

Neutrino masses from Cosmology

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Neutrino physics and cosmology

Neutrinos are the last particles of the Standard Model whose masses are unknown.

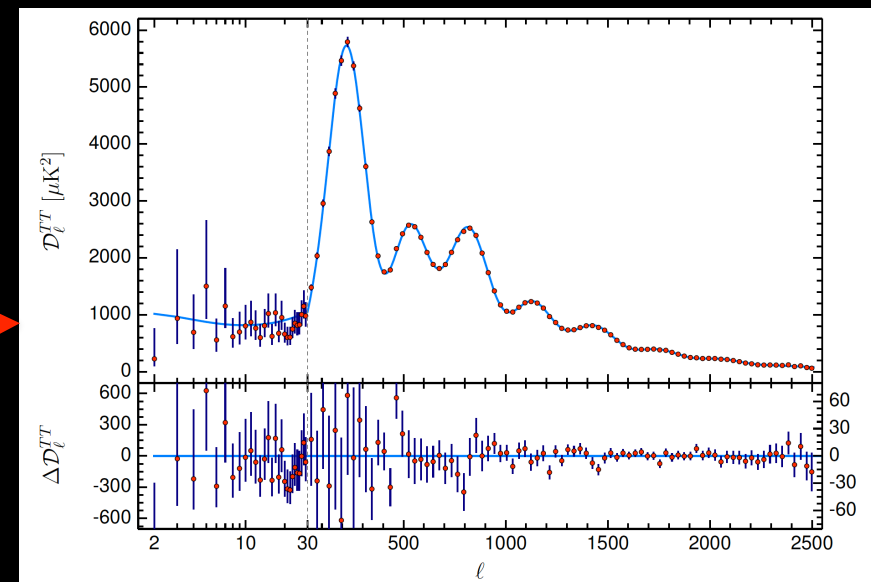
To measure their total mass with the cosmological data we can use the Cosmic Microwave Background (CMB) and the Large Scale Structure (LSS) measurements.

The Cosmic Microwave Background

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

From the map of the CMB anisotropies we can extract the temperature angular power spectrum.

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



Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H_0 , n_s , τ , A_s)

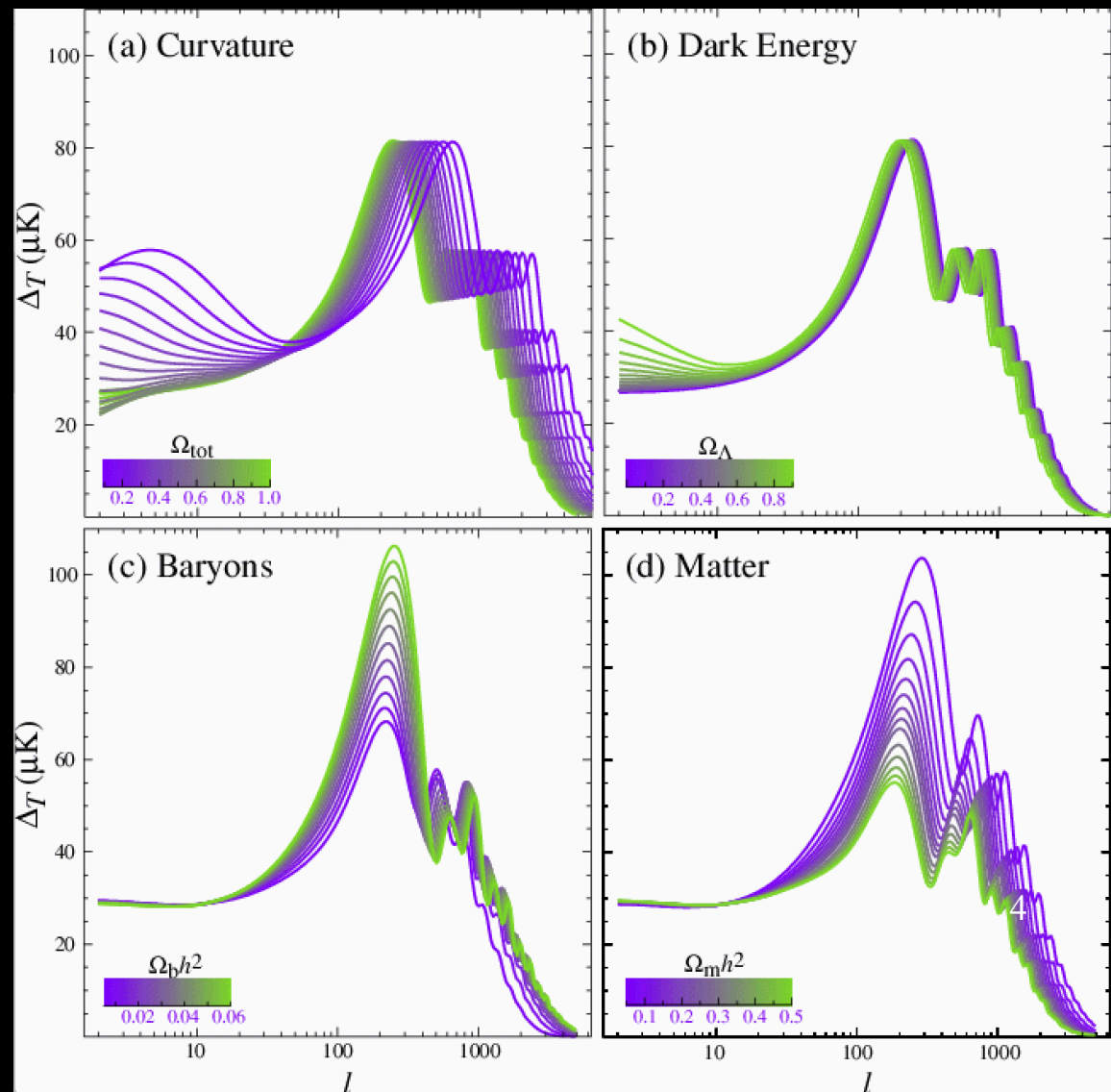


Theoretical model

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.

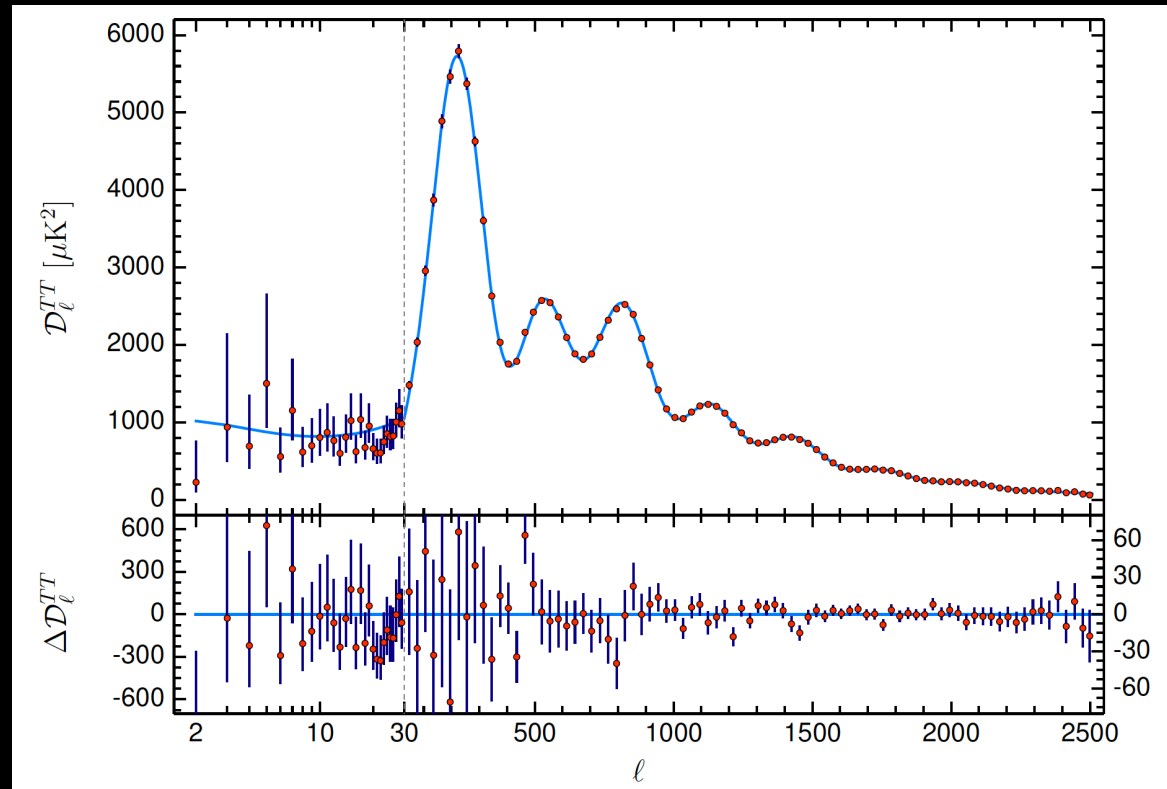
Wayne Hu's tutorial



Cosmological parameters:
($\Omega_b h^2$, $\Omega_m h^2$, H_0 , n_s , τ , A_s)

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

CMB from Planck

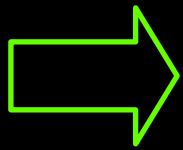
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s ⁻¹ Mpc ⁻¹] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011

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

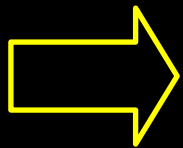
In the standard Λ CDM cosmological model, Σm_ν is fixed to 0.06 eV, so to obtain constraints on this parameter we have to consider this one parameter extension of the standard Λ CDM.

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 N_{eff} .



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.

Total neutrino mass

Because the shape of the CMB spectrum is related mainly to the physical evolution before recombination, the effect of the neutrino mass, can appear through a modified background evolution and some secondary anisotropy corrections.

Varying their total mass we vary:

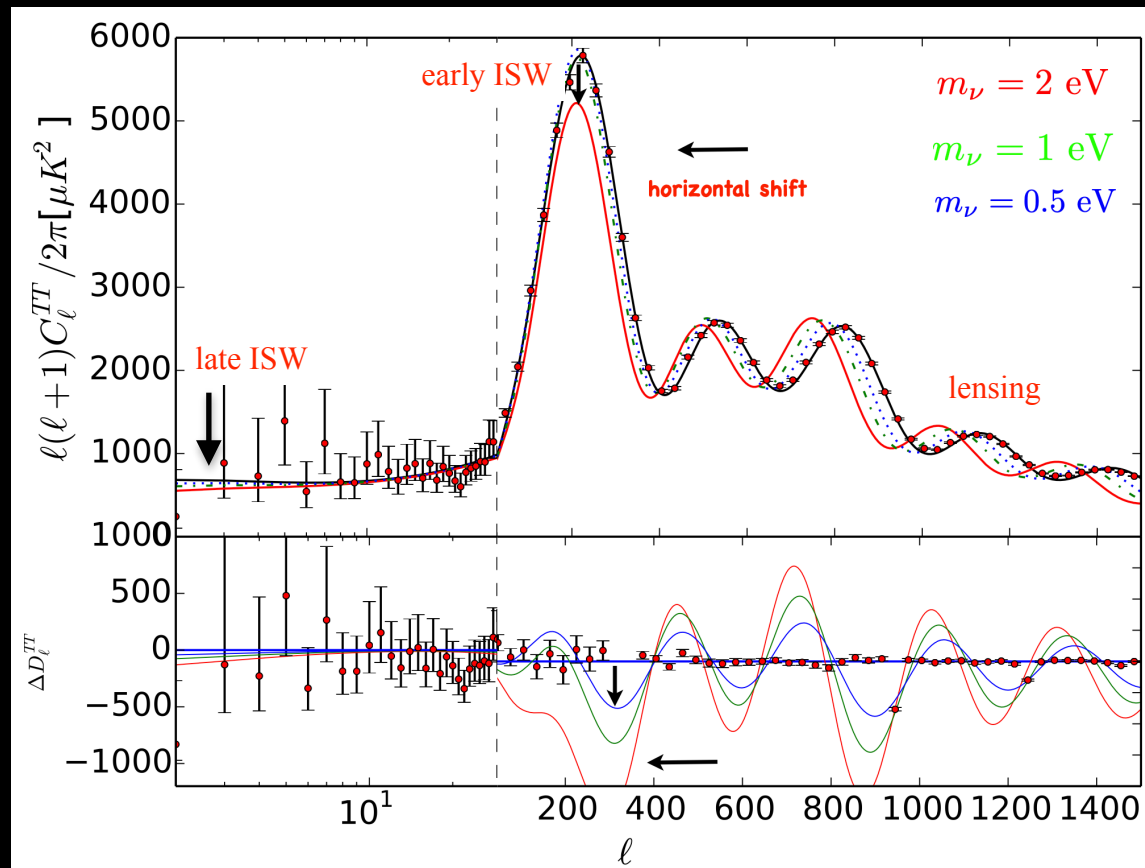
- ✓ The redshift of the matter-to-radiation equality z_{eq} ;
- ✓ The amount of matter density today.

$$\omega_M = \omega_b + \omega_{CDM} + (\sum m_\nu) / 93.14 \text{ eV}$$

Total neutrino mass and CMB

The **impact on the CMB** will be:

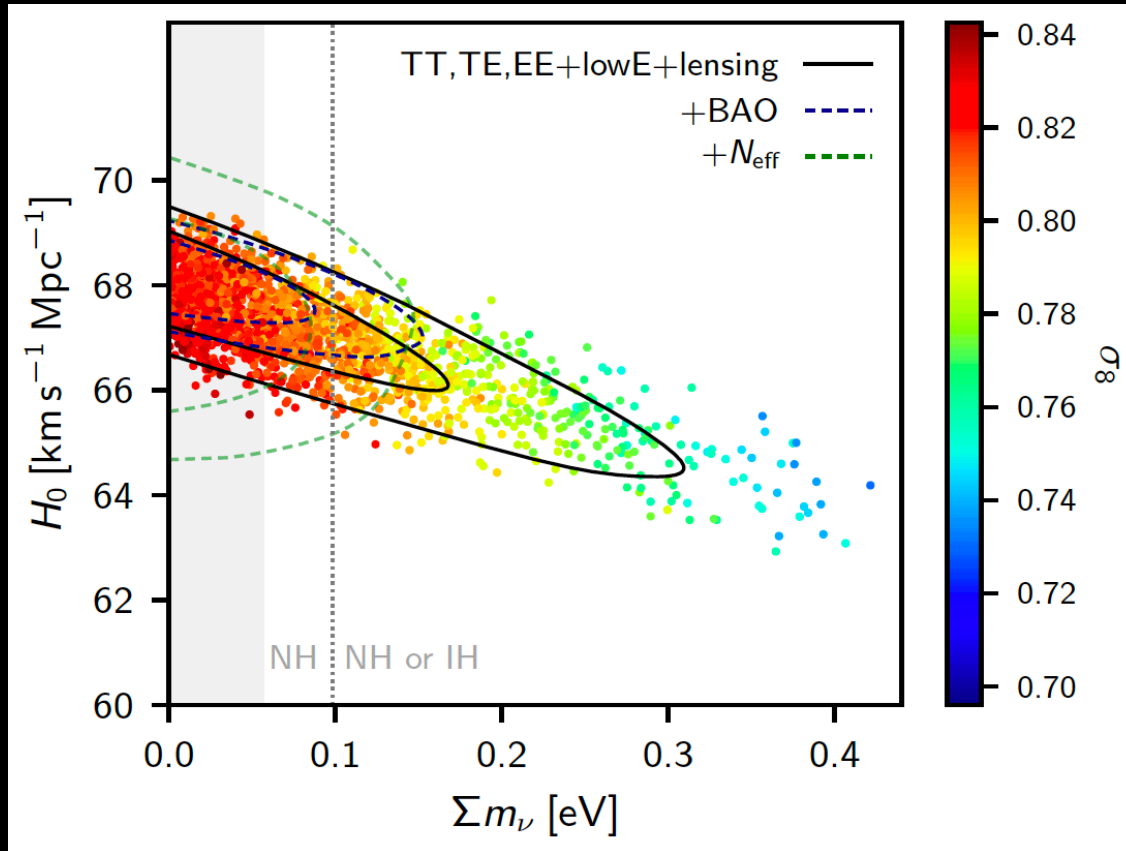
- The changing of the position and amplitude of the peaks;
- The slope of the low- ℓ tail of the spectrum, due to the late ISW effect;
- The damping of the high- ℓ tail, due to the lensing effect.



Credit figure: Olga Mena

Total neutrino mass

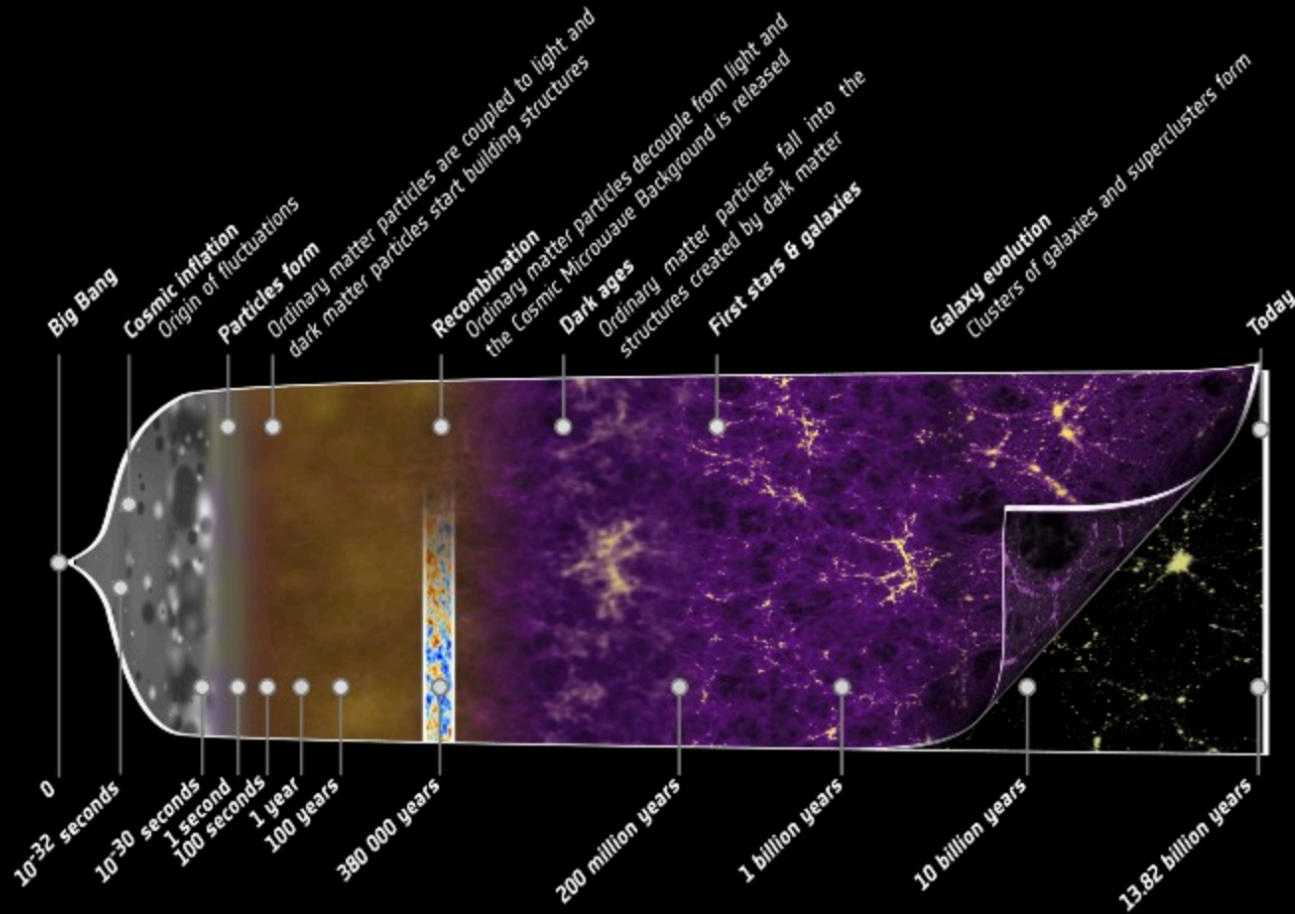
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



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

From Planck 2018 we have a very important upper limit on the total neutrino mass.

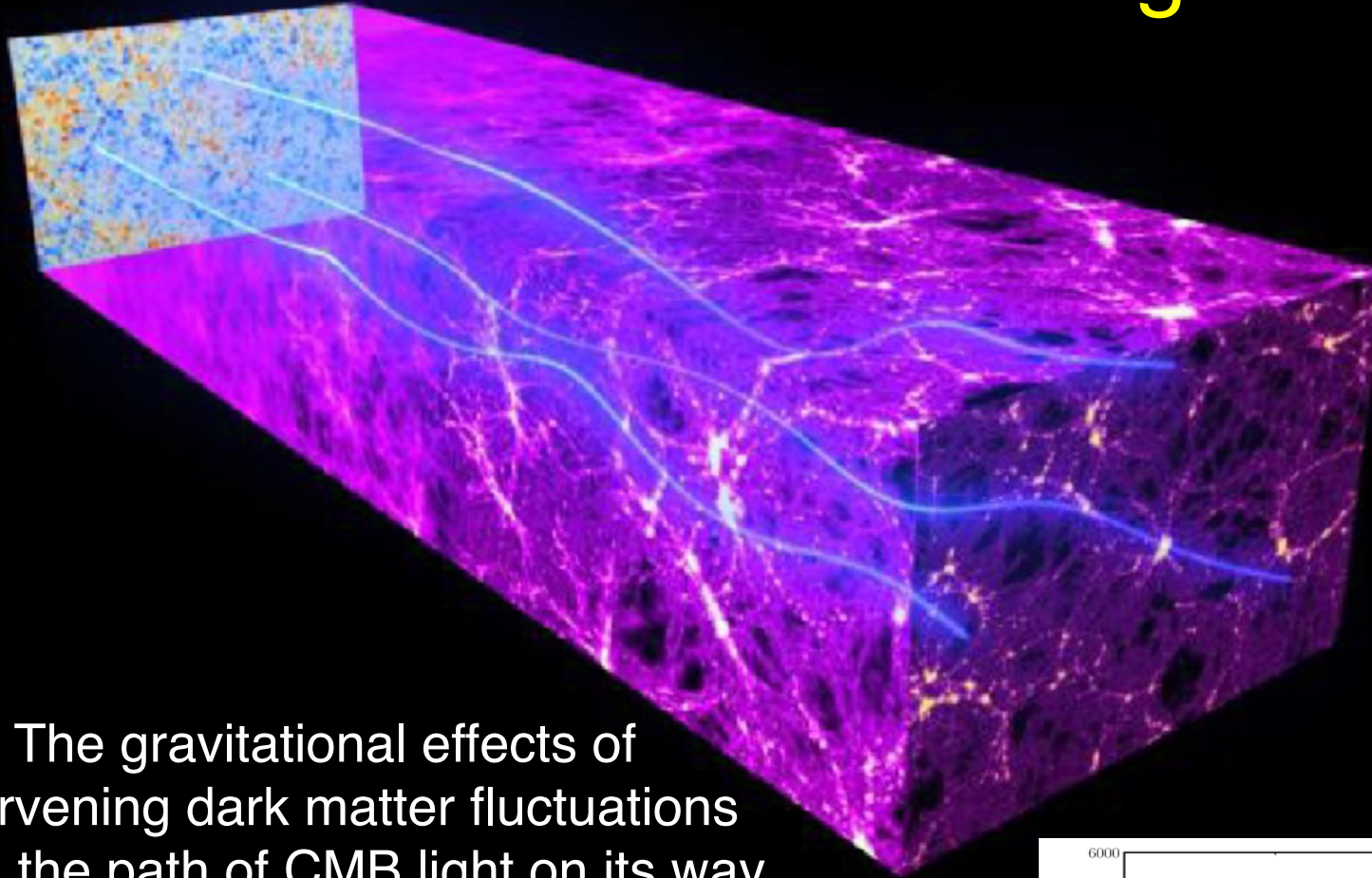
Total neutrino mass



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

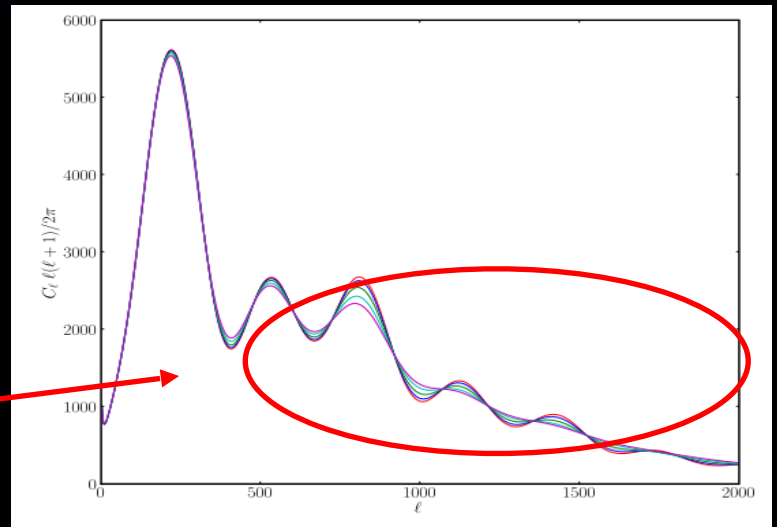
If primary CMB anisotropies form at recombination,
 when the CMB was at a temperature of $T \sim 0.3 \text{ eV}$,
 and a neutrino with a mass of $\sim (0.26/3) \sim 0.09 \text{ eV}$ is still relativistic at that epoch,
 how can we have with CMB data this amazing upper limit?

The CMB lensing

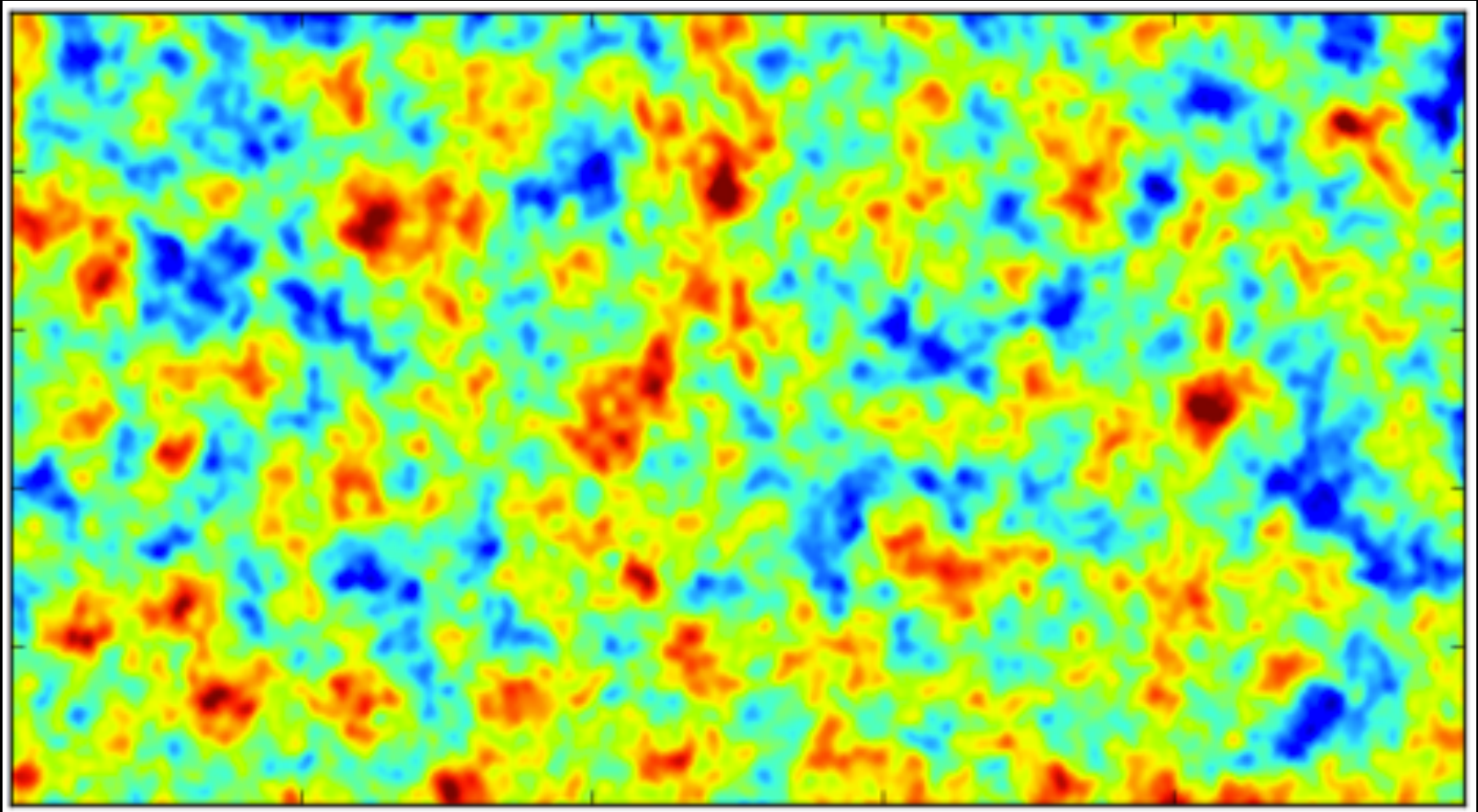


The gravitational effects of intervening dark matter fluctuations bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB.

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

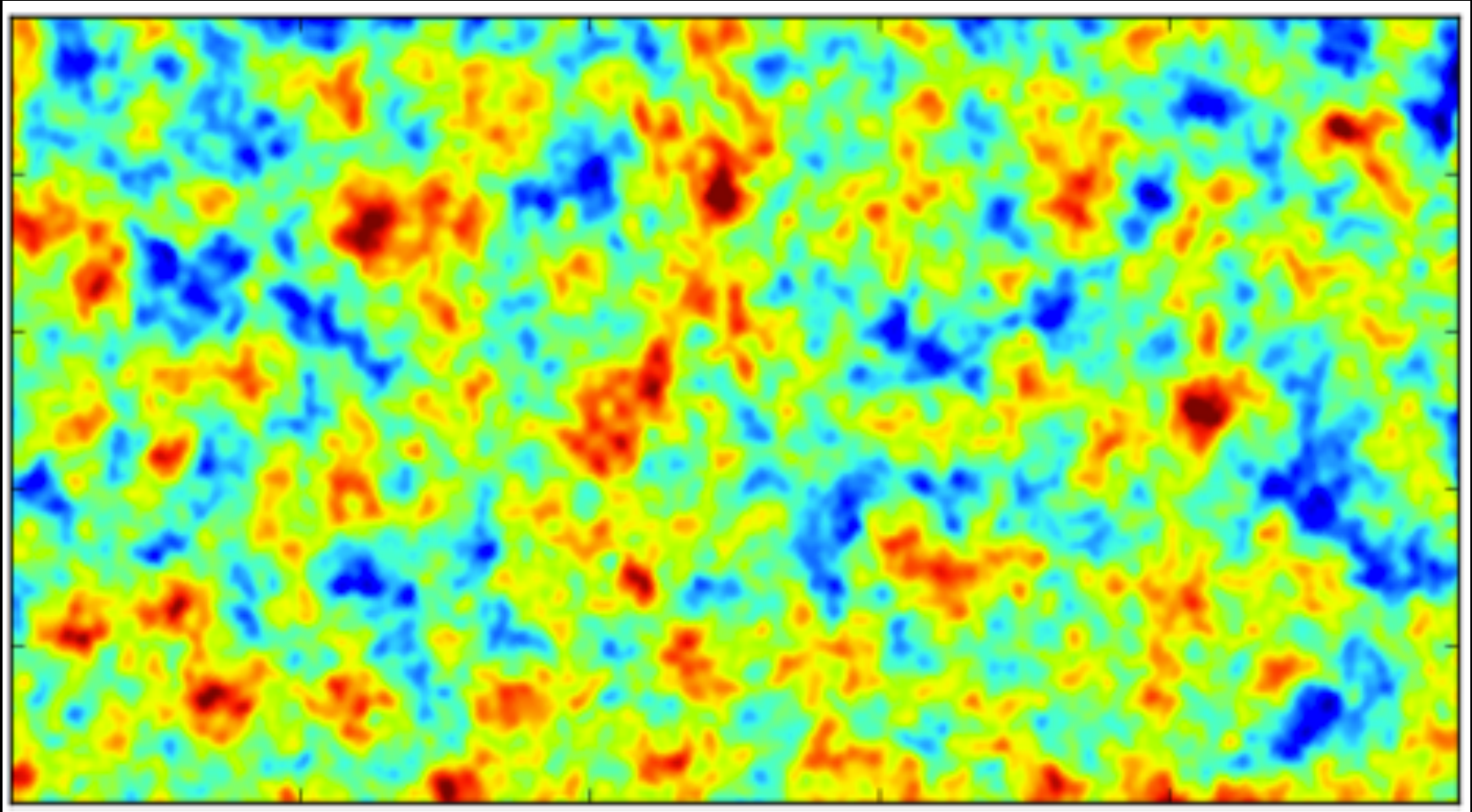


The CMB lensing



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

The CMB lensing



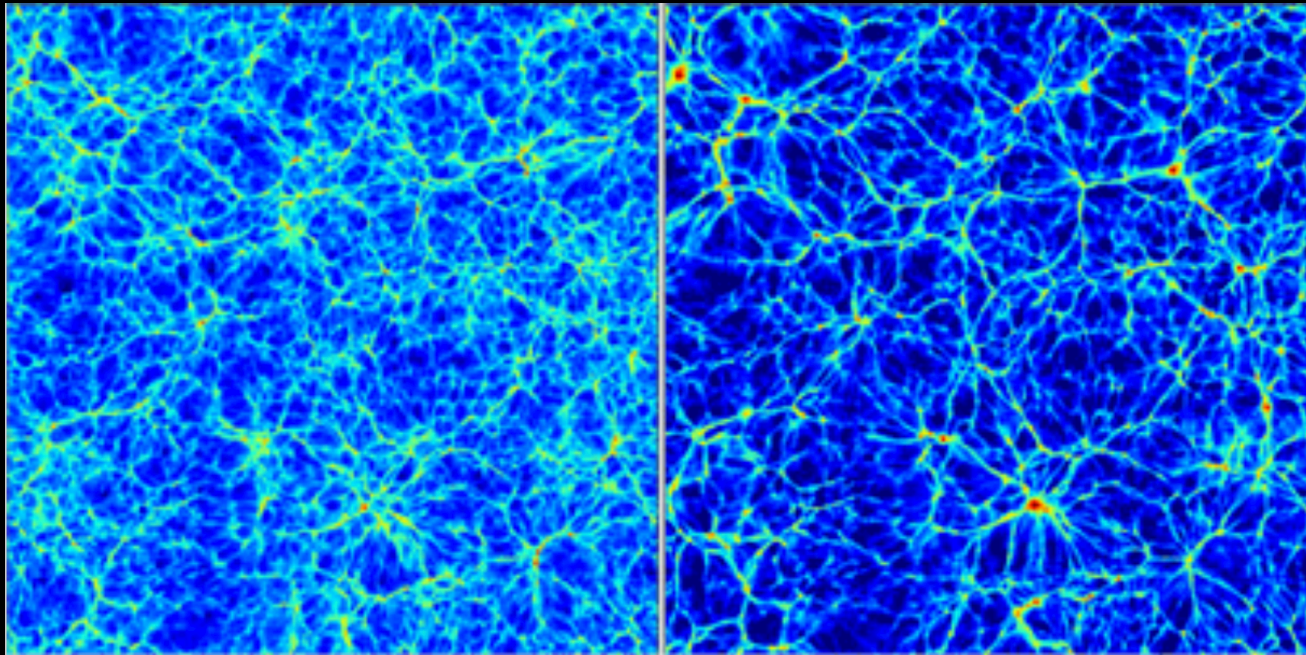
A simulated patch of CMB sky – **after dark matter lensing**

Massive neutrinos

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

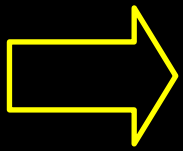
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]

These strong limits are completely due to the CMB lensing, indicating that we have a clear detection of the lensing signal in the CMB spectra.



In fact, massive neutrinos practically do not form structure. More massive is the neutrino less structure we have, less will be the CMB lensing. So a larger signal of lensing means a smaller neutrino mass.

Total neutrino mass



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.

Bond et al., *Phys.Rev.Lett.* 45 (1980) 1980-1984

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

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

Or the two-point correlation function in the configuration space

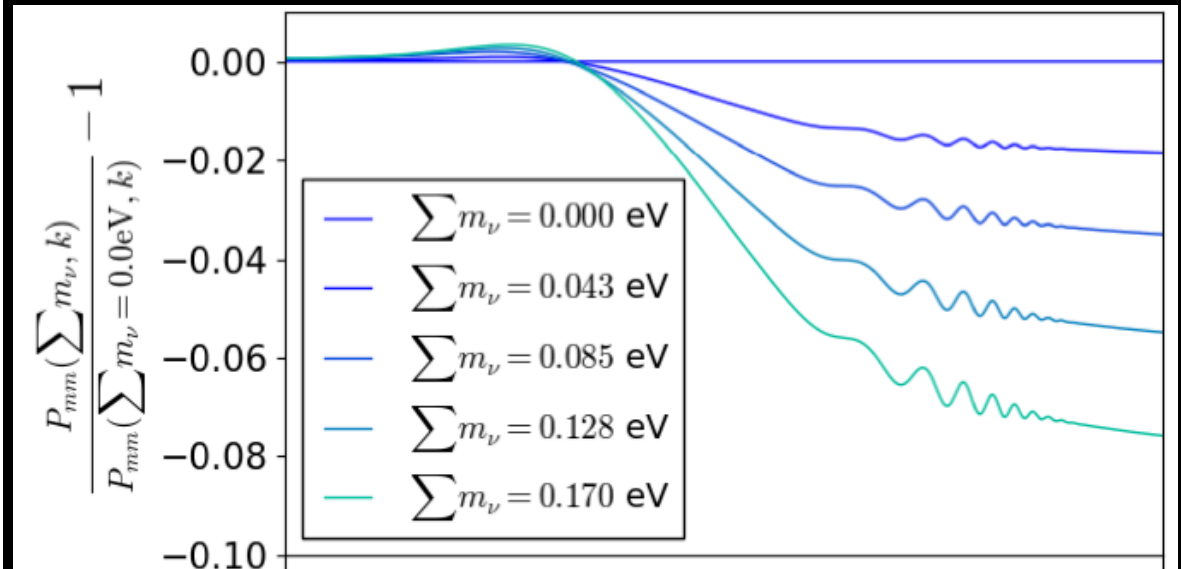
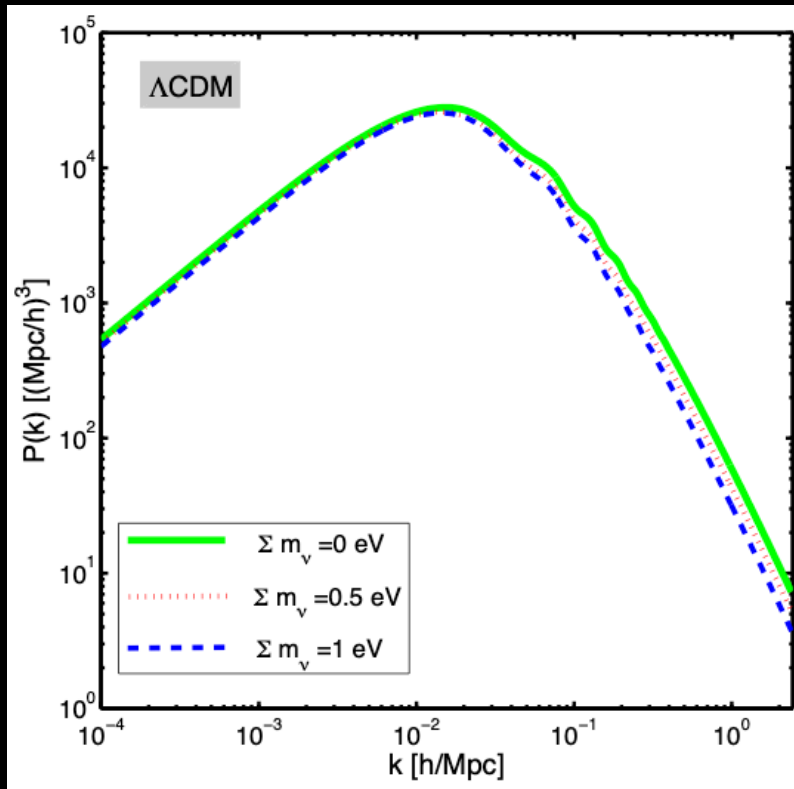
$$\xi(r) = \int \frac{d^3 k}{(2\pi)^3} P(k) e^{i\mathbf{k} \cdot (\mathbf{x} - \mathbf{x}')} \equiv \xi_m(r)$$

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 non-relativistic matter fluctuation in Fourier space:

$$P(k, z) = \langle |\delta_m(k, z)|^2 \rangle$$

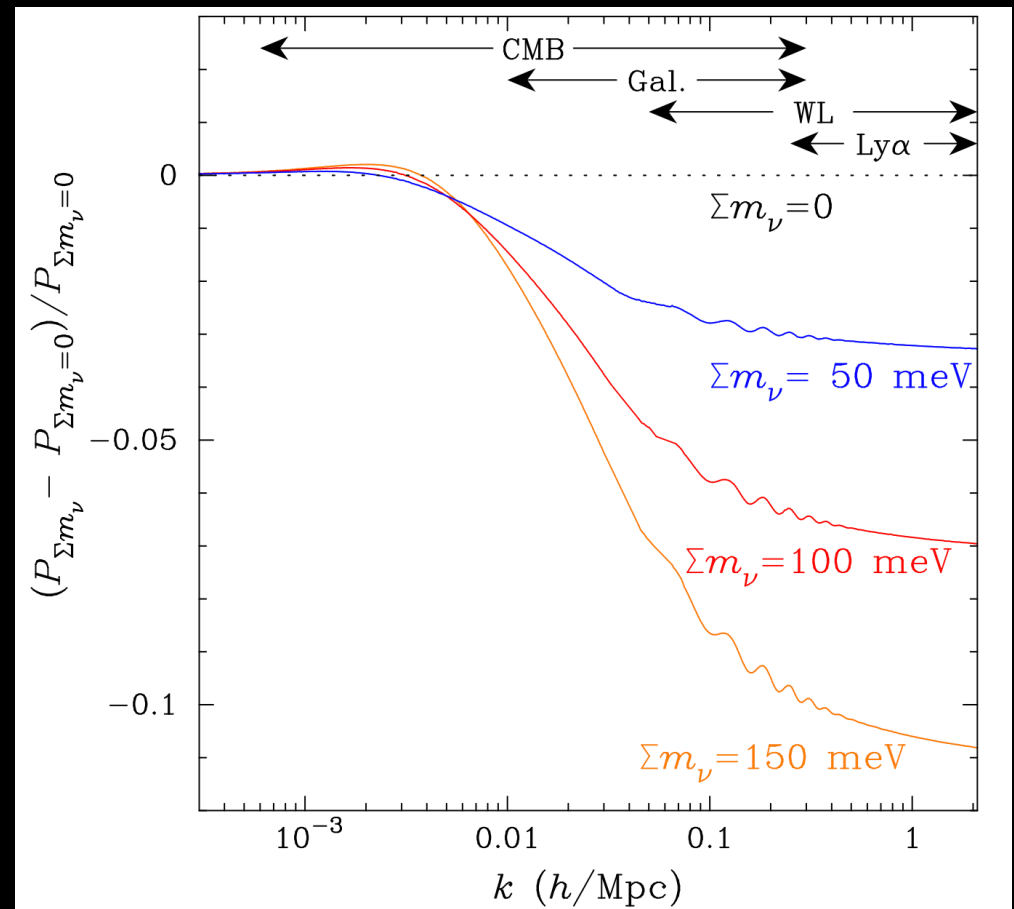
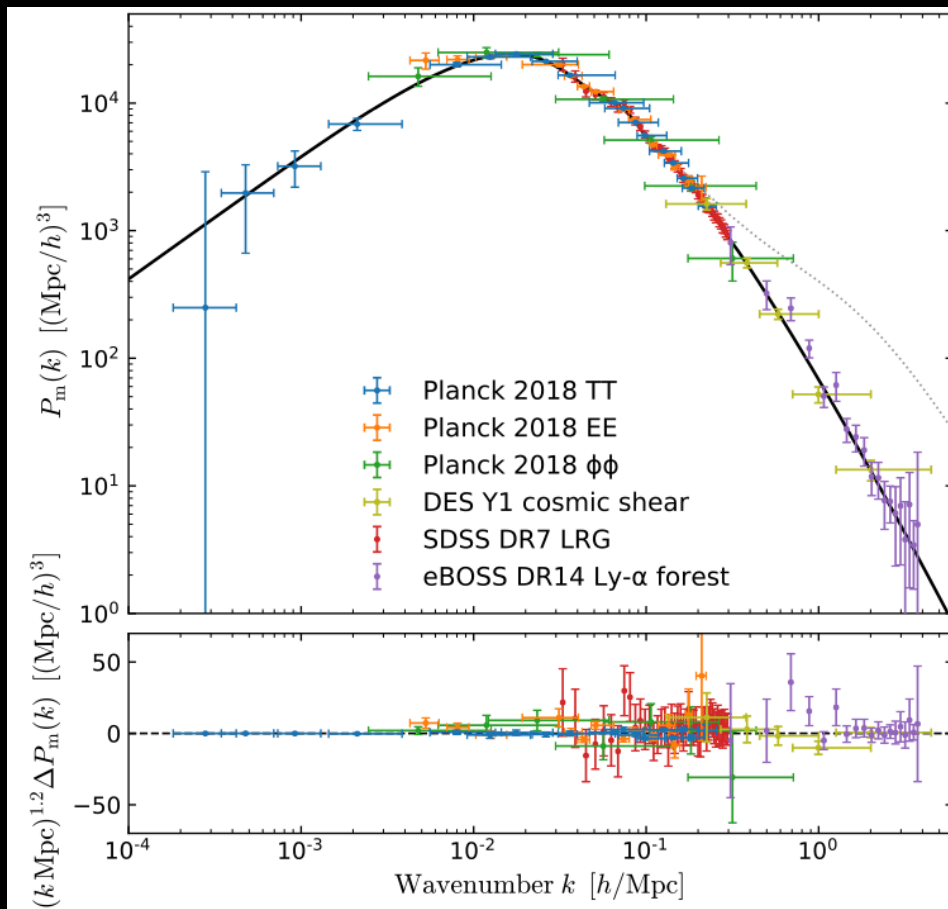


Whitford et al., arXiv:2112.10302

Matter power spectrum

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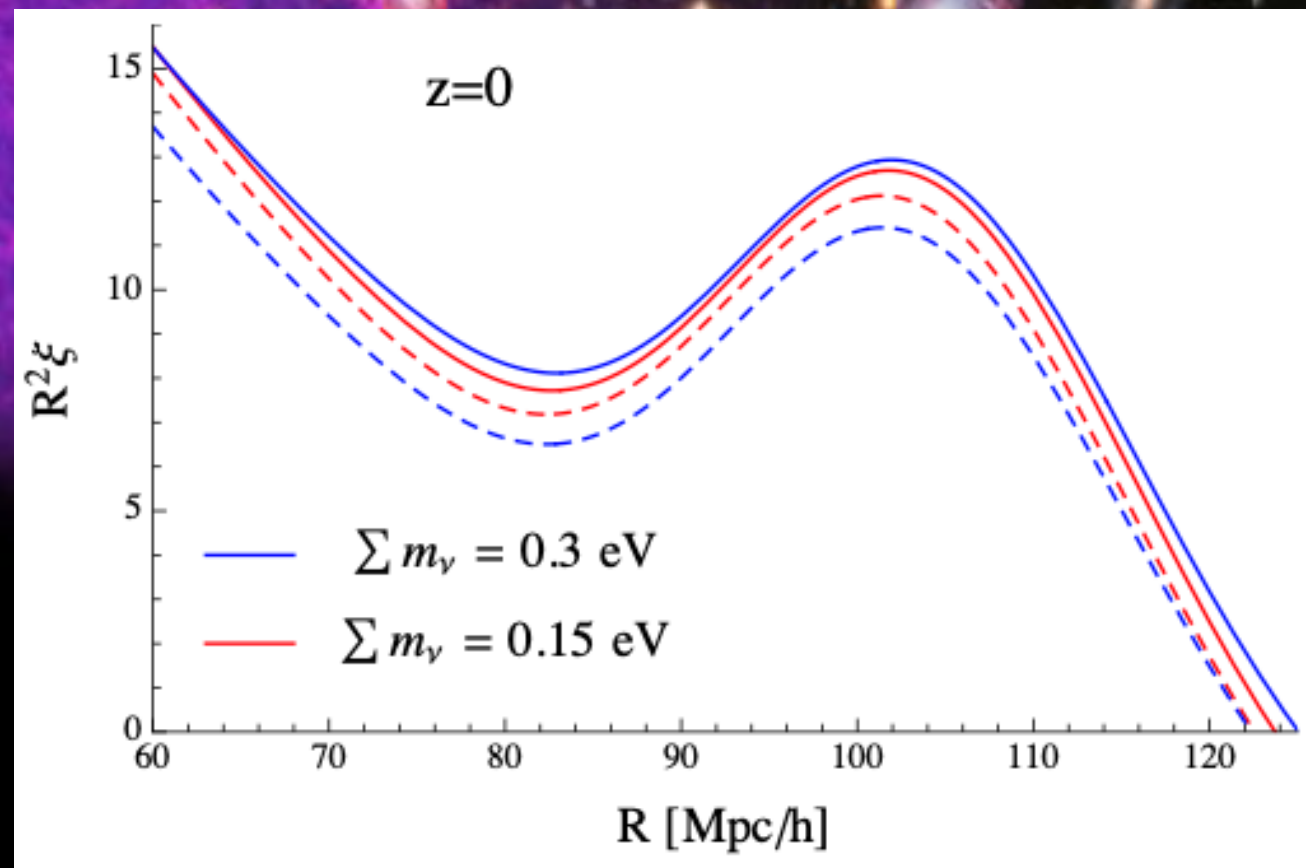
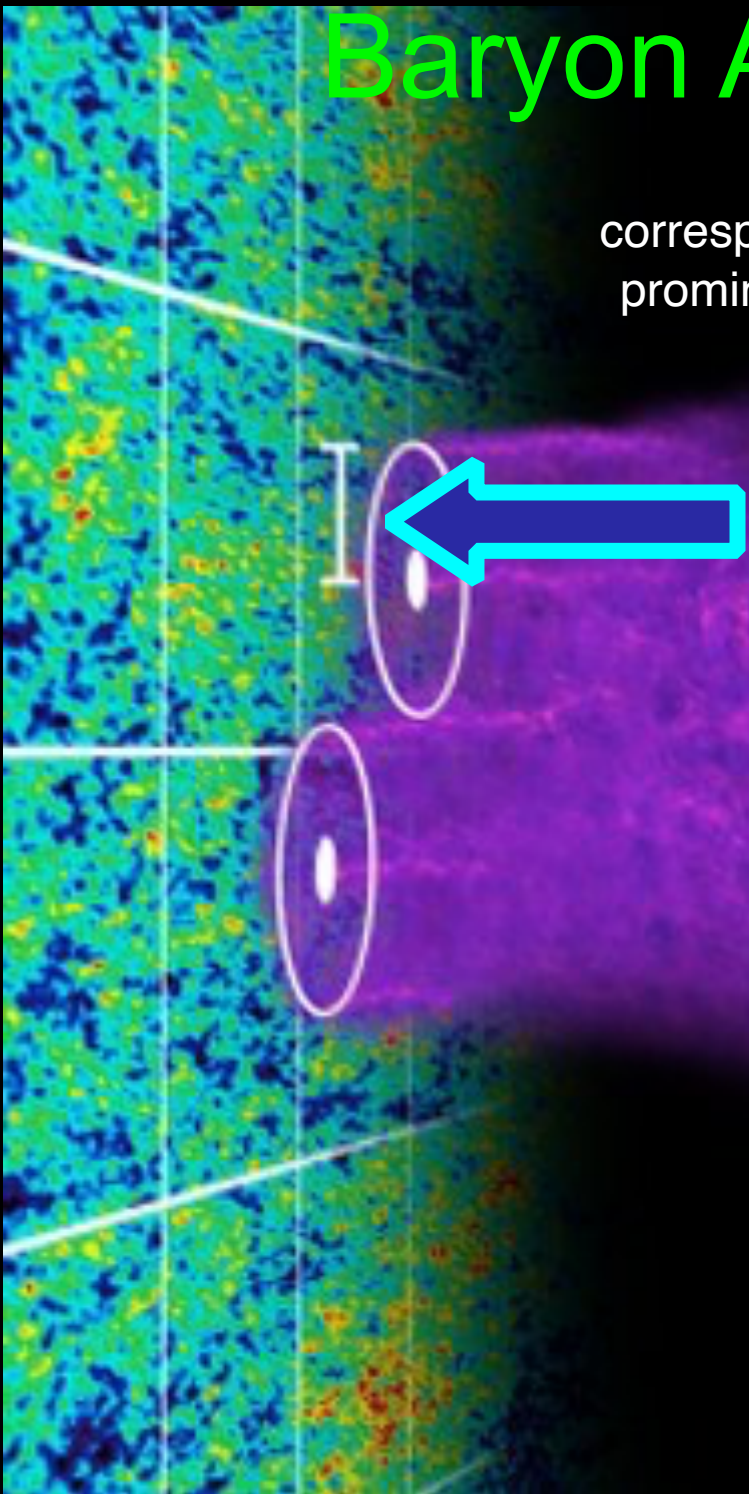
This can be obtained with measurements of the gravitational lensing of the CMB, the clustering and the weak lensing of galaxies, and the number density of galaxy cluster.



Baryon Acoustic Oscillations

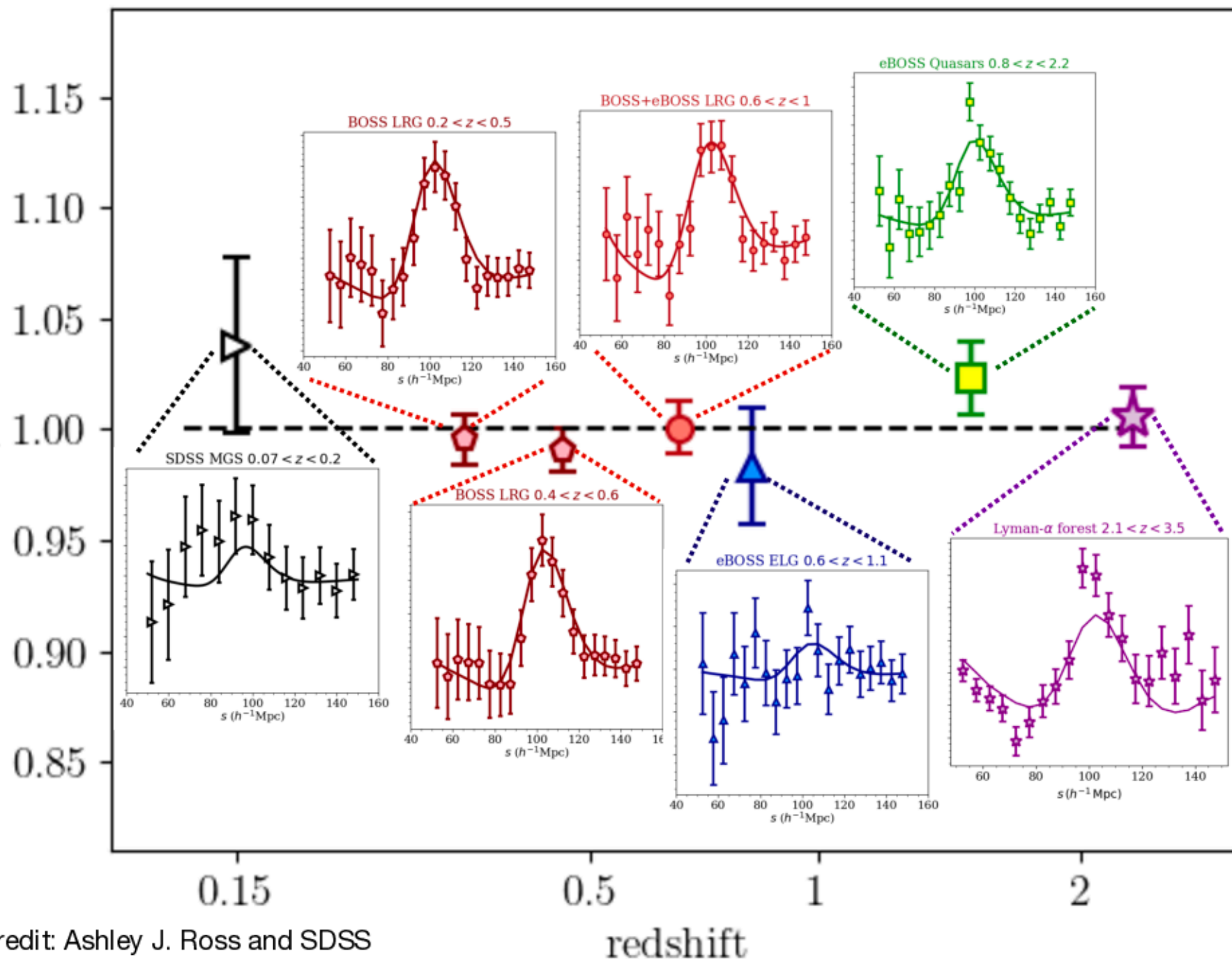
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The BAO peak of the galaxy correlation function, corresponding to the acoustic scale at decoupling, is one of the prominent observables in present day cosmology, and is very sensitive to massive neutrinos.



SDSS BAO Distance Ladder

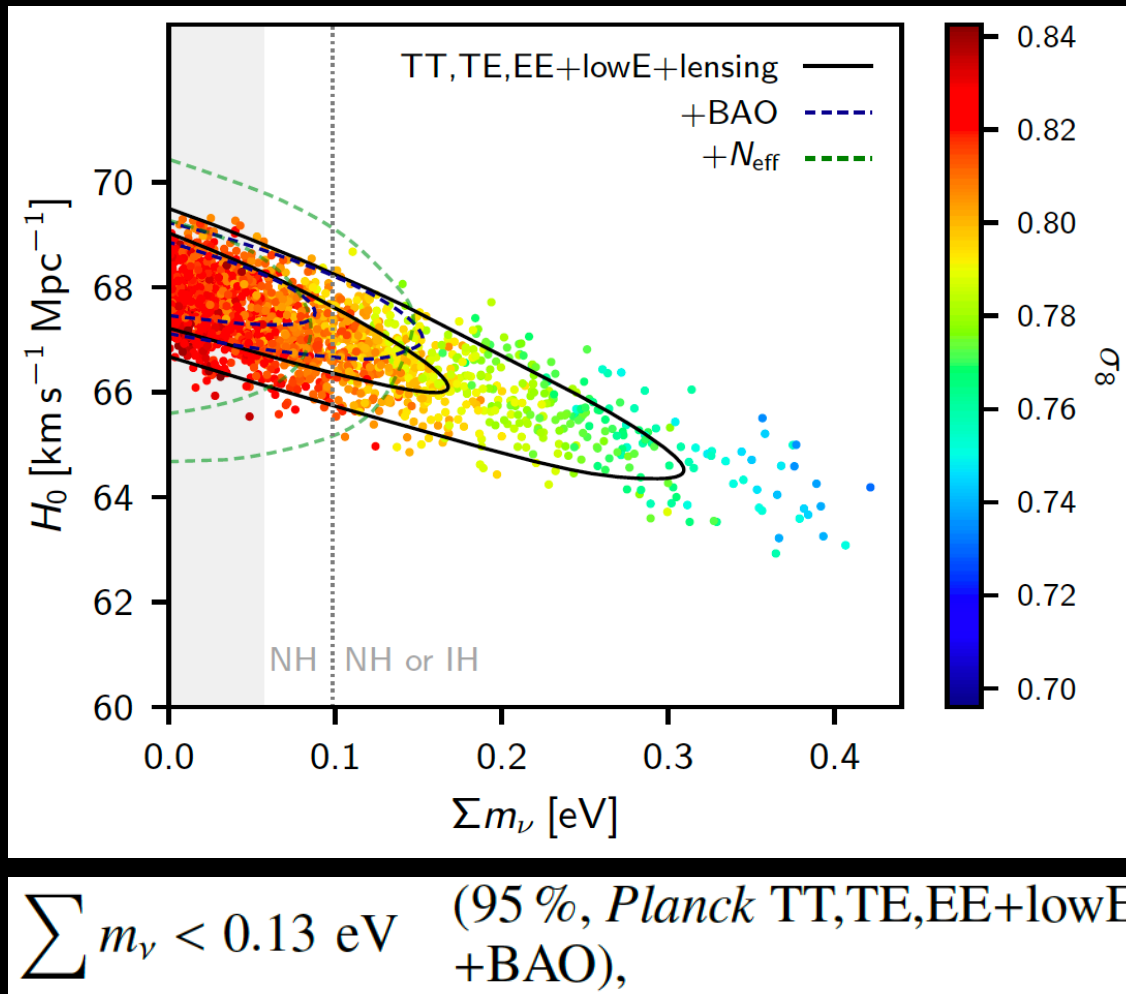
BAO Measurement/Planck 2018 Λ CDM



Credit: Ashley J. Ross and SDSS

Total neutrino mass

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



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.

Mass ordering

In the cosmological analysis, usually the **neutrino masses are assumed to be degenerate ($m_i=m\geq 0$) and the lower bound of total neutrino mass ($\Sigma m_\nu=m_1+m_2+m_3$) is placed to 0 (in the unphysical region)**. Although the CMB is essentially blind to the mass splitting, now the bounds are strong enough that the neutrino mass-squared splitting can no longer be considered negligible.

For this reason, in [Capozzi, Di Valentino et al., *Phys.Rev.D* 104 \(2021\) 8, 083031](#) we consider separately the NO and IO cases.

The absolute ν masses are unknown. However, lower bounds are set by oscillation data by zeroing the lightest m_i :

$$(m_1, m_2, m_3) \geq \begin{cases} (0, \sqrt{\delta m^2}, \sqrt{|\Delta m^2| + \delta m^2/2}) & \text{(NO)} \\ (\sqrt{|\Delta m^2| - \delta m^2/2}, \sqrt{|\Delta m^2| + \delta m^2/2}, 0) & \text{(IO)} \end{cases}$$

Therefore, we assume in our analysis these corresponding lower bounds:

$$\Sigma = m_1 + m_2 + m_3 \gtrsim \begin{cases} 0.06 \text{ eV} & \text{(NO)} \\ 0.10 \text{ eV} & \text{(IO)} \end{cases}$$

Mass ordering

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + $m_\beta + m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2

We implement separately the NO and IO options in the code used for the analysis, so the masses m_i entering in the definition of Σ obey the δm^2 and Δm^2 constraints.

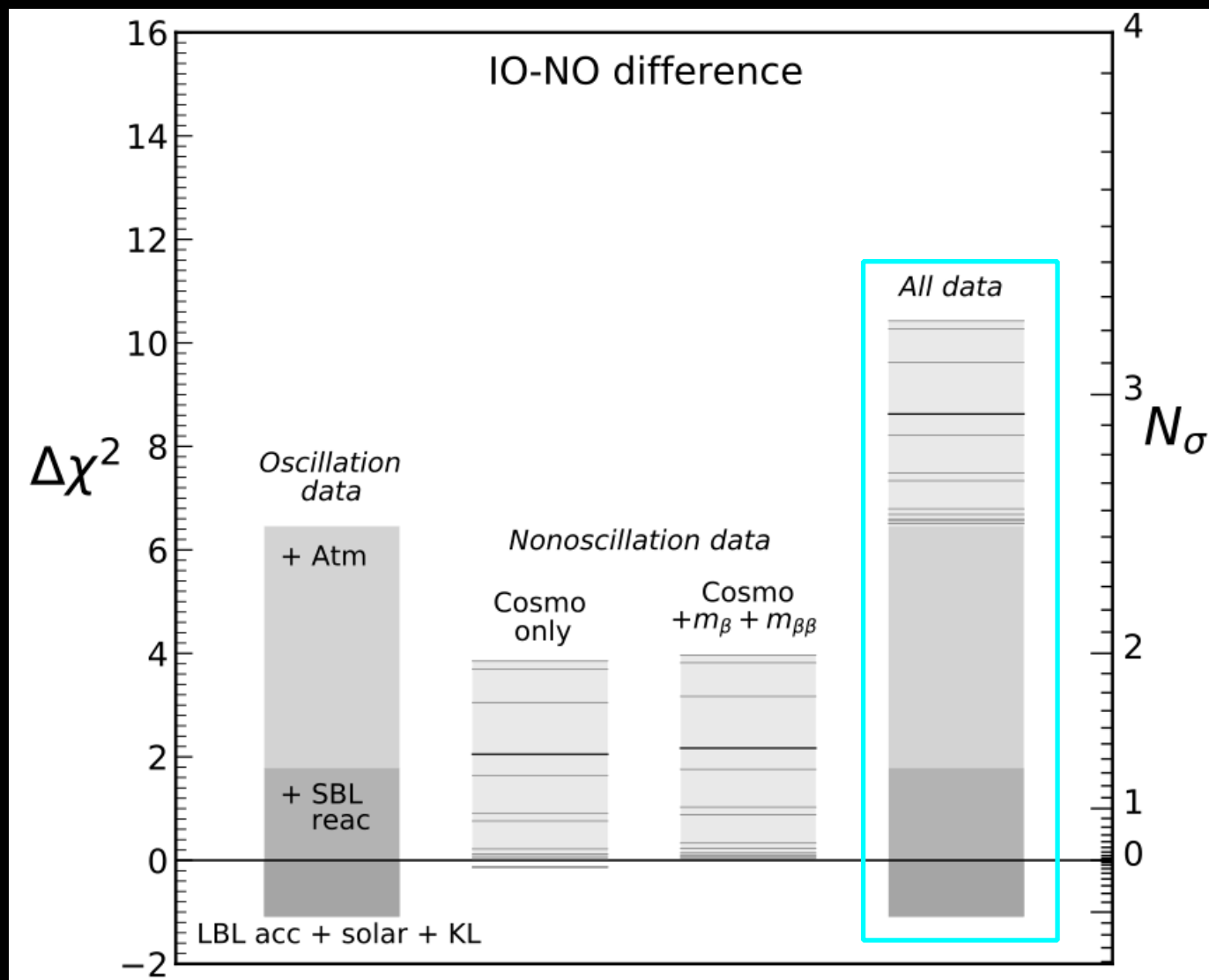
The obtained posterior probability functions $p(\Sigma)$ in NO and IO, are transformed into $\chi^2(\Sigma)$ functions by applying the standard Neyman construction and the Feldman-Cousins method. The main cosmological fit results, obtained in this way, are summarized in the table, in terms of upper bounds (at 2σ level) on the sum of neutrino masses Σm_ν for NO.

Mass ordering

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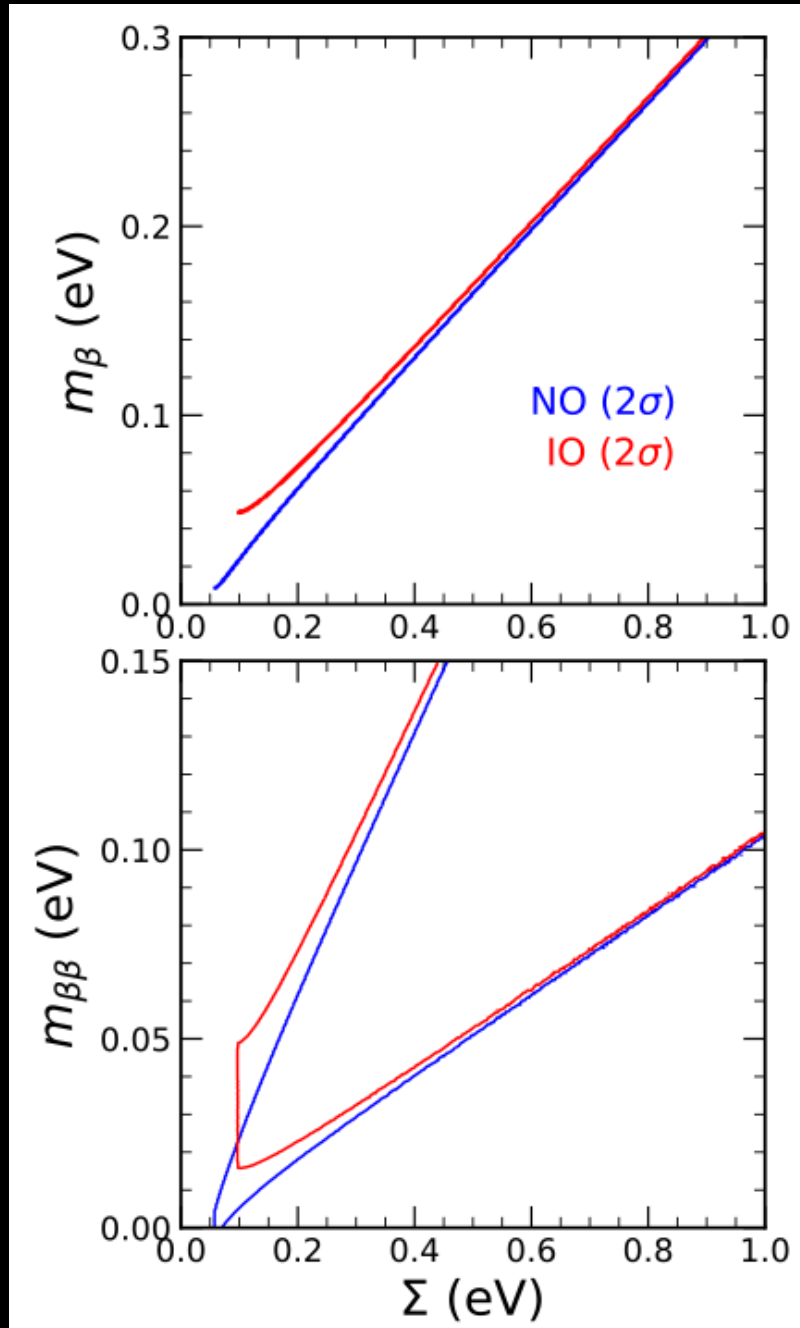
Although we can see, as expected, a weak sensitivity of cosmological data to the mass ordering, **the normal ordering is generally preferred.**

Moreover, **the overall preference for NO from cosmological data exceeds 1σ when using the BAO data**, and they are associated with the strongest constraints on the sum of neutrino masses ($\Sigma m_\nu < 0.15$ eV at 2σ).



Although none of the single oscillation or nonoscillation datasets provides compelling evidences for NO, by combining the cosmology with oscillation and nonoscillation data, using a frequentist analysis, we find the global preference for NO at the typical level of 2.5-3 σ .

Constraints on the absolute neutrino mass

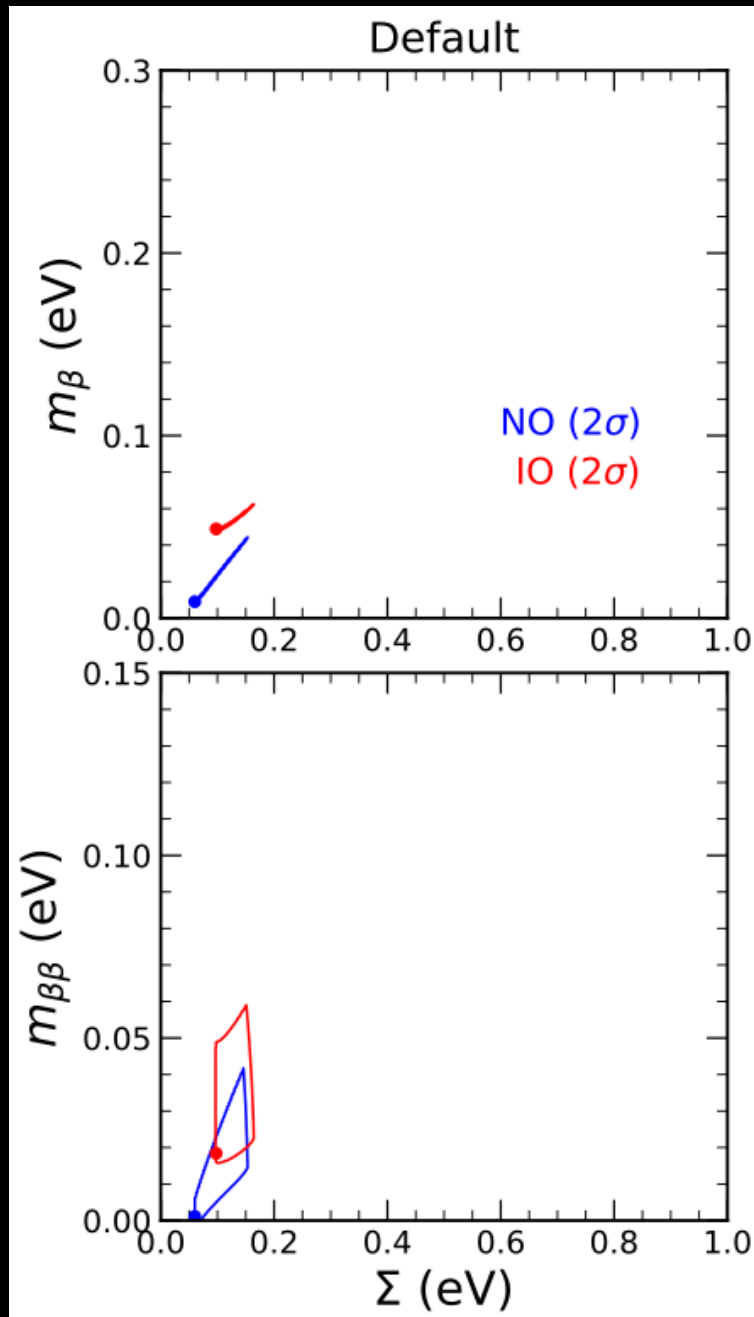


The nonoscillation observables (m_β , $m_{\beta\beta}$, Σm_ν) are strongly and positively correlated, via their common dependence on the absolute neutrino mass scale.

Here we can see the correlation bands at 2σ for the pairs $(\Sigma m_\nu, m_\beta)$ and $(\Sigma m_\nu, m_{\beta\beta})$ in linear scales, including only the constraints from oscillation data, for NO and IO taken separately.

In the top panel, the bands have a tiny width, reflecting the small fractional errors on the oscillation parameters (δm^2 , Δm^2 , θ_{12} , θ_{13}) relevant for the pair $(m_\beta, \Sigma m_\nu)$. In the bottom panel, the widening of the bands is almost entirely due to the unknown Majorana phases in $m_{\beta\beta}$.

Constraints on the absolute neutrino mass



The cosmological bounds on Σm_ν dominate—via correlations—the constraints on m_β and $m_{\beta\beta}$, which are squeezed to the relatively small 2σ regions around the best fits (dot), located close to the lowest possible values for Σm_ν in both NO and IO.

It appears that the current KATRIN experiment (probing $m_\beta > 0.2$ eV) is not expected to find any signal, while planned $0\nu\beta\beta$ experiments are expected to probe at least the region covered by both NO and IO ($m_{\beta\beta} > 0.02$ eV). The region covered only by NO ($m_{\beta\beta} < 0.02$ eV) is more difficult to probe, and becomes eventually prohibitive as $m_{\beta\beta}$ vanishes.

Redshift Space Distortions

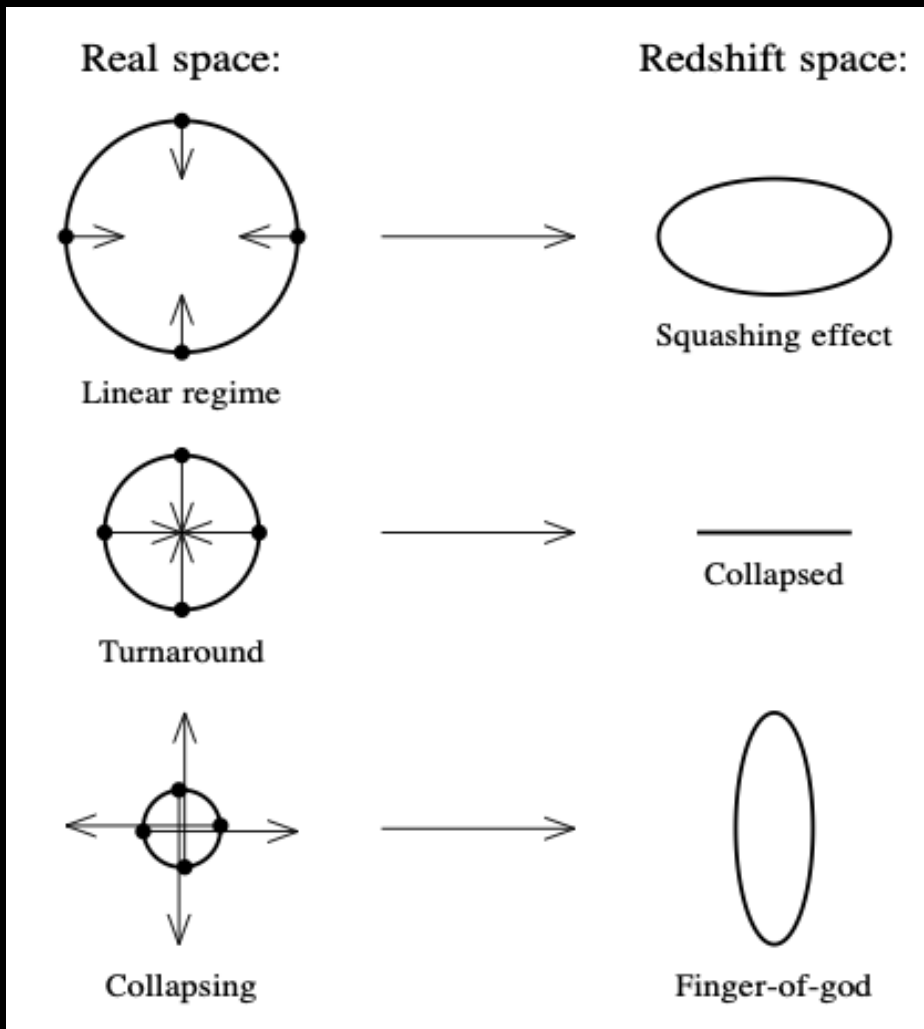
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Analysing the clustering in the redshift space, you can study the Redshift Space Distortions (RSD). We will have a reduction or increase of the growth of structure along the radial direction, because of the peculiar velocities (anisotropic clustering).

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.

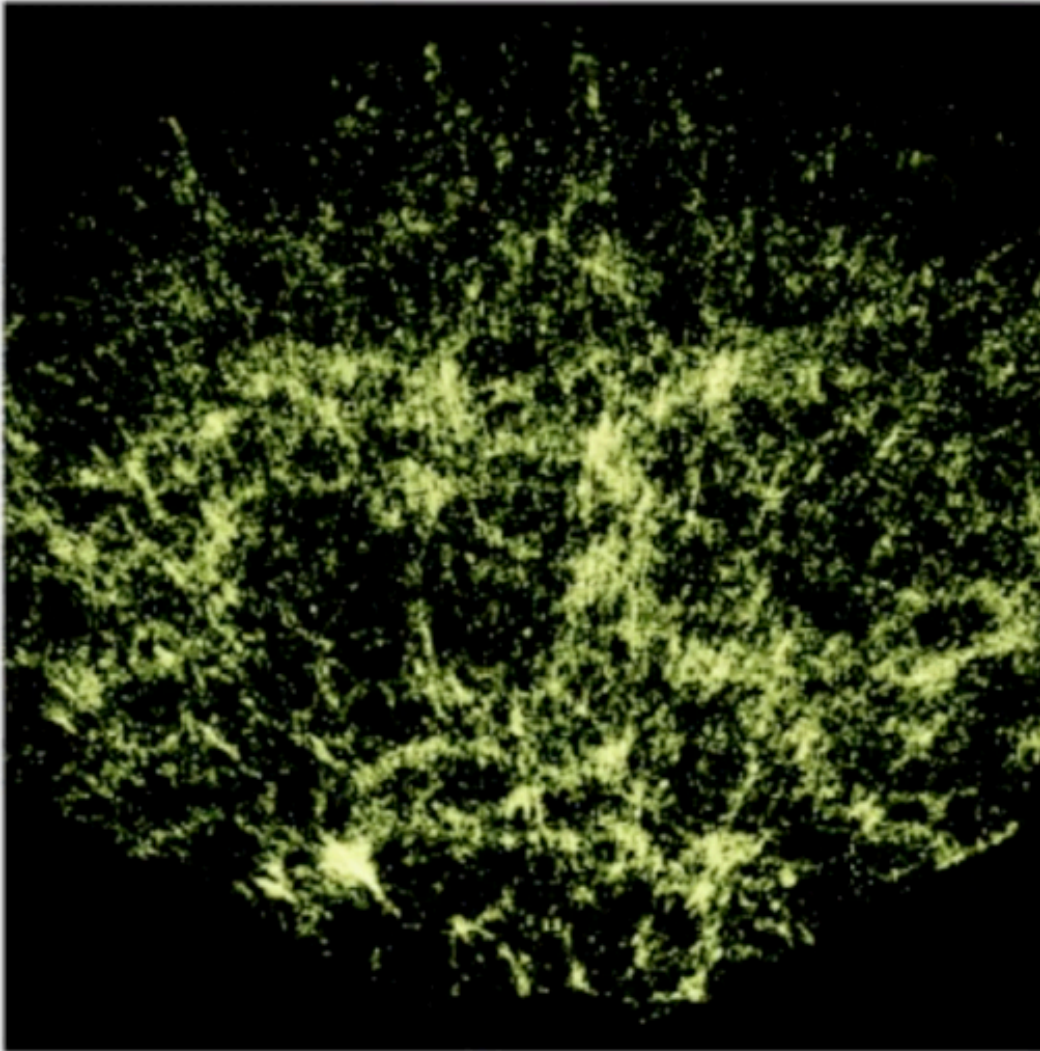
At smaller scales, the spatial distribution of galaxies appears to be elongated due to their velocity dispersion along the line of sight, producing the fingers-of-god.



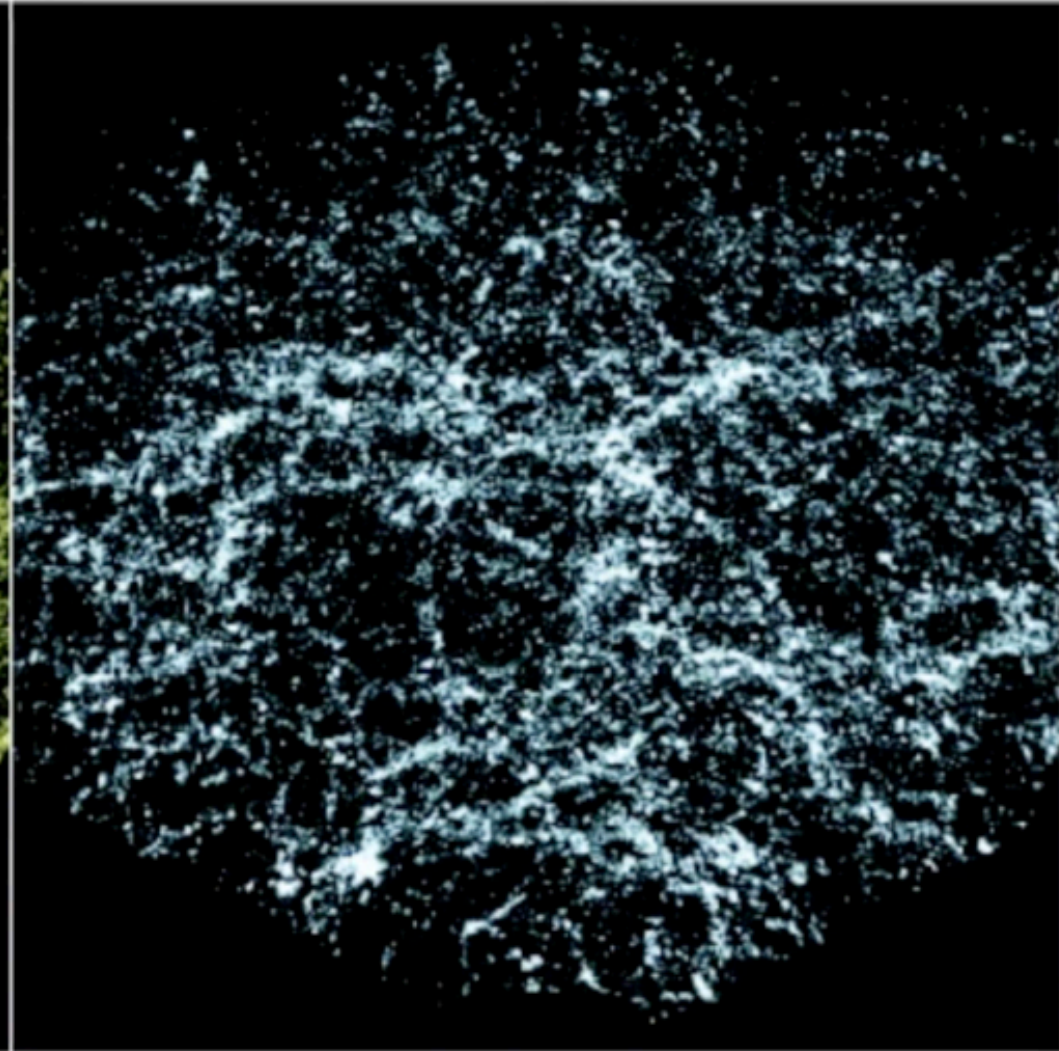
Redshift Space Distortions

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Observed 'redshift' space



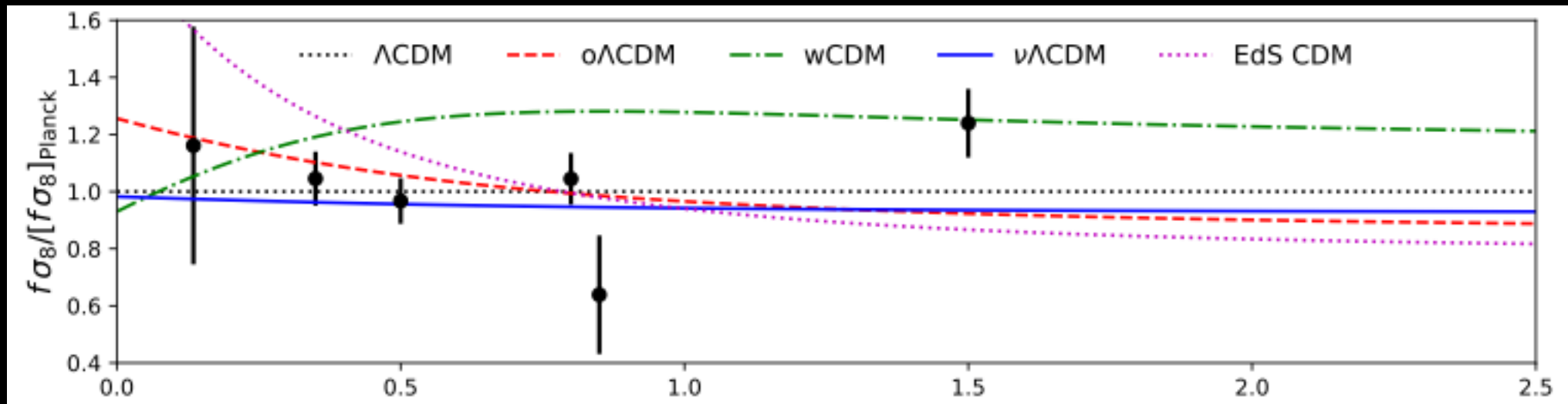
True 'real' space



slide from Héctor Gil-Marín

Redshift Space Distortions

30

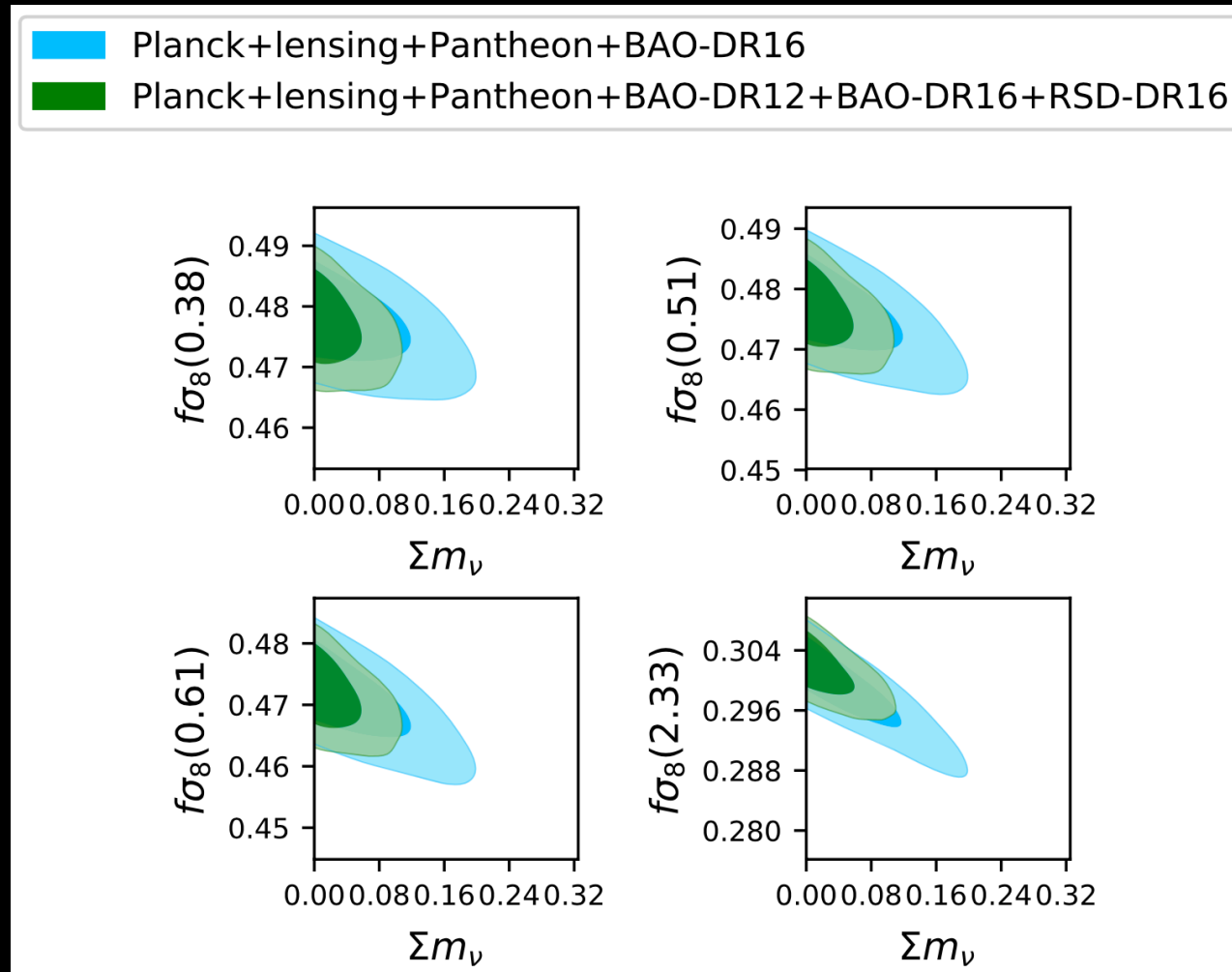


eBOSS collaboration, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

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.

Constraints on the total neutrino mass



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

Constraints on the total neutrino mass

Constraints at 95% CL

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

When we add the latest RSD from eBOSS DR16 LRGs and QSOs samples to Planck+lensing+SN Ia data obtain stronger constraints on the total neutrino mass.

Constraints on the total neutrino mass

Constraints at 95% CL

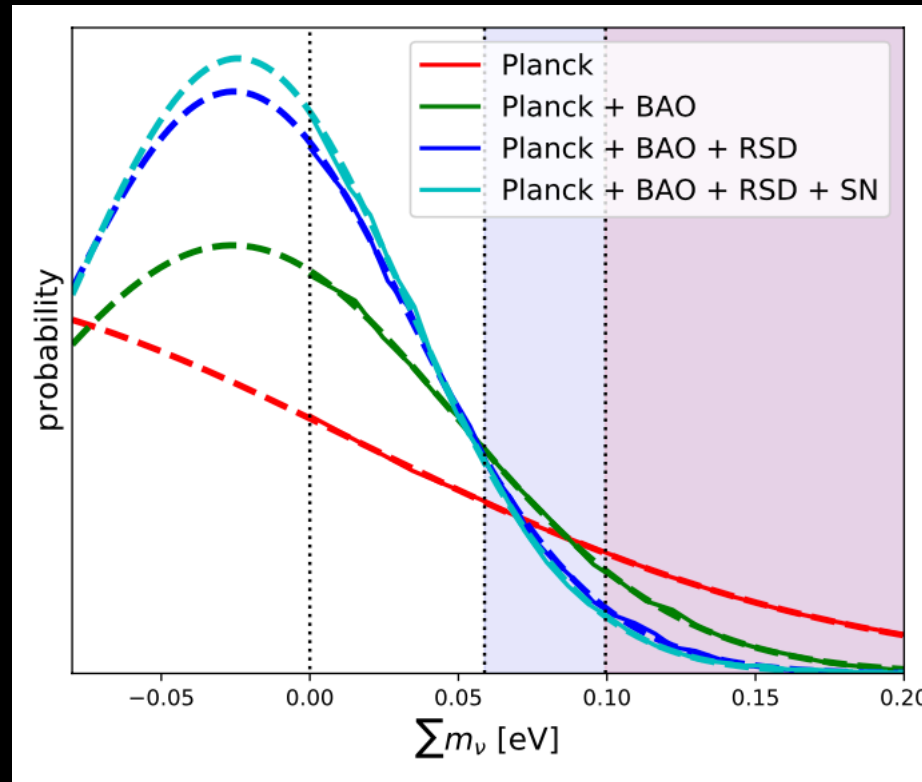
Planck+lensing +Pantheon	Σm_ν [eV]
+ DR12 <i>BAO only</i>	< 0.116
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+DR12 <i>BAO only</i> + DR16 <i>BAO only</i>	< 0.121
+DR12 <i>BAO only</i> + DR16 <i>BAO+RSD</i>	< 0.0866
+DR12 <i>BAO+RSD</i> + DR16 <i>BAO only</i>	< 0.125
+DR12 <i>BAO+RSD</i> + DR16 <i>BAO+RSD</i>	< 0.0934

When we add the latest RSD from eBOSS DR16 LRGs and QSOs samples to Planck+lensing+SN Ia data obtain stronger constraints on the total neutrino mass.

The most constraining upper bounds $\Sigma m_\nu < 0.087$ eV at 95% CL is obtained when this dataset is combined with the BAO BOSS DR12 LRG measurements.

In other words, cosmological measurements currently prefer values of Σm_ν as close to zero as possible, disfavouring the minimal allowed value for IO at more than 2σ , but also the NO at more than 68% CL ($\Sigma m_\nu < 0.037$ eV).

Constraints on the total neutrino mass

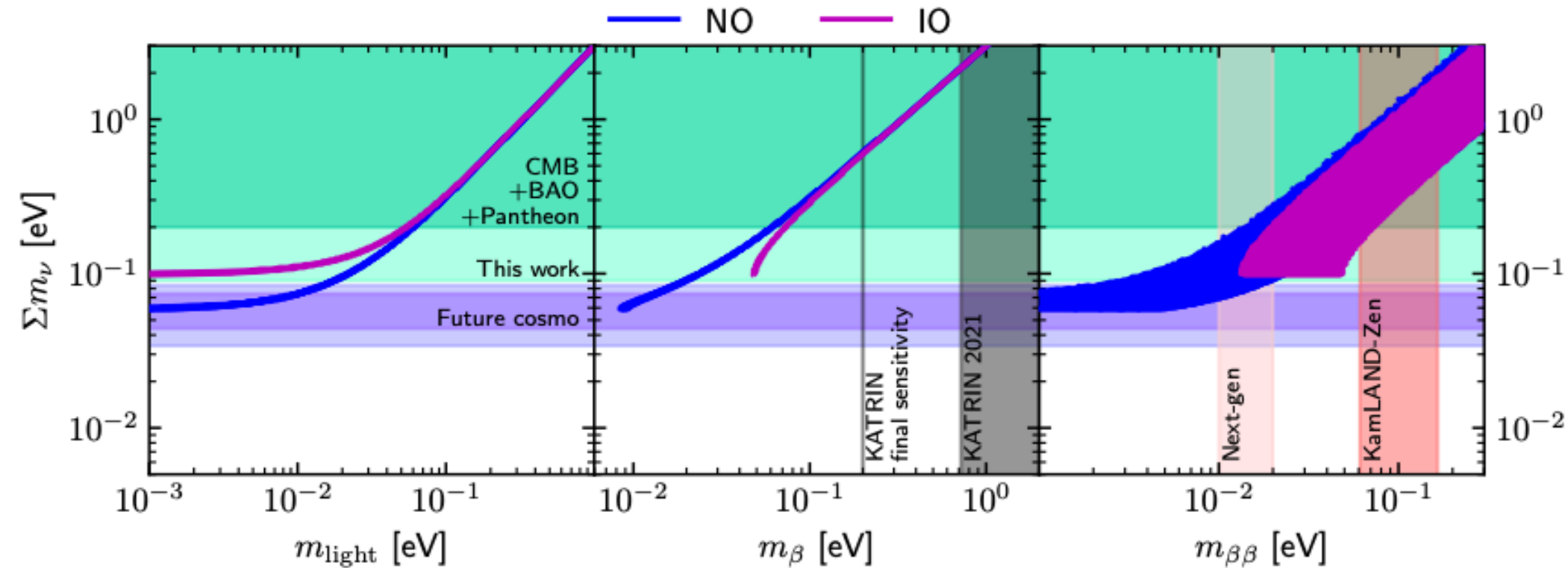


eBOSS collaboration, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

Actually the **total neutrino** mass preferred by the cosmological data is **null or negative!!**

Although this is still not statistically significant, it shows a first hint of a **tension between cosmology and neutrino oscillation experiments.**

Constraints on the total neutrino mass

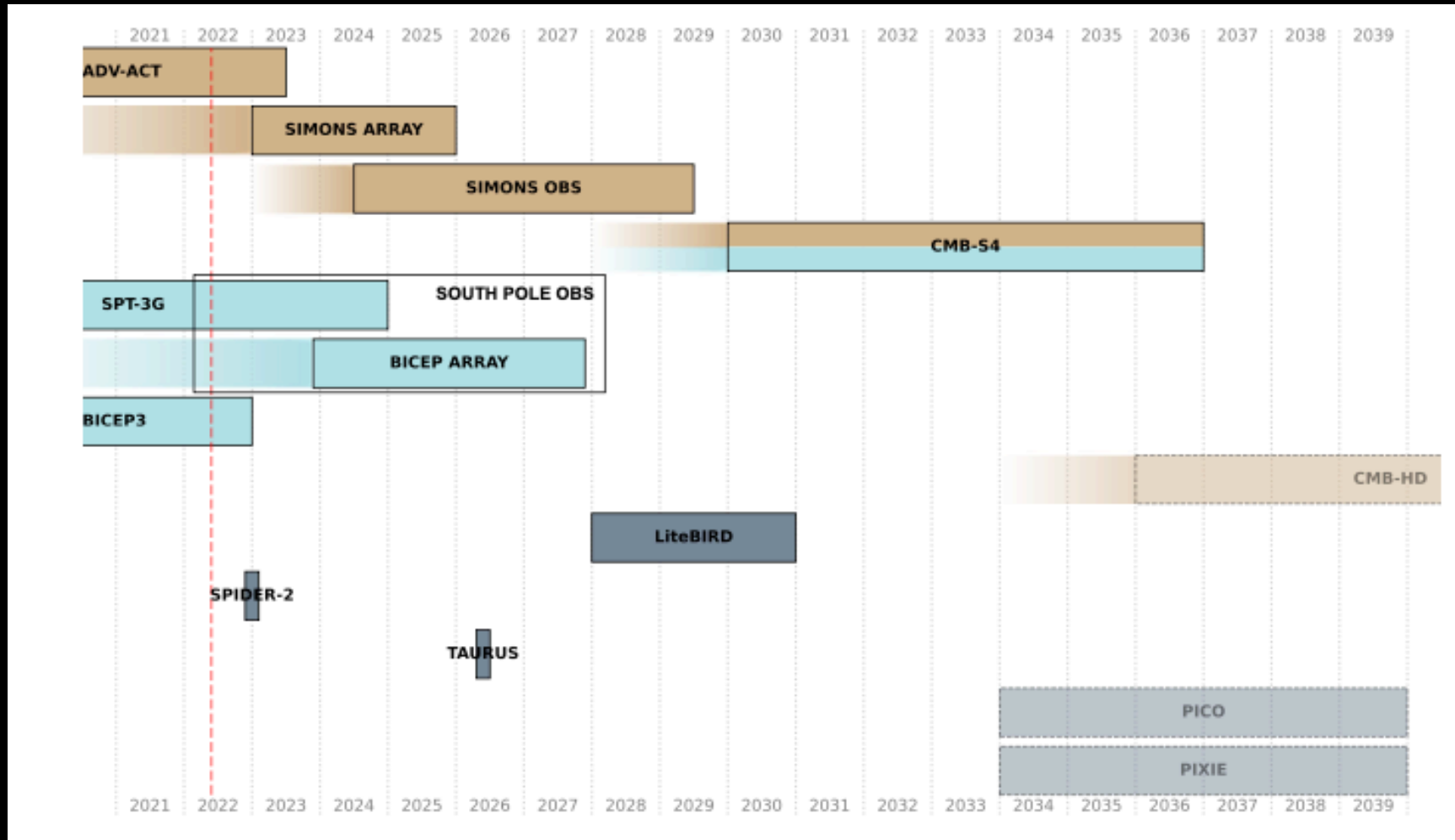


As in the previous cases, here too we illustrate, the theoretical expectations within each mass ordering, the three observables for neutrino masses: beta-decay (m_β), neutrinoless double beta decay $m_{\beta\beta}$ and the cosmological measured quantity Σm_ν .

The light green horizontal band depicts our most constraining bound, i.e. $\Sigma m_\nu < 0.087$ eV at 95% CL: this very tight limit has crucial implications for direct neutrino mass laboratory searches, that are not expected to find any signal.

How much neutrinos
constraints could be
improved in the future
with cosmology?

Timeline of current and future ground-based CMB experiments

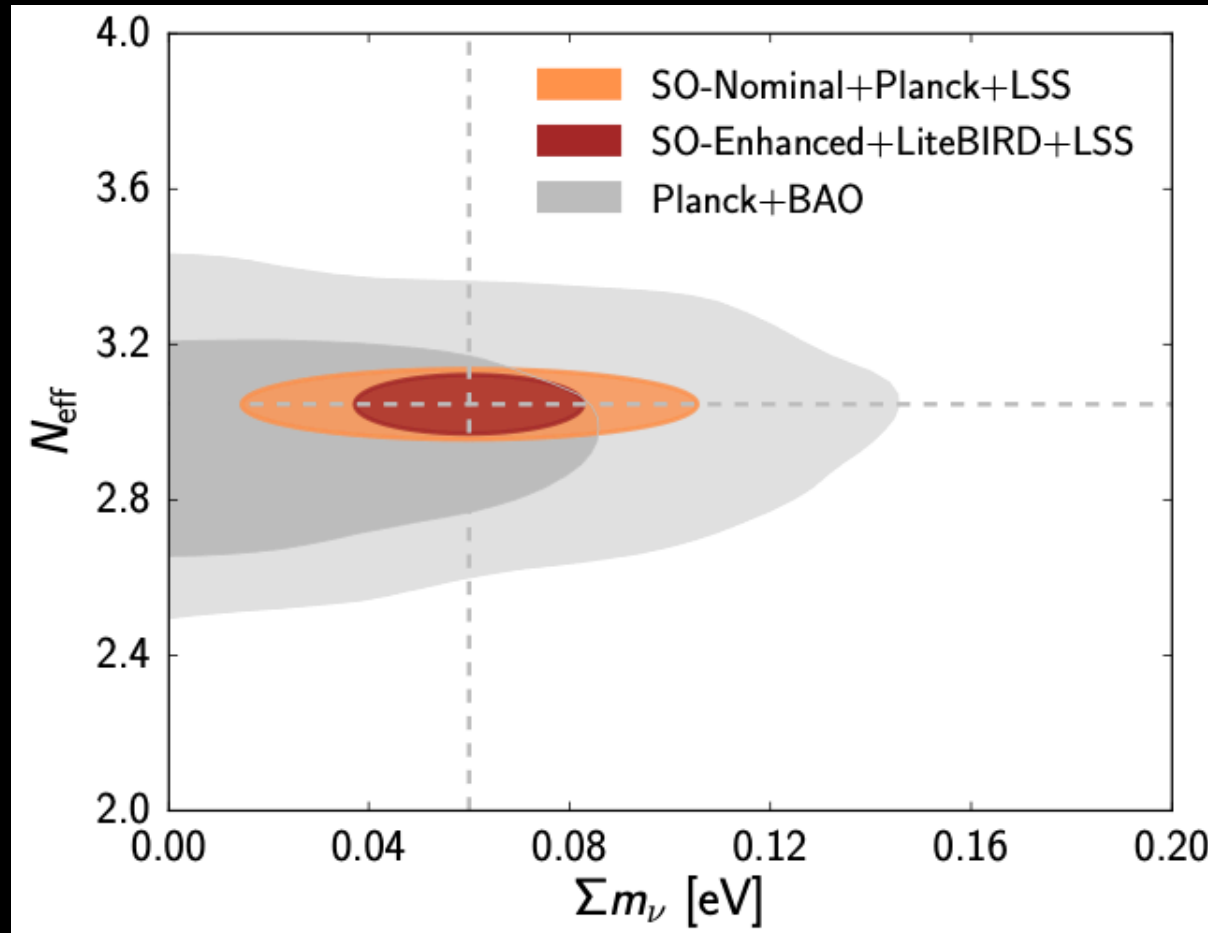


Chang et al. 2022, SNOWMASS, arXiv:2203.07638

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Ground-based CMB telescopes are at the moment the proposals with the highest probability of being realised. However, they need large angular scale measurements (as Planck or future experiments) and a perfect a priori knowledge of the foregrounds.

Simons Observatory

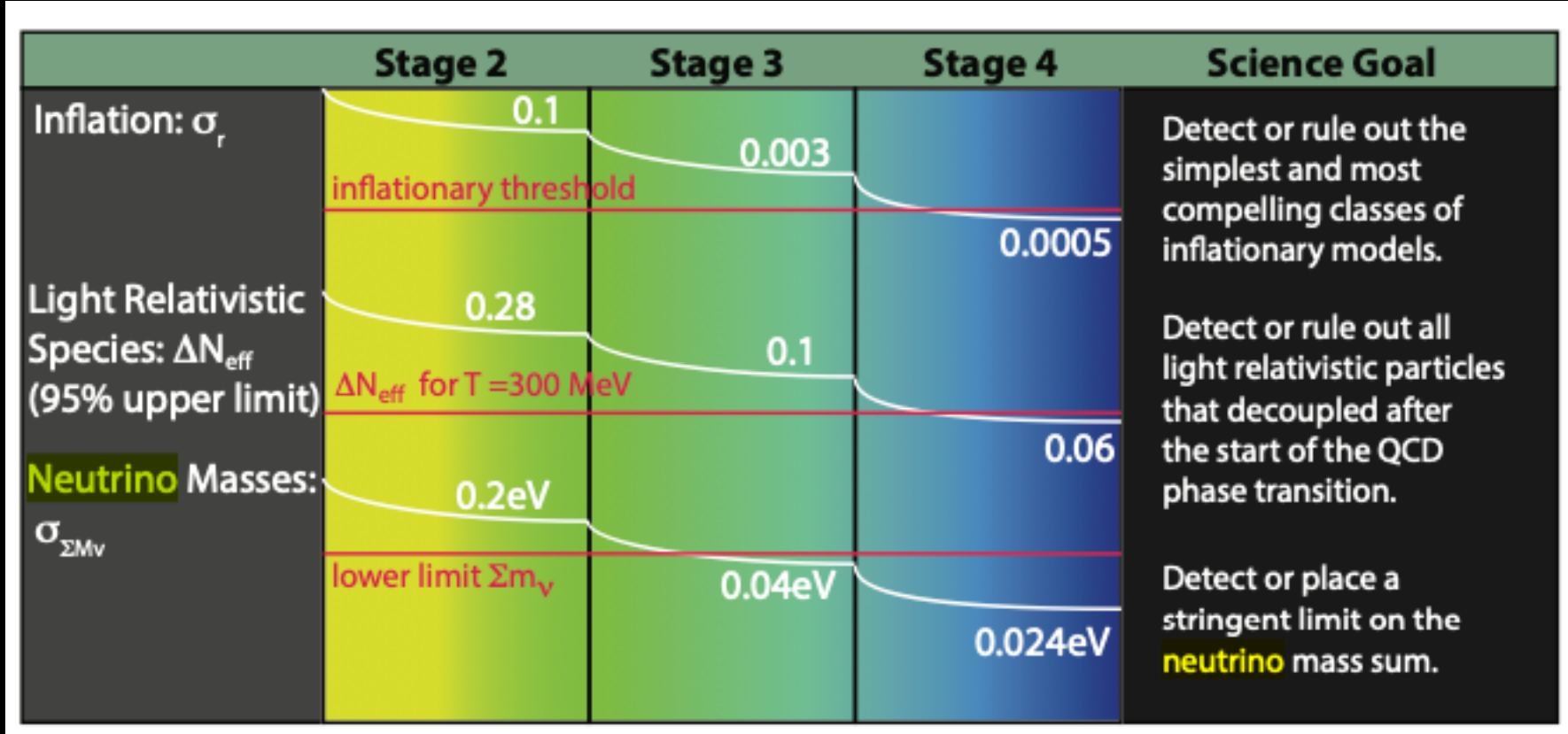


Abitbol et al. 2022, Astro2020, arXiv:1907.08284

The Simons Observatory aims to measure the total neutrino mass $\sigma(\Sigma m_\nu) = 0.04$ eV when combined with DESI BAO and LSST weak lensing data.

When combined with LiteBIRD's future cosmic variance-limited measurements of the optical depth to reionisation SO can instead reach $\sigma(\Sigma m_\nu) = 0.02$ eV.

CMB-S4

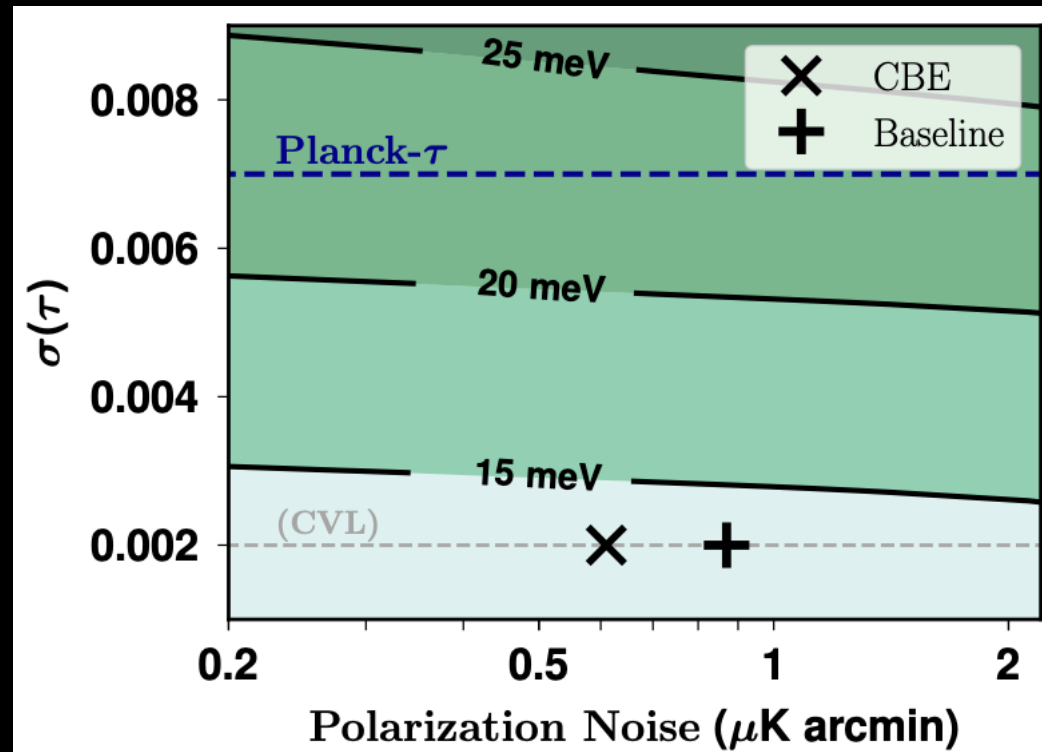


Chang et al. 2022, SNOWMASS, arXiv:2203.07638

When combined with BAO from DESI,
and the current measurement of the optical depth from Planck,
CMB-S4 measurements of the lensing power spectrum (or cluster abundances) will
provide a constraint on the sum of neutrino masses of $\sigma(\Sigma m_\nu) = 0.024 \text{ eV}$, and this
would improve to $\sigma(\Sigma m_\nu) = 0.014 \text{ eV}$ with better measurements of the optical depth.

PICO

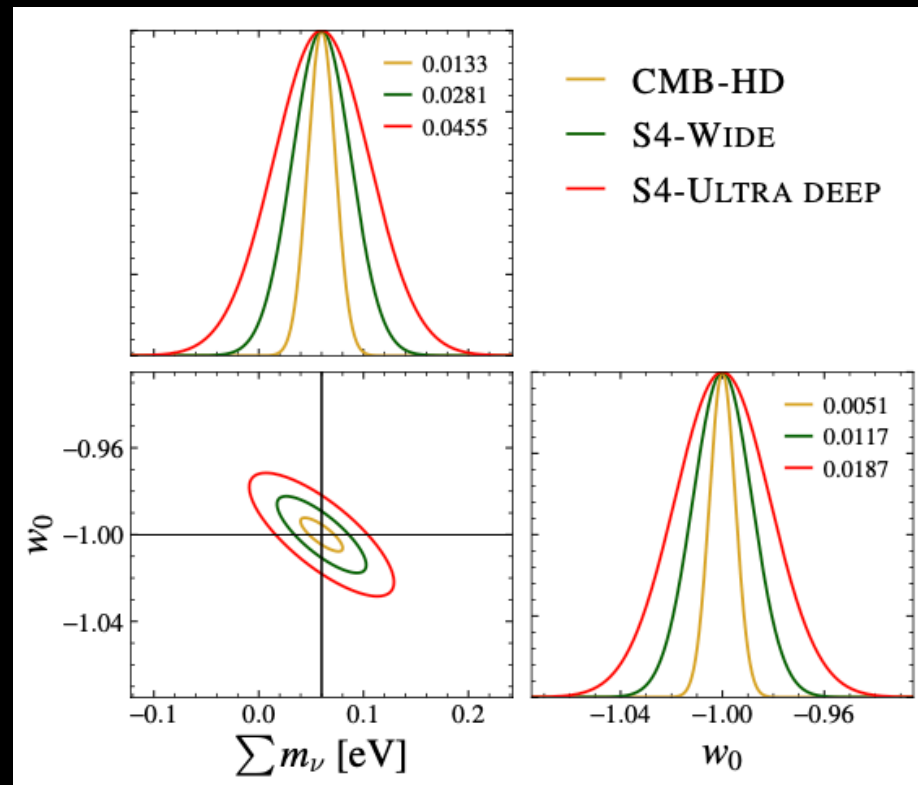
Hanany et al., NASA PICO collaboration, arXiv:1902.10541.



PICO + future BAO (DESI or Euclid) should reach $\sigma(\sum m_\nu) = 0.014$ eV, i.e. a 4σ detection of the minimum sum for the NO.

This is the only instrument that can measure very precisely all these neutrino properties (+ optical depth) with the same single dataset.

CMB-HD



Aiola et al. 2022, SNOWMASS, arXiv:2203.05728

CMB-HD, a futuristic millimetre-wave survey, could achieve an uncertainty on $\sigma(\sum m_\nu) = 0.013$ eV (at least 5σ detection for the sum of the neutrino masses), by measuring the gravitational lensing of the CMB and the thermal and kinetic SZ effect on small scales.

The Λ CDM model

The Λ CDM model

Among a number of possibilities introduced in the literature, the **Lambda Cold Dark Matter (Λ CDM) cosmological model** has been selected as the “**standard**” cosmological scenario, mainly because it is the mathematically simplest model, and provides a remarkable description of a wide range of astrophysical and cosmological probes.

However, **it still cannot explain its three key pillars:**
Dark Energy, Dark Matter and Inflation.

In addition, in the Λ CDM paradigm these are based on our simplest guesses:

- DE assumes its simplest form, that is the **cosmological constant**,
- the DM, for the structure formation in the late Universe, must be **pressureless, cold**, and stable on cosmological time scales.
- the theory of inflation is given by a **single, minimally coupled, slow-rolling scalar field**.

The Λ CDM model

Therefore, the 6 parameter Λ CDM model lacks the deep underpinnings a model requires to approach fundamental physics laws.

It can be rightly considered, at best, as an approximation of an underlying physical theory, yet to be discovered.

With the improvement of the number and the accuracy of the observations, deviations from Λ CDM may be expected.

And, actually, discrepancies among key cosmological parameters of the models have emerged with different statistical significance.

While some proportion of these discrepancies may have a systematic origin, their persistence across probes should require multiple and unrelated errors, strongly hinting at cracks in the standard cosmological scenario and the necessity of new physics.

These tensions can indicate a failure of the canonical Λ CDM model.

The H_0 tension exceeds 5σ !!

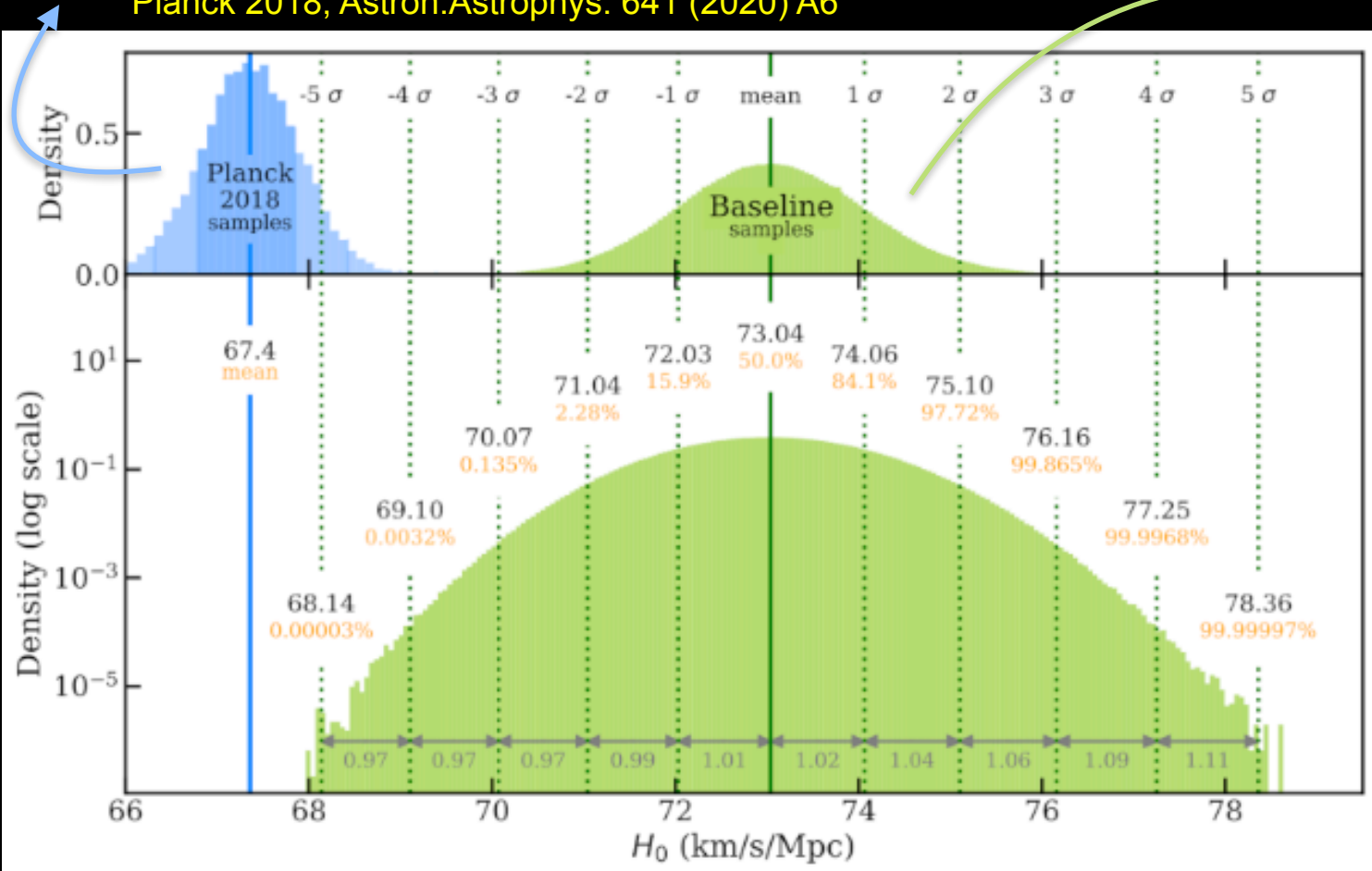
The H_0 tension is the most statistically significant, long-lasting and widely persisting disagreement we have currently in cosmology.

The Planck estimate assuming a “vanilla”

Λ CDM cosmological model:

$$H_0 = 67.27 \pm 0.60 \text{ km/s/Mpc}$$

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



The latest local measurements obtained by the SH0ES collaboration

$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$

Riess et al. *arXiv:2112.04510*

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

The H0 tension exceeds 5σ!!

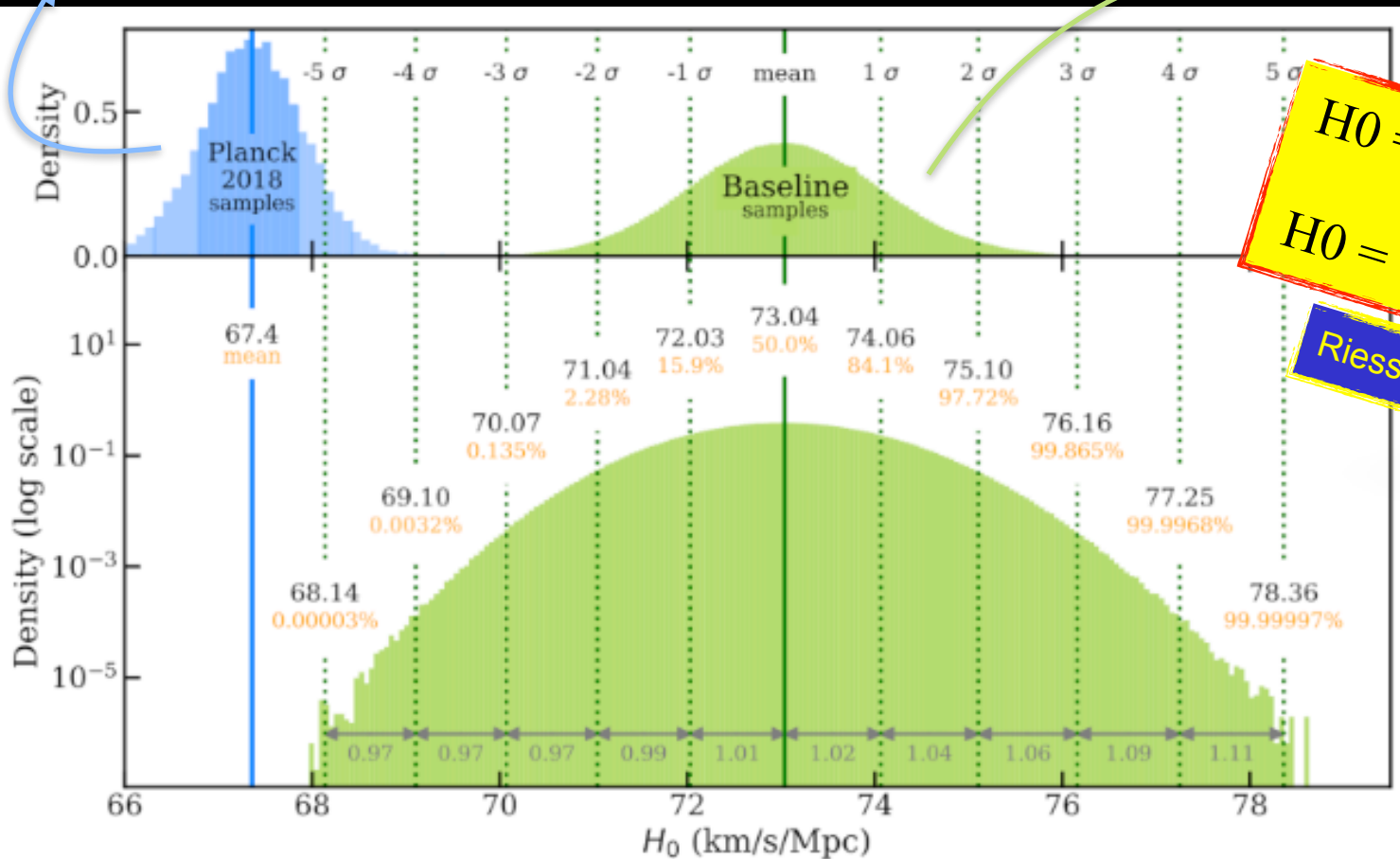
The H0 tension at 5.3σ

The Planck estimate assuming a “vanilla”

Λ CDM cosmological model:

$H_0 = 67.27 \pm 0.60$ km/s/Mpc

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



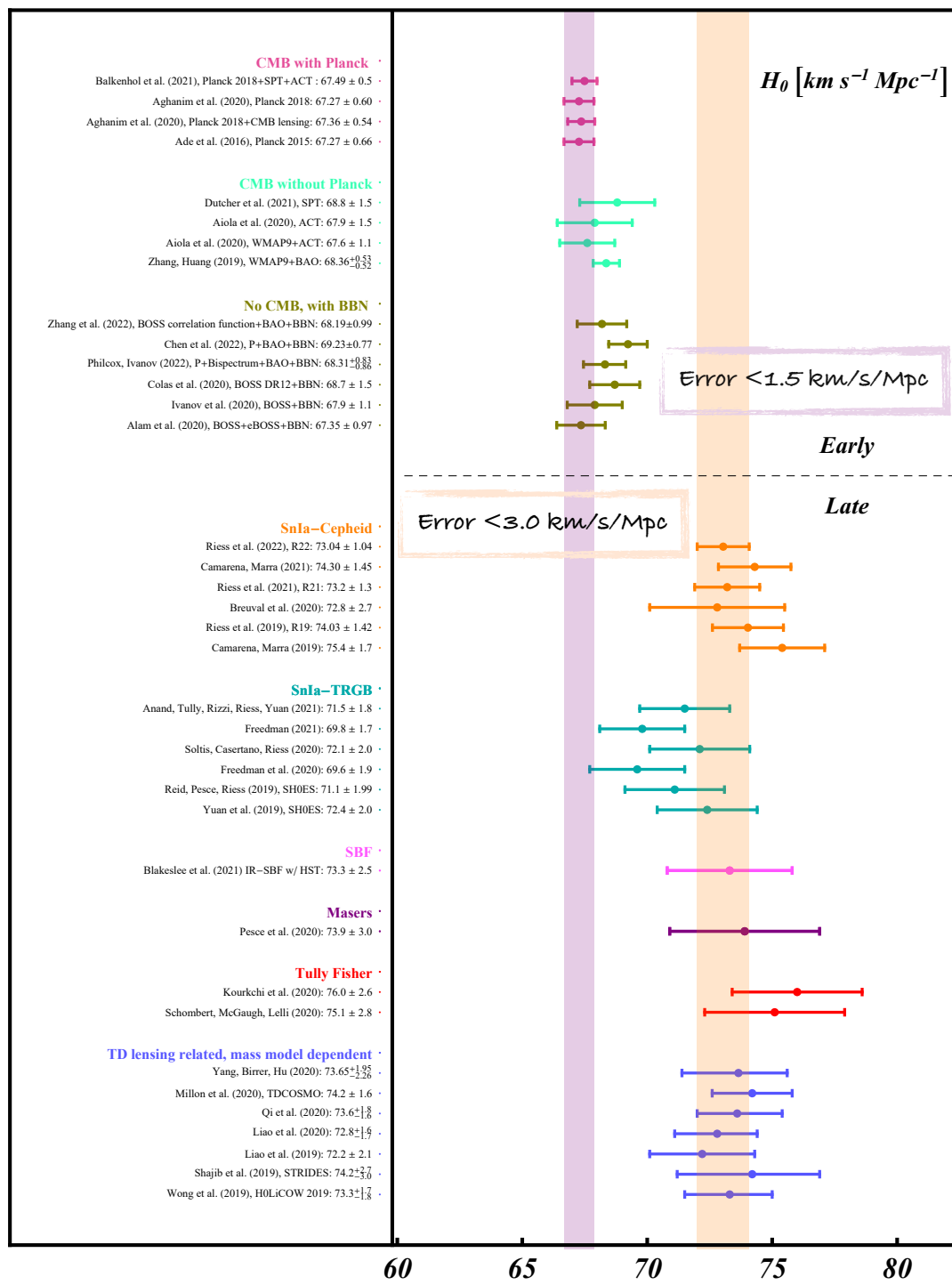
The latest local measurements are consistent with the Planck estimate

$H_0 = 73.01 \pm 0.99$ km/s/Mpc

$H_0 = 73.15 \pm 0.97$ km/s/Mpc

Riess et al. *arXiv:2208.01045* 2.04510

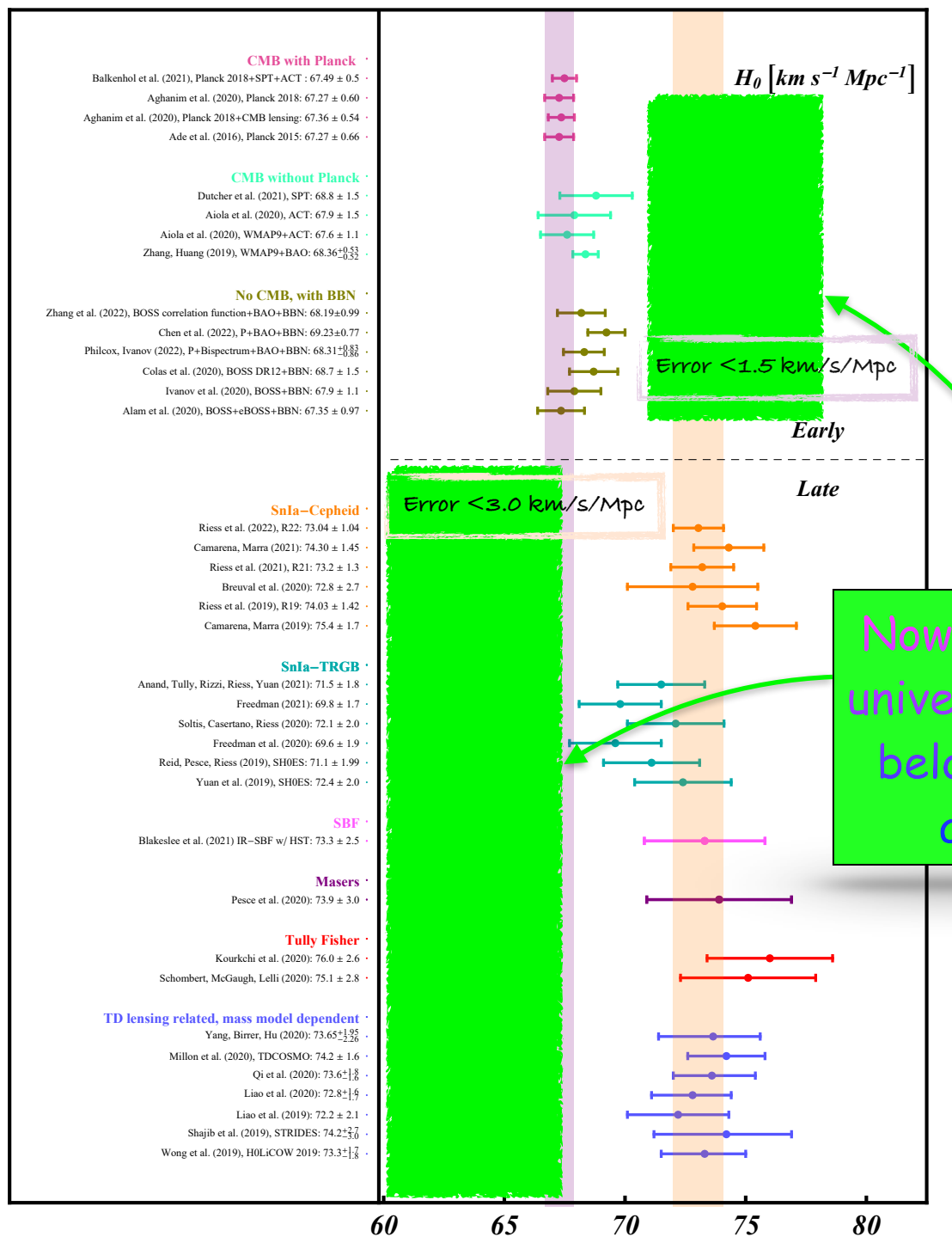
Riess et al.



High precision measurements of H_0

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

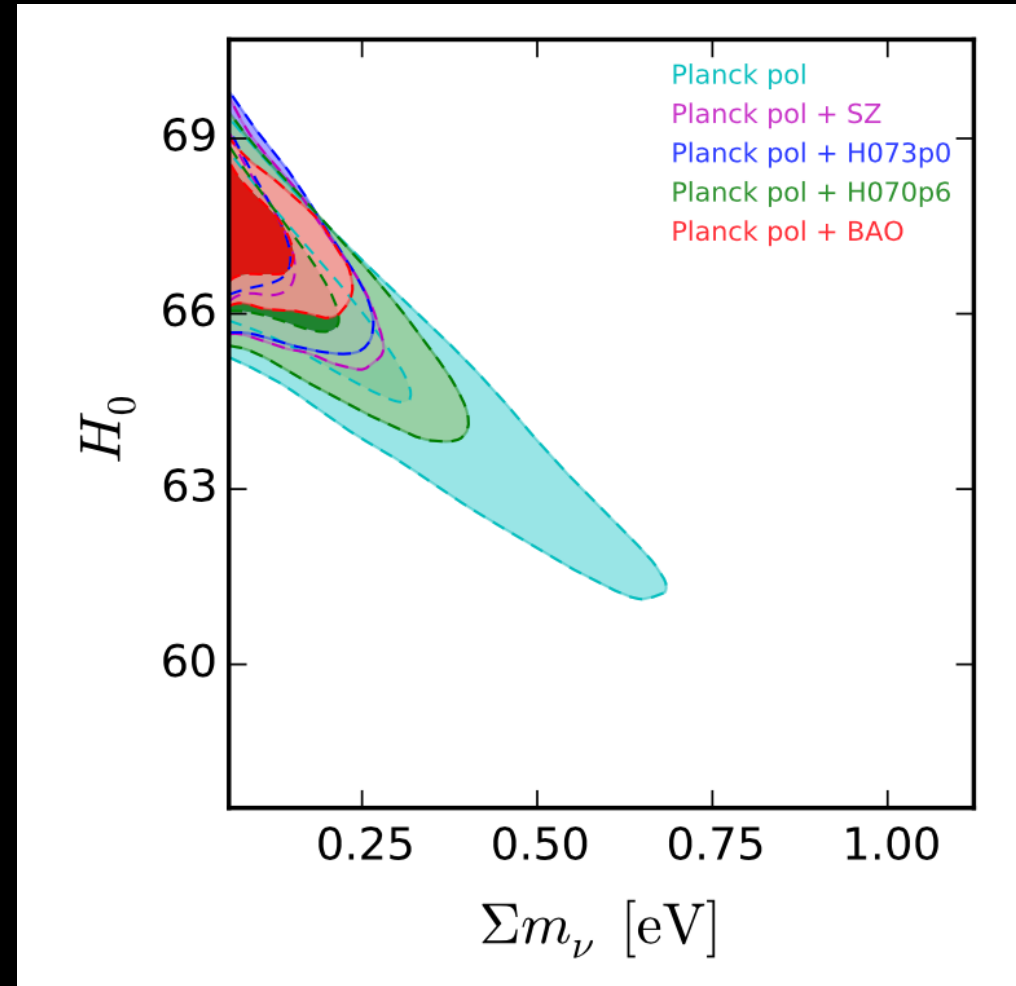
The orange vertical band corresponds to the H_0 value from SH0ES Team and the light pink vertical band corresponds to the H_0 value as reported by Planck 2018 team within a Λ CDM scenario.



H0 affects total neutrino mass

The H_0 value is very important for the determination of the **total neutrino mass**.

In fact, there exist a very important negative correlation between the Hubble constant and the sum of the neutrino masses.



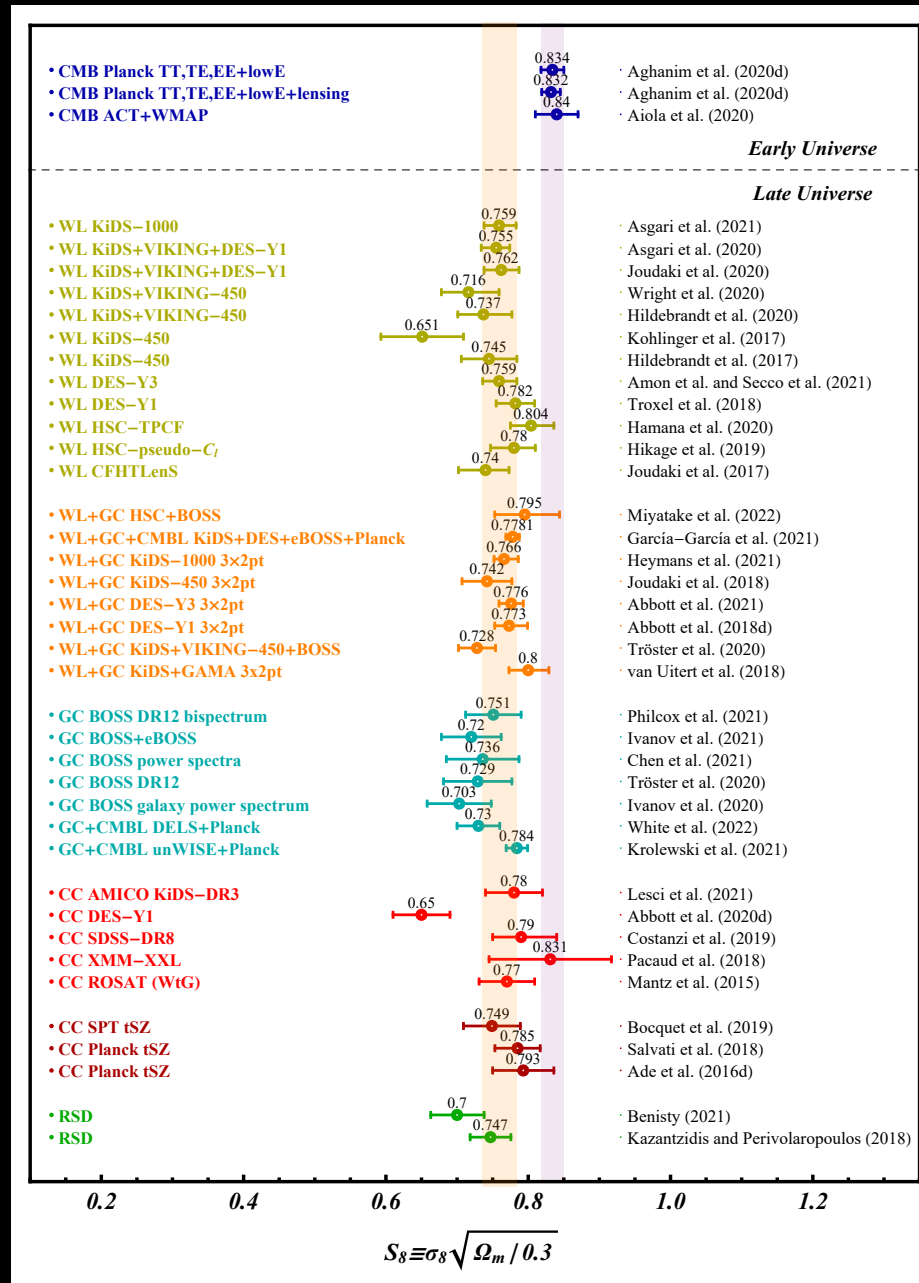
Di Valentino et al. Phys.Rev. D93 (2016) no.8, 083527

H0 affects Mass Ordering

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + $m_\beta + m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing + $H_0(\text{R19})$	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + $H_0(\text{R19})$	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing + $H_0(\text{R19})$	< 0.12 eV	3.7	< 0.12 eV	3.8

When adding a prior on H_0 as preferred by SH0ES the preference for the NO is stronger.

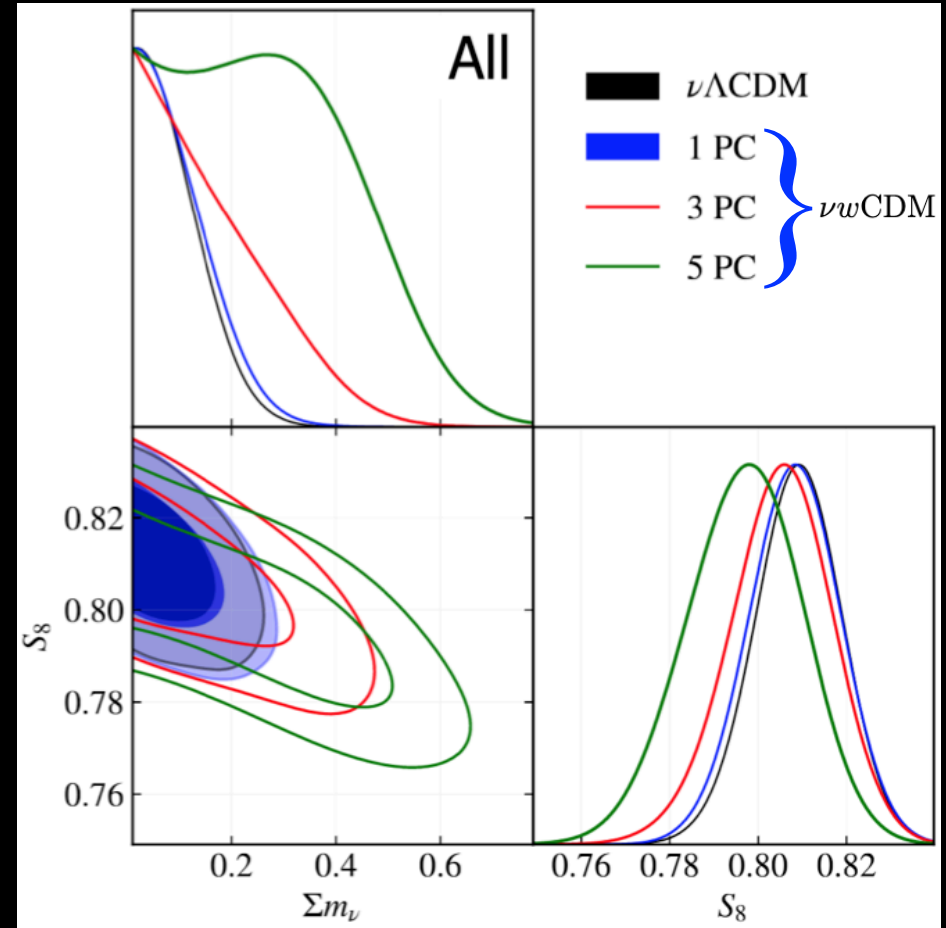
The S8 tension



S8 affects total neutrino mass

The S8 value can depend on the **total neutrino mass**.

In fact, massive neutrinos lower the clustering amplitude preferring a smaller value for S8.



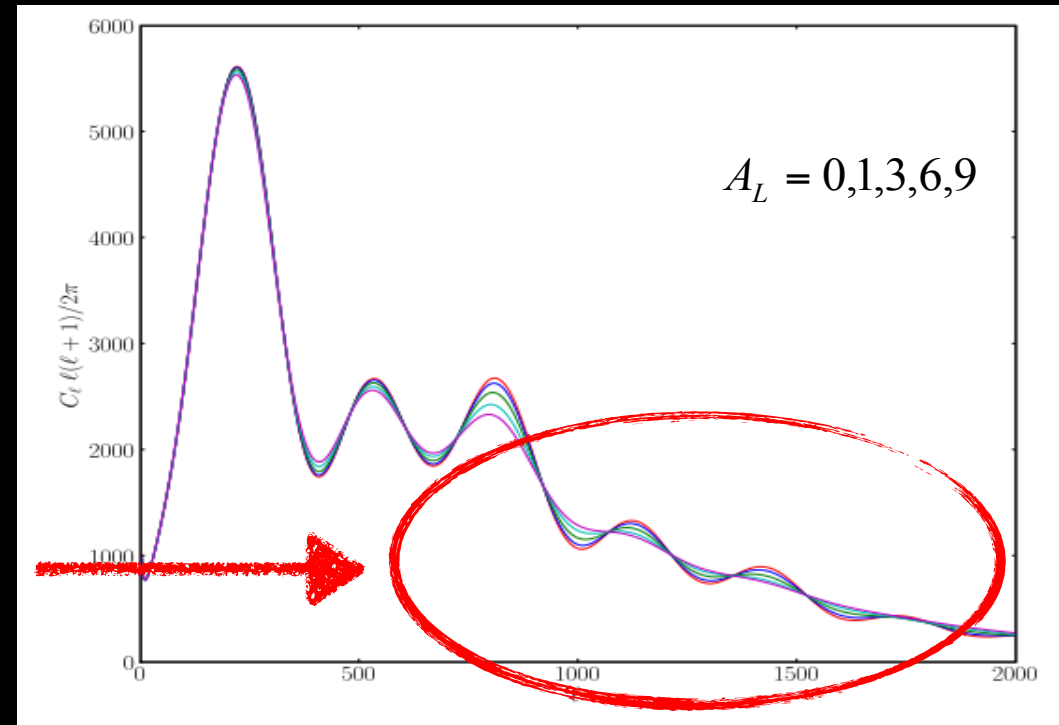
Diaz Rivero et al., [arXiv:1903.03125](#)

A_L internal anomaly

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

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

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



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

A_L : a failed consistency check

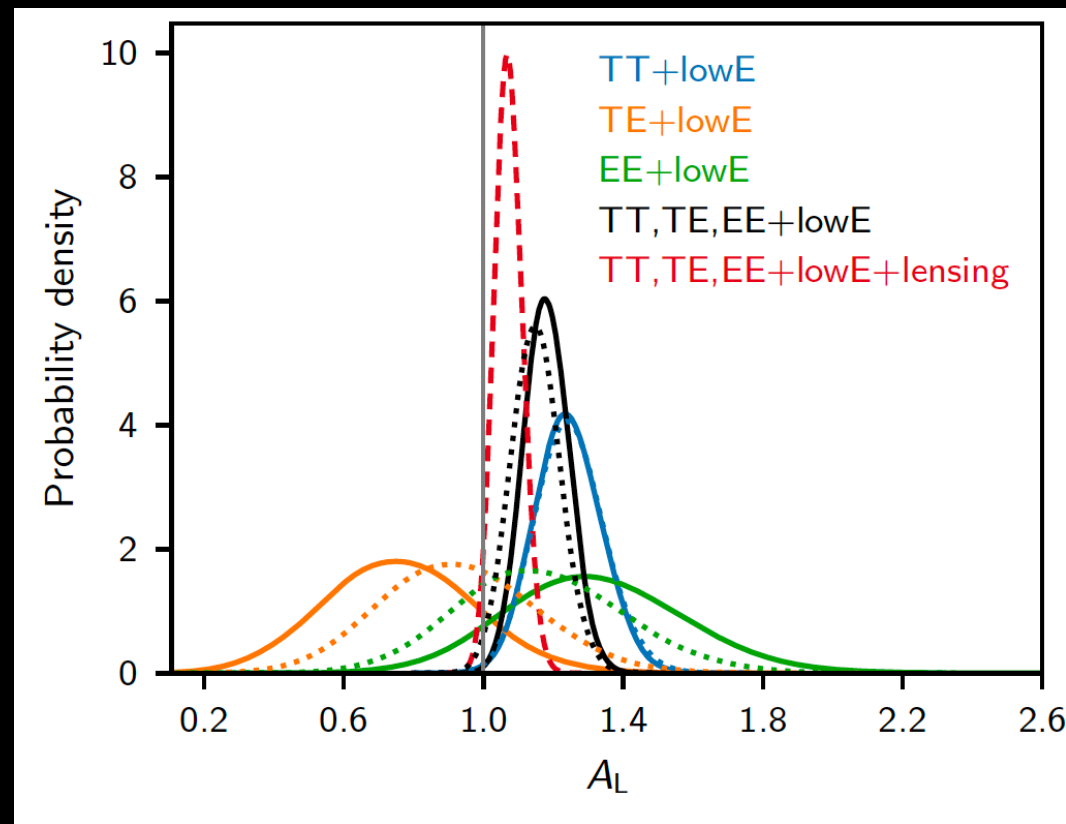
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for Λ CDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with $A_L = 1$.

However, the distributions of A_L inferred from the CMB power spectra alone indicate a preference for $A_L > 1$.

The joint combined likelihood shifts the value preferred by the TT data downwards towards $A_L = 1$, but the error also shrinks, increasing the significance of $A_L > 1$ to 2.8σ .

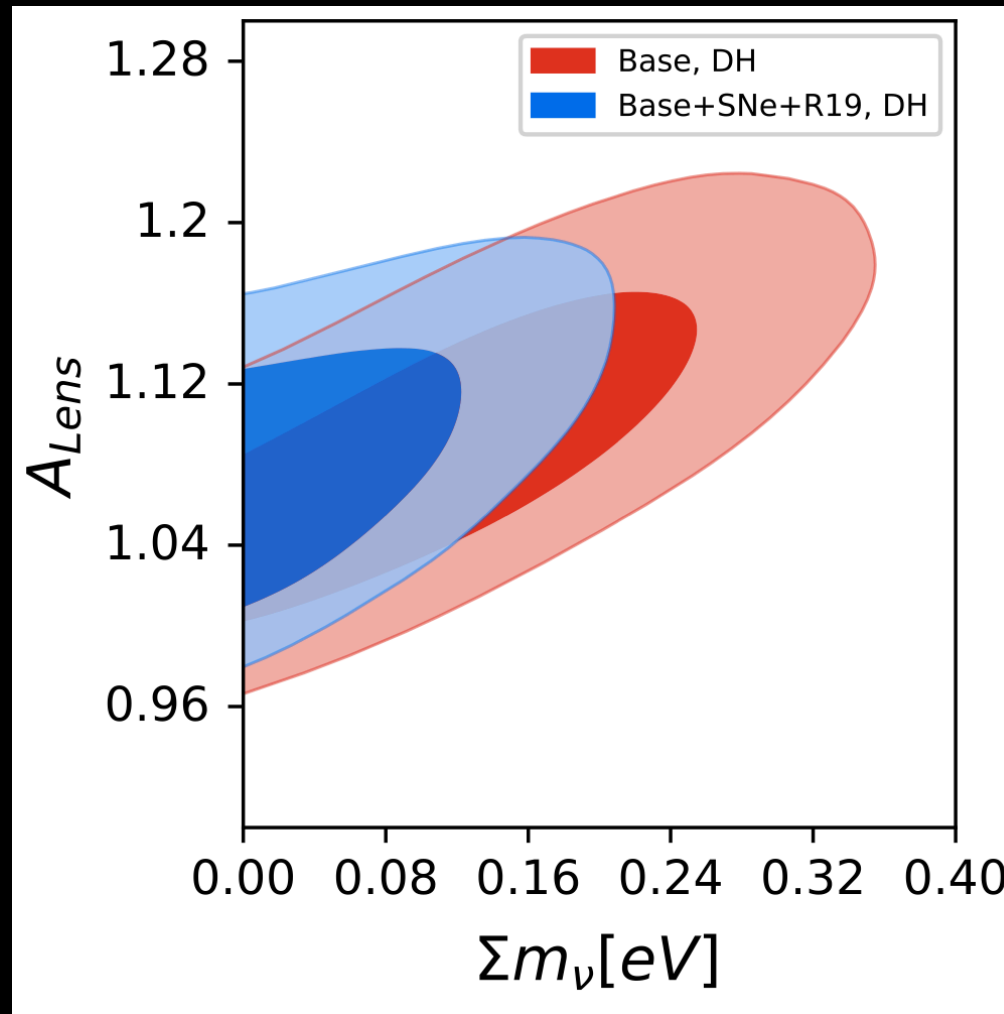
The preference for high A_L is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2 \sim 9$ when adding A_L for TT+lowE and 10 for TTTEEE+lowE.

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



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

A_L affects the total neutrino mass constraints



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

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

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

A_L affects mass ordering

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + $m_\beta + m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing + $H_0(\text{R19})$	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + $H_0(\text{R19})$	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing + $H_0(\text{R19})$	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2

For example, when A_L is free to vary, because of their correlation, the bounds on the total neutrino mass are strongly weakened, up to a factor of ~ 2 .

As a consequence, in these cases there is no more the preference for the normal ordering we have in the ΛCDM scenario.

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim⁵⁴, Y. Akrami^{15,57,59}, M. Ashdown^{65,5}, J. Aumont⁹⁵, C. Baccigalupi⁷⁸, M. Ballardini^{12,41}, A. J. Banday^{95,8}, R. B. Barreiro⁶¹, N. Bartolo^{29,62}, S. Basak⁸⁵, R. Battye⁶⁴, K. Benabed^{55,90}, J.-P. Bernard^{95,8}, M. Bersanelli^{72,45}, P. Bielewicz^{75,78}, J. J. Bock^{63,10}, J. R. Bond⁷, J. Borrill^{12,93}, F. R. Bouchet^{55,90}, F. Bou
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S. D. M. W

(Affiliation)

We present cosmological parameter results from the final isotropies, combining information from the temperature and improved measurements of large-scale polarization allow the cant gains in the precision of other correlated parameters. In many parameters, with residual modelling uncertainties estimated spatially-flat 6-parameter Λ CDM cosmology having a power from polarization, temperature, and lensing, separately and in baryon density $\Omega_b h^2 = 0.0224 \pm 0.0001$, scalar spectral index 68% confidence regions on measured parameters and 95% $100\theta_s = 1.0411 \pm 0.0003$. These results are only weakly dependent in many commonly considered extensions. Assuming the best-fit Hubble constant $H_0 = (67.4 \pm 0.5) \text{ km s}^{-1} \text{ Mpc}^{-1}$; matter density. We find no compelling evidence for extensions to the base- Λ CDM considering single-parameter extensions) we constrain the effective number of relativistic degrees of freedom $N_{\text{eff}} = 3.046$, and find that the tensor-to-scalar ratio r to prefer higher lensing amplitudes than predicted in base Λ CDM from the Λ CDM model; however, this is not supported by the BAO data. The joint constraint with BAO measurements on the dark-energy equation of state w_0 with Type Ia supernovae (SNe), the dark-energy equation of state w_0 constant. We find no evidence for deviations from a purely de Sitter universe. Using the Keck Array data, we place a limit on the tensor-to-scalar ratio r from deuterium abundances for the base- Λ CDM cosmology are in agreement with BAO, SNe, and some galaxy lensing observations including galaxy clustering (which prefers lower fluctuation amplitude). Measurements of the Hubble constant (which prefer a higher value) are favoured by the *Planck* data.

Key words: Cosmology; observations; Cosmology; theory; Cosmic background radiation; cosmological parameters

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$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\%, \textit{Planck} \text{ TT,TE,EE+lowE}), \quad (46b)$$

a detection of curvature at about 3.4σ

an apparent detection of curvature at well over 2σ . The 99% probability region for the TT,TE,EE+lowE result is $-0.095 < \Omega_K < -0.007$, with only about 1/10000 samples at $\Omega_K \geq 0$. This is not entirely a volume effect, since the best-fit χ^2 changes by $\Delta\chi^2_{\text{eff}} = -11$ compared to base Λ CDM when adding the one additional curvature parameter. The reasons for the pull towards

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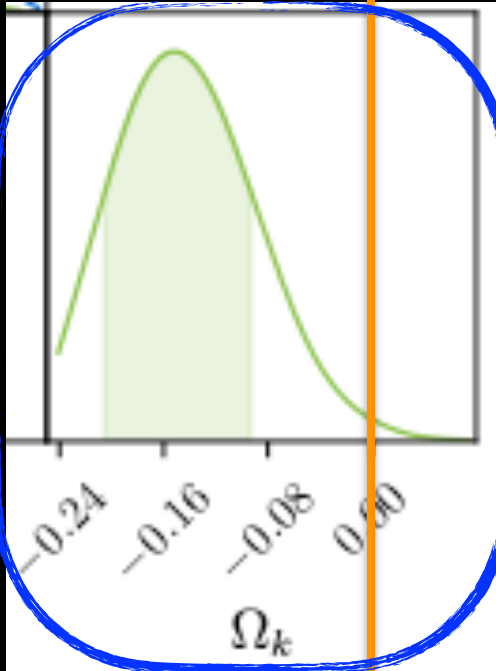
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Curvature of the universe

EFTofLSS to investigate FS data

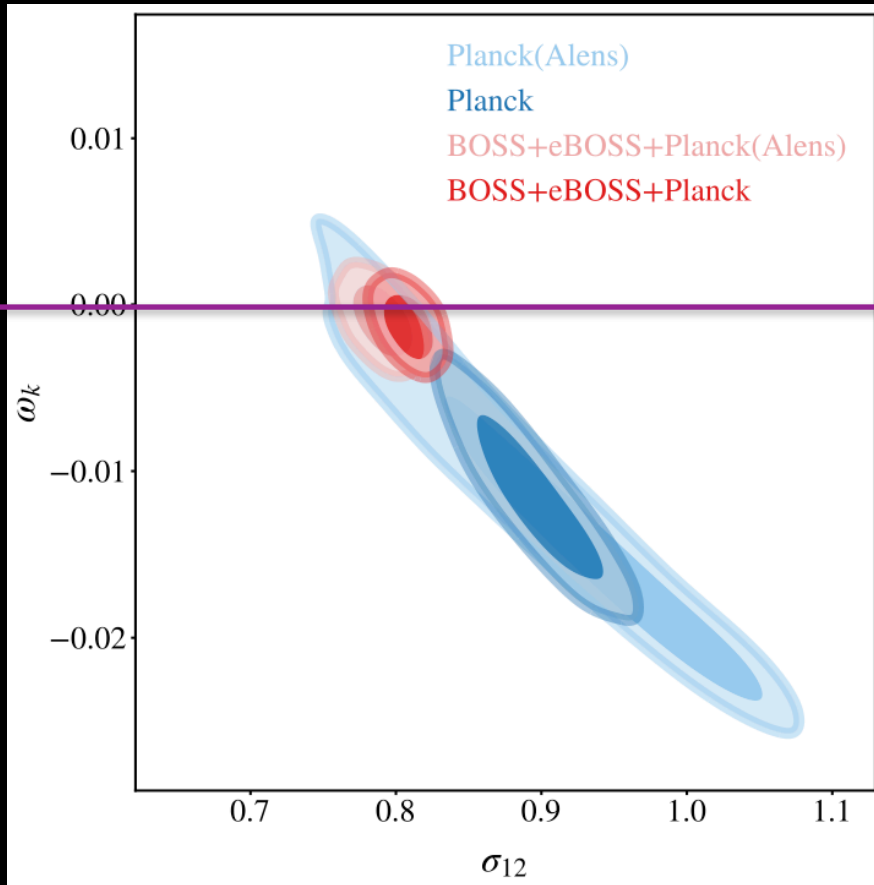
	$\ln(10^{10} A_s)$	h	$\Omega_{cdm} h^2$	Ω_m	Ω_k	n_s	$2 * \log(\mathcal{L})$
Flat, fixed n_s	$2.85^{+0.11}_{-0.12}$ (3.03)	$0.667^{+0.011}_{-0.011}$ (0.672)	$0.114^{+0.005}_{-0.004}$ (0.115)	$0.307^{+0.010}_{-0.011}$ (0.304)	-	-	367.2
Curved, fixed n_s	$2.55^{+0.21}_{-0.22}$ (2.77)	$0.686^{+0.015}_{-0.016}$ (0.665)	$0.115^{+0.004}_{-0.005}$ (0.111)	$0.291^{+0.014}_{-0.013}$ (0.302)	$-0.089^{+0.049}_{-0.046}$ (-0.042)	-	366.3
Flat, varying n_s	$2.80^{+0.14}_{-0.13}$ (2.97)	$0.669^{+0.012}_{-0.011}$ (0.668)	$0.117^{+0.009}_{-0.008}$ (0.114)	$0.312^{+0.017}_{-0.014}$ (0.304)	-	$0.950^{+0.04}_{-0.051}$ (0.972)	367.1
Curved, varying n_s	$2.19^{+0.29}_{-0.28}$ (2.62)	$0.707^{+0.021}_{-0.021}$ (0.686)	$0.127^{+0.011}_{-0.009}$ (0.116)	$0.300^{+0.016}_{-0.014}$ (0.295)	$-0.152^{+0.059}_{-0.053}$ (-0.089)	$0.878^{+0.053}_{-0.055}$ (0.932)	364.8



Glanville et al., *MNRAS* 517 (2022) 2, 3087-3100

In this paper they use EFTofLSS to simultaneously constrain measurements from the 6dFGS, BOSS, and eBOSS catalogues, in order to remove some of the assumptions of flatness that enter into other large-scale structure analyses. Fitting the FS data with a BBN prior they measure a **>2 σ preference for a closed universe.**

Beyond six parameters: extending Λ CDM+ Ω_k



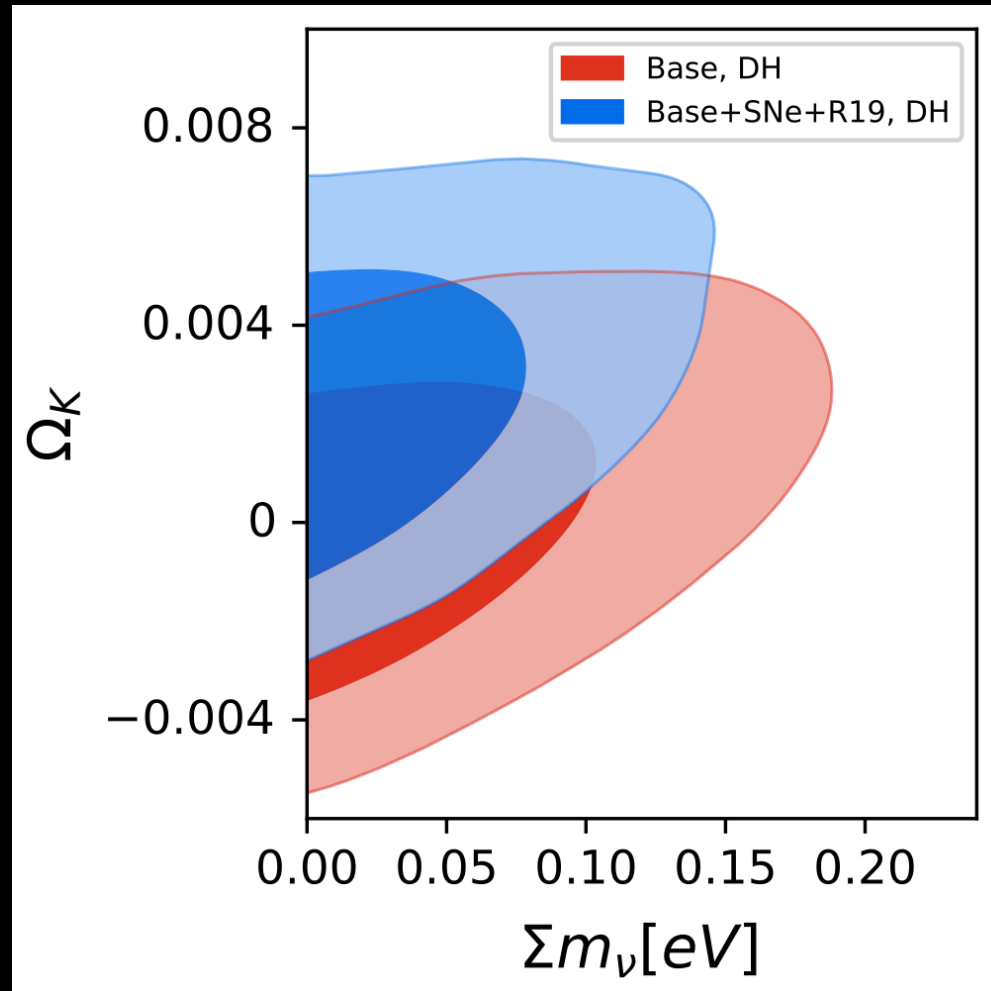
Semenaite et al., arXiv:2210.07304

A similar result has been obtained by analysing a wKCDM model, and the parameter $\omega_K = \Omega_k h^2$ that gives

$$\omega_K = -0.0116^{+0.0029}_{-0.0036}$$

i.e. a 4σ preference for a closed universe.

A curvature affects the total neutrino mass



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

There is a positive correlation between the curvature and
the total neutrino mass.

Model-marginalized total neutrino mass

Cosmological model	lnBF	$\sum m_\nu$ [eV]	N_{eff}	Ω_k	α_s	r	w_0	w_a	A_{lens}
+ $\sum m_\nu$	DH	0.0	< 0.0866	—	—	—	—	—	—
	NH	1.90	< 0.129	—	—	—	—	—	—
	IH	3.37	< 0.155	—	—	—	—	—	—
+ $\sum m_\nu + N_{\text{eff}}$	DH	3.54	< 0.0968	0.06 ± 0.17	—	—	—	—	—
	NH	5.33	< 0.131	0.11 ± 0.17	—	—	—	—	—
	IH	6.85	< 0.163	0.15 ± 0.17	—	—	—	—	—
+ $\sum m_\nu + \Omega_k$	DH	5.05	< 0.111	0.0009 ± 0.0019	—	—	—	—	—
	NH	6.48	< 0.143	0.0018 ± 0.0019	—	—	—	—	—
	IH	7.72	< 0.180	0.0023 ± 0.0019	—	—	—	—	—
+ $\sum m_\nu + \alpha_s$	DH	5.14	< 0.0908	—	-0.0044 ± 0.0066	—	—	—	—
	NH	6.81	< 0.128	—	-0.0043 ± 0.0067	—	—	—	—
	IH	8.33	< 0.157	—	-0.0046 ± 0.0067	—	—	—	—
+ $\sum m_\nu + r$	DH	4.15	< 0.0898	—	—	< 0.127	—	—	—
	NH	5.96	< 0.130	—	—	< 0.122	—	—	—
	IH	7.58	< 0.156	—	—	< 0.124	—	—	—
+ $\sum m_\nu + w_0$	DH	3.51	< 0.139	—	—	—	-1.046 ± 0.033	—	—
	NH	4.58	< 0.165	—	—	—	$-1.058^{+0.033}_{-0.030}$	—	—
	IH	6.68	< 0.204	—	—	—	$-1.070^{+0.038}_{-0.030}$	—	—
+ $\sum m_\nu + (w_0 > -1)$	DH	5.09	< 0.0848	—	—	—	< -0.962	—	—
	NH	7.16	< 0.125	—	—	—	< -0.967	—	—
	IH	8.85	< 0.157	—	—	—	< -0.968	—	—
+ $\sum m_\nu + w_0 + w_a$	DH	4.70	< 0.224	—	—	—	$-0.933^{+0.077}_{-0.089}$	$-0.52^{+0.43}_{-0.29}$	—
	NH	5.11	< 0.248	—	—	—	$-0.917^{+0.081}_{-0.090}$	$-0.65^{+0.42}_{-0.30}$	—
	IH	6.58	< 0.265	—	—	—	$-0.921^{+0.078}_{-0.095}$	$-0.68^{+0.45}_{-0.31}$	—
+ $\sum m_\nu + A_{\text{lens}}$	DH	3.52	< 0.166	—	—	—	—	—	$1.071^{+0.037}_{-0.043}$
	NH	4.12	< 0.189	—	—	—	—	—	$1.086^{+0.037}_{-0.043}$
	IH	4.91	< 0.216	—	—	—	—	—	$1.101^{+0.035}_{-0.041}$
model marginalized	DH	—	< 0.0866	—	—	—	—	—	—

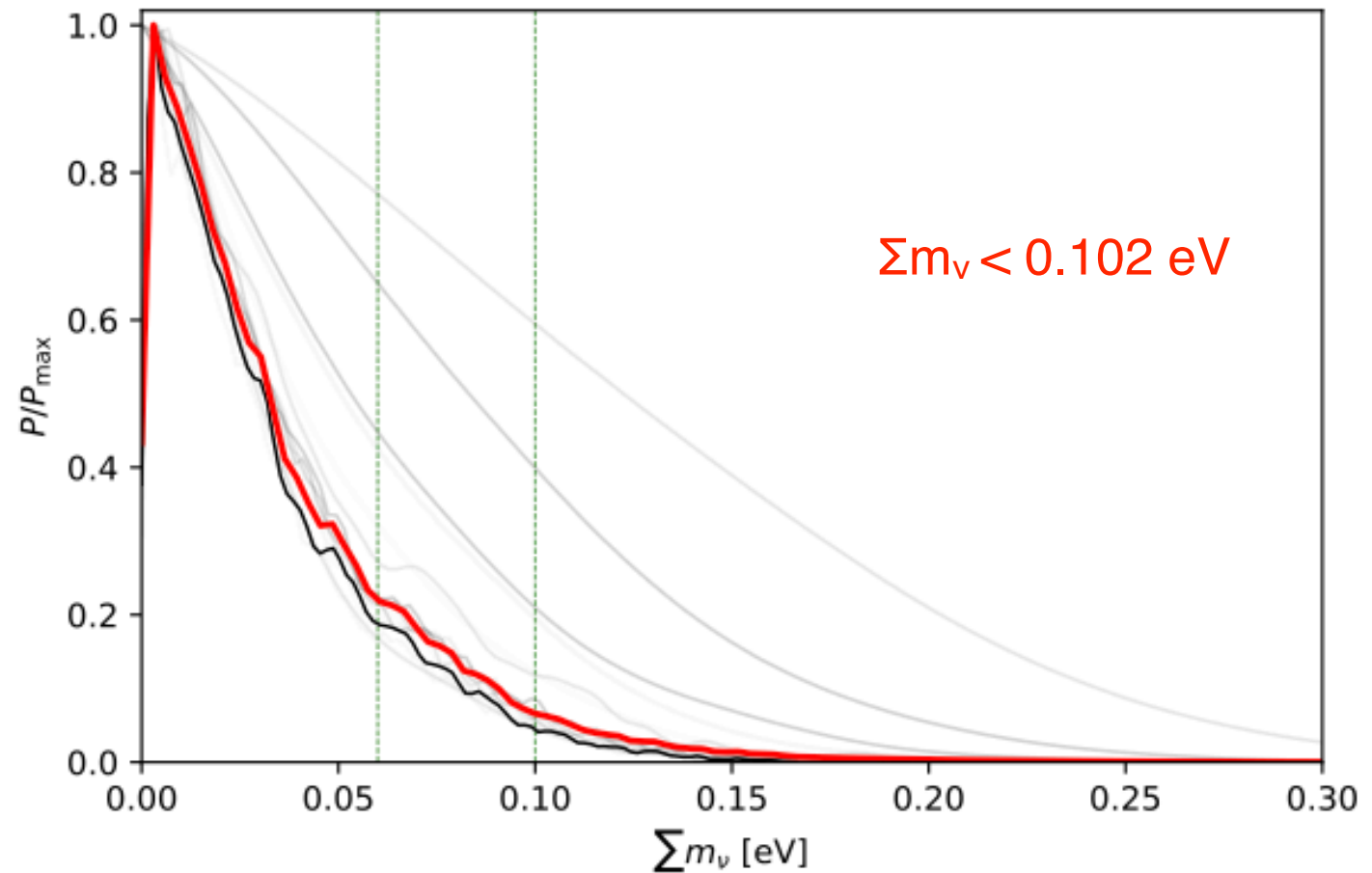
Di Valentino et al., *Phys.Rev.D* 106 (2022) 4, 043540

Here you can see how the upper limit at 95% CL on the total neutrino mass is affected by the cosmological scenario adopted for the **most powerful combination** Planck+lensing+Pantheon+BAO DR12+ BAO and RSD DR16.

Model-marginalized total neutrino mass

Cosmological model		lnBF	Σm_ν [eV]	N_{eff}	Ω_k	α_s	r	w_0	w_a	A_{lens}
+ Σm_ν	DH	0.0	< 0.0866	–	–	–	–	–	–	–
	NH	1.90	< 0.129	–	–	–	–	–	–	–
	IH	3.37	< 0.155	–	–	–	–	–	–	–
+ $\Sigma m_\nu + N_{\text{eff}}$	DH	3.54	< 0.0968	–	–	–	–	–	–	–
	NH	5.33	< 0.131	–	–	–	–	–	–	–
	IH	6.85	< 0.163	–	–	–	–	–	–	–
+ $\Sigma m_\nu + \Omega_k$	DH	5.05	< 0.111	–	–	–	–	–	–	–
	NH	6.48	< 0.143	–	–	–	–	–	–	–
	IH	7.72	< 0.180	–	–	–	–	–	–	–
+ $\Sigma m_\nu + \alpha_s$	DH	5.14	< 0.0908	–	–	–	–	–	–	–
	NH	6.81	< 0.128	–	–	–	–	–	–	–
	IH	8.33	< 0.157	–	–	–	–	–	–	–
+ $\Sigma m_\nu + r$	DH	4.15	< 0.0898	–	–	–	–	–	–	–
	NH	5.96	< 0.130	–	–	–	–	–	–	–
	IH	7.58	< 0.156	–	–	–	–	–	–	–
+ $\Sigma m_\nu + w_0$	DH	3.51	< 0.139	–	–	–	–	–	–	–
	NH	4.58	< 0.165	–	–	–	–	–	–	–
	IH	6.68	< 0.204	–	–	–	–	–	–	–
+ $\Sigma m_\nu + (w_0 > -1)$	DH	5.09	< 0.0848	–	–	–	–	–	–	–
	NH	7.16	< 0.125	–	–	–	–	–	–	–
	IH	8.85	< 0.157	–	–	–	–	–	–	–
+ $\Sigma m_\nu + w_0 + w_a$	DH	4.70	< 0.224	–	–	–	–	–	–	–
	NH	5.11	< 0.248	–	–	–	–	–	–	–
	IH	6.58	< 0.265	–	–	–	–	–	–	–
+ $\Sigma m_\nu + A_{\text{lens}}$	DH	3.52	< 0.166	–	–	–	–	–	–	–
	NH	4.12	< 0.189	–	–	–	–	–	–	–
	IH	4.91	< 0.216	–	–	–	–	–	–	–
model marginalized	DH	–	< 0.102	–	–	–	–	–	–	–

Di Valentino et al., *Phys.Rev.D* 106 (2022) 4, 043540

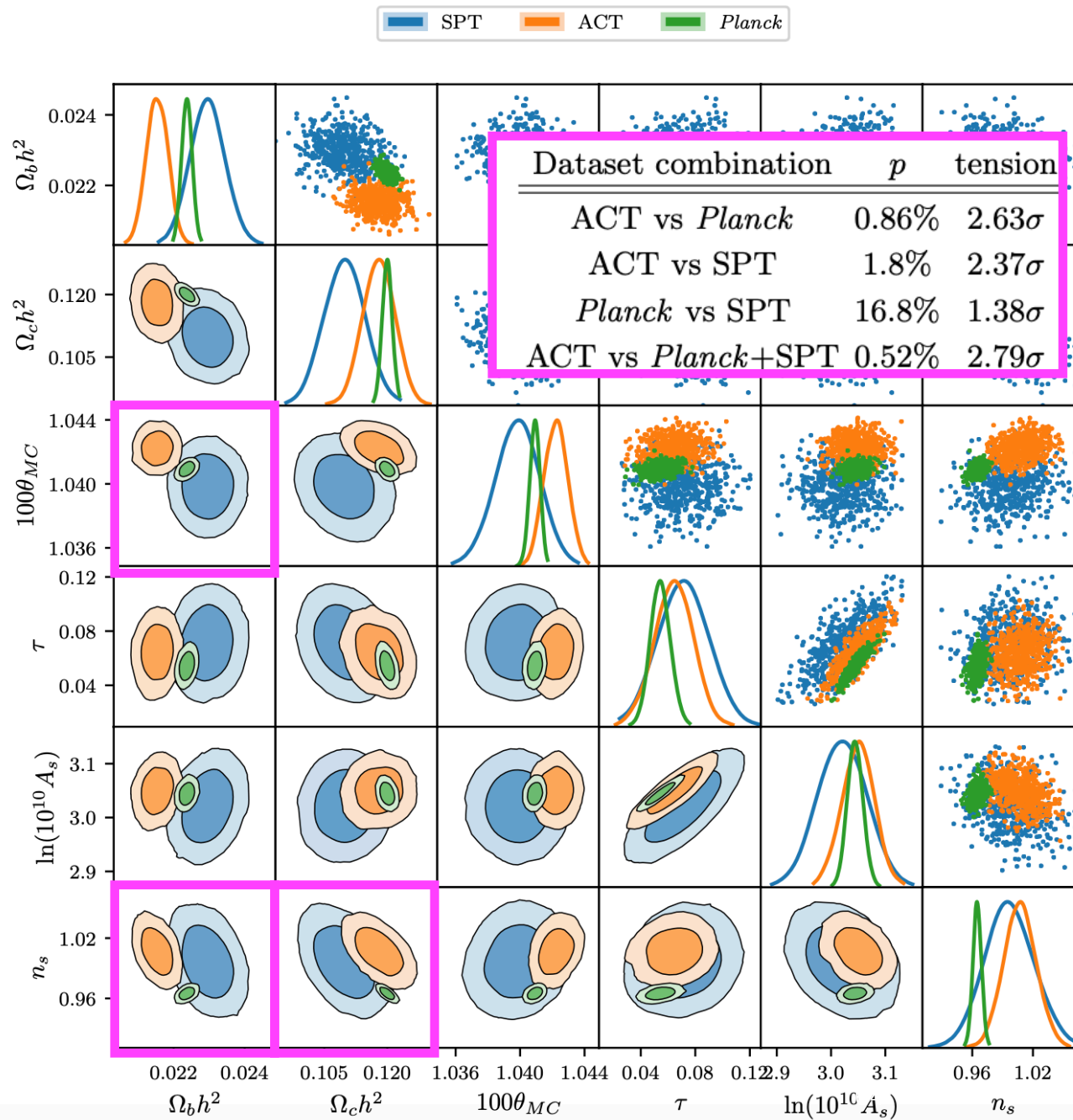


However, if we compute the model-marginalized limits on Σm_ν to minimise the role of parametrizations, priors and models, we find an extremely stable value, close to the minimal Λ CDM+ Σm_ν scenario.

Alternative CMB data

Alternative CMB vs Planck: Λ CDM

Handley and Lemos, arXiv:2007.08496 [astro-ph.CO]



Global tensions between CMB datasets.

For each pairing of datasets this is the tension probability p that such datasets would be this discordant by (Bayesian) chance, as well as a conversion into a Gaussian-equivalent tension.

Between Planck and ACT there is a 2.6σ tension.

Assuming Λ CDM

Alternative CMB vs Planck: Σm_ν

Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

Constraints at 68% CL	Σm_ν [eV]
Planck (+ A_{lens})	< 0.51
Planck+BAO (+ A_{lens})	< 0.19
Planck+Pantheon (+ A_{lens})	< 0.25
Planck+Lensing (+ A_{lens})	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	< 0.19
ACT-DR4+WMAP+Pantheon	< 0.25
ACT-DR4+WMAP+Lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+Lensing	< 0.37

Moreover, we have a mildly suggestion from both the **ACT-DR4** and **SPT-3G** data, when combined with WMAP, of a neutrino mass with $\Sigma m_\nu = 0.68 \pm 0.31$ eV and $\Sigma m_\nu = 0.46^{+0.14}_{-0.36}$ eV at 68% CL, respectively.

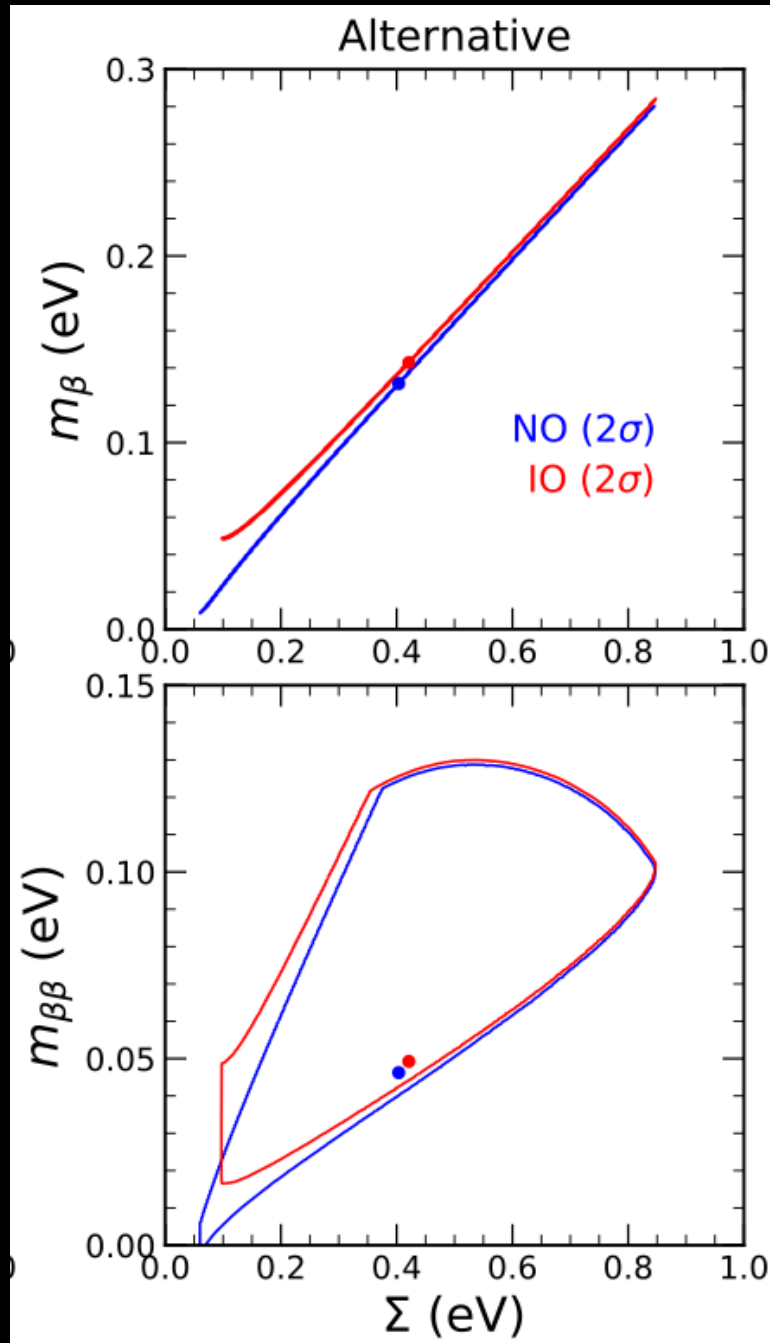
A combination of **Planck CMB+Lensing** constrain $\Sigma m_\nu = 0.41^{+0.17}_{-0.25}$ eV at 68% CL when a variation in the AL parameter is considered.

Mass ordering with alternative CMB data

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + $m_\beta + m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO-NO}}$
0	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + lensing + $H_0(\text{R19})$	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + $H_0(\text{R19})$	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + BAO + lensing + $H_0(\text{R19})$	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + τ_{prior}	< 1.21 eV	-0.1	< 1.00 eV	0.1
11	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE	< 1.12 eV	-0.1	< 0.87 eV	0.1
12	$\Lambda\text{CDM} + \Sigma$	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

In these cases, when the alternative CMB ACT-DR4 are considered,
there is no more the preference for the normal ordering
we have with the Planck data and AL fixed to one.

Alternative CMB data



Here we replaced the Planck data with the alternative combination (ACT + WMAP + lowE + lensing).

We can see an **interplay between cosmological and $0\nu\beta\beta$ data**: the first would prefer $\Sigma m_\nu \approx 0.58$ eV, implying relatively high values for the Majorana mass ($m_{\beta\beta} > 0.06$ eV); however, such values are disfavoured by $0\nu\beta\beta$ data at $> 1\sigma$.

A **best-fit** compromise is reached for intermediate values, $\Sigma m_\nu \sim 0.4$ eV and $m_{\beta\beta} \approx 0.05$ eV, surrounded by large 2σ allowed regions, **leading to a joint 2σ bound $\Sigma m_\nu < 0.85$ eV**, stronger than the bound from cosmology only. In all cases, current β -decay data play a minor role in the overall fit.

In this case, a much larger phase space is amenable to β decay and $0\nu\beta\beta$ decay searches.

Alternative CMB vs Planck: Σm_ν

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Constraints at 68% CL

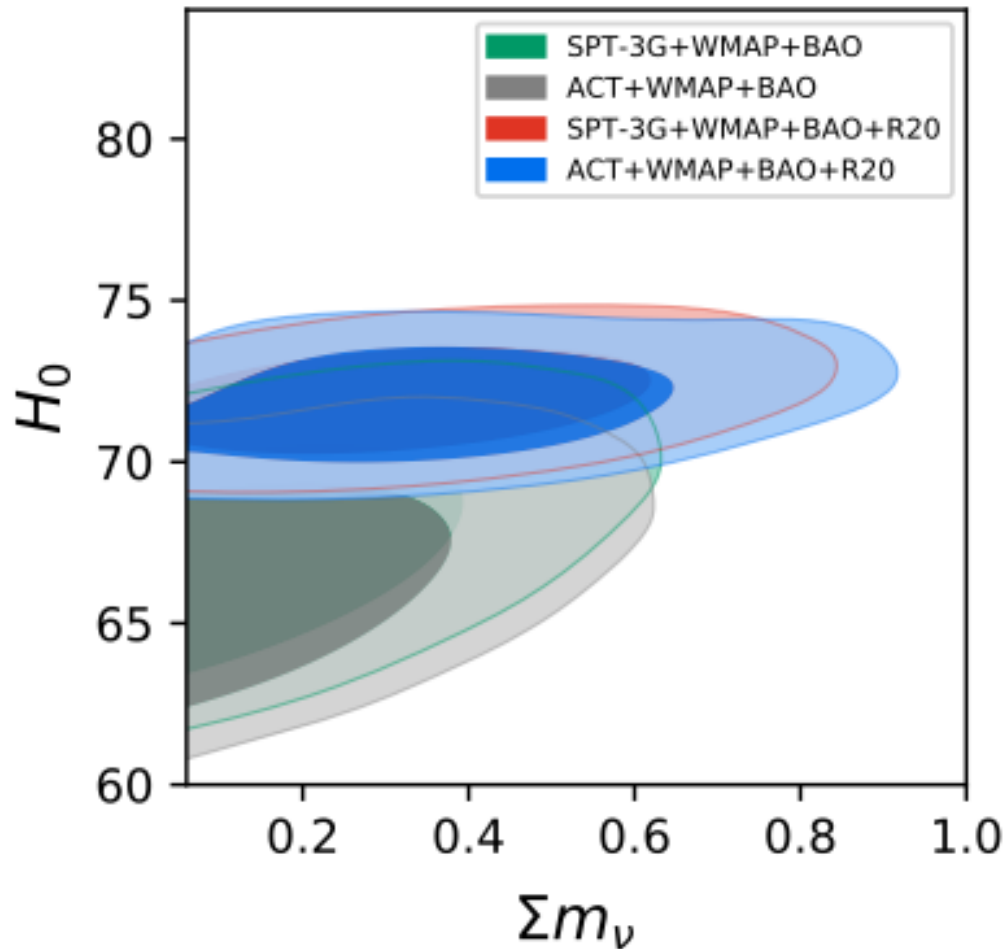
	Σm_ν [eV]
Planck (+ A_{lens})	< 0.50
Planck+BAO (+ A_{lens})	< 0.22
Planck+Pantheon (+ A_{lens})	< 0.47
Planck+Lensing (+ A_{lens})	$0.38^{+0.12}_{-0.28}$
ACT-DR4+WMAP	0.81 ± 0.28
ACT-DR4+WMAP+BAO	< 0.27
ACT-DR4+WMAP+Pantheon	0.71 ± 0.28
ACT-DR4+WMAP+Lensing	0.56 ± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	< 0.34
SPT-3G+WMAP	< 0.56
SPT-3G+WMAP+BAO	< 0.28
SPT-3G+WMAP+Pantheon	$0.46^{+0.11}_{-0.39}$
SPT-3G+WMAP+Lensing	< 0.39
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32

What about the 10 parameters extended model (+nrun+w+Neff)?

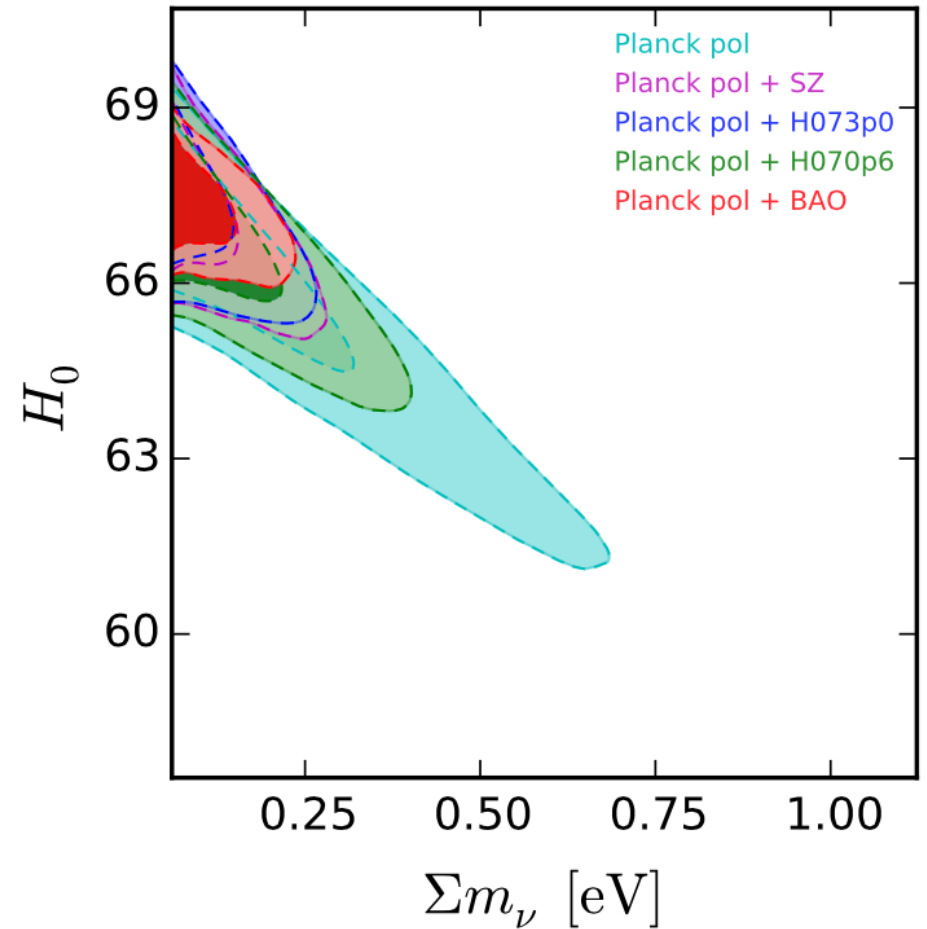
ACT-DR4 suggests a neutrino mass with $\Sigma m_\nu = 0.81 \pm 0.28$ eV and SPT-3G

$\Sigma m_\nu < 0.56$ eV at 68% CL.

10 parameters



standard Λ CDM

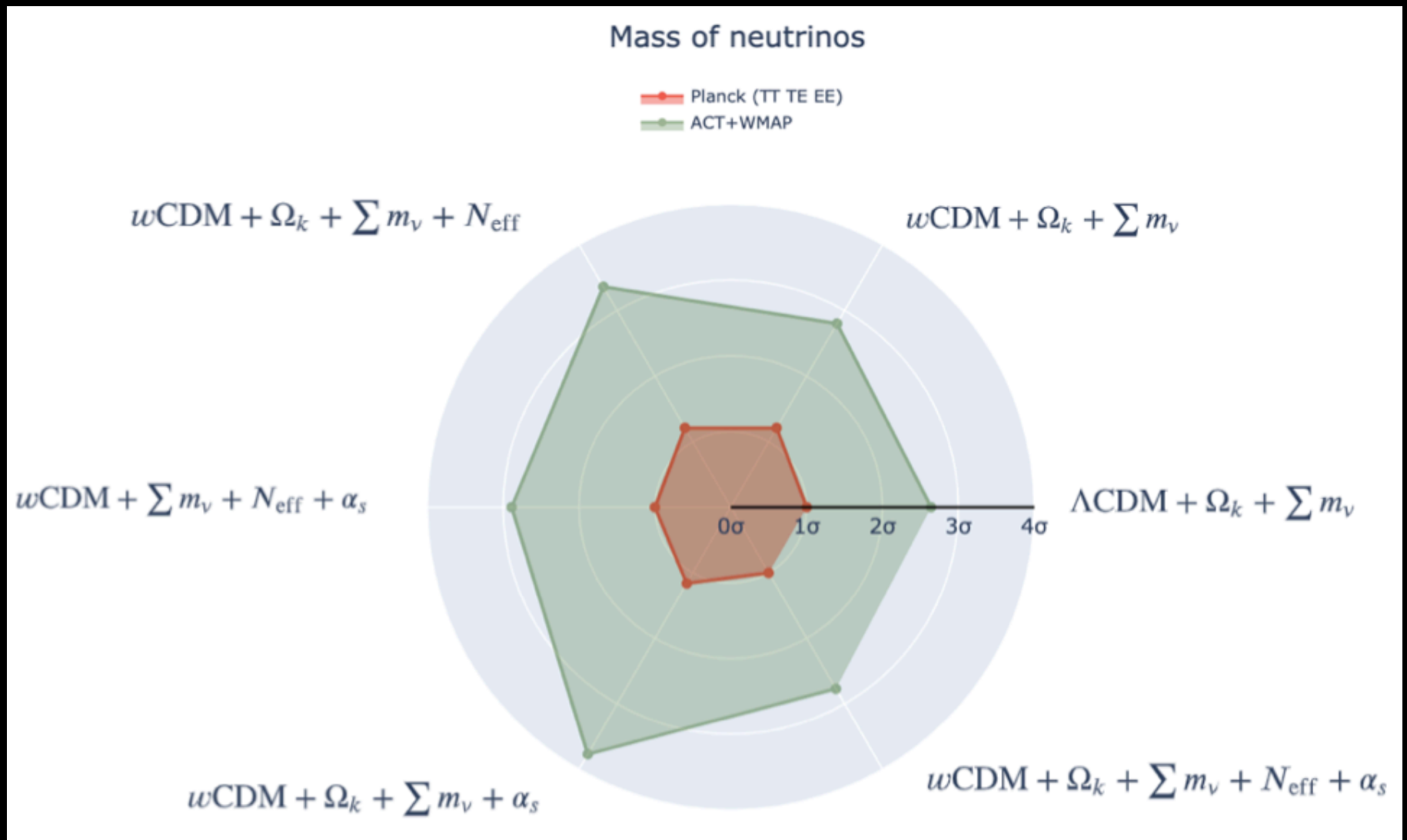


Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

Di Valentino et al. *Phys.Rev. D*93 (2016) no.8, 083527

When CMB and BAO data are considered in these extended cosmologies, they provide constraints on the Σm_ν vs H_0 plane that clearly show a correlation between these two parameters, that is exactly the opposite of what is obtained under standard Λ CDM.

ACT vs Planck: Σm_ν



Di Valentino et al., *Phys.Rev.D* 106 (2022) 10, 103506

And the indication we see in the simplest $\Lambda\text{CDM} + \Sigma m_\nu$ model is robust also in its extensions.

Conclusions:

With the cosmological data we can easily constrain the total neutrino mass.

The most stringent bound on the sum of neutrino masses is obtained for **Planck 2018+BAO+RSD** that are not in tension, giving a very robust $\Sigma m_\nu < 0.09 \text{ eV}$ at 95% CL.

NO appears to be favoured with respect to IO at $2.5\text{-}3\sigma$.

Alternatives CMB data indicate instead a preference for massive neutrinos $\Sigma m_\nu \sim 0.4 \text{ eV}$ and no indication for NO vs IO.

Warning!!

Some indication for anomalies and tensions are present in the cosmological data, and these could significantly affect the current cosmological constraints on the fundamental physics quantities, presenting a **serious limitation to the precision cosmology**. Until the nature of these anomalies (if new physics or systematic errors) is clear, we should be very conservative when considering cosmological constraints.

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.

[READ MORE](#)

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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