Constraining non-standard neutrino scenarios with Planck

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(based on work in collaboration with P. Fernandez, F. Forastieri, G.Mangano, G. Miele, P. Natoli, S. Pastor, O. Pisanti)

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THE COSMIC NEUTRINO BACKGROUND

- The presence of a background of relic neutrinos 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});

- Neutrinos keep the energy spectrum of a relativistic fermion in equilibrium:

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

- The present Universe is filled by a relic neutrino background with T = 1.9 K and n = 113 part/cm^3 per species (CνB)

The Cosmic Neutrino Background

The standard picture relies upon the following facts/ assumptions:

- weak interactions mantain neutrinos in equilibrium with the plasma down to T ~ 1 MeV
- perfect lepton symmetry;
- e^+e^- annihilation is the only mechanism for entropy generation after neutrino decoupling ;
- neutrinos are stable;
- in general, there are no interactions (beyond weak and gravitational) that could lead to neutrino scattering/ annihilation/decay

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_{eff} =3.046** for the three active neutrinos (Mangano et al., 2005).

The only unknown parameter is the mass.

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

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

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:

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

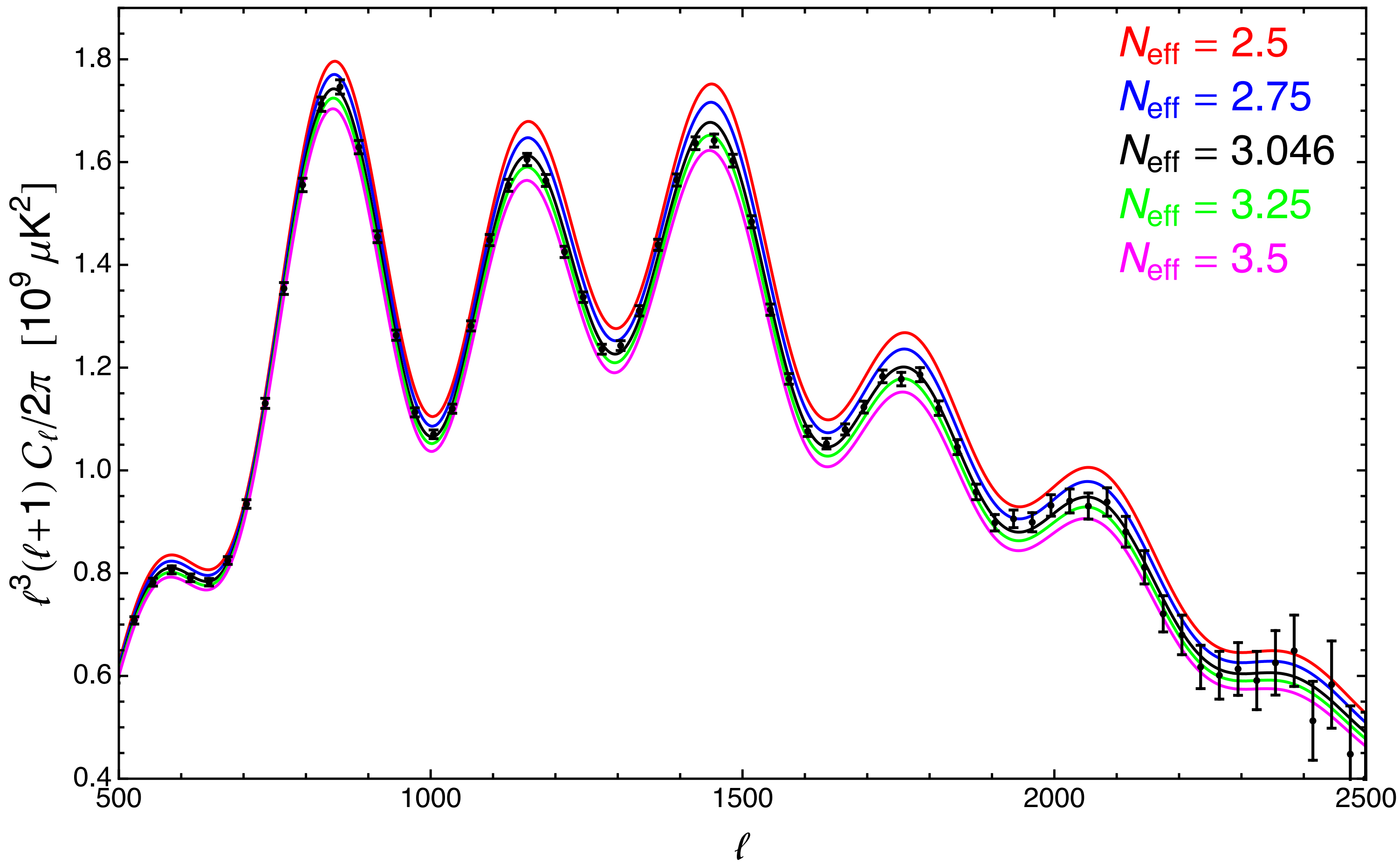
$$\dot{\theta} = k^2\left(\frac{1}{4}\delta - \Pi\right)\,,$$

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

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

The Cosmic Neutrino Background

This picture is consistent with current CMB observations:



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

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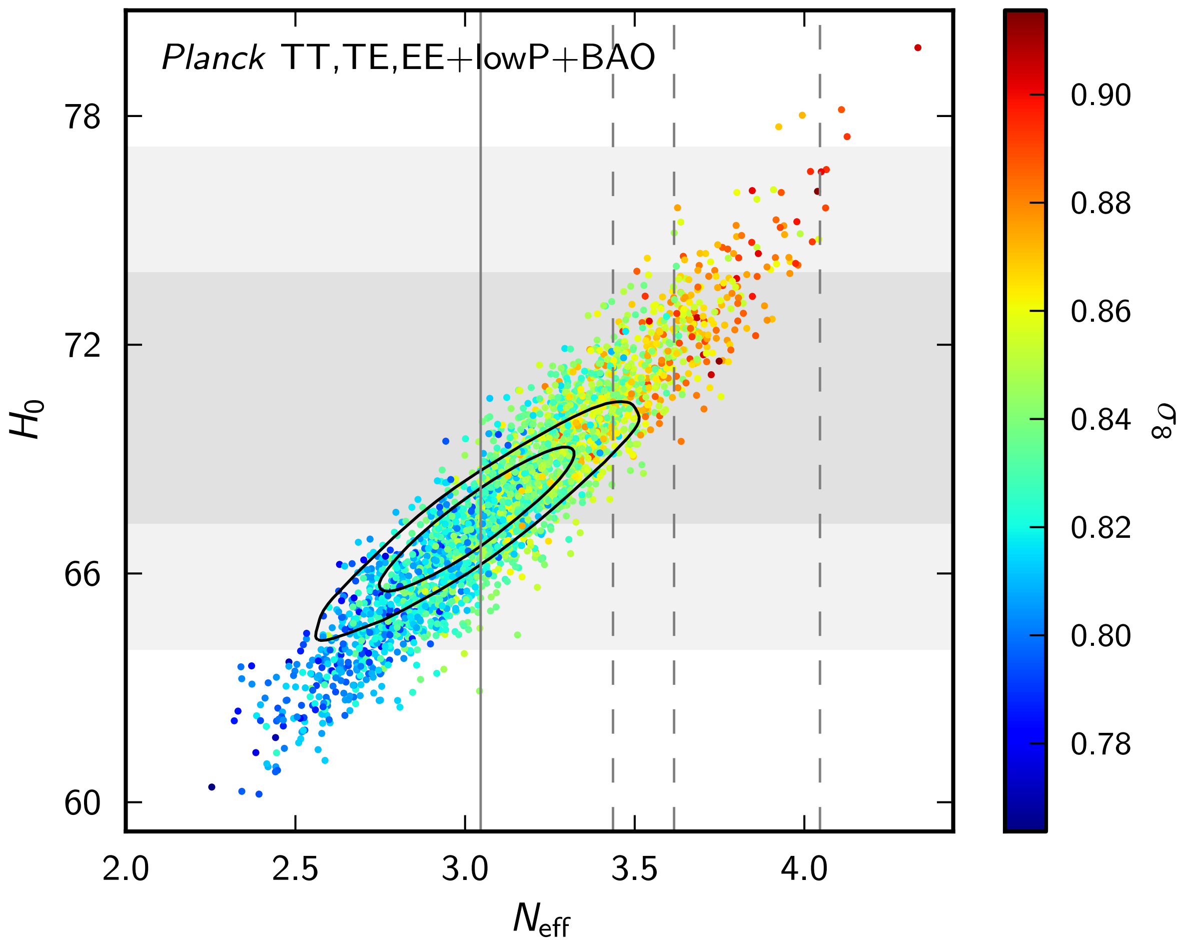


$N_{\mathrm{eff}} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

The Cosmic Neutrino Background

It is important however to test the standard picture by considering non-standard scenarios, e.g.

- Large lepton asymmetries
- Non-standard interactions (e.g. scalar interactions)
- Non-thermal distributions (like in low-reheating scenarios)

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.

THE MAJORON MODEL

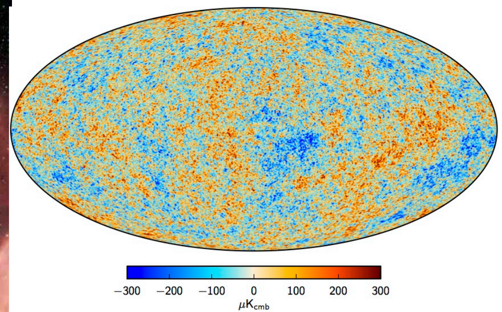
As a concrete example, in models in which neutrinos acquire mass through sponataneous breaking of lepton number, they couple to the NG boson of the broken symmetry – the Majoron:

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

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

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

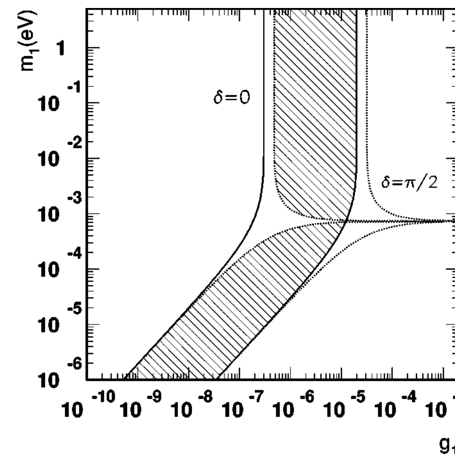
CONSTRAINTS ON SECRET INTERACTIONS

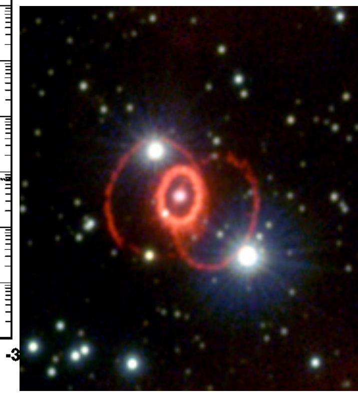


cosmology

$g_{ij} <$ (few) x 10^{-7}

(mass basis)

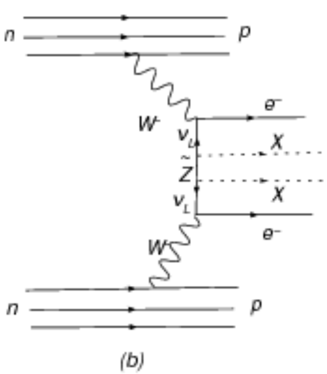


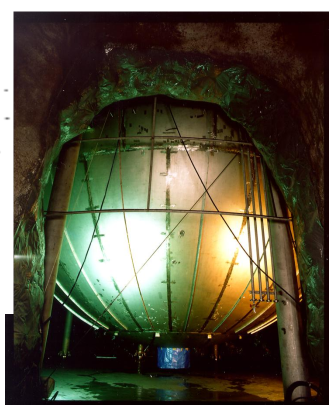


supernovae

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

(medium basis)





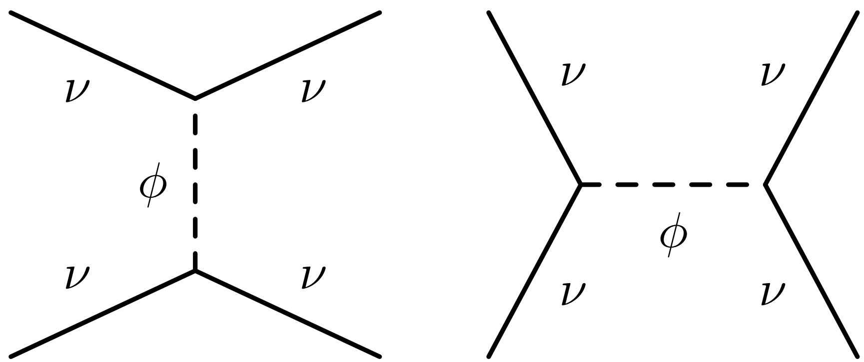
$0\nu2\beta$ decay

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

(flavor basis)

Secret Interactions and cosmological perturbations

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



In the UR limit, the cross section for binary processes (like νν scattering) mediated by a massless boson is

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

The interaction rate grows with temperature as

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

since the expansion rate grows faster with temperature (T^2 and $T^{3/2}$ in the RD and MD eras, respectively), the ratio Γ/H actually increases with time.

Neutrinos **recouple** at low temperatures, at z_{rec} implicitly defined by $\Gamma(z_{rec}) = H(z_{rec})$

In the following I write generically

$$\Gamma_{\nu\nu} = \gamma_{\nu\nu}^4 T \,,$$

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

(massles limit)

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

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

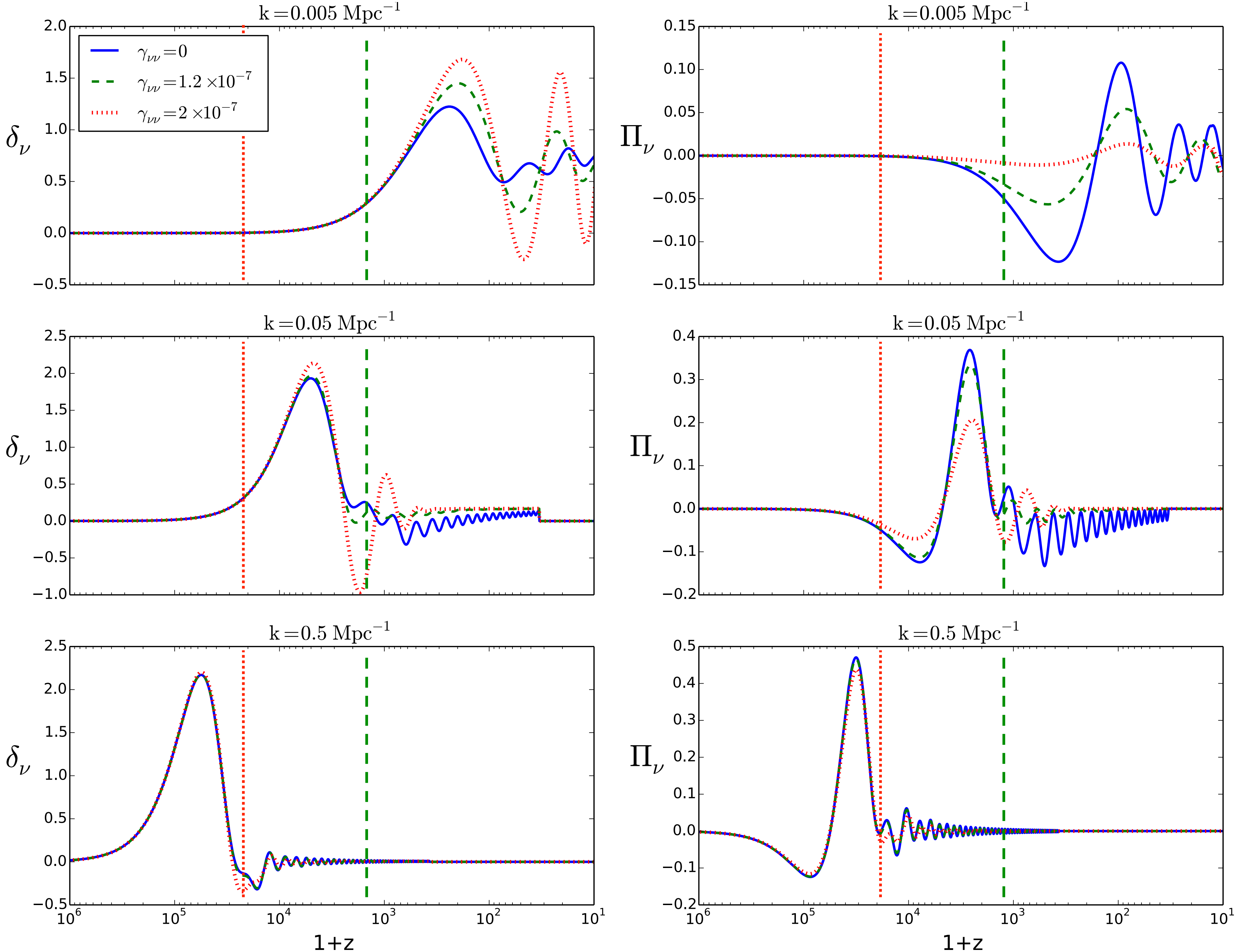
No coll. term for monopole and dipole due to conservation of particle number and momentum in 2⟷2 processes

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

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

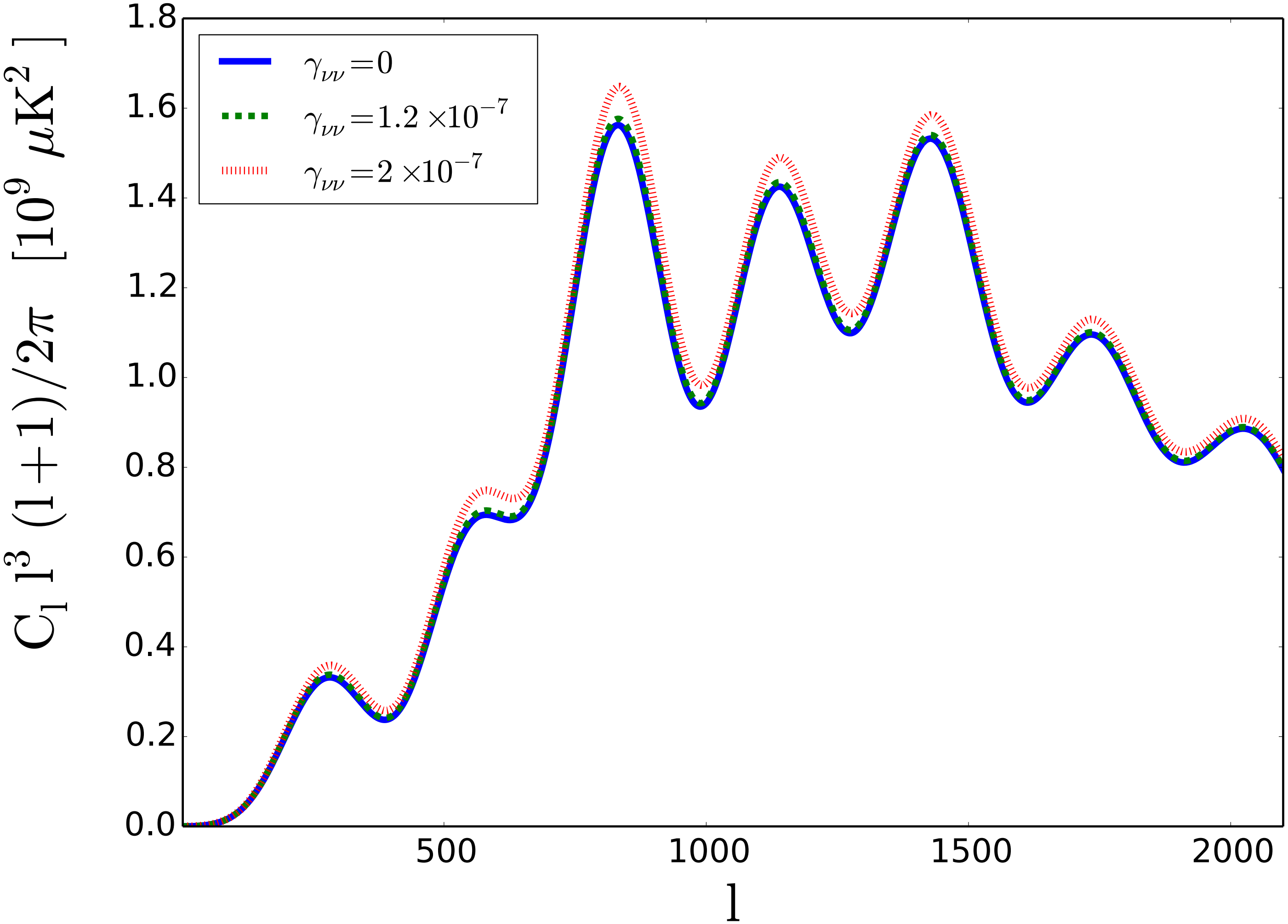
Higher order momenta are driven to zero by the collisions

⟶ energy is confined to the monopole and dipole



k = 0.005 Mpc^{-1}
$\gamma_{\nu\nu}$ = 0
$\gamma_{\nu\nu}$ = 1.2 ×10^{-7}
$\gamma_{\nu\nu}$ = 2 ×10^{-7}
δ_ν
Π_ν
k = 0.05 Mpc^{-1}
k = 0.5 Mpc^{-1}
1+z

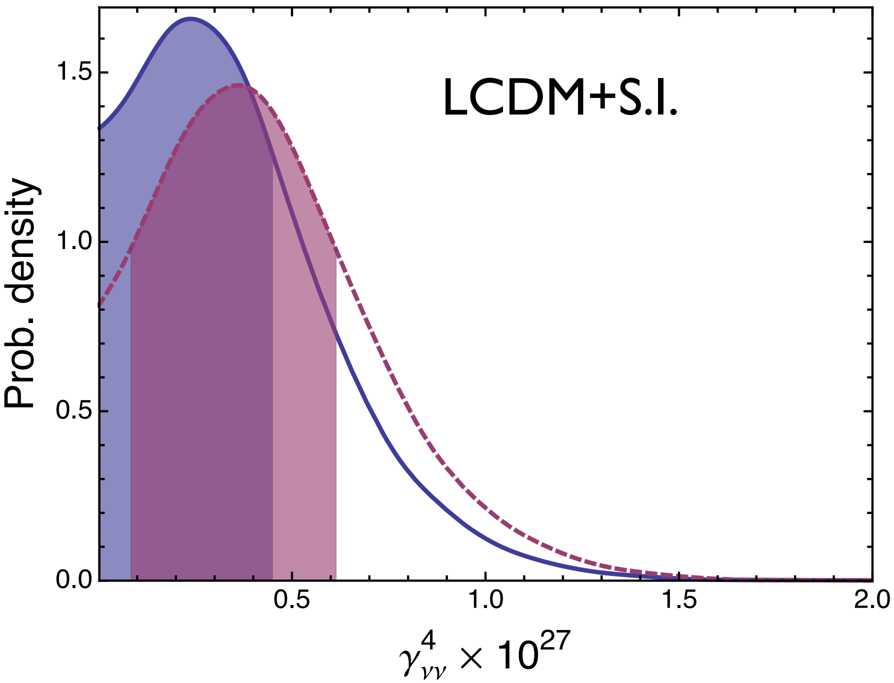
Scalar interactions in the CMB spectrum



Overall boost of the spectrum amplitude

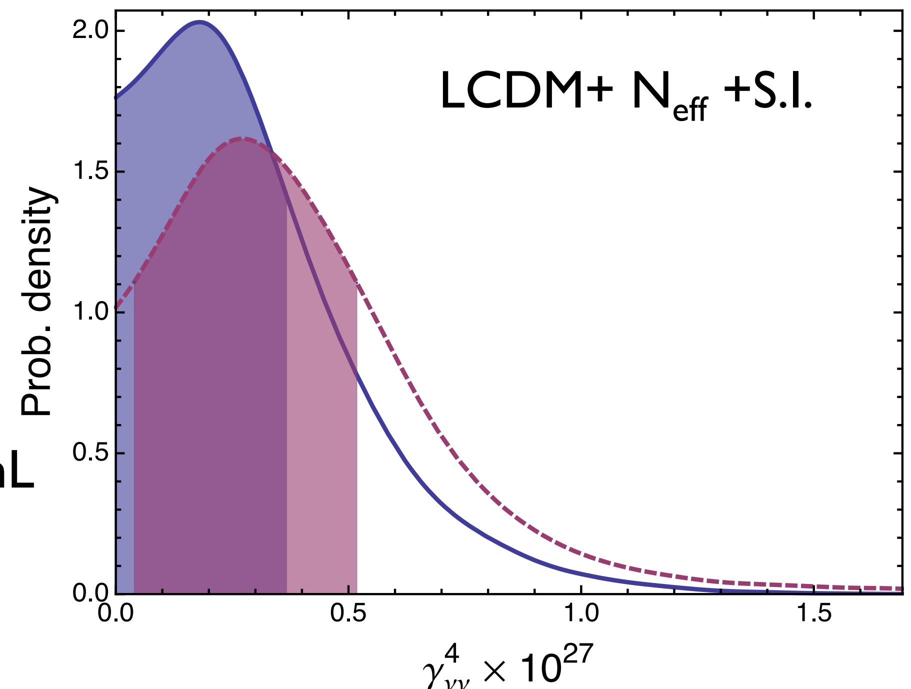
(Forastieri, ML, Natoli, 2015; see also Archidiadono, Hannestad 2013; Cyr-Racine, Sigurdsons 2013

CONSTRAINTS FROM PLANCK 2013



$\gamma_{\nu\nu} < 1.71 \times 10^{-7}$ Planck + WP

$\gamma_{\nu\nu} < 1.76 \times 10^{-7}$ Planck + WP + highL

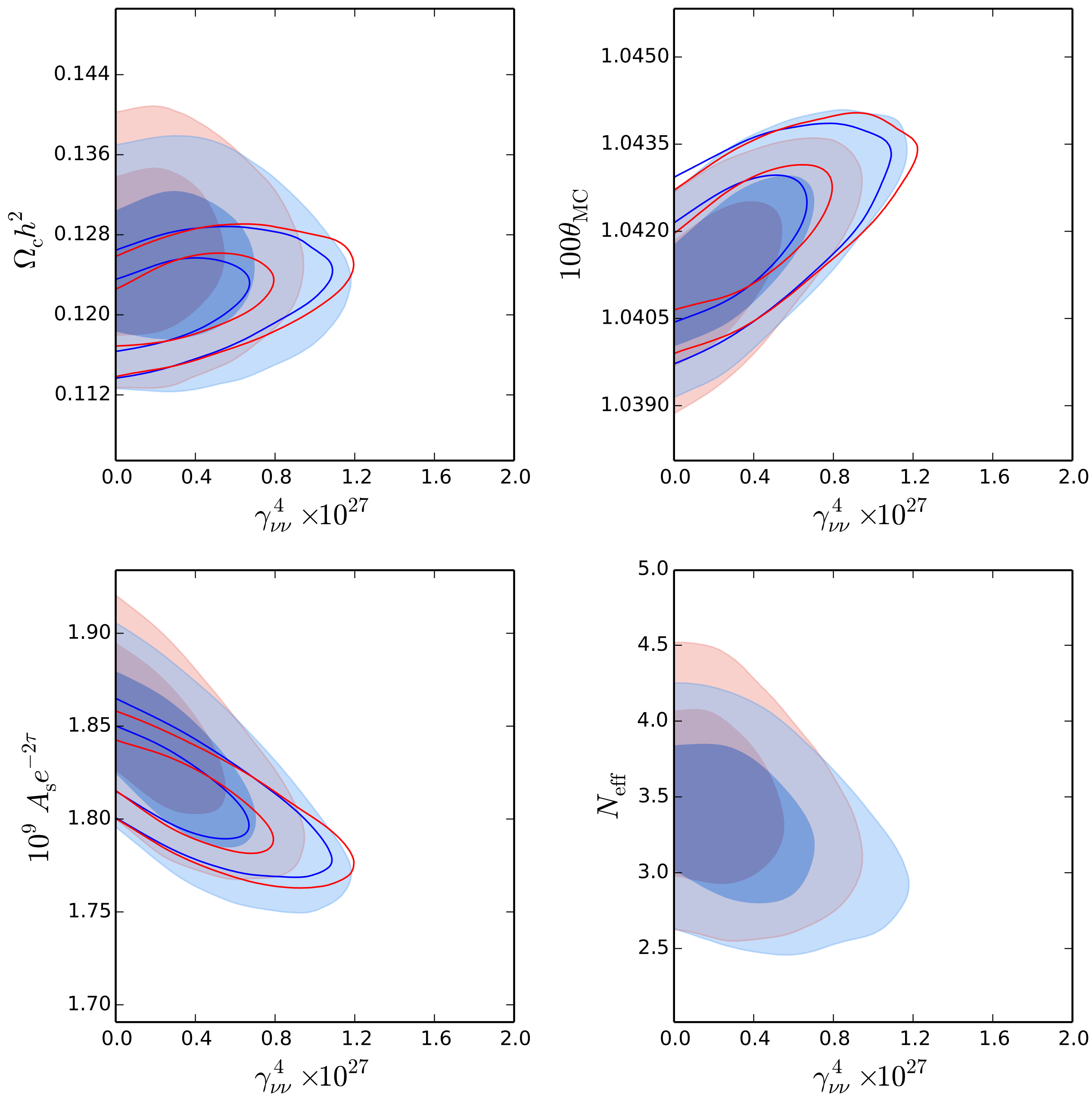


$\gamma_{\nu\nu} < 1.65 \times 10^{-7}$ Planck + WP

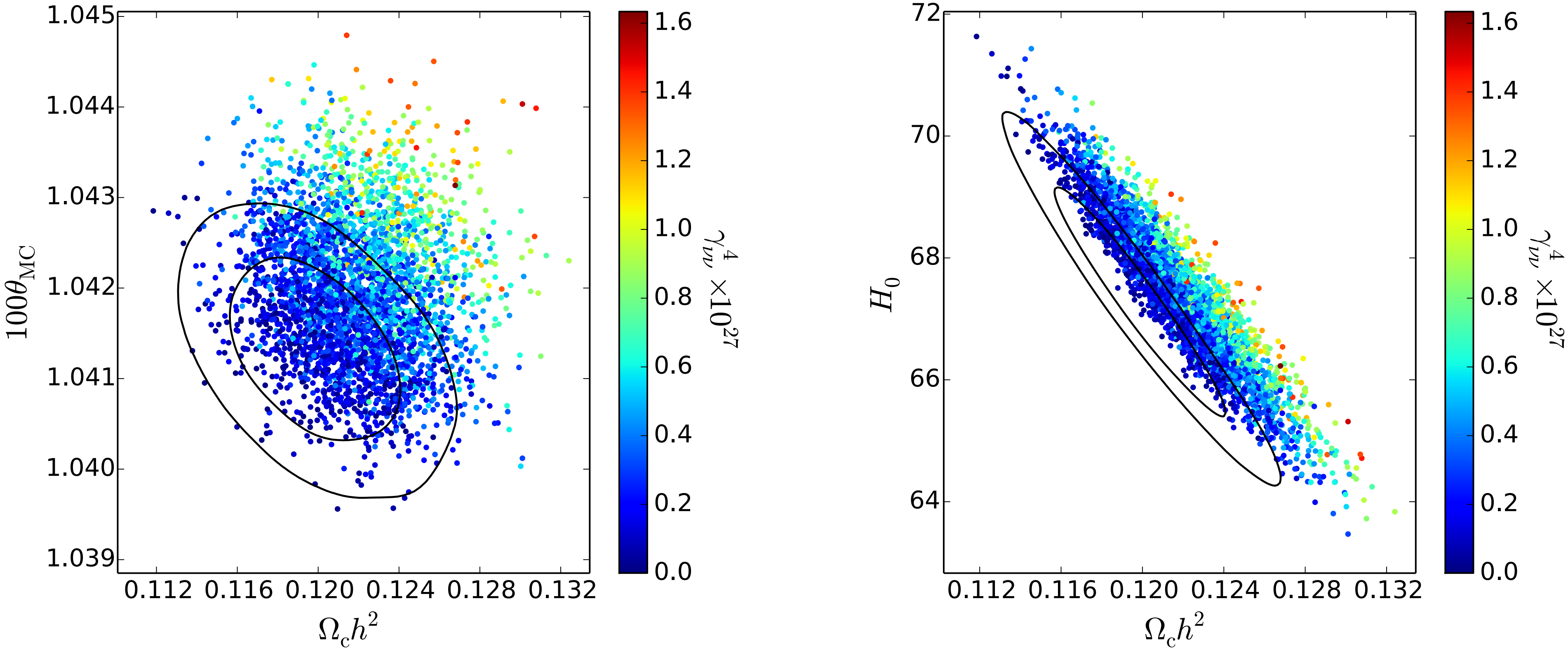
$\gamma_{\nu\nu} < 1.75 \times 10^{-7}$ Planck + WP + highL

(Forastieri, ML, Natoli, 2015)

Constraints from Planck 2013

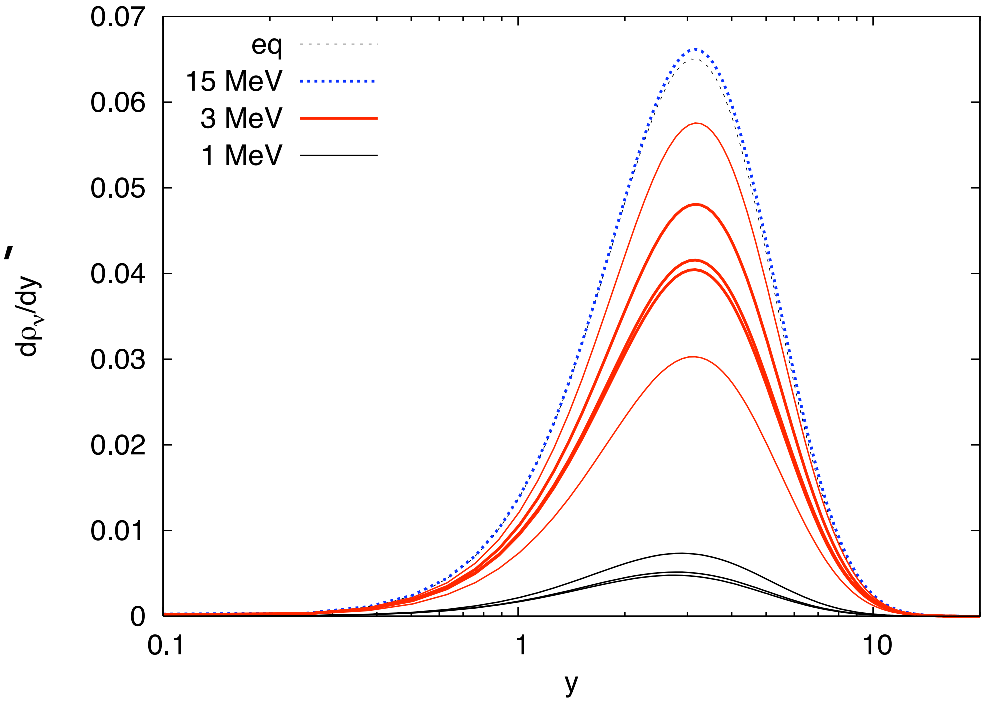


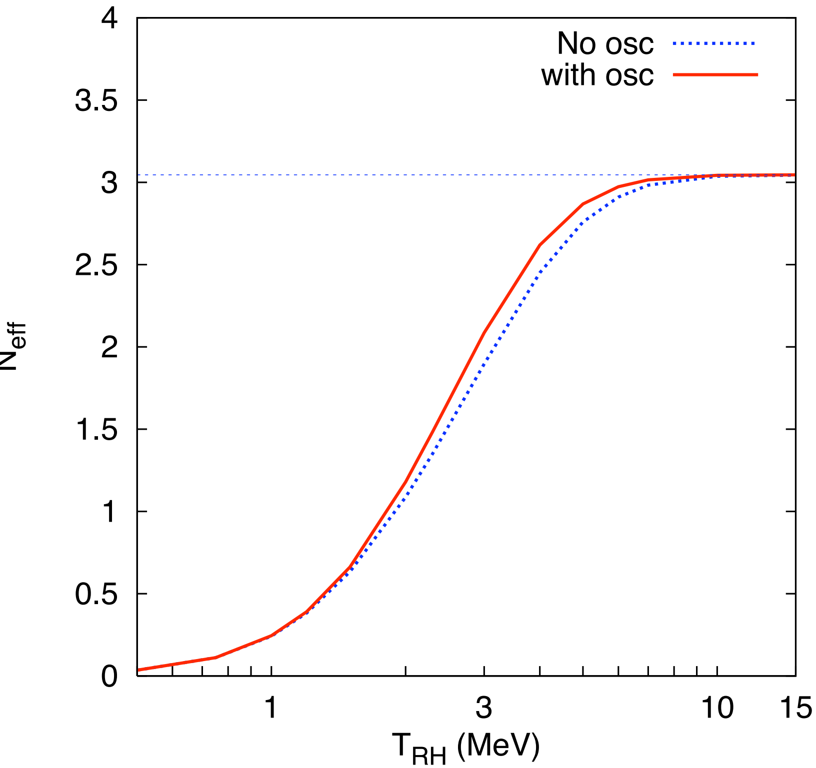
Constraints from Planck 2013



Low-reheating scenarios

For a very low reheating temperature ($T_{RH} \sim O(\text{MeV})$), thermalization of the neutrino background could be incomplete, leading to non-thermal distributions





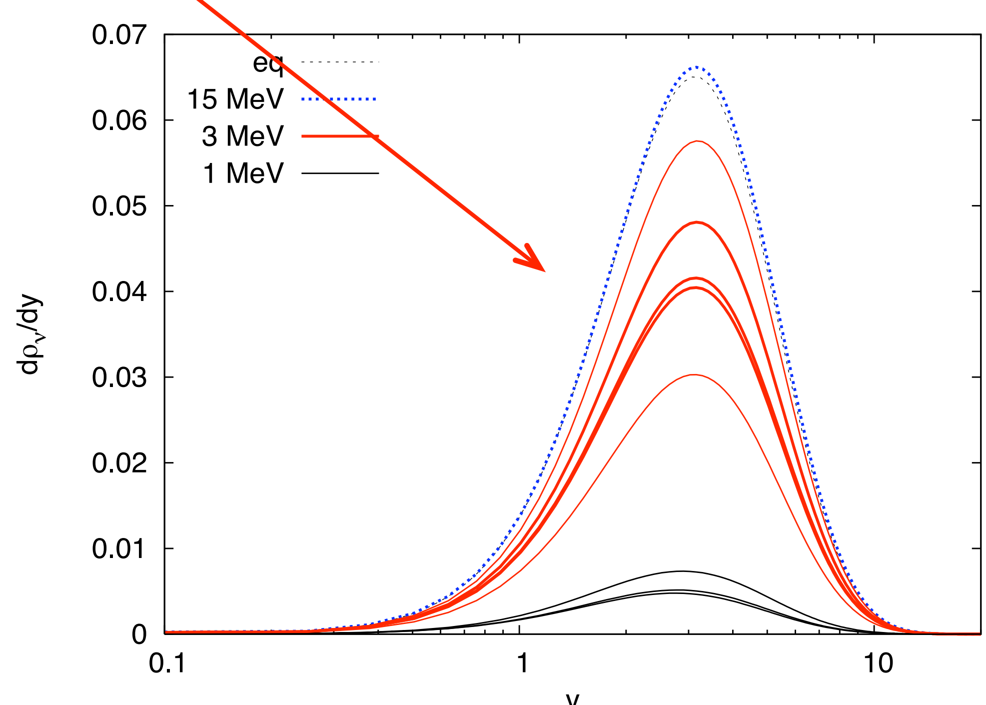
This leads to $N_{eff} < 3.046$

(see P. Fernandez talk!)

The Cosmic Neutrino Background

The modified distribution function is plugged in the Boltzmann equation:

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

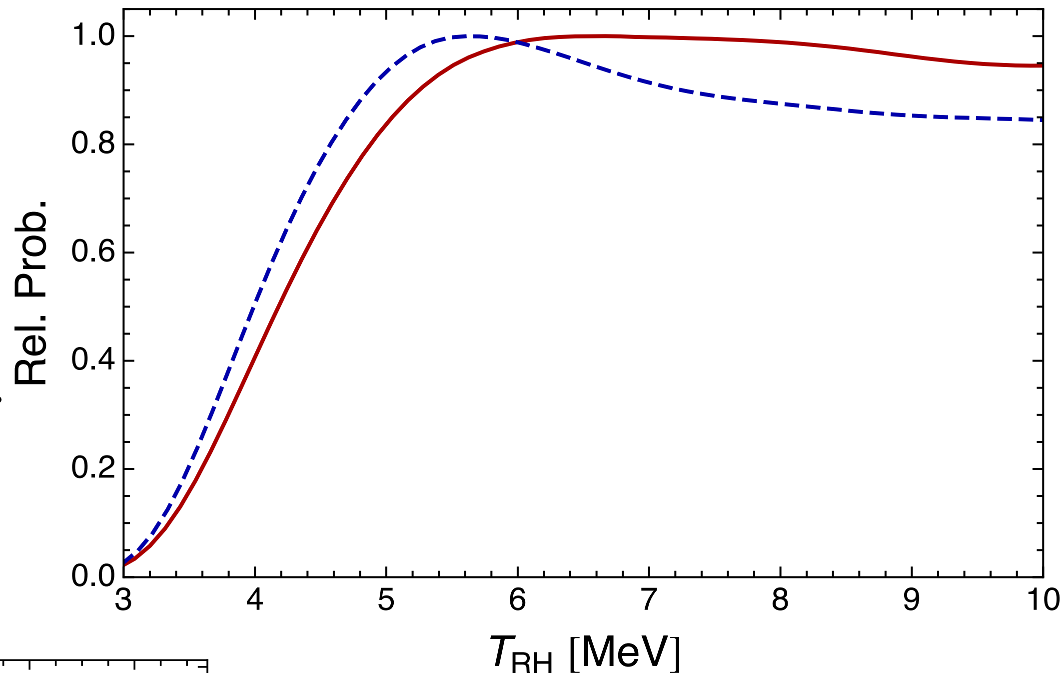


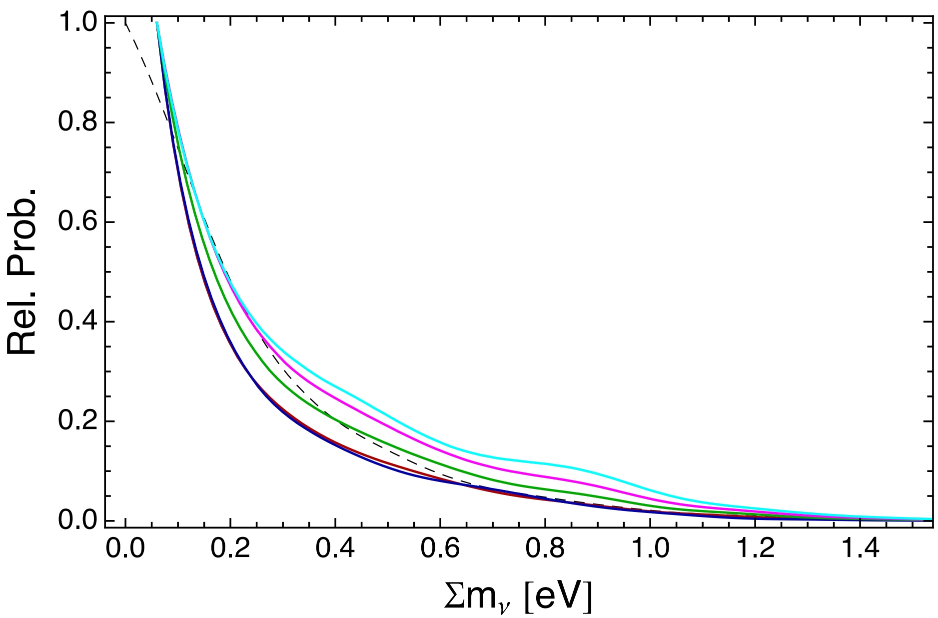
CONSTRAINTS ON T_{RH} FROM PLANCK 2015

$$T_{RH} \geq 4.7\,\text{MeV} \quad (\text{PlanckTT} + \text{lowP}),$$

$$T_{RH} \geq 4.4\,\text{MeV} \quad (\text{PlanckTTTEEE} + \text{lowP}).$$

Comparable constraints are obtained from BBN





$$\sum m_i \leq \begin{cases} 0.89\,\text{eV} & (T_{RH} \leq 7\,\text{MeV}) \\ 0.93\,\text{eV} & (T_{RH} \leq 6\,\text{MeV}) \\ 0.96\,\text{eV} & (T_{RH} \leq 5\,\text{MeV}) \end{cases}$$

(PlanckTT+lowP)

$$\sum m_i \leq 0.80\,\text{eV} \quad (T_{RH} = 15\,\text{MeV})$$

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 strenght of neutrino scalar interactions is constrained by CMB observations at the 10^{-7} level ($z_{rec} < 8000$), comparable to supernovae;
- low reheating temperature scenarios can also be tested; Planck 2015 constrains $T_{RH} > 4.7$ MeV;
- Mass limits are stable with respect to variation in the reheating temperature.