PASCOS 2026

PROBING THE NEUTRINO CHEMICAL POTENTIAL WITH COSMOLOGICAL OBSERVATIONS

In preparation, 2606.xxxx

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with R. Impavido [University of Ferrara], S. Gariazzo [IFIC, CSIC-UV - University of Torino], O. Mena [IFIC, CSIC-UV], D. Wang [IFIC, CSIC-UV]

This work has received funding from the European Union's Horizon Europe programme under Marie Skłodowska-Curie Actions – Staff Exchanges (SE) grant agreement No 101086085 -ASYMMETRY.

This work is based upon work from the COST Action CA21136 - "Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)", supported by COST - "European Cooperation in Science and Technology"

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Universitat de València

IFIC Institut de Física Corpuscular

Excelencia Severo Ochoa

Ayuda CEX2023-001292-S financiada por:

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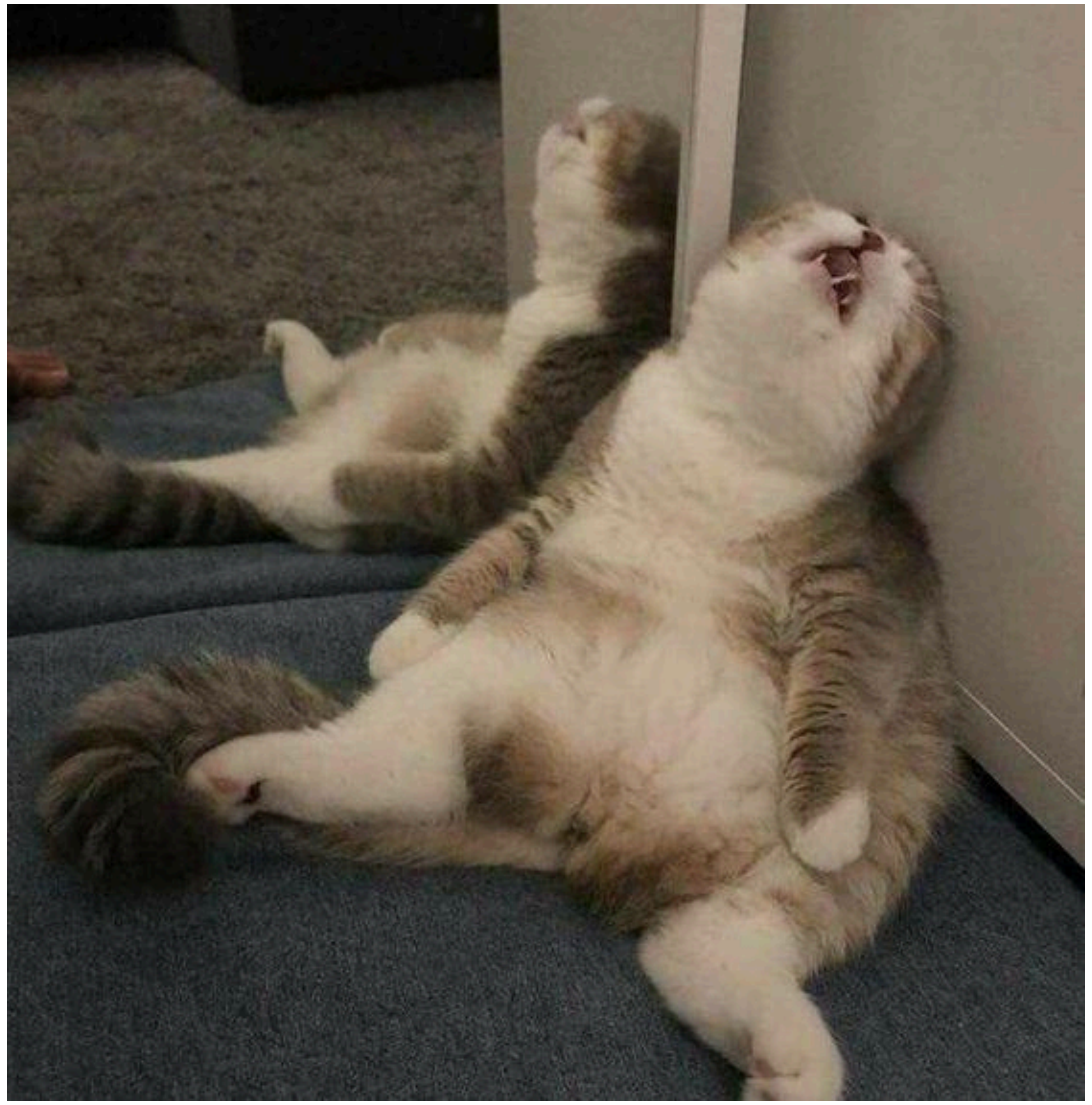
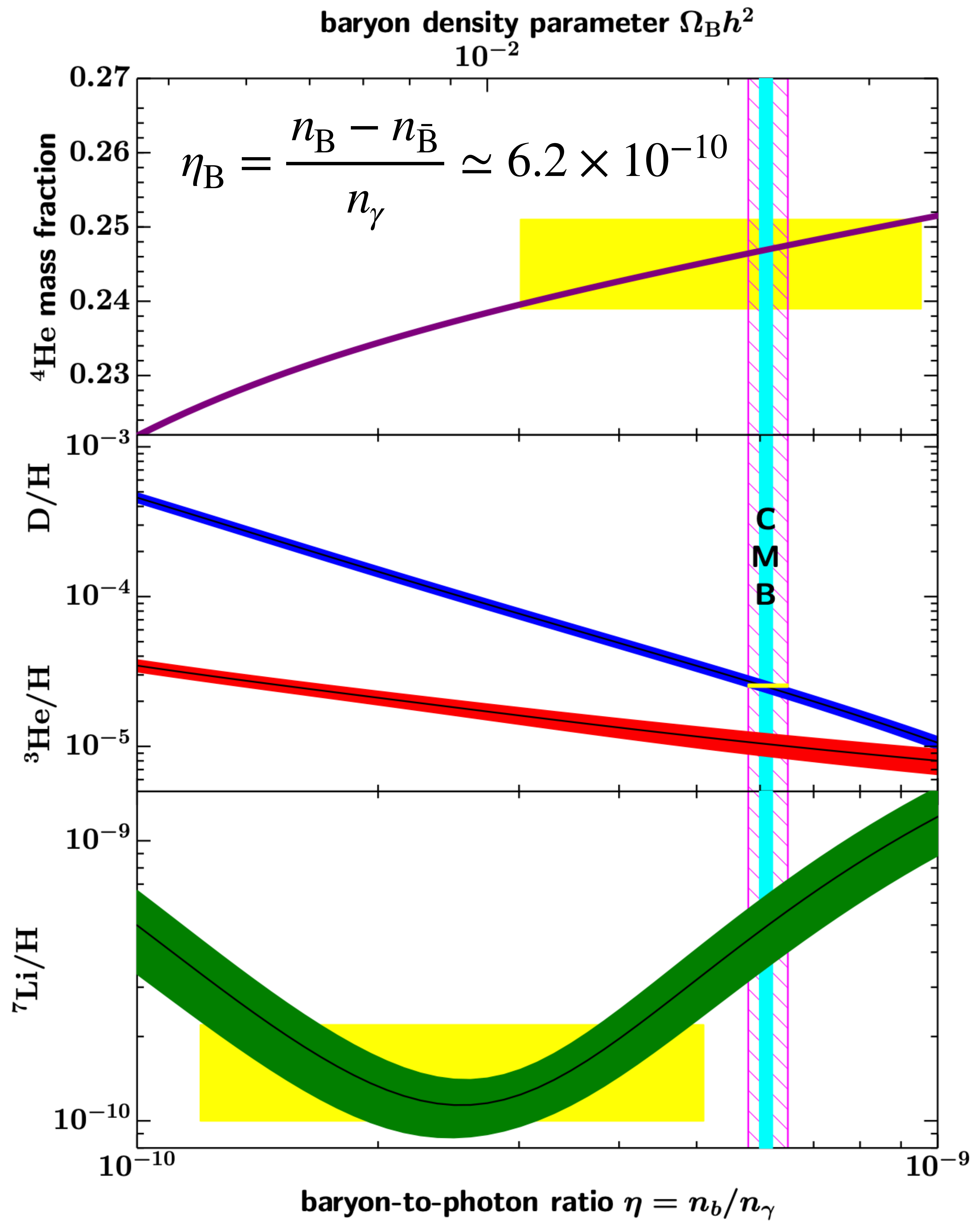
OUTLINE

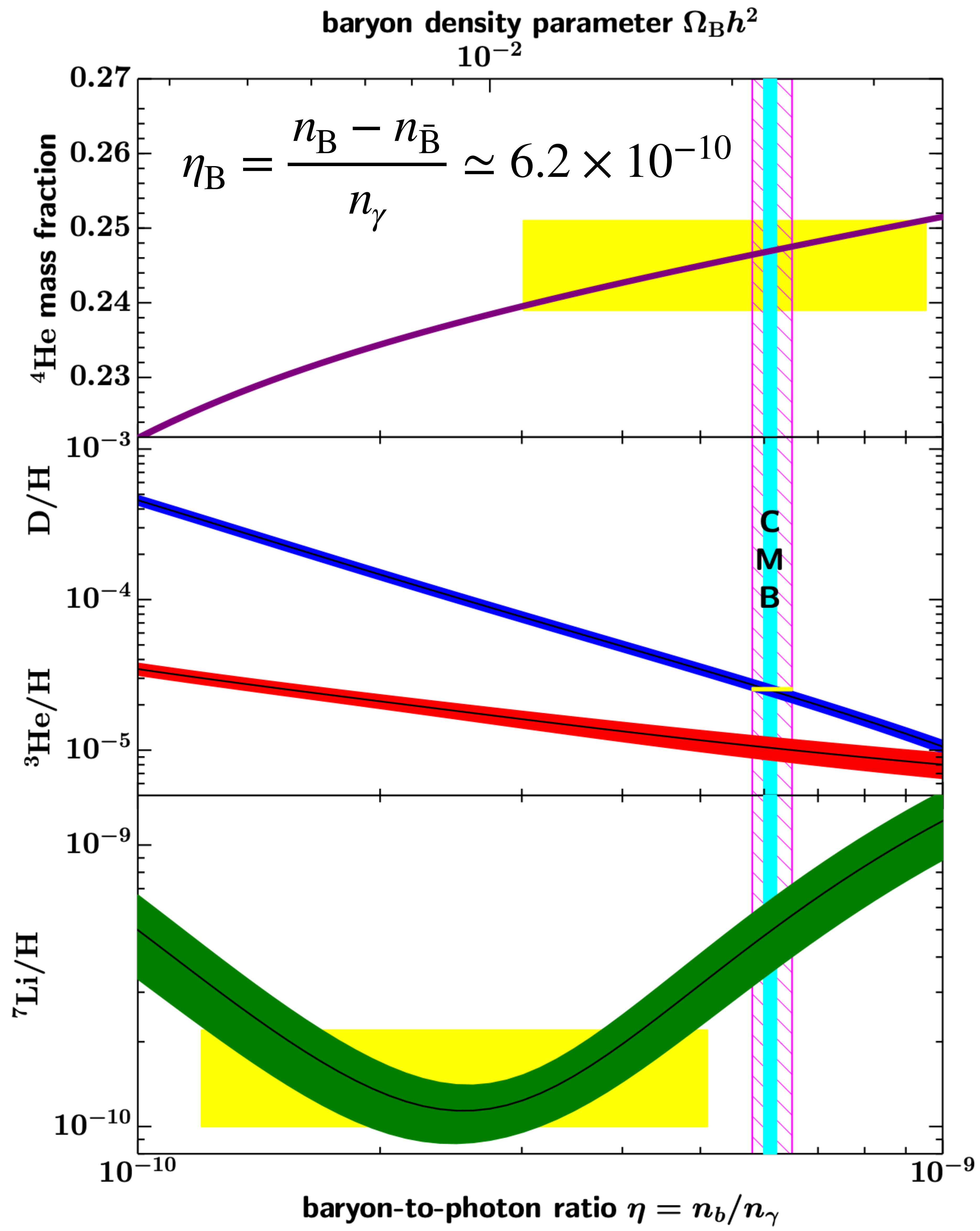
- Introduction
- Phenomenology
- Methodology
- Results
- Conclusions



THEORY



Credits: PDG



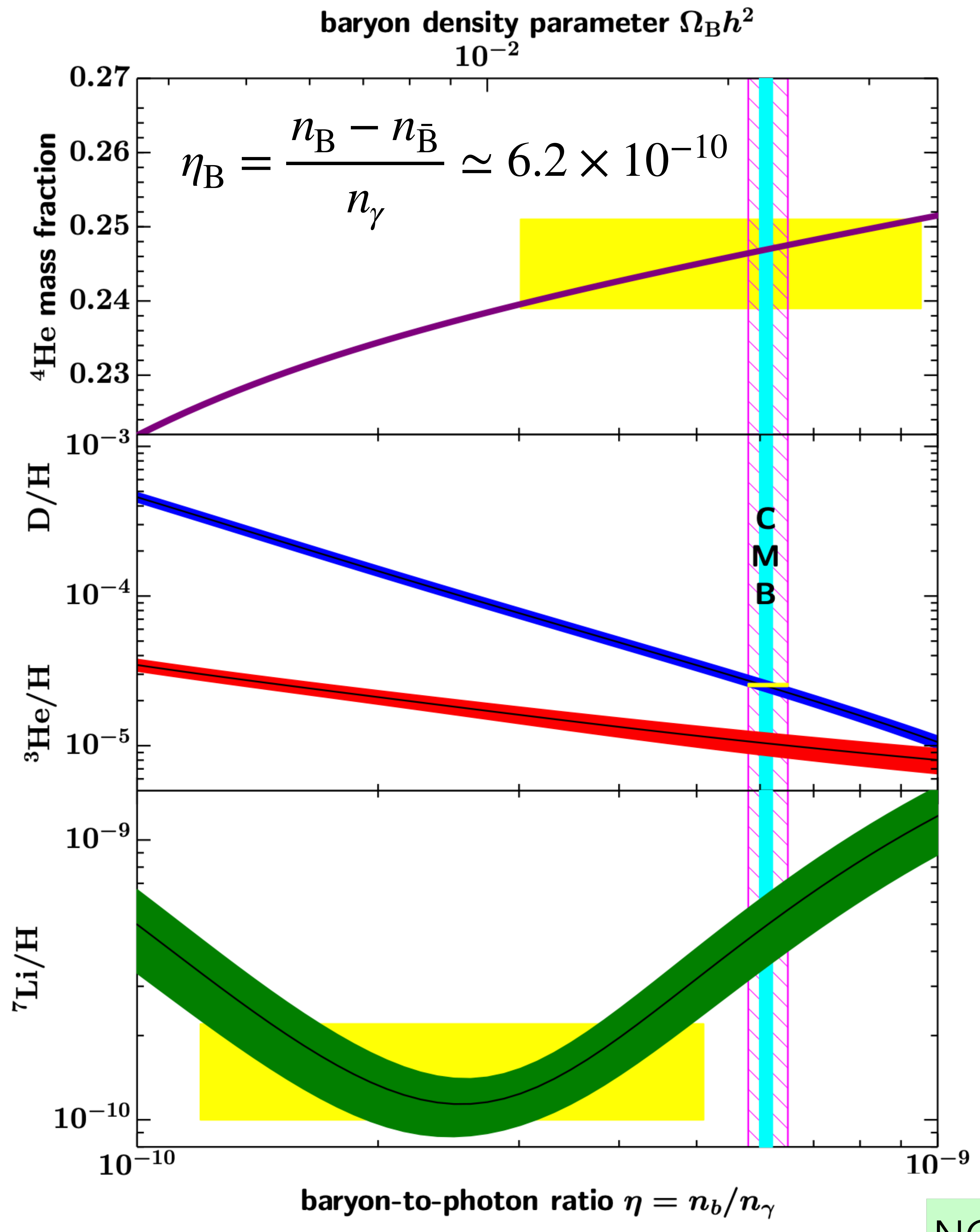
Credits: PDG

THEORY

The lepton asymmetry can be expressed in terms of the dimensionless chemical potential of neutrinos, $\xi_\nu = \mu_\nu / T$, also known as degeneracy parameter.

[F. Iocco et al., 0809.0631]

$$\eta_\nu = \frac{1}{n_\gamma} \sum_{\alpha=e,\mu,\tau} (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}) = \frac{1}{12\zeta(3)} \sum_{\alpha=e,\mu,\tau} \left[\frac{T_{\nu_\alpha}}{T_\gamma}\right]^3 \left(\pi^2 \xi_{\nu_\alpha} + \xi_{\nu_\alpha}^3\right)$$



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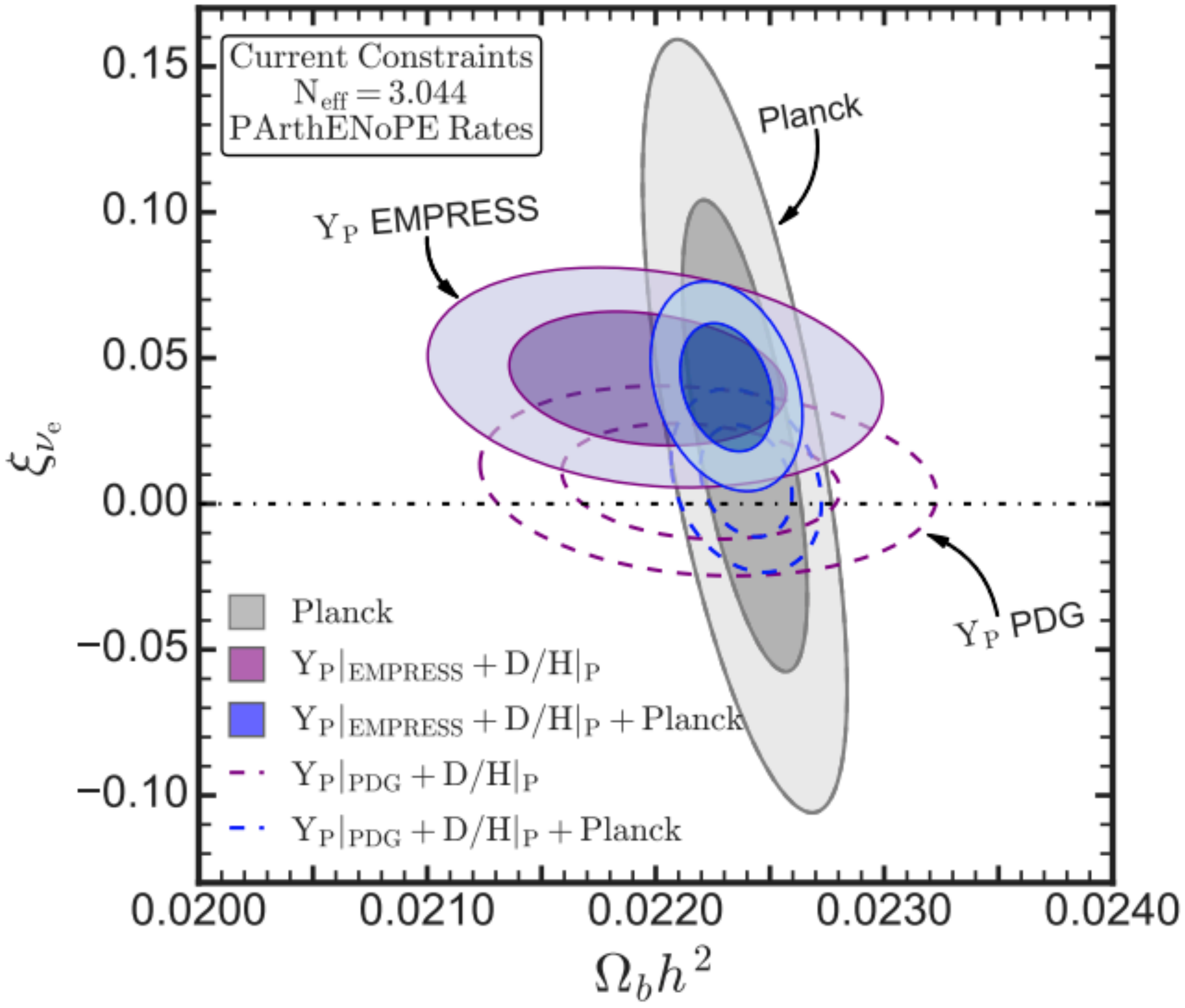
A non-zero neutrino chemical potential impacts the early Universe physics, by changing the value of $N_{\rm eff}$

$$\Delta N_{\rm eff}(\xi_\nu) = N_{\rm eff}^{\rm tot}(\xi_\nu) - N_{\rm eff}^{\rm std} \simeq \sum_{\alpha=e,\mu,\tau} \left[\frac{30}{7}\left(\frac{\xi_{\nu_\alpha}}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_{\nu_\alpha}}{\pi}\right)^4\right]$$

[C. Pitrou et al., 1801.08023]

NOTE: we always assume a constant $N_{\rm eff}^{\rm std} = 3.044$, but $N_{\rm eff}^{\rm tot}(\xi_\nu)$ will vary.

THEORY



[M. Escudero et al., 2208.03201]

Weak interaction rates:

$$n + \nu_e \leftrightarrow p + e^-$$

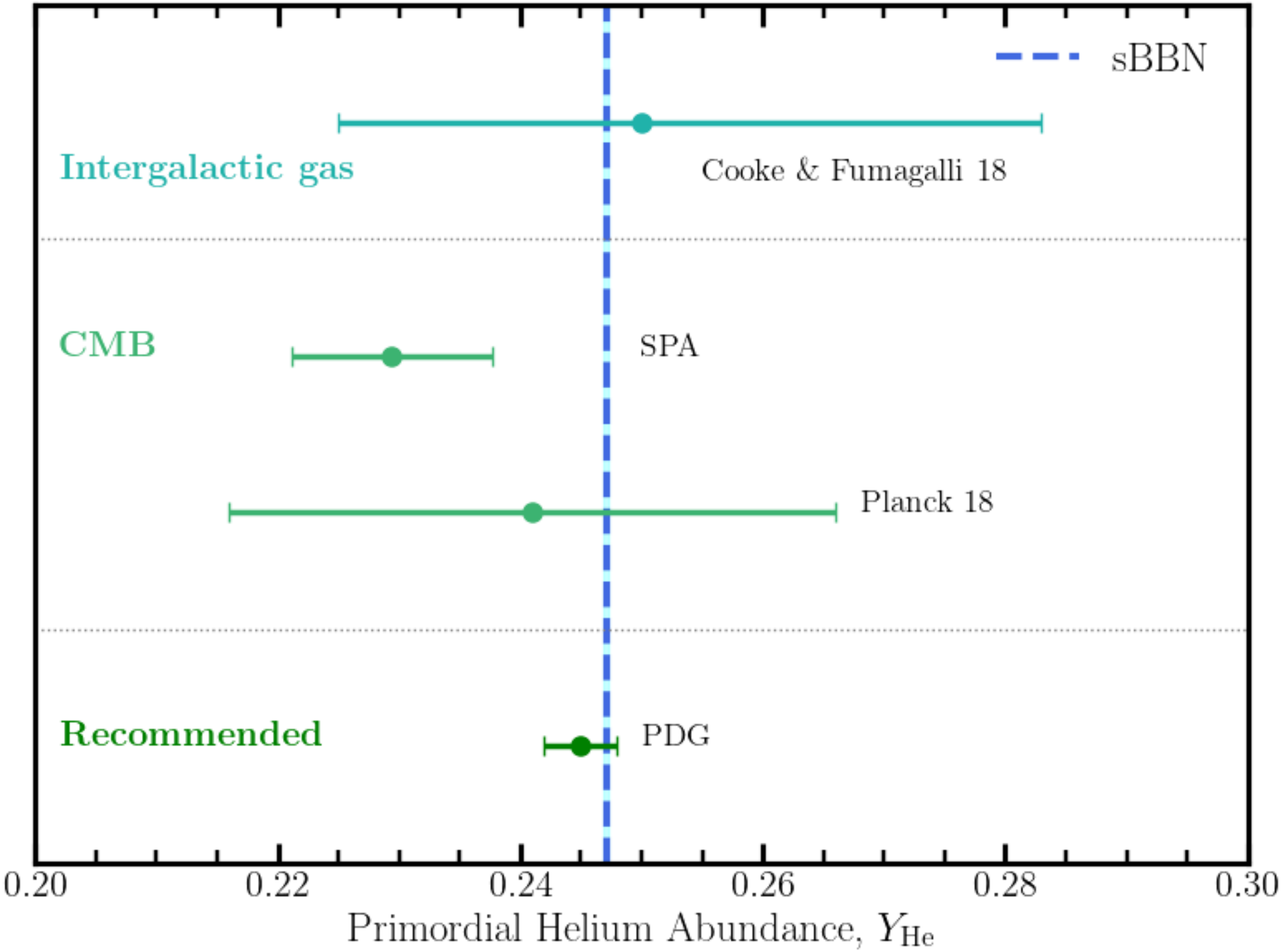
$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$Y_{\rm He} \simeq Y_{\rm He}^{\rm sBBN} e^{-0.96\xi_{\nu_e}}$$

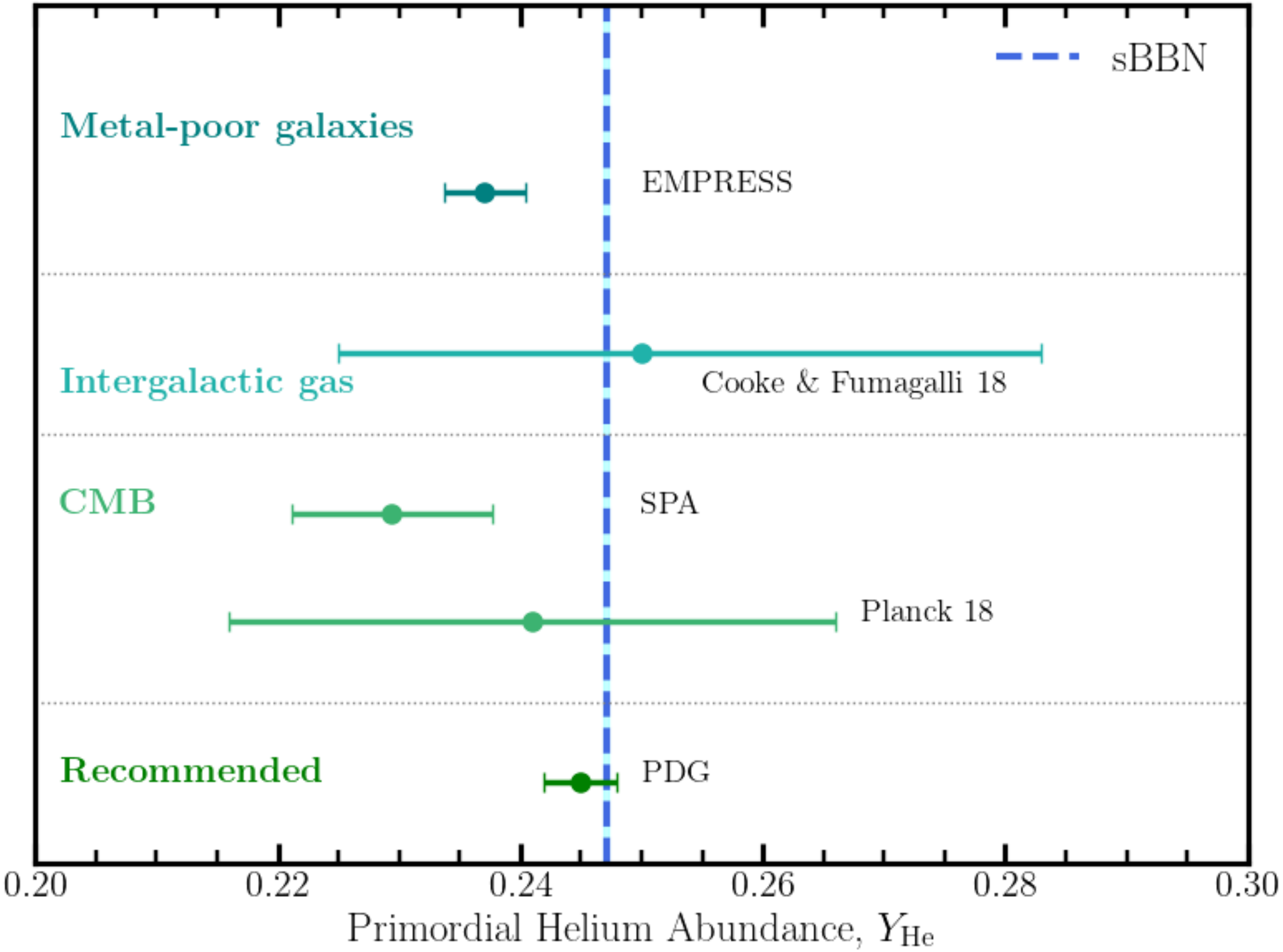
[C. Pitrou et al., 1801.08023]

THEORY



sBBN
Intergalactic gas
Cooke & Fumagalli 18
CMB
SPA
Planck 18
Recommended
PDG
0.20
0.22
0.24
0.26
0.28
0.30
Primordial Helium Abundance, Y_{He}

THEORY



sBBN
Metal-poor galaxies
EMPRESS
Intergalactic gas
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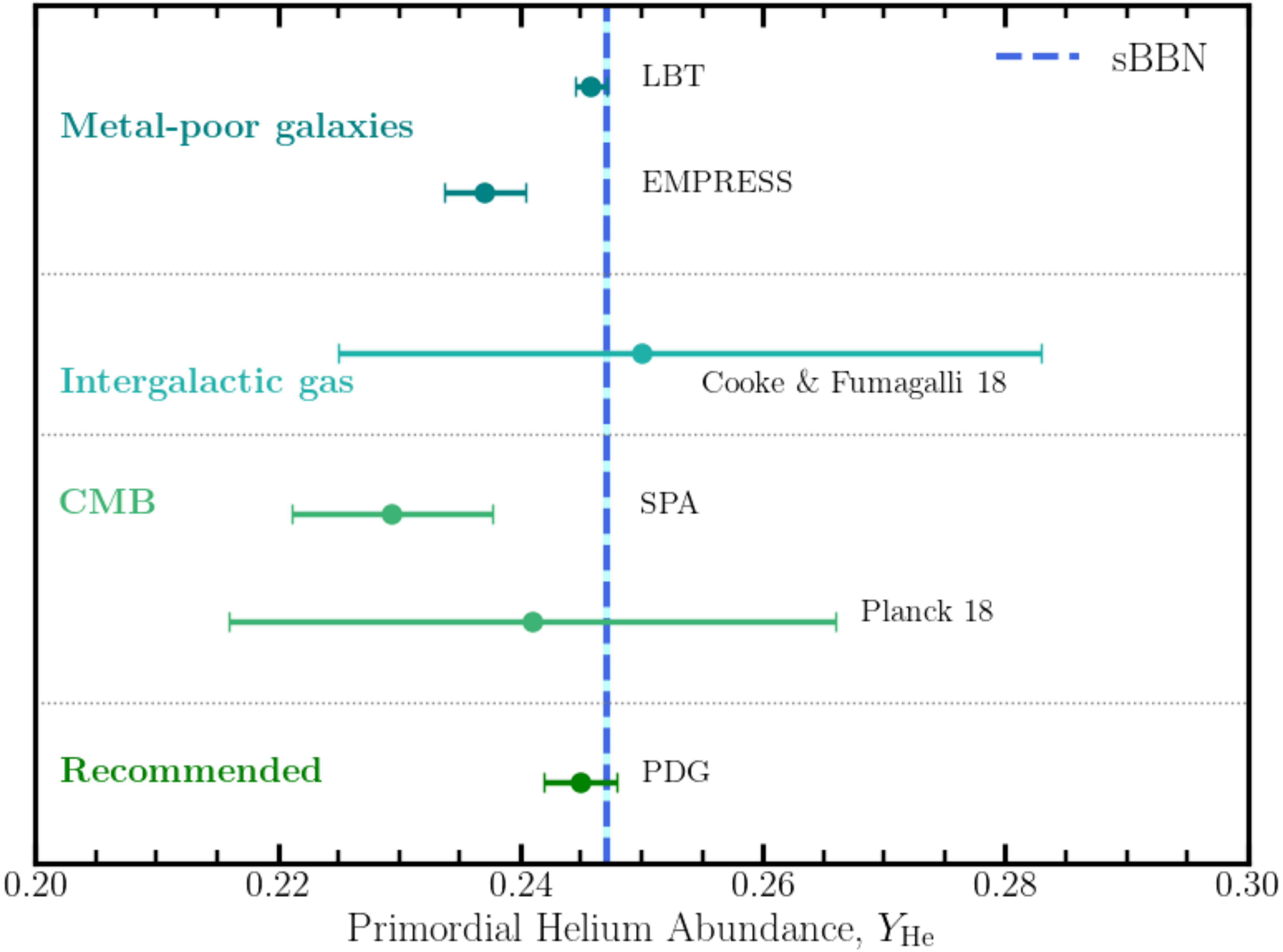

sBBN
LBT
Metal-poor galaxies
EMPRESS
Intergalactic gas
Cooke & Fumagalli 18
CMB
SPA
Planck 18
Recommended
PDG
0.20
0.22
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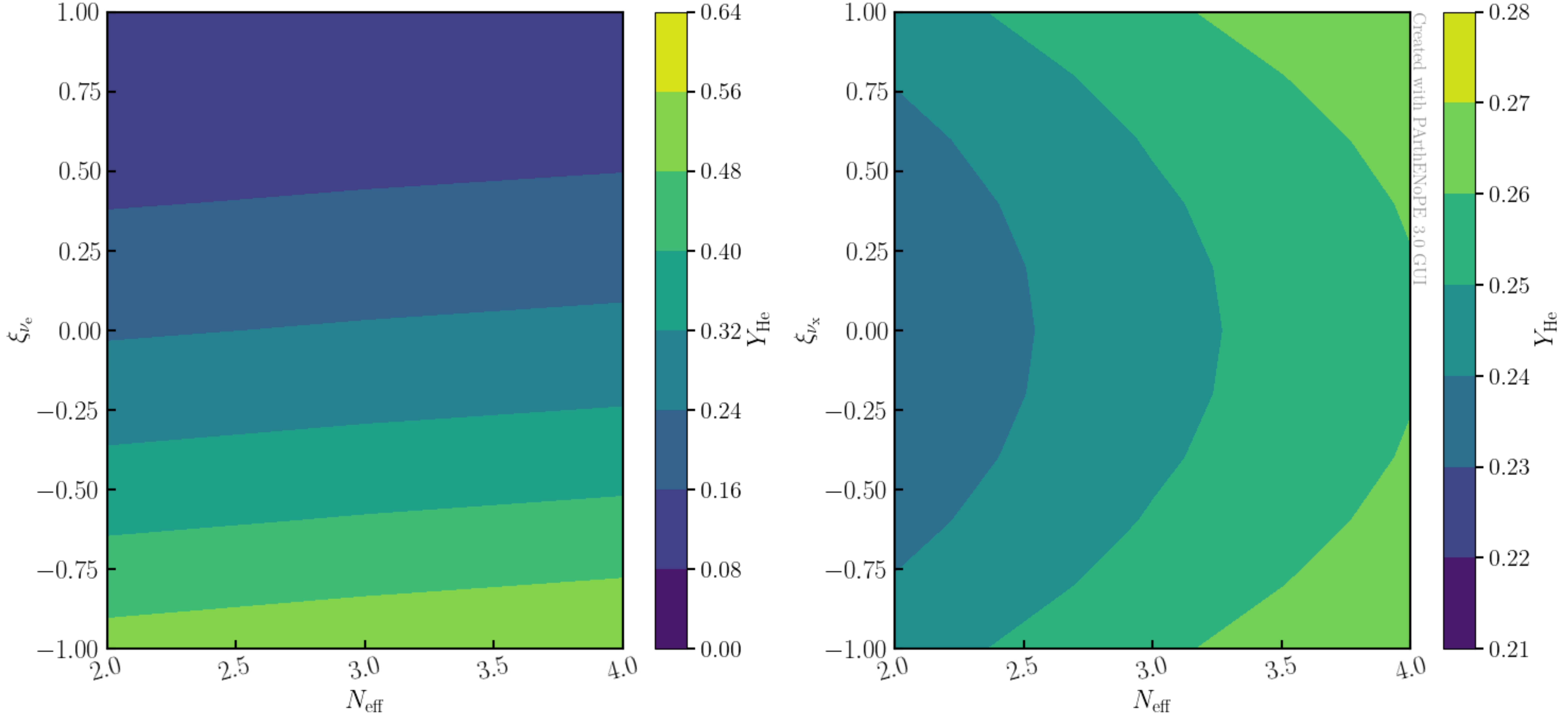
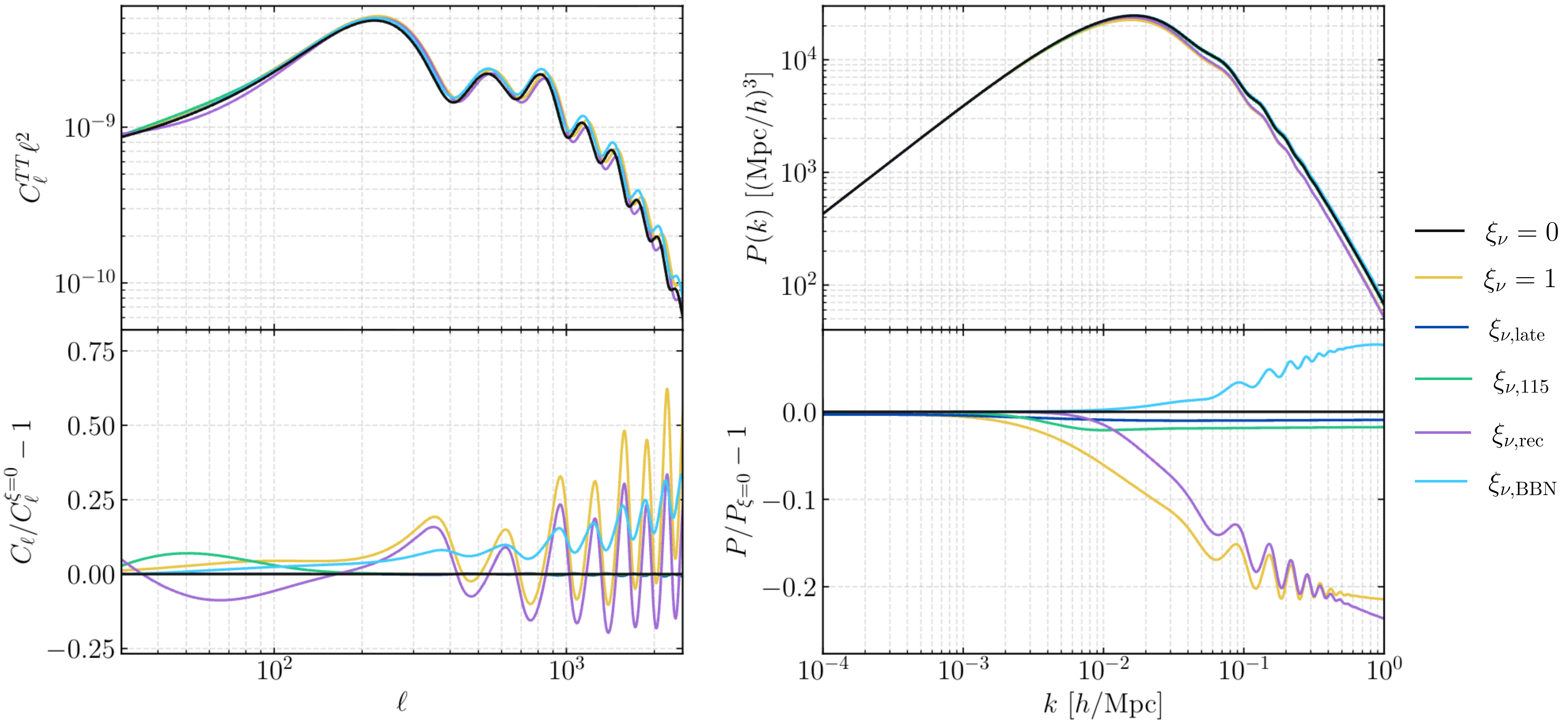
[P. Ghedini et al., 2606.xxxx]

BBN



Obtained with **`PArthENoPE 3.0 GUI`** [S. Gariazzo et al., 2103.05027]

CMB



[P. Ghedini et al., 2606.xxxx]

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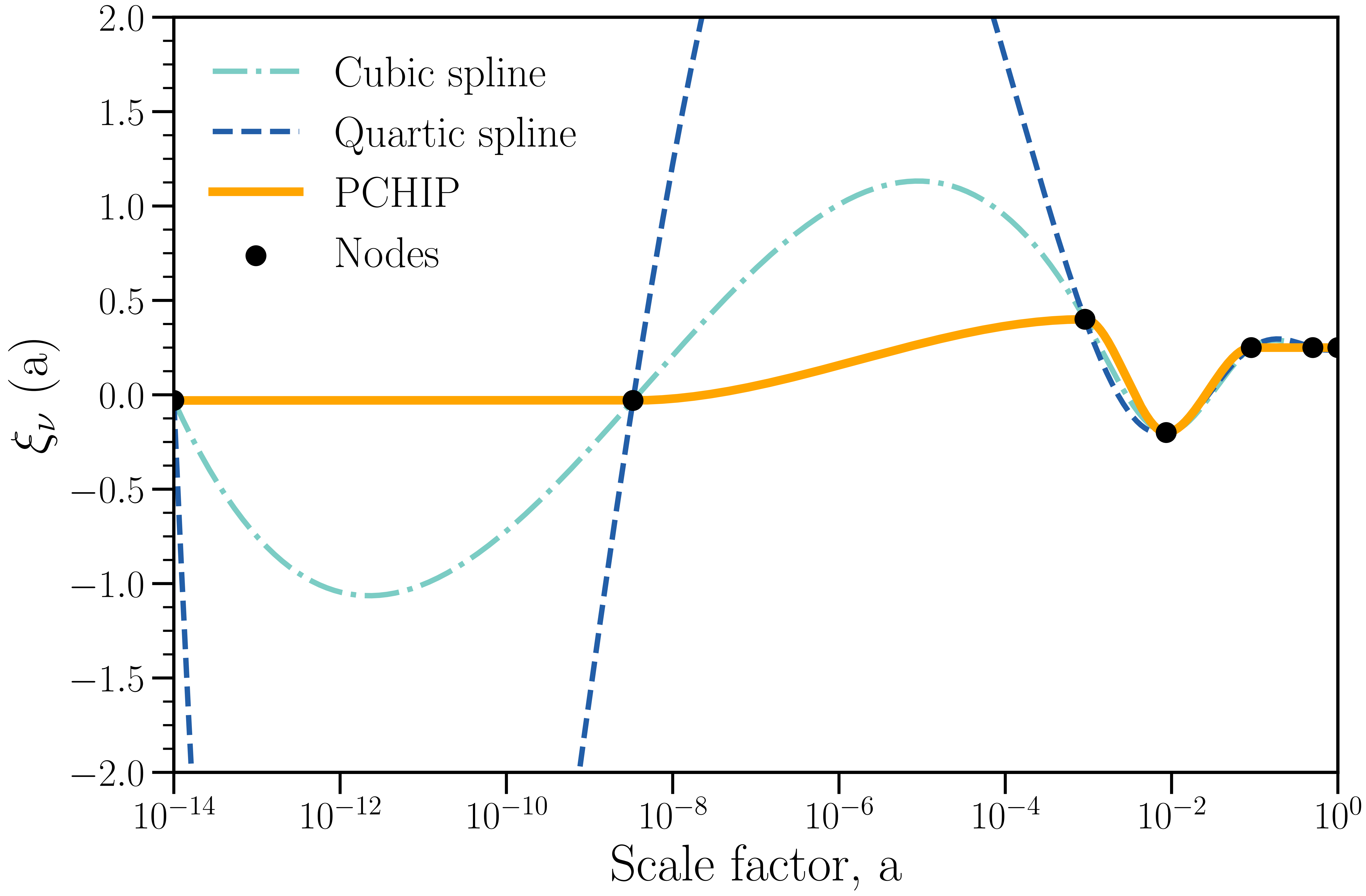
PCHIP FORMALISM

[Fritsch et al., 1980; S. Gariazzo et al., 1412.7405]

Piecewise
Cubic
Hermite
Interpolating
Polynomial

- ✓ Preserves the shape of the interpolated data points
- ✗ Depends on the number of nodes



[Adapted from P. Ghedini et al., 2512.16781]

COSMOLOGICAL SCENARIOS

We consider two different neutrino scenarios:

- **Case 3ν**: three degenerate neutrinos with $\sum m_\nu = 0.06$ eV

- **Case (1+2)ν**: one light neutrino, $m_{\nu_e} \sim \mathcal{O}(10^{-5})$ eV, and two degenerate neutrinos, $\sum m_{\text{degenerate}} = 0.06$ eV

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- **Case (1+2)ν**: one light neutrino, $m_{\nu_e} \sim \mathcal{O}(10^{-5})$ eV, and two degenerate neutrinos, $\sum m_{\text{degenerate}} = 0.06$ eV

For each case, we assume:

- $\xi_{\nu,\,\text{constant}}$: we consider it as a free constant parameter

- $\xi_{\nu,\,\text{PCHIP}}$: we assume it to be time-varying and we reconstruct it with the PCHIP method

DATA

BASELINE
(SPA + DESI)

- **CMB**: we consider temperature, polarisation and lensing measurements from **Planck18**, **ACT DR6** and **SPT-3G D1**

[N. Aghanim et al., 1807.06205; L. Pagano et al., 1908.09856; T. Louis et al., 2503.14452; E. Camphuis et al., 2506.20707; F. J. Qu et al., 2304.05202; F. Ge et al., 2411.06000]

- **BAO**: we consider BAO measurements from **DESI DR2**

[M. Abdul Karim et al., 2503.14738]

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* **BAO**: we consider BAO measurements from **DESI DR2**

[M. Abdul Karim et al., 2503.14738]

BBN POST PROCESSING†

[A. Matsumoto et al., 2203.09617; E.Aver et al., 2601.22238; PDG]

* **EMPRESS**: a $\sim 3\sigma$ lower value for $Y_{\rm He}$ is reported $Y_{\rm He} = 0.2370^{+0.0034}_{-0.0033}$ with respect to the standard value, $Y_{\rm He}^{\rm sBBN} = 0.24709 \pm 0.00017$

or

* **LBT**: the newest and most precise measurement of $Y_{\rm He}$ to date, $Y_{\rm He} = 0.2458 \pm 0.0013$

+

* **PDG**: we use the Deuterium value reported by the PDG, $D/H = (25.08 \pm 0.29) \times 10^{-6}$

† We also include the theoretical errors of `PArthENoPE`

INFERENCE

- Modified version of **CLASS**† as Boltzmann solver [D. Blas et al., 1104.2933]
- **Cobaya** for the MCMC analysis [J. Torrado et al., 2005.05290]
- **getdist** for plotting and statistical analysis [A. Lewis, 1910.13970]
- **PArthENoPE 3.0** for BBN predictions and tables [S. Gariazzo et al., 2103.05027]
- **MCEvidence** for computing the (log) Bayes factor [A. Heavens et al., 1704.03472]

†Available upon reasonable request.

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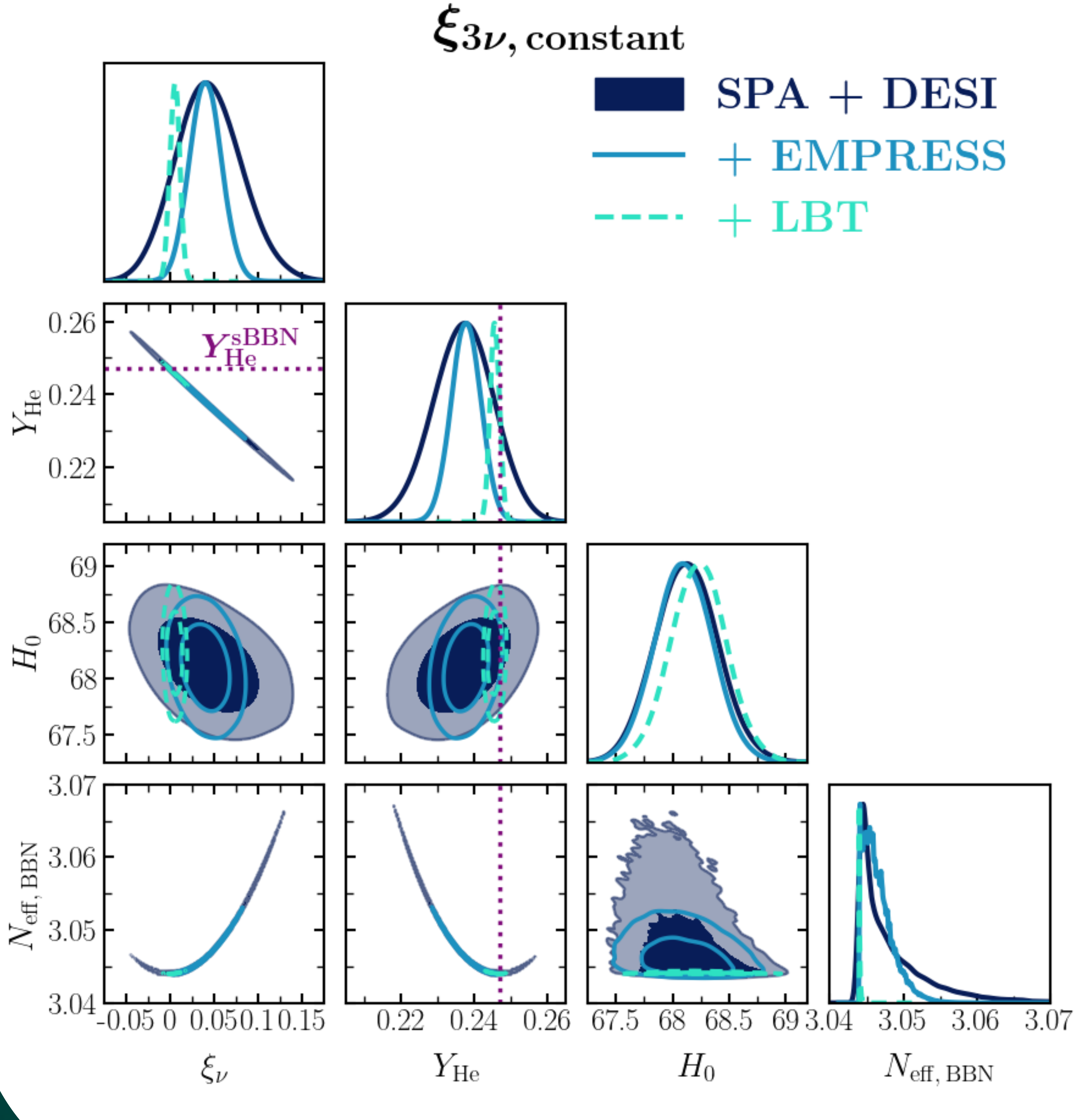
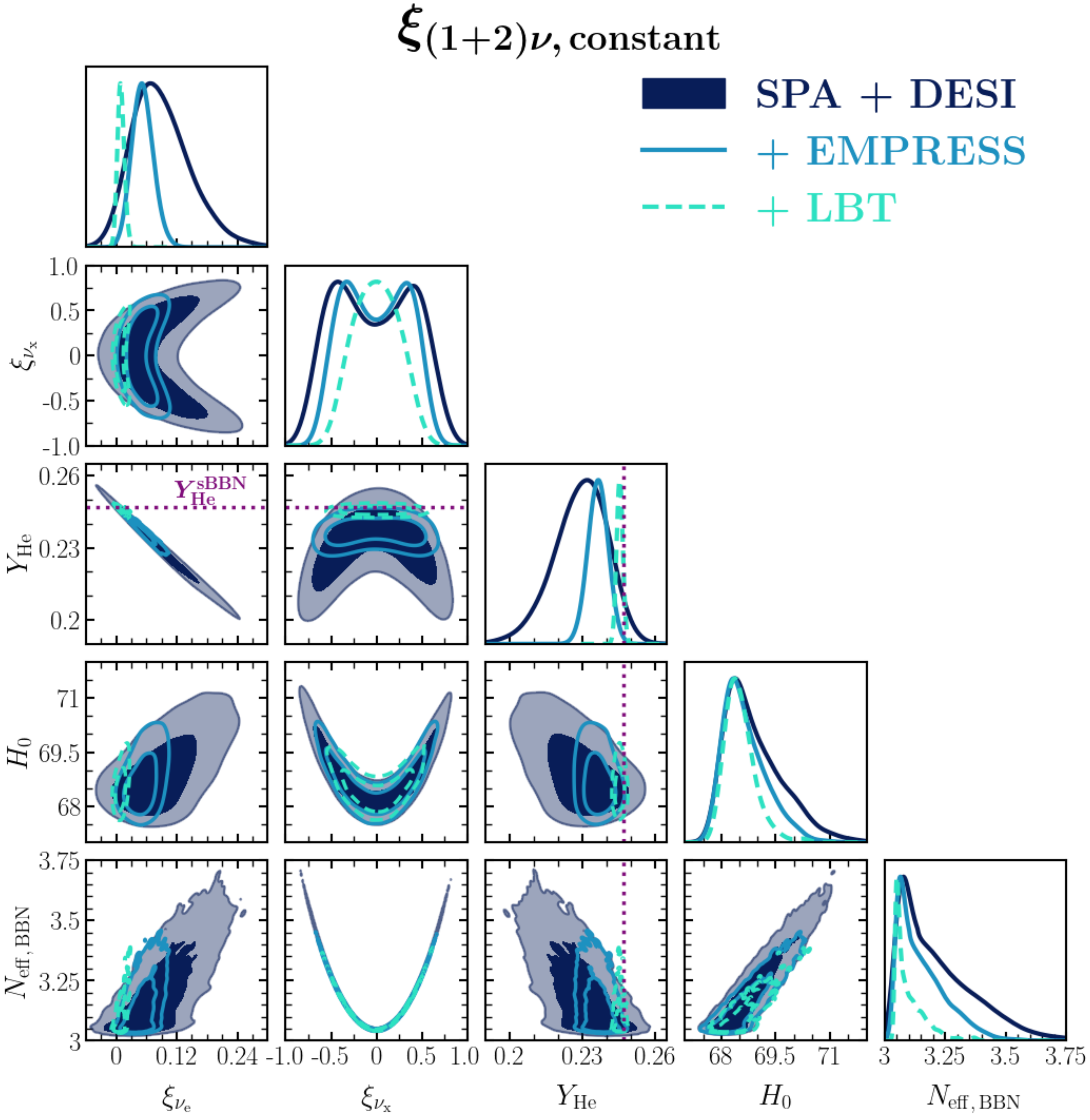
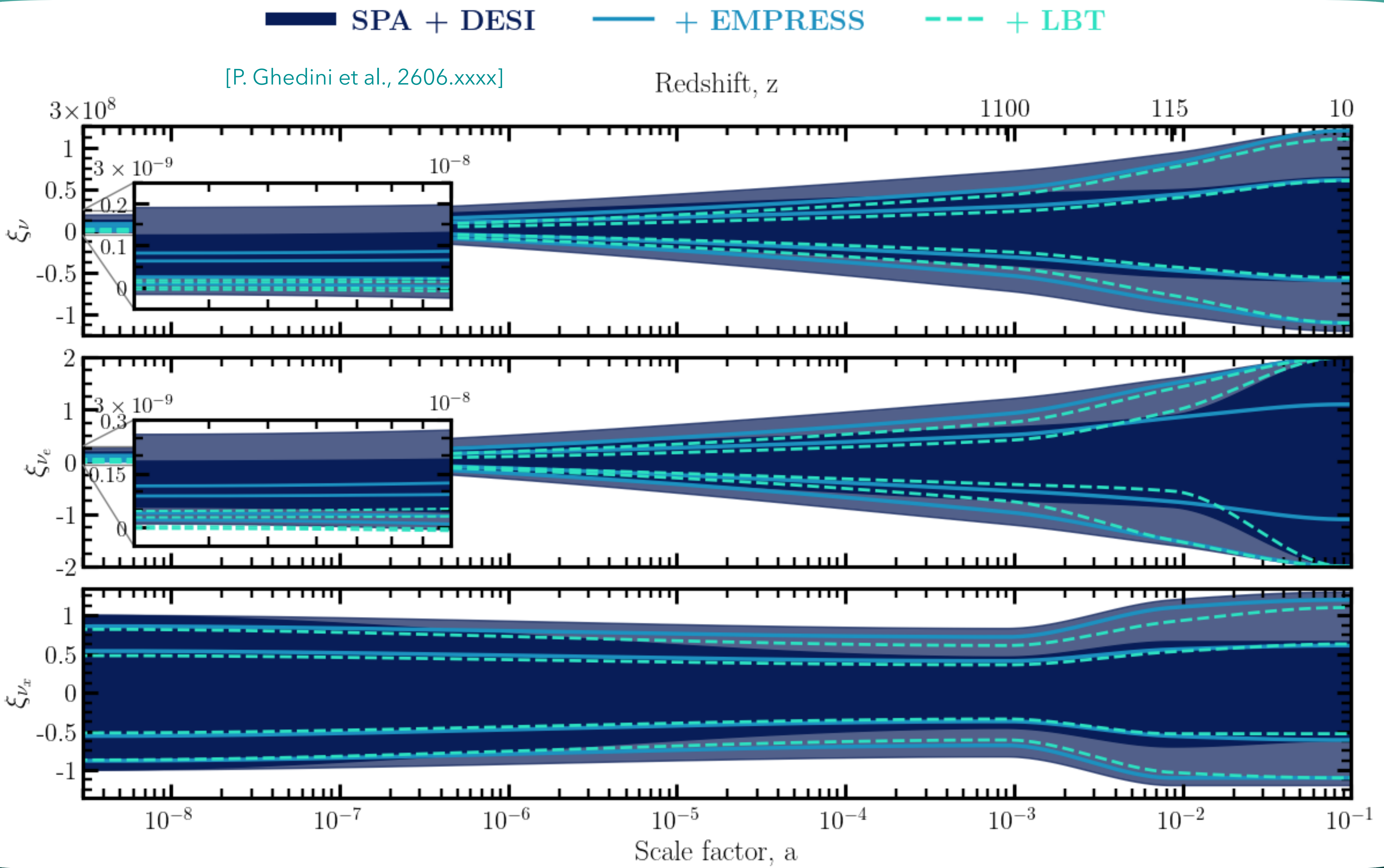
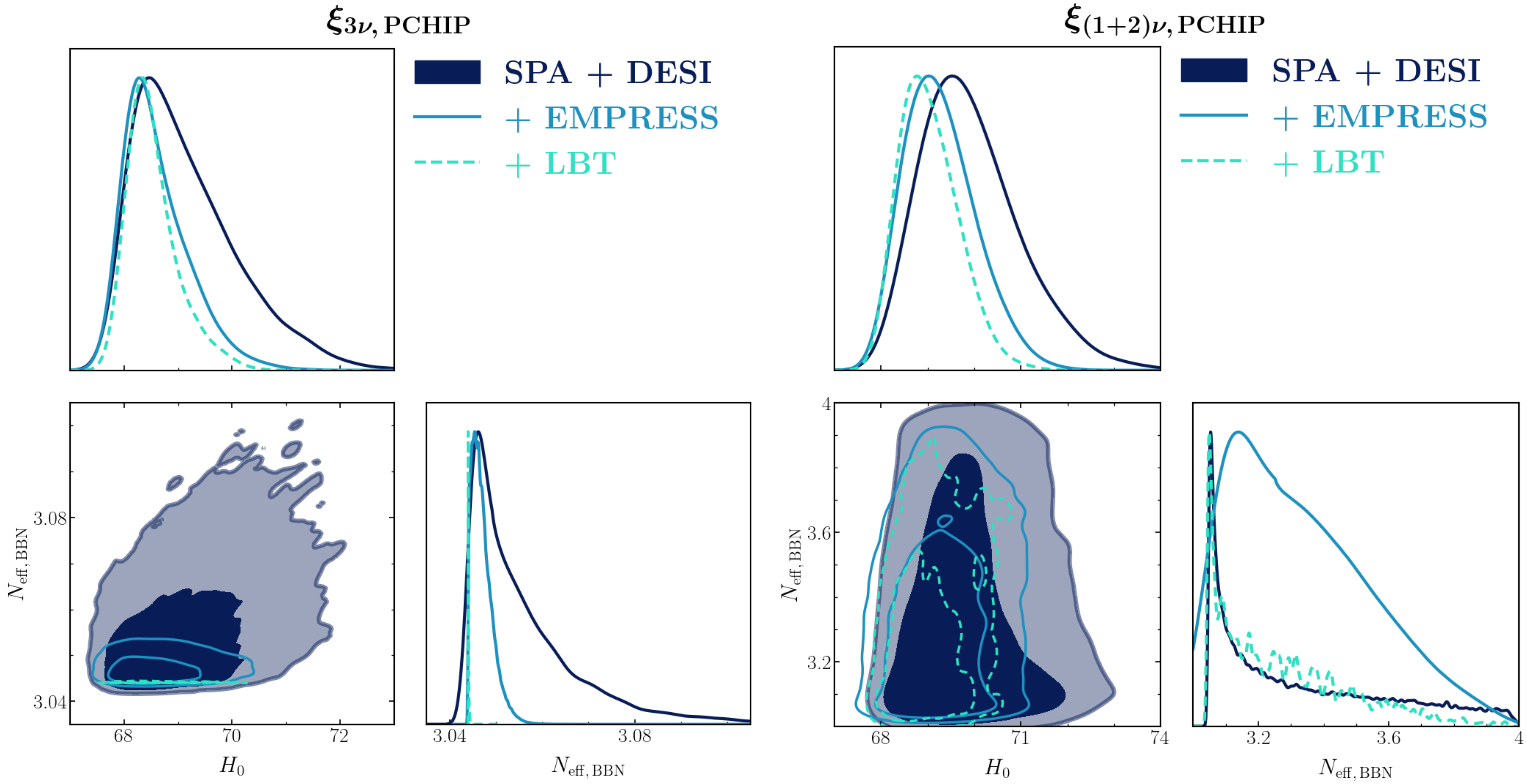




[P. Ghedini et al., 2606.xxxx]



SPA + DESI
+ EMPRESS
+ LBT
[P. Ghedini et al., 2606.xxxx]
Redshift, z
3×10^8
1100
115
10
ξ_ν
ξ_{ν_e}
ξ_{ν_x}
3×10^{-9}
10^{-8}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Scale factor, a



[P. Ghedini et al., 2606.xxxx]

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TAKE HOME MESSAGES

- Current data are not able to place tight constraints on ξ_{ν_x} as they can do on ξ_{ν_e}
- A higher value of H_0 is allowed since we get an increase in $N_{\rm eff}$
- We confirmed that BBN epoch is the time providing tightest constraints on ξ_ν

THANK YOU FOR THE ATTENTION!

Questions?

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BACK UP

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PCHIP FORMALISM

$h_j = x_{j+1} - x_j$ $t = x - x_j$

[Fritsch et al., 1980; S. Gariazzo et al., 1412.7405]

$$f(x; y_1, \ldots, y_N) = \frac{(h_j + 2t)(h_j - t)^2}{h_j^3} y_j + \frac{(3h_j - 2t)t^2}{h_j^3} y_{j+1} + \frac{t(h_j - t)^2}{h_j^2} d_j + \frac{t^2(h_j - t)}{h_j^2} d_{j+1}$$

$$\delta_j = \frac{y_{j+1} - y_j}{x_{j+1} - x_j}$$

- if $\delta_{j-1} \times \delta_j < 0 \rightarrow d_j = 0$;
- if $\delta_{j-1} \times \delta_j > 0$:

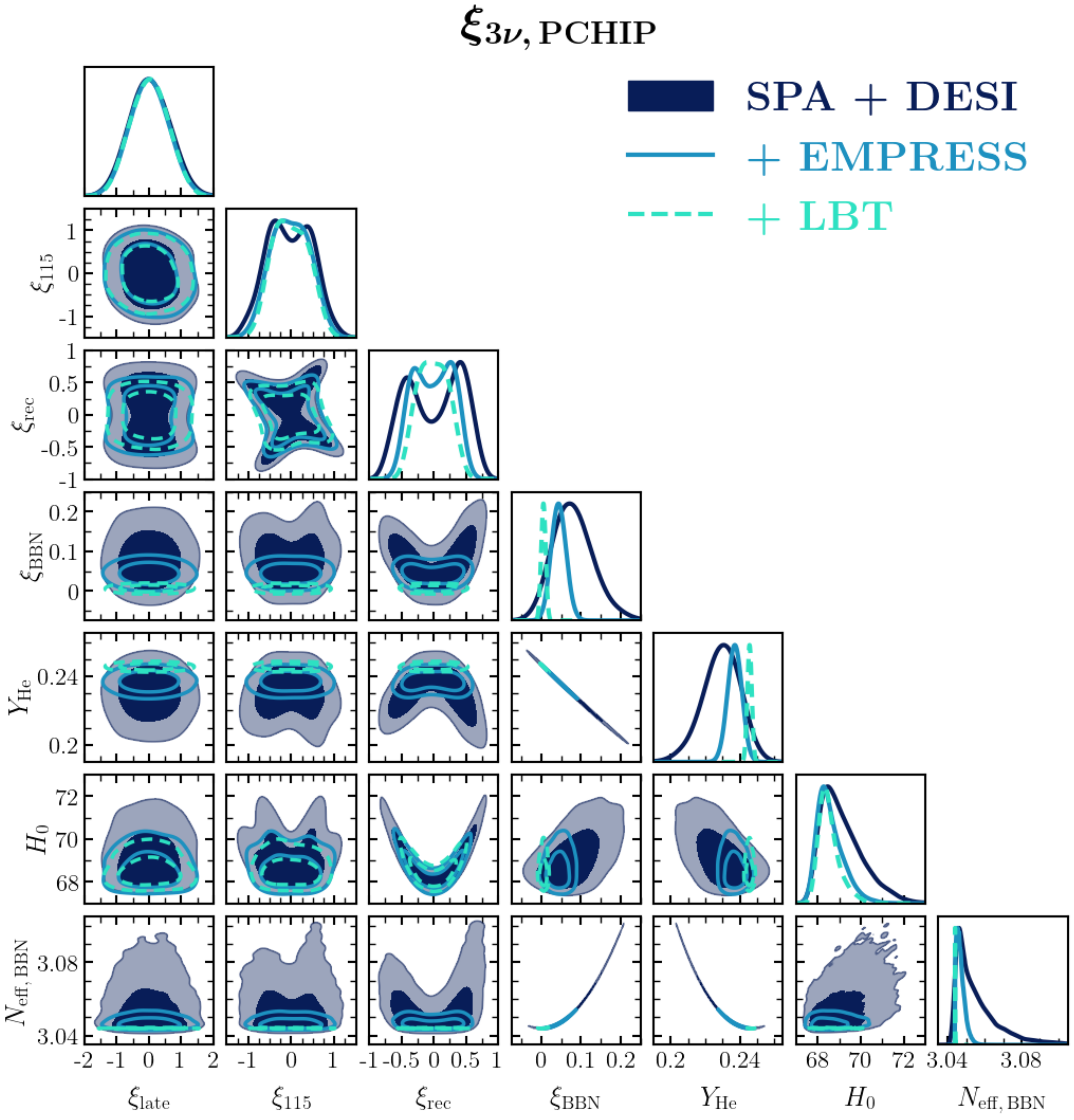
$$\frac{\omega_1 + \omega_2}{d_j} = \frac{\omega_1}{\delta_{j-1}} + \frac{\omega_2}{\delta_j}$$

$\omega_1 = 2h_j + h_{j+1}$ $\omega_2 = h_j + 2h_{j+1}$

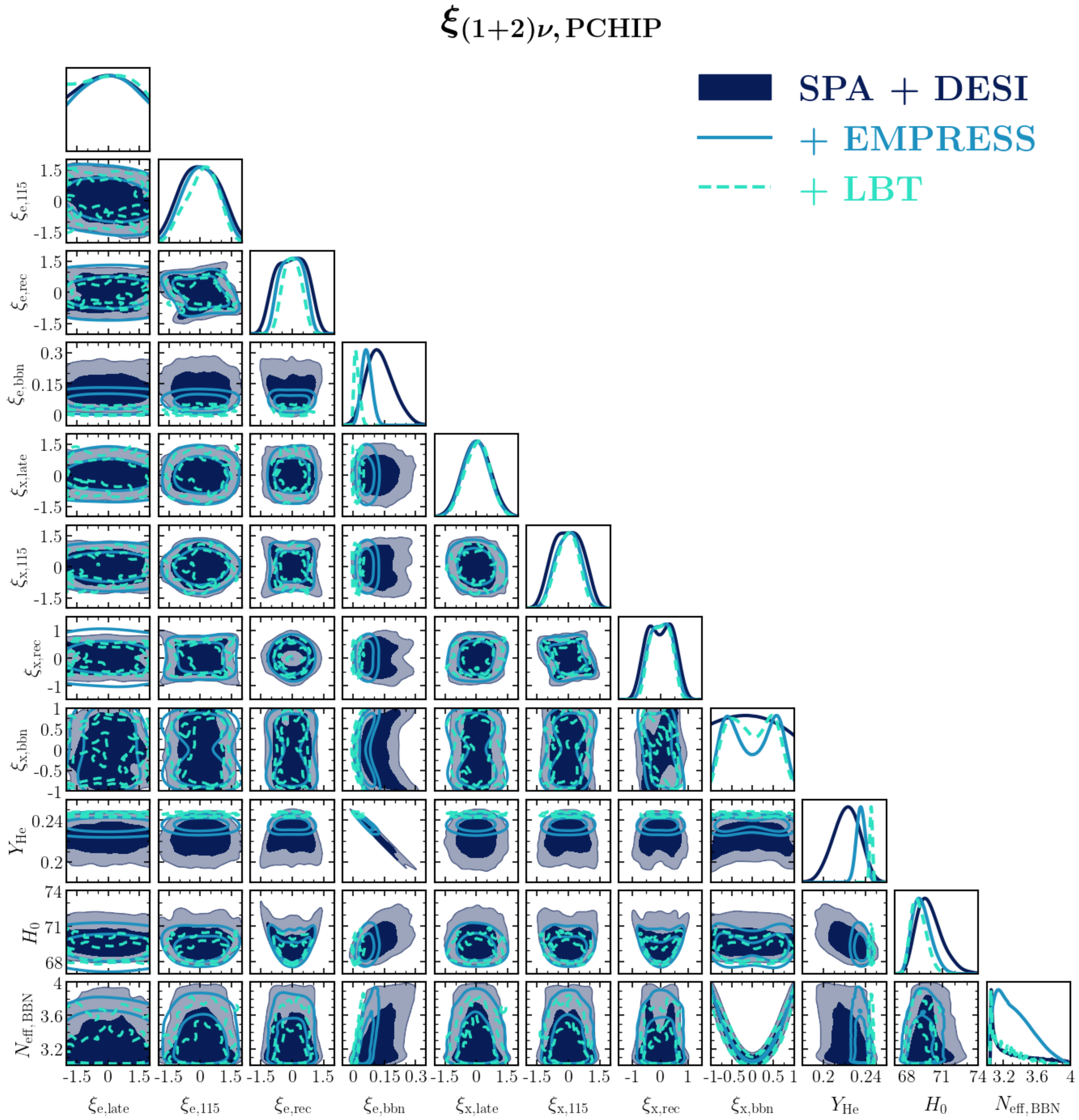
For the first and last $(1 \rightarrow N-1;\ 2 \rightarrow N-2)$ nodes:

$$d(h_1, h_2, \delta_1, \delta_2) = \frac{(2h_1 + h_2)\delta_1 - h_1\delta_2}{h_1 + h_2}$$

- if $\delta_1 \times d(h_1, h_2, \delta_1, \delta_2) < 0 \rightarrow d_1 = 0$;
- if $\delta_1 \times \delta_2 < 0$ & $|d(h_1, h_2, \delta_1, \delta_2)| > 3|\delta_1| \rightarrow d_1 = 3\delta_1$;
- else $d_1 = d(h_1, h_2, \delta_1, \delta_2)$



[P. Ghedini et al., 2606.xxxx]



[P. Ghedini et al., 2606.xxxx]

	$\xi_{3\nu,\,\text{constant}}$		
	SPA + DESI	**+ EMPRESS**	**+ LBT**
$\mathbf{100\theta_s}$	$1.04170^{+0.00048}_{-0.00047}$	$1.04171^{+0.00046}_{-0.00045}$	1.04178 ± 0.00044
$\boldsymbol{\tau_{\text{reio}}}$	$0.066^{+0.012}_{-0.011}$	$0.066^{+0.012}_{-0.011}$	$0.066^{+0.012}_{-0.011}$
$\mathbf{\log(10^{10}A_s)}$	$3.064^{+0.023}_{-0.021}$	$3.064^{+0.022}_{-0.020}$	$3.067^{+0.022}_{-0.021}$
$\boldsymbol{n_s}$	0.9692 ± 0.0098	0.9696 ± 0.0068	$0.9735^{+0.0057}_{-0.0058}$
$\boldsymbol{\Omega_c h^2}$	0.1179 ± 0.0012	0.1179 ± 0.0012	0.1179 ± 0.0012
$\boldsymbol{\Omega_b h^2}$	0.02240 ± 0.00025	0.02238 ± 0.00020	0.02247 ± 0.00018
$\boldsymbol{\xi_\nu}$	$0.044^{+0.077}_{-0.071}$	$0.041^{+0.036}_{-0.035}$	0.006 ± 0.011
$\boldsymbol{Y_{\text{He}}}$	$0.237^{+0.016}_{-0.017}$	$0.2378^{+0.0079}_{-0.0080}$	0.2456 ± 0.0025
$\boldsymbol{H_0}$	$68.13^{+0.56}_{-0.54}$	$68.10^{+0.51}_{-0.50}$	68.23 ± 0.49
$\boldsymbol{N_{\text{eff},\,\text{BBN}}}$	$3.048^{+0.011}_{-0.005}$	$3.0466^{+0.0042}_{-0.0027}$	$3.04409^{+0.00021}_{-0.00010}$
$\ln \mathcal{B}$	1.683 ± 0.017	0.285 ± 0.026	2.844 ± 0.069

	$\xi_{3\nu,\,\text{PCHIP}}$		
$\mathbf{100\theta_s}$	$1.04126^{+0.00080}_{-0.00093}$	$1.04152^{+0.00056}_{-0.00059}$	$1.04168^{+0.00050}_{-0.00052}$
$\boldsymbol{\tau_{\text{reio}}}$	$0.065^{+0.013}_{-0.011}$	0.066 ± 0.012	$0.067^{+0.013}_{-0.012}$
$\mathbf{\log(10^{10}A_s)}$	$3.072^{+0.026}_{-0.024}$	$3.070^{+0.025}_{-0.023}$	3.072 ± 0.023
$\boldsymbol{n_s}$	$0.973^{+0.013}_{-0.011}$	$0.9727^{+0.0096}_{-0.0091}$	$0.9759^{+0.0081}_{-0.0075}$
$\boldsymbol{\Omega_c h^2}$	$0.1213^{+0.0067}_{-0.0045}$	$0.1195^{+0.0037}_{-0.0027}$	$0.1189^{+0.0028}_{-0.0022}$
$\boldsymbol{\Omega_b h^2}$	0.02243 ± 0.00025	$0.02242^{+0.00022}_{-0.00021}$	$0.02250^{+0.00021}_{-0.00020}$
$\boldsymbol{\xi_{\nu,\,\text{late}}}$	0.0 ± 1.2	$0.0^{+1.2}_{-1.1}$	0.0 ± 1.1
$\boldsymbol{\xi_{\nu,115}}$	$-0.03^{+0.96}_{-0.98}$	-0.02 ± 0.83	$-0.02^{+0.78}_{-0.75}$
$\boldsymbol{\xi_{\nu,\,\text{rec}}}$	$0.02^{+0.69}_{-0.74}$	$-0.01^{+0.051}_{-0.052}$	$-0.01^{+0.44}_{-0.43}$
$\boldsymbol{\xi_{\nu,\,\text{BBN}}}$	$0.081^{+0.11}_{-0.098}$	$0.044^{+0.038}_{-0.036}$	0.006 ± 0.011
$\boldsymbol{Y_{\text{He}}}$	$0.229^{+0.021}_{-0.022}$	$0.2370^{+0.0081}_{-0.0082}$	0.2456 ± 0.0026
$\boldsymbol{H_0}$	$69.1^{+2.1}_{-1.5}$	$68.8^{+1.5}_{-1.2}$	$68.6^{+1.2}_{-0.88}$
$\boldsymbol{N_{\text{eff},\,\text{BBN}}}$	$3.056^{+0.028}_{-0.015}$	$3.0471^{+0.0046}_{-0.0032}$	$3.04410^{+0.00023}_{-0.00010}$
$\ln \mathcal{B}$	-0.877 ± 0.046	-1.734 ± 0.070	2.086 ± 0.053

[P. Ghedini et al., 2606.xxxx]

	$\xi_{(1+2)\nu,\,\mathrm{constant}}$		
	SPA + DESI	**+ EMPRESS**	**+ LBT**
$100\theta_s$	$1.04129^{+0.00080}_{-0.00092}$	$1.04148^{+0.00058}_{-0.00061}$	$1.04167^{+0.00049}_{-0.00055}$
τ_{reio}	$0.065^{+0.012}_{-0.011}$	$0.066^{+0.012}_{-0.011}$	$0.067^{+0.012}_{-0.011}$
$\log(10^{10}A_s)$	$3.067^{+0.023}_{-0.021}$	$3.067^{+0.022}_{-0.021}$	$3.069^{+0.021}_{-0.020}$
n_s	0.971 ± 0.010	$0.9725^{+0.0089}_{-0.0082}$	$0.9752^{+0.0072}_{-0.0066}$
$\Omega_c h^2$	$0.1205^{+0.0053}_{-0.0037}$	$0.1196^{+0.0036}_{-0.0027}$	$0.1188^{+0.0025}_{-0.0021}$
$\Omega_b h^2$	0.02242 ± 0.00025	$0.02244^{+0.00024}_{-0.00021}$	$0.02251^{+0.00020}_{-0.00019}$
ξ_{ν_e}	$0.09^{+0.12}_{-0.11}$	$0.052^{+0.045}_{-0.040}$	$0.009^{+0.015}_{-0.013}$
ξ_{ν_x}	$-0.02^{+0.73}_{-0.71}$	$-0.01^{+0.58}_{-0.59}$	$0.00^{+0.46}_{-0.45}$
Y_{He}	$0.229^{+0.021}_{-0.023}$	$0.2365^{+0.0082}_{-0.0084}$	0.2455 ± 0.0025
H_0	$68.9^{+1.7}_{-1.3}$	$68.7^{+1.3}_{-1.0}$	$68.52^{+0.90}_{-0.78}$
$N_{\mathrm{eff,\,BBN}}$	$3.22^{+0.33}_{-0.21}$	$3.15^{+0.21}_{-0.13}$	$3.10^{+0.13}_{-0.07}$
$\ln\mathcal{B}$	0.034 ± 0.031	-1.379 ± 0.052	2.707 ± 0.033

	$\xi_{(1+2)\nu,\,\mathrm{PCHIP}}$		
$100\theta_s$	$1.04087^{+0.00093}_{-0.00098}$	$1.04125^{+0.00065}_{-0.00068}$	$1.04148^{+0.00058}_{-0.00061}$
τ_{reio}	0.064 ± 0.012	0.066 ± 0.012	0.068 ± 0.012
$\log(10^{10}A_s)$	$3.076^{+0.030}_{-0.027}$	$3.077^{+0.027}_{-0.025}$	$3.079^{+0.024}_{-0.023}$
n_s	$0.974^{+0.014}_{-0.012}$	$0.976^{+0.011}_{-0.010}$	$0.9784^{+0.0092}_{-0.0086}$
$\Omega_c h^2$	$0.1238^{+0.0073}_{-0.0061}$	$0.1215^{+0.0047}_{-0.0040}$	$0.1203^{+0.0036}_{-0.0031}$
$\Omega_b h^2$	$0.02244^{+0.00024}_{-0.00025}$	0.02248 ± 0.00022	$0.02255^{+0.00020}_{-0.00018}$
$\xi_{\nu_e,\,\mathrm{late}}$	—	—	—
$\xi_{\nu_e,\,115}$	0.0 ± 1.6	0.0 ± 1.5	$0.1^{+1.3}_{-1.4}$
$\xi_{\nu_e,\,\mathrm{rec}}$	0.0 ± 1.2	-0.02 ± 0.94	$-0.01^{+0.76}_{-0.74}$
$\xi_{\nu_e,\,\mathrm{BBN}}$	$0.13^{+0.13}_{-0.12}$	$0.066^{+0.050}_{-0.045}$	$0.019^{+0.027}_{-0.022}$
$\xi_{\nu_x,\,\mathrm{late}}$	$0.0^{+1.3}_{-1.2}$	$0.0^{+1.2}_{-1.1}$	0.0 ± 1.1
$\xi_{\nu_x,\,115}$	0.0 ± 1.2	0.0 ± 1.1	$-0.03^{+0.95}_{-1.0}$
$\xi_{\nu_x,\,\mathrm{rec}}$	0.00 ± 0.83	0.02 ± 0.70	0.01 ± 0.60
$\xi_{\nu_x,\,\mathrm{BBN}}$	—	-0.01 ± 0.87	$-0.02^{+0.84}_{-0.85}$
Y_{He}	$0.222^{+0.023}_{-0.026}$	$0.2357^{+0.0083}_{-0.0084}$	$0.2455^{+0.0025}_{-0.0026}$
H_0	$69.9^{+2.2}_{-1.9}$	$69.3^{+1.6}_{-1.4}$	$69.0^{+1.3}_{-1.1}$
$N_{\mathrm{eff,\,BBN}}$	$3.33^{+0.60}_{-0.29}$	$3.32^{+0.45}_{-0.34}$	$3.27^{+0.44}_{-0.23}$
$\ln\mathcal{B}$	-4.799 ± 0.129	-5.621 ± 0.155	-2.854 ± 0.157

[P. Ghedini et al., 2606.xxxx]