Cosmology fits to neutrino masses

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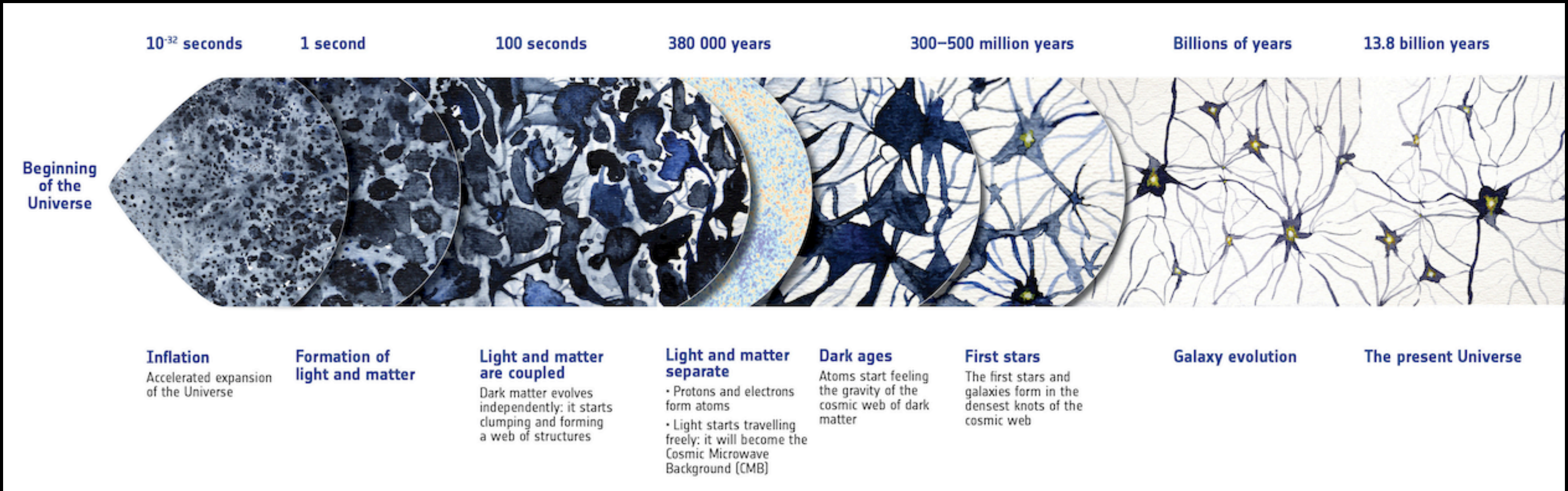
Neutrino physics and cosmology



Neutrinos are the last particles of the Standard Model whose masses are unknown.
To constrain their total mass using cosmological data, we rely on the Cosmic Neutrino Background at early times and the growth of structure at late times.
Therefore, the main cosmological probes that we can use are the Cosmic Microwave Background and the Large Scale Structure data.
With the cosmological data, we can place constraints not only on the total neutrino mass, but also on the neutrino effective number.

Why do we care about $\Sigma m\nu$ from cosmology?
Because it is the only way we can currently probe sub-eV masses, and these results already challenge what we expect from oscillation experiments.

CMB constraints

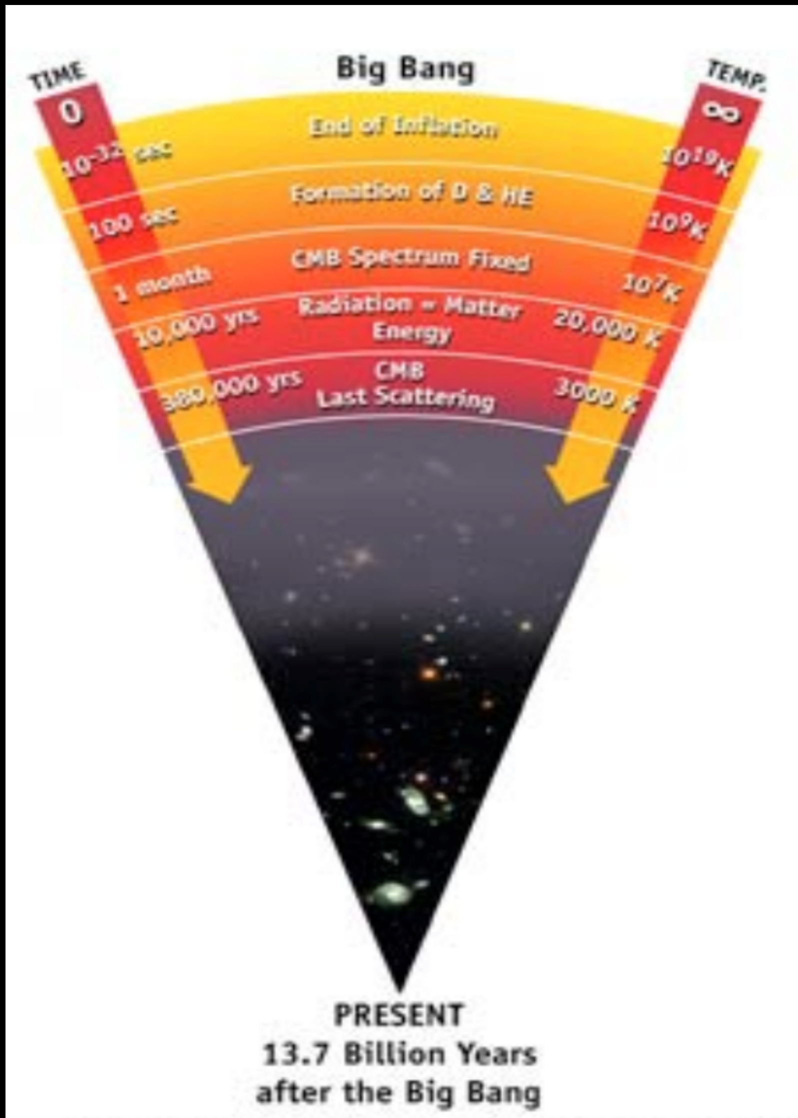


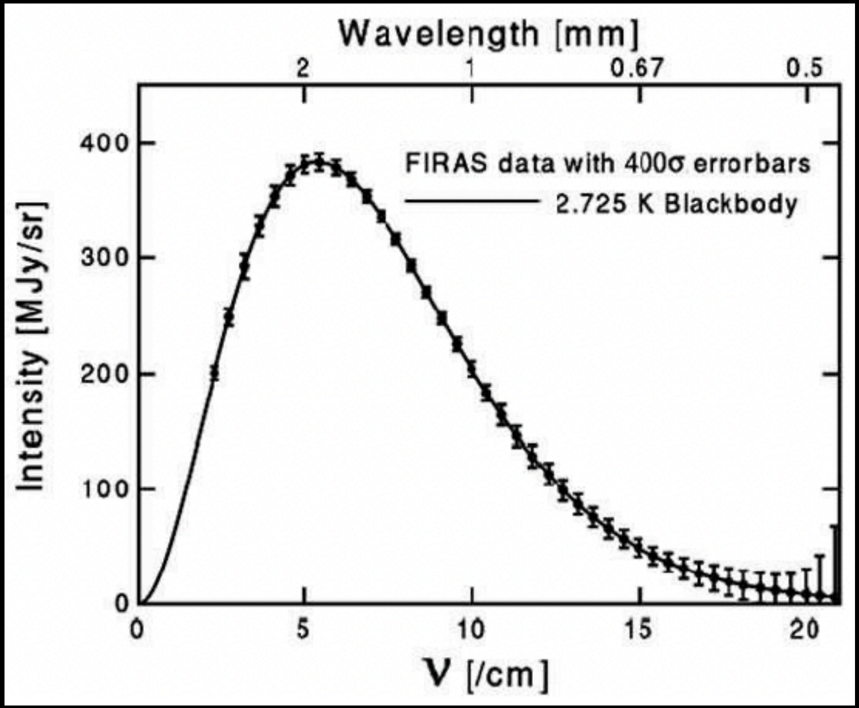
Figura: http://wmap.gsfc.nasa.gov

The Universe originates from a hot Big Bang.

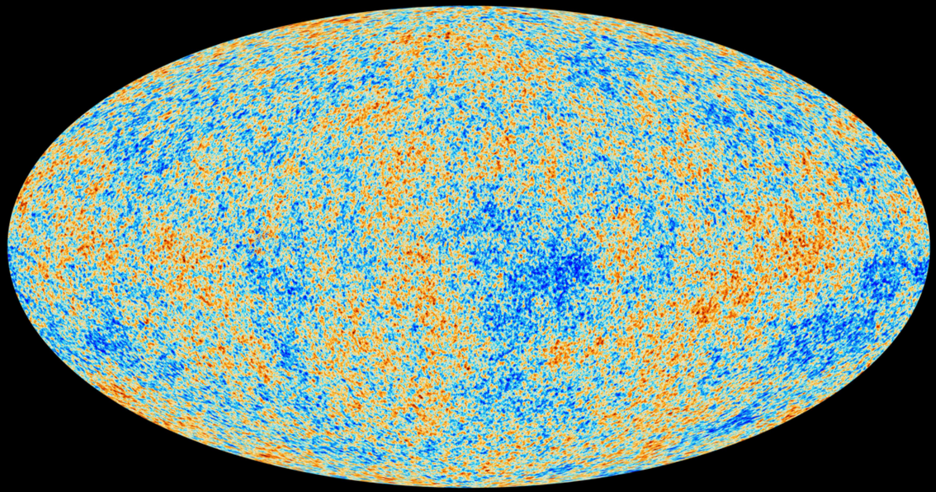
The primordial plasma in thermodynamic equilibrium cools with the expansion of the Universe. It goes through the phase of recombination, during which electrons and protons combine to form neutral hydrogen, and decoupling, where the Universe becomes transparent to the motion of photons.

The Cosmic Microwave Background (CMB) is the radiation coming from recombination, emitted about 13 billion years ago, just 380,000 years after the Big Bang.

The CMB retains the shape of the primordial universe in which photons were in thermodynamic equilibrium, exhibiting a thermal blackbody spectrum that has cooled with the expansion of the universe, reaching a temperature of T=2.725K today. This radiation coming from all directions is almost homogeneous, but also offers an image of the minuscule density differences present at recombination and bears witness to everything that happened to photons as they traveled to us. These effects result in small temperature variations among the photons themselves, on the order of 1/100000, known as anisotropies.

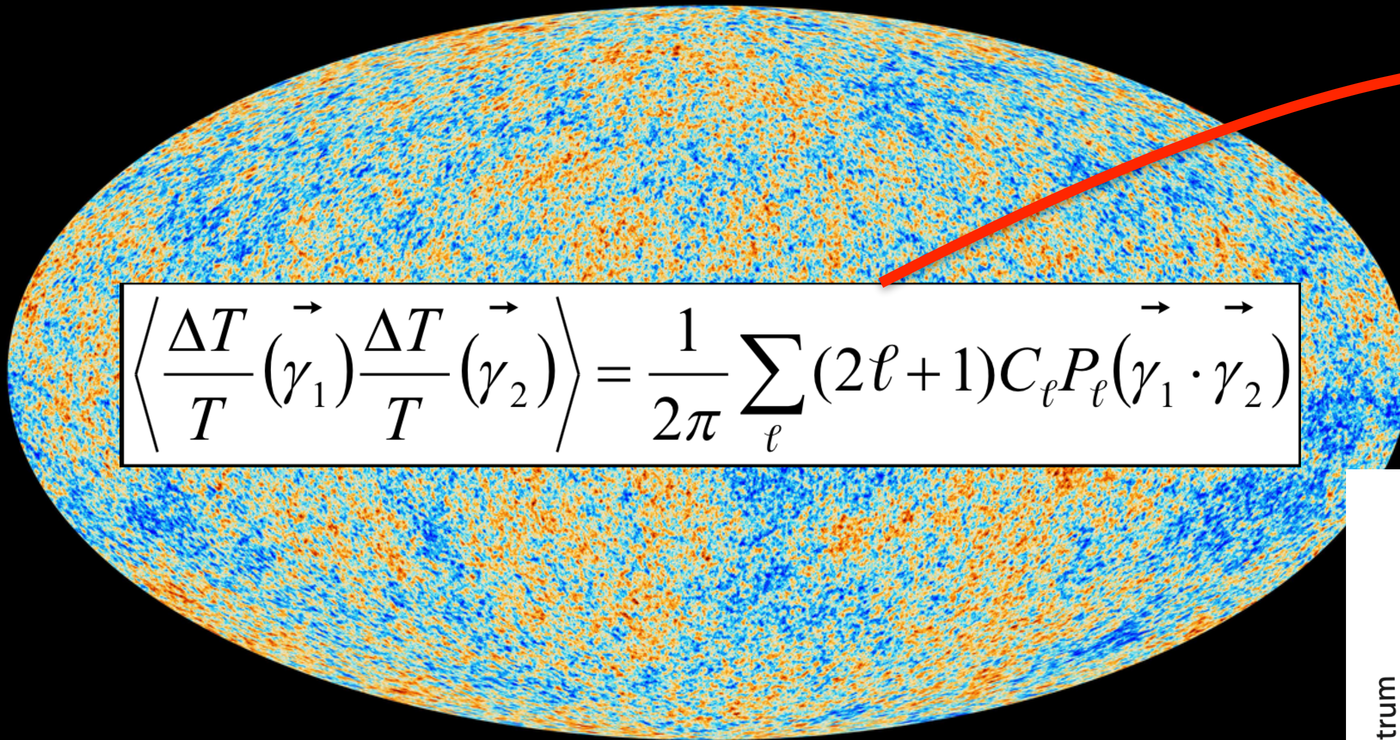


Wuensche & Villa, arXiv:1002.4902

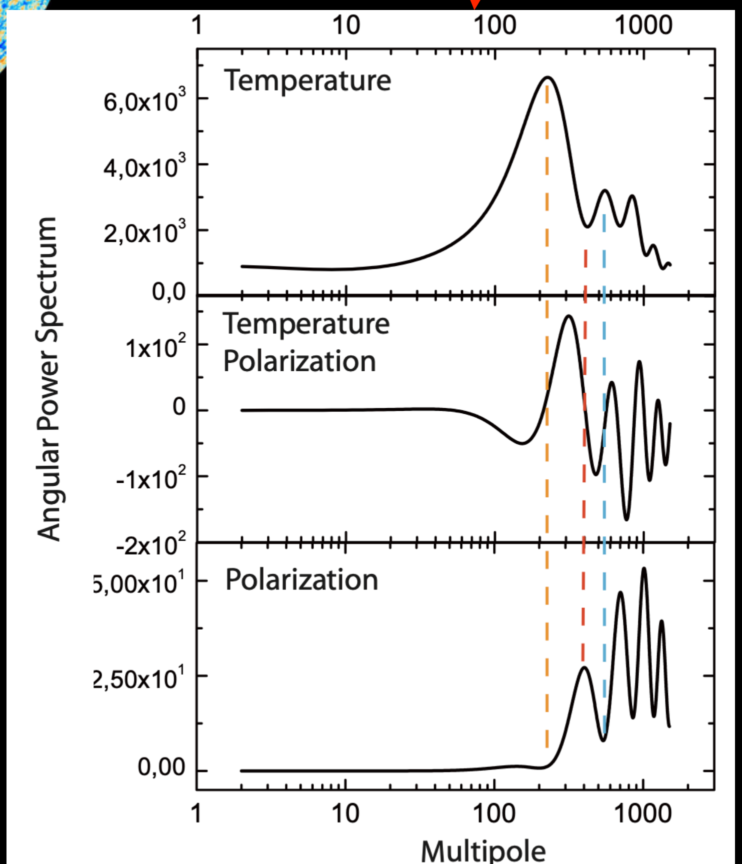


Planck collaboration, 2018

Planck 2018, Astron.Astrophys. 641 (2020) A6



$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$



We can extract 4 independent angular spectra from the CMB:

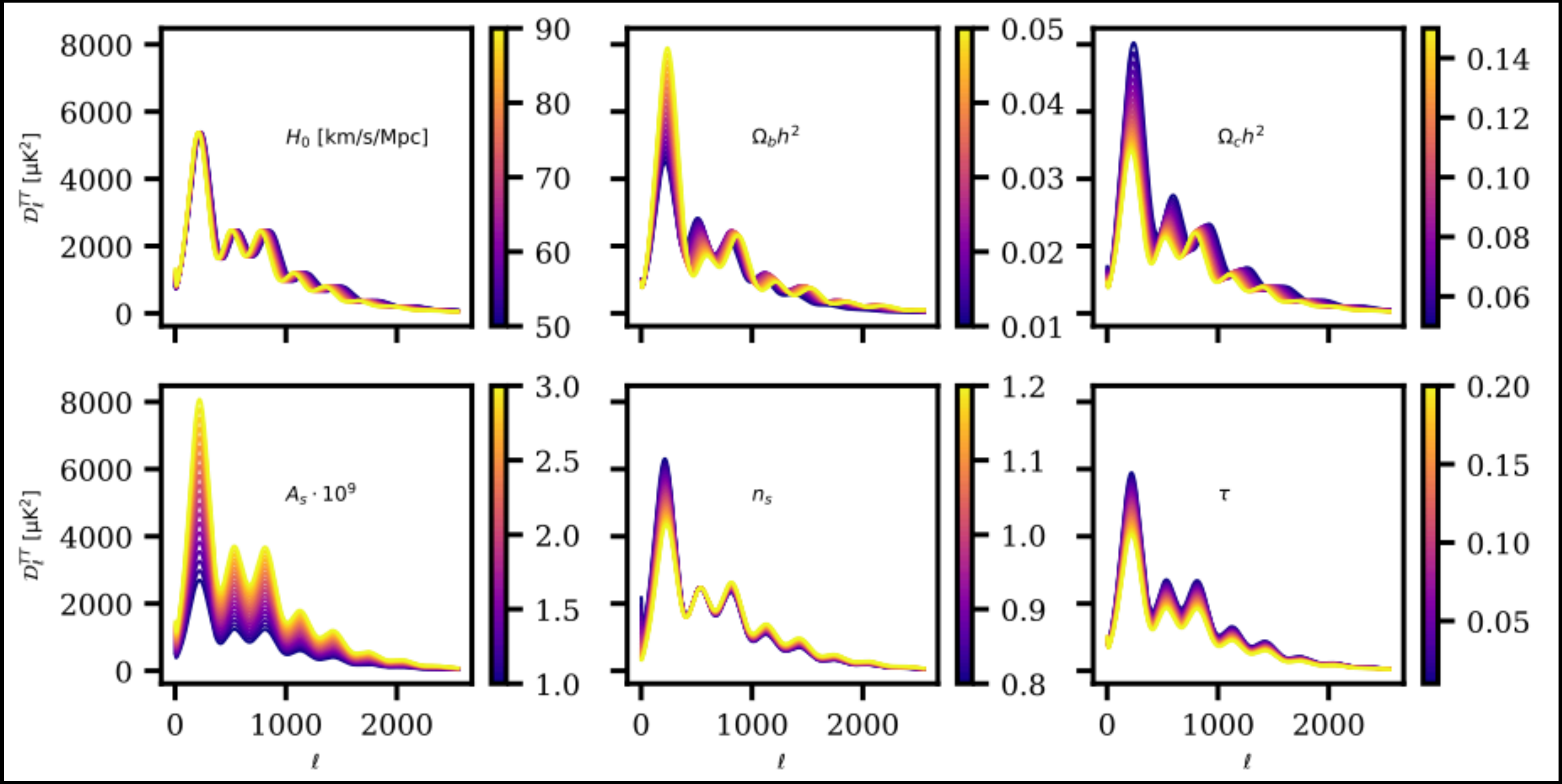
- Temperature
- Cross Temperature Polarization E
- Polarization type E (density fluctuations)
- Polarization type B (gravitational waves)

Borstnik et al., hep-ph/0401043

Cosmological parameters: ($\Omega_b h^2$, $\Omega_m h^2$, H0 , n_s , τ, As)

Theoretical model

We choose a set of cosmological parameters that describes our theoretical model and compute the angular power spectra. Because of the correlations present between the parameters, variation of different quantities can produce similar effects on the CMB.

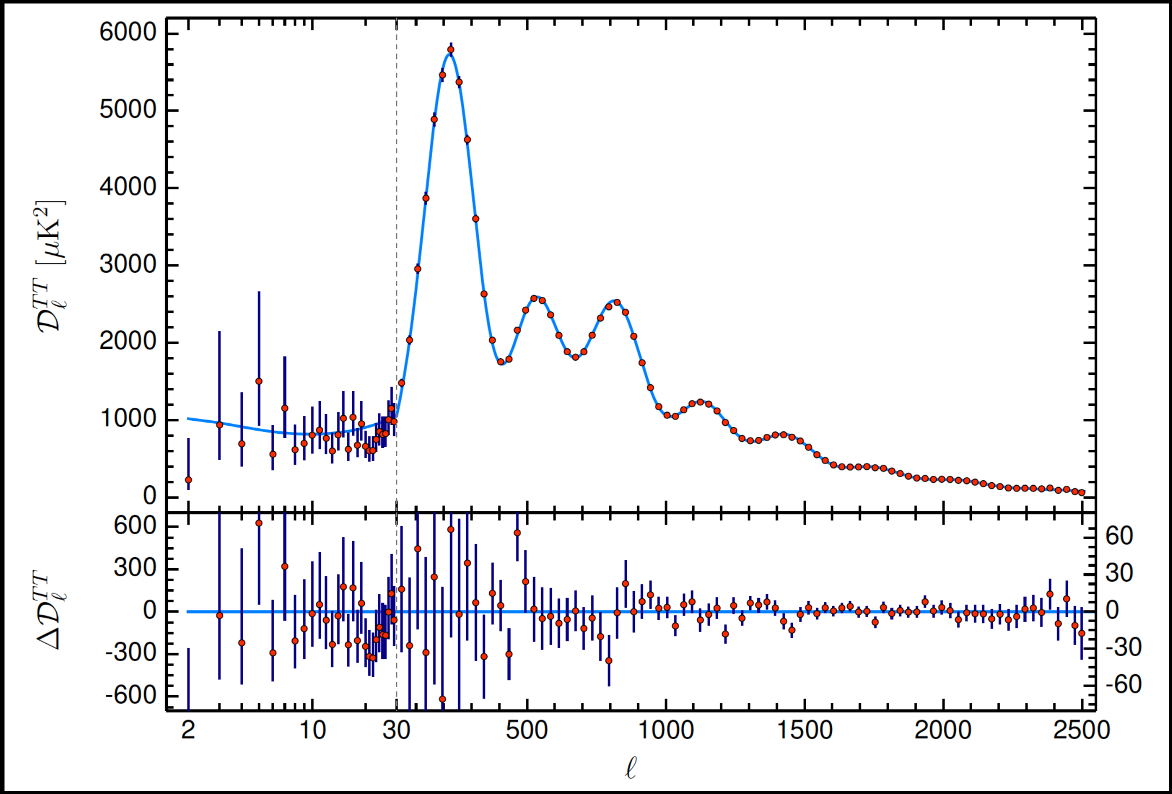


Lemos & Shah, arXiv:2307.13083

Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H0 , n_s , τ, As)

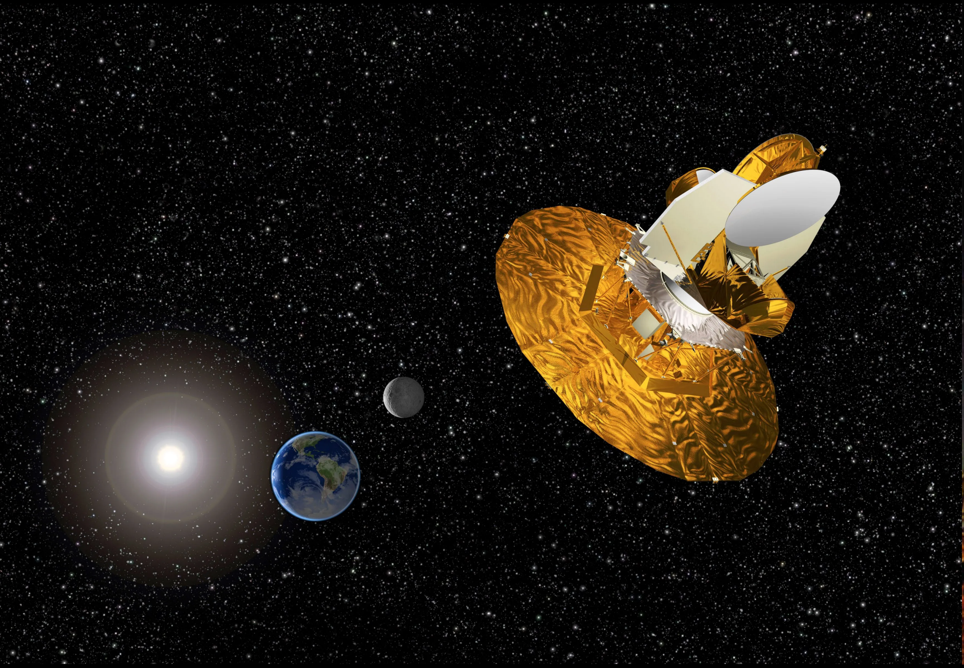
Theoretical model

We compare the angular power spectra we computed with the data and, using a bayesian analysis, we get a combination of cosmological parameter values in agreement with these.



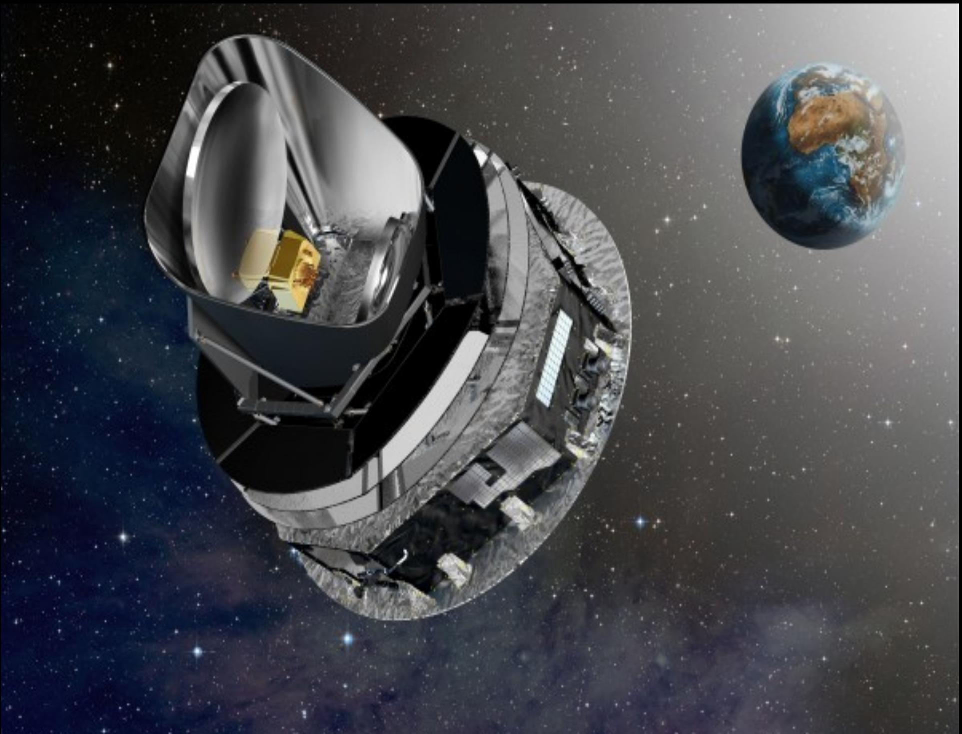
Planck 2018, Astron.Astrophys. 641 (2020) A6

Parameter constraints



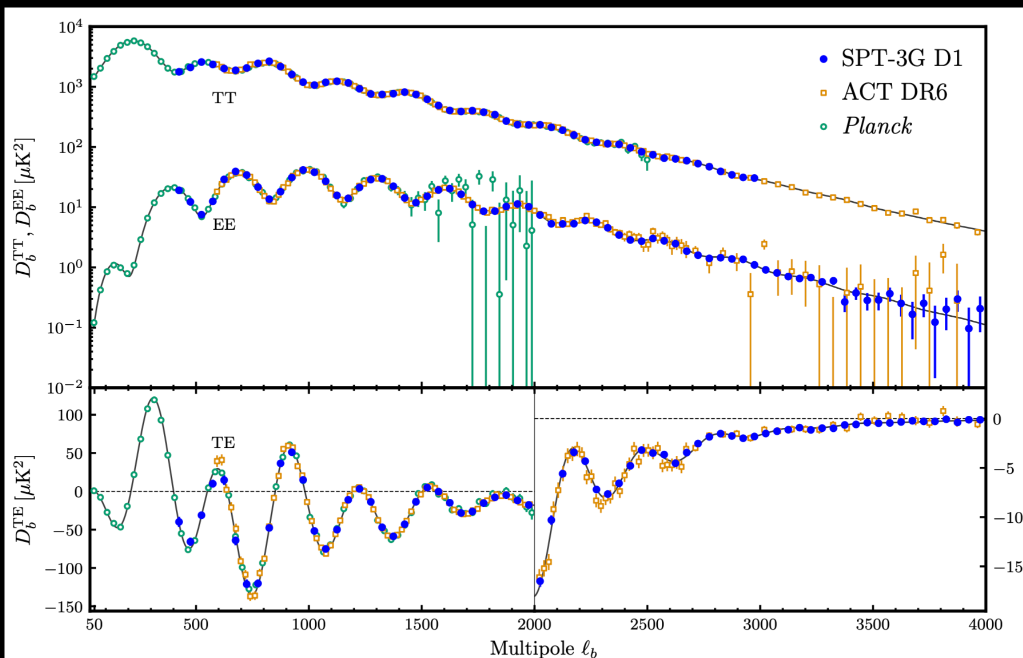
Satellite CMB telescopes

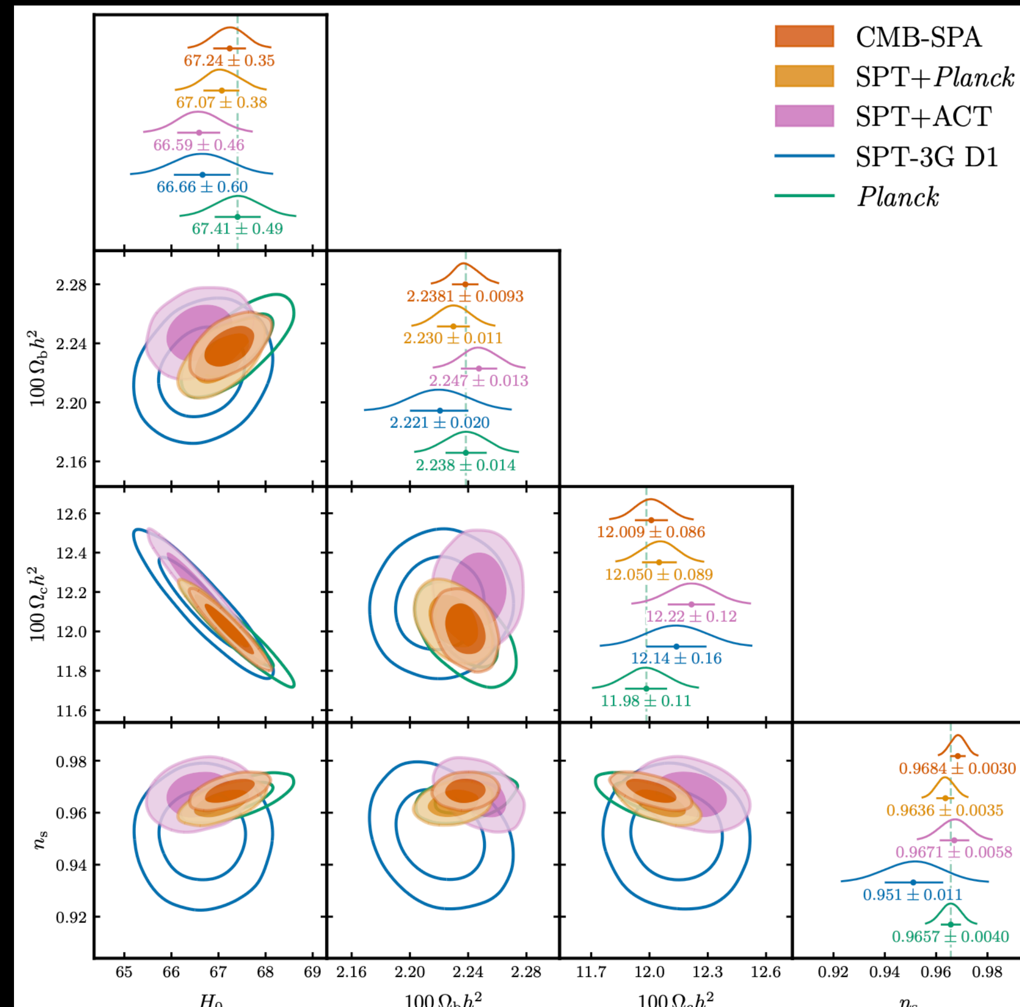
Ground based CMB telescopes



CMB constraints

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]





- The cosmological constraints are obtained assuming a cosmological model.
- The results are affected by the degeneracy between the parameters that induce similar effects on the observables.

The Cosmic Neutrino Background

When the rate of the weak interaction reactions, which keep neutrinos in equilibrium with the primordial plasma, becomes smaller than the expansion rate of the Universe, neutrinos decouple at a temperature of about:

$$T_{dec} \approx 1 MeV$$

After neutrinos decoupling, photons are heated by electrons-positrons annihilation. After the end of this process, the ratio between the temperatures of photons and neutrinos will be fixed, despite the temperature decreases with the expansion of the Universe. We expect today a Cosmic Neutrino Background at a temperature:

$$T_{\nu} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma} \approx 1.945 K \rightarrow kT_{\nu} \approx 1.68 \cdot 10^{-4} eV$$

With a number density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k, \bar{\nu}_k} \approx 0.1827 \cdot T_{\nu}^3 \approx 112 cm^{-3}$$

Neutrino physics and cosmology

If the total neutrino mass is of the order of 1 eV, neutrinos are radiation at the time of equality, and non-relativistic matter today.

We expect the transition to the non-relativistic regime after the time of the photon decoupling.

When neutrinos are relativistic, will contribute to the radiation content of the universe, through the effective number of relativistic degrees of freedom Neff.

When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.

The total neutrino mass and the CMB

Because the shape of the CMB spectrum is primarily influenced by the physical evolution before recombination, the effect of the total neutrino mass (not individual masses, Archidiacono et al. arXiv:2003.03354) appear through a modified background evolution and some secondary anisotropy corrections.

Varying the total neutrino mass we vary the amount of matter density today.

The total neutrino density today will be:

$$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\rm crit}^0} = \frac{\sum m_\nu}{93.14 h^2 \,\mathrm{eV}}$$

increasing the total non-relativistic matter density at late time

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

The total neutrino mass and the CMB

Increasing the total neutrino mass changes the total non-relativistic matter density at late times. This, in turn, shifts the redshifts of matter–radiation equality and matter–Λ equality, affecting the Integrated Sachs–Wolfe (ISW) effect.

The ISW effect (Sachs & Wolfe, ApJ 1967) occurs when photons are redshifted or blueshifted while passing through gravitational potentials that evolve over time.

Gravitational potentials remain constant during matter domination, so shifting the timing of equality affects when they begin to evolve, thereby changing the ISW signal.

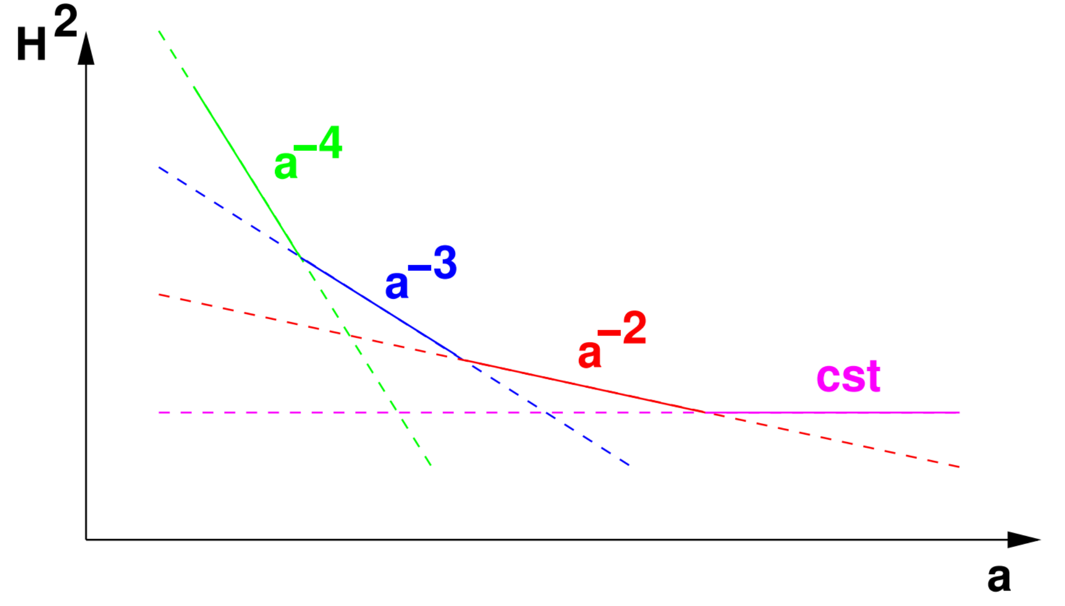
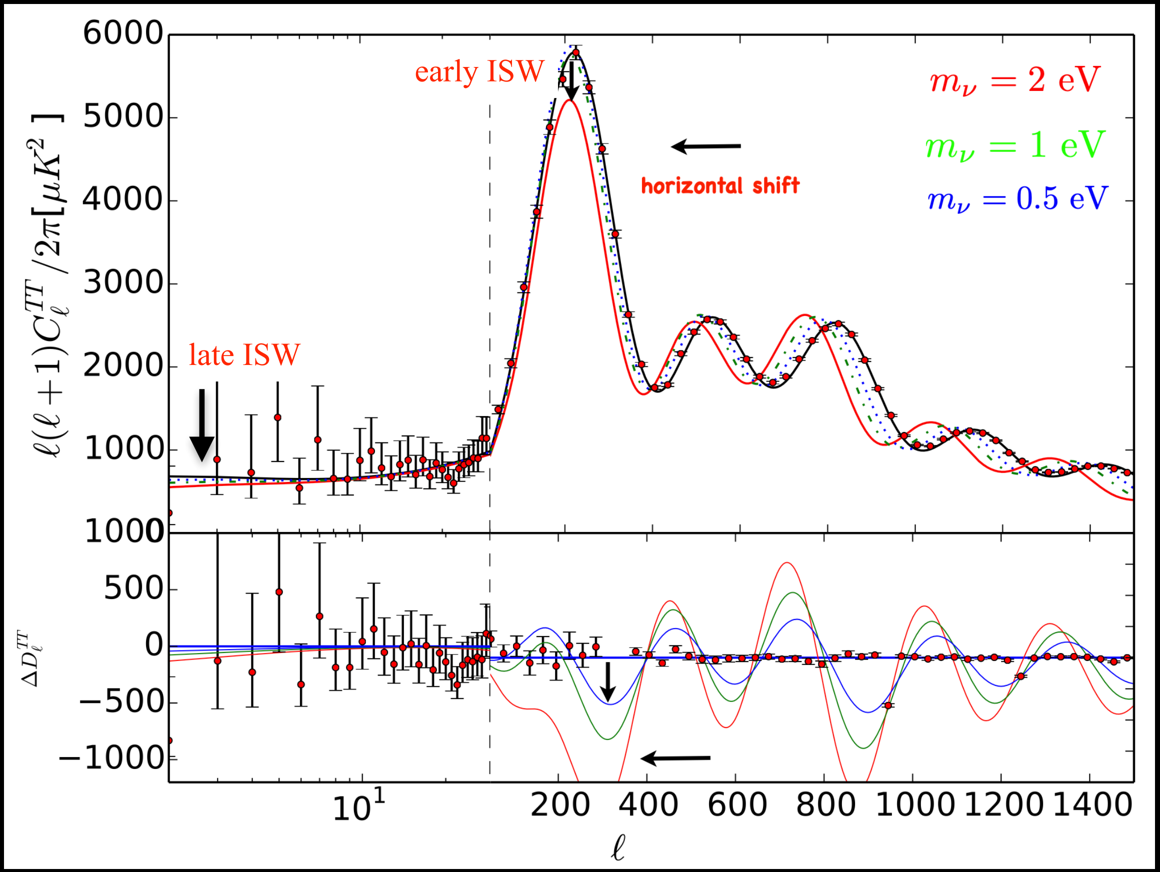


Figure 2.1: Evolution of the square of the Hubble parameter, in a scenario in which all typical contributions to the Universe expansion (radiation, matter, curvature, cosmological constant) dominate one after each other.

Lesgourgues, arxiv:astro-ph/0409426

The total neutrino mass and the CMB



Credit figure: Olga Mena

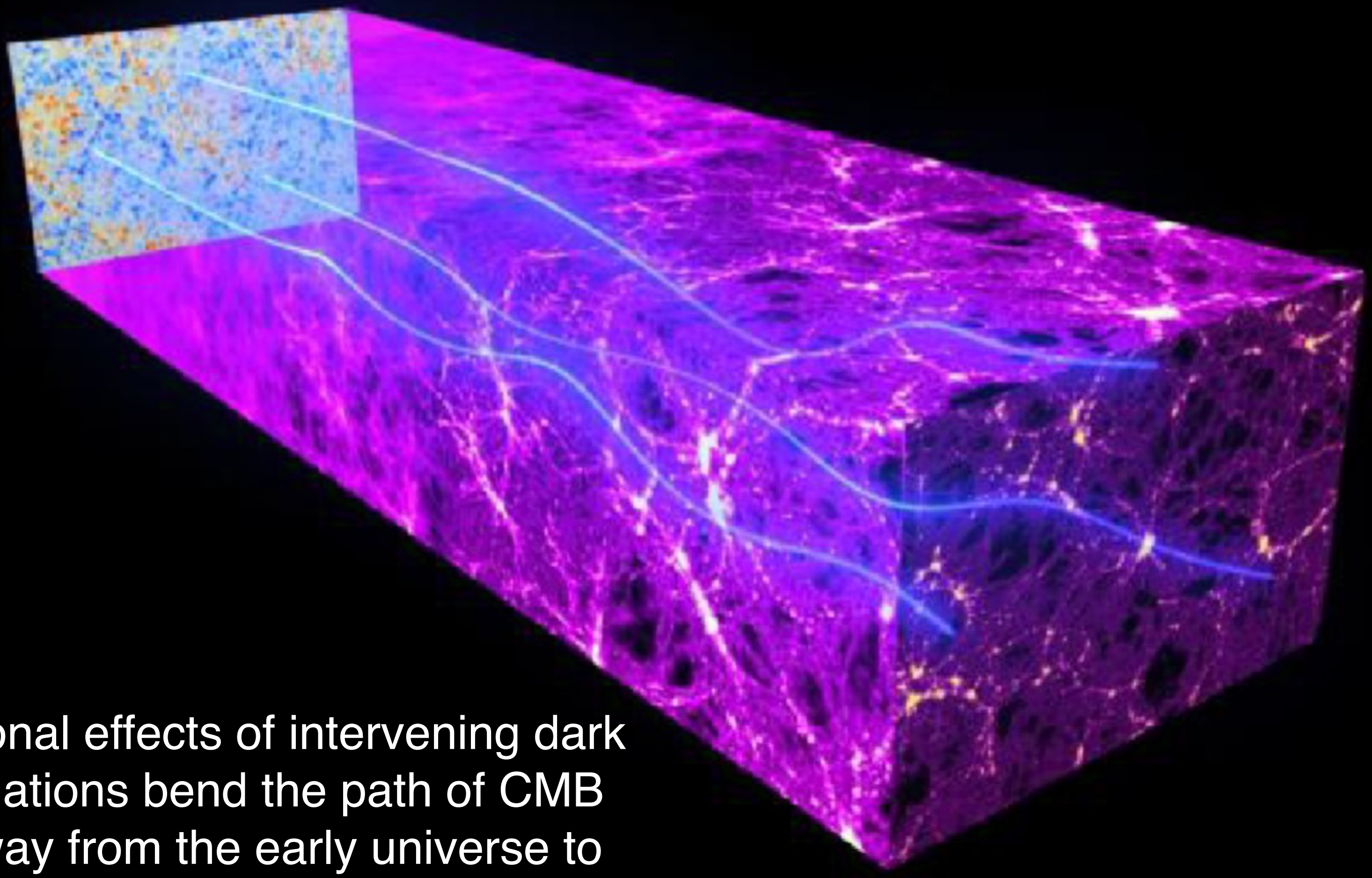
This means a decrease in the height of the first CMB acoustic peak for the early ISW, and a decrease of the plateau at low multipoles for the late ISW. However, the CMB is only marginally sensitive to the late ISW effect due to cosmic variance.

Moreover, a change in the non-relativistic matter density at late times can impact the angular diameter distance to the last scattering surface $d_A(z_{dec})$, which determines the overall position of CMB peaks.

$$d_A(z) = \frac{c}{H_0}\frac{1}{(1+z)}\int_0^z \frac{dz}{\left[\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}\right]^{1/2}}$$

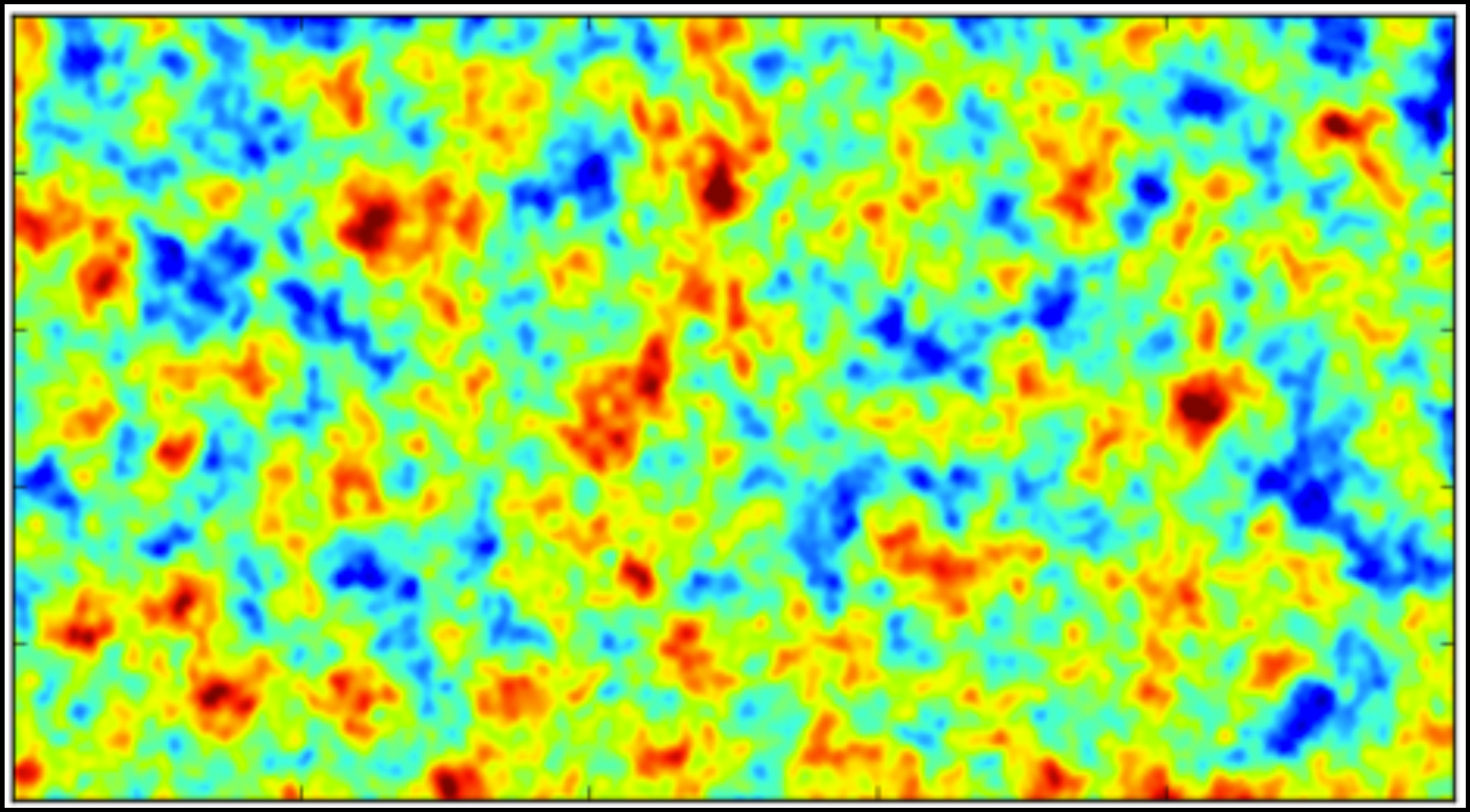
The total neutrino mass and the CMB

However, these effects are strongly degenerate with other cosmological parameters, so how can the CMB set strong constraints on Σm_ν?
This happens because of another secondary source of anisotropies: the CMB lensing.



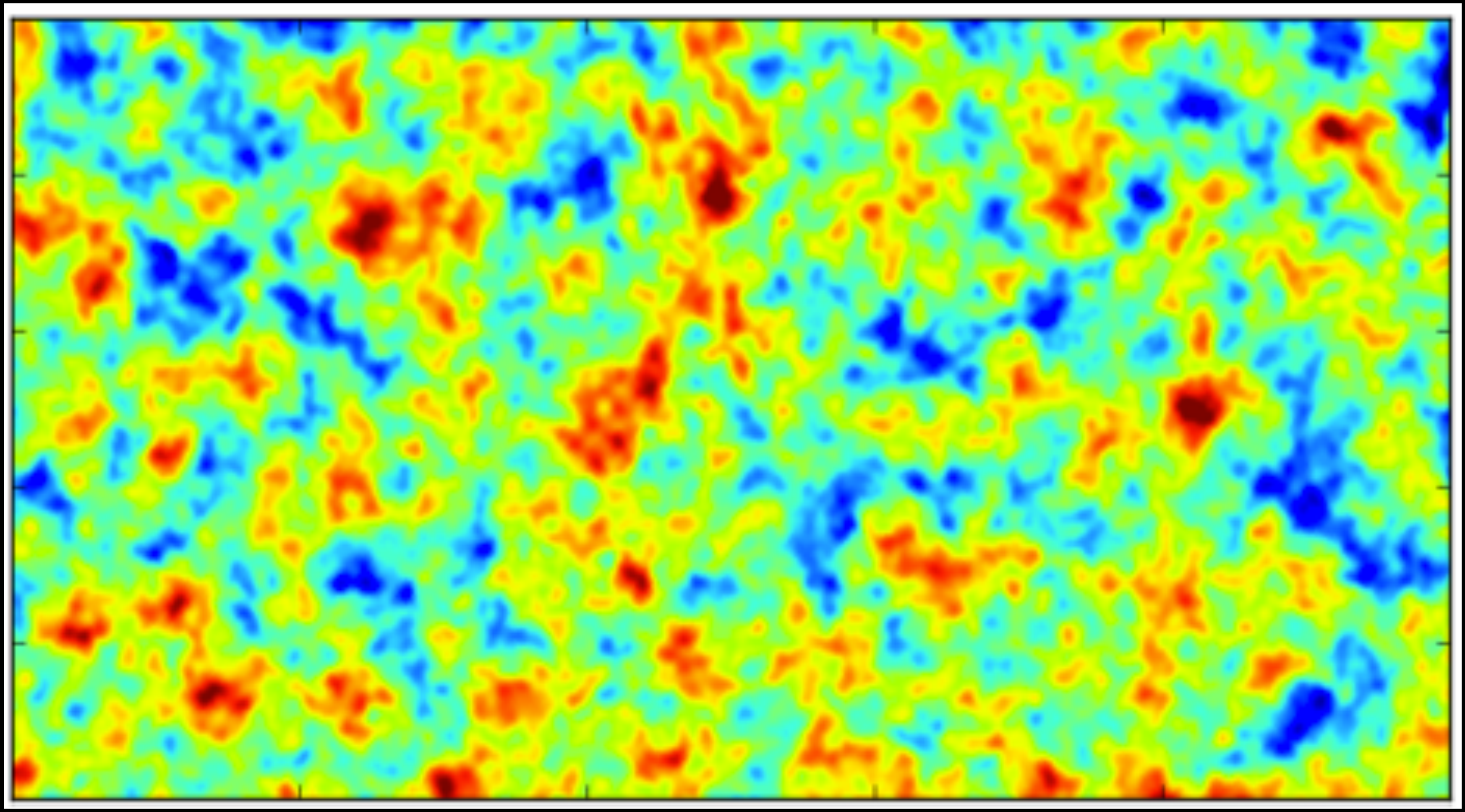
The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the telescope.
This "gravitational lensing" distorts our image of the CMB.

The CMB lensing



A simulated patch of CMB sky – **before dark matter lensing**

The CMB lensing



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The total neutrino mass and the CMB

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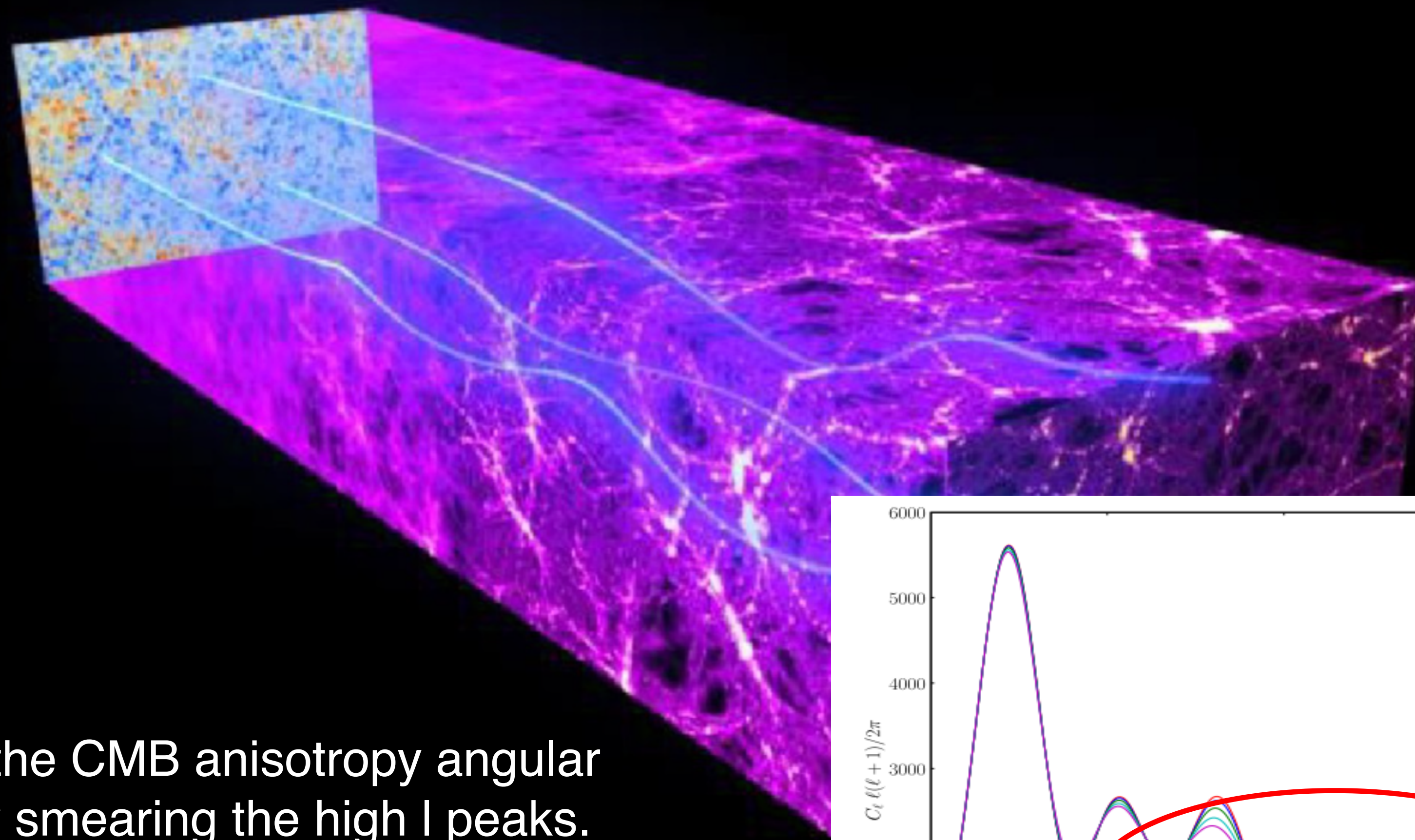
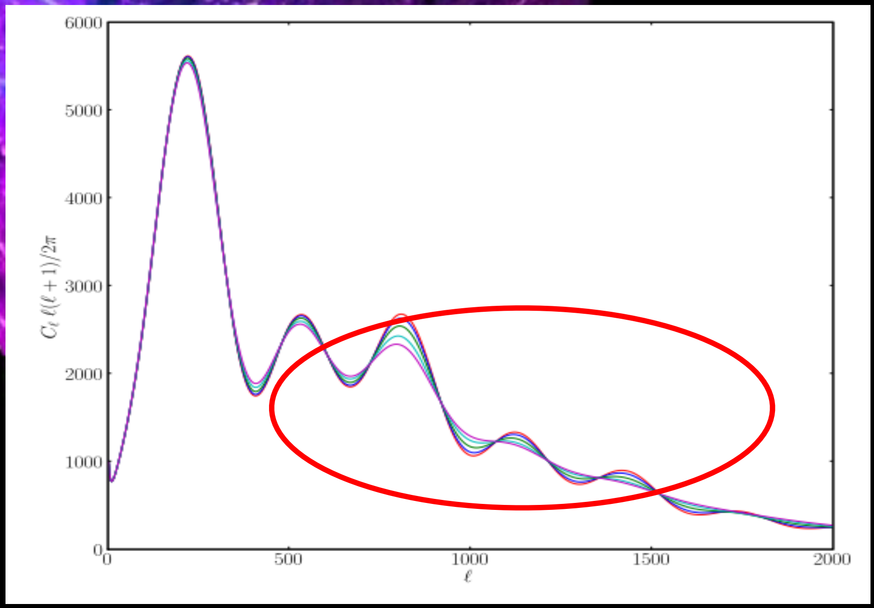
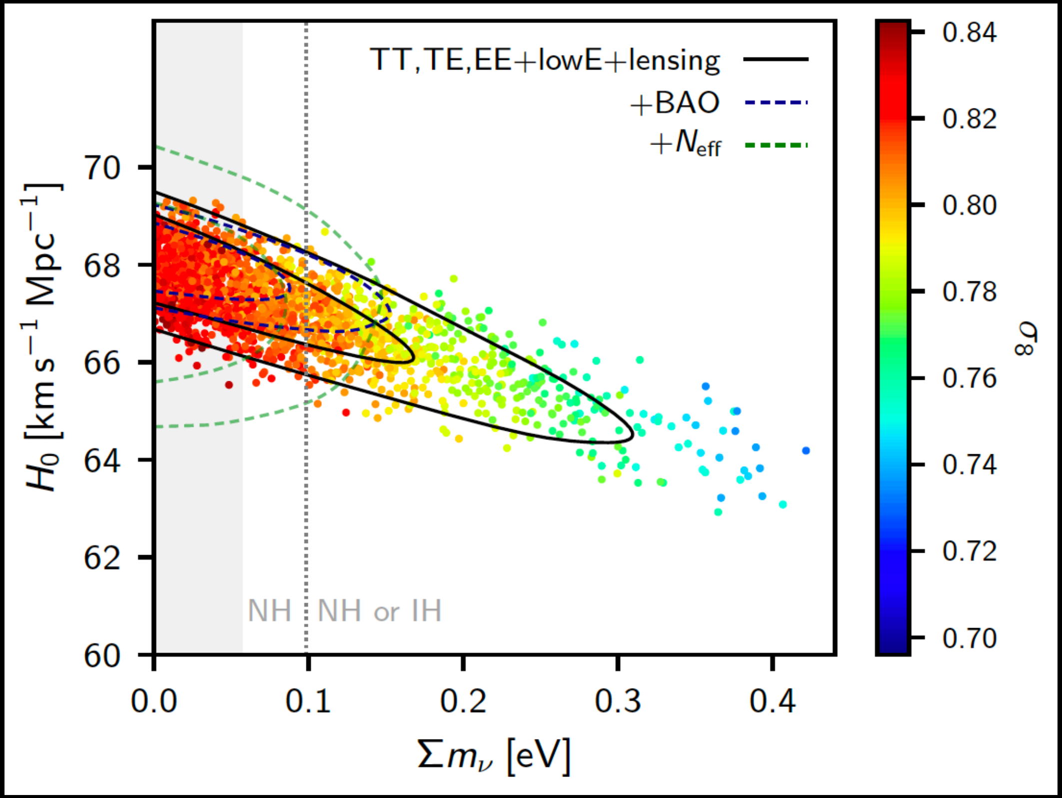


This affects the CMB anisotropy angular spectrum by smearing the high l peaks.



Total neutrino mass



Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

$$\sum m_\nu < 0.26 \text{ eV} \quad (95\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE})$$

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

$$\Sigma m_\nu < 0.58\,\text{eV for SPT+ACT,}$$

From CMB we have a very important upper limit on the total neutrino mass.

The total neutrino mass and the LSS

When neutrinos become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.

The main LSS observables are
the power spectrum of the matter fluctuations in Fourier space

$$\langle \delta_m(\boldsymbol{k})\, \delta_m(\boldsymbol{k}') \rangle = (2\pi)^3\, P(k)\, \delta_D^{(3)}(\boldsymbol{k} - \boldsymbol{k}')$$

Or the two-point correlation function in the configuration space

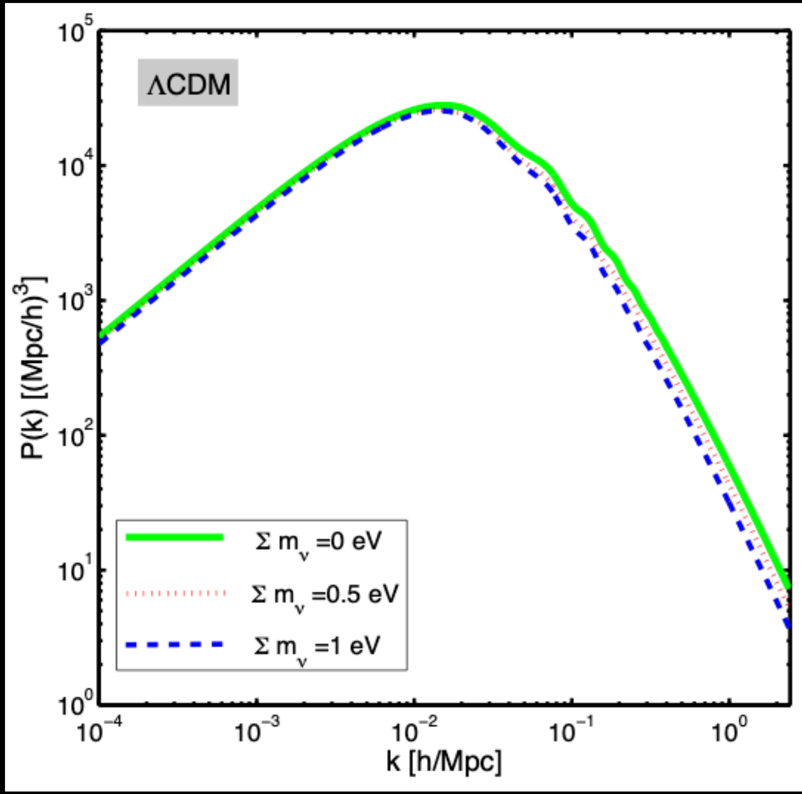
$$\xi(r) = \int \frac{d^3 k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} \equiv \xi_m(r)$$

Matter power spectrum

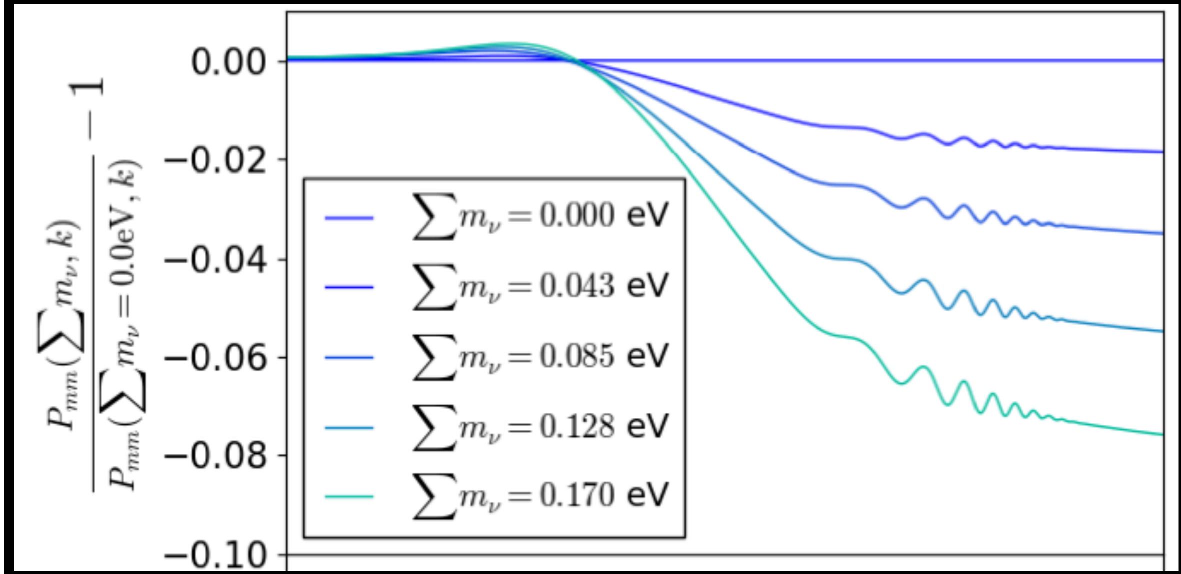
The shape of the matter power spectrum is the key observable for constraining the neutrino masses with cosmological methods.

This is defined as the two-point correlation function of the total non-relativistic matter fluctuation in Fourier space:

$$P(k,z) = \langle |\delta_{\rm m}(k,z)|^2 \rangle \Rightarrow \delta_{\rm m} = \frac{\sum_i \bar{\rho}_i \delta_i}{\sum_i \bar{\rho}_i}$$

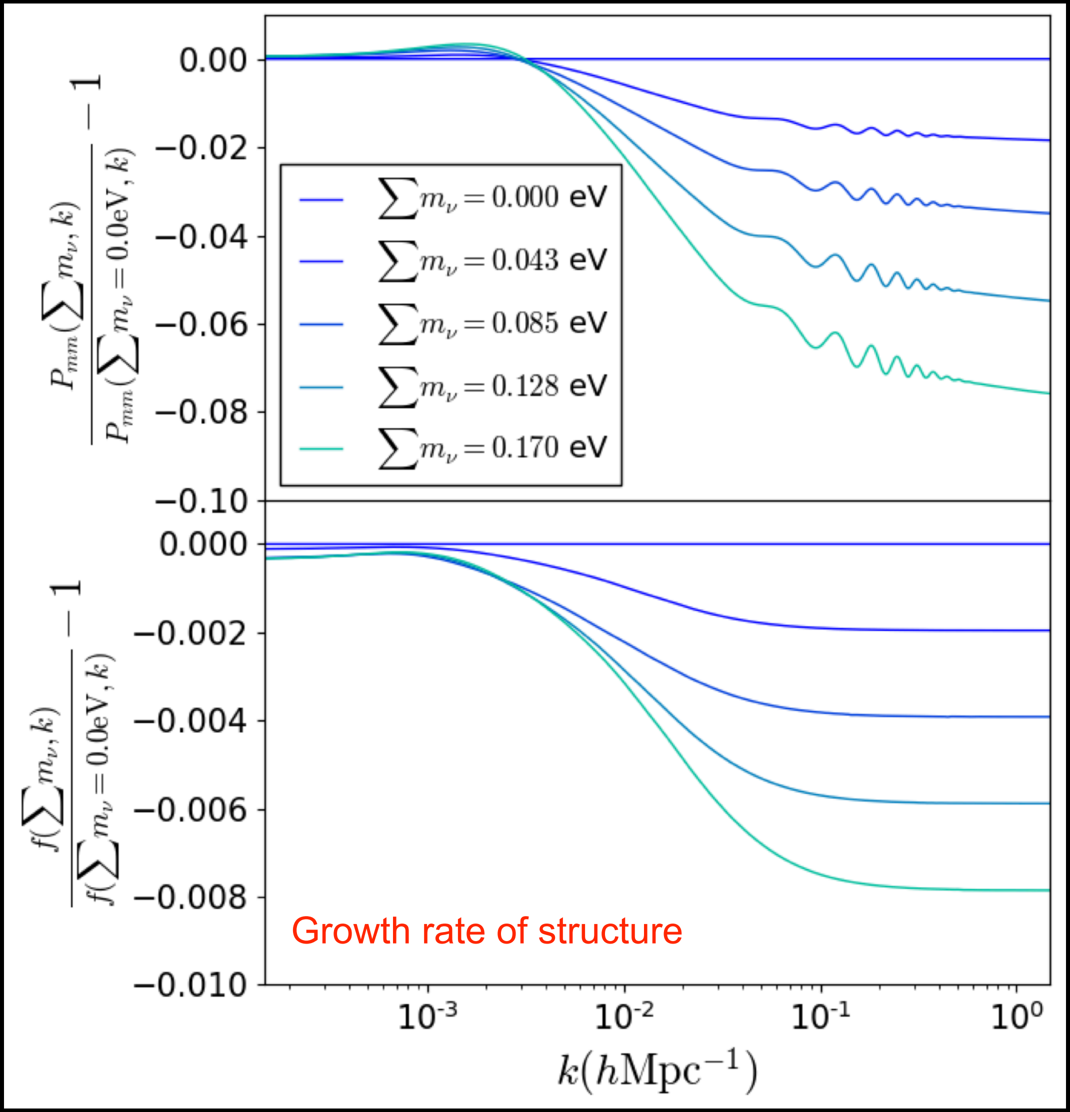


Chen & Xu, Phys.Lett.B 752



Whitford et al., arXiv:2112.10302

Matter power spectrum



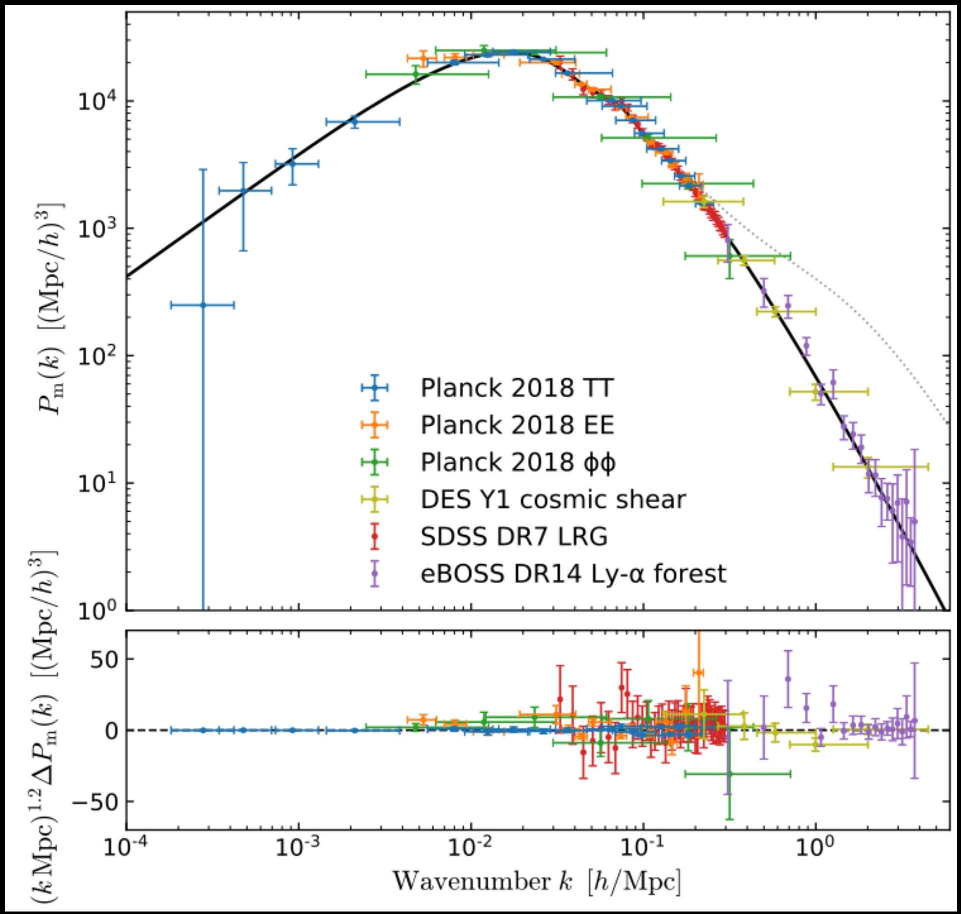
Whitford et al., arXiv:2112.10302

Neutrinos with sub-eV masses are hot thermal relics with very large thermal velocity exceeding the escape velocity of the gravitational potentials. Therefore they cluster only at scales larger than their free streaming scale.

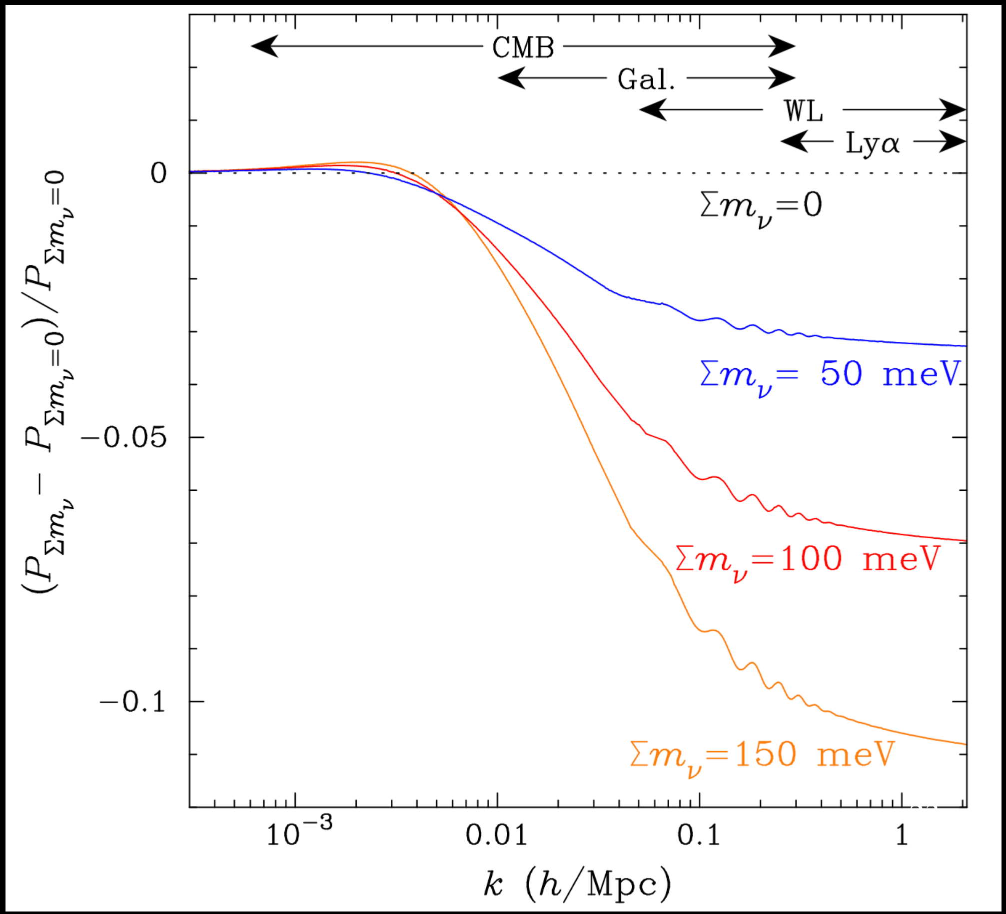
Massive neutrinos will suppress the structure formation at small scales, affecting the large scale structures (LSS). On larger scales, they cluster in the same way as cold dark matter.

Matter power spectrum

The power spectrum of total matter fluctuations can be obtained using measurements of CMB lensing, galaxy clustering and weak lensing, and the number density of galaxy clusters.



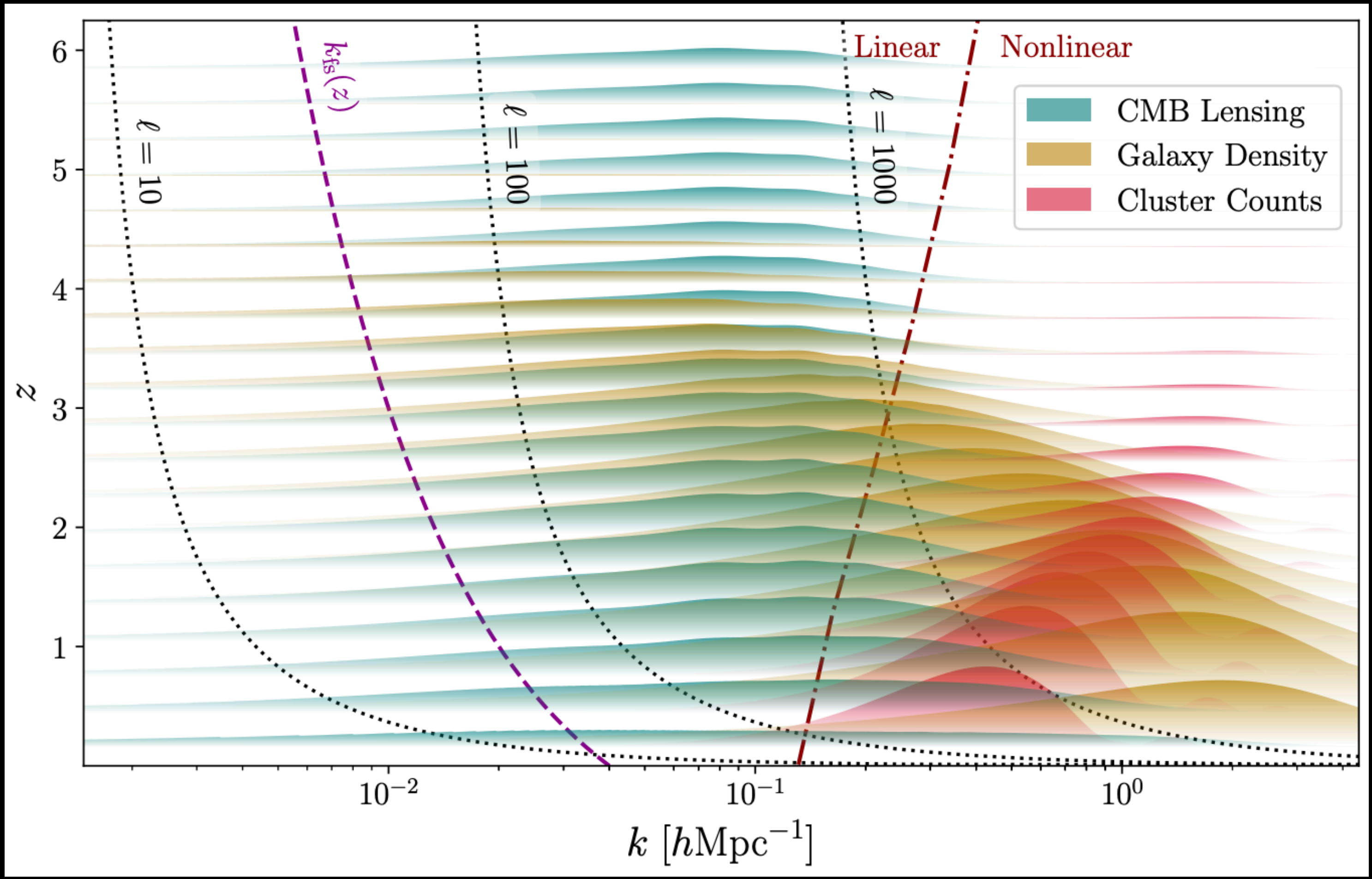
Chabanier et al, arXiv:1905.08103



Abazajian et al., Astropart.Phys. 63 (2015) 66-80

The total neutrino mass and the LSS

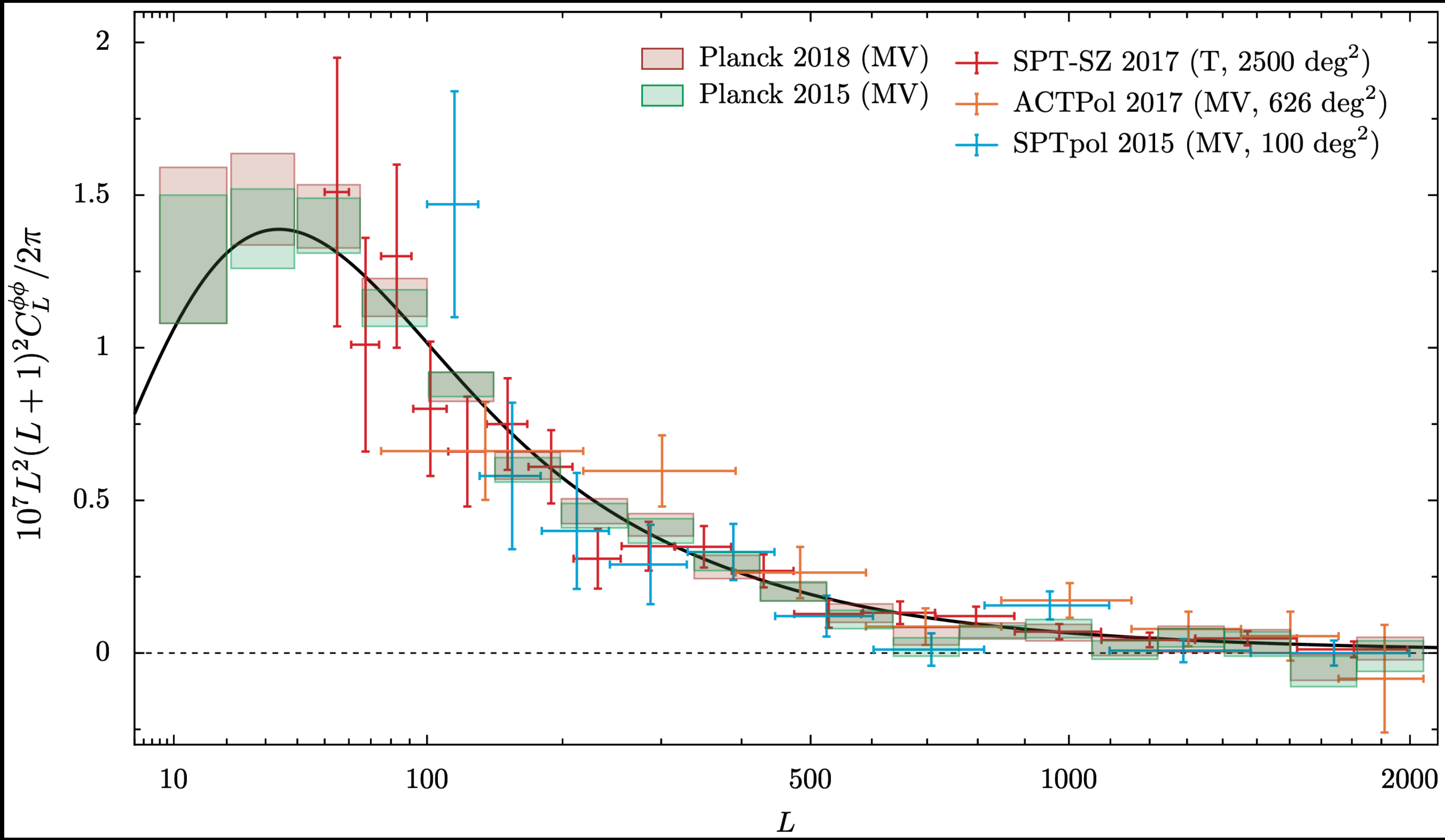
At k > 0.1h/Mpc, we begin to see deviations from the linear evolution, so the perturbation theory breaks down and we need N-body simulations (Elbers et al. MNRAS 2021/2022) or beyond perturbative regime (Effective Field Theory of Large-Scale Structure) to analyse the data.



Green & Meyers, arXiv:2111.01096

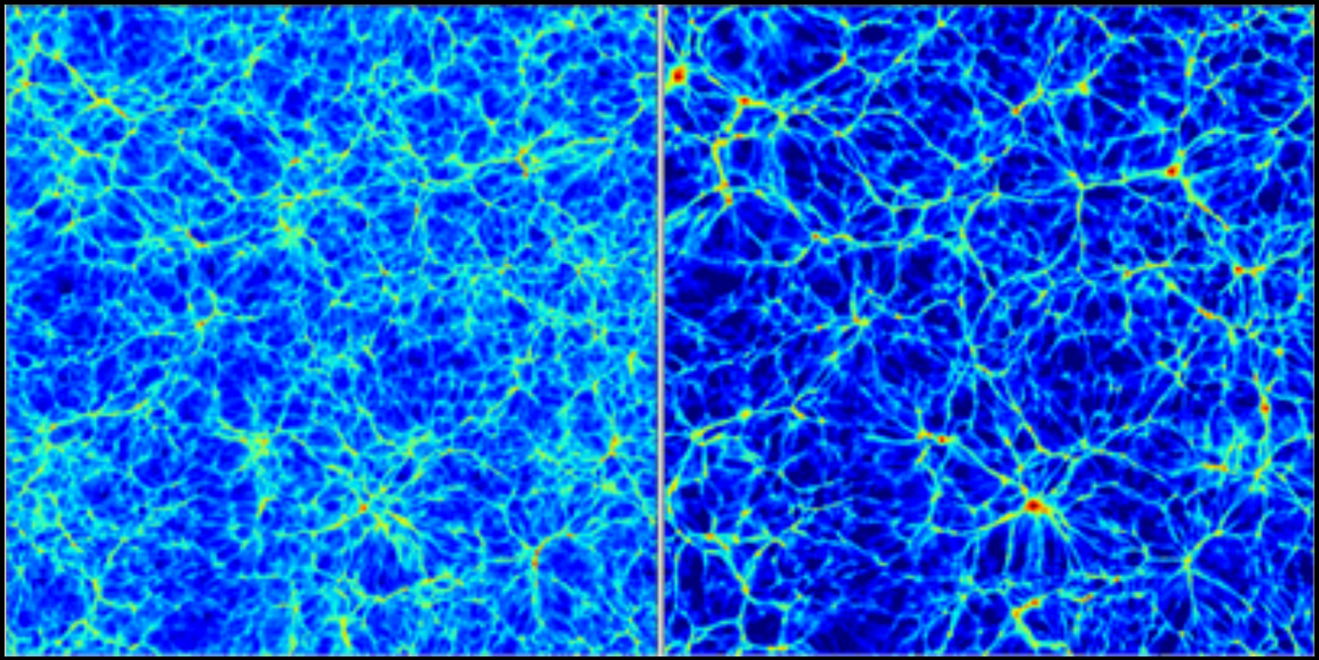
The total neutrino mass and the LSS

CMB lensing can be measured also in a different way,
i.e. using the trispectrum (or four-point correlation function) of the CMB maps,
resulting in a 40σ measurement of the lensing signal.



Planck collaboration, arXiv:1807.06210

The total neutrino mass and the LSS



Given that massive neutrinos practically do not form structure, the more massive the neutrinos, the less structure forms, and the weaker the CMB lensing signal. So a larger signal of lensing means a smaller neutrino mass.

$$\sum m_\nu < 0.24 \text{ eV} \quad (95\,\%,\ \text{TT,TE,EE+lowE+lensing}).$$

Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

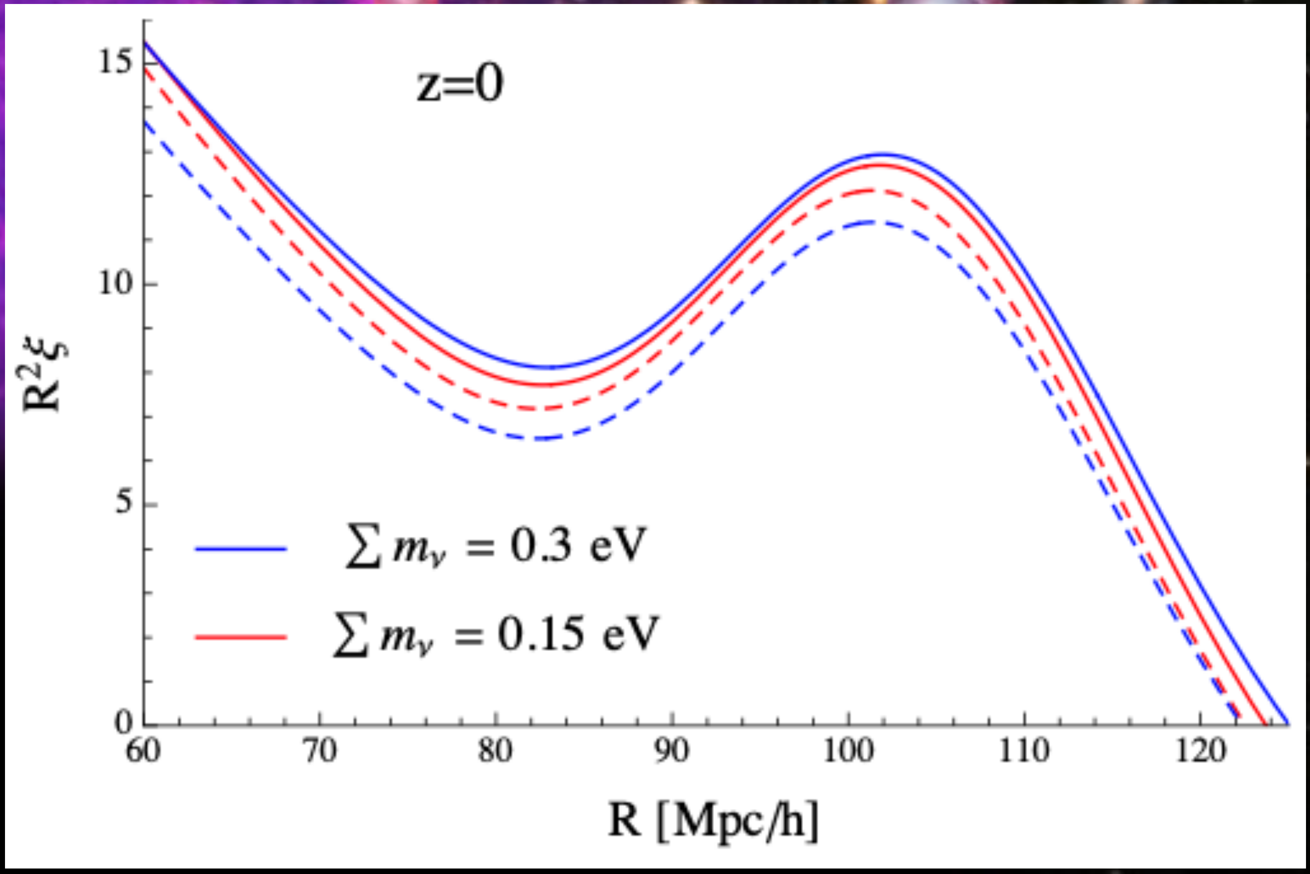
$$\Sigma m_\nu < 0.17\,\text{eV for CMB-SPA}.$$

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

These strong limits indicate that we have a clear detection of the lensing signal in the CMB spectra.

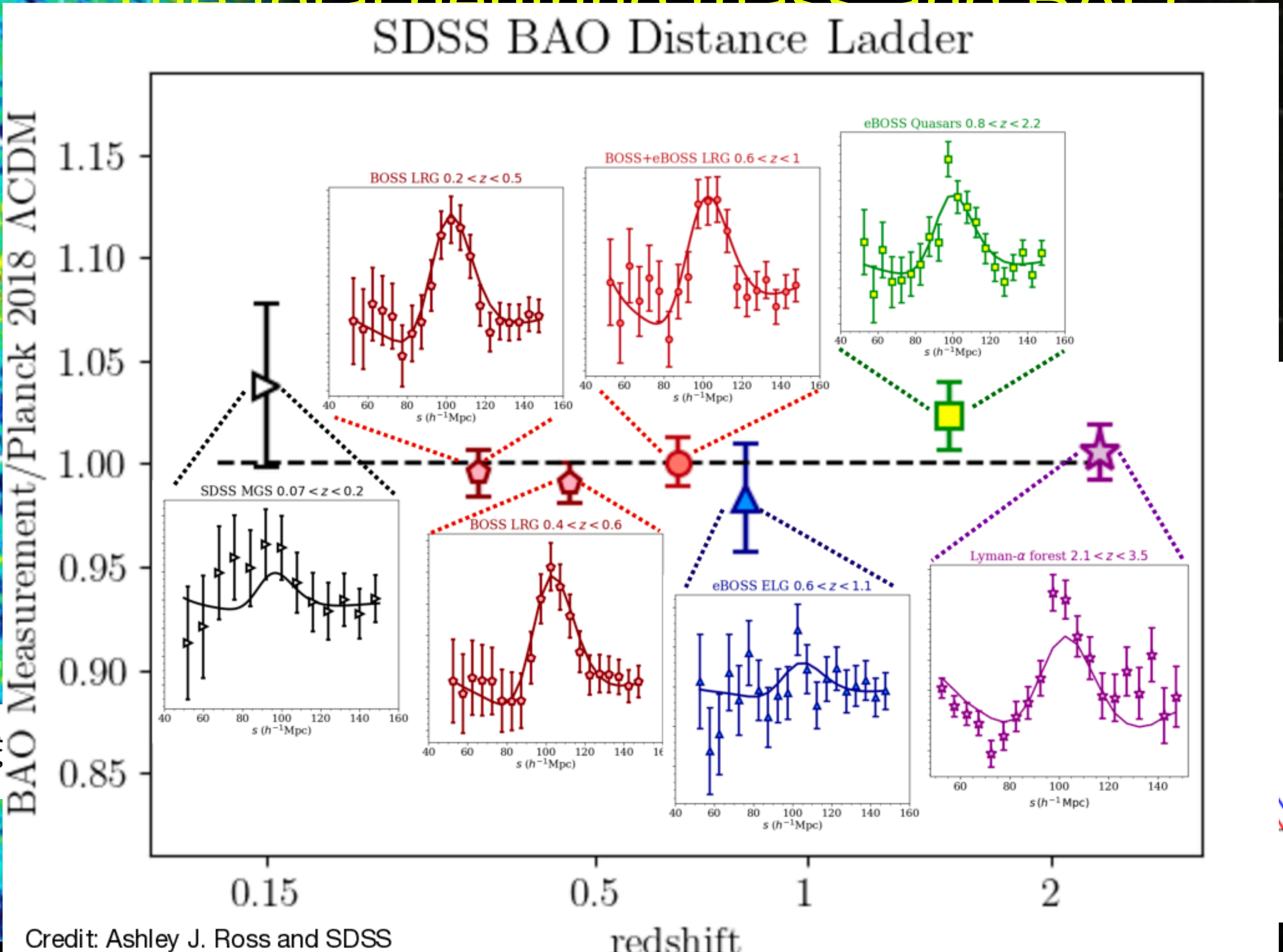
The total neutrino mass and BAO

$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}$$



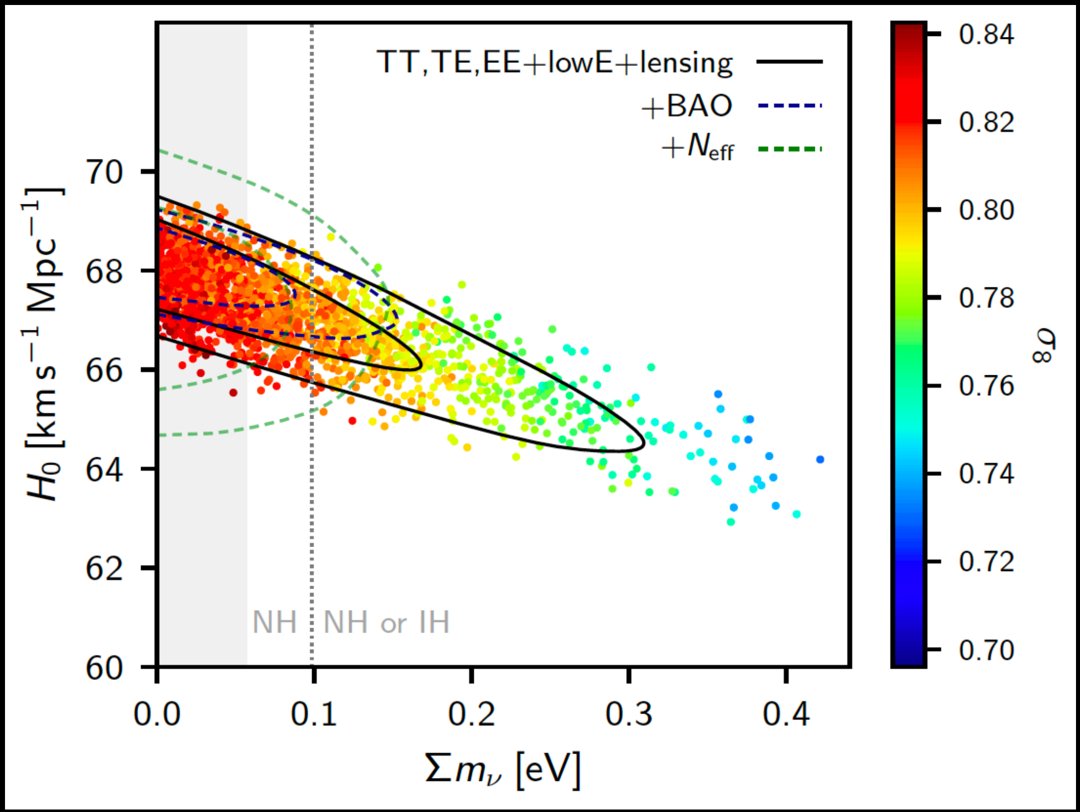
Peloso et al., *JCAP* 07 (2015) 001

The total neutrino mass and BAO



The total neutrino mass and BAO

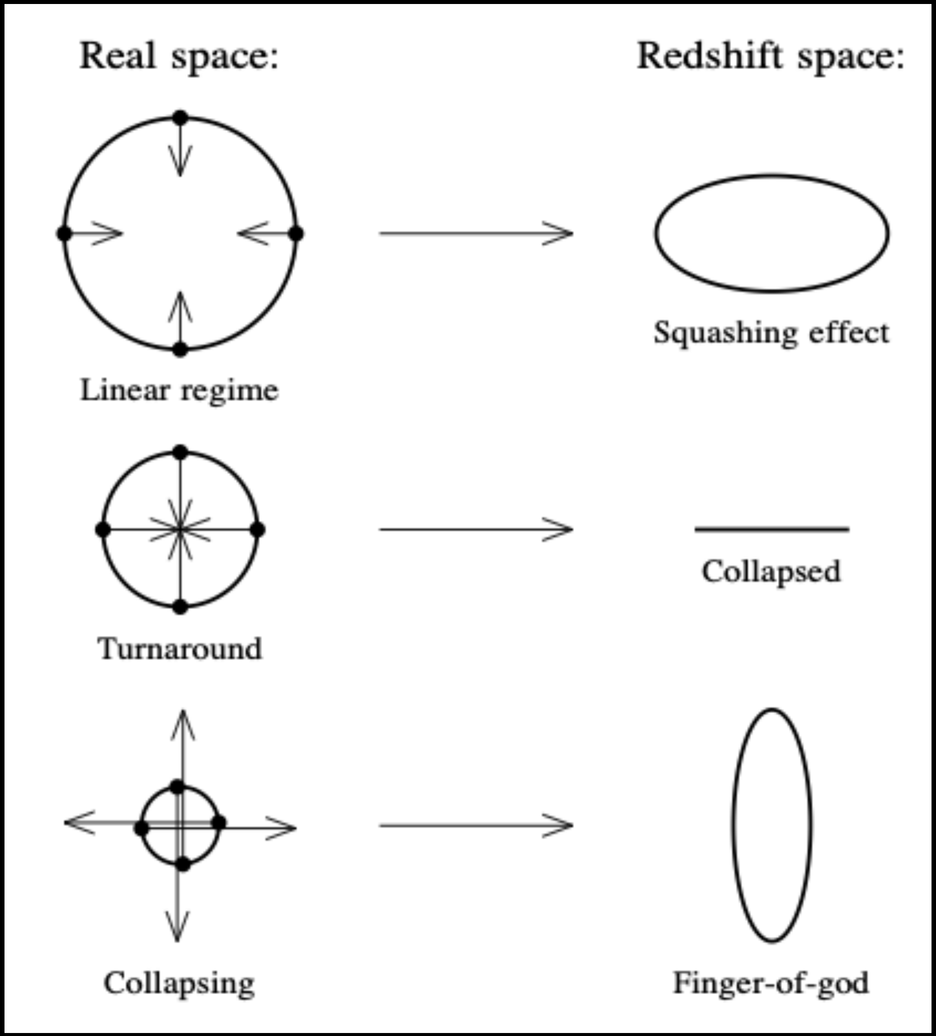
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



$$\sum m_\nu < 0.13\ \mathrm{eV} \quad (95\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE{+}BAO}),$$

The inclusion of additional low redshift probes is mandatory in order to sharpen the CMB neutrino bounds. The most stringent bound is obtained when adding the BAO data that are directly sensitive to the free-streaming nature of neutrinos. Actually, the geometrical information they provide helps in breaking the degeneracies among cosmological parameters.

Redshift Space Distortions



Hamilton, astro-ph/9708102 [astro-ph]

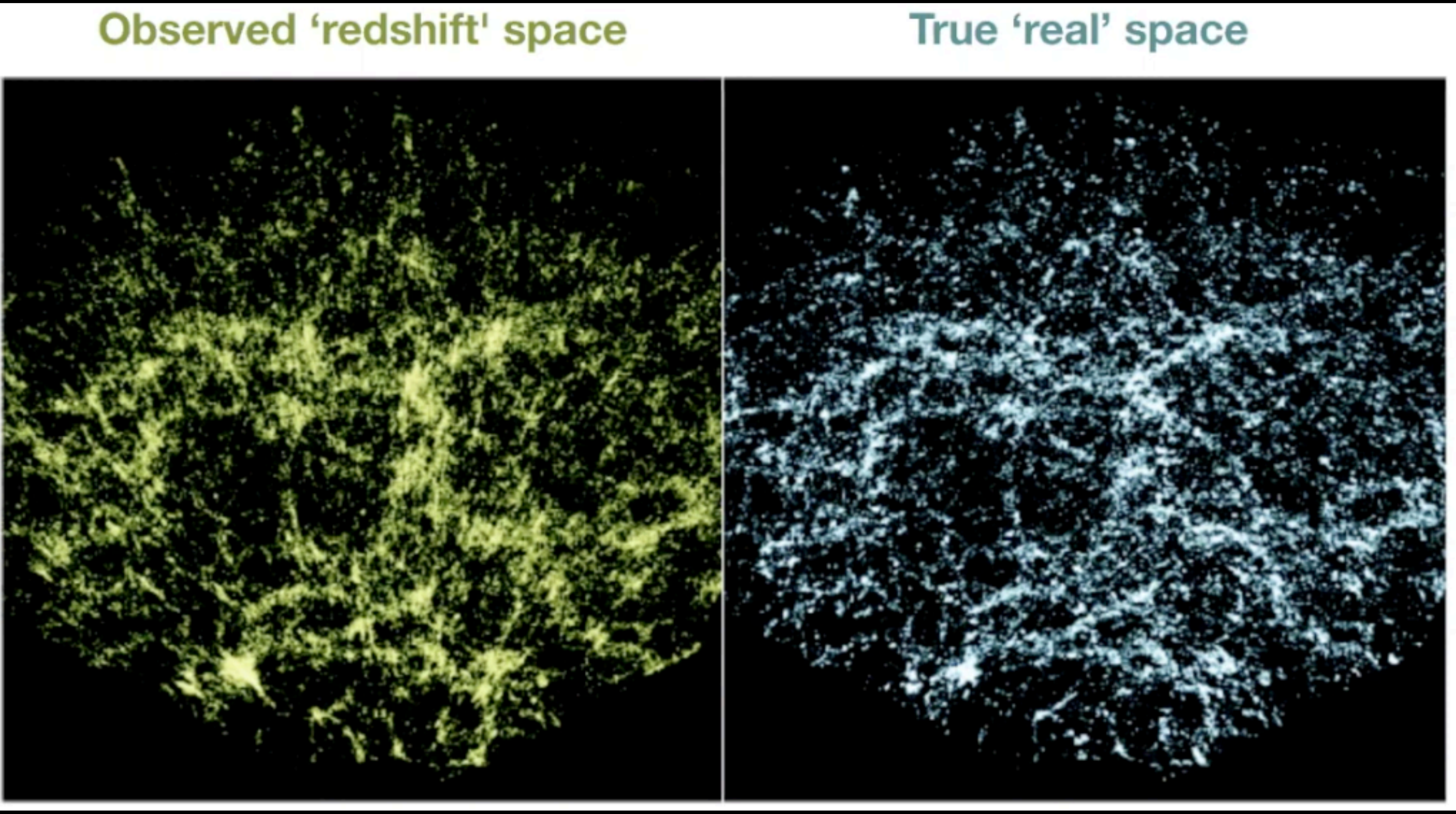
Analysing the clustering in the redshift space, you can study the Redshift Space Distortions (RSD). We will have a reduction or increase of the growth of structure along the radial direction, because of the peculiar velocities (anisotropic clustering).

Although the BAO shells are spherical in real space, distances obtained in redshift space contain contributions from peculiar velocities of the galaxies, and therefore the reconstructed distances suffer from distortions along the radial direction.

At large scales, the peculiar velocity of an infalling shell is small compared to its radius, and the shell appears squashed.

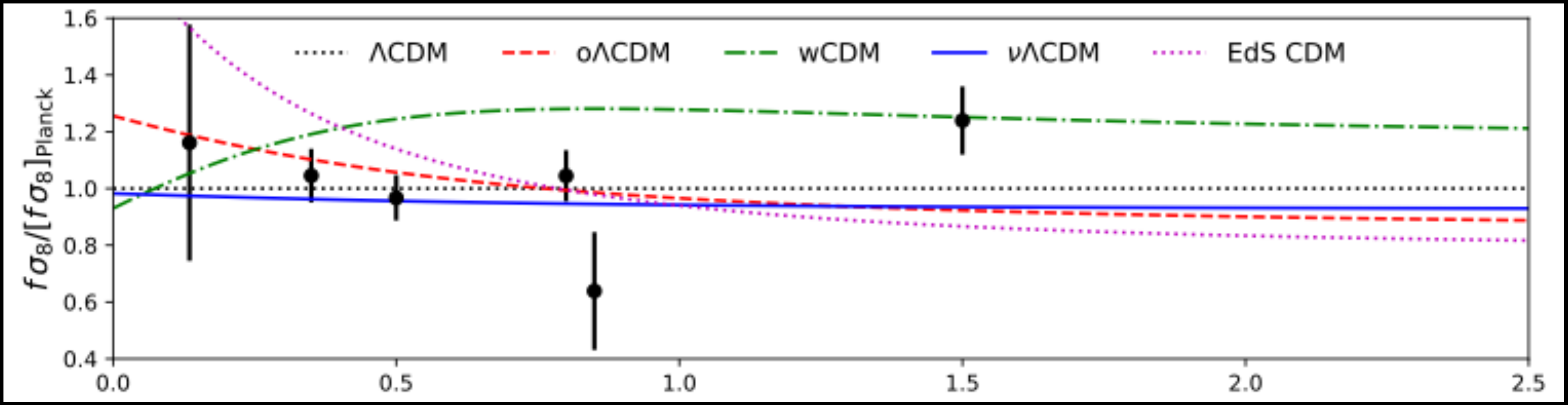
At smaller scales, the spatial distribution of galaxies appears to be elongated due to their velocity dispersion along the line of sight, producing the fingers-of-god.

Redshift Space Distortions



slide from Héctor Gil-Marín

The total neutrino mass and RSD



eBOSS collaboration, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

This RSD effect modifies the galaxy power spectrum and allows for an extraction of the product of the growth rate of structure (f) times the clustering amplitude of the matter power spectrum (σ_8), the well-known $f\sigma_8$ observable.

We can see in the figure that massive neutrinos prefer a lower value for the $f\sigma_8$ data.

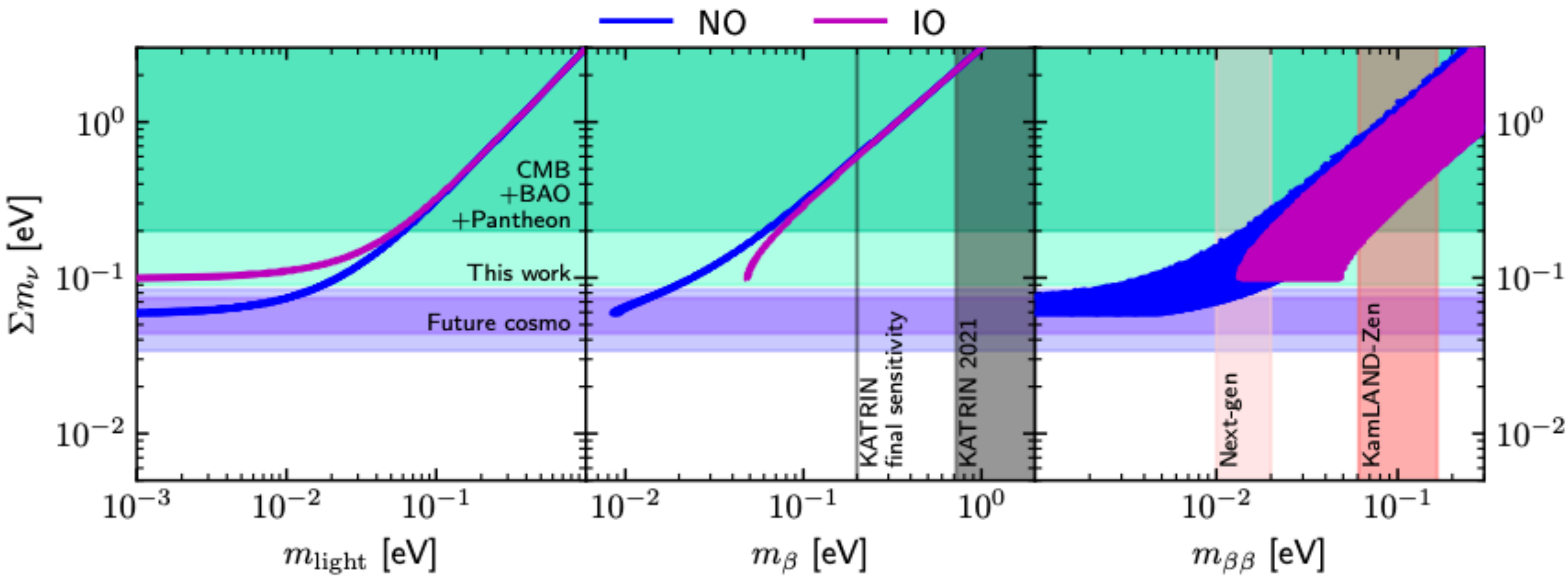
The total neutrino mass and RSD

Planck+lensing +Pantheon	Σm_ν [eV]
+ DR12 *BAO only*	< 0.116
+ DR12 *BAO+RSD*	< 0.118
+ DR16 *BAO only*	< 0.158
+DR16 *BAO+RSD*	< 0.101
+DR12 *BAO only* + DR16 *BAO only*	< 0.121
+DR12 *BAO only* + DR16 *BAO+RSD*	< 0.0866
+DR12 *BAO+RSD* + DR16 *BAO only*	< 0.125
+DR12 *BAO+RSD* + DR16 *BAO+RSD*	< 0.0934

Before DESI, the most constraining upper bounds was $\Sigma m_\nu < 0.087$ eV at 95% CL for a combination of all the available data.

Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083504

Constraints on the total neutrino mass



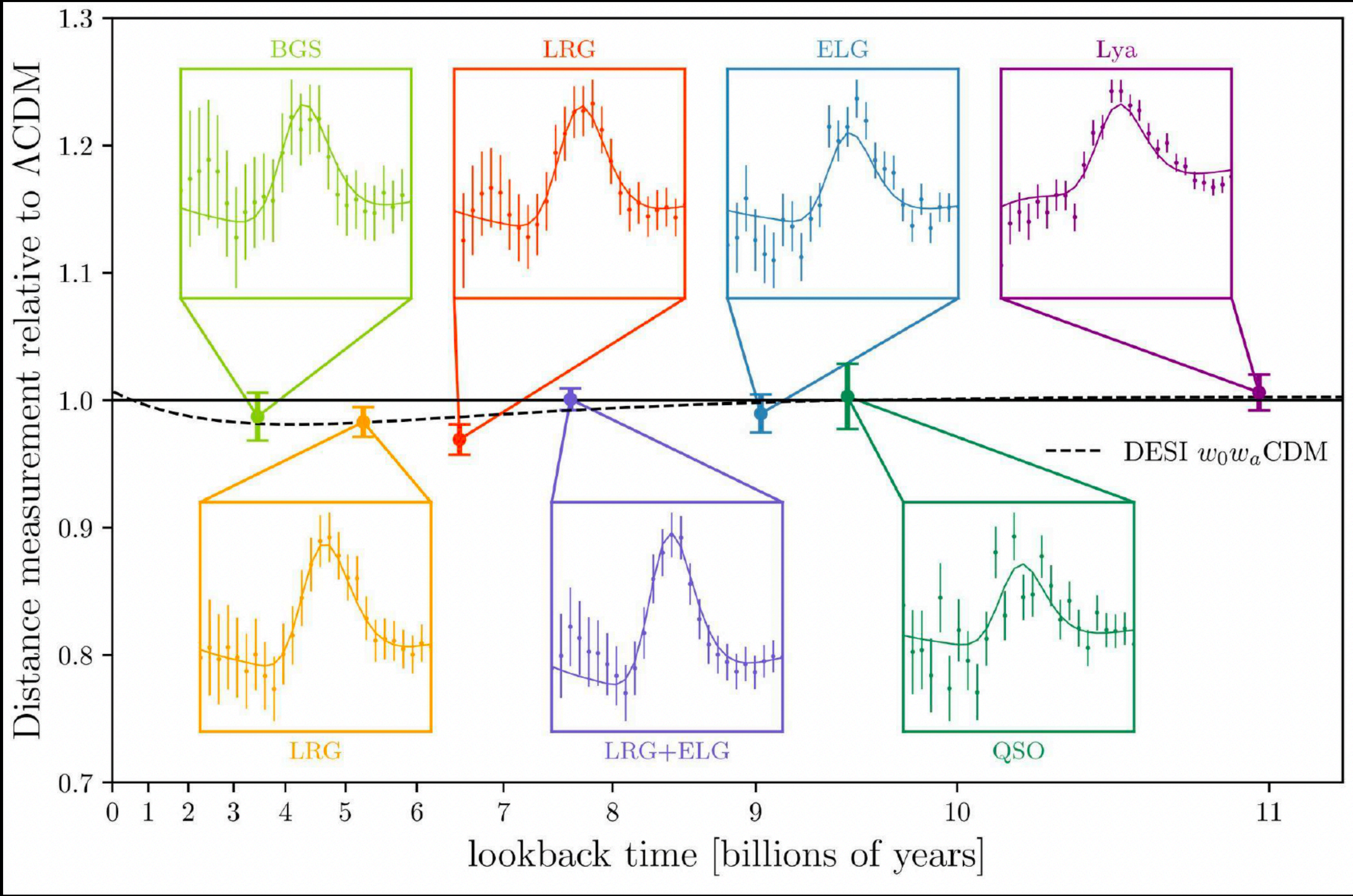
Here we illustrate the theoretical expectations within each mass ordering for the three observables of neutrino masses: beta-decay (m_β), neutrinoless double beta decay $m_{\beta\beta}$ and the cosmological measured quantity Σm_ν.

The light green horizontal band represents the most constraining bound before DESI, which is $\Sigma m_\nu < 0.087$ eV at 95% CL.

This very tight limit has crucial implications for direct neutrino mass laboratory searches, suggesting that they are not expected to detect any signal.

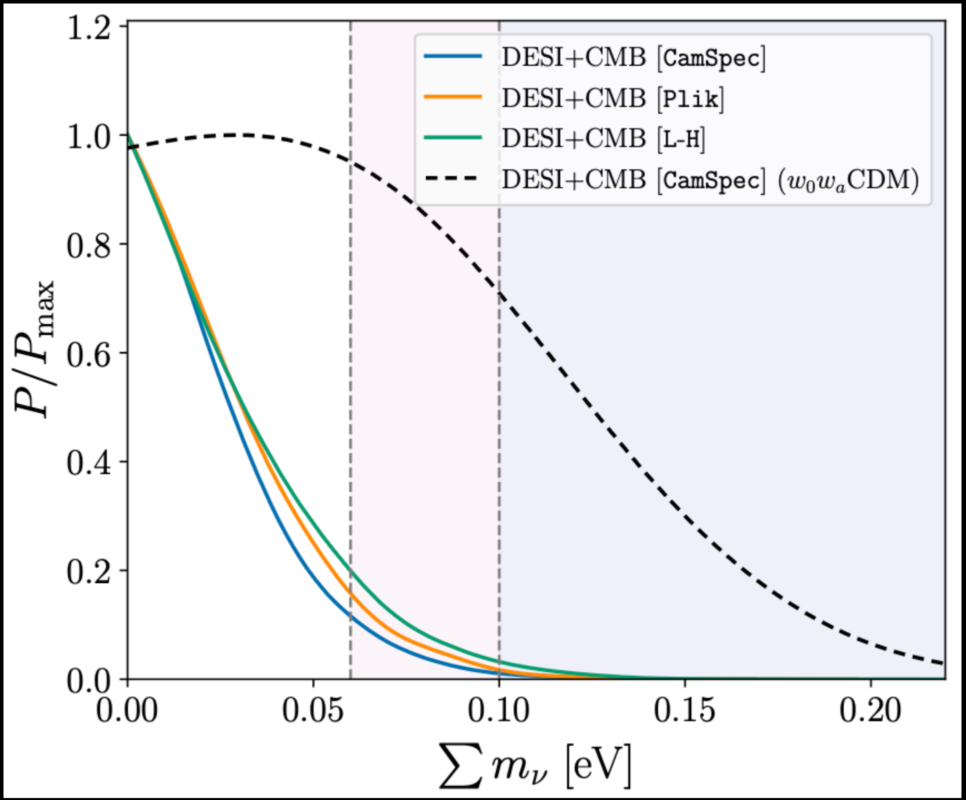
Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083504

New DESI BAO measurements



Credit: Arnaud de Mattia, CEA Saclay

New DESI BAO measurements

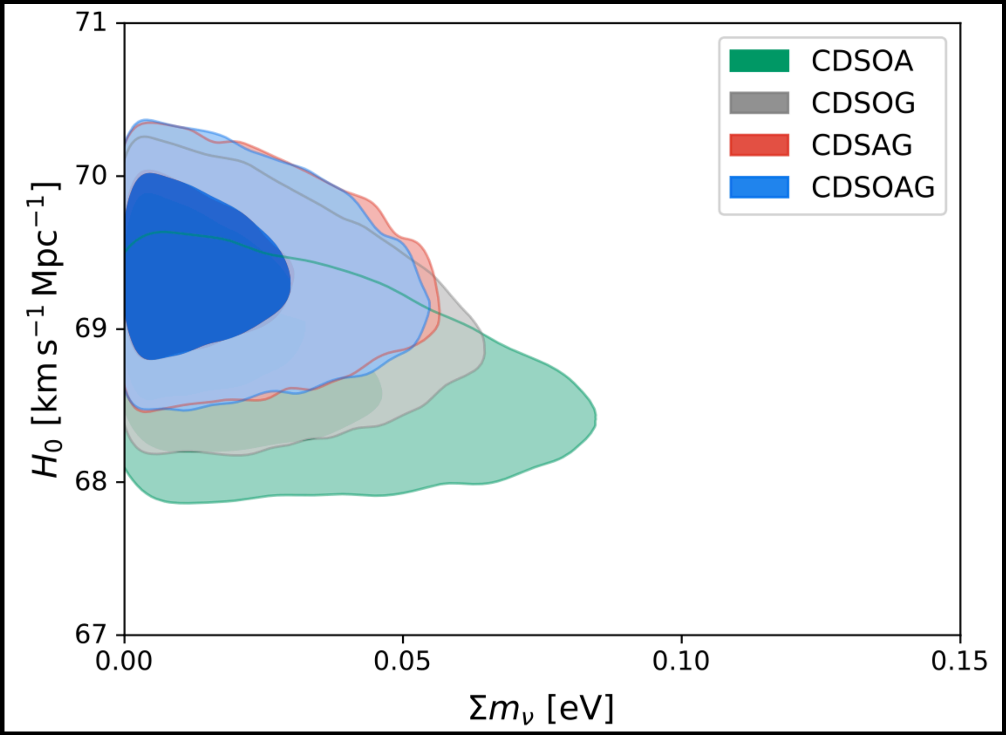


Model/Dataset	Ω_{m}	H_0 [km s^{-1} Mpc^{-1}]	$H_0 r_{\mathrm{d}}$ [100 km s^{-1}]	$\sum m_\nu$ [eV]
ΛCDM+$\sum m_\nu$				
DESI BAO+CMB [Camspec]	0.3009 ± 0.0037	68.36 ± 0.29	100.96 ± 0.48	< 0.0642
DESI BAO+CMB [L-H]	0.2995 ± 0.0037	68.48 ± 0.30	101.16 ± 0.49	< 0.0774
DESI BAO+CMB [Plik]	0.2998 ± 0.0038	68.56 ± 0.31	101.09 ± 0.50	< 0.0691

DESI collaboration, Abdul Karim et al., arXiv:2503.14738

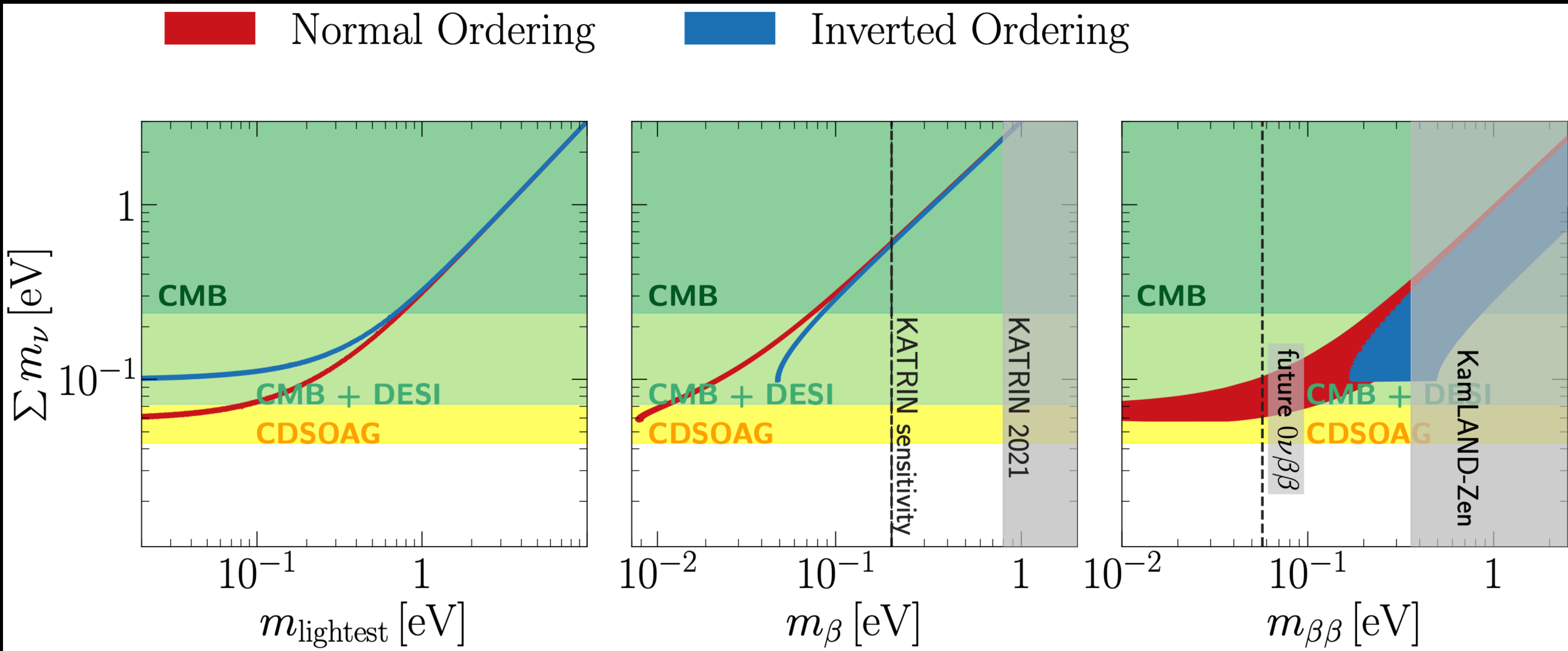
Tightest neutrino mass constraints

Wang, Mena, Di Valentino and Gariazzo, *Phys.Rev.D* 110 (2024) 10, 103536



The tightest bound we find here is $\Sigma m_\nu < 0.043$ eV at 95% CL after combining Planck CMB with DESI BAO, Type Ia Supernovae, Gamma Ray Bursts, cosmic chronometers, and galaxy clusters, highlighting a clear tension between neutrino oscillation measurements and cosmological constraints.

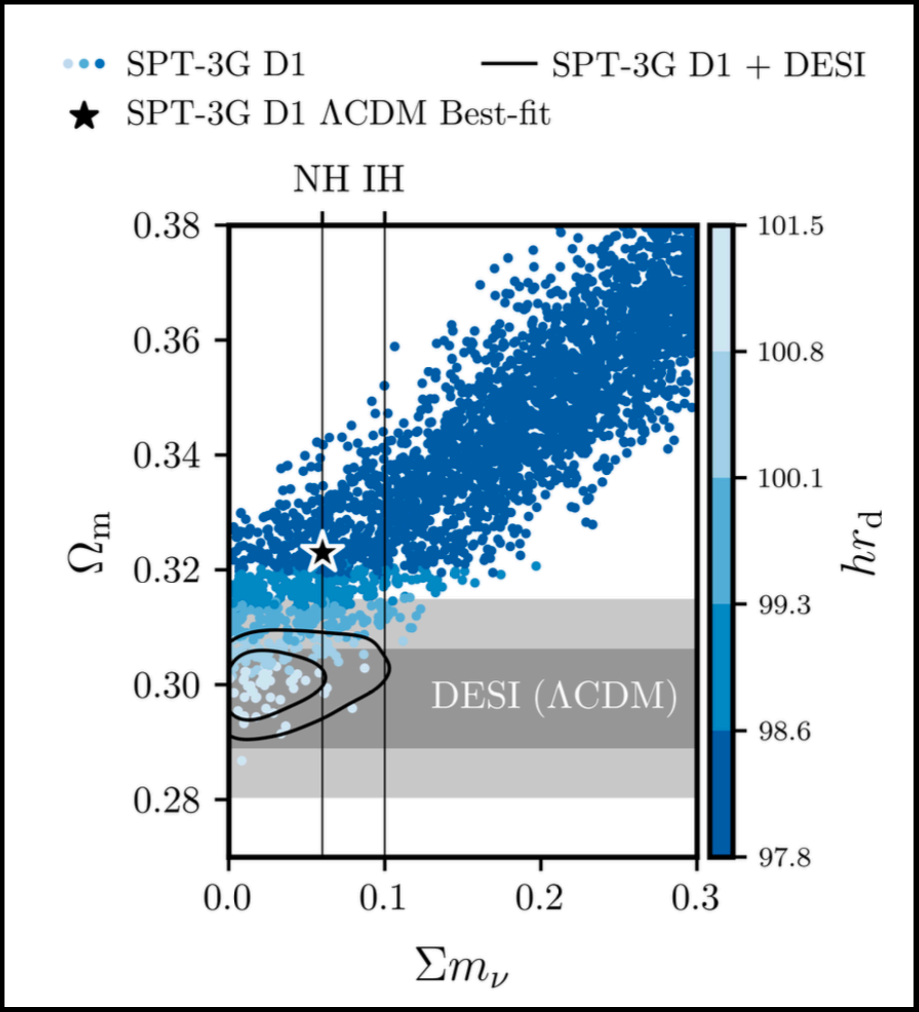
Constraints on the total neutrino mass



The light green horizontal band represents the most constraining bound after DESI, which is Σmν < 0.072 eV at 95% CL,
while the yellow band indicates the tightest bound available in the literature after combining with other cosmological probes, which is Σmν < 0.043 eV at 95% CL, significantly below the minimal value allowed by oscillation data.

Wang, Mena, Di Valentino and Gariazzo, *Phys.Rev.D* 110 (2024) 10, 103536

Constraints on the total neutrino mass



When adding DESI to SPT-3G D1 and CMB-SPA, we find at the 95% confidence level:

$$\Sigma m_\nu < 0.081\,\text{eV for SPT-3G D1 + DESI,} \quad (96)$$

$$\Sigma m_\nu < 0.048\,\text{eV for CMB-SPA + DESI.} \quad (97)$$

As expected, adding BAO data tightens the constraint substantially. While the upper limit derived from SPT data alone is consistent with neutrino oscillation data, with a posterior that peaks slightly away from zero, the CMB-SPA+DESI combination appears to rule out the normal and inverted hierachies at 97.9% and 99.9% confidence, respectively. Moving Σm_ν close to zero reduces the best-fit χ^2 value by 7.8 points for joint CMB and BAO analyses compared to the minimal value for the normal hierarchy, which for one additional parameter corresponds to a $2.8\,\sigma$ significance (see Table VII).

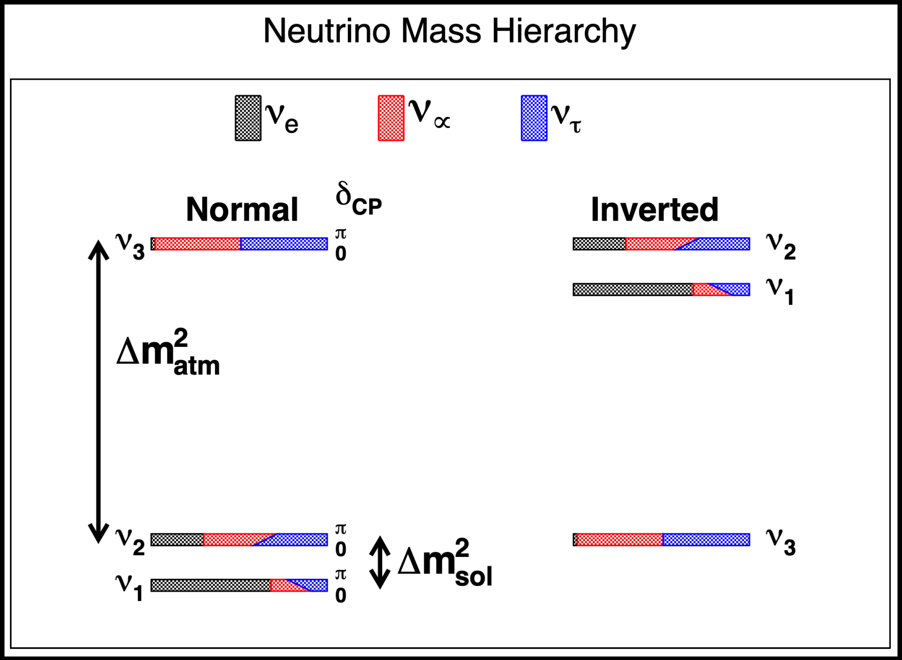
The drive toward as low of a value for Σm_ν as allowed

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

Neutrino mass ordering

At this point, we should discuss mass ordering.

Even though the absolute masses of neutrinos ν are unknown, lower bounds on the total neutrino mass are established through global analyses of oscillation data. These analyses provide the best-fit values for the standard model mass splitting.



Qian and Vogel, arXiv:1505.01891

By setting the lightest neutrino mass to zero, we can determine the lower bounds on the total neutrino mass for the normal or inverted ordering:

$$\sum m_\nu > \begin{cases} (0.0591 \pm 0.00027)\,\mathrm{eV} & \text{(NO)} \\ (0.0997 \pm 0.00051)\,\mathrm{eV} & \text{(IO)} \end{cases}$$

Neutrino mass ordering

The upper bounds obtained are strongly dependent on the choice of the prior for Σmν used in the cosmological analysis.

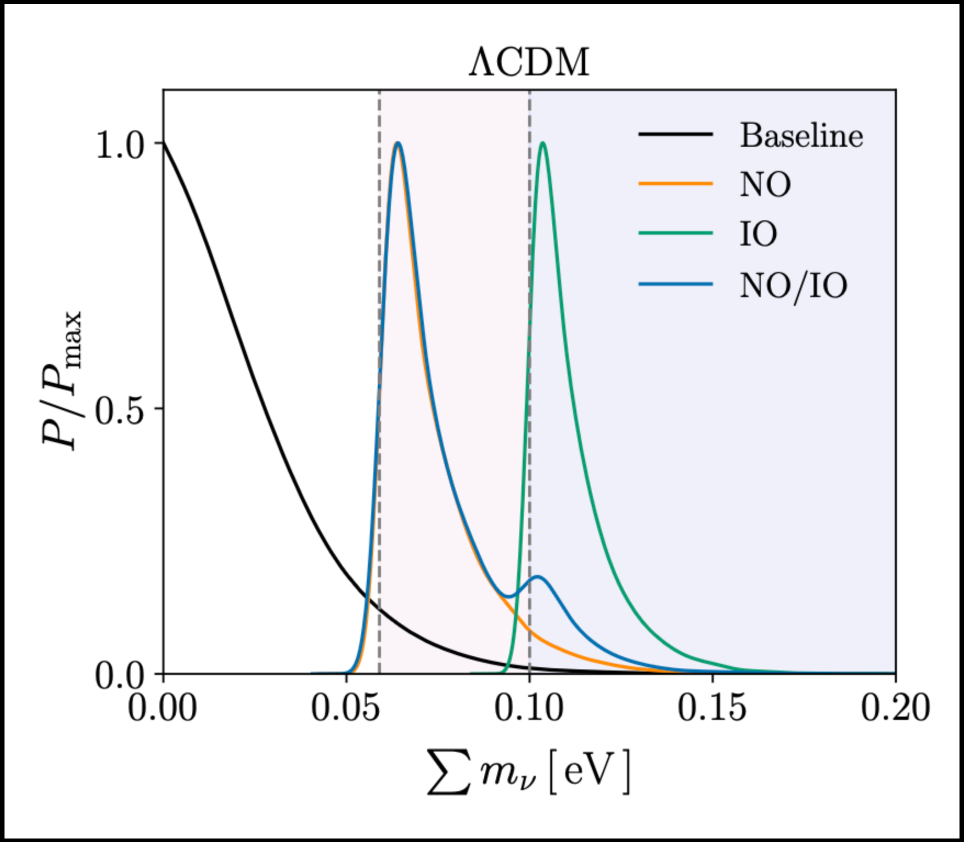
DESI DR2 BAO + CMB:

$$\sum m_\nu < 0.0642\,\mathrm{eV} \quad (95\%).$$

$$\sum m_\nu < 0.105\,\mathrm{eV} \quad (95\%;\ \sum m_\nu \geq 0.059\,\mathrm{eV}),$$

$$\sum m_\nu < 0.135\,\mathrm{eV} \quad (95\%;\ \sum m_\nu \geq 0.10\,\mathrm{eV}),$$

DESI collaboration, Elbers et al., arXiv:2503.14744



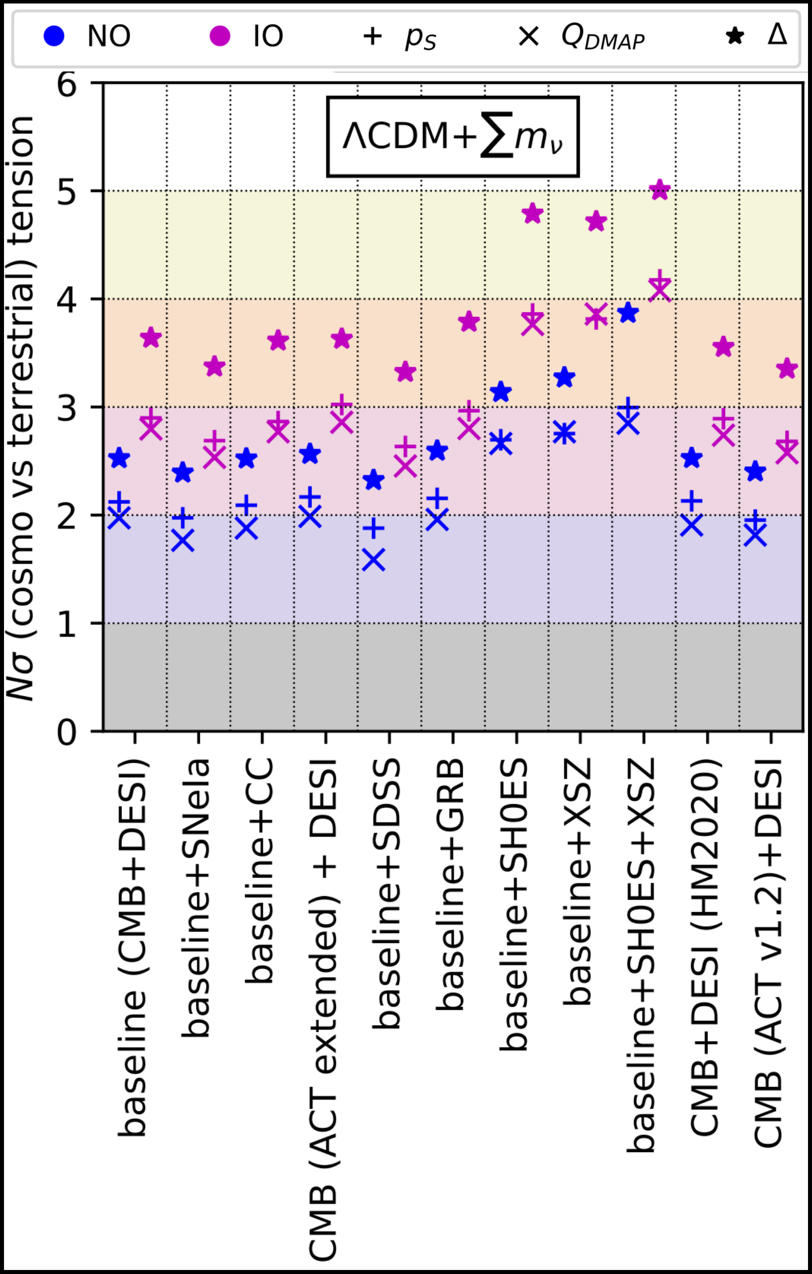
Neutrino mass ordering

Dataset combination	ΛCDM+$\sum m_\nu$	
	$\sum m_\nu$ (eV)	$B_{\mathrm{NO,IO}}$
baseline (CMB + DESI)	< 0.072	8.1
baseline + SNeIa	< 0.081	7.0
baseline + CC	< 0.073	7.3
baseline + SDSS	< 0.083	6.8
baseline + SH0ES	< 0.048	47.8
baseline + XSZ	< 0.050	46.5
baseline + GRB	< 0.072	8.7
aggressive combination (baseline + SH0ES + XSZ)	< 0.042 eV	72.6
CMB (with ACT "extended" likelihood)+DESI	< 0.072	8.0
CMB+DESI (with 2020 `HMCode`)	< 0.074	7.5
CMB (with `v1.2` ACT likelihood)+DESI	< 0.082	7.4

Jiang, Giarè, Gariazzo, Dainotti, Di Valentino, et al.,
JCAP 01 (2025) 153

95% CL upper limits on the sum of the neutrino masses Σm_ν
and Bayes factor for normal ordering versus inverted ordering $B_{\mathrm{NO,IO}}$
(with values of $B_{\mathrm{NO,IO}} > 1$ indicating a preference for the normal ordering)
in light of different dataset combinations.

Constraints on the total neutrino mass



Jiang, Giarè, Gariazzo, Dainotti, Di Valentino, et al., *JCAP* 01 (2025) 153

This is the quantification of the tension between cosmology and terrestrial constraints on the masses and mass splittings. For NO this is around 2.5σ, and increases to approximately 3.5σ for IO, when excluding the most extreme cases involving SH0ES and XSZ.

The ΛCDM model

“Cosmologists are often in error but never in doubt”
Lev Landau

So far, we’ve seen that cosmology is incredibly powerful in constraining neutrino masses, pushing upper limits well below 0.1 eV, in some cases down to 0.043 eV.

But there’s a catch…
These bounds rely heavily on the assumptions of the ΛCDM model, and on the internal consistency of the datasets.

So before we celebrate percent-level precision, we need to ask:
Are these constraints as reliable as they seem?

Let’s now take a closer look at the tensions.

All the models are wrong, but some are useful

Among the various cosmological models proposed in literature, the Lambda cold dark matter (ΛCDM) scenario has been adopted as the standard cosmological model, due to its simplicity and its ability to accurately describe a wide range of astrophysical and cosmological observations.

However, despite its incredible success, ΛCDM harbours large areas of phenomenology and ignorance. For example, it still cannot explain key concepts in our understanding of the structure and evolution of the Universe, at the moment based on unknown quantities, which, paradoxically, are also the largest components of the model. In addition, their physical evidence comes from cosmological and astrophysical observations only, without strong theoretical motivations.

The ΛCDM model

Three unknown pillars:

- an early stage of accelerated expansion (Inflation) which produces the initial, tiny, density perturbations, needed for structure formation.
- a clustering matter component to facilitate structure formation (Dark Matter),
- an energy component to explain the current stage of accelerated expansion (Dark Energy).

Specific solutions for ΛCDM:

- Inflation is given by a single, minimally coupled, slow-rolling scalar field;
- Dark Matter is a pressureless fluid made of cold, i.e., with low momentum, and collisionless particles;
- Dark Energy is a cosmological constant term.

The ΛCDM model

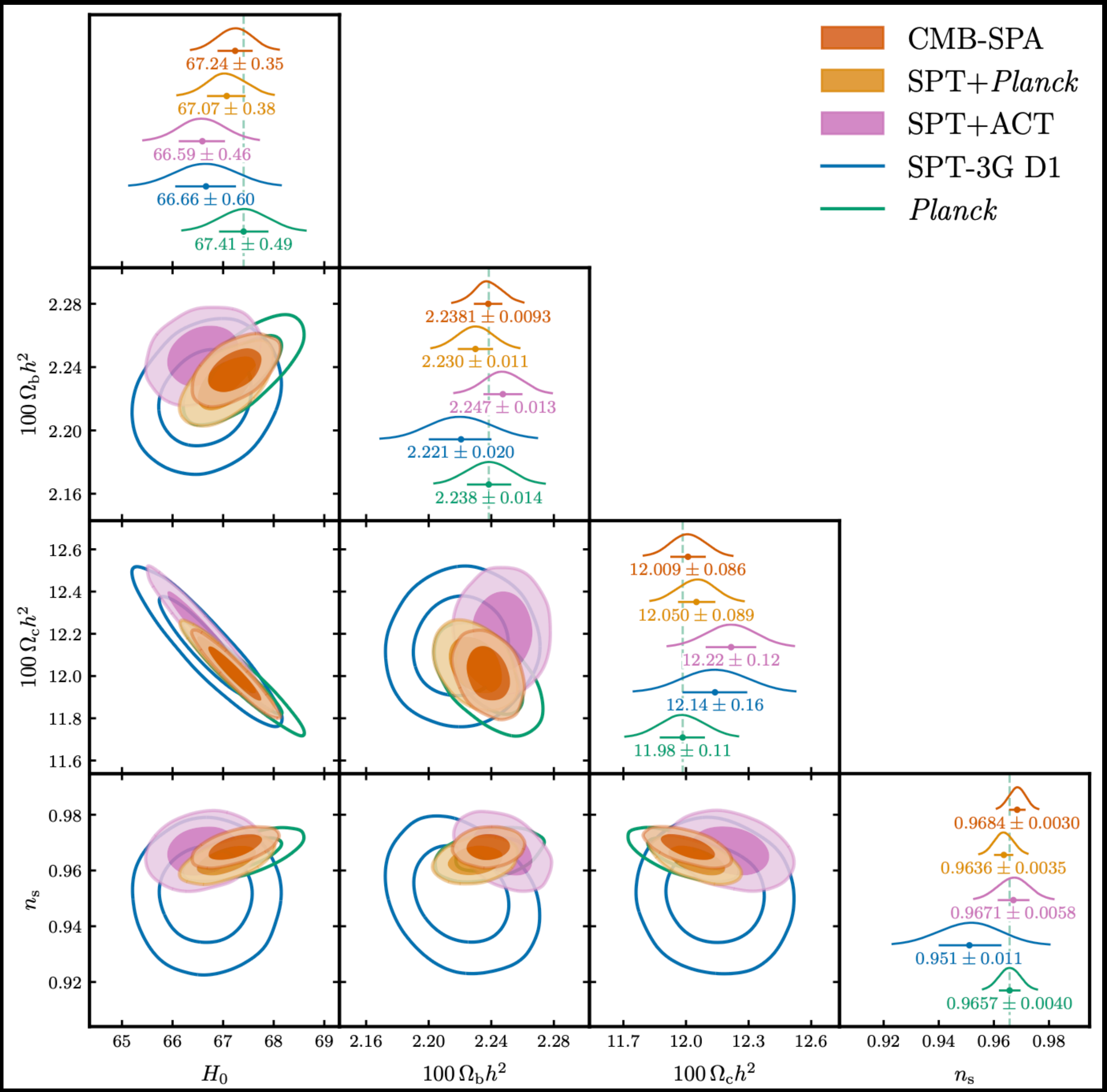
Despite its theoretical shortcomings, ΛCDM remains the preferred model due to its ability to accurately describe observed phenomena.
However, the ΛCDM model with its six parameters is not based on deep-rooted physical principles and should be considered, at best, an approximation of an underlying physical theory that remains undiscovered.

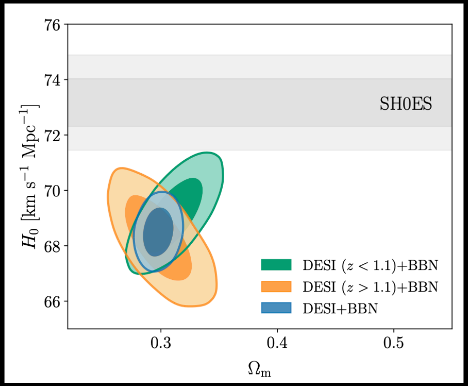
Hence, as observations become more numerous and accurate, deviations from the ΛCDM model are expected to be detected.
And in fact, discrepancies in important cosmological parameters, have already arisen in various observations with different statistical significance.

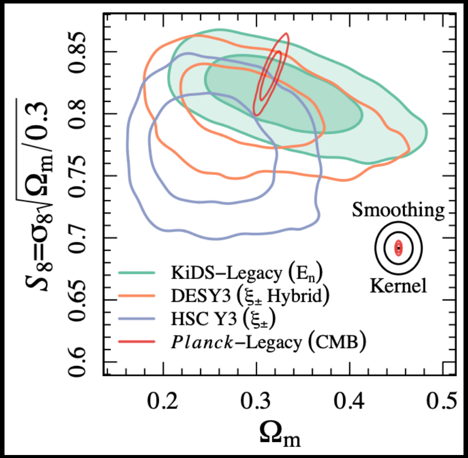
While some of these tensions may have a systematic origin, their recurrence across multiple probes suggests that there may be flaws in the standard cosmological scenario, and that new physics may be necessary to explain these observational shortcomings.

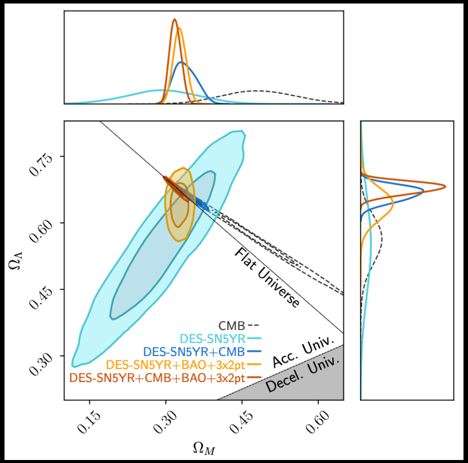
Therefore, the persistence of these tensions could indicate the failure of the canonical ΛCDM model.

1. A flat ΛCDM model is in agreement with the data









But what does it mean that ΛCDM agrees well with each probe?

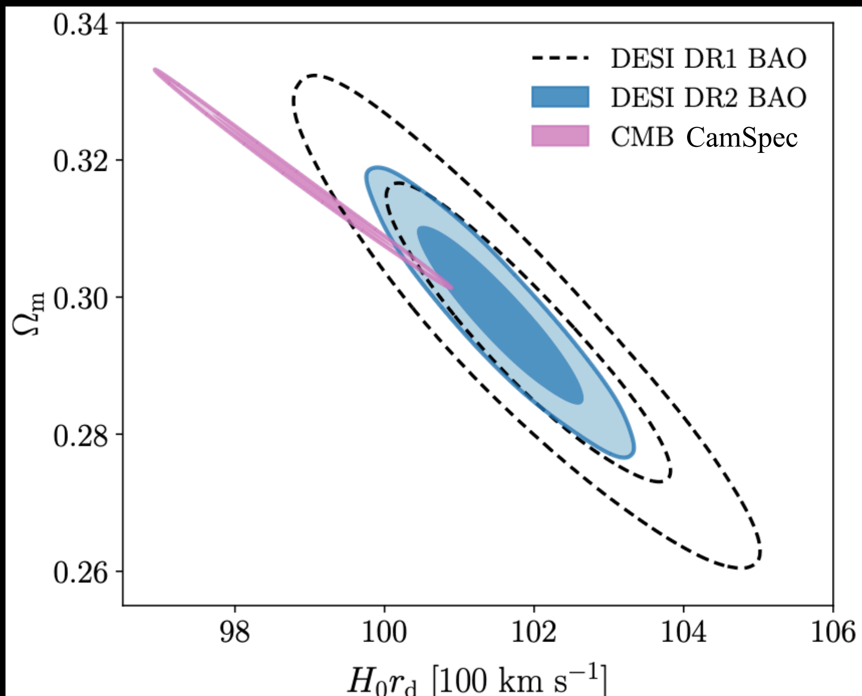
In a Bayesian framework, all models can, in principle, agree with the data.
What matters is whether they are disfavoured due to a poor fit
or because another model is preferred.
Therefore, to me, this means that ΛCDM provides a good fit to the data
and shows no clear signs of deviation, even when extended.

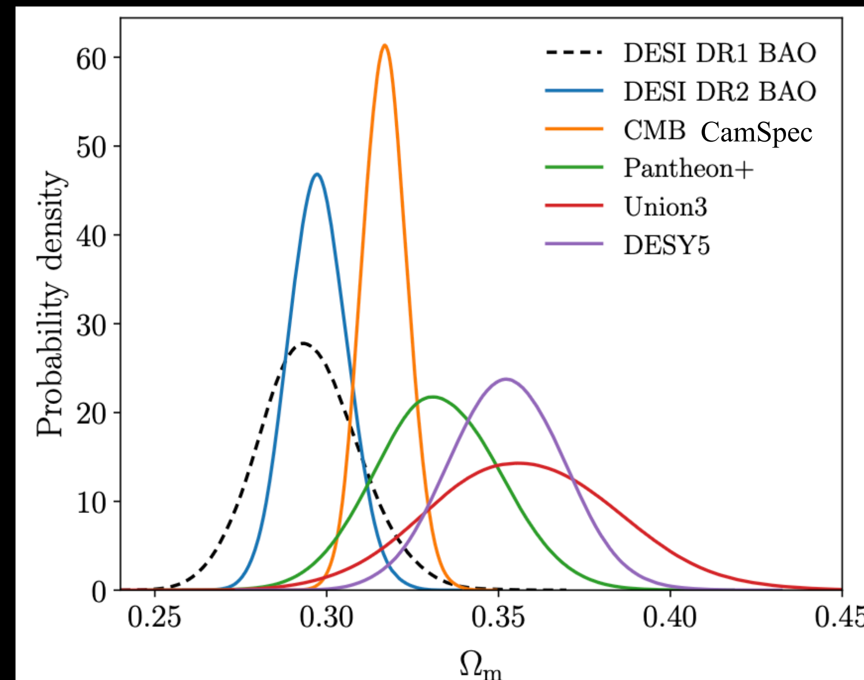
However, currently the cosmological parameters inferred
from different probes are not the same.

This means ΛCDM appears differently depending on the dataset!

Tensions and Disagreements in ΛCDM

DESI collaboration, Abdul Karim et al., arXiv:2503.14738





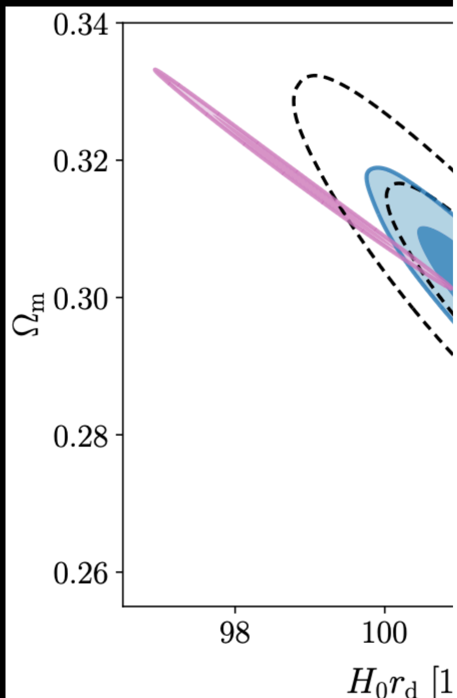
the corresponding 2 × 2 posterior parameter covariances. Converting this χ^2 into a probability-to-exceed (PTE) value, we find it is equivalent to a 2.3σ discrepancy between BAO and CMB in ΛCDM, increased from 1.9σ in DR1. However, we note that this reduces to 2.0σ if CMB lensing is excluded. This discrepancy is part of the reason why more models with a more flexible background expansion history than ΛCDM, such as the evolving dark

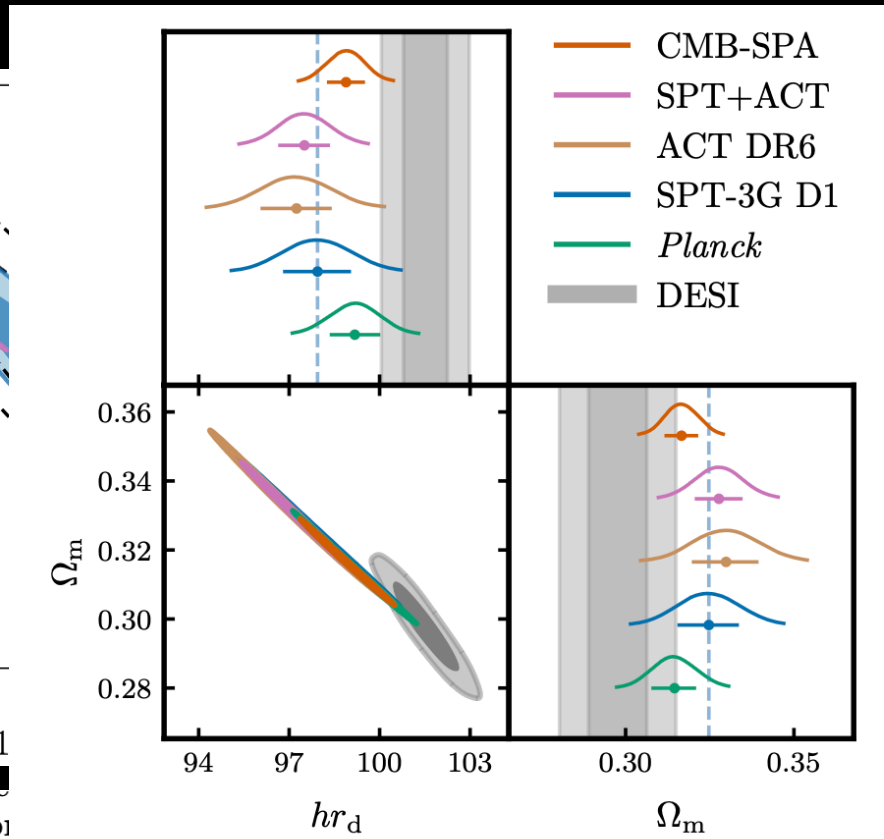
Finally, as in [38], we note a mild to moderate discrepancy between the recovered values of Ω_m from DESI and SNe in the context of the ΛCDM model. This is shown in the marginalized posteriors in Figure 10: the discrepancy is 1.7σ for Pantheon+, 2.1σ for Union3, and 2.9σ for DESY5, with all SNe samples preferring higher values of Ω_m though with larger uncertainties. For ΛCDM we do not report joint constraints on parameters from any combination of DESI and SNe data. However, as with

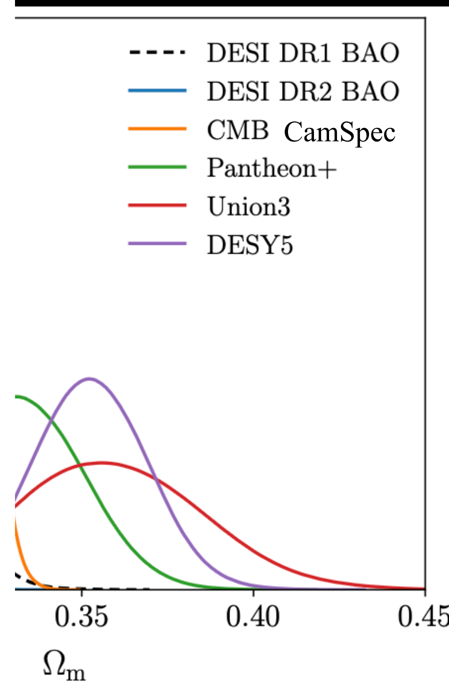
The same ΛCDM cannot fit 2 datasets together!

Tensions and Disagreements in ΛCDM

SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]







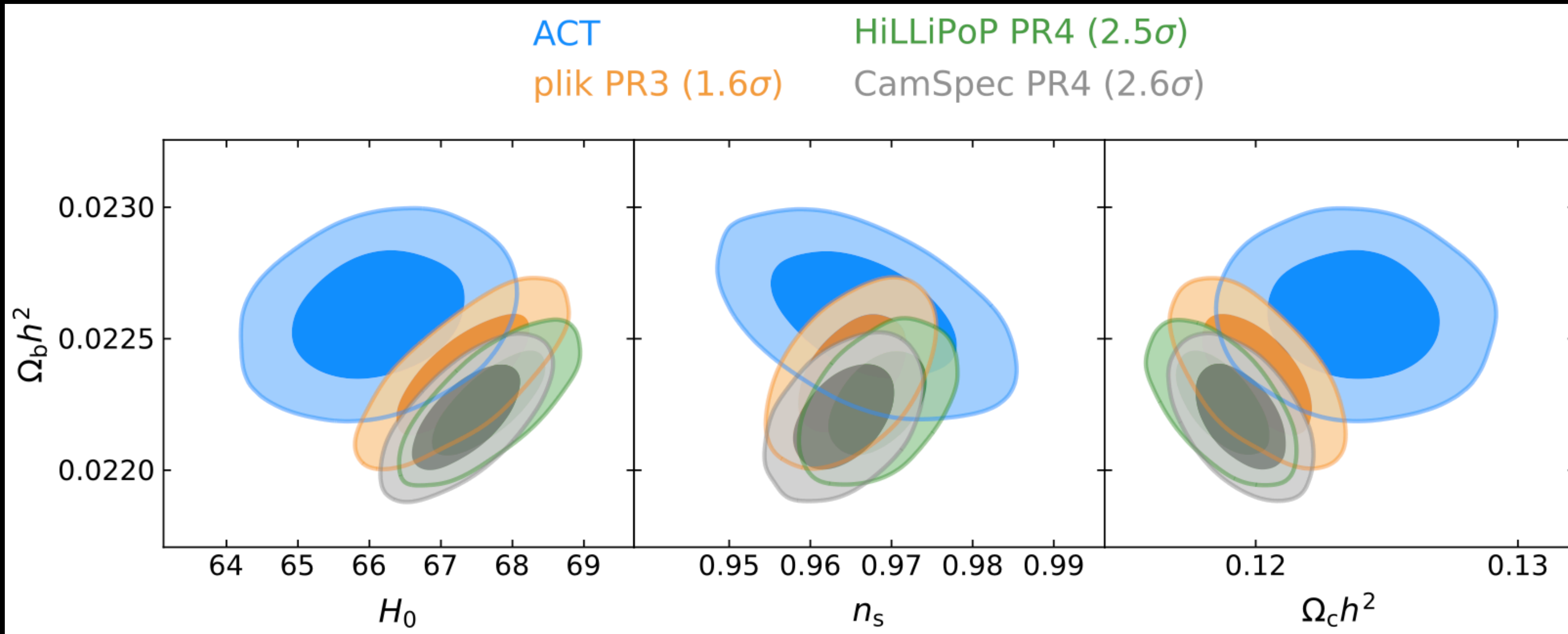
Converting this χ^2 into a pr
value, we find it is equivalent
tween BAO and CMB in ΛC
in DR1. However, we note t
CMB lensing is excluded. Thi
reason why more models with
expansion history than ΛCDM

	$100\,\Omega_m$	hr_d [Mpc]	Distance to DESI
CMB-SPA	31.66 ± 0.50	98.89 ± 0.63	$2.8\,\sigma$
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	$3.7\,\sigma$
SPT+*Planck*	31.89 ± 0.54	98.63 ± 0.67	$3.0\,\sigma$
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	$3.1\,\sigma$
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	$2.5\,\sigma$
Planck	31.45 ± 0.67	99.18 ± 0.84	$2.0\,\sigma$
DESI	29.76 ± 0.87	101.52 ± 0.73	

e a mild to moderate discrep-
values of Ω_m from DESI and
ΛCDM model. This is shown
ors in Figure 10: the discrep-
+, 2.1σ for Union3, and 2.9σ
mples preferring higher values
uncertainties. For ΛCDM we
ints on parameters from any
SNe data. However, as with

The same ΛCDM cannot fit 2 datasets together!

CMB tension in ΛCDM



In Figure 37 we show the comparison of the ACT DR6 results with those from different versions of the *Planck* likelihoods, as discussed in §8. The agreement between ACT and *Planck* is closest for the Plik PR3 at 1.6σ, neglecting correlations between the data and using the four-dimensional parameter distribution that discards the amplitude and optical depth; the PR4 analyses for both Camspec and Hillipop have small shifts to lower baryon and CDM densities compared to PR3, and result in an overall 2.6σ separation in the four-dimensional parameter space.

ACT collaboration, Louis et al., arXiv:2503.14452

2. Indication for DDE

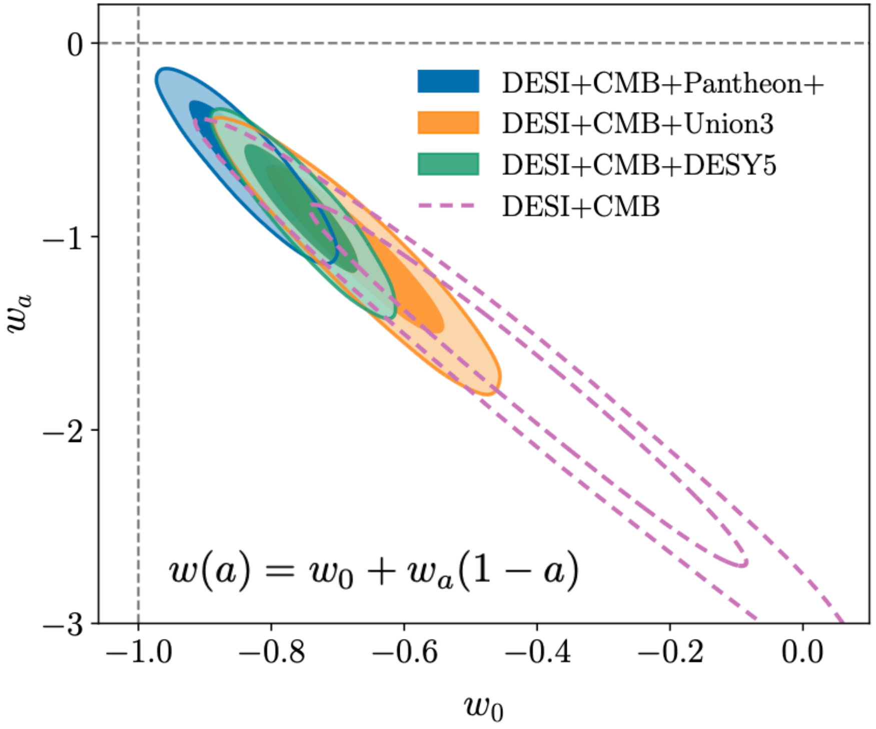
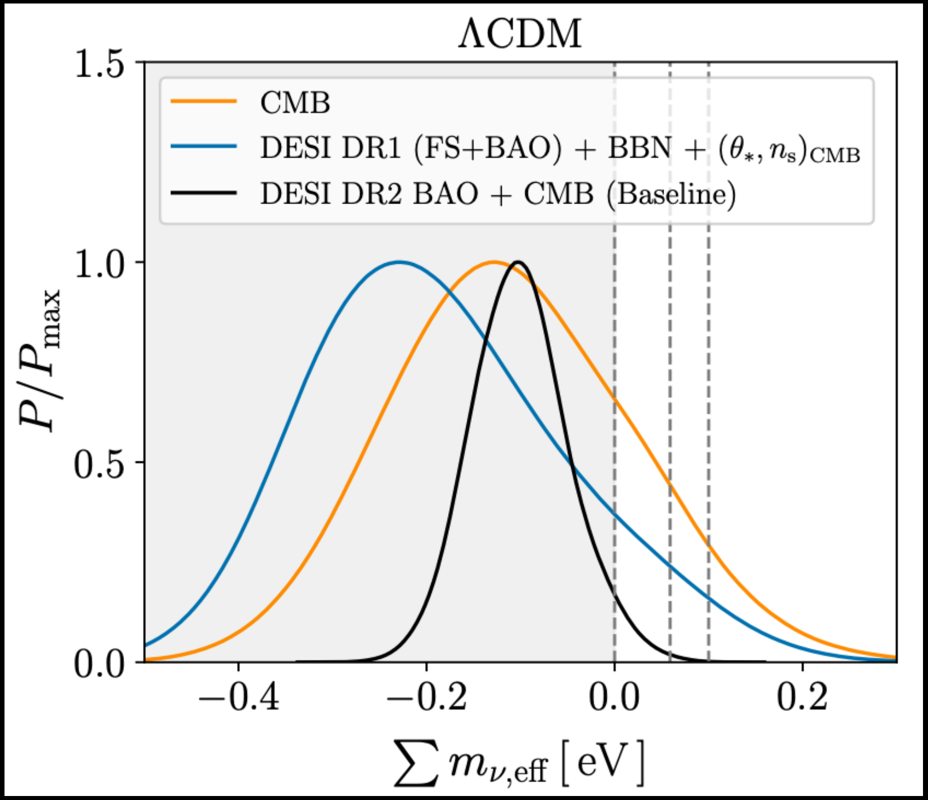


FIG. 11. Results for the posterior distributions of w_0 and w_a, from fits of the w_0w_aCDM model to DESI in combination with CMB and three SNe datasets as labelled. We also show the contour for DESI combined with CMB alone. The contours enclose 68% and 95% of the posterior probability. The gray dashed lines indicate $w_0 = -1$ and $w_a = 0$; the ΛCDM limit ($w_0 = -1$, $w_a = 0$) lies at their intersection. The significance of rejection of ΛCDM is 2.8σ, 3.8σ and 4.2σ for combinations with the Pantheon+, Union3 and DESY5 SNe samples, respectively, and 3.1σ for DESI+CMB without any SNe.

Datasets	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	−4.7	1.7σ	−0.8
DESI+$(\theta_*, \omega_b, \omega_{bc})_{\rm CMB}$	−8.0	2.4σ	−4.4
DESI+CMB (no lensing)	−9.7	2.7σ	−5.9
DESI+CMB	−12.5	3.1σ	−8.7
DESI+Pantheon+	−4.9	1.7σ	−0.7
DESI+Union3	−10.1	2.7σ	−6.0
DESI+DESY5	−13.6	3.3σ	−9.3
DESI+DESY3 (3×2pt)	−7.3	2.2σ	−2.8
DESI+DESY3 (3×2pt)+DESY5	−13.8	3.3σ	−9.1
DESI+CMB+Pantheon+	−10.7	2.8σ	−6.8
DESI+CMB+Union3	−17.4	3.8σ	−13.5
DESI+CMB+DESY5	−21.0	4.2σ	−17.2

DESI collaboration, Abdul Karim et al., arXiv:2503.14738

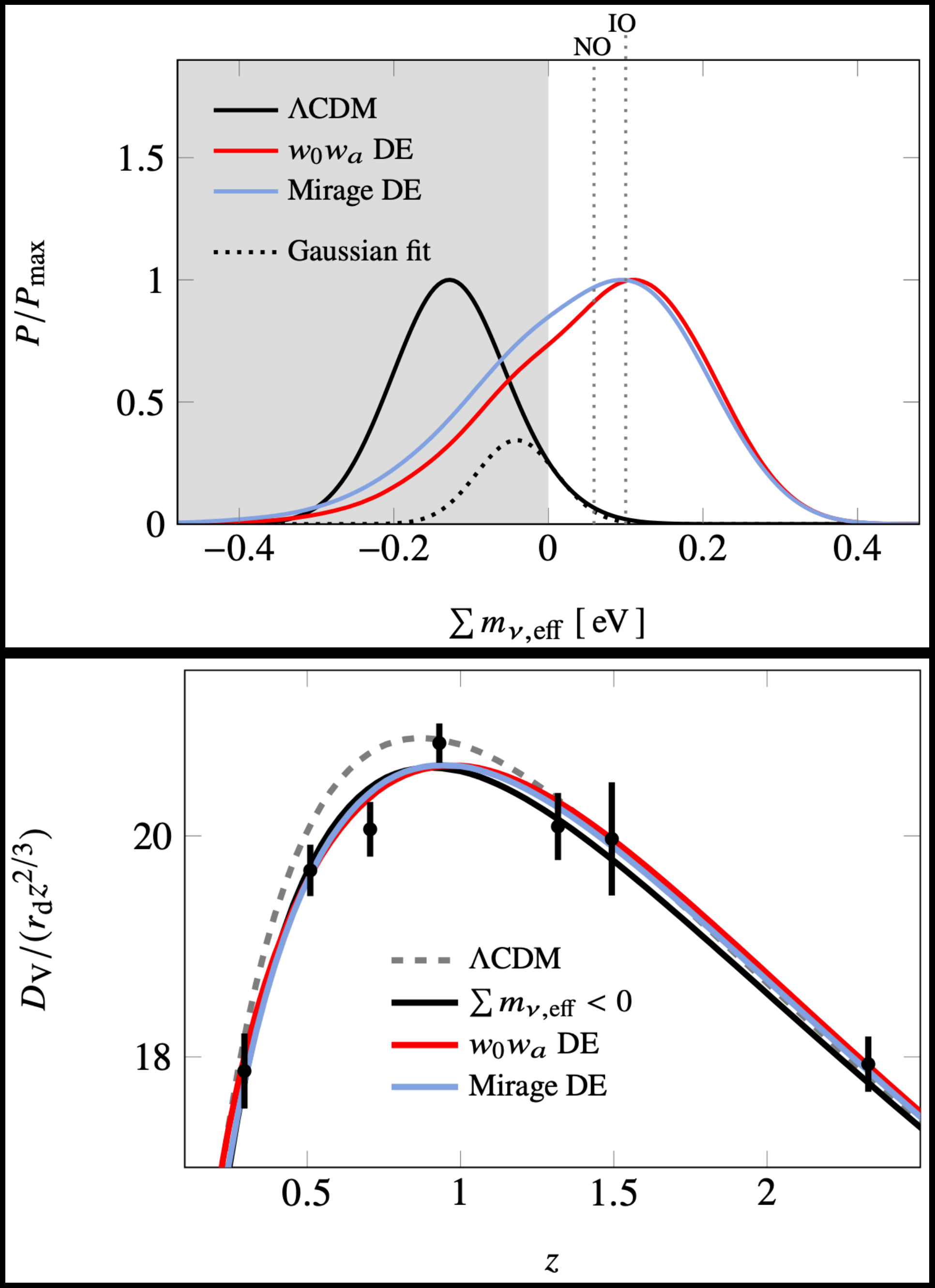
3. Indication for negative neutrino mass



Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$\sum m_{\nu,\mathrm{eff}}$ [eV]
ΛCDM+$\sum m_{\nu,\mathrm{eff}}$			
DESI BAO+CMB (Baseline)	0.2953 ± 0.0043	68.92 ± 0.38	$-0.101^{+0.047}_{-0.056}$
DESI BAO+CMB (`plik`)	0.2948 ± 0.0043	69.06 ± 0.39	$-0.099^{+0.050}_{-0.061}$
DESI BAO+CMB (`L-H`)	0.2953 ± 0.0044	68.89 ± 0.39	$-0.067^{+0.054}_{-0.064}$

DESI collaboration, Elbers et al., arXiv:2503.14744

3. Indication for negative neutrino mass



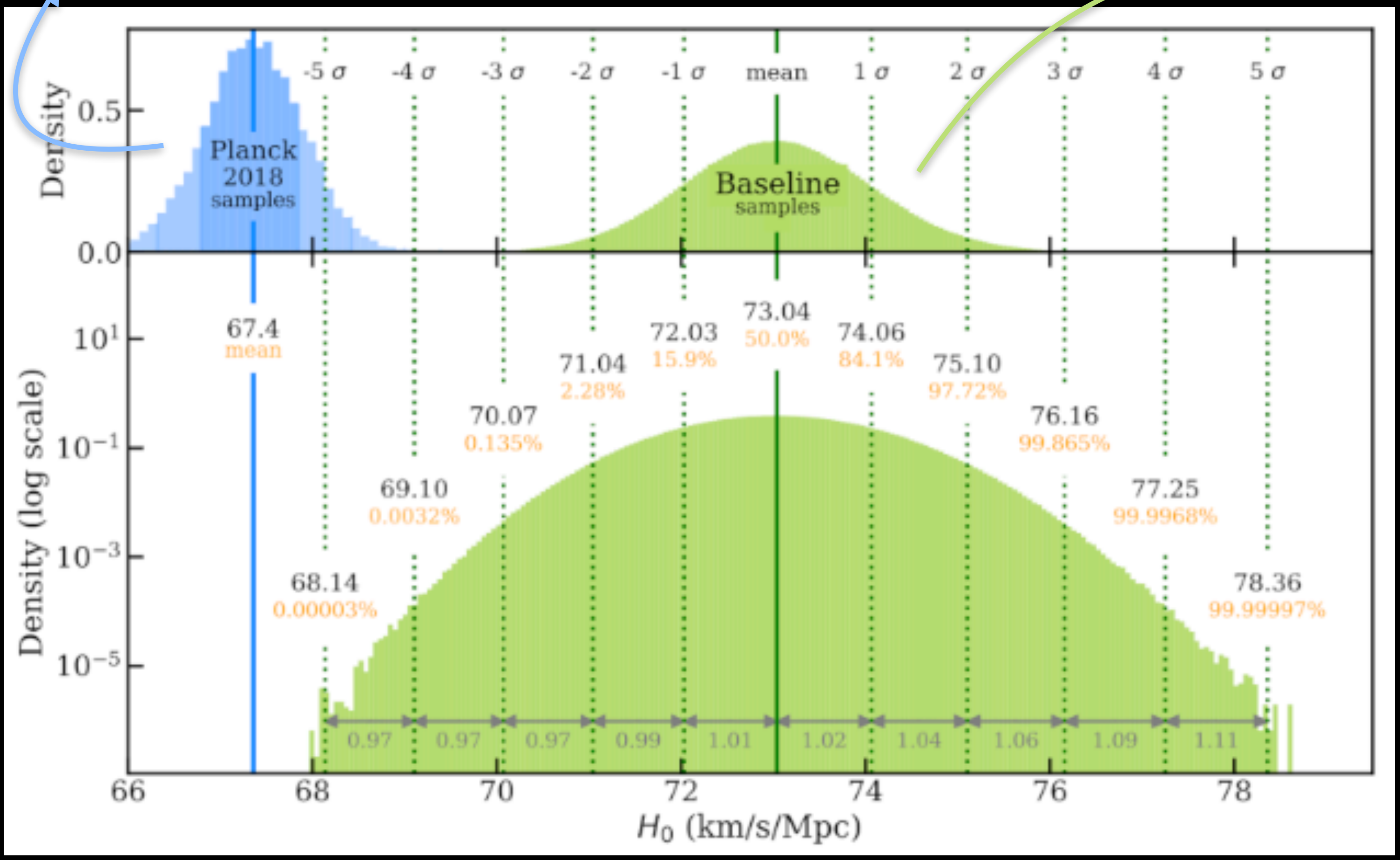
However, introducing more freedom in the DE sector, and in particular considering a dynamical DE as preferred by the BAO DESI data, we can restore larger neutrino masses, more in agreement with laboratory data.

Elbers al., arXiv:2407.10965

4. H0 tension

The H0 tension is the most statistically significant, long-lasting and widely persisting disagreement between:

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.36 ± 0.54 km/s/Mpc
Planck 2018, Astron.Astrophys. 641 (2020) A6



The latest local measurements obtained by the SH0ES collaboration

H0 = 73.04 ± 1.04 km/s/Mpc

Riess et al. arXiv:*2112.04510*

5σ = one in 3.5 million implausible to reconcile the two by chance

4. H0 tension

The H0 tension is the most statistically significant, long-lasting and widely

arXiv > astro-ph > arXiv:2506.20707

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 25 Jun 2025]

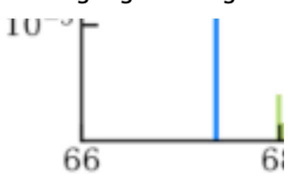
SPT-3G D1: CMB temperature and polarization power spectra and cosmology from 2019 and 2020 observations of the SPT-3G Main field

E. Camphuis, W. Quan, L. Balkenhol, A. R. Khalife, F. Ge, F. Guidi, N. Huang, G. P. Lynch, Y. Omori, C. Trendafilova, A. J. Anderson, B. Ansarinejad, M. Archipley, P. S. Barry, K. Benabed, A. N. Bender, B. A. Benson, F. Bianchini, L. E. Bleem, F. R. Bouchet, L. Bryant, M. G. Campitiello, J. E. Carlstrom, C. L. Chang, P. Chaubal, P. M. Chichura, A. Chokshi, T.-L. Chou, A. Coerver, T. M. Crawford, C. Daley, T. de Haan, K. R. Dibert, M. A. Dobbs, M. Doohan, A. Doussot, D. Dutcher, W. Everett, C. Feng, K. R. Ferguson, K. Fichman, A. Foster, S. Galli, A. E. Gambrel, R. W. Gardner, N. Goeckner-Wald, R. Gualtieri, S. Guns, N. W. Halverson, E. Hivon, G. P. Holder, W. L. Holzapfel, J. C. Hood, A. Hryciuk, F. Kéruzoré, L. Knox, M. Korman, K. Kornoelje, C.-L. Kuo, K. Levy, A. E. Lowitz, C. Lu, A. Maniyar, E. S. Martsen, F. Menanteau, M. Millea, J. Montgomery, Y. Nakato, T. Natoli, G. I. Noble, A. Ouellette, Z. Pan, P. Paschos, K. A. Phadke, A. W. Pollak, K. Prabhu, S. Raghunathan, M. Rahimi, A. Rahlin, C. L. Reichardt, M. Rouble, J. E. Ruhl, E. Schiappucci, A. Simpson, J. A. Sobrin, A. A. Stark, J. Stephen, C. Tandoi, B. Thorne, C. Umilta, J. D. Vieira, A. Vitrier, Y. Wan, N. Whitehorn, W. L. K. Wu, M. R. Young, J. A. Zebrowski

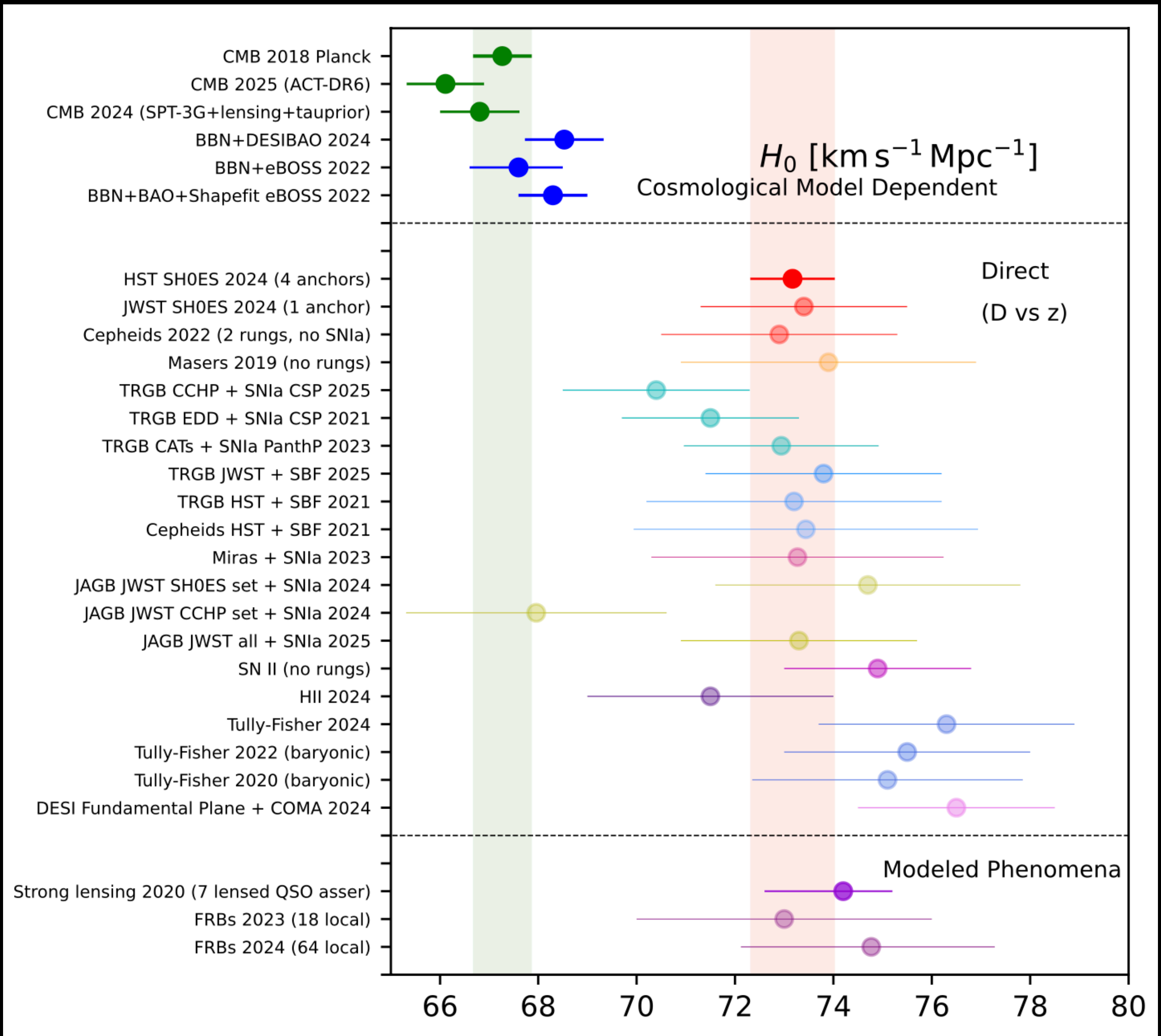
We present measurements of the temperature and E-mode polarization angular power spectra of the cosmic microwave background (CMB) from observations of 4% of the sky with SPT-3G, the current camera on the South Pole Telescope (SPT). The maps used in this analysis are the deepest used in a CMB TT/TE/EE analysis to date. The maps and resulting power spectra have been validated through blind and unblind tests. The measurements of the lensed EE and TE spectra are the most precise to date at l=1800-4000 and l=2200-4000, respectively. Combining our TT/TE/EE spectra with previously published SPT-3G CMB lensing results, we find parameters for the standard LCDM model consistent with Planck and ACT-DR6 with comparable constraining power. We report a Hubble constant of $H_0 = 66.66 \pm 0.60$ km/s/Mpc from SPT-3G alone, 6.2 sigma away from local measurements from SH0ES. For the first time, combined ground-based (SPT+ACT) CMB primary and lensing data have reached Planck's constraining pow... CMB constraints to date, with $H_0 = 67.24 \pm$ ... CDM; however, we observe a 2.8 sigma d... ...els. The combination of CMB and ... ...ion of state. It also drives mild preferenc... ...universe. This work highlights the growi...

Parameter	*Planck*	SPT-3G D1	ACT DR6	SPT+ACT	SPT+*Planck*	CMB-SPA
Sampled						
$10^4\theta_s^\star$	104.184 ± 0.029	104.171 ± 0.060	104.157 ± 0.030	104.158 ± 0.025	04.176 ± 0.026	104.162 ± 0.023
$100\,\Omega_b h^2$	2.238 ± 0.014	2.221 ± 0.020	2.257 ± 0.016	2.247 [illegible]	230 ± 0.011	2.2381 ± 0.0093
$100\,\Omega_c h^2$	11.98 ± 0.11	12.14 ± 0.16	12.26 ± 0.17	[illegible]	050 ± 0.089	12.009 ± 0.086
n_s	0.9657 ± 0.0040	0.951 ± 0.011	0.9682 ± 0.0[illegible]	[illegible]	$.9636 \pm 0.0035$	0.9684 ± 0.0030
$\log(10^{10} A_s)$	3.042 ± 0.011	3.054 ± 0.015	3.038 ± 0.012	[illegible] ± 0.011	$.046 \pm 0.010$	3.0479 ± 0.0099
τ_{reio}	0.0535 ± 0.0056	0.0506 ± 0.0059	0.0513 ± 0.0060	0.0514 ± 0.0059	$.0538 \pm 0.0054$	0.0559 ± 0.0055
Derived						
H_0 [km/s/Mpc]	67.41 ± 0.49	66.66 ± 0.60	66.51 ± 0.64	66.59 ± 0.46	7.07 ± 0.38	67.24 ± 0.35

6.7 sigma



Latest H0 measurements



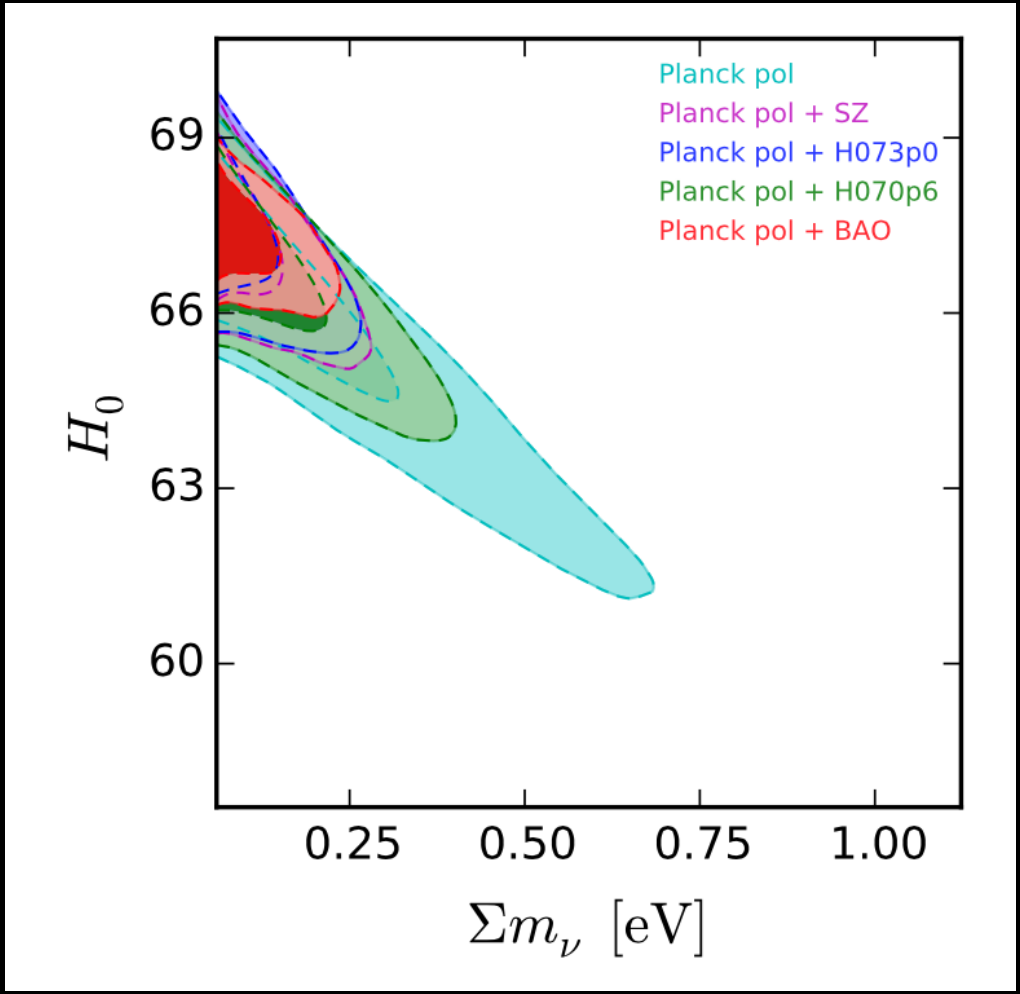
CosmoVerse network, Di Valentino et al., Phys.Dark Univ. 49 (2025) 101965

Hubble constant measurements made by different astronomical missions and groups over the years.

The red vertical band corresponds to the H0 value from SH0ES Team and the grey vertical band corresponds to the H0 value as reported by Planck 2018 team within a ΛCDM scenario.

4. H0 tension

The H0 value is very important for the determination of the
total neutrino mass.
In fact, there exist a strong negative correlation between the Hubble constant and the sum of the neutrino masses.

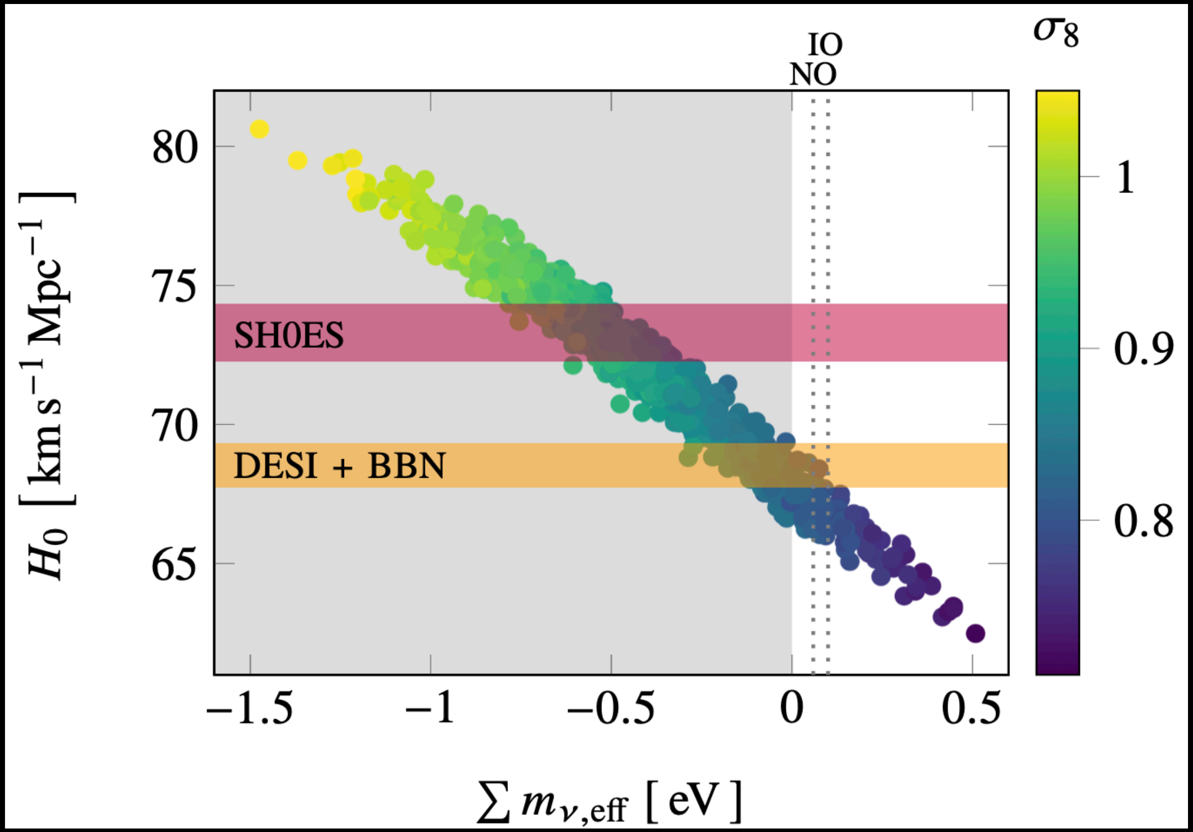


Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

4. H0 tension

We can see a clear geometrical degeneracy between these two parameters. To reconcile the SH0ES measurement of H0 with Planck we need a negative effective neutrino mass of

$$\sum m_{\nu,\mathrm{eff}} = -0.5 \pm 0.1\ \mathrm{eV}$$



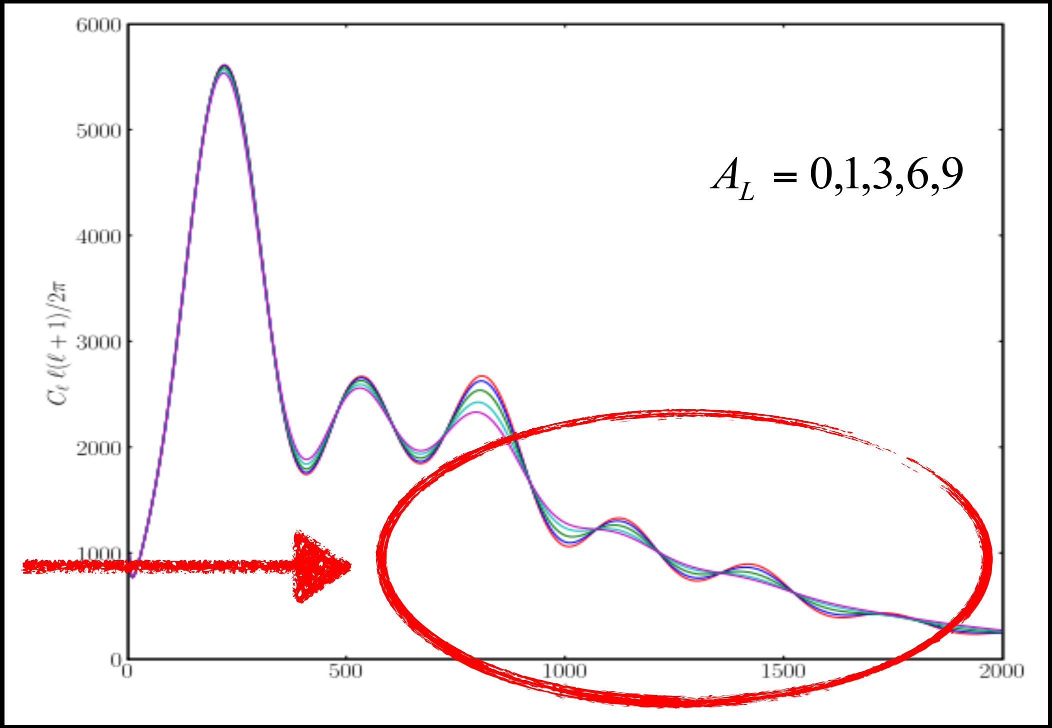
Elbers al., arXiv:2407.10965

5. A_L problem

Its effect on the power spectrum is the smoothing of the acoustic peaks, increasing AL.

Interesting consistency checks is if the amplitude of the smoothing effect in the CMB power spectra matches the theoretical expectation AL = 1 and whether the amplitude of the smoothing is consistent with that measured by the lensing reconstruction.

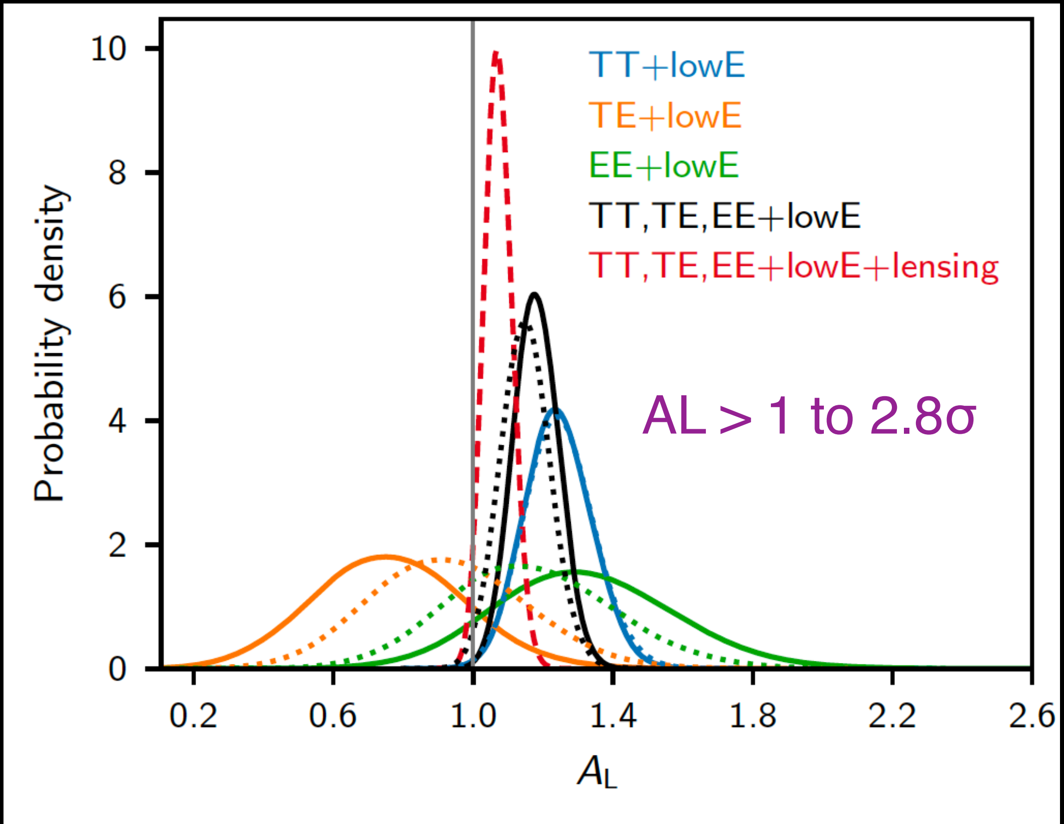
If AL =1 then the theory is correct, otherwise we have a new physics or systematics.



Calabrese et al., Phys. Rev. D, 77, 123531

5. A_L problem

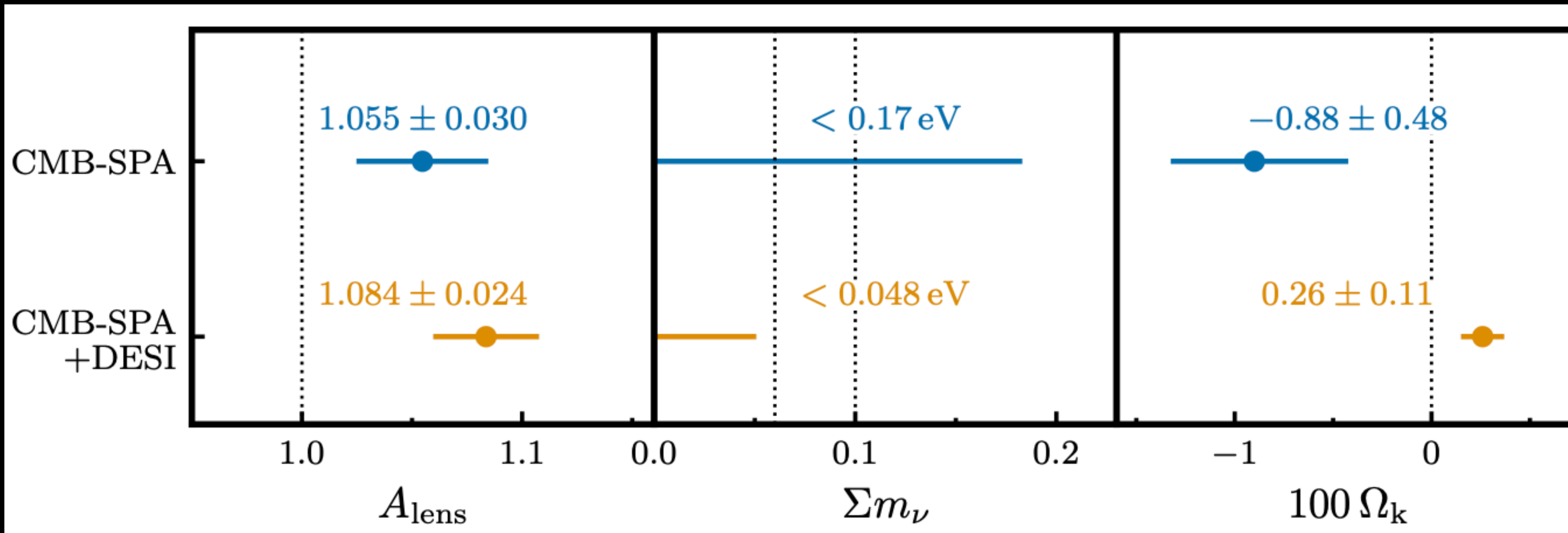
Planck 2018, Astron.Astrophys. 641 (2020) A6



$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{,}TE{,}EE{+}lowE}),$$

The preference for a high AL is not merely a volume effect in the full parameter space; the best fit improves by $\Delta\chi^2 \approx 9$ when adding AL for TT+lowE, and by ≈ 10 for TTTEEE+lowE.

5. SPT A_L problem



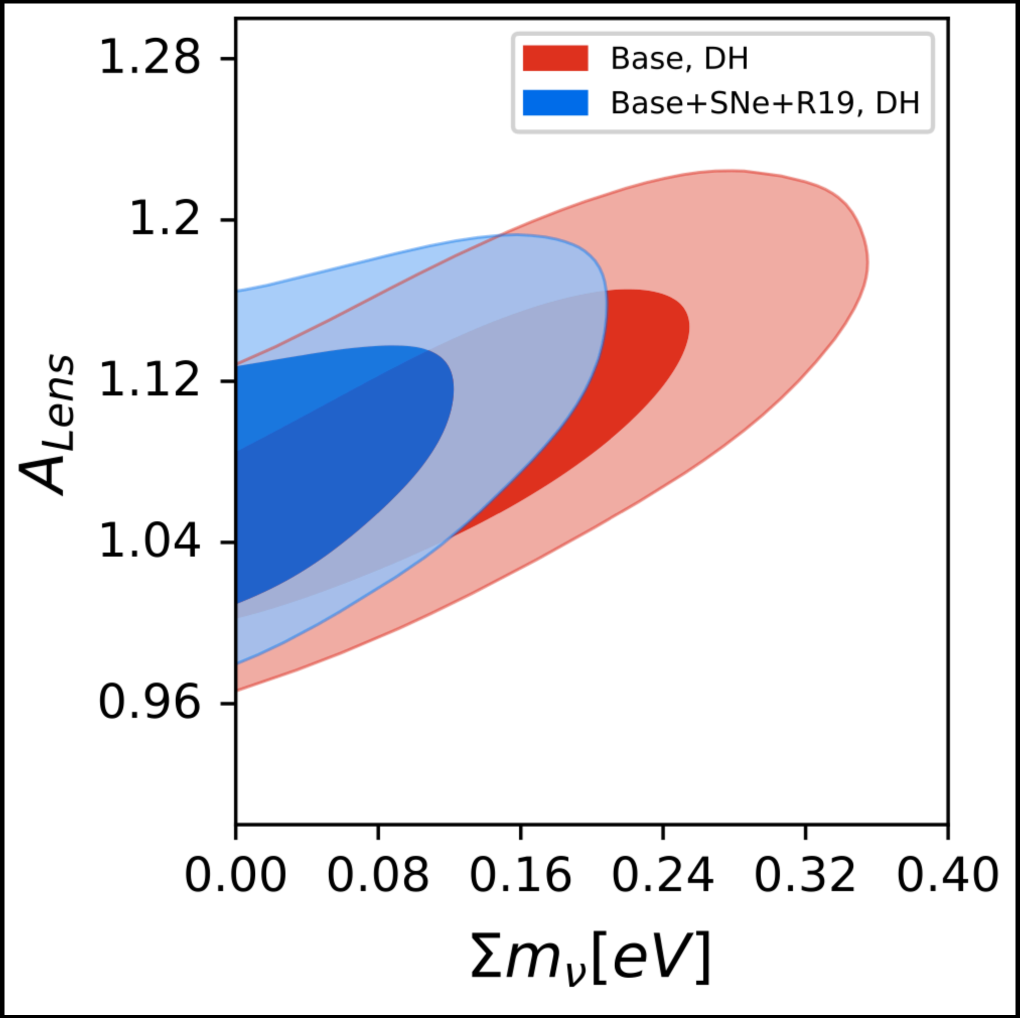
SPT-3G D1, arXiv:2506.20707 [astro-ph.CO]

$$A_{\mathrm{lens}} = 1.084 \pm 0.035 \text{ for SPT-3G D1 + DESI,} \quad (74)$$
$$A_{\mathrm{lens}} = 1.092 \pm 0.026 \text{ for SPT+ACT + DESI,} \quad (75)$$
$$A_{\mathrm{lens}} = 1.084 \pm 0.024 \text{ for CMB-SPA + DESI.} \quad (76)$$

which are deviations from the standard model prediction of $2.4\,\sigma$, $3.5\,\sigma$, and $3.5\,\sigma$, respectively. We note that

The preference for a high AL is at the 3.5σ level without Planck, but when combining SPT with DESI. This leads to a very strong upper limit on the total neutrino mass and favors a non-flat universe.

5. A_L problem



Choudhury and Hannestad, arXiv:1907.12598 [astro-ph.CO]

There is a very strong positive correlation between Alens and the total neutrino mass.

Therefore, to be conservative, we need to take into account this wrong amount of lensing when constraining Σm_ν.

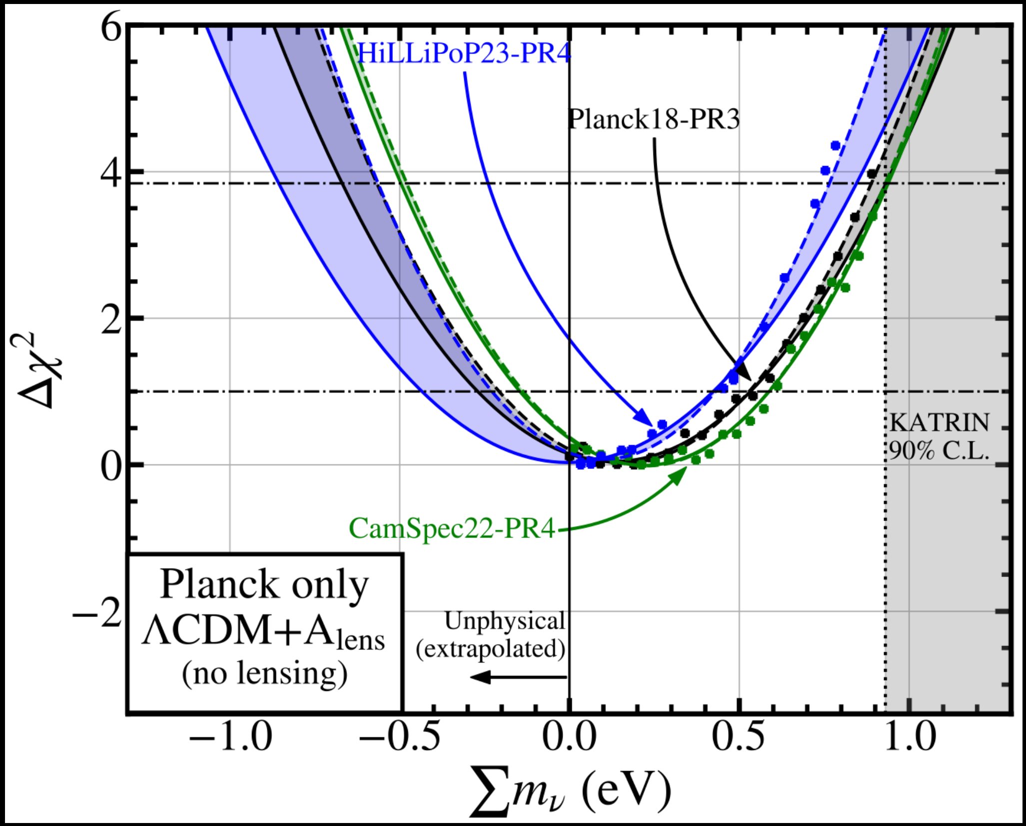
5. A_L problem

#	Model	Data set	Σ (2σ)
1	ΛCDM + Σ	Plik	< 0.175 eV
2		Plik+DESI	< 0.065 eV
3		Plik+DESI+PP	< 0.073 eV
4		Plik+DESI+DESy5	< 0.091 eV
5		camspec	< 0.193 eV
6		camspec+DESI	< 0.064 eV
7		camspec+DESI+PP	< 0.074 eV
8		camspec+DESI+DESy5	< 0.088 eV
9	ΛCDM+Σ+$A_{\rm lens}$	Plik	< 0.616 eV
10		Plik+DESI	< 0.204 eV
11		Plik+DESI+PP	< 0.255 eV
12		Plik+DESI+DESy5	< 0.287 eV

For example, when A_{lens} is free to vary, because of their correlation, the bounds on the total neutrino mass are strongly weakened, up to a factor of ~3.

Capozzi et al., *Phys.Rev.D* 111 (2025) 9, 093006

5. A_L problem

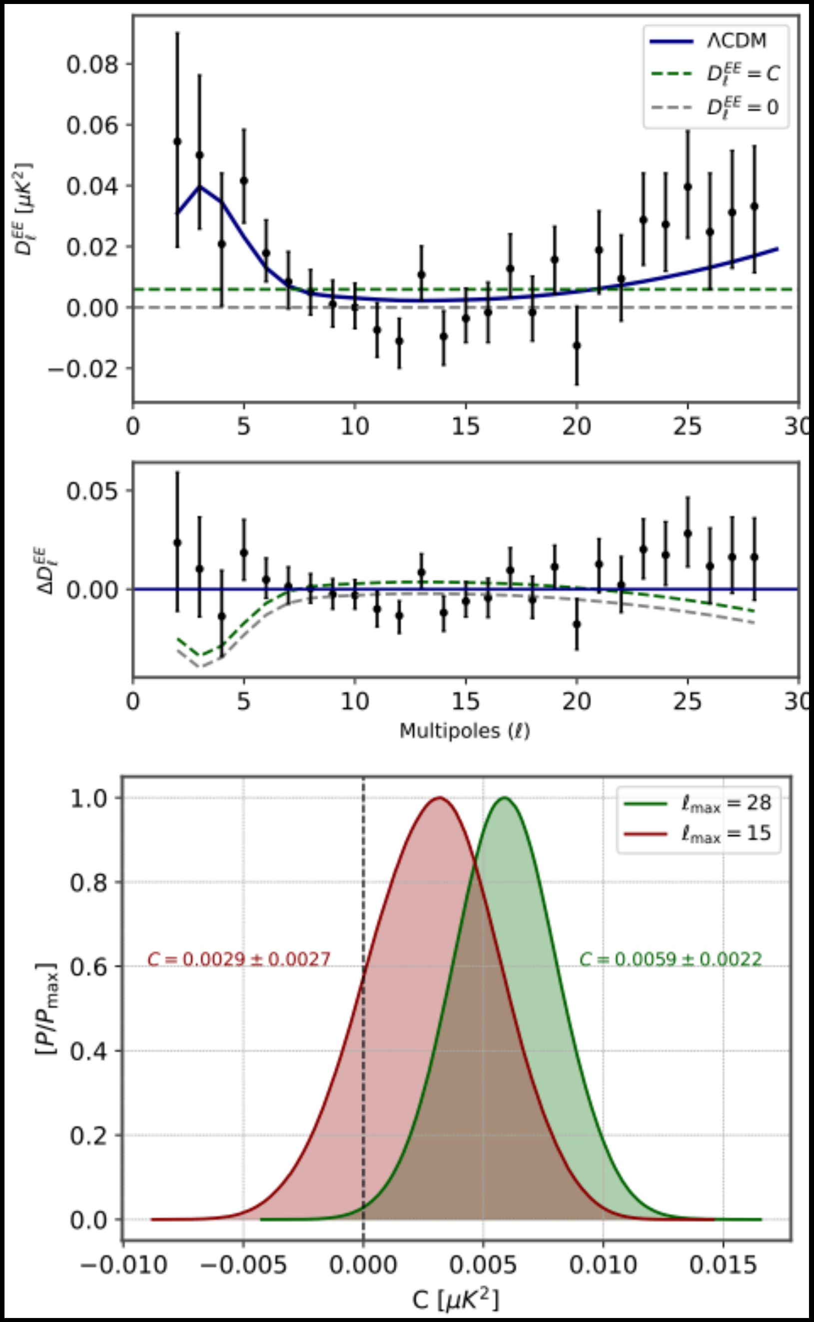


Naredo-Tuero et al., arXiv:2407.13831

Neutrino mass profile likelihoods using the full Planck temperature and polarization data in the ΛCDM model, while allowing the unphysical AL parameter to vary, show that the bounds are significantly relaxed.

6. The optical depth

$$C_\ell^{EE} \propto \tau^2/\ell^4$$

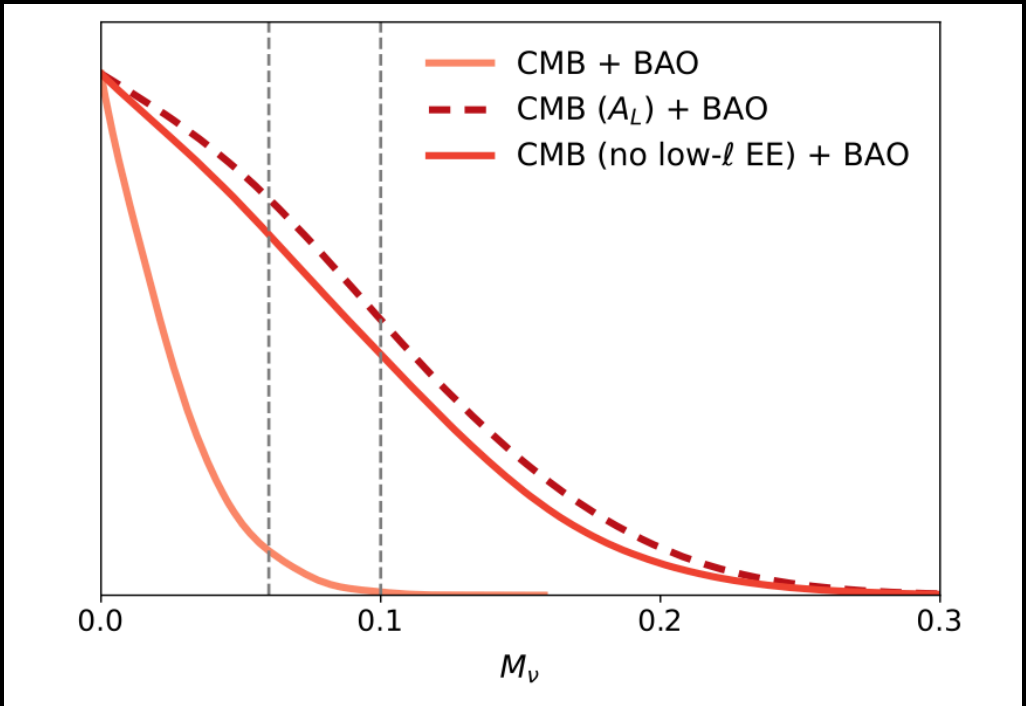


Reionization leaves an imprint on the large-scale CMB E-mode polarization (EE) and causes a suppression of temperature anisotropies at smaller scales (proportional to $A_s e^{-2\tau}$).
Planck measured $\tau = 0.054 \pm 0.008$ at 68% CL, a significant improvement over the WMAP9 value of $\tau = 0.089 \pm 0.014$.
However, the low-ℓ EE signal is extremely weak, in the cosmic variance limited region, and close to the detection threshold.

We tested the EE spectrum: fitting it with a flat line (i.e., no reionization bump) yields a p-value of 0.063.
If we focus only on data points at $2 \leq l \leq 15$, the case C=0 (no signal) falls within the 1σ range.
This raises concerns that measurements near the noise level may be significantly affected by statistical fluctuations or foreground uncertainties.

Giarè, Di Valentino, Melchiorri, Phys.Rev.D 109 (2024) 10, 103519

6. The optical depth



Jhaveri et al., arXiv:2504.21813

In the CMB TT spectrum, massive neutrinos suppress small-scale power, which can be compensated by increasing the optical depth τ.

Since TT measures $A_s e^{-2\tau}$, raising τ requires raising As, but As also controls structure growth, that is entangled with Σmν effects.

This degeneracy means CMB-only data allow biased Σmν values; low-ℓ polarization is essential to pin down τ and break the degeneracy.

The apparent CMB+BAO preference for negative neutrino masses could be an artifact of the τ–Σmν degeneracy.

Allowing either a free lensing amplitude AL or dropping low-ℓ EE τ constraints both restore consistency with minimal neutrino masses.

In other words: the “negative neutrino mass” problem disappears if τ is allowed to rise, highlighting that τ systematics strongly impact cosmological neutrino mass bounds.

Conclusions:

Cosmology now probes relics and interactions beyond the reach of laboratory experiments, offering unique access to the total neutrino mass.
The tightest cosmological bound on the sum of neutrino masses is
$\Sigma m\nu < 0.043$ eV (95% CL),
and this value is in tension with neutrino oscillation experiments.

At the same time, persistent anomalies challenge the ΛCDM framework:

- The >6σ H_0 tension
- The CMB lensing anomaly (AL > 1)
- Low optical depth, possible negative $\Sigma m\nu$, and hints of DDE

Why does it matter? If tensions reflect new physics, or they're due to systematics, then the tight neutrino bounds we've quoted may be misleading.
Either way, we need to understand them.

Precision cosmology is only meaningful when the data are internally consistent and trustworthy. Otherwise, we risk confusing artifacts for discoveries, and turning "precision" into a false sense of certainty.

We must let the data speak honestly, even if that means questioning our models, methods, or assumptions, before claiming to measure the universe to percent-level accuracy.

Thank you!

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Addressing observational tensions in cosmology with systematics and fundamental physics

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WG1 – Observational Cosmology and systematics

Unveiling the nature of the existing cosmological tensions and other possible anomalies discovered in the future will require a multi-path approach involving a wide range of cosmological probes, various multiwavelength observations and diverse strategies for data analysis.

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WG2 – Data Analysis in Cosmology

Presently, cosmological models are largely tested by using well-established methods, such as Bayesian approaches, that are usually combined with Monte Carlo Markov Chain (MCMC) methods as a standard tool to provide parameter constraints.

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WG3 – Fundamental Physics

Given the observational tensions among different data sets, and the unknown quantities on which the model is based, alternative scenarios should be considered.

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