NEUTRINO NON-STANDARD INTERACTIONS IN COSMOLOGY

Massimiliano Lattanzi
INFN, sezione di Ferrara

ASI/COSMOS WORKSHOP ON ΛCDM
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THE COSMIC NEUTRINO BACKGROUND

The presence of a background of relic neutrinos (***CνB***) is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});
- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

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

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species
- Free parameters: the three masses (but cosmological evolution mostly depends on their sum)

The Cosmic Neutrino Background

Weak cross section: $\sigma \simeq G_F^2 T^2$

Weak interaction rate $\Gamma = n\langle\sigma v\rangle \sim G_F^2 T^5$

Expansion rate $H \simeq \frac{T^2}{m_\mathrm{p}}$

Interactions become ineffective when $T=T_\mathrm{d}$ such that

$$1 \simeq \frac{\Gamma}{H} \sim G_F^2 T^3 m_\mathrm{p} \sim \left(\frac{T}{\mathrm{MeV}}\right)^3$$

Given this, we can use conservation laws to compute the temperature, density, etc… of neutrinos at a given time.

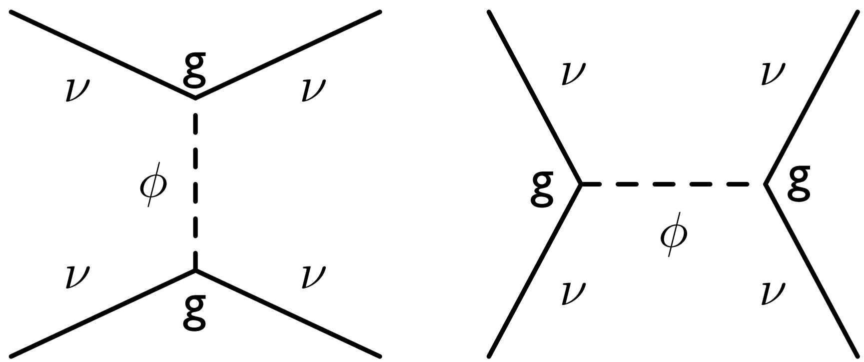
THE COSMIC NEUTRINO BACKGROUND

Why ν non-standard interactions?

- Why not? nuNSI are grounded in particle physics models and might be related to neutrino mass generation (e.g. Majoron models)
- Why not (II)? Relic ν's are extremely difficult to detect directly. It is a good idea to test their properties.
- Might help in explaining the LCDM tensions….

COSMOLOGICAL PHENOMENOLOGY OF νNSI

Collisional processes affect the perturbation evolution of relic neutrinos



Two limiting regimes:

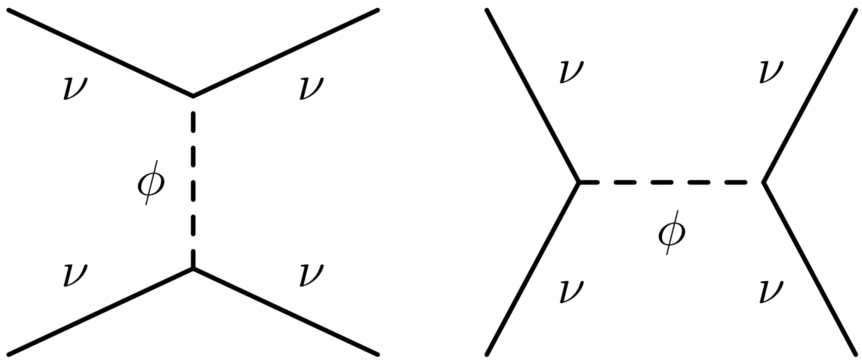
Light mediator ($M_\phi << T$) $\quad \langle \sigma v \rangle \sim \frac{g^4}{E^2} \sim \frac{g^4}{T^2}$

Heavy mediator ($M_\phi >> T$) $\quad \langle \sigma v \rangle \sim \frac{g^4}{M_\phi^4} E^2 \sim G_\phi^2 T^2$

$$G_\phi \equiv \frac{g^2}{M_\phi^2}$$

COSMOLOGICAL PHENOMENOLOGY OF νNSI

Collisional processes can suppress stress and affect the perturbation evolution of cosmological neutrinos



In the UR limit:

$$\sigma \sim \frac{g^4}{s} \sim \frac{g^4}{T^2}$$

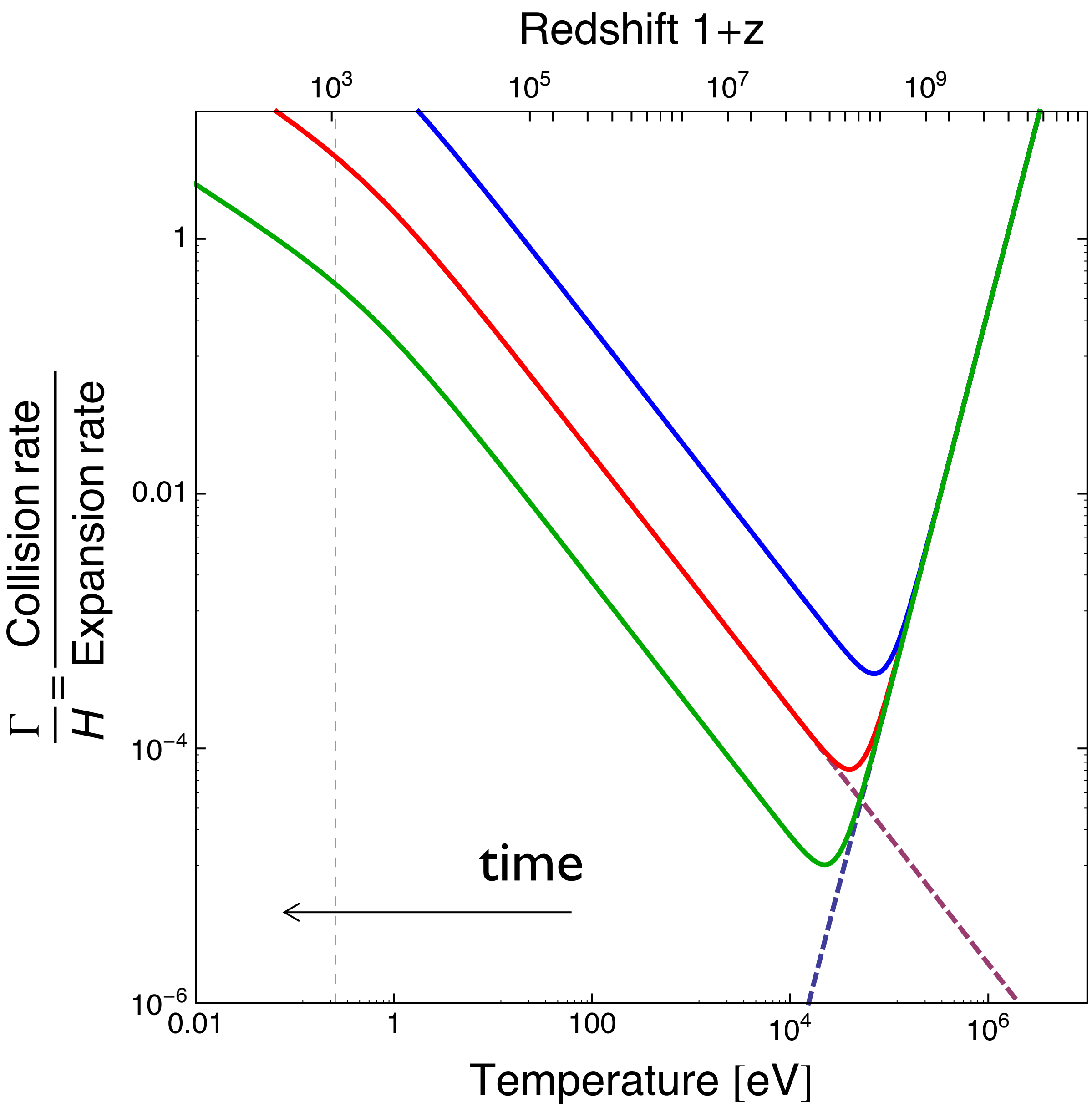
e.g., in simple majoron models: $\sigma \simeq \frac{1}{32\pi}\frac{g^4}{s}$

$$\longrightarrow \quad \Gamma_{\nu\nu} = \langle \sigma_{\mathrm{bin}} v \rangle n_{\mathrm{eq}} \propto g^4 T\,,$$

H grows as T^2 (RD) and $T^{3/2}$ (MD) so the ratio Γ/H *increases* with time. Neutrinos **recouple** at low temperatures!
In the following I write generically

$$\Gamma_{\nu\nu} = (\dots) \times \frac{g^4}{T_\nu^2} \times \frac{3\zeta(3)}{2\pi^2} T_\nu^3 = g_{\mathrm{eff}}^4 \times \frac{3\zeta(3)}{2\pi^2} T_\nu$$

COSMOLOGICAL PHENOMENOLOGY OF νNSI



Light mediator

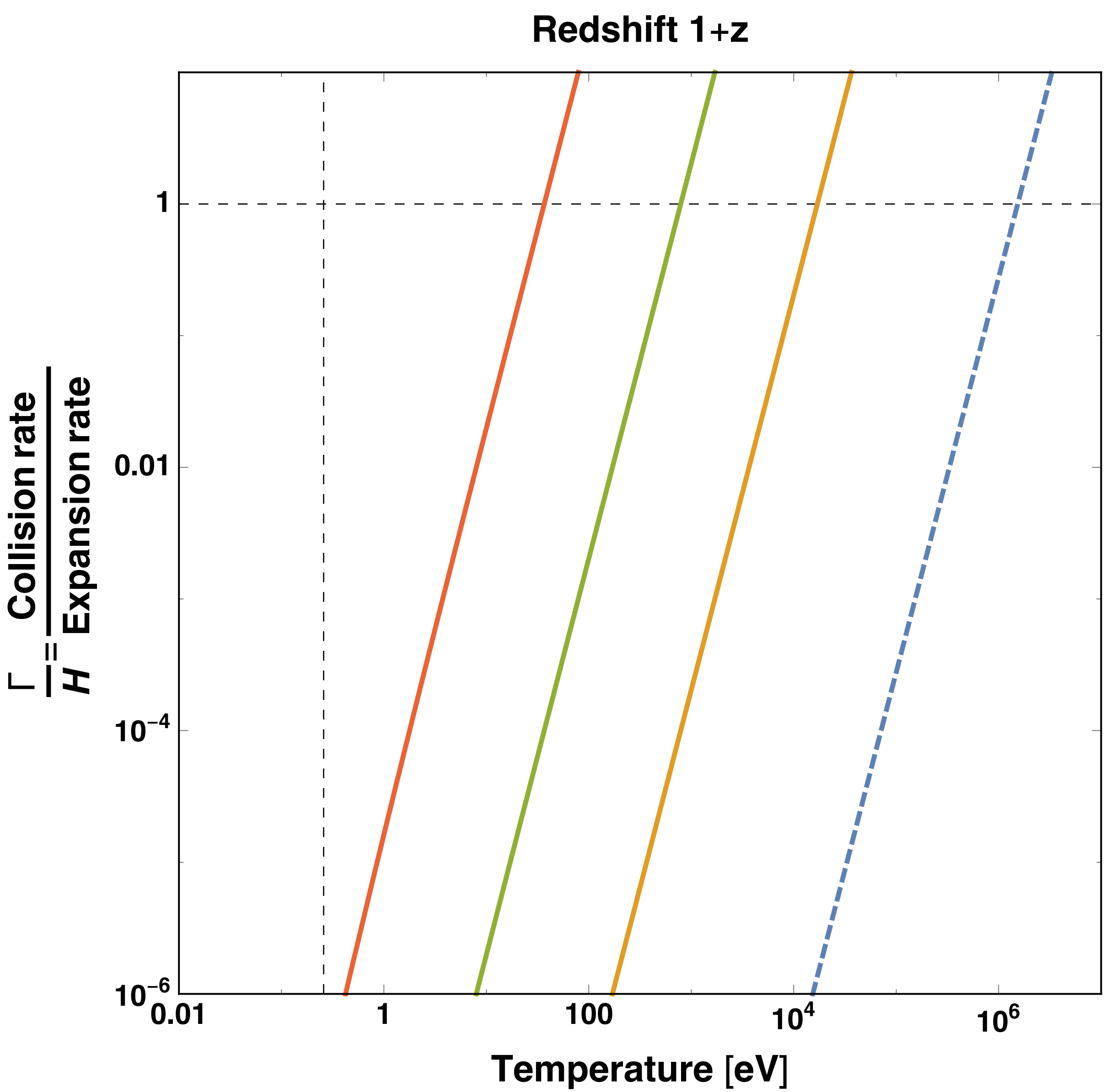
$$\frac{\Gamma}{H} \sim \frac{g^4 M_{\rm Pl}}{T}$$

g_{eff} = 1.5 x 10^{-7}

g_{eff} = 2.7 x 10^{-7}

g_{eff} = 5 x 10^{-7}

COSMOLOGICAL PHENOMENOLOGY OF νNSI



Heavy mediator

$$\frac{\Gamma}{H} \sim G_\phi^2 T^3 M_{\mathrm{Pl}}$$

$G_\phi = (10\ \mathrm{GeV})^{-2}$

$G_\phi = (1\ \mathrm{GeV})^{-2}$

$G_\phi = (0.1\ \mathrm{GeV})^{-2}$

Cosmological Phenomenology of νNSI

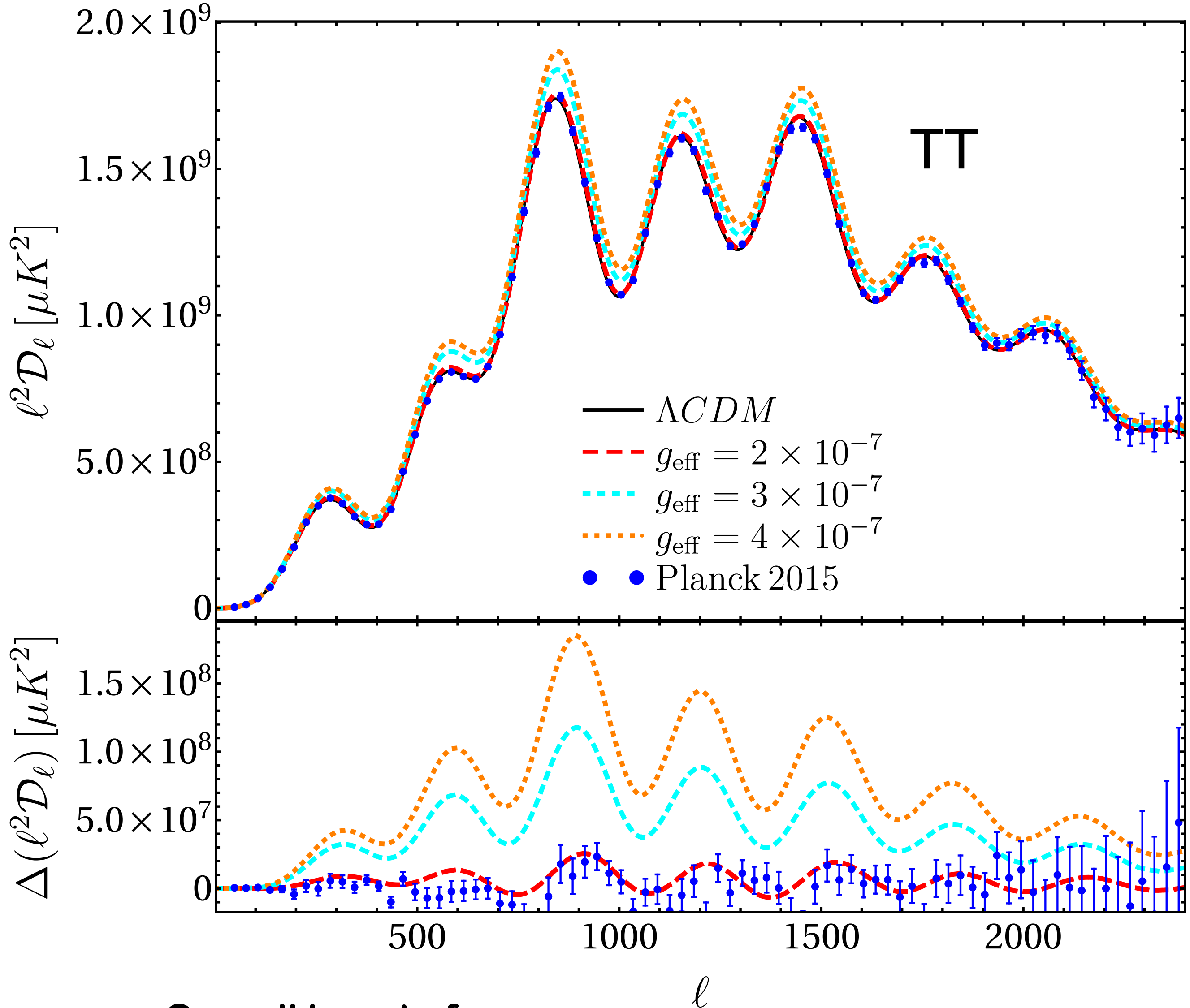
Neutrino free-streaming affects photon perturbations in two ways (Bashinsky & Seljak 2004):

- by "pulling" ahead photon-baryon wavefronts: this imprints a phase shift in the CMB power spectra

- by making gravitational potentials decay away more rapidly: this suppresses the amplitude of the spectrum

Both effects happen at the time the perturbation enters the horizon, and are relevant during the RD era

Light mediator case



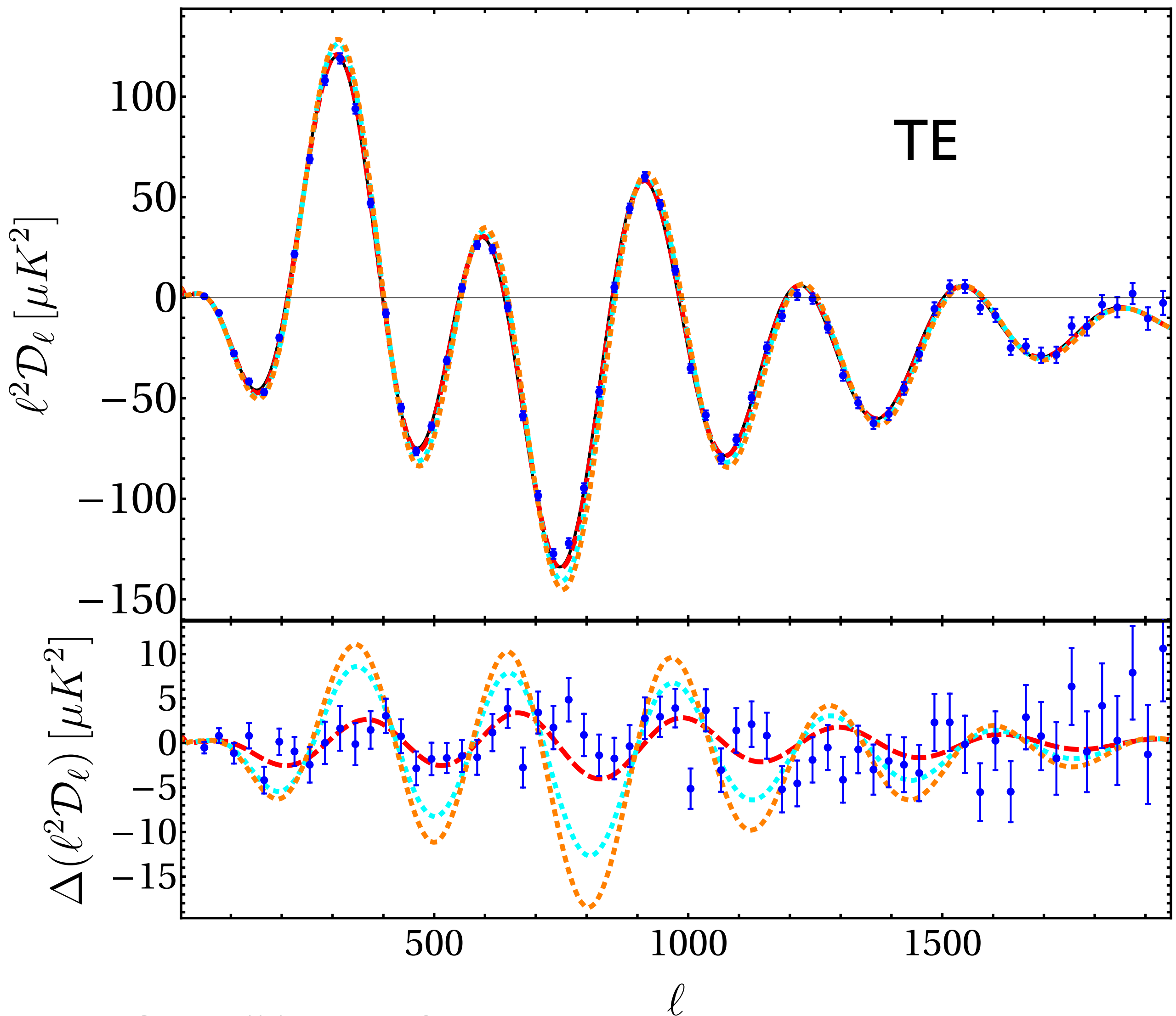
Scales entering the horizon between recoupling and equality are affected

Data points are from Planck 2015

Overall boost of the spectrum amplitude + phase shift

(Forastieri, ML, Natoli, 2015, 2019; see also Archidiadono, Hannestad 2013; Cyr-Racine, Sigurdson 2013)

Light mediator case



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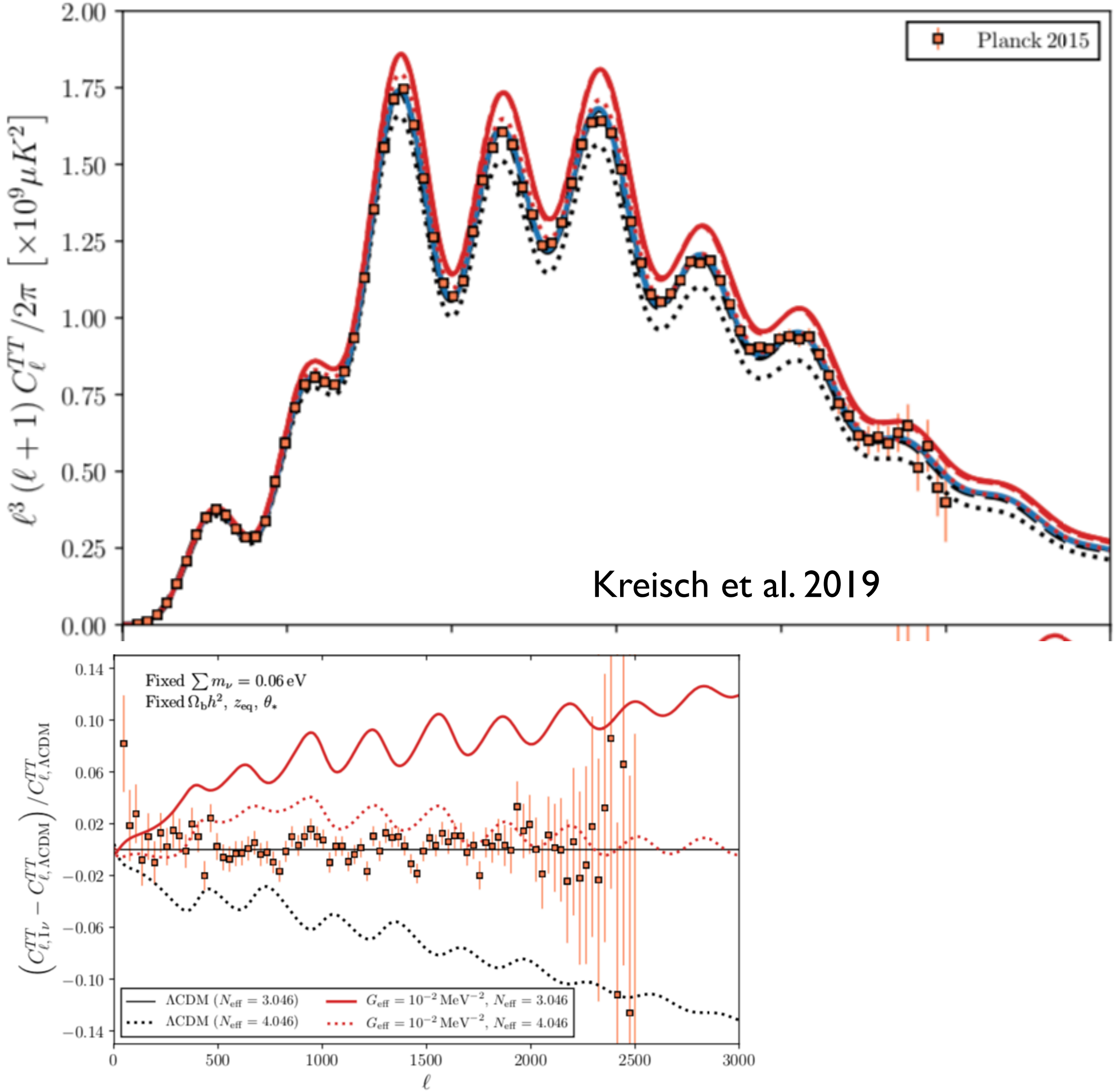
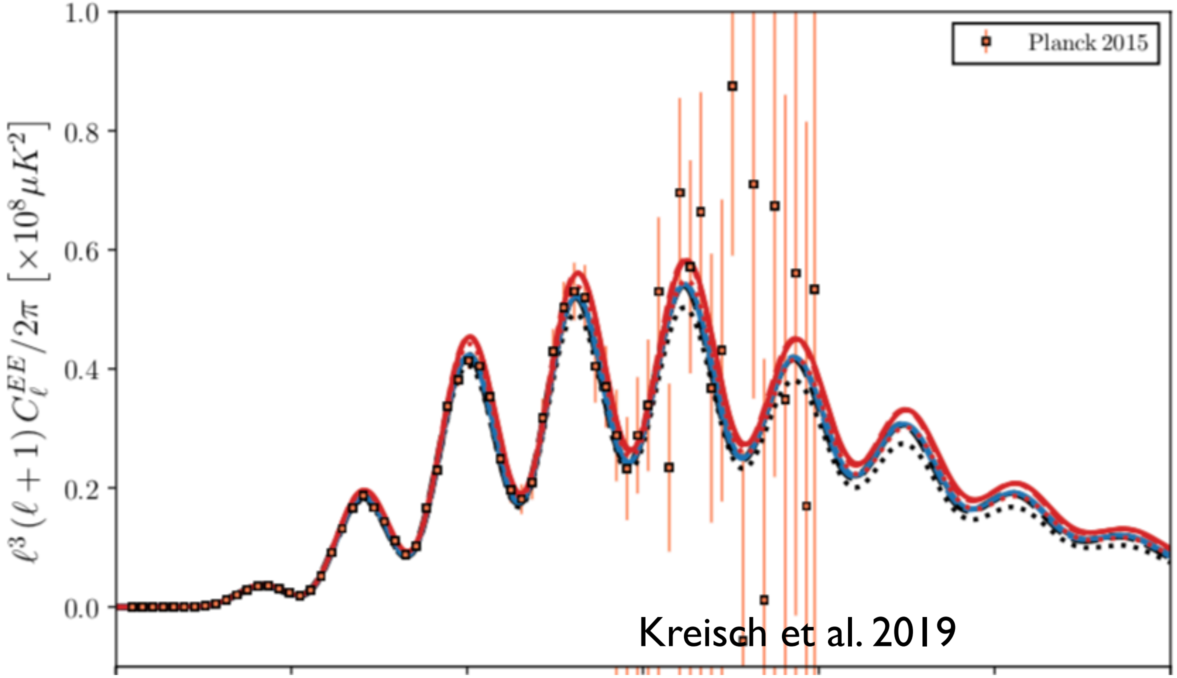
Heavy mediator case

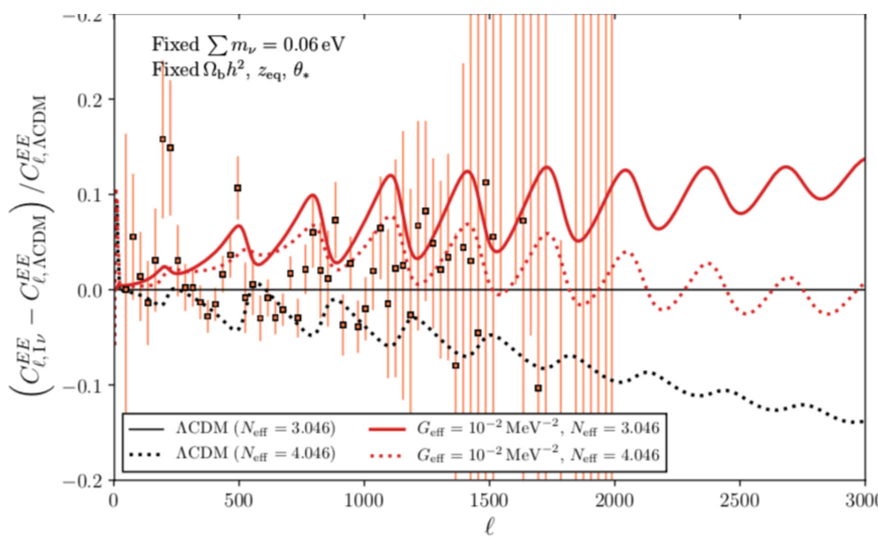
Scales entering the horizon before decoupling are affected



Heavy mediator case



Kreisch et al. 2019



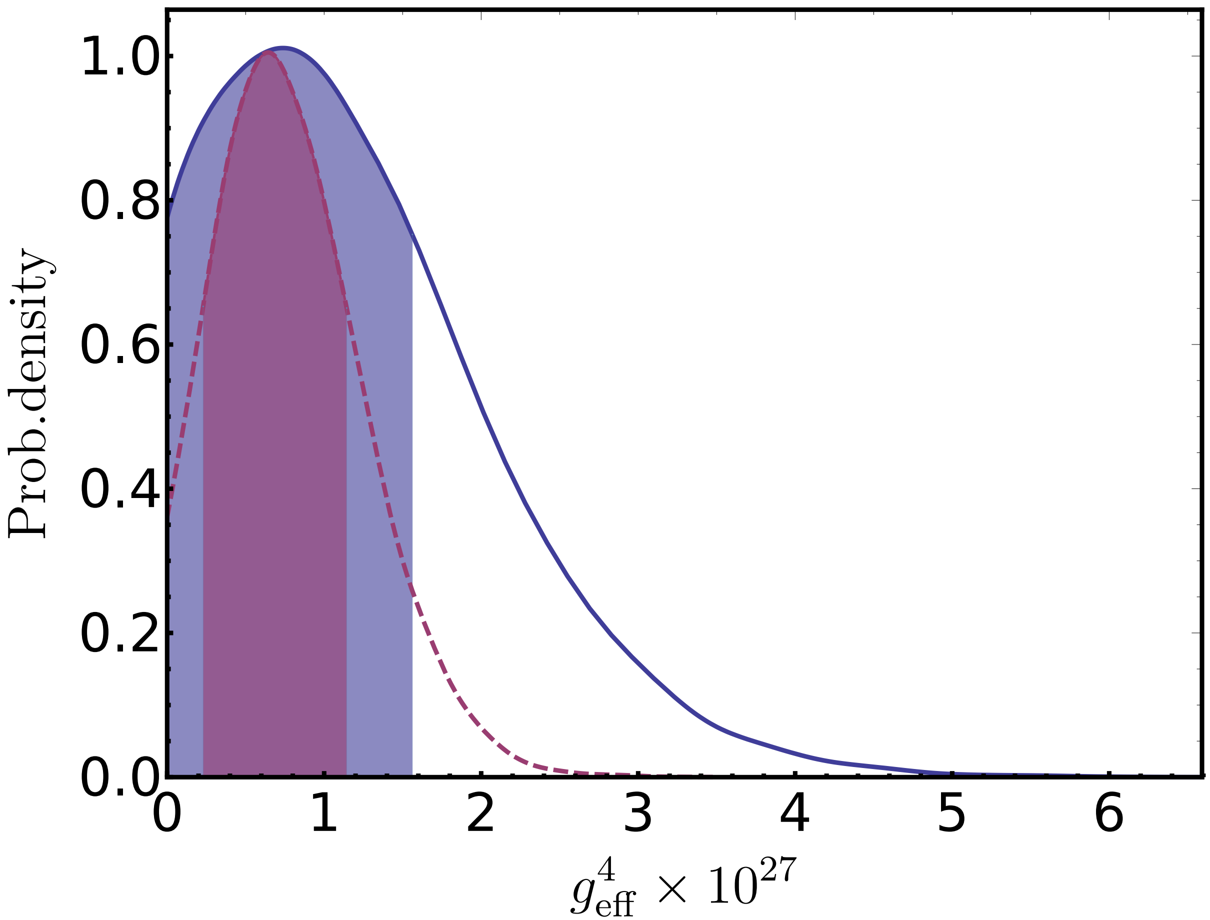
Scales entering the horizon before decoupling are affected

Constraints on NSI from Planck 2015

Light mediator case

PlanckTT(TEEE) +lowP

$g < 2.3\ (2.0) \times 10^{-7}$



$z_{rec} < 5050\ (2500)$

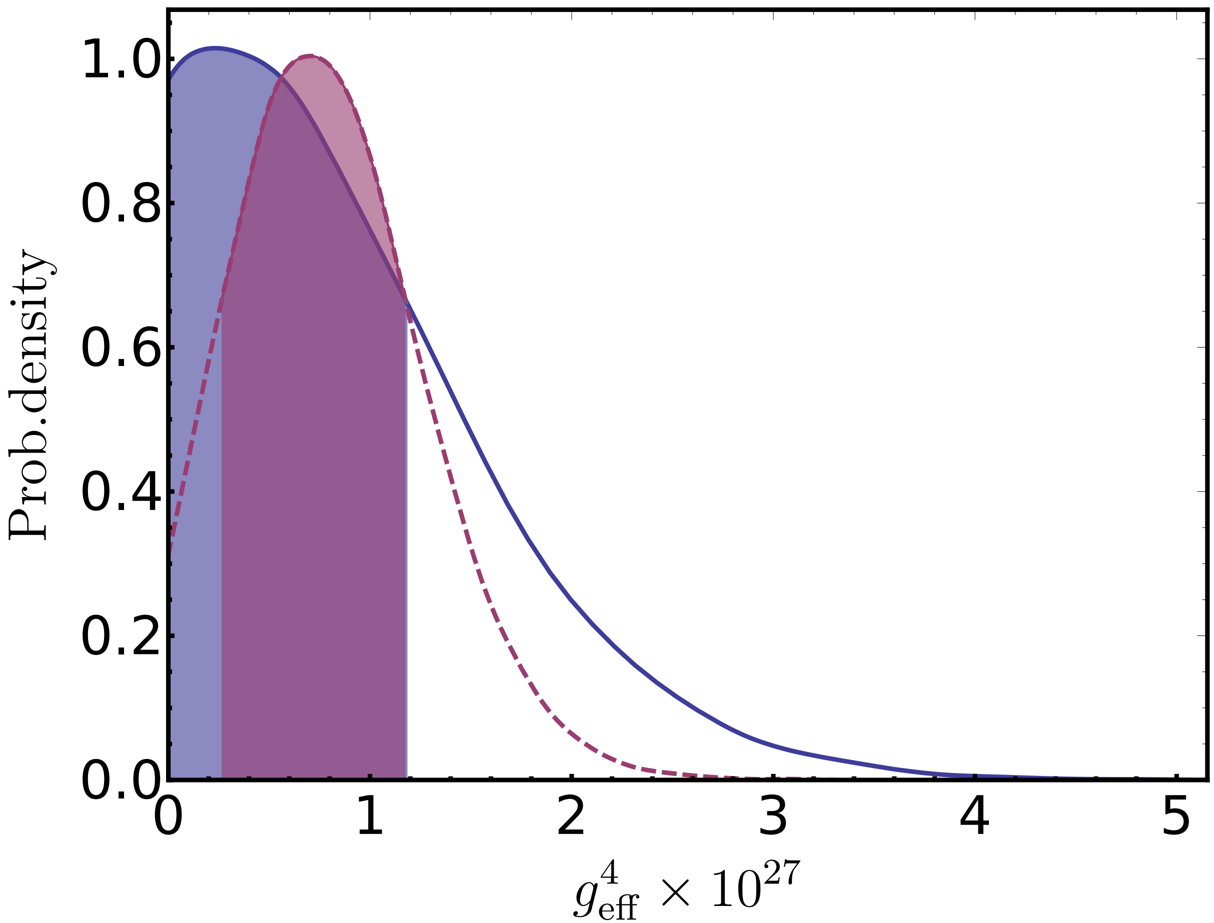
Limits are 95% CL

Forastieri, ML, Natoli, arXiv:1904.07810

CONSTRAINTS ON NSI FROM PLANCK 2015

Light mediator case

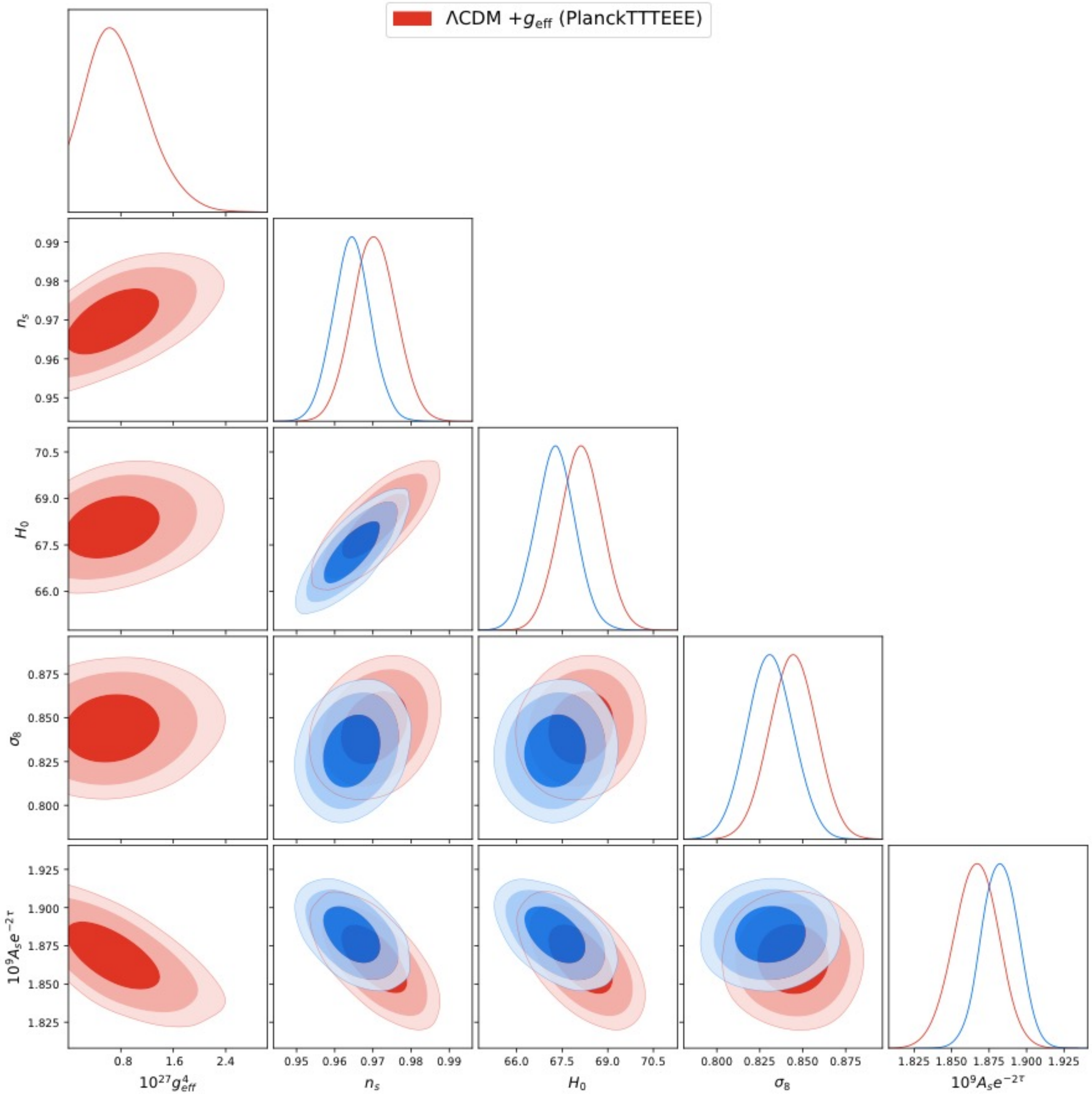
PlanckTT(TEEE) +lowP+lensing
$g < 2.2\ (2.0) \times 10^{-7}$



$z_{rec} < 3800\ (2300)$

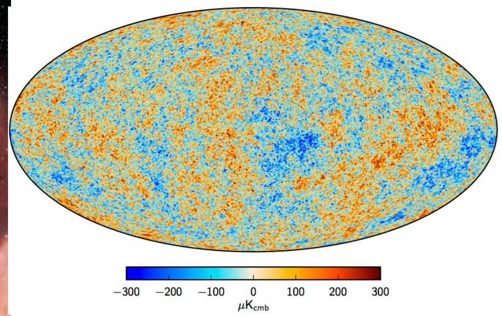
Forastieri, ML, Natoli,
arXiv:1904.07810

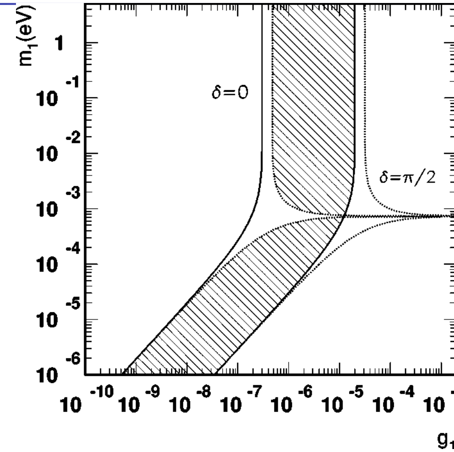
Limits are 95% CL

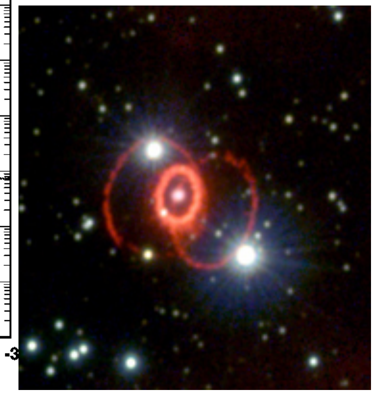


ΛCDM $+g_{\rm eff}$ (PlanckTTTEEE)
$10^{27}g_{eff}^4$
n_s
H_0
σ_8
$10^9A_se^{-2\tau}$

Constraints on Non-Standard Interactions







cosmology

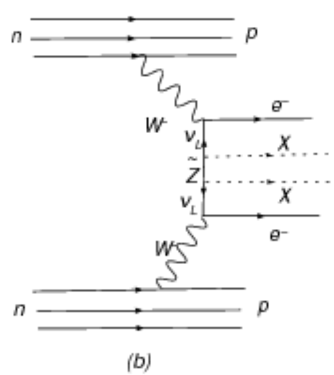
$g_{ij} < 2 \times 10^{-7}$

(mass basis)

Supernovae: $g_{i'j'} < 3 \times 10^{-7}$ or $g_{i'j'} > 2 \times 10^{-5}$

(medium basis)

$$\boxed{\mathcal{L} \supset h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi\,,}$$

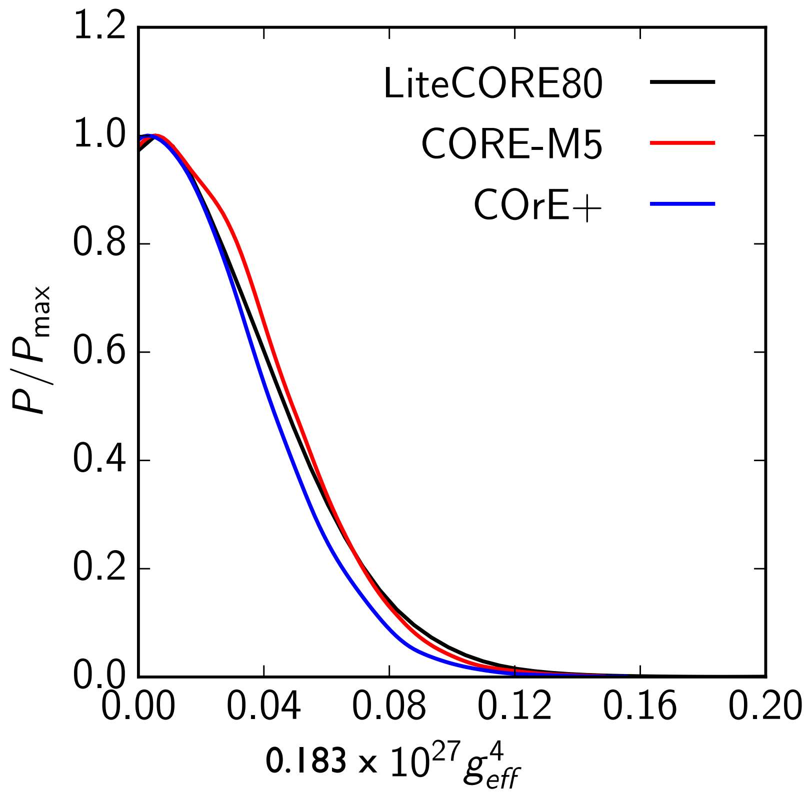


$0\nu2\beta$ decay

$g_{ee} < (0.8 \div 1.6) \times 10^{-5}$

(flavor basis)

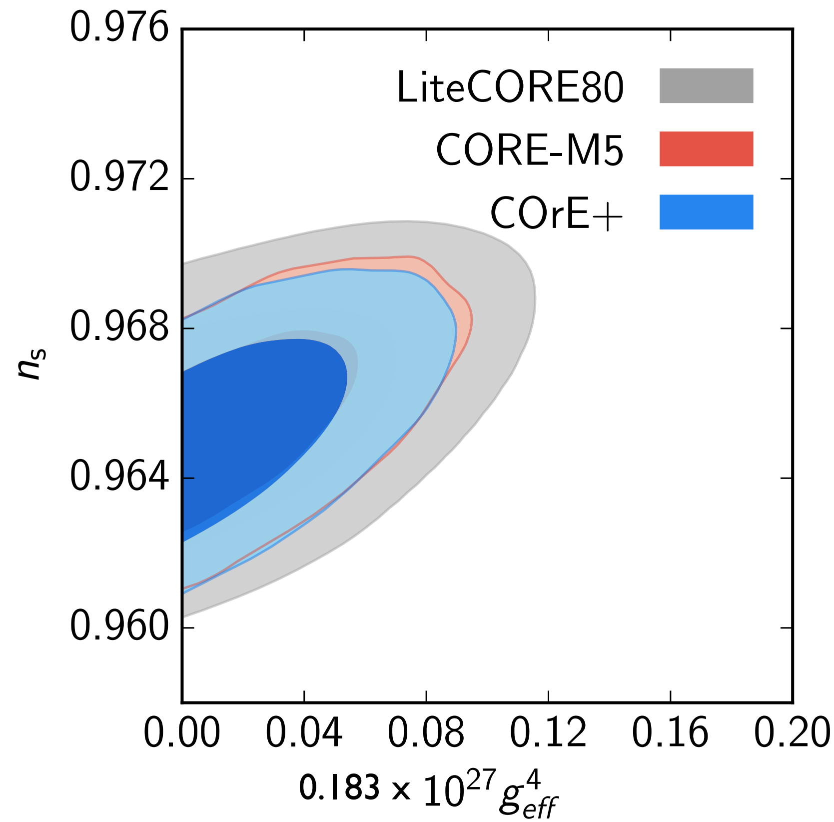
Sensitivity of future experiments for NSI



$g_{eff}^4 < 0.4 \times 10^{-27}$

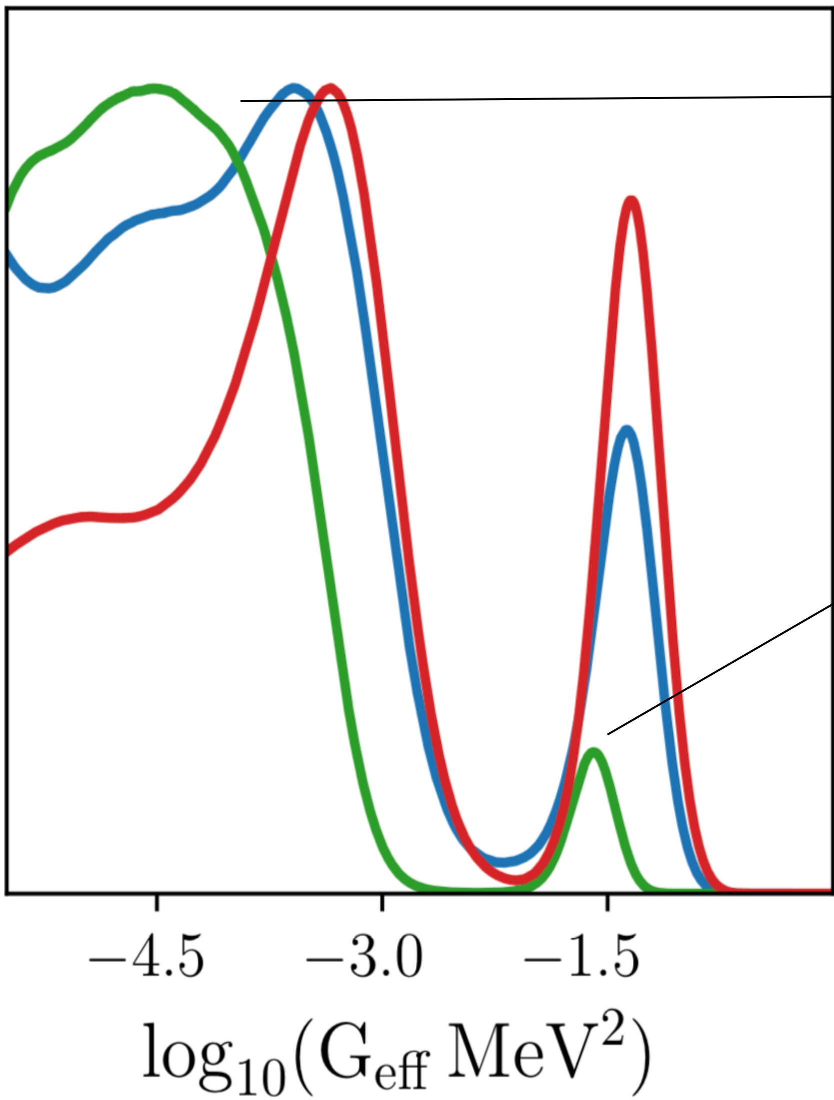
Core Parameters paper
arXiv: 1612.00021

Future generation CMB can improve limits by nearly one order of magnitude



CONSTRAINTS ON NSI FROM PLANCK 2015

Heavy mediator case



$G_{\rm eff} < 1.4 \times 10^2 \,{\rm GeV}^{-2}$

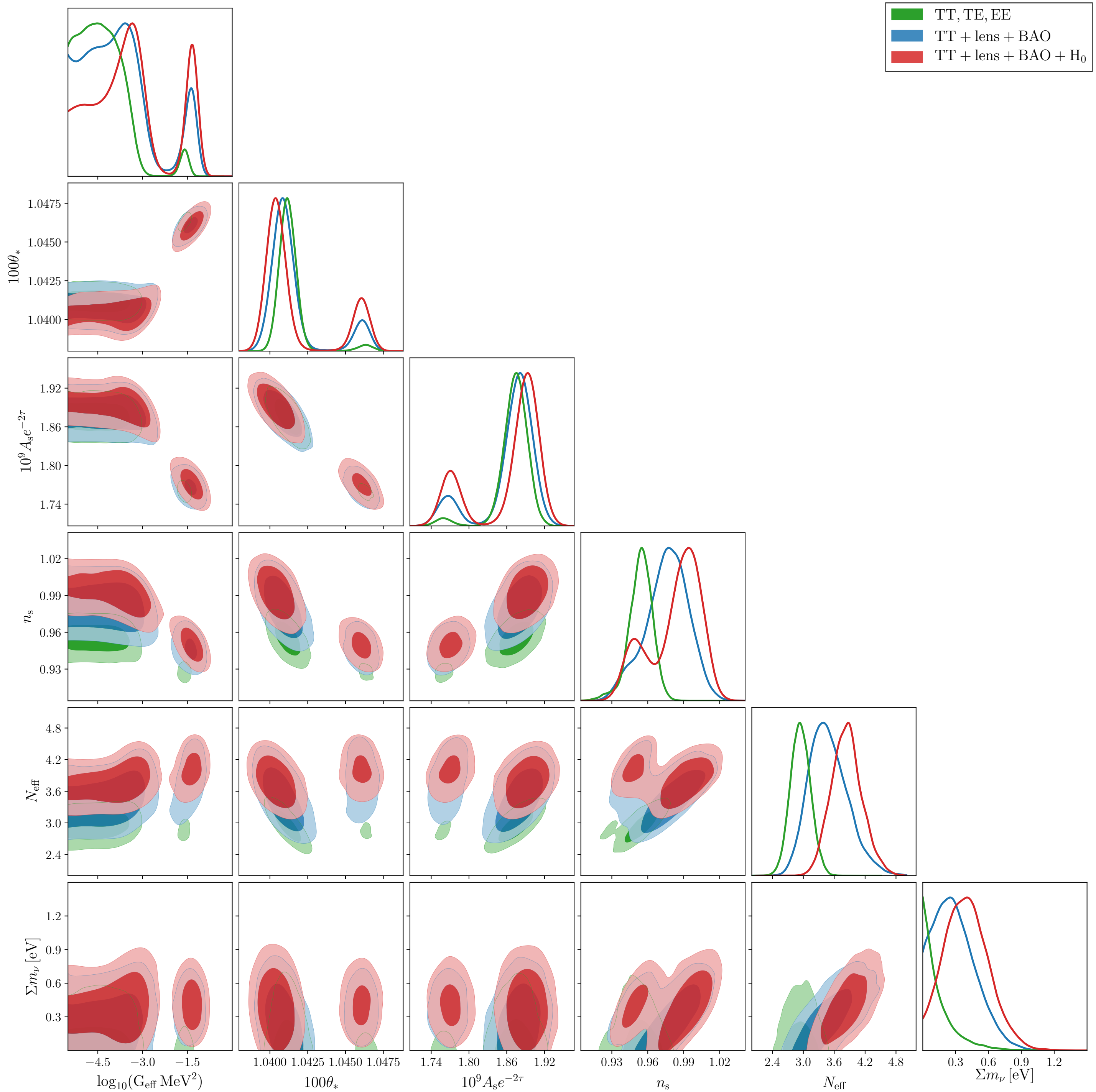
$G_{\rm eff} = (2.5^{+0.8}_{-0.5}) \times 10^4 \,{\rm GeV}^{-2}$

PlanckTTTEEE

PlanckTT+lens+BAO

PlanckTT+lens+BAO+H0

Kreisch et al. 2019



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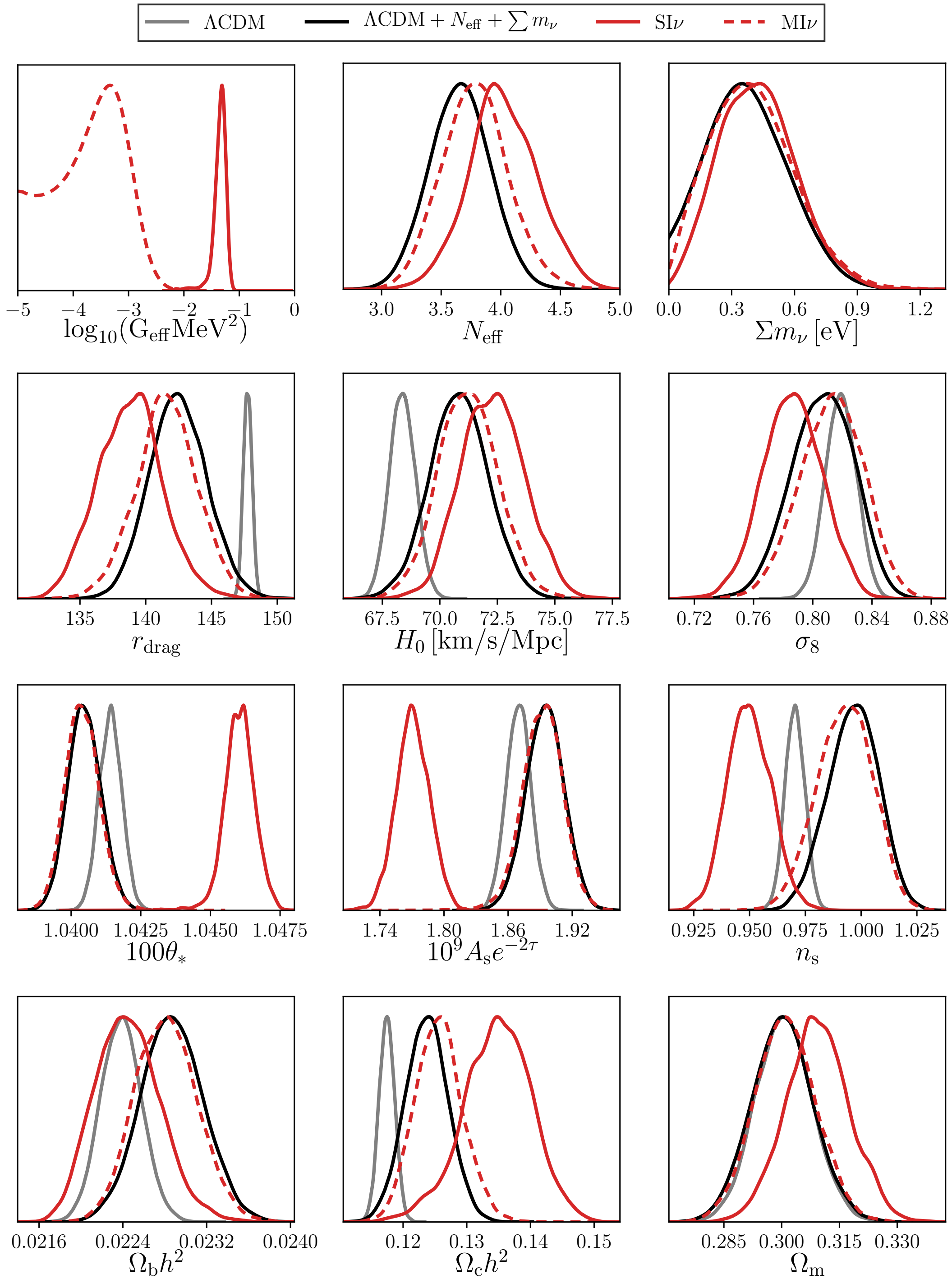

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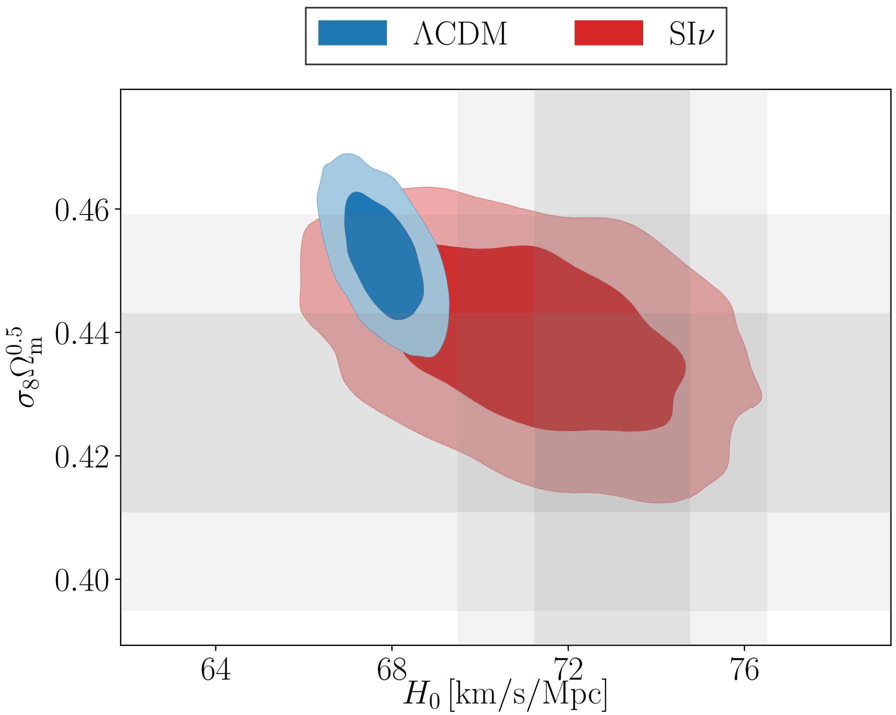
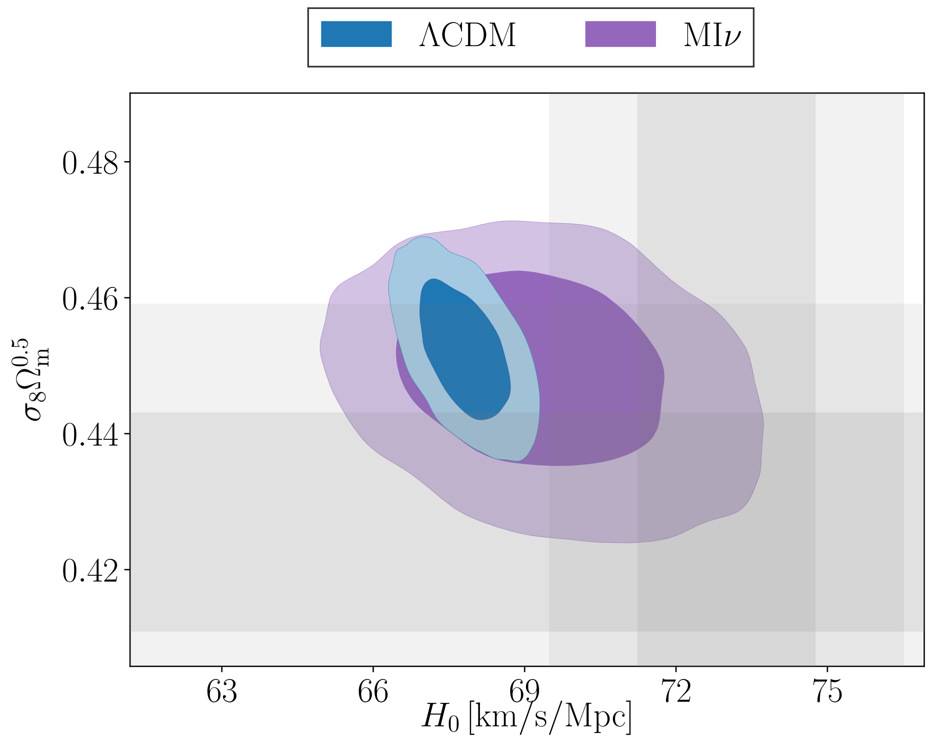


PlanckTT+lens+BAO



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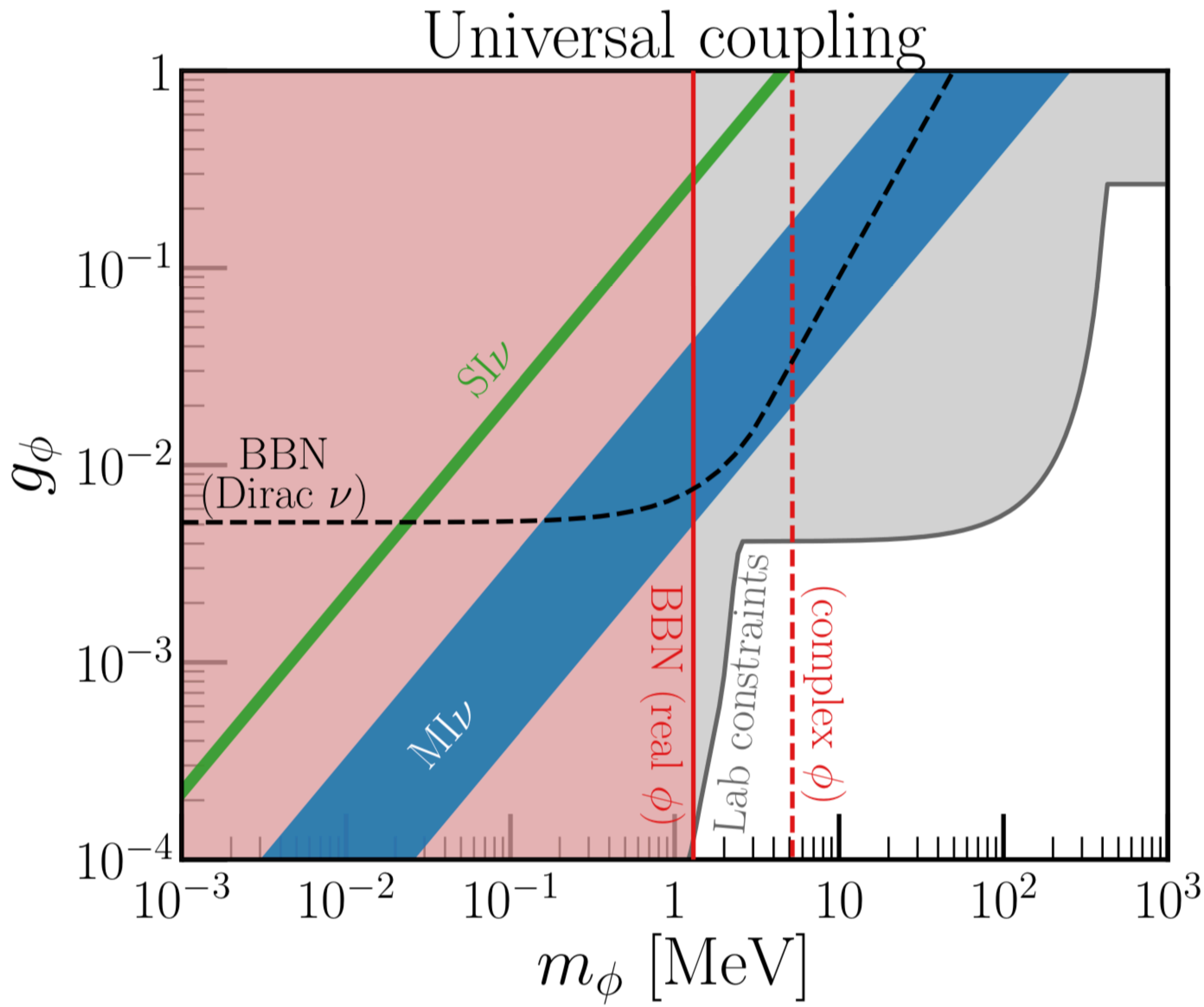


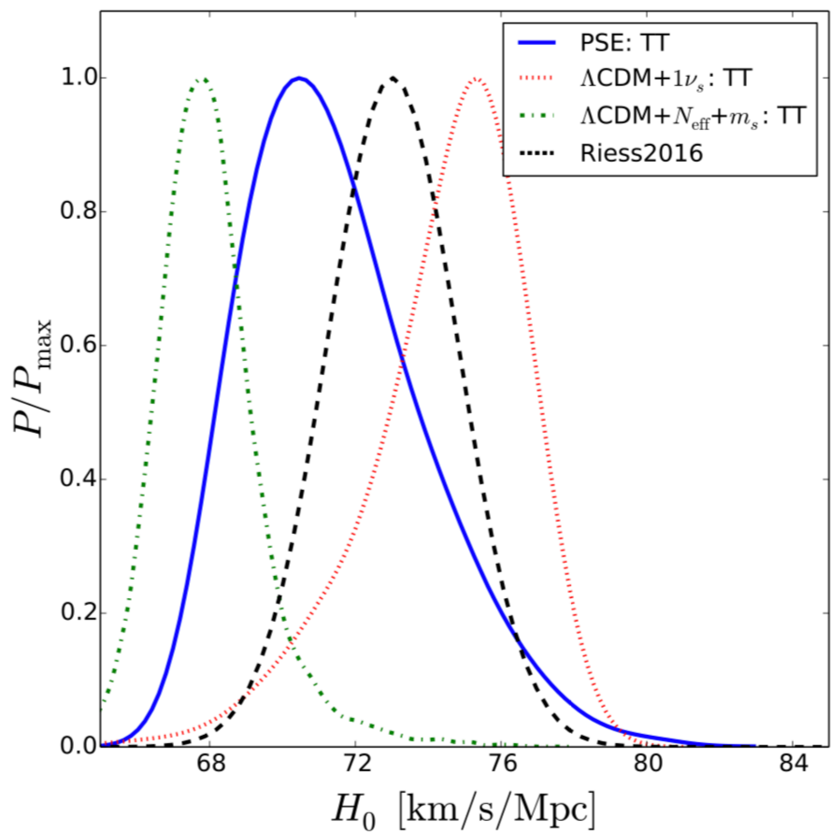
Blinov et al., 2019

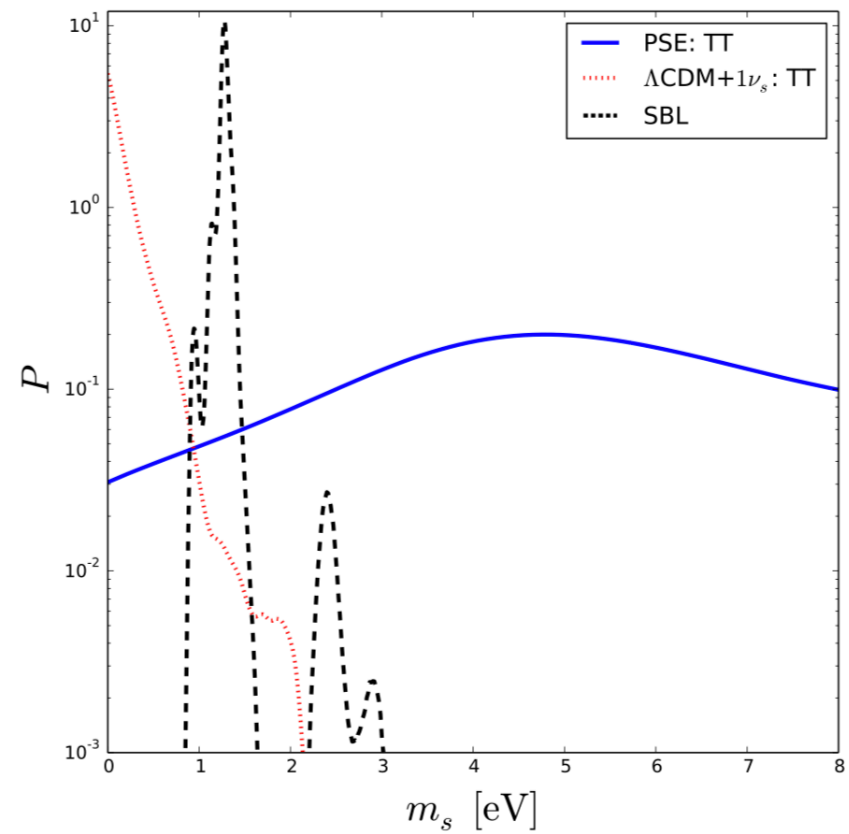
Summary

- Cosmological observations are in good agreement with the standard picture of the evolution of the neutrino background;
- the precision of the available data allows to test non-standard scenarios with high accuracy;
- the strength of neutrino interactions mediated by a light particle is constrained by CMB observations at the 10^{-7} level ($z_{rec} < 4000$ from PlanckTT+lowP+lensing);
- Models with a heavy mediator might help in solving the LCDM tensions
- However, building a particle physics model that is also compatible with other constraints seems not to be straightforward

BACKUP SLIDES

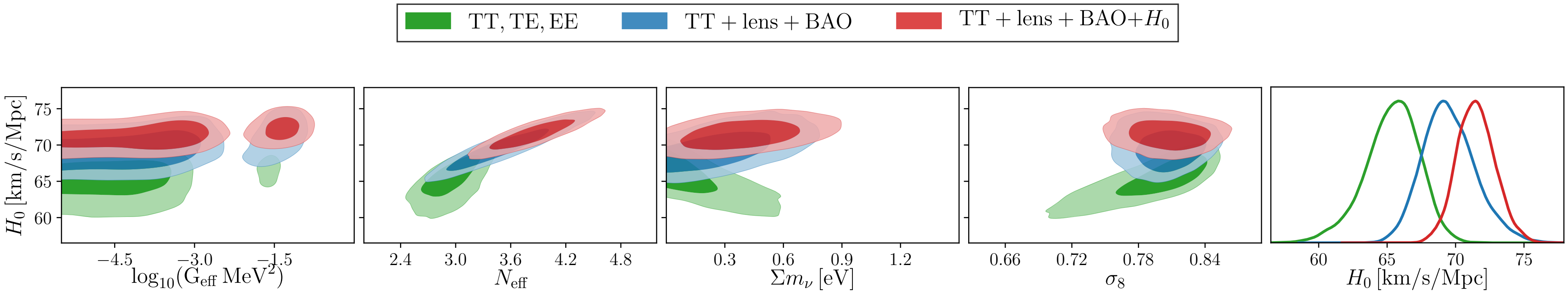
Pseudoscalar interactions in the sterile sector (Archidiacono et al. 2015; 2016)

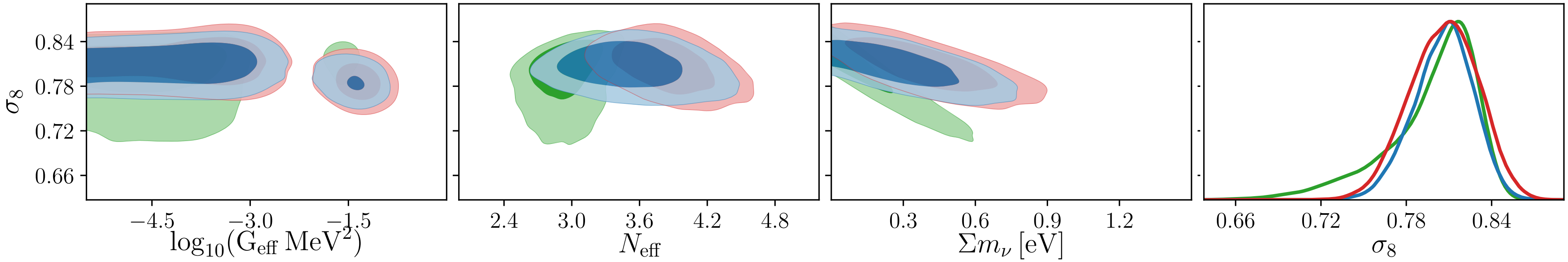




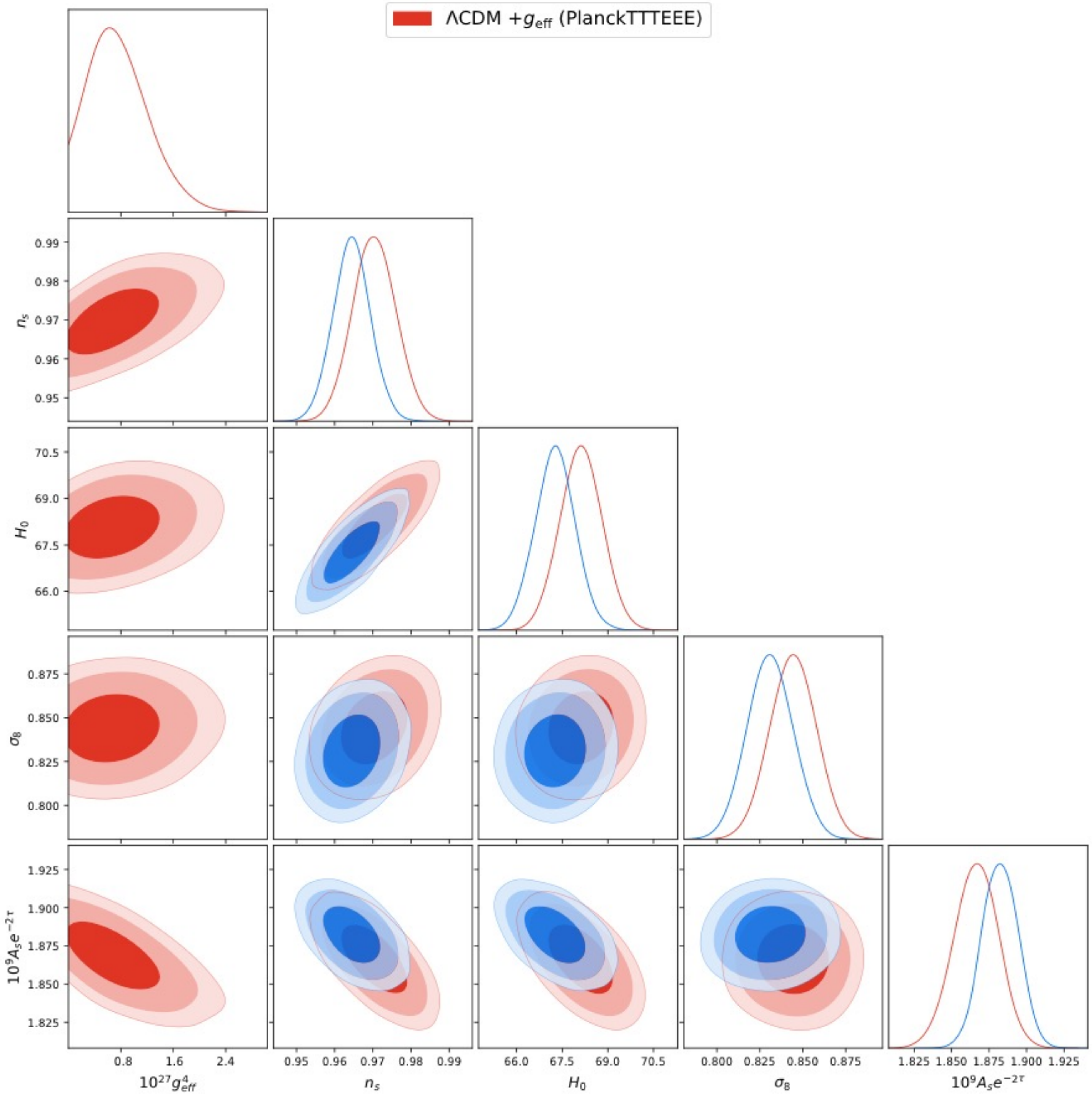
Parameter	Strongly Interacting Neutrino Mode	Moderately Interacting Neutrino Mode
$\Omega_{\rm b}h^2$	$0.02245^{+0.00029}_{-0.00033}$	0.02282 ± 0.00030
$\Omega_{\rm c}h^2$	$0.1348^{+0.0056}_{-0.0049}$	$0.1256^{+0.0035}_{-0.0039}$
$100\theta_{\rm MC}$	1.04637 ± 0.00056	$1.04062^{+0.00049}_{-0.00056}$
τ	0.080 ± 0.031	$0.127^{+0.034}_{-0.029}$
$\sum m_\nu$ [eV]	$0.42^{+0.17}_{-0.20}$	$0.40^{+0.17}_{-0.23}$
$N_{\rm eff}$	4.02 ± 0.29	3.79 ± 0.28
$\log_{10}(\mathrm{G_{eff}MeV^2})$	$-1.35^{+0.12}_{-0.066}$	$-3.90^{+1.0}_{-0.93}$
$\ln(10^{10}A_s)$	3.035 ± 0.060	$3.194^{+0.068}_{-0.056}$
$n_{\rm s}$	0.9499 ± 0.0098	$0.993^{+0.013}_{-0.012}$
H_0 [km/s/Mpc]	72.3 ± 1.4	71.2 ± 1.3
$\Omega_{\rm m}$	0.3094 ± 0.0083	0.3010 ± 0.0080
σ_8	0.786 ± 0.020	$0.813^{+0.023}_{-0.020}$
$10^9 A_{\rm s}$	$2.08^{+0.11}_{-0.13}$	2.44 ± 0.15
$10^9 A_{\rm s}e^{-2\tau}$	1.771 ± 0.016	$1.892^{+0.019}_{-0.017}$
r_* [Mpc]	136.3 ± 2.4	139.1 ± 2.3
$100\theta_*$	1.04604 ± 0.00056	$1.04041^{+0.00058}_{-0.00064}$
$D_{\rm A}$ [Gpc]	13.03 ± 0.23	13.37 ± 0.21
$r_{\rm drag}$ [Mpc]	138.8 ± 2.5	141.6 ± 2.3

Kreisch et al. 2019

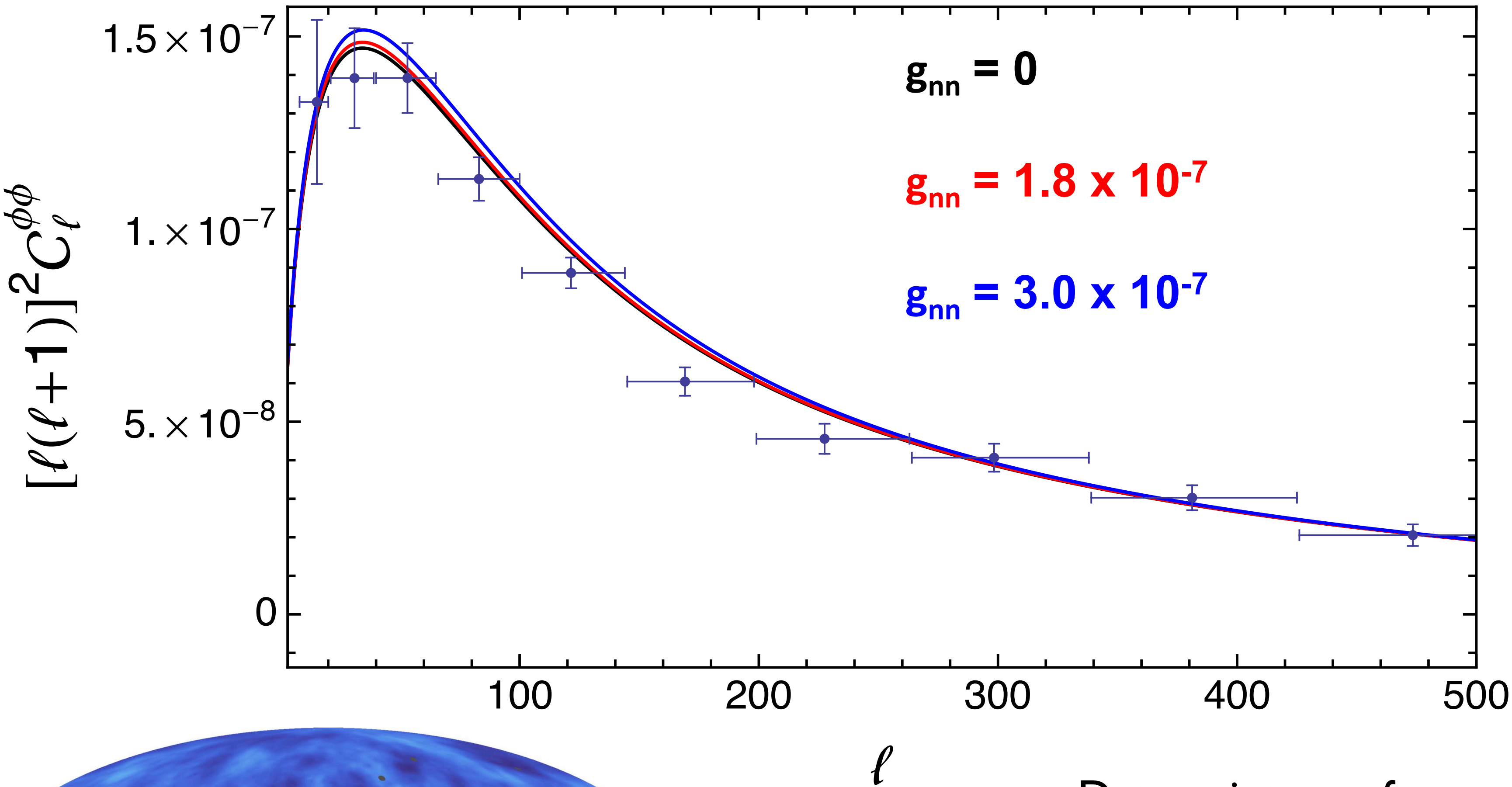


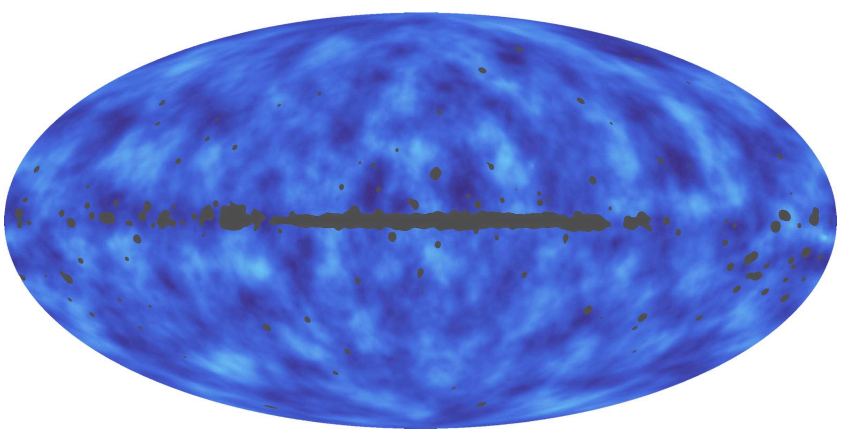


Kreisch et al. 2019


ΛCDM $+g_{\rm eff}$ (PlanckTTTEEE)
n_s
H_0
σ_8
$10^9 A_s e^{-2\tau}$
$10^{27} g_{eff}^4$
n_s
H_0
σ_8
$10^9 A_s e^{-2\tau}$

LENSING AND INTERACTING NEUTRINOS





Data points are from Planck 2015

Lensing potential estimated from the four-point correlation function

NSI AND COSMOLOGICAL PERTURBATIONS

Neutrino perturbations in the presence of collisions

$$\frac{\partial \Psi}{\partial \tau} + ik\mu\frac{q}{\epsilon}\Psi + \frac{d\ln f_0}{d\ln q}\left[\dot{\eta} - \frac{\dot{h}+6\dot{\eta}}{2}\mu^2\right] = \frac{1}{f_0}\hat{C}[f]\,,$$

Relaxation time approx. : $\hat{C}[f] \simeq -\frac{1}{\tau_c}\delta f$

(massless limit)

$$\dot{\delta} = -\frac{4}{3}\theta - \frac{2}{3}\dot{h}\,,$$

$$\dot{\theta} = k^2\left(\frac{1}{4}\delta - \Pi\right)\,,$$

$$\dot{\Pi} = \frac{4}{15}\theta - \frac{3}{10}kF_3 + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta} - a\Gamma\Pi\,,$$

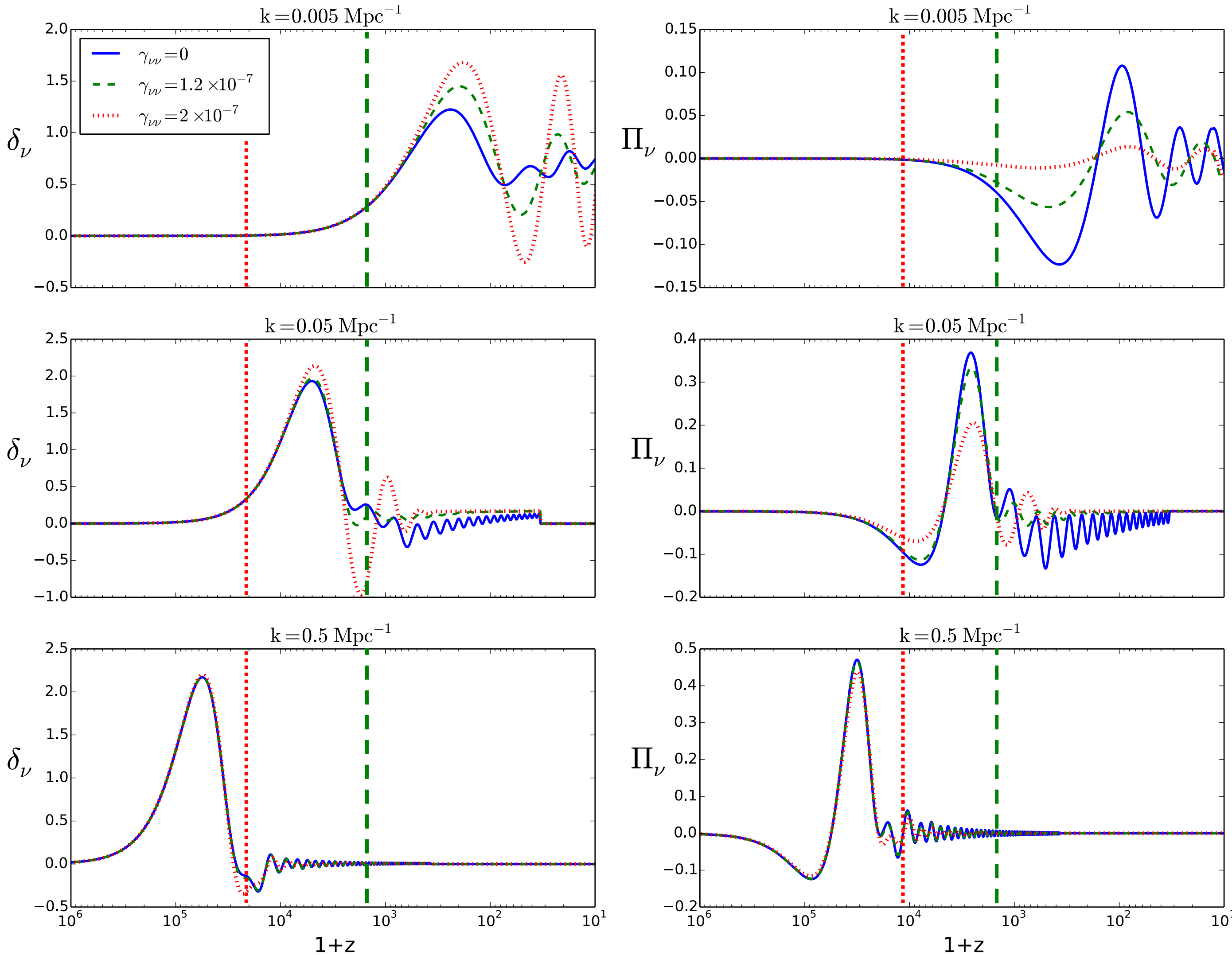
$$\dot{F}_\ell = \frac{k}{2\ell+1}\left[\ell F_{\ell-1} - (\ell+1)F_{\ell+1}\right] - a\Gamma F_\ell \quad (\ell \geq 3)\,.$$

No coll. term for monopole and dipole due to conservation of particle number and momentum in 2$\longleftrightarrow$2 processes

Higher order momenta are driven to zero by the collisions

$\longrightarrow$ fluctuations are confined to the monopole and dipole

NSI AND COSMOLOGICAL PERTURBATIONS



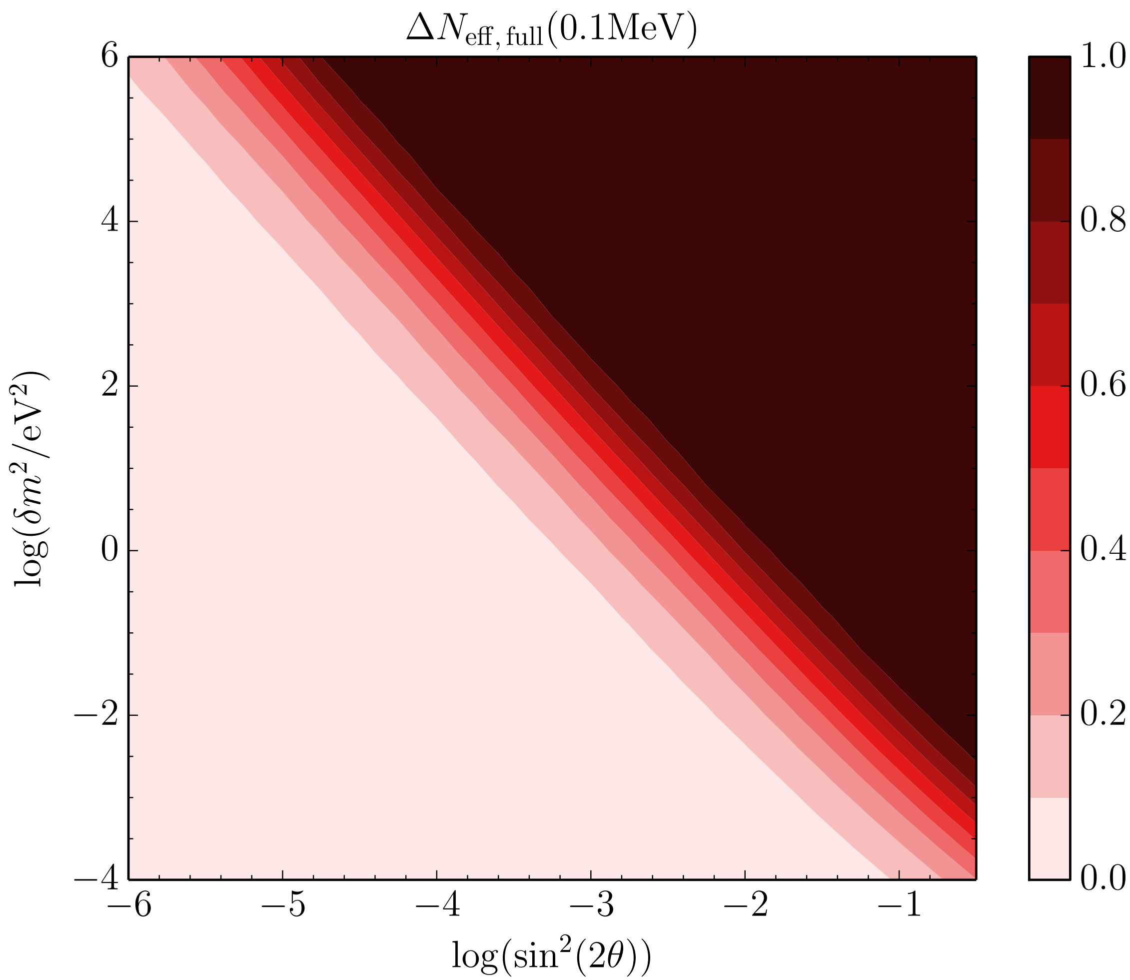
Higher order momenta are driven to zero by the collisions

$\longrightarrow$ fluctuations are confined to the monopole and dipole

1 eV for the real mass is allowed by Planck.

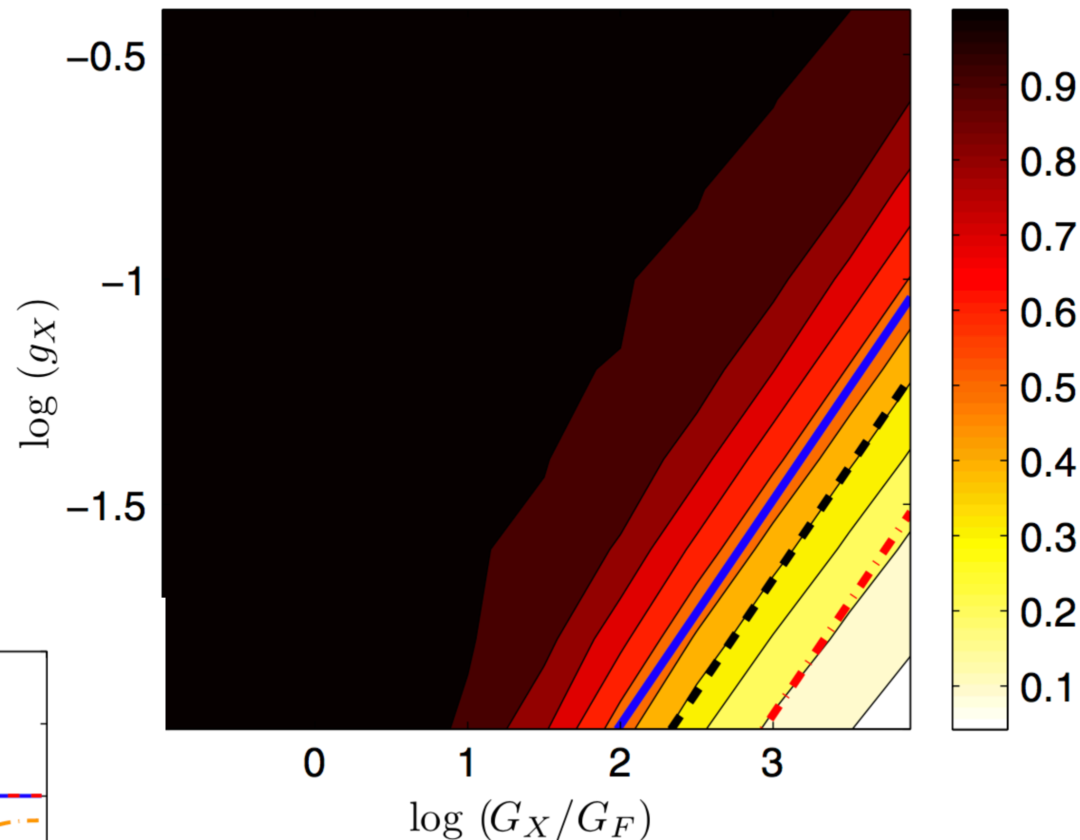
However, for $m_s \sim 1$eV and $\sin^2 2\theta \sim 0.1$ (the preferred SBL solution) full thermalization ($\Delta N_{eff} \sim 1$) is expected.

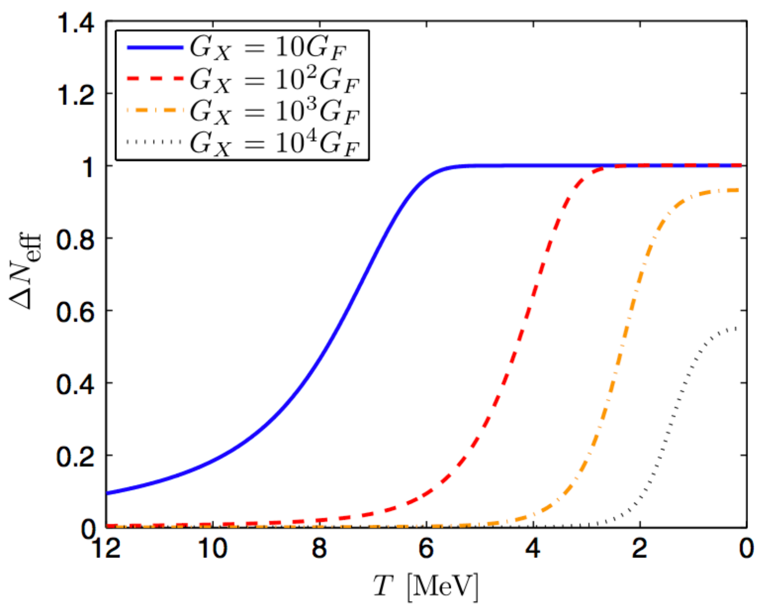
This is at odds with Planck constraints



Hannestad et al. 2015

A possible solution: new ("secret") neutrino interactions in the sterile sector can prevent production in the early Universe

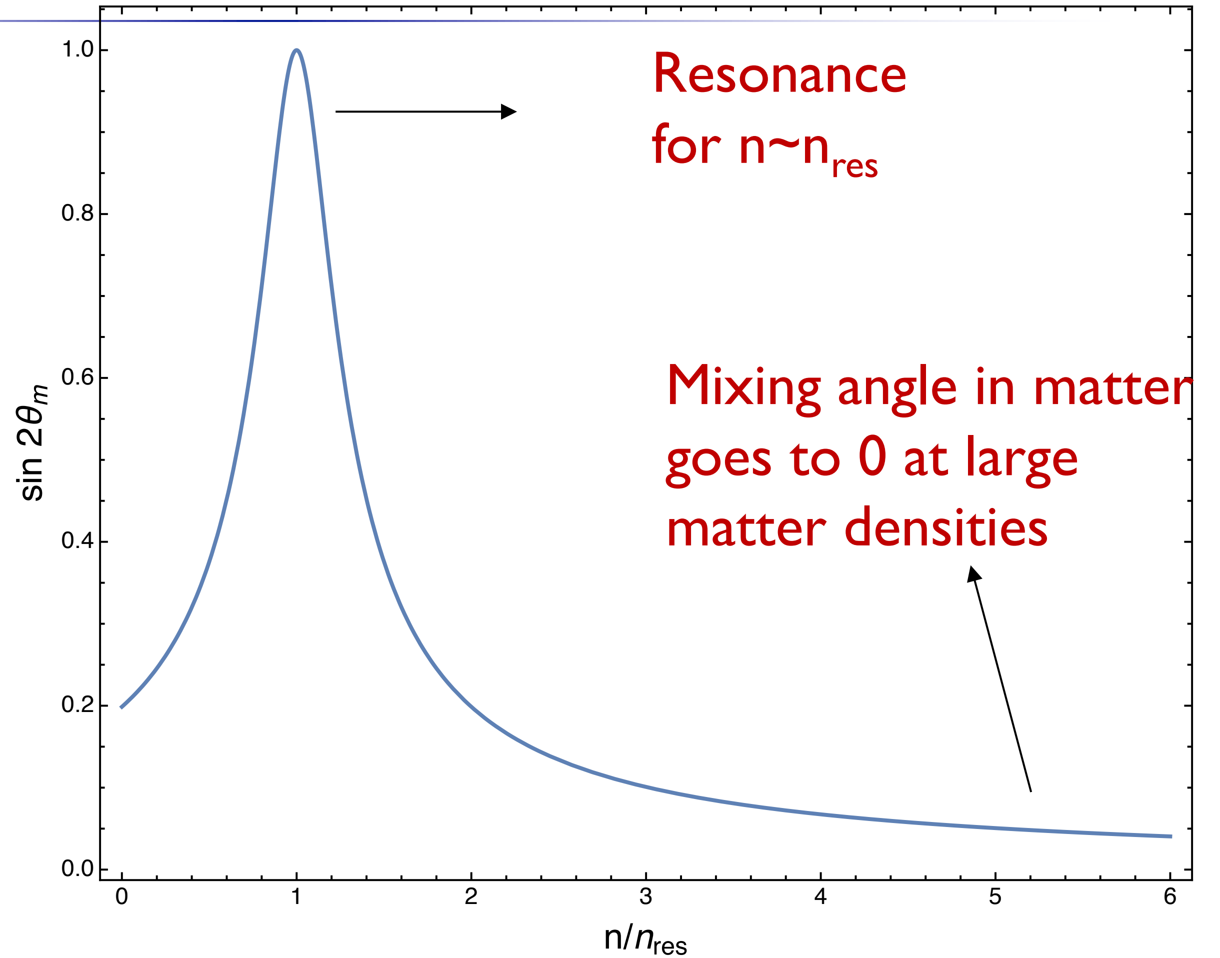




Hannestad et al. 2014

MSW effect

Mixing angle in matter is changed due to the effect of neutrino – matter (usually electrons) scattering



In ordinary matter (i.e., weak interactions) $$n_{\rm res} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F}$$

For secret vector interactions, $G_F \rightarrow G_X$

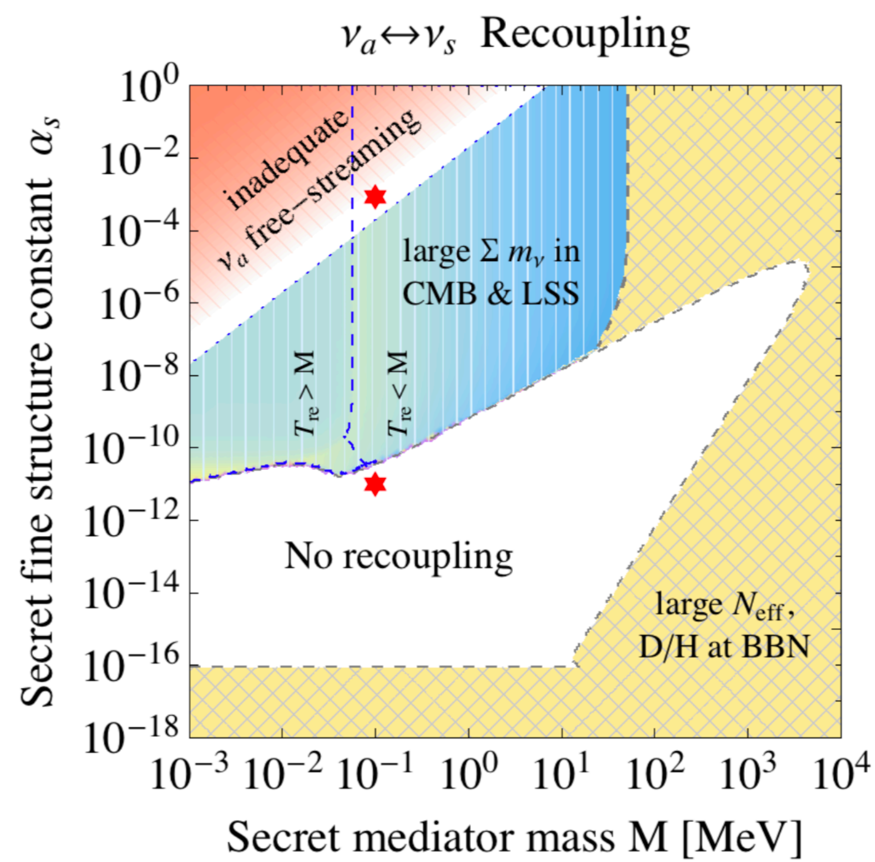
Interactions mediated by a massive gauge boson X (Hannestad et al. 2014; Dasgupta & Kopp 2014; Bringmann et al 2014; Mirizzi et al 2015; Chu,Dasgupta,Kopp 2015)

$$\mathcal{L}_s = g_X \bar{\nu}_s \gamma_\mu \frac{1}{2}(1-\gamma_5)\nu_s X^\mu$$

Production of sterile neutrinos is suppressed BUT "secret" collisions can still lead to a significant late-time (T<<1 MeV) abundancy

Tensions with CMB/LSS?

The mechanism also reduces N_{eff} = 2.7

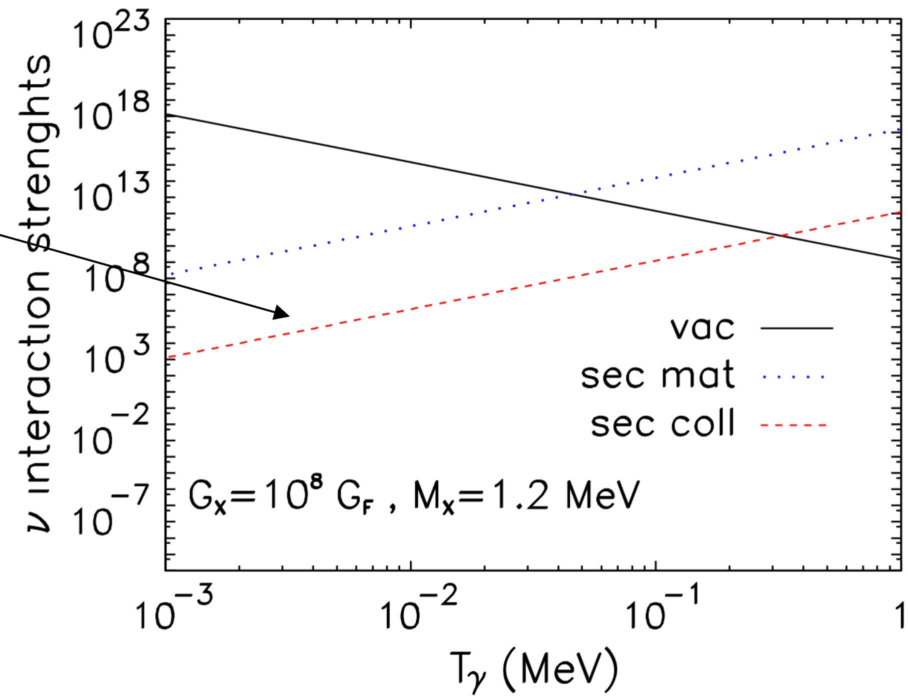


STERILE PRODUCTION AT T < 1MEV

For $g_X > 10^{-2}$ and $M_X < 10$ MeV, it is still possible to copiously produce neutrinos at low (T<1 MeV) temperatures, through an interplay between vacuum oscillations and collisions ("*scattering-induced decoherence*") (Saviano et al 2014; Mirizzi et al 2015;)

Relaxation rate to chemical equilibrium:

$$\Gamma_t \simeq \langle P(\nu_\alpha \to \nu_s)\rangle_{\rm coll}\Gamma_X .$$



Number conservation and flavour equilibration imply

$n_{s,after} = n_{a,after} = 3/4\ n_{a,before}$

Then collisions lead to thermalization and

$$T_\nu = \left(\frac{3}{4}\right)^{1/3} T_\nu^{\rm std} \quad \Longrightarrow \quad N_{\rm eff} = 4\times\left(\frac{3}{4}\right)^{4/3} \simeq 2.7$$

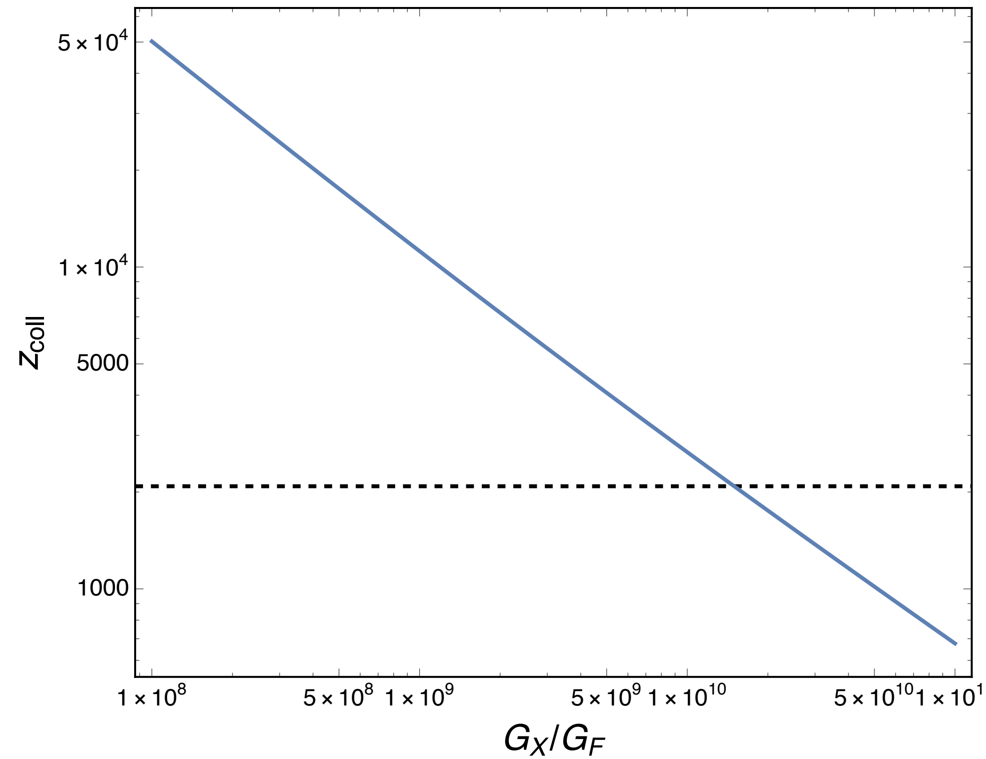
FREE-STREAMING OF INTERACTING STERILES

However, for $m_s \sim 1 eV$ and $T_n \sim (3/4)^{1/3} T_n^{std}$, the density of free-streaming species is possibly too large

Problem with structure formation?

If G_X is large enough ($> 10^{10}\ G_F$) free-streaming is suppressed until the sterile state becomes non-relativistic.

Large G_X will leave an imprint in CMB spectrum (see e.g. Cyr-Racine & Sigurdson 2014; Lancaster et al 2016; for active neutrinos)



SECRET INTERACTIONS AND COSMOLOGICAL PERTURBATIONS

In arXiv:1704.00626 we have studied the effect of collisions in the sterile sector on the evolution of cosmological pertubations and on the CMB spectrum.
Startinh point is the collisional Boltzmann eqn for neutrinos (monopole and dipole of the collision term are – 0)

$$\frac{\partial \Psi_i}{\partial \tau} + i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\Psi_i + \frac{d\ln f_0}{d\ln q}\left[\dot{\phi} - i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\psi\right] = -\Gamma_{ij}\Psi_j\,,$$

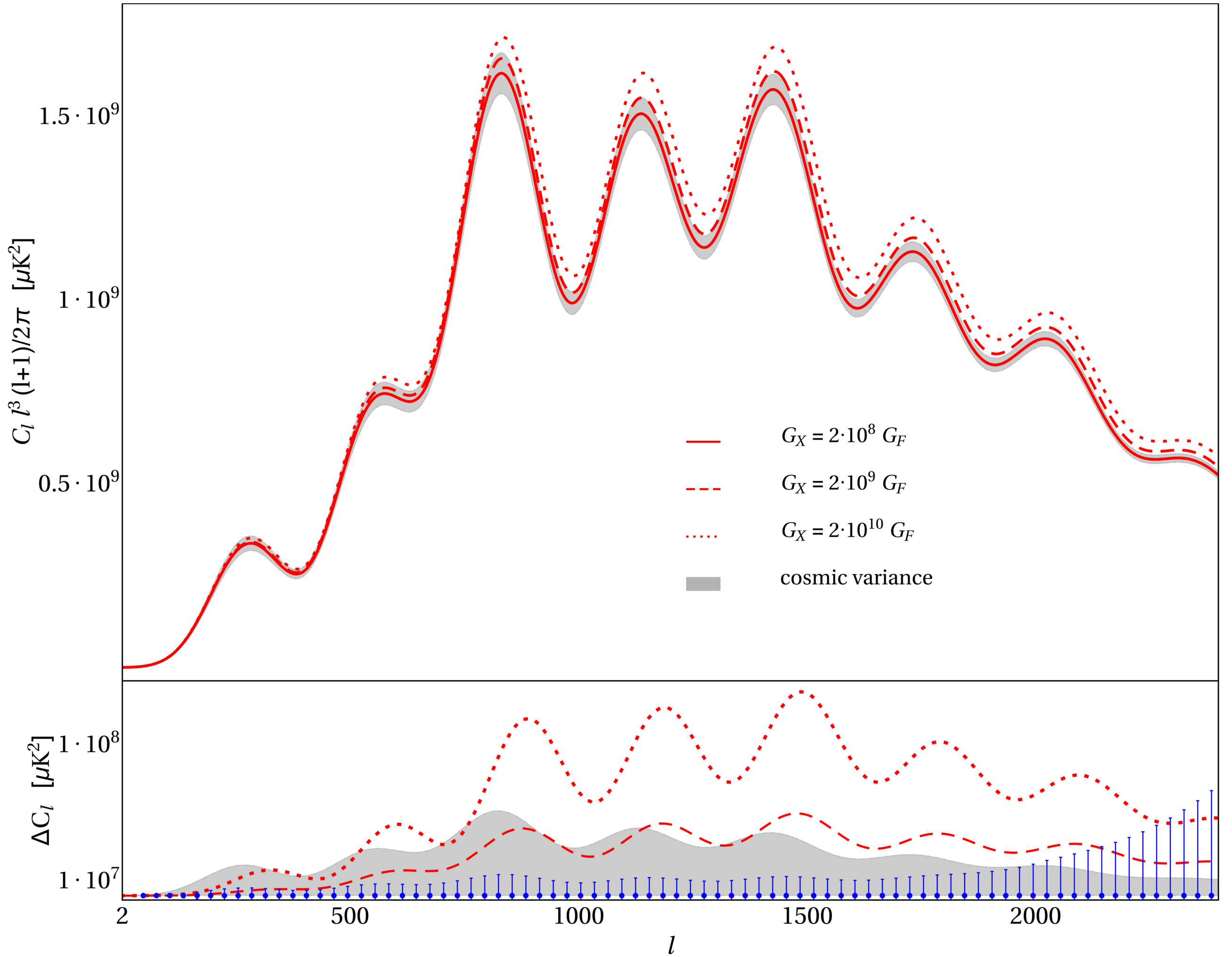
$$\Gamma_{ij} = \begin{bmatrix} \sin^2\theta_s & 0 & 0 & \sin\theta_s\,\cos\theta_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \sin\theta_s\,\cos\theta_s & 0 & 0 & \cos^2\theta_s \end{bmatrix} (3/2)(\zeta(3)/\pi^2)\,aG_X^2\,T_\nu^5\,.$$

We have assumed $\nu_s \simeq \sin\theta_s\nu_1 + \cos\theta_s\nu_4$, with $\theta_s = 0.1$

SECRET INTERACTIONS AND COSMOLOGICAL PERTURBATIONS

Collisions push power towards the lowest multipoles (ell=0, 1)

Increase in density and pressure fluctuations below a critical scale



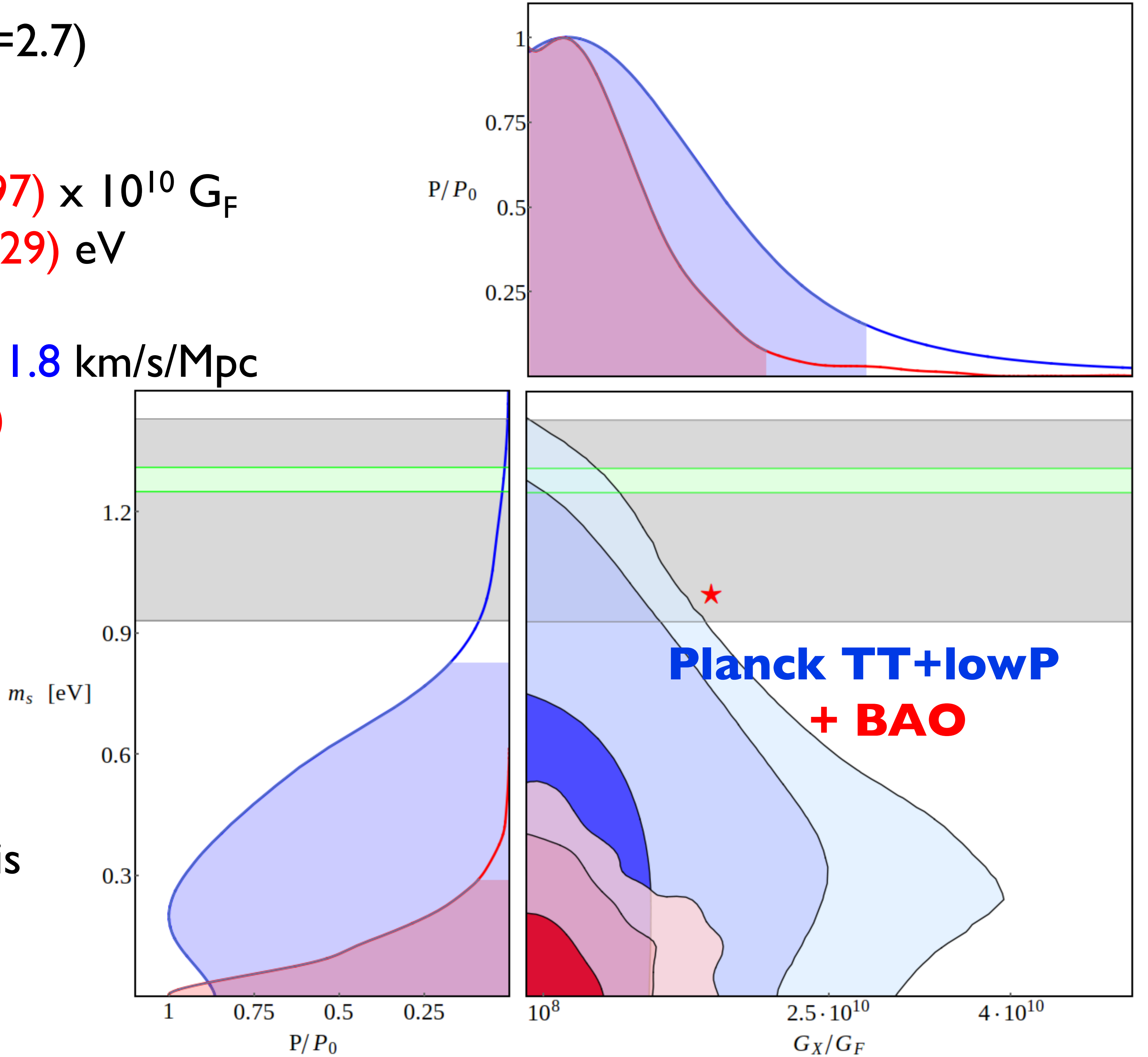
ΛCDM (N_{eff}=2.7)
+ m_s + G_X

G_X < 2.8 (1.97) x 10^{10} G_F
m_s < 0.82 (0.29) eV

H_0 =62.6 +/- 1.8 km/s/Mpc
(65.3 +/- 0.7)

(G_X > 10^8
is always
assumed)

The mass
constraint is
still there!



Parameter	ΛCDM	SΛCDM_GX0	SΛCDM	SΛCDM_Broad	SΛCDM_Narrow
$\chi^2_{\rm min}$	11265.1	11272.8	11269.0	11275.2	11277.6

Table 4. Best-fit χ^2 values for the models under consideration, for the PlanckTT+lowP dataset.

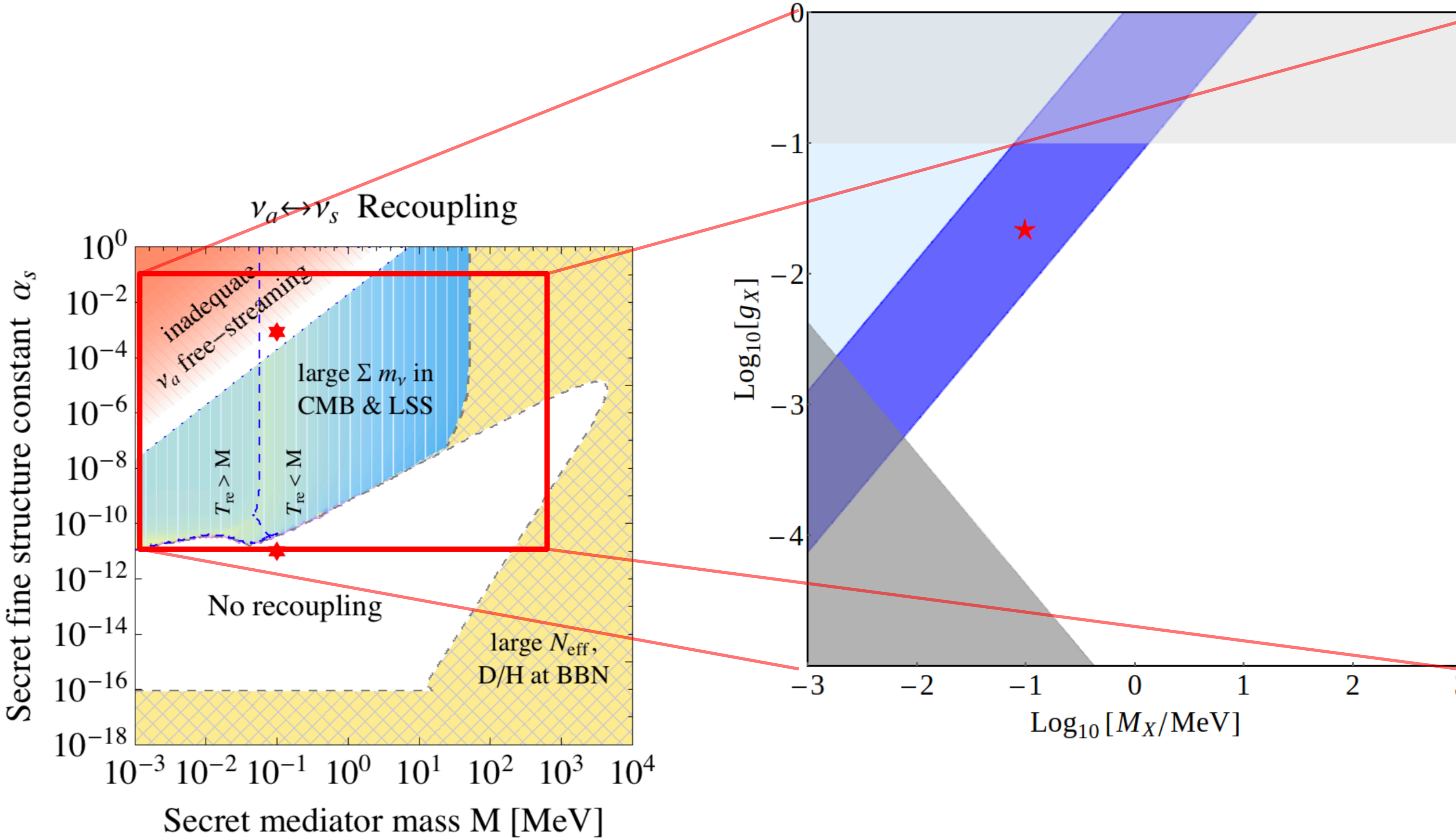
The model is mildly disfavoured ($\Delta\chi^2 = 4$) with respect to standard LCDM
(mainly because of low $N_{\rm eff}$) – this is independent of SBL anomalies

If we impose a "large" (~ eVish) sterile neutrino mass, as per SBL anomalies, the model becomes strongly disfavoured:

$$0.93\,\mathrm{eV} < m_s < 1.43\,\mathrm{eV}, \quad \Delta\chi^2 = 10.1$$

$$m_s = 1.27 \pm 0.03\,\mathrm{eV}, \quad \Delta\chi^2 = 12.5$$

(note that this numbers do not take into account H0 tension)



$\nu_a \leftrightarrow \nu_s$ Recoupling
Secret fine structure constant α_s
Secret mediator mass M [MeV]
inadequate ν_a free-streaming
large $\Sigma\, m_\nu$ in CMB & LSS
$T_{re} > M$
$T_{re} < M$
No recoupling
large N_{eff}, D/H at BBN
$\mathrm{Log}_{10}[g_X]$
$\mathrm{Log}_{10}[M_X/\mathrm{MeV}]$

The Cosmic Neutrino Background

Perturbations of non-interacting neutrinos evolve according to:

$$\frac{\partial \Psi}{\partial \tau} + ik\mu\frac{q}{\epsilon}\Psi + \frac{d\ln f_0}{d\ln q}\left[\dot{\eta} - \frac{\dot{h}+6\dot{\eta}}{2}\mu^2\right] = 0$$

In the massless limit, after integrating over momentum and expanding the angular dependence:

$$\dot{\delta} = -\frac{4}{3}\theta - \frac{2}{3}\dot{h}\,,$$

$$\dot{\theta} = k^2\left(\frac{1}{4}\delta - \Pi\right)\,,$$

$$\dot{\Pi} = \frac{4}{15}\theta - \frac{3}{10}kF_3 + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta},$$

$$\dot{F}_\ell = \frac{k}{2\ell+1}\left[\ell F_{\ell-1} - (\ell+1)F_{\ell+1}\right] \quad (\ell \geq 3)\,.$$

The Majoron Model

As a concrete example, in models in which neutrinos acquire mass through sponataneous breaking of lepton number, they couple to the NG boson of the broken symmetry – the Majoron:

$$\mathcal{L}_Y = Y_u \bar{Q}_L \Phi^* u_L^c + Y_d \bar{Q}_L \Phi d_L^c + Y_e \bar{L}_L \Phi e_L^c + \\ + Y_\nu \bar{L}_L \Phi^* \nu_L^c + \tilde{Y}_\nu L_L^T \Delta L_L + \frac{Y_R}{2} \nu_L^c \nu_L^c \sigma + H.c.\,,$$

In the see-saw limit $<\Delta> << <\Phi> << <\sigma>$ the majoron is the following combination of the Higgs fields:

$$J \propto v_3 {v_2}^2 \Im(\Delta^0) - 2 v_2 {v_3}^2 \Im(\Phi^0) + v_1 ({v_2}^2 + 4 {v_3}^2) \Im(\sigma)$$

Secret neutrino interactions

Consider a new ("hidden") neutrino (pseudo)scalar interaction mediated by a light boson (like e.g. in Majoron models):

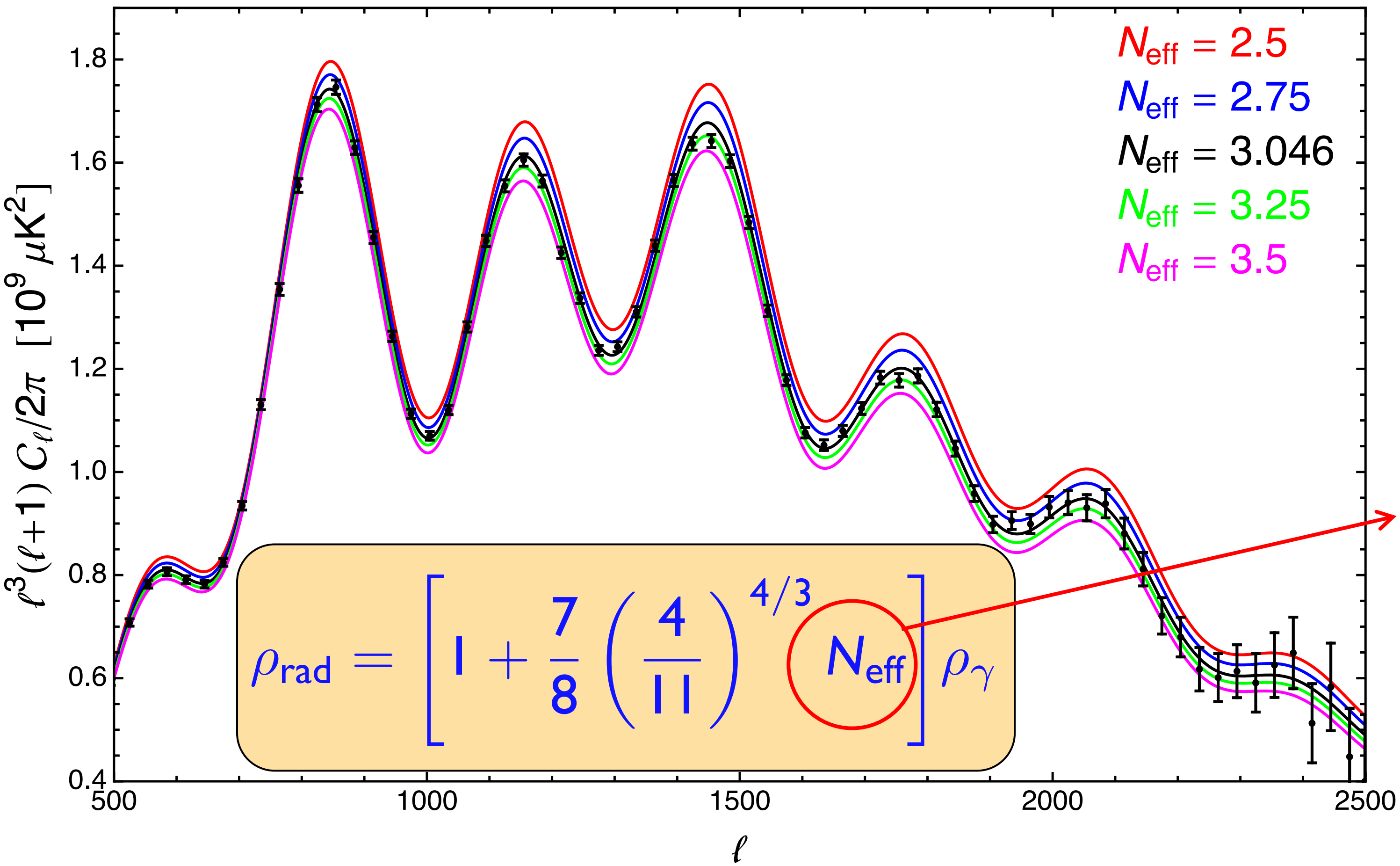
$$\mathcal{L} \supset h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + h.c. ,$$

This induces processes like

- neutrino-neutrino scattering
- neutrino-neutrino annihilation to phi's
- neutrino decay (needs off-diagonal couplings)
- neutrinoless double beta decay.

Effective number of relativistic species

Planck 2018 + BAO: Neff = 2.99+/- 0.17



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

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.045** (updated calculation from de Salas & Pastor 2016; see also Dolgov 2002, Mangano et al. 2005)

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

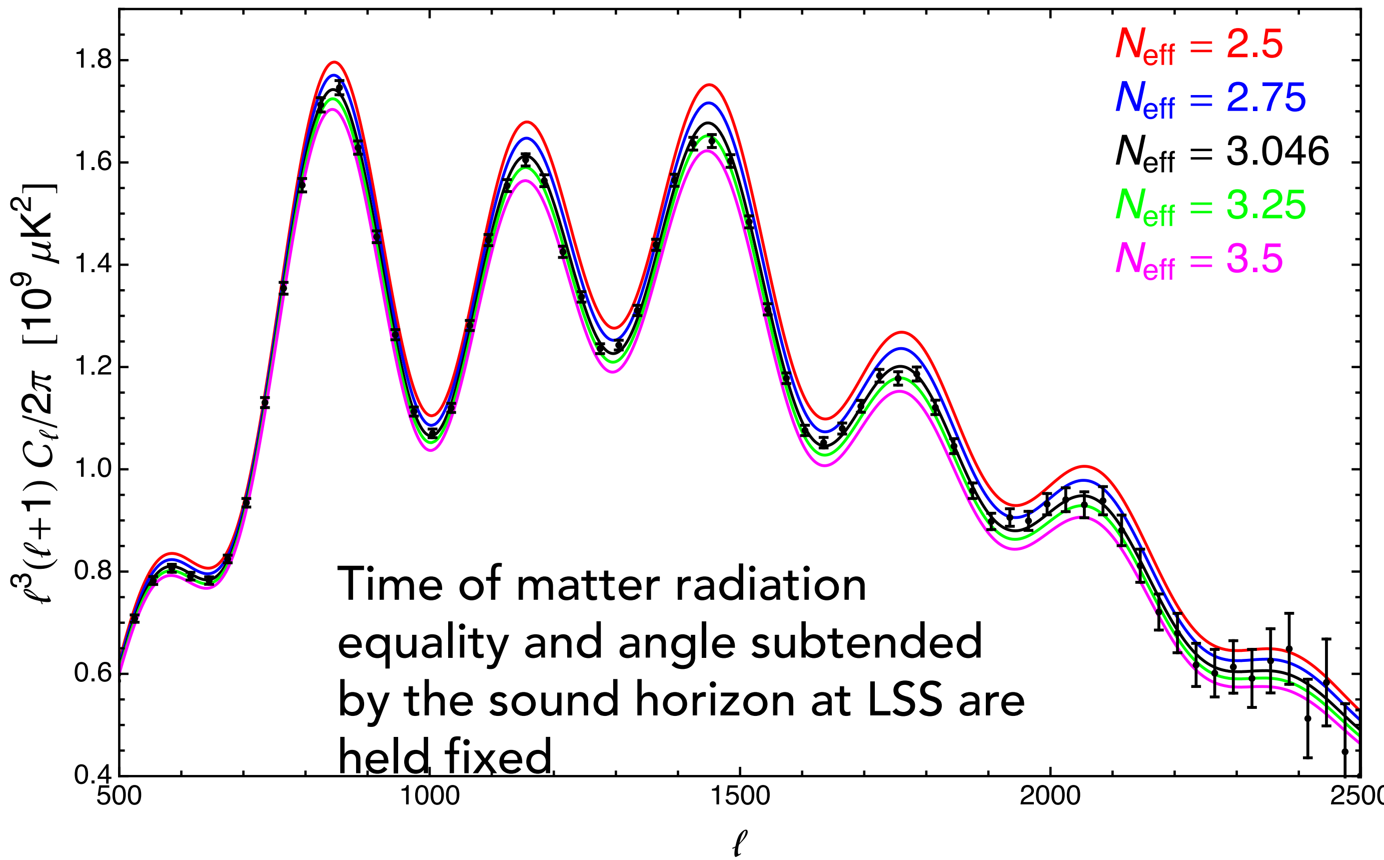
The Cosmic Neutrino Background

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

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Increasing N_{eff} makes the Universe younger at recombination and increases the angular scale of the photon diffusion length

increased Silk damping and reduced power in the damping tail.



Time of matter radiation equality and angle subtended by the sound horizon at LSS are held fixed

(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)

Sterile neutrino parameterization

A full description of the sterile sector would require to specify (for each sterile species) its mass m_s and the **full form of the distribution function.**

Two notable cases are often considered:

- thermally distributed with arbitrary temperature T_s;
- à la Dodelson-Widrow: distributed proportionally to active neutrinos with an arbitrary scaling factor χ_s (depends on the mixing angle).

This two models are equivalent from the point of view of cosmological observations as they can be remapped in the same effective model

STERILE NEUTRINO PARAMETERIZATION

In this phenomenological reparameterization

$$m_s^{\text{eff}} \equiv \left(94.1\,\Omega_s h^2\right)\ \text{eV}$$

Effective mass (sets non-relativistic energy density)

Effective number of degrees of freedom (sets relavistic energy density)

$$\Delta N_{\text{eff}} = \begin{cases} (T_s/T_\nu)^4 & \text{thermal} \\ \chi_s & \text{DW} \end{cases}$$

To go back to the real mass:

$$m_s = \begin{cases} m_s^{\text{eff}}\,(T_s/T_\nu)^{-3} = m_s^{\text{eff}}/\Delta N_{\text{eff}}^{3/4} & \text{thermal} \\ m_s^{\text{eff}}/\chi_s = m_s^{\text{eff}}/\Delta N_{\text{eff}} & \text{DW} \end{cases}$$

Planck constraints on massless sterile neutrinos

Planck constraints on N_{eff} alone (can be regarded as a massless limit for the sterile)

$N_{eff} = 3.13 \pm 0.32$ (PlanckTT+lowP)

$N_{eff} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

$N_{eff} = 2.99 \pm 0.20$ (PlanckTT,TE,EE+lowP)

$N_{eff} = 3.04 \pm 0.18$ (PlanckTT,TE,EE+lowP+BAO)

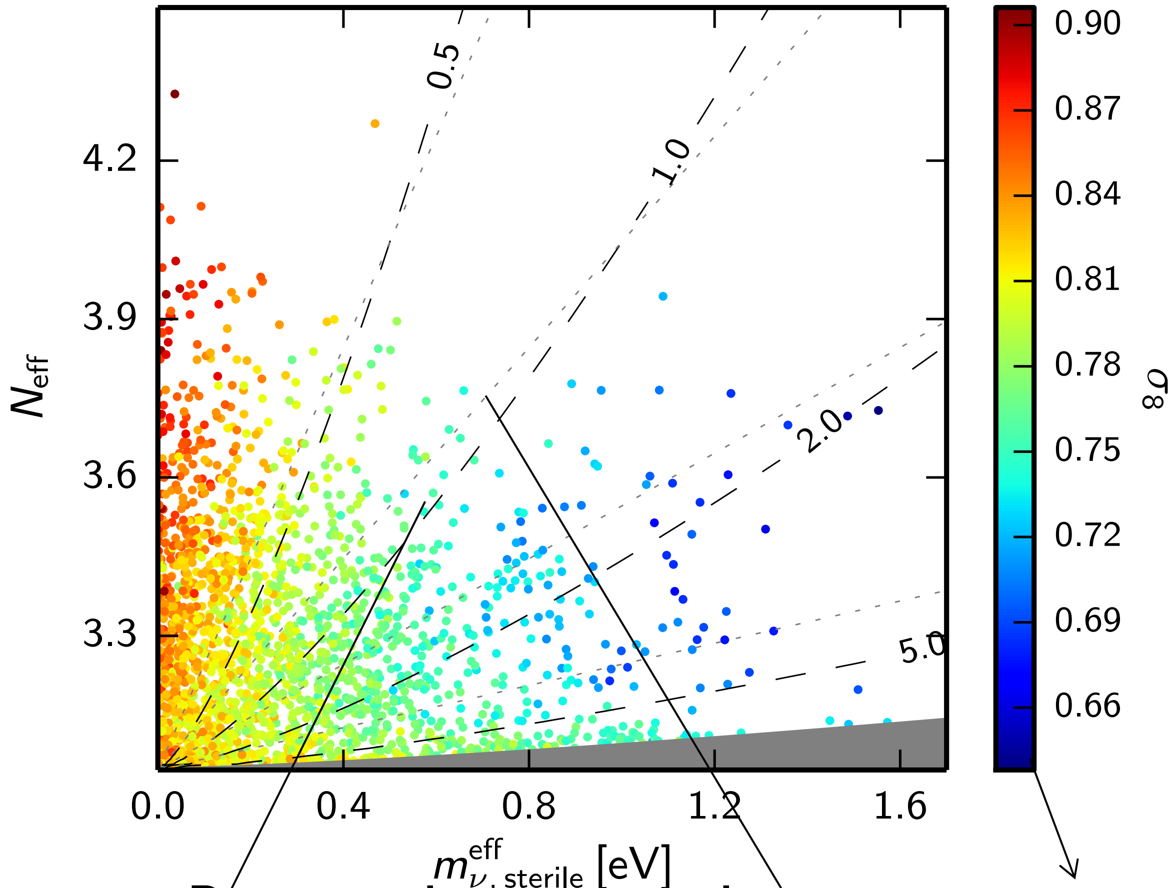
(uncertainties are 68% CL)

$N_{eff} = 4$ (i.e., one extra thermalized neutrino)
is excluded at between ~ 3 and 5 sigma.

Planck 2015 XIII

Planck constraints on massive sterile neutrinos

Early energy density



Present-day energy density

Planck TT+lowP+lensing+BAO

$N_{\rm eff} < 3.7$

$m^{eff}_{sterile} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

Amplitude of density fluctuations

Lines of constant m_s (thermal)

Lines of constant m_s (DW)

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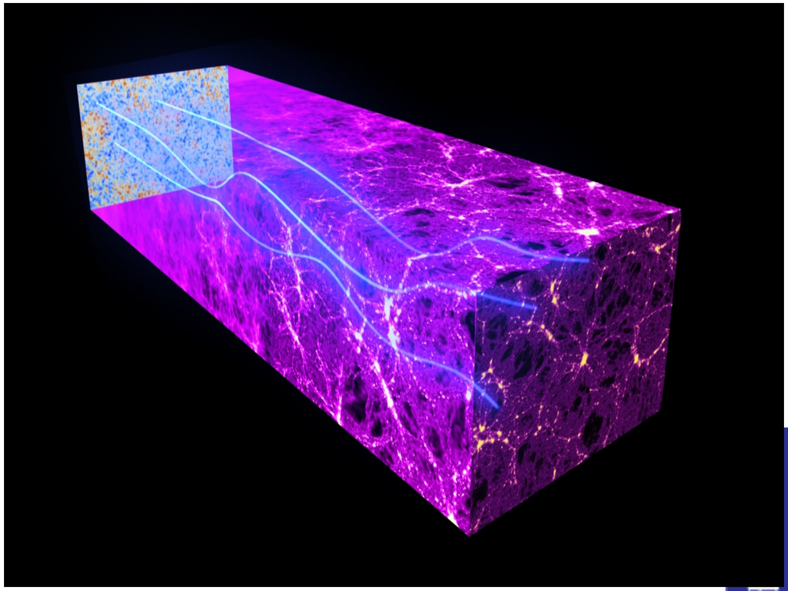
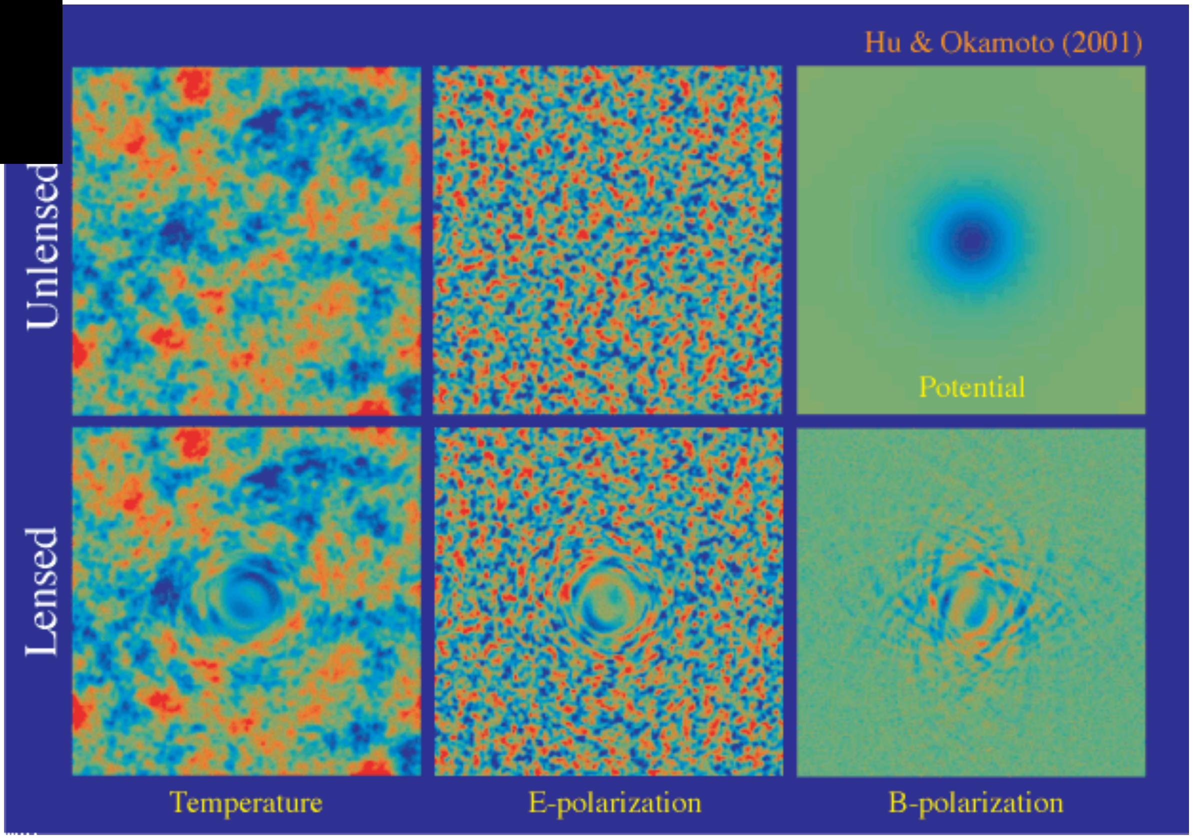
CMB Lensing



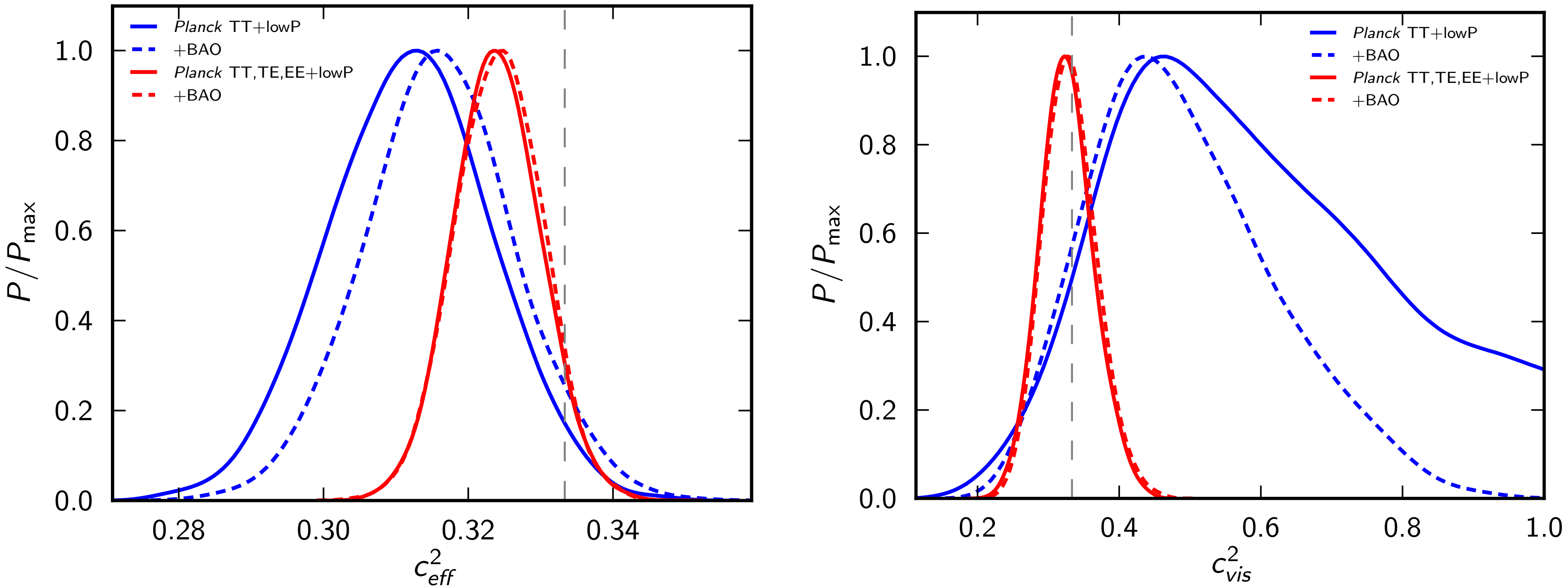
The CMB anisotropy pattern is distorted ("blurred") by the weak lensing effect due to the intervening structures between us and the last scattering surface



The effect is relevant at small scales (~ % effect at sub-degree scales) and results in a smearing of the power spectrum at high multipoles. It also induces a non-gaussian signal.

CMB lensing probes the matter distribution of the Universe.

Probing CνB perturbations



Parameter	PlanckTT+lowP 95 % limits	PlanckTT+SIMlow 95 % limits	PlanckTTTEEE+lowP 95 % limits	PlanckTTTEEE+SIMlow 95 % limits
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.053^{+0.044}_{-0.046}$	$-0.040^{+0.038}_{-0.041}$	$-0.039^{+0.032}_{-0.034}$
Σm_ν [eV]	< 0.715	< 0.585	< 0.492	< 0.340
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$2.97^{+0.58}_{-0.53}$	$2.99^{+0.41}_{-0.39}$	$2.91^{+0.39}_{-0.37}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.242^{+0.039}_{-0.040}$	$0.250^{+0.026}_{-0.027}$	$0.244^{+0.026}_{-0.026}$
$dn_{\rm s}/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.014}_{-0.014}$	$-0.003^{+0.014}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.111	< 0.0987	< 0.111
w	$-1.54^{+0.62}_{-0.50}$	$-1.57^{+0.61}_{-0.49}$	$-1.55^{+0.58}_{-0.48}$	$-1.59^{+0.58}_{-0.46}$
$A_{\rm L}$	$1.22^{+0.21}_{-0.20}$	$1.23^{+0.20}_{-0.18}$	$1.15^{+0.16}_{-0.15}$	$1.15^{+0.13}_{-0.12}$

). Constraints on 1-parameter extensions of the base ΛCDM model obtained using the PlanckTT likelihood in combin

The Cosmic Neutrino Background

The neutrino energy density is expressed in terms of the effective number of relativistic species

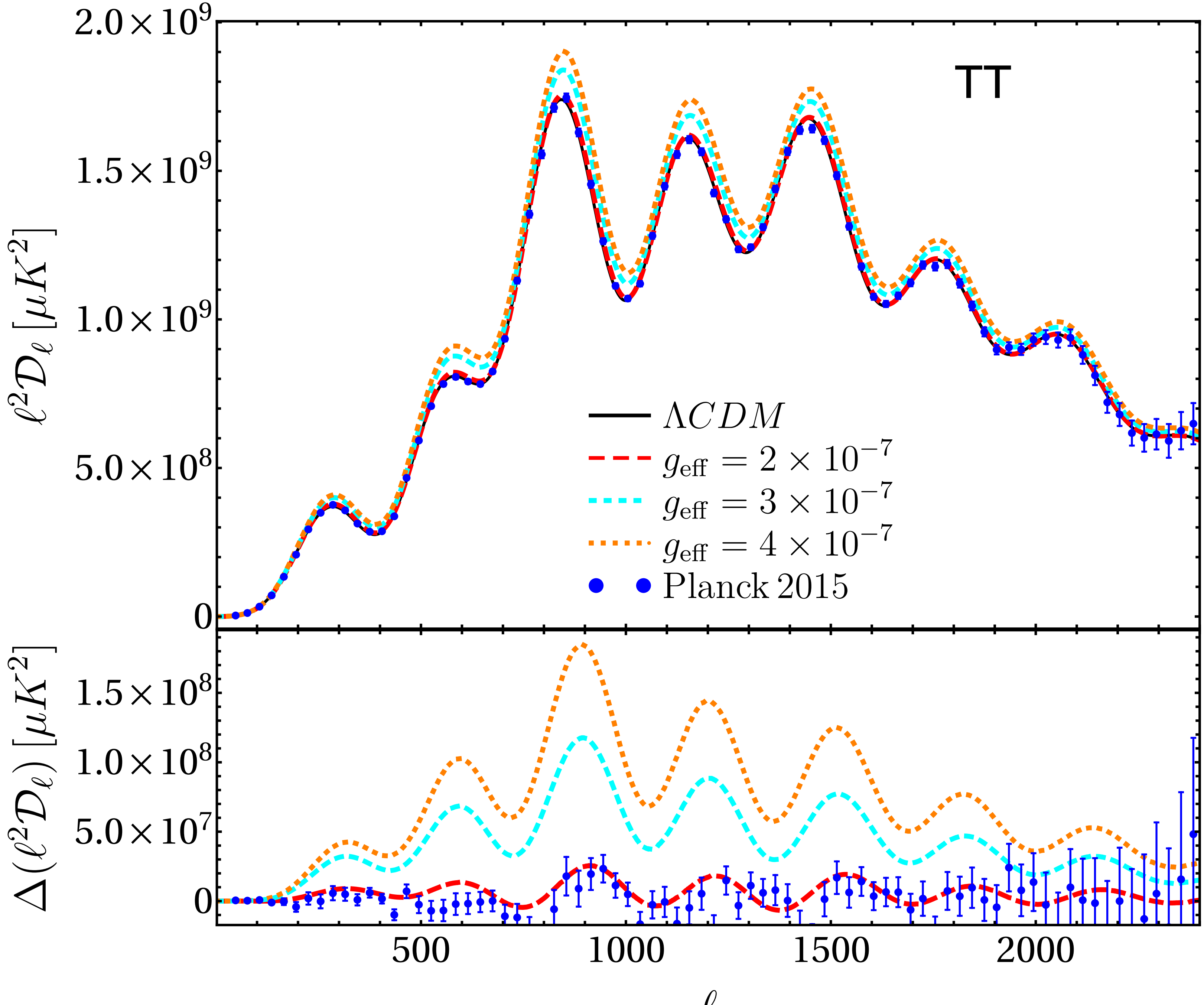
$$\rho_{\rm rad} \equiv \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

assuming the standard thermal history, **$N_{\rm eff}$ =3.046** for the three active neutrinos (Mangano et al., 2005).

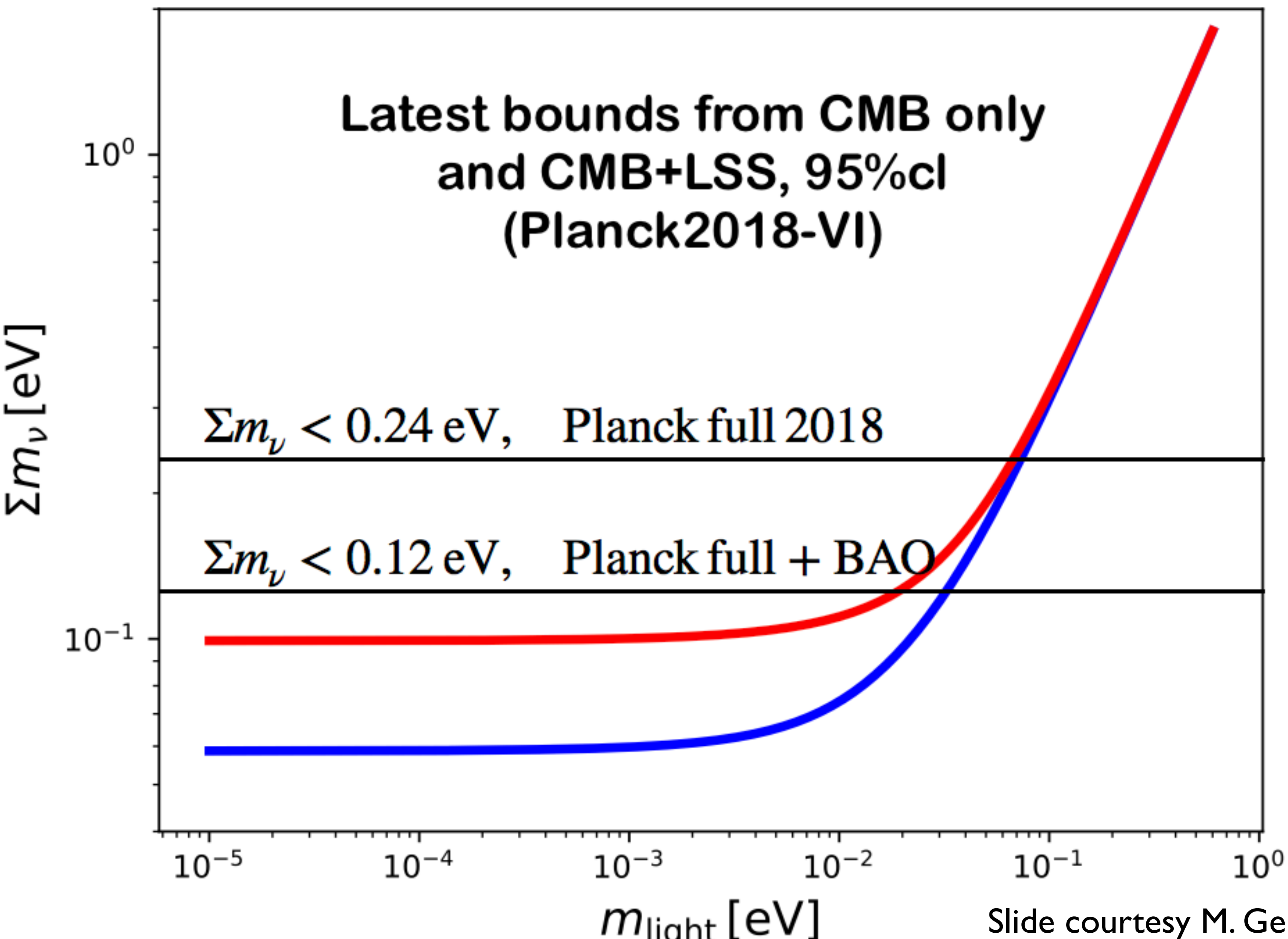
The only unknown parameter is the mass.

$$\rho_\nu = \sum_\nu m_\nu n_\nu = \left(\sum_\nu m_\nu\right)\frac{1}{4\pi^3}\int f(p)\,d^3p$$

$$\Longrightarrow \quad \Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2\ \mathrm{eV}}$$

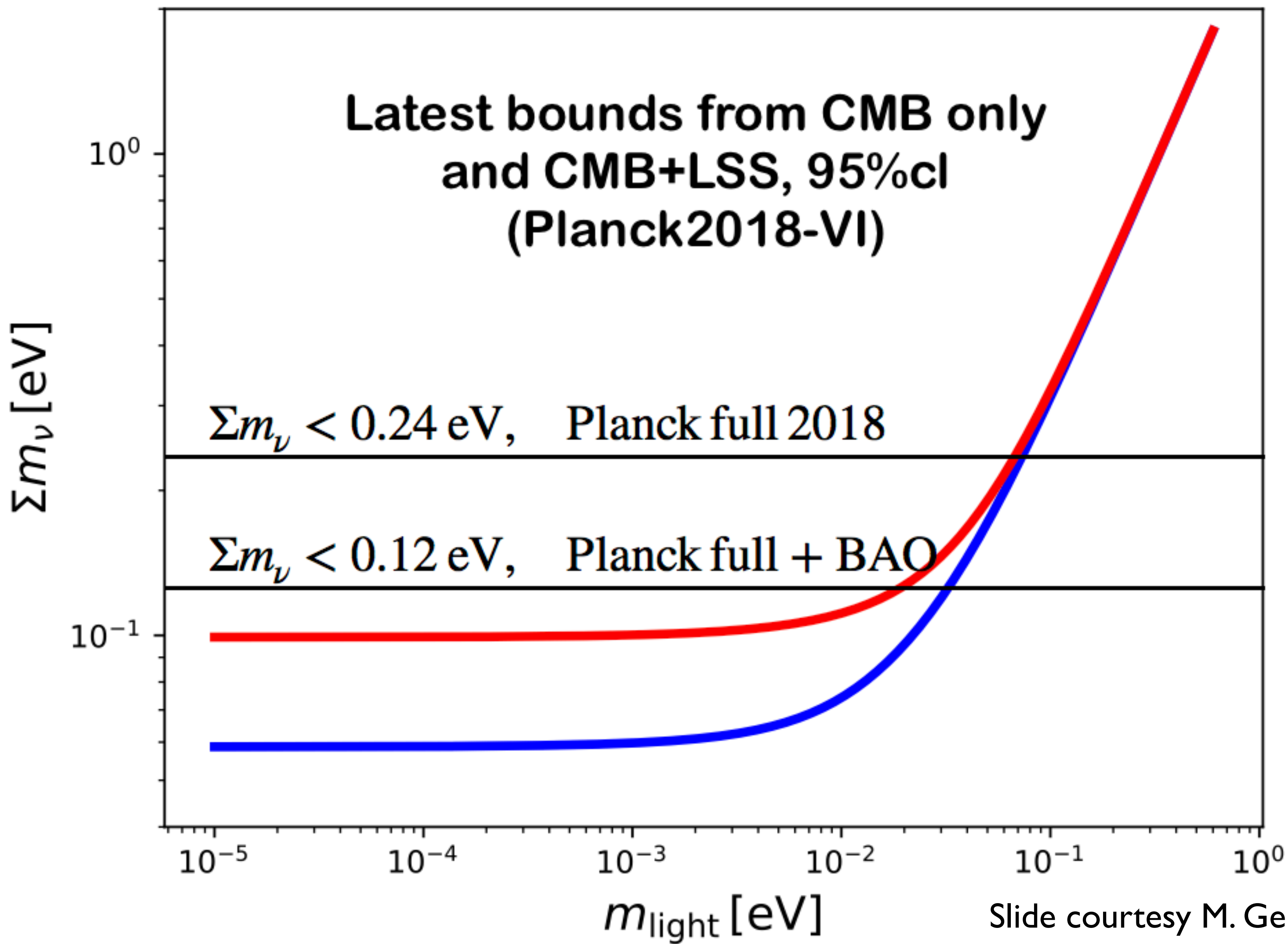


TT
ΛCDM
$g_{\rm eff} = 2 \times 10^{-7}$
$g_{\rm eff} = 3 \times 10^{-7}$
$g_{\rm eff} = 4 \times 10^{-7}$
Planck 2015
$\ell^2\mathcal{D}_\ell\,[\mu K^2]$
$\Delta(\ell^2\mathcal{D}_\ell)\,[\mu K^2]$
ℓ
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
1.5×10^8
1.0×10^8
5.0×10^7
0
500
1000
1500
2000



Slide courtesy M. Gerbino

See M. Archidiacono's and I. Oldengott's talks!



Slide courtesy M. Gerbino

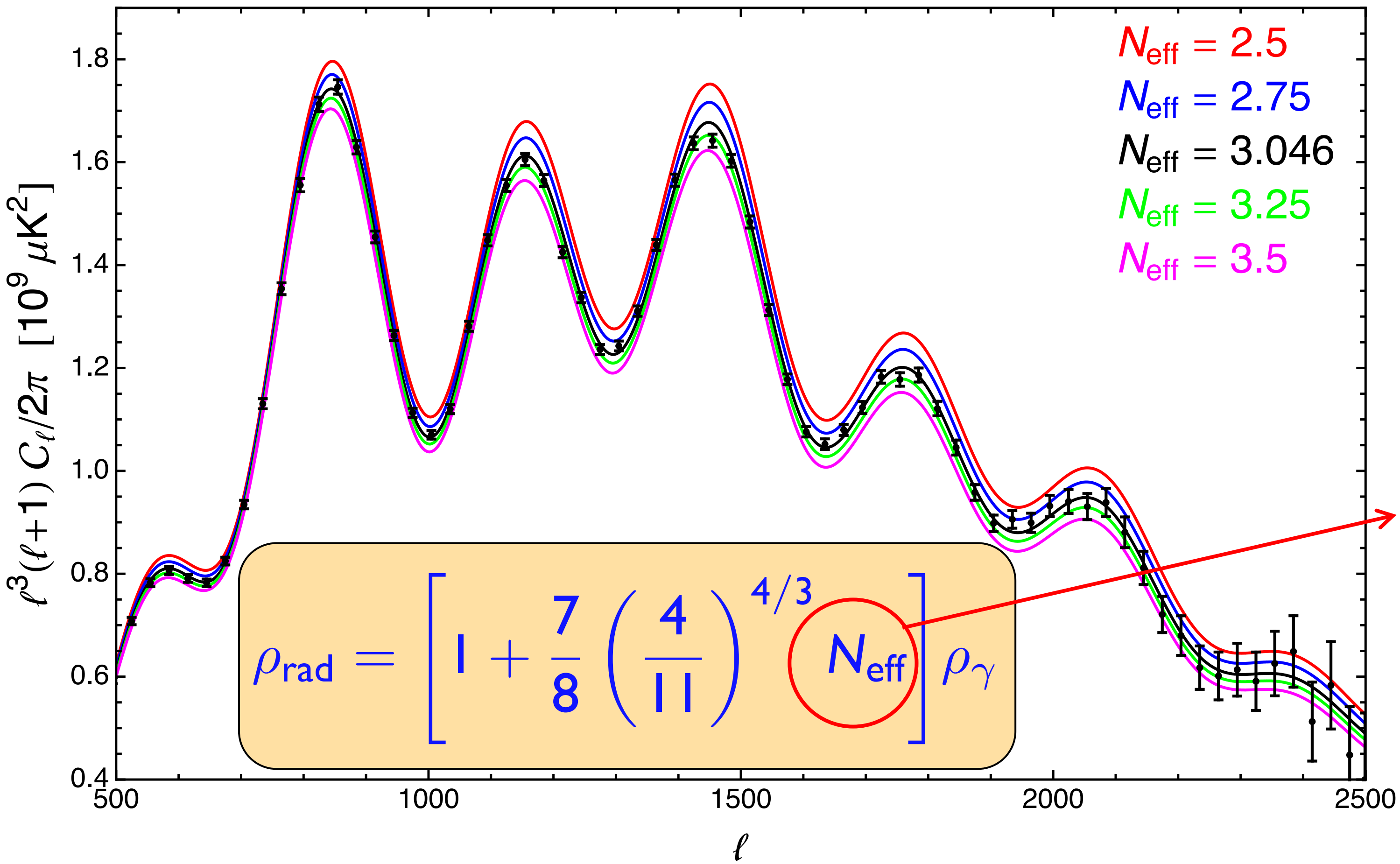
The Cosmic Neutrino Background

The ΛCDM(+ν) model assumes:

- only weak and gravitational interactions for ν's;
- no sterile neutrinos or other light relics;
- perfect lepton symmetry (zero chemical potential);
- no entropy generation after neutrino decoupling beyond e^+e^- annihilation;
- neutrinos are stable;
- in general, there are no interactions that could lead to neutrino scattering/annihilation/decay

Effective number of relativistic species

Planck 2018 + BAO: Neff = 2.99+/- 0.17



Energy density in units of “standard” neutrino density (thermally distributed with T=1.9 K)

Due to non-instantaneous decoupling, the standard expectation is **$N_{\rm eff}$ = 3.045** (updated calculation from de Salas & Pastor 2016; see also Dolgov 2002, Mangano et al. 2005)

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

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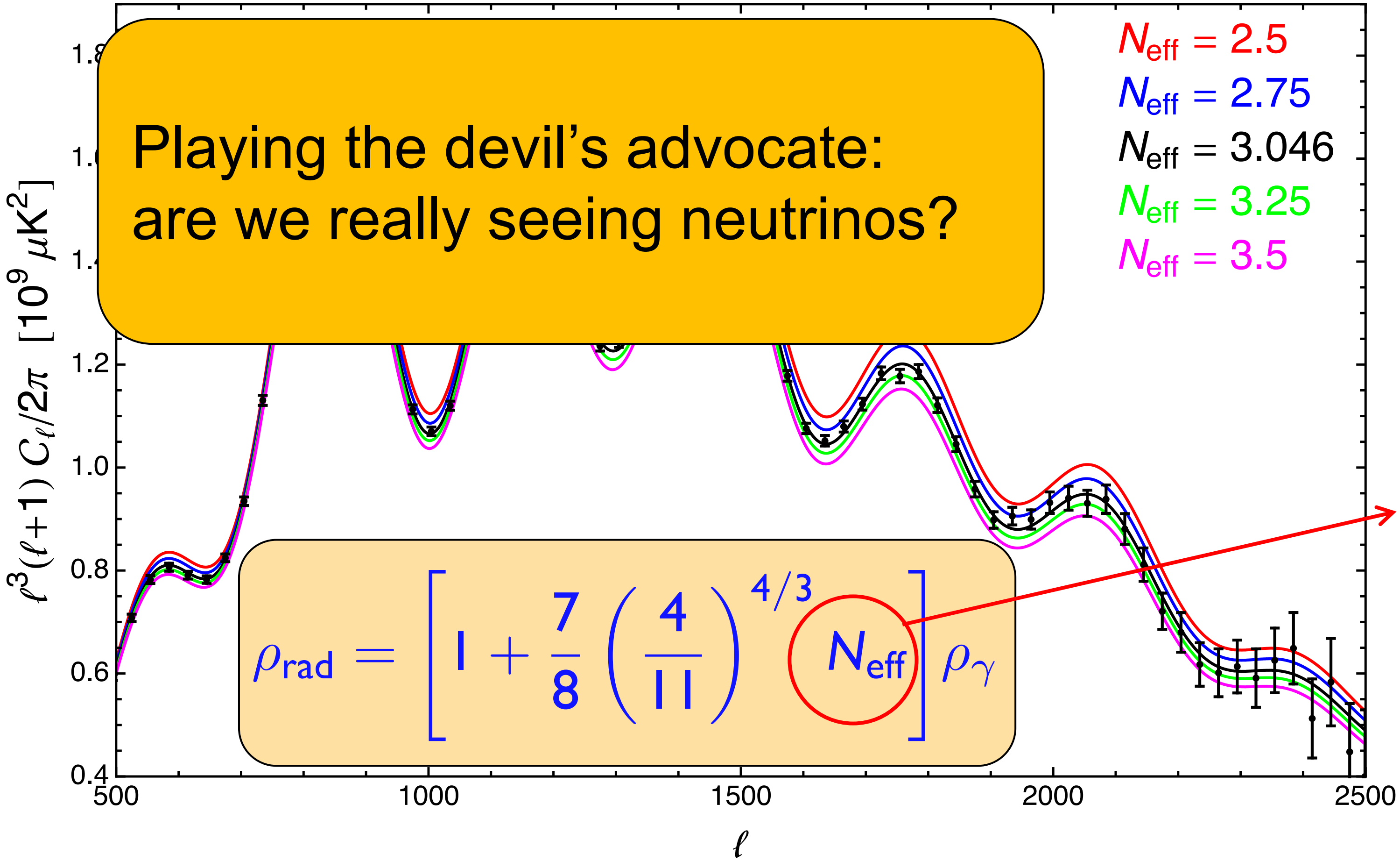

Playing the devil's advocate: are we really seeing neutrinos?

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

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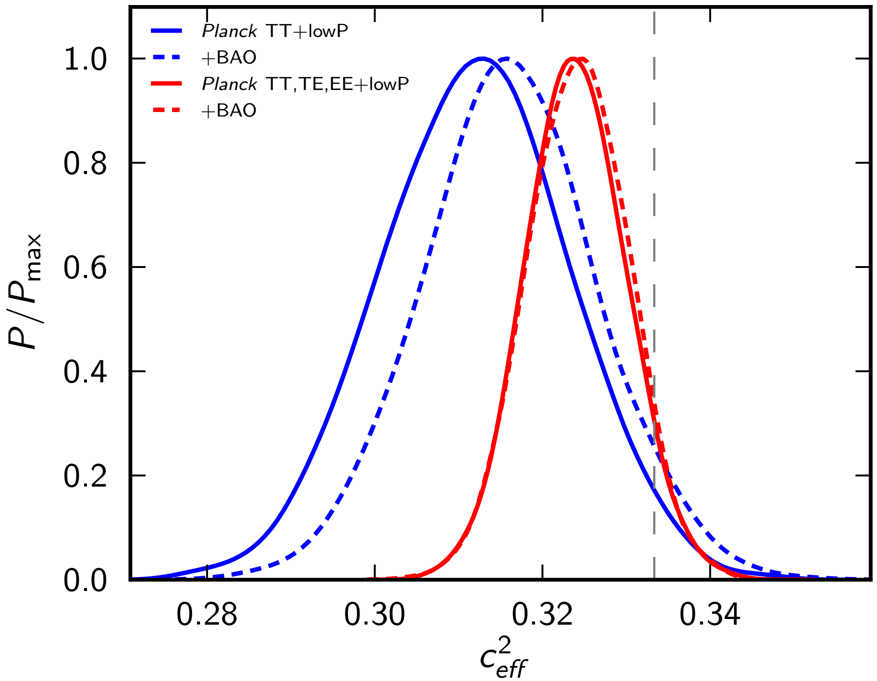
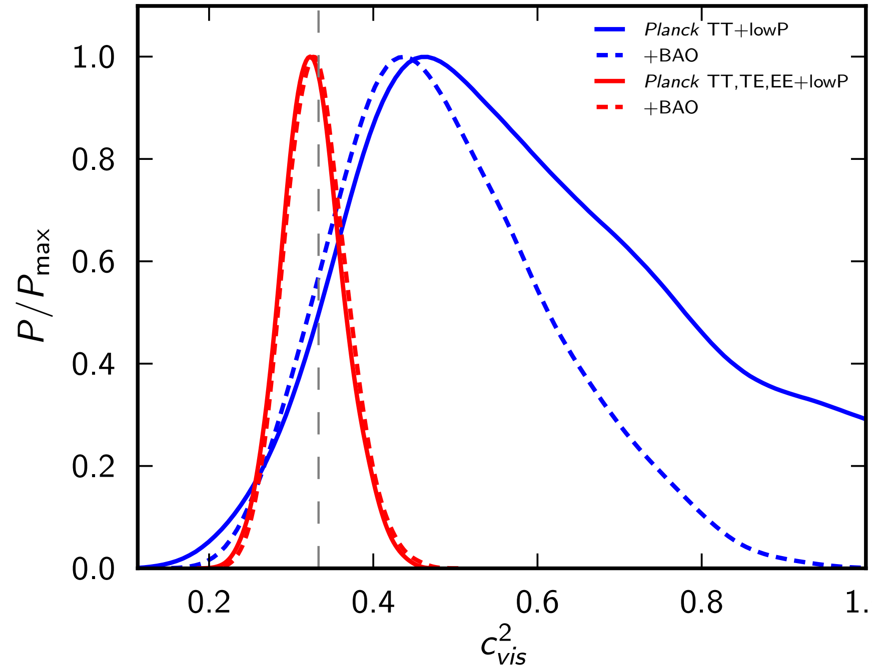
Probing CνB perturbations

Parameterized by the effective ν sound speed and viscosity
Consistent with free-streaming neutrinos ($c^2_{vis} = c^2_{eff} = 1/3$)





PlanckTT+lowP+BAO

$c^2_{eff} = 0.316 \pm 0.010$
$c^2_{vis} = 0.44^{+0.15}_{-0.10}$

PlanckTT,TE,EE+lowP+BAO

$c^2_{eff} = 0.3242 \pm 0.0059$
$c^2_{vis} = 0.331 \pm 0.037$

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Example: Implications for Majoron models

A simple realization of scalar neutrino interactions is found in Majoron models, in which neutrino masses arise from the spontaneous violation of lepton number

$$\mathcal{L}_\nu = y_\Phi \bar{L}\Phi\nu_R - \frac{1}{2} y_\sigma \sigma \overline{\nu_R^c}\nu_R + h.c.$$

When the scalar singlet σ acquires a vev $v_1 >> v_\Phi$ it generates the large mass term M (a Majorana mass term for the rh neutrinos) in the see saw mass matrix

$$M = \frac{y_\sigma v_\sigma}{\sqrt{2}}$$

Diagonalization of the mass matrix yields small neutrino masses $m_\nu \sim y_\Phi^2 v_\Phi^2 / y_\sigma v_\sigma$ and an interaction term between the neutrino mass eigenstates and the majoron J = Im(σ)

$$\mathcal{L}_Y = \frac{iJ}{2} g_{ij}\bar{\nu}_i\gamma_5\nu_j \quad \text{with} \quad g_{ij} \simeq \frac{m_{\nu,i}}{v_\sigma}\delta_{ij} \sim \frac{y_\Phi^2}{y_\sigma}\cdot\frac{v_\Phi^2}{v_\sigma^2}\delta_{ij}$$

Our results on the scattering rate imply that

$$v_\sigma \frac{y_\sigma^{1/2}}{y_\Phi} > 300\,\mathrm{TeV}$$

The Cosmic Neutrino Background

The ΛCDM(+ν) model assumes:

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The Cosmic Neutrino Background

Possible extensions to the standard picture:

- Non-standard interactions, e.g. scalar interactions (scattering will affect neutrino free streaming; decay changes N_{eff})

- Non-thermal distributions, e.g. low-reheating scenarios) ($N_{eff} < 3.046$, suppression of the spectrum)

- Sterile neutrinos

  ($N_{eff} > 3.046$, another free streaming species)

- Large lepton asymmetries ($N_{eff} > 3.046$, larger average velocity)

THE COSMIC NEUTRINO BACKGROUND

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