



Neutrinos in cosmology: Challenges and future perspectives

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Outline

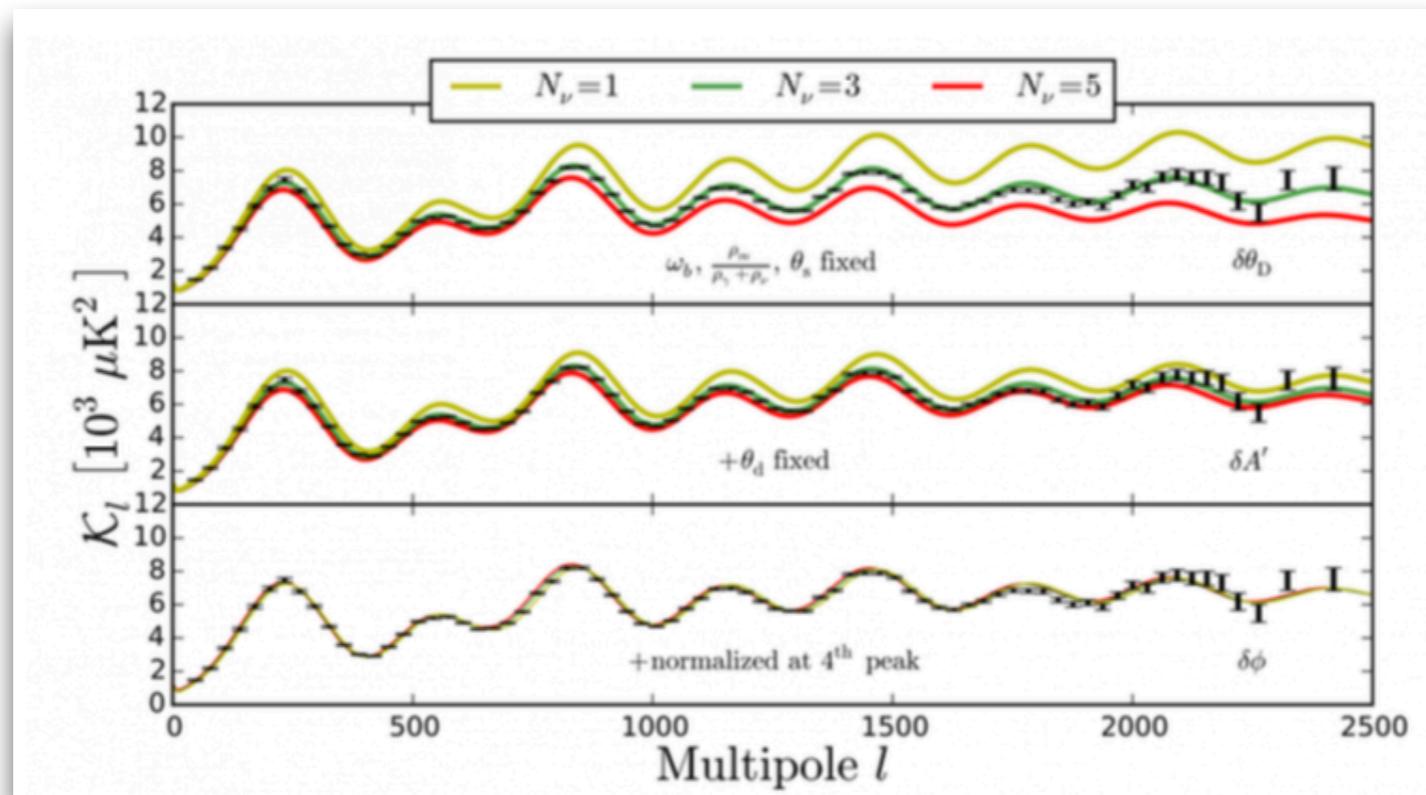
1. Introduction and Motivation
2. Theoretical framework
 - 2.1.Cosmic Neutrino Background (CNB)
 - 2.2.Models and data analysis
 - 2.3.Results
3. Summary and conclusions

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Introduction and motivation

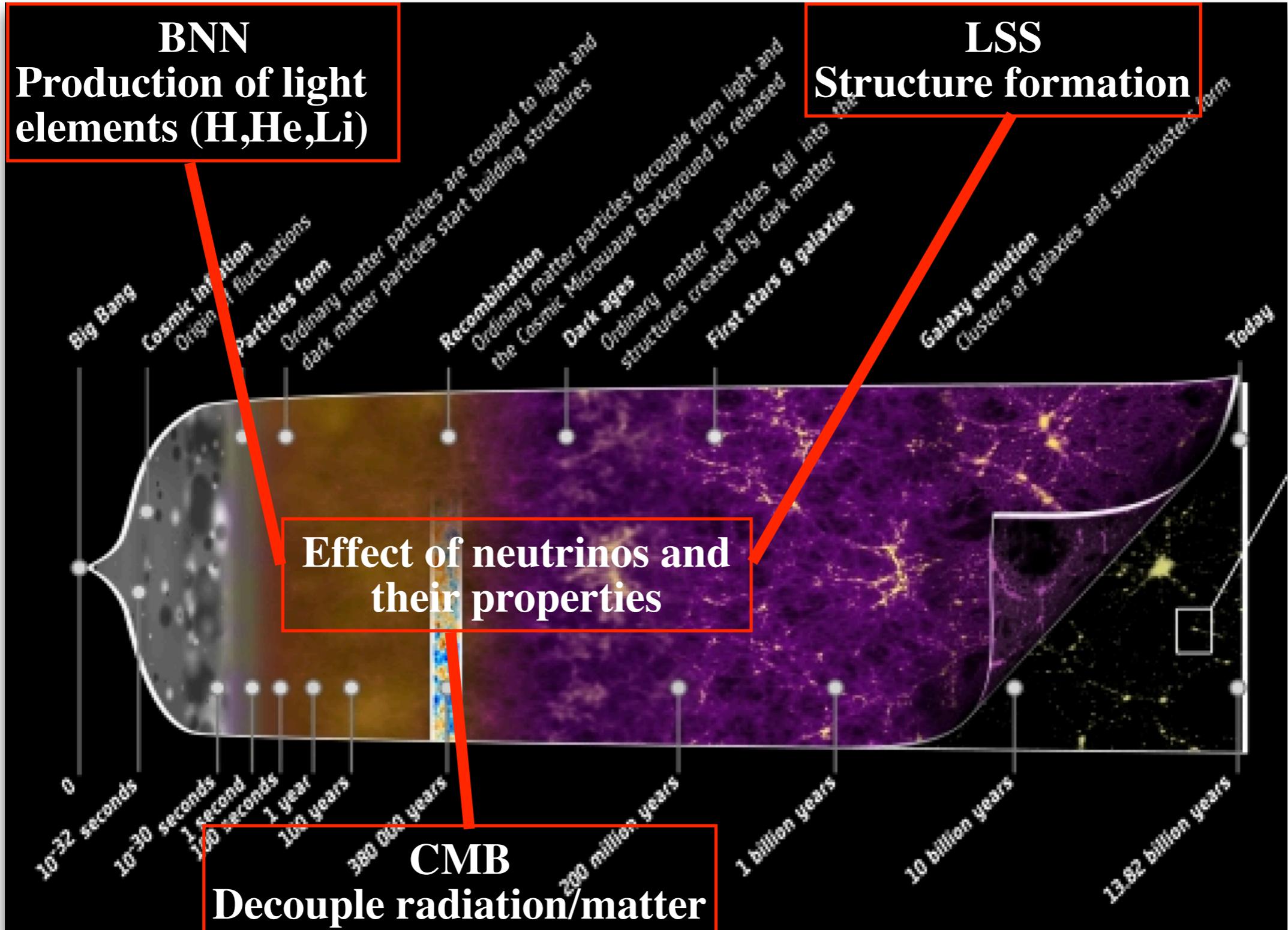
- 1.The existence of a cosmic neutrino background (CNB), or also called relic neutrinos, is a consequence of the thermal history of the universe where the neutrinos become to stream freely at $kBT \sim 1$ MeV.
- 2.Unlike the cosmic microwave background (CMB), the CNB not was yet been detected directly and such direct detection proves to be difficult [Betts et al. \(2013\)](#). ($1.9 \text{ }^{\circ}\text{K} \approx 0.00017 \text{ eV}$)
- 3.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.



Introduction and motivation

- 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 $kBT \sim 1$ MeV.
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- 3.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



Introduction and motivation

Implications

1. Particle physics: Physics beyond the standard model.
2. Cosmology: Neutrinos are the second most abundant particle in the universe and thus can affect different epochs in cosmic history.

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)

Einstein Equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi GT_{\mu\nu}$$

$g_{\mu\nu}$: metric

$$\rightarrow R_{\mu\nu} = \Gamma_{\mu\nu,\alpha}^\alpha - \Gamma_{\mu\alpha,\nu}^\alpha + \Gamma_{\beta\alpha}^\alpha \Gamma_{\mu\nu}^\beta + \Gamma_{\beta\nu}^\alpha \Gamma_{\mu\alpha}^\beta$$

$$R = g^{\mu\nu} R_{\mu\nu}$$

Christoffel symbols



Isotropic, uniform, expanding universe:

Cosmological principle

$$g_{\mu\nu} = diag(-1, a^2, a^2, a^2)$$

FRW metric

Scale factor



$$\rightarrow d\tau^2 = dt^2 - a^2 |\vec{dr}|^2$$



Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

$$R_{00} = \dots = -3 \frac{\ddot{a}}{a}$$

$$R_{ij} = \dots = \delta_{ij}(2\dot{a}^2 + a\ddot{a})$$

$$\rightarrow R = -R_{00} + \frac{1}{a^2} R_{ii} = 6 \left[\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a} \right)^2 \right]$$

Left-hand side of Einstein Equation:

Scale factor

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \dots = \left(\frac{\dot{a}}{a} \right)^2$$

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

For the right-hand side, we assume a perfect isotropic fluid:

$$T_{\mu\nu} = \text{diag}(\rho, P, P, P)$$

► Energy density

Pressure

Putting everything together for the 00 element of Einstein Equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

Energy content of the Universe
dictate its evolution

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

Same equation, new nomenclature:

$$H = \dot{a}/a$$

$$H_0 = \dot{a}/a)_{\text{today}}$$

$$\rho_{cr} = 3H_0^2/8\pi G$$

$$\Omega_i = \rho_i/\rho_{cr}$$

$$\frac{H^2}{H_0^2} = \sum_i \frac{\rho_i}{\rho_{cr}} = \sum_i \Omega_i$$

Friedmann Equation

and some numbers:

$$H_0 = 67.3 \pm 1.2 \text{ km/s/Mpc} = h \times (100 \text{ km/s/Mpc})$$

latest Planck results

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

Same equation, new nomenclature:

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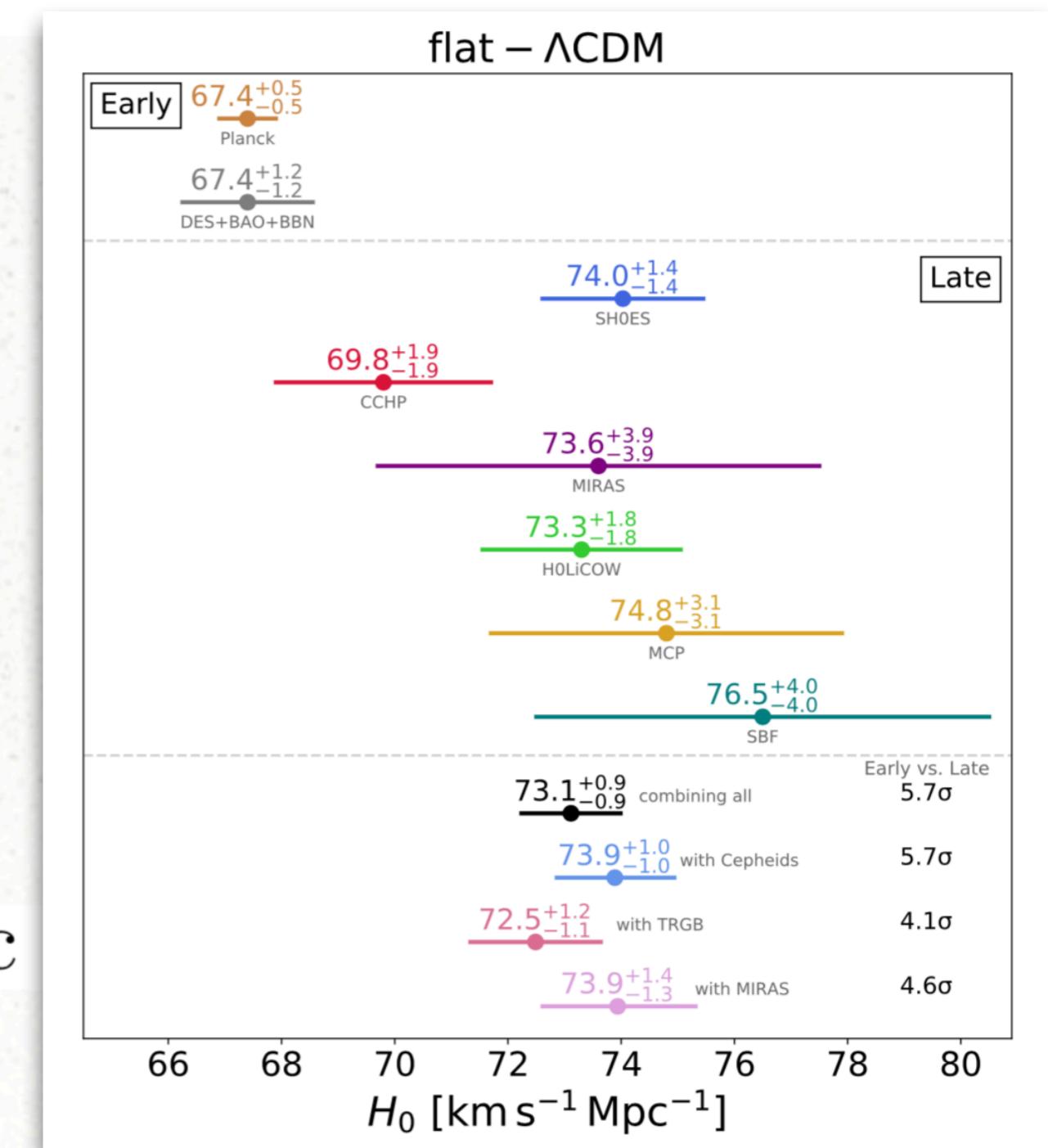
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and some numbers:

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Hubble tensión



Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

Energy Conservation:

$$T_{\nu,\mu}^{\mu} = \frac{\partial T_{\nu}^{\mu}}{\partial x^{\mu}} + \Gamma_{\alpha\mu}^{\mu} T_{\nu}^{\alpha} - \Gamma_{\nu\mu}^{\alpha} T_{\alpha}^{\mu} = 0$$

For $\nu = 0$:

$$\frac{\partial \rho}{\partial t} + \frac{\dot{a}}{a} [3\rho + 3P] = 0$$

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

Radiation (in thermal equilibrium): $P = \rho/3$

$$\frac{\partial \rho}{\partial t} + 4\frac{\dot{a}}{a}\rho = \frac{1}{a^4} \frac{\partial}{\partial t} [\rho a^4] = 0$$

$\rho \sim a^{-4}$

How does the Universe evolve?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \frac{\rho_0}{a^4} \rightarrow a(t) = \left(\frac{32\pi G\rho_0}{3}\right)^{1/4} t^{1/2}$$

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

(non-relativistic) matter: $P \sim v^2 \ll \rho$

$$\frac{\partial \rho}{\partial t} + 3\frac{\dot{a}}{a}\rho = \frac{1}{a^3} \frac{\partial}{\partial t} [\rho a^3] = 0$$

$\rho \sim a^{-3}$

How does the Universe evolve?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \frac{\rho_0}{a^3} \rightarrow a(t) = \left(\frac{18\pi G \rho_0}{3}\right)^{1/3} t^{2/3}$$

Cosmic Neutrino Background (CvB)

Important equations of Universe evolution

Cosmological Constant:

$$\rho = \text{constant} = -P$$

$$\rho \sim a^0$$

How does the Universe evolve?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_0 \rightarrow a(t) = \exp\left[\left(\frac{8\pi G\rho_0}{3}\right)^{1/2} t\right]$$

Cosmic Neutrino Background (CvB)

Back to Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \left[\frac{\rho_0^{rad}}{a^4} + \frac{\rho_0^{nr}}{a^3} + \rho_\Lambda \right]$$

ρ_0^{rad} : photons and neutrinos

ρ_0^{nr} : atoms and cold dark matter

ρ_Λ : cosmological constant

Cosmic Neutrino Background (CvB)

Back to Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \left[\frac{\rho_0^\gamma}{a^4} + \frac{\rho_0^\nu}{a^4} + \frac{\rho_0^{CDM}}{a^3} + \frac{\rho_0^{mat.}}{a^3} + \rho_\Lambda \right]$$

1978 Nobel, Penzias and Wilson
2006 Nobel, Mather and Smoot

2011 Nobel, Perlmutter, Schmidt and Riess

Our concern here

$$\frac{\rho_0^\nu}{a^3} \sim \frac{\sum m_\nu}{a^3}$$

Cosmic Neutrino Background (CvB)

Some numbers from Planck 2018

Parameter	TT+lowE 68 % limits	TT+lowE-S2 68 % limits	TTTEEE+lowE 68 % limits	TTTEEE+lowE-S2 68 % limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02214 ± 0.00021	0.02236 ± 0.00015	0.02237 ± 0.00015
$\Omega_c h^2$	0.1206 ± 0.0021	0.1205 ± 0.0021	0.1202 ± 0.0014	0.1201 ± 0.0013
$100\theta_{\text{MC}}$	1.04077 ± 0.00047	1.04080 ± 0.00047	1.04090 ± 0.00031	1.04090 ± 0.00031
τ	0.0522 ± 0.0080	$0.0574^{+0.0056}_{-0.0069}$	$0.0544^{+0.0070}_{-0.0081}$	$0.0590^{+0.0058}_{-0.0068}$
$\ln(10^{10} A_s)$	3.040 ± 0.016	3.051 ± 0.013	3.045 ± 0.016	3.054 ± 0.013
n_s	0.9626 ± 0.0057	0.9631 ± 0.0056	0.9649 ± 0.0044	0.9651 ± 0.0043
H_0	66.88 ± 0.92	66.95 ± 0.90	67.27 ± 0.60	67.32 ± 0.60
Ω_m	0.321 ± 0.013	0.320 ± 0.013	0.3166 ± 0.0084	0.3158 ± 0.0082
Ω_Λ	0.679 ± 0.013	0.680 ± 0.013	0.6834 ± 0.0084	0.6842 ± 0.0082
σ_8	0.8118 ± 0.0089	0.8155 ± 0.0083	0.8120 ± 0.0073	0.8153 ± 0.0067
z_{re}	7.50 ± 0.82	8.04 ± 0.60	7.68 ± 0.79	8.14 ± 0.60
$10^9 A_s$	2.092 ± 0.034	2.113 ± 0.028	$2.101^{+0.031}_{-0.034}$	2.120 ± 0.028
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.884 ± 0.014	1.884 ± 0.012	1.884 ± 0.012
Age/Gyr	13.830 ± 0.037	13.827 ± 0.036	13.800 ± 0.024	13.798 ± 0.024

CvB and basic equations

Friedmann equation

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

$$E(a, \Omega_i) = \frac{H(a, \Omega_i)}{H_0}$$

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

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

$$\xi_\nu = \mu_\nu / T_{\nu 0}$$

→ Lepton asymmetry

Chemical potential

$$T_{\nu 0} \approx 1.9K$$

Current temperature CvB

$$\mu_\nu = 0$$

→ Majorana particles
Neutrinos = Antineutrinos

$$\mu_\nu \neq 0$$

→ Dirac particles
Neutrinos ≠ Antineutrinos

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

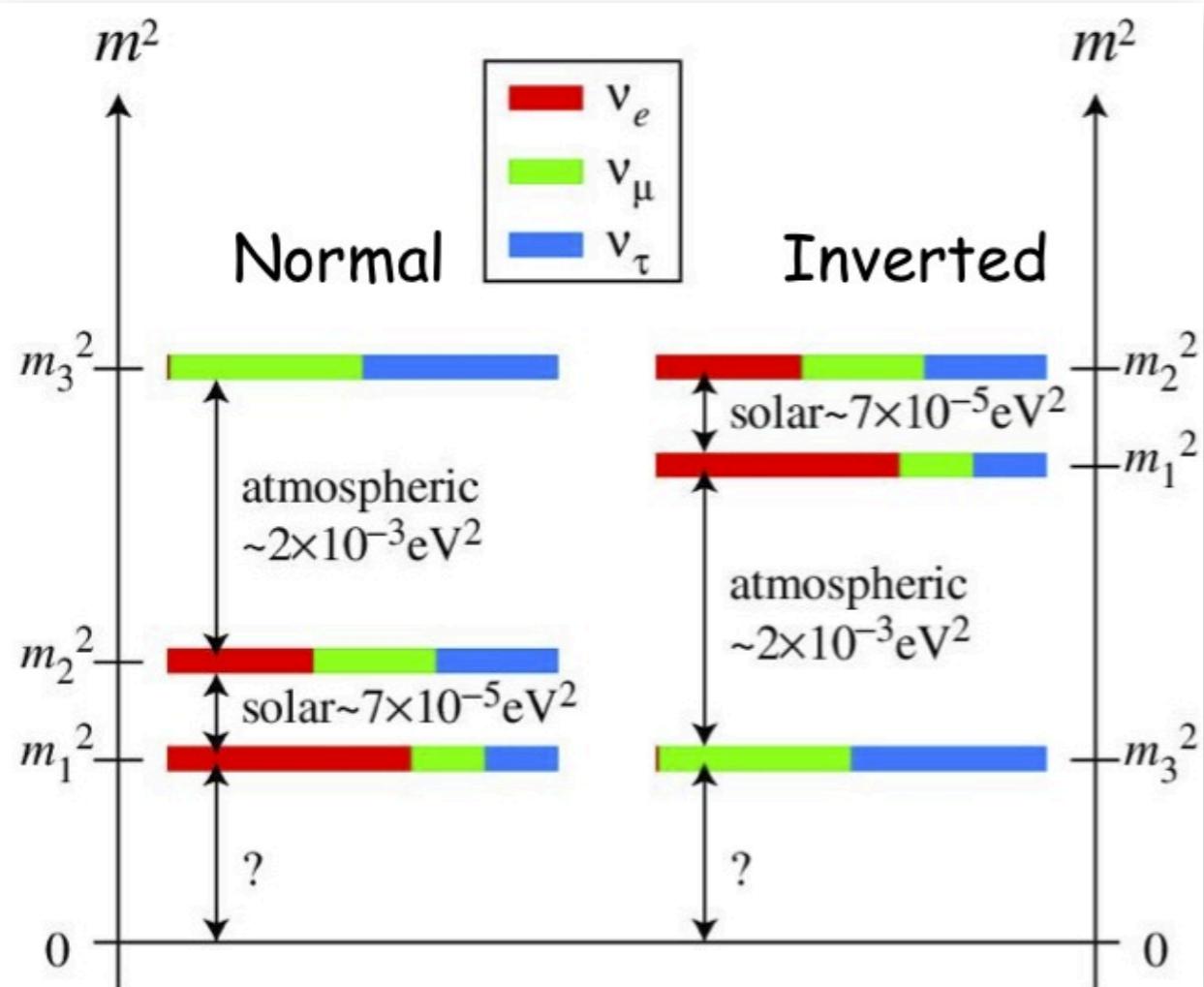
- Primordial Grav Waves (PGWs)
- Sterile neutrino
- Goldstone boson
- Lepton asymmetry (Matter/antimatter)
- In general “Dark radiation”

CvB and basic equations

Friedmann equation

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

$\Omega_m = \Omega_{cdm} + \Omega_b + \Omega_\nu \rightarrow$ 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

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

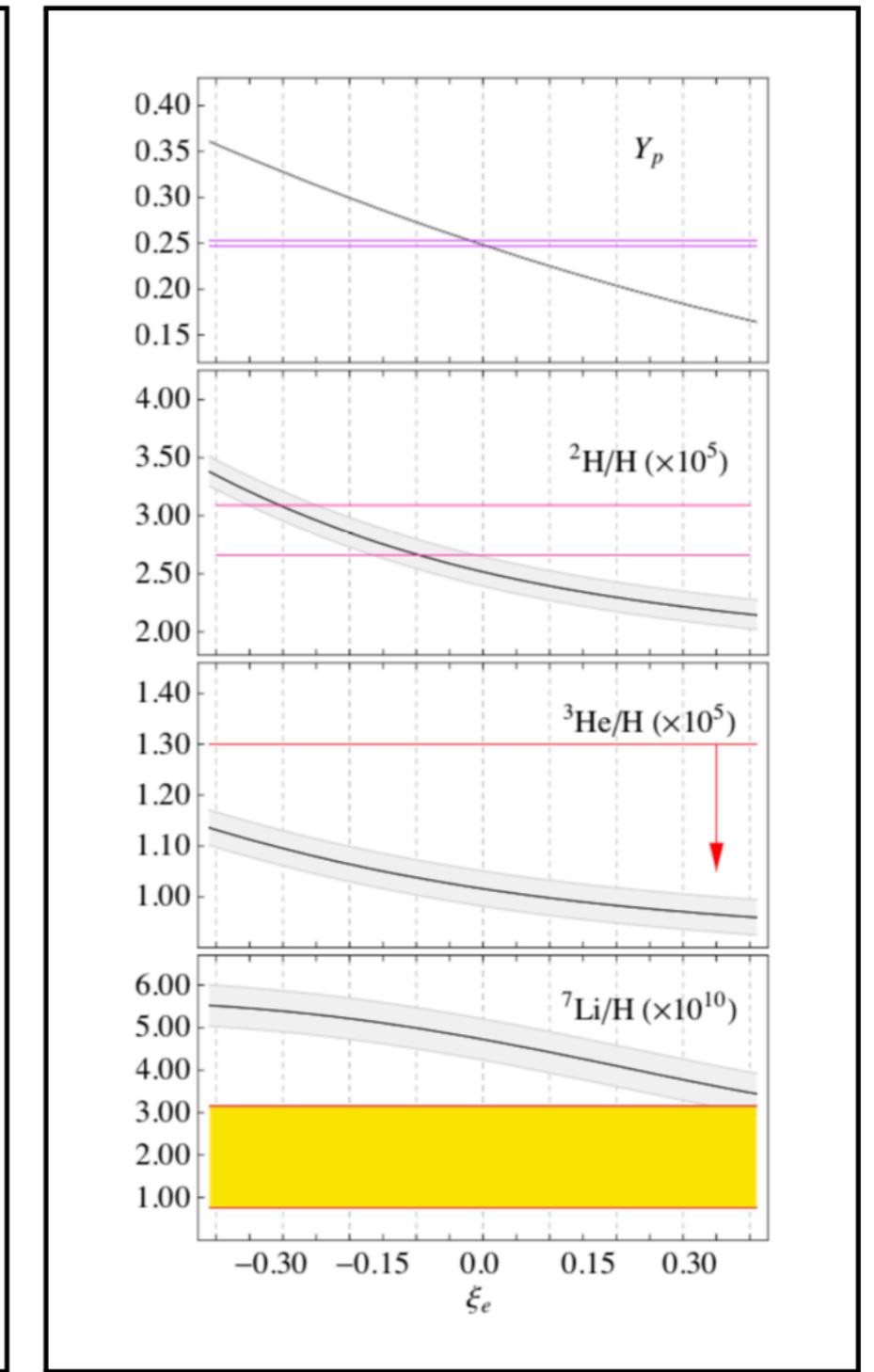
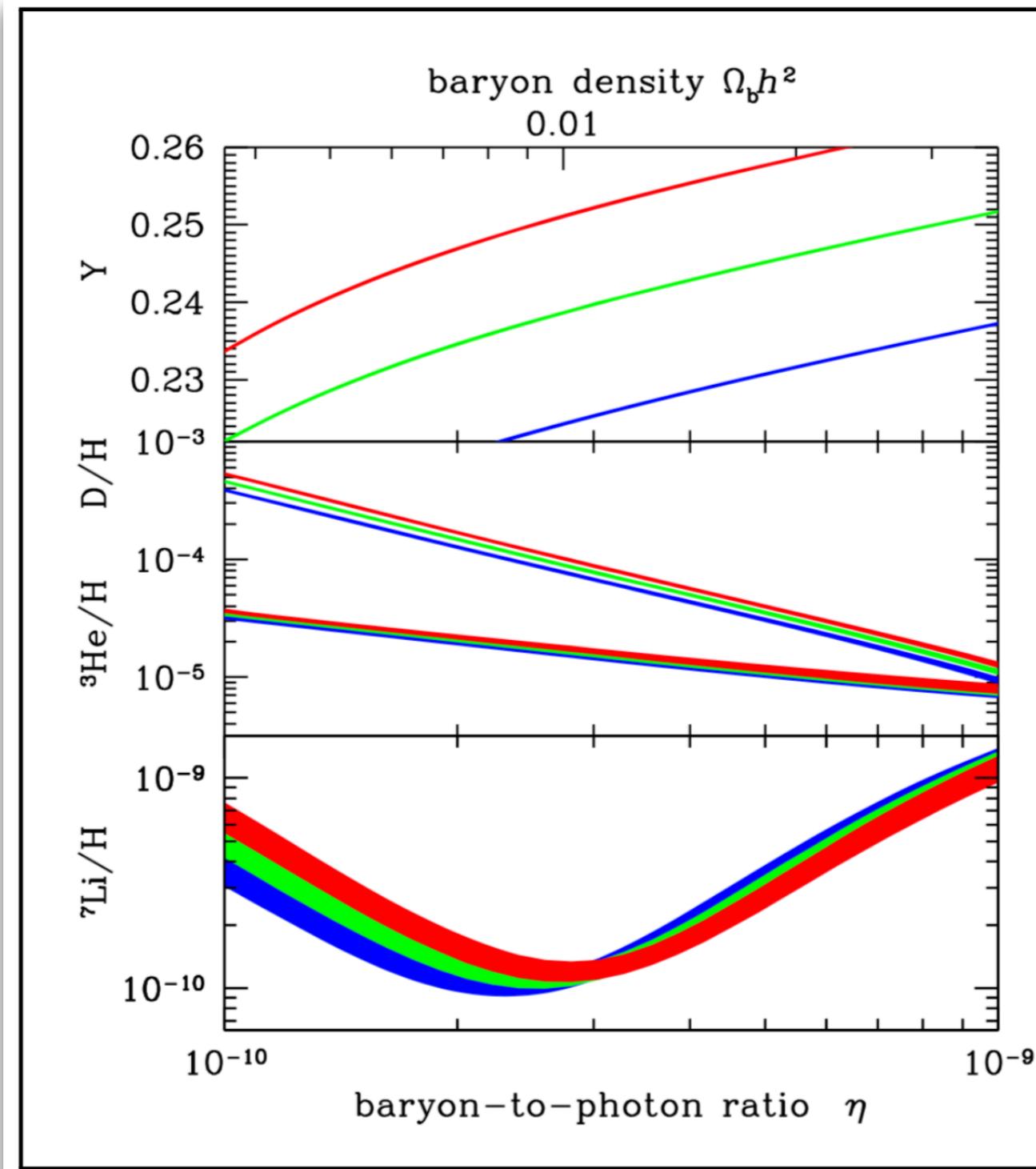
$$E_{\nu_i}^2 = q^2 + a^2 m_{\nu_i}^2 \rightarrow \text{Neutrino mass}$$

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

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

CvB and Big Bang Nucleosynthesis (BBN)

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



CvB and Cosmic Microwave Background (CMB)

- Sound horizon at recombination

$$l_a \equiv \frac{\pi}{\theta_*} = \pi \frac{D_*}{r_*} .$$

Diameter distance from recombination

Sound horizon at recombination

$$r_s(z) = \int_z^\infty dz' \frac{c_s(z')}{H(z')} ,$$

$$c_s(z) = \frac{1}{\sqrt{3}} \left(1 + \frac{3\rho_b(z)}{4\rho_\gamma(z)} \right)^{-\frac{1}{2}} ,$$

and

$$D_M(z) = \int_0^z \frac{dz'}{H(z')} .$$

- Damping scale at recombination

$$l_D \equiv k_D D_* ,$$

with

$$k_D = \left(\frac{1}{6} \int_{z_*}^\infty \frac{dz}{H(z)\tau'} \frac{R^2 + 16(1+R)/15}{(1+R)^2} \right)^{-\frac{1}{2}}$$

Differential of Optical depth



$$\tau(z) = \int_0^z dz \frac{\sigma_T n_e(z)}{(1+z)H(z)} .$$

$$\tau' \equiv \frac{\sigma_T n_e(z)}{1+z}, \quad R(z) \equiv \frac{3\omega_b}{4\omega_\gamma} \frac{1}{1+z}$$

- Hubble horizon at matter-radiation equality

$$l_{\text{eq}} \equiv k_{\text{eq}} D_* = \frac{H(z_{\text{eq}})}{1+z_{\text{eq}}} D_* .$$

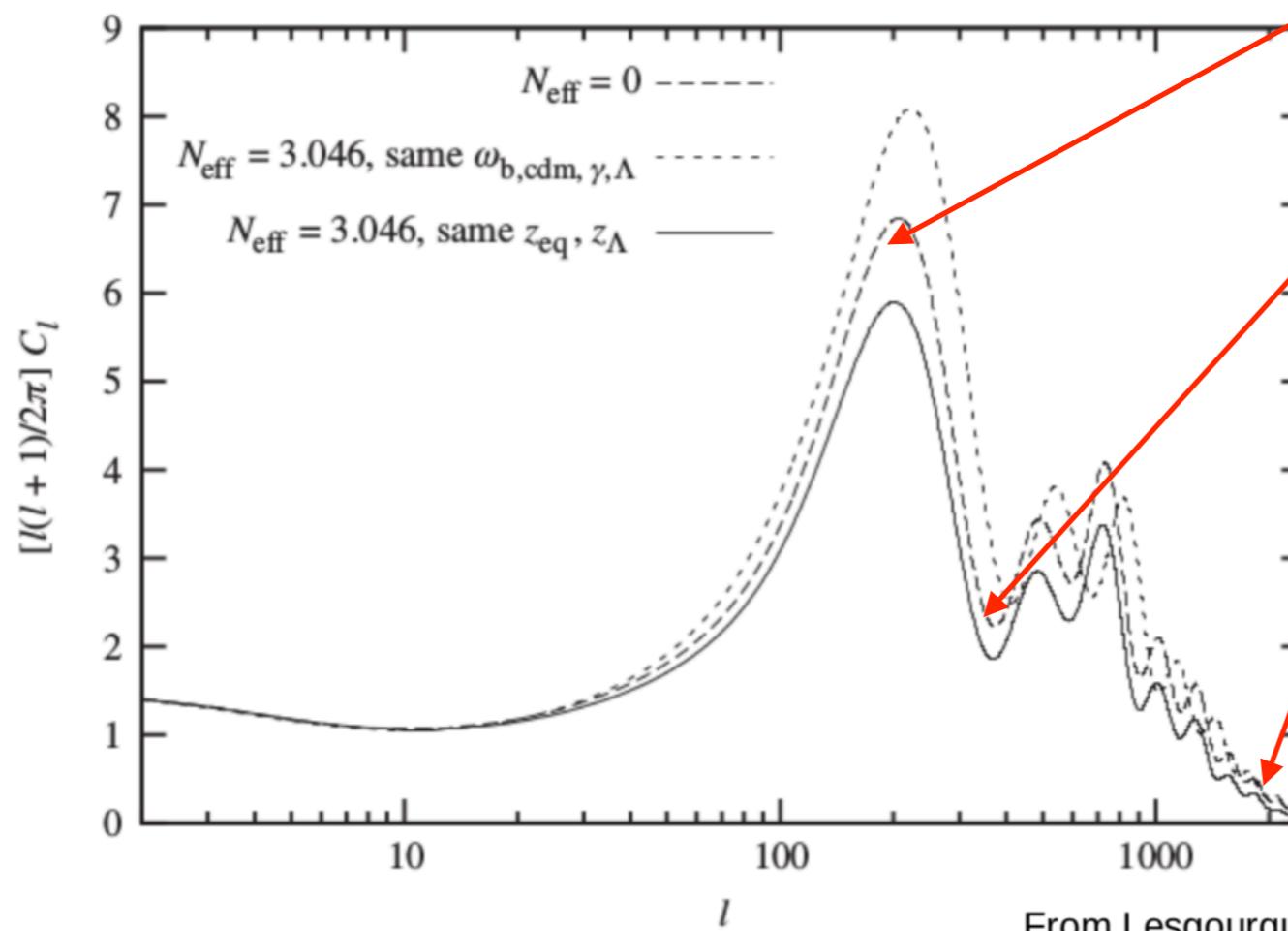
CvB and Cosmic Microwave Background (CMB)

CMB anisotropies:

(Massless) Neutrinos affect anisotropies through:

- matter-radiation energy density equality time
- perturbations

Hubble horizon at matter-radiation equality



Data	Experiments	Observables	Reference
CMB	Planck 2018 [1] (TT,TE,EE +lowE+lensing)	l_a	301.757
		l_{eq}	144.14
		l_D	1954.7

$$z_{\text{cmb}} = 1048[1 + 0.00124(\Omega_b h^2)^{-0.738}][1 + g_1(\Omega_m h^2)^{g_2}],$$

$$g_1 = \frac{0.0783(\Omega_b h^2)^{-0.238}}{1 + 39.5(\Omega_b h^2)^{0.763}}, \quad g_2 = \frac{0.560}{1 + 21.1(\Omega_b h^2)^{1.81}}.$$

From Lesgourges et al,
"Neutrino Cosmology"

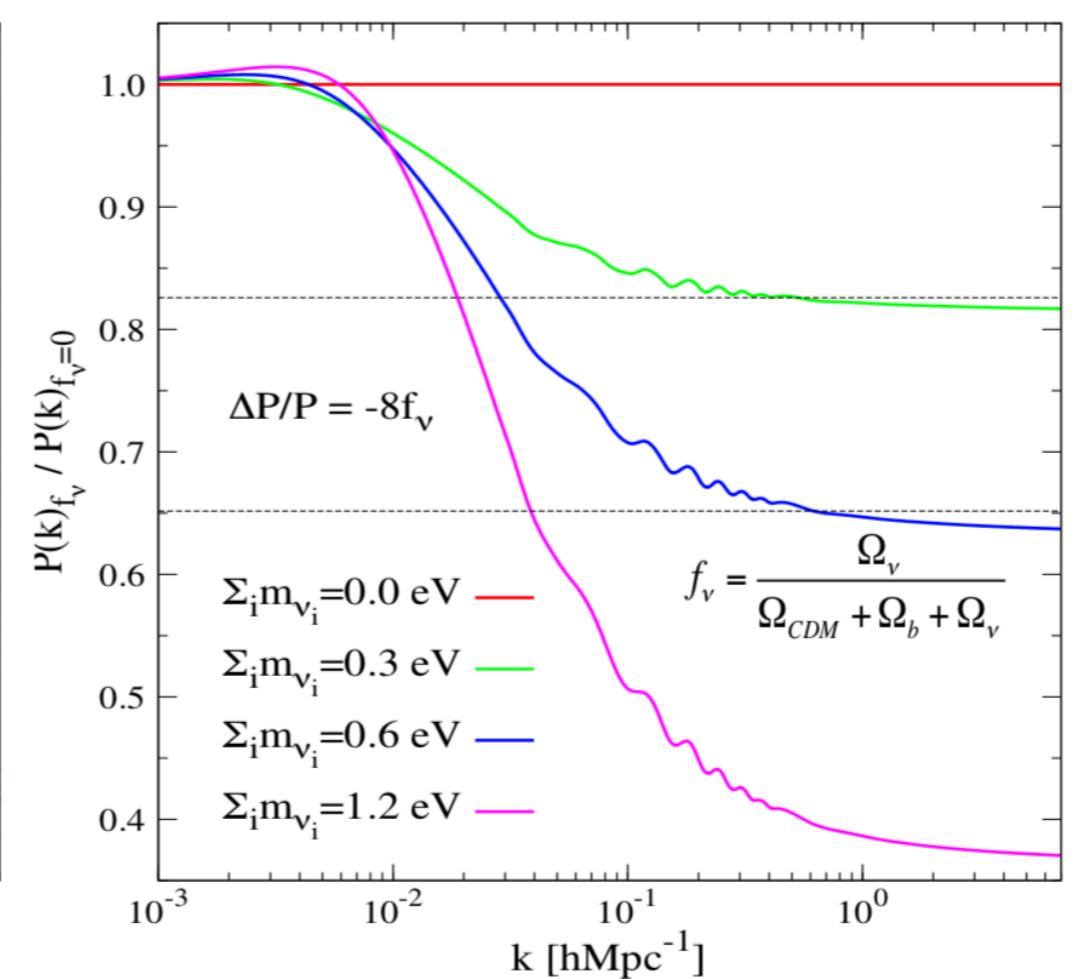
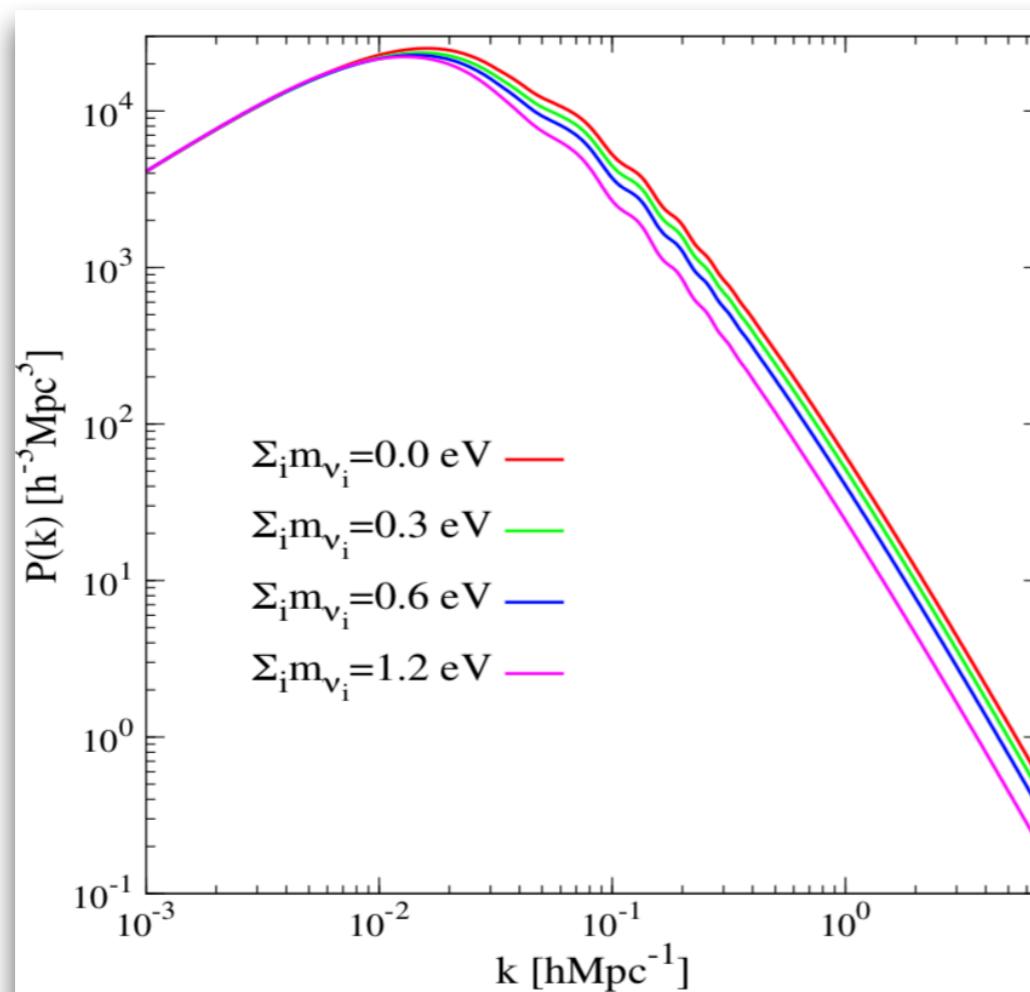
CvB and Large Scale Structure (LSS)

$$\frac{k^3}{2\pi^2} P(k, z) = \delta_H^2 \left(\frac{ck}{H_0} \right)^{3+n} T^2(k, z) D_1^2(z)/D_1^2(0).$$

Power spectrum of matter

$$\sigma_R = \left[\int_0^\infty \frac{dk}{k} \frac{k^3}{2\pi^2} P(k) \left| \tilde{W}_R(k) \right|^2 \right]^{1/2},$$

Mass fluctuación R= 8 Mpc



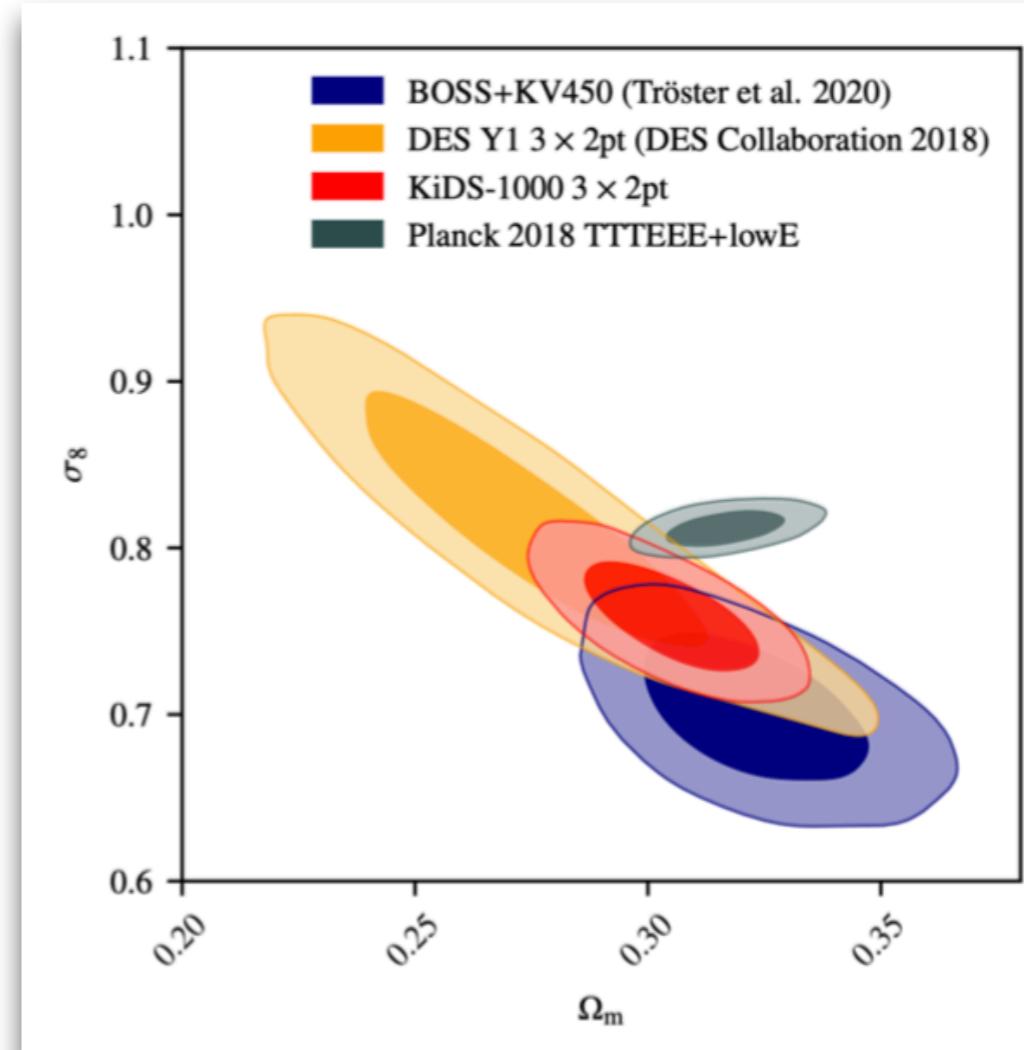
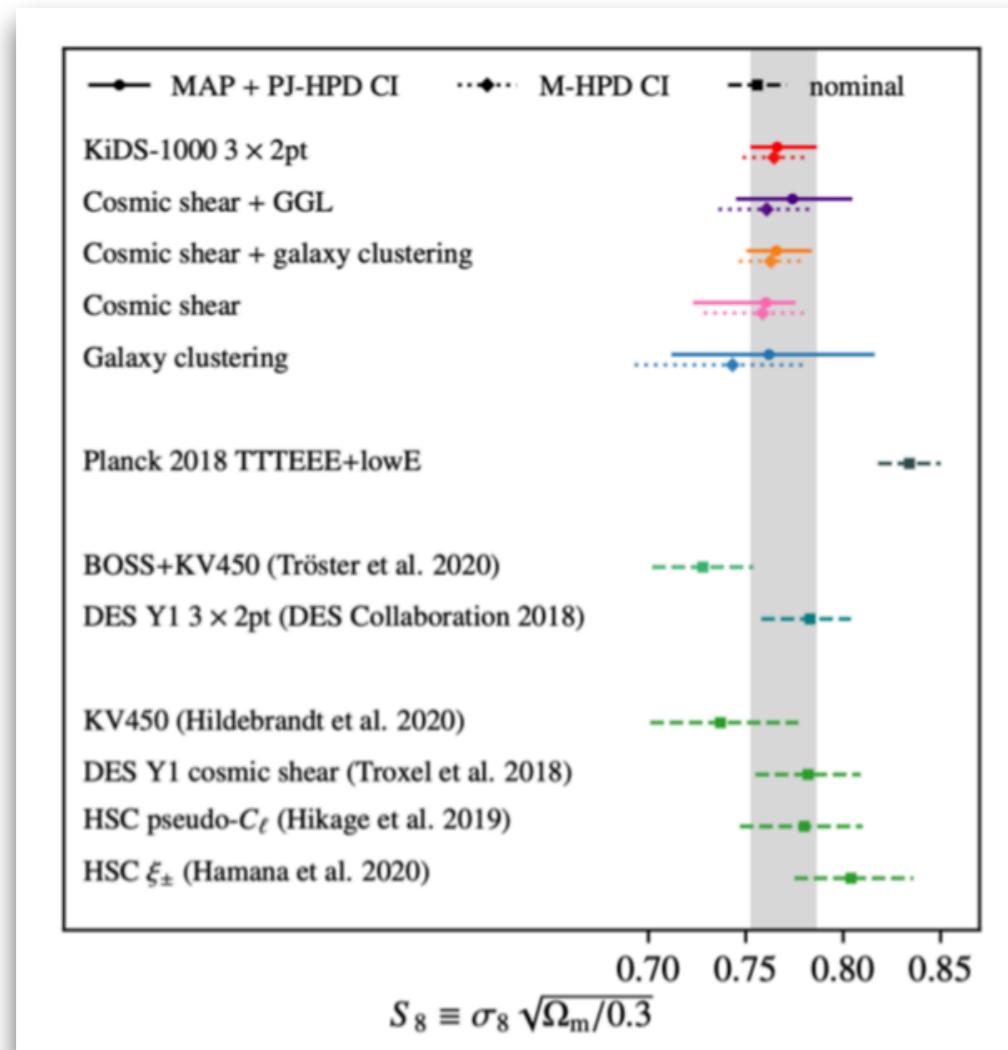
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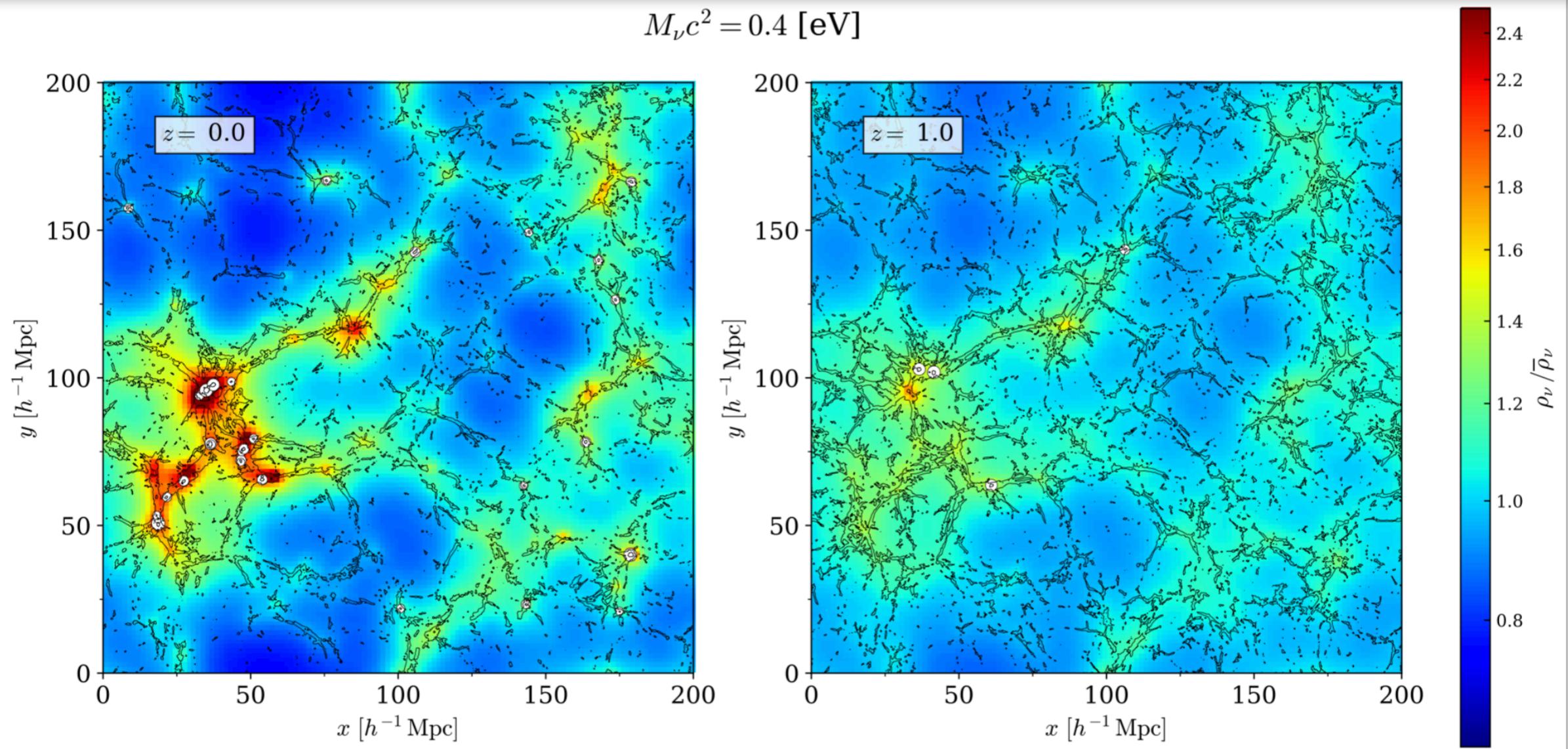
Mass fluctuación R= 8 Mpc



CvB and Large Scale Structure (LSS)

Cosmological Vlasov–Poisson Simulations of Structure Formation with Relic Neutrinos: Nonlinear Clustering and the Neutrino Mass

KOHJI YOSHIKAWA,¹ SATOSHI TANAKA,² NAOKI YOSHIDA,^{3,4,5} AND SHUN SAITO^{6,4}



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Cosmic Neutrino Background (CvB)

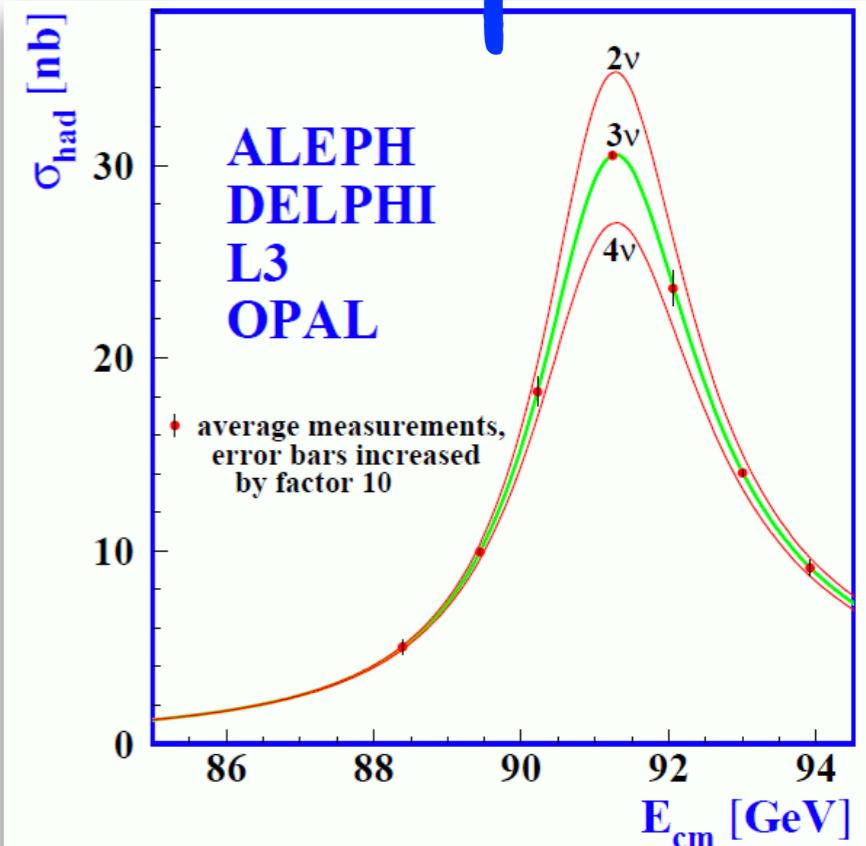
Effective number of relativistic species $\rightarrow N_{\text{eff}} = 3.0$

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

Planck team [Ade et al. \(2016\)](#) within the Λ 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_{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



Models and data analysis

We consider two different models. First, let us take Λ 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., Λ 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

- 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 σ_8 is the linear amplitude of fluctuations on 8 Mpc/h and α, β 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.

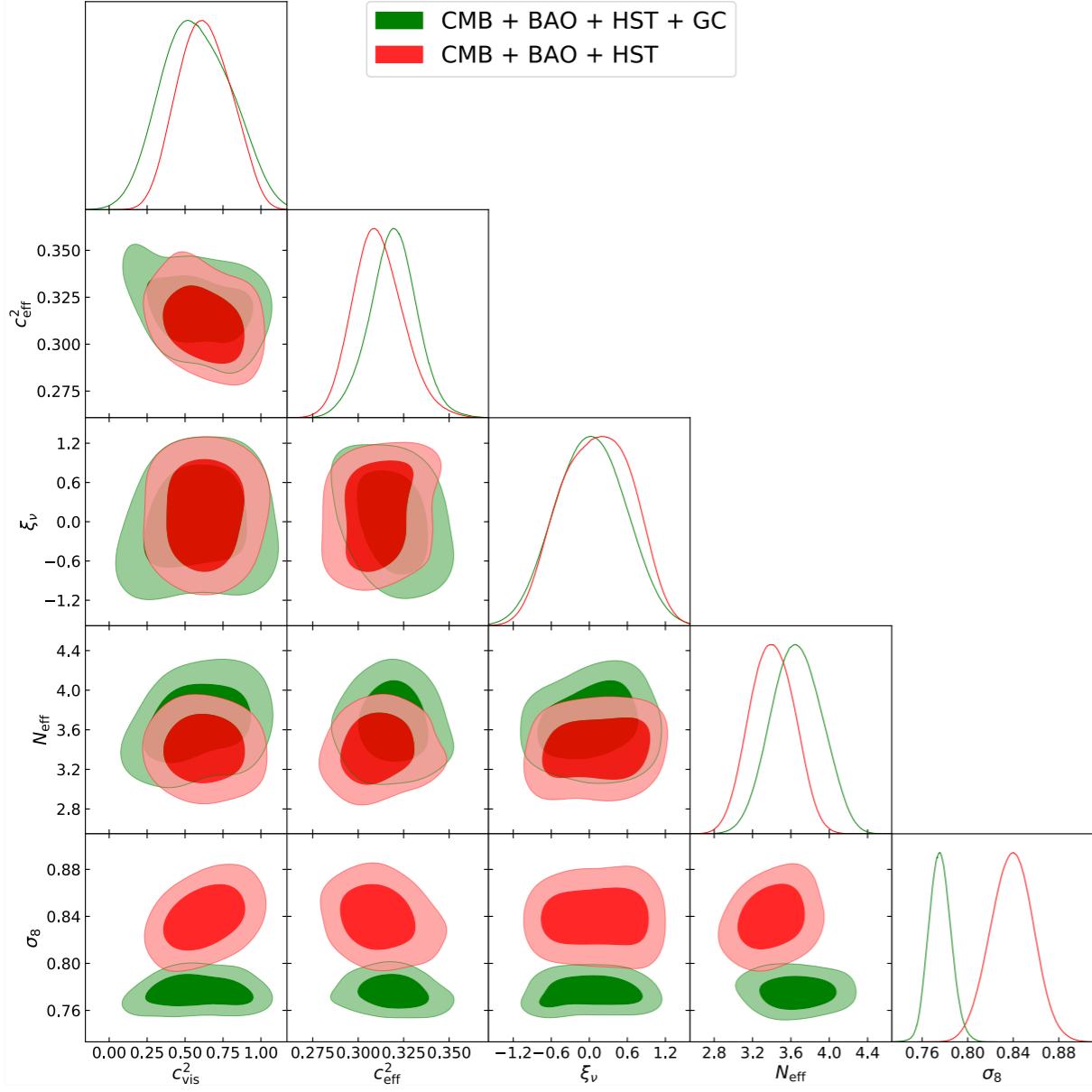


Table 2. Constraints at 68% CL and 95% CL on some parameters of the model I using two distinct data set. The parameter H_0 is in the units of $\text{km s}^{-1} \text{ Mpc}^{-1}$ and $\sum m_\nu$ is in units of eV.

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

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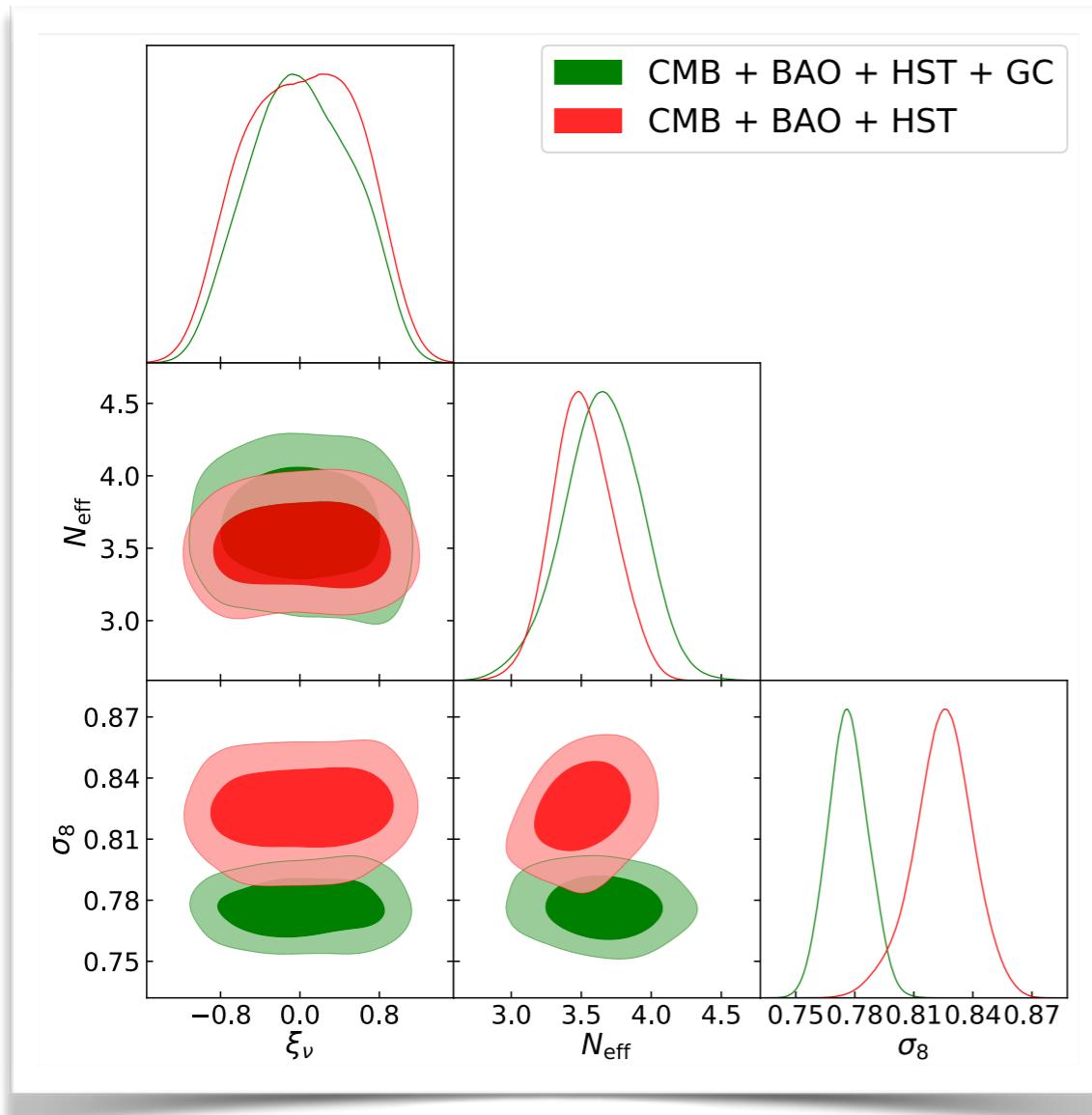


Table 3. Constraints at 68% CL and 95% CL on some parameters of the model II using two distinct data set. The parameter H_0 is in the units of $\text{km s}^{-1} \text{ Mpc}^{-1}$ and $\sum m_\nu$ is in units of eV.

Parameter	CMB + BAO + H_0	CMB + BAO + H_0 + GC
$\sum m_\nu$	$< 0.18 (< 0.30)$	$< 0.52 (< 0.64)$
ξ	$0.05^{+0.56+0.97}_{-0.56-0.99}$	$-0.02^{+0.51+0.92}_{-0.51-0.89}$
N_{eff}	$3.49^{+0.21+0.44}_{-0.23-0.42}$	$3.65^{+0.28+0.57}_{-0.28-0.60}$
Ω_Λ	$0.703^{+0.009+0.015}_{-0.008-0.016}$	$0.706^{+0.008+0.015}_{-0.008-0.016}$
Y_{He}	$0.2537^{+0.0028+0.0056}_{-0.0028-0.0056}$	$0.2557^{+0.0038+0.0071}_{-0.0032-0.0077}$
H_0	$70.5^{+1.3+2.7}_{-1.3-2.6}$	$71.2^{+1.4+2.6}_{-1.4-2.7}$
σ_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.

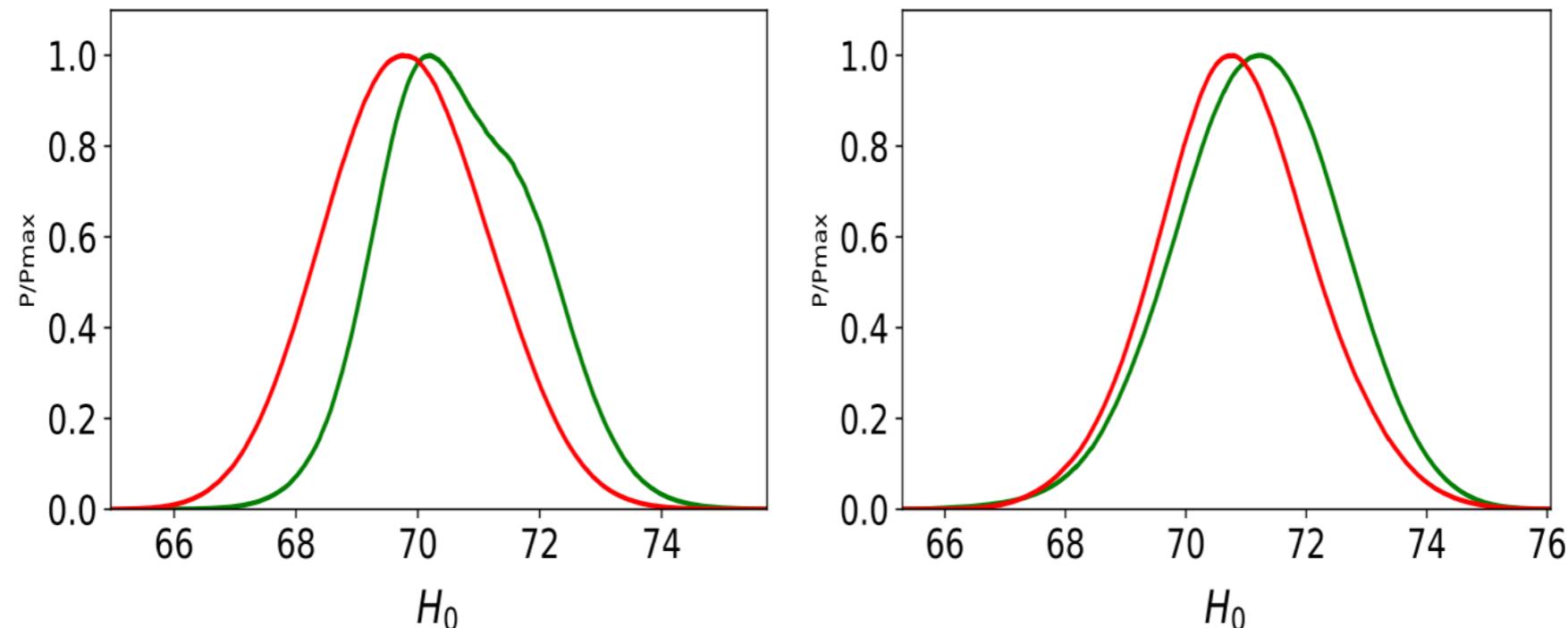
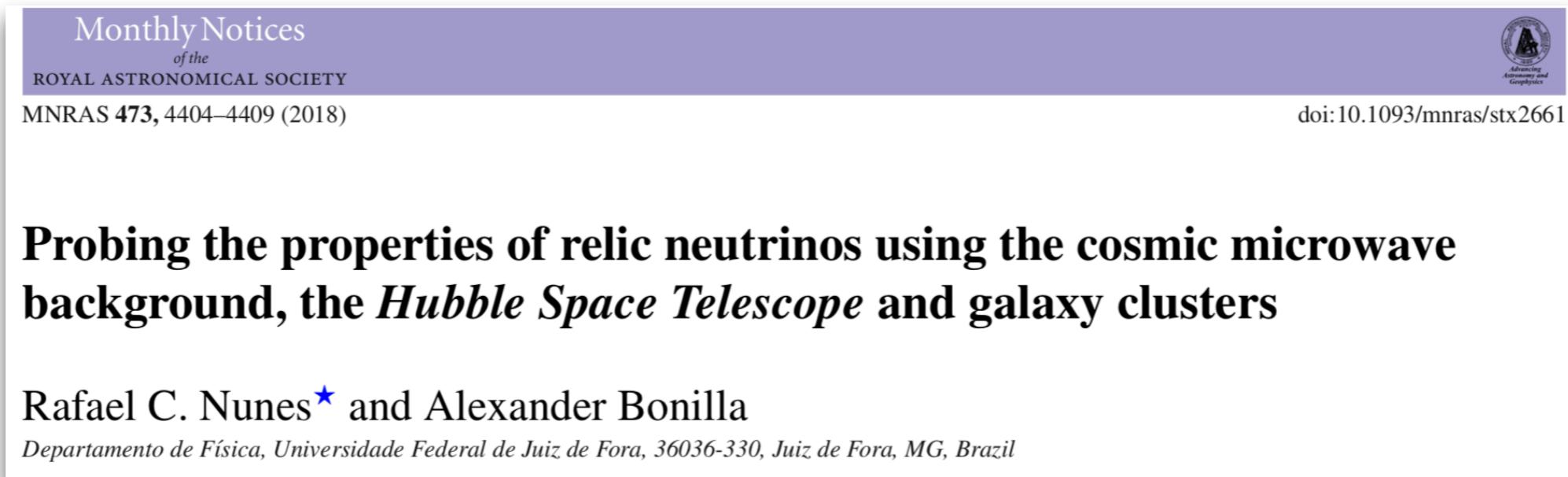
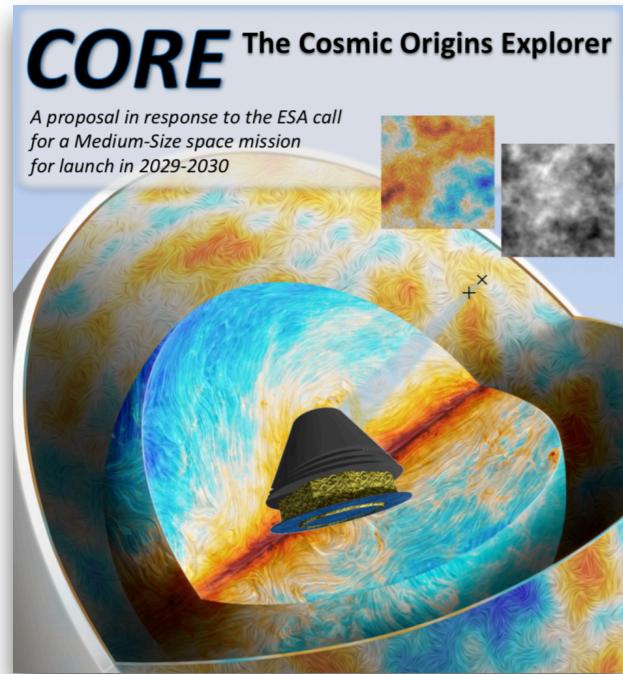


Figure 3. The likelihoods of the parameter H_0 for model I (left panel) and model II (right panel), in red (CMB + BAO + HST) and green (CMB + BAO + HST + GC).

Results



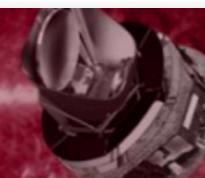
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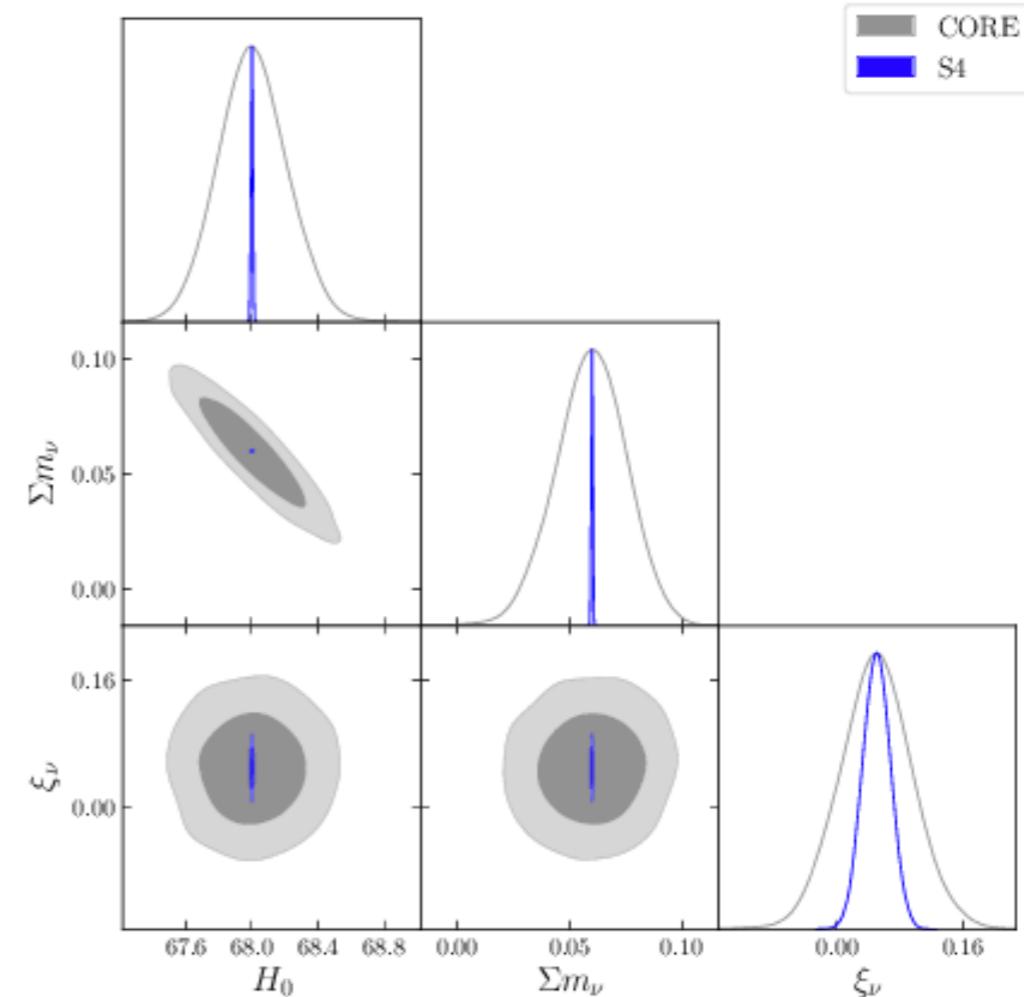
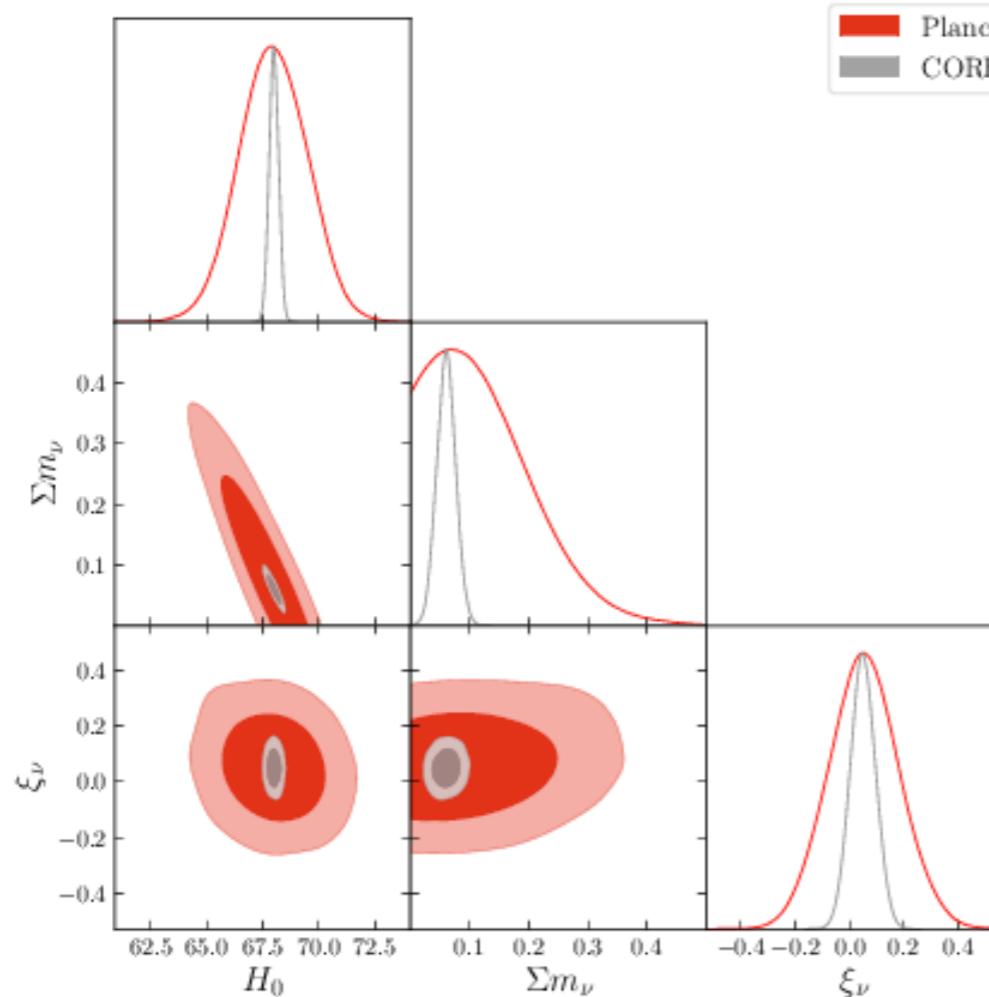
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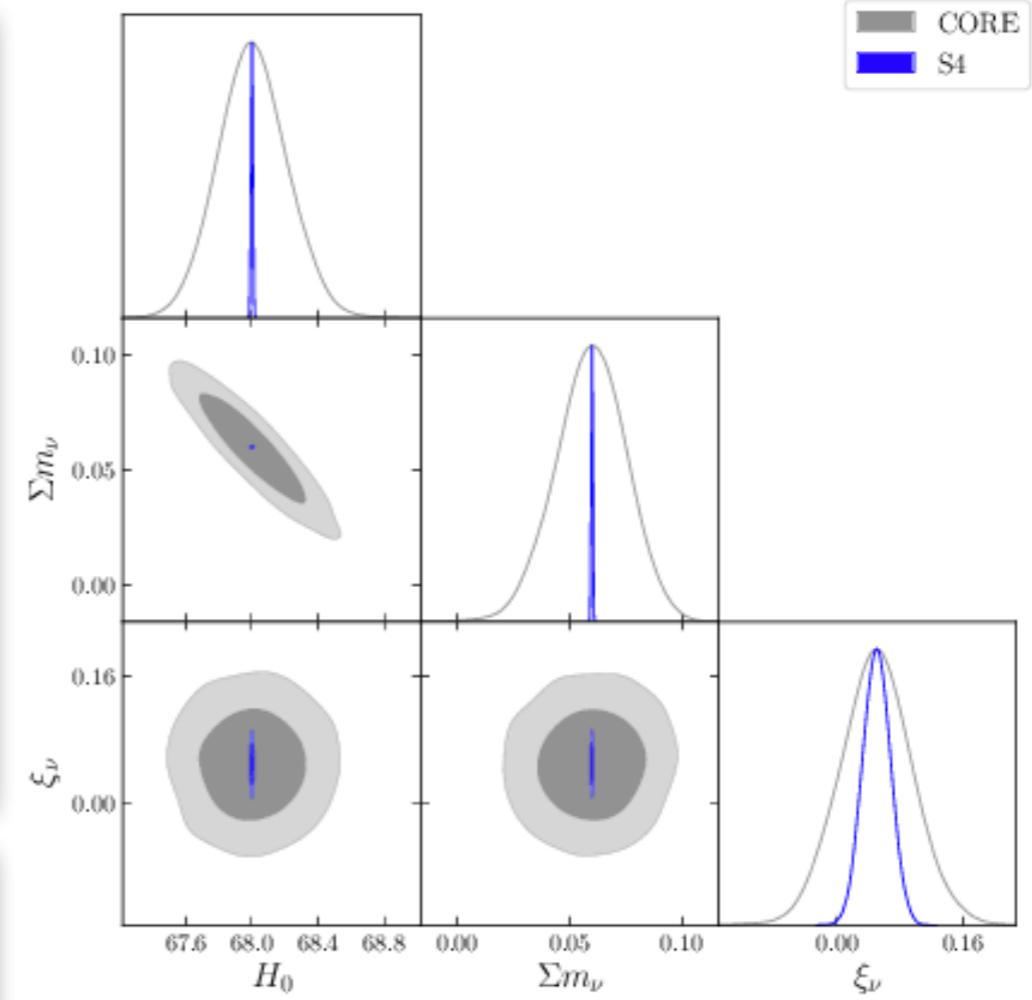
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Parameter	Fiducial value	$\sigma(\text{CORE})$	$\sigma(\text{S4})$
$10^2 \omega_b$	2.22	0.000057	0.00012
ω_{cdm}	0.11919	0.00037	0.0000093
H_0	68.0	0.32	0.0088
$\ln 10^{10} A_s$	3.0753	0.0056	0.0035
n_s	0.96229	0.0022	0.0054
τ_{reio}	0.055	0.0028	0.00025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



Outline

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

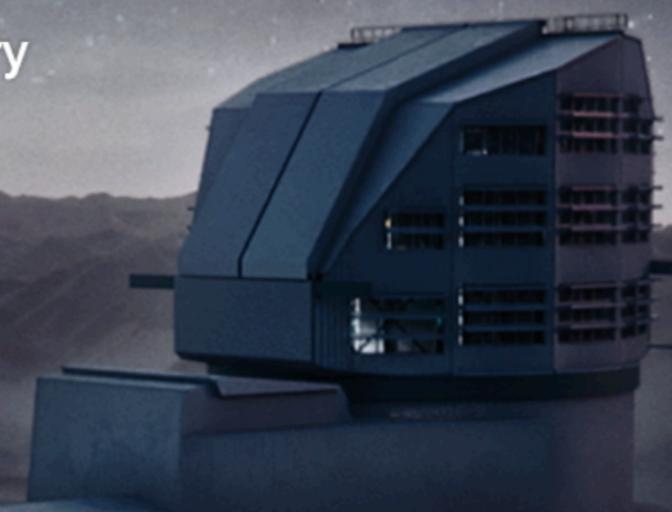
Summary and conclusions

- ▶ With CMB-S4, we find $\xi_\nu = 0.05 \pm 0.027$ (± 0.043) at 68 % CL (95 % CL). These constraints can rule out the null hypothesis up to 2σ CL on ξ_ν . 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 $\Delta N_{\text{eff}}^{\xi_\nu} = 0.002 \pm 0.019$ (± 0.030) for Planck $\Delta N_{\text{eff}}^{\xi_\nu} = 0.0022 \pm 0.0083$ (± 0.013), CORE and $\Delta N_{\text{eff}}^{\xi_\nu} = 0.0022 \pm 0.0045$ (± 0.0059) S4..

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