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Neutrino mass and number constraints from cosmology

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Institute for Theoretical Particle Physics and Cosmology

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Setting the stage

- Neutrino expected to be in thermal equilibrium until T~1 MeV, number density = 68% of CMB photons for T<0.5 MeV: constitute the Cosmic Neutrino background (CνB)

- Indirect proof of CνB from BBN+primordial abundances, CMB anisotropies, and large scale structure of the universe

- $$N_{\rm eff} = \frac{\text{(energy density of neutrinos + possible other light/massless relics)}}{\text{(energy density of one neutrino family in instantaneous decoupling limit)}}$$

- $N_{\rm eff} \simeq 3$ in absence of extra relics (light sterile νs, axions, dark radiation)

The Cosmic Neutrino Background (CνB)

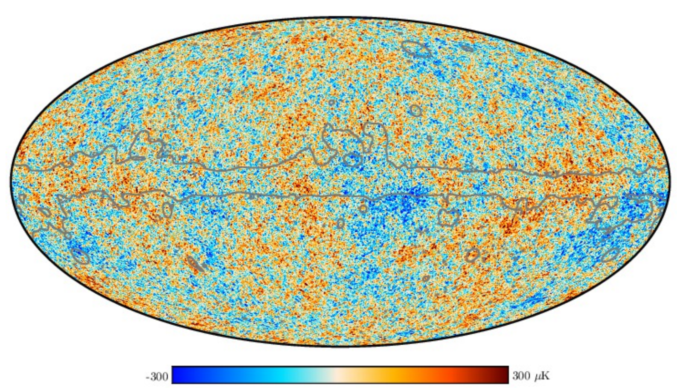
- Precise study of neutrino decoupling (flavour effects, QED corrections) predict $N_{\rm eff} = 3.044$ (Froustey et al. 2020, Bennett et al. 2020)
- Today, $n_\nu^0 = 339.5 {\rm cm}^{-3}$, $T_\nu^0 = 1.7 \times 10^{-4} {\rm eV} = 1.9\ {\rm K}$
- Direct detection very difficult due to low momentum (high energy resolution, background events…)
- Future attempts with PTOLEMY (Tritium β-decay stimulated by CνB neutrino capture) ⇒ *talk by M. Messina (Wednesday)*

The Cosmic Neutrino Background (CνB)

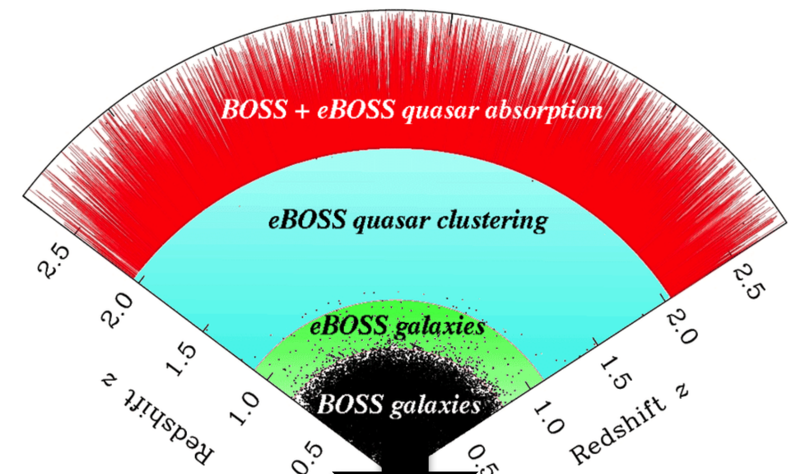
- $T_\nu < |\Delta m^2|^{1/2}_{\rm sol,atm}$: at least 2 mass eigenstates non-relativistic today
- Each eigenstate :
  - radiation till non-relativistic transition at $z_{\rm NR} \sim m_i/[0.53\ \rm meV] - 1$,
  - then, fraction of Dark Matter
- Today $\Omega_\nu = (\Sigma_i m_i)/[93.12\, h^2 \rm eV] \geq$ 0.5% of matter components (Mangano et al. 2005, updated by Froustey & Pitrou);
- cosmology probes this combination, i.e. $M_\nu = \Sigma_i m_i$, not enough sensitivity to individual m_i's (JL, Pastor, Perotto 2004; …; Archidiacono, JL, Hannestad 2020)

Cosmological observables

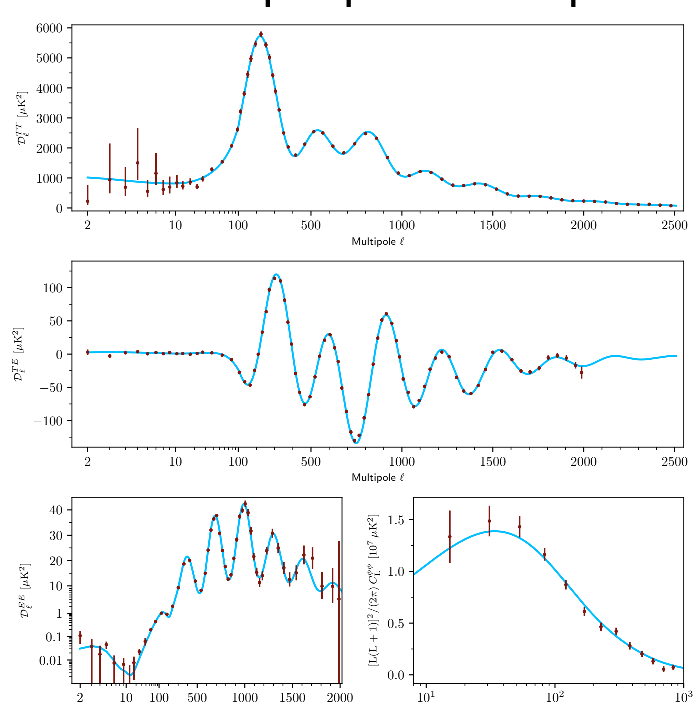
CMB temperature/polarisation maps



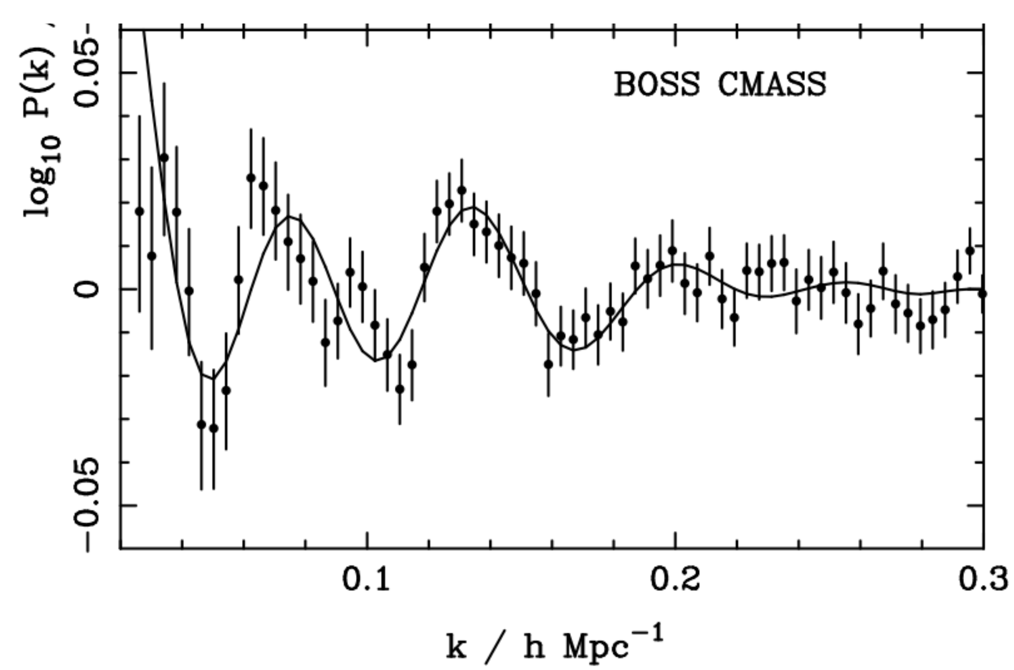
Galaxy distribution and lensed shapes



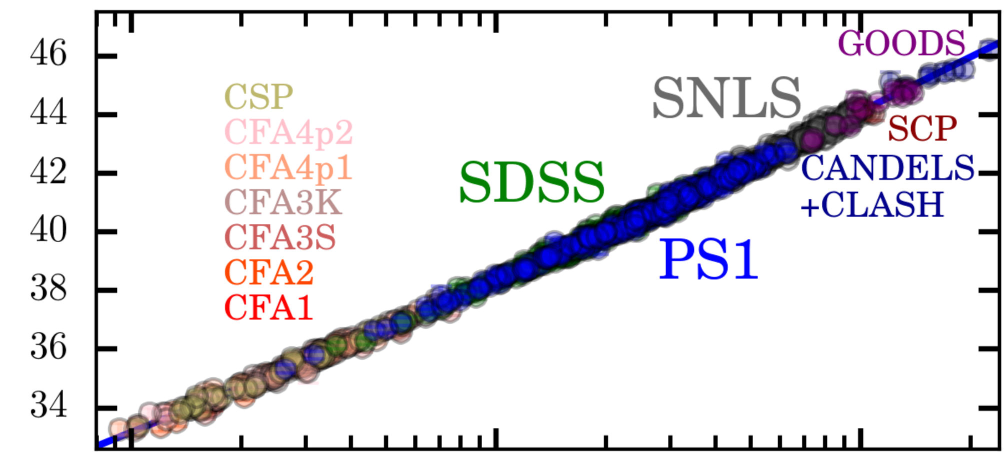
CMB temp./polar. spectrum



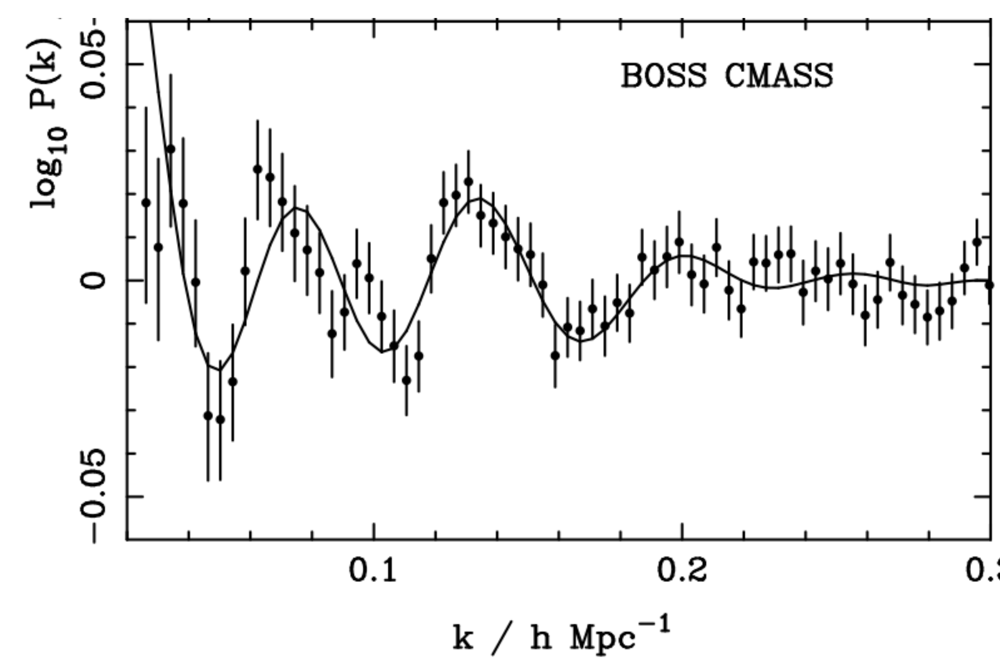
LSS (matter) power spectrum



Cosmological observables



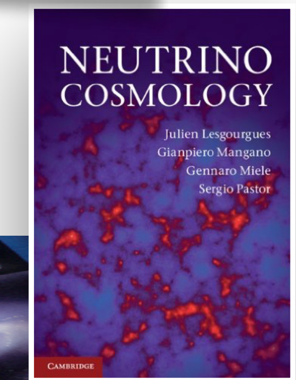
- Probes of background expansion:
  - from distance ladder (luminosity of cepheids, supernovae)
  - from robust geometrical information contained in LSS spectrum
    (BAO = Baryon Acoustic Oscillations,
    RSD = Redshift Space Distorsions)

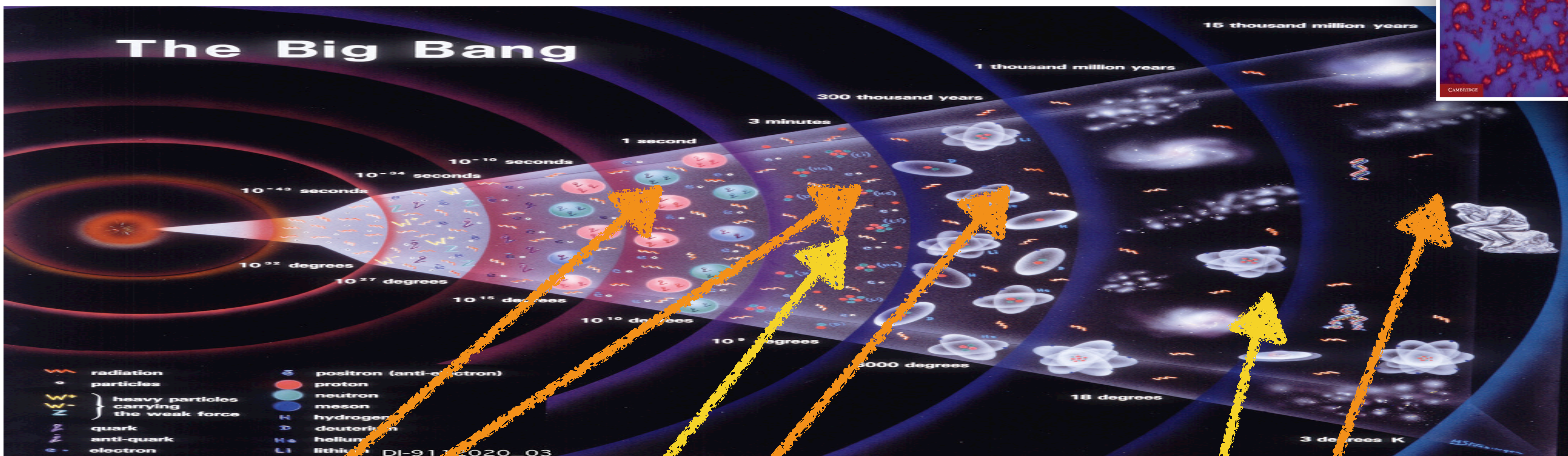


- Primordial Deuterium / Helium and theory of BBN

Neutrino effects on cosmological observables

JL & Pastor Pys. Rep. 2016; JL, Mangano, Miele, Pastor “Neutrino Cosmology” CUP;
Drewes et al. 2016; Gerbino & Lattanzi 2017 ; RPP of PDG: JL & Verde “Neutrinos in Cosmology”;





relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

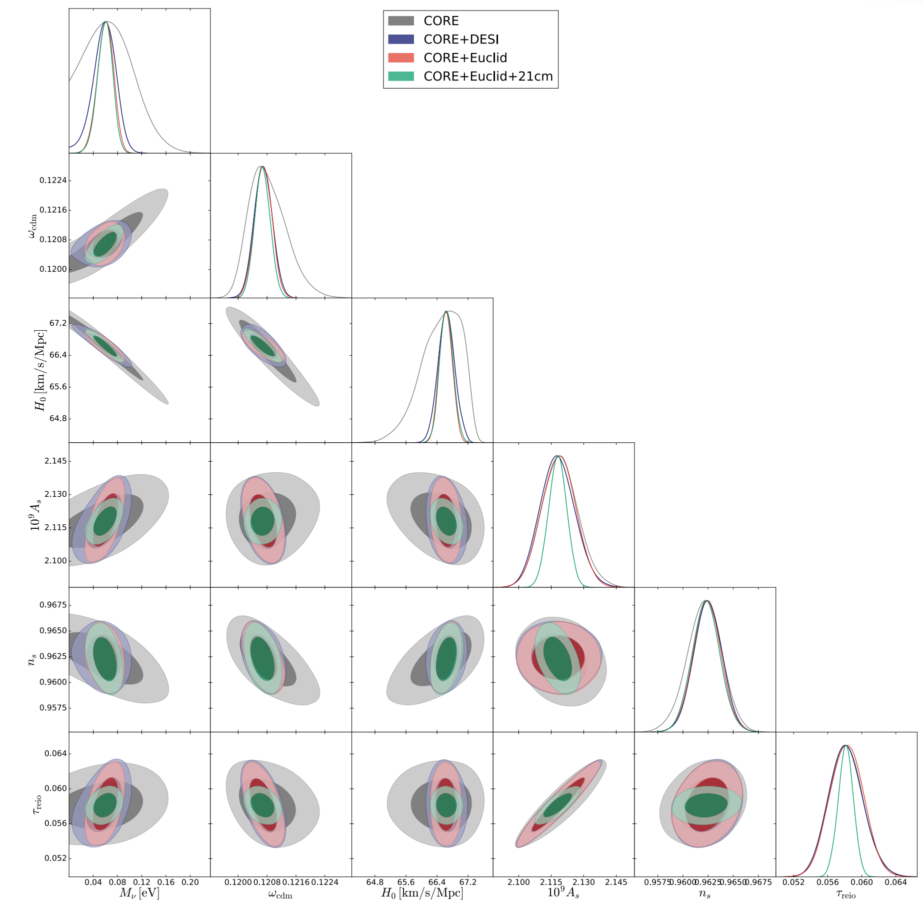
non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

neutrino free-streaming slows down CMB photon clustering

neutrino free streaming slows down late ordinary/dark matter clustering

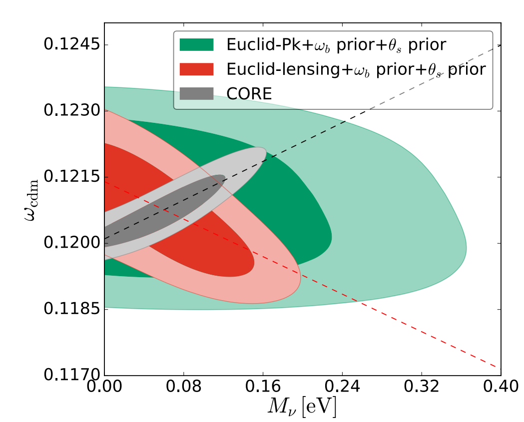
Cosmological bounds are model dependent!

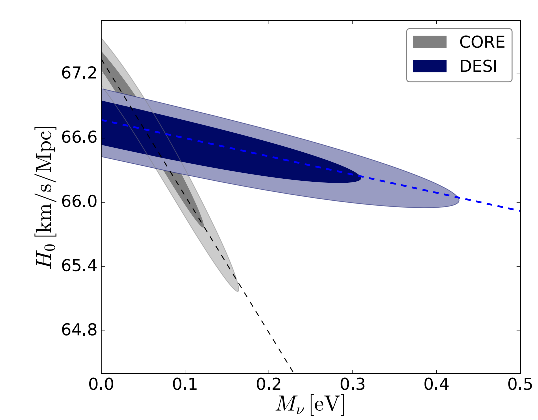
Global fit of cosmological model to data: bound are model-dependent (can be relaxed when adding new ingredients)



e.g. Archidiacono et al. 1610.09852

Model-dependence decreases quickly over the years (more types of independent observations, smaller error bars)





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Model dependance

What do we do with cosmological tensions appearing in ΛCDM framework:

- on current Hubble rate H_0 ?
  (5σ, dominated by one collaboration, SH0ES Riess et al. 2112.04510)
- on matter spectrum amplitude S_8 ?
  ($2-3\sigma$, found by many collaborations: KiDS, DES, CHFTLens, etc.) ?

… and to a lesser extent:

- (n_s, Ω_m) tension between Lyman-α forest spectrum and CMB
- Small-scale CMB polarisation anisotropies from ACT versus SPT-3G
- internal consistency of Planck data ("A_L anomaly" -> *not a concern for me* (fluctuating unphysical parameter, look-elsewhere effect, decreased to 1.5σ in recent re-analysis of Rosenberg et al. 2022)

Model dependance

What do we do with cosmological tensions appearing in ΛCDM framework:

1. Assume they will go away (systematics). Fit neutrino parameters ($N_{\rm eff}, M_\nu$) in:
   1. Minimal ΛCDM
   2. Most obvious extensions (light relics, dynamical DE, curvature, T/S…)
   3. Models with more freedom (beyond-Einstein gravity, non-trivial Dark Sector…)

2. Assume they are “real”, investigate new scenarios accommodating the tension, explore neutrino bounds within that framework

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⇒ this talk

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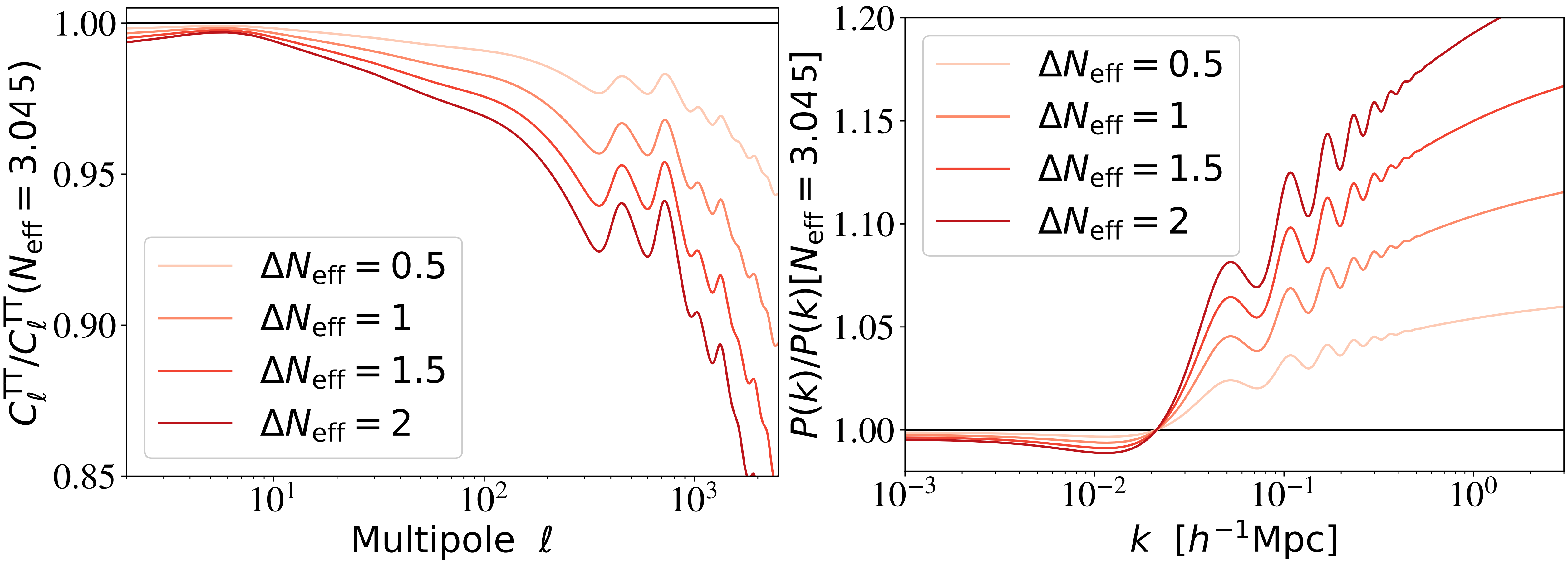
⇒ talk by O. Mena

Impact of $N_{\rm eff}$

Measuring $N_{\rm eff}$ or $\Delta N_{\rm eff} = N_{\rm eff} - 3.044$ with cosmological observables may :

- Confirms presence of CνB
- Confirm standard thermal history of the universe (reheating, neutrinos decoupling, positron annihilation…)
- Bound non-thermal corrections from e.g. late decays into neutrinos
- Bound existence of additional light relics (light sterile νs, axions, dark radiation…)
- Together with Helium abundance, bound new physics around time of Nucleosynthesis

Impact of $N_{\rm eff}$



Fixed $\{\Omega_r, \Omega_m, \Omega_\Lambda\}$

(from RPP, JL & Verde)

Measurement of $N_{\rm eff}$

(from RPP, JL & Verde)

	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$	[22]
” + BAO + R21	ΛCDM+$N_{\rm eff}$	3.34 ± 0.14 (68%CL)	[11]
Pl18[TT,TE,EE+lowE+lensing] + BAO	” +5-params.	2.85 ± 0.23 (68%CL)	[23]

- Compatible with BBN + Helium (+ Deuterium) bounds (even after LUNA update: see Pisanti et al. 2021, Pitrou et al. 2021)

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- Provides bounds on neutrino asymmetry

$$\left| \sum_{\alpha=e,\mu,\tau} \frac{n^{\rm dec}_{\nu_\alpha} - \bar{n}^{\rm dec}_{\nu_\alpha}}{n^{\rm dec}_\gamma} \right| < 0.084 \qquad (95\%, \quad {\rm Planck TT, TE, EE + lowP + lensing})$$

(Oldengott & Schwarz 2017)

- BBN / Helium more sensitive through beta decay and oscillations

$$-0.071 < \sum_{\alpha=e,\mu,\tau} \frac{n^{\rm ini}_{\nu_\alpha} - \bar{n}^{\rm ini}_{\nu_\alpha}}{n^{\rm ini}_\gamma} < 0.054 \qquad (95\%, \quad {\rm WMAP + Helium})$$

(Castorina et al. 2012)

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(De Valentino et al. 2020)

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- Global fit, in principle model-dependent, in practise not so much for simple extensions of ΛCDM (De Valentino et al. 2020)
- Hubble tension ?… positive $H_0 - N_{\rm eff}$ correlation. Discussions about $N_{\rm eff} > 3$ as a solution. Currently disfavoured.

Probes of CνB

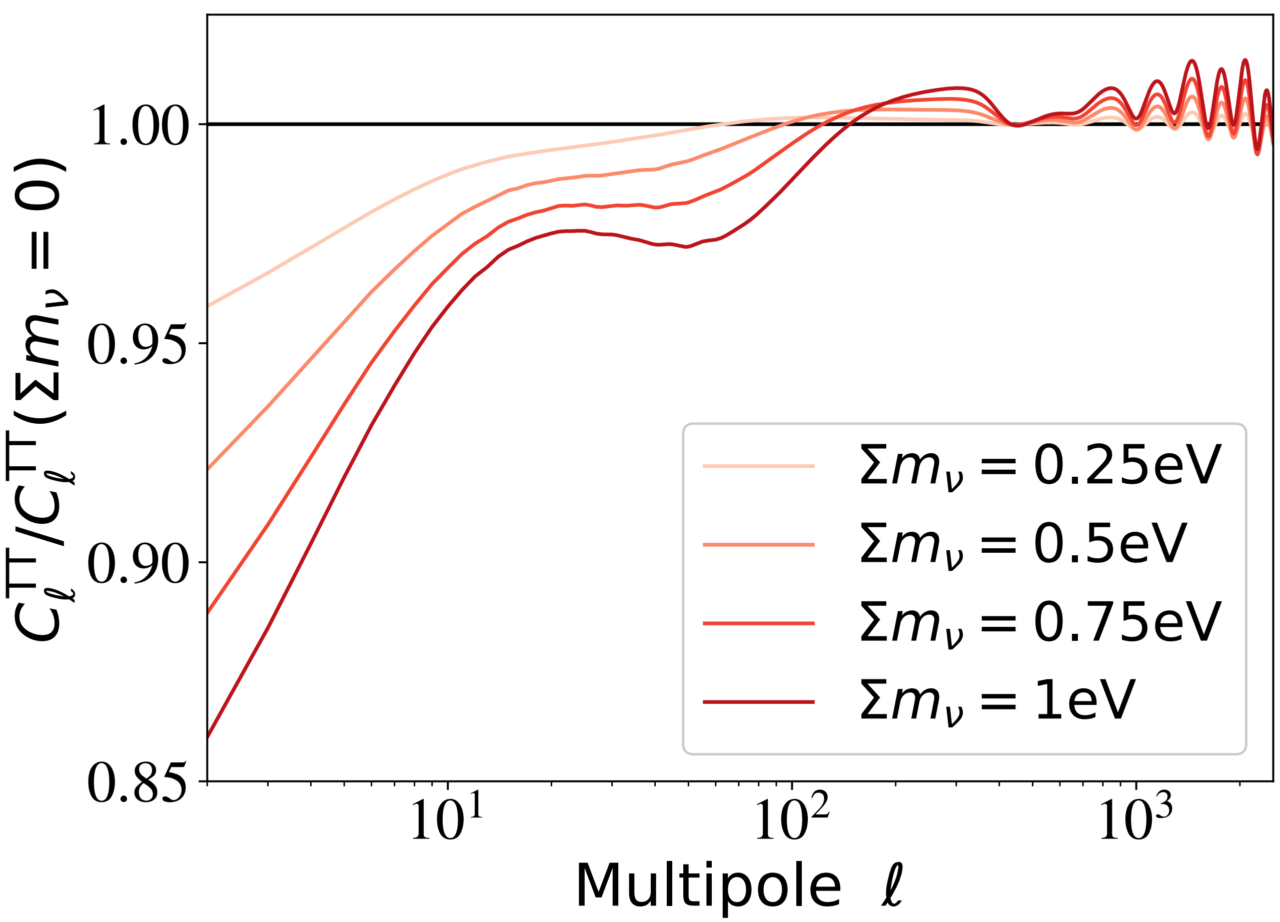
- measured $N_{\rm eff}$ compatible with prediction 3.044 (although… H_0 tension)
- details of acoustic oscillations in CMB and LSS spectra probe neutrino drag effect : indicate free streaming ultra-relativistic species. CνB detected at level of its background and perturbations

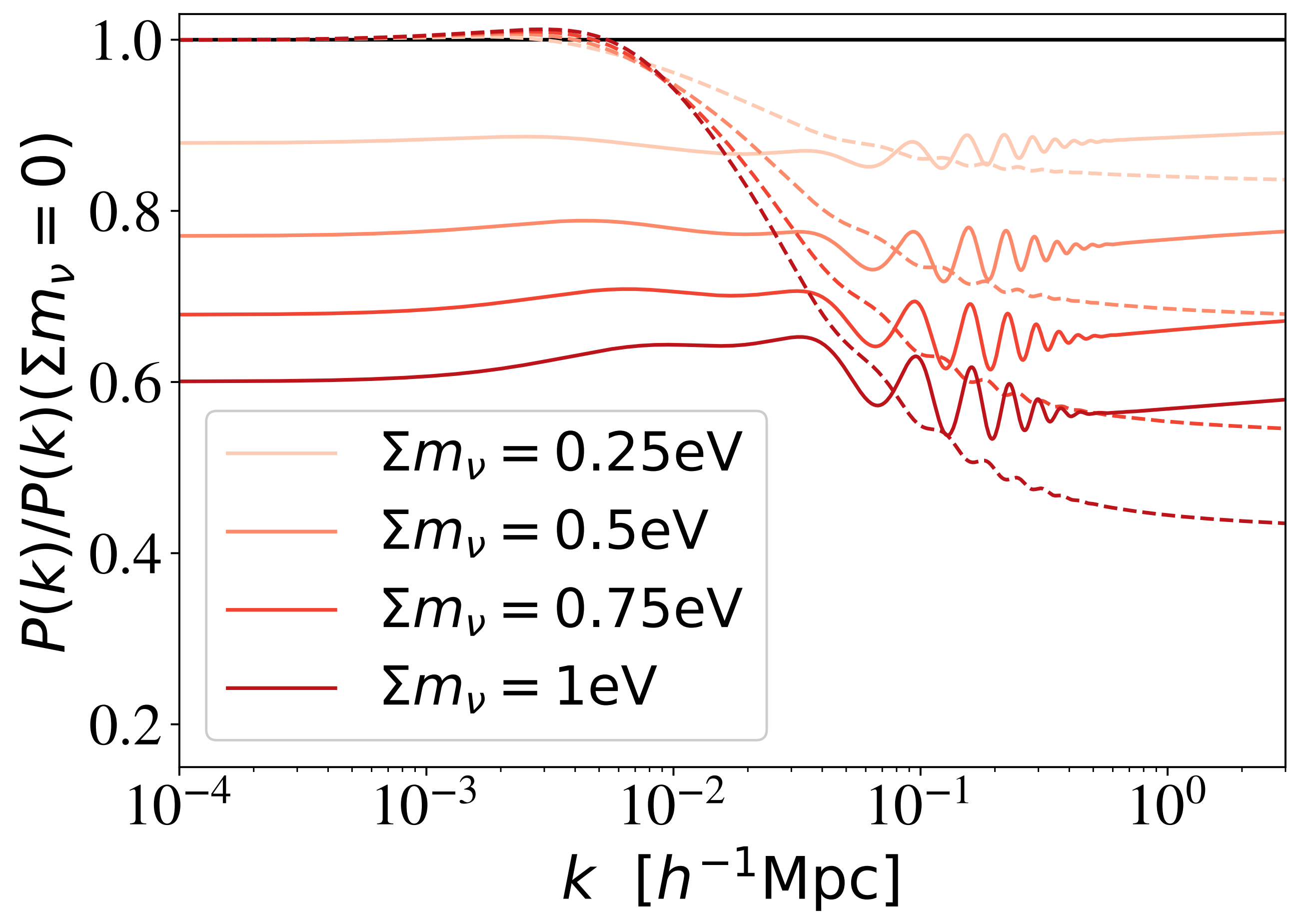
(Bashinky & Seljak 2004 , Audren et al. 2015, Baumann et al. 2019, …)

- Limits on non-standard neutrino self-interactions: $\log_{10}(G_{\rm eff}{\rm MeV}^2) < -0.8$

(Park et al. 2019)

Impact of Σm_ν





Fixed $\{\omega_b, \omega_c, \tau, \theta_s\}$

(from RPP, JL & Verde)

Bounds on Σm_ν

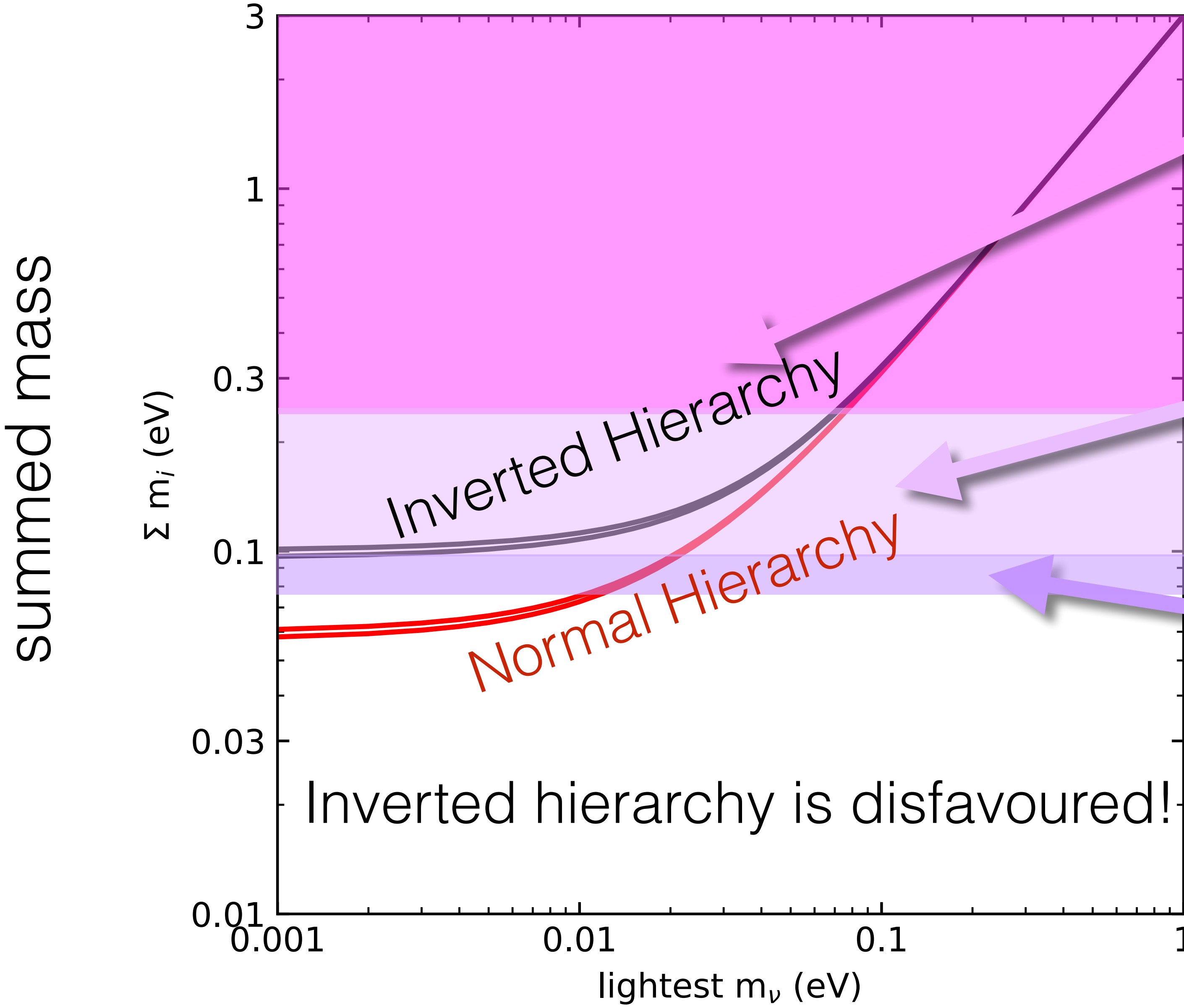
(from RPP, JL & Verde)

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[23]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[22]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[22]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]
Pl18[TT,TE,EE+lowE+lensing] + BAO + RSD + Pantheon.	ΛCDM+$\sum m_\nu$	< 0.087	[dVGM]

2021: new eBOSS and DES data

Bounds on Σm_ν

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB temperature and polarisation from Planck
$\Sigma_i m_i$ < 260 meV (95%CL)

CMB + conservative LSS information (BAO + RSD from BOSS):
$\Sigma_i m_i$ < 100 meV (95%CL)

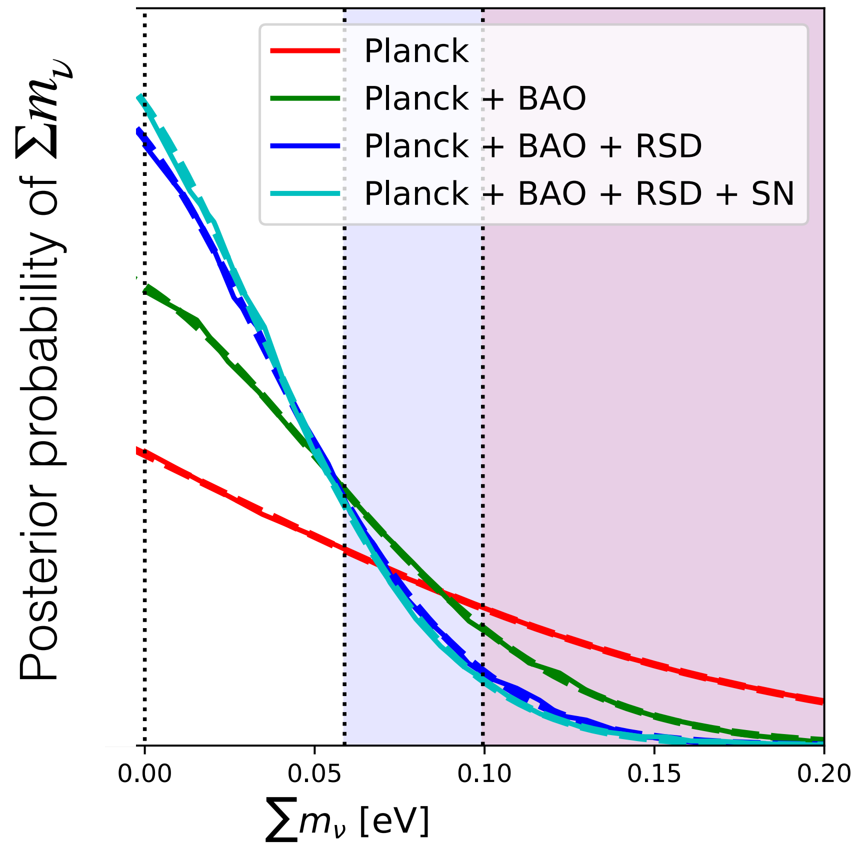
CMB + BAO + more agressive LSS:
either: + Ly-α from BOSS
or: + lensing + RSD + SNIa)
$\Sigma_i m_i$ < 87 meV (95%CL)

Palanque-Delabrouille et al. 2020
Di Valentino et al. 2021

Model dependance

Shall we be concerned about posterior peaking in zero?:

- $\sigma(\Sigma m_\nu)$ reducing to ~0.05 eV, and still no hint of a posterior peaking anywhere above 0 eV



From Alam et al. 2020 (eBOSS)

- May be the consequence of only the randomness of instrumental errors + underlying theory (cosmic variance), with still acceptable level of probability
- Or, like tensions, sign of systematics or using wrong model…

Bounds on Σm_ν

(from RPP, JL & Verde)

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- Crucial role of CMB (WMAP+SPT: similar bounds, WMAP+ACT: twice weaker bounds) (Di Valentino & Melchiorri 2021)
- Robustness against simple LCDM extensions (De Valentino et al. 2020)
- Negative $M_\nu - H_0$ correlation: Inclusion of direct Hubble measurement from SH0ES makes bounds even stronger but subject to caution

Is inverted hierarchy excluded ?

Calculation of Bayesian evidence using laboratory (oscillations, KATRIN)+ cosmological data:

- Decisive evidence for NH according to Jimenez et al. 2022 - driven by cosmology
- Only moderate evidence for NH according to Gariazzo et al. 2022 - driven by oscillation data

Main issue = Bayesian prior dependence of the results (discussed by both groups). Second group ensures that prior alone gives 1:1 odds for NH/IH.

My take: two many self-consistency issues in cosmological data / standard model for including current bounds in such detailed statistical analyses.

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If S_8 tension is “real”, but not H_0 tension

- Naive explanation: M_ν~0.6eV… ruled out by CMB in all simple ΛCDM extensions
- List of alternative mechanisms reducing growth of matter fluctuations on small scales and compatible with CMB, BAO, Weak Lensing, Lyman-α…
- Modified gravity (e.g. f(R)), cold+warm DM, (self-)interacting DM, DM with 2-body decay… (Boyarsky et al. 0812.0010; Buen-Abad et al. 1708.09406; Becker et al. 2010.04074; Heimersheim et al. 2008.08486; Abellan et al. 2008.09615; …)

Neutrino mass bounds depend on each case, but usually CMB+BAO sets barrier around 0.13 eV, unlikely to be challenged by these models which have minimal impact on CMB…

If H_0 tension is “real”

- Naive explanation in terms of $N_{\rm eff} \sim 5$ ruled out by both CMB and BBN
- No very simple alternative compatible with CMB, BAO, Pantheon (= high-z supernovae)… Price to pay is high (Schöneberg et al. 2021):
    1. Shifted recombination (variation of particle masses (Hart & Chluba 2020) ? Inhomogeneous recombination (Jedamzik & Pogosian 2020) ?);
    2. Non-minimal Dark Radiation: self-interactions, density increasing after BBN (possible precise scenarios: Majoron (Escudero & Witte 2021), Wess-Zumino (Aloni et al. 2011), …);
    3. Early Dark Energy; Modified gravity …
- Neutrino mass bounds depend on each case, could be significantly released (e.g. like for self-interacting neutrinos of Cyr-Racine et al.), more work needed…
- Same if both tensions are ``real''…

Prospects on mass measurement

- Future LSS surveys: DESI, Euclid, LSST, SPHEREx, SKA…
- Future CMB observations: Simons Observatory, CMB-Stage4, LiteBird
- Planck+Euclid: at least ~ 2σ
- Should grow to 3-4σ with new CMB data (SO, CMB-S4) and better LSS data
- Could reach 5σ after better measurements of reionization and 21cm fluctuations (radioastronomy: SKA, …)
- Null detection would be revolutionary (NSI, neutrino decay…)
- Possible shift of paradigm could reshuffle conclusions…