Cosmology with three years of DESI BAO data

DESI Collaboration

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The distance-redshift relation

One of our main goals is to probe the cosmic expansion history.

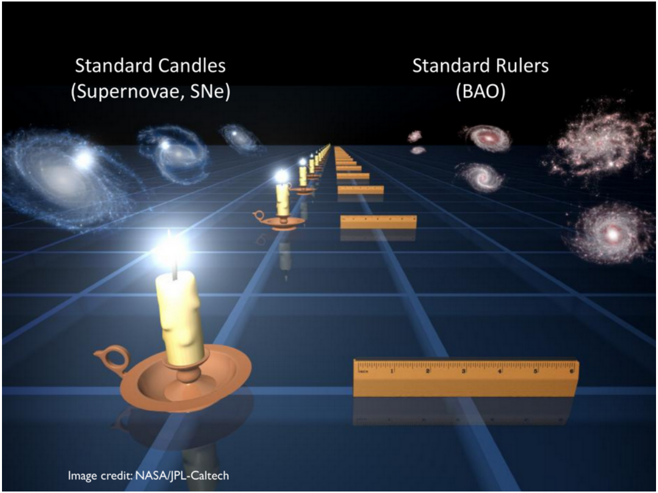
The distance-redshift relation depends on the energy density of various matter components:

$$D_{\mathrm{M}}(z) = \frac{c}{H_0} \int_0^z \mathrm{d}z' \frac{H_0}{H(z')},$$

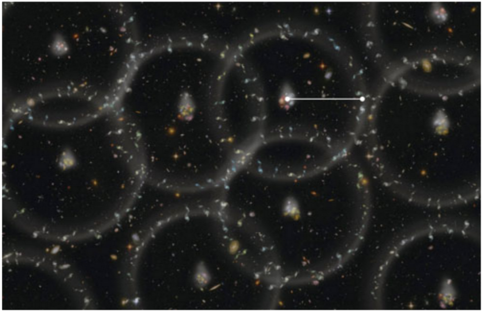
$$\frac{H(z)^2}{H_0^2} = \Omega_{\mathrm{r}}(1+z)^4 + \Omega_{\mathrm{m}}(1+z)^3 + \Omega_{\mathrm{DE}}(z),$$

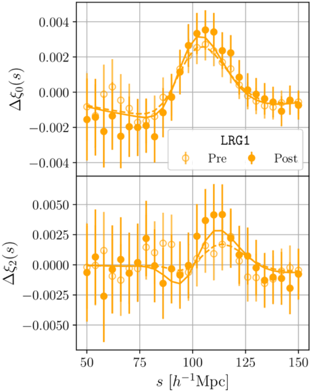
where Ω_{r} is the density of radiation, Ω_{m} the density of matter (including massive neutrinos), and Ω_{DE} that of dark energy.

The distance-redshift relation



Baryon Acoustic Oscillations (BAO)





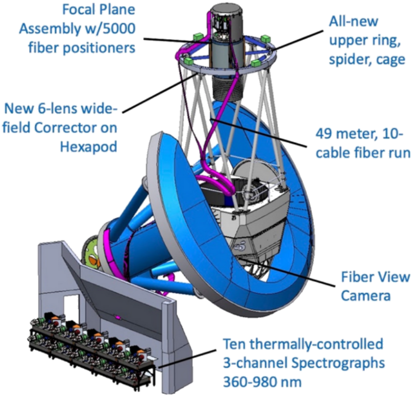
Artist's impression (left) and DESI DR1 measurements (right).

Dark Energy Spectroscopic Instrument

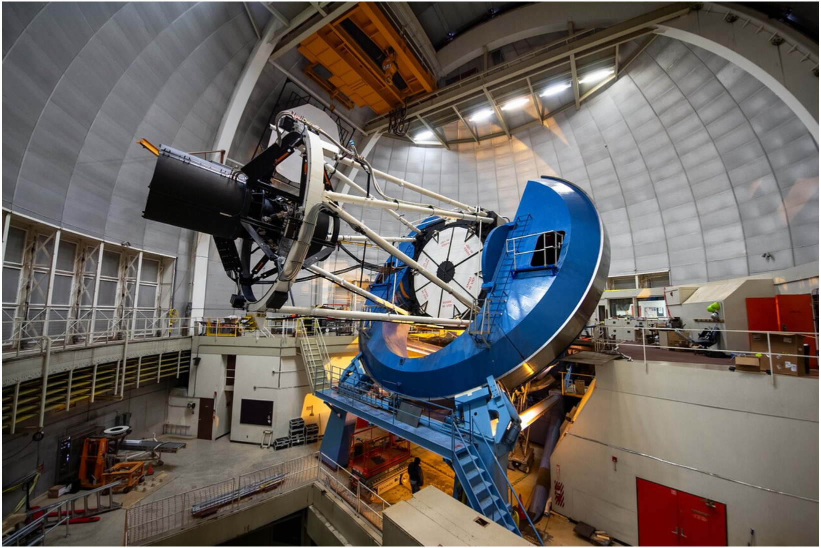
DESI is a fiber-fed multi-object spectrograph, installed on the Mayall 4-meter telescope.

It uses 5000 robotic arms to position fibers on the focal plane.

The fibers are fed to ten 3-channel spectrographs.



Dark Energy Spectroscopic Instrument



The DESI DR2 sample

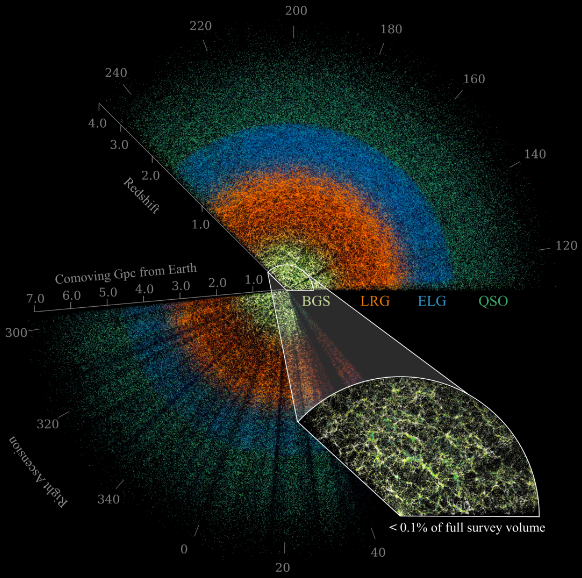
DESI observed over 30M galaxy and quasar redshifts after 3 years, 14M of which are used in the latest analysis.

This represents a factor 2.4 improvement over DR1.

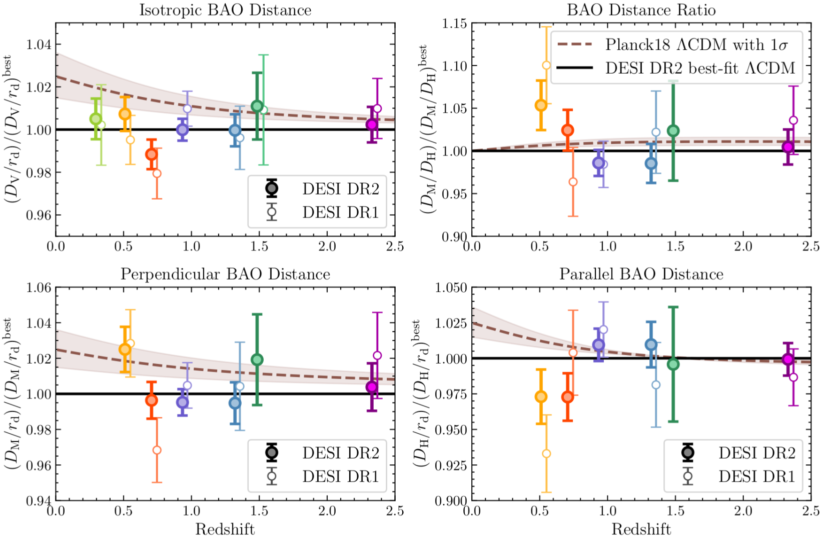
Tracer	DR1	**DR2**
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**

Dark Energy Spectroscopic Instrument

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



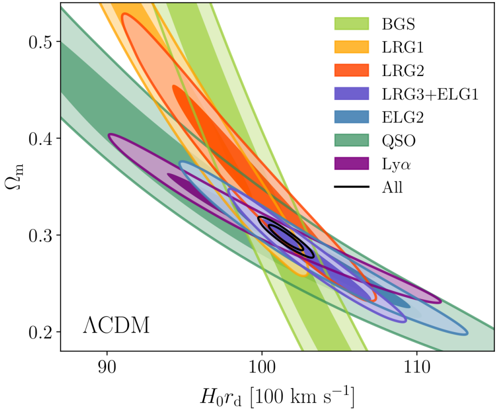
BAO distance measurements



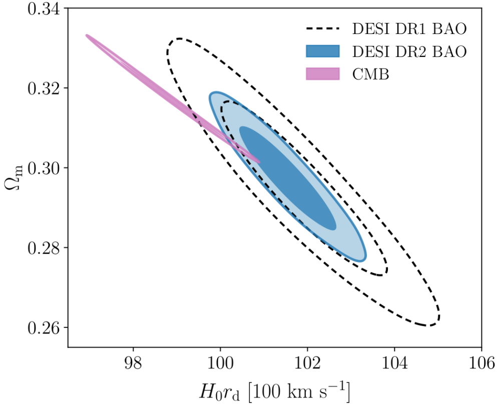
Mutual Consistency of DESI Tracers

Increasing the effective redshift of the sample induces a counter clockwise rotation in the degeneracy direction.

All DESI tracers are mutually consistent. Their combination provides the tightest constraints.



Constraints in ΛCDM



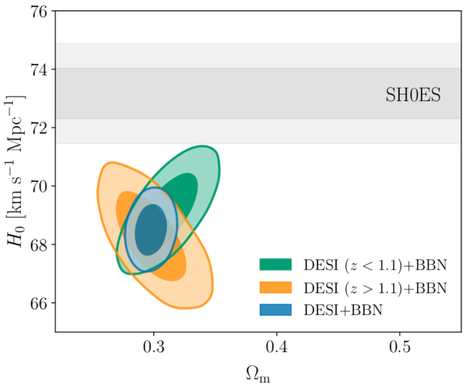
Compared to DR1, there is a 40% improvement in precision in Ω_m and $H_0 r_d$.

Discrepancy with the CMB: 2.3σ.

$$\Omega_m = 0.2975 \pm 0.0086,$$
$$H_0 r_d = (101.54 \pm 0.73)\,\text{Mpc}.$$

Constraints in ΛCDM

We can also constrain H_0 independently of the CMB, finding $H_0 = (68.51 \pm 0.58)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This is still in tension with SH0ES.

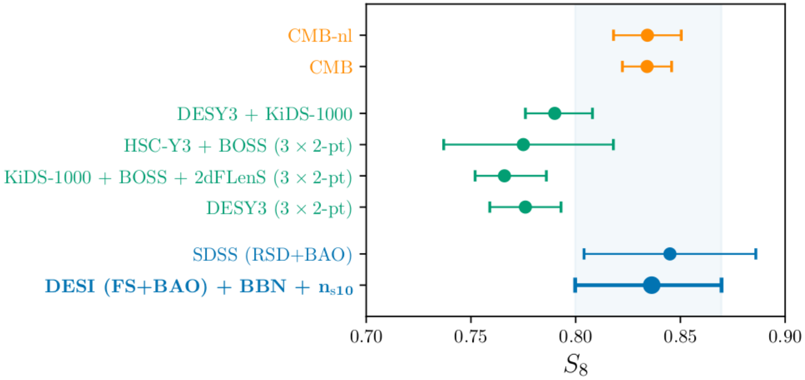


Constraints in ΛCDM

The combination of the amplitude of clustering, σ_8, and the matter density, Ω_m, that is best measured by weak lensing surveys is

$$S_8 = \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}.$$

With DESI DR1 full-shape power spectrum analysis, we find $S_8 = 0.836 \pm 0.035$ consistent with the CMB.



Dark energy results

DR1 Dark energy results

We characterize dark energy by its equation of state, $w = P/\rho$.
A cosmological constant has $w = -1$.

Last year, DESI found hints of dynamical dark energy with an equation of state that evolves as

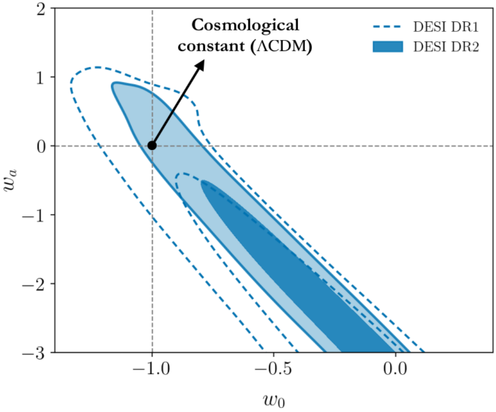
$$w(a) = w_0 + w_a(1 - a),$$

when combining DESI DR1 data with CMB and SN Type 1a.

Dynamical dark energy

BAO data alone do not rule out ΛCDM with DR1 nor DR2.

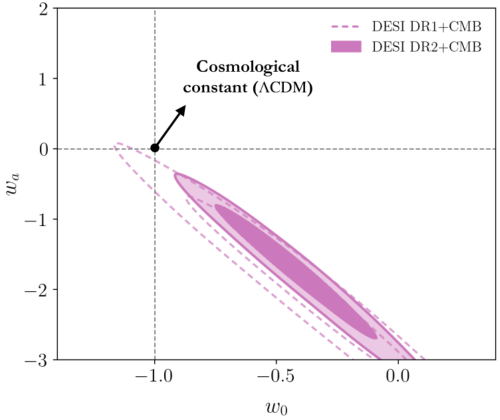
But defines a degeneracy direction in the (w_0, w_a)-plane, restricting joint constraints with other probes.



Dynamical dark energy

Combined with CMB data, there is a clear preference for $w_0 > -1$ and $w_a < 0$.

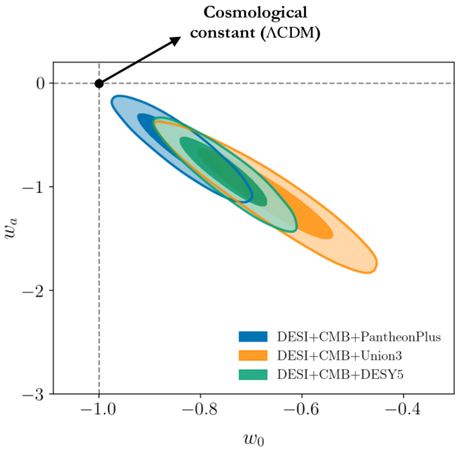
The preference for $w_0 w_a$CDM from BAO+CMB increases from 2.6σ (DR1) to 3.1σ (DR2).



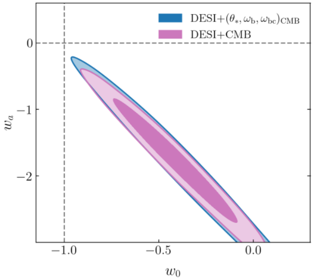
Dynamical dark energy

Significance of rejection of ΛCDM:

- DESI+CMB+Pantheon+: 2.8σ
- DESI+CMB+Union3: 3.8σ
- DESI+CMB+DESY5: 4.2σ

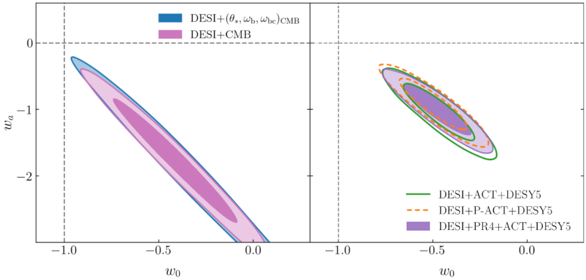


Dynamical dark energy



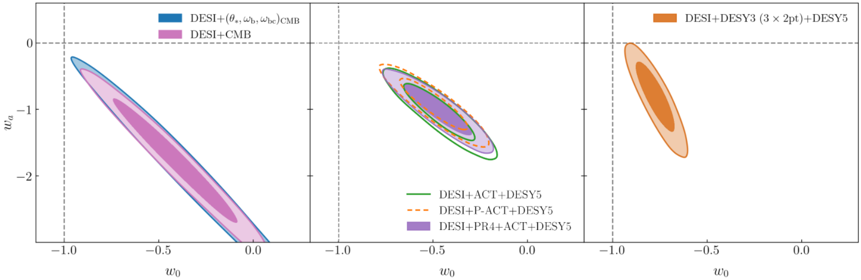
Combining with robust early-Universe priors on $(\theta_*, \omega_{\mathrm{b}}, \omega_{\mathrm{bc}})$ derived from the CMB shows a preference for evolving dark energy with a significance of 2.4σ.

Dynamical dark energy



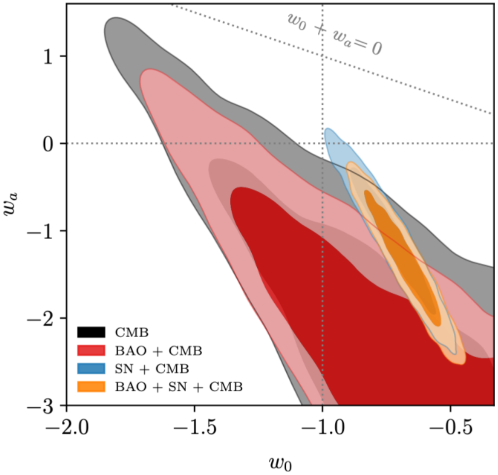
With the latest CMB results from ACT DR4, the preference for $w_0 w_a$CDM remains and is not sensitive to the degree to which *Planck* data is replaced with ACT.

Dynamical dark energy



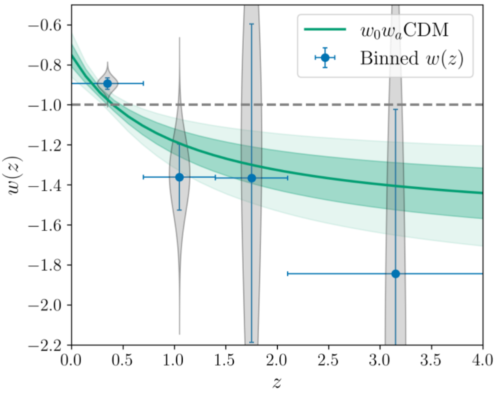
Replacing the CMB with DESY3 3×2pt (weak lensing), we obtain a constraint coming entirely from low-redshift cosmological probes (BAO, weak lensing, SNe).

DES Collaboration (2025)



Recently, the Dark Energy Survey (DES) also found a preference for $w_0 w_a$CDM from CMB+BAO+SNe at the 3.2σ-level, independent of DESI.

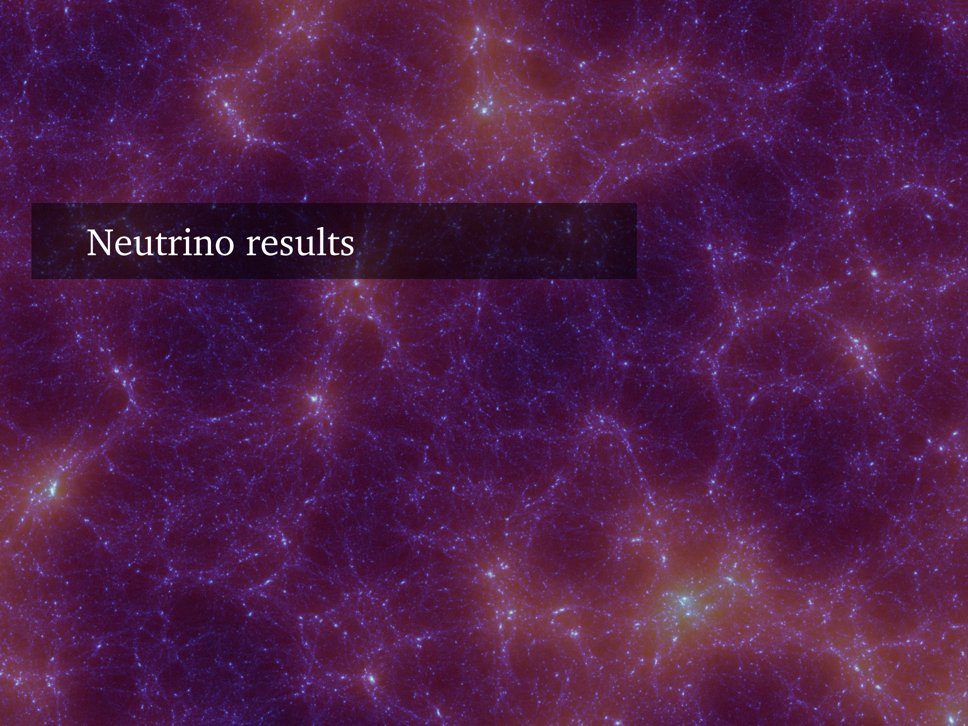
Binned constraints on $w(z)$



Binned reconstruction of $w(z)$ consistent with our w_0w_aCDM constraints.

Supporting paper: Extended Dark Energy analysis using DESI DR2 BAO measurements (Lodha et al., 2025).

Neutrino results



Cosmic neutrinos at different epochs

In ΛCDM, neutrinos are non-negligible throughout cosmic history. We can probe both the effective number of neutrino species, N_{eff}, and the sum of their masses, $\sum m_\nu$.

Observable	Temperature	Properties
Big Bang Nucleosynthesis	$\mathcal{O}(1\,\text{MeV})$	N_{eff}
Cosmic Microwave Background	$\mathcal{O}(1\,\text{eV})$	$\sum m_\nu, N_{\text{eff}}$
Large-scale structure	$\ll 1\,\text{eV}$	$\sum m_\nu, (N_{\text{eff}})$
Late-time expansion history	$\ll 1\,\text{eV}$	$\sum m_\nu$

Cosmology can also probe many BSM neutrino properties: lifetime, interactions, etc.

Neutrino masses in cosmology

After neutrinos become non-relativistic, their energy density is

$$\rho_\nu \cong \frac{\sum m_\nu}{93.14h^2}(1+z)^3,$$

where $h = H_0/(100\,\mathrm{km\,s^{-1}\,Mpc^{-1}})$ is the Hubble parameter.

The cosmic neutrino density is related to N_{eff} at early times and $\sum m_\nu$ at late times.

Latest DESI Constraints

I will show results for three kinds of analyses:

- Cosmic Microwave Background (CMB) only
- DESI Full Shape (FS) with limited CMB information
- Full combination of DESI and CMB

Latest DESI Constraints

With DR2 DESI has improved its constraints on $\sum m_\nu$ and N_{eff}.

DESI DR2 BAO + CMB:

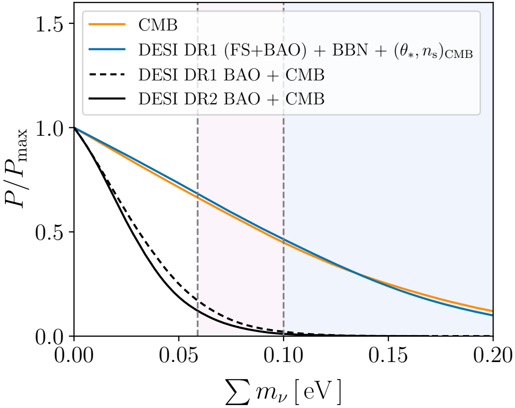
$$N_{\mathrm{eff}} = 3.23^{+0.35}_{-0.34}\ (95\%),$$

consistent with the SM prediction $N_{\mathrm{eff}} = 3.044$.

And our strongest bound,

$$\sum m_\nu < 0.064\,\mathrm{eV}\ (95\%),$$

to date on the sum of neutrino masses.



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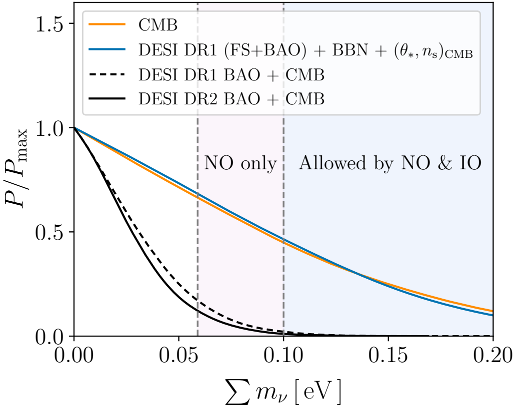


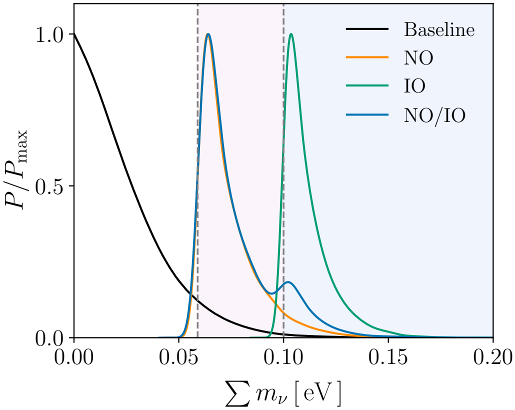
Preference for normal ordering

Using global constraints on the mass splittings, Δm_{21}^2 and $|\Delta m_{31}^2|$, we place constraints on the lightest neutrino mass, m_l.

DESI DR2 BAO + CMB:

$$m_l < 0.023\,\mathrm{eV}\ (95\%),$$

and a Bayes factor of 10 in favor of the NO.



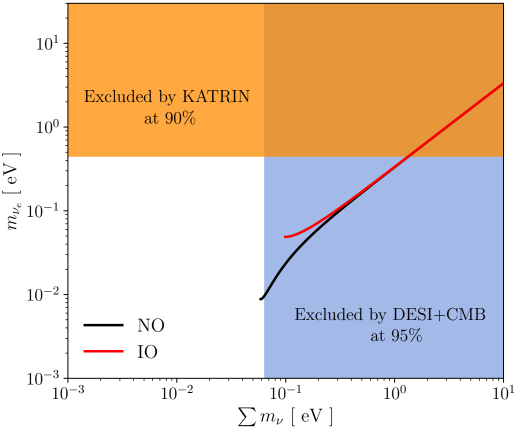
Comparison with KATRIN

We can also compare with the KATRIN constraint on the effective electron anti-neutrino mass, $m_{\nu,e}$.

DESI DR2 BAO + CMB:

$$\sum m_\nu < 0.064\,\mathrm{eV}\ (95\%),$$

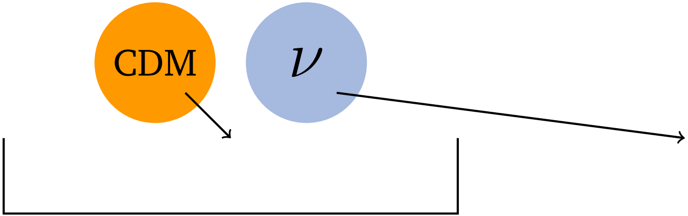
and a Bayes factor of 10 in favor of the NO.



Neutrino free streaming

Where is the information coming from?

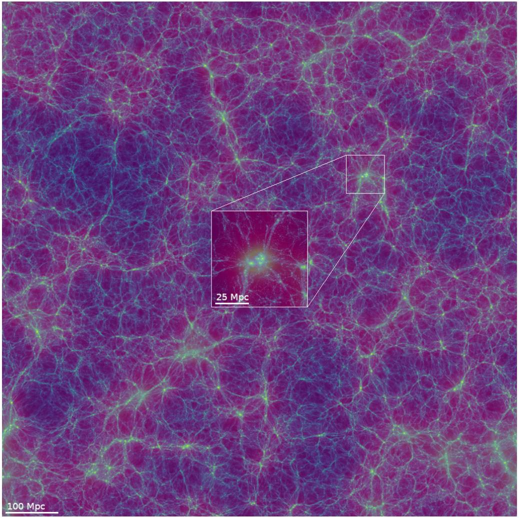
Neutrino free streaming provides a distinctive signature.



Neutrinos are a form of hot dark matter. They free stream over shallow gravitational potential wells because of their large thermal velocities.

Simulating the free streaming effect

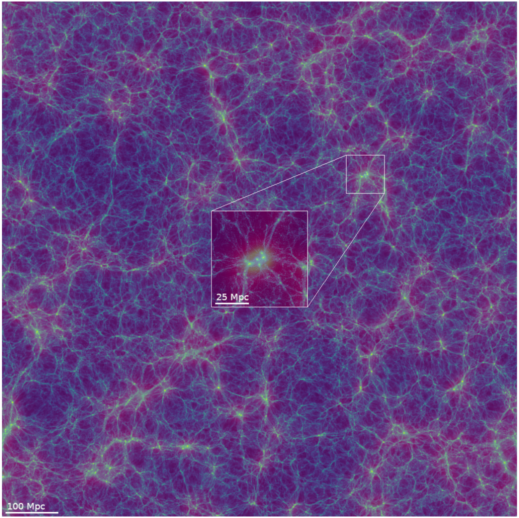
Small neutrino mass, $\sum m_\nu = 0.06\,\mathrm{eV}$



Images from the FLAMINGO simulations.

Simulating the free streaming effect

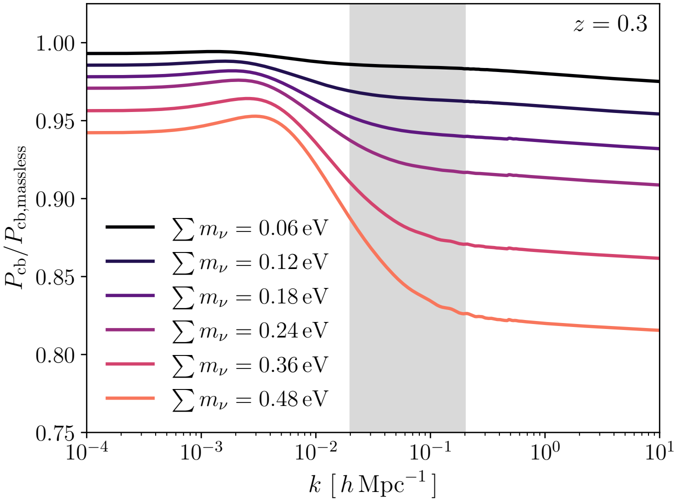
Large neutrino mass, $\sum m_\nu = 0.48\,\mathrm{eV}$



Images from the FLAMINGO simulations.

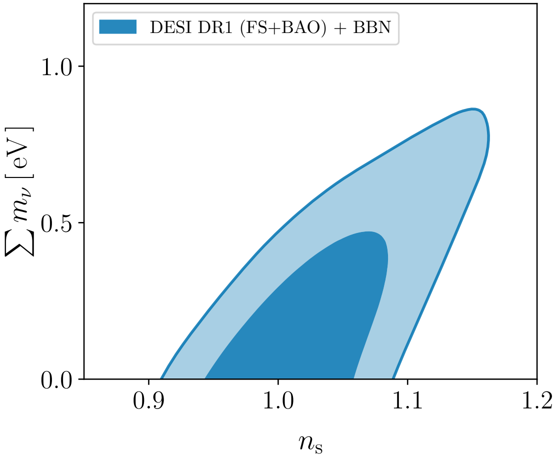
Neutrino mass from free streaming

Massive neutrinos change the shape of the power spectrum on scales measured by DESI.



Neutrino mass from free streaming

Information on $\sum m_\nu$ can be derived from the shape of the galaxy power spectrum.



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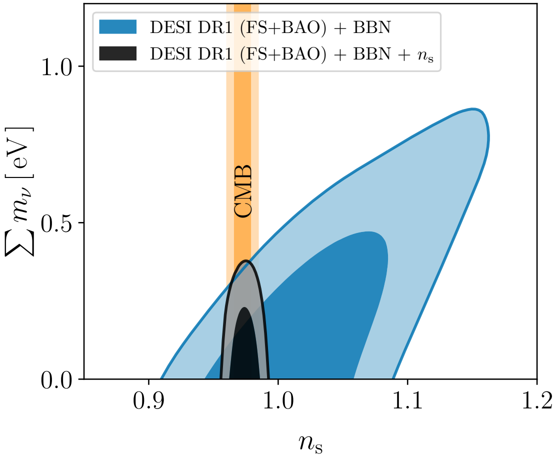
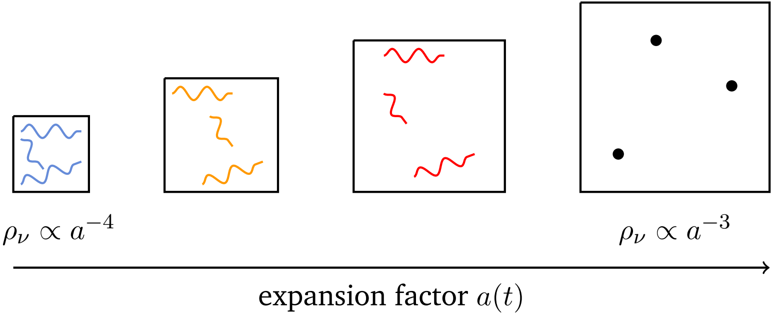


Here, n_s is a Gaussian prior on the slope of the power spectrum.

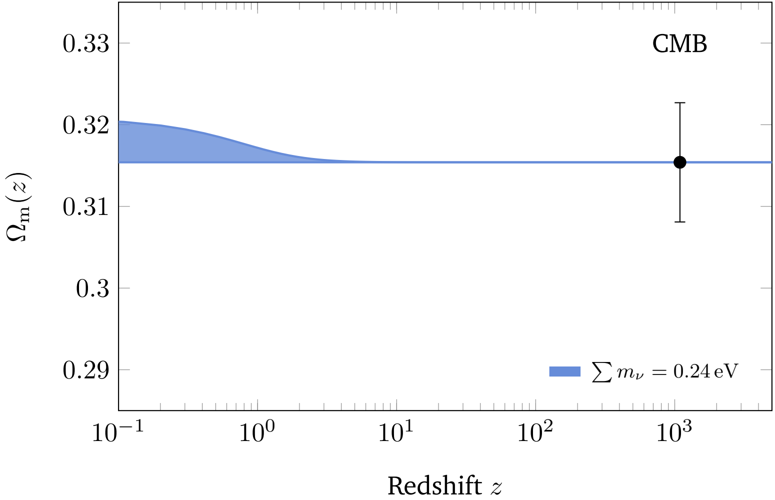
Scaling of neutrino density

The energy density of neutrinos dilutes more slowly after they become non-relativistic (at $z \sim 100$ for $m_\nu = 0.06\,\mathrm{eV}$).



Evolution of the matter density

In ΛCDM, we expect a late-time increase in the matter density due to massive neutrinos.



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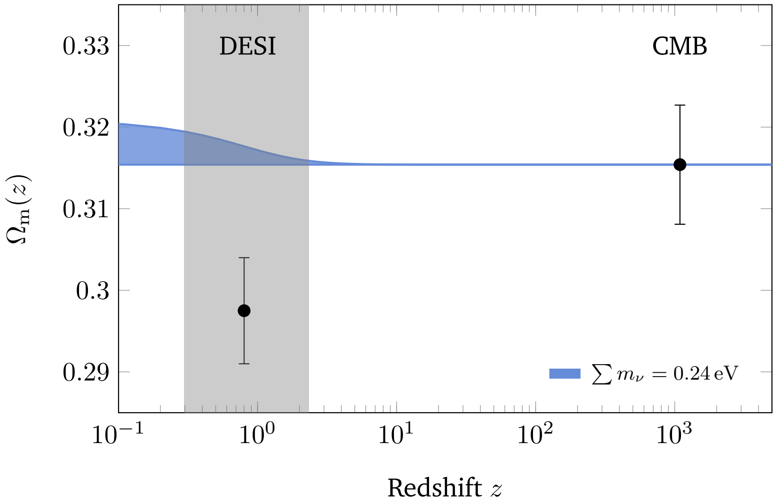


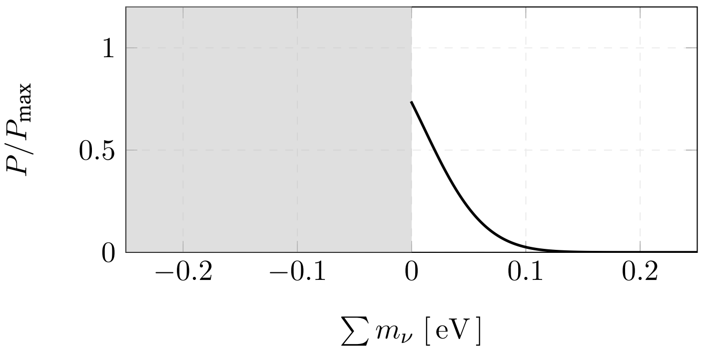
Effective neutrino masses

Motivating different priors

Our choice of prior depends on the question.

Are cosmic neutrinos compatible with experimental data?

$$\sum m_\nu \overset{?}{>} 0\,\mathrm{eV}.$$



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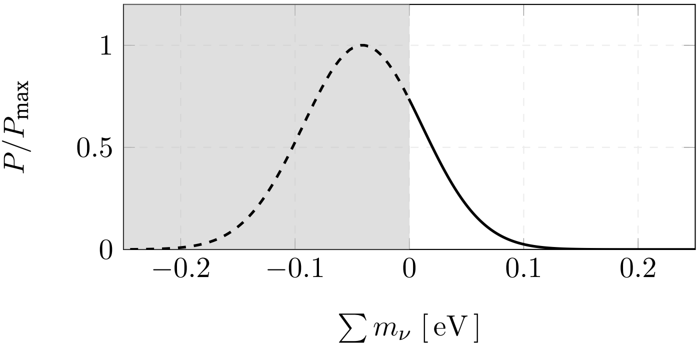


Effective neutrino masses: definitions

Let's follow the data.

The Einstein equations only depend on the neutrino energy:

$$\epsilon = \sqrt{p^2 + a^2 m_\nu^2}.$$

To model 'negative effective neutrino masses', we introduce an effective neutrino energy

$$\epsilon_{\text{eff}} = -\sqrt{p^2 + a^2 m_\nu^2} \ \text{ if } \ m_\nu < 0, \ \text{ else } \ \sqrt{p^2 + a^2 m_\nu^2}.$$

The result is a reversal of all familiar neutrino effects.

This is merely a mathematical continuation of the model. We do not actually propose that neutrino masses are negative.

Effective neutrino masses

We do not actually propose that neutrino masses are negative. This is similar to N_{eff}, where we do not propose that there exists half a neutrino.

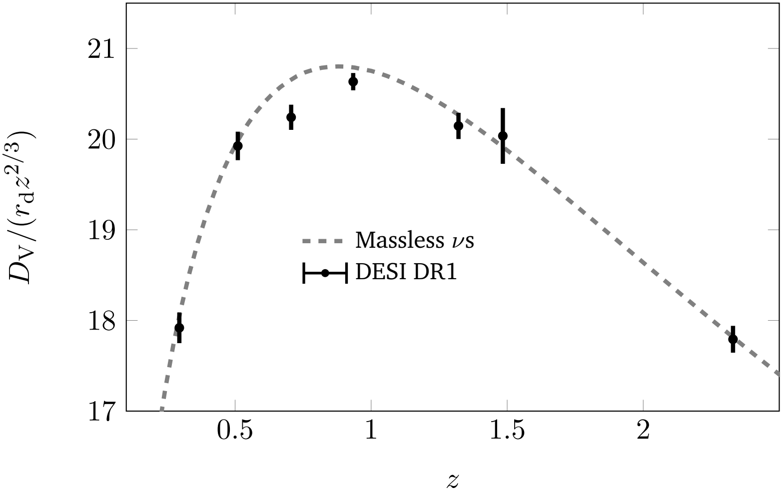
> "... any evidence for negative values should be interpreted as a signature of unidentified systematic errors or possibly of new physics which may be unrelated to neutrinos ..."

It's a signal that the data prefer:

- Reduced late-time $\Omega_{\text{m}} \in H(z)^2 a^3 / H_0^2$
- Enhanced clustering on small scales

Effect on distances

We illustrate the effect on the isotropic BAO distances, $D_{\rm V}/r_{\rm d}$.
The fit improves for $\sum m_{\nu,\rm eff} < 0$.



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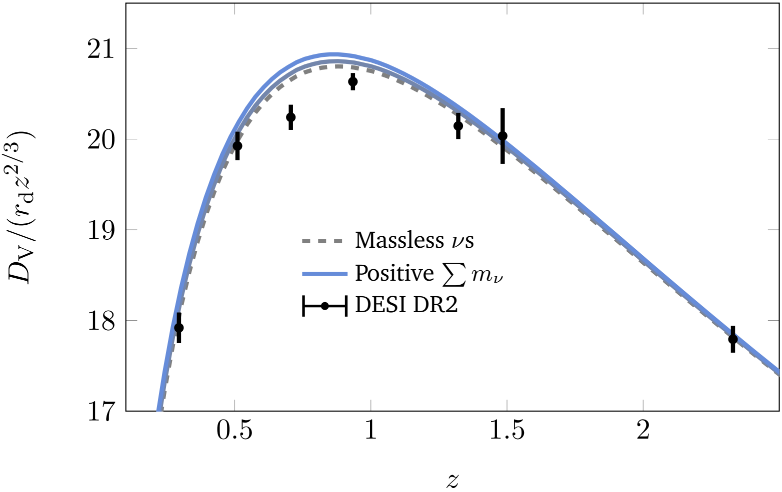

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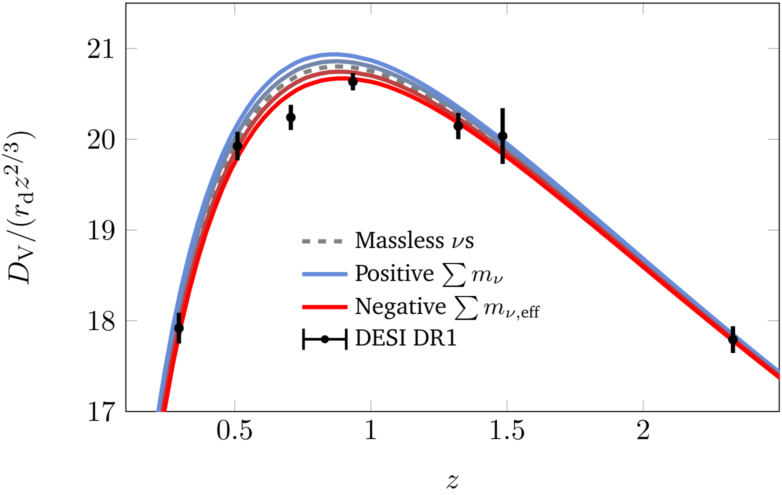


Preference for negative effective masses

The DR2 BAO + CMB results are in 3.0σ tension with the oscillations bound, $\sum m_\nu > 0.059\,\mathrm{eV}$.

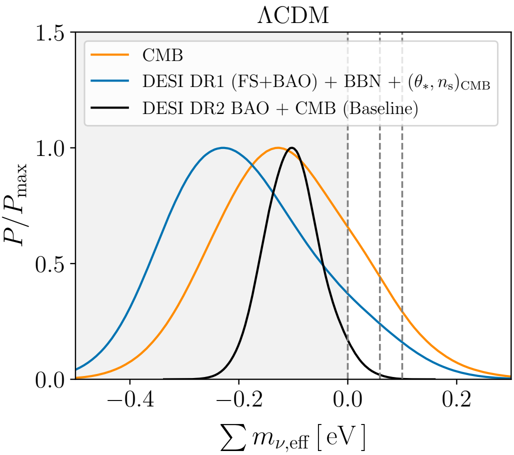
DESI DR2 BAO + CMB:

$$\sum m_{\nu,\mathrm{eff}} = -0.10^{+0.05}_{-0.06}\,\mathrm{eV}.$$

CMB alone:

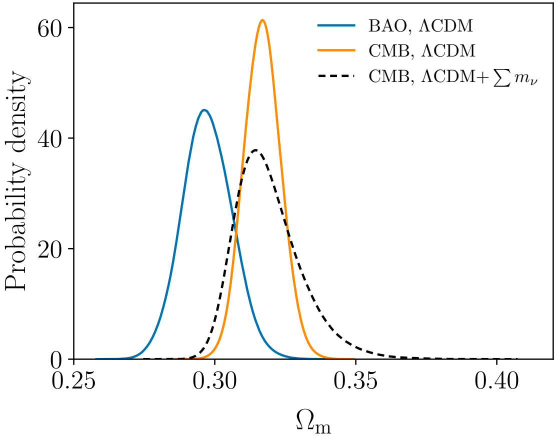
$$\sum m_{\nu,\mathrm{eff}} = -0.11^{+0.12}_{-0.14}\,\mathrm{eV},$$

both at 68%.



Agreement on Ω_m

Both CMB and DESI agree on Ω_m when allowing negative effective neutrino masses.



Allowing $\sum m_{\nu,\mathrm{eff}} < 0$ resolves internal CMB tensions.

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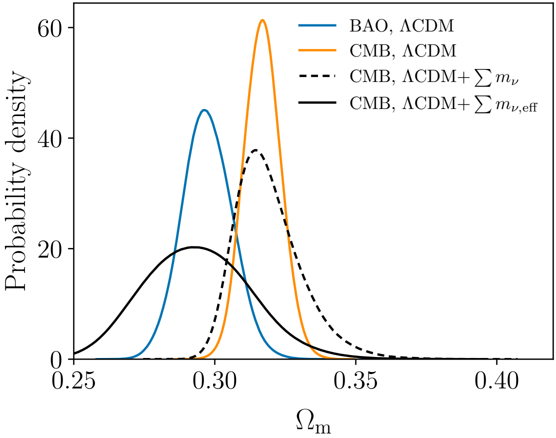
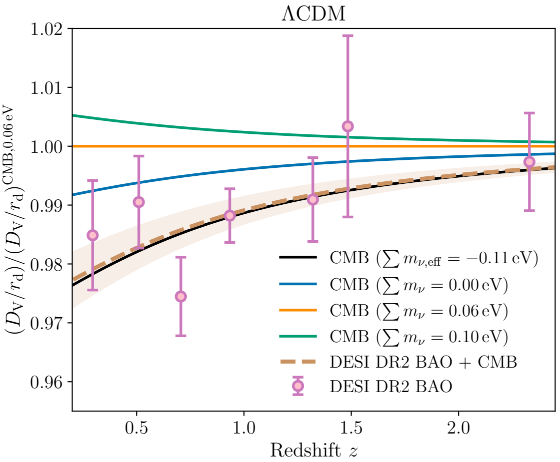


Allowing $\sum m_{\nu,\mathrm{eff}} < 0$ resolves internal CMB tensions.

Agreement on $H_0 r_\mathrm{d}$

Both CMB and DESI agree on $H_0 r_\mathrm{d}$ at the same negative effective neutrino mass.



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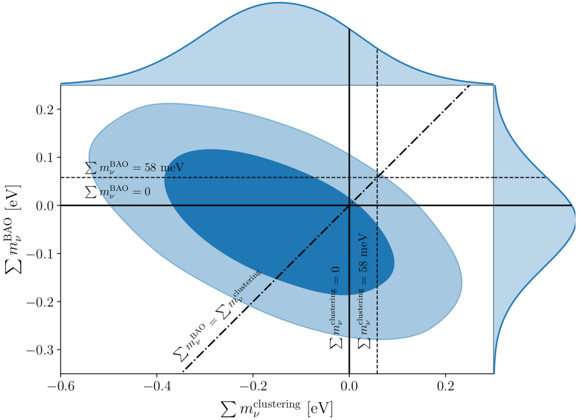
Separating the effects

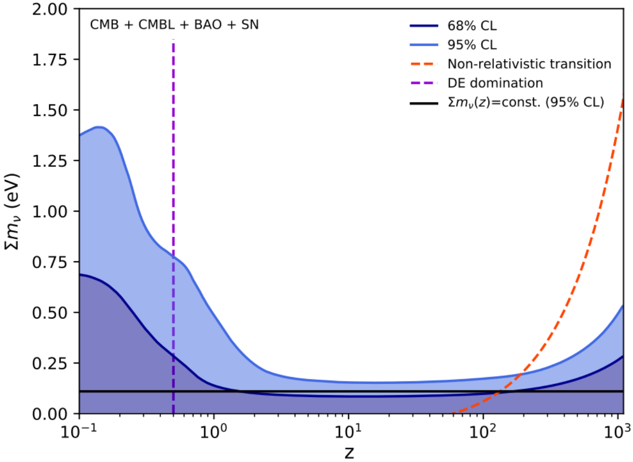
Another approach is to fit separately for the neutrino effects on the expansion history and on clustering (Graham et al., 2025).



Addressing either the preference for negative masses from clustering or expansion could be enough to solve the other.

Relaxing the bounds

Neutrino mass bounds can be relaxed with non-standard neutrino properties, e.g. decay or late-time generation.



Lorenz et al. (2021)

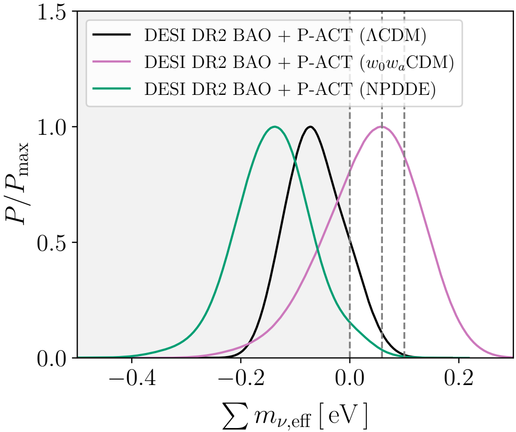
Relation to dark energy

Positive neutrino masses are allowed when going from ΛCDM to $w_0 w_a$CDM, but only if one allows $w < -1$.

DESI DR2 BAO + P-ACT:

$$\sum m_{\nu,\mathrm{eff}} = 0.04^{+0.10}_{-0.08}\,\mathrm{eV},$$

assuming $w_0 w_a$CDM.



Latest developments

Latest CMB data

This year, we saw new CMB data from ACT and SPT. Compared to *Planck*, the tension with DESI has increased.

DESI DR2 + latest CMB:

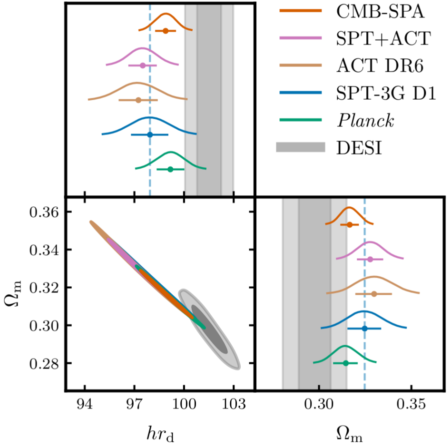
$$w_0 = -0.41 \pm 0.20,$$
$$w_a = -1.78 \pm 0.55,$$

preferred at 3.2σ over ΛCDM.

Standard neutrino masses,

$$\sum m_\nu < 0.048\,\mathrm{eV} \quad (95\%),$$

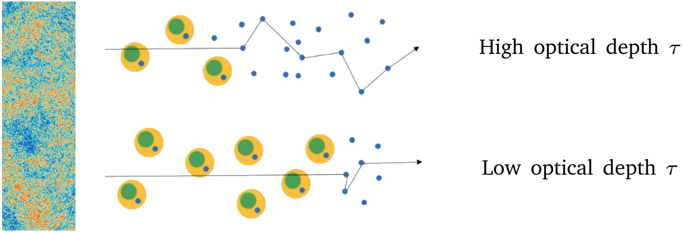
in tension with oscillation bounds.



Source: SPT / Camphuis et al. (2025)

CMB optical depth

Free electrons generated during reionization scatter Cosmic Microwave Background (CMB) photons.



Source: Emma Chapman

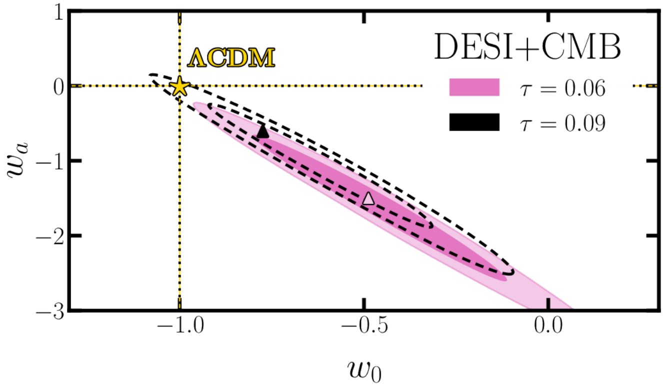
The amount of scattering is quantified by the optical depth,

$$\tau = n_{\mathrm{H}} c \sigma_{\mathrm{T}} \int_0^{z_{\max}} \mathrm{d}z \, x_{\mathrm{e}}(z) \frac{(1+z)^2}{H(z)},$$

where $x_{\mathrm{e}}(z)$ is the electron density and n_{H} the hydrogen density.

Tensions between DESI and CMB

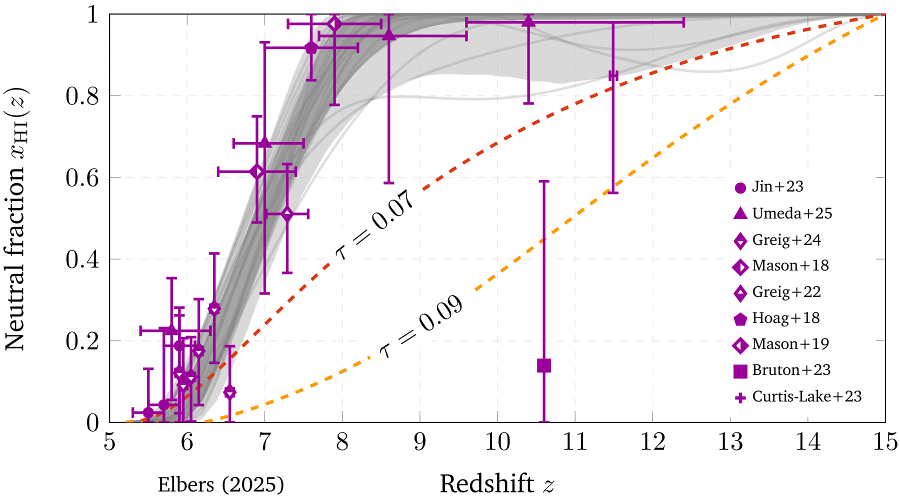
This weakens the evidence for evolving dark energy from the combination of DESI and CMB data (Sailer+25, Jhaveri+25).



To recover ΛCDM within 2σ, one must exclude both supernovae and large-scale CMB measurements.

Gaussian process reconstruction

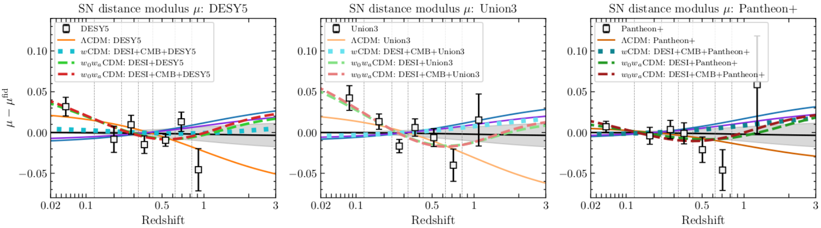
But gradual histories with $\tau \approx 0.07$ and $\tau \approx 0.09$, required to reconcile DESI BAO and CMB data, are ruled out by $x_{\rm HI}(z)$ data.



Elbers (2025)

Supernova outlook

Supernovae are crucial to probe the recent evolution at $z < 0.1$, but calibration between different samples remains challenging.



The release of new cosmology-ready SN samples from ZTF (DR2.5) and Rubin-LSST are highly anticipated.

Forthcoming DESI releases

DESI will soon present various new analyses:

- Full-shape power spectrum analysis based on DR2
- Higher-order clustering information from the bispectrum
- Cross-correlation with CMB lensing and cosmic shear
- BAO from DR3 (5-year sample)

The survey has been extended and will run for 8 years ($\sim$2028), with plans for DESI-II to begin in 2029.

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Conclusions

- Evidence for evolving dark energy has increased with DR2 BAO: 3.2σ from DESI+CMB alone.
- DESI has placed its strongest limit on the sum of neutrino masses assuming the cosmological ΛCDM model:

$$\sum m_\nu < 0.064\,\mathrm{eV}\ (95\%).$$

- Cosmological data seem to indicate a preference for 'negative effective neutrino masses'
- This result challenges the ΛCDM model and could point to evolving dark energy