

Neutrino cosmology with three years of DESI BAO data

DESI Collaboration

Willem Elbers

Institute for Computational Cosmology, Durham University

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DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



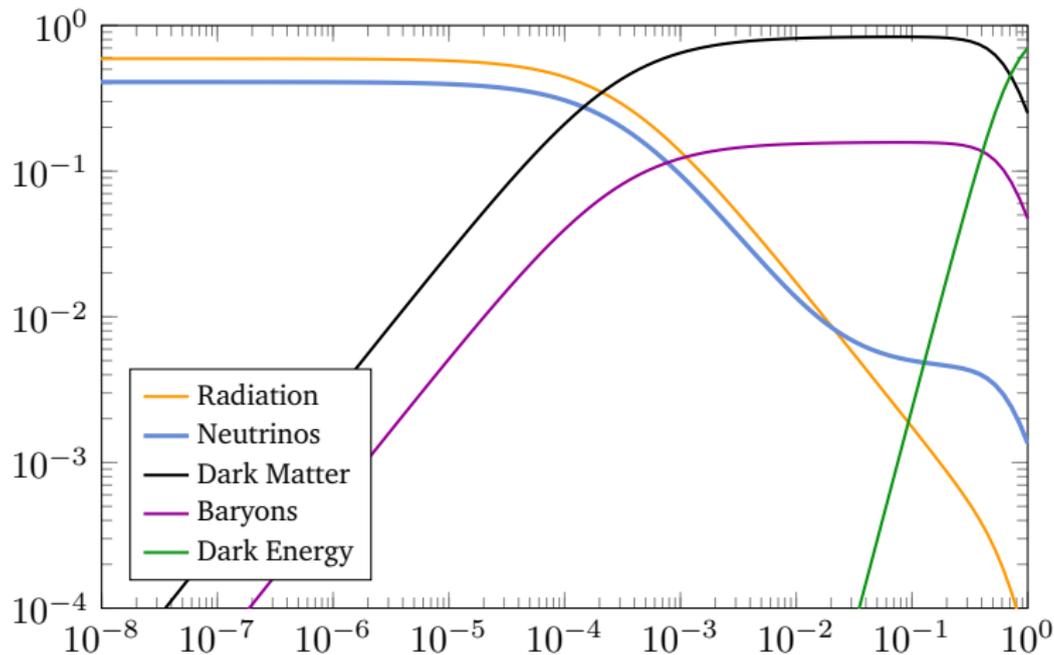
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Components of Λ CDM

In Λ CDM, the neutrino contribution is non-negligible today and much greater in the early Universe.



Cosmic neutrinos at different epochs

We can observe the cosmic neutrino background throughout cosmic history, probing both the effective number of neutrino species, N_{eff} , and the sum of their masses, $\sum m_\nu$.

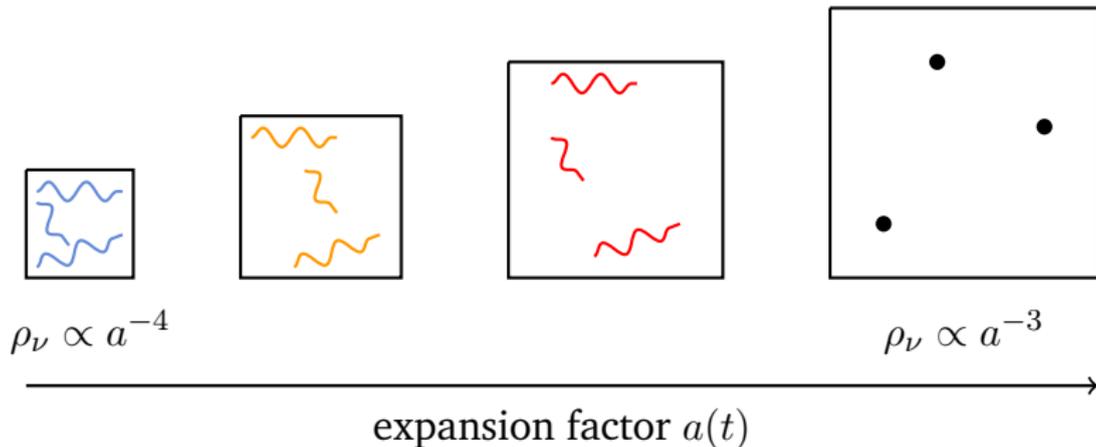
Observable	Temperature	Properties
Big Bang Nucleosynthesis	$\mathcal{O}(1 \text{ MeV})$	N_{eff}
Cosmic Microwave Background	$\mathcal{O}(1 \text{ eV})$	$\sum m_\nu, N_{\text{eff}}$
Large-scale structure	$\ll 1 \text{ eV}$	$\sum m_\nu, (N_{\text{eff}})$
Late-time expansion history	$\ll 1 \text{ eV}$	$\sum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

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



Scaling of neutrino density

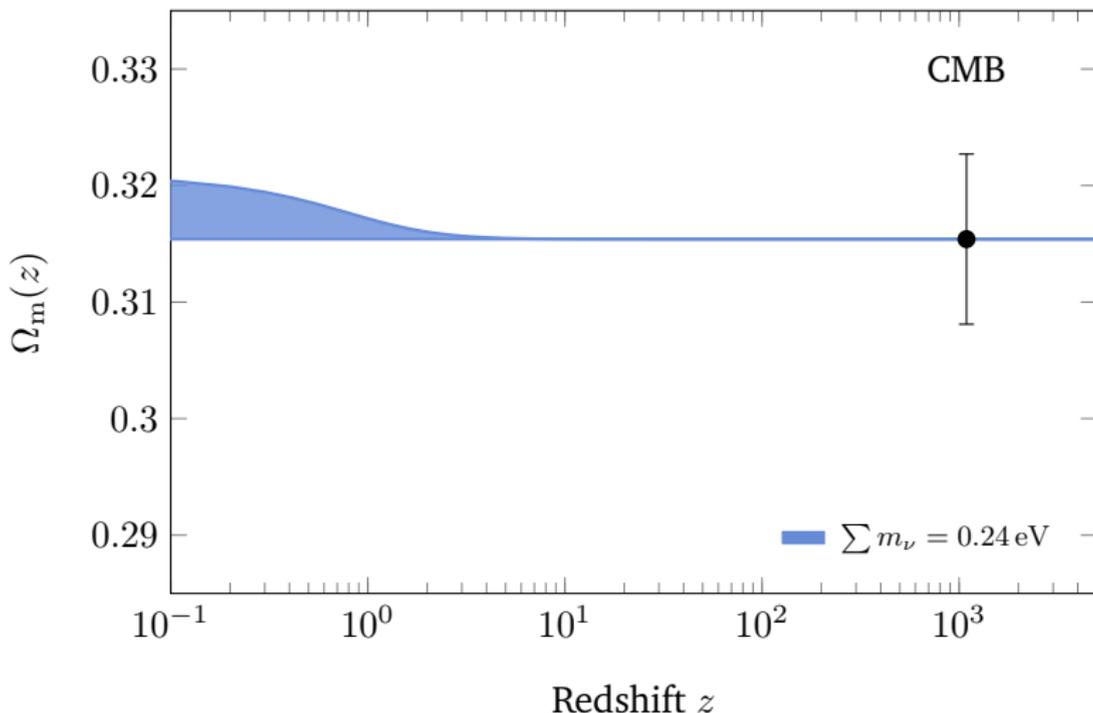
The energy density of neutrinos dilutes more slowly after they become non-relativistic (at $z \sim 100$ for $m_\nu = 0.06$ eV).





Evolution of the matter density

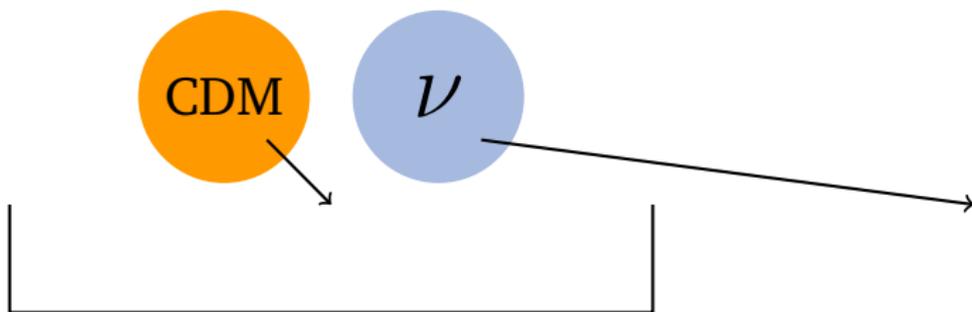
In Λ CDM, we expect a late-time increase in the matter density due to massive neutrinos.





Neutrino free streaming

Neutrino free streaming provides another distinctive signature.

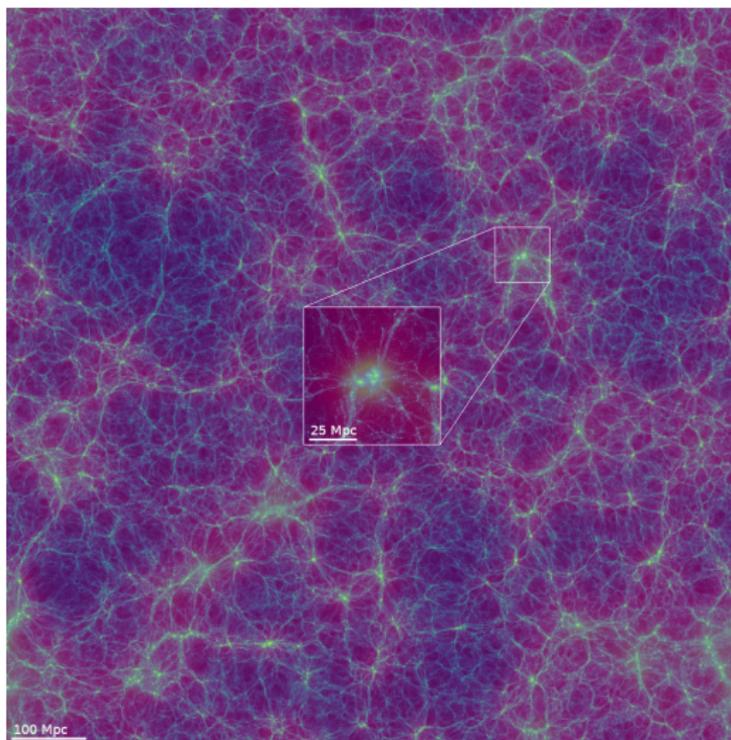


Neutrinos are a form of hot dark matter. They free stream over shallow gravitational potential wells because of their large thermal velocities.



Simulating the free streaming effect

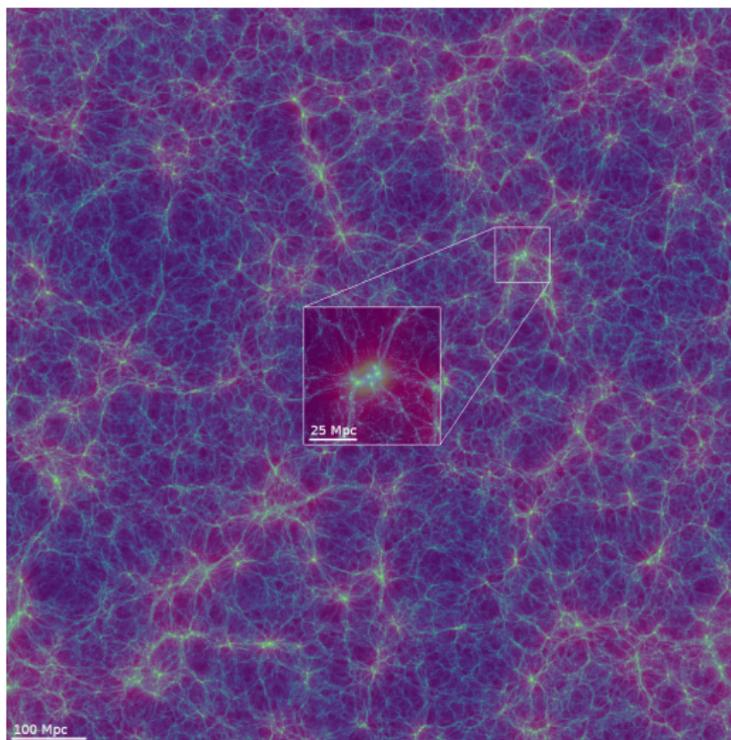
Small neutrino mass, $\sum m_\nu = 0.06 \text{ eV}$





Simulating the free streaming effect

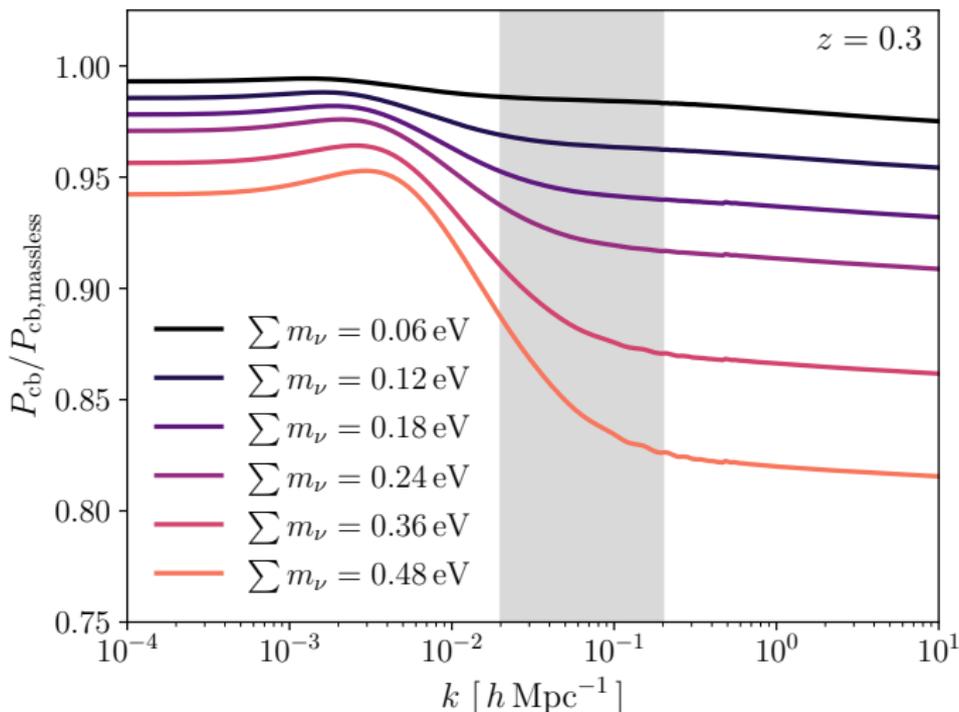
Large neutrino mass, $\sum m_\nu = 0.48 \text{ eV}$





Neutrino mass from free streaming

Massive neutrinos change the [shape of the power spectrum](#) on scales measured by DESI.



The DESI Experiment



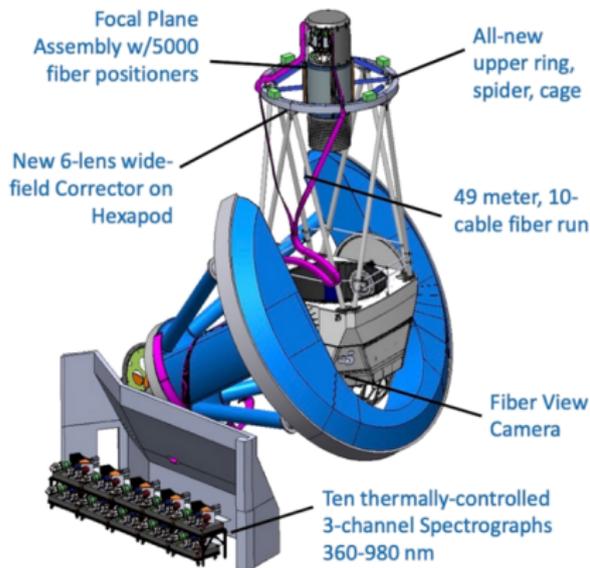


Dark Energy Spectroscopic Instrument

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

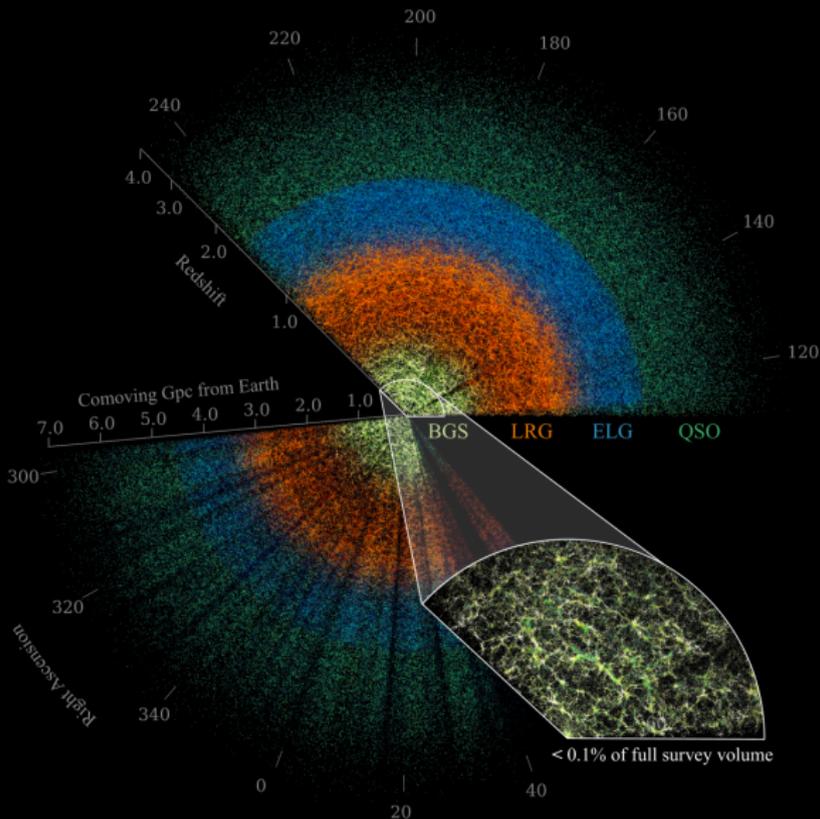
DESI observed over 30M galaxy and quasar redshifts after 3 years, 14M of which are used in the latest analysis.

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



The distance-redshift relation

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

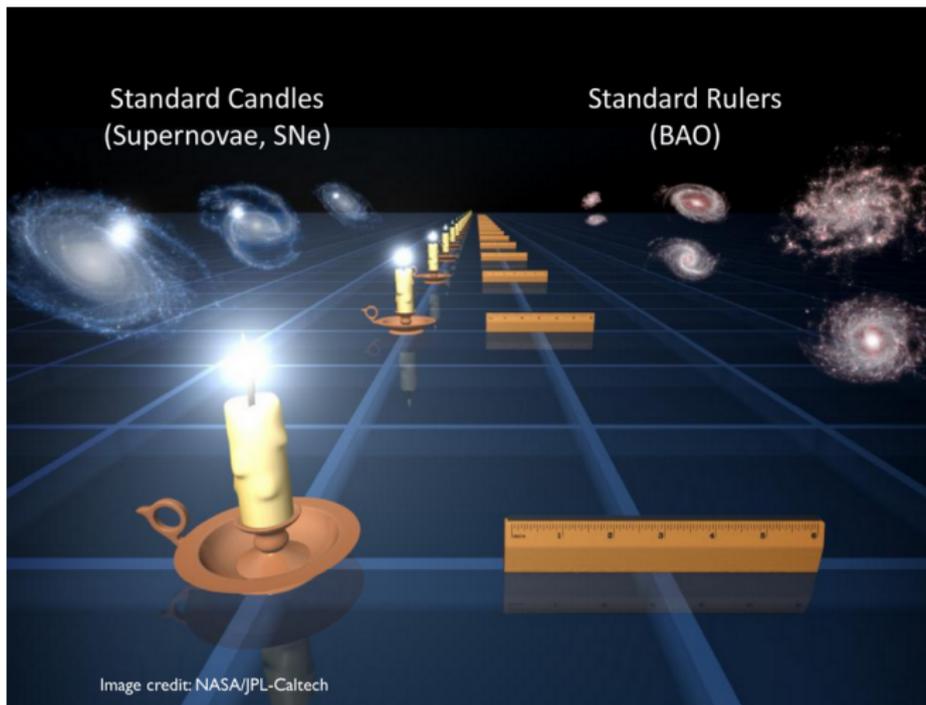
$$D_M(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')},$$

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

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

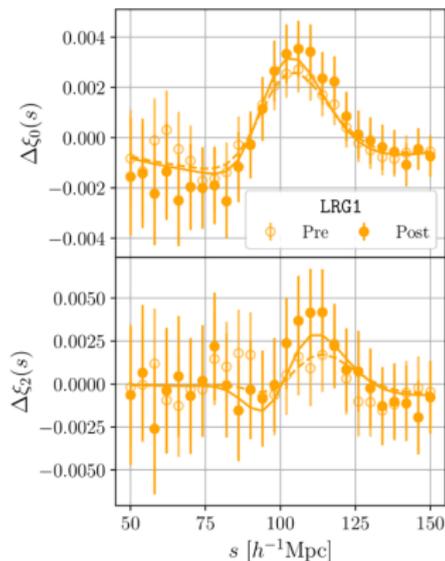
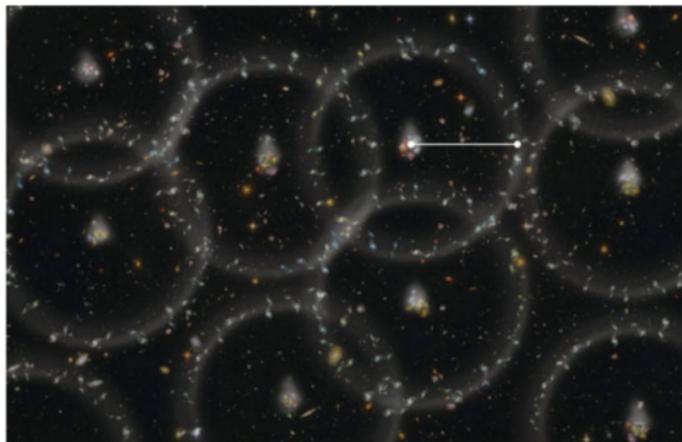


The distance-redshift relation



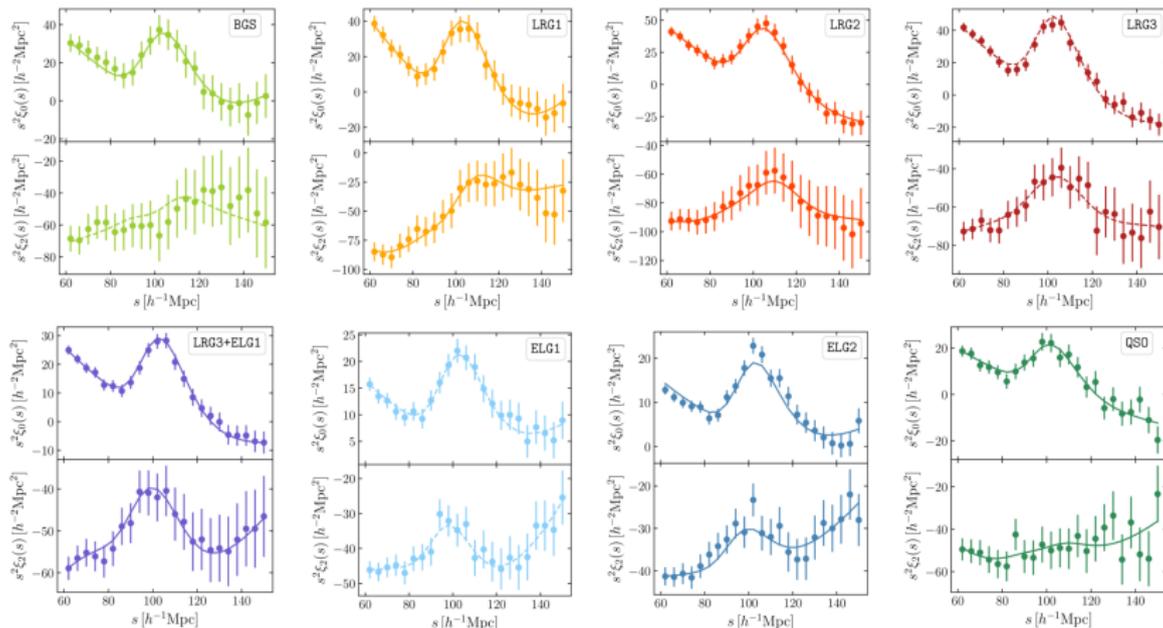


Baryon Acoustic Oscillations (BAO)



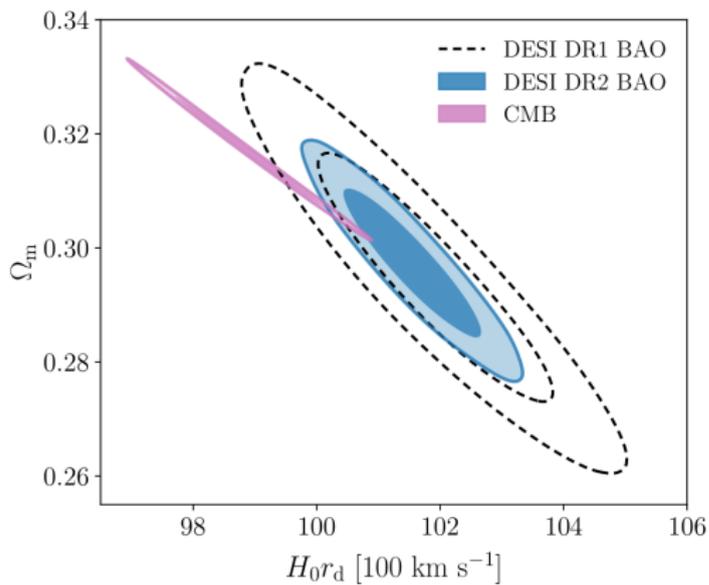
Artist's impression (left) and DESI DR1 measurements (right).

Galaxy clustering measurements



Key Paper II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints (DESI, 2025).

Constraints in Λ CDM



BAO primarily allow precise measurements of Ω_m and $H_0 r_d$.

$$\Omega_m = 0.2975 \pm 0.0086,$$

$$H_0 r_d = (101.54 \pm 0.73) \text{ Mpc}.$$

Mild discrepancy with the CMB: 2.3σ .



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

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

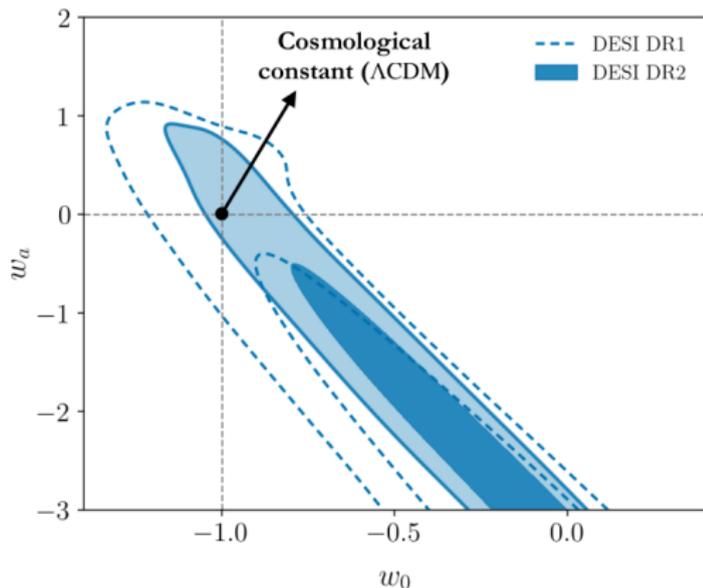
when combining DESI DR1 data with CMB and SN Type 1a.



Dynamical dark energy

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

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

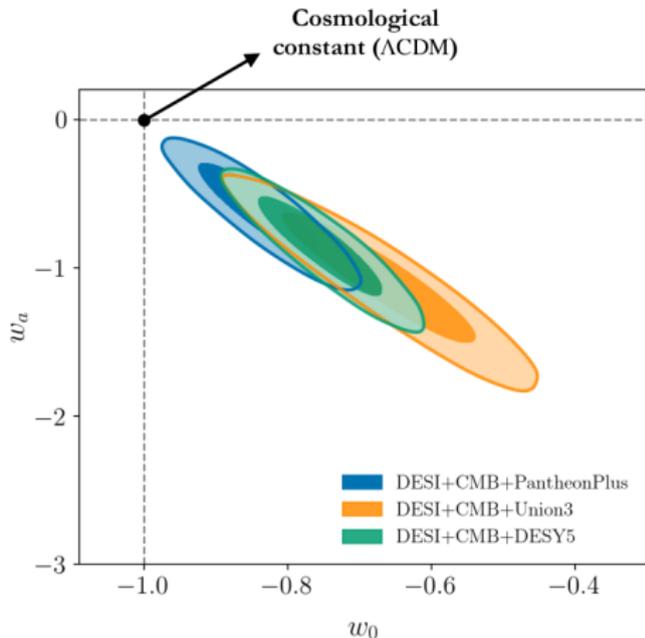


Dynamical dark energy

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

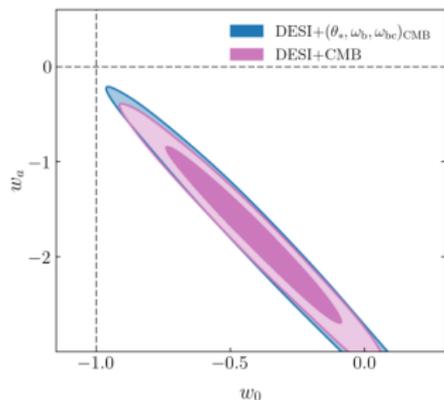
Significance of rejection of Λ CDM:

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



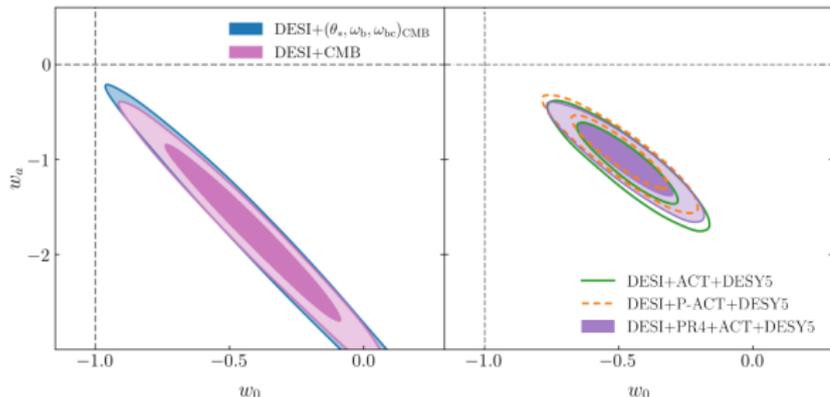


Dynamical dark energy



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

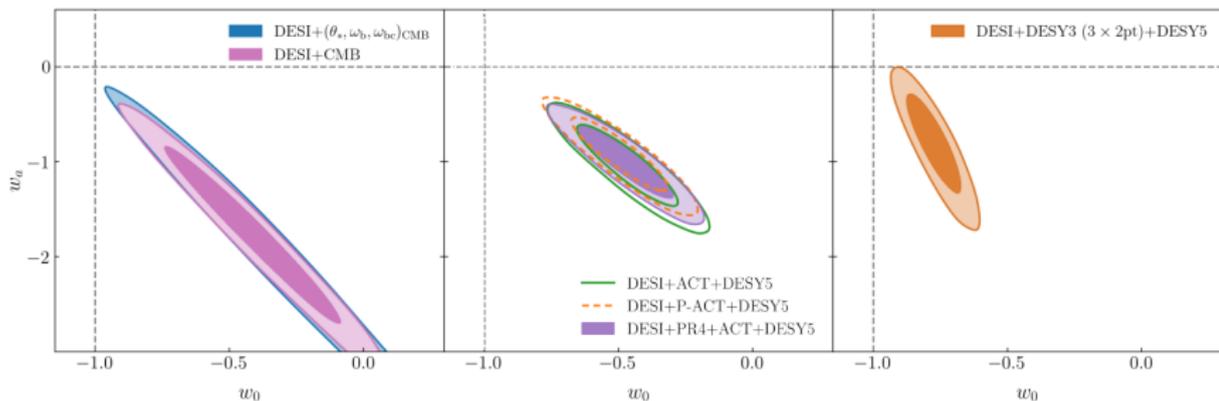
Dynamical dark energy



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

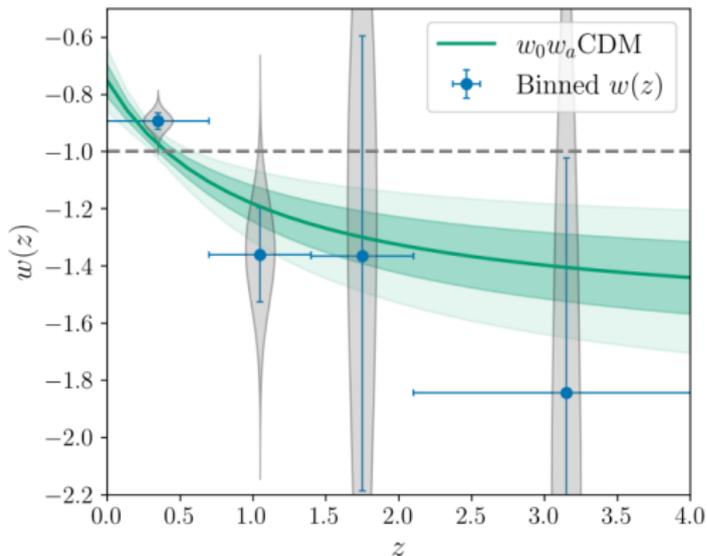


Dynamical dark energy



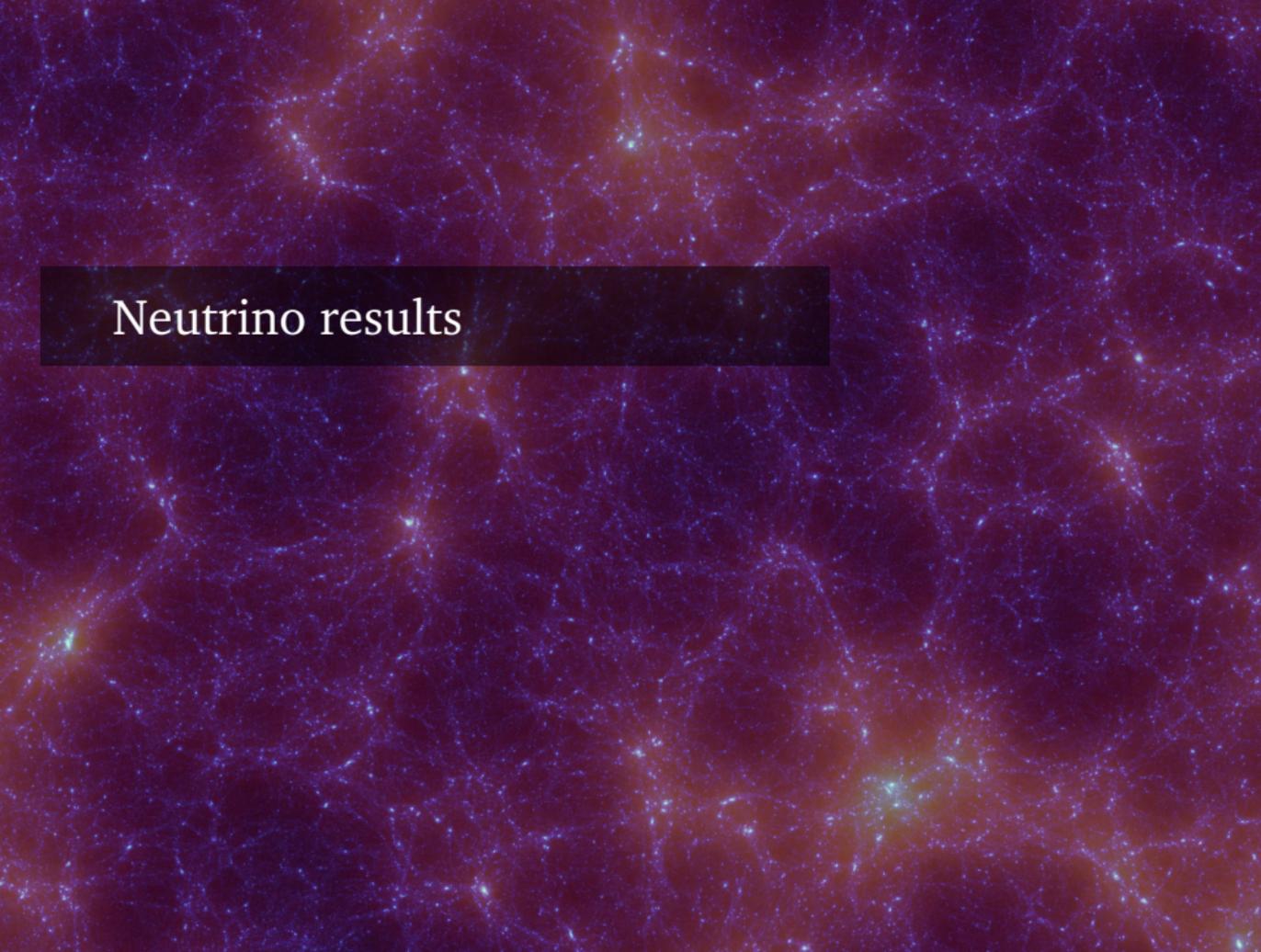
Replacing the CMB with DESY3 $3 \times 2pt$ (weak lensing), we obtain a constraint coming entirely from low-redshift cosmological probes (BAO, weak lensing, SNe).

Binned constraints on $w(z)$



Binned reconstruction of $w(z)$ is consistent with our w_0w_a CDM constraints.

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

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are represented by thin, glowing blue lines, while the clusters are shown as denser regions of orange and yellow light. The background is a deep, dark blue.

Neutrino results



Latest DESI Constraints

I will show results for three kinds of analyses:

- ▶ Cosmic Microwave Background (CMB) only
- ▶ DESI Full Shape (FS) with limited BBN & 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:

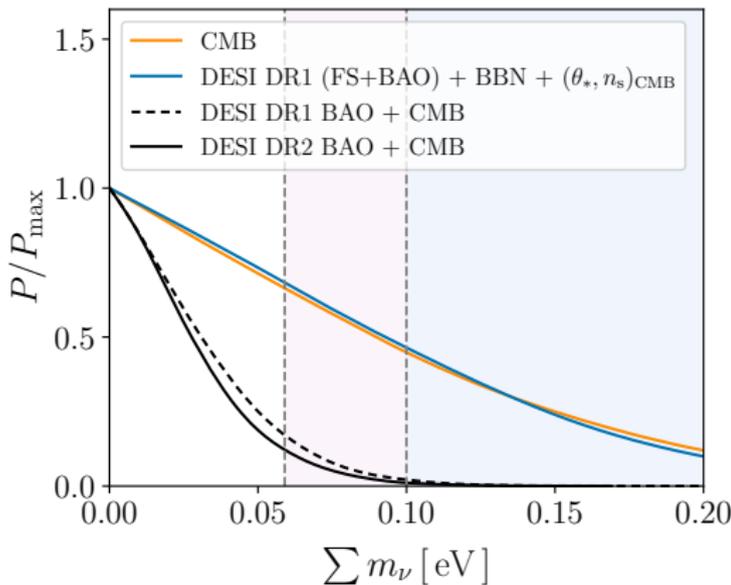
$$N_{\text{eff}} = 3.23^{+0.35}_{-0.34} \text{ (95\%)},$$

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

And our strongest bound,

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

to date on the sum of neutrino masses.





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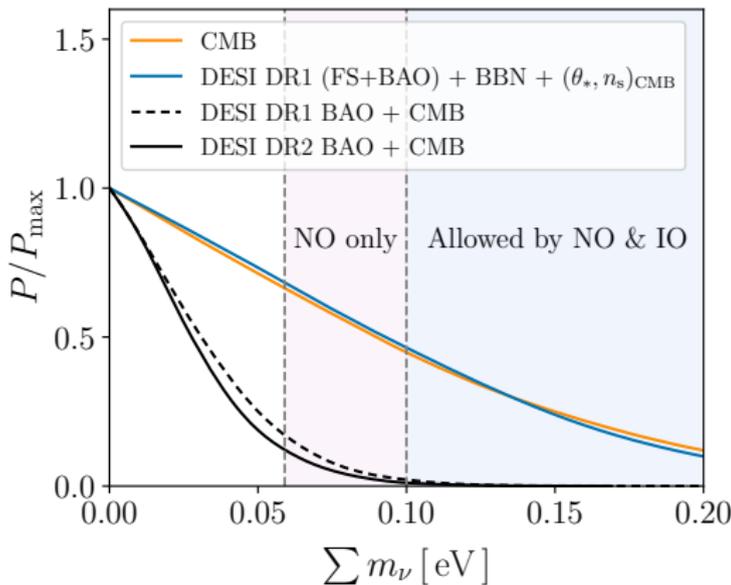
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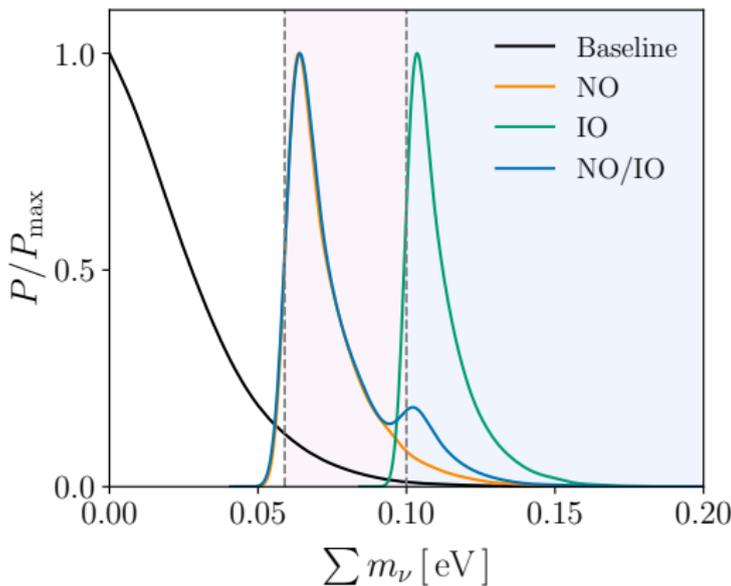
Preference for normal ordering

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:

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

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





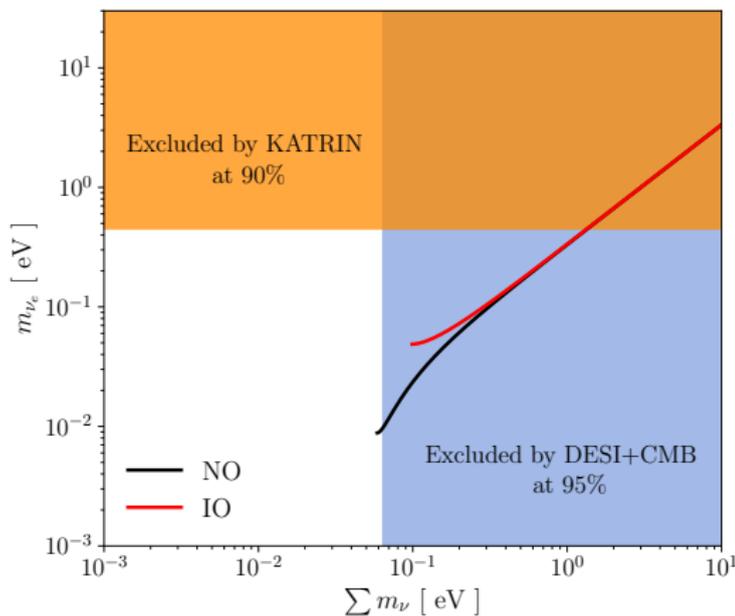
Comparison with KATRIN

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

DESI DR2 BAO + CMB:

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

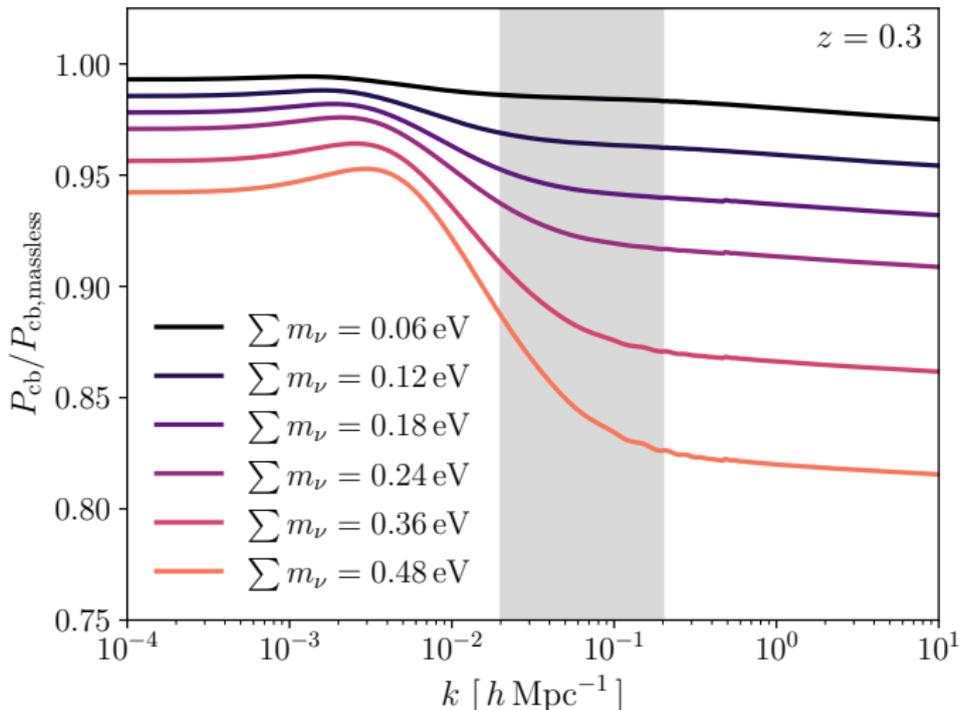
and a Bayes factor of 10
in favor of the NO.





Neutrino mass from free streaming

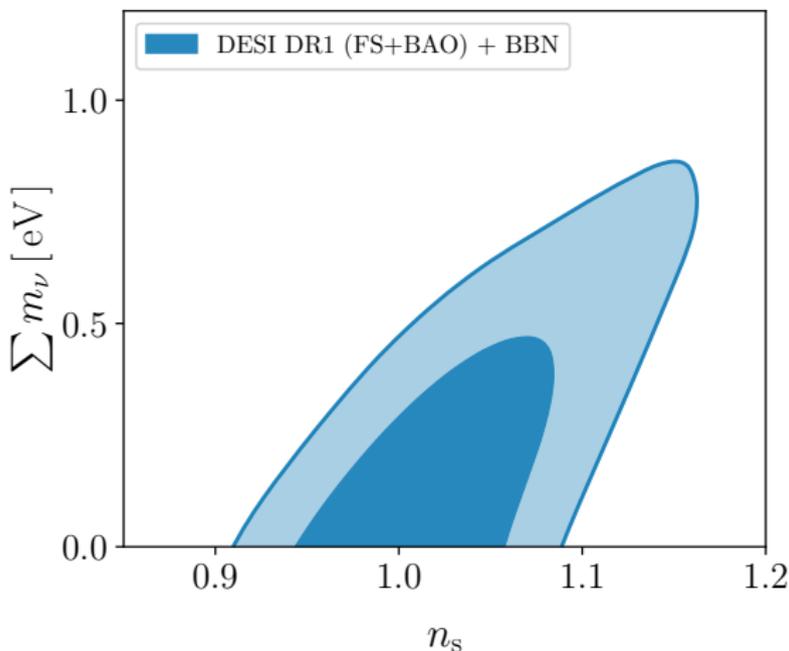
Massive neutrinos change the [shape of the power spectrum](#) on scales measured by DESI.





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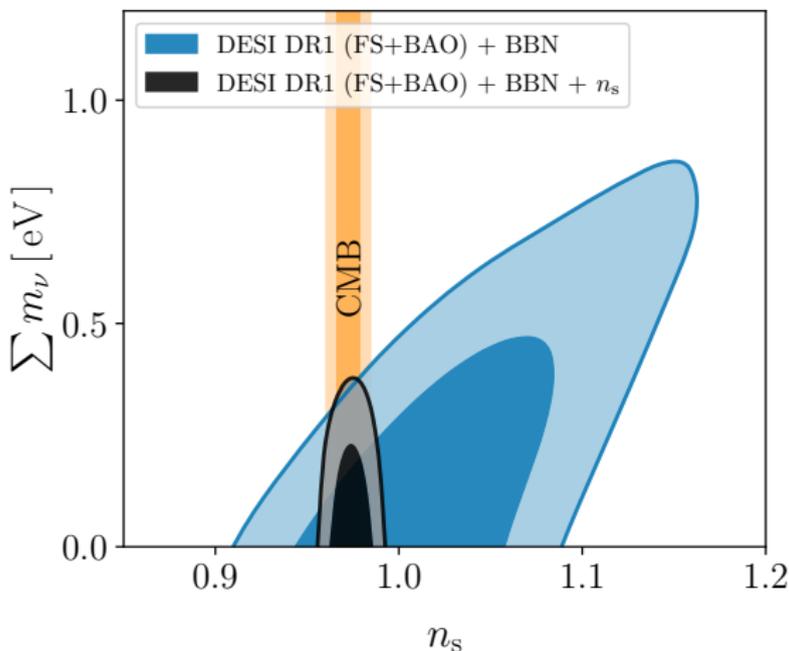
Information on $\sum m_\nu$ derived from the power spectrum shape.





Neutrino mass from free streaming

Information on $\sum m_\nu$ derived from the power spectrum shape.

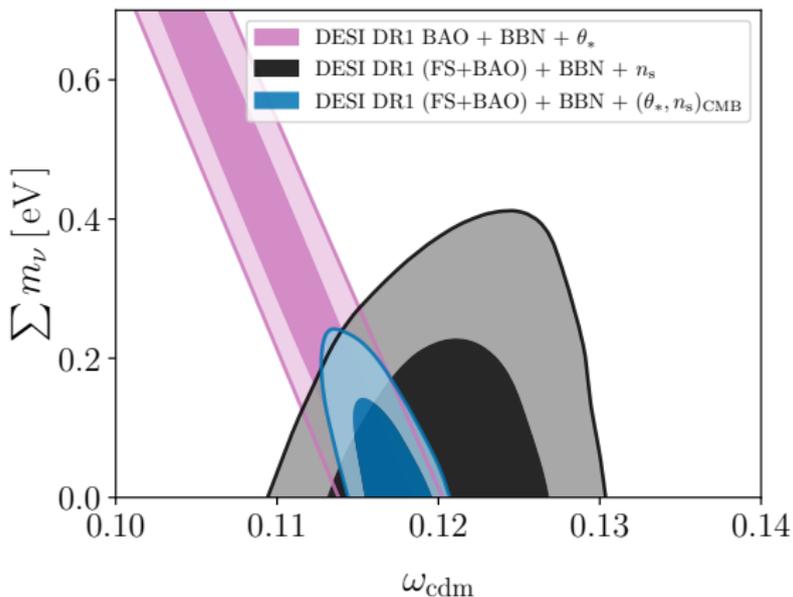


Here, n_s is a Gaussian prior on the slope of the power spectrum.



Neutrino mass from free streaming

We can derive a complementary constraint using DESI in two ways, exploiting both geometric and growth information.



Here, we use a correlated CMB prior on θ_* and n_s .

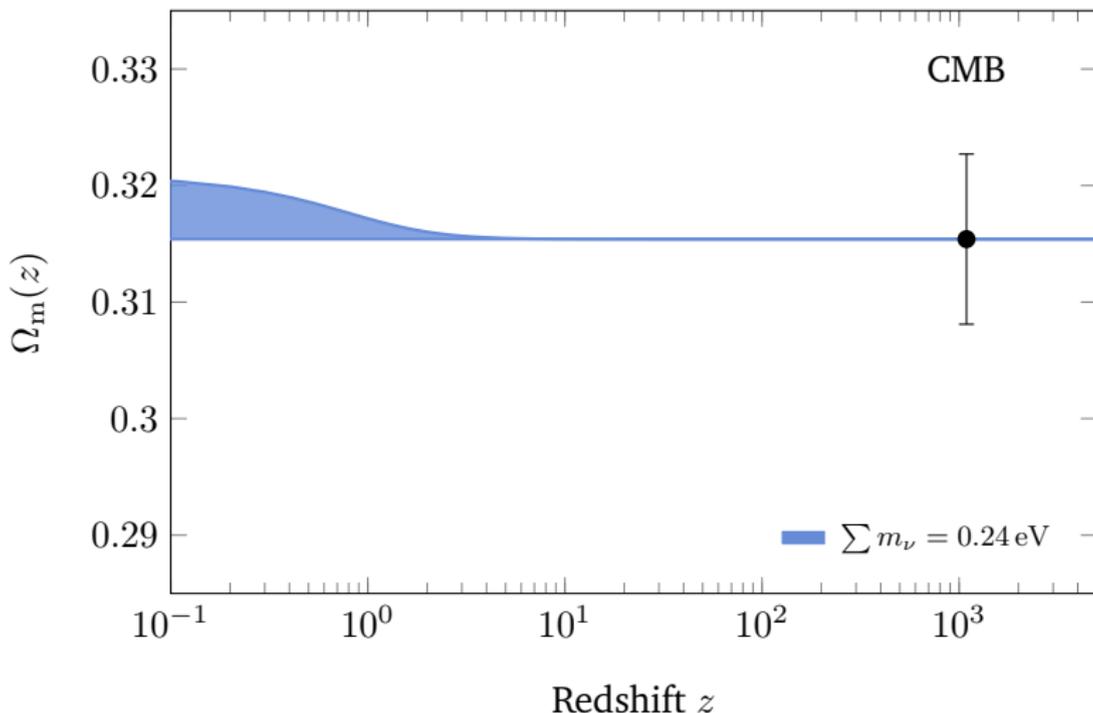


Effective neutrino masses



Evolution of the matter density

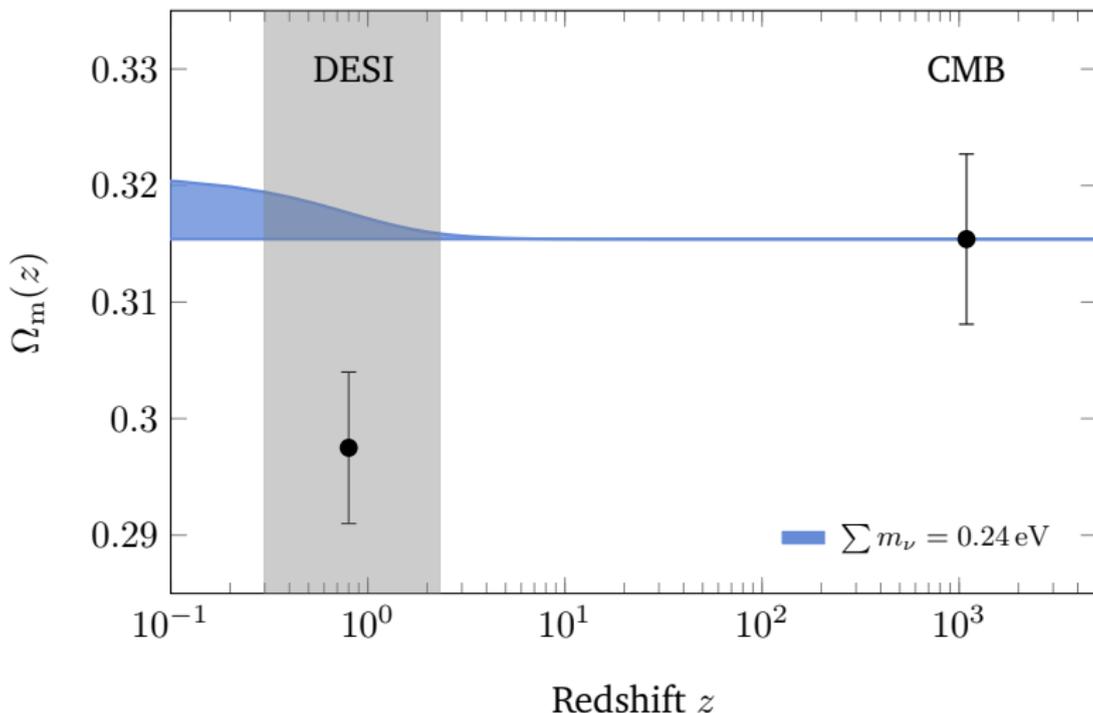
In Λ CDM, we expect a late-time increase in the matter density due to massive neutrinos.





Evolution of the matter density

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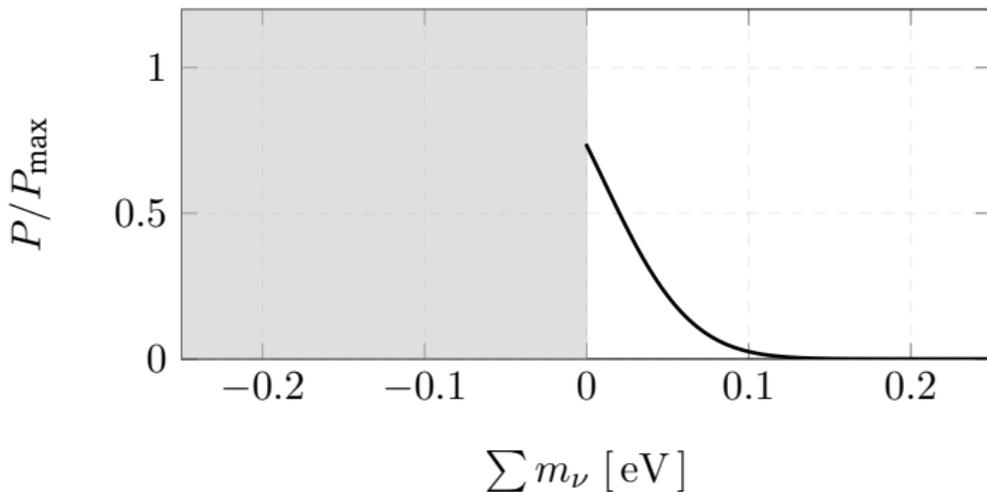


Motivating different priors

Our choice of prior depends on the question.

Are cosmic neutrinos compatible with experimental data?

$$\sum m_\nu \stackrel{?}{>} 0 \text{ eV}.$$



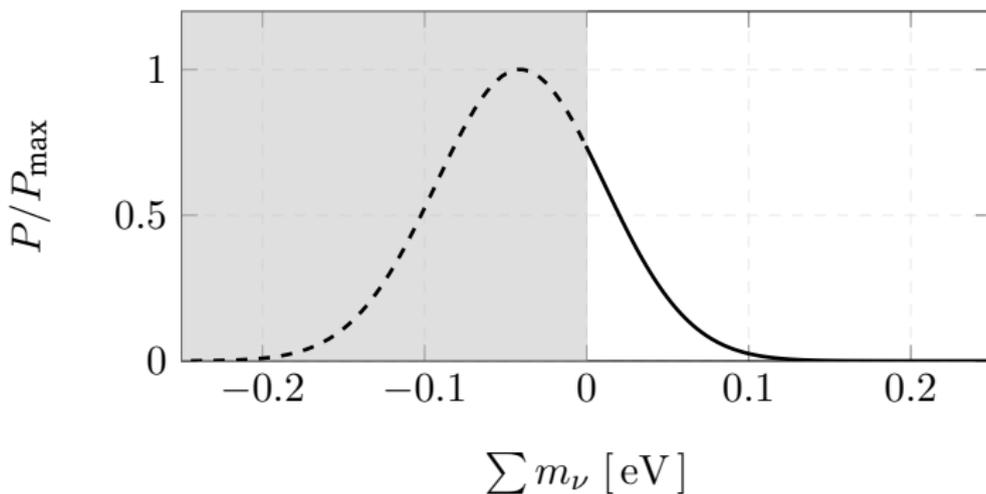


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Effective neutrino masses: definitions

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 $\Omega_m \in H(z)^2 a^3 / H_0^2$
- ▶ Enhanced clustering on small scales

Preference for negative effective masses

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

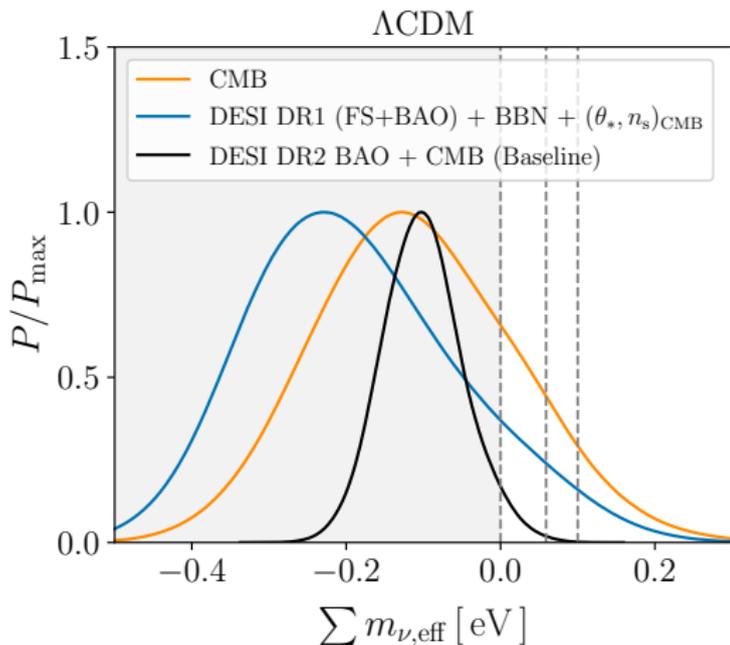
DESI DR2 BAO + CMB:

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

CMB alone:

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

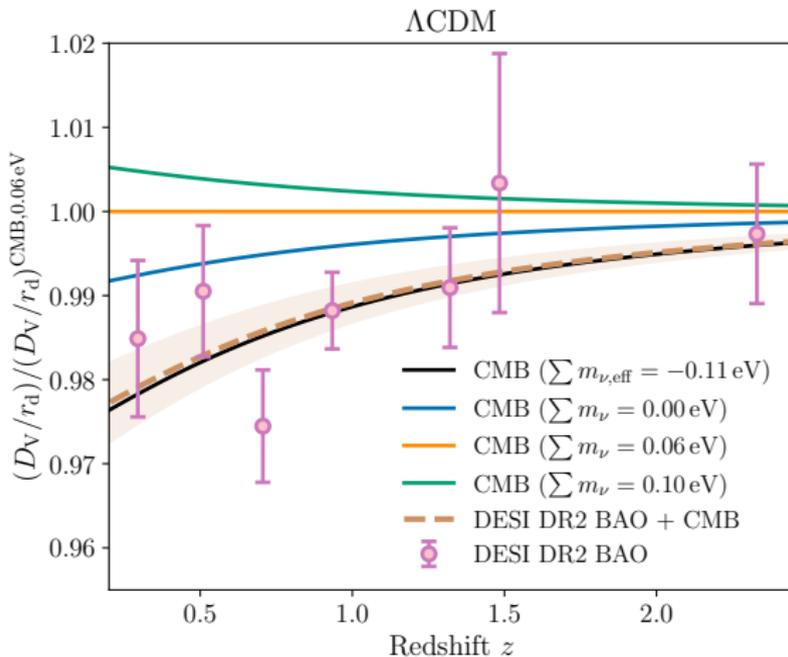
both at 68%.





Agreement on $H_0 r_d$

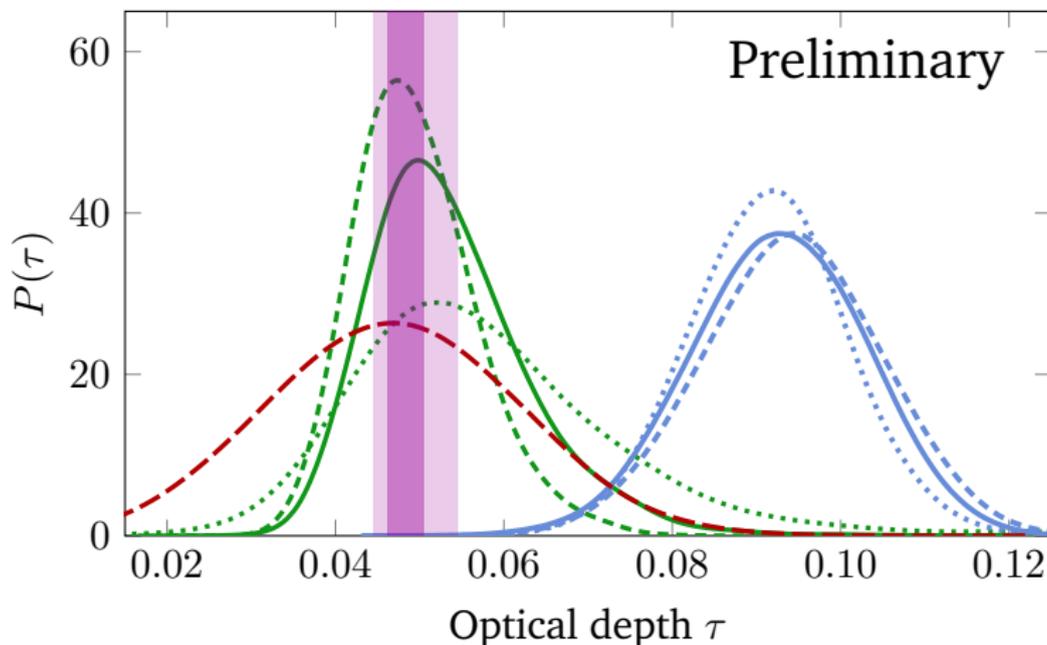
Both CMB and DESI agree on $H_0 r_d$ at the same negative effective neutrino mass.





Large-scale CMB systematics?

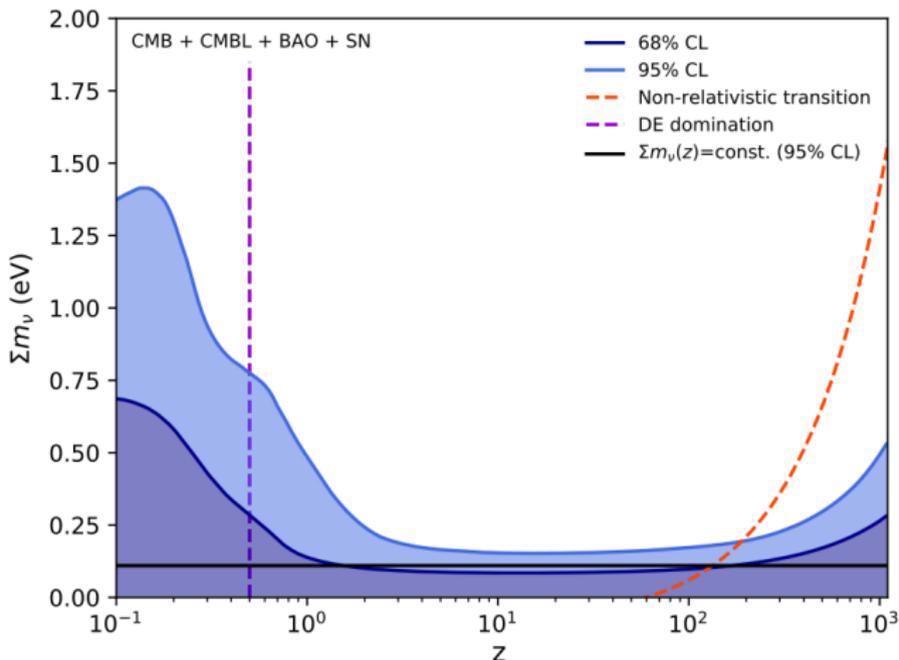
Could this be a result of systematics in the large-scale CMB polarization measurements? Perhaps, but this would violate other constraints on reionization (Elbers, in prep.).





Relaxing the bounds

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



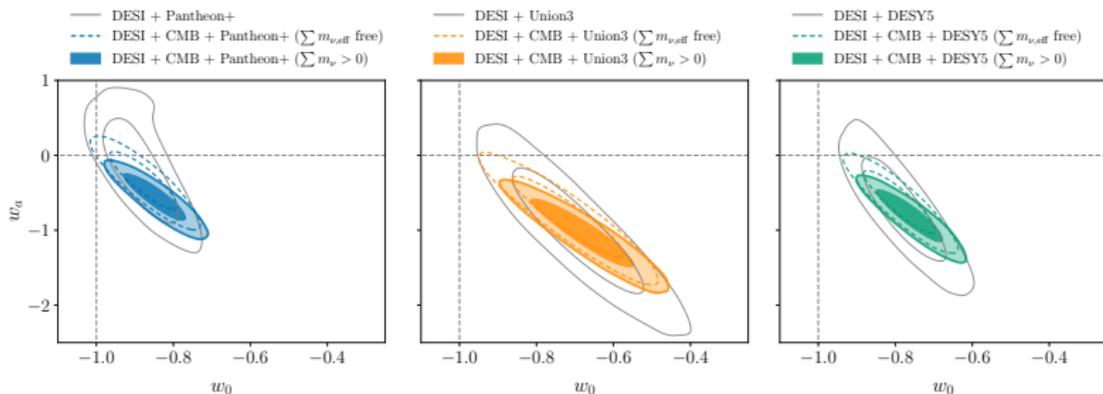
Lorenz et al. (2021)

Dark energy results

Neutrino masses are degenerate with the dark energy equation of state. As discussed, we parametrize its evolution as

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

Results for DESI DR2 data with CMB and SN Type 1a:





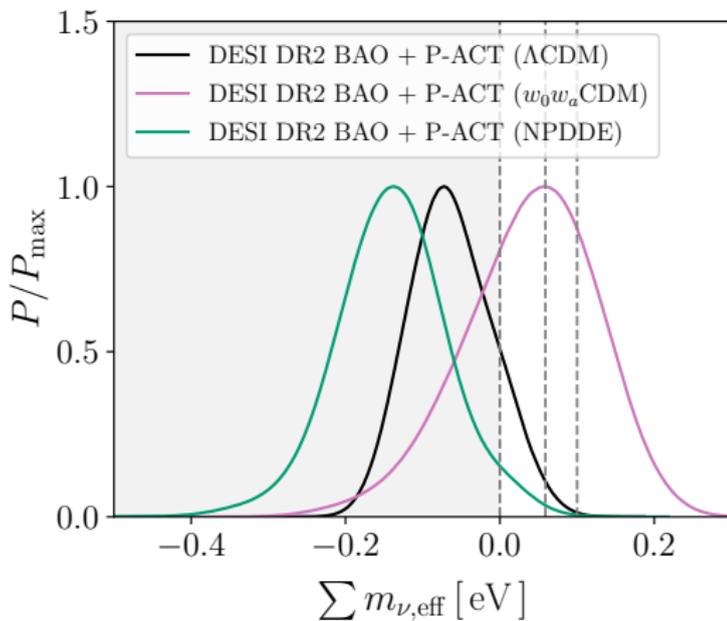
Relation to dark energy

Positive neutrino masses are allowed when going from Λ CDM to w_0w_a CDM, but only if one allows $w < -1$.

DESI DR2 BAO + P-ACT:

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

assuming w_0w_a CDM.





Conclusions

- ▶ Evidence for evolving dark energy has increased with DR2 BAO: 3.1σ from DESI+CMB alone.
- ▶ DESI has placed its strongest limit on the sum of neutrino masses assuming the cosmological Λ CDM model:

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

- ▶ Cosmological data seem to indicate a preference for ‘negative effective neutrino masses’
- ▶ This result challenges the Λ CDM model and could point to evolving dark energy or non-standard neutrino properties