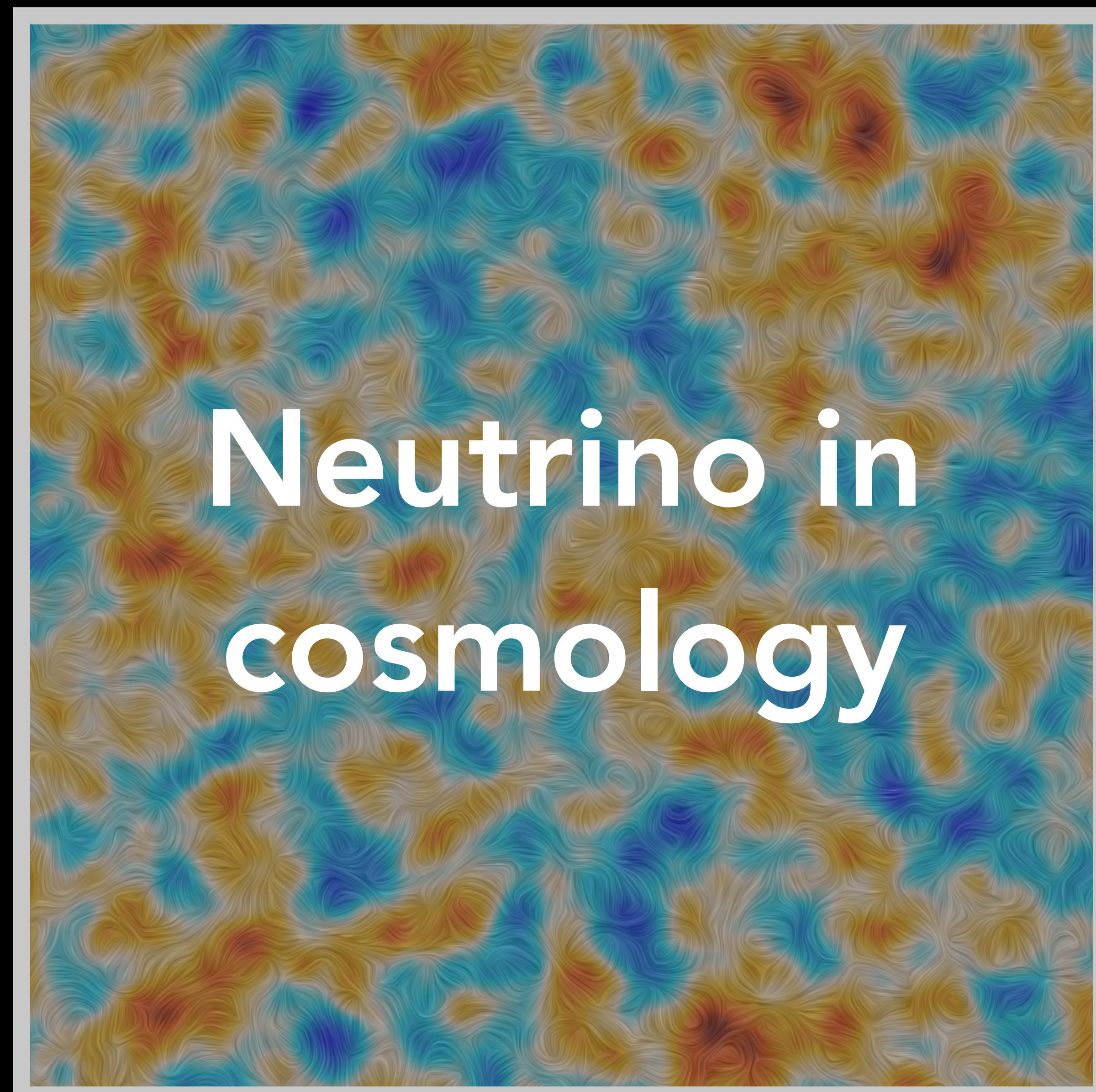
GIF 2022, LPNHE, Paris, 6.09.2022



Neutrino in cosmology

Julien Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

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)

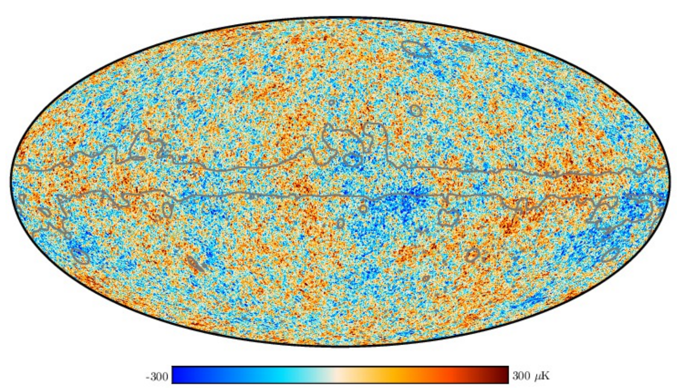
- Precise study of neutrino decoupling (flavour effects, QED corrections) predict $N_{\rm eff} = 3.044$ (Froustey et al. 2020, Bennett et al. 2020)
- Today, $n_\nu^0 = 339.5 \mathrm{cm}^{-3}$, $T_\nu^0 = 1.7 \times 10^{-4} \mathrm{eV} = 1.9\ \mathrm{K}$
- Direct detection very difficult due to low momentum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

The Cosmic Neutrino Background (CνB)

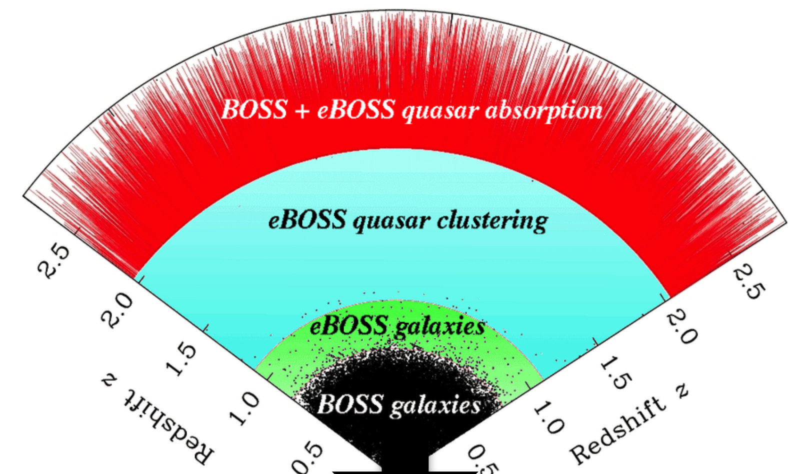
- $T_\nu < |\Delta m^2|^{1/2}_{\rm sol,atm}$: at least 2 mass eigenstates non-relativistic today
- Each eigenstate :
  - radiation till non-relativistic transition at $z_{\rm NR} \sim m_i/[0.53 \text{ meV}] - 1$,
  - then, fraction of Dark Matter
- Today $\Omega_\nu = (\Sigma_i m_i)/[93.12\, h^2 \text{eV}] \geq$ 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

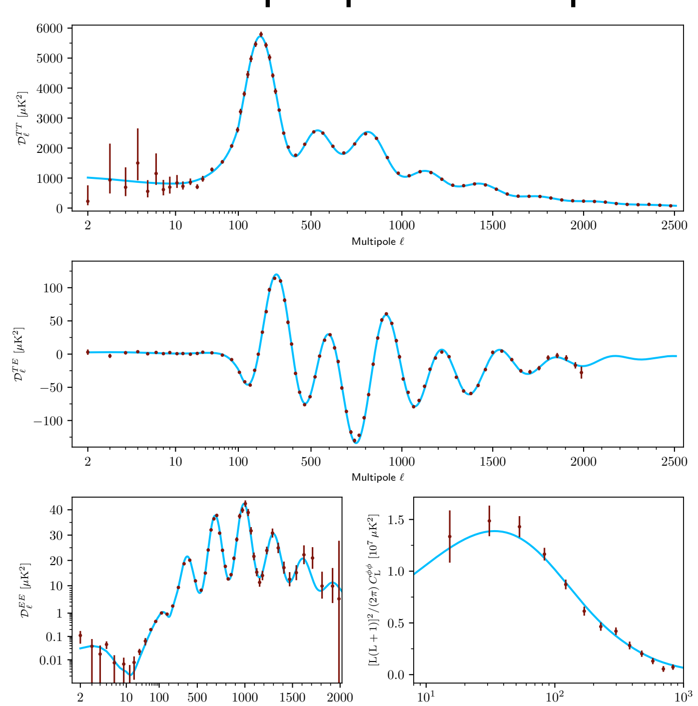
CMB temperature/polarisation maps



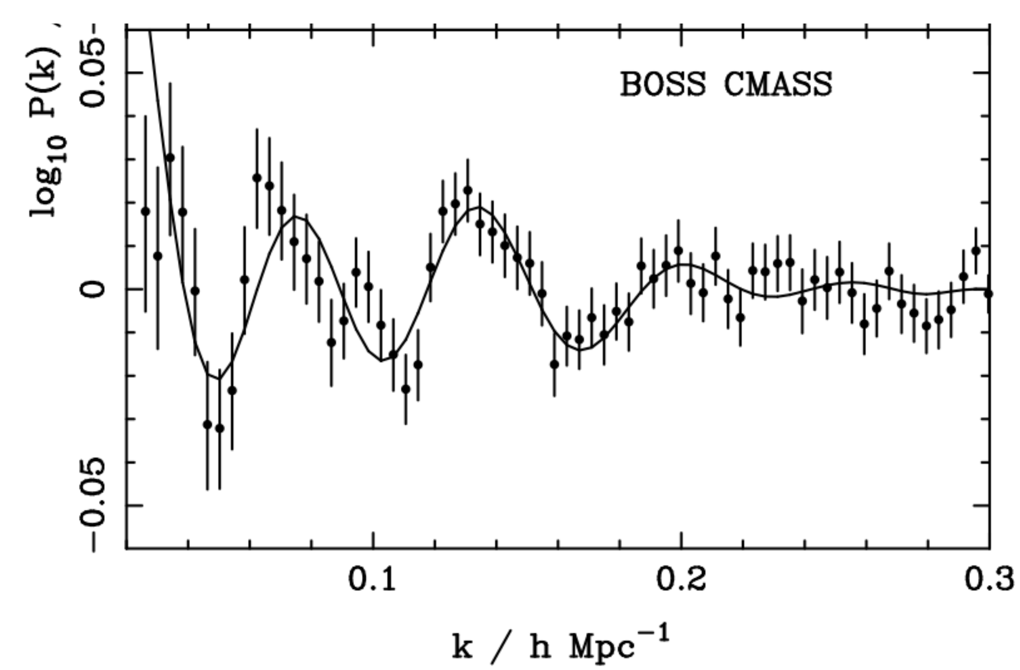
Galaxy distribution and lensed shapes



CMB temp./polar. spectrum

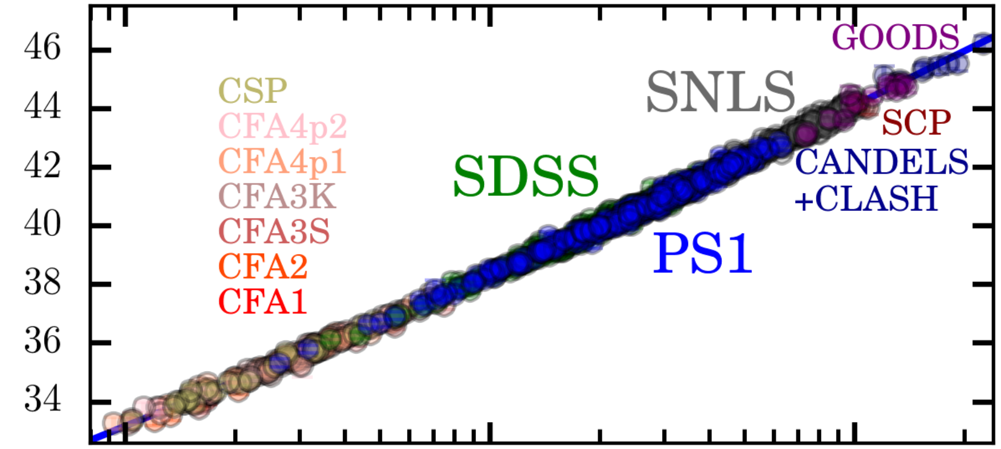


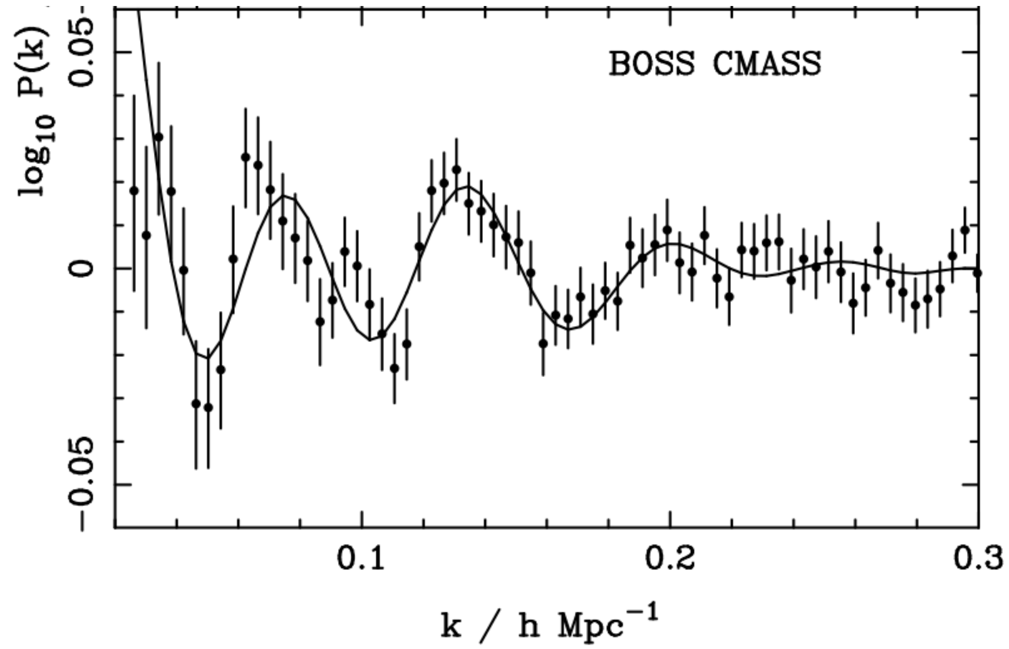
LSS (matter) power spectrum



Cosmological observables

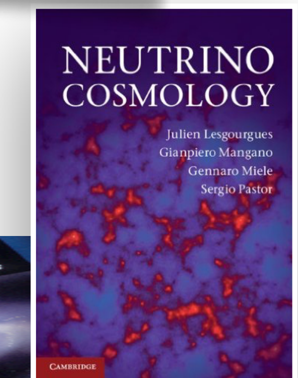
- Probes of background expansion:
  - from distance ladder (luminosity of cepheids, supernovae)
  - from robust geometrical information contained in LSS spectrum
    (scale of BAO = Baryon Acoustic Oscillations)
- Primordial Deuterium / Helium and theory of BBN

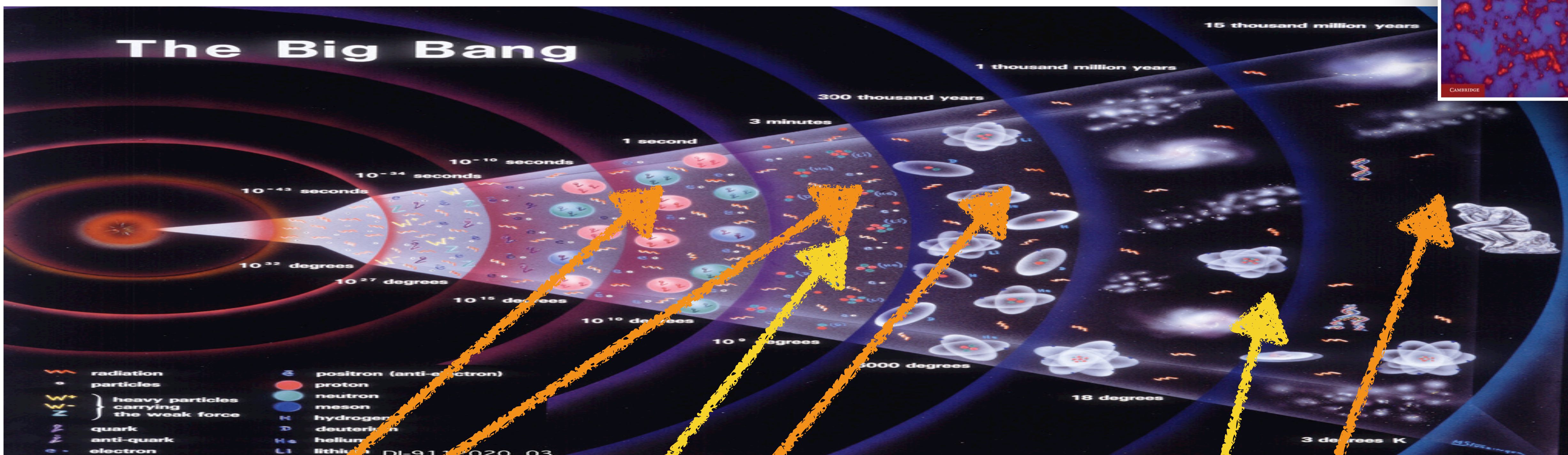




Neutrino effects on cosmological observables

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)

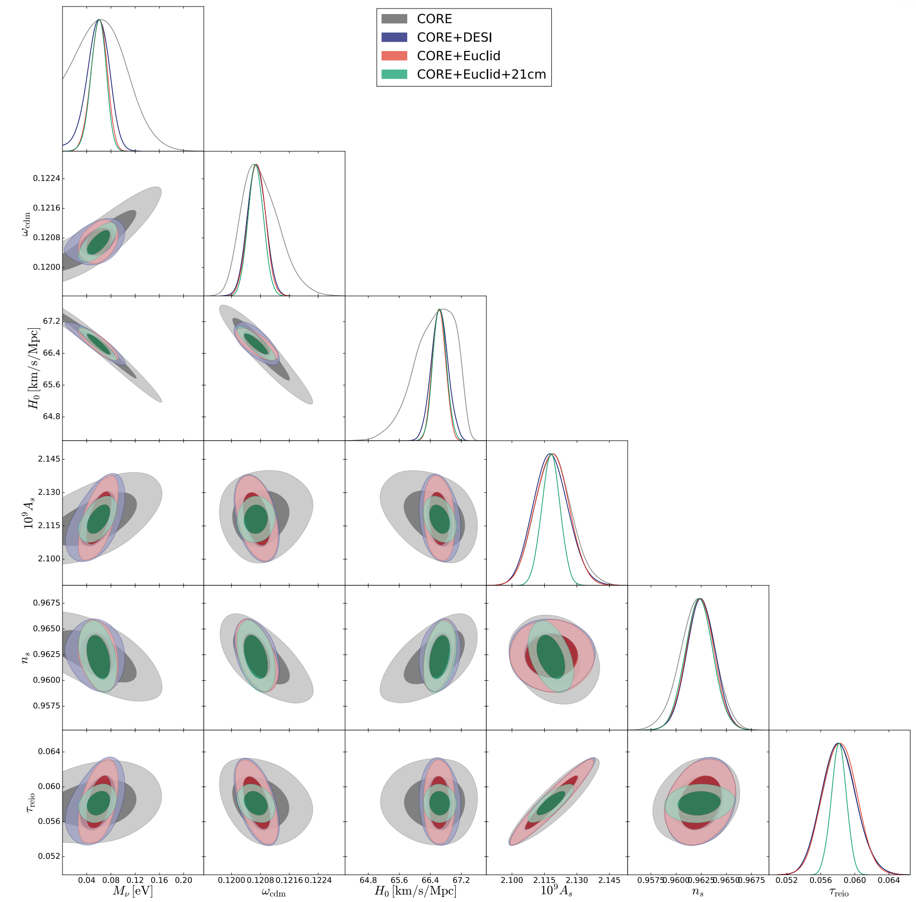
non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

neutrino free-streaming slows down CMB photon clustering

neutrino free streaming slows down late ordinary/dark matter clustering

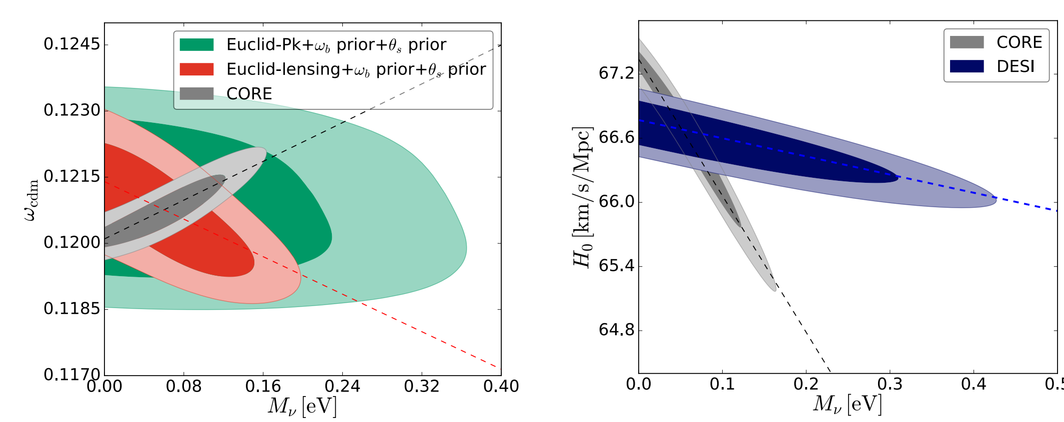
Cosmological bounds are model dependent!

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)



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_{eff}, M_ν) 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

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…)

$\Rightarrow$ most of this lecture

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

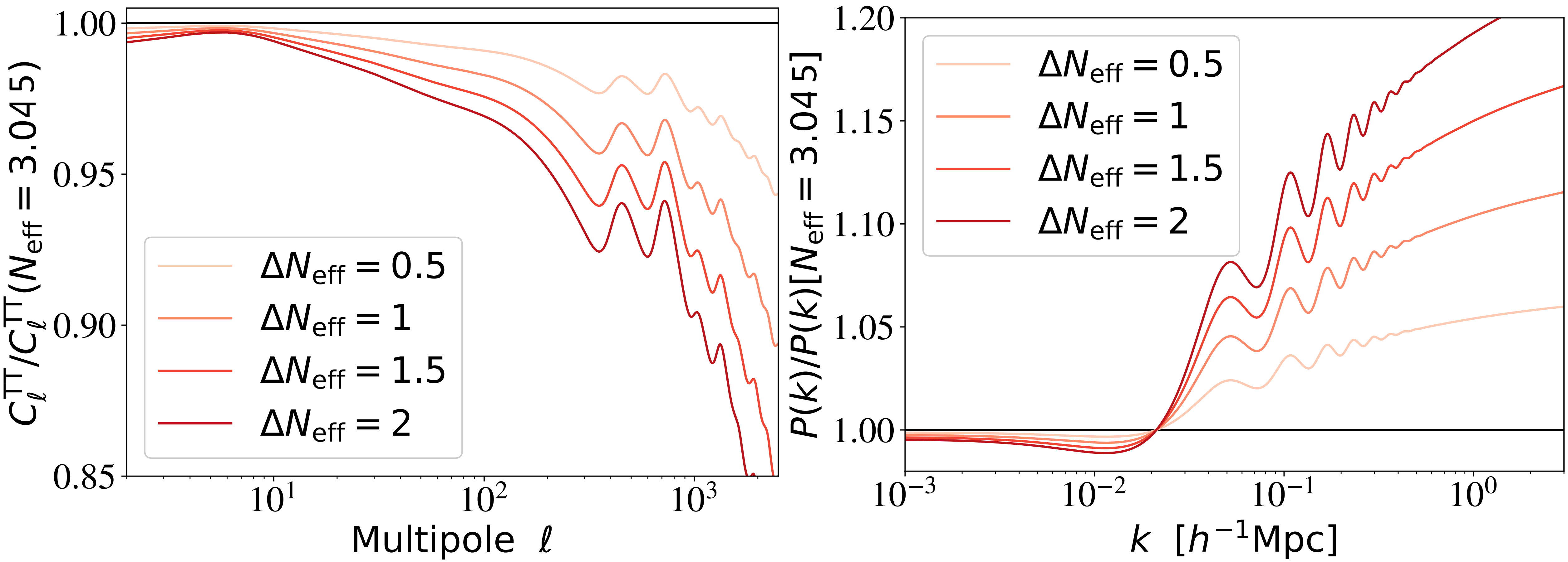
$\Rightarrow$ few examples at the end

Impact of N_{eff}

Measuring N_{eff} or $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.044$ 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 $\{z_{\rm eq}, \omega_b, \frac{d_s}{d_A}(z_{\rm dec})\} \Rightarrow$ decreasing ω_b/ω_c

(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)

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]

- Provides bounds on neutrino asymmetry

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

(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)

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]

- Global fit, in principle model-dependent, in practise not so much for simple extensions of ΛCDM

(De Valentino et al. 2020)

Measurement of N_{eff}

(from RPP, JL & Verde)

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

- Global fit, in principle model-dependent, in practise not so much for simple extensions of ΛCDM

(De Valentino et al. 2020)

- Hubble tension ?… positive $H_0 - N_{\mathrm{eff}}$ correlation. Discussions about $N_{\mathrm{eff}} > 3$ as a solution. Currently disfavoured.

Probes of CνB

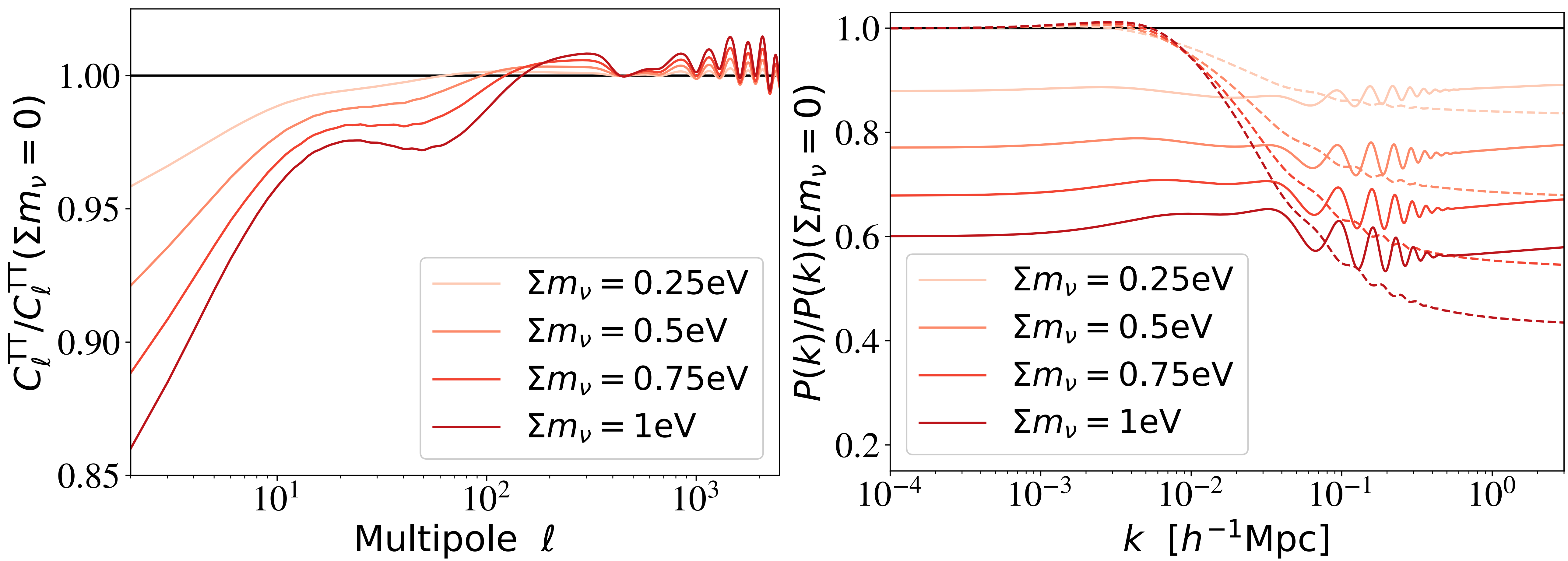
- measured $N_{\rm eff}$ compatible with prediction 3.044 (although… H_0 tension)
- details of acoustic oscillations in CMB and LSS spectra probe neutrino drag effect : indicate free streaming ultra-relativistic species. CνB detected at level of its background and perturbations

(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]

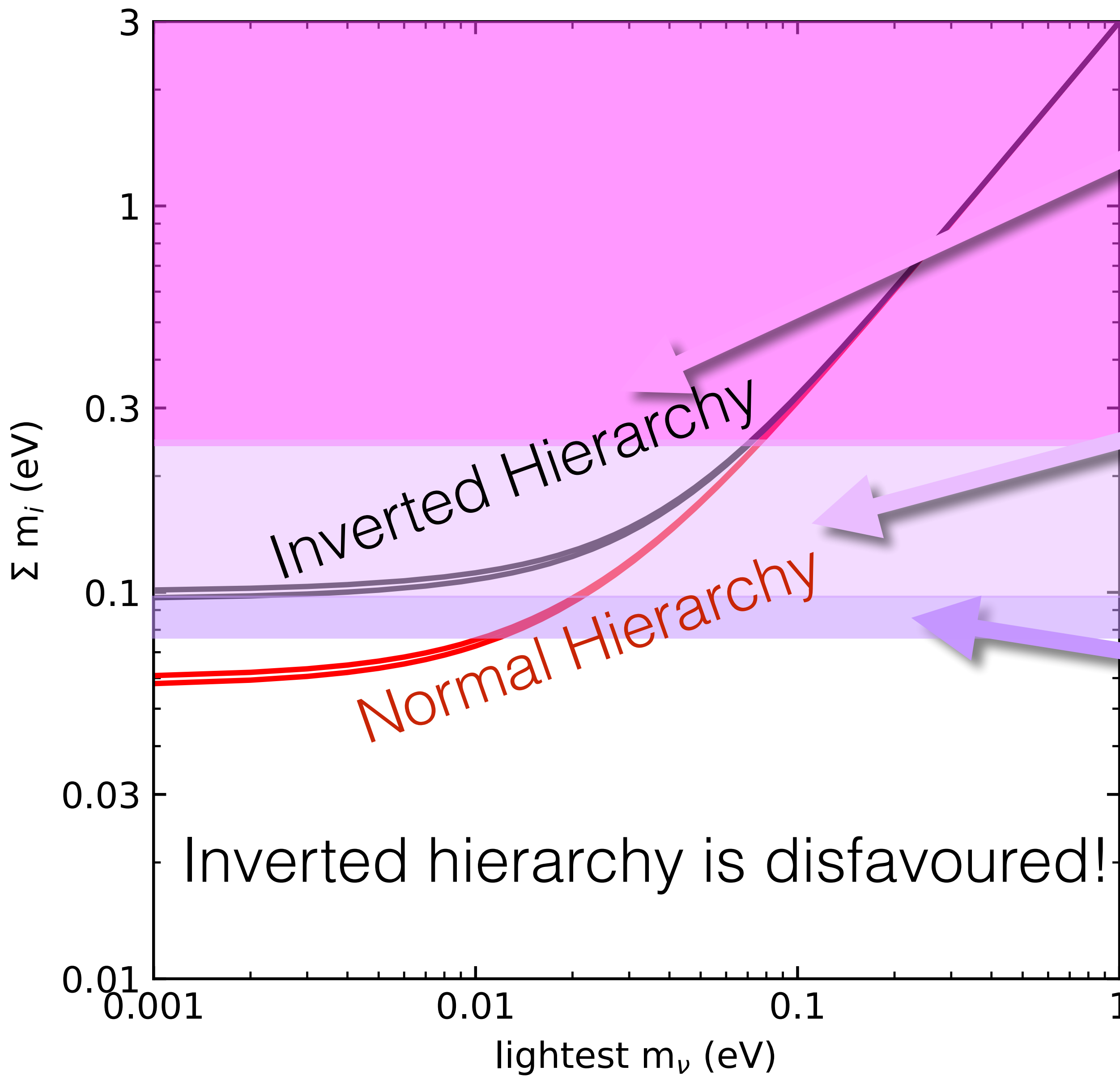
2021: new eBOSS and DES data

Institute for Theoretical Particle Physics and Cosmology RWTH AACHEN UNIVERSITY

Bounds on Σm_ν

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

summed mass



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)

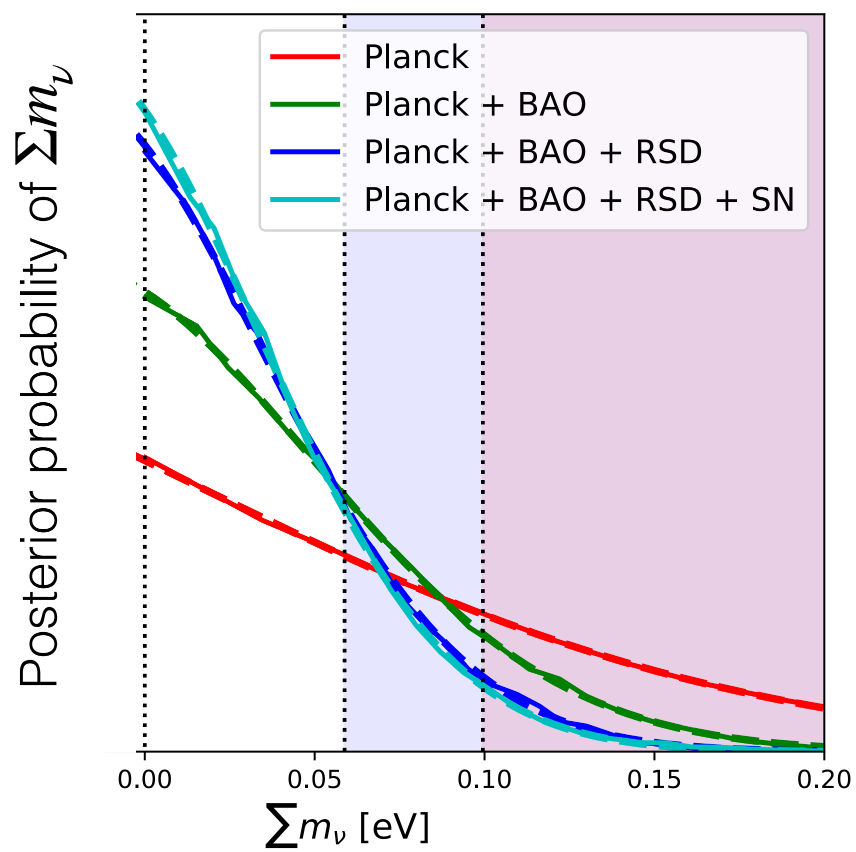
CMB + BAO + more agressive LSS:
either: + Ly-α from BOSS
or: + lensing + RSD + SNIa)
$\Sigma_i m_i$ < 87 meV (95%CL)

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)

	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]

- 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.

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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…

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY