TPC10, Paris, 16.12.2021

Cosmological constraints on neutrino masses and couplings

Julien Lesgourgues

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

Plan

- The Cosmic Neutrino Background (CνB)
- Standard effect of M_ν and mass bounds
- Models with non-standard neutrino physics inspired by:
  - H_0 tension: self-interacting nu, light majoron
  - S_8 tension: DR interacting with DM, heavy majoron
  - possible oscillation anomaly: secret interactions
  - Data preference for $M_\nu = 0$: decaying and mass-varying neutrinos
  - (3.5keV line and small-scale CDM crisis: keV sterile neutrinos)

The Cosmic Neutrino Background (CνB)

- Neutrino expected to be in thermal equilibrium until T~1 MeV, number density ~ 68% of CMB photons for T<0.5 MeV
- Indirect proof of CνB from BBN+primordial abundances, CMB maps, 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 (axions, dark radiation)

The Cosmic Neutrino Background (CνB)

- Precise study of neutrino decoupling (flavour effects, QED corrections) predict $N_{\rm eff} = 3.044 \pm 0.001$

  (Froustey et al. 2020, Bennett et al. 2020, Escudero 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)

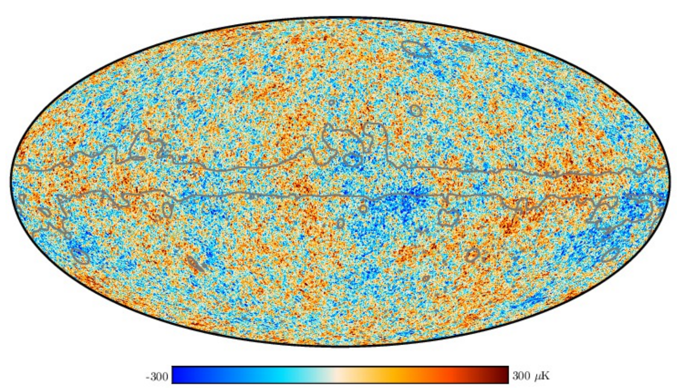
The Cosmic Neutrino Background (CνB)

- $T_\nu < |\Delta m^2|^{1/2}_{\rm sol,atm}$: at least 2 mass eigenstates non-relativistic today
- Each eigenstate :
  - radiation till $z_{\rm NR} \sim m_i/[0.53\ \mathrm{meV}] - 1$,
  - then, fraction of Dark Matter
- Today $\Omega_\nu = (\Sigma_i m_i)/[93.12\, h^2 \mathrm{eV}] \geq$ 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 individual m_i's (JL, Pastor, Perotto 2004; …; Archidiacono, JL, Hannestad 2020)

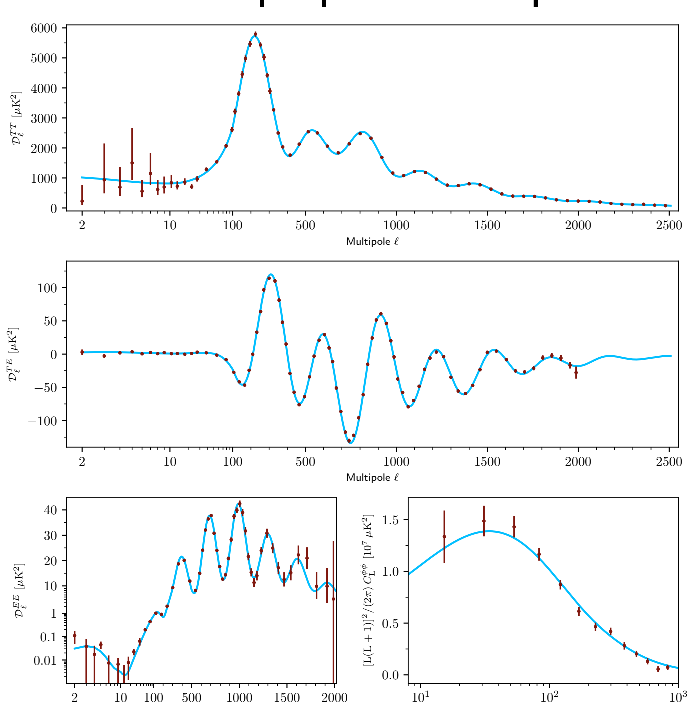
Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Cosmological observables

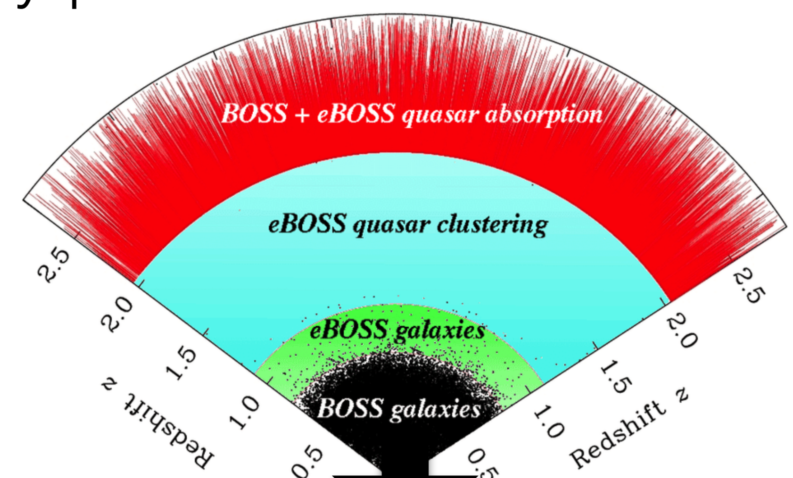
CMB temperature/polarisation



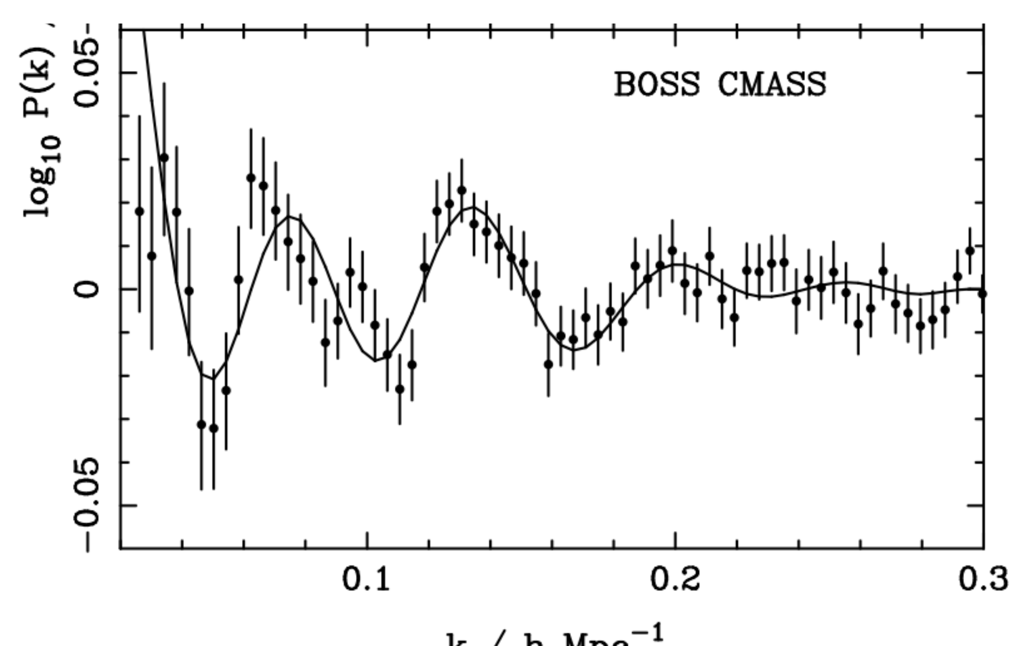
CMB temp/polar spectrum



Galaxy positions and weak lensing

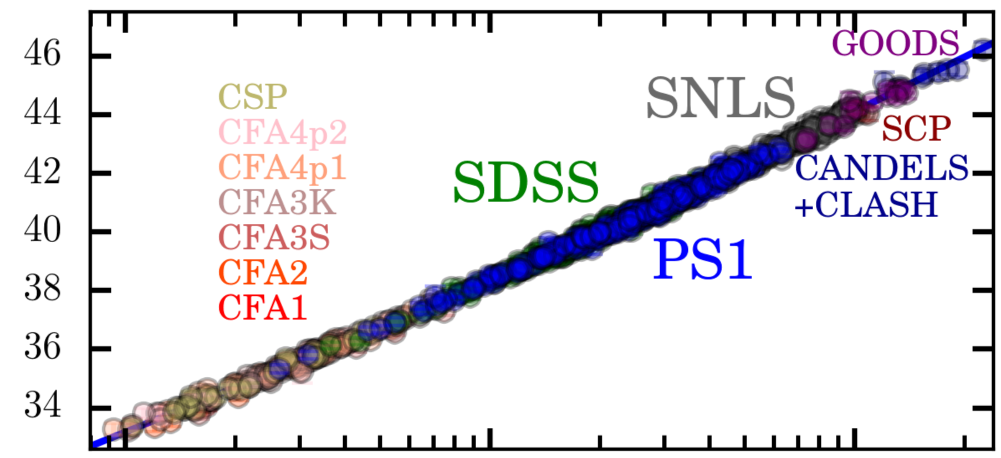


LSS (matter) power spectrum

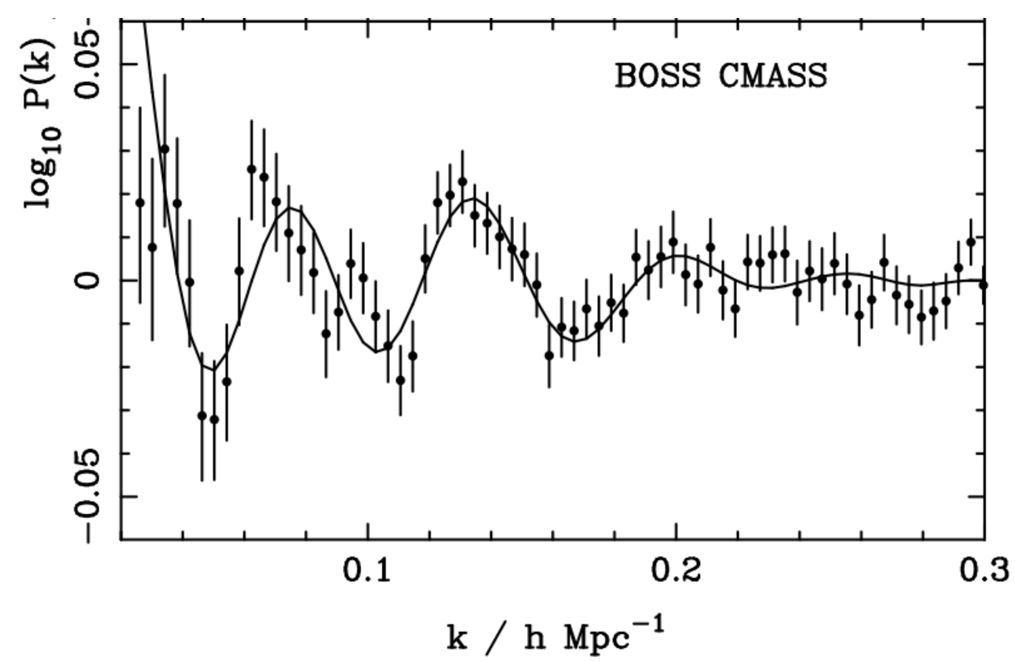


Cosmological observables

- Probes of background expansion from distance ladder (luminosity of cepheids, supernovae)



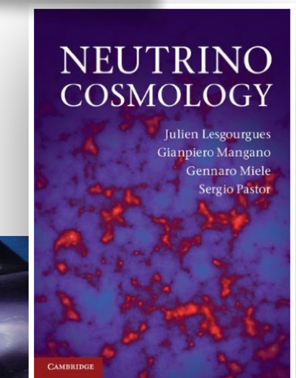
- Probes of background expansion extracted from robust geometrical information in LSS spectrum (Baryon Acoustic Oscillations)

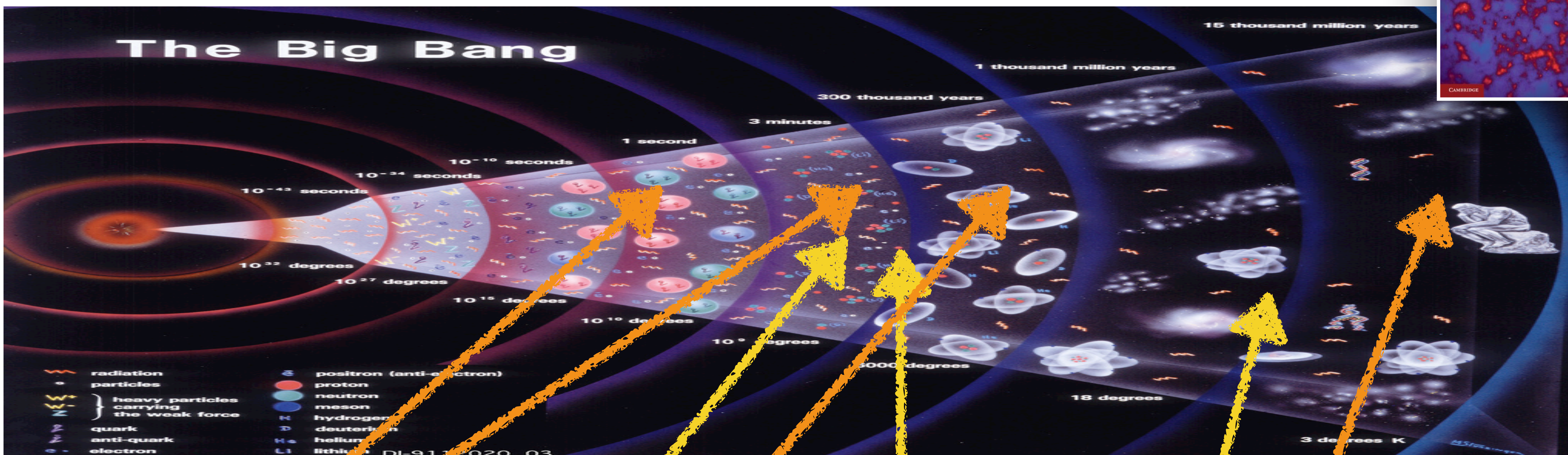


- Primordial Deuterium / Helium and theory of BBN

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)

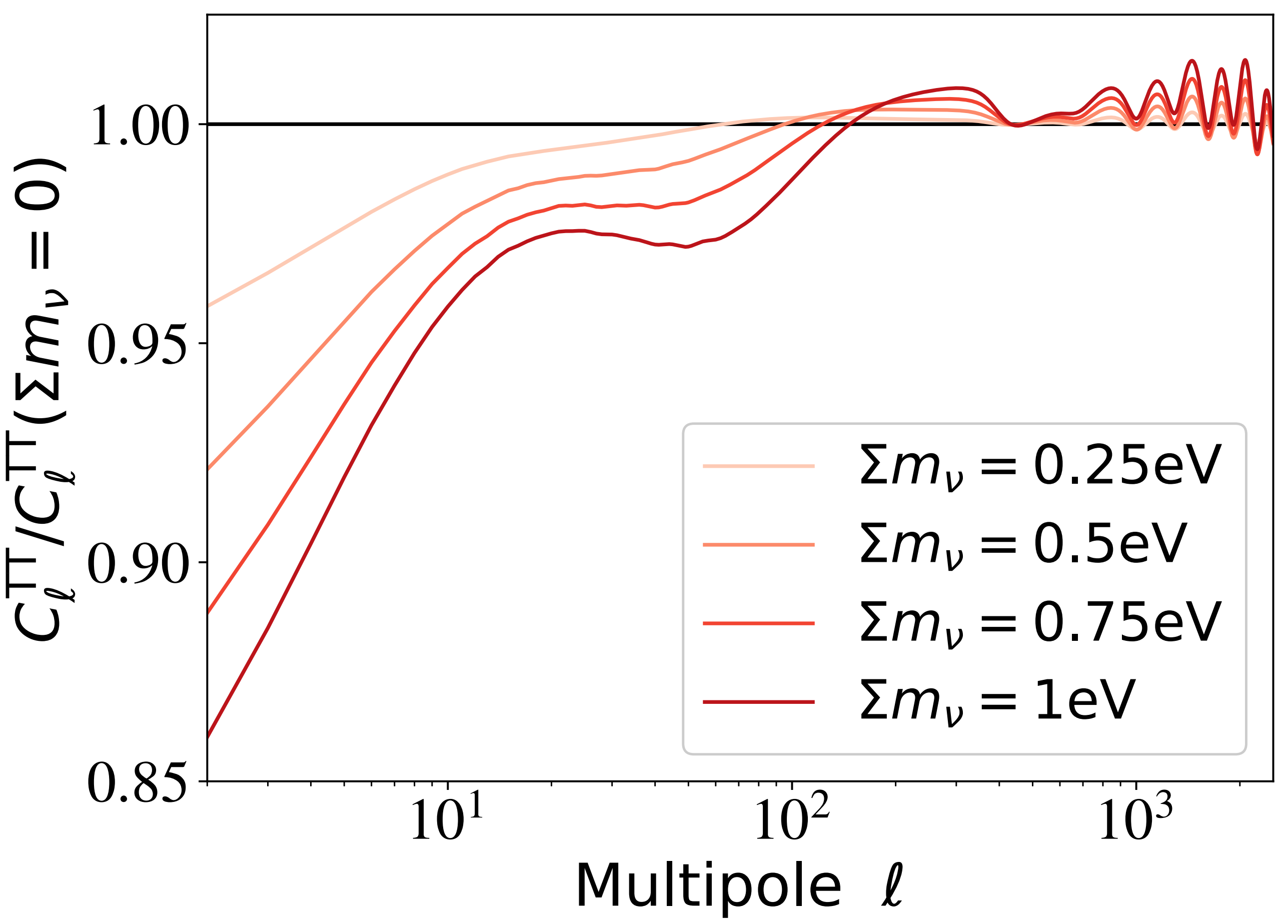
non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

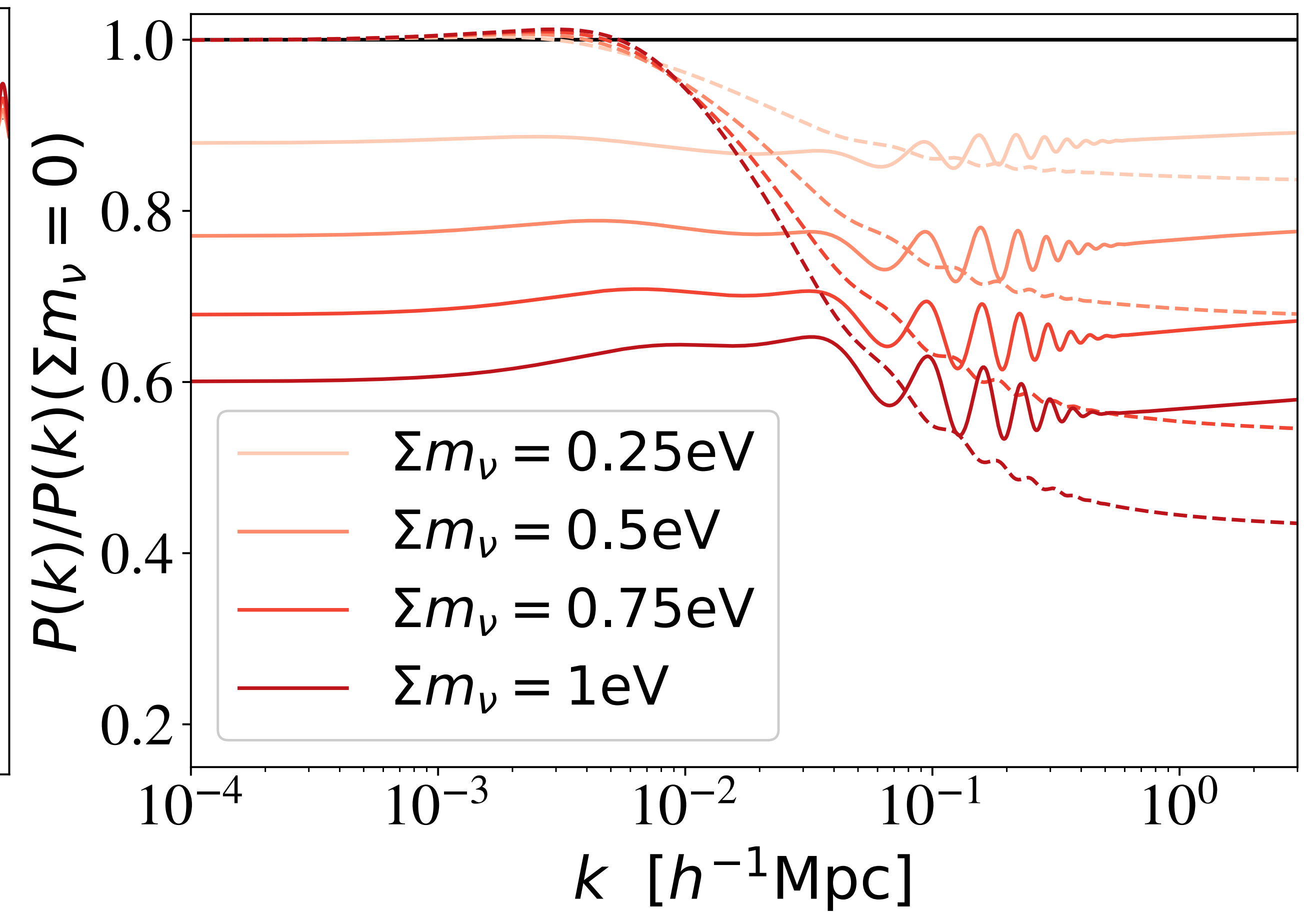
neutrino slow down early dark matter clustering

neutrino propagation and dispersion velocity

neutrino slow down late ordinary/dark matter clustering

Impact of Σm_ν



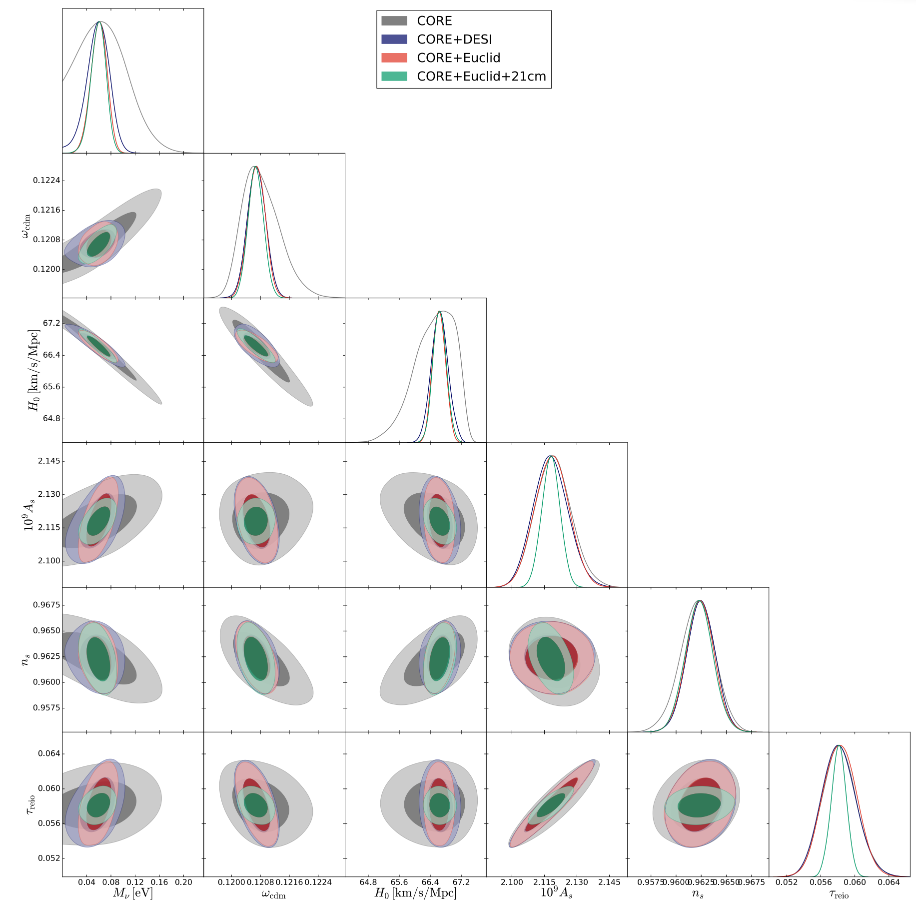


Fixed $\{\omega_b, \omega_c, \tau, \theta_s\}$

(from RPP, JL & Verde)

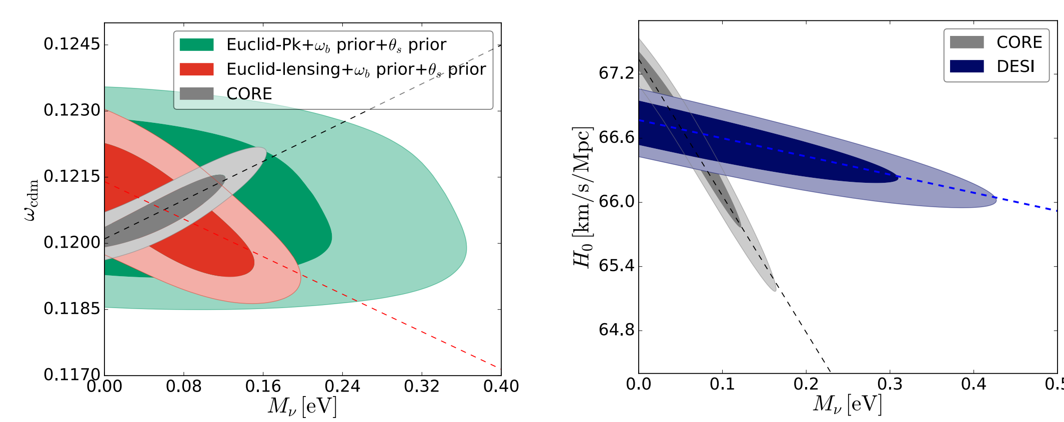
Model dependance

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

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…)

3. Assume that H_0 is “real”, investigate new scenarios accommodating the tension, explore neutrino bounds within that framework

4. Same if S_8 tensions “real”

5. Same if both tensions are “real”

Model dependance

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

- on H_0 (5σ, dominated by one collaboration, Riess et al. 2112.04510) ?
- on S_8 ($2-3\sigma$, found by many collaborations) ?

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…)
    3. Models with more freedom (beyond-Einstein gravity, non-trivial Dark Sector…)

3. Assume that H_0 is "real", investigate new scenarios accommodating the tension, explore neutrino bounds within that framework

4. Same if S_8 tensions "real"

5. Same if both tensions are "real"

Bounds on Σm_ν

(from RPP, JL & Verde)

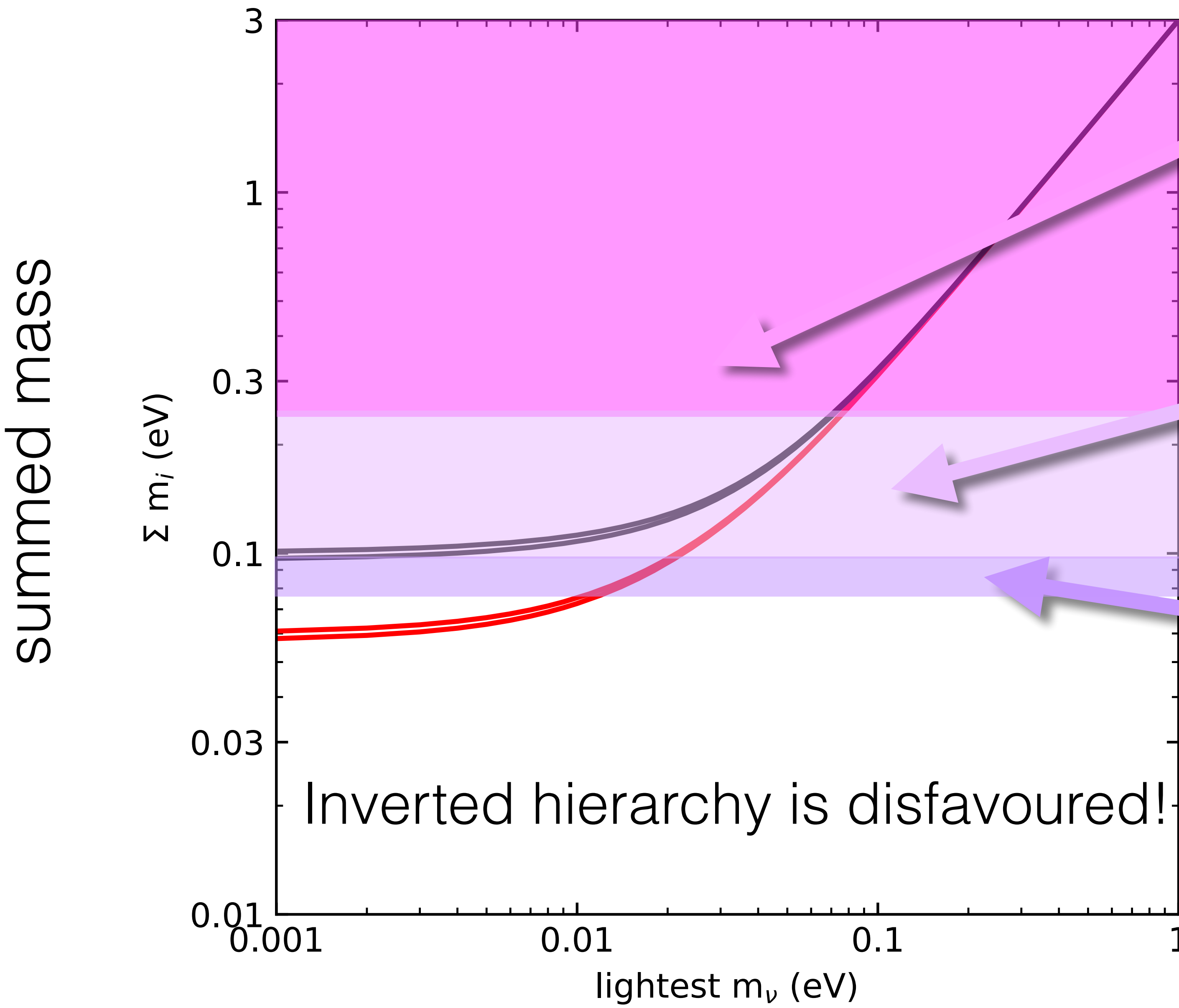
	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT,TE,EE+lowE]+BAO	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+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]

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



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 + more agressive LSS information (Lya from BOSS):
$\Sigma_i m_i$ < 87 meV (95%CL)

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 + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[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+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]

- Robustness against simple LCDM extensions (De Valentino et al. 2020)

H0 tension and neutrinos

Three avenues:

1. Change in late cosmological evolution (DE, decaying DM, beyond-Einstein gravity effects showing up at late times)feature between z~0-0.1 (SH0ES) and z~0.1-1.3 (BAO/high-z SNIa)
   - Difficulty: simultaneous compatibility with all observables
2. Increase $N_{\rm eff}$ to change sound horizon r_s and make sound angular scale $\theta_s = r_s/d_A$ compatible with larger H_0
   - Difficulty: other ingredients must counteract other effects of increasing $(N_{\rm eff}, H_0)$: enhanced Silk damping, acoustic peak shift from neutrino drag… ⇒ new interactions in dark sector and/or neutrino sector
     - Self-interacting DR, potentially also interacting with DM: Buen-Abad et al. 1505.03542, 1708.09406; JL et al. 1507.04351
     - self-interacting neutrinos: Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Kreisch et al. [1902.00534]…
     - Neutrinos coupled to Majoron: Escudero & Witte 1909.04044, 2004.01470, 2103.03249
3. Other changes in early cosmological evolution, still leading to shift in sound horizon r_s: early DE, early MG, inhomogeneous recombination from primordial magnetic fields, running of fundamental constants…
   - Less constrained but more ad hoc?

Non-standard neutrino self-interactions (+extra relics)

Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Di Valentino et al. [1710.02559], Kreisch et al. [1902.00534], Park et al. [1904.02625]

- Neutrinos cluster more than free-streaming ones: reduced the "bad effects" of increasing N_{eff} (e.g. neutrino drag) and of increasing M_ν.

- High-interaction case accommodates N_{eff}~2.8-4.5 and M_ν~0.05-0.55 eV (95%CL)! M_ν bounds released by factor 4.5

- Now ruled out with better CMB data (Planck polarisation spectra) (Schöneberg et al. 2021) and direct laboratory bounds (ββ and meson decay) Blinov et al. [1905.02727])

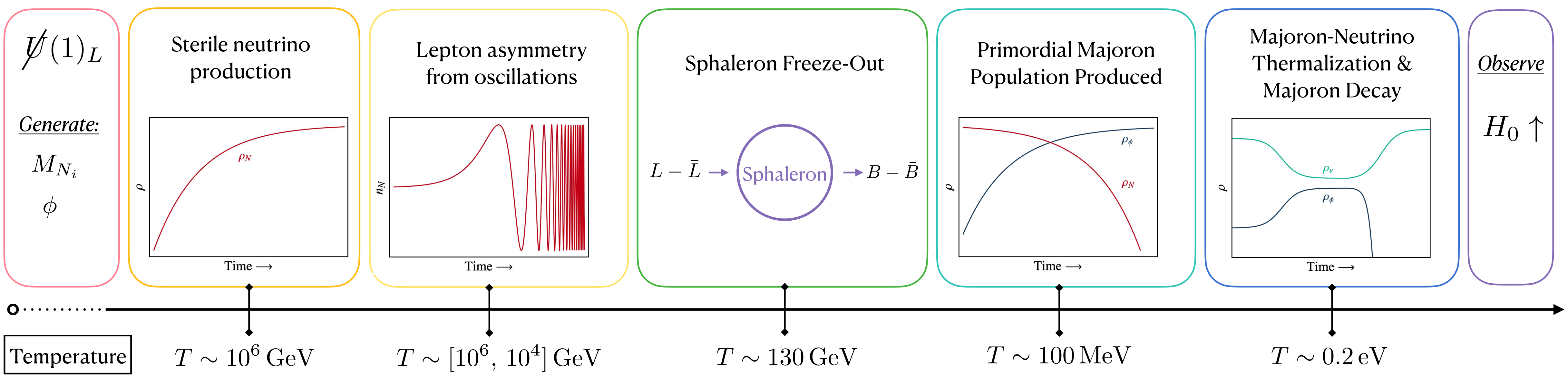
- Limits on non-standard neutrino self-interactions (Schöneberg et al. 2021):

$$\log_{10}(G_{\rm eff}\,{\rm MeV}^2) < -0.8$$

H0 tension and neutrinos

(light) Majoron scenario of Escudero & Witte 1909.04044, 2004.01470, 2103.03249:

- O(eV)-mass Majoron ϕ = pseudo-Goldstone of spontaneously broken $U(1)_L$
- small Yukawa-like couplings to active neutrinos
- $T \sim \phi$: interactions between majoron and active neutrinos (inverse neutrino decay):
  - Majoron thermalize and contribute to N_{eff} ,
  - active neutrinos do not free-stream
- $T < \phi$: Majoron decays into active neutrinos, which free-stream



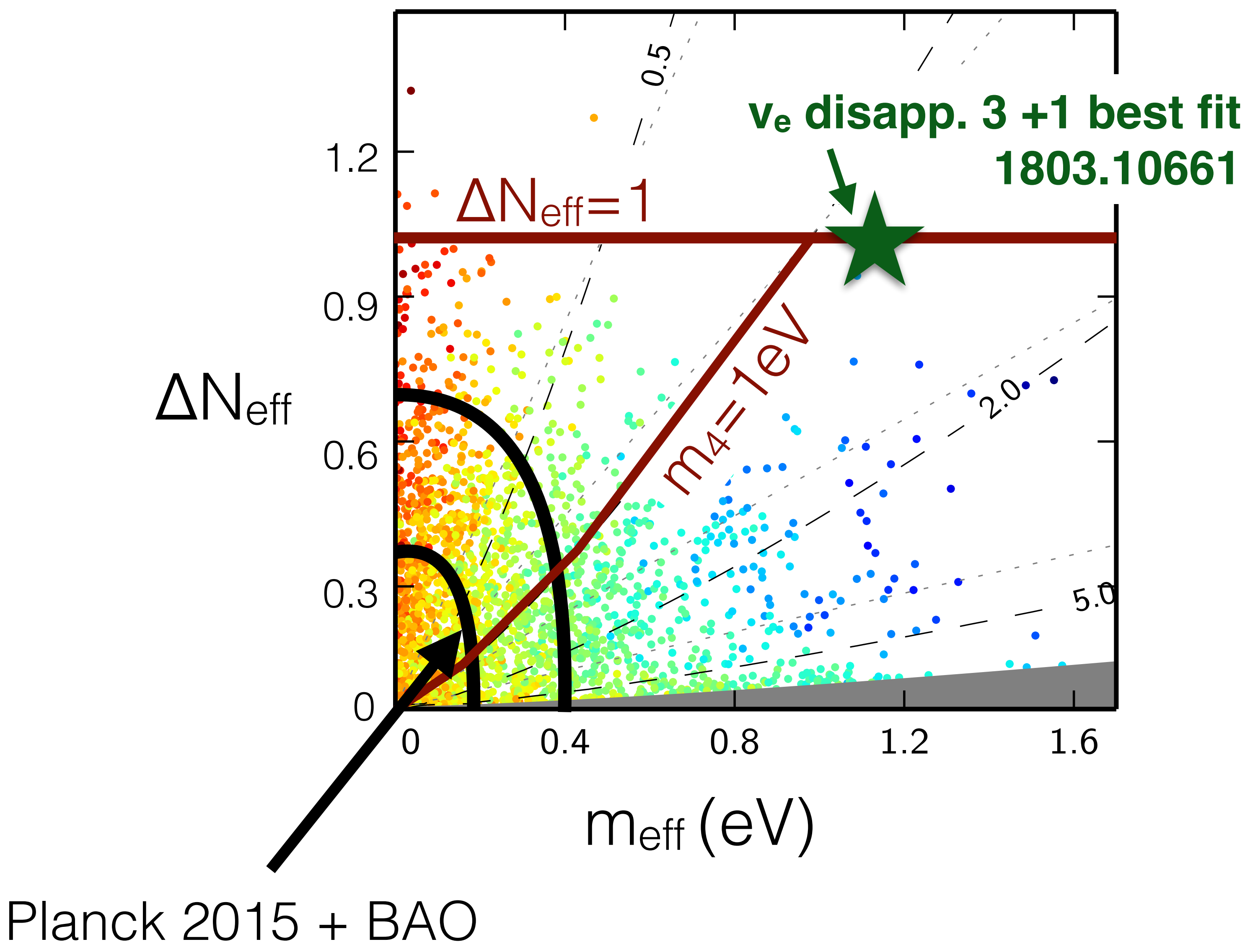
S8 tension and neutrinos

Does not work:

- Standard neutrino mass $\sum m_\nu$ (z_{NR} close to z_{dec} -> early ISW; not enough CMB lensing)
- Most decaying DM models (decay between z~1000 and z~1 into electromagnetic components: strong energy injection bounds; into neutrinos / dark radiation -> late ISW) (Chudaykin et al. 1602.08121, Poulin et al. 1606.02073, DES 2011.04606, …)

Works well:

- Many Modified Gravity (MG) models (e.g. f(R))
- Feebly interacting DM (with relativistic particles: photons or DR; collisional damping) (Becker et al. 2010.04074)
- Cold + Warm DM (small fraction of ~keV DM) (Boyarsky et al. 0812.0010)
- Long-lived CDM decaying into massless+massive but lighter particle; possibly (heavier) Majoron decaying into active + sterile neutrinos; possible connection with (heavier) Majoron and with Xenon-1T (Abellan et al. 2008.09615); not a solution to Hubble tension
- Cannibal DM (inelastic scattering 3->2 causing slow transition from radiation-like to matter-like (Heimersheim et al. 2008.08486)
- Connection with small-scale CDM crisis…



MicroBoone 2021: $\nu_\mu \to \nu_e$ disfavored

see however Denton 2111.05793 on ν_e disapp.

Neutrino oscillation anomalies

How to suppress the ν_4 density in both relativistic and non-relativistic regimes?

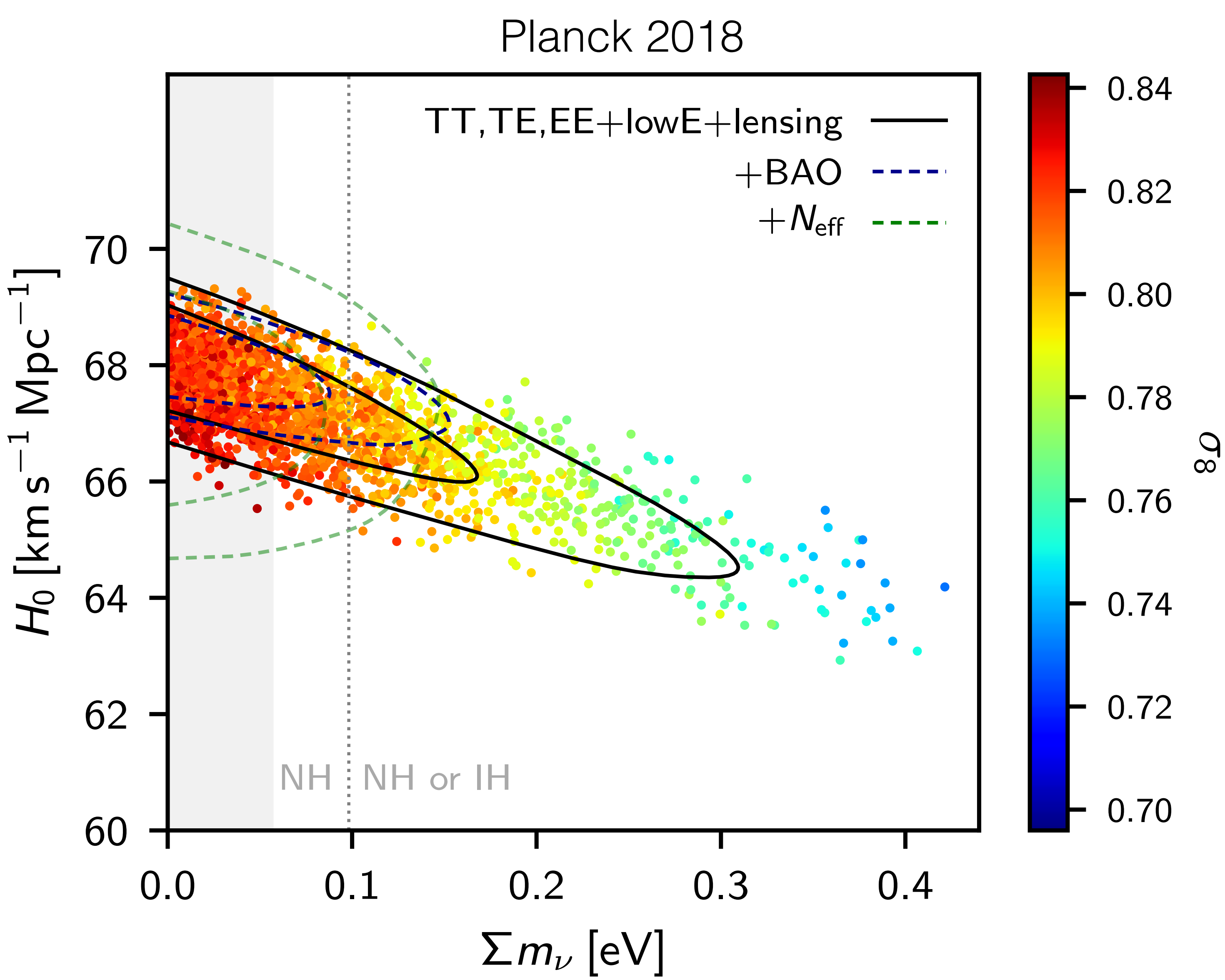
- Low-temperature reheating — Gelmini et al. 2014, de Salas et al. 2015
- Leptonic asymmetry and resonant oscillations… *issues with BBN* (μ_e)

  Di Bari et al. 2001; …; Hannestad, Tambora & Tram 2012; Mirizzi et al. 2012; Saviano et al. 2013
- Non Standard Interaction (passing bounds on fifth force and SN energy loss…)
  - ν_4 interacts with (dark) gauge boson

    Dasgupta, Kopp 2015 ; Saviano et al. 2014; Mirizzi et al. 2014; Chu, Dasgupta, Kopp 2015
  - ν_4 interacts with (dark) pseudoscalar

    Hannestad et al. 2013; Saviano et al. 2014; Archidiacono et al. 2016, 2020, 2021
    - ν_4 production is suppressed, ϕ-ν_s recouple —> neutrinos as relativistic fluid, ν_4 annihilate into ϕ at late times… solves also H0 tension, but bad fit to recent CMB data (Planck high-l temperature and polarisation)

Absence of preliminary evidence for neutrino mass



Could be statistical fluke, but isn't the data trending towards $M_\nu < 0.06$ eV ?

Absence of preliminary evidence for neutrino mass

- Invisible neutrino decay into:
  - lighter neutrino ($\ll 0.1$ eV) + scalar (Majoron again!) Barenboim et al. 2011.01502. Joint bounds on decaying neutrino lifetime and mass (which could be arbitrarily large).
  - Same in the framework of see-saw (more constrained). Escudero et al. 2007.04994. $M_\nu \sim 1$ eV still possible.
  - Dark Radiation. Chacko et al. 2002.08401: could be probed by Euclid if decay takes place late enough.
- Mass-varying neutrinos coupled to scalar field (Fardon et al. astro-ph/0309800). Mass varies with time and location. Instability problems (small-scale neutrino lumps, Wetterich et al.).
- Neutrino mass generated at late times (phase transition after recombination, Dvali and Funcke 1602.03191). Lorenz et al. 1811.01991, 2102.13618. No significant evidence for the model, but bound relaxed to $M_\nu \leq 1.4$ eV. Solves S_8 tension (no impact on H_0).

keV-mass sterile neutrinos

Review in Drewes et al. 1807.07938

- Sterile neutrino = elegant candidate for DM
- WDM: potential solution to CDM small-scale crisis
- Lyman-alpha bounds partially evaded by resonant production (more like mixed C+WDM than usual thermal WDM)
- 3.5keV line in X-ray data potentially explained by radiative decay $N \longrightarrow \nu + \gamma$ of 7keV sterile neutrinos
- Controversy: high-resolution Lyman-alpha bounds and bounds from Milky Way satellite tend to exclude 7keV sterile neutrinos even with resonant production; are these analyses robust?

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 and better LSS data
- Could reach 5σ after better measurements of reionization and 21cm fluctuations (radioastronomy)
- Null detection would be revolutionary (NSI, neutrino decay…)
- Possible shift of paradigm could reshuffle conclusions…