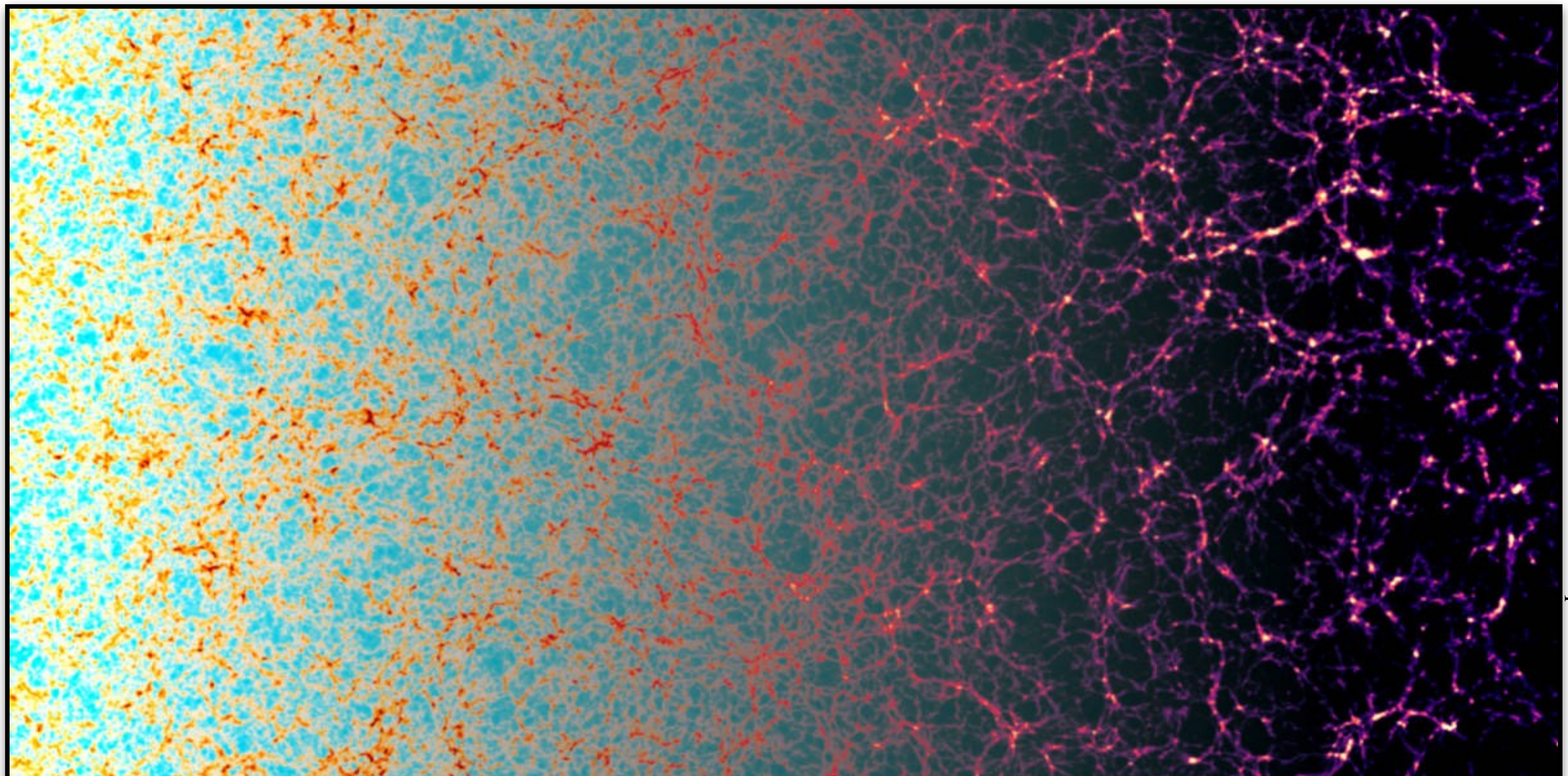
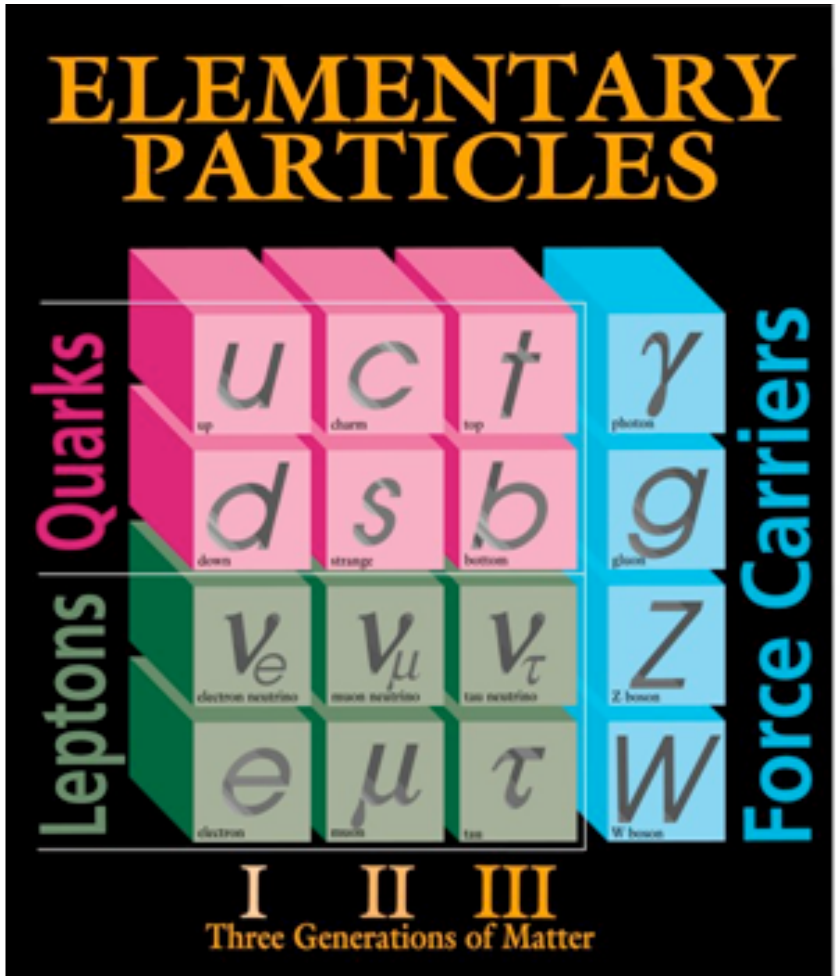


Neutrinos in cosmology

Matthieu TRISTRAM
CNRS

Neutrinos in particle physics



At the time the Standard Model of particle physics was constructed, it was assumed that:

- neutrinos have exactly **zero mass**;
- **three neutrinos**: one for each of the three charged leptons;
- **lepton number is conserved** separately for each of the three lepton families;
- neutrinos and antineutrinos are distinct;
- all neutrinos are **left-handed**.

Mass

- Fermions only have intrinsic mass because of interactions with the Higgs field (but require both left- and right-handed)
- Neutrinos acquire mass through the **seesaw** mechanism (right-handed neutrinos with very large Majorana masses are added)

Oscillations

- Neutrino oscillation arises from **mixing** between the flavor and mass eigenstates of neutrinos

Neutrino mixing

flavours
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
masses

- **Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix**

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{21} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}e^{i\eta_1} & 0 & 0\\ 0 & e^{i\eta_2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\|\Delta m^2_{31,32}\|$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\|\Delta m^2_{31,32}\|$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\|\Delta m^2_{31,32}\|$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

[de Salas et al., Phys. Letter B 782 633–640 (2018)]

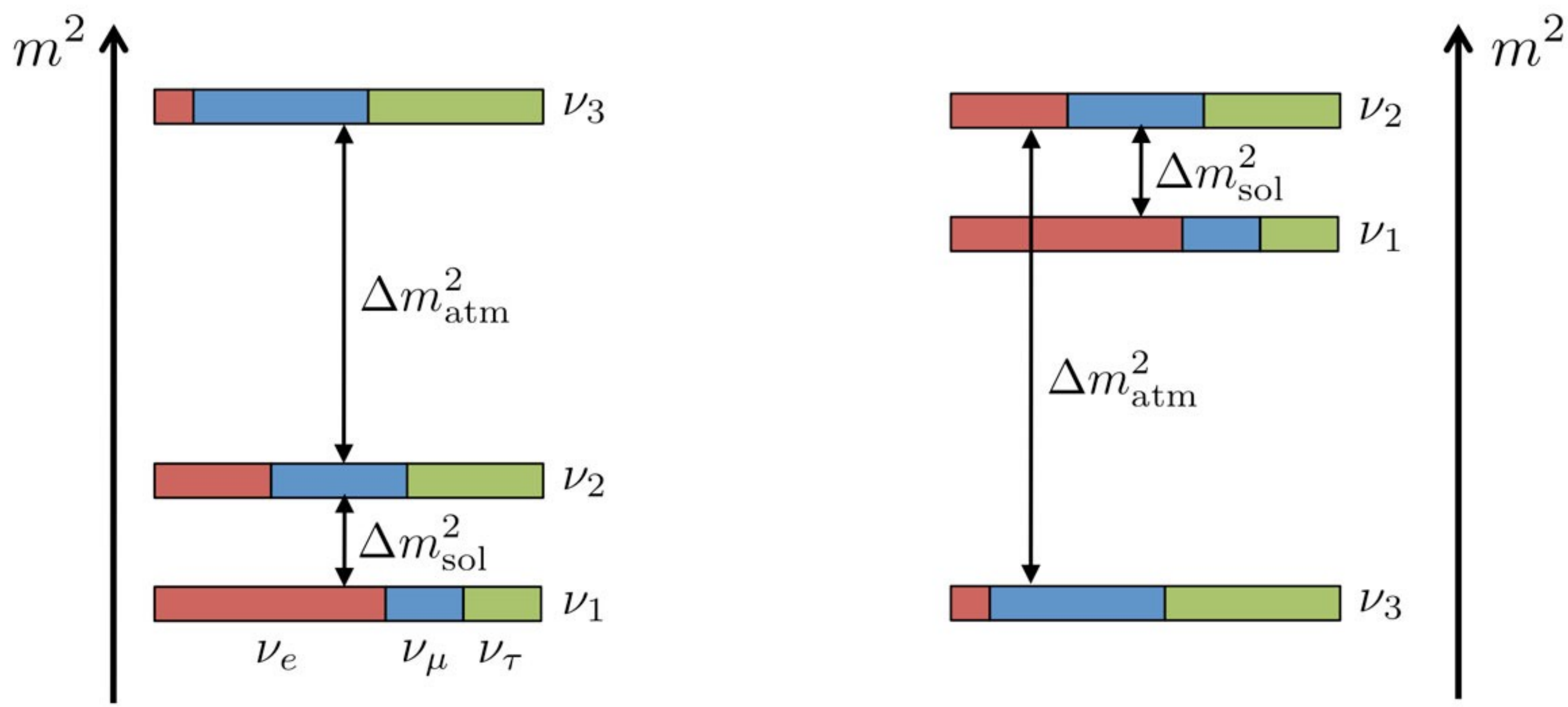
Current constraints from global analysis

$\Delta m^2{}_{21} \approx (7.55 \pm 0.2) \cdot 10^{-5}$ eV^2
$|\ \Delta m^2{}_{31}\ |\ \approx (2.50 \pm 0.03) \cdot 10^{-3}$ eV^2

Neutrino ordering

- **constraints on the sum of neutrino masses have consequences on the neutrino ordering**

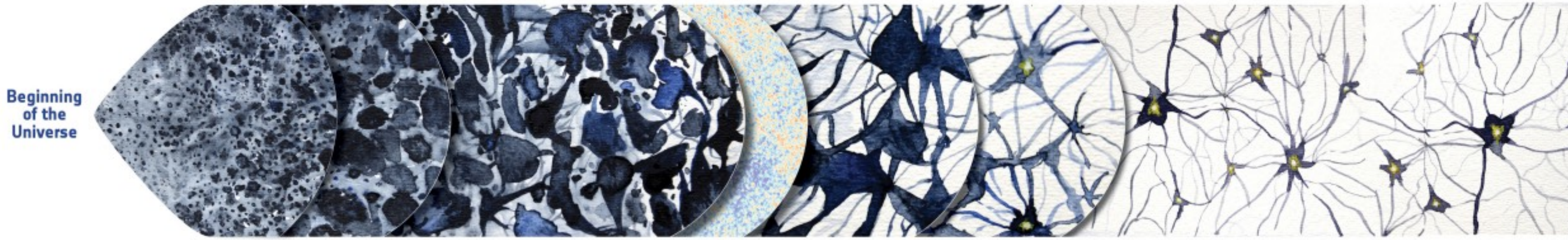
Normal Ordering (NO) | Inverted Ordering (IO)



$\sum m_\nu > 0.06$ eV | $\sum m_\nu > 0.10$ eV

no measurement of the neutrino mass scale,
but at least **two masses neutrinos** today

Neutrinos in cosmology



T ~ 1 MeV
neutrino decoupling

T~0.01 MeV
BBN

T~0.1 eV
photon decoupling

T~m_ν
non-relativistic transition

0.001 eV

neutrino relativistic (radiation)

neutrino non-relativistic (matter)

contribution to **early expansion**

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

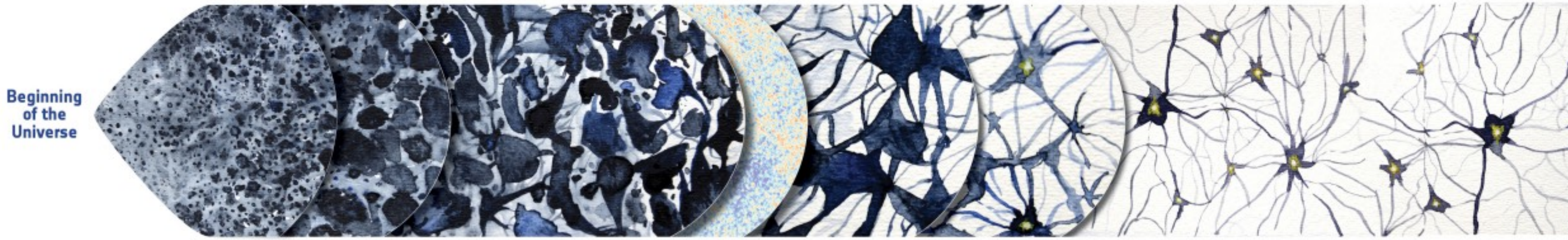
contribution to **late expansion rate** (acoustic angular scale)

neutrino **free-streaming** slows down CMB photon clustering

neutrino **free-streaming** slows down late matter clustering

[Lesgourgues & Pastor, Phys. Rep. 2016]

Neutrinos in cosmology



T ~ 1 MeV neutrino decoupling	T~0.01 MeV BBN	T~0.1 eV photon decoupling	T~m_ν non-relativistic transition	0.001 eV

neutrino relativistic
(radiation)

$$\rho_\nu \propto (T_\nu/T_\gamma)^4 N_{\rm eff}$$

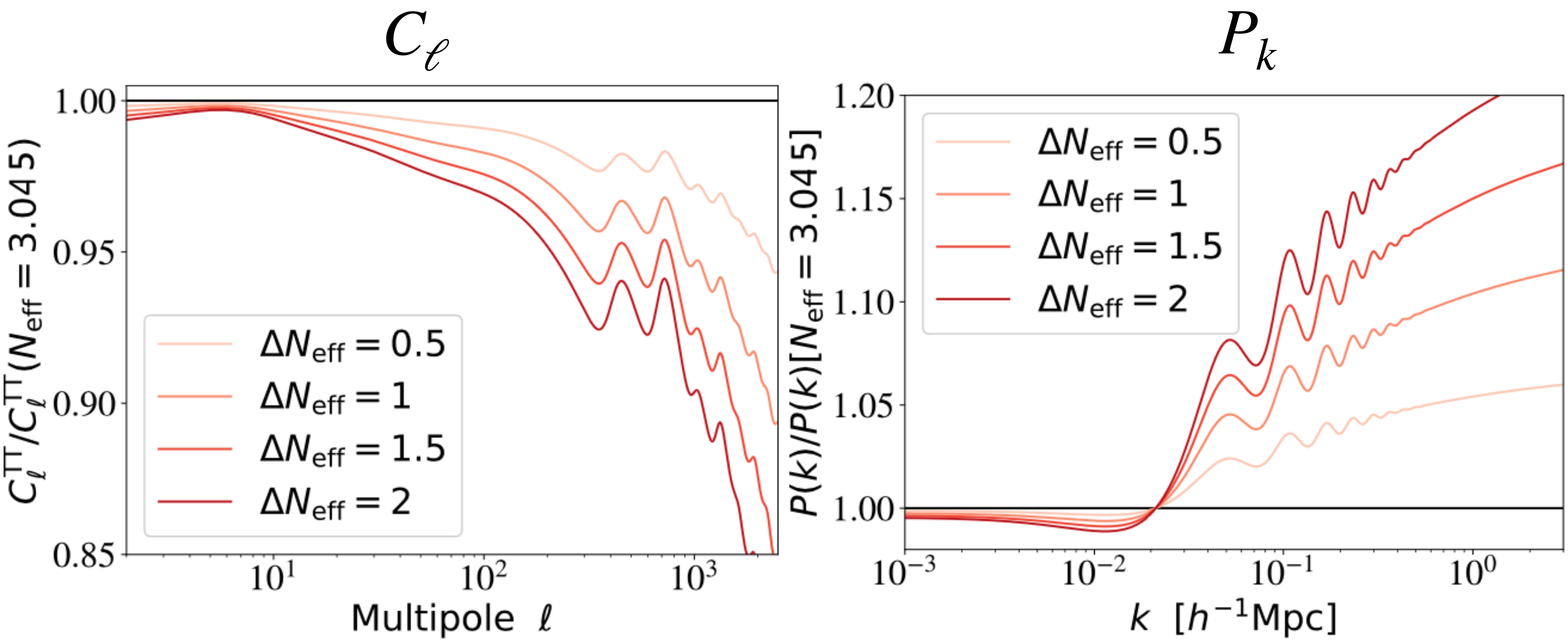
$$N_{\rm eff} \equiv \frac{\rho_{rad} - \rho_\gamma}{\rho_\nu} = 3.045$$

neutrino non-relativistic
(matter)

$$\rho_\nu \propto \Sigma m_\nu (T_\nu/T_\gamma)^3$$

Effective number relativistic species

[Lesgourgues & Verde, PDG (2019)]

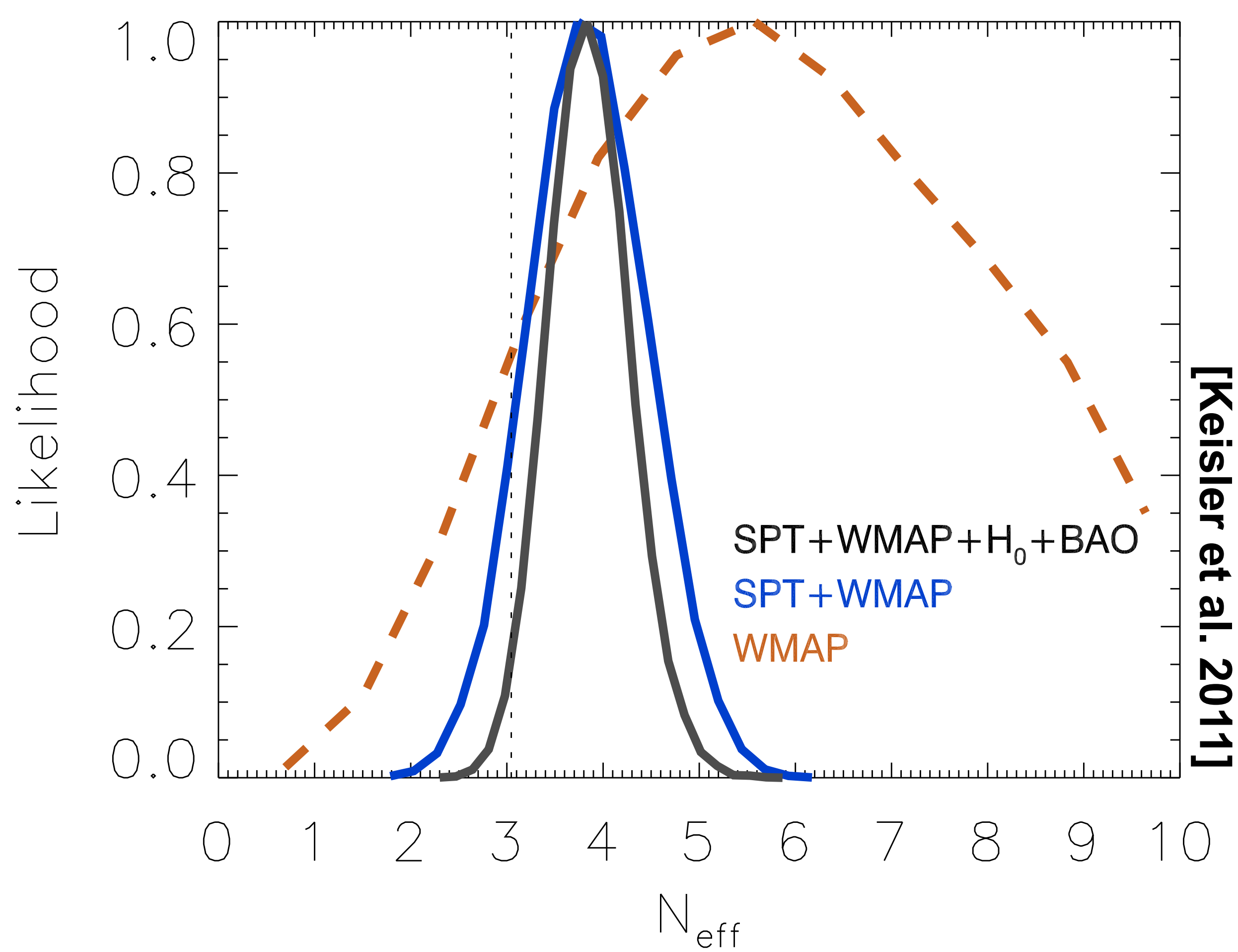


Effective number relativistic species

- **CMB sensitive to the number of relativistic species at decoupling**
  - standards neutrinos : $N_{eff} = 3.045$
  - confuse situation since WMAP + SPT + ACT...

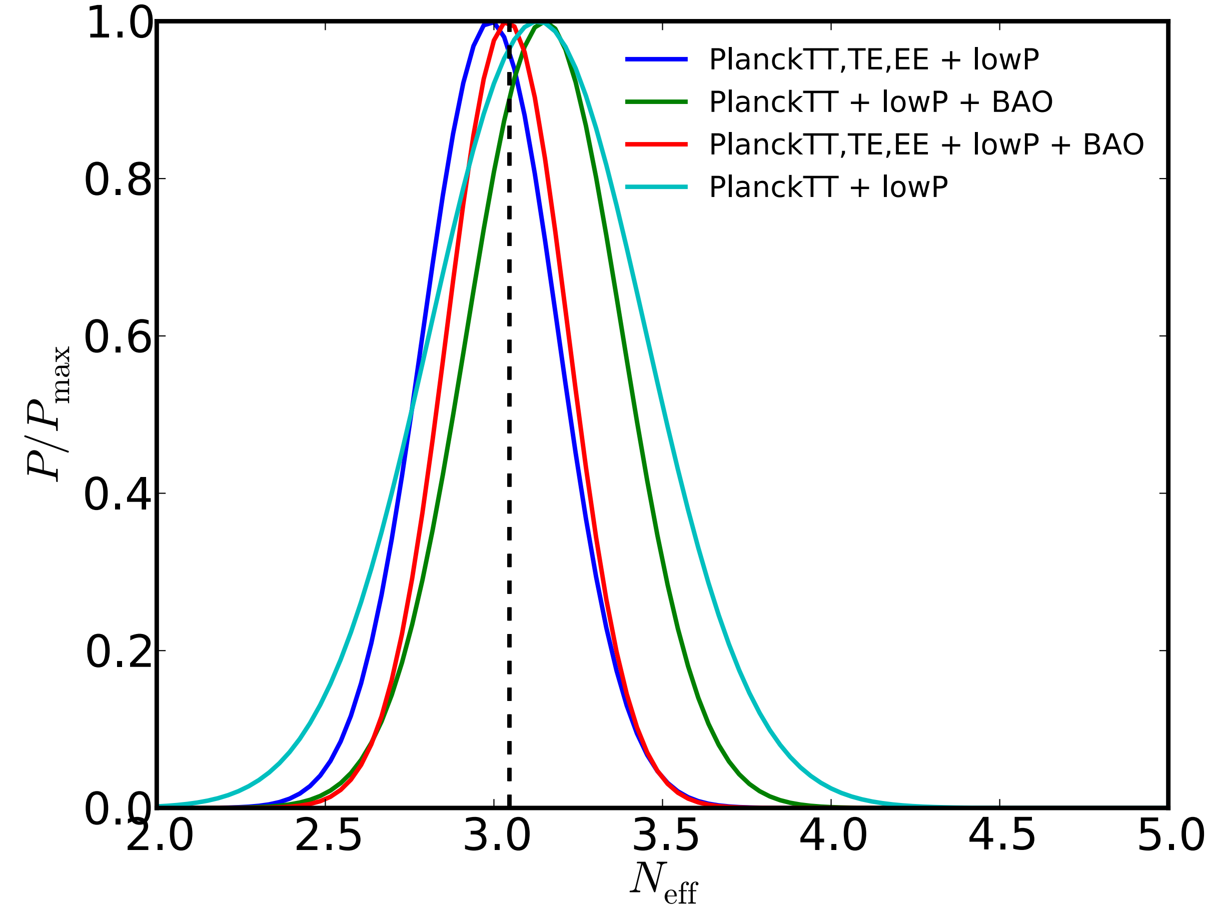
$$\rho = N_{\rm eff} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_\gamma.$$

WMAP + SPT



[Keisler et al. 2011]

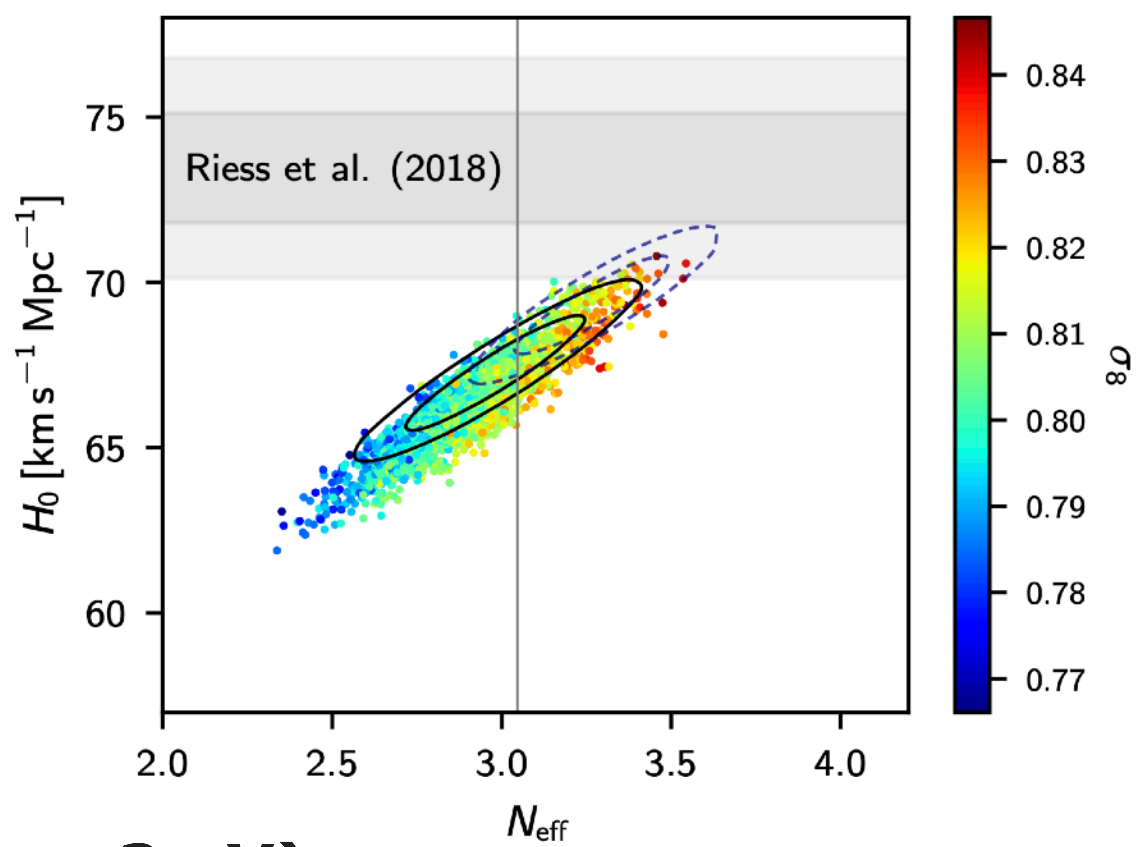
Planck



compatible with 3

Neff constraints

[Planck 2018 results. VI]



- **Current constraints from Planck**

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \text{(95 \%, TT,TE,EE+lowE+lensing +BAO).}$$

- **Allowing for massive sterile neutrino (m_ν < 2 eV)**

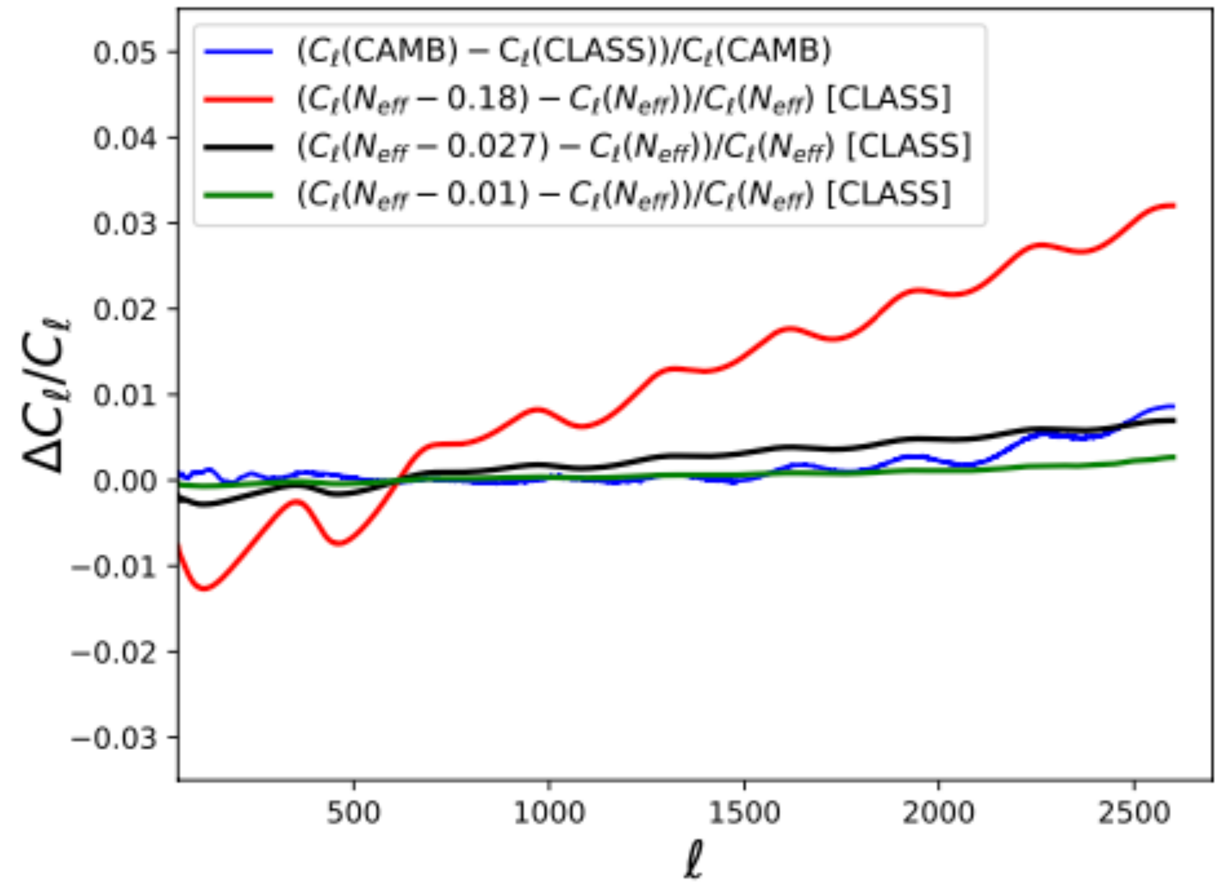
$$\left.\begin{array}{r} N_{\rm eff} < 3.34, \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.23\ \text{eV}, \end{array}\right\} \text{95 \%, } \textit{Planck}\text{ TT,TE,EE+lowE +lensing+BAO.}$$

one thermalised sterile neutrino is **excluded at 6σ** irrespective to its mass

Neff in practice

[Henrot-Versillé et al., A&A 623 A9 (2019)]

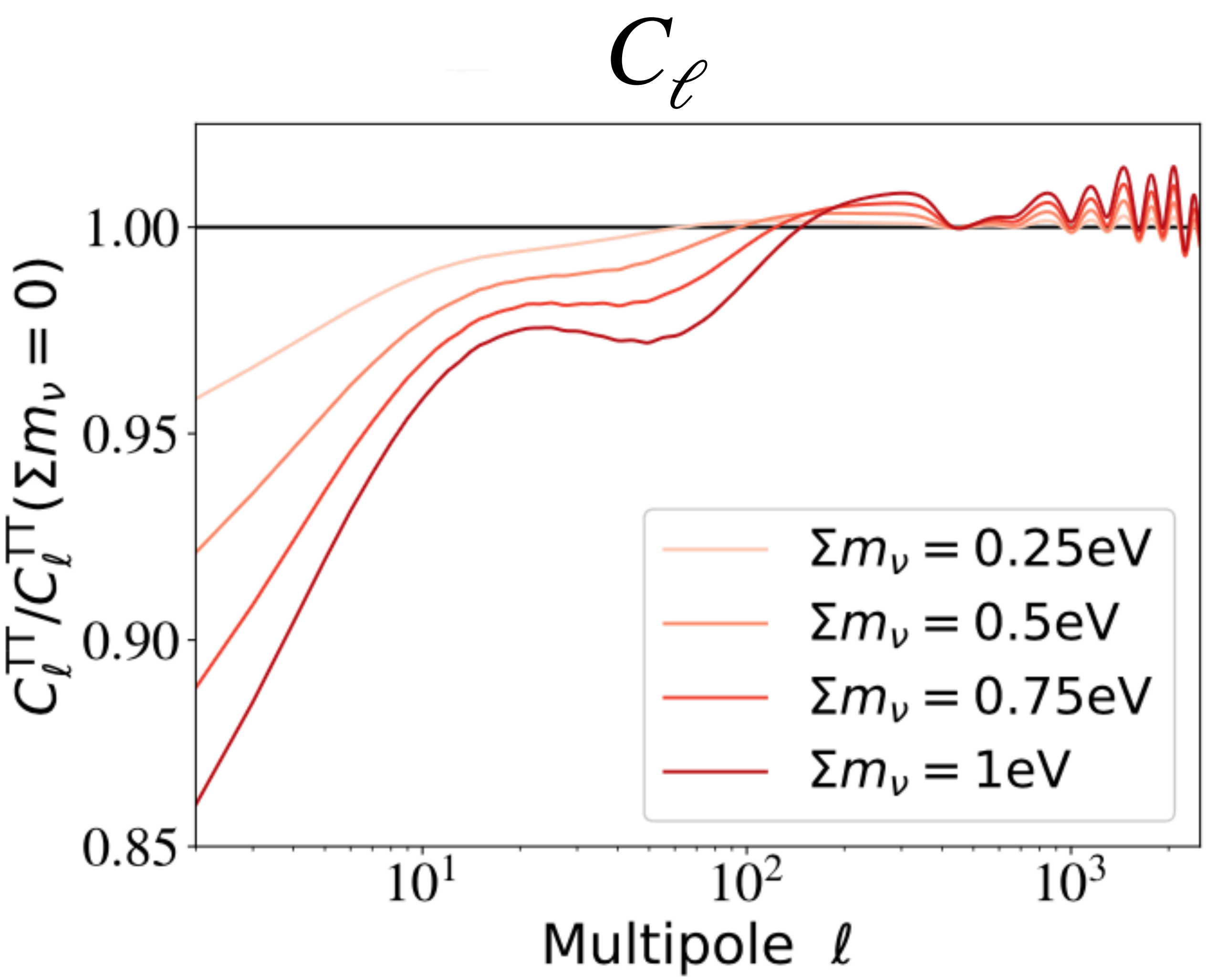
- **systematics**
  - Boltzmann code
  - Likelihood systematics
  - Statistical analysis systematics

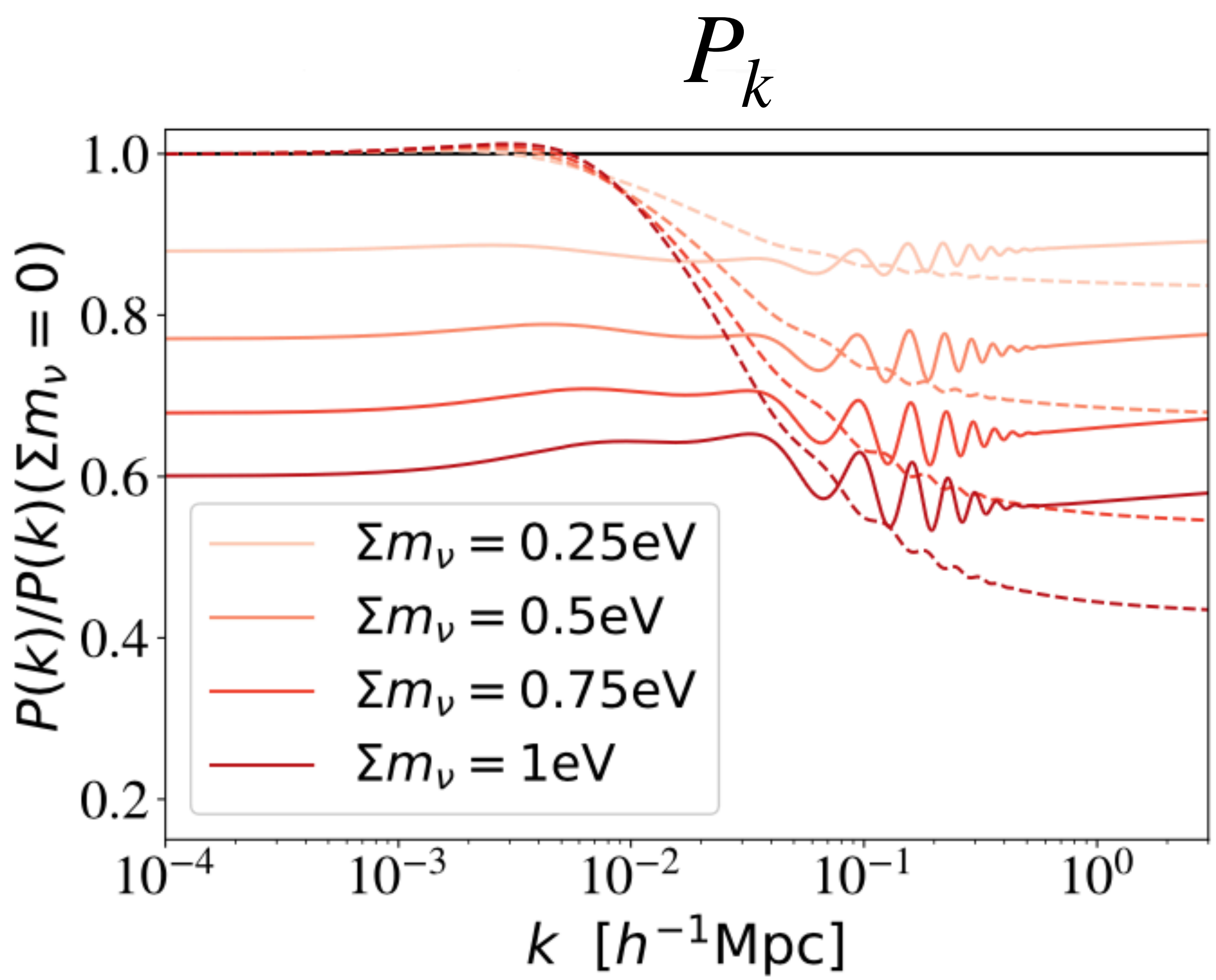


	Planck $\mathcal{L}$ +lowTEB+BAO	Config	$N_{\rm eff}$
1	PlikALL♯	MCMC/CAMB	3.04 ± 0.18
	Boltzmann code and sampler systematics		
2	PlikALL	MCMC/CLASS	$3.03^{-0.17}_{+0.17}$
	Likelihood systematics		
3	CamSpecALL♯	MCMC/CAMB	2.89 ± 0.19
4	hlpALL	MCMC/CLASS	$2.92^{-0.15}_{+0.15}$
5	hlpALLps	MCMC/CLASS	$2.86^{-0.14}_{+0.15}$
	Statistical analysis systematics		
6	PlikALL	Profile/CLASS	$3.00^{+0.19}_{-0.20}$
7	hlpALL	Profile/CLASS	$2.87^{+0.15}_{-0.14}$
8	hlpALLps	Profile/CLASS	2.85 ± 0.14
9	hlpALLps (Plik-like)	Profile/CLASS	$2.90^{+0.17}_{-0.16}$

Neutrino mass scale

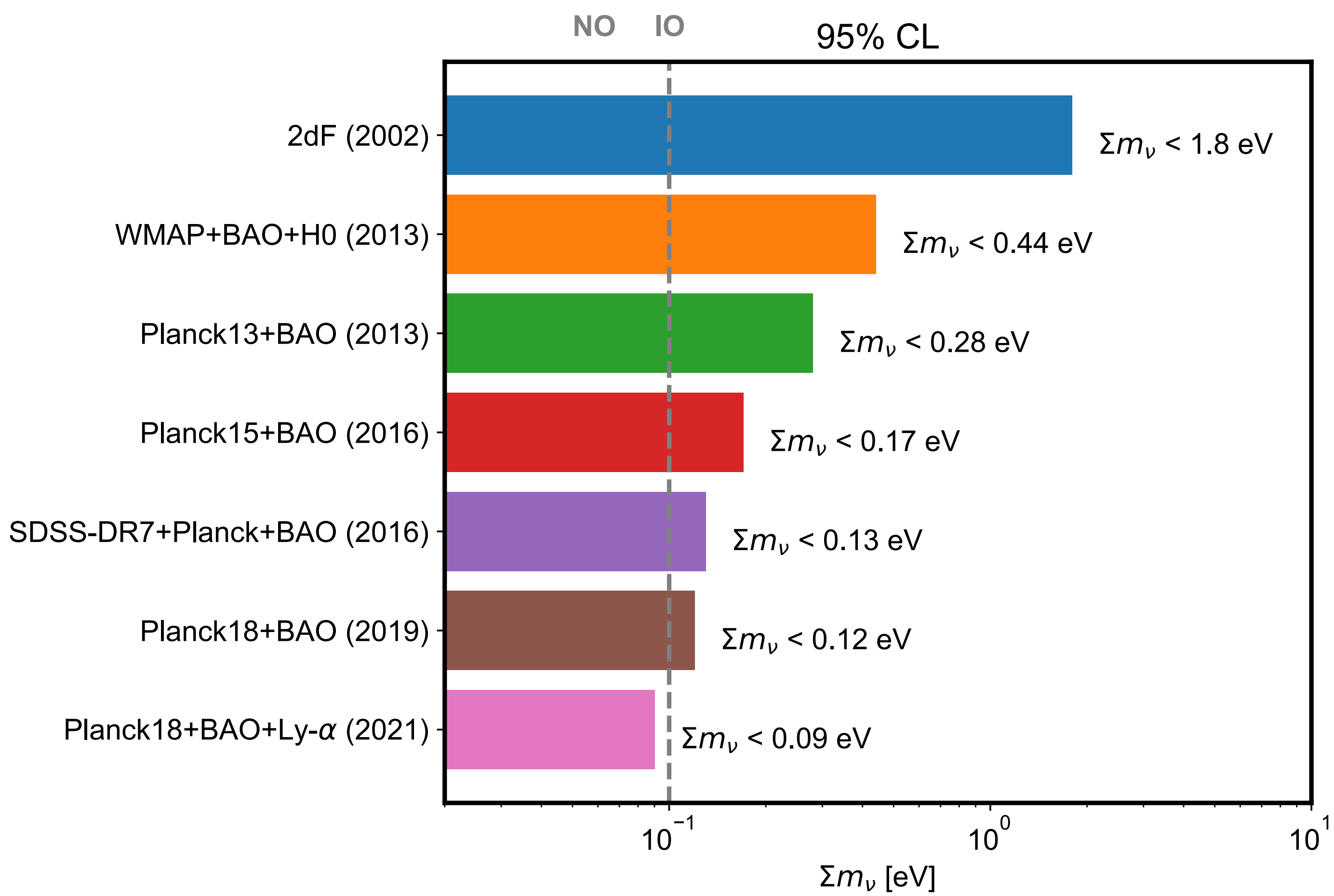
[Lesgourgues & Verde, PDG (2019)]



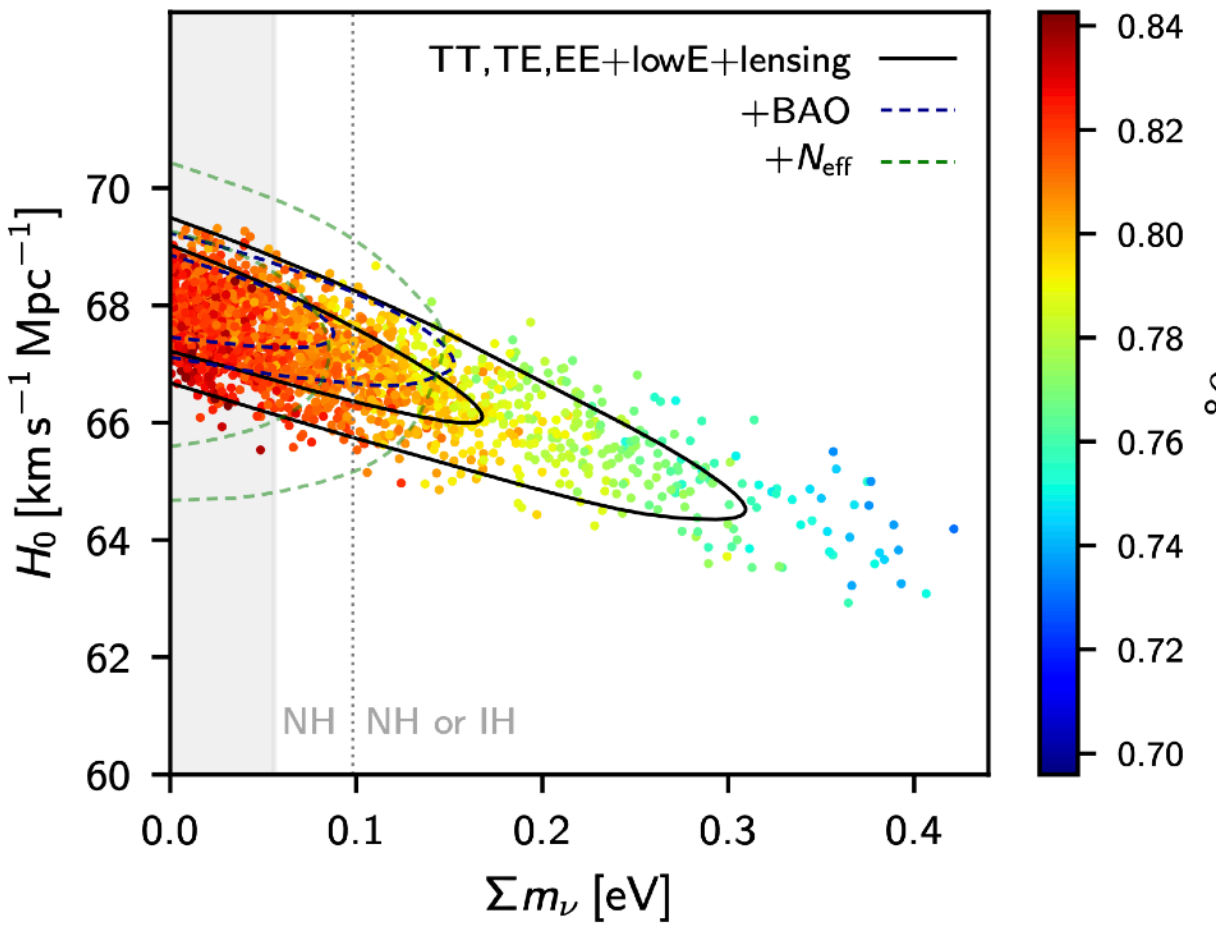


Constraints on Σmν

- **Huge improvement in the last two decades**



[Planck 2018 results. VI]

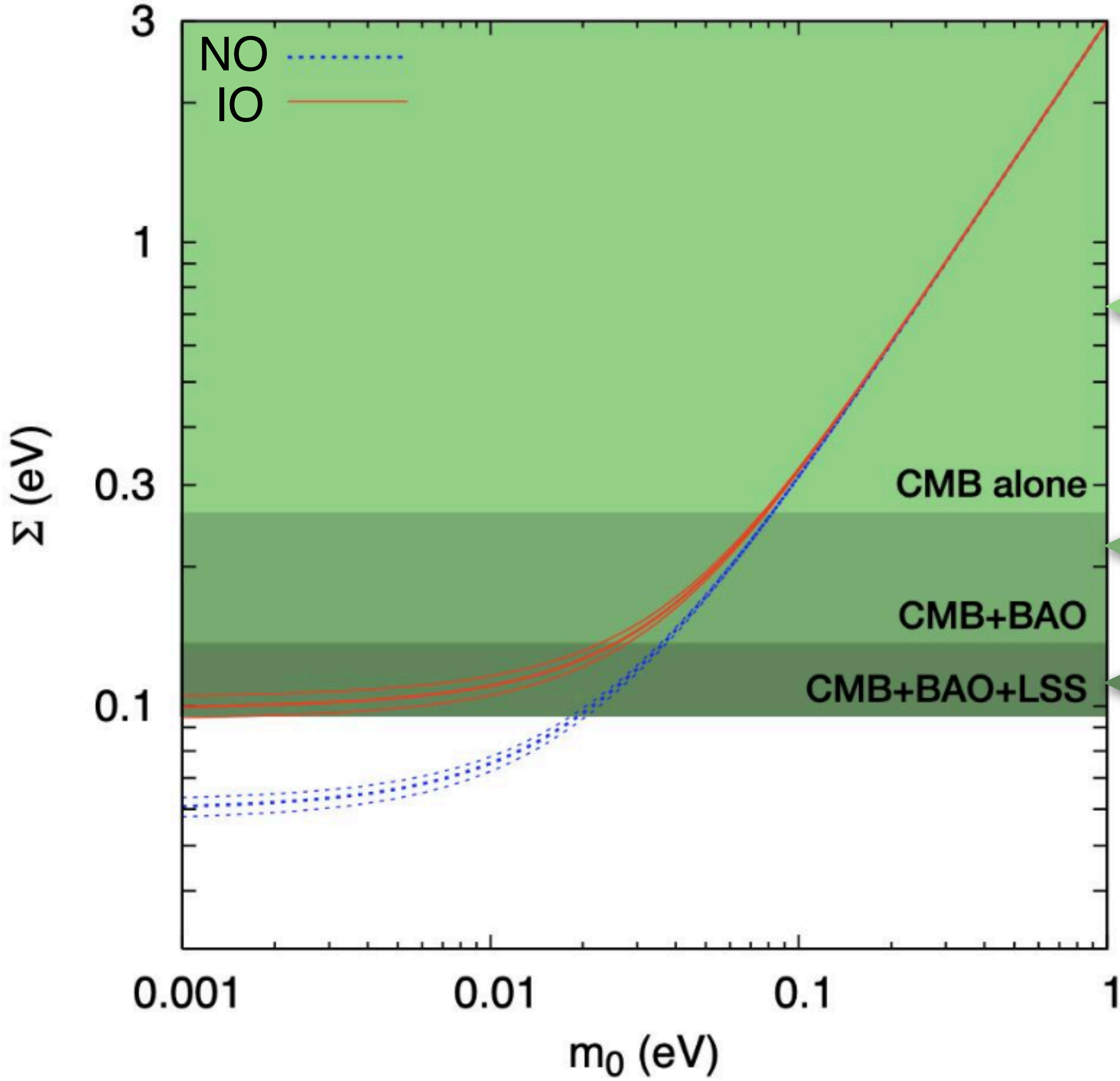


Neutrino mass constraints

[Lesgourgues & Verde, PDG (2019)]

	Model	95% CL (eV)	
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[Planck 2018 results. VI]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[Planck 2018 results. VI]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[Planck 2018 results. VI]
CMB + probes of background evolution + LSS			
Pl18[TT+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.12	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE+lensing] + BAO+Pantheon	ΛCDM+$\sum m_\nu$	< 0.11	[Planck 2018 results. VI]
Pl18[TT,TE,EE+lowE+lensing] + BAO+ Lyman-α	ΛCDM+$\sum m_\nu$	< 0.09	[Palanque-Delabrouille et al. (2020)]

Neutrino ordering



95% CL

CMB alone
$\Sigma m_\nu < 0.26$ eV

CMB+BAO
$\Sigma m_\nu < 0.13$ eV

CMB+BAO+Ly-α
$\Sigma m_\nu < 0.09$ eV

Neutrino ordering

- **with increasing sensitivity, reaching now $\sigma(\Sigma m_\nu)$ ~ 0.05 eV**

Can we already rule-out the Inverted Ordering (IO) ?

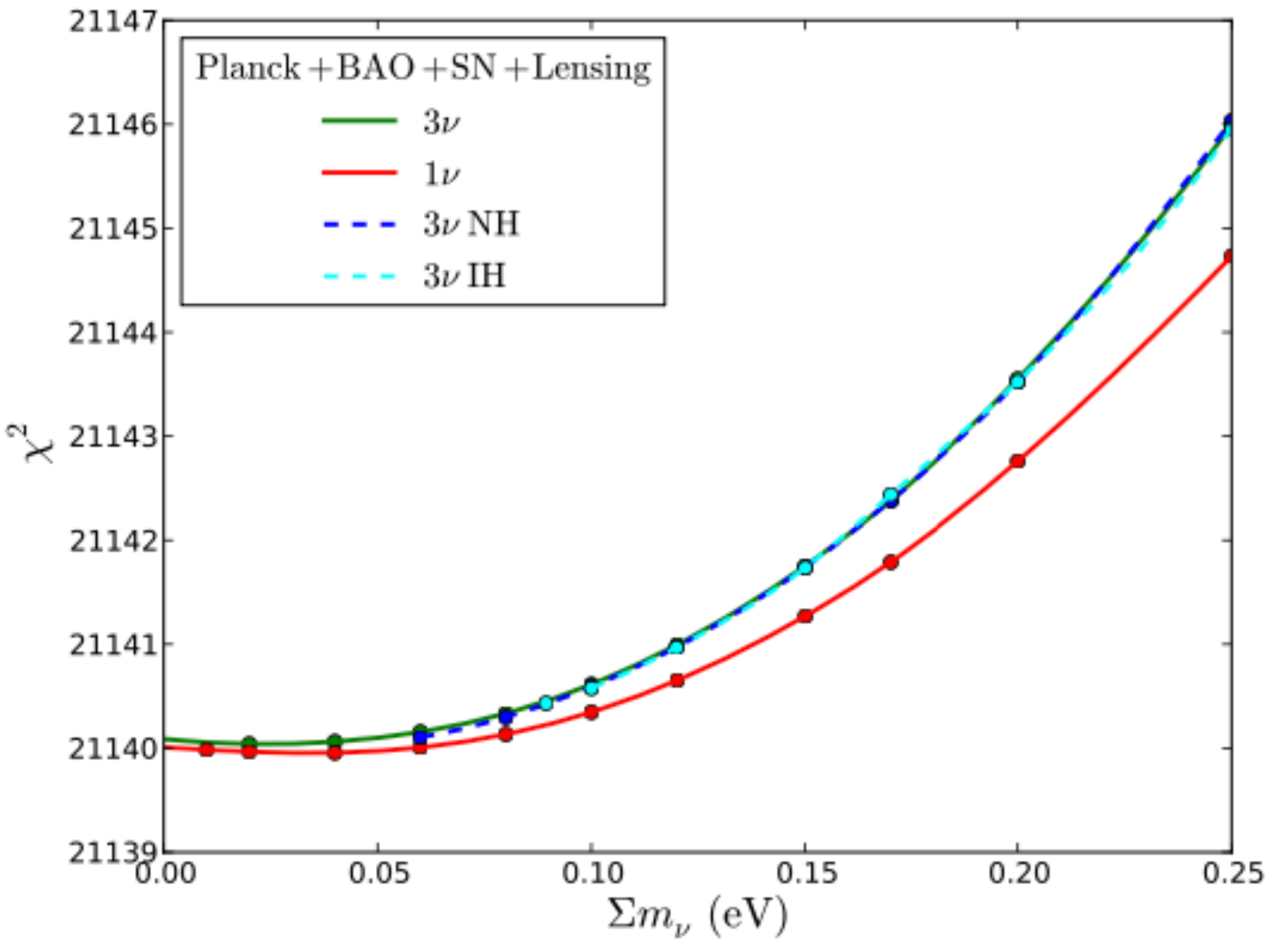
Bayesian evidence using cosmology + laboratory (oscillations, KATRIN) data:

- **Jimenez et al. (03.2022)** "Strong if not decisive evidence for NO"
- **Gariazzo et al. (05.2022)** "No conclusive evidence for NO"

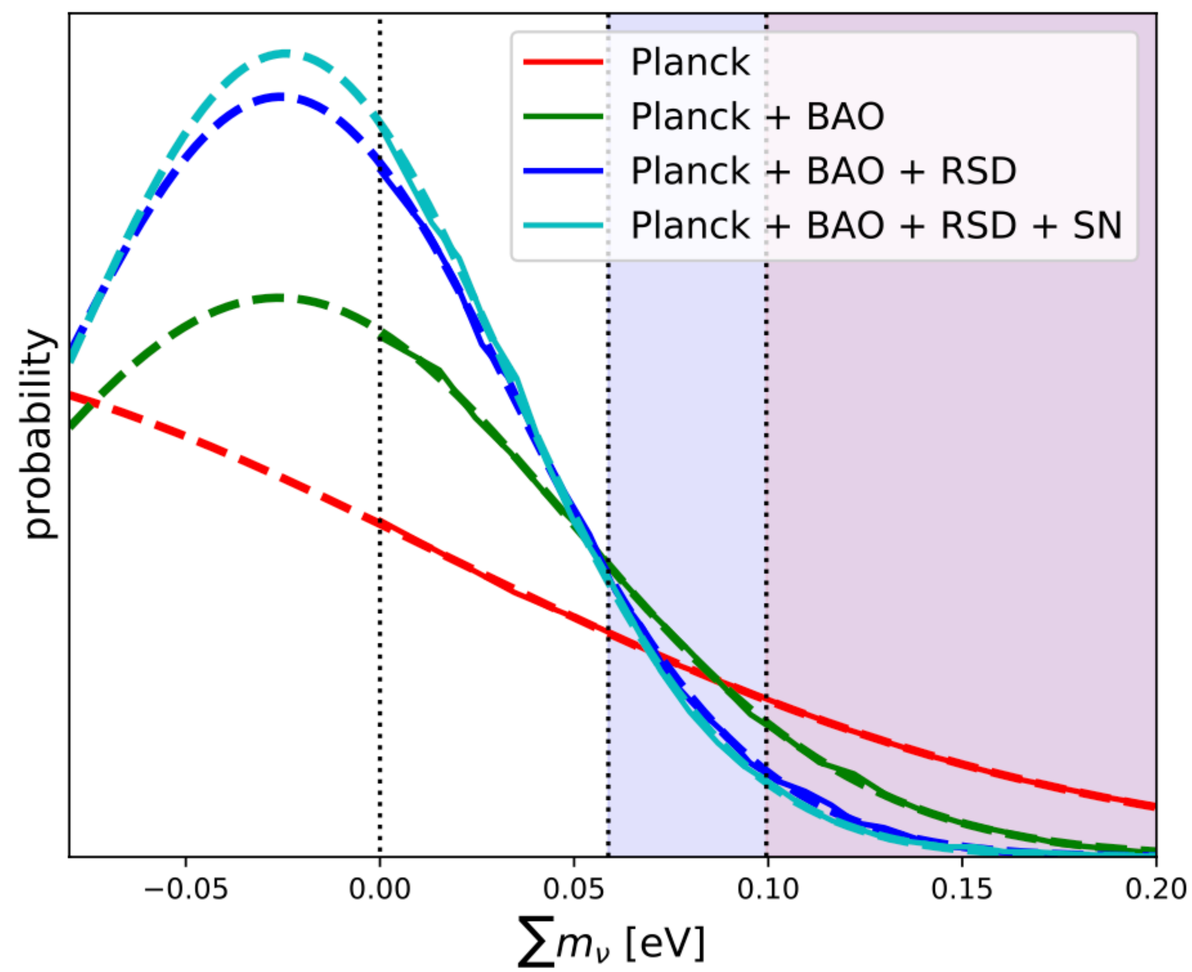
not yet...

Model dependance

[Couchot et al. (2017)]



eBOSS [Alam et al. (2020)]



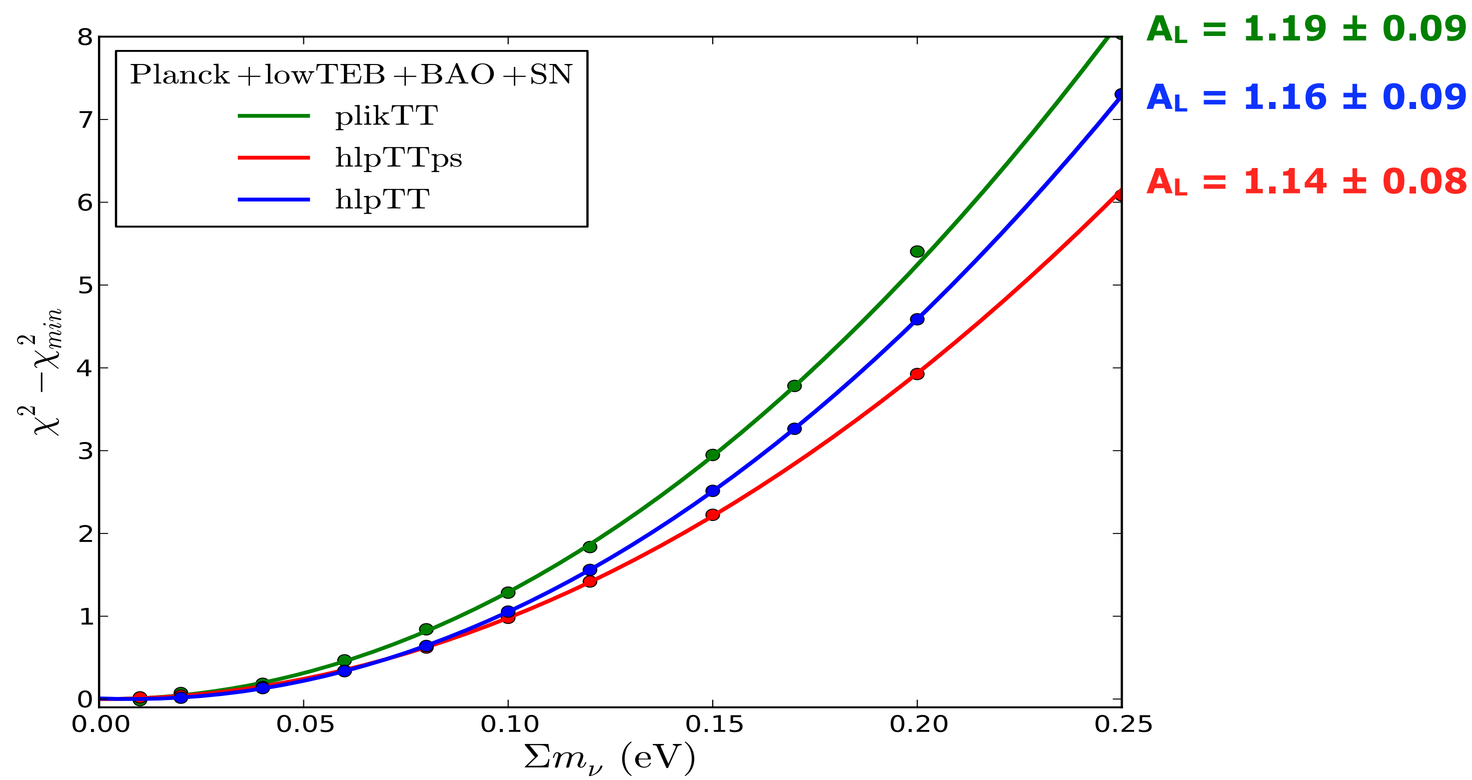
- profile likelihoods depend on the neutrino assumptions

- posteriors peak at negative values of Σm_ν

  $2 * \sigma(\Sigma m_\nu) > 95\%$ CL

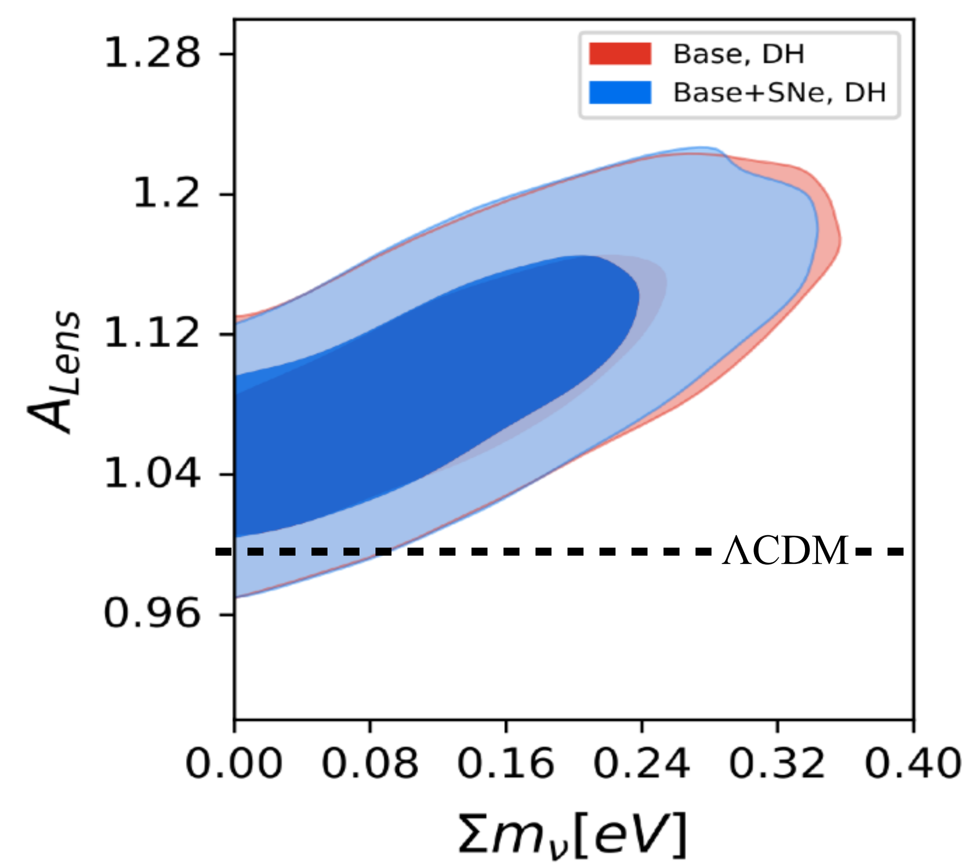
Neutrino mass in practice

- **CMB tension on A_L shows up on the neutrino sector**
  - high value for A_L → **artificially tighter constraints** on Σm_ν



	ΛCDM+	
PlanckTT+lowTEB BAO+SNIa 2015	Σm_ν limit (eV)	ΛCDM $+A_L$
hlpTT	0.18	1.16±0.09
hlpTTps	0.20	1.14±0.08
PlikTT	0.17	1.19±0.09

[Couchot et al. (2017)]

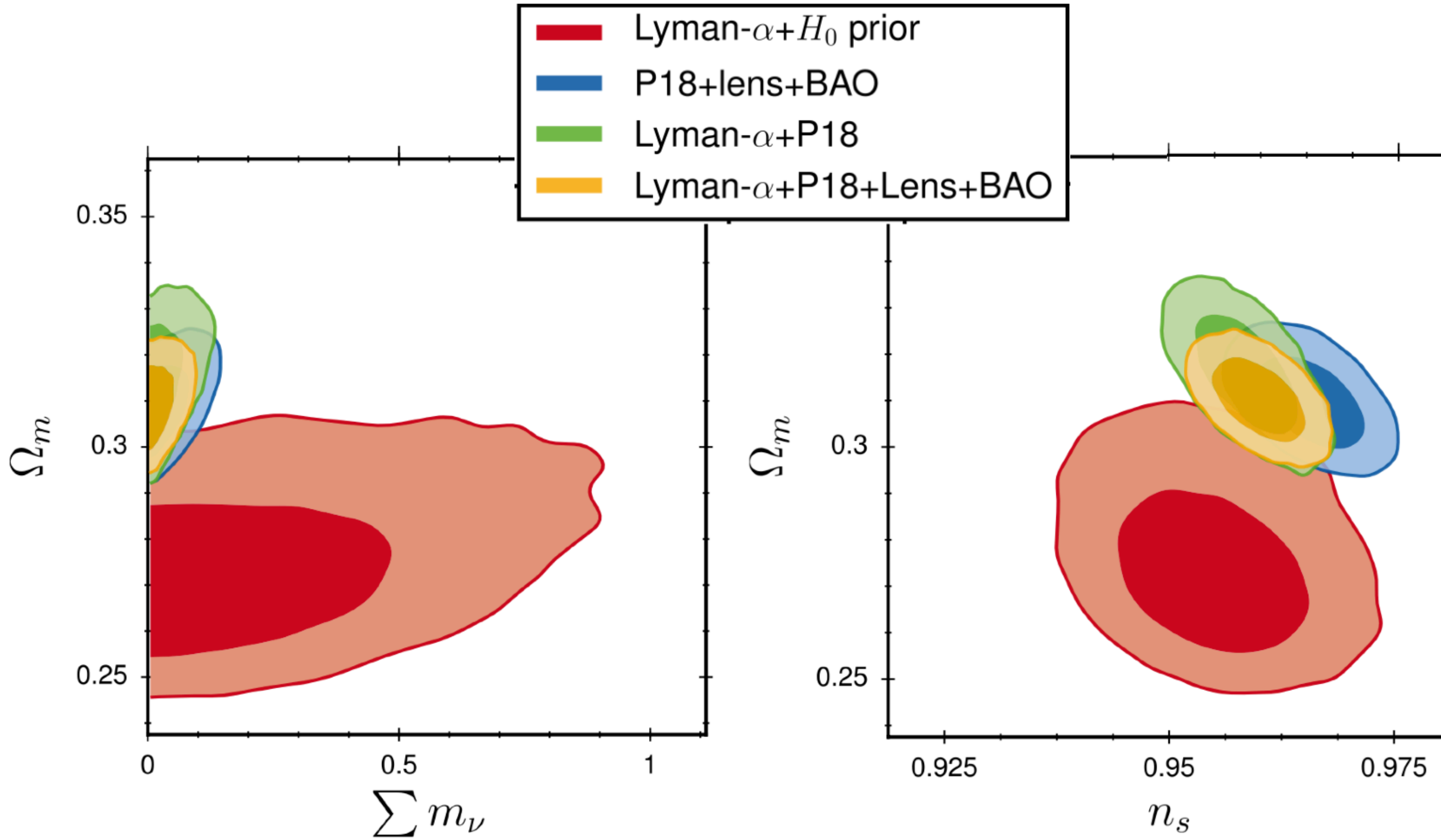


[Choudhury & Hannestad (2019)]

Neutrino mass in practice

[Palanque-Delabrouille et al. 2020]

- **Ly-a tension n_s-Ω_m shows up on the neutrino sector**



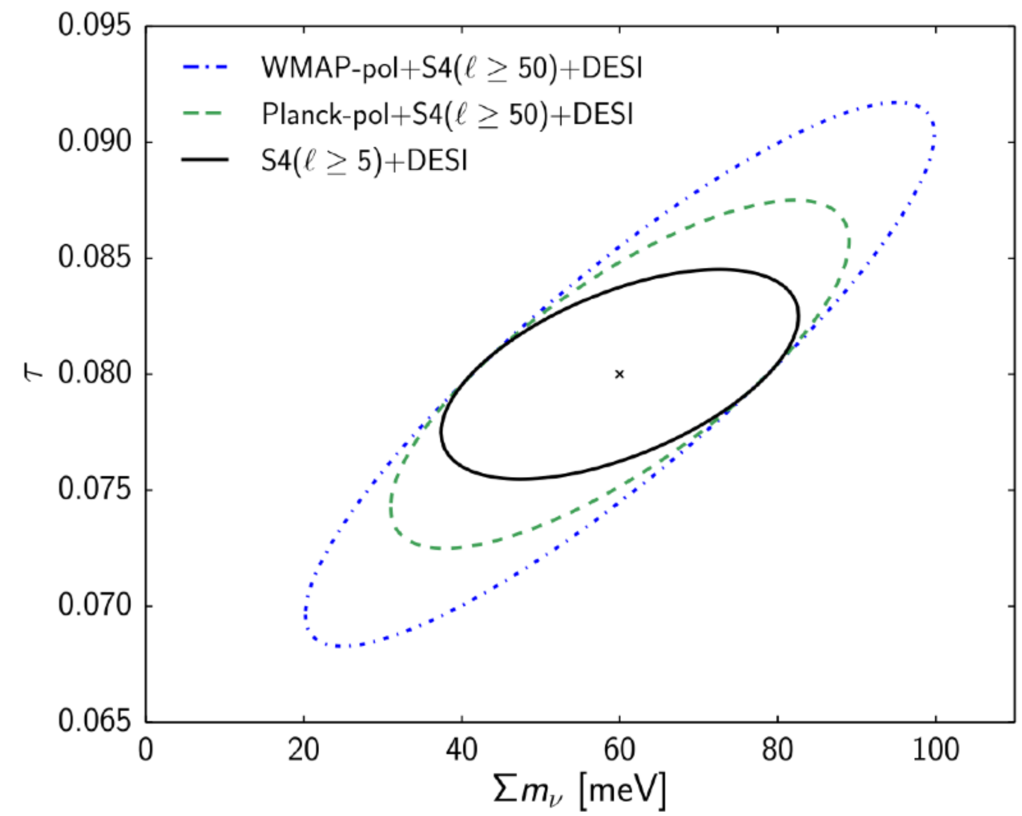
Prospects

- **Future LSS surveys: DESI, Euclid, LSST, SPHEREx, SKA...**
- **Future CMB observations: Simons Observatory (SO), CMB-S4, LiteBIRD**
  - better measurement of the CMB lensing
  - cluster count
  - SZ measurement

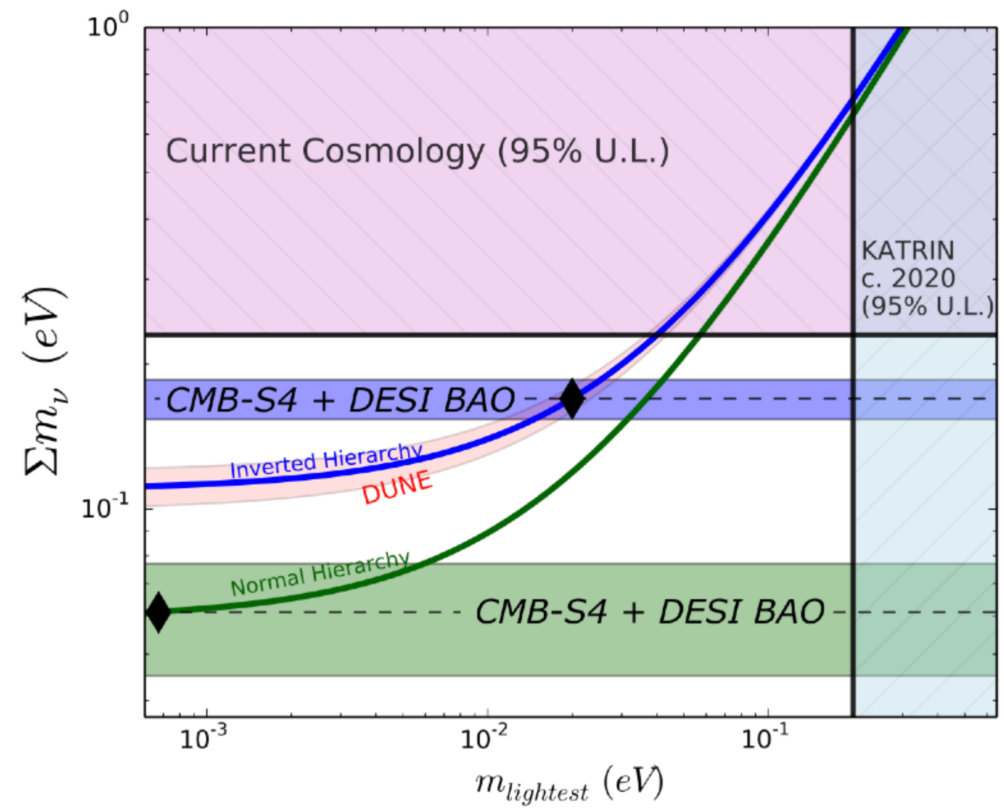
- **But also "oscillation" experiments**
  - beta-decay KATRIN (limited)
  - JUNO, T2HK
  - DUNE through the sign of Δm_{31} and δ_{CP}

Forecasts Σm_ν

- **Short-term: ~2025**
  - DESI+Euclid+Planck $\sigma(\Sigma m_\nu)$ ~20 meV
  - limited by $\sigma(\tau)$ = 0.006
  - 3-4σ on neutrino masses
- **Mid-term: ~2030**
  - DESI/LSST+CMB-S4+LiteBird $\sigma(\Sigma m_\nu)$ ~15 meV
  - 4-5σ on neutrino masses
- **Long-term: ~2035**
  - MSE+CMB-S4 $\sigma(\Sigma m_\nu)$ ~8 meV
  - Mass hierarchy at ~5σ



[Allison et al. (2015)]

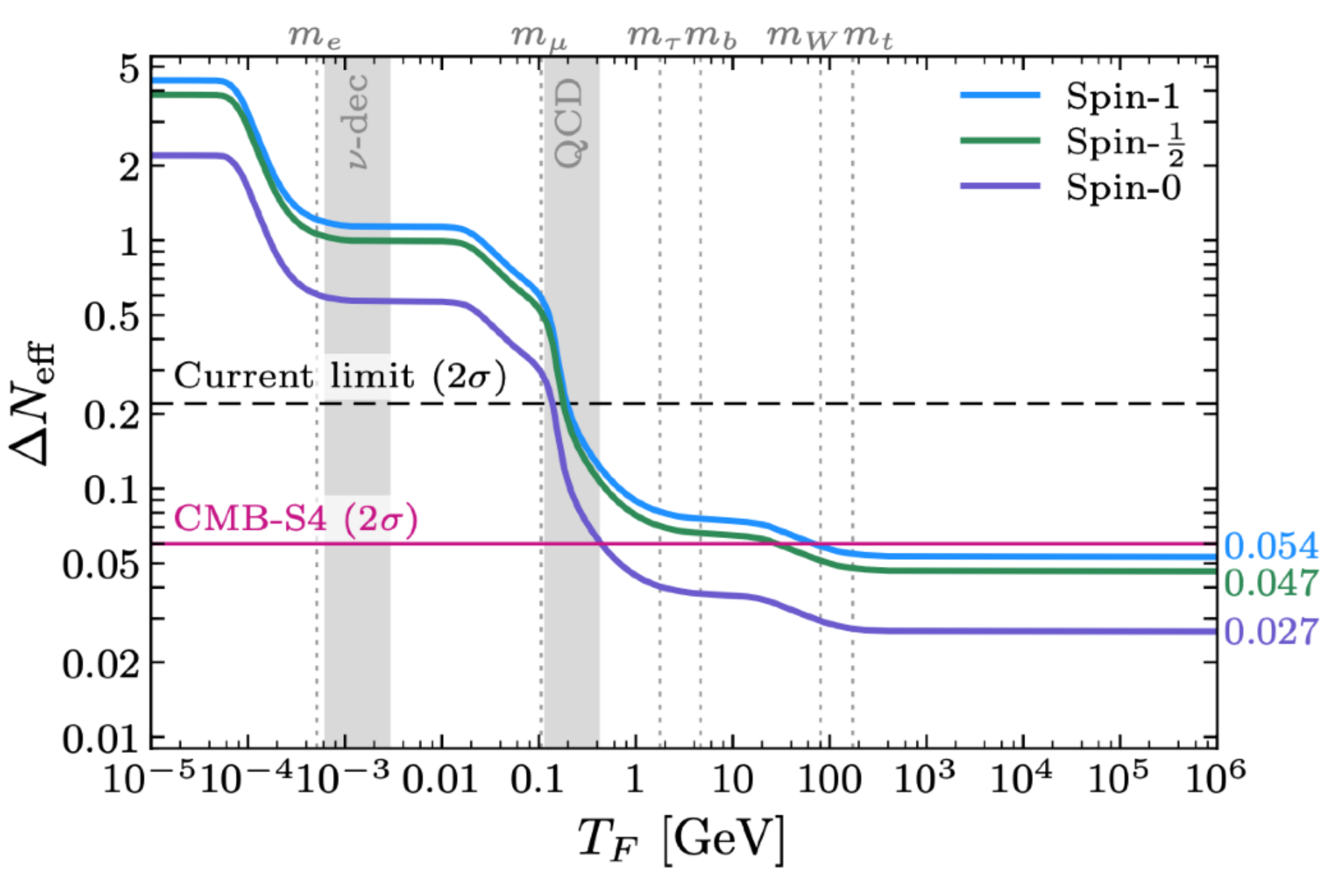


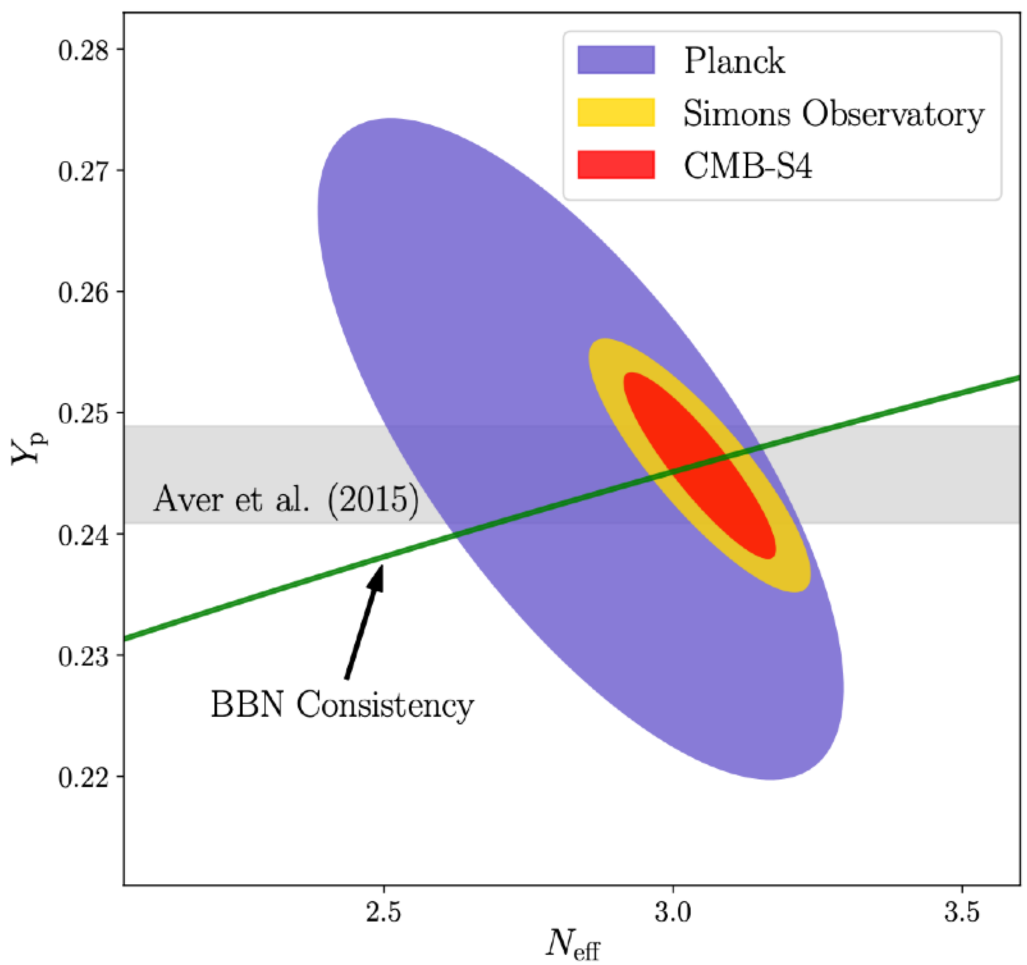
[CMB-S4 Science book (2016)]

Forecasts N_{eff}

[CMB-S4 Science Case (2019)]

- **Light relics**





σ(N_{eff}) = 0.013 for 2σ threshold
sensitivity to any light thermal relic
(massless particle decoupling at T_F)

σ(N_{eff}) ~ 0.05 (SO)
σ(N_{eff}) ~ 0.03 (CMB-S4)

Prospects

- **Future LSS surveys: DESI, Euclid, LSST, SPHEREx, SKA...**
- **Future CMB observations: Simons Observatory (SO), CMB-S4, LiteBIRD**
  - better measurement of the CMB lensing
  - cluster count
  - SZ measurement

- **But also "oscillation" experiments**
  - beta-decay KATRIN (limited)
  - JUNO, T2HK
  - DUNE through the sign of Δm_{31} and δ_{CP}

- Cosmological measurements are **model dependant**
- Neutrino impact is **small** and **correlated** with other type of effects (cosmological and systematics)
- **Tensions between datasets can create bias** in the neutrino constraints

→ **need to be very conservative and propagate all relevant uncertainties when considering cosmological constraints on the neutrino sector**