Inferring total neutrino mass from cosmological probes

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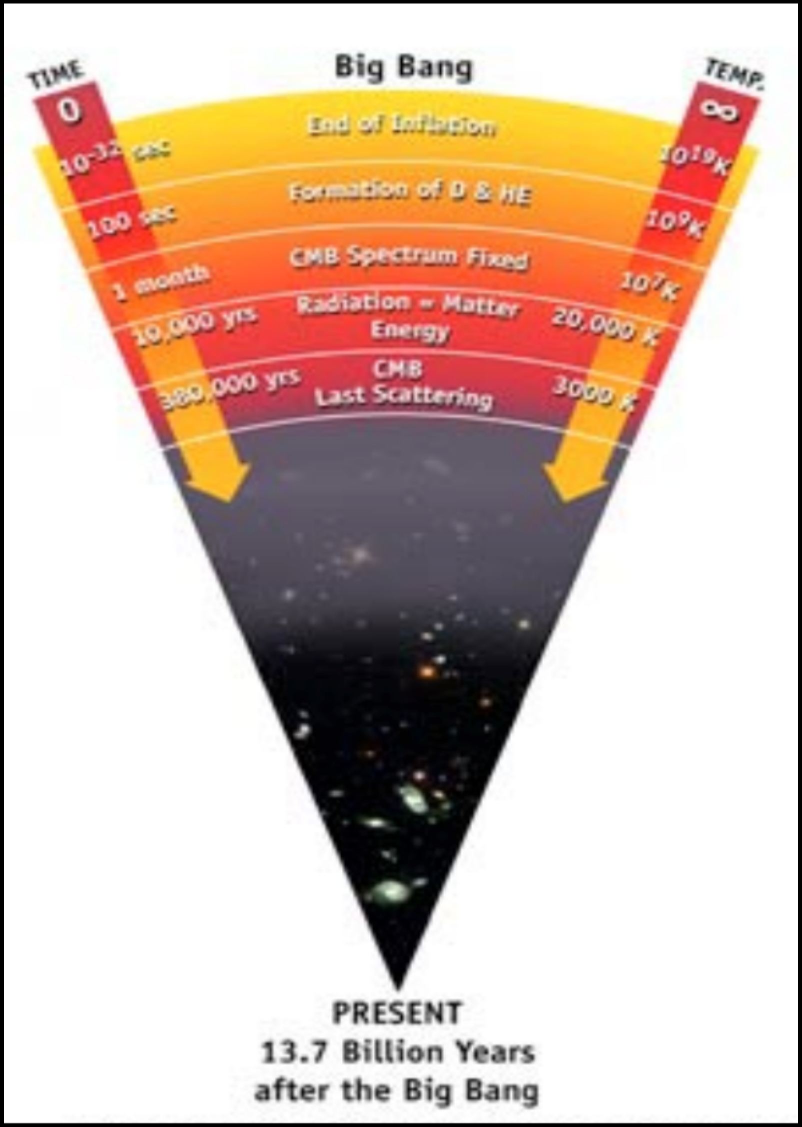
Neutrino physics and cosmology

Neutrinos are the last particles of the Standard Model whose masses are unknown.
To measure their total mass with the cosmological data we depend on the creation of a Cosmic Neutrino Background at early times, and the growth of structures at late times.

Therefore, the main cosmological probes that we can use are the Cosmic Microwave Background (CMB) and the Large Scale Structure (LSS) data.

Introduction to CMB



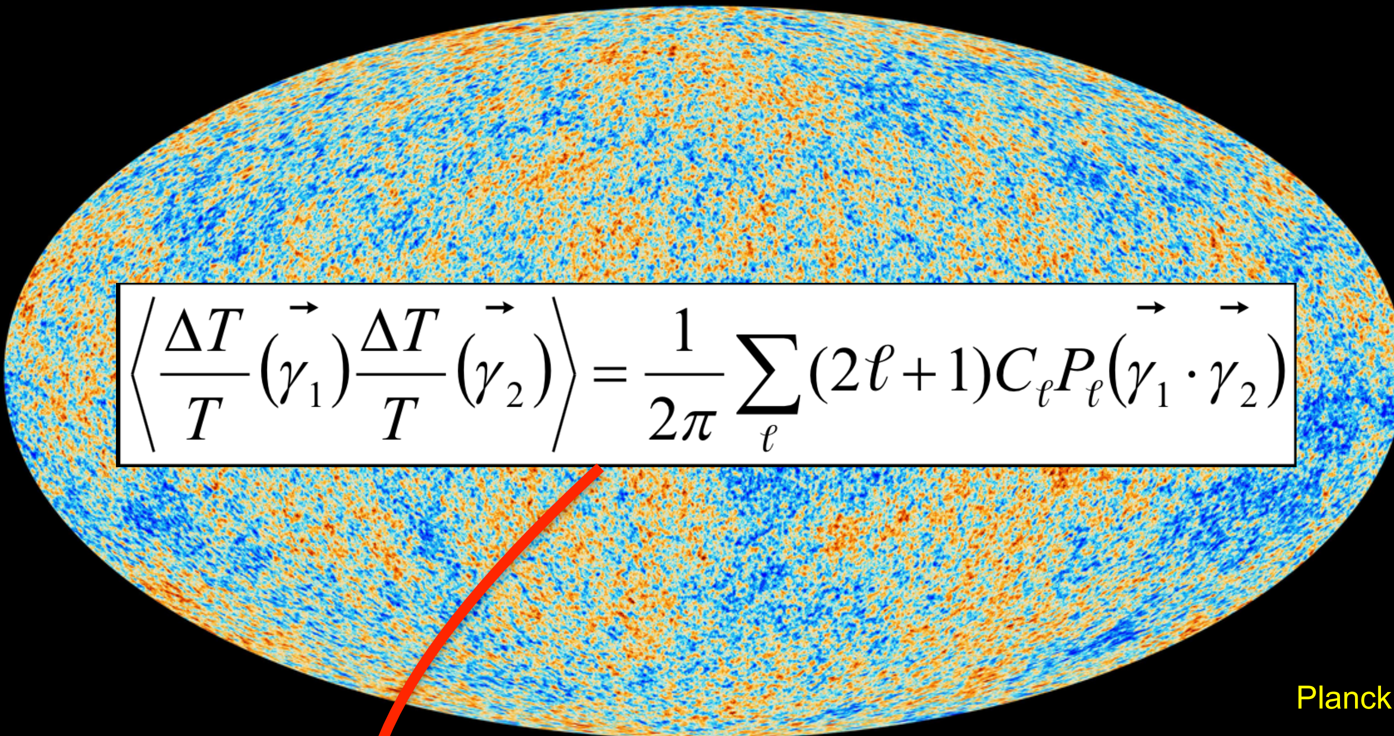
The Universe originates from a hot Big Bang.

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

The Cosmic Microwave Background (CMB) is the radiation from recombination, emitted about 13 billion years ago, just 400,000 years after the Big Bang.

The CMB provides an unparalleled probe of the early Universe and today it is a black body a temperature T=2.726K.

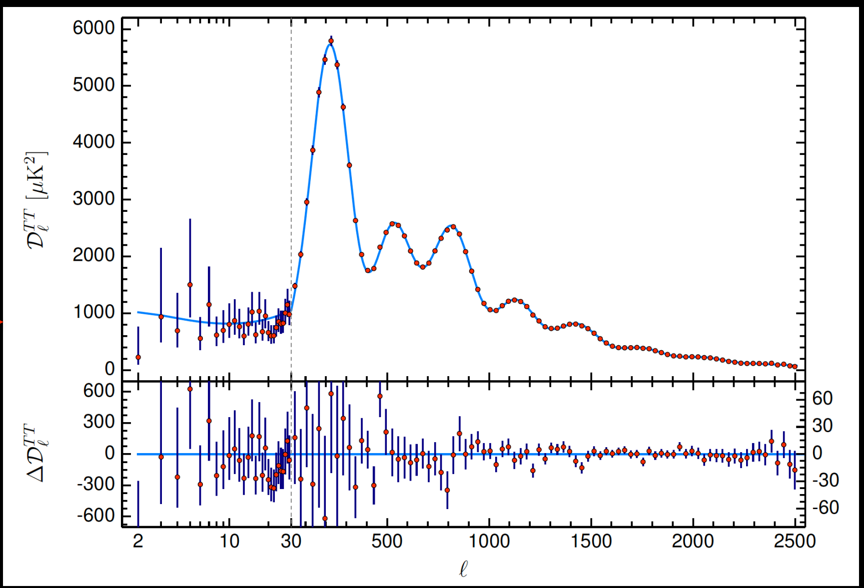
Introduction to CMB



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

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

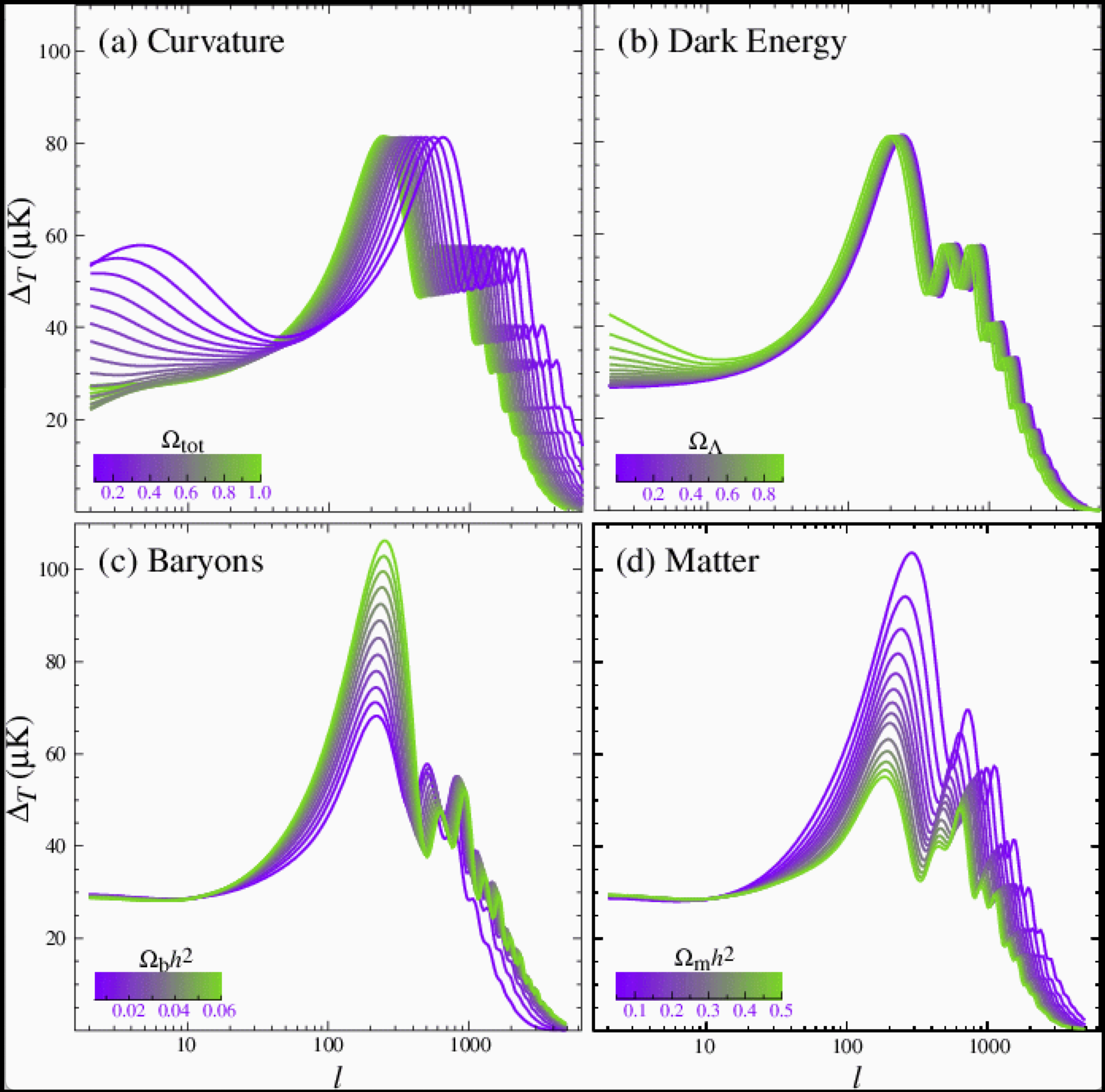
Planck 2018, Astron.Astrophys. 641 (2020) A6



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

Theoretical model

Wayne Hu's tutorial



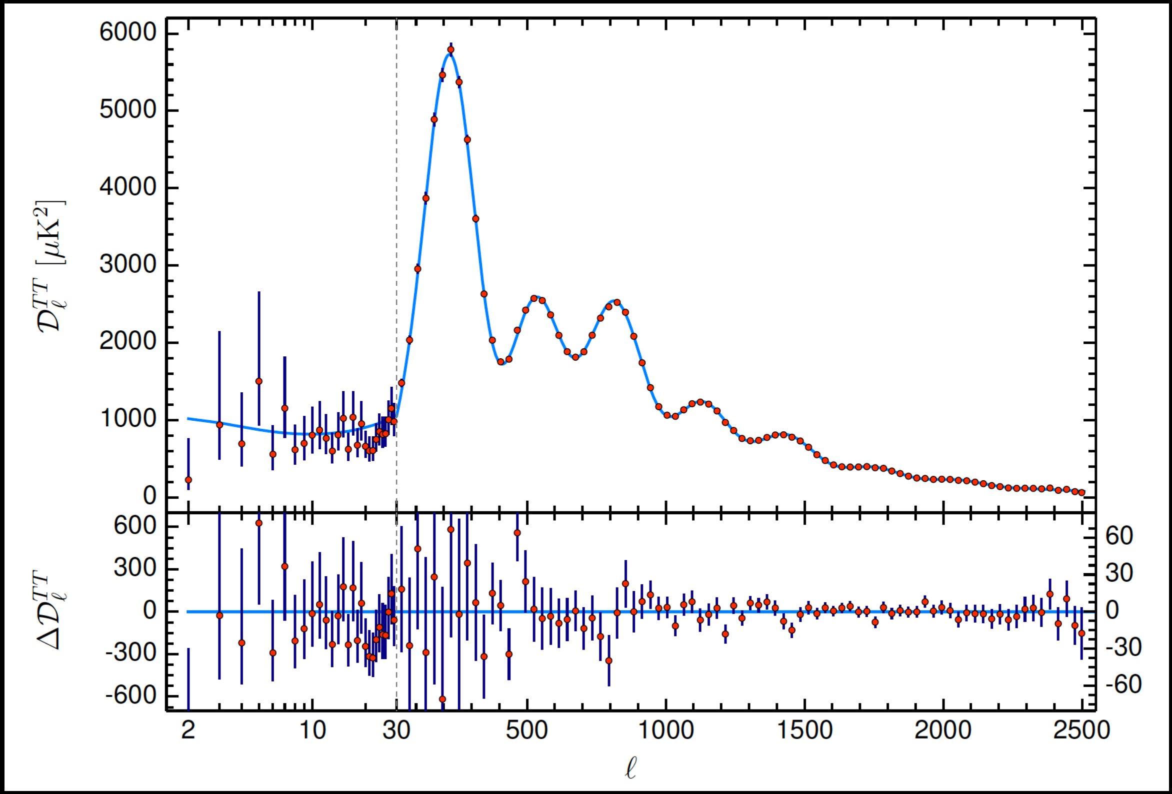
We choose a set of cosmological parameters that describes our theoretical model and compute the angular power spectra.

Due to the correlations between the parameters, variation in different quantities can produce similar effects on the CMB.

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 them.



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

Parameter constraints

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:

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

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 (CNB) at a temperature:

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

With a number density of:

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

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.

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

Total neutrino mass and CMB

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 zeq;
- The amount of matter density today.

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

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.

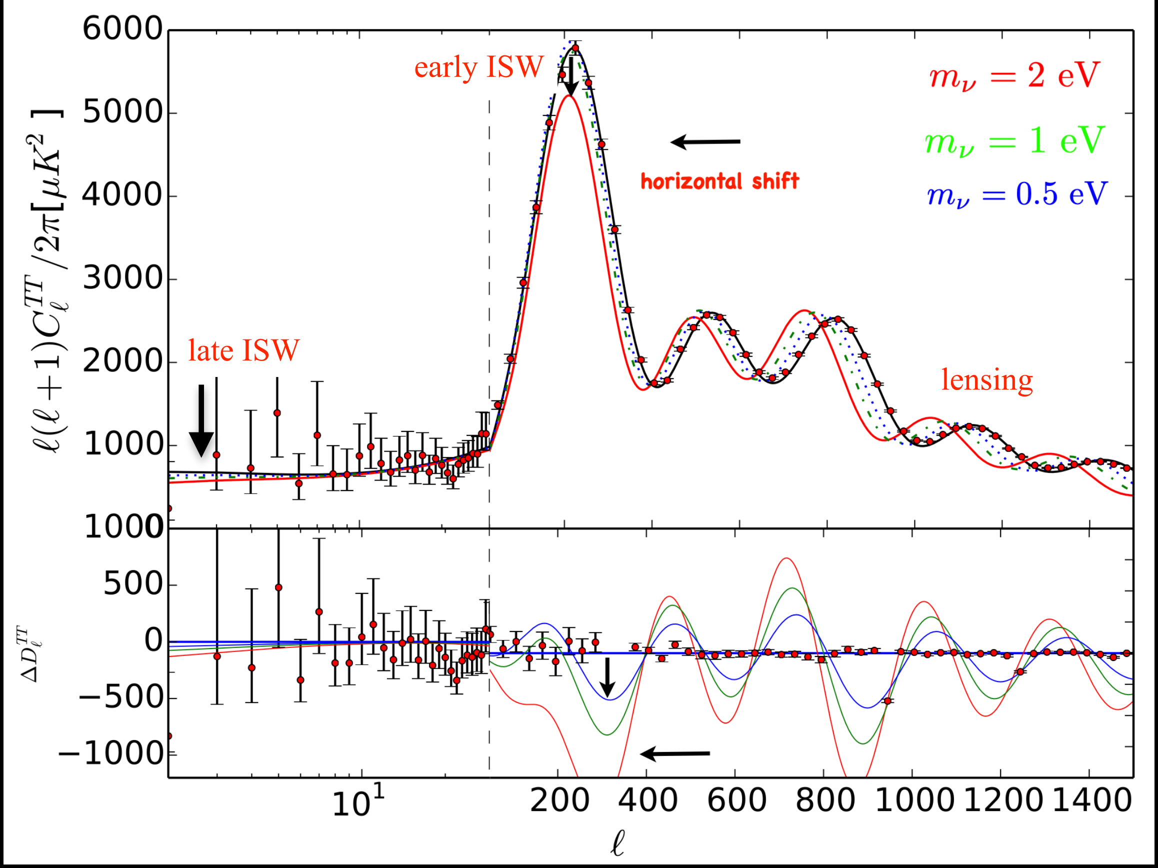
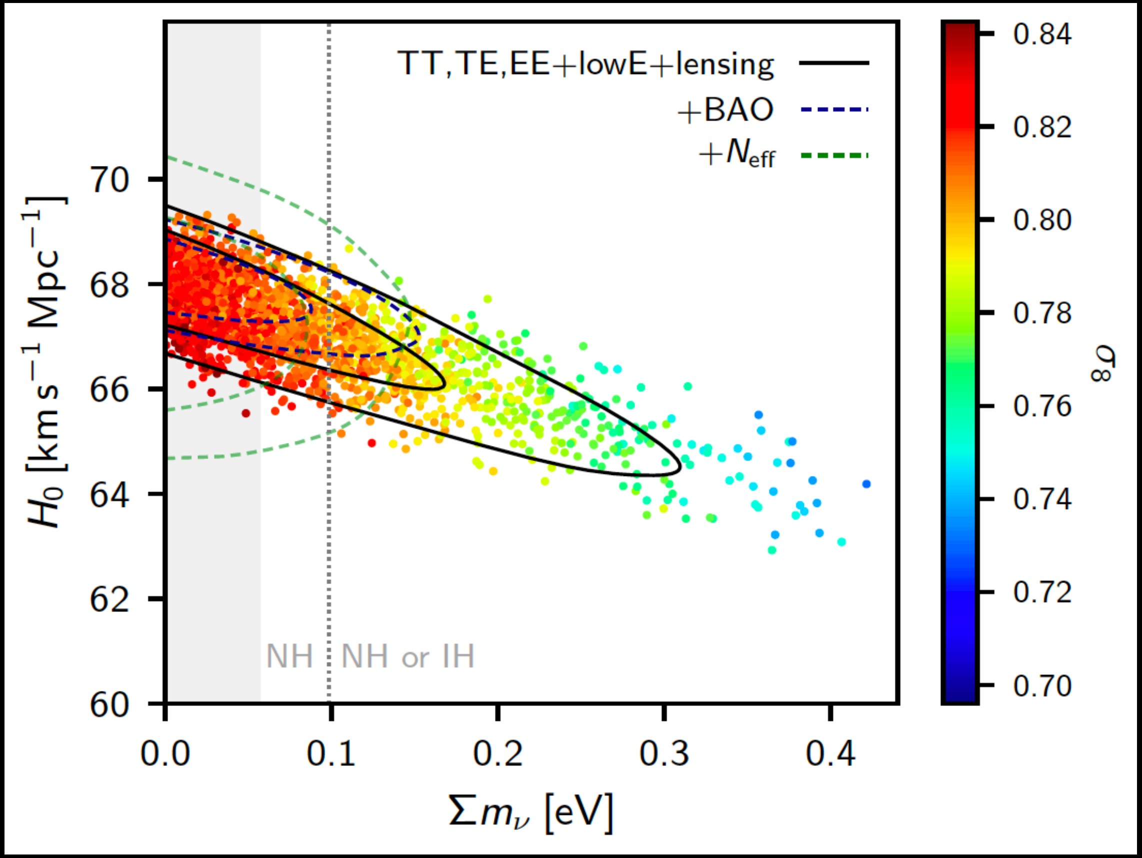


Figure from Olga Mena

Total neutrino mass and CMB

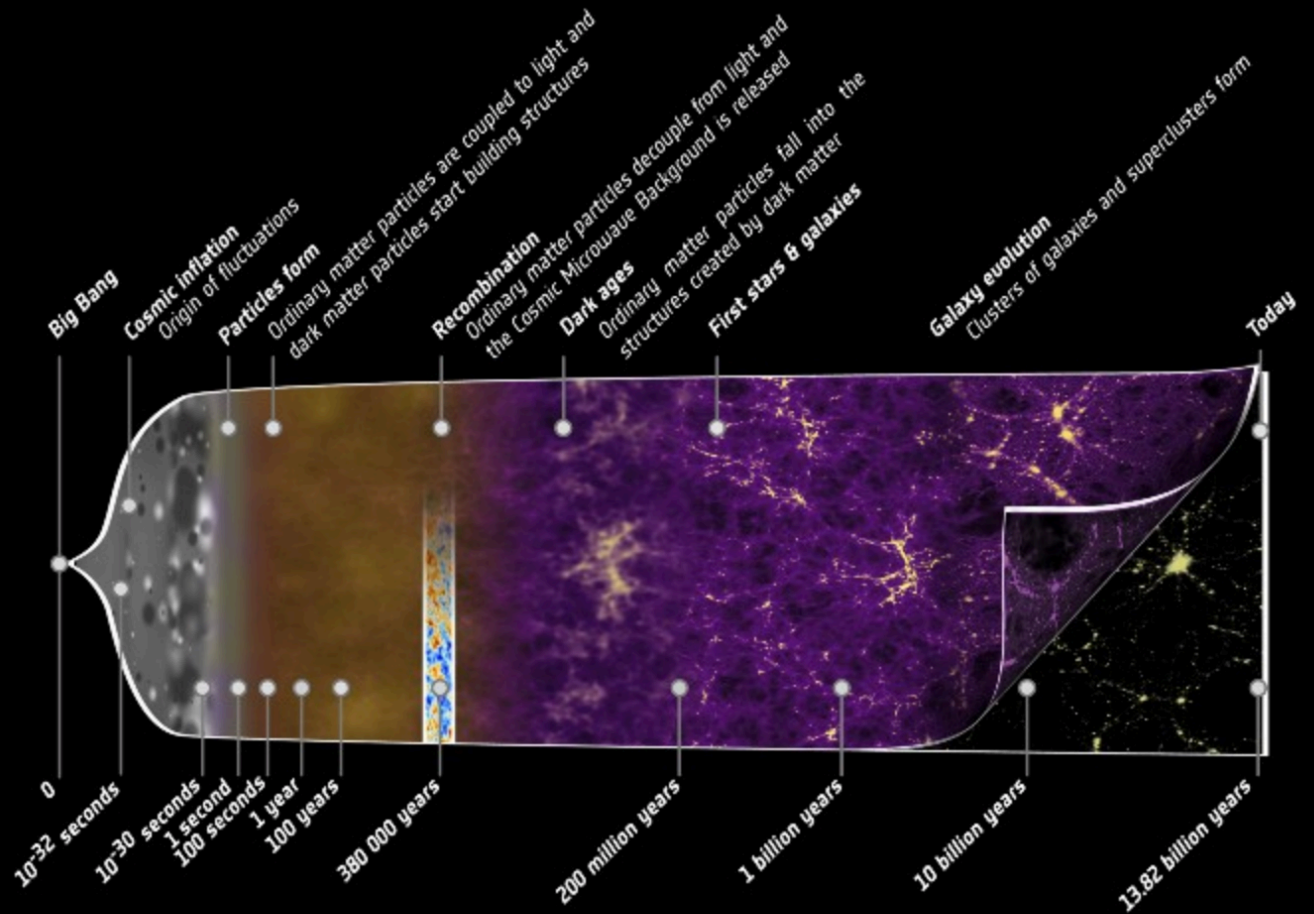
Planck 2018, Aghanim et al., arXiv:1807.06209 [astro-ph.CO]



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

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

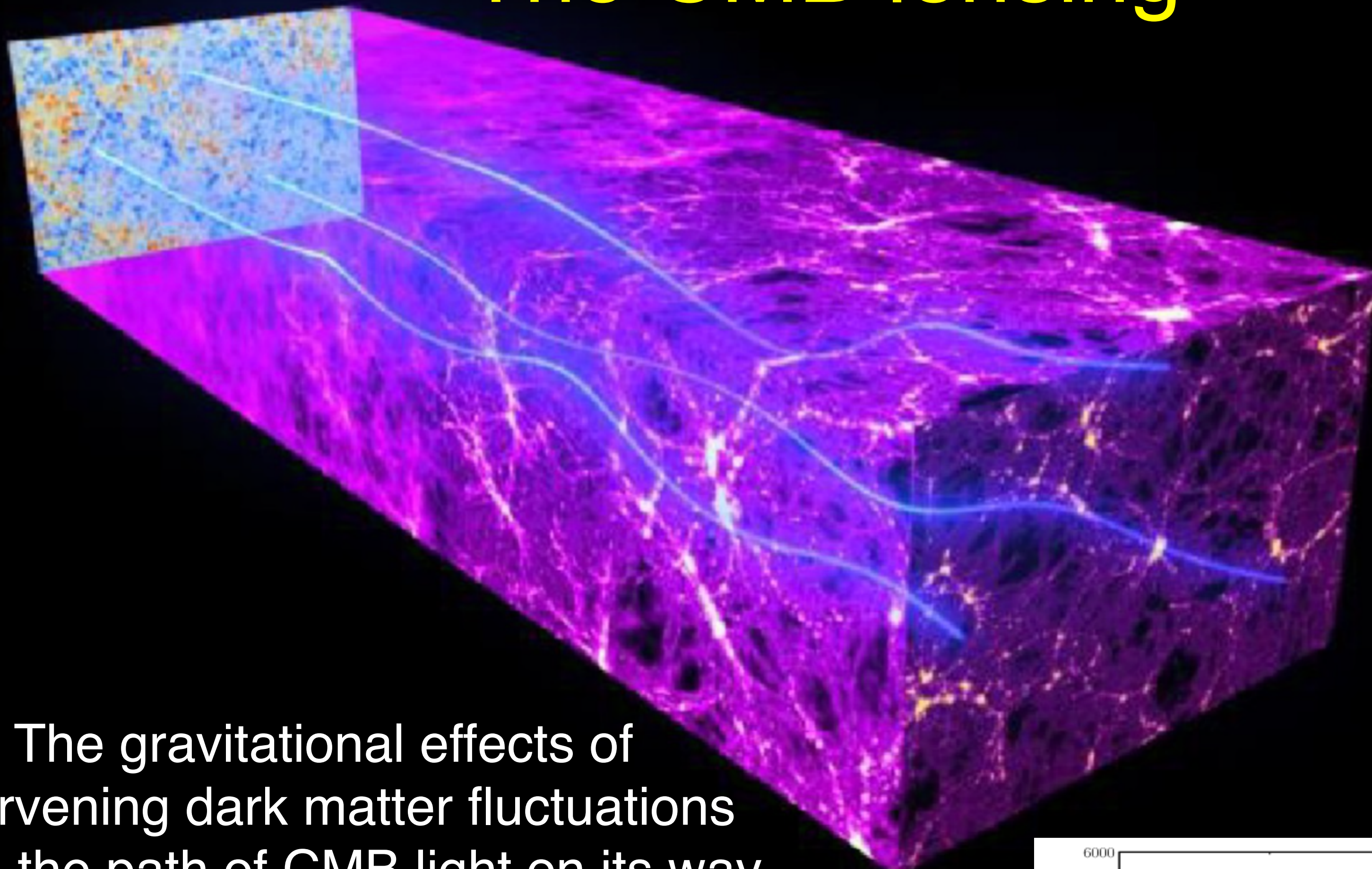
Total neutrino mass and CMB



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

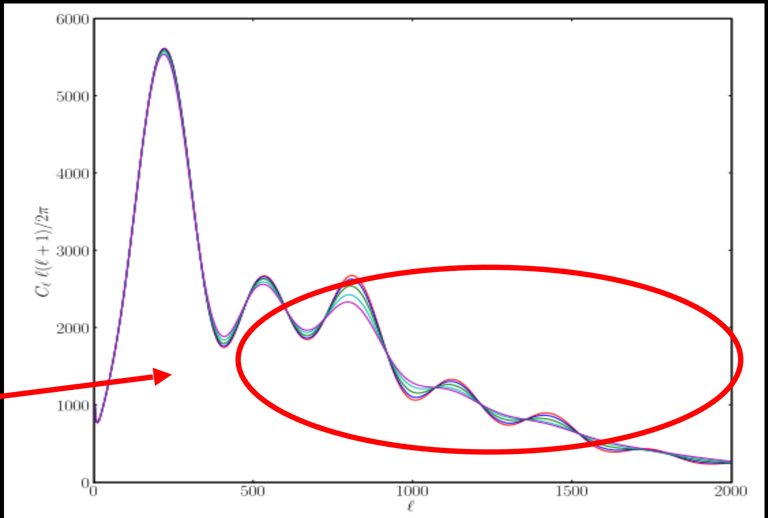
If primary CMB anisotropies form at recombination,
when the CMB was at a temperature of T~0.3 eV,
and a neutrino with a mass of ~(0.26/3)~0.09 eV is still relativistic at that epoch,
how can we have with CMB data this amazing upper limit?

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.

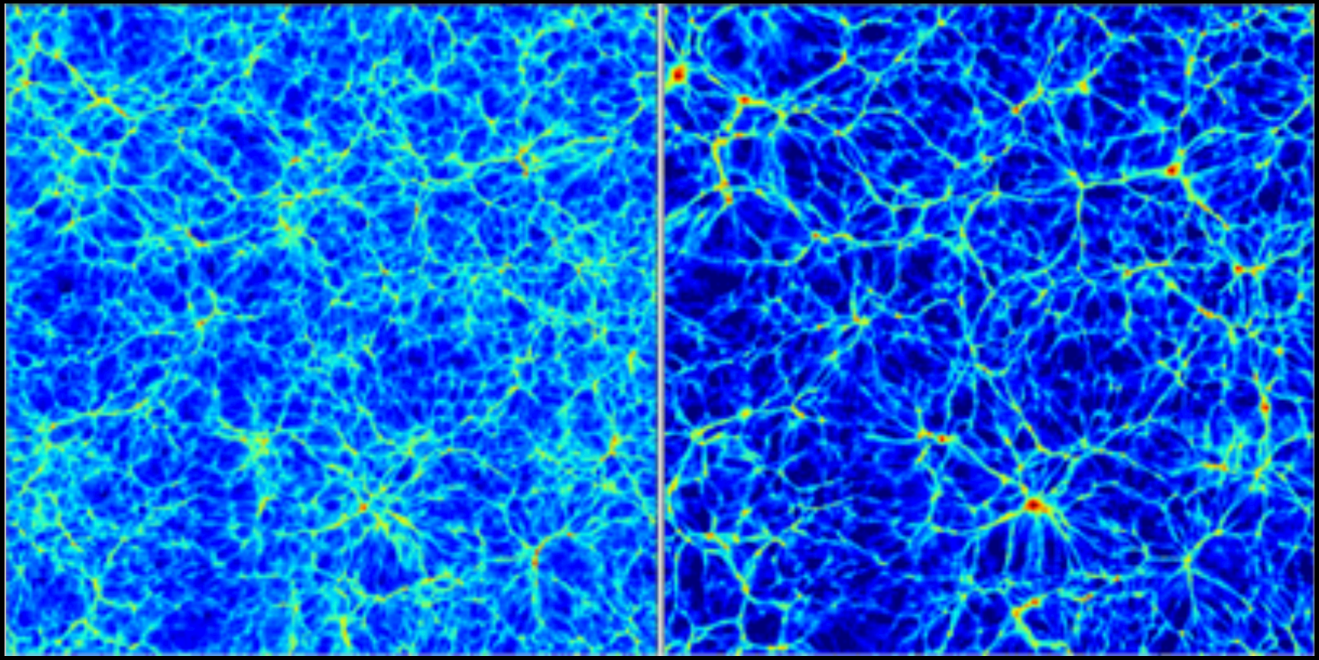


Massive neutrinos and CMB lensing

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

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 and LSS

When neutrinos become non-relativistic, will only cluster on 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 non-relativistic matter fluctuations in Fourier space

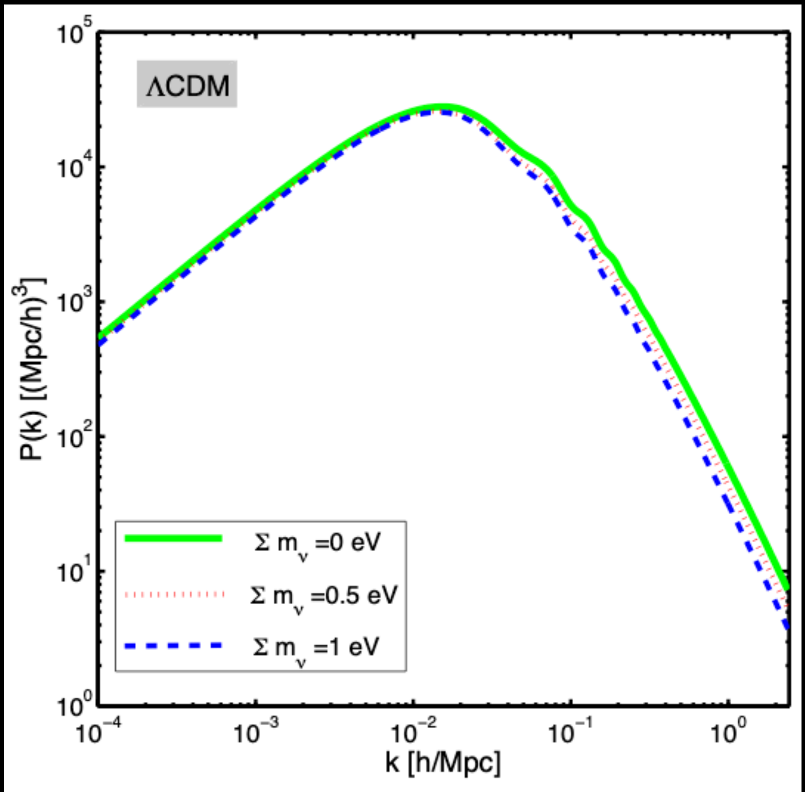
$$\langle \delta_m(\boldsymbol{k})\, \delta_m(\boldsymbol{k}') \rangle = (2\pi)^3\, P(k)\, \delta_D^{(3)}(\boldsymbol{k} - \boldsymbol{k}')$$

Or the two-point correlation function in the configuration space

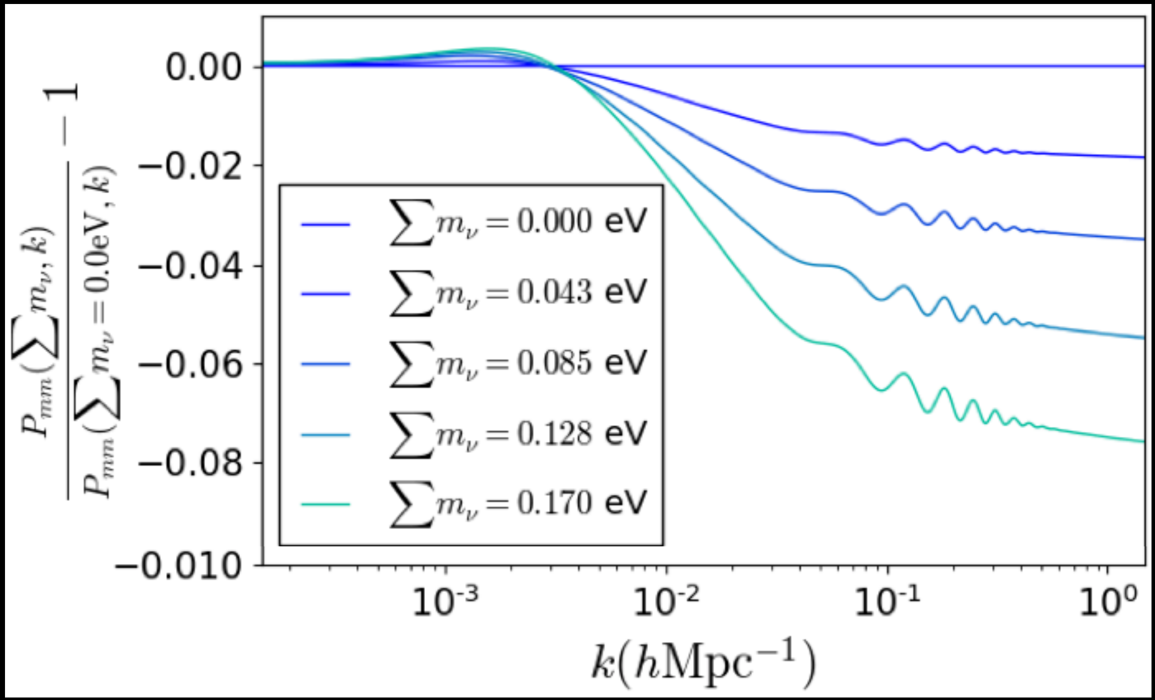
$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} \equiv \xi_m(r)$$

Matter power spectrum

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



Chen & Xu, Phys.Lett.B 752

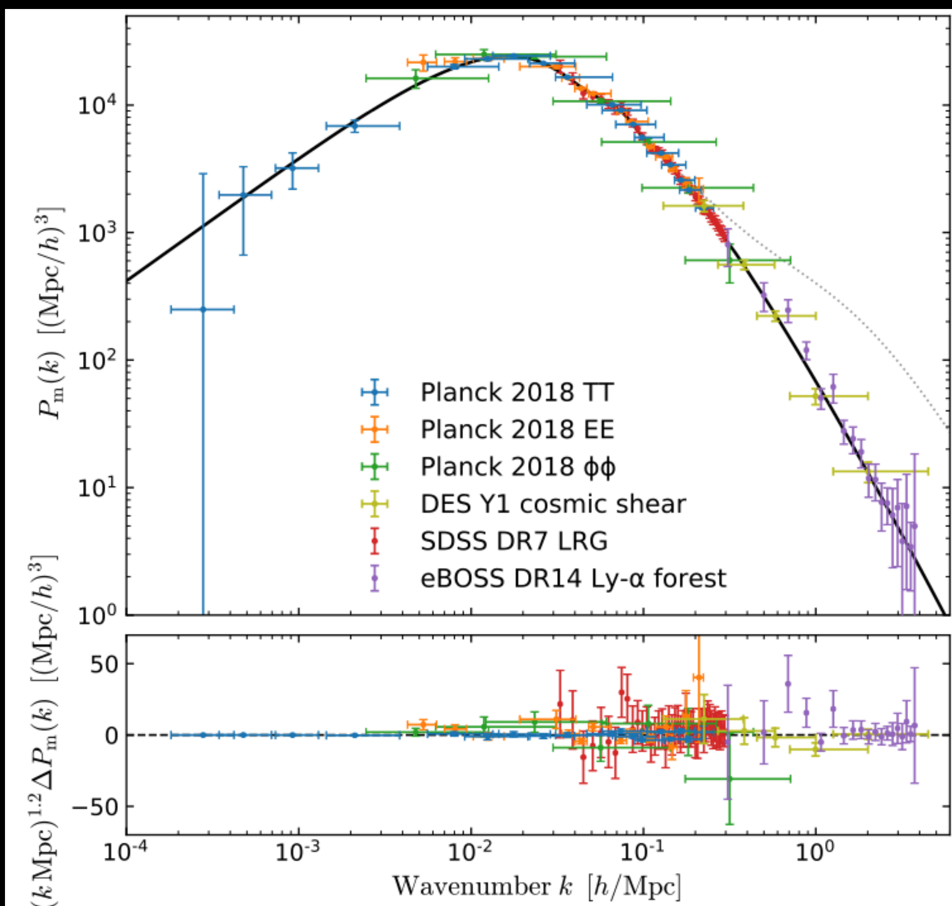


Whitford et al., arXiv:2112.10302

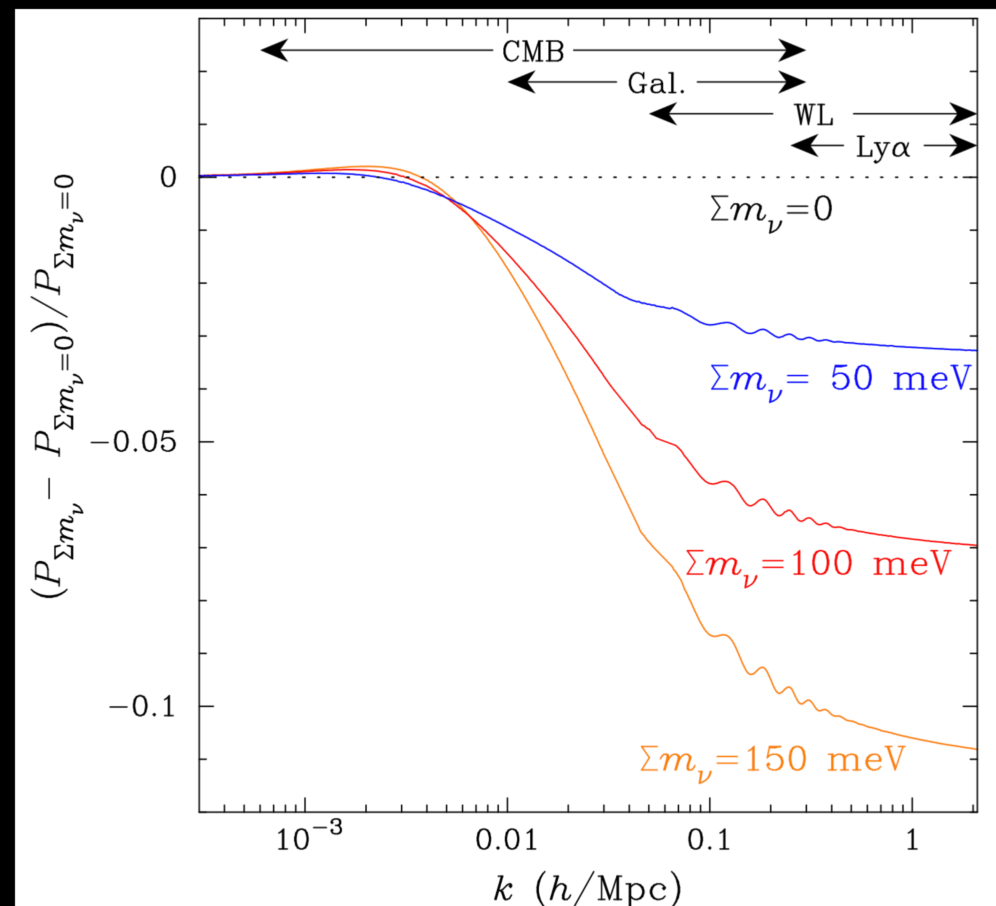
Matter power spectrum

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

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.



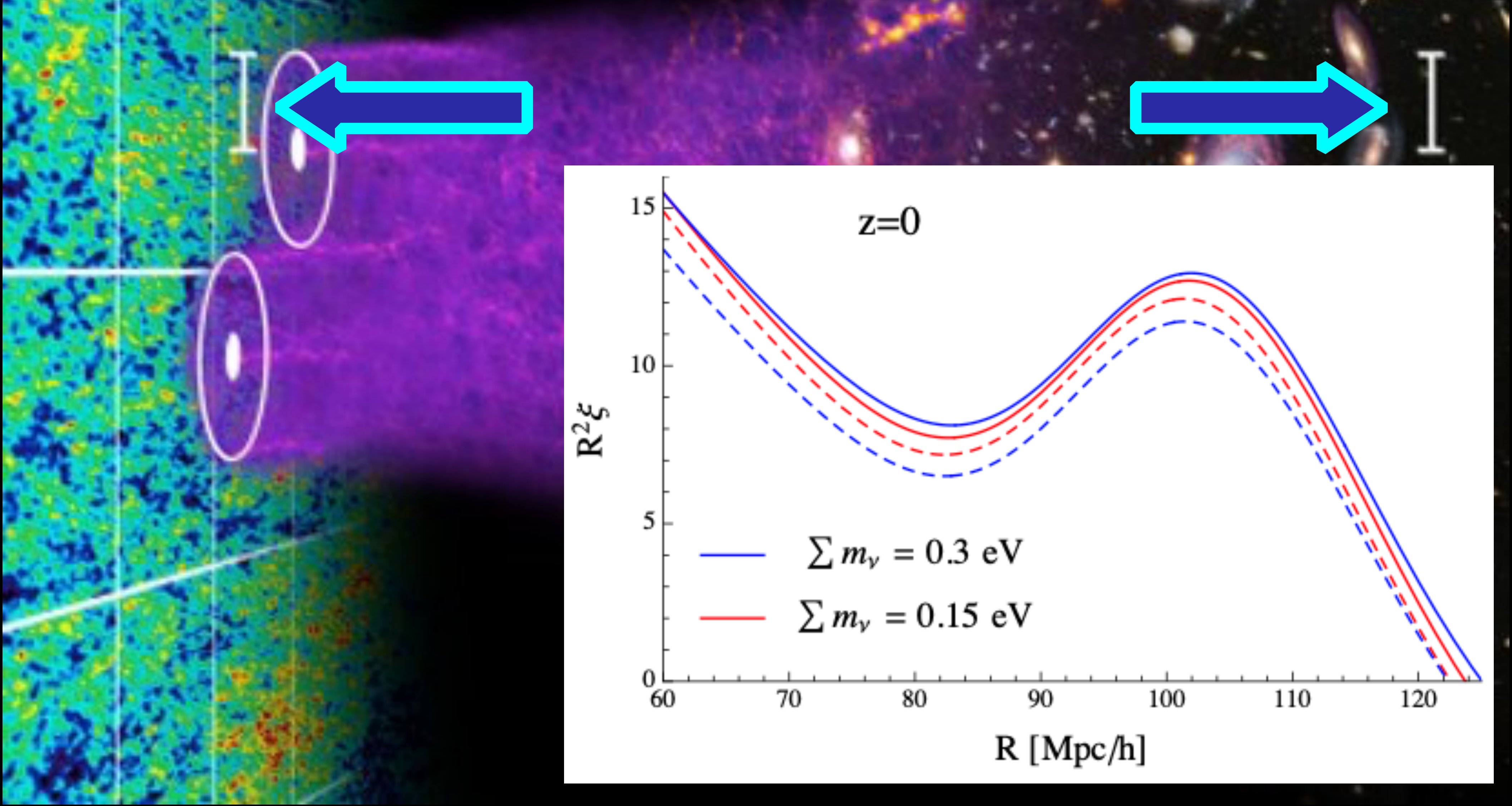
Chabanier et al, arXiv:1905.08103



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

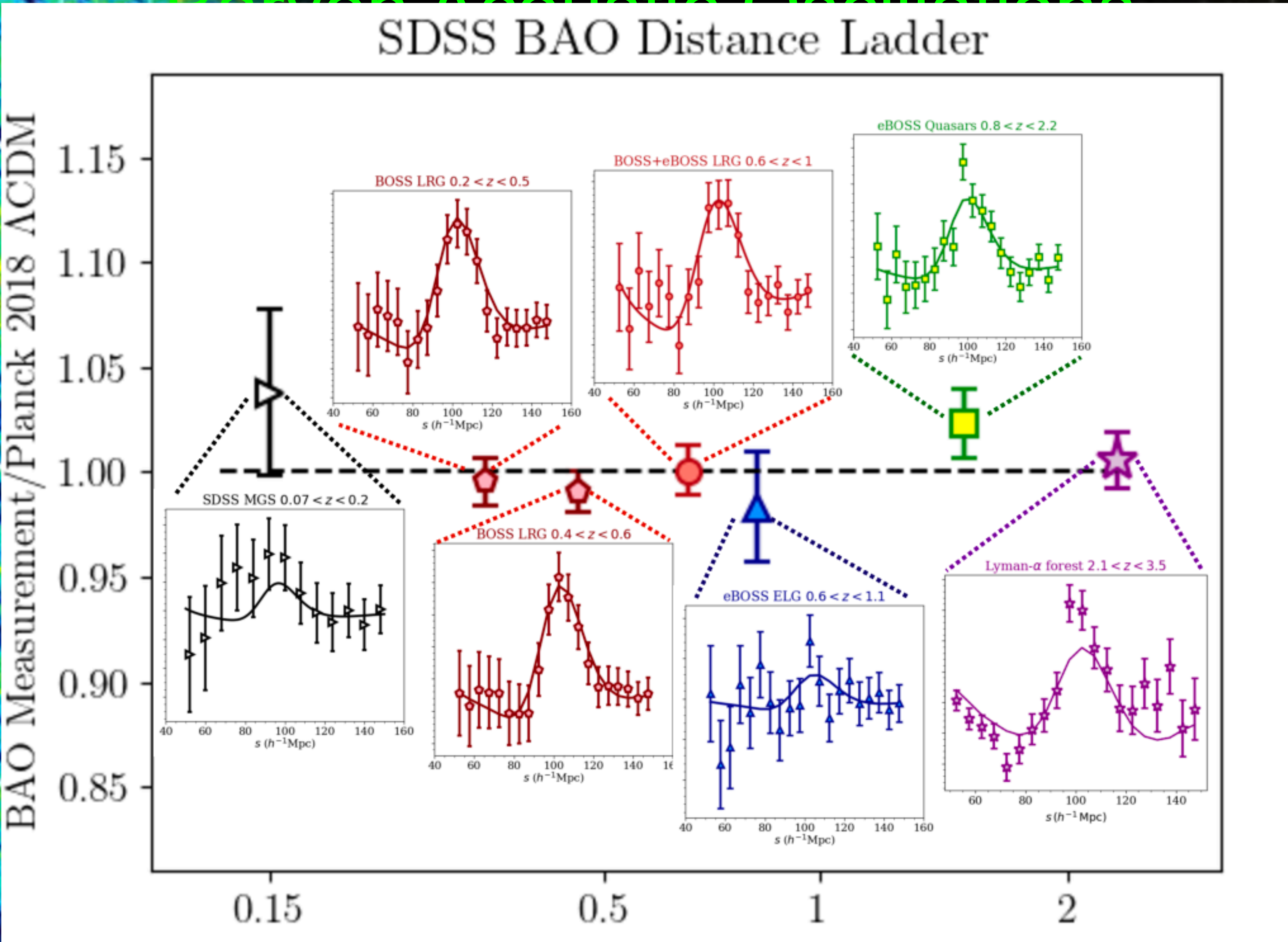
Baryon Acoustic Oscillations

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.



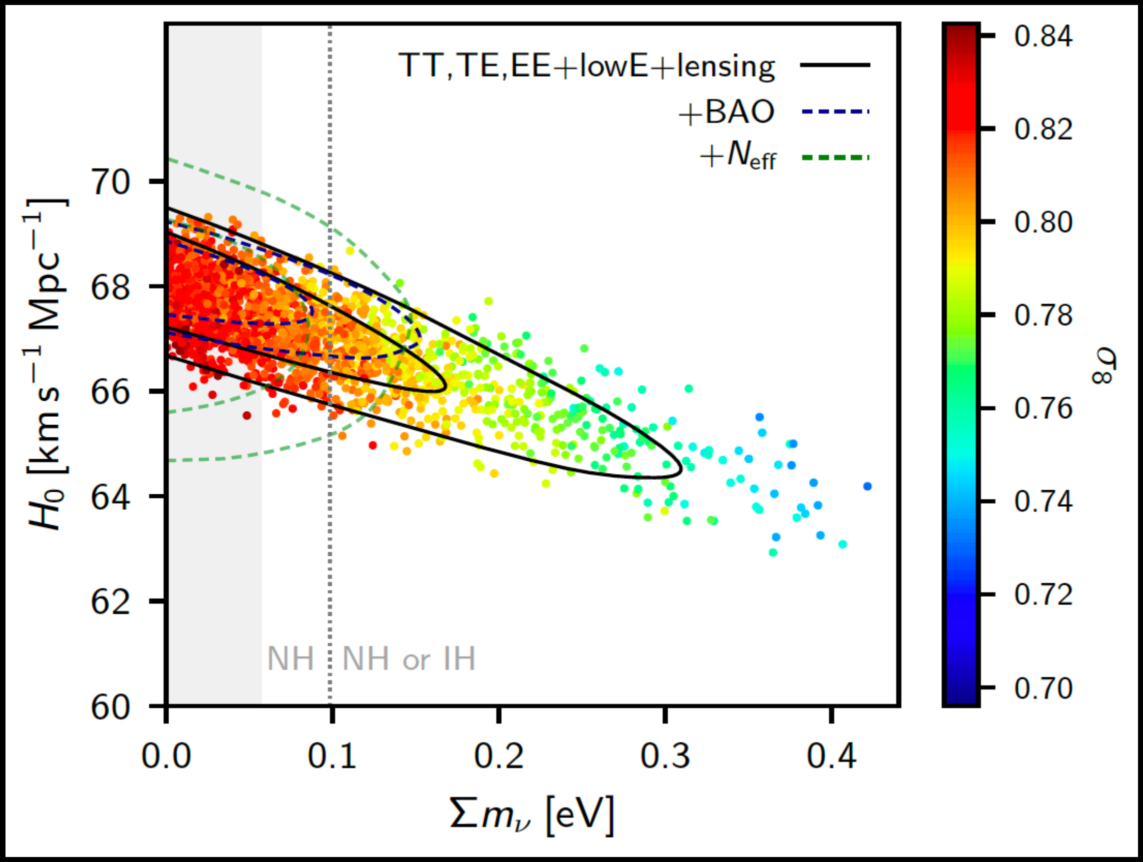
Peloso et al., *JCAP* 07 (2015) 001

Baryon Acoustic Oscillations



Credit: Ashley J. Ross and SDSS

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



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

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.

Mass ordering

In the cosmological analysis, usually the neutrino masses are assumed to be degenerate (m_i=m≥0) and the lower bound of total neutrino mass ($\Sigma=m_1+m_2+m_3$) 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:

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

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

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

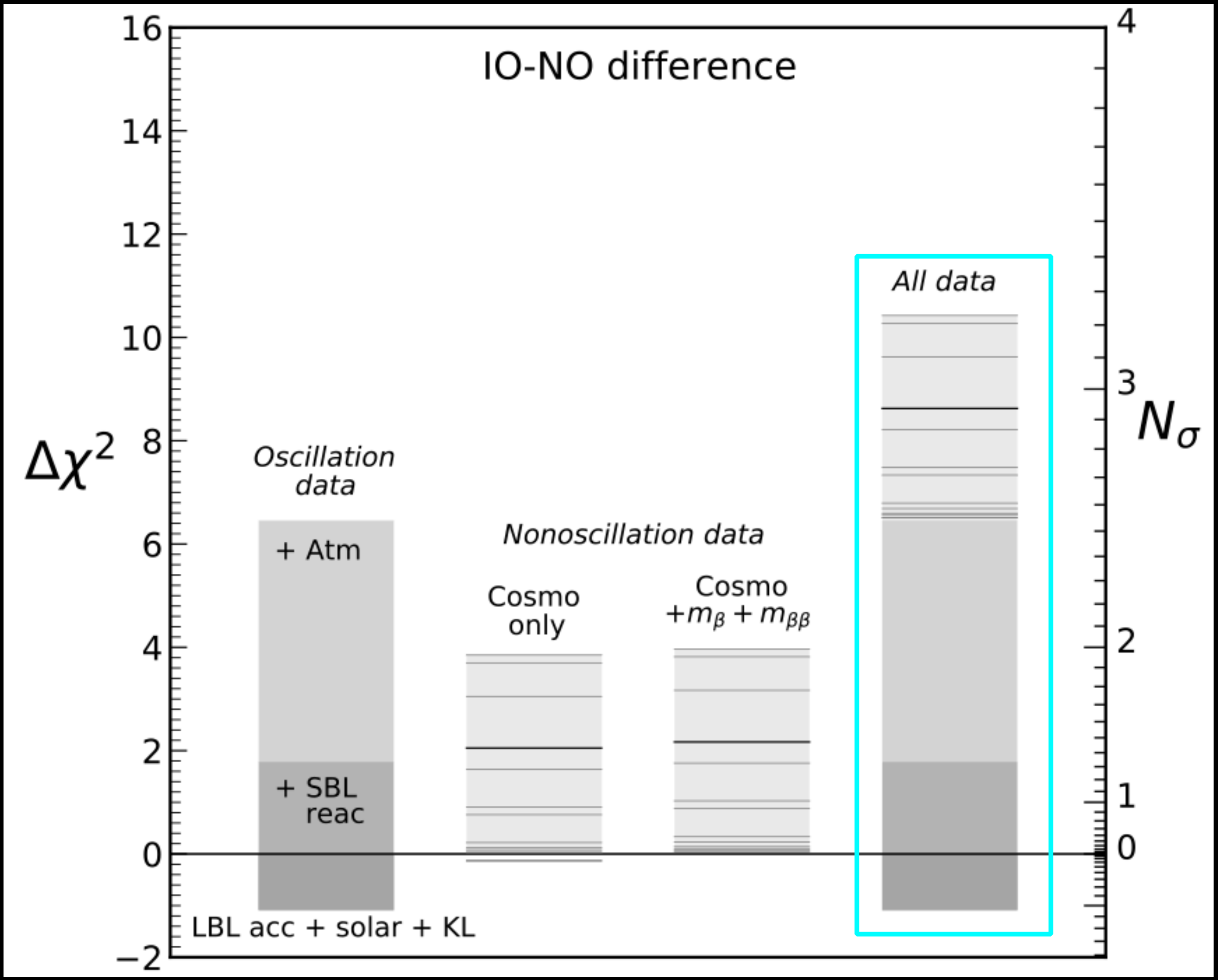
Mass ordering

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

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 (Σ < 0.15 eV at 2σ).

Capozzi, Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083031

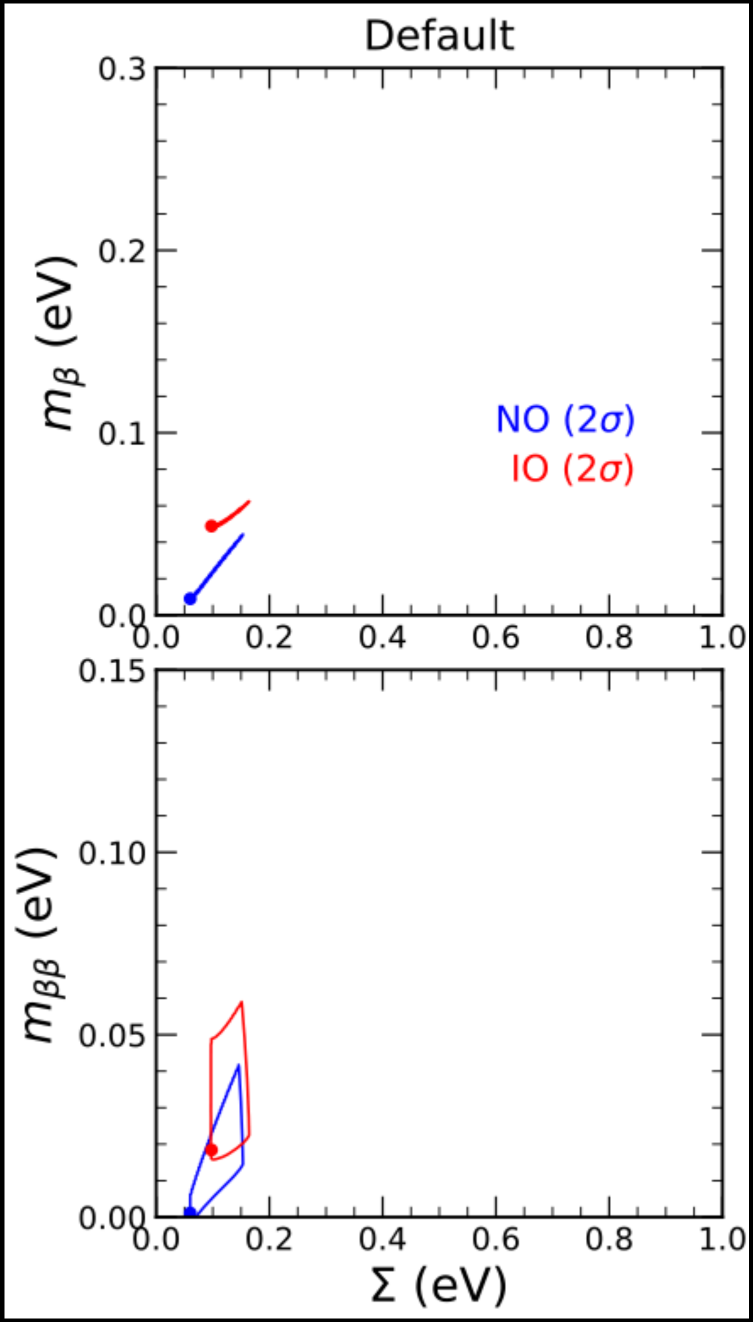


Although none of the single oscillation or nonoscillation datasets provides compelling evidences for NO, by combining the cosmology with oscillation and nonoscillation data, using a frequentist analysis,

we find the global preference for NO at the typical level of 2.5-3 σ.

Capozzi, Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083031

Constraints on the absolute neutrino mass

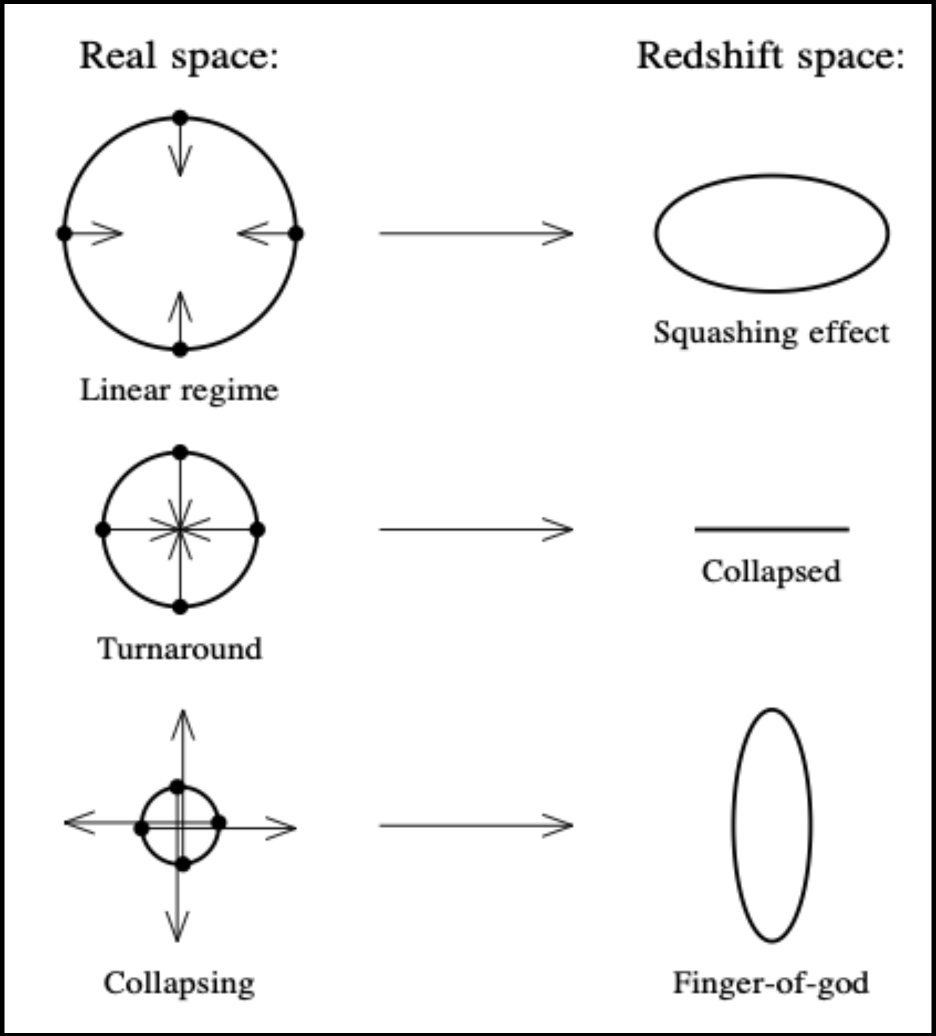


The cosmological bounds on Σ dominate—via correlations—the constraints on m_β and $m_{\beta\beta}$, which are squeezed to the relatively small 2σ regions around the best fits (dot), located close to the lowest possible values for Σ in both NO and IO.

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

Capozzi, Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083031

Redshift Space Distortions



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

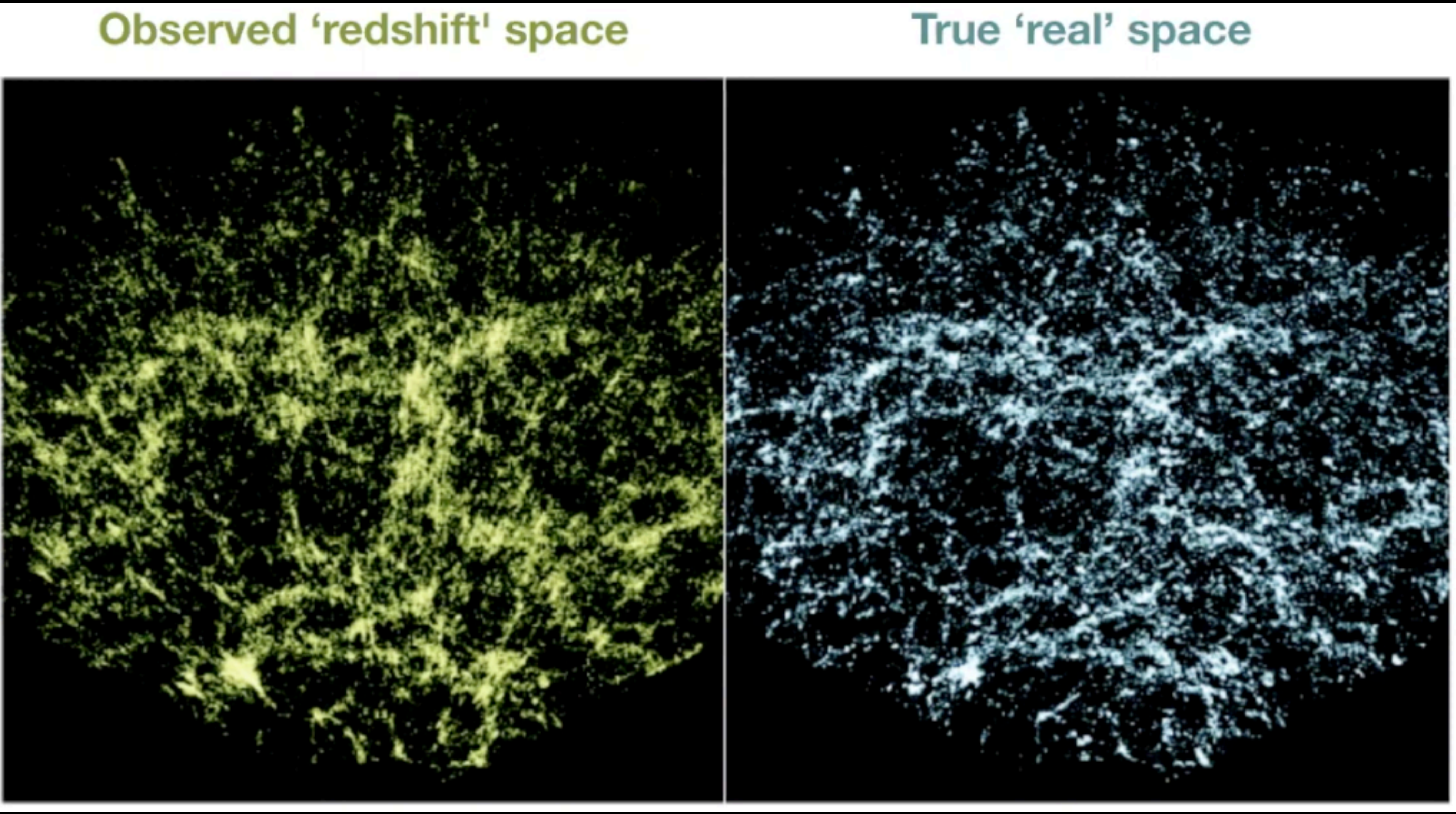
Analysing the clustering in the redshift space, you can study the Redshift Space Distortions (RSD). We will have a reduction or increase of the growth of structure along the radial direction, because of the peculiar velocities (anisotropic clustering).

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.

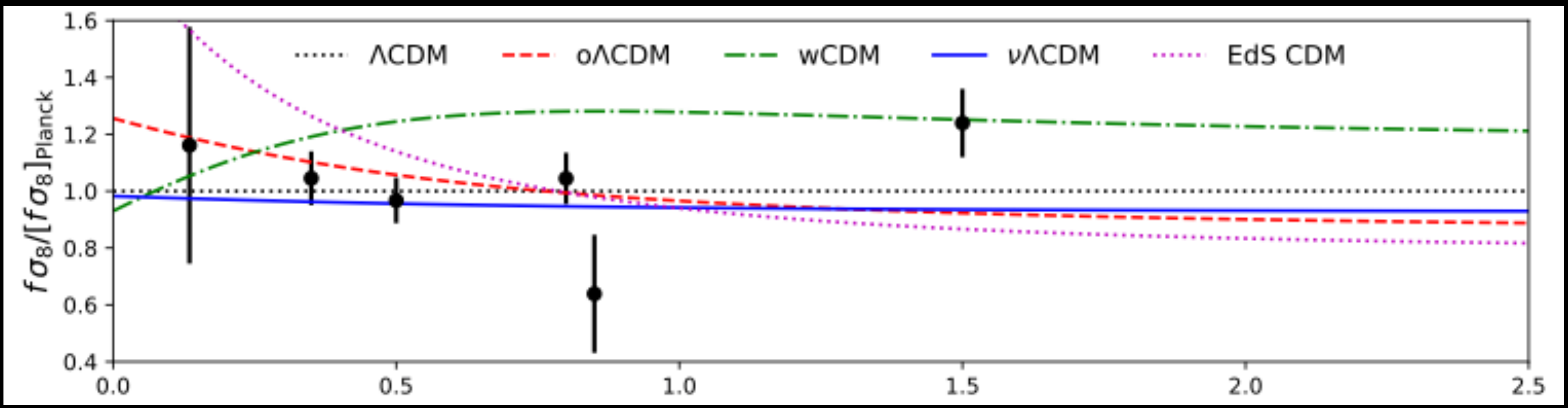
At smaller scales, the spatial distribution of galaxies appears to be elongated due to their velocity dispersion along the line of sight, producing the fingers-of-god.

Redshift Space Distortions



slide from Héctor Gil-Marín

Redshift Space Distortions

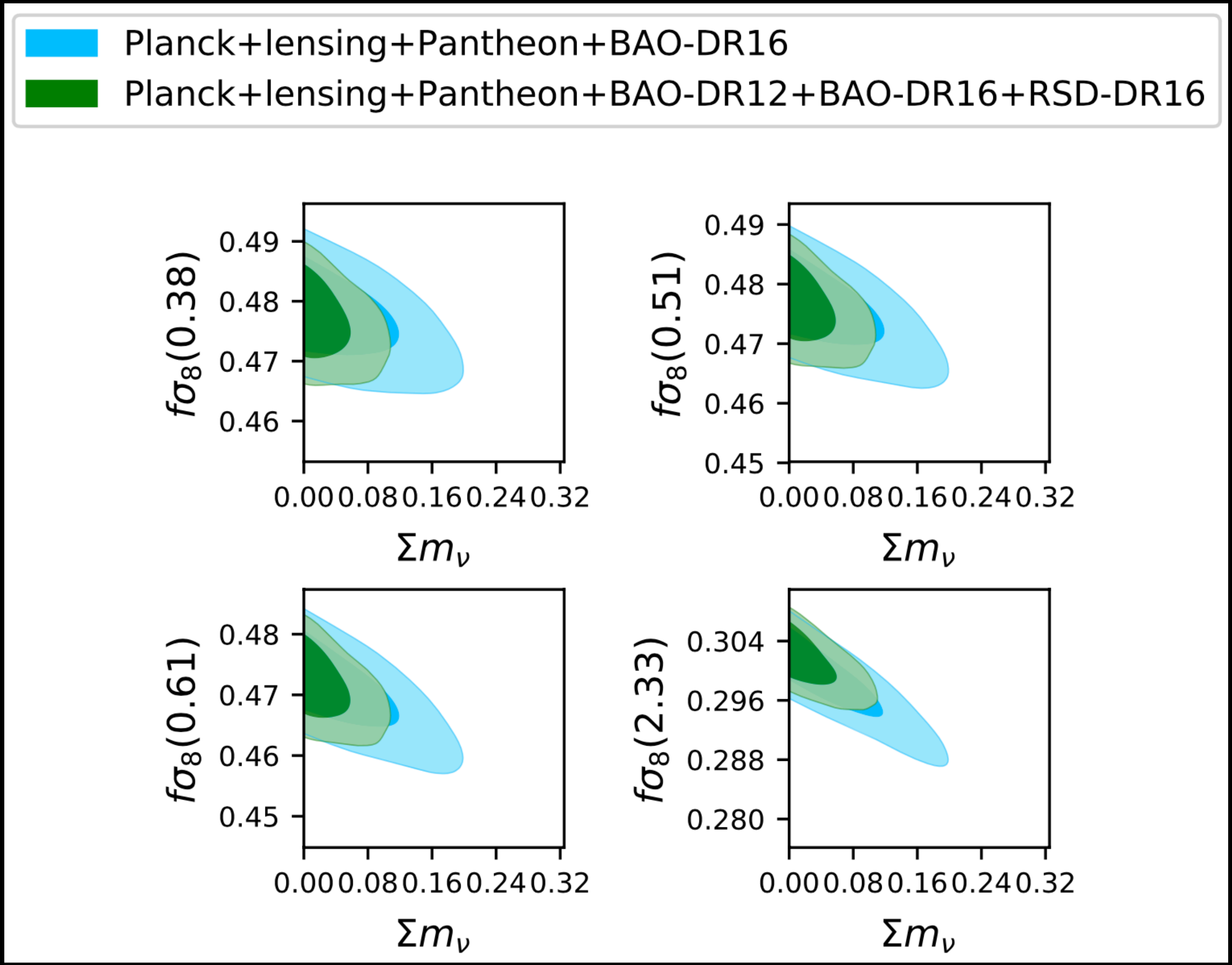


eBOSS collaboration, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

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.

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

Constraints on the total neutrino mass

Constraints at 95% CL

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

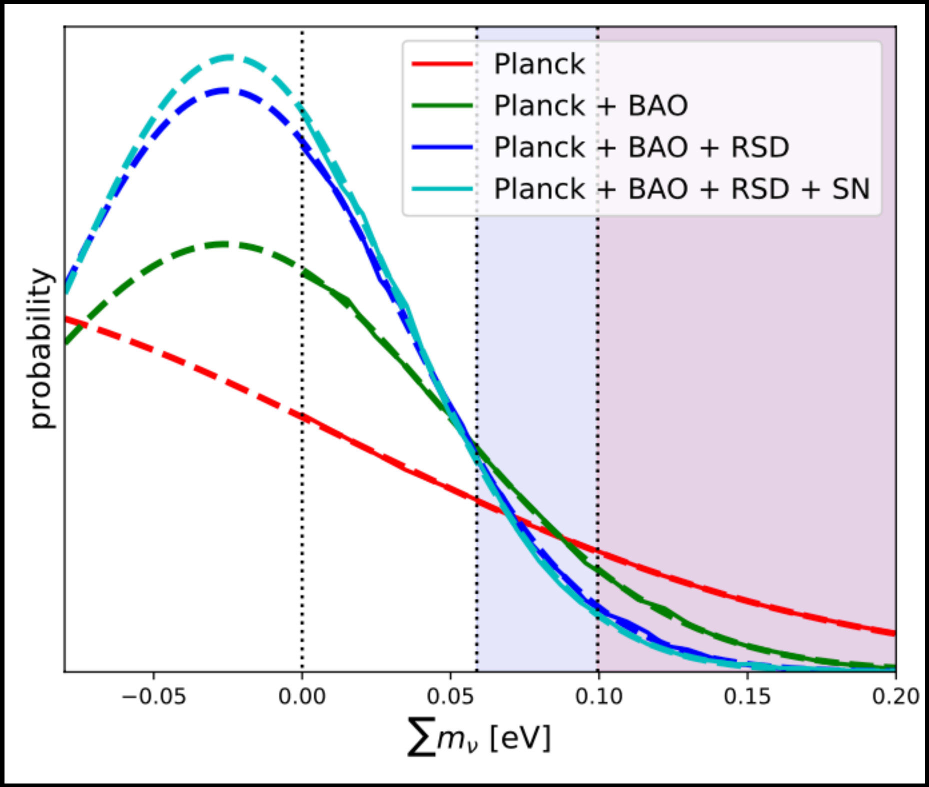
When we add the latest RSD from eBOSS DR16 LRGs and QSOs samples to Planck+lensing+SNIa data obtain stronger constraints on the total neutrino mass.

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).

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

Constraints on the total neutrino mass

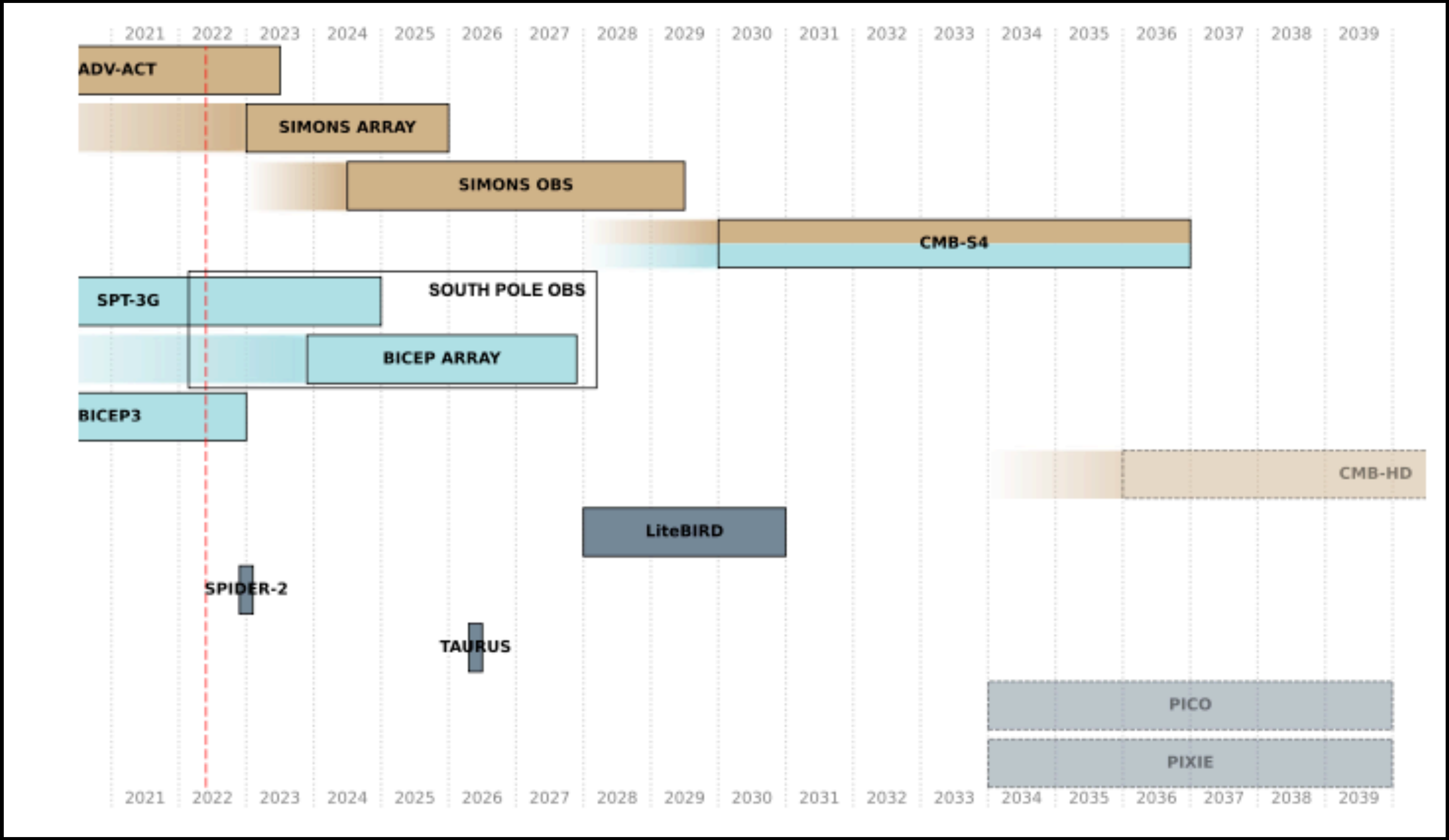


eBOSS collaboration, Alam et al., *Phys.Rev.D* 103 (2021) 8, 083533

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.

How much these constraints could be improved in the future?

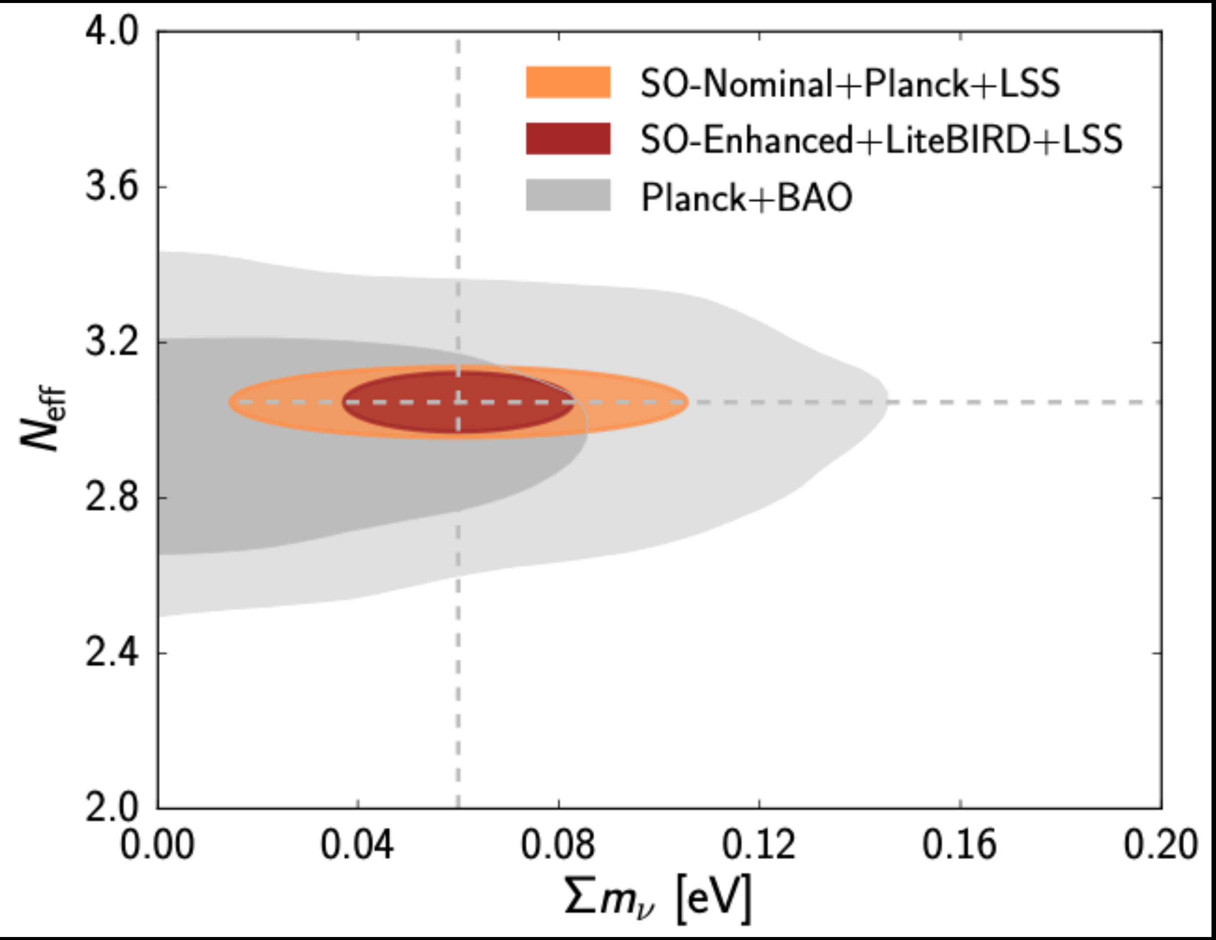
Timeline of current and future ground-based CMB experiments



Chang et al. 2022, SNOWMASS, arXiv:2203.08093

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

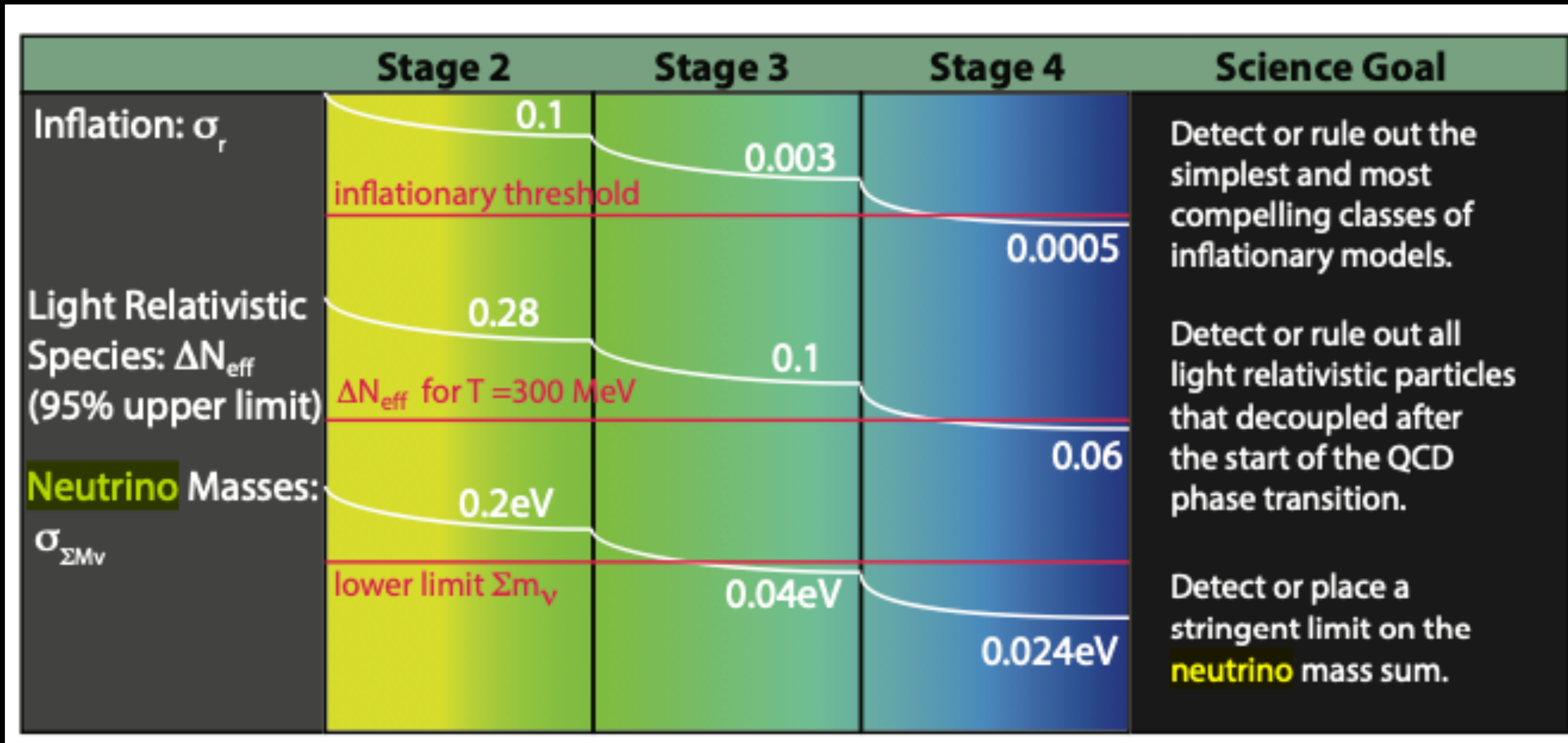
Simons Observatory



Abitbol et al. 2022, Astro2020, arXiv:1907.08284

The Simons Observatory aims to measure the total neutrino mass $\sigma(\sum m_V) = 0.04$ 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 deionisation SO can instead reach $\sigma(\sum m_V) = 0.02$ eV.

CMB-S4

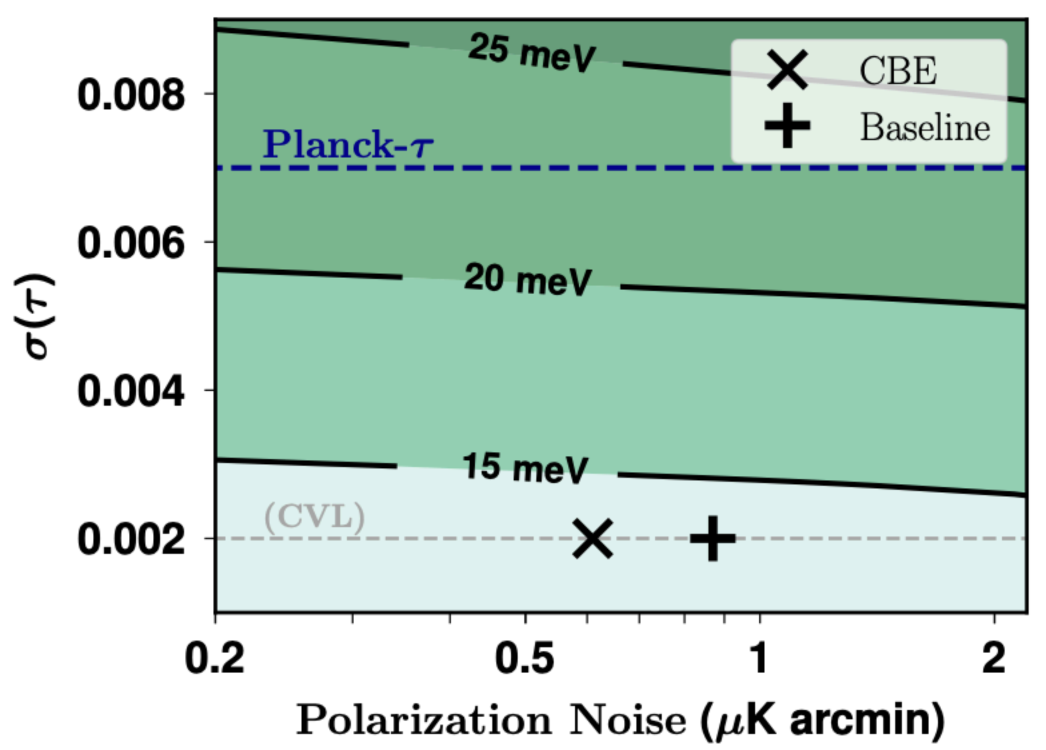


Chang et al. 2022, SNOWMASS, arXiv:2203.08093

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 $\sigma(\sum m_\nu)$ = 0.024 eV, and this would improve to $\sigma(\sum m_\nu)$ = 0.014 eV with better measurements of the optical depth.

PICO

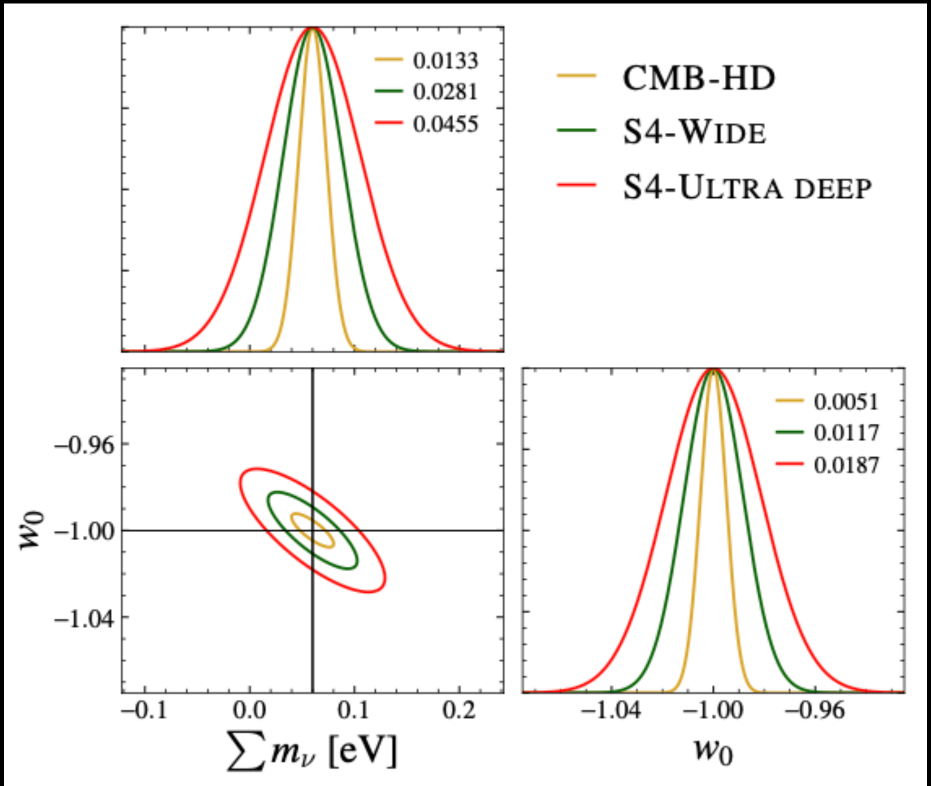
Hanany et al., NASA PICO collaboration, arXiv:1902.10541.



PICO + future BAO (DESI or Euclid) should reach σ ($\sum m_\nu$) = 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 ΛCDM model

The ΛCDM model

Among a number of cosmological models introduced in the literature, the Lambda Cold Dark Matter (ΛCDM) cosmological model is the mathematically simplest model, and has now practically been selected as the "standard" cosmological scenario, because it provides a remarkable description of a wide range of astrophysical and cosmological probes.

However, despite its marvelous fit to the available observations, ΛCDM harbours large areas of phenomenology and ignorance. For example, it still cannot explain key pillars in our understanding of the structure and evolution of the Universe, namely, Dark Energy, Dark Matter and Inflation.

The ΛCDM model

In the ΛCDM paradigm these three pillars are our simplest guesses.

- DE assumes its simplest form, that is the cosmological constant, without any strong physical basis.
- The nature of DM is still a mystery except for its gravitational interaction, as suggested by the observational evidence. We know, however, that DM is essential for structure formation in the late Universe, so most of it must be pressure-less, cold, and stable on cosmological time scales. Moreover, despite the significant efforts in the last decades to investigate DM and the physics beyond the SM of particle physics, in laboratory experiments and from devised astrophysical observations, no evidence pointing to the dark matter particle has been found.
- Finally, even though the theory of inflation has solved a number of crucial puzzles related to the early evolution of the Universe, in the standard model this is given by a single, minimally coupled, slow-rolling scalar field.

The ΛCDM model

Therefore, the 6 parameter ΛCDM 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.
In this situation, we must be careful not to cling to the model too tightly or to risk missing the appearance of departures from the paradigm.

With the improvement of the number and the accuracy of the observations, deviations from ΛCDM may be expected.
And, actually, discrepancies among key cosmological parameters of the models have emerged with different statistical significance.

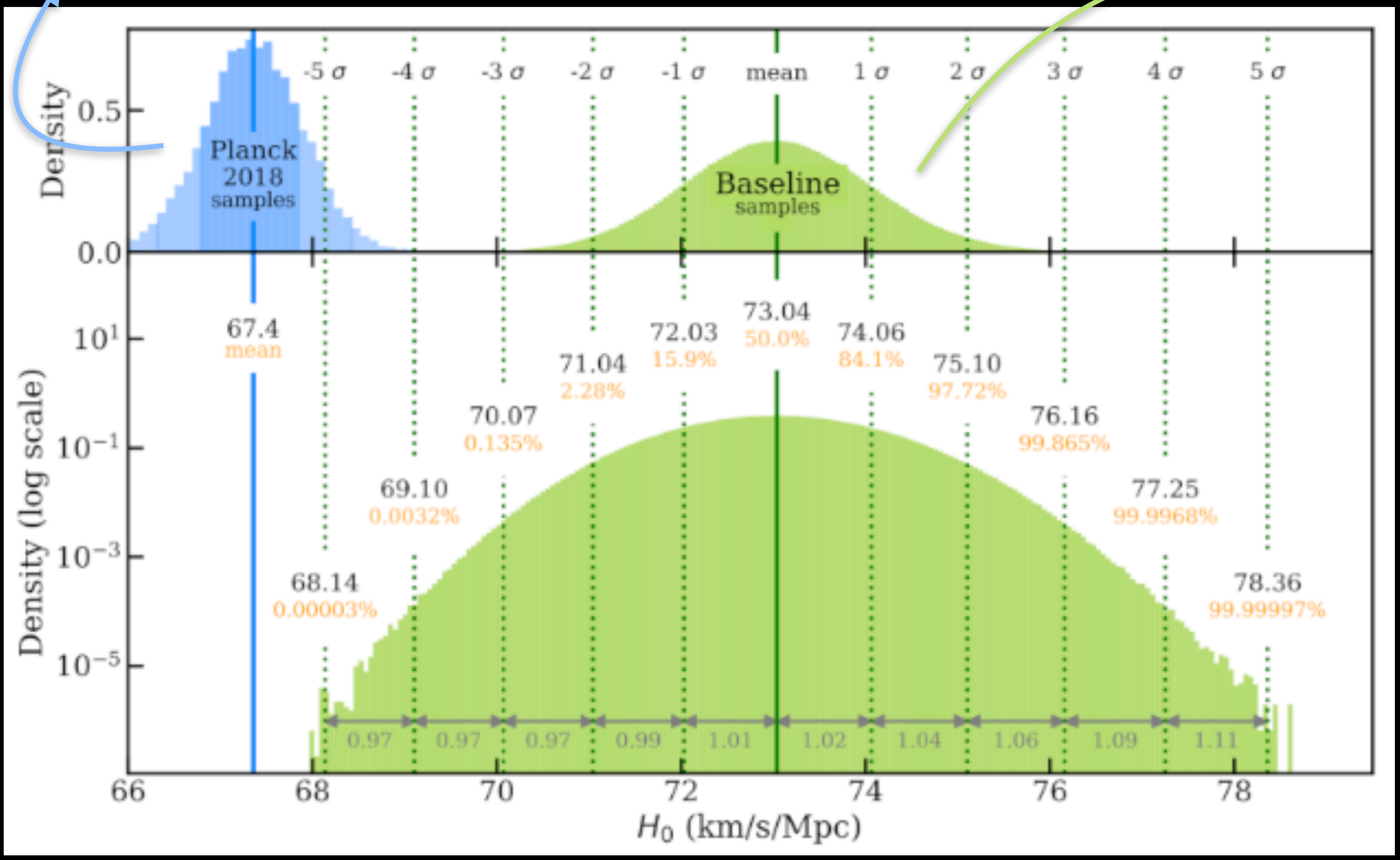
While some proportion of these discrepancies may have a systematic origin, their persistence across probes should require multiple and unrelated errors, strongly hinting at cracks in the standard cosmological scenario and the necessity of new physics.

These tensions can indicate a failure of the canonical ΛCDM model.

The H0 tension at 5σ!!

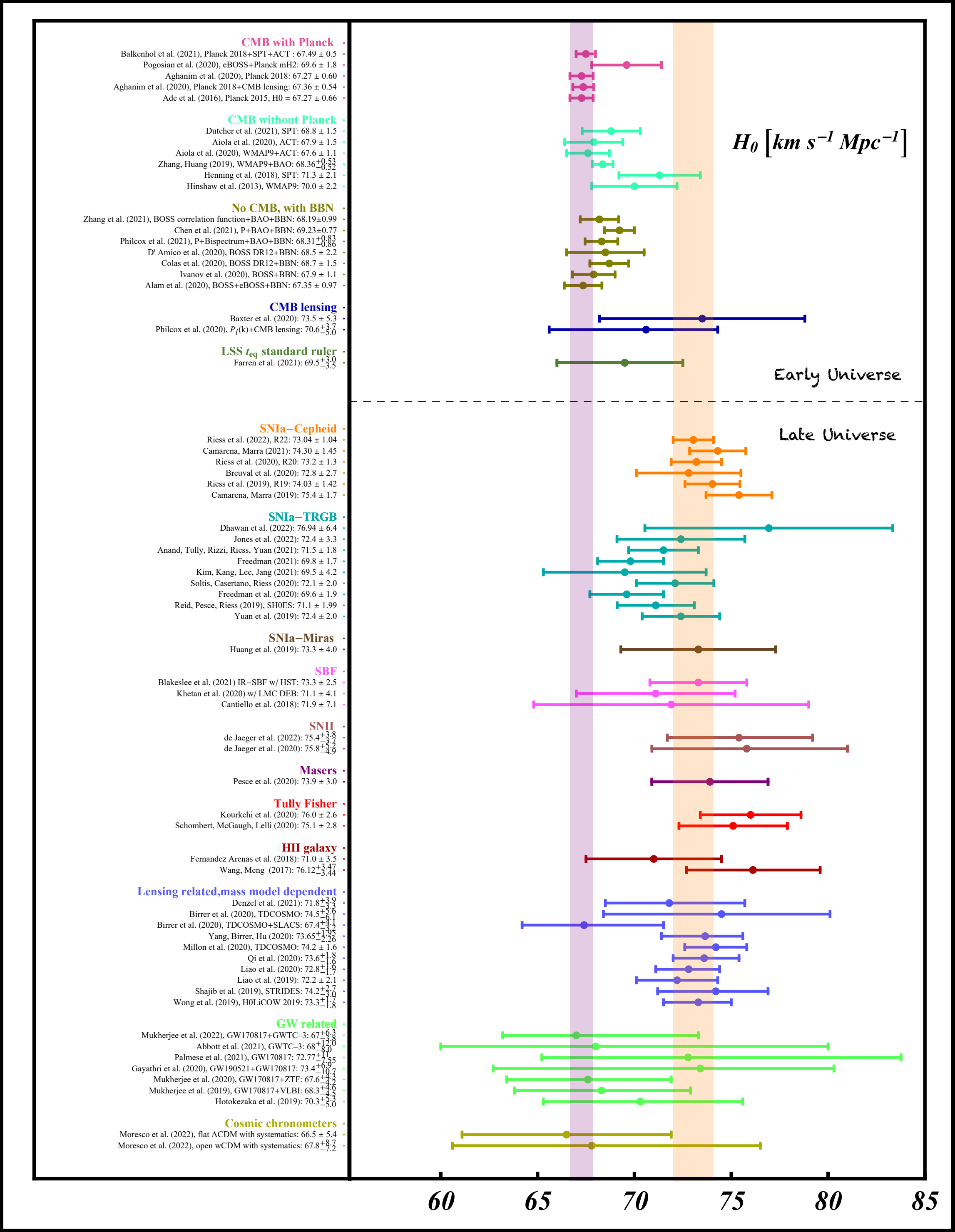
The H0 tension is the most statistically significant, long-lasting and widely persisting disagreement between:

The Planck estimate assuming a “vanilla" ΛCDM cosmological model:
H0 = 67.27 ± 0.60 km/s/Mpc
Planck 2018, Astron.Astrophys. 641 (2020) A6



The latest local measurements obtained by the SH0ES collaboration (R21).

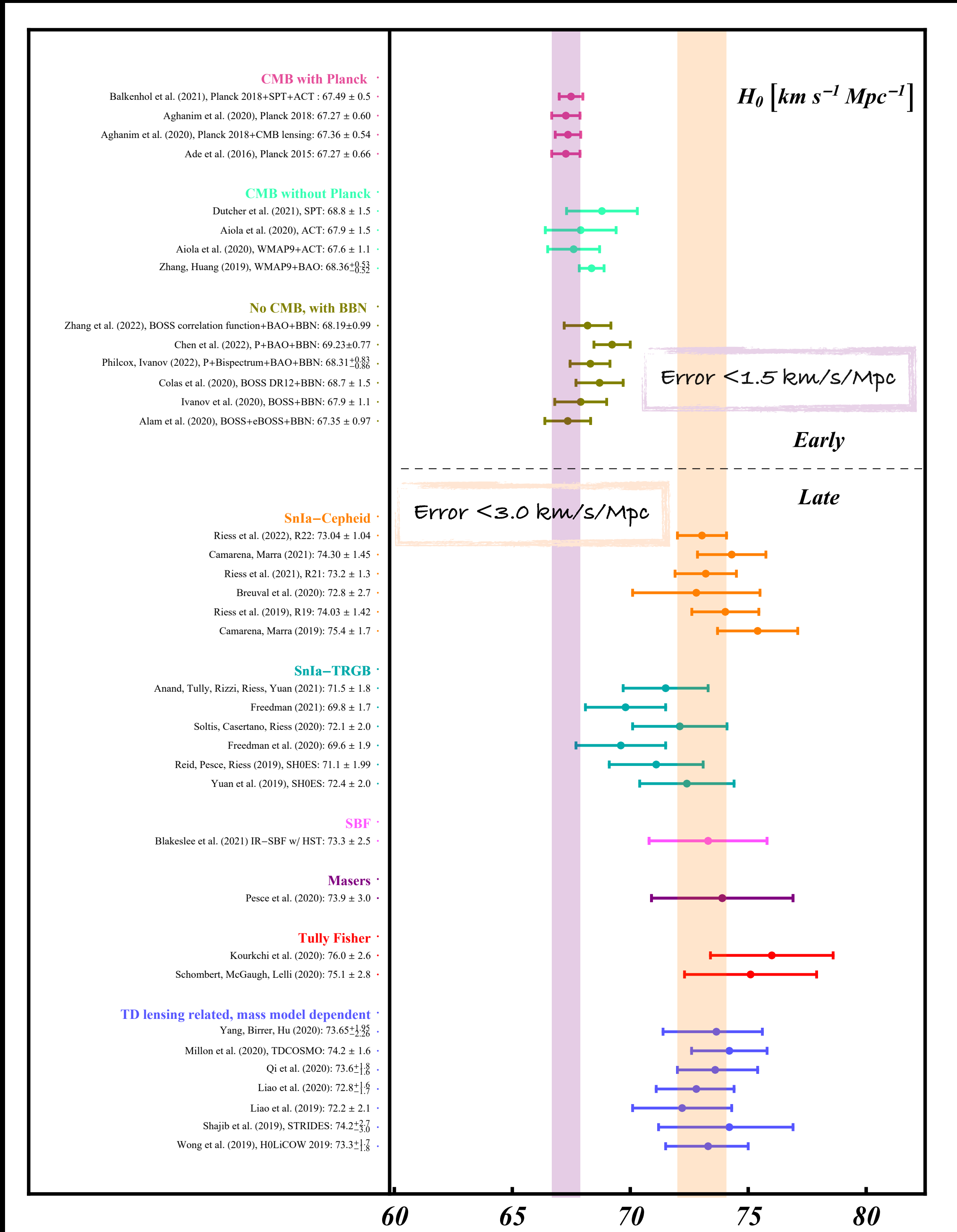
H0 = 73.04 ± 1.04 km/s/Mpc
Riess et al. arXiv:*2112.04510*



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

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

Abdalla et al., *JHEAp* 34 (2022) 49-211



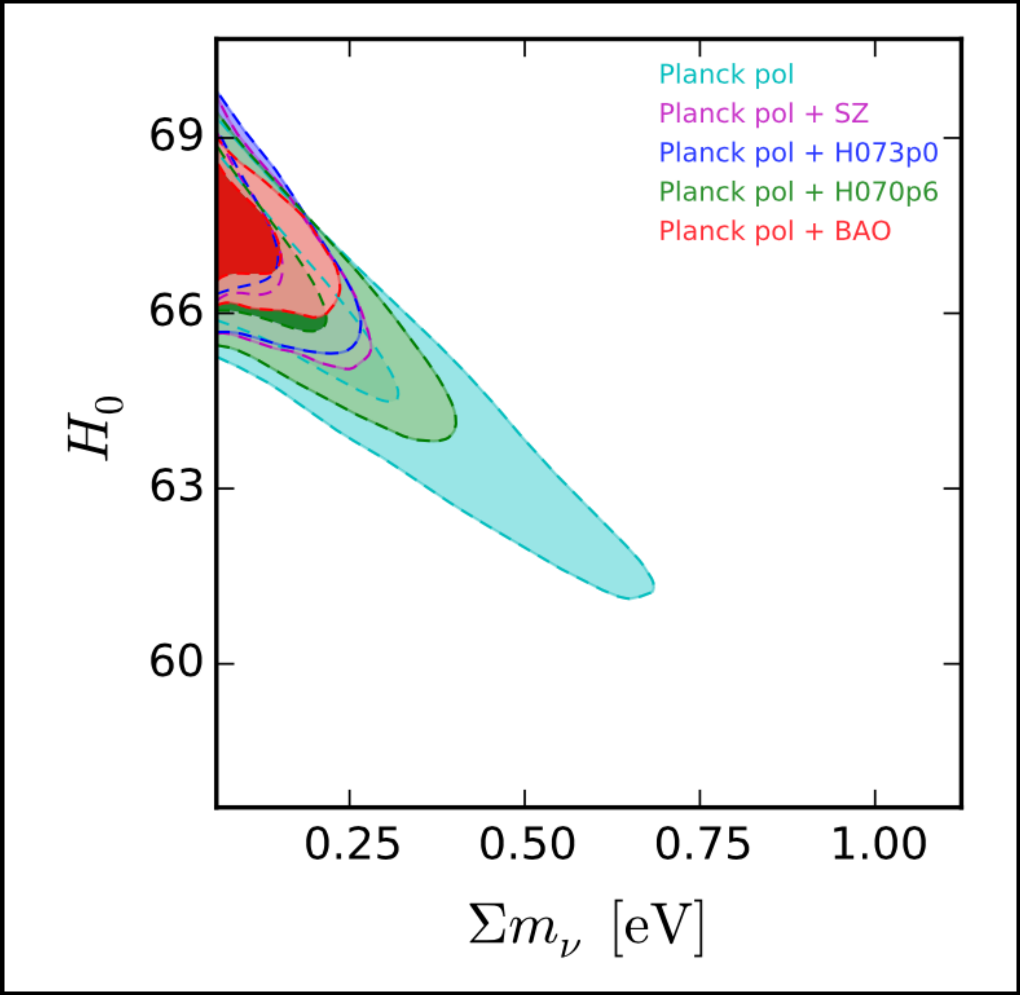
Abdalla et al., *JHEAp* 34 (2022) 49-211

High precision measurements of H0

The high precision and consistency of the data at both ends present strong challenges to the possible solution space and demands a hypothesis with enough rigor to explain multiple observations – whether these invoke new physics, unexpected large-scale structures or multiple, unrelated errors.

H0 affects total neutrino mass

The H0 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

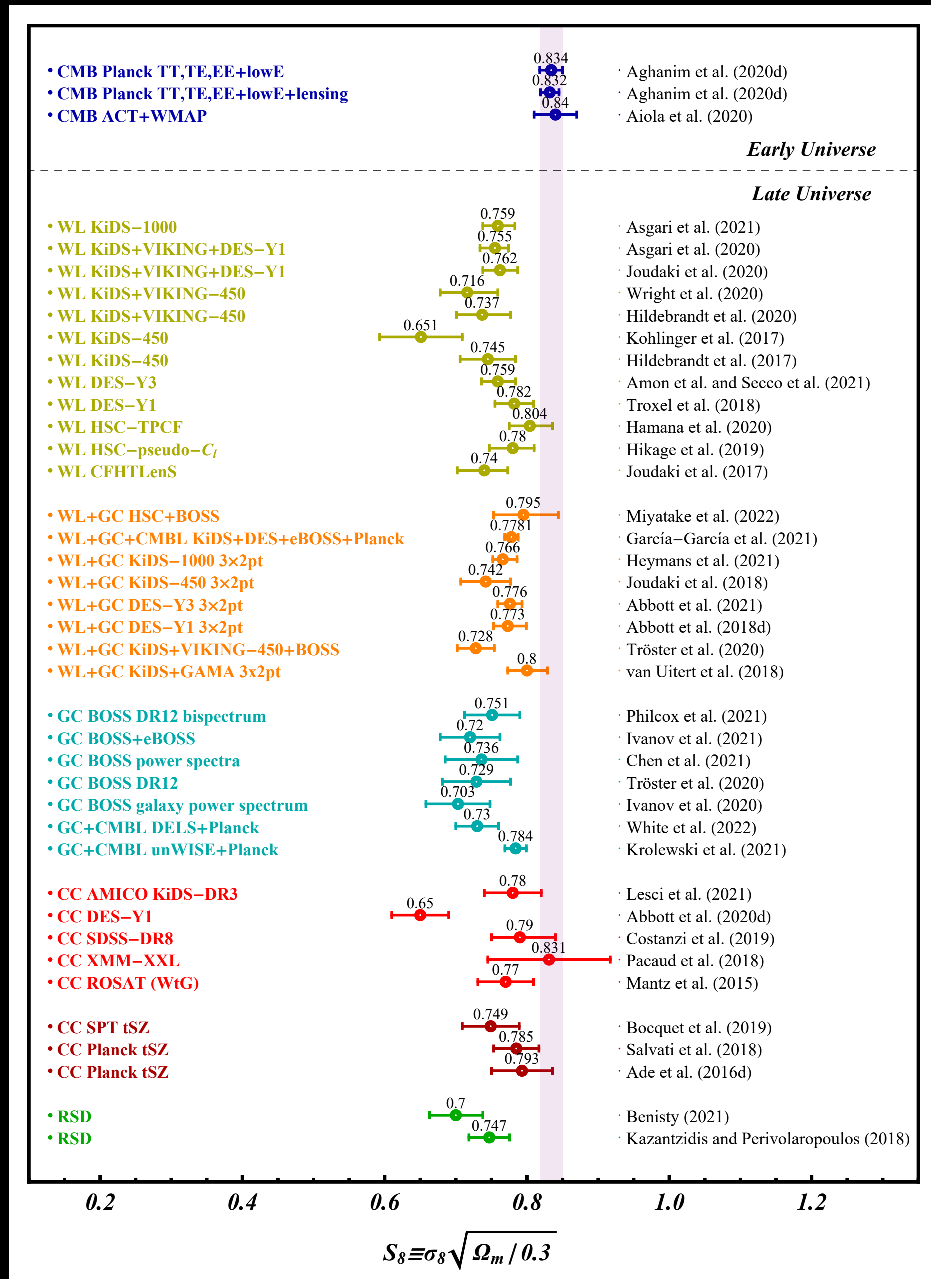
H0 affects Mass Ordering

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

When adding a prior on H0 as preferred by SH0ES the preference for the NO is stronger.

Capozzi, Di Valentino et al., *Phys.Rev.D* 104 (2021) 8, 083031

The S8 tension

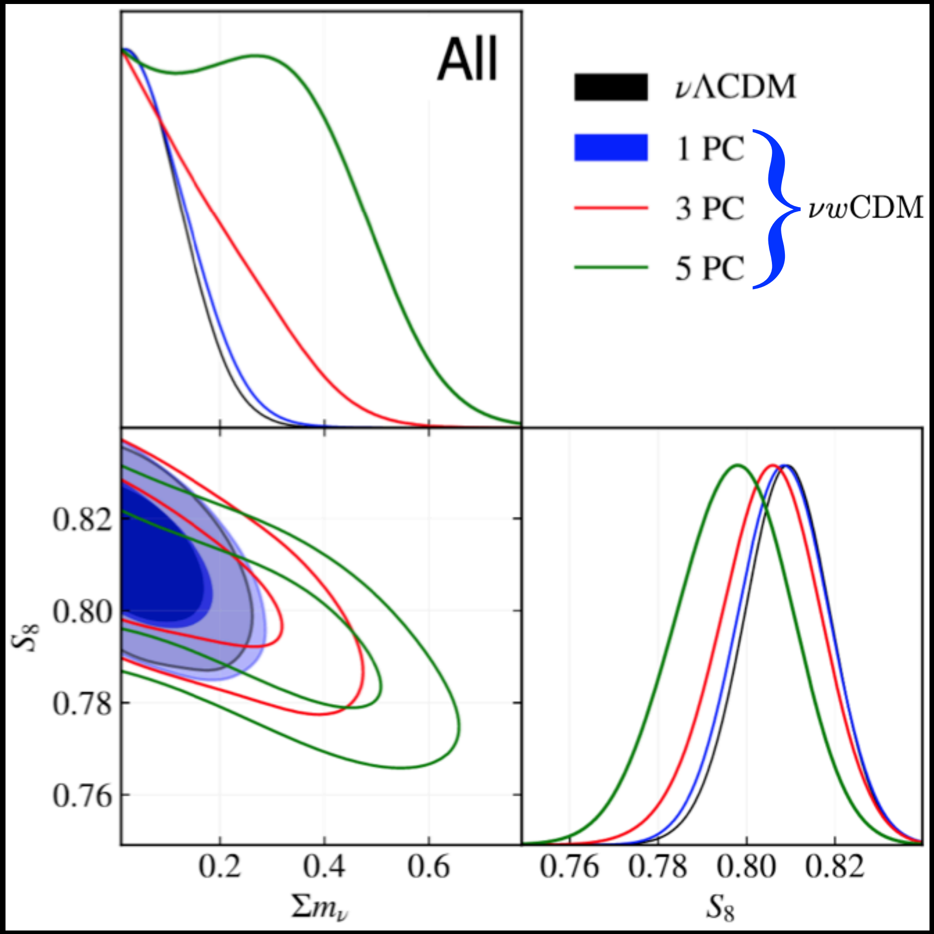


Abdalla et al., *JHEAp* 34 (2022) 49-211

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.



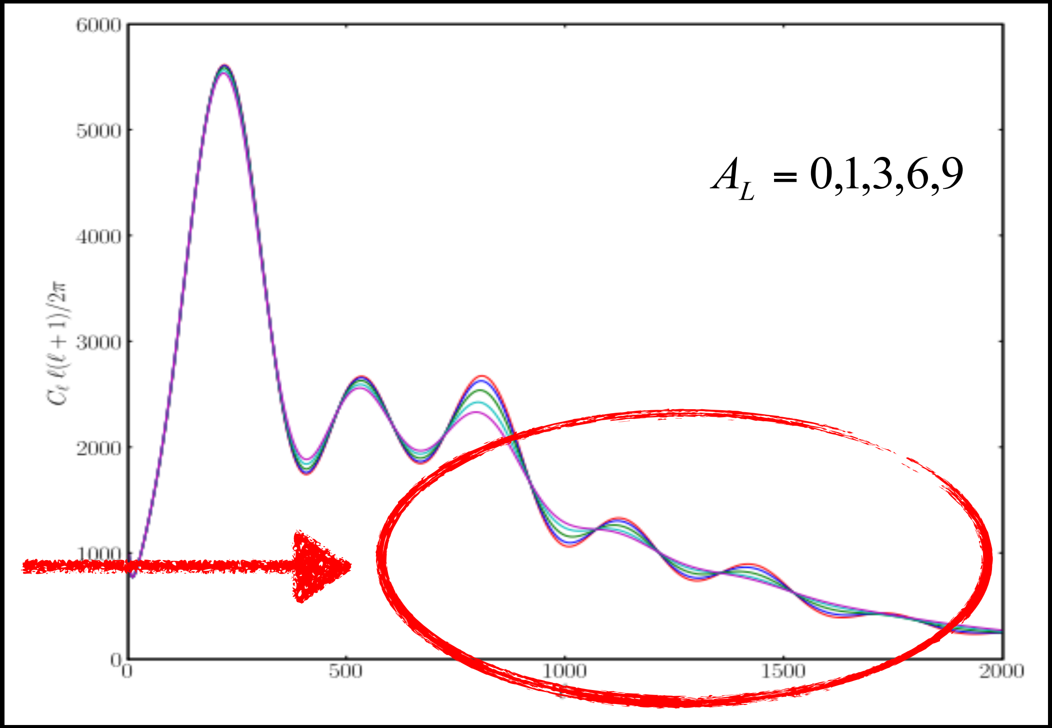
Diaz Rivero et al., *arXiv:1903.03125*

A_L internal anomaly

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

A_L : a failed consistency check

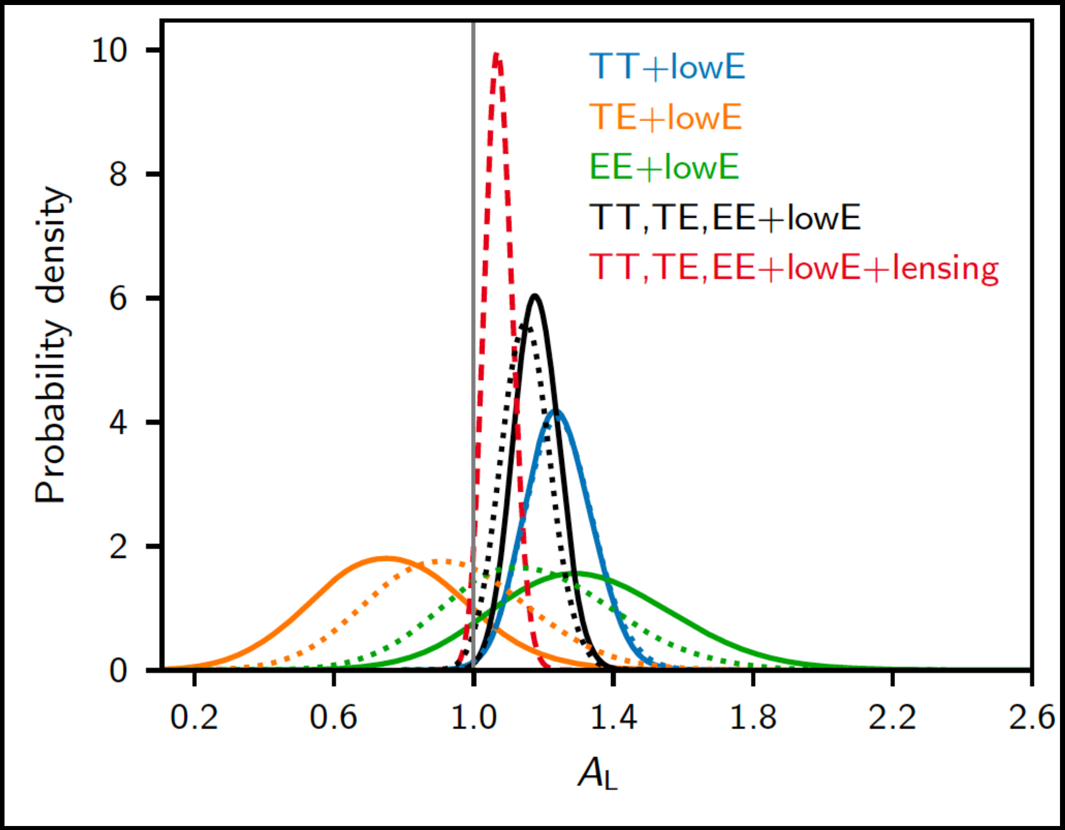
The Planck lensing-reconstruction power spectrum is consistent with the amplitude expected for ΛCDM models that fit the CMB spectra, so the Planck lensing measurement is compatible with AL = 1.

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

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

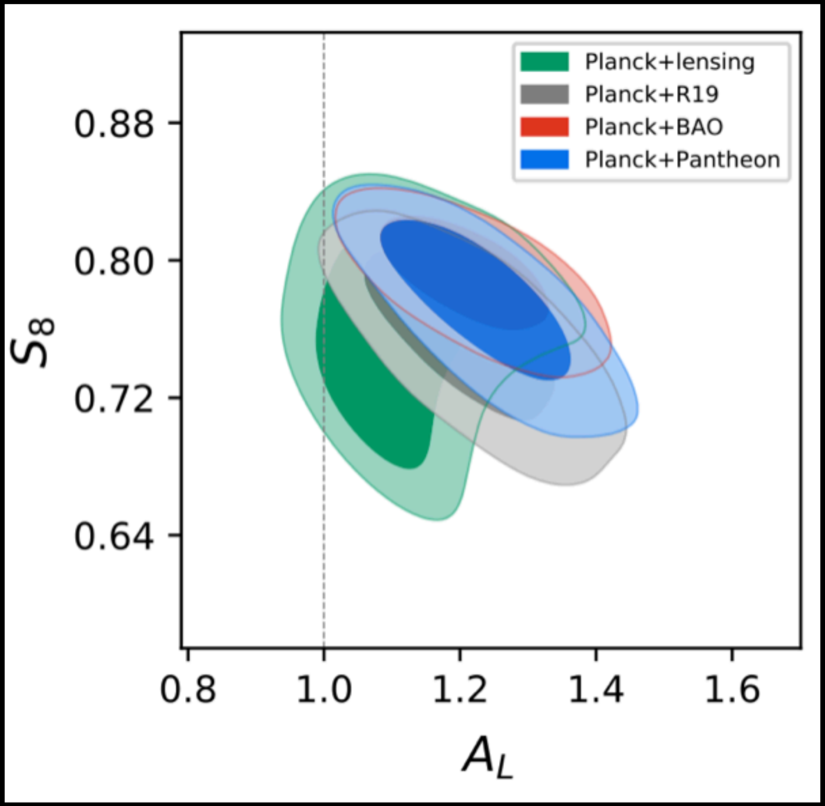
The preference for high AL is not just a volume effect in the full parameter space, with the best fit improved by $\Delta\chi^2 \sim 9$ when adding AL for TT+lowE and 10 for TTTEEE+lowE.

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



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

A_L can explain the S8 tension



Di Valentino, Melchiorri and Silk, *JCAP* 01 (2020) 013

A_L that is larger than the expected value at about 3 standard deviations even when combining the Planck data with BAO and supernovae type Ia external datasets.

A_L affects mass ordering

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

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 ~2.

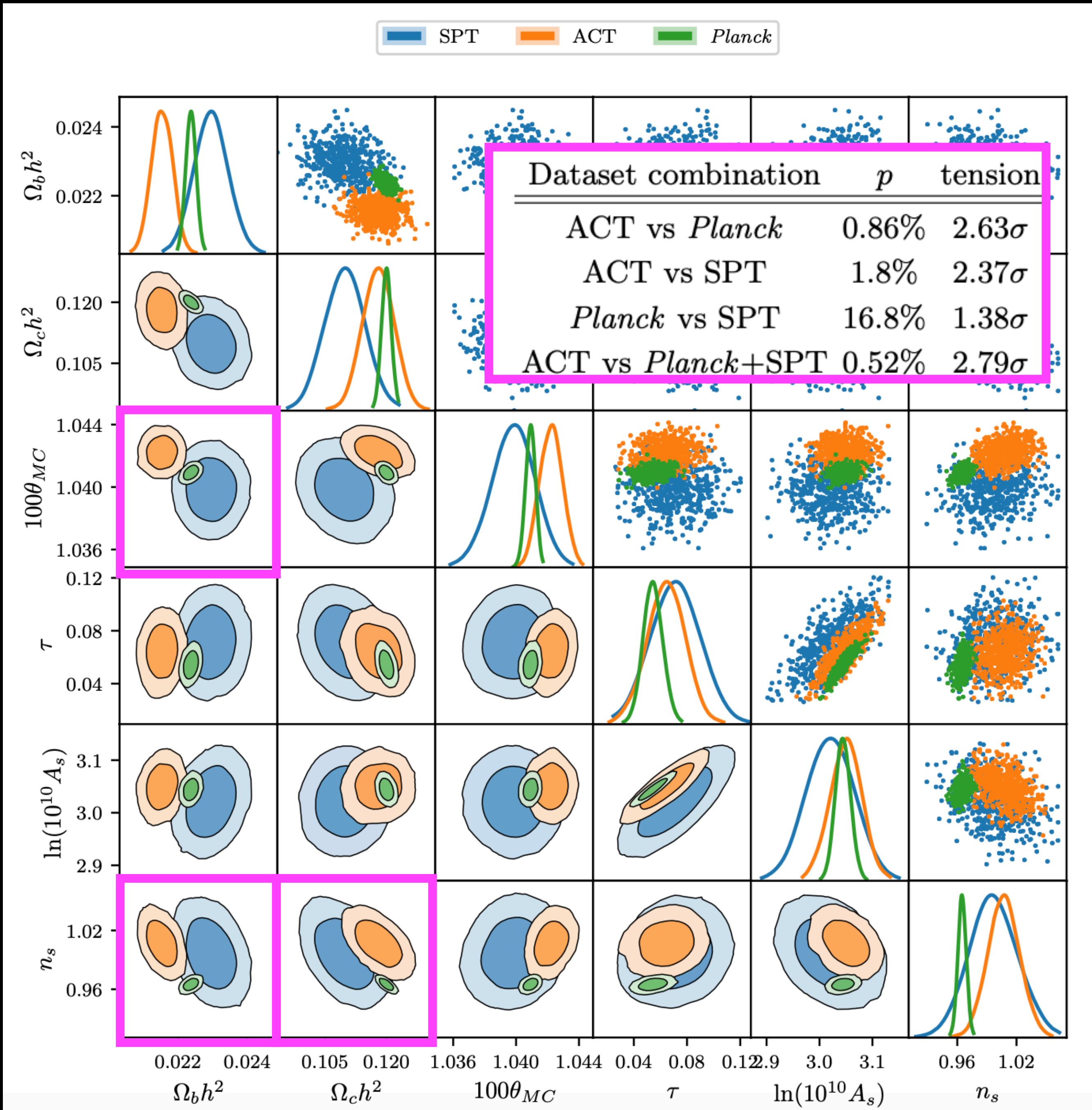
As a consequence, in these cases there is no more the preference for the normal ordering we have in the LCDM scenario.

Capozzi et al., *Phys.Rev.D* 104 (2021) 8, 083031

Alternative CMB data

Alternative CMB vs Planck: LCDM

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



Dataset combination	p	tension
ACT vs *Planck*	0.86%	2.63σ
ACT vs SPT	1.8%	2.37σ
Planck vs SPT	16.8%	1.38σ
ACT vs *Planck*+SPT	0.52%	2.79σ

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 LCDM

Alternative CMB vs Planck: Σmν

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

Constraints at 68% CL	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.51
Planck+BAO ($+A_{\rm lens}$)	< 0.19
Planck+Pantheon ($+A_{\rm lens}$)	< 0.25
Planck+Lensing ($+A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
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

We found that both the ACT-DR4 and SPT-3G data, when combined with WMAP, mildly suggest 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.

Alternative CMB vs Planck: Σmν

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

Constraints at 68% CL	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.51
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Planck+Pantheon ($+A_{\rm lens}$)	< 0.25
Planck+Lensing ($+A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
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

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

Alternative CMB vs Planck: Σmν

Constraints at 68% CL

	Σm_ν [eV]
Planck ($+A_{\rm lens}$)	< 0.50
Planck+BAO ($+A_{\rm lens}$)	< 0.22
Planck+Pantheon ($+A_{\rm lens}$)	< 0.47
Planck+Lensing ($+A_{\rm lens}$)	$0.38^{+0.12}_{-0.28}$
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

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

What about the 10 parameters extended model?

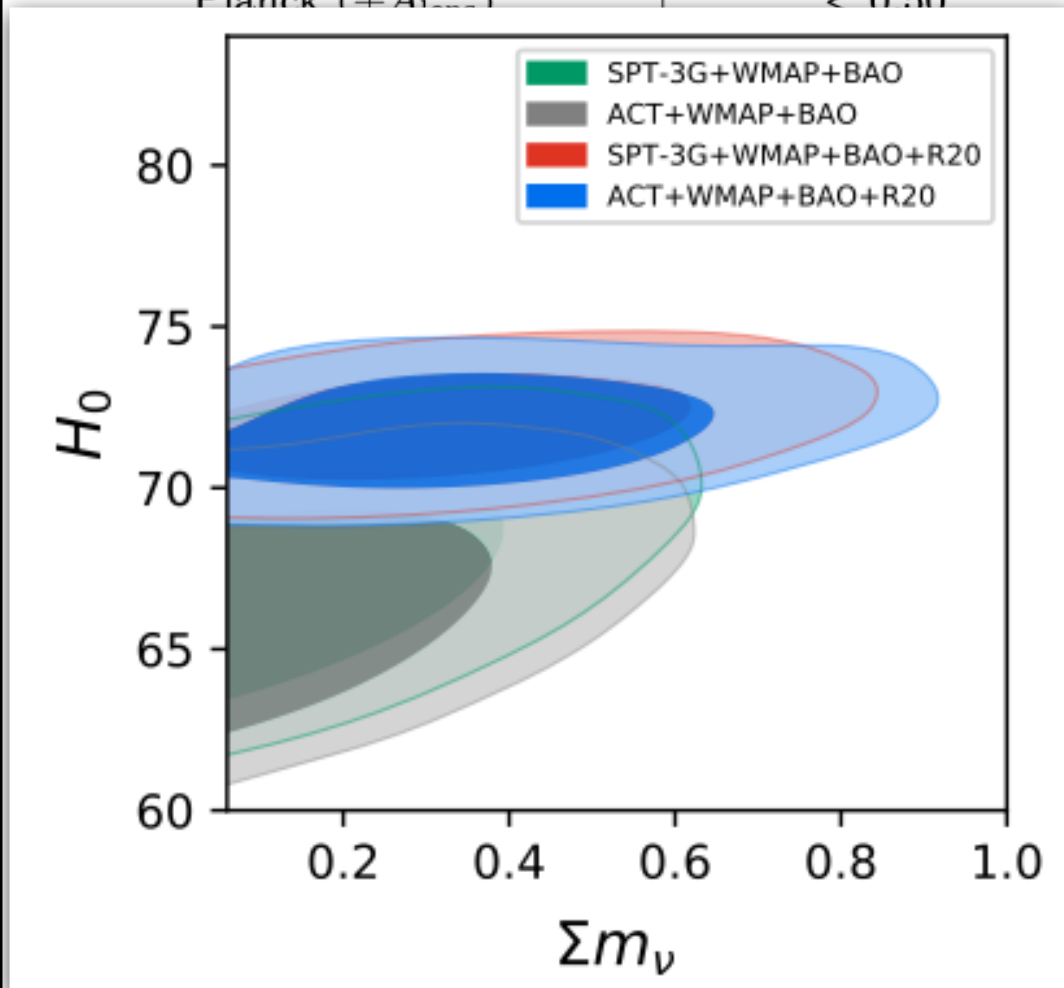
ACT-DR4 suggests a neutrino mass with Σmν = 0.81 ± 0.28 eV and SPT-3G Σmν < 0.56 eV at 68% CL.

Alternative CMB vs Planck: Σmν

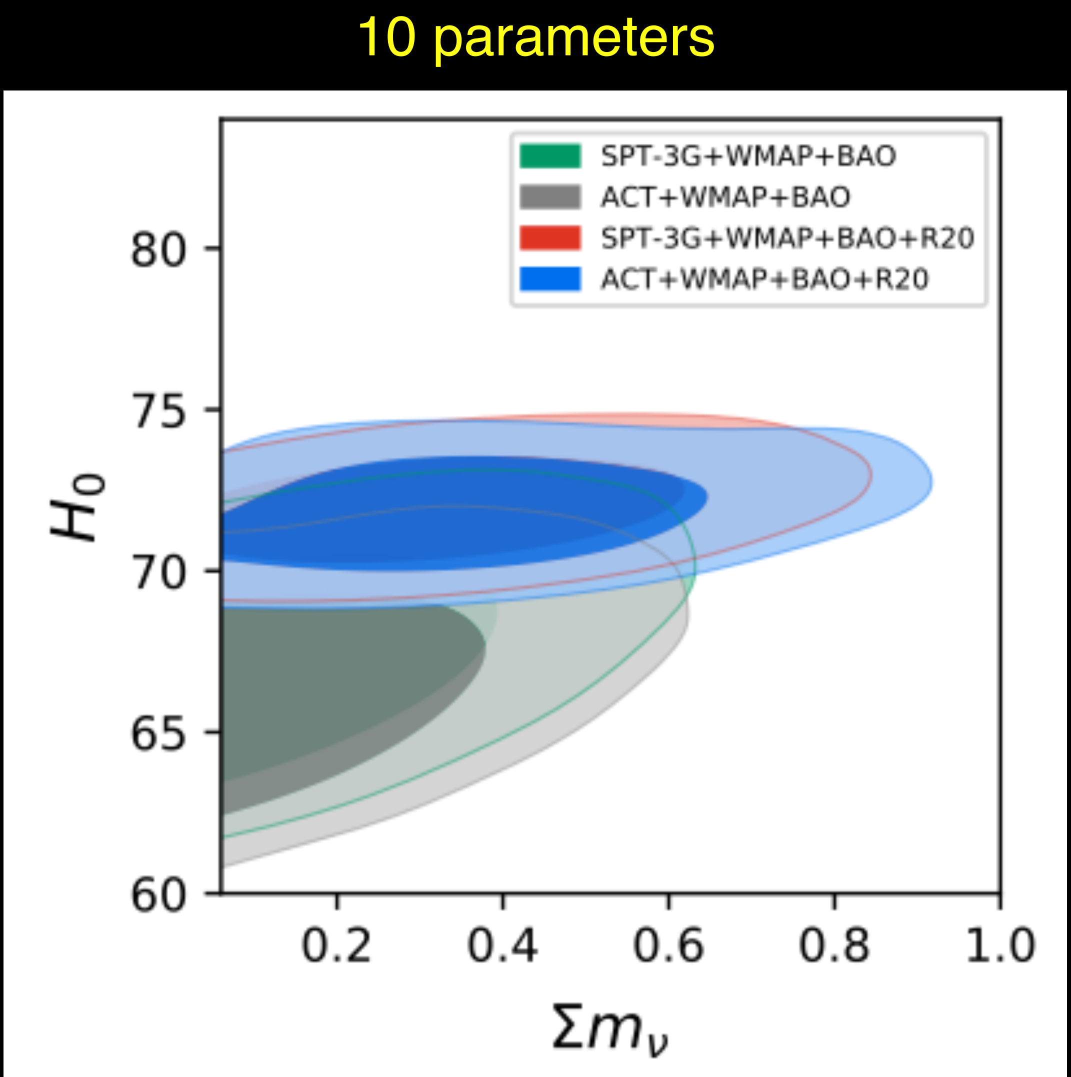
Di Valentino and Melchiorri, 2022 *ApJL* **931** L18

Constraints at 68% CL

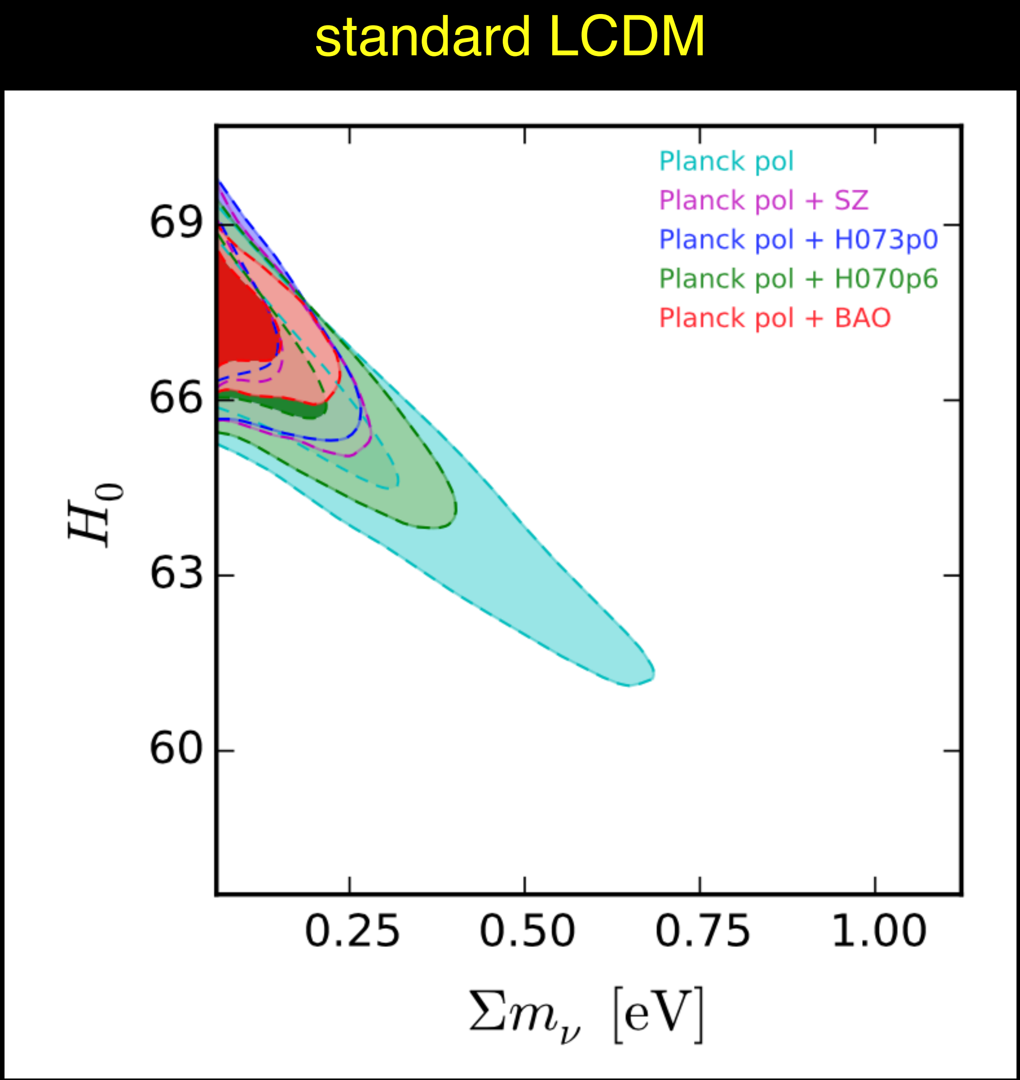
	Σm_ν [eV]
Planck (+A_{lens})	< 0.50
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	< 0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	< 0.32



When CMB and BAO constraints are considered in these extended cosmologies, they provide constraints on the Σmν vs H0 plane that clearly show a correlation between these two parameters, that is exactly the opposite of what is obtained under standard LCDM.



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



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

Mass ordering with alternative CMB data

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
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3	ΛCDM + Σ	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	ΛCDM + Σ	Planck TT, TE, EE + lensing + H_0(R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
5	ΛCDM + Σ	Planck TT, TE, EE + BAO + H_0(R19)	< 0.13 eV	3.1	< 0.13 eV	3.2
6	ΛCDM + Σ	Planck TT, TE, EE + BAO + lensing + H_0(R19)	< 0.12 eV	3.7	< 0.12 eV	3.8
7	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	ΛCDM + Σ	ACT + WMAP + τ_{prior}	< 1.21 eV	−0.1	< 1.00 eV	0.1
11	ΛCDM + Σ	ACT + WMAP + Planck lowE	< 1.12 eV	−0.1	< 0.87 eV	0.1
12	ΛCDM + Σ	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 Alens fixed to one.

Capozzi et al., *Phys.Rev.D* 104 (2021) 8, 083031

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 $\Sigma m_\nu < 0.09$eV at 95% CL.

NO appears to be favoured with respect to IO at 2.5-3σ.

Alternatives CMB data indicate instead a preference for massive neutrinos $\Sigma m_\nu \sim 0.4$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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