CNB essentials 3: Bounds on neutrino properties from cosmology

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ASTROPARTICLES
Astroparticles and High Energy Physics Group

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Bounds on N_{eff}

Relativistic particles in the universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_{\mathrm{rad}} = \rho_\gamma + \rho_\nu + \rho_x = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \boxed{N_{\mathrm{eff}}}\right]$$

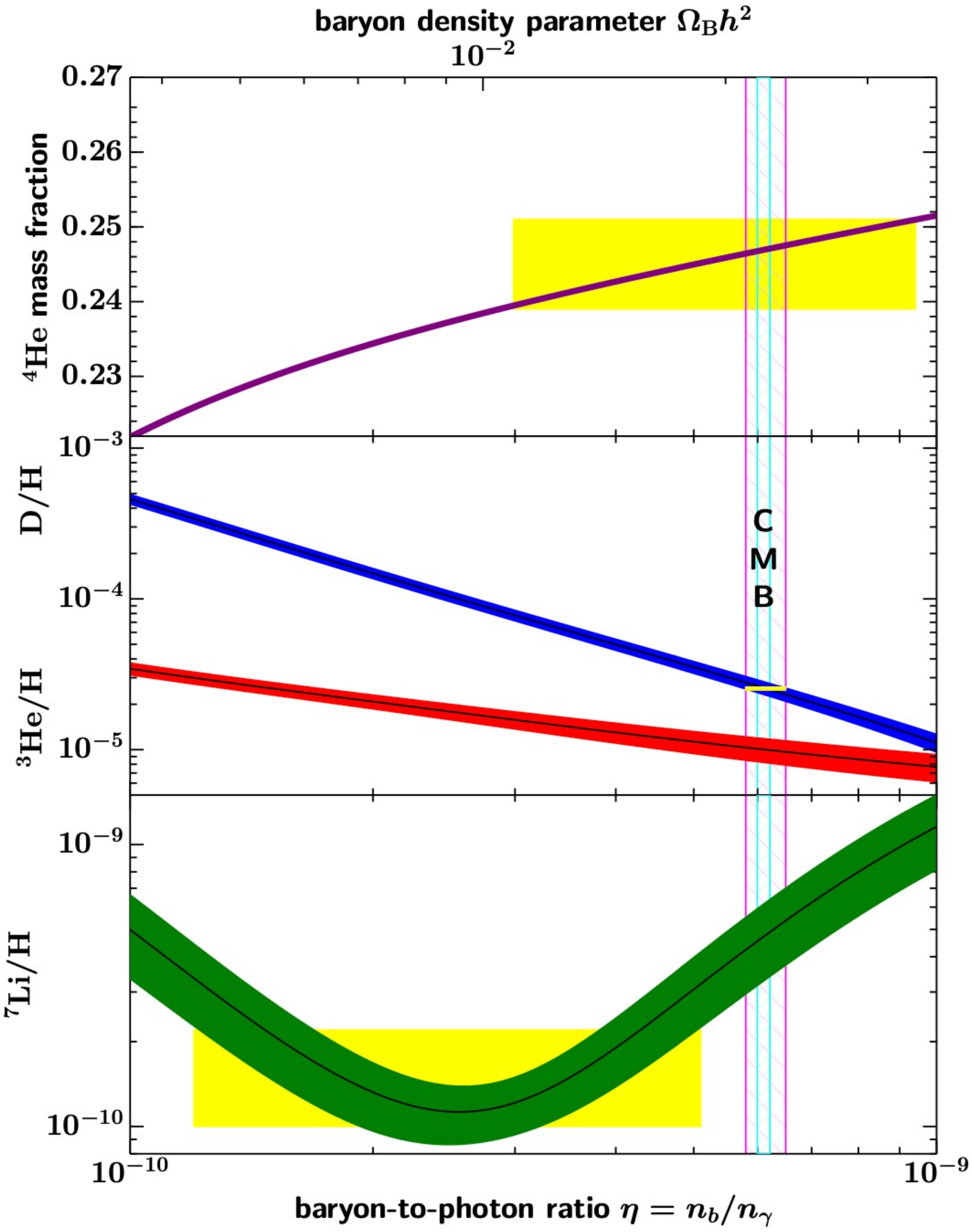
effective number of relativistic neutrino species

(effective number of neutrinos)

N_{eff} is a way to measure the ratio $\dfrac{\rho_\nu + \rho_x}{\rho_\gamma}$

Number of light neutrino types (LEP data) $N_\nu = 2.984 \pm 0.008$

BBN: Predictions vs Observations



$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

$$5.8 \leq \eta_{10} \leq 6.5$$
$$(95\%\ \mathrm{CL})$$

Fields, Molaro & Sarkar,
PDG 2020

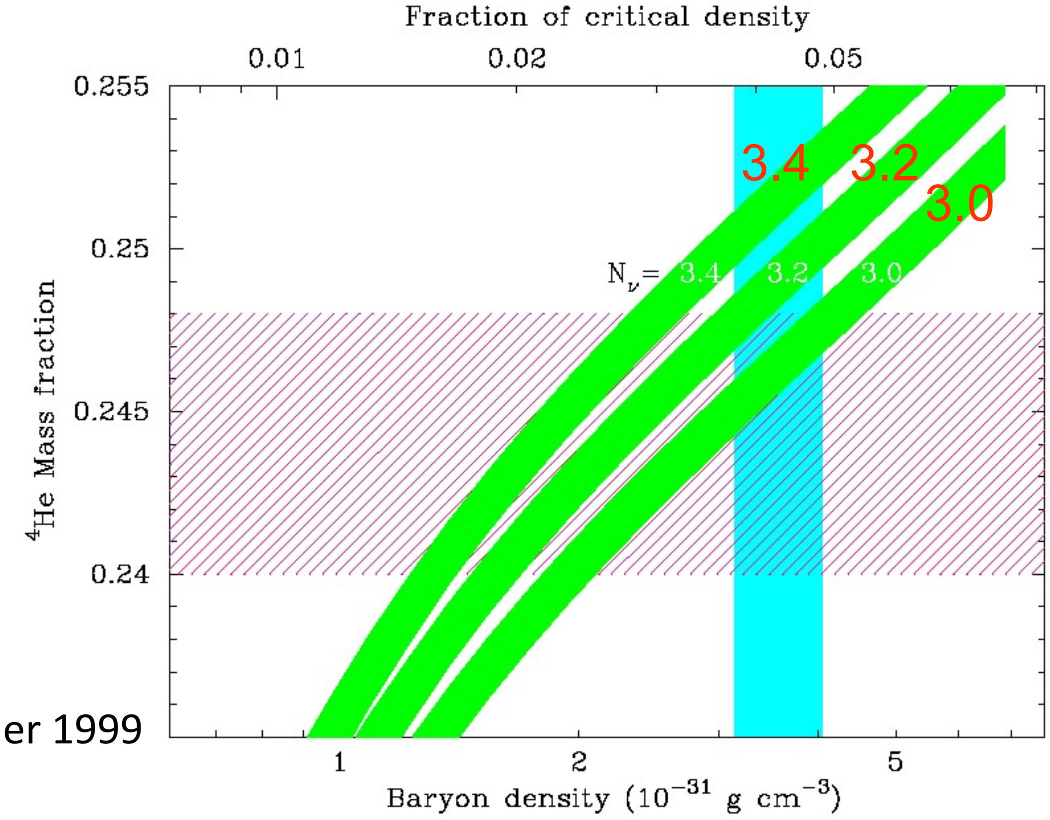
Effect of neutrinos on Primordial Nucleosynthesis

1. **$N_{\rm eff}$** fixes the **expansion rate** during BBN

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$

$\rho(N_{\rm eff})>\rho_0 \rightarrow \uparrow {}^4\mathrm{He}$

$$\Delta Y_{\rm p} \simeq 0.013\,\Delta N_{\rm eff}$$

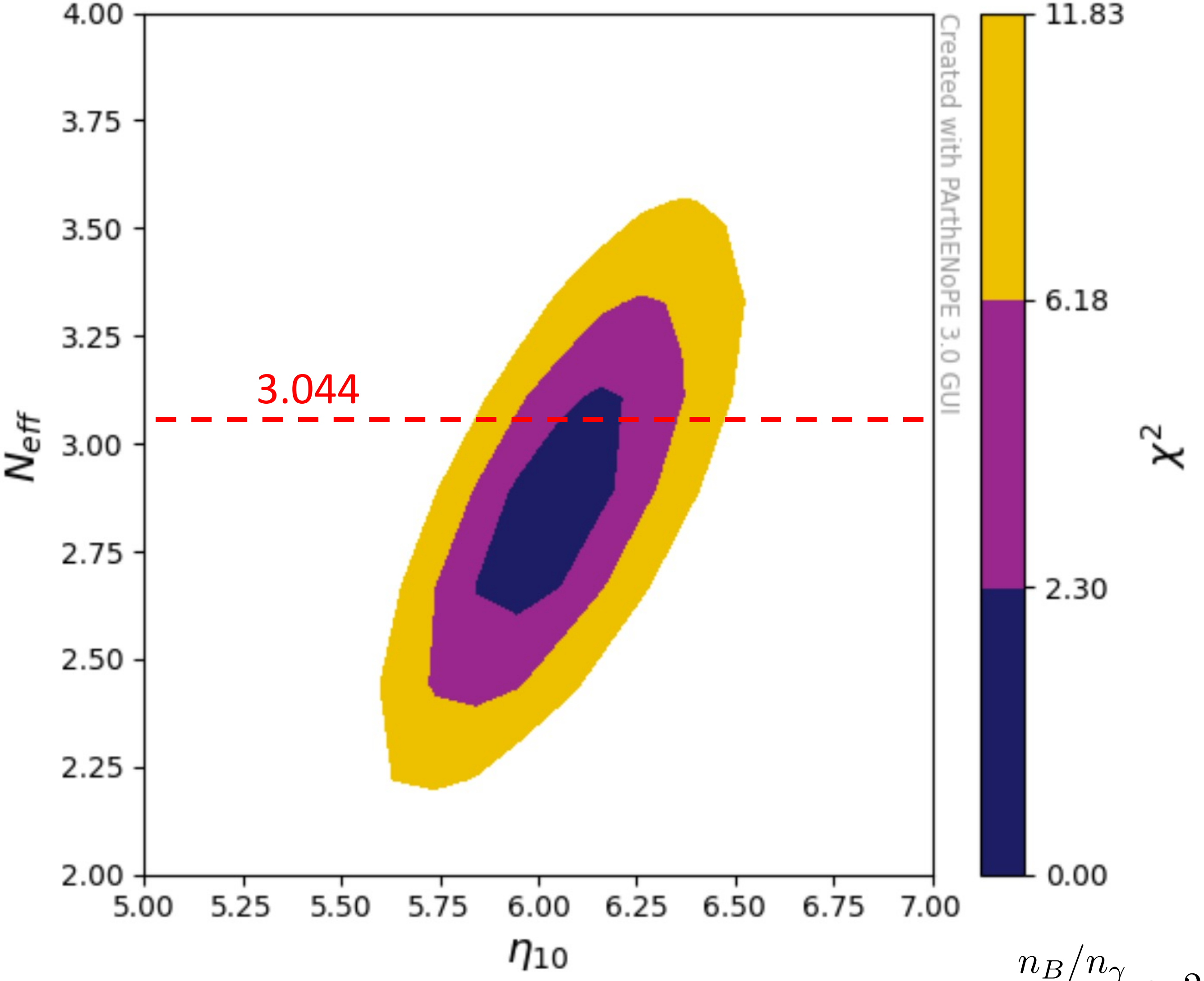


Burles, Nollett & Turner 1999

2. Direct effect of **electron** neutrinos and antineutrinos on the **n-p reactions**

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

BBN: allowed ranges for N_{eff}



$$5.6 < \eta_{10} < 6.6$$

$$2.3 < N_{\text{eff}} < 3.4$$

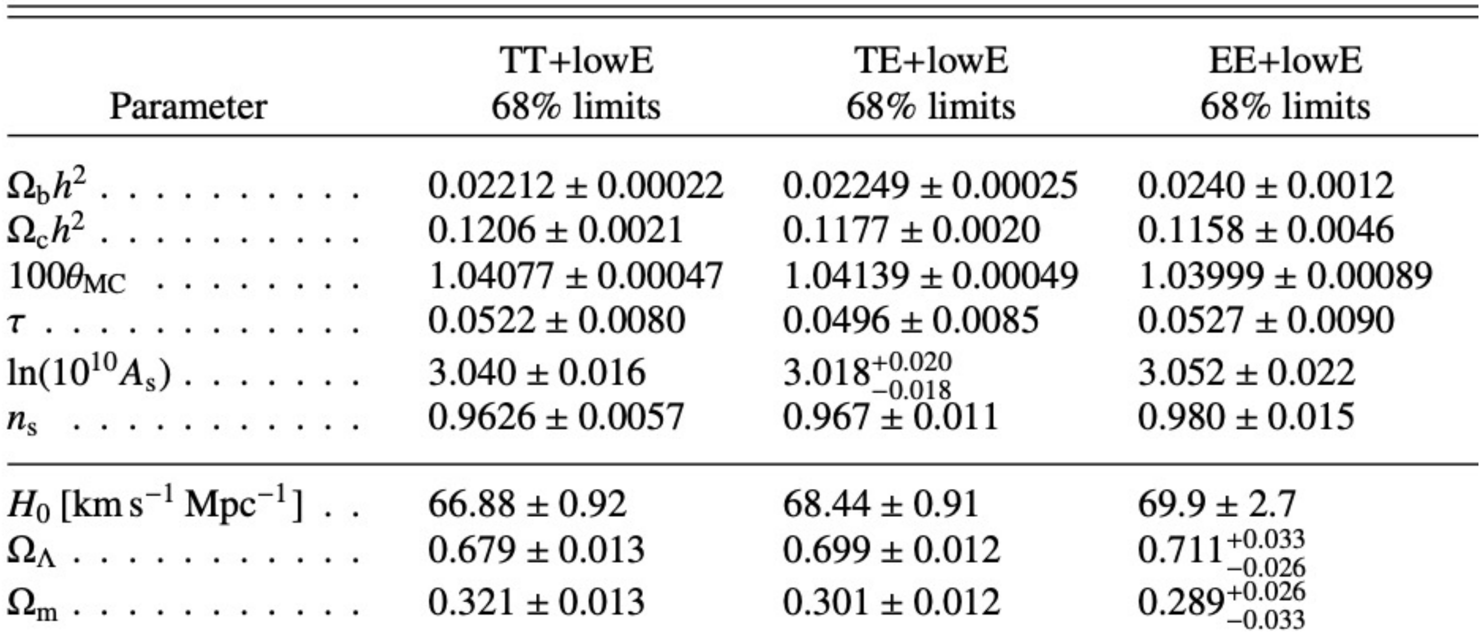
(95% CL)

$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

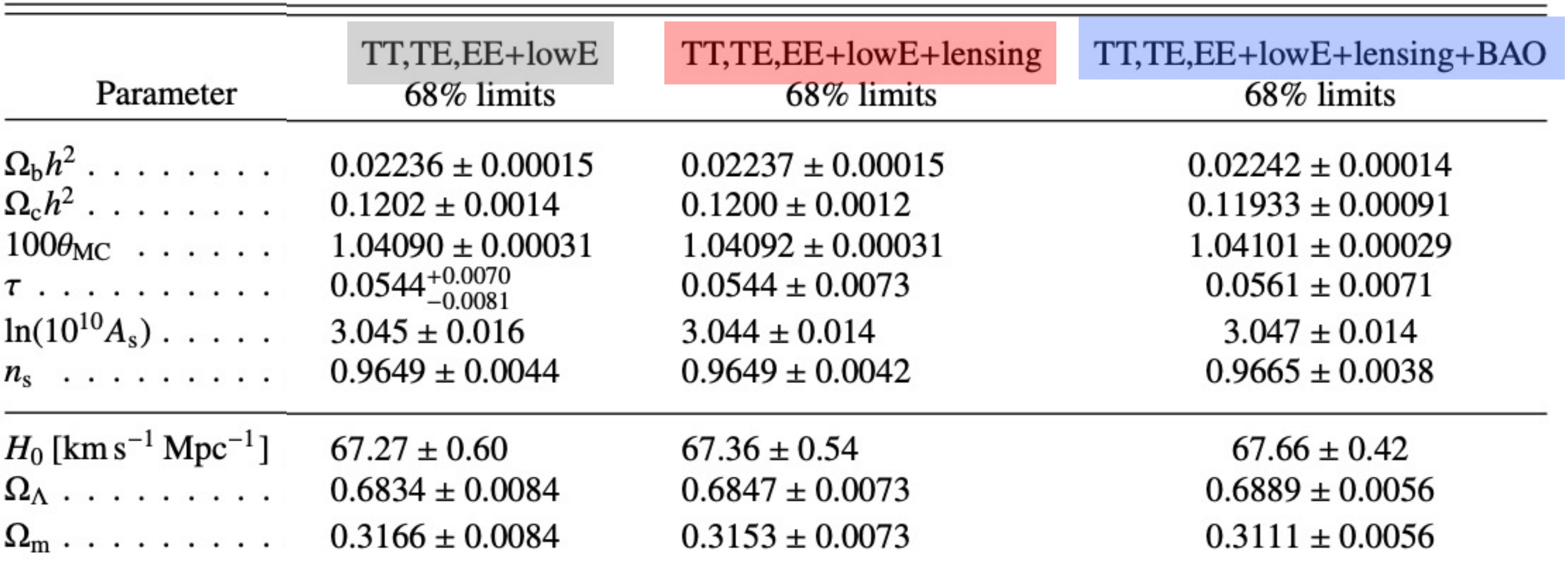
^{4}He and D bounds

PArthENoPE BBN code, S Gariazzo et al, arXiv:2103.05027

The minimal ΛCDM model fits very well Planck data



Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015
H_0 [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$



Parameter	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056

CMB anisotropies
+ other data

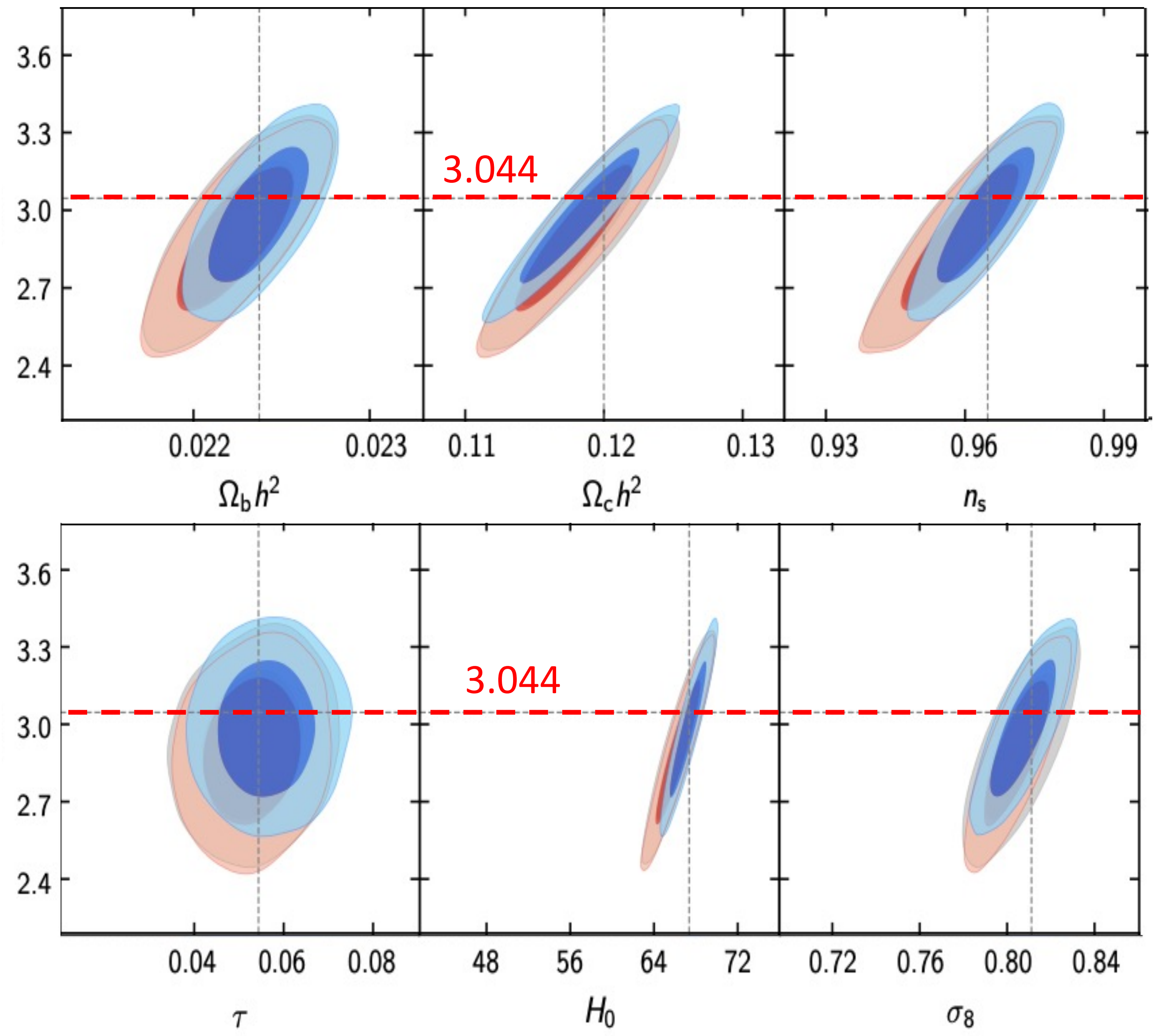
$N_{\rm eff} \lesssim 17$ (2001) early CMB data

$N_{\rm eff} = 4.2^{+1.2}_{-1.7}$ (2005) WMAP+...

Planck: 1-parameter extensions of the ΛCDM model

68+95%
Conf regions

Planck TT, TE, EE + lowE **+ lensing** **+ lensing + BAO**



N_{eff}

Planck Collab,
A&A **641** (2020) A6

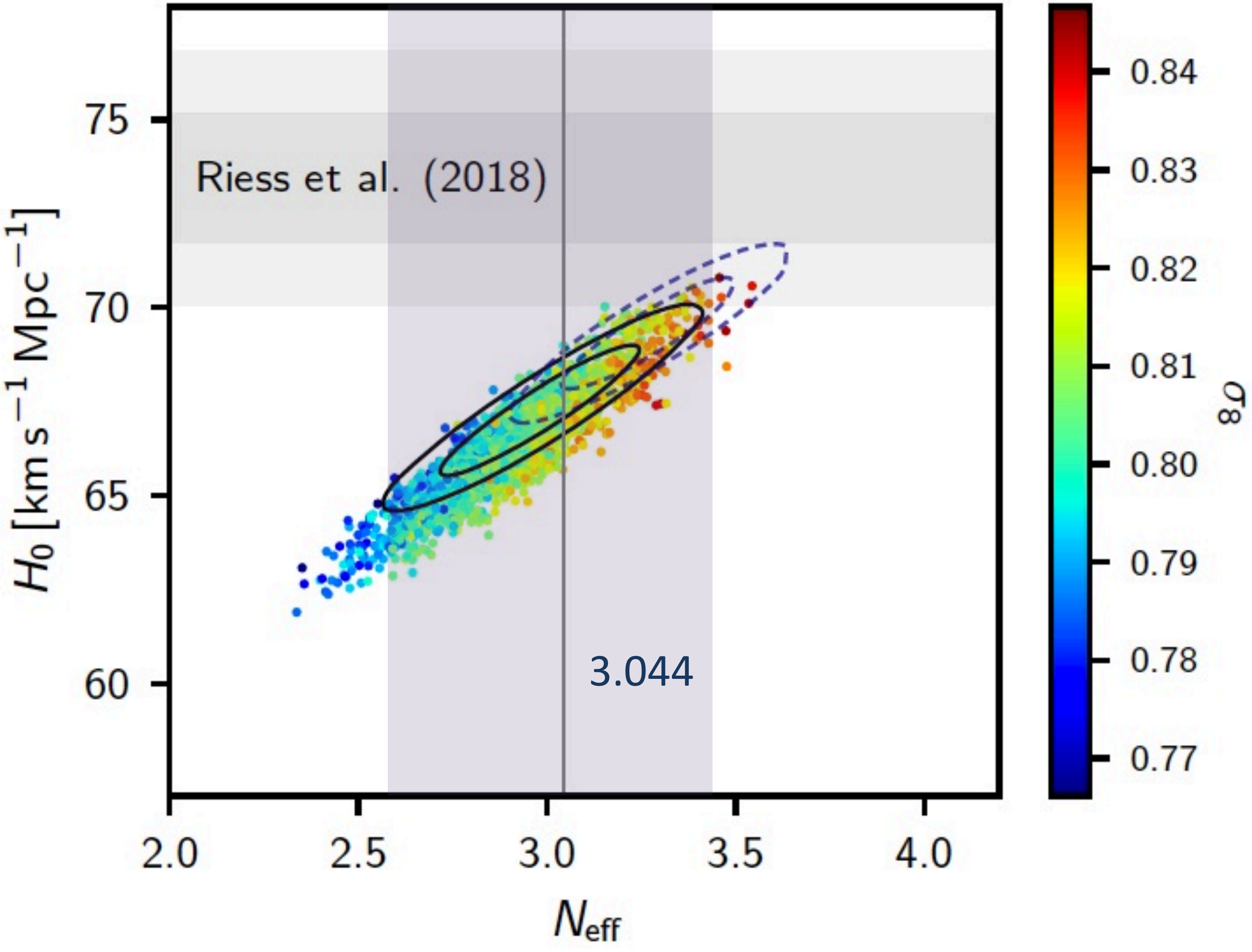
$$N_{\rm eff} \lesssim 17$$ (2001) early CMB data

$$N_{\rm eff} = 4.2^{+1.2}_{-1.7}$$ (2005) WMAP+…

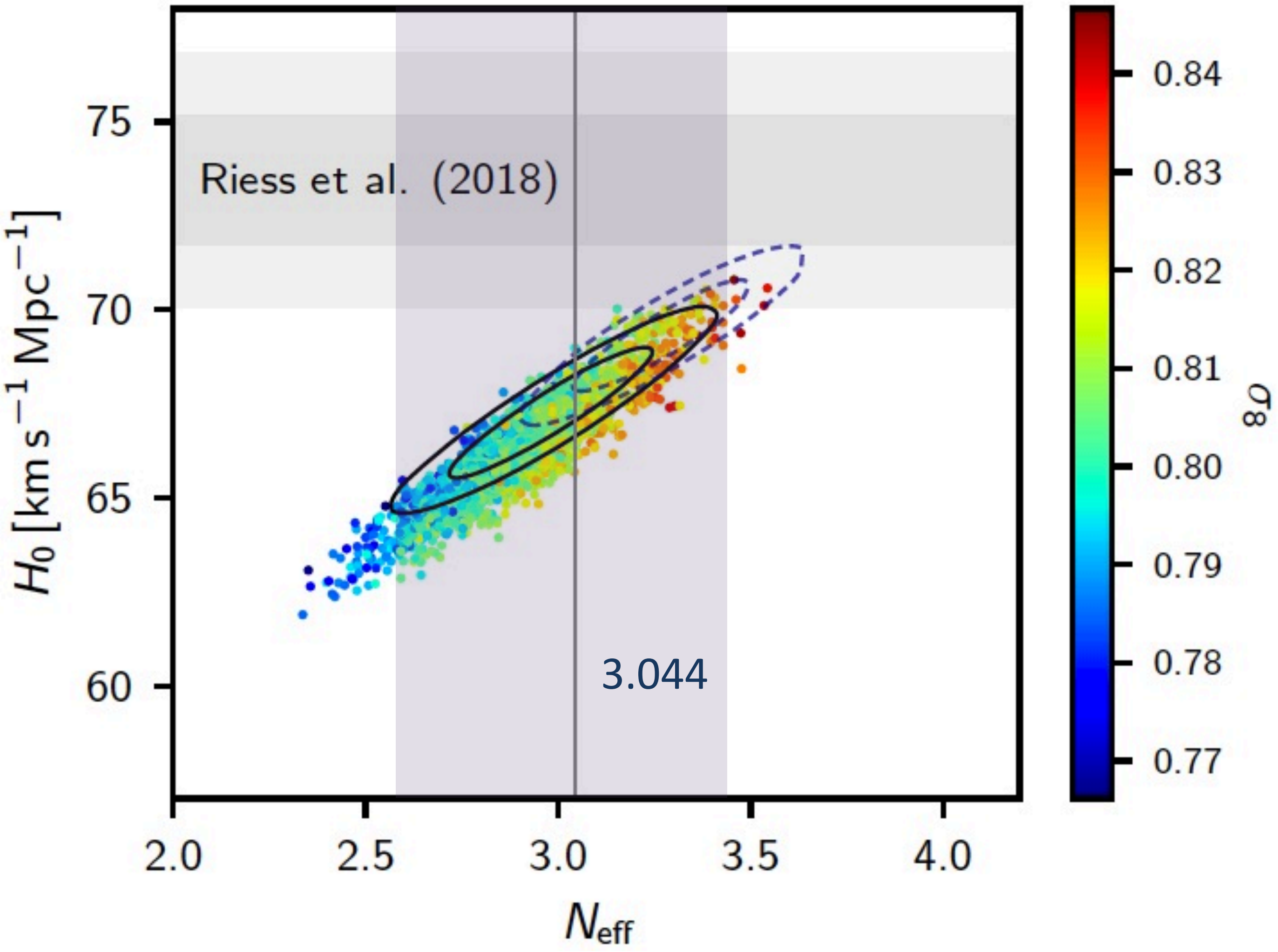
CMB anisotropies
+ other data

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$$ (2018) Planck

(95%, TT,TE,EE+lowE+lensing+BAO)



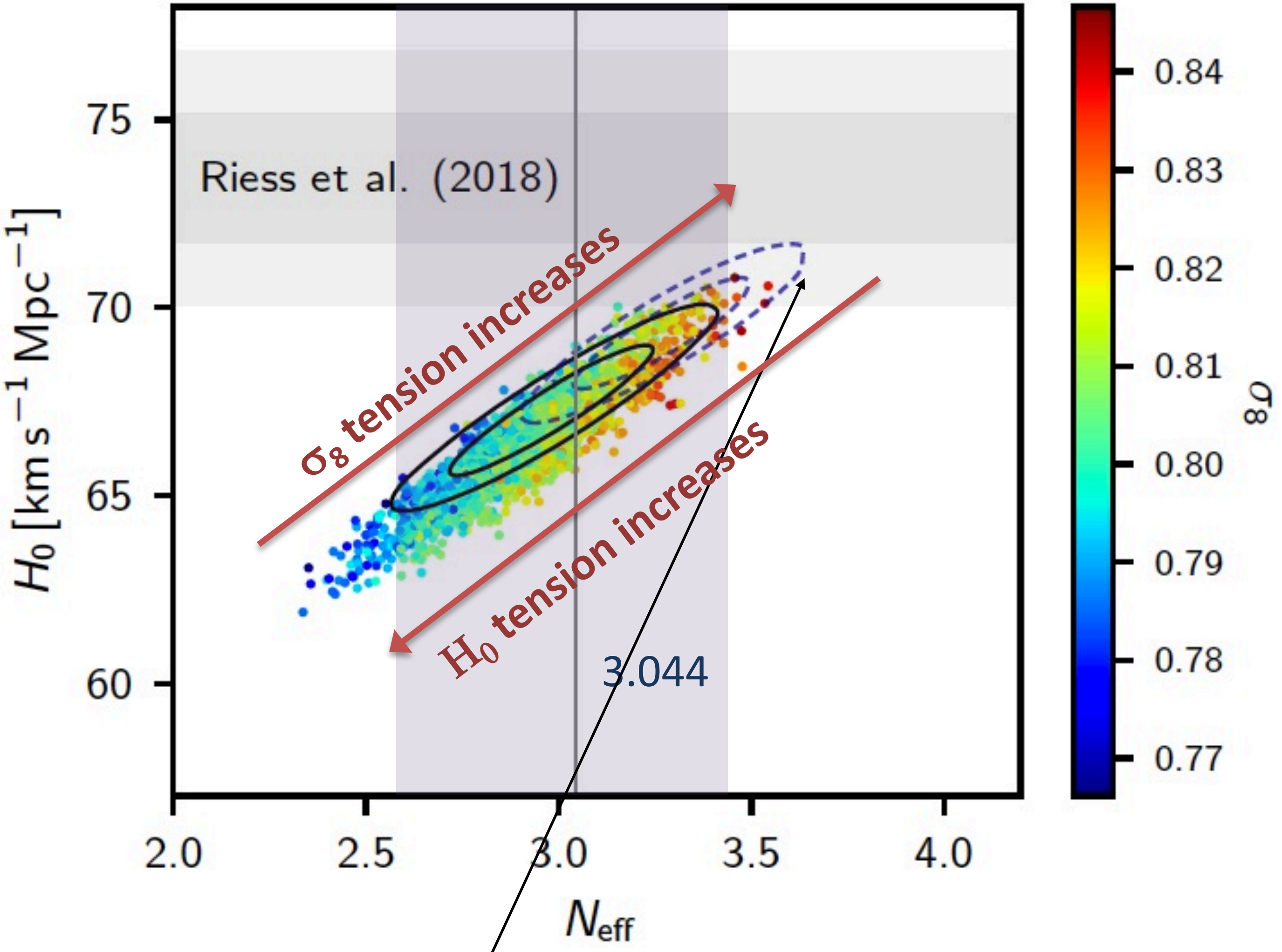
CMB anisotropies
+ other data



$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%, *Planck* TT,TE,EE+lowE).

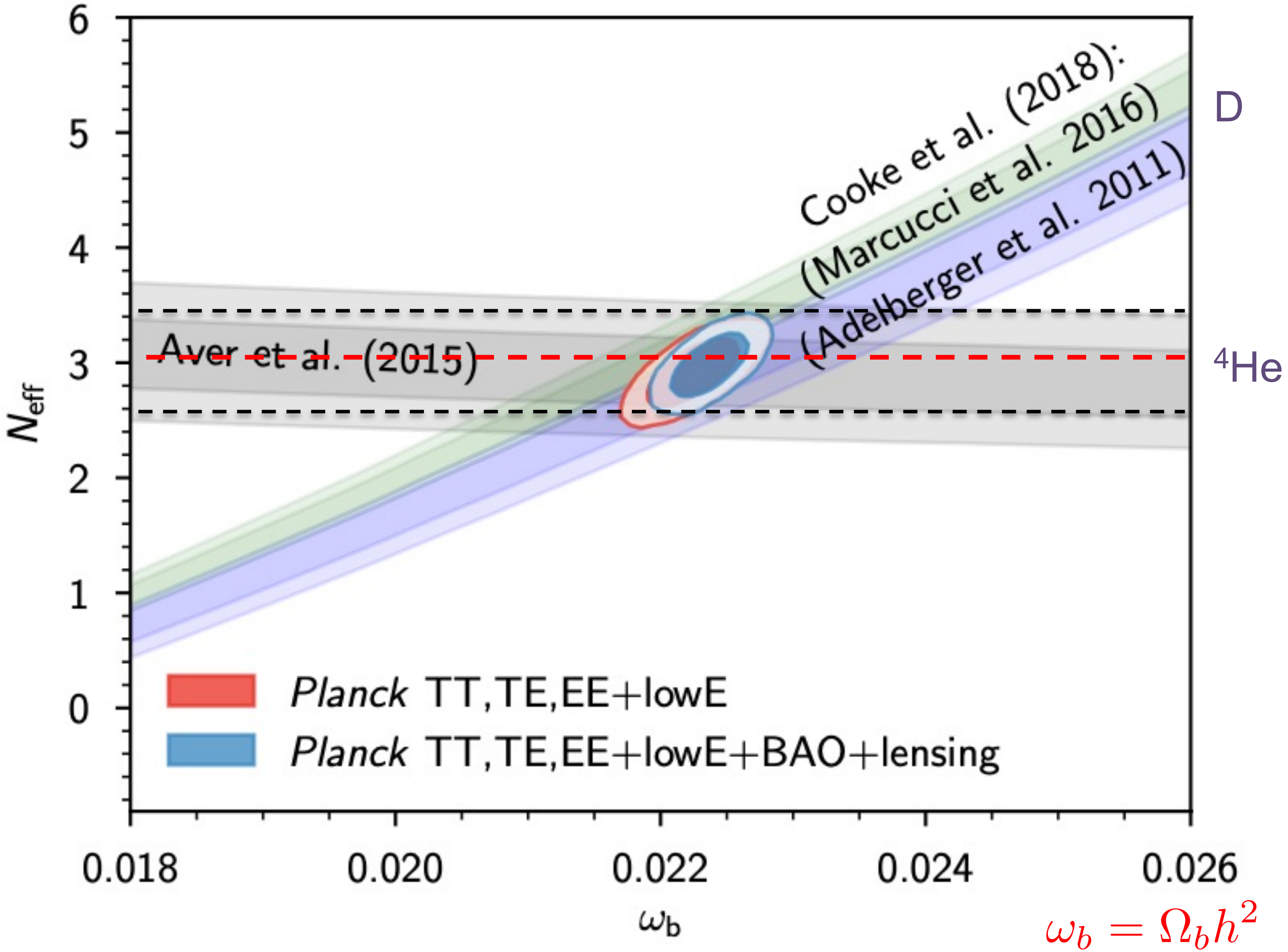
$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95%, TT,TE,EE+lowE+lensing+BAO)

CMB anisotropies
+ other data



$$\left.\begin{aligned} N_{\rm eff} &= 3.27 \pm 0.15 \\ H_0 &= (69.32 \pm 0.97)\,{\rm km\,s^{-1}\,Mpc^{-1}} \end{aligned}\right\} \begin{array}{l} 68\%,\ {\rm TT,TE,EE+lowE+} \\ {\rm lensing+BAO+R18.} \end{array}$$

Comparison: allowed ranges for N_{eff} and BBN



$\omega_b = \Omega_b h^2$

Planck Coll, A&A **641** (2020) A6

N_{eff} with non-standard neutrino-electron interactions

Non-standard neutrino-electron interactions

Non-standard interactions (**NSI**) between **neutrinos** and **electrons** can be parametrised as follows:

$$\mathcal{L}_{\mathrm{NSIe}} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon^X_{\alpha\beta} \left(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\overline{e}\gamma_\mu P_X e\right)$$

with $X \in \{L, R\}$

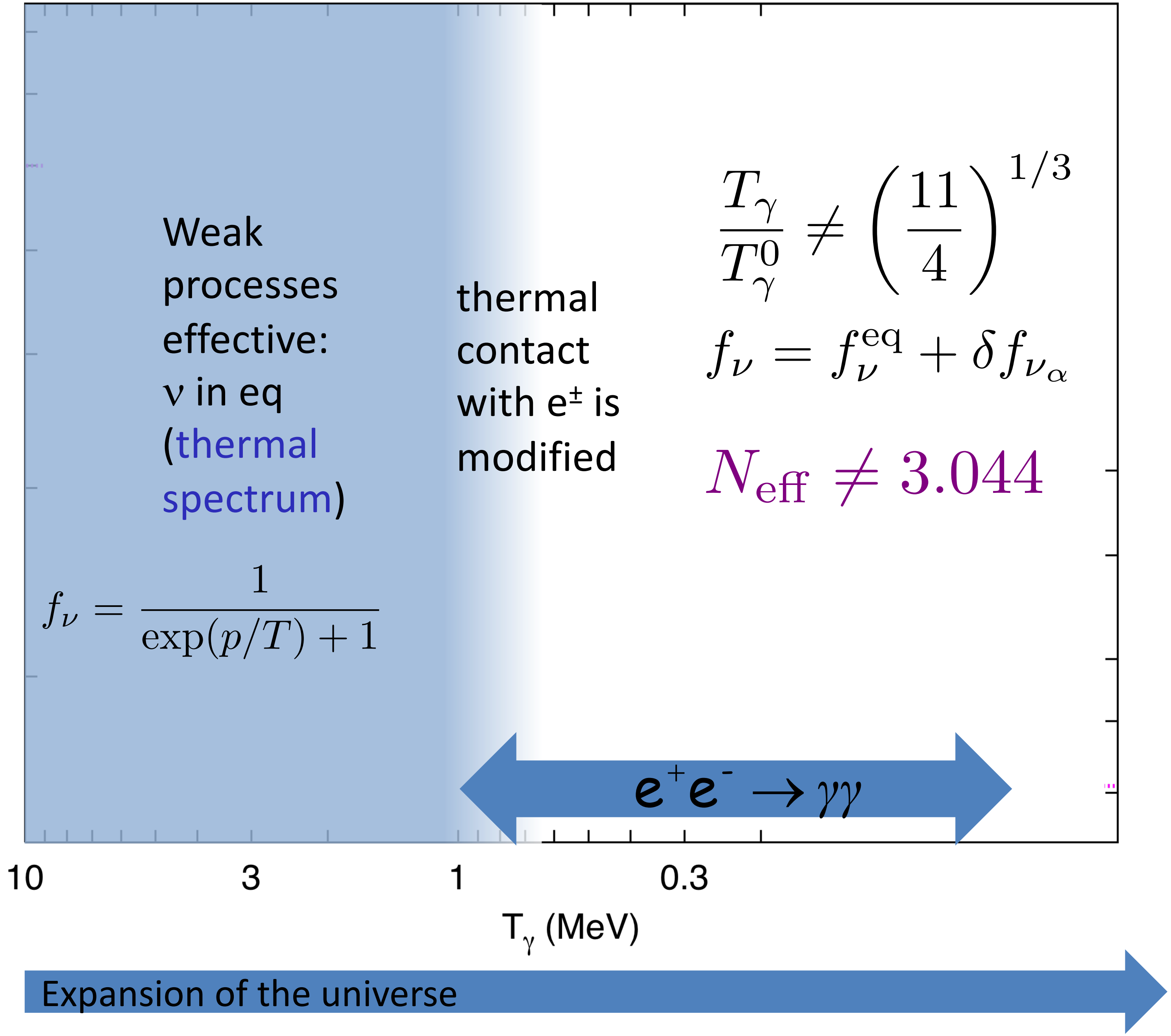
$\alpha, \beta \in \{e, \mu, \tau\}$

Dimensionless coefficients $\varepsilon^X_{\alpha\beta}$ quantify the strength of the interactions with respect to the SM

$\varepsilon^X_{\alpha\alpha}$ Non-universal NSI

$\varepsilon^X_{\alpha\beta}(\text{with } \alpha \neq \beta)$ Flavour-changing ($\alpha \neq \beta$) NSI

N_{eff} with non-standard neutrino-electron interactions



Weak processes effective: ν in eq (thermal spectrum)

$$f_\nu = \frac{1}{\exp(p/T)+1}$$

thermal contact with e± is modified

$$\frac{T_\gamma}{T_\gamma^0} \neq \left(\frac{11}{4}\right)^{1/3}$$

$$f_\nu = f_\nu^{\mathrm{eq}} + \delta f_{\nu_\alpha}$$

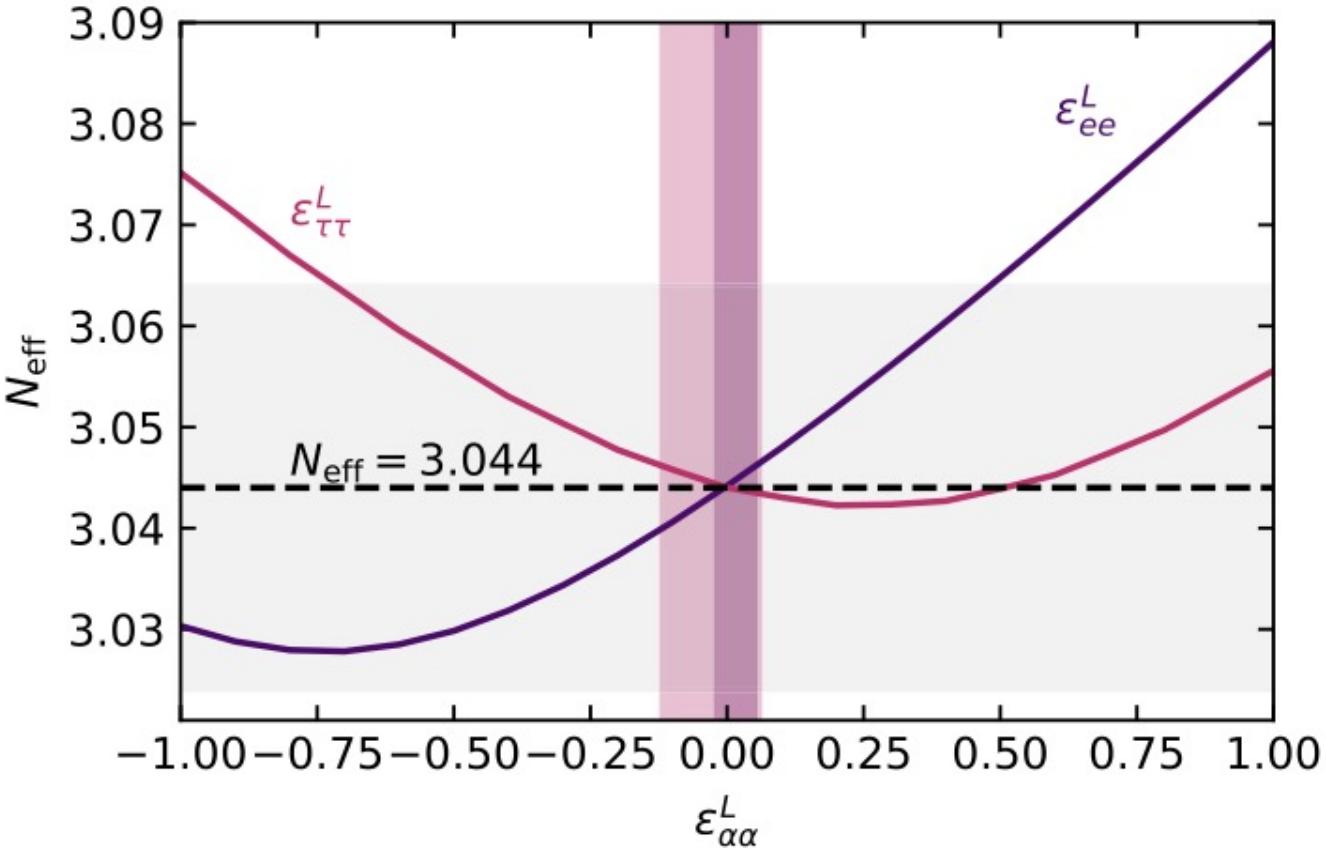
$$N_{\mathrm{eff}} \neq 3.044$$

$e^+e^- \rightarrow \gamma\gamma$

Expansion of the universe

N_{eff} with only one NSI parameter

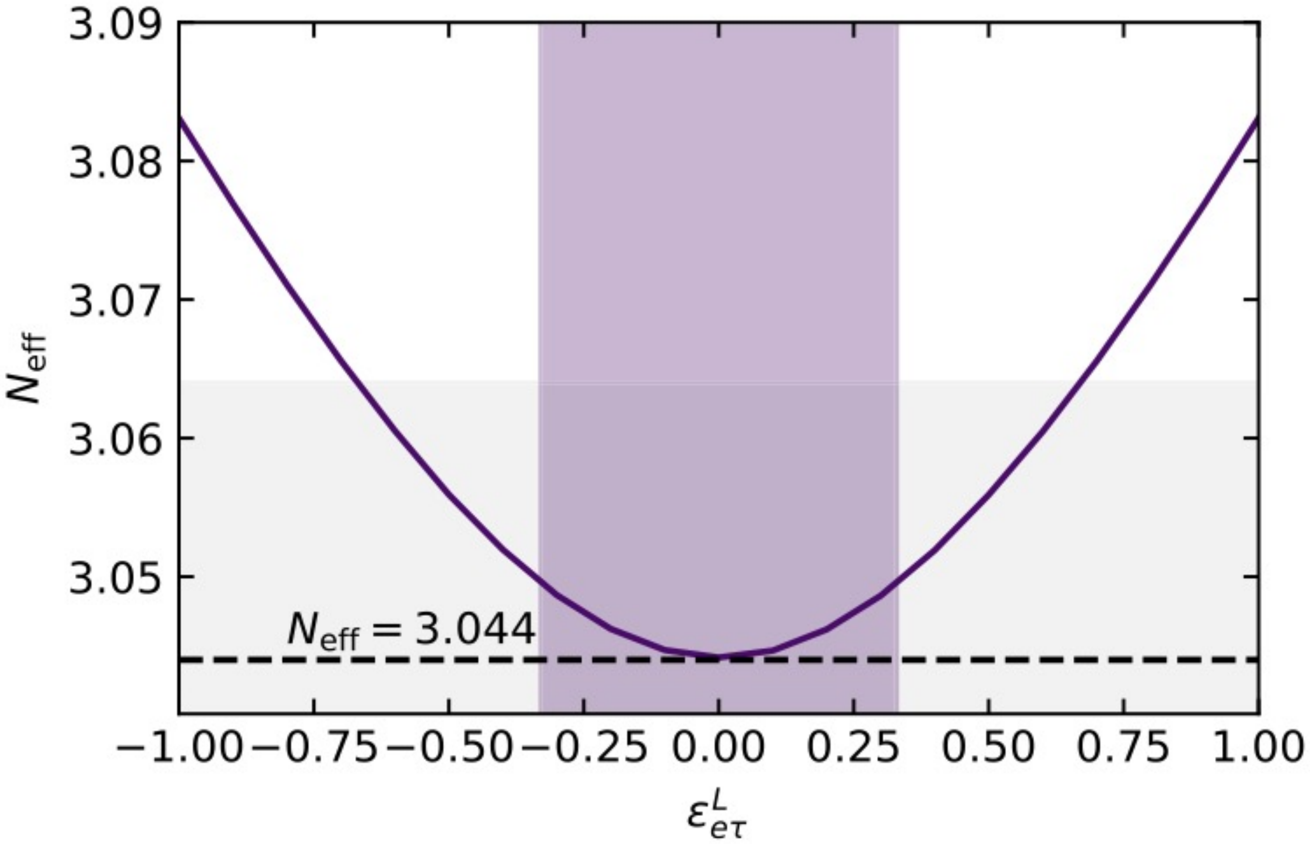
N_{eff} for non-universal NSI



PF de Salas et al, PLB **820** (2021) 136508

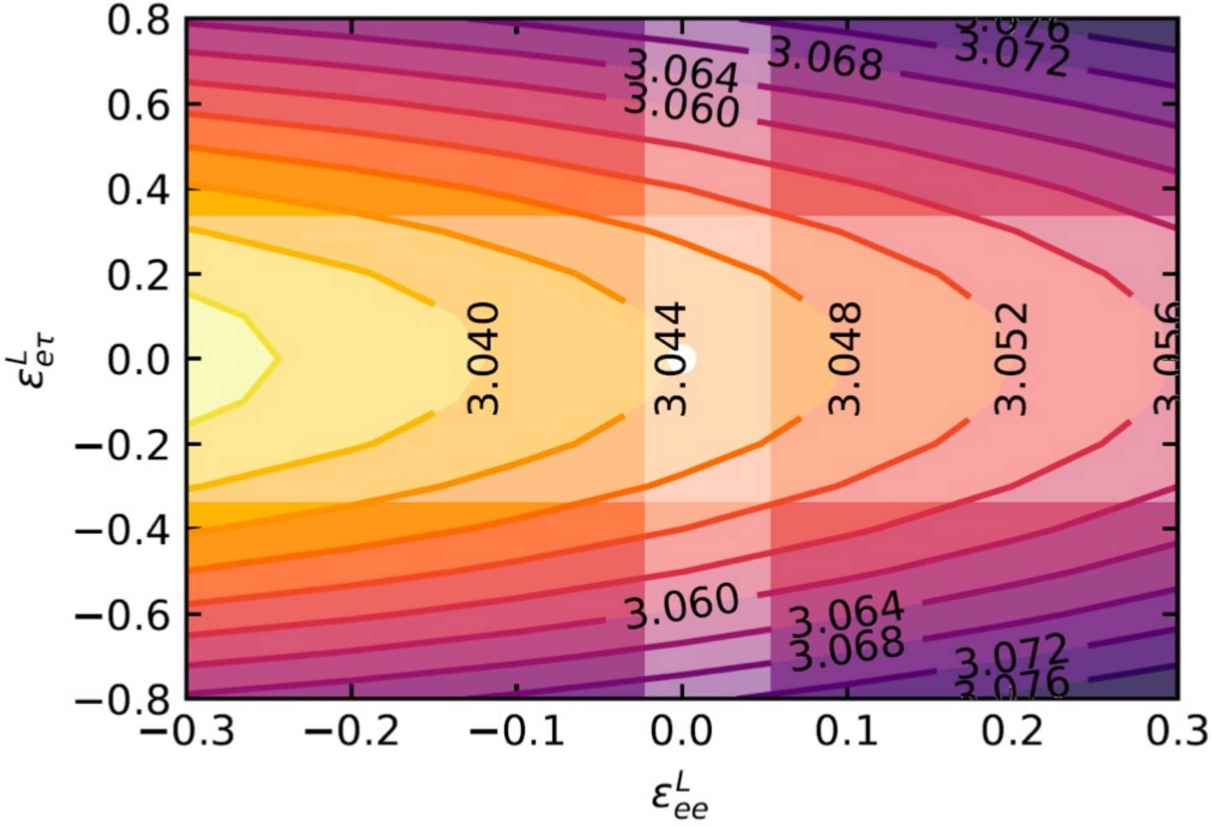
N_{eff} with only one NSI parameter

N_{eff} for flavour-changing NSI



PF de Salas et al, PLB **820** (2021) 136508

N_{eff} varying 2 NSI parameters

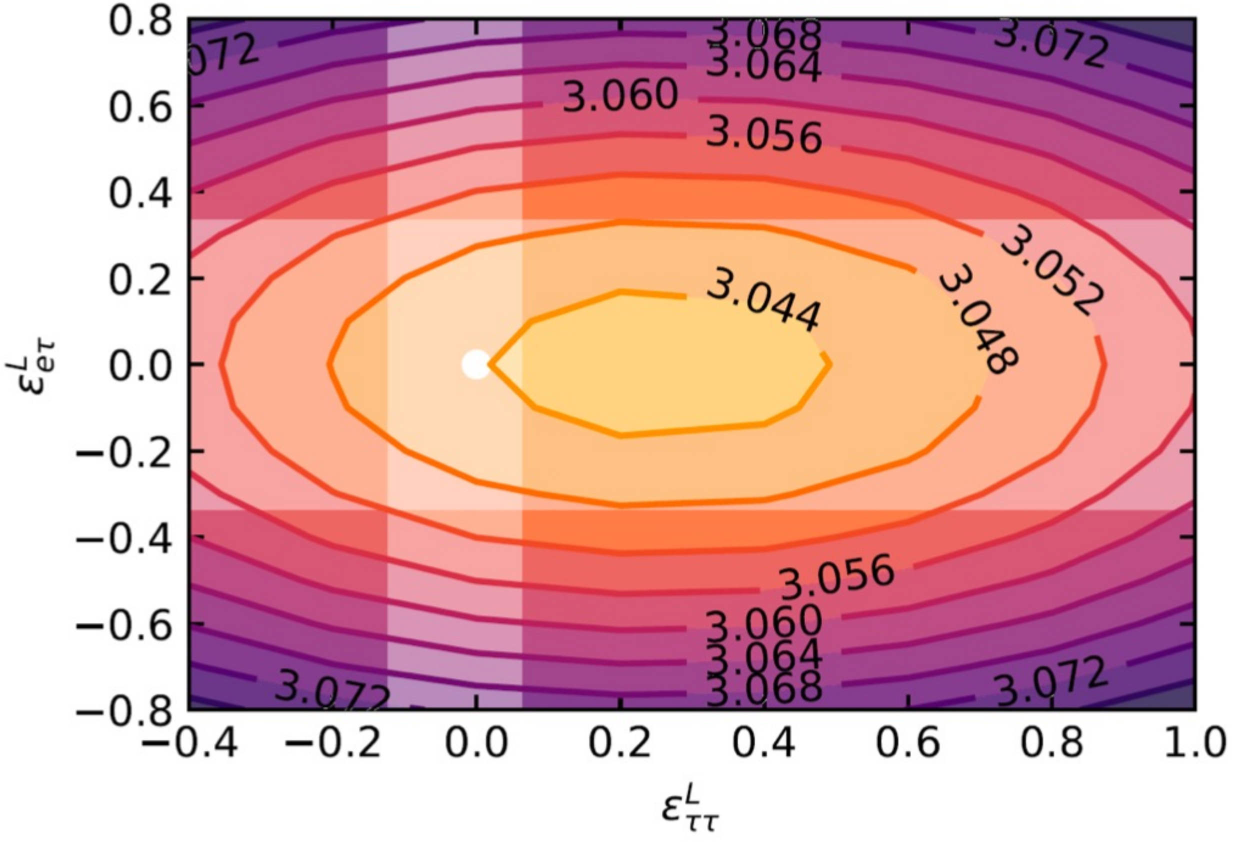


Future determinations of Neff are expected to have an error of 0.02-0.03

White shaded bands correspond to terrestrial bounds on NSI.

PF de Salas et al, PLB **820** (2021) 136508

N_{eff} varying 2 NSI parameters



Future determinations of Neff are expected to have an error of 0.02-0.03

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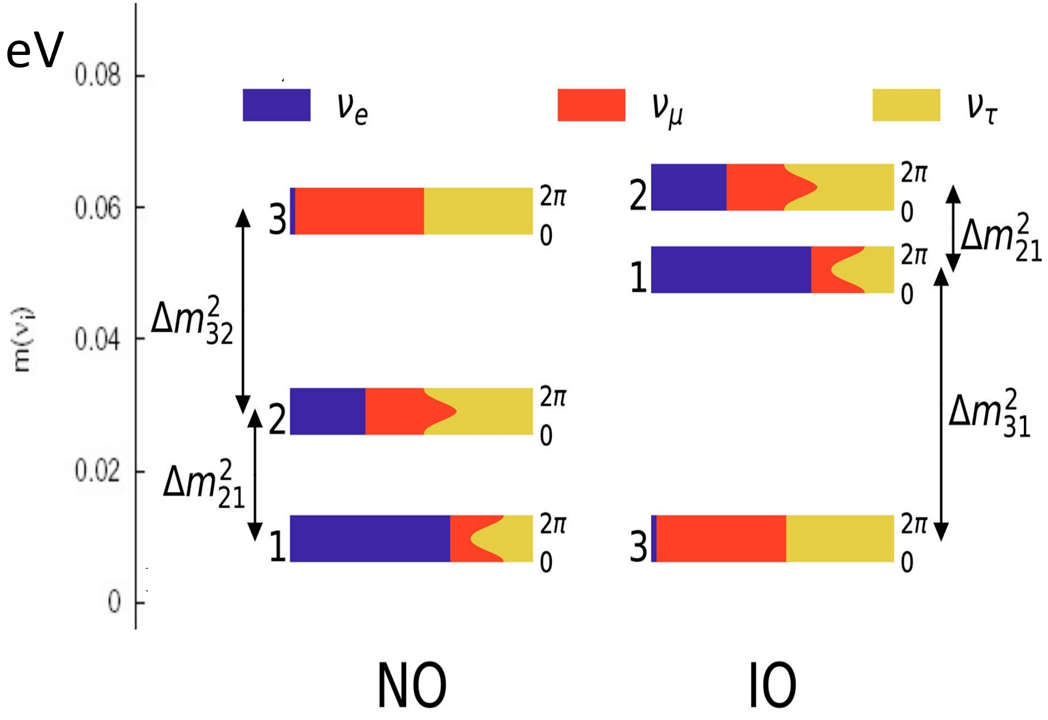
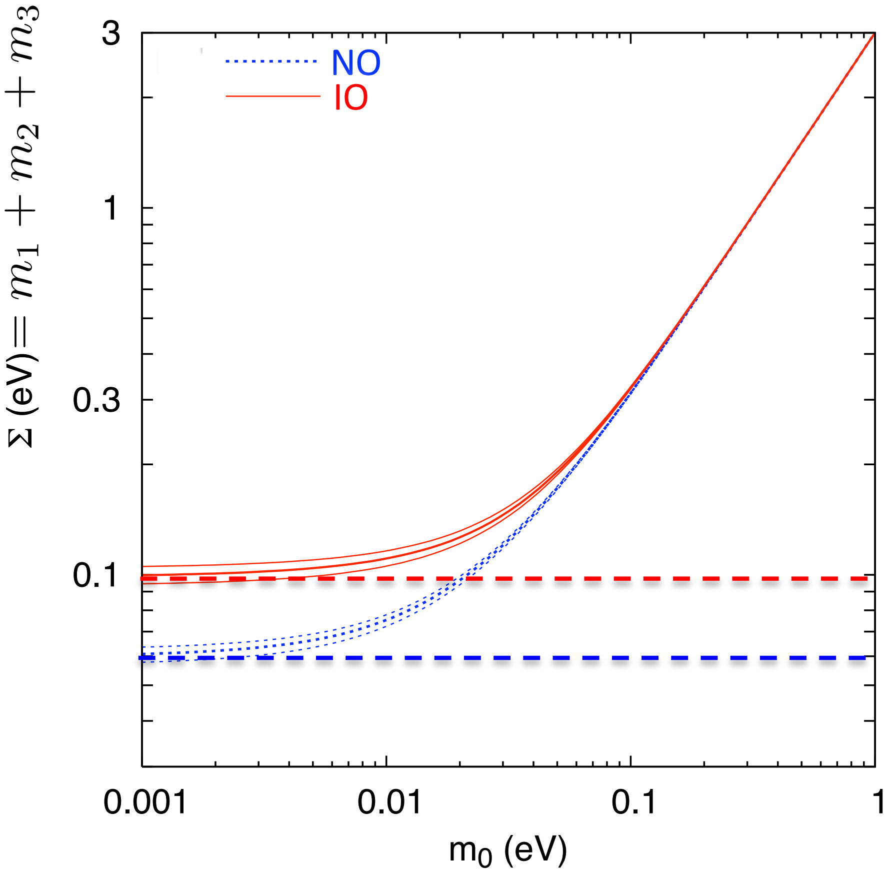
PF de Salas et al, PLB **820** (2021) 136508

Bounds on neutrino masses

Neutrino masses

Data on flavour oscillations do not fix the absolute scale of neutrino masses





$$0.06\,(0.1)\,\mathrm{eV} \lesssim \sum_i m_{\nu_i} \lesssim 2.4\,\mathrm{eV}$$

Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \mathrm{eV}} \qquad \Omega_\nu < 1 \rightarrow \sum_i m_i \lesssim 46\ \mathrm{eV}$$

$$\Omega_\nu < \Omega_m \simeq 0.3 \rightarrow \sum_i m_i \lesssim 15\ \mathrm{eV}$$

- They stream freely until non-relativistic (collisionless phase mixing) ⇒ **Neutrinos are HOT Dark Matter** (large thermal motion)

- First structures to be formed when Universe became matter –dominated are very large

- Ruled out by structure formation ⇒ CDM

Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

Cosmological bounds on neutrino mass(es)

A unique cosmological bound on m_ν DOES NOT exist !

Different analyses have found upper bounds on neutrino masses, since they depend on

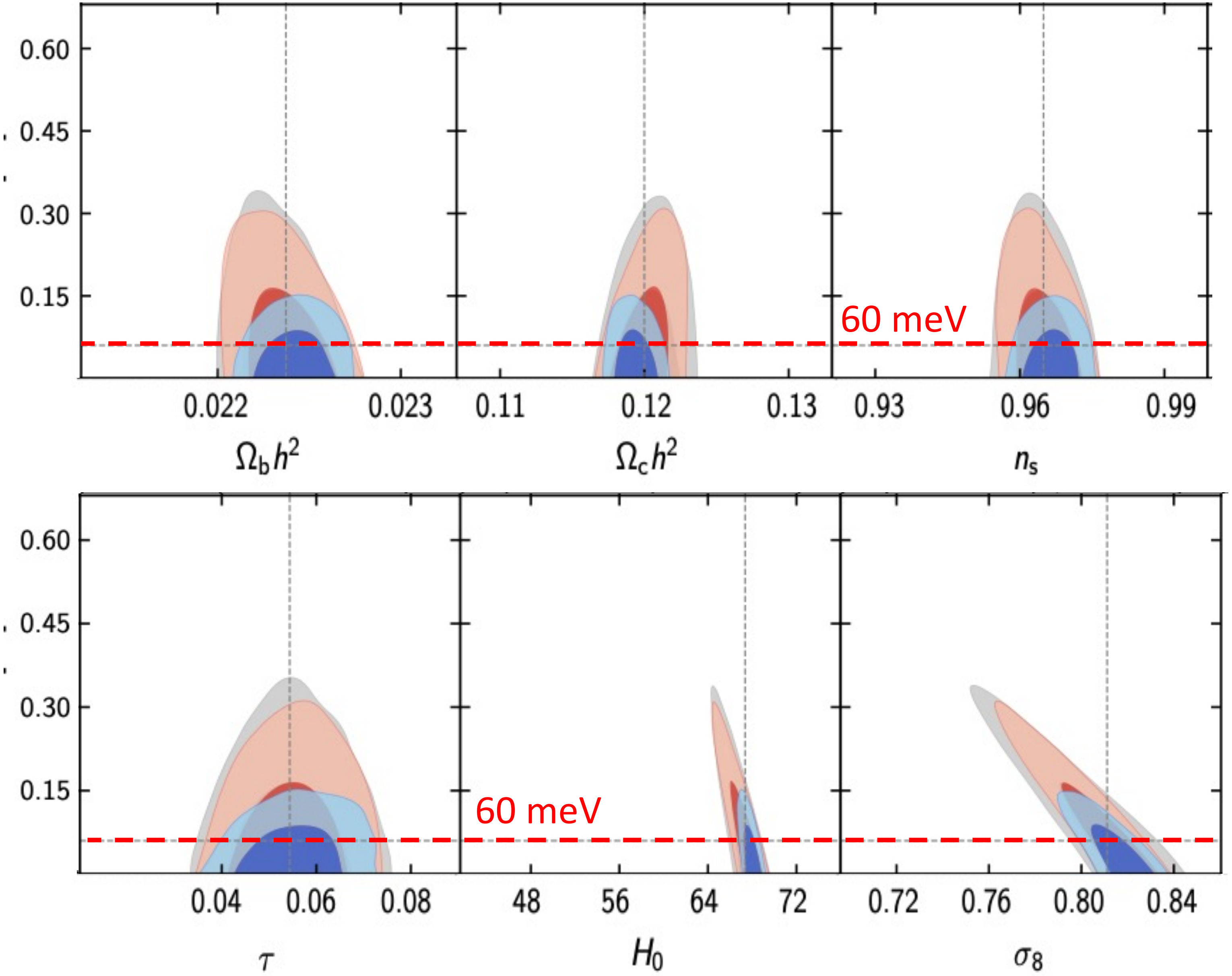
- The combination of cosmological data used
- The assumed cosmological model: number of parameters (problem of parameter degeneracies)
- The properties of relic neutrinos

Planck: 1-parameter extensions of the ΛCDM model

68+95%
Conf regions

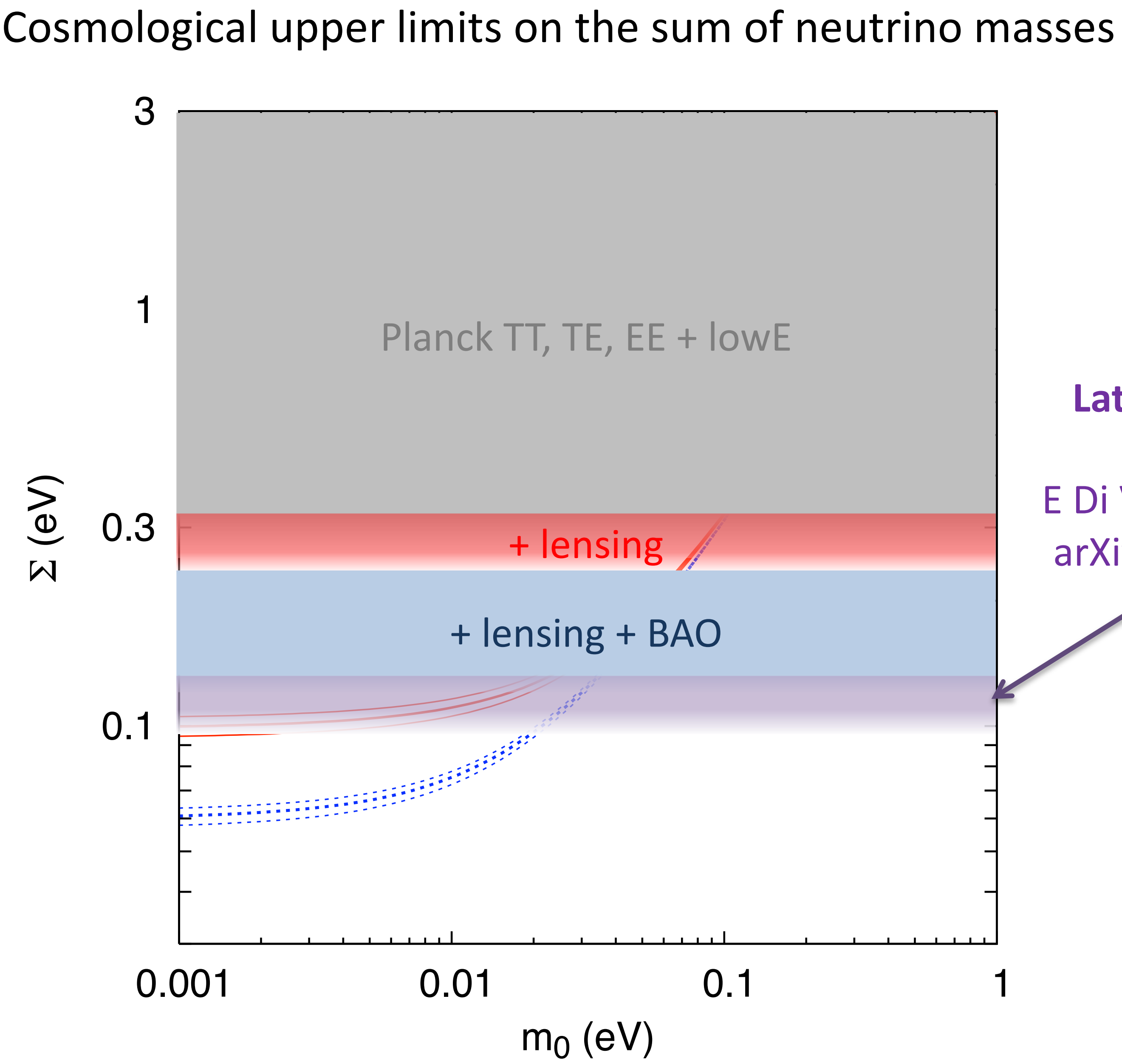
Planck TT, TE, EE + lowE + lensing + lensing + BAO

Σm_ν
(eV)



Planck Collab,
A&A **641** (2020) A6

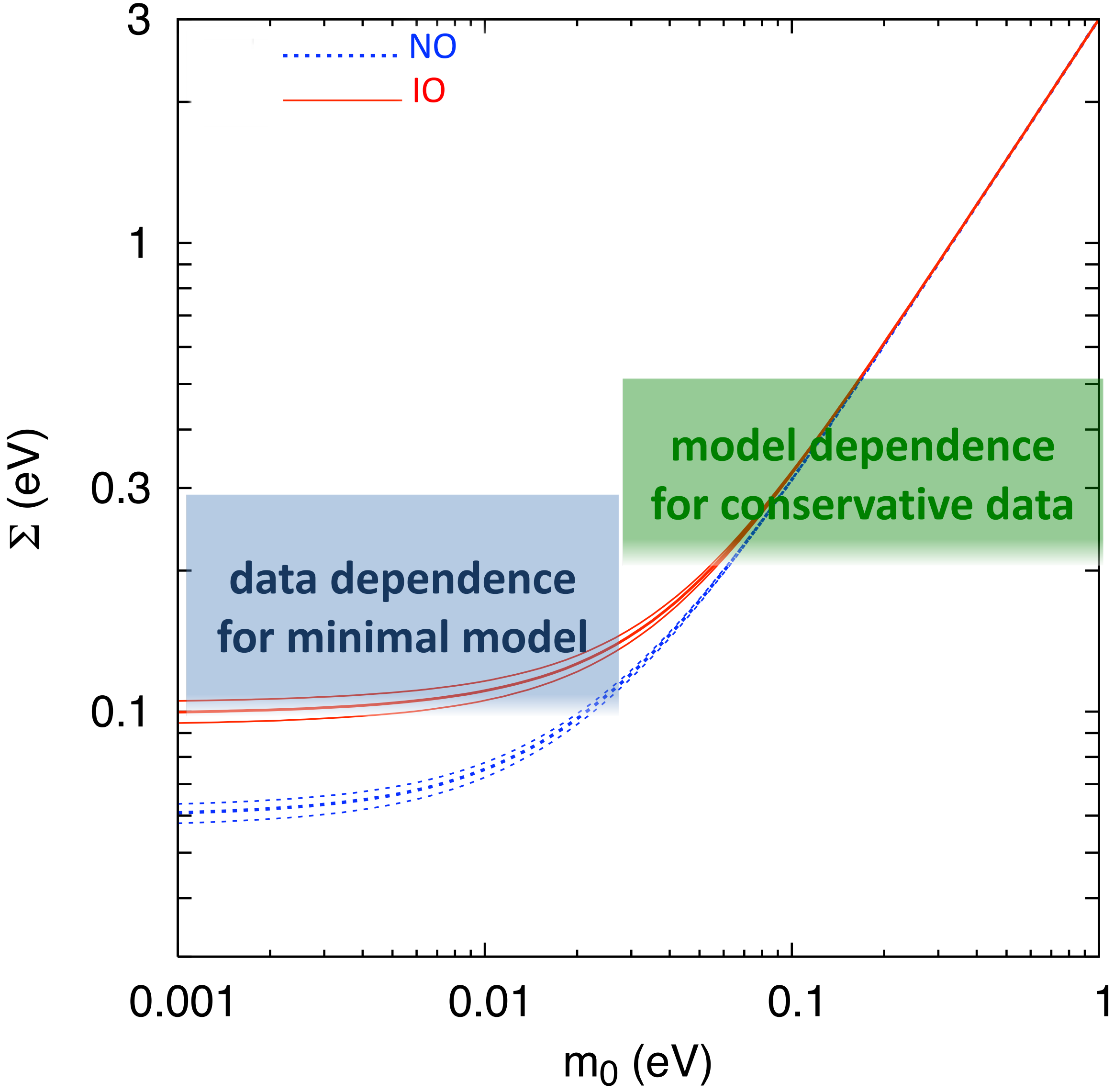
Bounds on Σm_ν from Planck (+other cosmo data)



Latest analyses
see e.g.
E Di Valentino et al
arXiv:2106.15267

Bounds on Σm_ν from Planck (+other cosmo data)

Cosmological upper limits on the sum of neutrino masses



Probing the absolute neutrino mass scale

Searching for non-zero neutrino mass in laboratory experiments

- Tritium beta decay: measurements of endpoint energy

$$^3H \rightarrow\ ^3He + e^- + \bar{\nu}_e$$

$m_\beta < 2.2$ eV (95% CL)   Mainz

Current experiment (KATRIN) **$m(\nu_e) < 0.8$ eV** (90% CL)

- Neutrinoless double beta decay: if Majorana neutrinos

$$(A, Z) \rightarrow\ (A, Z+2) + 2e^-$$

experiments with ^{76}Ge, ^{130}Te, ^{136}Xe and other isotopes:
$m_{\beta\beta} < 60\text{-}600$ meV , depending on NME

Probing the absolute neutrino mass scale

Tritium β decay	$m_\beta = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$	80 meV

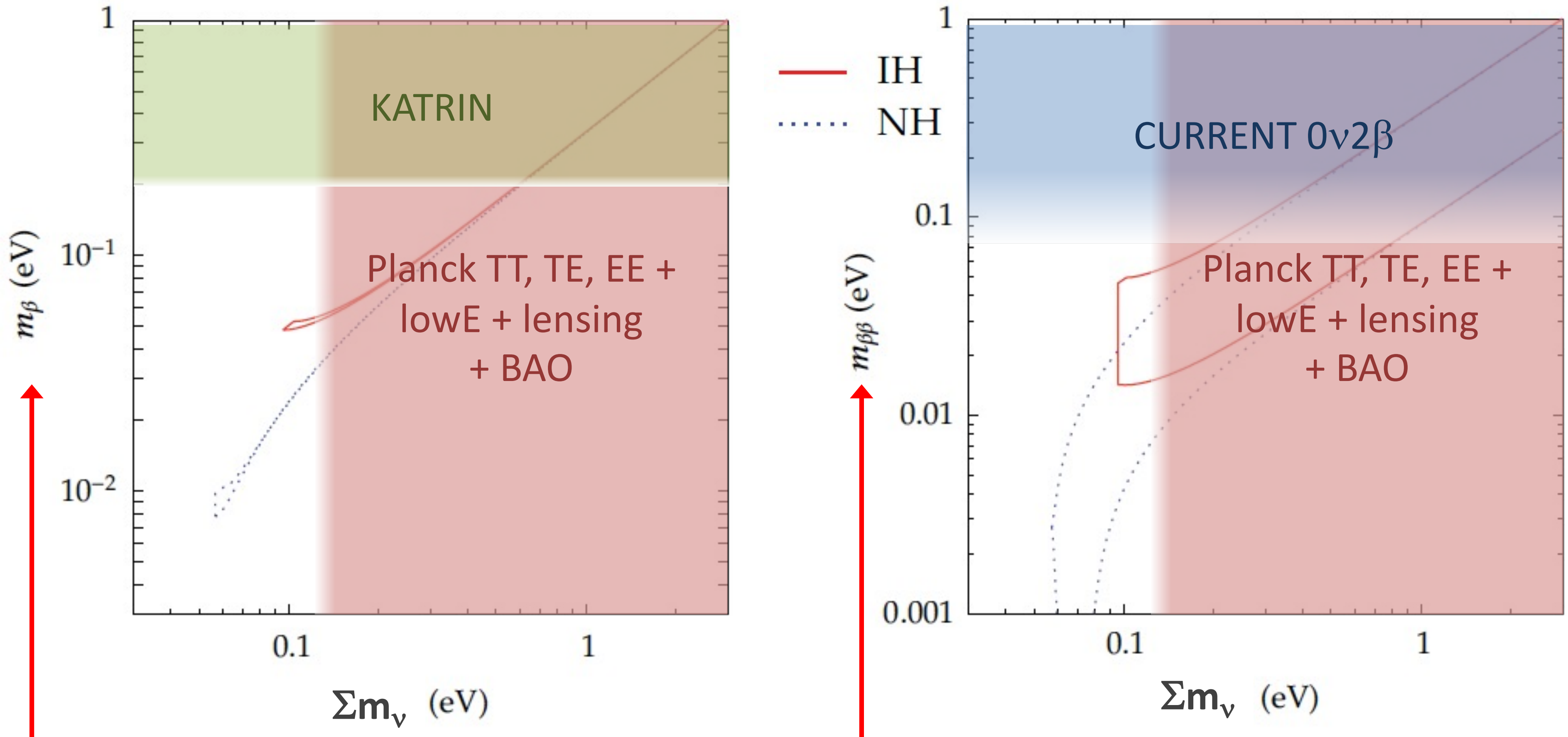
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

Neutrinoless double beta decay	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	$<$ 60-600 meV

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

Cosmology	$\sim \sum_i m_i$	$<$ 90-500 meV

Tritium β decay, 0ν2β and Cosmology



$$\left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{1/2}$$

$$\left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Bounds on active-sterile oscillations (3+1 case)

Mixing of four neutrino states?

Additional neutrino (sterile) **states** introduced in order to explain some anomalies in experimental data

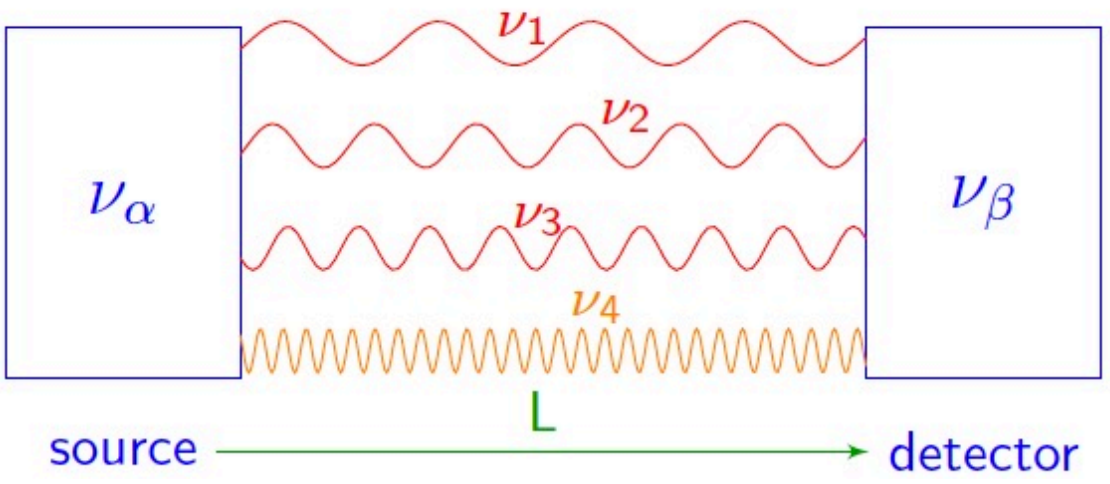
4 flavour neutrinos, **4** massive neutrinos

4x4 mixing matrix
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

We consider **3 (active)** + **1 (sterile)**, a perturbation of the 3-neutrino case

$$m_4 \gg m_\ell$$
$$\ell = 1, 2, 3$$

$$\Delta m^2_{41} \simeq 1 \text{ eV}^2$$
$$\simeq \Delta m^2_{42}$$
$$\simeq \Delta m^2_{43}$$



6 angles

3 Dirac CP phases

3 Majorana CP phases

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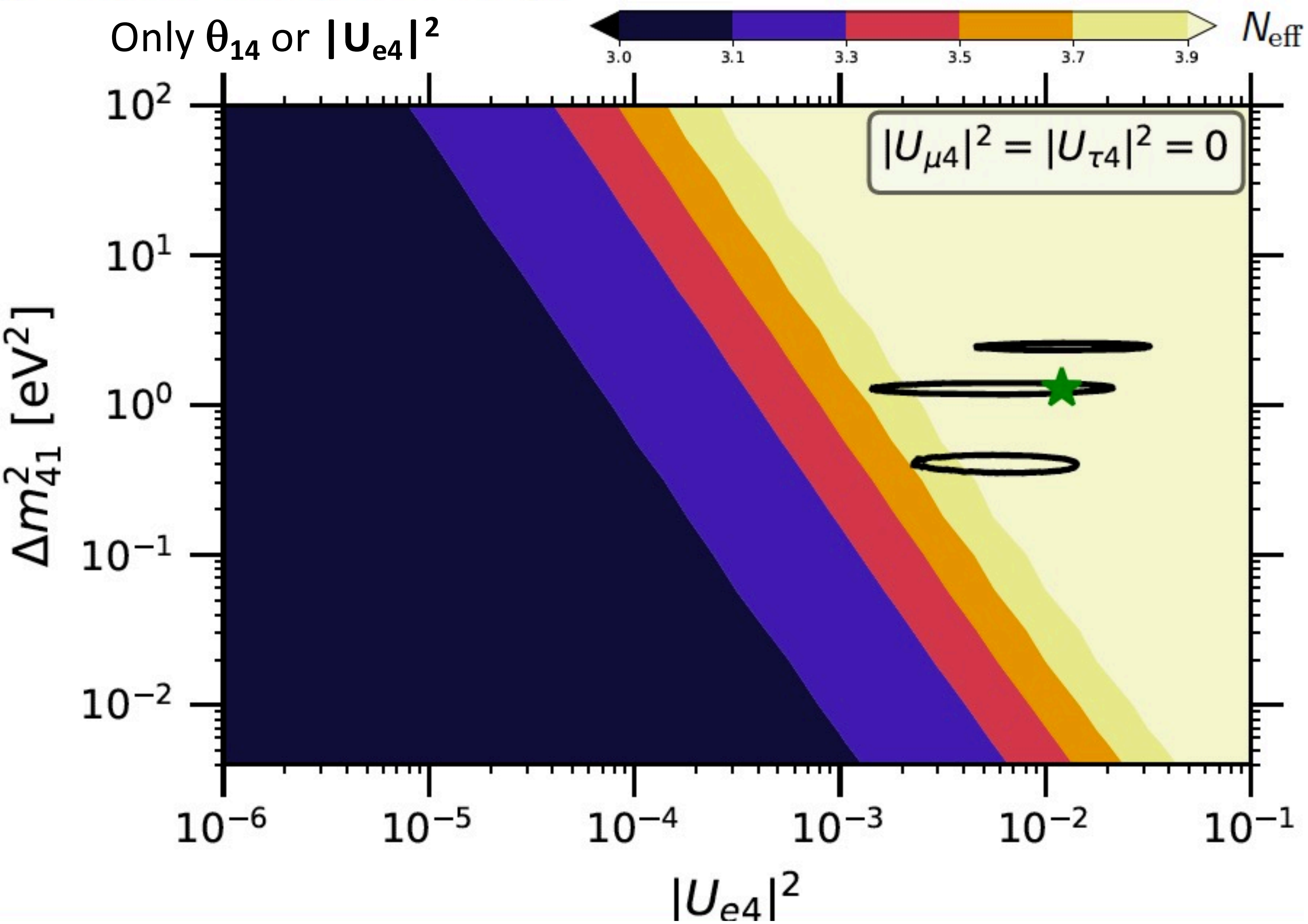
We consider **3 (active)** + **1 (sterile)**, a perturbation of the 3-neutrino case

$$\begin{aligned} |U_{e4}|^2 &= \sin^2\theta_{14}, \\ |U_{\mu 4}|^2 &= \cos^2\theta_{14}\sin^2\theta_{24}, \\ |U_{\tau 4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}, \\ |U_{s4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}. \end{aligned}$$

Results: final value of N_{eff} and sterile mixing parameters

Only θ_{14} or $|U_{e4}|^2$



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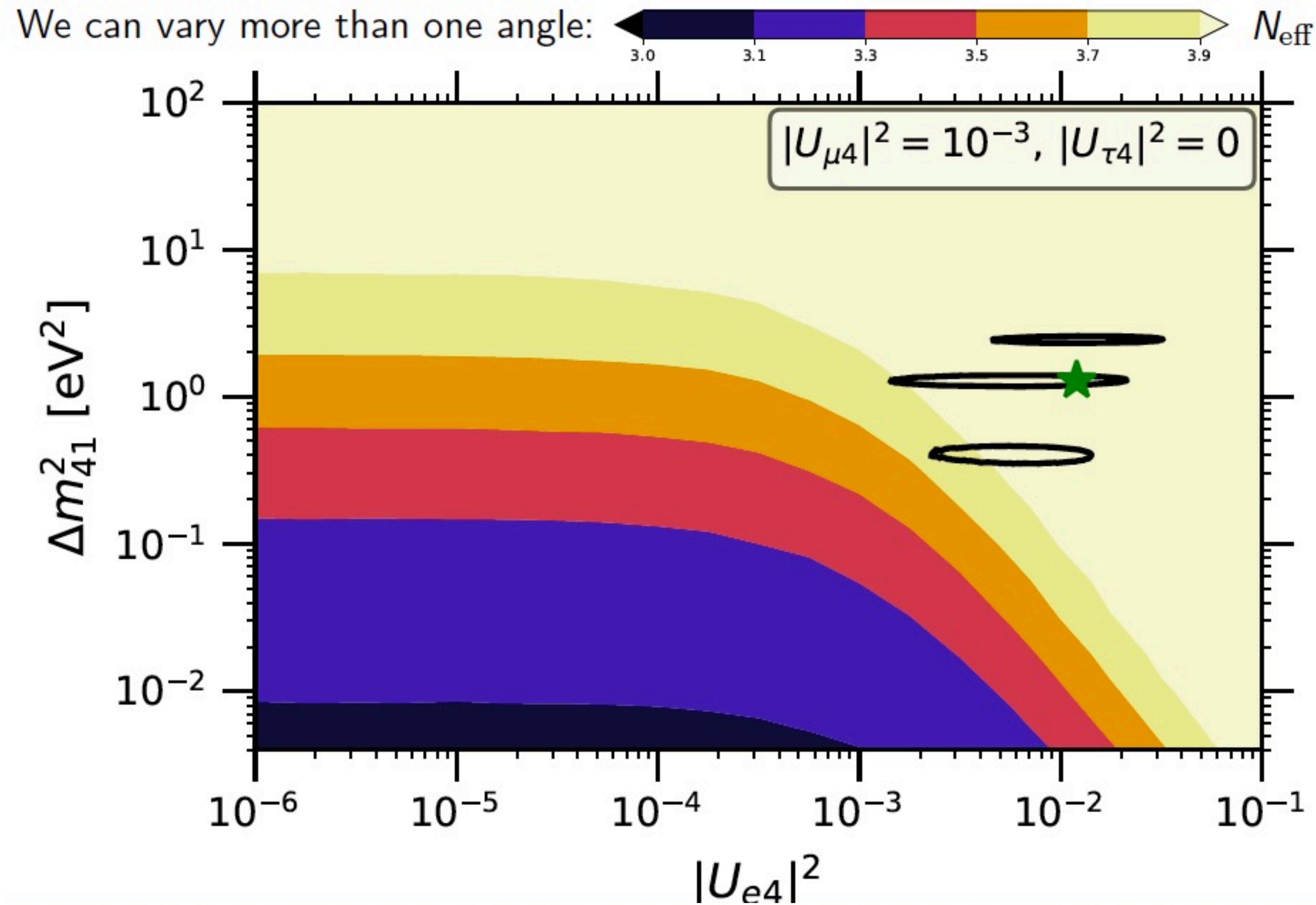
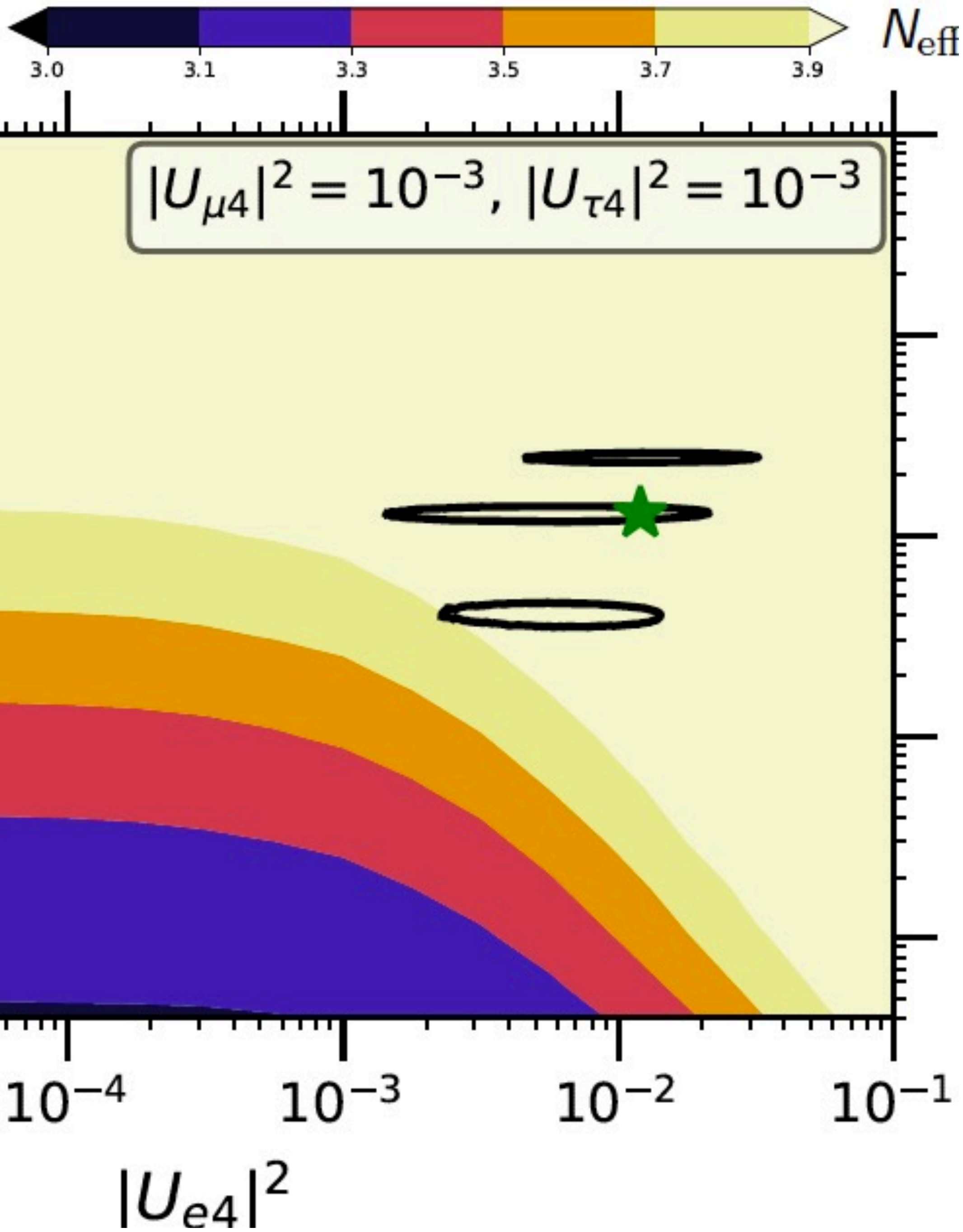


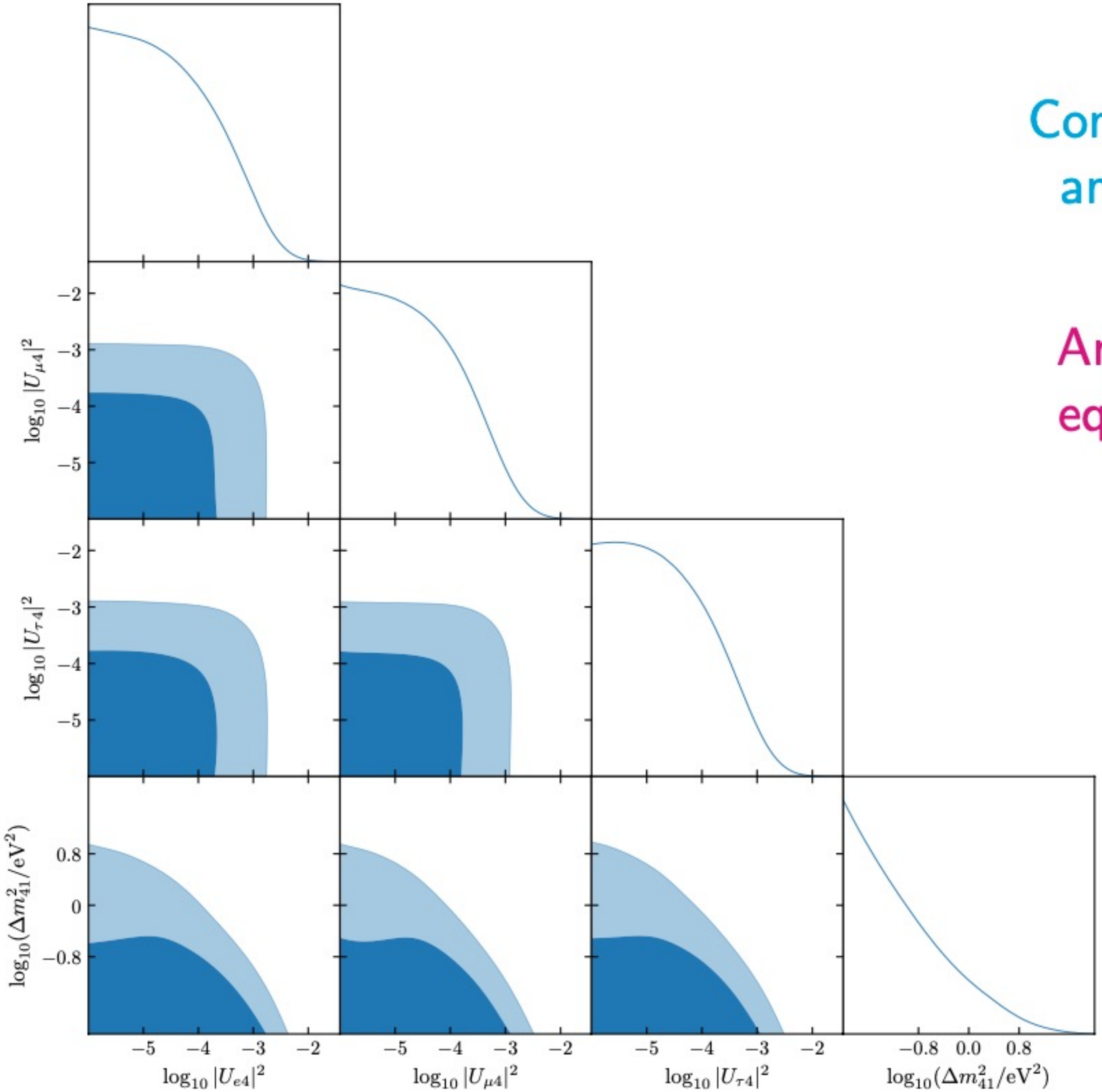
Results: final value of N_{eff} and sterile mixing parameters

We can vary more than one angle:



Cosmological bounds on active-sterile mixing parameters

Use multi-angle results from `FortEPiaNO` to derive constraints on $|U_{\alpha 4}|^2$:



Constraints come from N_{eff} and late-time density Ω_s

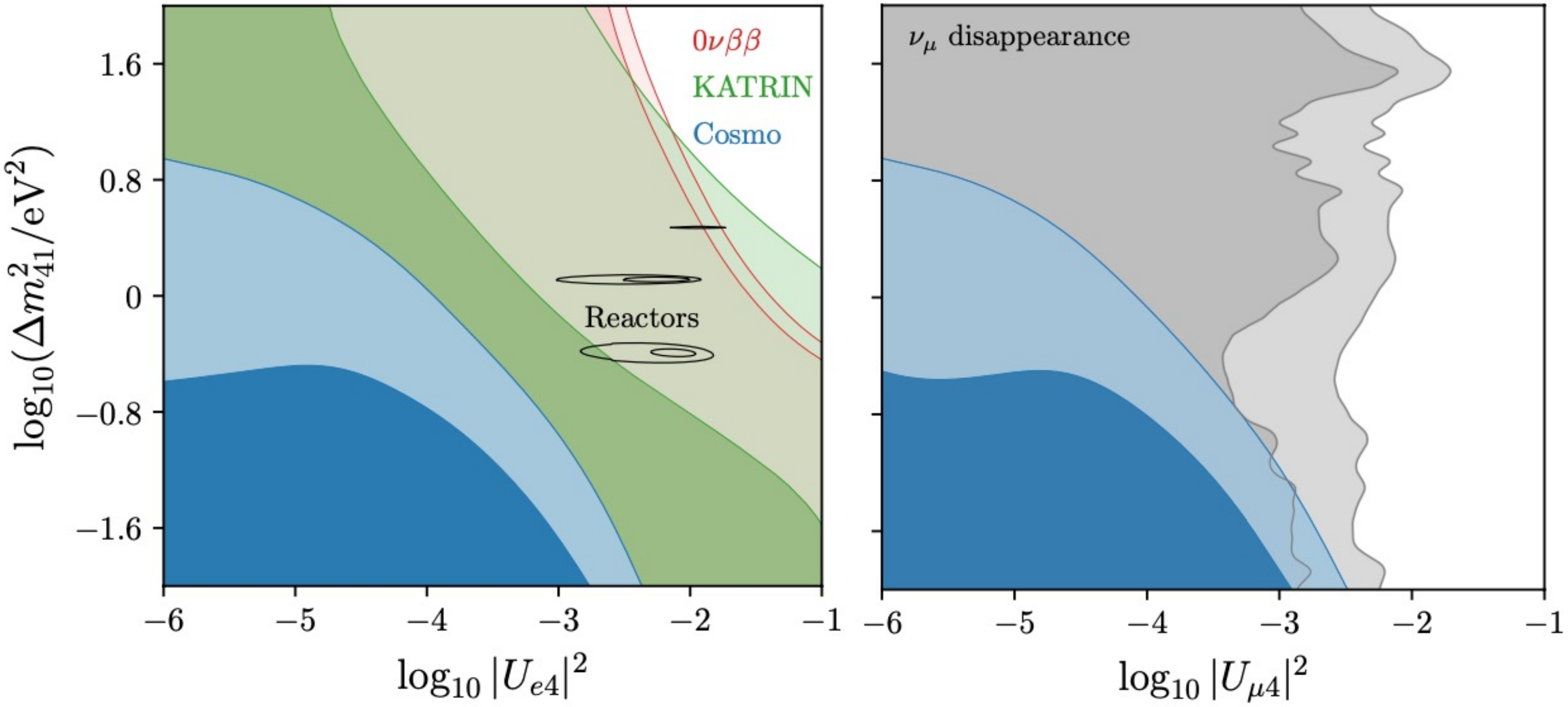
Angles $|U_{\alpha 4}|^2$ are almost equivalent for cosmology

S Hagstotz et al, arXiv:2003.02289

Bounds on active-sterile mixing parameters

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!



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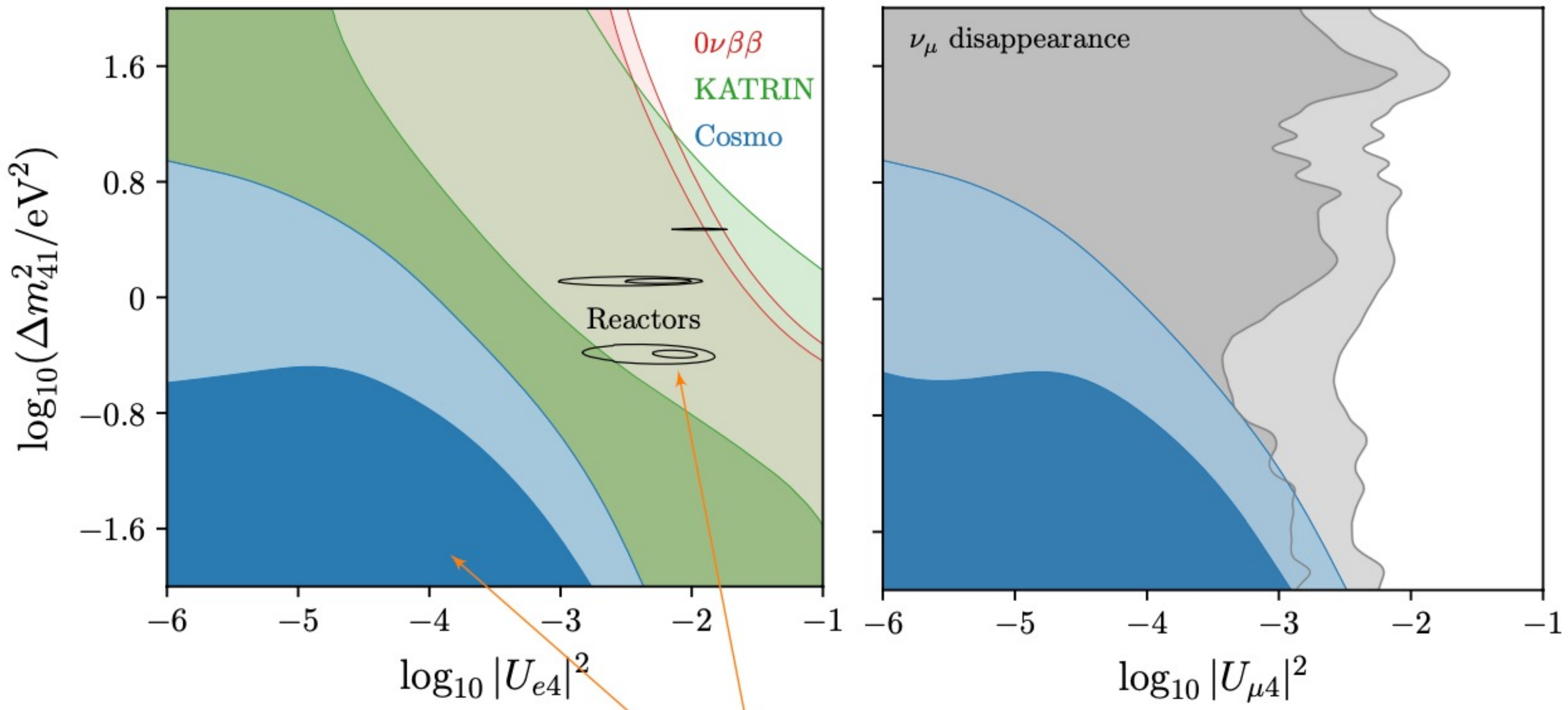
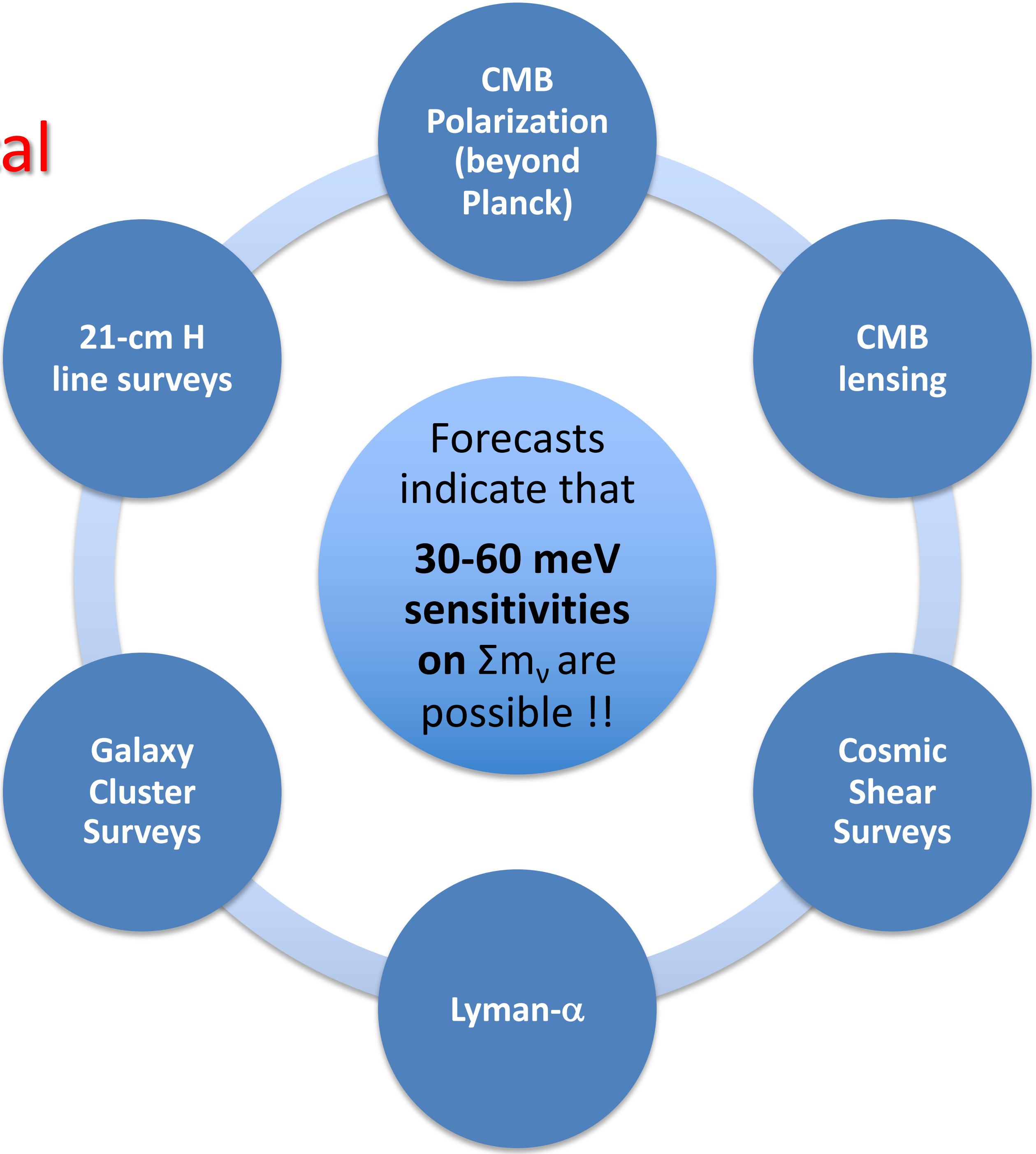


S Hagstotz et al, arXiv:2003.02289

Warning: tension between reactor experiments and CMB bounds!

Future sensitivities on neutrino physics from cosmology

Future cosmological data



CMB Polarization (beyond Planck)

CMB lensing

Cosmic Shear Surveys

Lyman-α

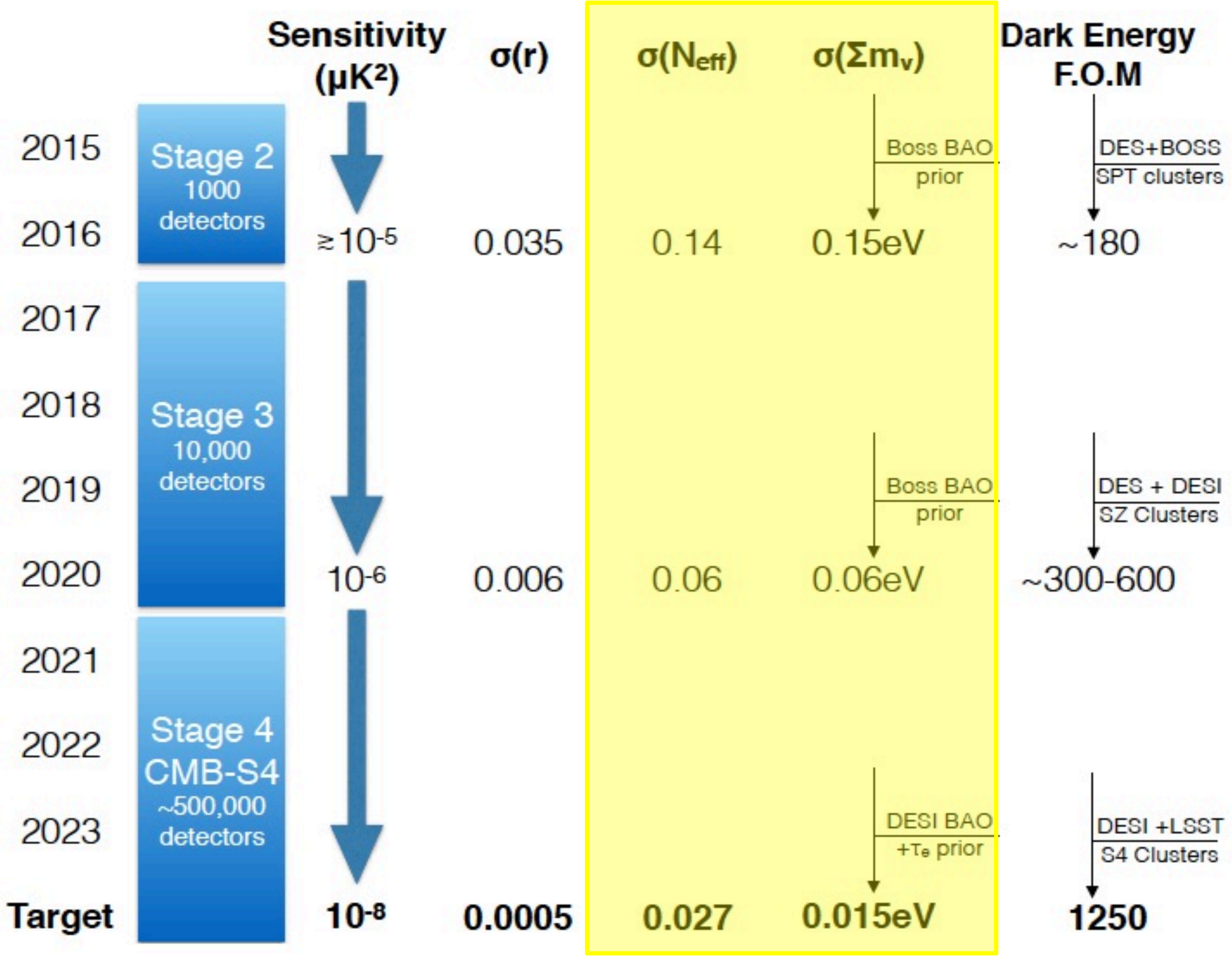
Galaxy Cluster Surveys

21-cm H line surveys

Forecasts indicate that

30-60 meV sensitivities on Σm_ν are possible !!

Future sensitivities on N_{eff} and neutrino masses



		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+T_e$ prior	DESI +LSST S4 Clusters
Target		$\mathbf{10^{-8}}$	**0.0005**	**0.027**	**0.015eV**	**1250**

CMB-S4 Science Book, 1610.02743

End