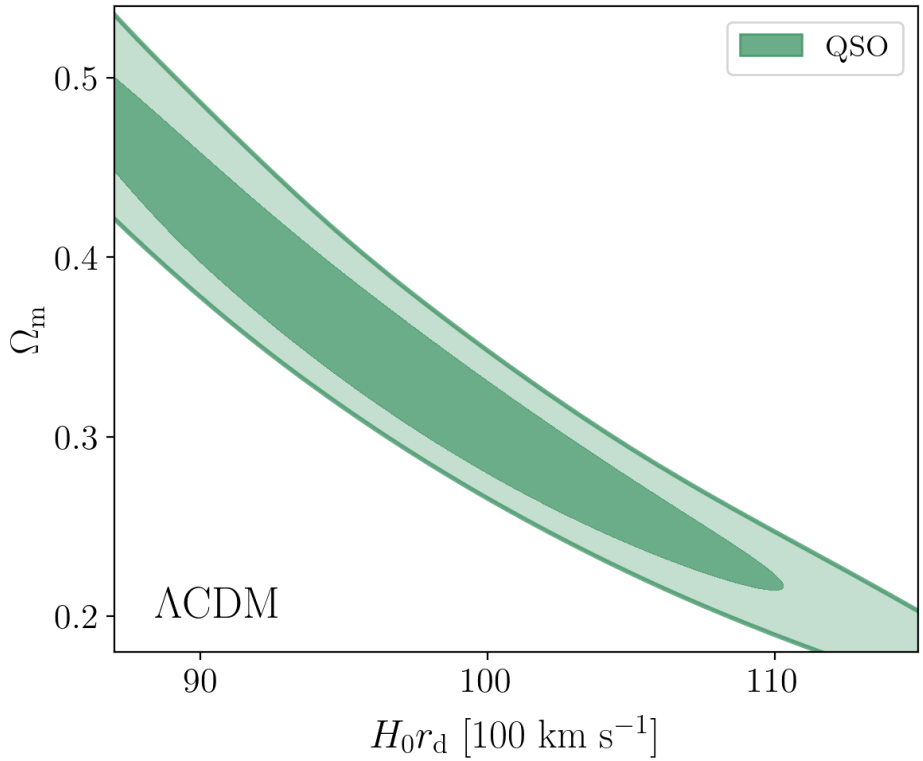
$$D_V(z) = \left[z D_M^2(z) D_H(z) \right]^{1/3}$$



DESI 2025

DESI 2025: ΛCDM

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



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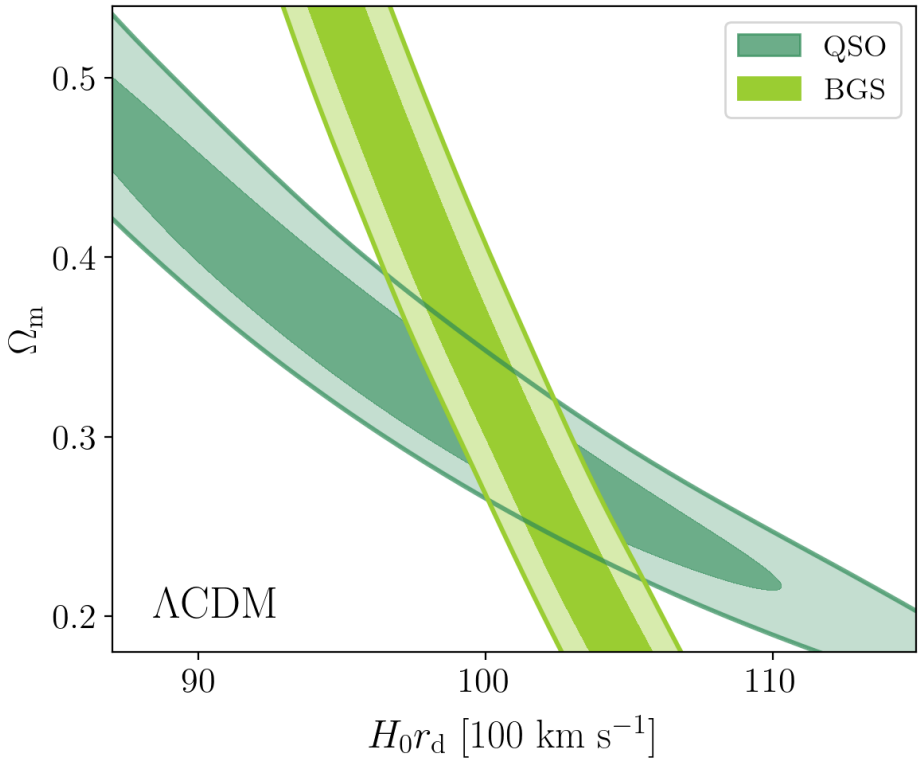

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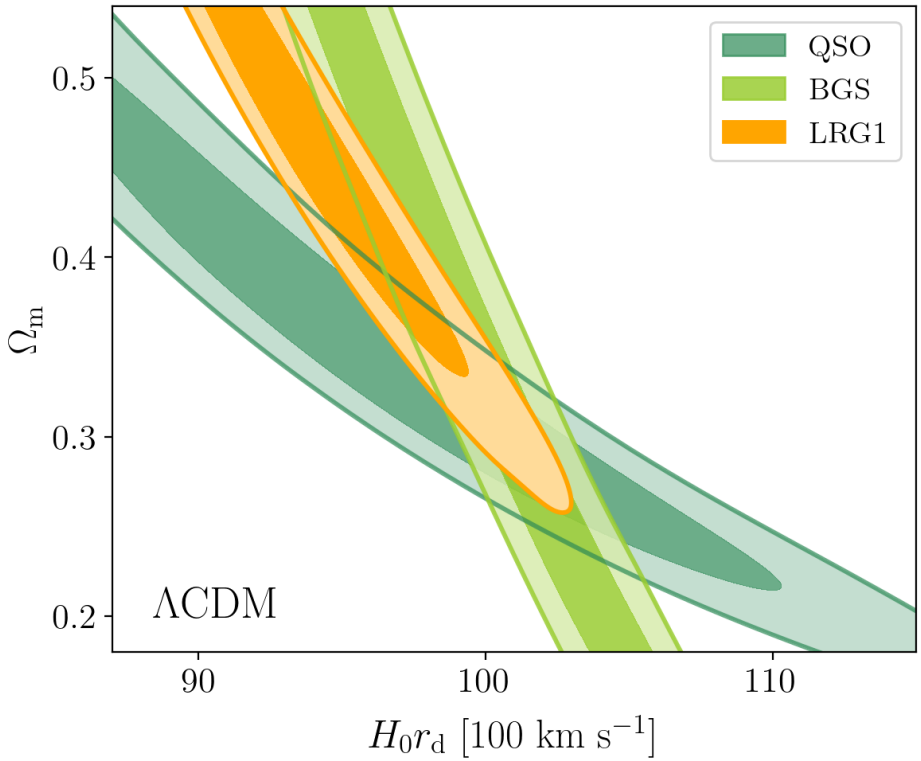

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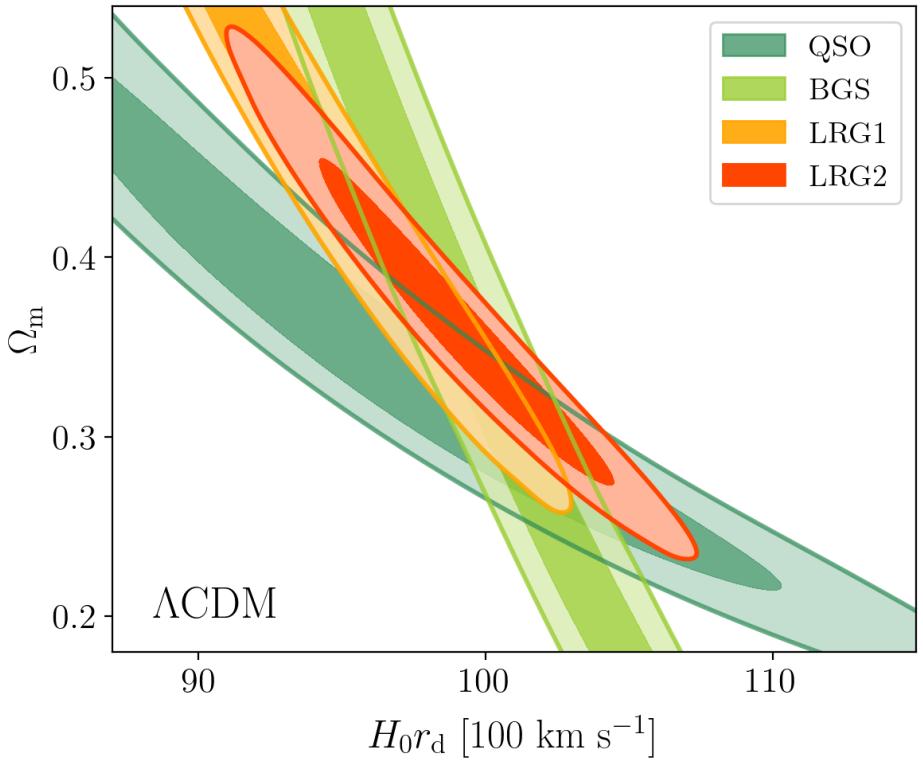

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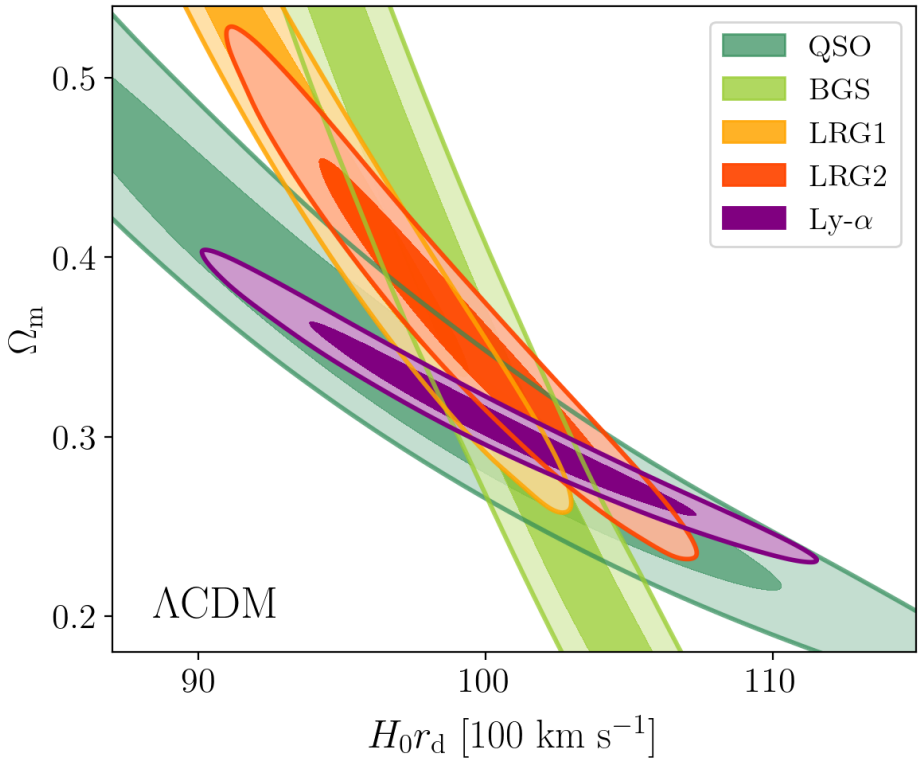

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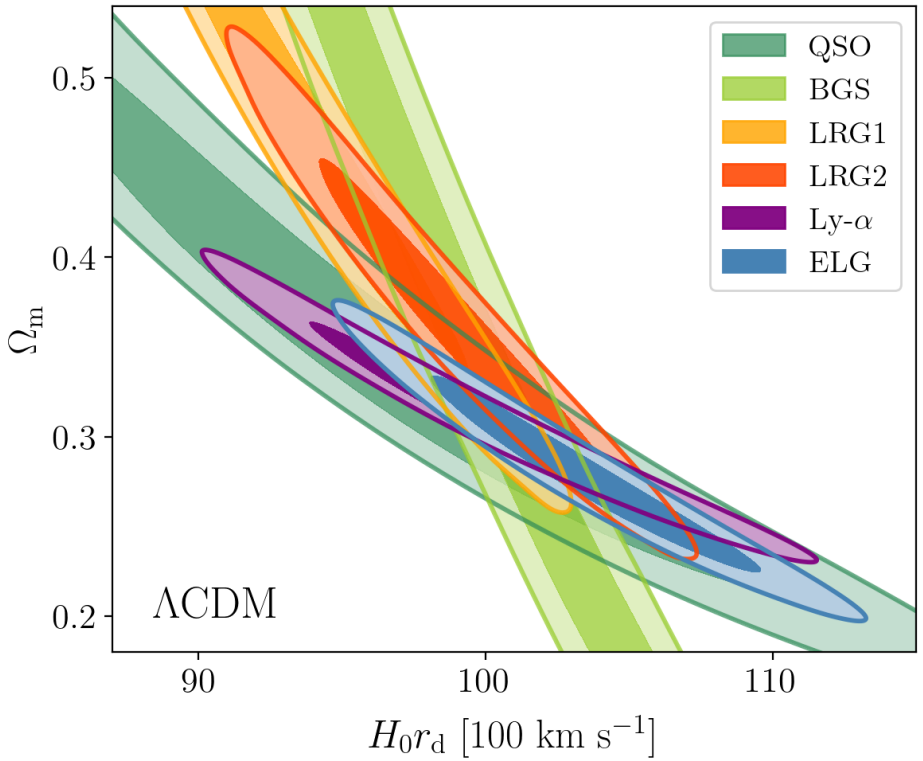

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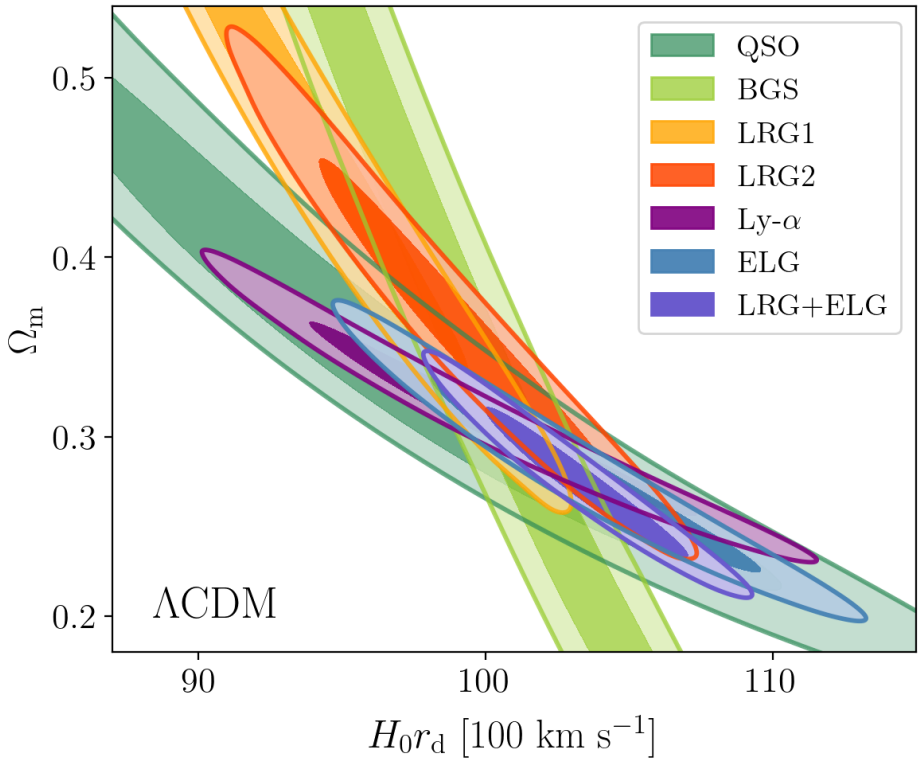

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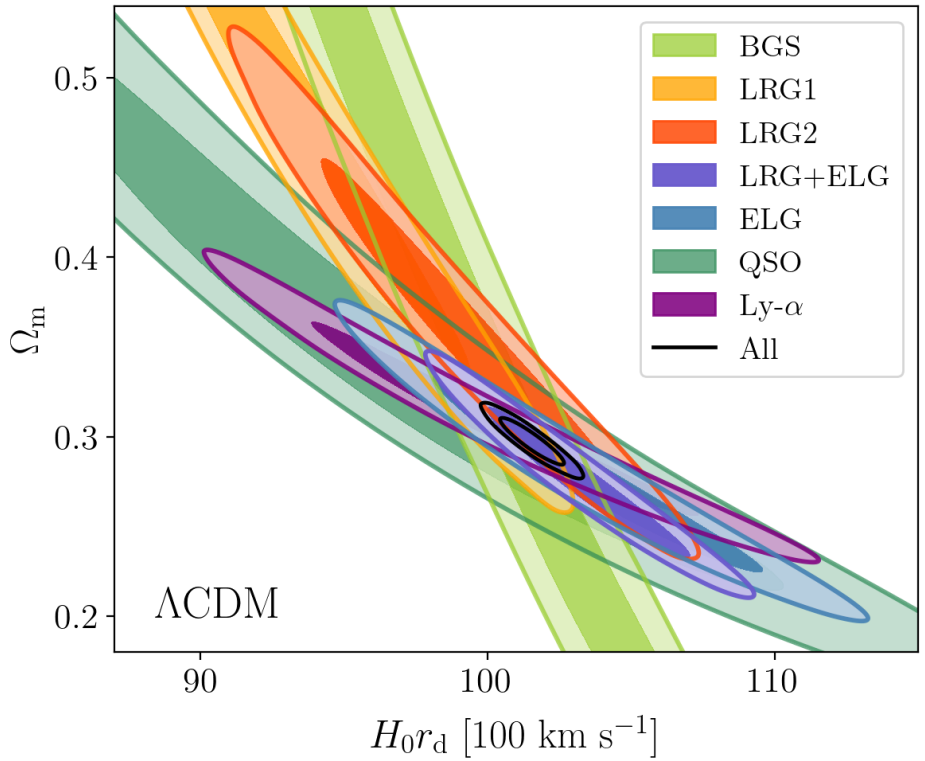


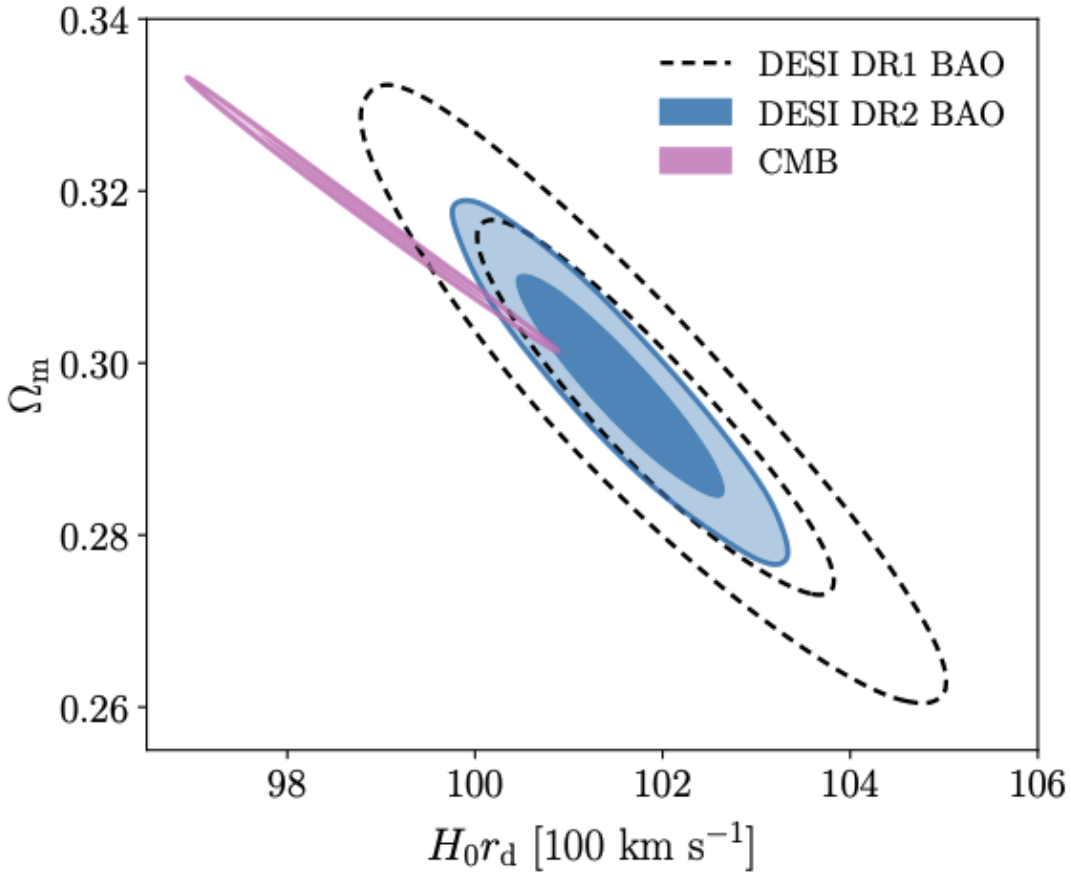
$$\Omega_m = 0.2975 \pm 0.0086 \quad (2.9\%)$$

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

DESI 2025

DESI 2025: ΛCDM

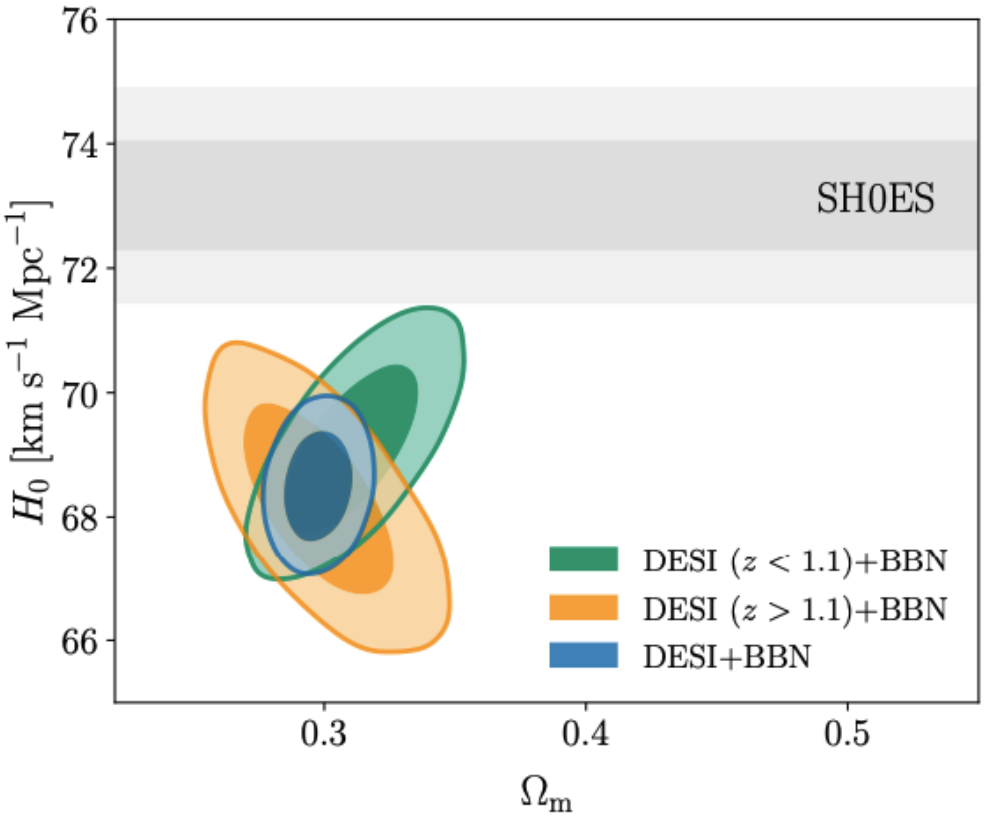
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$$



$\rightarrow$ 2.3σ tension between DESI and the CMB (2σ 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

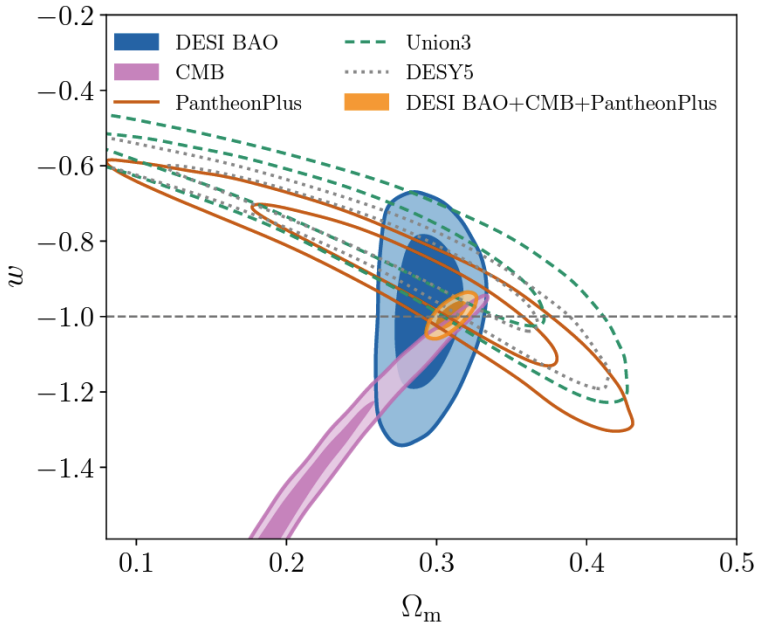


- DESI + BBN gives a 0.8% constraint on H_0 ($68.51 \pm 0.58\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- Planck has a 0.74% constraint ($67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- 4.5σ tension with SH0ES (no CMB involved!)

DESI 2025, Schoeneberg (2024)

DESI 2025: ωCDM

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



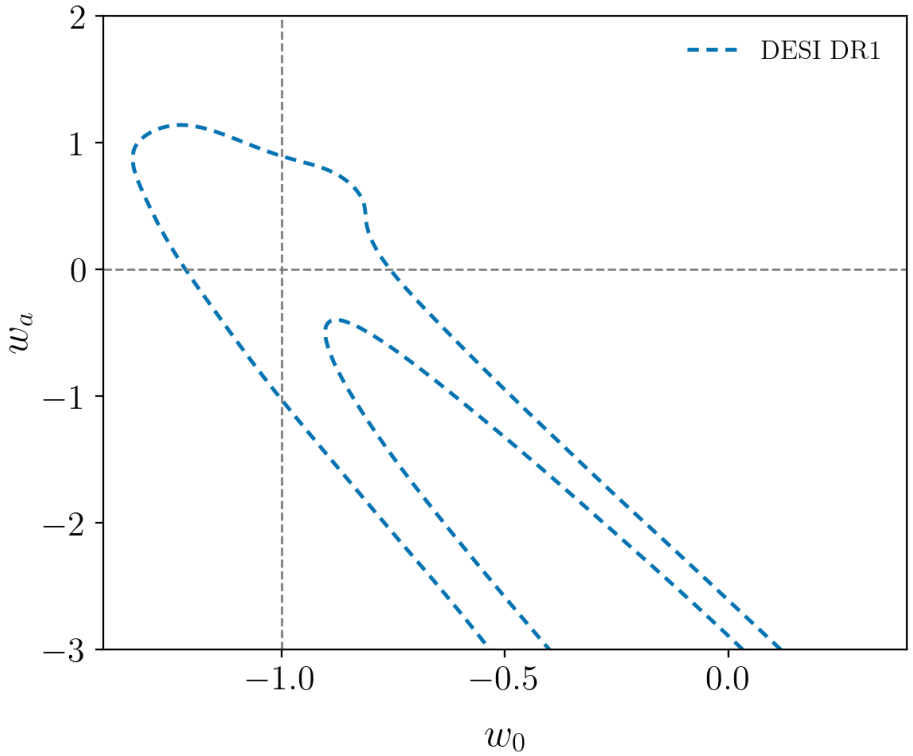
$$\left.\begin{aligned}\Omega_m &= 0.2969 \pm 0.0089\\ \omega &= -0.916 \pm 0.078\end{aligned}\right\}$$ DESI

$$\left.\begin{aligned}\Omega_m &= 0.3098 \pm 0.0050\\ \omega &= -0.971 \pm 0.021\end{aligned}\right\}$$ DESI + CMB + DESY5

DESI 2024/2025

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

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



DESI 2025

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

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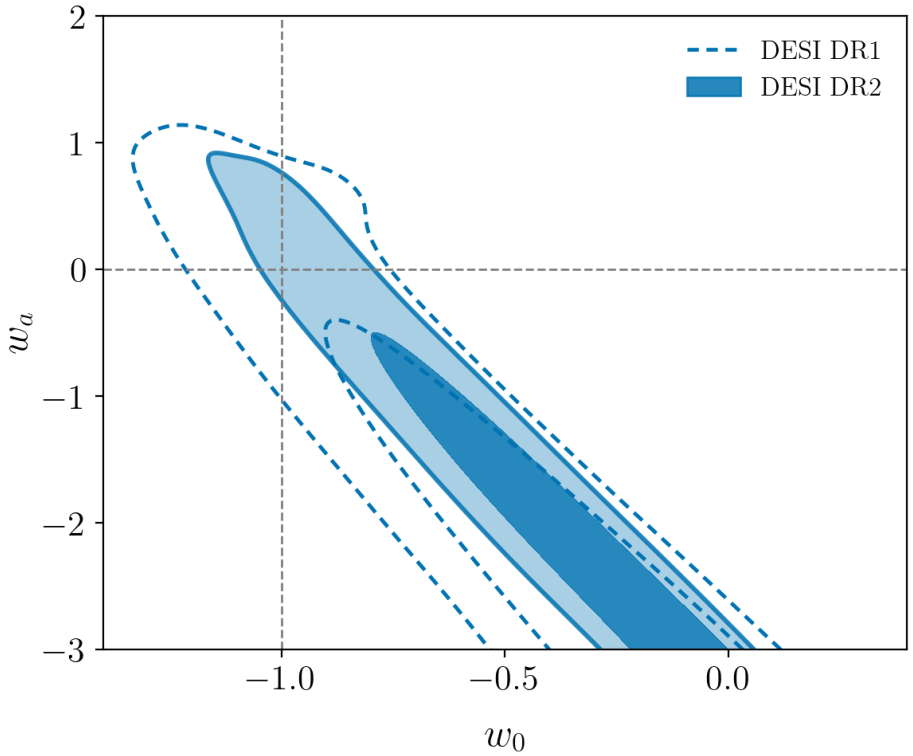

DESI 2025

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

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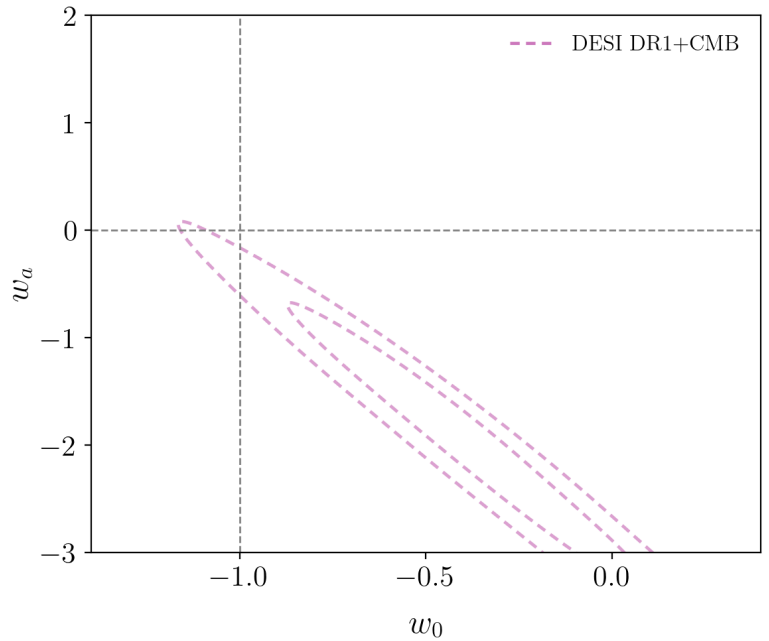
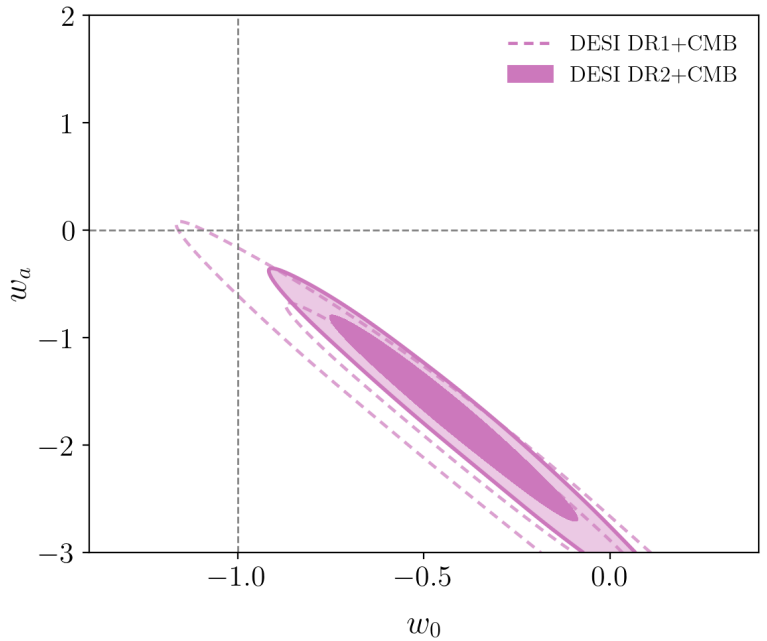


- DESI + CMB has a 3.1σ preference for evolving DE
-
-
-

DESI 2025

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

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



- DESI + CMB has a 3.1σ preference for evolving DE
-
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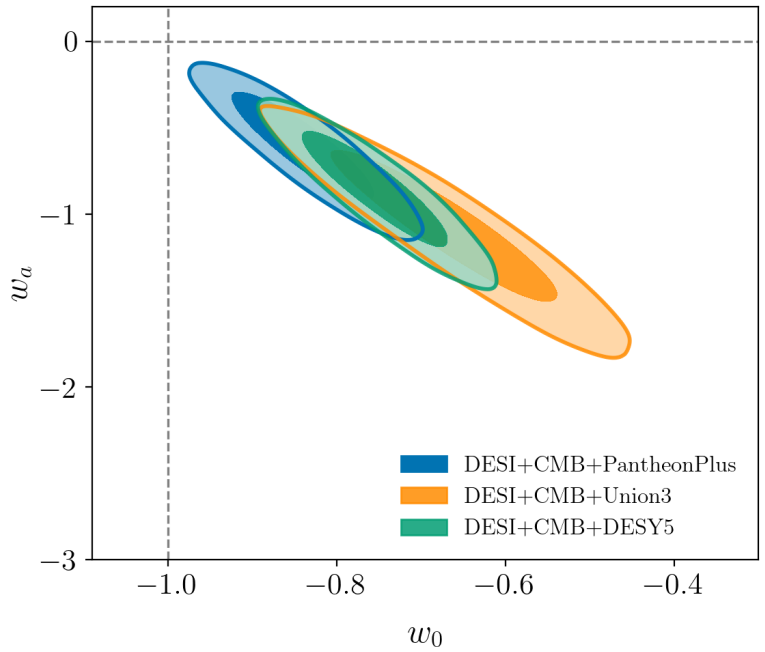
DESI 2025

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

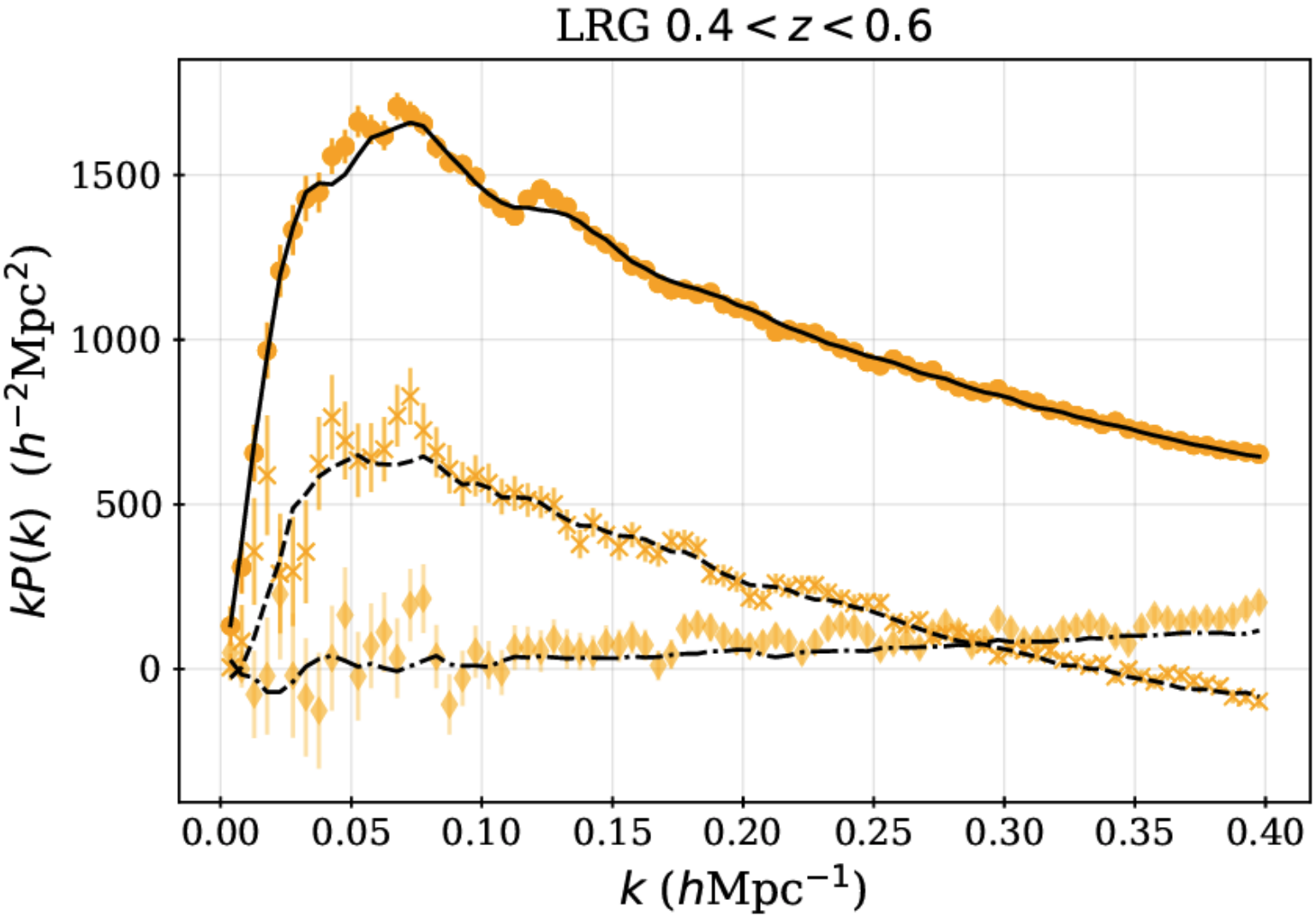
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)}e^{-3\omega_a\frac{z}{1+z}}}$$



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

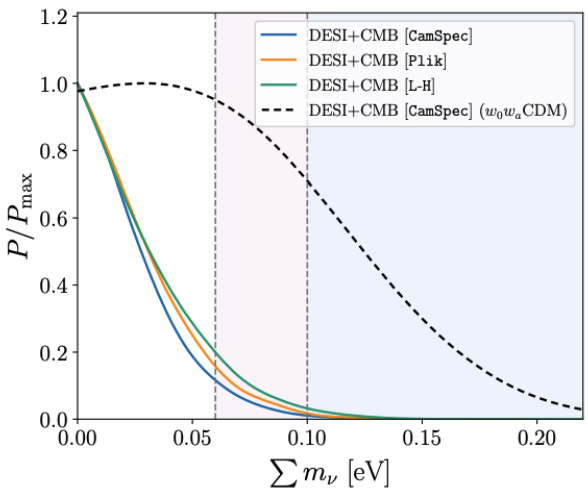
DESI 2025

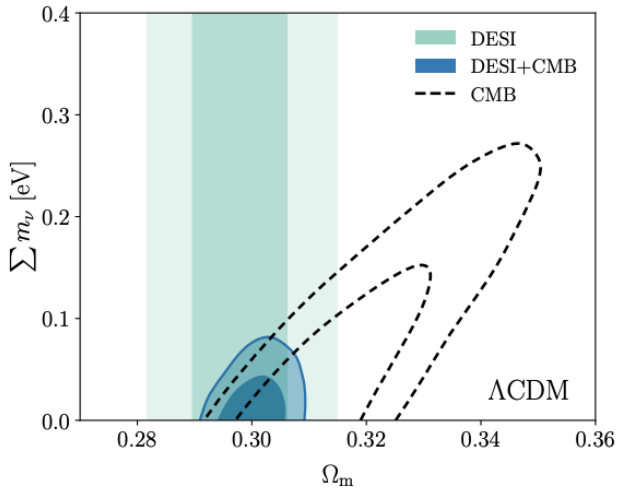
DESI 2025: Full-shape constraints from DR1



DESI 2025

DESI 2025: Constraining the neutrino mass





$|\Delta m^2_{31}| \simeq 2.56 \times 10^{-3}\,\text{eV}^2$

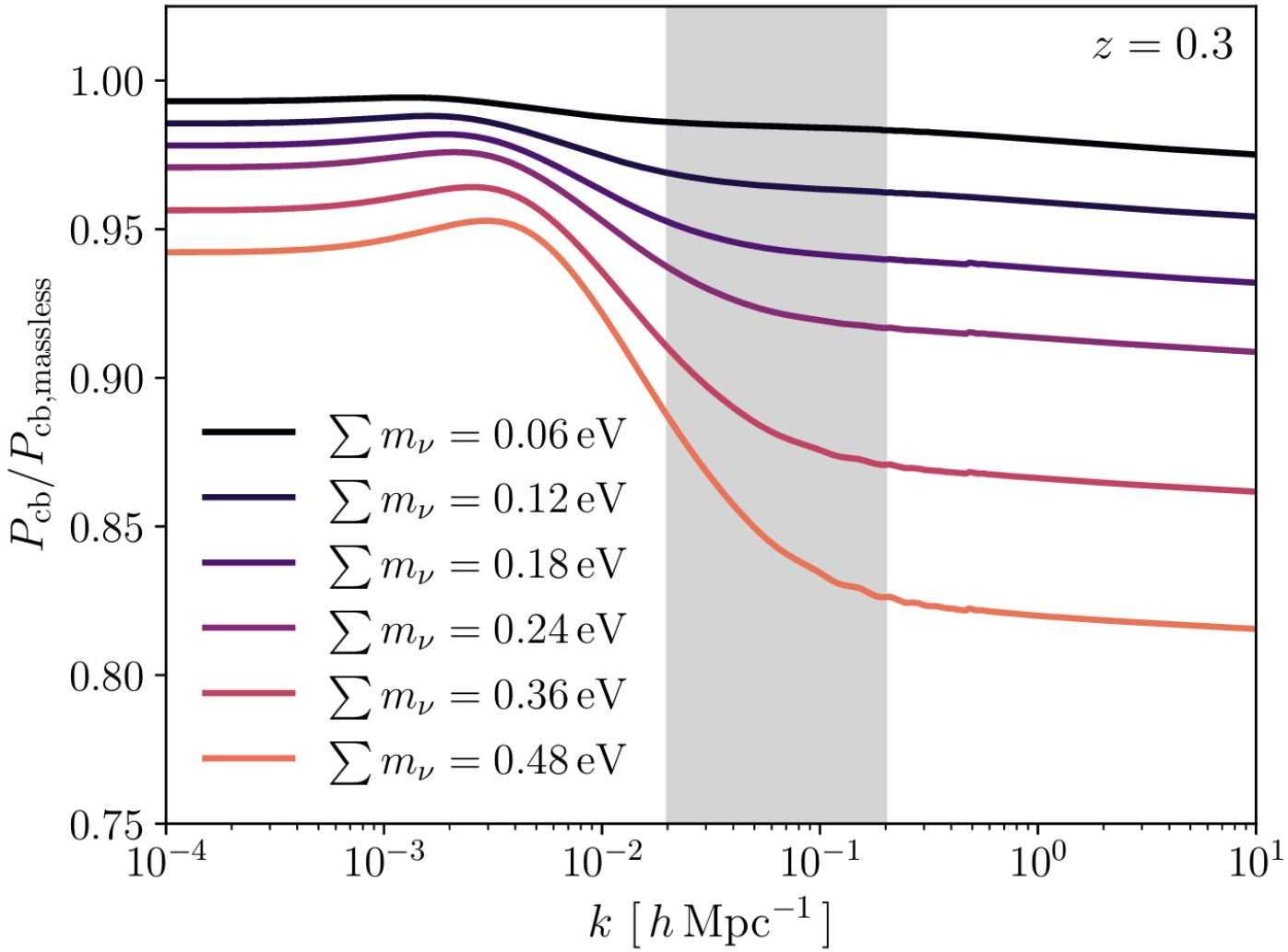
$\Delta m^2_{21} \simeq 7.37 \times 10^{-5}\,\text{eV}^2$

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

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

DESI 2025, PDG (2018), KATRIN 2022

Constraints from free streaming

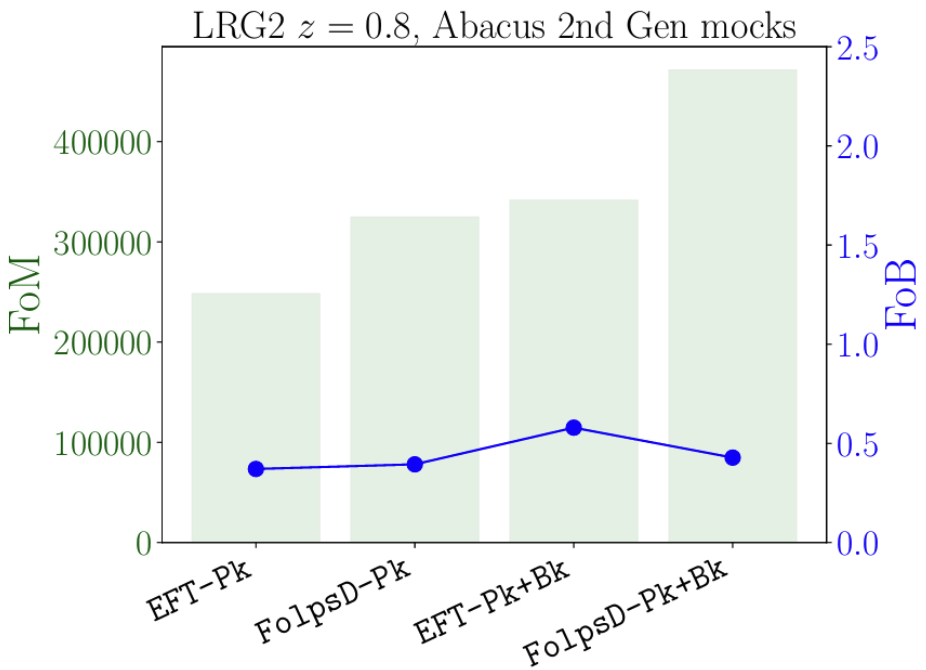


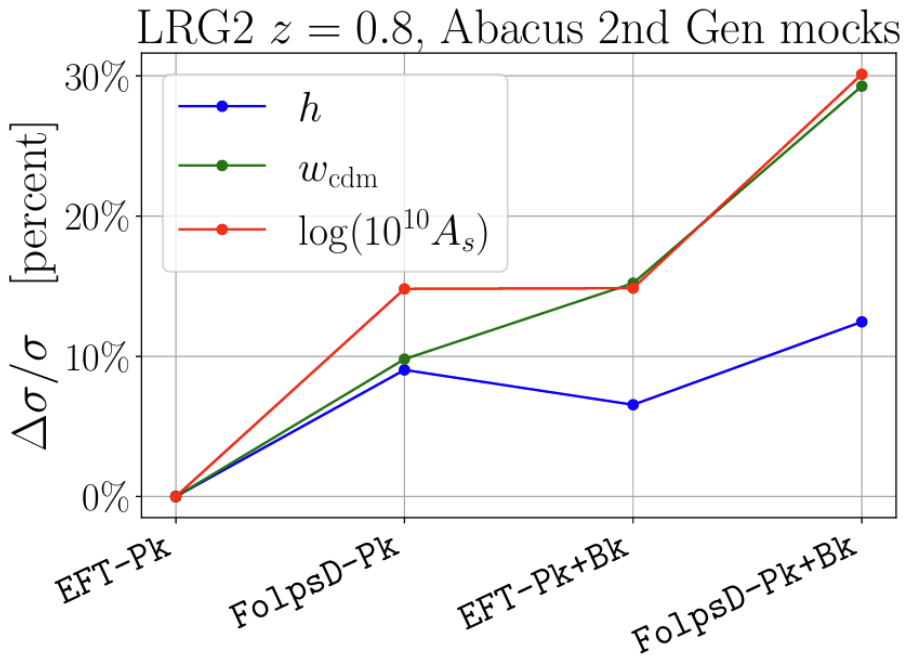
DESI DR1 (FS+BAO) + BBN + n_s : $\sum m_\nu < 0.3\,eV$ (95%)

Elbers et al. (2025)

Outlook

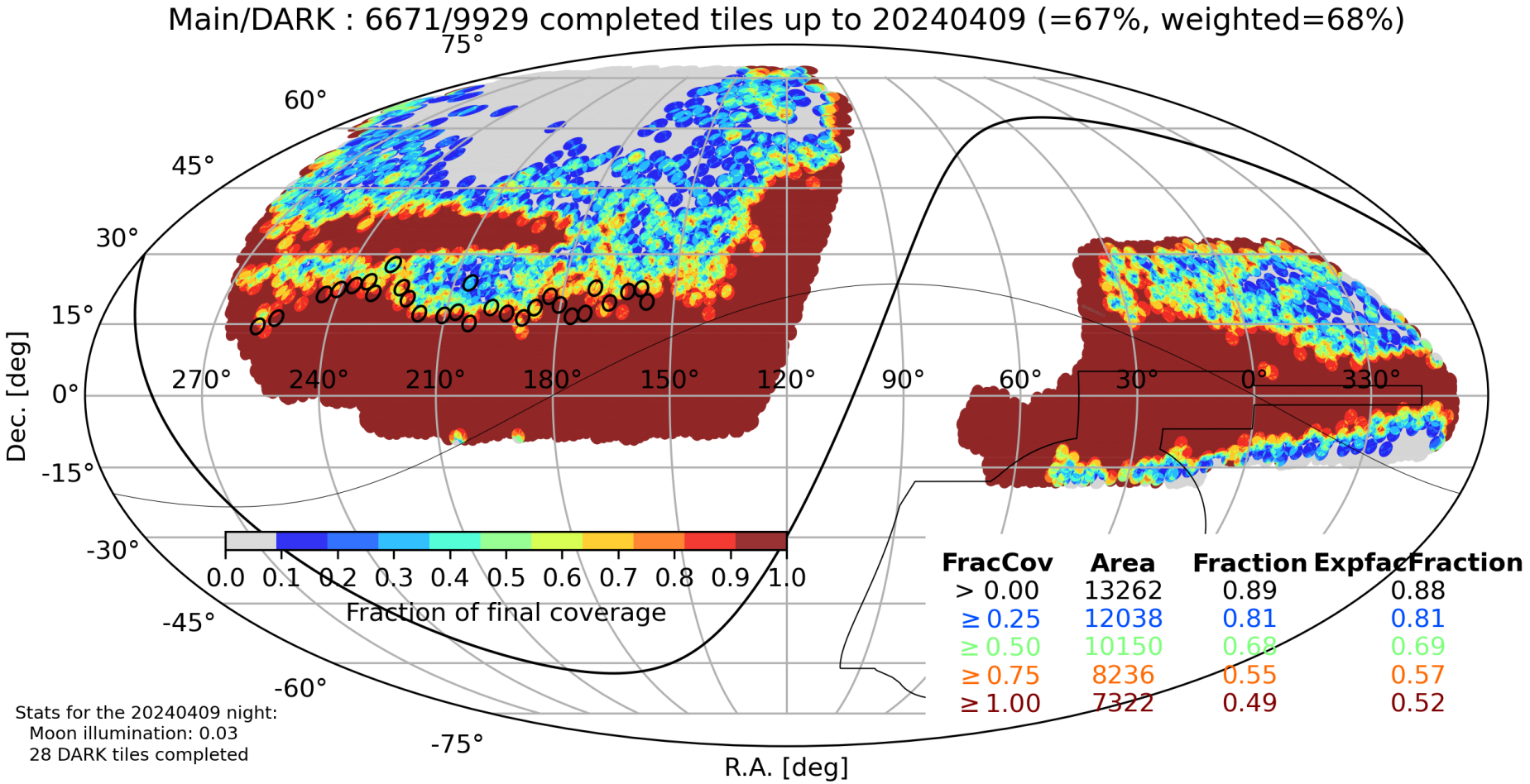
- We are currently running a mock challenge for the DR2 full-shape analysis
- Within DESI we produced much better mock datasets for DR2 to tests our models and derive covariance matrices
- Unblinding is this month and papers are to be published in Sep.





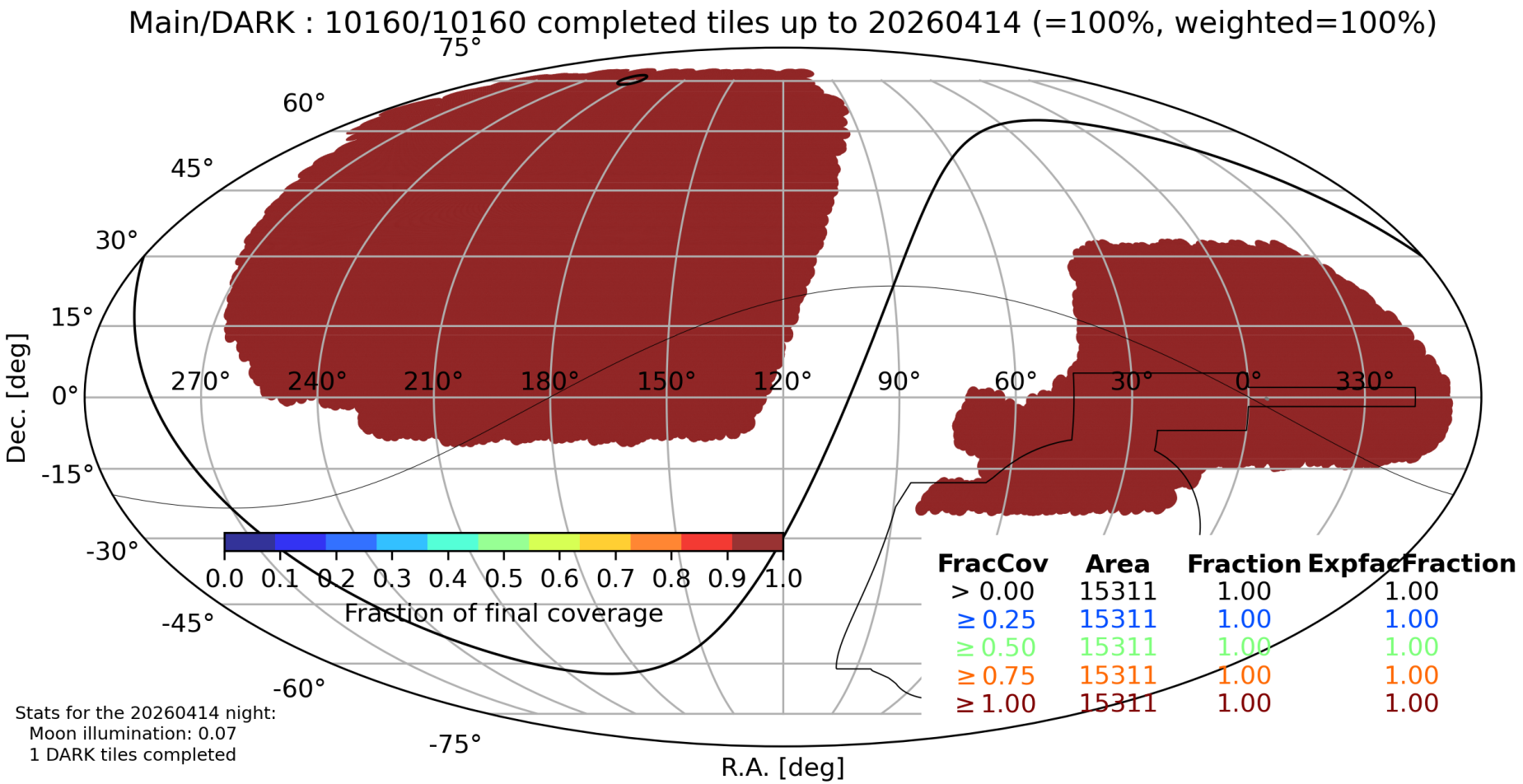
Bansal et al. (2026), see also Eggemeier et al. (2025)

Outlook



DESI 2025

Outlook



DESI 2025

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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