Prospects for the measurement of the absolute neutrino mass in cosmology

Yvonne Y. Y. Wong

UNSW Sydney

International Symposium on Neutrino Physics and Beyond, HKUST,

February 19 – 21, 2024

Measuring neutrino masses with cosmology…

Cosmological neutrino mass bounds go back a long way.

- Cowsik & McClelland (1972): $\sum m_\nu < 24\,\mathrm{eV}$
- Hinges on prediction of a **thermal background of neutrinos**.

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

The cosmic neutrino background…

Standard model predictions

Thermal background produced 1s after the big bang.

- **Present-day number density:**

$$n_{C\nu B} \simeq 110 \text{ cm}^{-3}$$

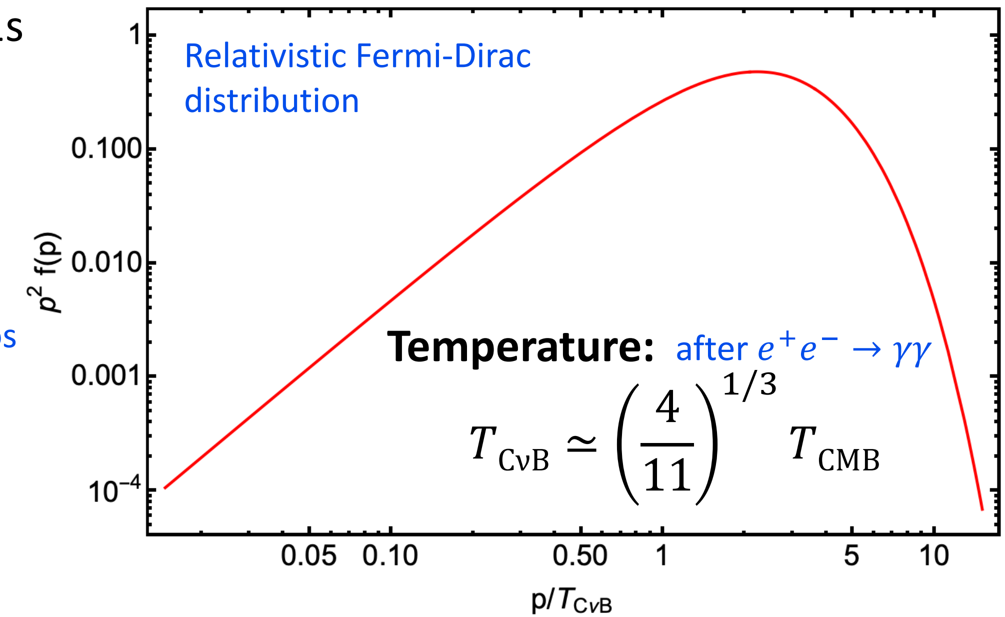
Per family of neutrinos +antineutrinos

- **Total energy density** in non-relativistic neutrinos:

$$\Omega_{C\nu B} \simeq \frac{\sum m_\nu}{93\, h^2 \text{ eV}}$$

Neutrino (hot) dark matter

Reduced Hubble parameter



Temperature: after $e^+e^- \to \gamma\gamma$

$$T_{C\nu B} \simeq \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

$$\Omega_{C\nu B} \lesssim 1$$

Demand no overclosure

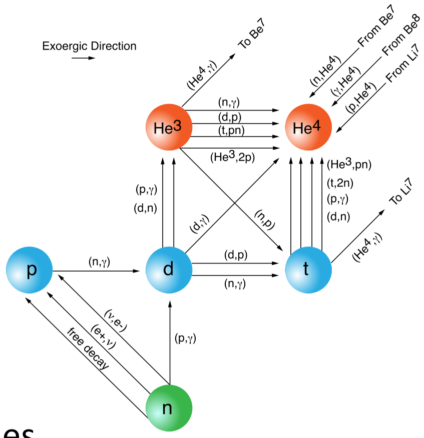
$$\sum m_\nu \lesssim 24 - 45 \text{ eV}$$

Cowsik & McClelland bound; depending on h

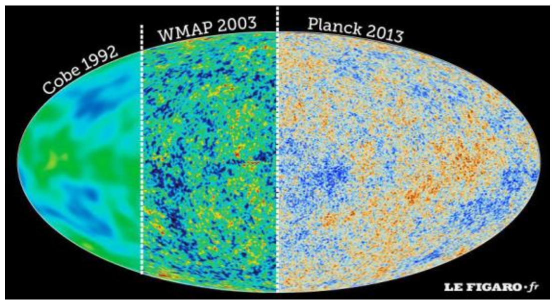
Modern cosmological neutrino mass bounds…

… are based on how the **properties of the CνB** affect the events that take place after its formation.

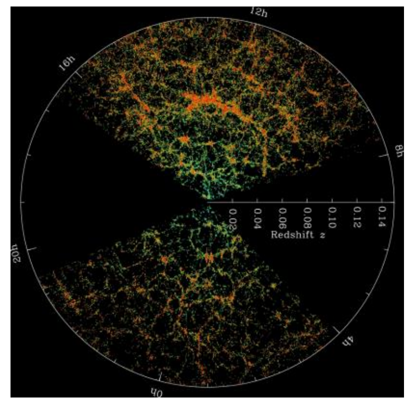
Light element abundances



CMB anisotropies



Large-scale matter distribution

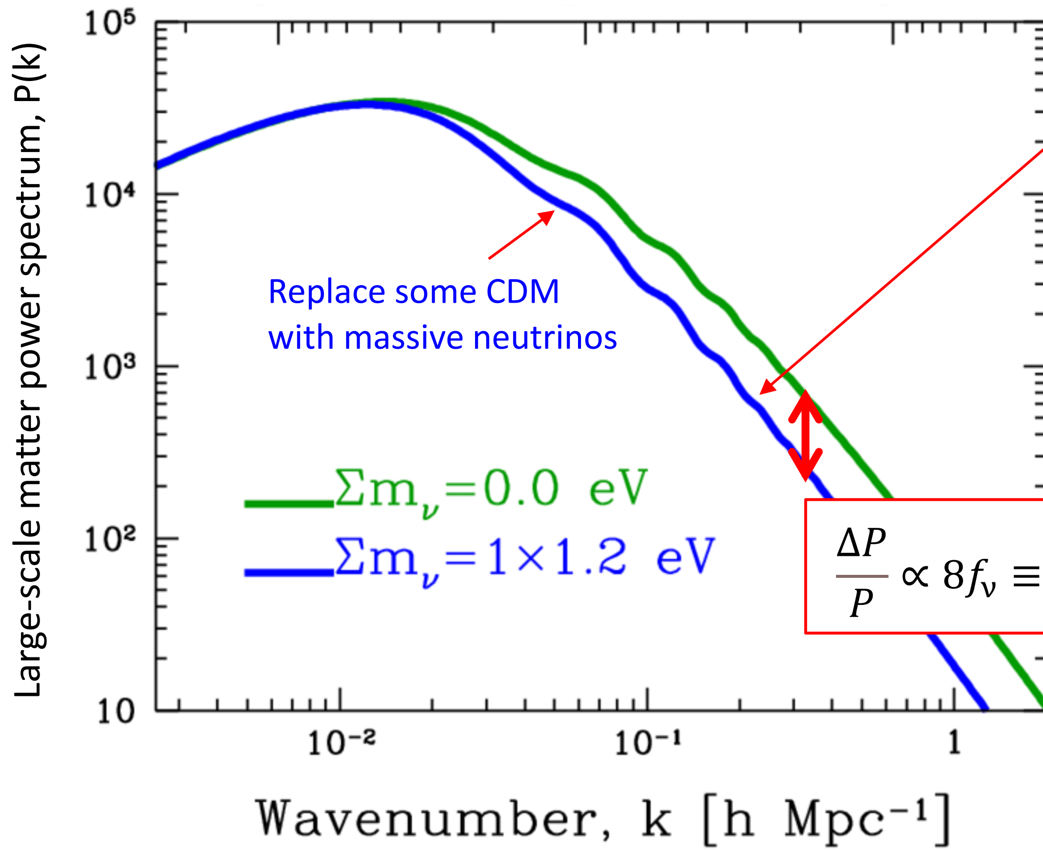


Properties of the CνB probed:

- Light element abundances: N_{eff} (expansion rate)
- CMB anisotropies: N_{eff} (expansion rate); $\sum m_\nu$ **(perturbation growth)**; Interactions (free-streaming); Lifetime (free-streaming)
- Large-scale matter distribution: $\sum m_\nu$ **(perturbation growth)**

Large-scale matter power spectrum…

From linear perturbation theory



Suppression of power due to free-streaming induced potential decay

f_ν = Neutrino fraction

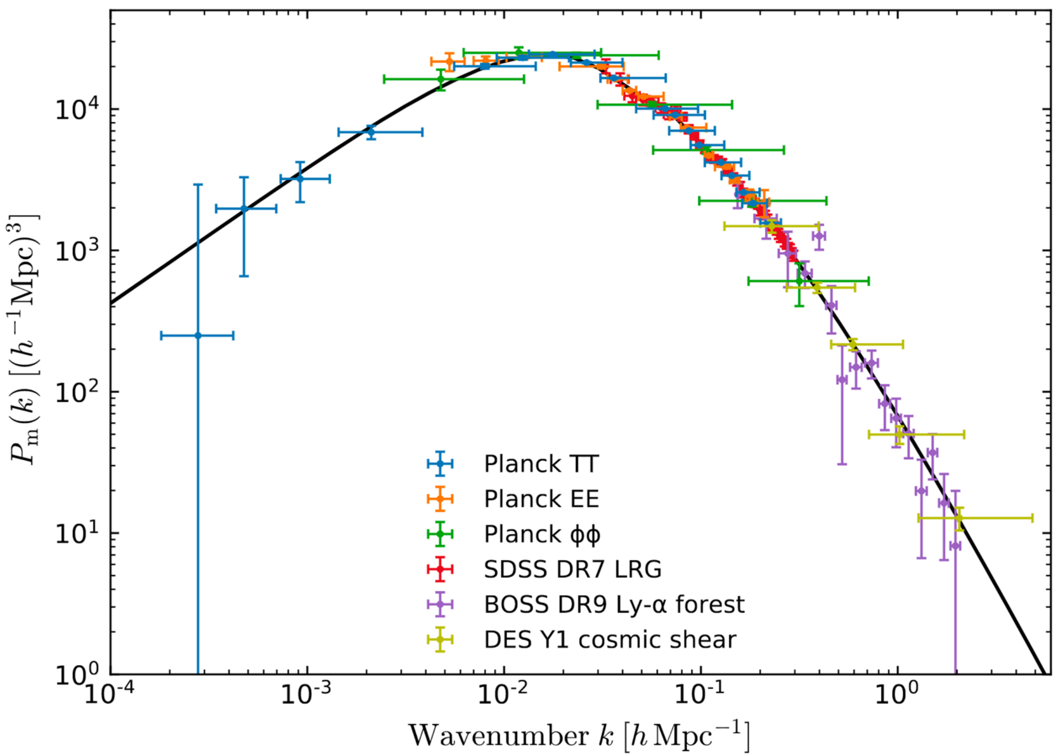
$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8\,\frac{\Omega_\nu}{\Omega_m}$$

The larger the mass sum, the stronger the suppression.

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\mathrm{eV}}$$

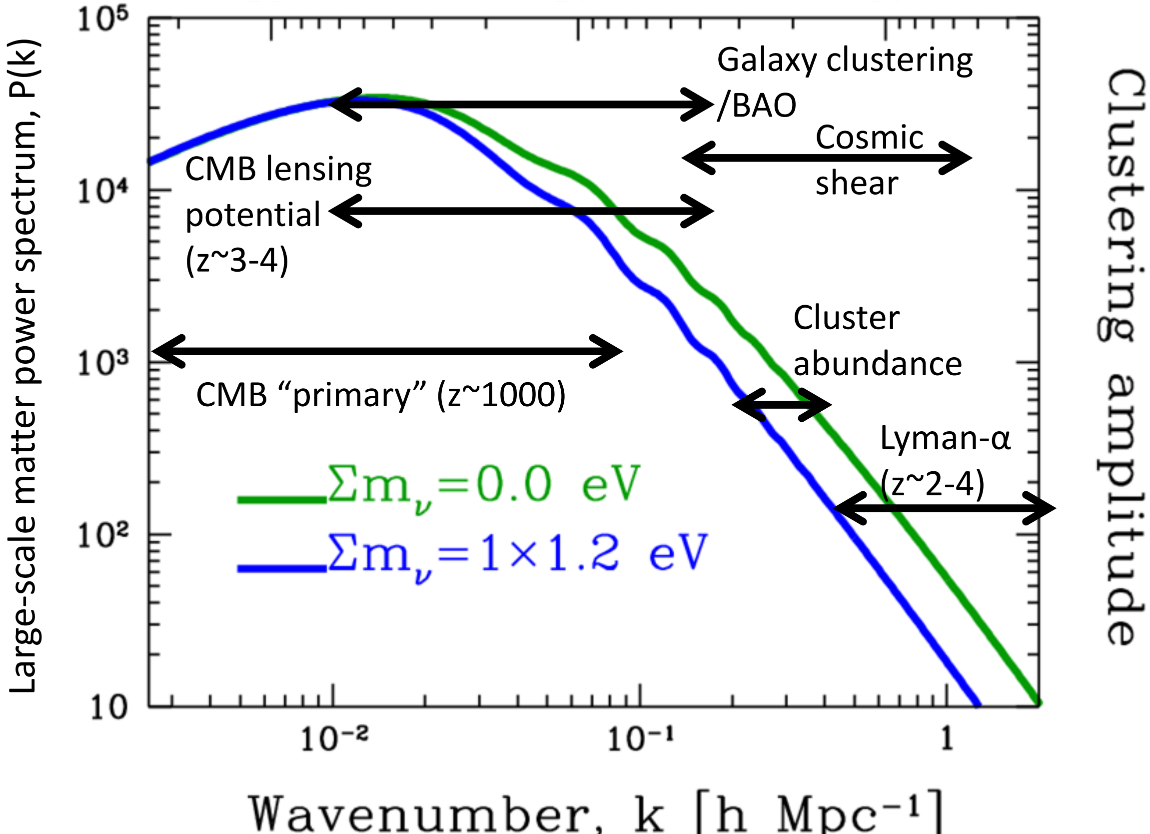
Who can measure it?

Large-scale power spectrum measurements circa 2018

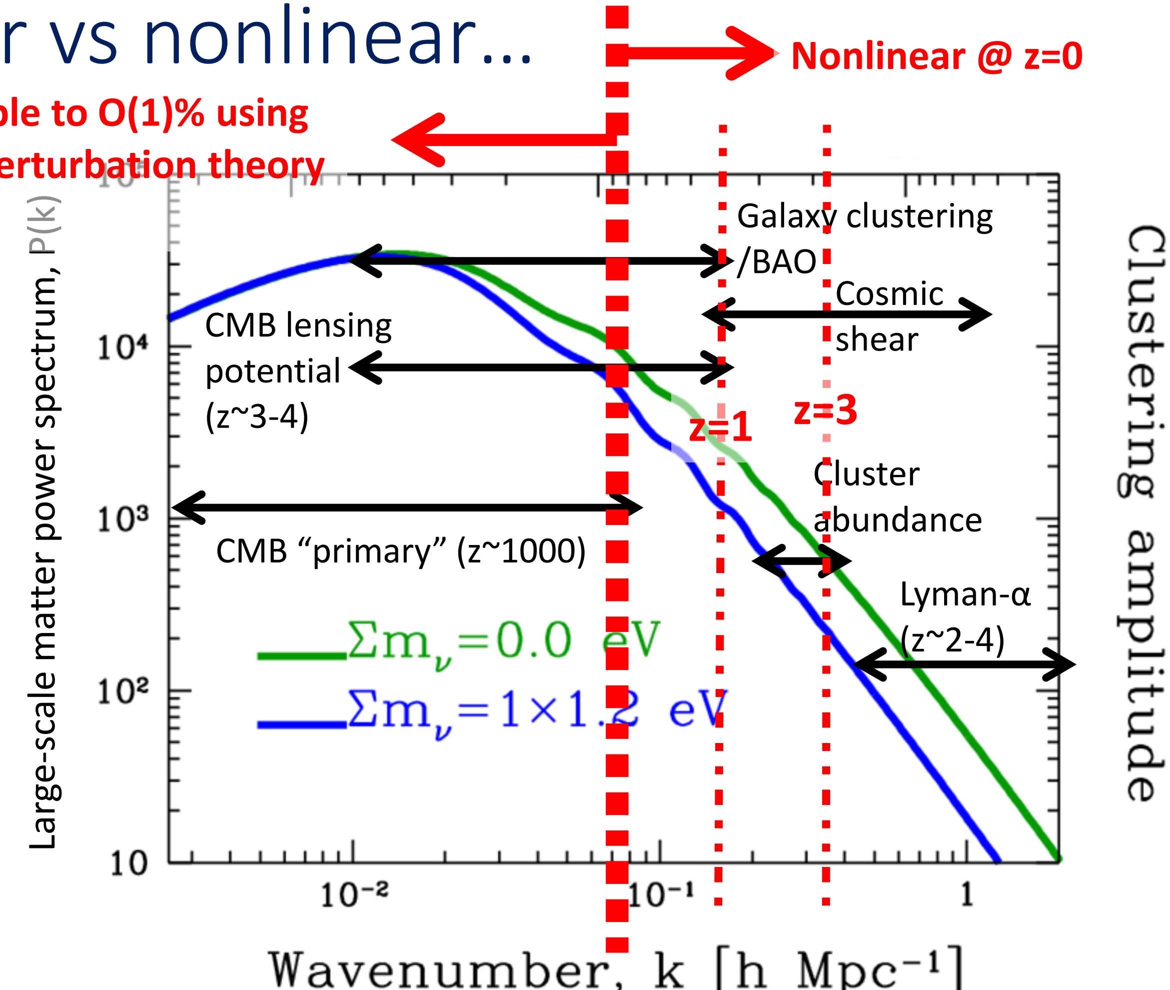


Akrami et al. 2018

Who can measure it?



Linear vs nonlinear…



There are nonlinearities and nonlinearities…

	Nonlinear Dark matter (collisionless)	**Baryonic astrophysics @ k ~ 1/Mpc**	**Empirical tracers or proxies**
CMB	No	No	No
BAO	Mild	No	Mild
Cosmic shear	Yes	No	No
Galaxy power spectrum	Yes	No	Assume galaxy number density tracks DM density
Cluster abundance	Yes	No	X-ray temperature, cluster richness as proxies for mass
Lyman alpha	Yes	Hydrogen distribution	No
Calculable from first principles (i.e., described by a Lagrangian)?	**Yes**	**No**	**No**

Constraints on the neutrino mass sum…

ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Two different high-ℓ likelihood functions

		+CMB lensing	+BAO (non-CMB)	+CMB lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 number	0.72	0.68	0.21	n/a
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
2015 number	0.49	0.59	0.17	n/a

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Do you need to believe any of it?

Or to what extent should you trust these bounds?

There are certainly assumptions…

To even constrain neutrino mass cosmologically, there must be a cosmic neutrino background to begin with.

- There is **no reason** to think that this is not the case:
  - Cosmological data is consistent with there being 3 neutrino families.
  - Also consistent with them not interacting much amongst themselves or with other constituents.
- But even then there are caveats and some (small) room for play.

Caveat 1: which mass ordering...

Bounds on the mass sum do depend to an extent on the neutrino mass ordering assumed in the fit.

- Using different mass ordering can **change the bounds by up to ~40%**.
- ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Planck 2018 TT+TE+EE+lowE+lensing+BAO

$$\sum m_\nu < 0.121 \text{ eV}$$ Degenerate

$$\sum m_\nu < 0.146 \text{ eV}$$ Normal hierarchy

$$\sum m_\nu < 0.172 \text{ eV}$$ Inverted hierarchy

Official Planck benchmark: $\sum m_\nu < 0.12$ eV

Roy Choudhury & Hannestad 2019

Caveat 2: model dependence...

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

All bounds so far come from a ΛCDM+neutrino 7-parameter fit.

- Can test for how adding more fit parameters change the bound.

	Model	Degenerate	Normal	Inverted
	Baseline ΛCDM+Σm_ν	**0.121**	**0.146**	**0.172**
Primordial tensors	+ r	0.115	0.142	0.167
	+ w	0.186	0.215	0.230
Dynamical dark energy	+ $w_0 w_a$	0.249	0.256	0.276
Dynamical dark energy	+ $w_0 w_a$, $w(z) > -1$	0.096	0.129	0.157
Spatial curvature	+ Ω_k	0.150	0.173	0.198

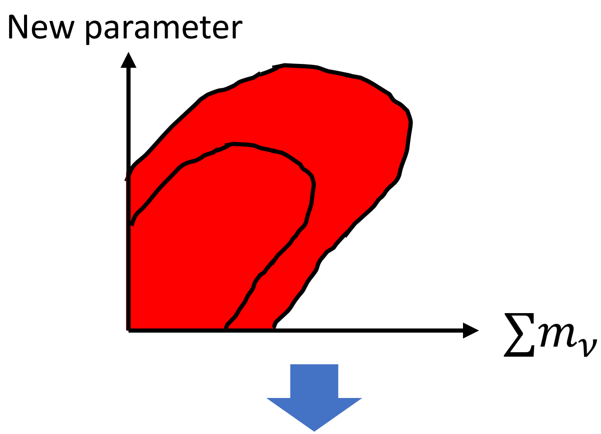
Roy Choudhury & Hannestad 2019

- This sort of game can buy you a factor ~2 relaxation, but typically no more.
- But it does not always work in the desired direction → blame it on **Bayesian stats**.

Blame it on Bayesian statistics…

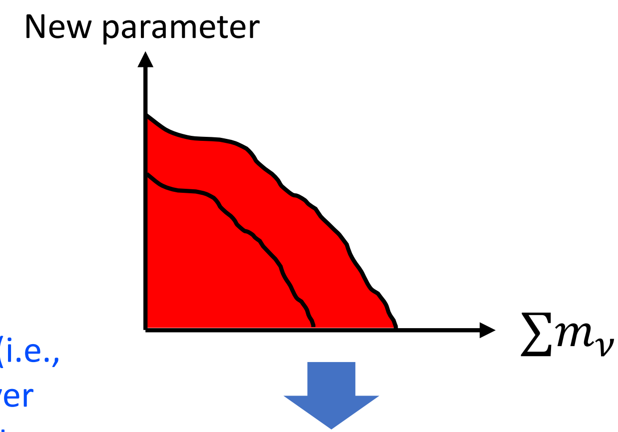
These X% credible intervals correspond to the **fractional area under the 1D marginalised posterior**.

- They depend on what degeneracy directions the additional parameters bring into the game.



Relaxed bound on $\sum m_\nu$

Marginalise (i.e., integrate) over new parameter



Tighter bound on $\sum m_\nu$

Caveat 3: more data ≠ improved bounds…

- Sometimes the extra data do bring in genuinely new physics info.
  - The resulting improvements are noticeably big.
  - **You need to pay attention to these**.

Constraints on the neutrino mass sum…

ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

		+CMB lensing	+BAO (non-CMB)	+CMB lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 number	0.72	0.68	0.21	n/a
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
2015 number	0.49	0.59	0.17	n/a

Add high-ℓ polarisation

Two different high-ℓ likelihood functions

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Constraints on the neutrino mass sum…

ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

		+CMB lensing	+BAO (non-CMB)	+CMB lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 number	0.72	0.68	0.21	n/a
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
2015 number	0.49	0.59	0.17	n/a

Add BAO

Two different high-ℓ likelihood functions

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Caveat 3: more data ≠ improved bounds…

- Sometimes the extra data do bring in genuinely new physics info.
  - The resulting improvements are noticeably big.
  - **You need to pay attention to these**.

- **Marginally improved bounds** (~20%) are sometimes just accidents of marginal incompatibility of the different data sets
  - The inference process (and even how we define X% bounds) can end up translating the incompatibility into an "improved measurement".

  → It could easily have gone the other way to become a "worse measurement".
  - **You really shouldn't read too much into these**.

Constraints on the neutrino mass sum…

ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

		+CMB lensing	+BAO (non-CMB)	+CMB lensing+BAO
Planck2018 TT+lowE	**0.54**	**0.44**	**0.16**	**0.13**
2015 number	0.72	0.68	0.21	n/a
Planck2018 TT +lowE+TE+EE	**0.26**	**0.24**	**0.13**	**0.12**
Planck2018 TT +lowE+TE+EE [CamSpec]	**0.38**	**0.27**	n/a	**0.13**
2015 number	0.49	0.59	0.17	n/a

Add CMB lensing

Two different high-ℓ likelihood functions

Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Aghanim et al. [Planck] 2018
Ade et al. [Planck] 2015

Caveat 4: non-standard neutrino physics…

You can also **alter the physics and properties of the CνB** to physically relax cosmological constraints.

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

- Neutrino decay: $\sum m_\nu \lesssim 0.42$ eV — Abellán, Chacko, Dev, Du, Poulin & Tsai 2022
- Neutrino spectral distortion: $\sum m_\nu \lesssim 0.37$ eV — Oldengott, Barenboim, Kahlen, Salvado & Schwarz 2019; Alvey, Escudero & Sabti 2022
- Late-time neutrino mass generation: $\sum m_\nu \lesssim 1.46$ eV — Dvali & Funcke 2016; Lorenz, Funcke, Löffler & Calabrese 2021
- …

These "physics" games can usually buy you more room for play, if you will accept the non-standard neutrino physics.*

* IMHO, these are no less palatable than the large r, Ω_k, or dynamical DE of Caveat 2.

Take-home message…

Probably the best you can do now re cosmological neutrino mass bounds is to treat them as ballpark figures.

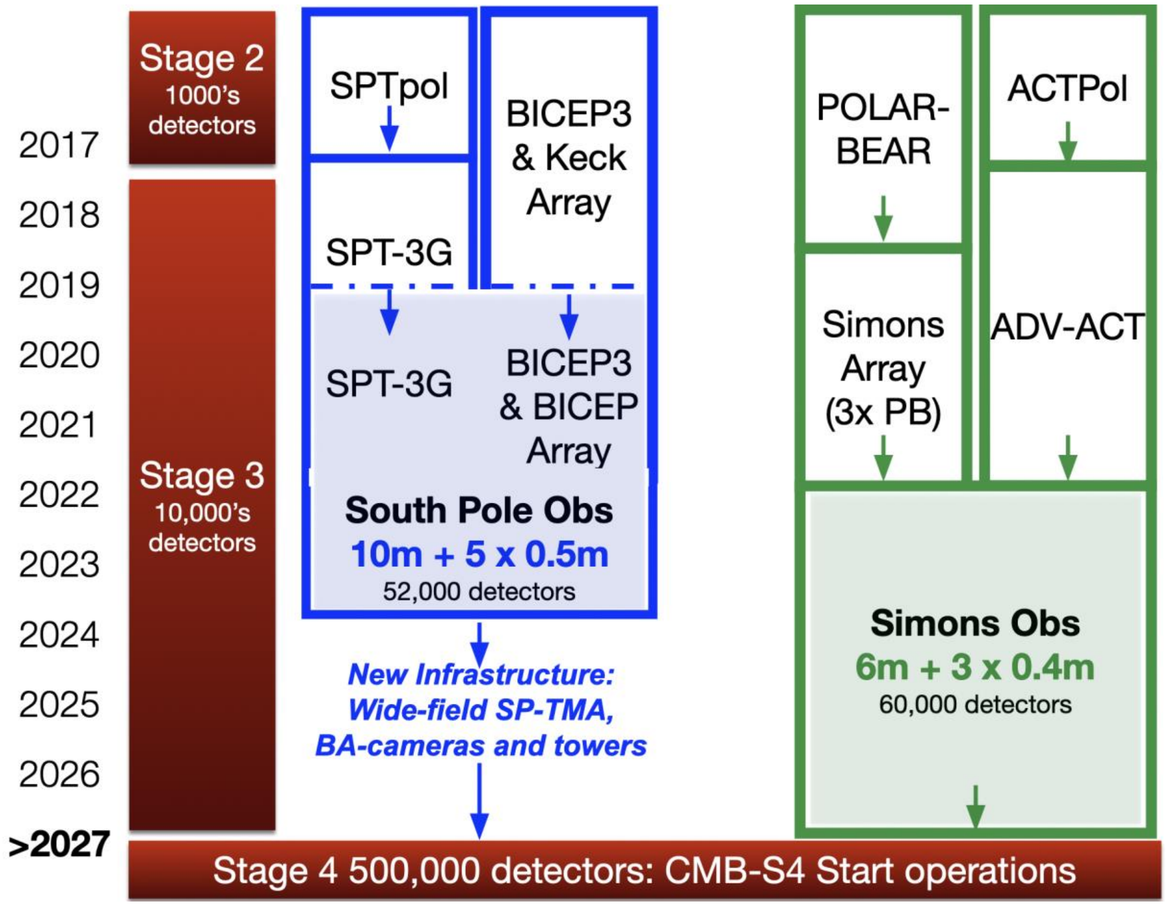
- You can evade the tightest constraints to a good extent, but **it's not like anything goes**.

- In the same vein, please **do not over-interpret bounds**.
  - That second significant digit doesn't mean much.
  - Anything from marginal incompatibility of data sets to a bad choice of fit parameters/priors could shift bounds by 10-20%.

Future probes…

What to expect in the future?

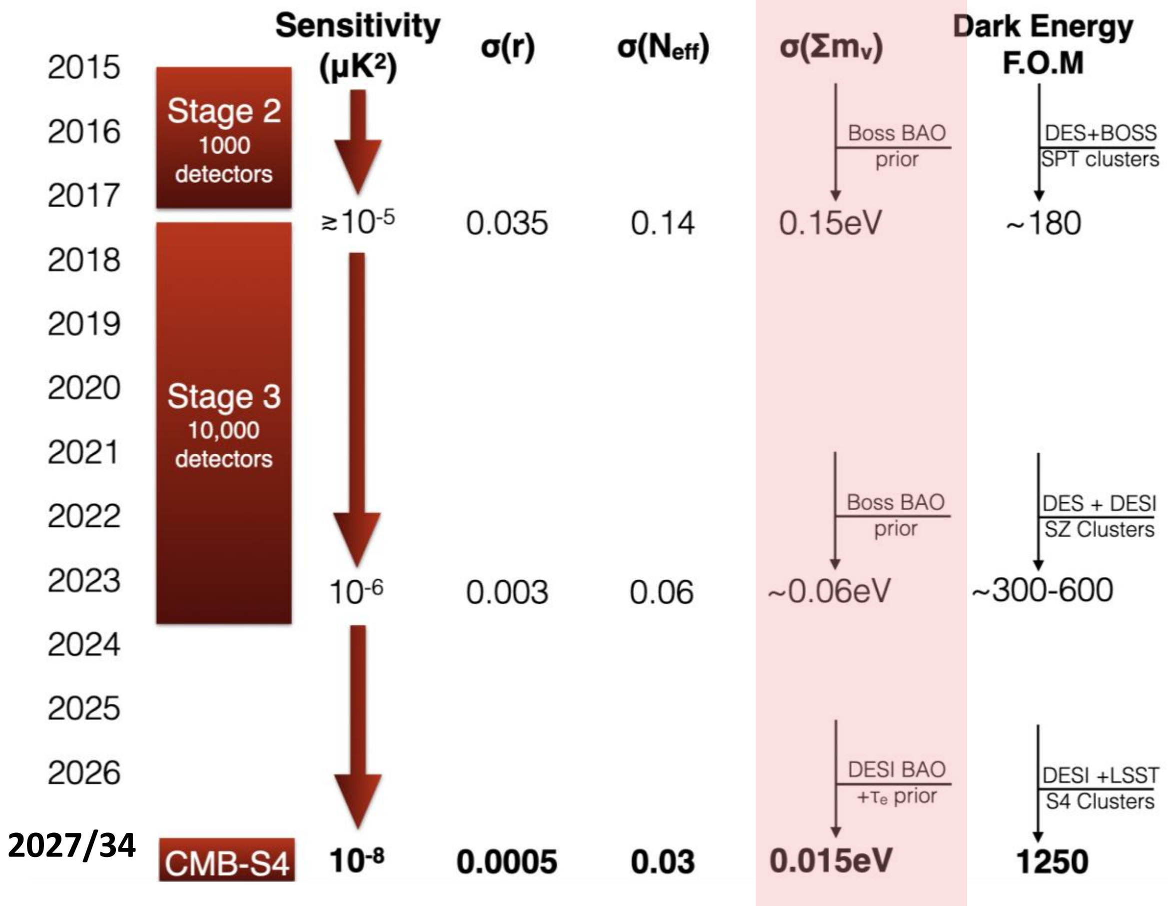
CMB observations



John Carlstrom

What to expect in the future?

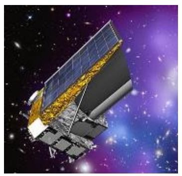
CMB observations



John Carlstrom

What to expect in the future?

Galaxies, cosmic shear, clusters, etc.

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to $N_{\rm eff}$
	**ESA Euclid**	Launched 2023	$0.011 - 0.02$ eV	0.05
	**LSST**	202X	0.015 eV	0.05

These numbers mean, if the true neutrino mass sum is $\sum m_\nu = 0.06$ eV, then it is possible to measure it with $(3-5)\sigma$ significance.

Do you need to believe these forecasts?

Yes and no.

- Forecasts are just that: **an estimate** of what an instrument can do under an assumed set of conditions.*

  - * including our ability to predict theoretically the observables given an underlying cosmology theory.

  - Clearly, some observables are inherently under better control than others (see **nonlinearities** slide).

- So, again, your best bet is to treat these forecasted sensitivities as **ballpark figures**.

What it takes for me (Y^3W) to believe it?

Suppose one of these future probes announces a cosmological detection of the neutrino mass sum. Would I believe it?

- I might pay attention, depending on who is announcing it (again, refer to **nonlinearities** slide).
- But I won't believe any of it until **multiple observations/data combinations** point to the same mass sum value with some statistical significance.

Summary…

These is no doubt that neutrino masses induce some non-trivial effects on cosmological observables.

- You can even turn this around and use cosmological observables to “measure” the neutrino mass.
- But please please please don’t over-interpret bounds or forecasted sensitivities. They are best treated as ballpark figures.
- Until **multiple observation**s have measured the same neutrino mass sum value, take all “measurements” *cum grano salis*.

Also summarised in Antel et al., Feebly Interacting Particles: FIPs 2022 workshop report, *Eur.Phys.J.C* 83 (2023) 1122 [arXiv:2305.01715 [hep-ph]].

Extra slides…

Neutrino masses & perturbation growth...

Cold dark matter only

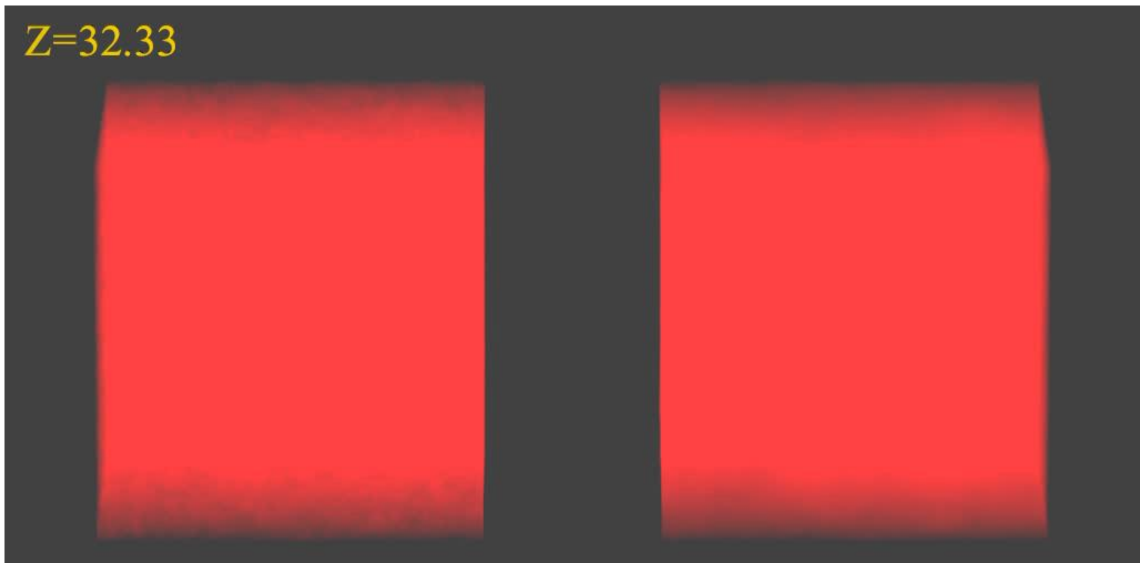
$\Omega_{\mathrm{CDM}} \approx 25\%$

Cold dark matter + neutrinos ($\sum m_\nu = 6.9$ eV)

$\Omega_{\mathrm{CDM}} \approx 10\%$

$\Omega_\nu = \dfrac{\sum m_\nu}{93\, h^2} \approx 15\%$

$256\, h^{-1}\mathrm{Mpc}$

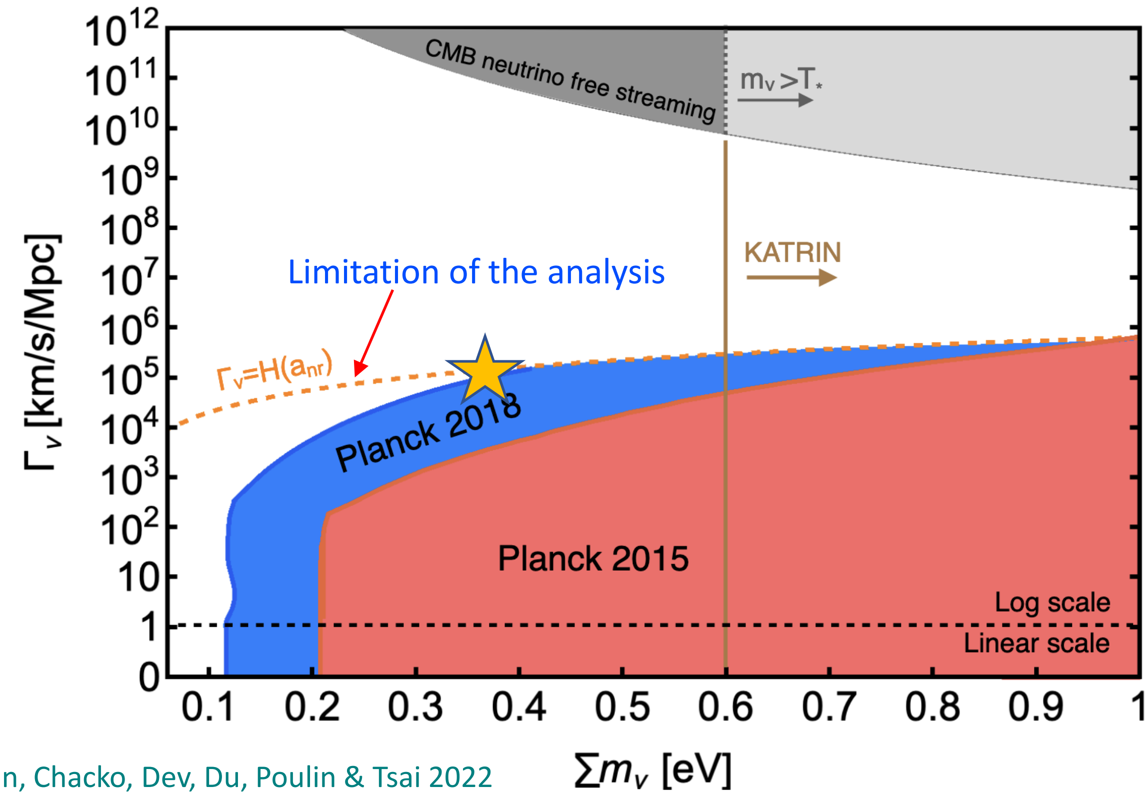


Simulations by Troels Haugbølle

Non-relativistic neutrino decay…

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

… into dark radiation



Abellán, Chacko, Dev, Du, Poulin & Tsai 2022

If neutrinos decay with a **lifetime**

$$\tau_\nu \sim 0.1 \text{ Myr}$$

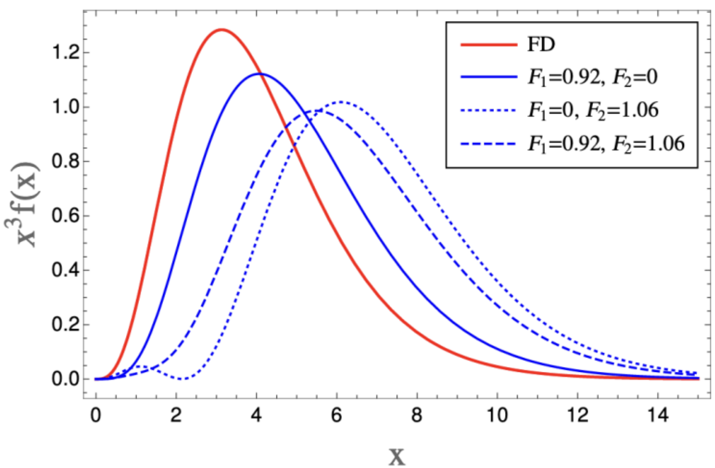
then it is possible to accommodate

$$\sum m_\nu \lesssim 0.42 \text{ eV}$$

Planck+BAO+SN

Neutrino spectral distortion…

Enhancing the average momentum (via decay, interaction, etc.) while maintaining the early-time neutrino energy density (i.e., N_{eff}) relaxes the neutrino mass bound.



Planck 2015

	TT+lowP (95 % CL)	TT+lowP+BAO (95 % CL)
FD	$\sum m_\nu < 0.73$ eV	$\sum m_\nu < 0.18$ eV
$F_1 = 0.92, F_2 = 0$	$\sum m_\nu < 0.95$ eV	$\sum m_\nu < 0.26$ eV
$F_1 = 0, F_2 = 1.06$	$\sum m_\nu < 1.45$ eV	$\sum m_\nu < 0.37$ eV
$F_1 = 0.92, F_2 = 1.06$	$\sum m_\nu < 1.34$ eV	$\sum m_\nu < 0.32$ eV

Oldengott, Barenboim, Kahlen, Salvado & Schwarz 2019

- If you're adventurous and take a Gaussian momentum distribution, you could even relax the bound to $\sum m_\nu \lesssim 3$ eV. Alvey, Escudero & Sabti 2022

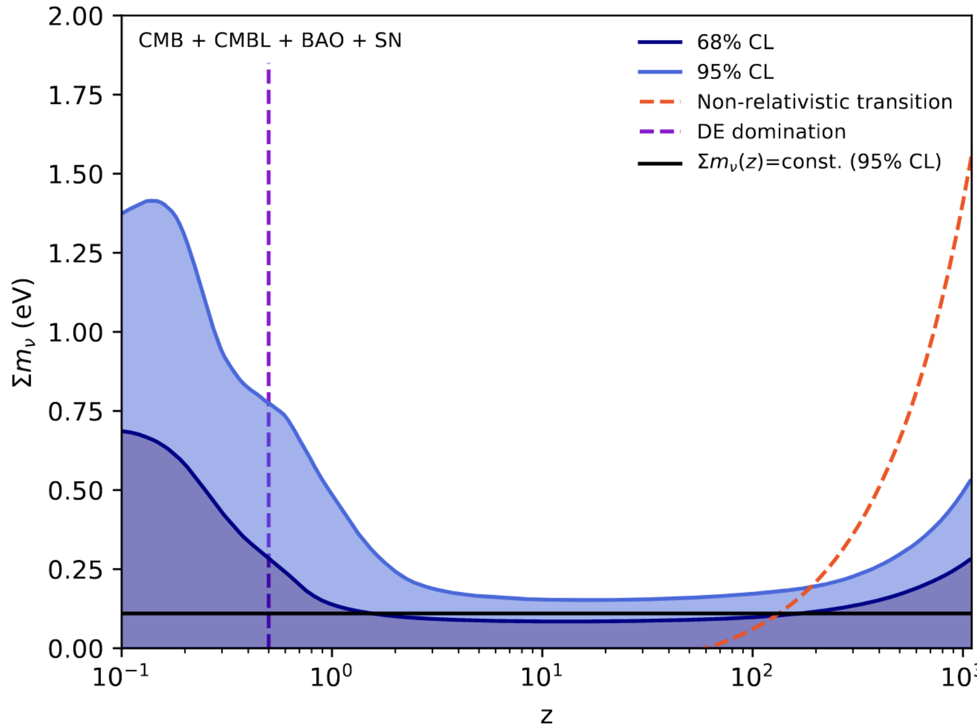
Late-time ν mass generation...

Official Planck benchmark:
$\sum m_\nu < 0.12$ eV

Late-time mass through a phase transition at $T \sim \text{meV}$ Dvali & Funcke 2016

- But phenomenologically, if neutrinos pick up masses only after $z \sim 1$, then this is allowed:

$$\sum m_\nu \lesssim 1.46 \text{ eV}$$



Lorenz, Funcke, Löffler & Calabrese 2021