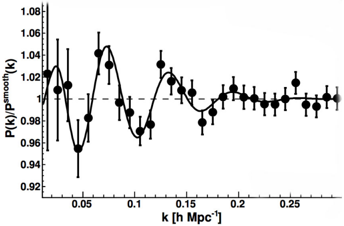
Cosmology with the Euclid and Dark Energy Spectroscopic Instrument (DESI)

Florian Beutler



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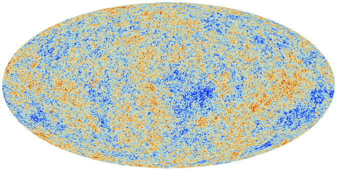
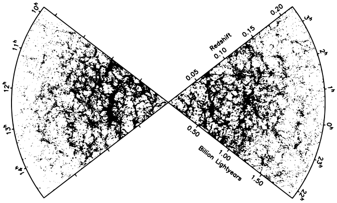


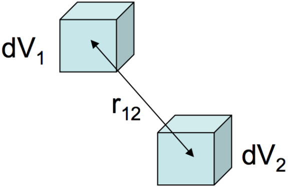


1. Measure the position of galaxies (RA, DEC + redshift).
2. The CMB tells us the initial conditions for today's distribution of matter.
3. How the initial density fluctuations in the CMB evolved from redshift 1100 to today depends on Ω_m, Ω_Λ, H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



- Two-point function:

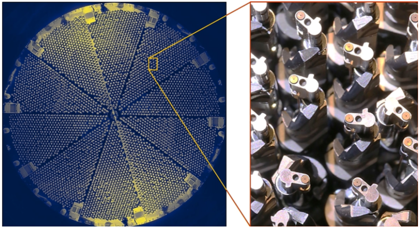
$$\xi(\mathbf{r}) \overset{\text{homogeneity}}{=} \langle \delta(\mathbf{x}+\mathbf{r})\delta(\mathbf{x}) \rangle \begin{cases} \overset{\text{isotropy}}{=} & \xi(r) \\ \overset{\text{anisotropy}}{=} & \xi_\ell(r) = \int_{-1}^{1} d\mu\, \xi(r,\mu)\mathcal{L}_\ell(\mu) \end{cases}$$

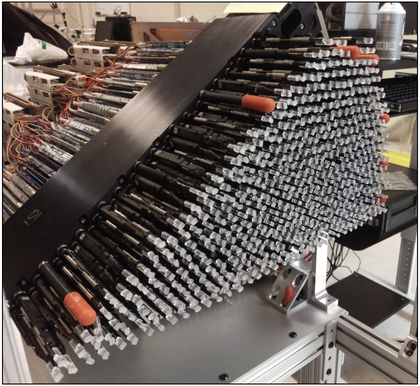
- ...and in Fourier-space:

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

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 schedule

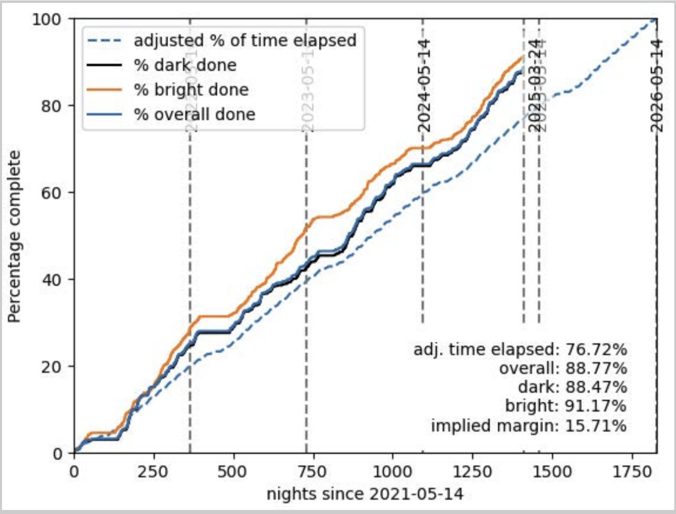


Figure 1. Survey progress. Solid curves give the survey progress as a function of time in different programs. The dashed curve shows the weather-adjusted fraction of the five-year survey elapsed.

DESI schedule

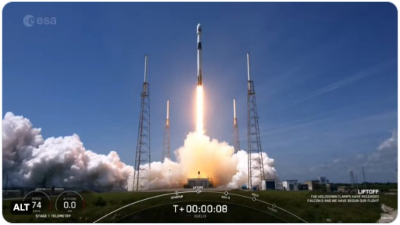
The ESA Euclid mission

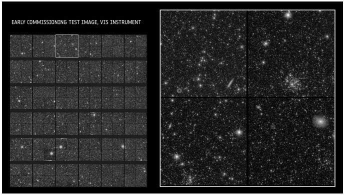
- Launch**ed** in July 2023 → L2 point
- Space-based weak lensing + gal. clustering survey over 15 000 deg^2
- 30 million emission line galaxies over the redshift range 0.7 to 2.0
- Slitless spectroscopy (grism)

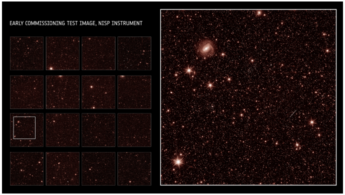
ESA's Euclid mission
@ESA_Euclid

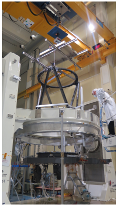
🚀 Liftoff for the #DarkUniverse 🕵️ detective that aims to shed light on the nature of #DarkMatter & #DarkEnergy

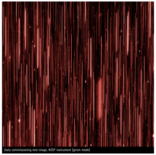
👏 #ESAEuclid

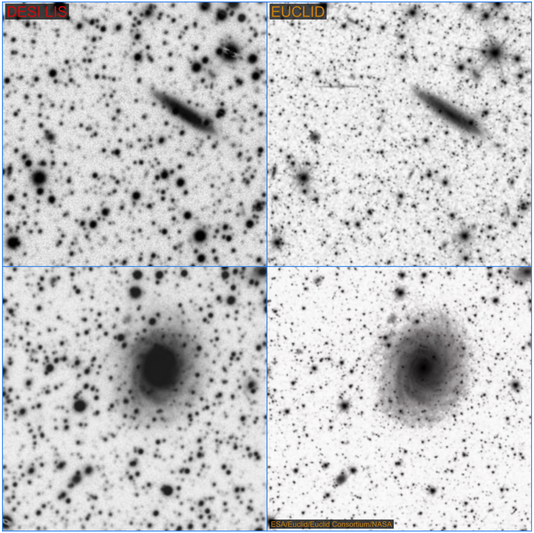






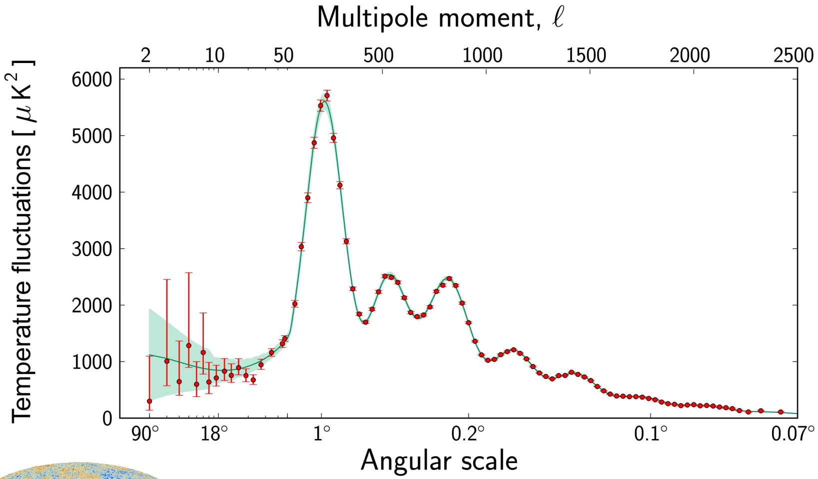


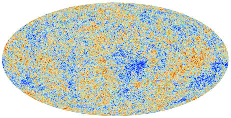




DESI (4m) Euclid (1.2m)

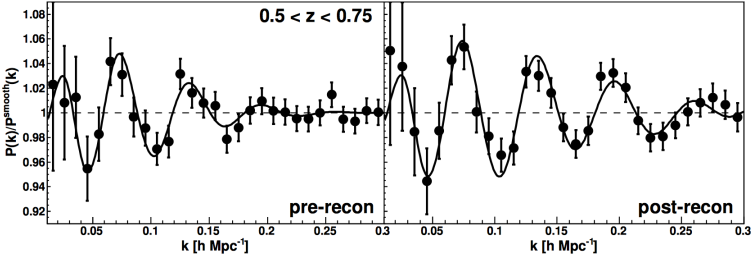
What are Baryon Acoustic Oscillations?





Planck collaboration

Baryon Acoustic Oscillations in BOSS

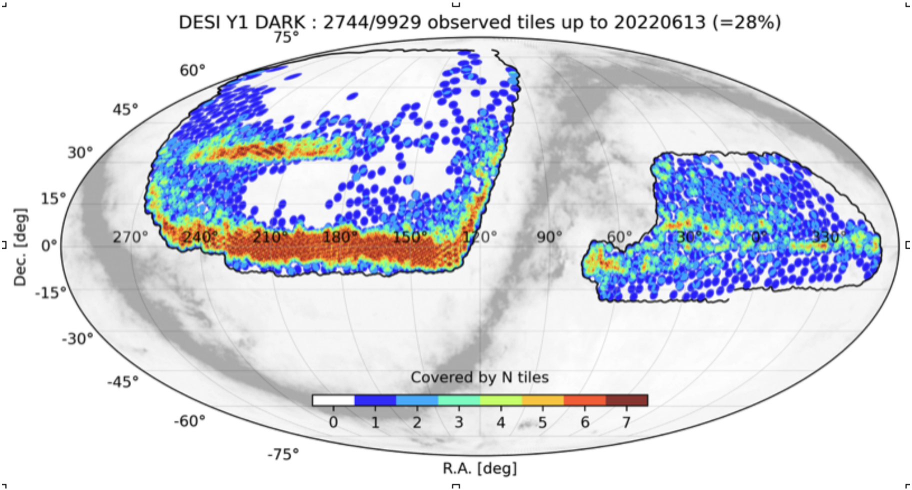


- BAO are the most robust observable we can extract from LSS
- The observables are

$$\frac{D_M(z)}{r_d} = \int_0^z \frac{cdz'}{r_d H(z')}$$
$$\frac{D_H(z)}{r_d} = \frac{c}{H(z)r_d} = c\left[H_0 r_d\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}\right]^{-1}$$

- We require a calibration of the ruler to constrain H_0

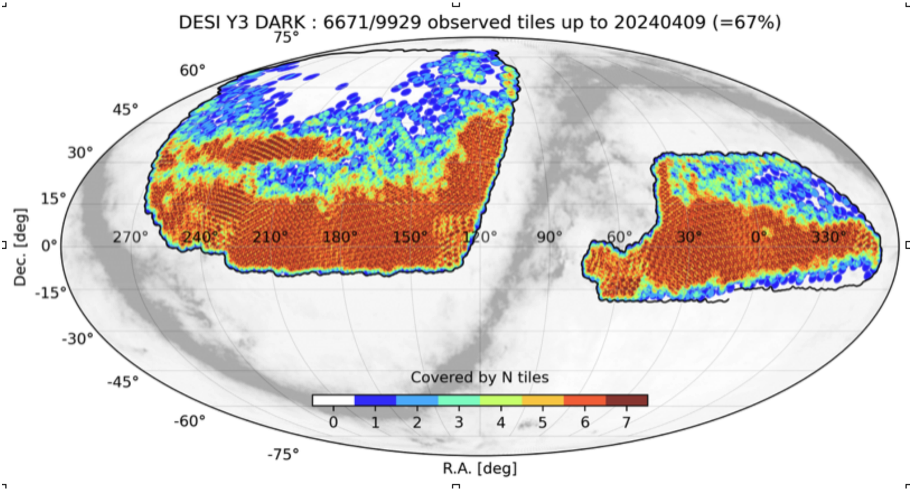
$$r_d = \int_{z_d}^{\infty}\frac{c_s(z)}{H(z)}dz = 147.05\,\mathrm{Mpc}\times\left(\frac{\omega_b}{0.02236}\right)^{-0.13}\left(\frac{\omega_{bc}}{0.1432}\right)^{-0.23}\left(\frac{N_{\rm eff}}{3.04}\right)^{-0.1}$$



- 5.7 million unique redshifts

DESI 2025

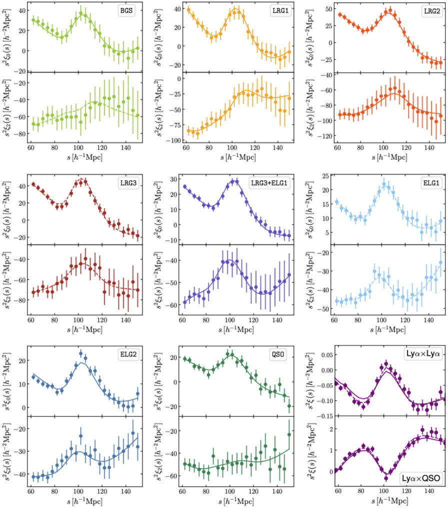
DESI 2025: Data Release 2



- 14 million unique redshifts (7 times as big as SDSS)

DESI 2025: Measurements (5.6 - 14.7σ)

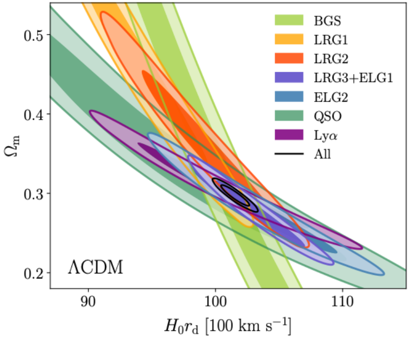
$$D_V(z) = \left[z D_M^2(z) D_H(z) \right]^{1/3}$$

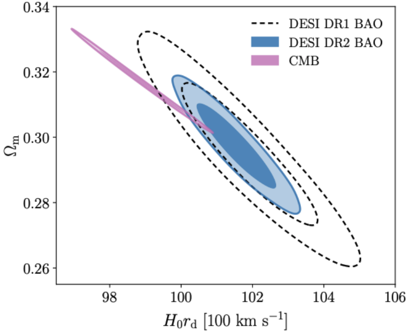


DESI 2025

DESI 2025: ΛCDM

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





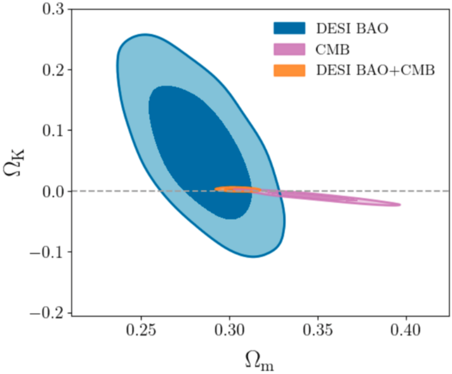
$$\Omega_m = 0.2975 \pm 0.0086 \quad (2.9\%)$$

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

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

DESI 2025

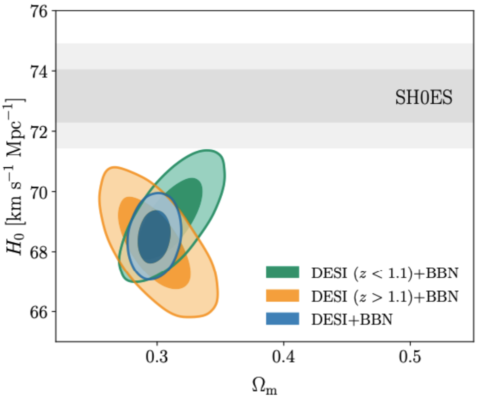
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + (1-\Omega_m-\Omega_K)}$$



- DESI: $\Omega_K = 0.025 \pm 0.041$
- CMB: $\Omega_K = -0.0107^{+0.0064}_{-0.0053}$
- CMB+DESI: $\Omega_K = 0.0023 \pm 0.0011$

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

DESI 2024/2025

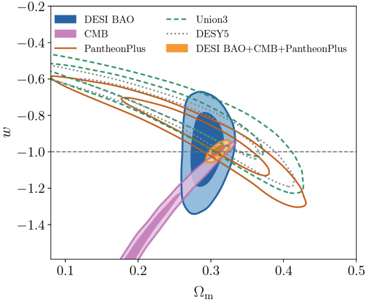


- DESI + BBN gives a 0.8% constraint on H_0 ($68.51 \pm 0.58\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- Planck has a 0.74% constraint ($67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- 4.5σ tension with SH0ES (no CMB involved!)

DESI 2025

DESI 2025: ωCDM

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



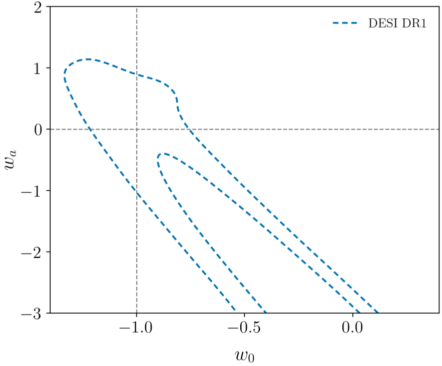
$$\left.\begin{aligned}\Omega_m &= 0.2969 \pm 0.0089\\ \omega &= -0.916 \pm 0.078\end{aligned}\right\}\quad \text{DESI}$$

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

DESI 2024/2025

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

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



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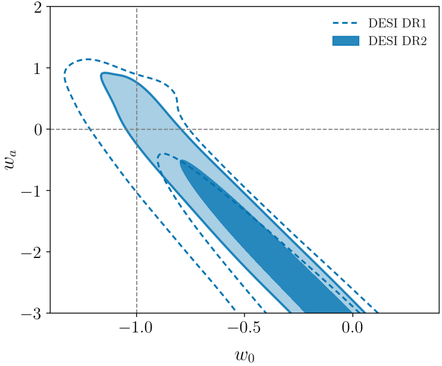

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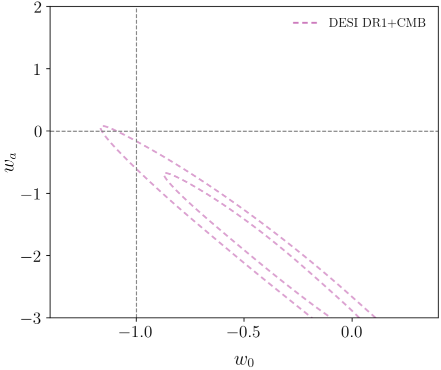

- DESI + CMB has a 3.1σ preference for evolving DE
-

DESI 2025

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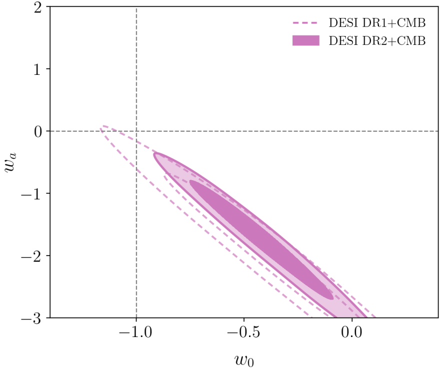

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DESI 2025

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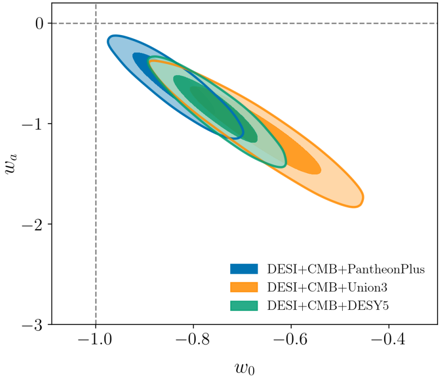
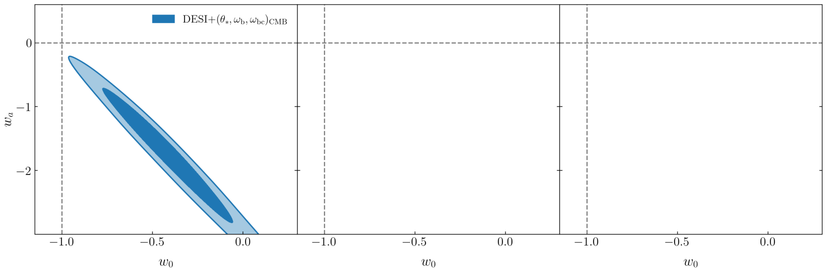


- DESI + CMB has a 3.1σ preference for evolving DE
- This can increase when including SN datasets (between 2.8 and 4.2σ)

DESI 2025

More details



- Combining DESI with early-Universe CMB priors on $(\theta^*, \omega_b, \omega_{bc})$ shows preference for evolving dark energy at the 2.4σ level (3.1σ for the full CMB).
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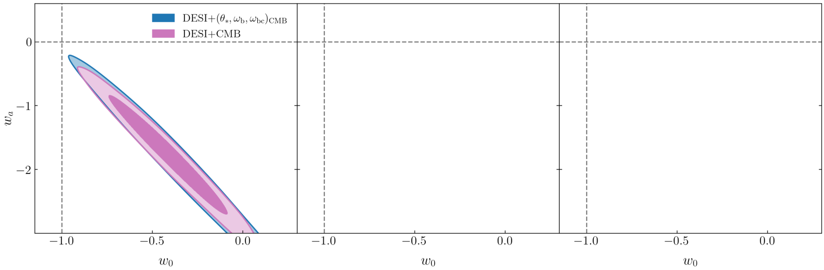
DESI 2025

More details



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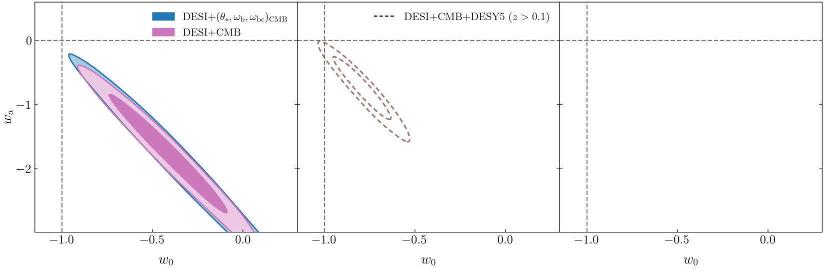
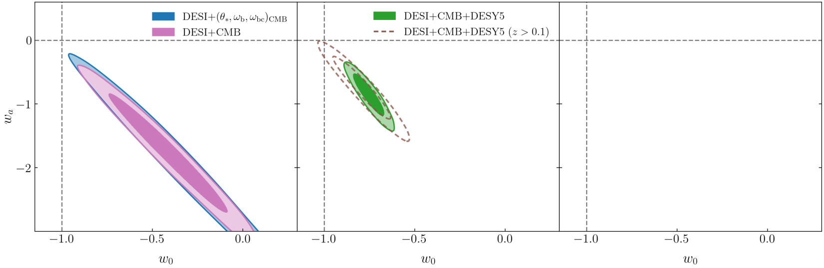


- Combining DESI with early-Universe CMB priors on $(\theta^*, \omega_b, \omega_{bc})$ shows preference for evolving dark energy at the 2.4σ level (3.1σ for the full CMB).
- Excluding $z < 0.1$ SNe reduces the statistical significance, but the best-fit values for $\omega_0\omega_a$ remain far from ΛCDM $\rightarrow 2.4\sigma$.
-

DESI 2025

More details



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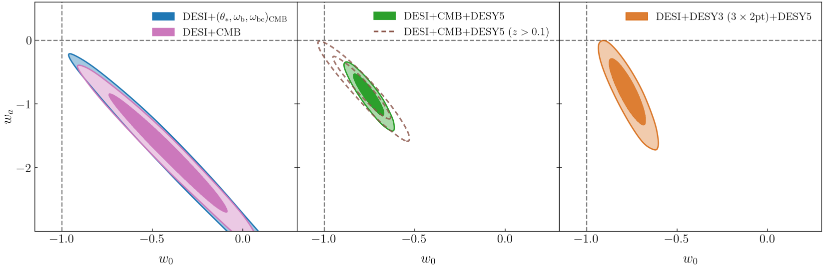
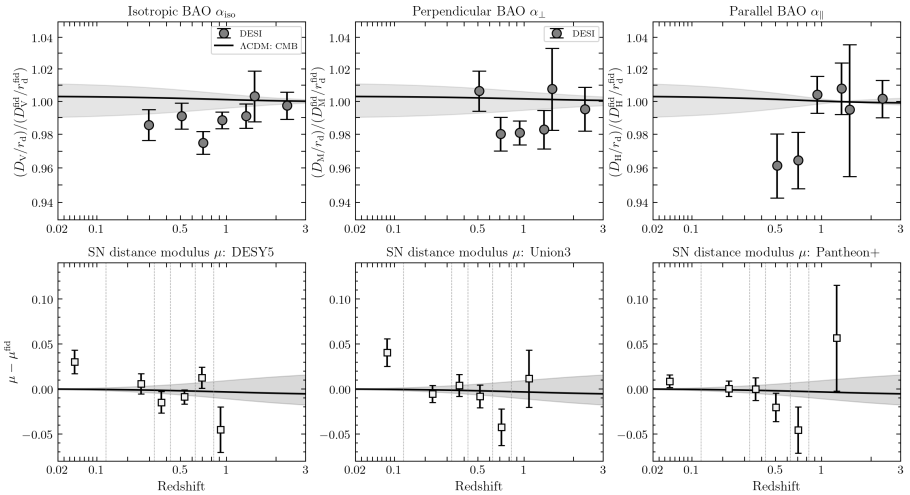


- Combining DESI with early-Universe CMB priors on $(\theta^*, \omega_b, \omega_{bc})$ shows preference for evolving dark energy at the 2.4σ level (3.1σ for the full CMB).
- Excluding $z < 0.1$ SNe reduces the statistical significance, but the best-fit values for $\omega_0\omega_a$ remain far from ΛCDM $\rightarrow 2.4\sigma$.
- Replacing the CMB with DESY3 3x2pt (weak lensing), we obtain a constraint coming entirely from low-redshift cosmological probes (BAO, weak lensing, SNe)$\rightarrow 3.3\sigma$.

DESI 2025

Where is the tension?



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

DESI 2025

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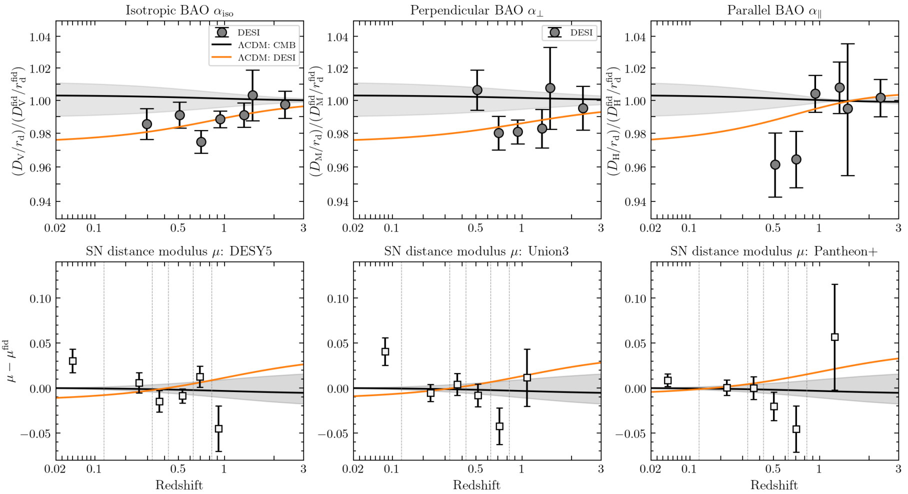

$$\Omega_m^{\rm CMB} = 0.3169 \pm 0.0065 \quad \Omega_m^{\rm DESI} = 0.2975 \pm 0.0086$$

DESI 2025

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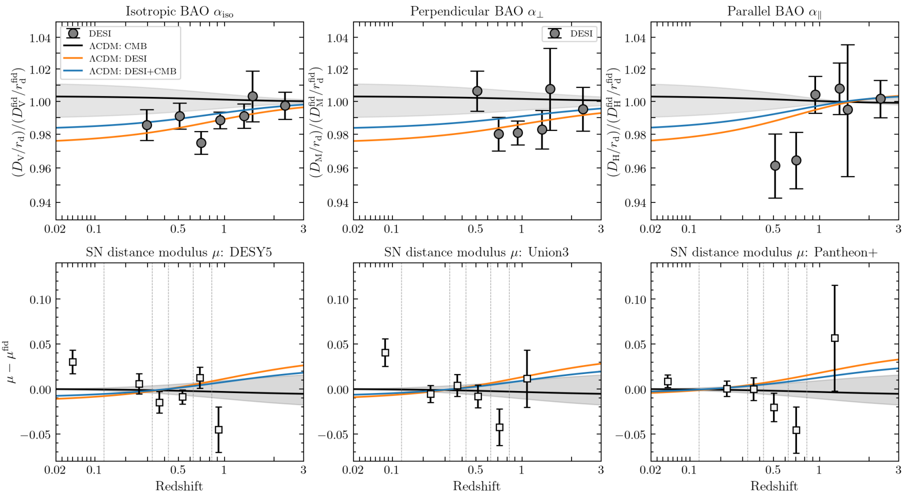

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DESI 2025

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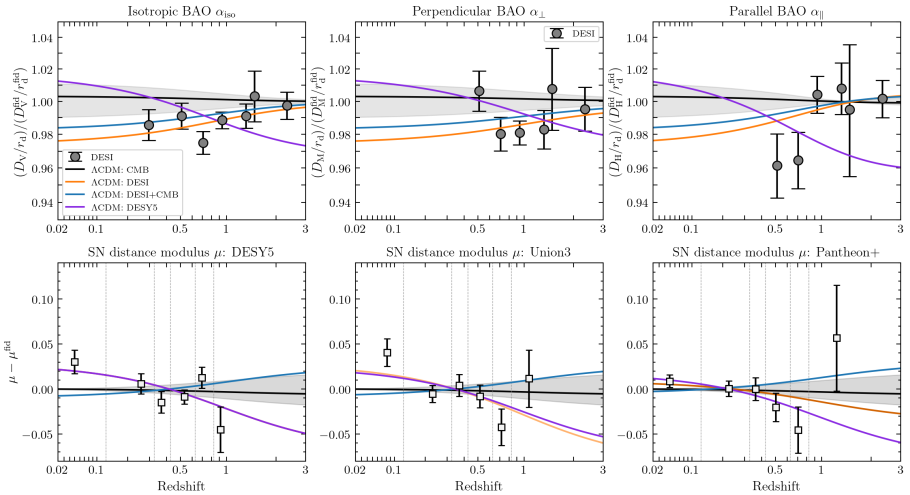

$$\Omega_m^{\rm CMB} = 0.3169 \pm 0.0065 \quad \Omega_m^{\rm DESI} = 0.2975 \pm 0.0086 \quad \Omega_m^{\rm DESY5} = 0.351 \pm 0.017$$

DESI 2025

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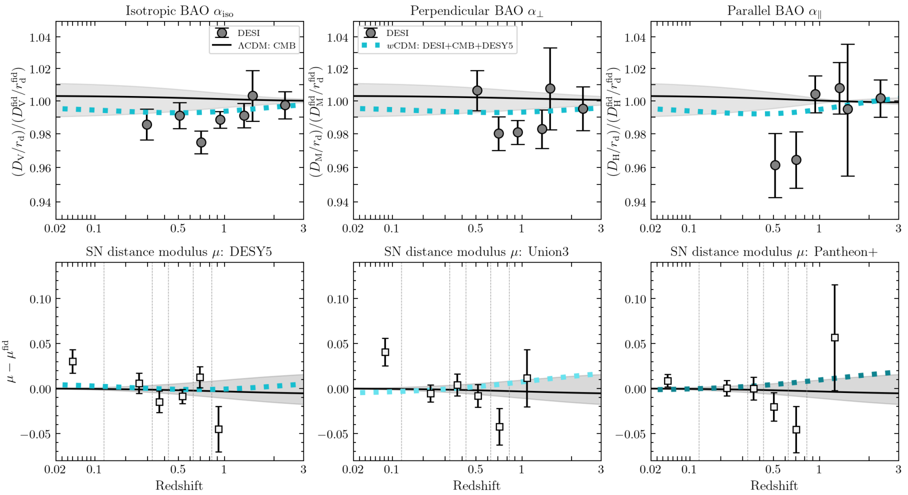
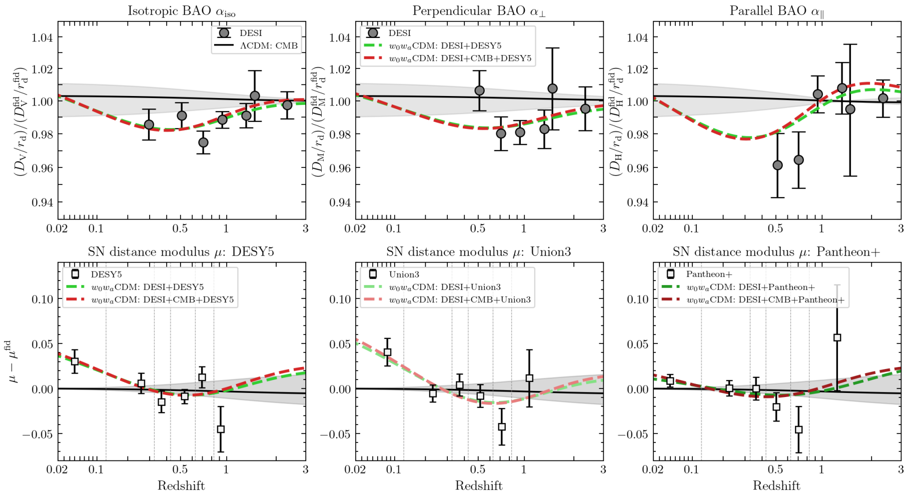


→ ωCDM does not have enough freedom to fit BAO, CMB and SN simultaneously.

DESI 2025

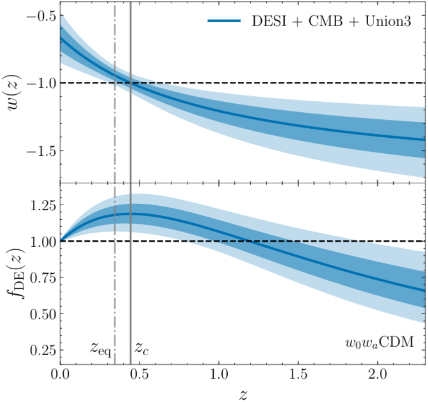
Where is the tension?

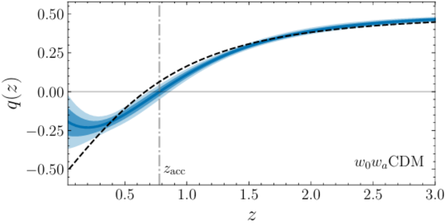


→ $\omega_0\omega_a$CDM has enough flexibility to fit simultaneously all three datasets.

DESI 2025

Implications

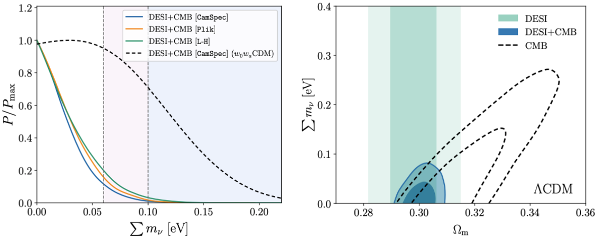




$$q(z) = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{d\ln H}{d\ln(1+z)} - 1$$

$$f_{\mathrm{DE}}(z) = \frac{\rho_{\mathrm{DE}}(z)}{\rho_{\mathrm{DE},0}}$$

DESI 2025



$|\Delta m^2_{31}| \simeq 2.56\times10^{-3}\,\mathrm{eV}^2$

$\Delta m^2_{21} \simeq 7.37\times10^{-5}\,\mathrm{eV}^2$

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

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

DESI 2025, PDG (2018), KATRIN 2022

Summary

1. DESI and CMB are in slight tension within ΛCDM (Ω_m-$H_0 r_d$ plane).

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2. Within ΛCDM, DESI+CMB give the tightest upper bounds for the sum of neutrino masses to date, in increasing tension with the lower bounds from neutrino oscillation experiments.

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1. DESI and CMB are in slight tension within ΛCDM (Ω_m-$H_0 r_d$ plane).
2. Within ΛCDM, DESI+CMB give the tightest upper bounds for the sum of neutrino masses to date, in increasing tension with the lower bounds from neutrino oscillation experiments.
3. The points above hint at a growing incompatibility between different datasets when interpreted within ΛCDM.

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2. Within ΛCDM, DESI+CMB give the tightest upper bounds for the sum of neutrino masses to date, in increasing tension with the lower bounds from neutrino oscillation experiments.
3. The points above hint at a growing incompatibility between different datasets when interpreted within ΛCDM.
4. Evidence for evolving dark energy has increased with the DR2 BAO data (3.1σ from DESI+CMB alone), 2.8σ to 4.2σ when also including SNe. This also reconciles the discrepancies between datasets mentioned above. Some red flags...

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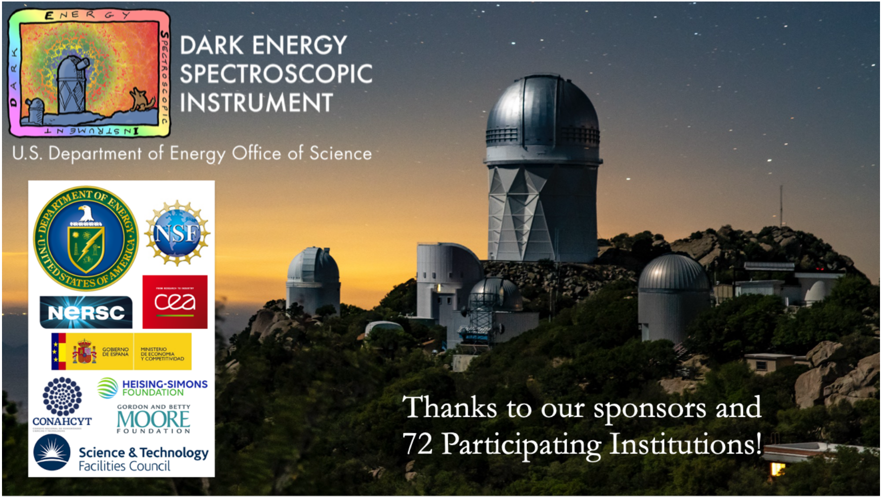
5. More to come! Y5 observing will end early 2026! A 2-year extension is already scheduled to extend the footprint and increase completeness, which will keep DESI busy till 2028.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