Probing secret interactions in the neutrino sector through CMB observations

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Outline

0) Brief theoretical introduction
1) (Pseudo)scalar neutrino interaction with Planck 2013 data.
2) (Pseudo)scalar interactions with Planck 2015 data.
3) Secret interaction among sterile massive neutrinos.
4) Extend the study to massive neutrinos normal and inverted hierarchy.

Standard cosmology

ΛCMD parameter

$\Omega_b h^2$ [Baryon density]

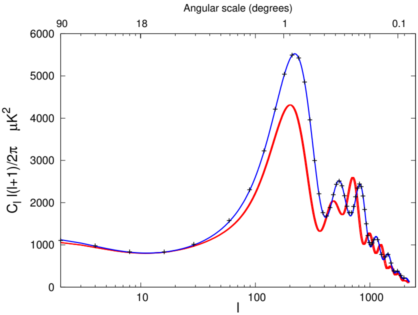
$\Omega_c h^2$ [Dark matter density]

100Θ [$\mathrm{d_A}$ to LSS sound horizon]

n_s [Scalar spectral index]

τ [Reionization optical depth]

$ln(10^{10} A_s)$ [Fluctuation amplitude]



10σ detection of extra-relativistic content Believing in the standard model of particle (SM) The only suitable candidates are neutrinos.
Massless neutrinos:

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

CMB (Planck) measure:

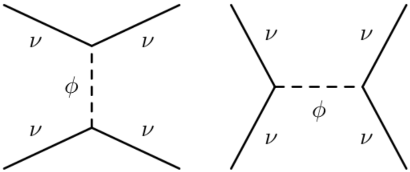
$N_{\rm eff} = 2.99 \pm 0.20\,(Planck TTTEEE + lowP)$

Massive neutrinos add another parameter $\sum m_\nu$.

Planck constraints (PlanckTT)

$\sum m_\nu < 0.72\,\mathrm{eV}$ 95% C.L.

Non-standard interactions: (Pseudo)scalar



Lagrangian

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

This induces a series of processes mediated by a massless scalar (h_{ij}) or pseudoscalar (g_{ij}) boson.

If νs are relativistic, the cross section has the form:

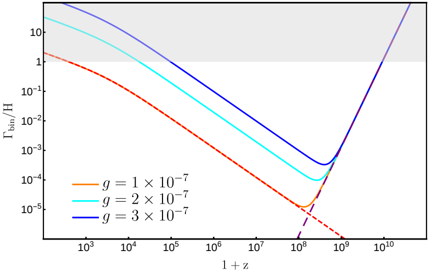
$$\sigma_{\nu\nu} \sim \frac{g_{ij}^4}{s} \simeq \frac{g_{ij}^4}{T_\nu^2}$$

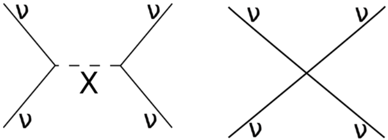
and the scattering rate:

$$\Gamma_{\nu\nu} \sim <\sigma_{\nu\nu} v> n_\nu \simeq g_{ij}^4 T_\nu$$

Interaction rate vs Hubble rate:

$$\frac{\Gamma_{\nu\nu}}{H_r} \propto T_\nu^{-1}, \qquad \frac{\Gamma_{\nu\nu}}{H_m} \propto T_\nu^{-1/2}$$





It behaves like the standard Weak interaction:

$$\sigma_x = G_x^2 T_\nu^2$$

and the reaction rate is:

$$\Gamma_x = G_x^2 T_\nu^5$$

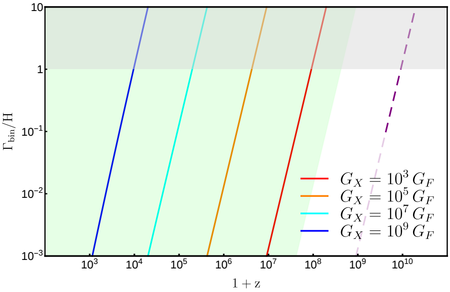
the interaction is turned on at early times:

$$\frac{\Gamma_x}{H_m} \propto T_\nu^{\frac{7}{2}}, \qquad \frac{\Gamma_x}{H_r} \propto T_\nu^3$$

Lagrangian

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

Processes mediated by a massive vector boson X.



Usual parametrization

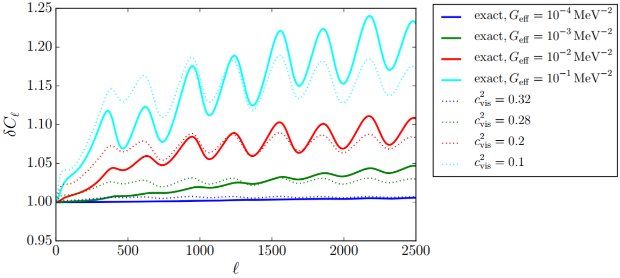
Usually constrained using 2 parameters $c_{\rm vis}$ and $c_{\rm eff}$.

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h} + H(1-3c_{\rm eff}^2)\left(\delta_\nu + 4H\theta_\nu \frac{\theta_\nu}{k^2}\right) ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \frac{k^2}{4}(1-3c_{\rm eff}^2)\left(\delta_\nu + 4H\theta_\nu \frac{\theta_\nu}{k^2}\right) ,$$

$$2\dot{\sigma}_\nu = \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{15}\dot{\eta} - (1-3c_{\rm vis}^2)\left(\frac{8}{15}\theta_\nu + \frac{4}{15}\dot{h} + \frac{8}{15}\dot{\eta}\right) .$$

$c_{\rm eff}^2$ and $c_{\rm vis}^2 = 1/3 \to$ standard free-streaming case
$c_{\rm vis}^2 = 0 \to$ tight-coupling regime ???
If the initial $\ell \geq 2$ moments should be non zero, (pseudoscalar int) $\to c_{vis}^2 = 0$ does not drive $F_{\nu 2}$ to zero.
"Has this parametrization anything to do with particle scattering." [Oldengott et al.]



Pseudoscalar interaction between active massless neutrinos

Goals achieved:

- Constraints on secret interactions among neutrinos from CMB data
- Development of a modified code able to evolve both (pseudo)scalar and Fermi-like interaction in the massless neutrino sector:
  - Arbitrary number of massless neutrinos
  - Interacting matrix with possible off-diagonal components

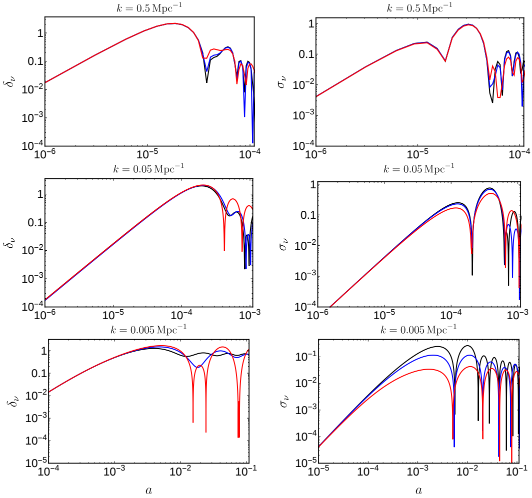
More accurate approach with respect what is done in literature.
Massless Boltzmann equation:

$$\frac{\partial F_\nu}{\partial \tau} + ik\mu F_\nu = -\frac{2}{3}\dot{h} - \frac{4}{2}\left(\dot{h} + 6\dot{\eta}\right) P_2(\mu) - a\Gamma F_\nu \,,$$

Interacting hierarchy:

$$\begin{aligned}
\dot{\delta}_\nu &= -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h}\,, \\
\dot{\theta}_\nu &= k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) \\
\dot{\sigma}_\nu &= \frac{4}{15}\theta_\nu - \frac{3}{10}kF_{\nu 3} + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta} - a\Gamma\sigma_\nu \,, \\
\dot{F}_{\nu\ell} &= \frac{k}{2\ell+1}\left[\ell F_{\nu(\ell-1)} - (\ell+1)\, F_{\nu(\ell+1)}\right] - a\Gamma F_{\nu\ell}\,. \qquad (\ell \geq 3)
\end{aligned}$$

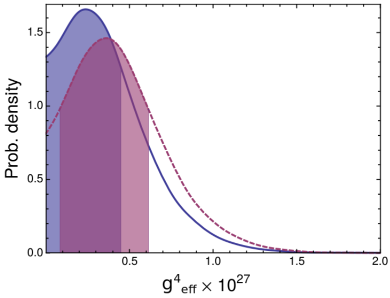
We parametrize the interaction using an effective coupling $\Gamma = g_{\rm eff}^4\, T_\nu$.

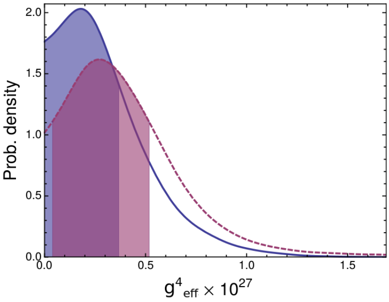


Interaction strength	Recoupling redshift	Wave number	multipole
$g_{\rm eff} = 1.8 \times 10^{-7}$	$z_{\rm rec} \sim 1.2 \times 10^3$	$k_{\rm rec} \sim 0.029\,\mathrm{Mpc}^{-1}$	$\ell_{\rm rec} \sim 420$
$g_{\rm eff} = 2.8 \times 10^{-7}$	$z_{\rm rec} \sim 1.2 \times 10^4$	$k_{\rm rec} \sim 0.153\,\mathrm{Mpc}^{-1}$	$\ell_{\rm rec} \sim 2150$
$g_{\rm eff} = 3.8 \times 10^{-7}$	$z_{\rm rec} \sim 4.5 \times 10^4$	$k_{\rm rec} \sim 0.495\,\mathrm{Mpc}^{-1}$	$\ell_{\rm rec} \sim 7000$

[(Pseudo)scalar] Results [ΛCDM + g_{eff}] Planck 2013 data

Analysis carried on using CAMB and CosmoMC (Fortran90 pubblic codes)





Constraints ΛCMD $+g_{\rm eff}$:

$g_{eff} \leq 1.77 \cdot 10^{-7}\,(95\% cl)$

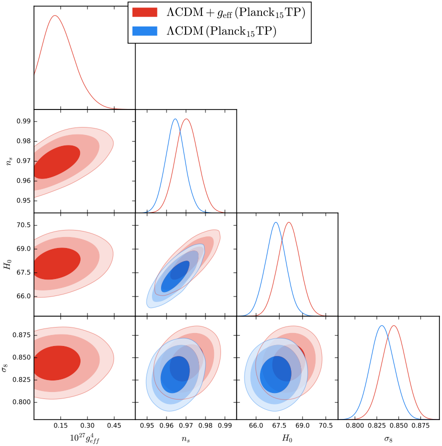
$g_{eff} \leq 1.79 \cdot 10^{-7}\,(95\% cl)$

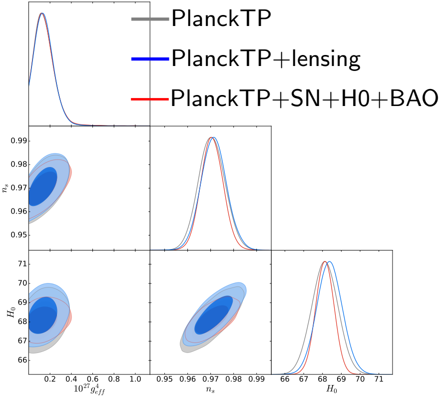
Constraints ΛCMD $+g_{\rm eff} + N_{\rm eff}$:

$g_{eff} \leq 1.64 \cdot 10^{-7}\,(95\% cl)$

$g_{eff} \leq 1.74 \cdot 10^{-7}\,(95\% cl)$

[(Pseudo)scalar] Results [ΛCDM + g_{eff}] Planck 2015 data





Constraints on g_{eff}:

$g_{eff} \leq 1.33 \cdot 10^{-7}$ (95%*cl*)

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Goodness of fit

	Planck$_{15}$TP		Planck$_{15}$TT	
	ΛCDM	$\Lambda\text{CDM} + g_{\text{eff}}$	ΛCDM	$\Lambda\text{CDM} + g_{\text{eff}}$
χ^2_{plik}	2435.7	2431.6	766.4	765.7
χ^2_{lowTEB}	10496.6	10496.6	10496	10496.6
χ^2_{prior}	12.3	11.8	2.7	1.9
χ^2_{CMB}	12932.3	12929.1	11262.4	11261.3
$-\log(\text{Like})$	12944.7	12941.4	11265.1	11264.3
$\Delta\chi^2_{\text{min}}$		-3.3		-0.8
$-\ln(\text{mean Like})$	12953.1	12950.5	11275.9	11275.7
$\Delta\chi^2$		-2.6		-0.2

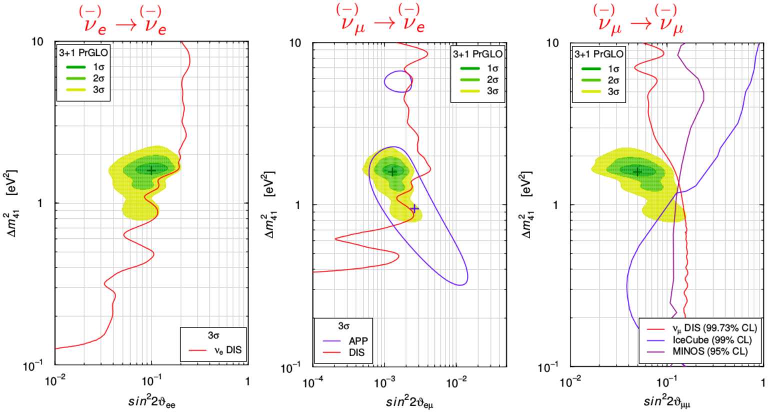
Fermi-like interaction among sterile and active neutrinos

Goals achieved:

- Constraints on secret interactions among sterile massive neutrinos from CMB data
- Development of a modified code able to evolve (pseudo)scalar and Fermi-like interaction in the massive neutrino sector.
  - Arbitrary number of massless and massive neutrinos
  - Massless and massive eigenstates can be weighted with "personalized" $N_{\rm eff}$
  - Interaction matrix with massive and massless off-diagonal elements
  - Possibility of chose between normal and inverted hierarchy

Short Baseline (SBL) anomalies

Short baseline laboratory experiments (SBL) show anomalies that can be fitted by light sterile neutrinos. (Gallium, MiniBooNE, Reactor, LSND)
light $\rightarrow$ $m_{\nu s} \sim O(\mathrm{eV})$



[Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]

Sterile neutrinos

The immediate interpretation is a light sterile neutrino, however the introduction of an extra component impacts on N_{eff} depending on the model assumed:

a) Thermal distribution of sterile νs
b) Dodelson-Widrow (depending on a scale factor χ_s)

Cosmologically speaking we parametrize phenomenologically in this way:

$$\rho_\nu + \rho_x = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 \left(N_{eff}^{SM} + \Delta N_{eff} \right) \qquad (2)$$

Extra degrees of freedom

$$\Delta N_{eff} = \begin{cases} \left(\frac{T_s}{T_\nu}\right)^4 & [a] \\ \chi_s & [b] \end{cases}$$

mass of the sterile

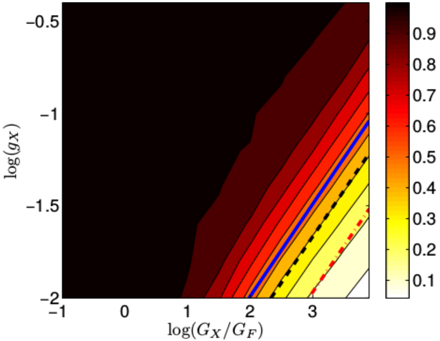
$$m_s = \begin{cases} m_s^{eff} \left(\frac{T_s}{T_\nu}\right)^3 = m_s^{eff} \Delta_{Neff}^{\frac{3}{4}} & [a] \\ \frac{m_s^{eff}}{\chi_s} = \frac{m_s^{eff}}{\Delta_{Neff}} & [b] \end{cases}$$

Compatible with the prediction of the SM, this excludes a possible extra thermalized neutrino (sterile or active) at 3 and 5σ

Sterile neutrinos having non-standard interactions

[Hannestad et al., 2013]

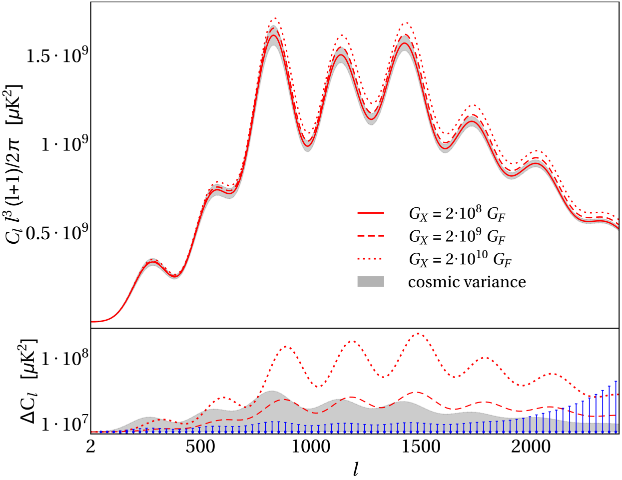
Introducing a new secret interaction between sterile neutrinos mediated by a massive boson having $M_X < M_{W^\pm}$ can suppress the thermalization.



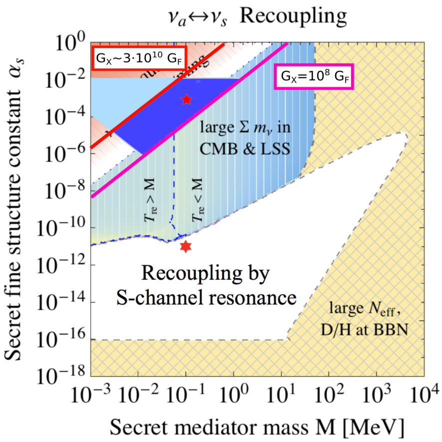
Color legend corresponds to ΔN_{eff}.
Solid, dashed, and dot-dashed lines are $M_X = 300\,\mathrm{MeV}$, $200\,\mathrm{MeV}$ and $100\,\mathrm{MeV}$ respectively.

We use CAMB and CosmoMC.
Introducing a collisional term in the Boltzmann equation.

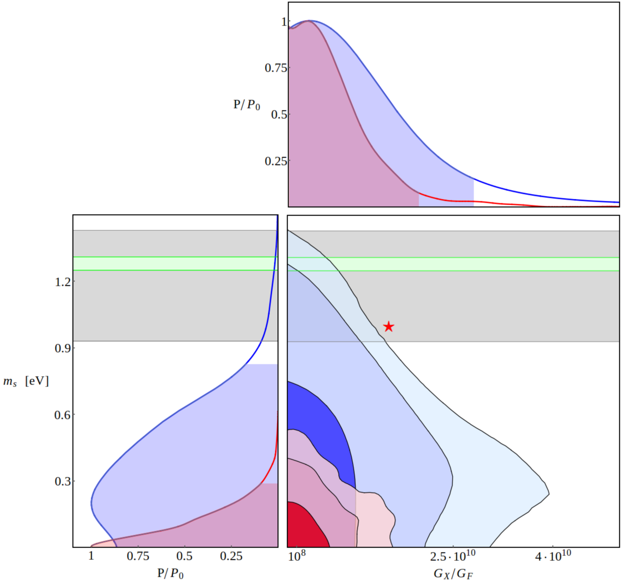
$$\frac{\partial \Psi_i}{\partial \tau} + i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\Psi_i + \frac{d\ln f_0}{d\ln q}\left[\dot{\eta} - \frac{\dot{h}+6\dot{\eta}}{2}\left(\hat{k}\cdot\hat{n}\right)^2\right] = -\Gamma_{ij}\Psi_j\,,$$



Constraints



Results (Constraints)



(PlanckTT)
(PlanckTT+BAO)

Broad
Narrow

The red star at $G_X = 1.5 \times 10^{10} G_F$ and $m_s = 1$ eV is representative of the strongly self-interacting scenario described in [X. Chu, et. al 2015]

Thanks

Massive interacting cross section

Theoretical cross sections

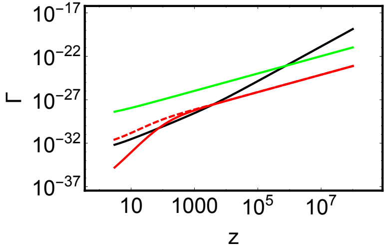
In case of pseudoscalar interaction between massive neutrinos:

$$\nu\nu \longleftrightarrow \nu\nu) \quad \frac{d\sigma}{dt} = \frac{g^4}{32\pi s^2}$$

$$\nu j \longleftrightarrow \nu j) \quad \frac{d\sigma}{dt} = \frac{g^4}{32\pi s^2}\left(\frac{t}{s} + \frac{s}{t+s} + 3\right)$$

$$\nu\nu \longleftrightarrow jj) \quad \frac{d\sigma}{dt} = \frac{g^4}{32\pi s^2}\left(-\frac{1}{2}\right)\left(\frac{s}{t} + \frac{t}{t+s} + 3\right)$$

$[\nu\nu \to \nu\nu]$



$[\nu J \to \nu J]$