



# Progress on Old and New Themes in cosmology (PONT) 2020

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## Forecast on lepton asymmetry from future CMB experiments

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# Outline

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1. Introduction and Motivation
2. Theoretical framework
  - 2.1.Cosmic Neutrino Background (CNB)
  - 2.2.Models and data analysis
  - 2.3.Results
3. Summary and conclusions

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# Introduction and motivation

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- 1.The existence of a cosmic neutrino background (CNB), or also called relic neutrinos, is a consequence of the thermal history of the universe where the neutrinos become to stream freely at  $T \sim 1$  MeV.
- 2.Unlike the cosmic microwave background (CMB), the CNB not was yet been detected directly and such direct detection proves to be difficult [Betts et al. \(2013\)](#). ( $1.9 \text{ }^{\circ}\text{K} \approx 0.00017 \text{ eV}$ )
- 3.Recently the authors in [Follin et al. \(2015\)](#) interpreted data about damping of acoustic oscillations of the CMB, shows a detection of the temporal phase shift generated by neutrino perturbations.
- 4.The properties the massive neutrinos play an important role on the dynamics of the universe inferring direct changes on important cosmological sources and consequently in the determination of cosmological parameters (see [Dol- gov \(2002\)](#); [Lesgourgues & Pastor \(2006\)](#); [Abazajian et al. \(2015\)](#) for review).
- 5.The effects of the relic neutrinos on the CMB and LSS are only gravitational, since they are decoupled (free streaming particles) at the time of recombination.

# Introduction and motivation

## Implications

1. Particle physics: Physics beyond the standard model (Neutrinos oscillations and mechanics).
2. Cosmology: Neutrinos are the second most abundant particle in the universe and thus can affect different epochs in cosmic history.
3. Astronomy: Account for neutrino oscillations to estimate expected fluxes.

## Open questions

1. What is the hierarchical ordering of neutrino mass?
2. What is the absolute mass scale of neutrinos?
3. What is the nature of the neutrino? Dirac or Majorana?



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# Cosmic Neutrino Background (CvB)

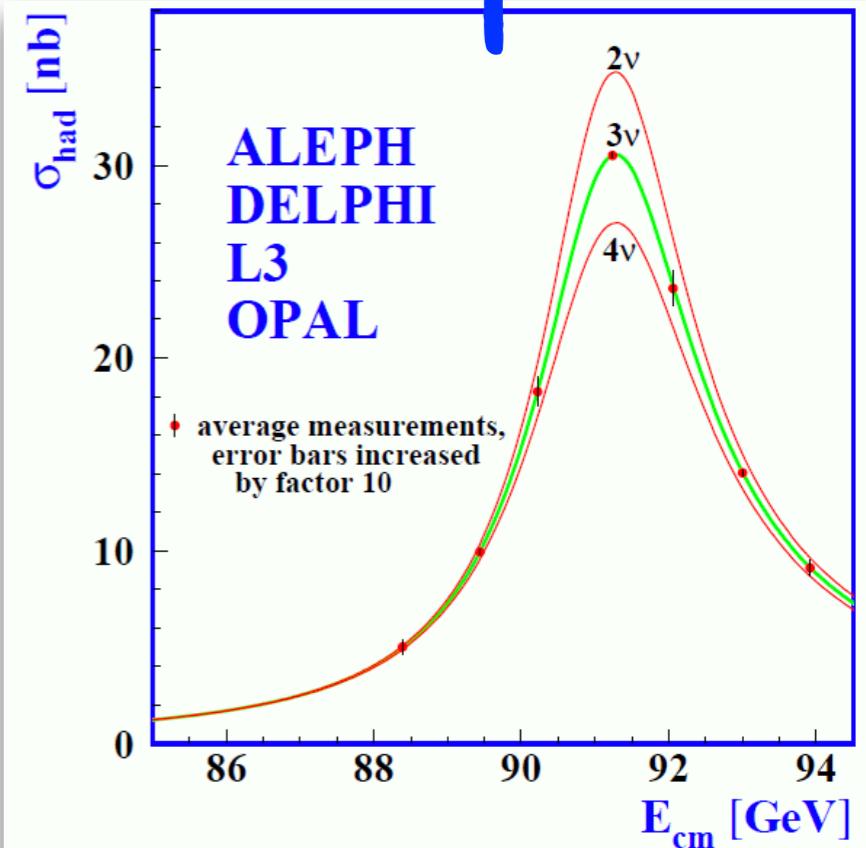
Effective number of relativistic species  $\rightarrow N_{\text{eff}} = 3.0$

The standard parameters that characterize these effects on cosmological sources are the effective number of species  $N_{\text{eff}}$  and the total neutrino mass  $\sum m_\nu$ .

Planck team Ade et al. (2016) within the  $\Lambda$ CDM +  $\sum m_\nu$  model has constrained  $\sum m_\nu < 0.194$  eV (from CMB alone), and  $N_{\text{eff}} = 3.04 \pm 0.33$  at 95% CL. The value of  $N_{\text{eff}}$  via theoretical calculations is well determined within of the standard model  $N_{\text{eff}} = 3.046$  Lesgourgues et al. (2013).

The evidence of any positive deviation from this value can be a signal that the radiation content of the Universe is not only due to photons and neutrinos, but also to some extra relativistic relics called in the literature of dark radiation and parameterized by  $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$ .

From particle physics

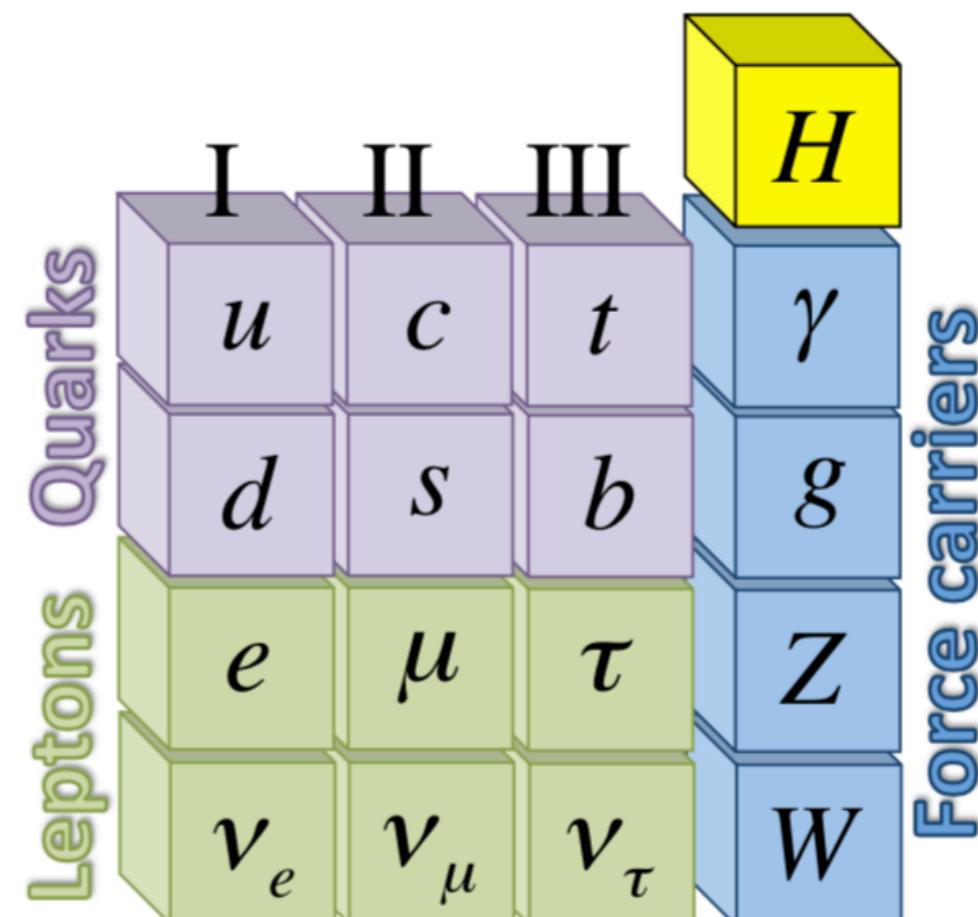
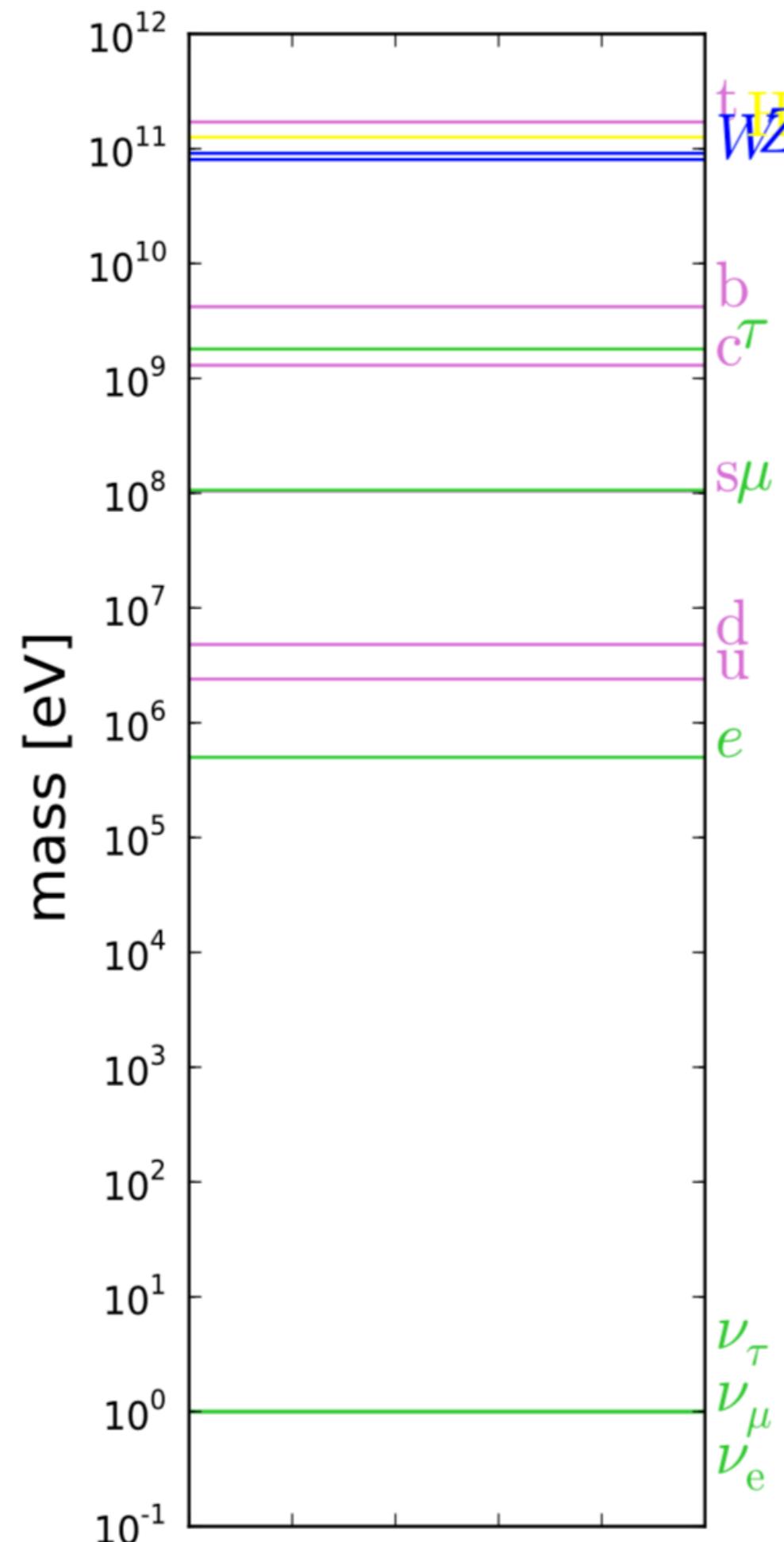


# Neutrinos

- Neutrinos have mass
- What are the neutrino masses?

$$\sum m_\nu \geq 0.06 \text{ eV} \quad m(\bar{\nu}_e) \leq 2.3 \text{ eV}$$

1. *Impact on cosmology*
2. *Weigh neutrinos with cosmology*



# CvB and basic equations

## Friedmann equation

$$E^2(a, \Omega_i) = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_X e^{3 \int_a^1 \frac{da'}{a'} (1+w(a'))}$$

Radiation density + relativistic neutrinos

$$\rho_r = (\rho_\gamma + \rho_\nu) = \left(1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right) \rho_\gamma,$$

$$N_{\text{eff}} = 3.046$$

→ Effective number of relativistic species

$$\Delta N_{\text{eff}}^{\xi_\nu} = \frac{60}{7} \left(\frac{\xi_\nu}{\pi}\right)^2 + \frac{30}{7} \left(\frac{\xi_\nu}{\pi}\right)^4$$

$$\xi_\nu = \mu_\nu / T_{\nu 0} \rightarrow \text{Lepton asymmetry}$$

Chemical potential

$$T_{\nu 0} \approx 1.9K \quad \text{Current temperature CvB}$$

$$\mu_\nu = 0$$

→ Majorana particles  
Neutrinos = Antineutrinos

$$\mu_\nu \neq 0$$

→ Dirac particles  
Neutrinos ≠ Antineutrinos

Any excess in  $N_{\text{eff}}$  can be due to:

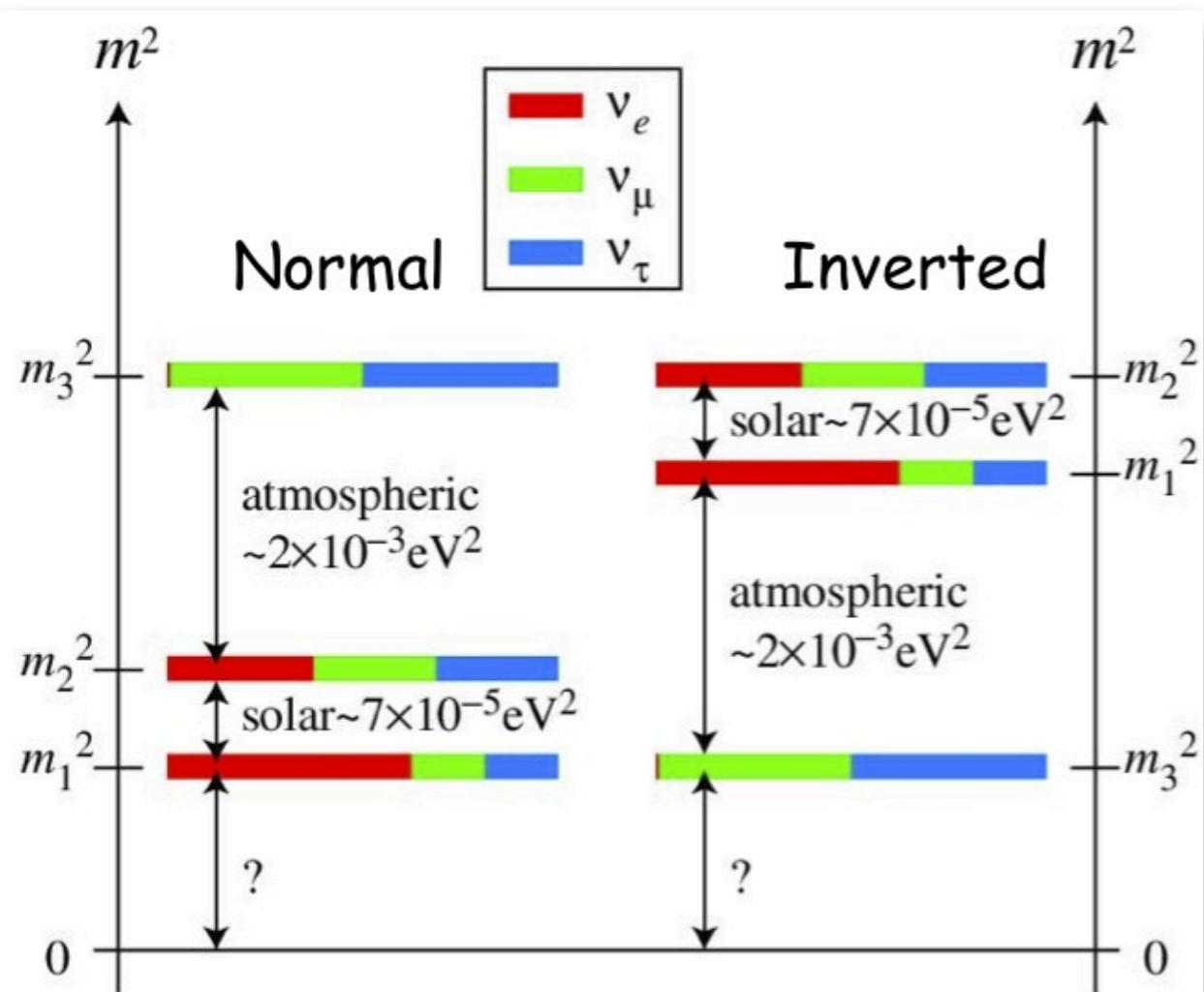
- Primordial Grav Waves (PGWs)
- Sterile neutrino
- Goldstone boson
- Lepton asymmetry (Matter/antimatter)
- Dark radiation/Photon (X17 boson, Recently detected), New Force in nature...?

# CvB and basic equations

## Friedmann equation

$$E^2(a, \Omega_i) = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_X e^{3 \int_a^1 \frac{da'}{a'} (1+w(a'))}$$

Matter energy density + non relativistic neutrinos



$$\rho_{\nu_i} + \rho_{\bar{\nu}_i} = T_\nu^4 \int \frac{d^3 q}{2(\pi)^3} E_{\nu_i} (f_{\nu_i}(q) + f_{\bar{\nu}_i}(q))$$

Fermi-Dirac phase space distribution

$$f_{\nu_i}(q) = \frac{1}{e^{E_{\nu_i}/T_\nu - \xi_\nu} + 1}, \quad f_{\bar{\nu}_i}(q) = \frac{1}{e^{E_{\bar{\nu}_i}/T_\nu + \xi_{\bar{\nu}}} + 1},$$

$$E_{\nu_i}^2 = q^2 + a^2 m_{\nu_i}$$

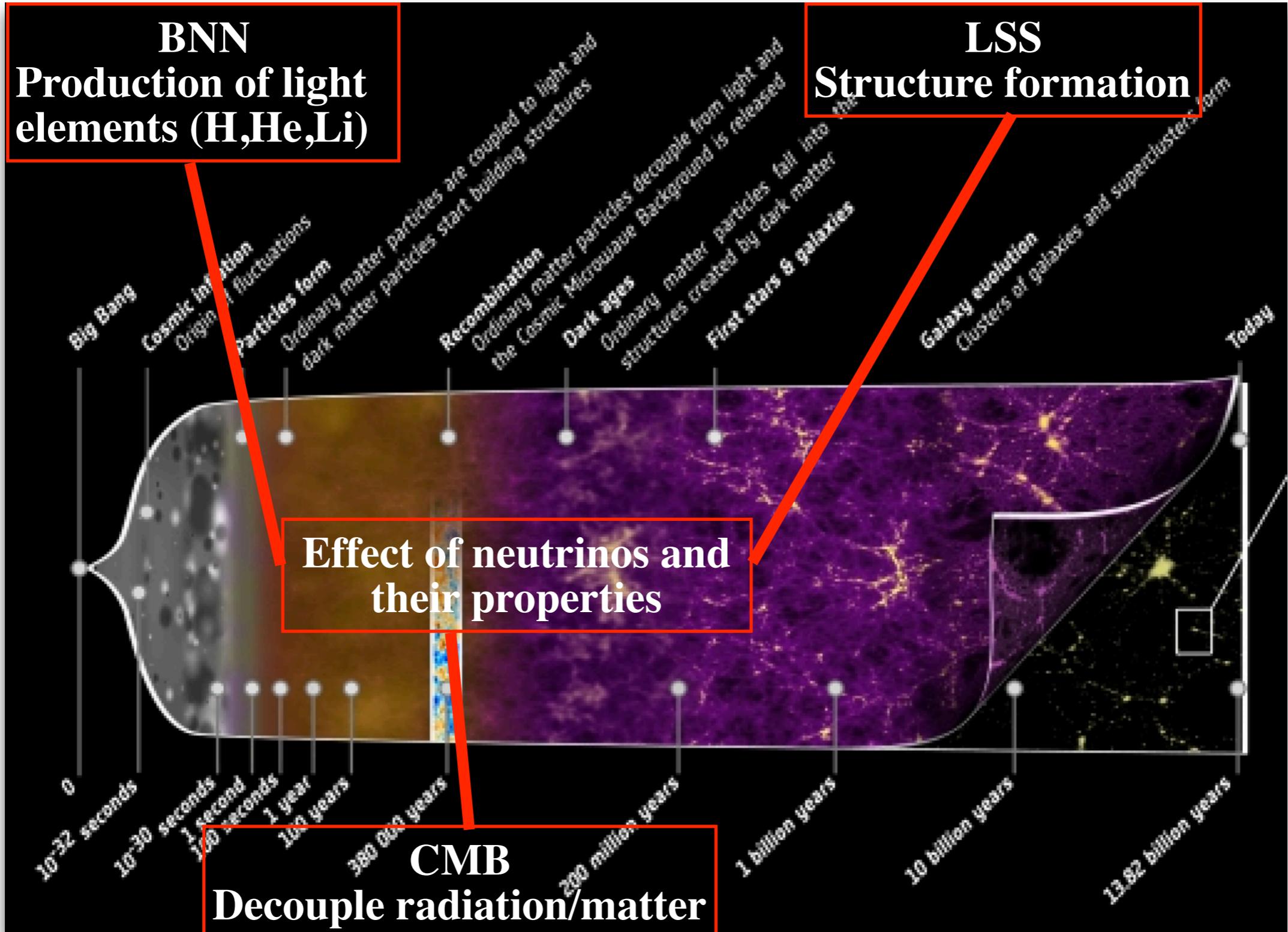
→ Neutrino mass

$$\Omega_M = \Omega_{\text{CDM}} + \Omega_b + \Omega_\nu$$

$$\Sigma m_\nu < 0.12 \text{ eV}$$

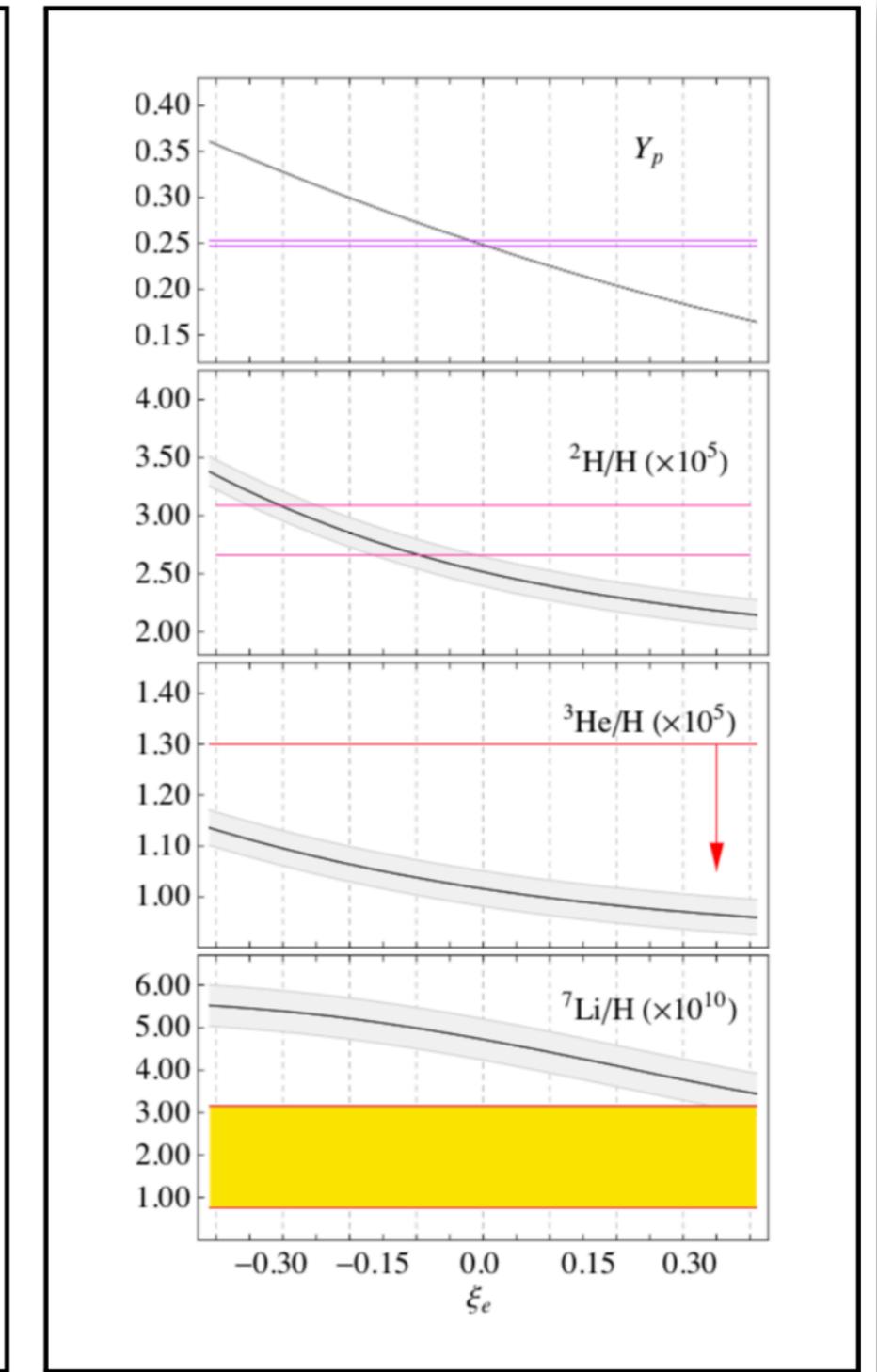
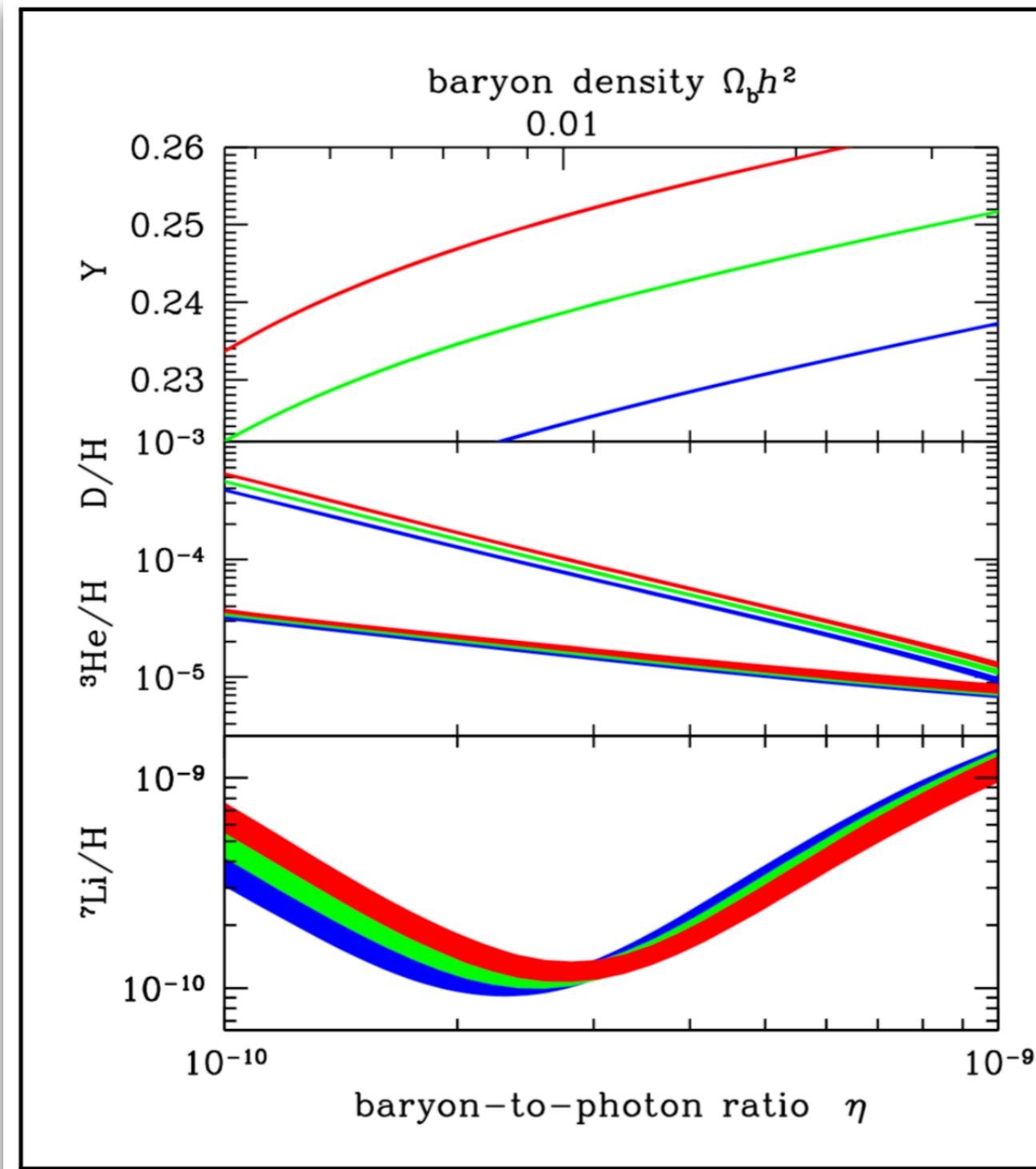
$$\Omega_\nu = \frac{\Sigma_i m_{\nu_i}}{93.14 h^2 \text{ eV}}$$

# Introduction and motivation

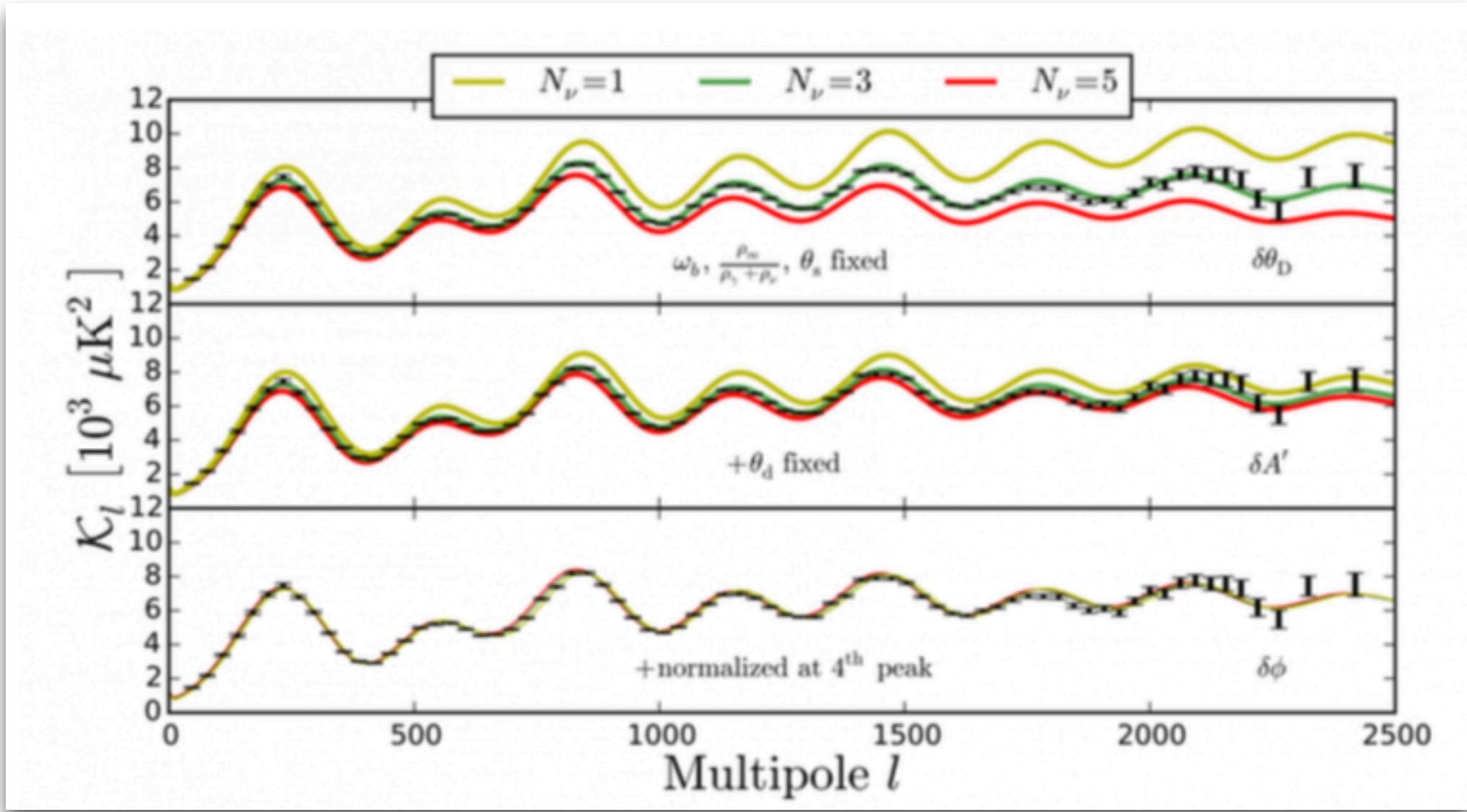


# CvB and Big Bang Nucleosynthesis (BBN)

$N_{eff} = 4$   
 $N_{eff} = 3$   
 $N_{eff} = 2$

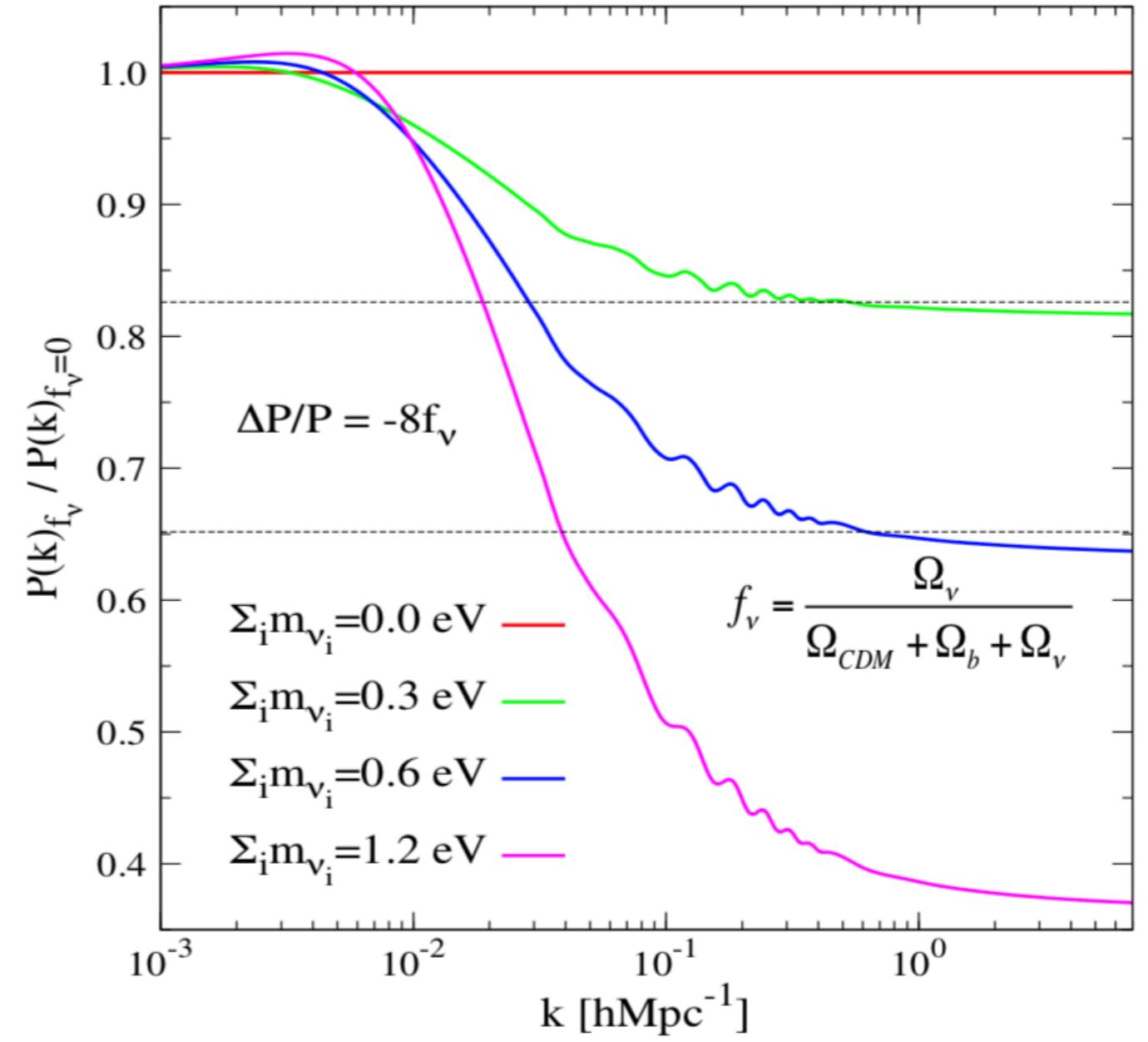
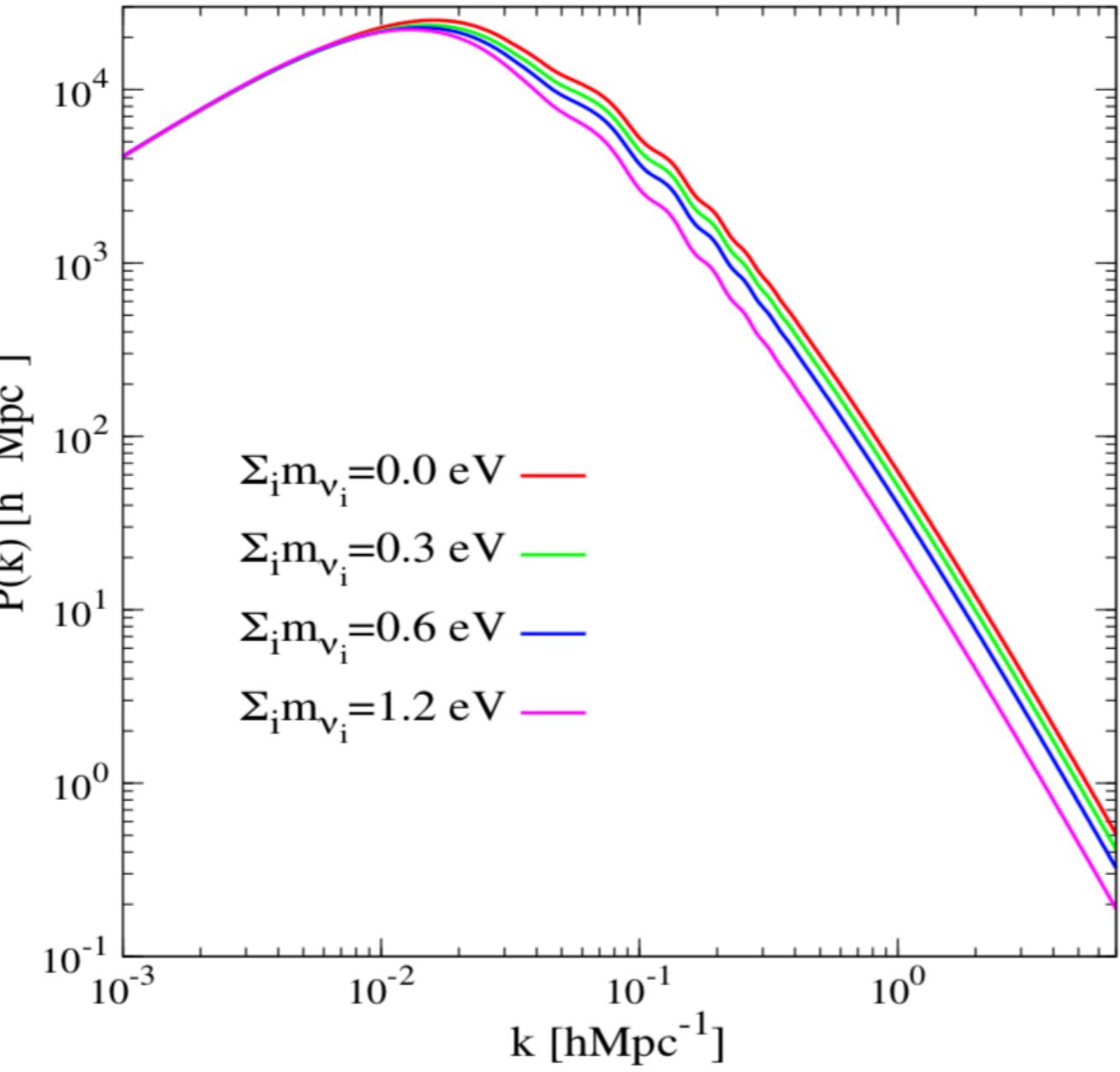


# CvB and Cosmic Microwave Background (CMB)



Follin et al. (2015)

# CvB and Large Scale Structure (LSS)



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# Models and data analysis

We consider two different models. First, let us take  $\Lambda$ CDM +  $N_{\text{eff}} + \sum m_\nu + c_{\text{eff}}^2 + c_{\text{vis}}^2 + \xi$  (Model I). Then, we take a particular case of the model I when  $c_{\text{eff}}^2 = c_{\text{vis}}^2 = 1/3$ , i.e.,  $\Lambda$ CDM +  $N_{\text{eff}} + \sum m_\nu + \xi$  (Model II).

**Sound speed parameter**

**Viscosity parameter**

**Parameterizes the anisotropic stress**

The evolution of standard neutrinos (non-interacting free-streaming neutrinos) is obtained for

Any deviation of these values can represent interactions with other relativistic particles

# Models and data analysis

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- 1.**CMB:** We consider a conservative data set from Planck 2015 comprised of the likelihoods of temperature power spectrum (TT), low-polarisation and lensing reconstruction.
- 2.**BAO:** The BAO measurements from the Six Degree Field Galaxy Survey (6dF) [Beutler et al. \(2011\)](#), the Main Galaxy Sample of Data Release 7 of Sloan Digital Sky Survey (SDSS-MGS) [Ross et al. \(2015\)](#), the LOWZ and CMASS galaxy samples of the Baryon Oscillation Spectroscopic Survey (BOSS-LOWZ and BOSS-CMASS, respectively) [Anderson et al. \(2014\)](#), and the distribution of the LymanForest in BOSS (BOSS-Ly) [Font-Ribera et al. \(2014\)](#).
- 3.**HST:** We also include the new local value of  $H_0$  as measured by [Riess et al. \(2016\)](#) with a 2.4 % determination, which yields  $H_0 = 73.02 \pm 1.79$  km/s/Mpc.
- 4.**GC:** The measurements from the abundance of galaxy clusters (GC) are a powerful probe of the growth of cosmic structures. The cosmological information enclosed in the cluster abundance is efficiently parameterized by  $S_8 = \sigma_8 (\Omega_m / \alpha)^{\beta}$ , where  $\sigma_8$  is the linear amplitude of fluctuations on 8 Mpc/h and  $\alpha, \beta$  are the fiducial value adopted in each survey analysis.

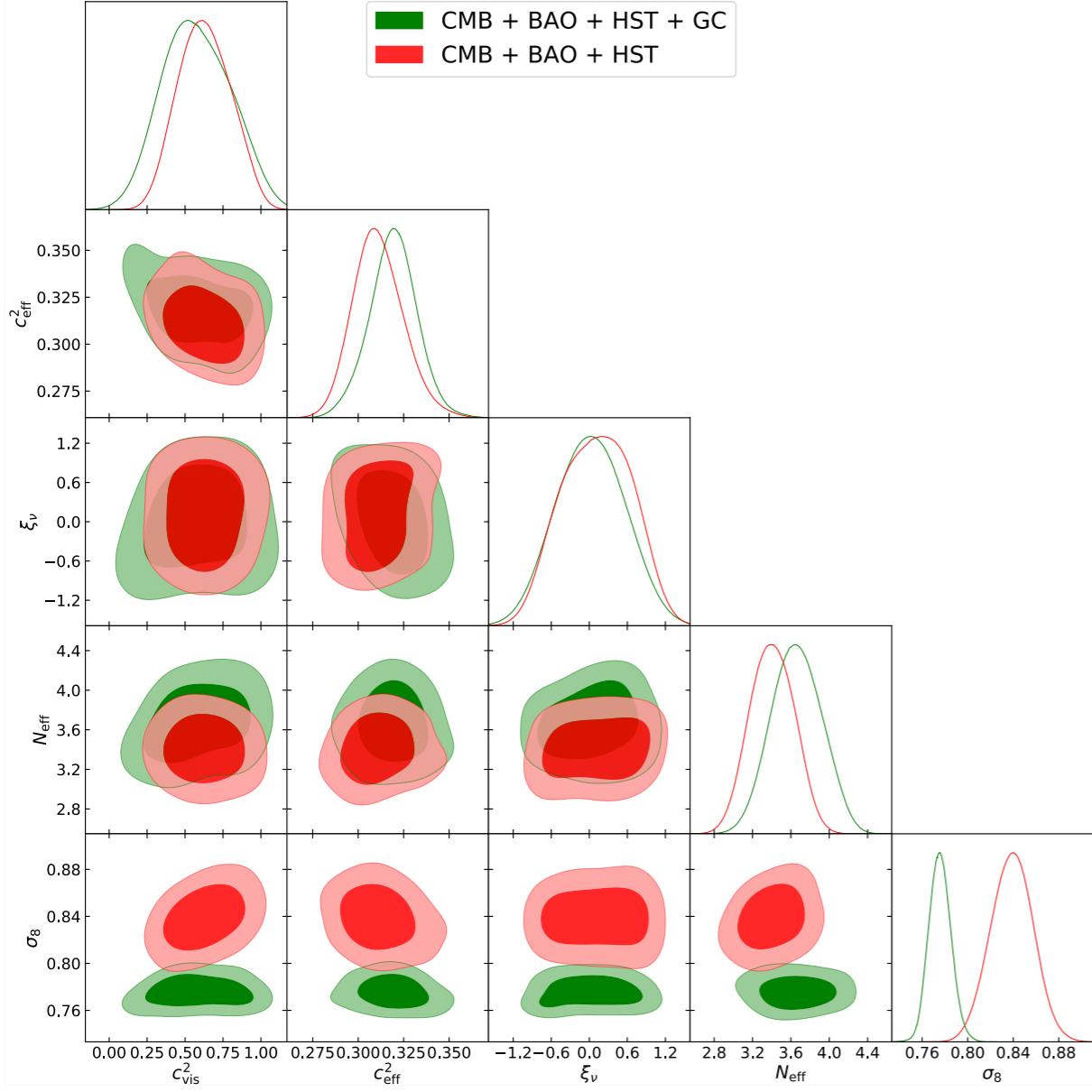
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# Results

We use the publicly available CLASS ([Blas et al. 2011](#)) and Monte Python ([Audren et al. 2013](#)) codes.



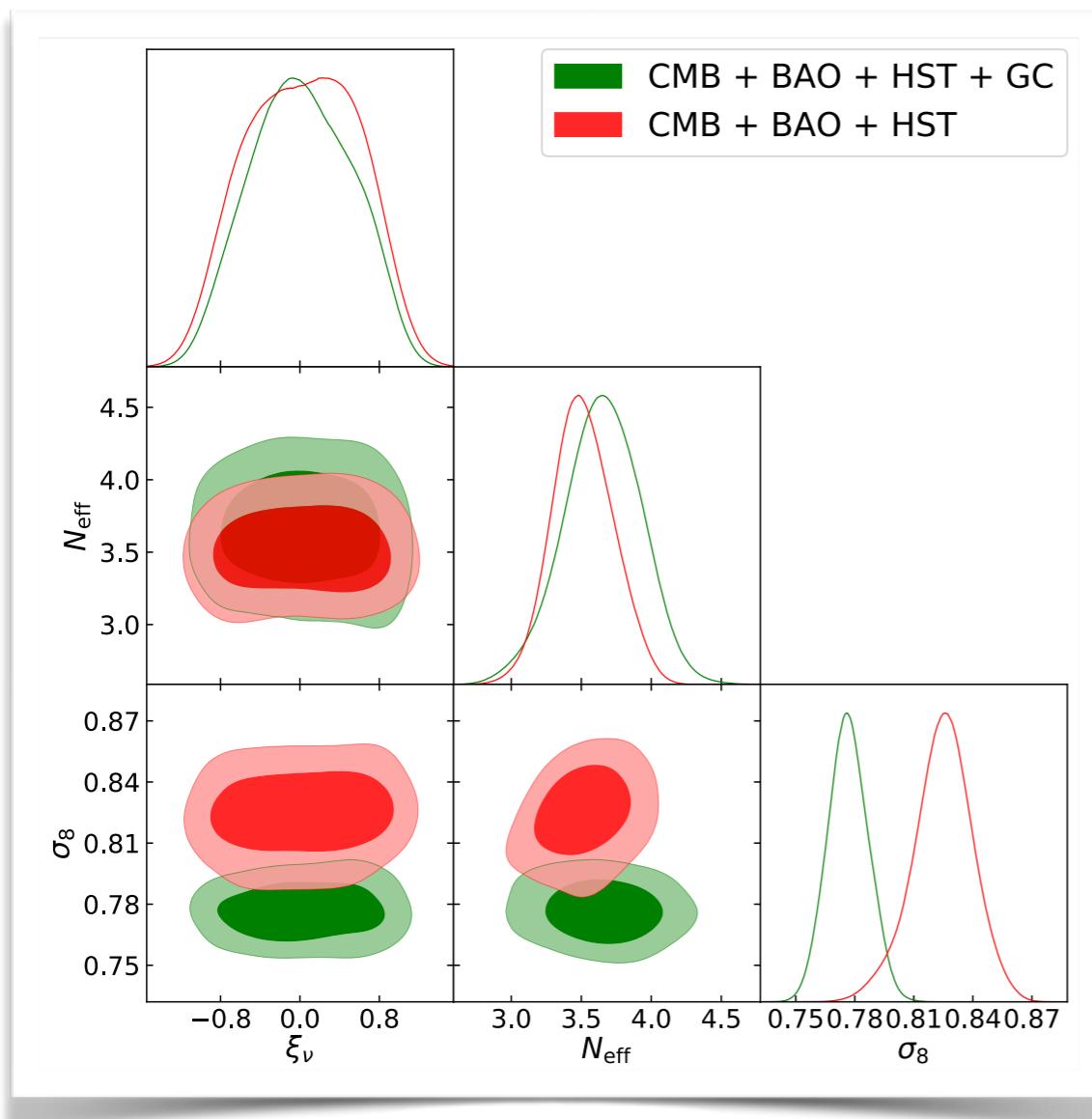
**Table 2.** Constraints at 68% CL and 95% CL on some parameters of the model I using two distinct data set. The parameter  $H_0$  is in the units of  $\text{km s}^{-1} \text{ Mpc}^{-1}$  and  $\sum m_\nu$  is in units of eV.

Parameter	CMB + BAO + $H_0$	CMB + BAO + $H_0$ + GC
$\sum m_\nu$	$< 0.24 (< 0.36)$	$< 0.64 (< 0.81)$
$c_{\text{vis}}^2$	$0.63^{+0.17+0.32}_{-0.17-0.32}$	$0.58^{+0.22+0.40}_{-0.25-0.40}$
$c_{\text{eff}}^2$	$0.311^{+0.012+0.028}_{-0.015-0.027}$	$0.319^{+0.013+0.024}_{-0.013-0.027}$
$\xi$	$0.1^{+0.54+1.0}_{-0.54-1.0}$	$0.02^{+0.50+0.90}_{-0.50-0.85}$
$N_{\text{eff}}$	$3.41^{+0.23+0.43}_{-0.23-0.42}$	$3.66^{+0.26+0.48}_{+0.26-0.49}$
$\Omega_\Lambda$	$0.706^{+0.008+0.016}_{-0.008-0.016}$	$0.706^{+0.008+0.015}_{-0.008-0.015}$
$Y_{He}$	$0.2523^{+0.0029+0.0054}_{-0.0029-0.0056}$	$0.2557^{+0.0032+0.0059}_{-0.0032-0.0063}$
$H_0$	$69.8^{1.3+2.5}_{1.3-2.5}$	$70.7^{+1.2+2.4}_{-1.2-2.2}$
$\sigma_8$	$0.839^{+0.018+0.036}_{-0.018-0.037}$	$0.776^{+0.010+0.019}_{-0.010-0.019}$

**Figure 1.** One-dimensional marginalized distribution and 68% CL and 95% CL regions for some selected parameters of the model I.

# Results

We use the publicly available CLASS ([Blas et al. 2011](#)) and Monte Python ([Audren et al. 2013](#)) codes.



**Table 3.** Constraints at 68% CL and 95% CL on some parameters of the model II using two distinct data set. The parameter  $H_0$  is in the units of  $\text{km s}^{-1} \text{ Mpc}^{-1}$  and  $\sum m_\nu$  is in units of eV.

Parameter	CMB + BAO + $H_0$	CMB + BAO + $H_0$ + GC
$\sum m_\nu$	$< 0.18 (< 0.30)$	$< 0.52 (< 0.64)$
$\xi$	$0.05^{+0.56+0.97}_{-0.56-0.99}$	$-0.02^{+0.51+0.92}_{-0.51-0.89}$
$N_{\text{eff}}$	$3.49^{+0.21+0.44}_{-0.23-0.42}$	$3.65^{+0.28+0.57}_{-0.28-0.60}$
$\Omega_\Lambda$	$0.703^{+0.009+0.015}_{-0.008-0.016}$	$0.706^{+0.008+0.015}_{-0.008-0.016}$
$Y_{He}$	$0.2537^{+0.0028+0.0056}_{-0.0028-0.0056}$	$0.2557^{+0.0038+0.0071}_{-0.0032-0.0077}$
$H_0$	$70.5^{+1.3+2.7}_{-1.3-2.6}$	$71.2^{+1.4+2.6}_{-1.4-2.7}$
$\sigma_8$	$0.823^{+0.016+0.030}_{+0.014-0.032}$	$0.777^{+0.010+0.020}_{-0.010-0.019}$

**Figure 2. One-dimensional marginalized distribution and 68% CL and 95% CL regions for some selected parameters of the model II**

# Results

We use the publicly available CLASS ([Blas et al. 2011](#)) and Monte Python ([Audren et al. 2013](#)) codes.

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MNRAS **473**, 4404–4409 (2018)

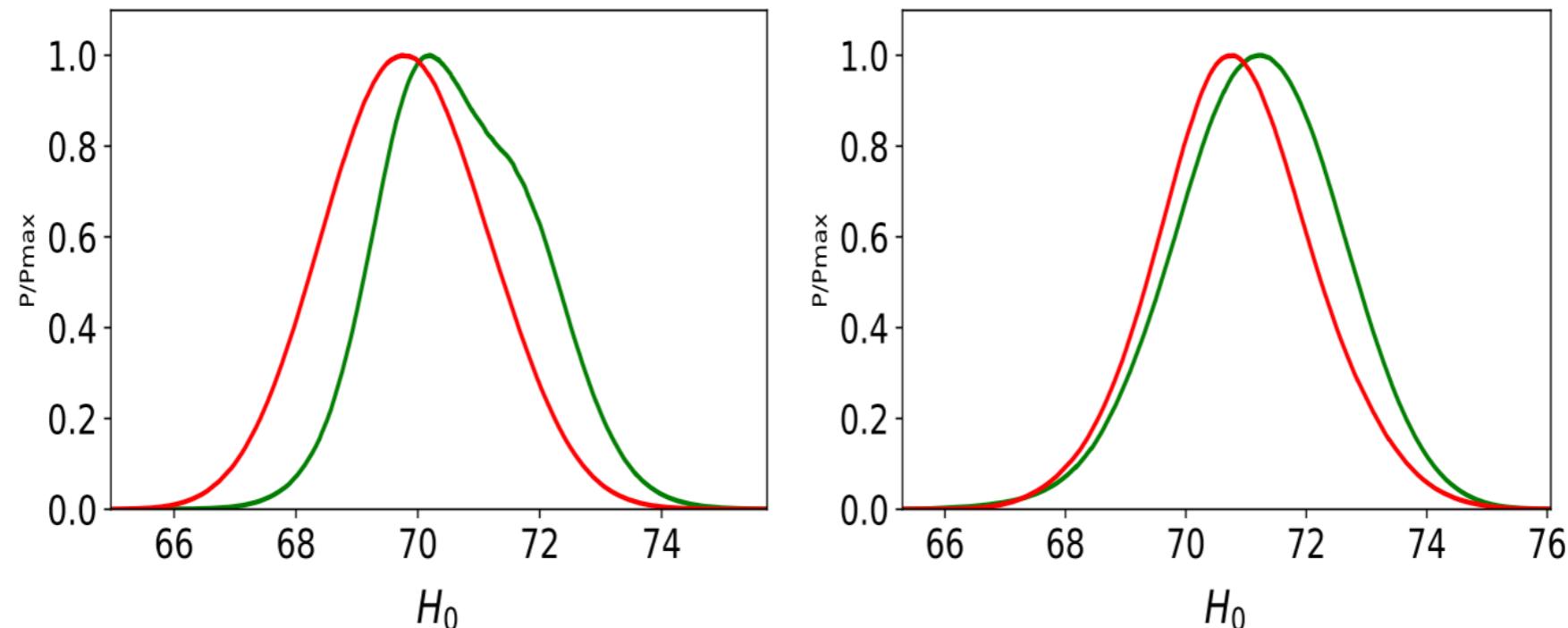
doi:10.1093/mnras/stx2661

**Advancing  
Astronomy and  
Geophysics**

**Probing the properties of relic neutrinos using the cosmic microwave background, the *Hubble Space Telescope* and galaxy clusters**

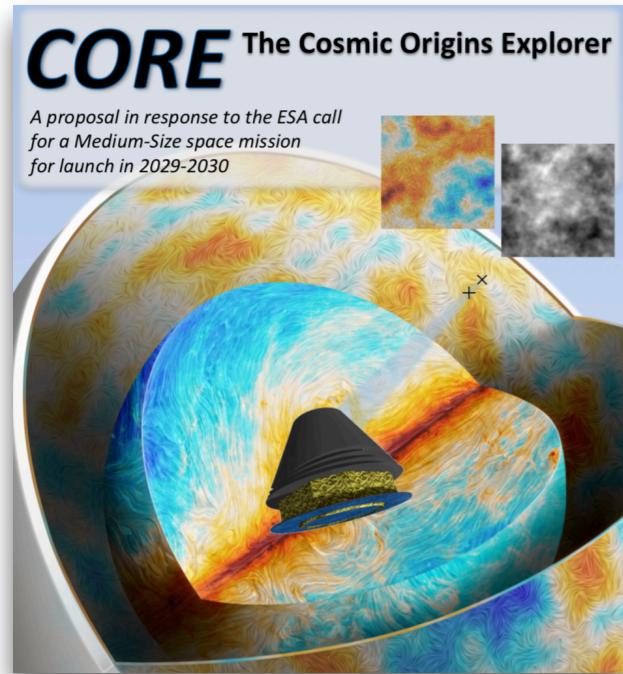
Rafael C. Nunes<sup>★</sup> and Alexander Bonilla

*Departamento de Física, Universidade Federal de Juiz de Fora, 36036-330, Juiz de Fora, MG, Brazil*



**Figure 3.** The likelihoods of the parameter  $H_0$  for model I (left panel) and model II (right panel), in red (CMB + BAO + HST) and green (CMB + BAO + HST + GC).

# Results



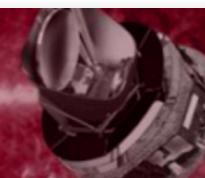
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**Mon.Not.Roy.Astron.Soc. 485 (2019) no.2, 2486-2491**  
(2019-05-11)  
DOI: [10.1093/mnras/stz524](https://doi.org/10.1093/mnras/stz524)  
e-Print: [arXiv:1810.06356 \[astro-ph.CO\]](https://arxiv.org/abs/1810.06356) | [PDF](#)

Planck Legacy Archive



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**CMB-S4**  
Next Generation CMB Experiment



# Results

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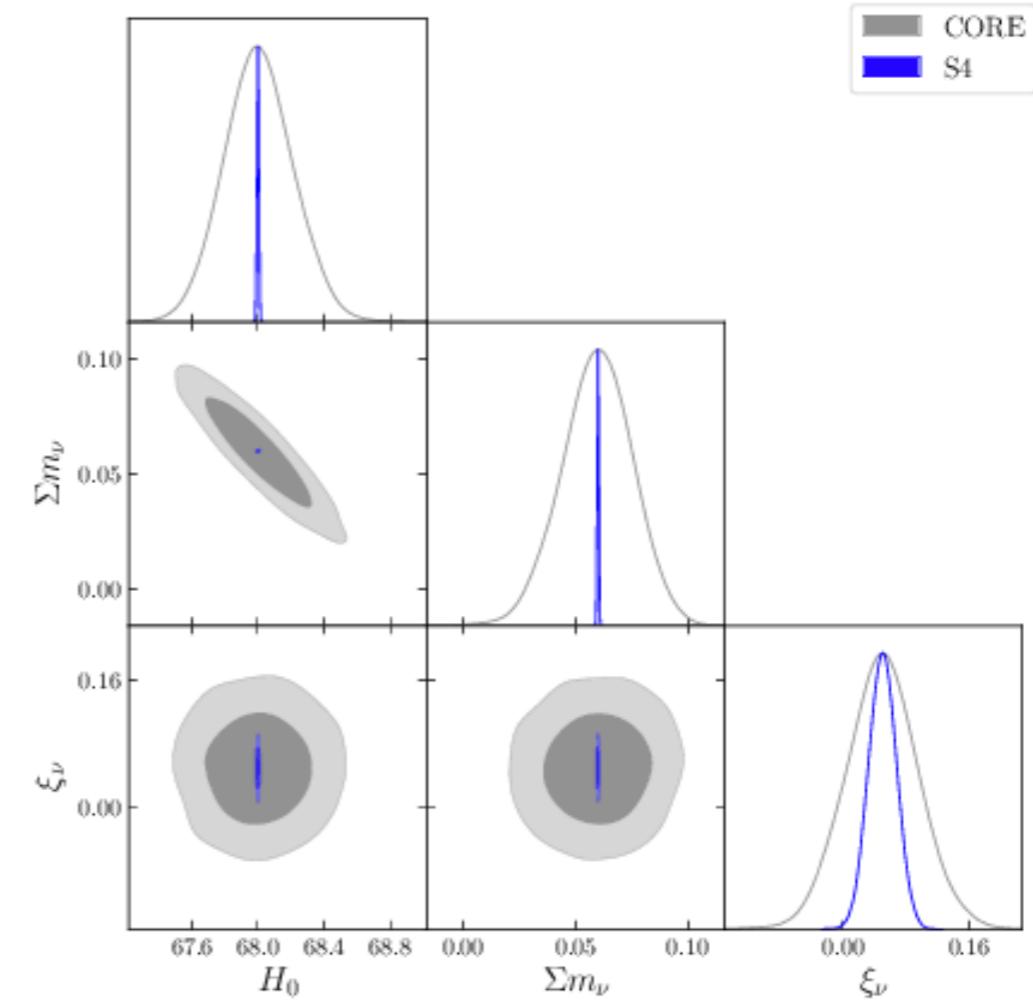
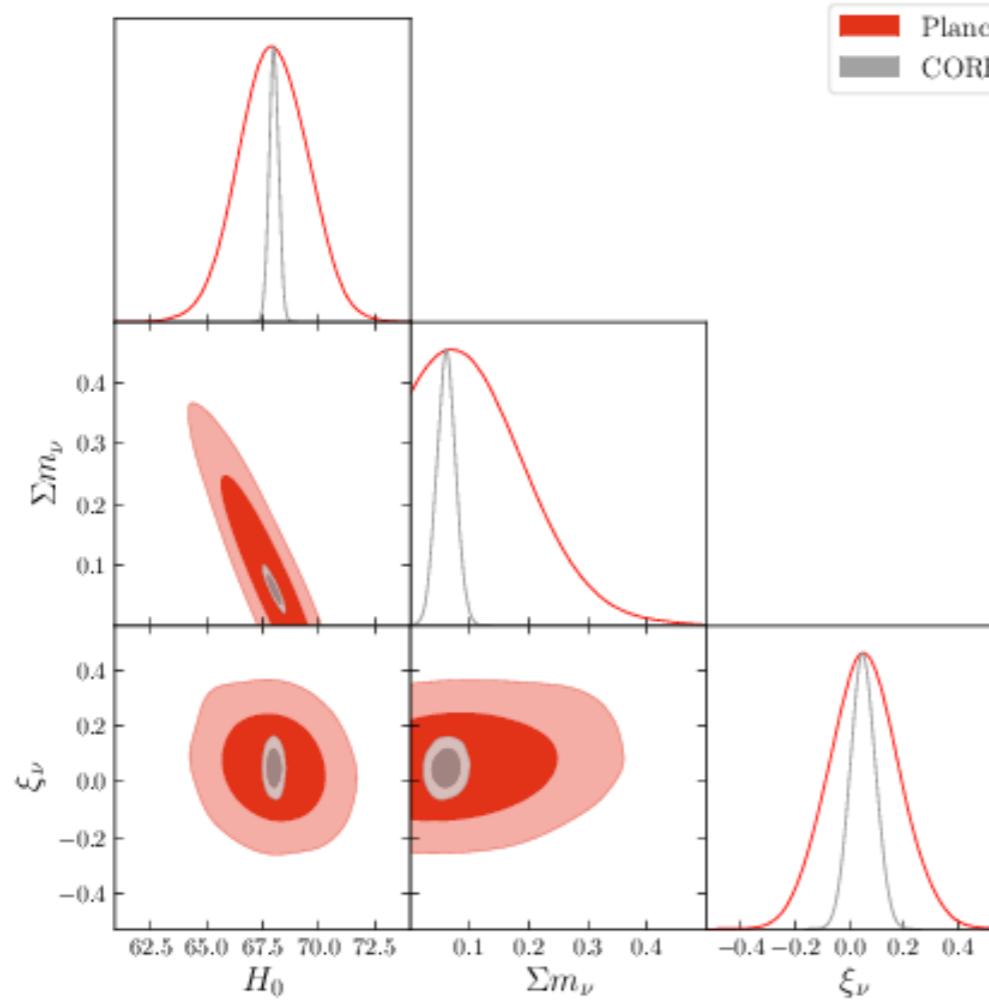
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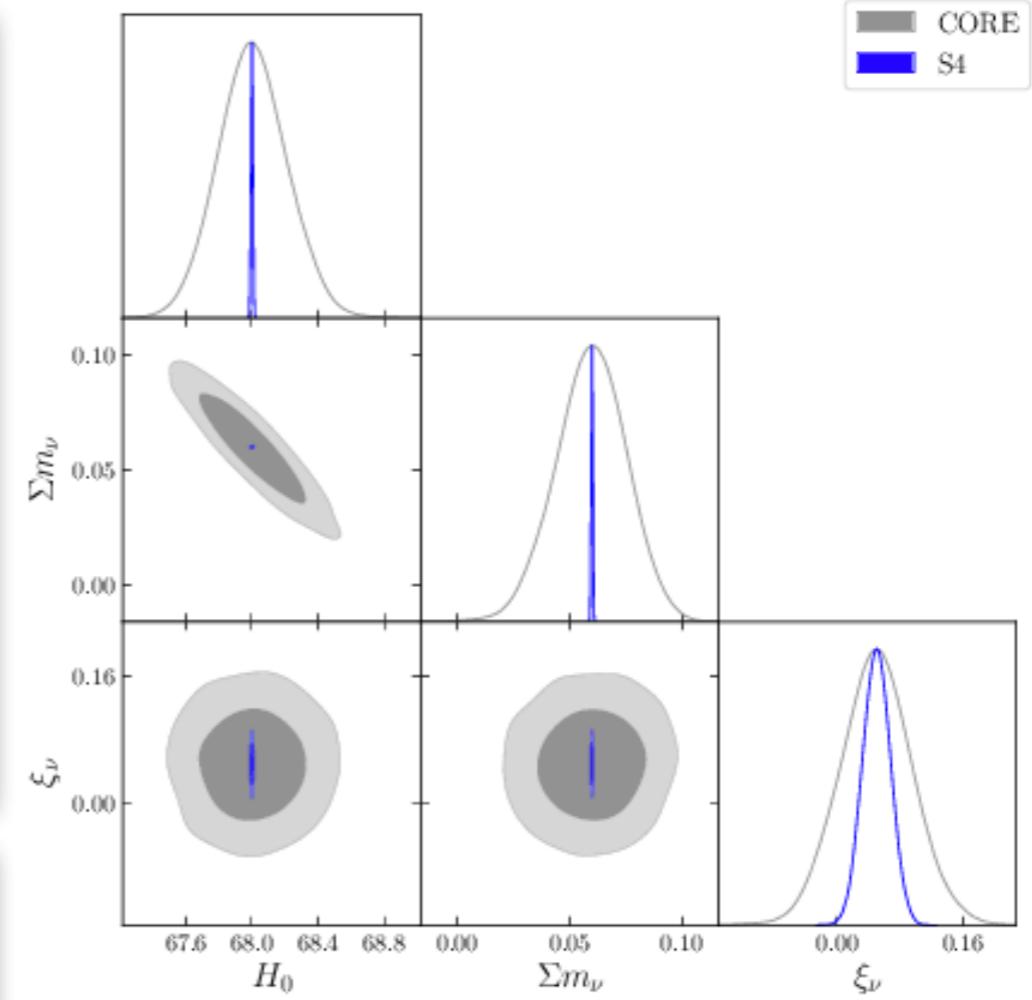
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Parameter	Fiducial value	$\sigma(\text{CORE})$	$\sigma(\text{S4})$
$10^2 \omega_b$	2.22	0.000057	0.00012
$\omega_{cdm}$	0.11919	0.00037	0.0000093
$H_0$	68.0	0.32	0.0088
$\ln 10^{10} A_s$	3.0753	0.0056	0.0035
$n_s$	0.96229	0.0022	0.0054
$\tau_{\text{reio}}$	0.055	0.0028	0.00025
$\sum m_\nu$	0.06	0.024	0.00053
$\xi_\nu$	0.05	0.071	0.027

Table 2. Summary of the observational constraints from both CORE and S4 experiments. The notation  $\sigma(\text{CORE})$  and  $\sigma(\text{S4})$ , represents the 68 % CL estimation on the fiducial values.

Following the Planck collaboration, we fix the mass ordering of the active neutrinos to the normal hierarchy with the minimum masses allowed by oscillation experiments, i.e.,  $\sum m_\nu = 0.06$  eV.



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# Summary and conclusions

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- ▶ With CMB-S4, we find  $\xi_\nu = 0.05 \pm 0.027$  ( $\pm 0.043$ ) at 68 % CL (95 % CL). These constraints can rule out the null hypothesis up to  $2\sigma$  CL on  $\xi_\nu$ . In this perspective the neutrinos can be Dirac particles against the null hypothesis and no Majorana.
- ▶ For neutrino mass scale, we find  $0.021 < \sum m_\nu \lesssim 0.1$  eV and  $0.05913 < \sum m_\nu \lesssim 0.061$  eV at 95 % CL for CORE and S4, respectively, thus, unfavorable to inverted hierarchy scheme mass in both cases.
- ▶ We note that  $\Delta N_{\text{eff}}^{\xi_\nu} = 0.002 \pm 0.019$  ( $\pm 0.030$ ) for Planck  $\Delta N_{\text{eff}}^{\xi_\nu} = 0.0022 \pm 0.0083$  ( $\pm 0.013$ ), CORE and  $\Delta N_{\text{eff}}^{\xi_\nu} = 0.0022 \pm 0.0045$  ( $\pm 0.0059$ ) S4..

End...?

Any collaboration will be welcome...!



GRACIAS  
ARIGATO  
SHUKURIA  
JUSPAKAR

DANKSCHEEN

SPASSIBO NUHUN SNACHALHYUA CHALTU TASHAKKUR ATU YAQHANYELAY SUKSAMA EKHMET HUI YUSPAGARATAM

MAAKE DHANYABAAD WABEEJA MAITEKA HATUR GUI

KOMAPSUMNIDA ANHIA SPASIBO DENKAUJA UNHALCHEESH

MAKE ATTO MERSI EKOJU SIKOMO

LAH PALLIES

BAIKA GAEJTHO MERASTAWHY SANCO

GOZAIMASHITA AGUYJE FAKAAUE

EFCHARISTO

BOLZİN

TINGKI BİYAN SHUKRIA

THANK YOU MERCI

MINMONCHAR MAKETAI

