

Cosmological constraints on non-standard neutrino interactions

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Based on [M.Lattanzi, F.Forastieri, P.Natoli (in preparation)] and [F. Forastieri et al. (JCAP 1707 (2017) no.07, 038)]

Non-standard interactions among neutrinos are usually considered of two types:

- (Pseudo)scalar interactions
- Fermi-like interactions

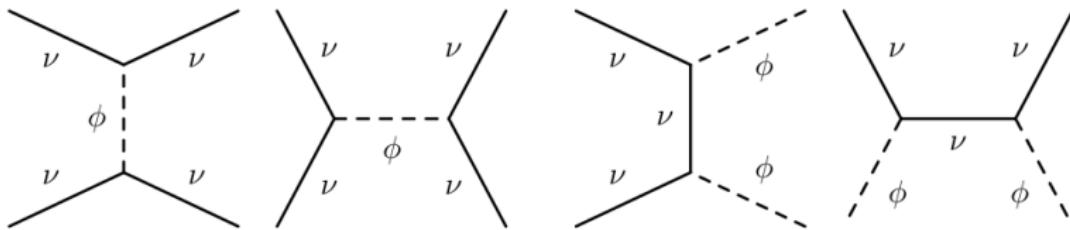
Parametrizations:

- 1) Phenomenological method (dark matter) with c_{eff}^2 and c_{vis}^2 modulate the acoustic oscillations in the Boltzmann Eqs.
[M.Archidiacono et al., 2014, T.L.Smith et al., 2013]
- 2) Constraining an effective neutrino recoupling z_{rec} (rough transition between tightly coupled and free-streaming).
[F.Cyr-Racine et al., 2013, M.Archidiacono et al., 2014]
- 3) Performing a detailed calculation of the scattering term.
[M.Oldengott et al., 2015, M.Oldengott et al., 2017]

Non-standard interactions: (Pseudo)scalar

Lagrangian

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



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

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

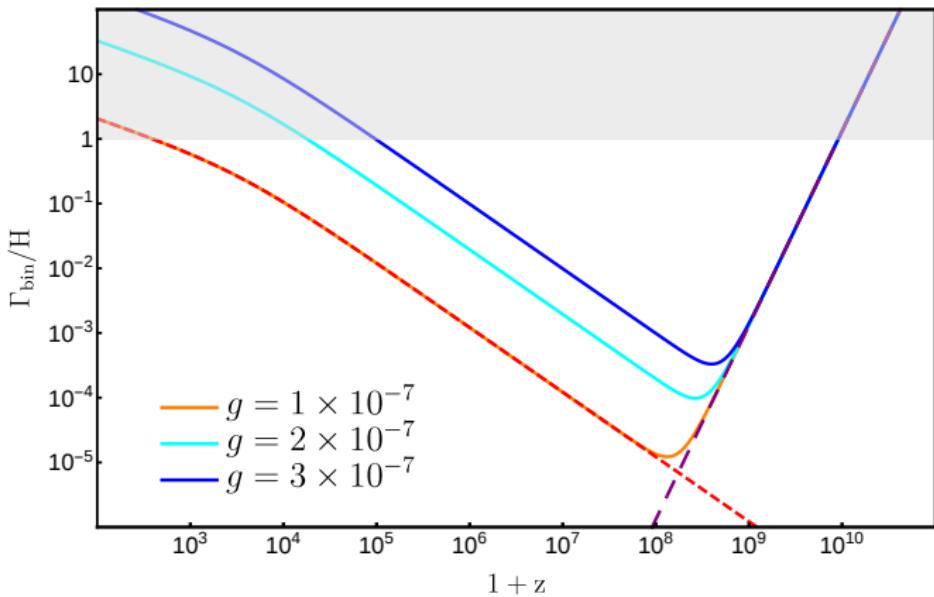
and the scattering rate:

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

Interaction rate vs Hubble rate:

$$\frac{\Gamma_{\text{bin}}}{H_r} \simeq \frac{g_{ij}^4}{T_\nu}, \quad \frac{\Gamma_{\text{bin}}}{H_m} \simeq \frac{g_{ij}^4}{T_\nu^{1/2}}$$

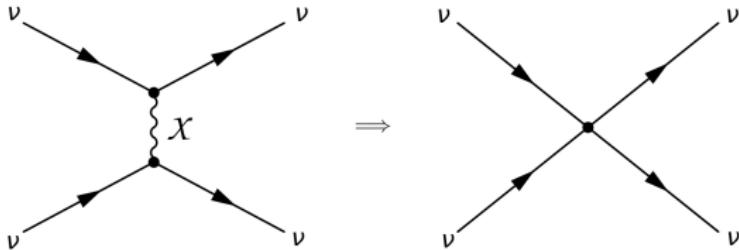
Non-standard interactions: (Pseudo)scalar



Non-standard interaction: Fermi-like

Lagrangian

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



It behaves like the standard Weak interaction:

$$\sigma_{\text{bin}} = G_X^2 T_\nu^2 = \frac{g_X^2}{m_X^2} T_\nu^2$$

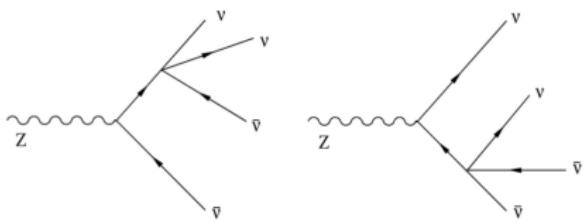
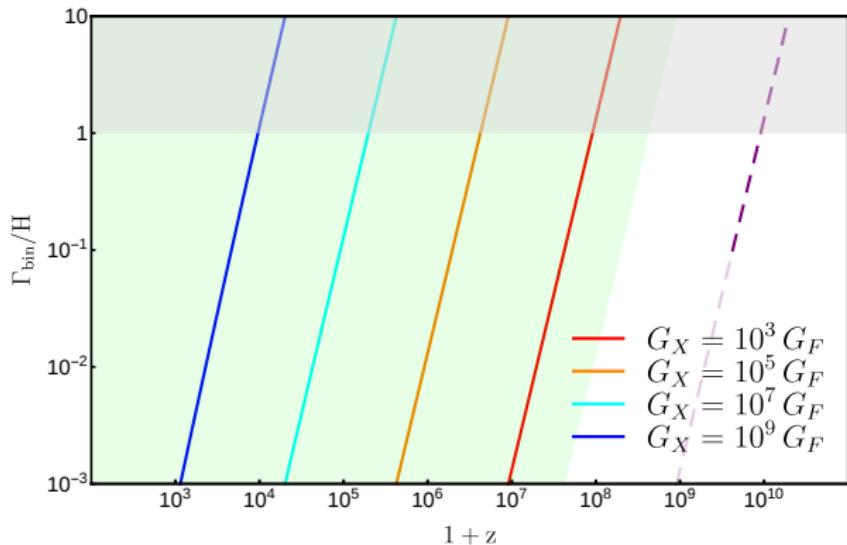
and the reaction rate is:

$$\Gamma_{\text{bin}} = G_X^2 T_\nu^5$$

the interaction is turned on at early times:

$$\frac{\Gamma_{\text{bin}}}{H_m} \simeq G_X^2 T_\nu^{\frac{7}{2}}, \quad \frac{\Gamma_{\text{bin}}}{H_r} \simeq G_X^2 T_\nu^3$$

Non-standard interaction: Fermi-like



[M. Bilenky and A. Santamaria (1999)]
If strong Fermi-like interactions exist, in
collider an invisible
 $\Gamma_{\text{inv}} = 3\Gamma(Z^0 \rightarrow \nu\bar{\nu})^{\text{SM}} + \Delta\Gamma_{\text{inv}}$
This can be translated into:
 $G_X \lesssim \text{few} \times 10^2 G_F$

Parametrization:

The Relaxation time approximation, that provides a collisional operator:

$$\left(\frac{\partial f}{\partial \tau} \right)_c \sim \frac{1}{\tau_{\text{col}}} (f_0 - f),$$

where $\tau_{\text{col}} \equiv \Gamma^{-1}$ is the relaxation factor.

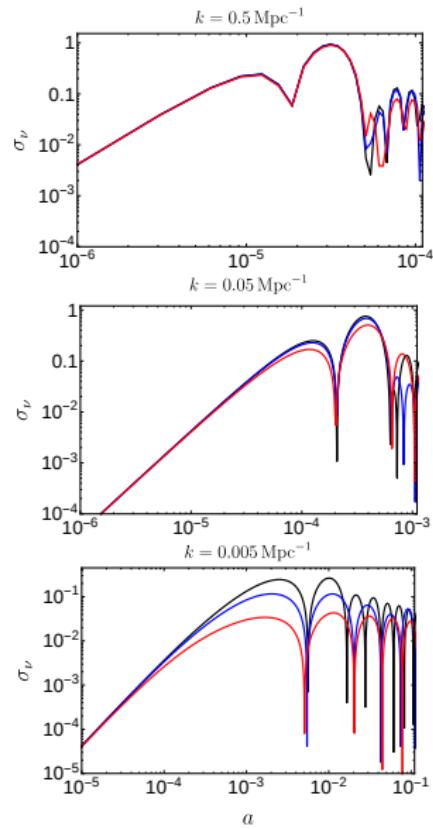
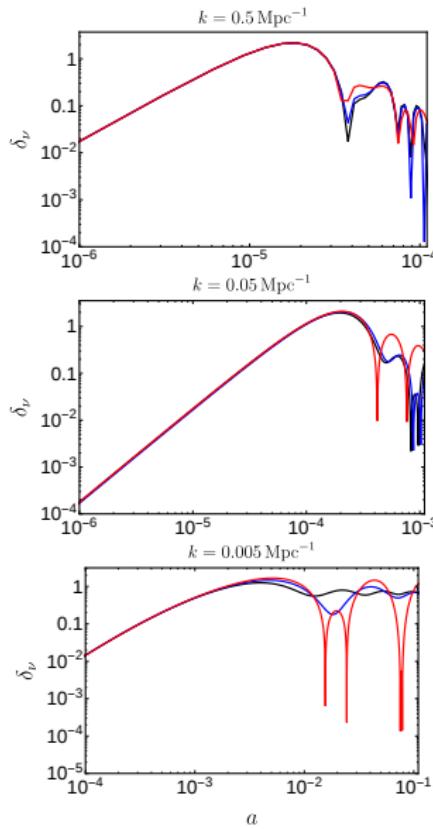
$$\begin{aligned} \frac{1}{f_0} \left(\frac{\partial f}{\partial \tau} \right)_c &= \frac{1}{f_0} (\Gamma(f_0 - f)) , \\ &= -\Gamma \Psi \end{aligned}$$

We parametrize the interaction using an effective coupling constant, this choice guarantees the inclusion of many models attributable to a (pseudo)scalar like interaction.
Taking into account that $n_\nu = (3/2) \times \zeta(3)/\pi^2 \times T_\nu^3$ for each neutrino family

Effective parametrization

$$\Gamma = 0.183 \times g_{\text{eff}}^4 T_\nu$$

(Pseudo)scalar Boltzmann formalism



Legend:

Black $\rightarrow \Lambda$ CDM

Blue $\rightarrow g_{\text{eff}} = 1.8 \times 10^{-7}$
Red $\rightarrow g_{\text{eff}} = 2.8 \times 10^{-7}$

Recoupling redshift:

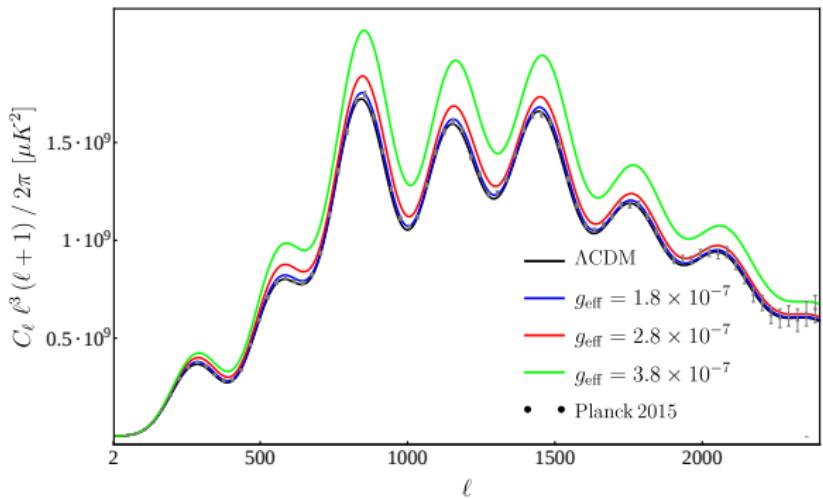
Blue $\rightarrow z_{\text{rec}} = 1.2 \times 10^3$
Red $\rightarrow z_{\text{rec}} = 1.2 \times 10^4$

Corresponding k :

Blue $\rightarrow k_{\text{rec}} = 0.03 \text{ Mpc}$
Red $\rightarrow k_{\text{rec}} = 0.15 \text{ Mpc}$

Relatively large scales
 $k < k_{\text{rec}}$ the effect is
larger compared to relative
small scales $k > k_{\text{rec}}$.

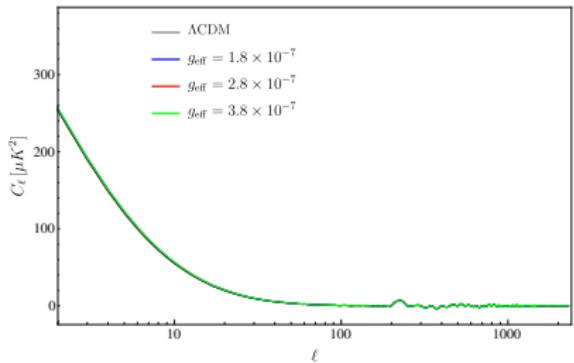
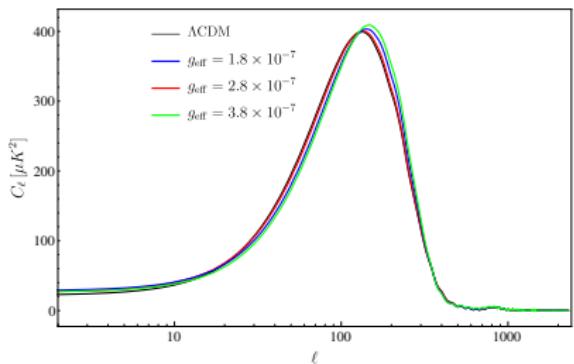
Effect on the anisotropies power spectrum



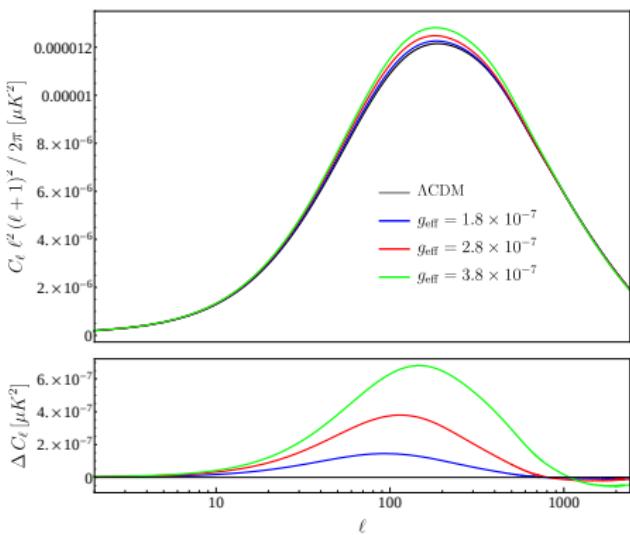
$$\Theta_\ell(k) = \int_0^{\tau_0} d\tau g(\tau) [\Theta_0(k, \tau) + \psi(k, \tau)] j_\ell[k(\tau_0 - \tau)] \\ \int_0^{\tau_0} d\tau g(\tau) \frac{i v_b(k, \tau)}{k} \frac{d}{d\tau} j_\ell[k(\tau_0 - \tau)] \\ + \int_0^{\tau_0} d\tau e^{-\tau_c} [\dot{\psi}(k, \tau) - \dot{\phi}(k, \tau)] \times j_\ell[k(\tau_0 - \tau)]$$

Effect on the anisotropies power spectrum

ISW contribution (early-ISW and late-ISW)

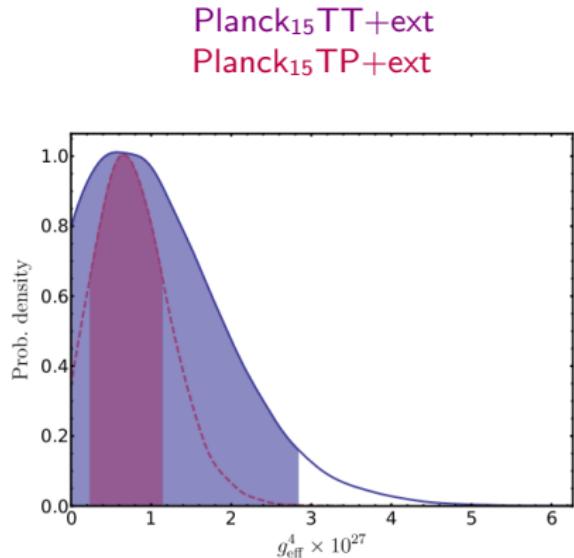
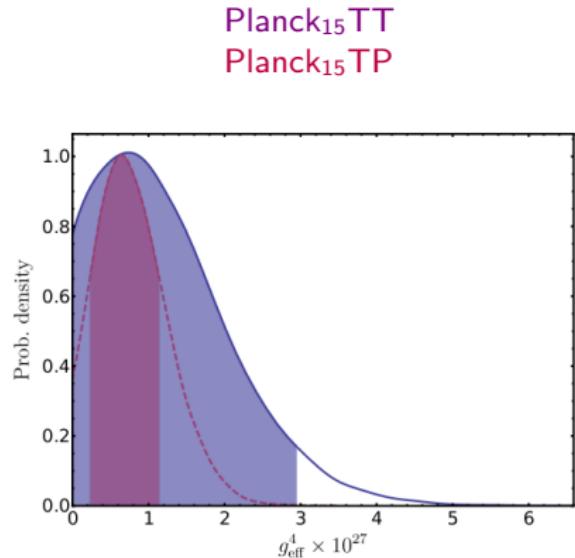


Lensing spectrum:



Neutrinos play a role in the large-scale formations: the presence of an extra free-streaming fluid drops the number of structures having dimension smaller than the free-streaming wavelength

Results [Λ CDM + g_{eff}]



Constraints using Planck₁₅ TT:

$$g_{eff} \leq 2.3 \cdot 10^{-7} \text{ (95\% CL)}$$

Constraints using Planck₁₅ TP:

$$g_{eff} \leq 2 \cdot 10^{-7} \text{ (95\% CL)}$$

$$g_{eff} = 1.7_{-1.4}^{+0.45} \cdot 10^{-7} \text{ (68\% CL)}$$

Comparison with other constraints

Λ CDM+ g_{eff} :

$$g_{\text{eff}} \leq 2 \cdot 10^{-7} \text{ (95% CL)}$$

$$g_{\text{eff}} = 1.7_{-1.4}^{+0.45} \cdot 10^{-7} \text{ (68% CL)}$$

Constraints on z_{rec} :

$z_i \sim 1600$ [M.Archidiacono et al., 2013]

Translated to g_{ii} ($g_{ii} \lesssim 1.2 \times 10^{-7}$) using:

$$g_{ii} \sim 1.1 \times 10^{-7} (z_i/3000)^{1/4} \text{ RD}$$

$$g_{ii} \sim 1.1 \times 10^{-7} (z_i/1088)^{1/8} \text{ MD}$$

Constraints from SN 1987A:

$$3 \times 10^{-7} \leq g \leq 2 \times 10^{-5}$$

[R.Tomas et al., 2001]

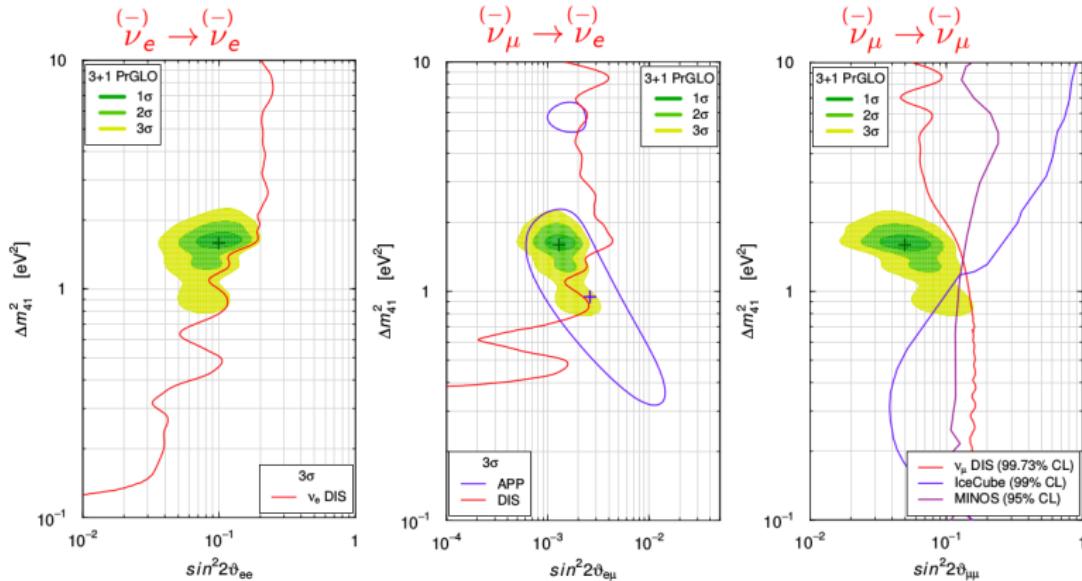
Constraints from $0\beta\beta\nu$:

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

[J.Albert et al., 2014]

Fermi-like: Short Baseline (SBL) anomalies

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



[Gariazzo et al., (2016)]

Sterile neutrinos and non-standard interactions

The immediate interpretation is a light sterile neutrino, usually parametrized phenomenologically in this way:

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

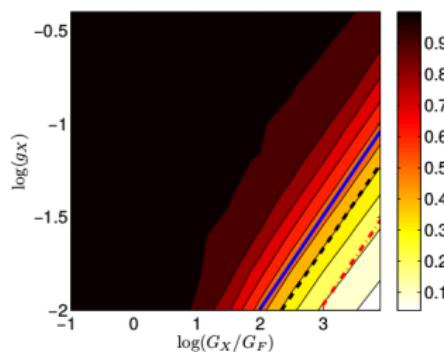
Where in case of thermal distribution

$$\Delta N_{\text{eff}} = \left(\frac{T_s}{T_\nu} \right)^4$$

Tension with CMB constraints

CMB excludes a possible extra thermalized neutrino (sterile or active) at 3 and 5 σ

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



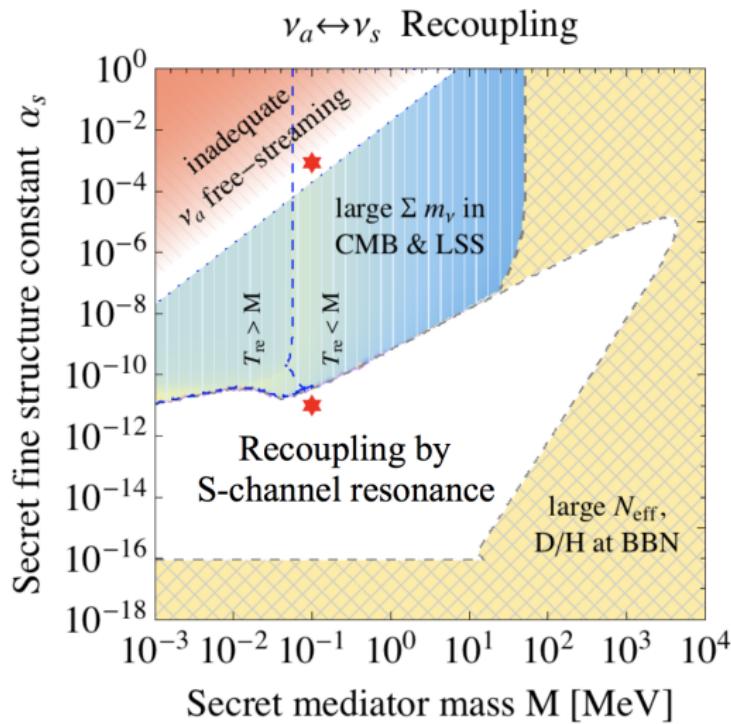
[Hannestad et al., 2013]

[A.Mirizzi et al. 2016]

Large coupling constant ($G_X \sim 10^4 - 10^5 \text{ Gev}^{-2}$) \rightarrow copious production of sterile neutrinos by the scattering \rightarrow quick flavor equilibration.

$$\rho_\nu^{in} = 3 \cdot \frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma, \quad \rho_\nu^{fin} = 4 \cdot \left(\frac{3}{4} \right)^{\frac{4}{3}} \frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma, \quad N_{\text{eff}} = 4 \cdot \left(\frac{3}{4} \right)^{\frac{4}{3}} \sim 2.7.$$

State of the art:

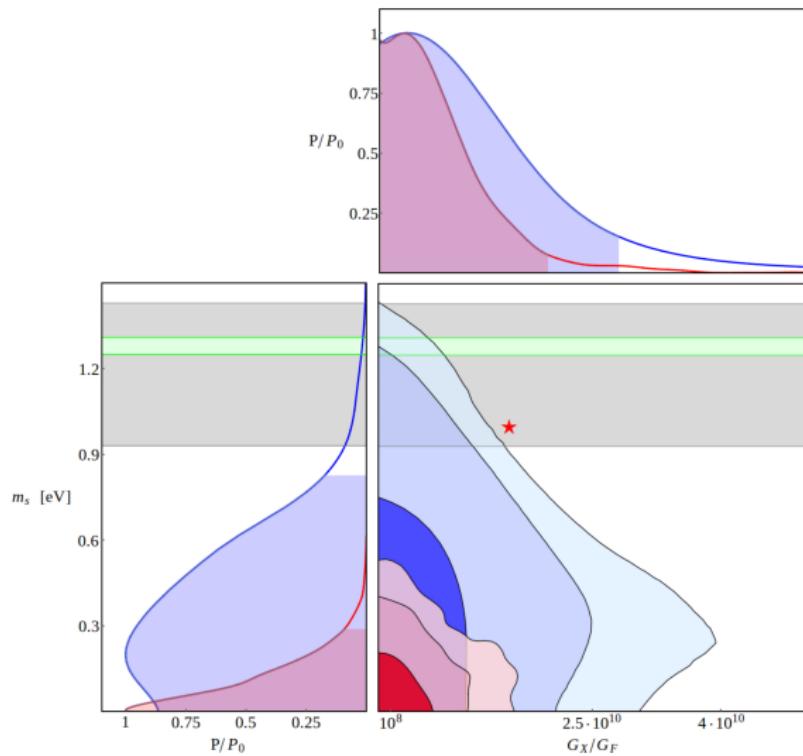


Plane with contributions from LSS, CMB (mass), BBN, free streaming.

Here $\alpha_s \sim g_x^2 / 4\pi$

Red stars are the best-fits (small and large values of G_x)

Results [Λ CDM]



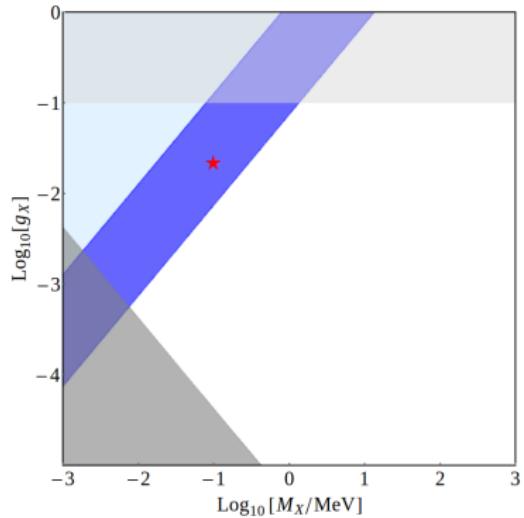
(PlanckTT)
(PlanckTT+BAO)

Broad
Narrow

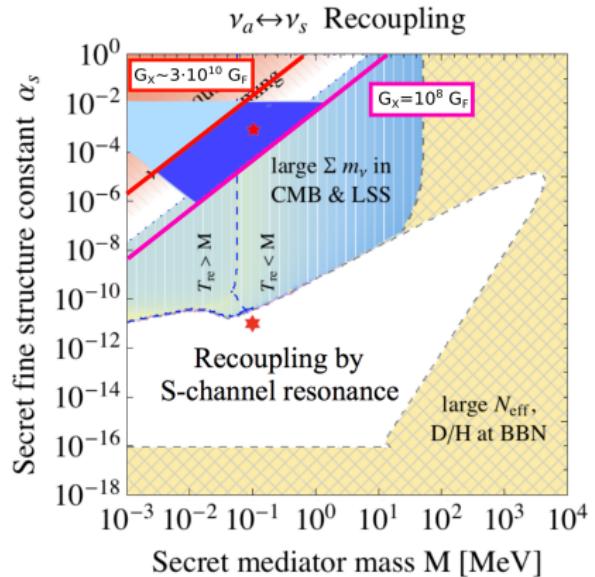
The red star at $G_X = 1.5 \times 10^{10} G_F$ and $m_s = 1$ eV is representative of the strongly self-interacting scenario described in [X. Chu, et. al 2015]

[F. Forastieri et al., 2017]

Results [Λ CDM]



[F.Forastieri et al., 2017]



[X. Chu, et. al 2015]

Blue regions are excluded by this study, light-blue due to upper limit in G_X , dark-blue cause the mass bound. Gray regions are not allowed by the approximations: light-gray cause the non-perturbative regime $g_X > 0.1$, dark-gray 4-point is not valid.

Conclusions

- Constraints on (pseudo)scalar secret interactions among active massless neutrinos
- The effective strength of non-standard interactions is:

$$g_{\text{eff}} \leq 2 \cdot 10^{-7} \text{ (95% CL)} [\text{Planck}_{15} \text{TP}]$$

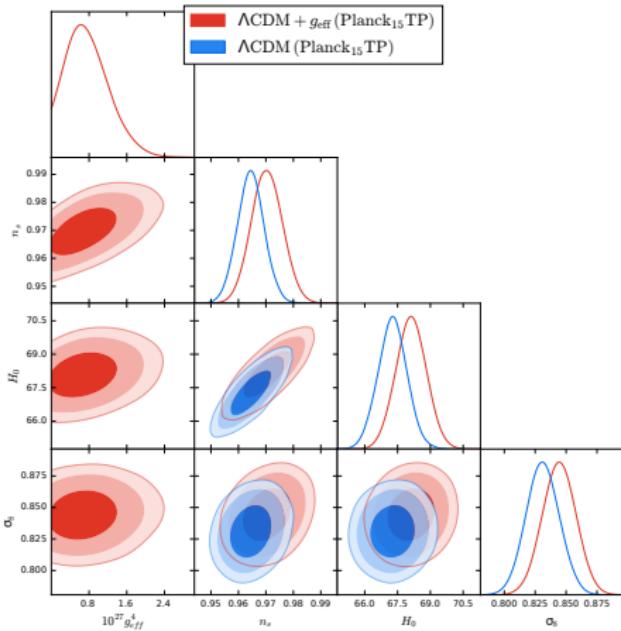
$$g_{\text{eff}} = 1.7^{+0.45}_{-1.4} \cdot 10^{-7} \text{ (68% CL)} [\text{Planck}_{15} \text{TP}]$$

- The goodness of fit for all considered models is comparable with the Λ CDM ones
- We have tested neutrino SBL anomalies with CMB data considering the existence of a Fermi-like non-standard neutrino interaction in order to avoid the increase in N_{eff} due to the thermalization of the sterile eigenstate.
- The interactions is rejected by cosmological data, in particular using PlanckTT+BAO dataset
- Using different data the $\alpha_s - M_X$ parameter space is extremely reduced. No space for sterile Fermi-like interacting neutrinos.
- Moreover imposing the sterile mass suggested by SBL it enlarge the H0 tension with the HST measurement and introduce a $4 - 5\sigma$ shift also in the n s parameter with respect the standard Λ CDM value.

Thanks

Back Slides

Results, [Λ CDM + g_{eff}] focus on n_s and H_0



Constraints on n_s :

$$n_s = 0.964 \pm 0.005 \text{ [}\Lambda\text{CDM]}$$

$$n_s = 0.973 \pm 0.006 \text{ [}\Lambda\text{CDM}+g_{eff}\text{]}$$

Constraints on H_0 [km/s/Mpc]:

$$H_0 = 67.2 \pm 0.6 \text{ [}\Lambda\text{CDM]}$$

$$H_0 = 73.24 \pm 1.74 \text{ [Riess et al.]}$$

$$H_0 = 68.12 \pm 0.69 \text{ [}\Lambda\text{CDM}+g_{eff}\text{]}$$

Constraints on σ_8 :

$$\sigma_8 = 0.831 \pm 0.013 \text{ [}\Lambda\text{CDM]}$$

$$\sigma_8 = 0.745 \pm 0.039 \text{ [KiDS-450]}$$

$$\sigma_8 = 0.844 \pm 0.013 \text{ [}\Lambda\text{CDM}+g_{eff}\text{]}$$

It measures the amplitude of the (linear) power spectrum on the scale of $8h^{-1}$ Mpc

Starting from the general Boltzmann-Einstein collisional equation:

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

Different regimes:

- Massless regime
- Quasi-massless regime $\epsilon_v \equiv m^2/2q^2$ and $v \simeq 1 - a^2 \epsilon_v$
- Massive regime

+

Tight-coupling approximation

We have rewritten the harmonic expansion form of the Boltzmann equation introducing the collisional term and a perturbation term.

Massive Boltzmann formalism

$$\begin{aligned}\nu'_\ell &= \frac{k\nu}{(2\ell+1)} \left[\ell\nu_{(\ell-1)} - (\ell+1)\nu_{(\ell+1)} \right] + \frac{8}{15}k\sigma\delta_{\ell 2} - \frac{4}{3}kZ\delta_{\ell 0} \\ &\quad - a\Gamma\nu_\ell (1 - \delta_{\ell 0}) (1 - \delta_{\ell 1}) \\ \nu_\ell &= J_\ell + \epsilon_v \Delta J_\ell\end{aligned}$$

$$\begin{aligned}J'_\ell + \epsilon_v \Delta J'_\ell &= \frac{k(1 - a^2 \epsilon_v)}{(2\ell+1)} \left[\ell(J_{(\ell-1)} + \epsilon_v \Delta J_{(\ell-1)}) - (\ell+1)(J_{(\ell+1)} + \epsilon_v \Delta J_{(\ell+1)}) \right] \\ &\quad + \frac{8}{15}k\sigma\delta_{\ell 2} - \frac{4}{3}kZ\delta_{\ell 0} - a\Gamma(J_\ell + \epsilon_v \Delta J_\ell) (1 - \delta_{\ell 0}) (1 - \delta_{\ell 1})\end{aligned}$$

Massive Boltzmann formalism

Massless regime:

$$J'_0 = -k J_1 - \frac{4}{3} k Z$$

$$J'_1 = \frac{k}{3} (J_0 - 2 J_2)$$

$$J'_2 = \frac{k}{5} (2 J_1 - 3 J_3) - \frac{8}{15} k \sigma - a \Gamma J_2$$

$$J'_\ell = \frac{k}{(2\ell+1)} \left[\ell J_{(\ell-1)} - (\ell+1) J_{(\ell+1)} \right] - a \Gamma J_\ell \quad (\ell \geq 3)$$

Quasi-massless regime:

$$\Delta J'_0 = -k \Delta J_1 + k a^2 J_1$$

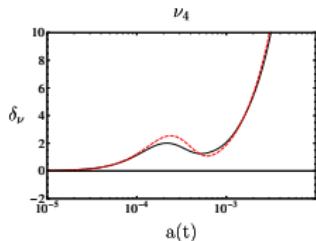
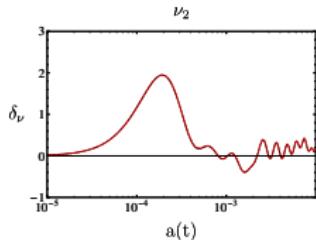
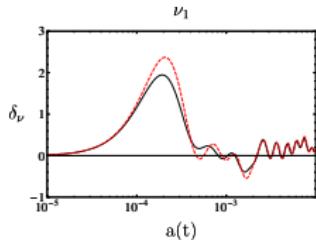
$$\Delta J'_1 = \frac{k}{3} (\Delta J_0 - 2 \Delta J_2) - \frac{k a^2}{3} (J_0 - 2 J_2)$$

$$\Delta J'_\ell = \frac{k}{2\ell+1} (\ell \Delta J_{(\ell-1)} - (\ell+1) \Delta J_{(\ell+1)})$$

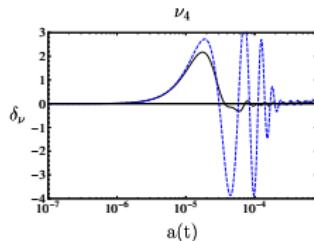
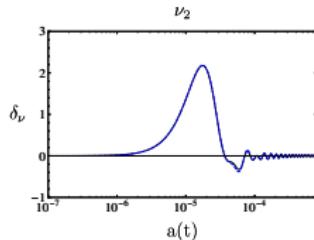
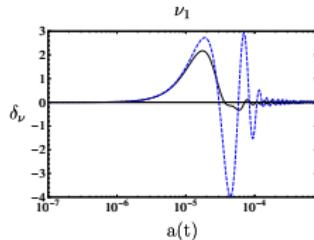
$$- \frac{k a^2}{2\ell+1} (\ell J_{(\ell-1)} - (\ell+1) J_{(\ell+1)}) - a \Gamma \Delta J_\ell \quad (1 \geq 2)$$

Fermi-like massive Boltzmann formalism

$$k = 0.05 \text{ Mpc}^{-1}$$



$$k = 0.5 \text{ Mpc}^{-1}$$



Legend:

Black $\rightarrow \Lambda\text{CDM}$

Blue/Red

$\rightarrow G_X = 10^{10} G_F$

Decoupling redshift:

Blue/Red $\rightarrow z_{\text{dec}} \sim \times 10^5$

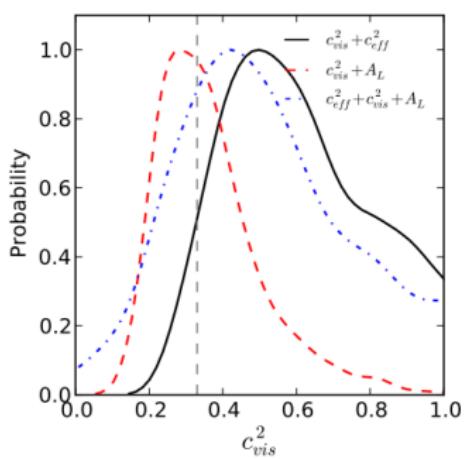
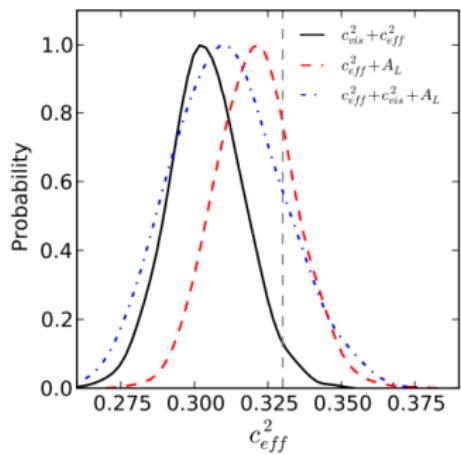
Corresponding k :

Blue/Red

$\rightarrow k_{\text{dec}} = 0.2 \text{ Mpc}$

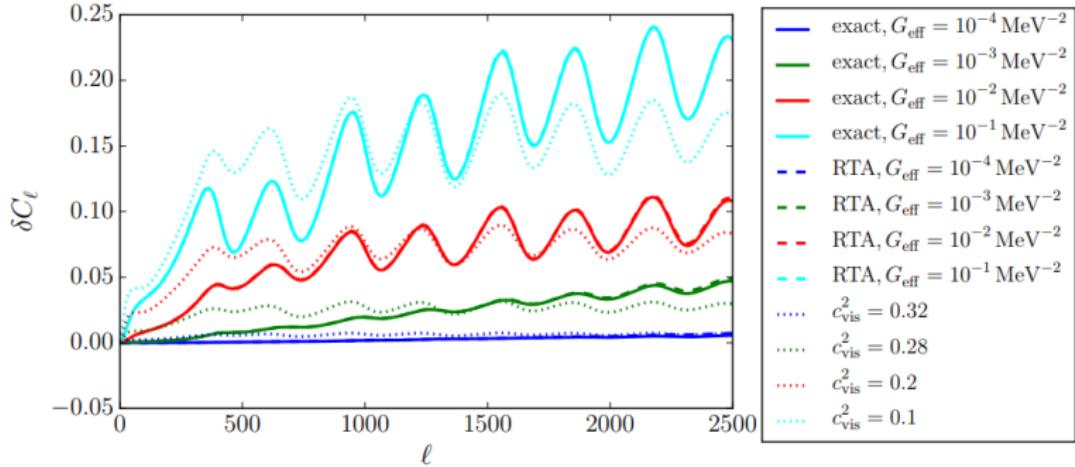
Other parametrizations

$$\begin{aligned}\dot{\delta}_\nu &= -\frac{4}{3}\theta_\nu - \frac{2}{3}\dot{h} + H(1-3c_{\text{eff}}^2) \left(\delta_\nu + 4H\theta_\nu \frac{\theta_\nu}{k^2} \right), \\ \dot{\theta}_\nu &= k^2 \left(\frac{1}{4}\delta_\nu - \sigma_\nu \right) - \frac{k^2}{4}(1-3c_{\text{eff}}^2) \left(\delta_\nu + 4H\theta_\nu \frac{\theta_\nu}{k^2} \right), \\ 2\dot{\sigma}_\nu &= \frac{8}{15}\theta_\nu - \frac{3}{5}kF_{\nu 3} + \frac{4}{15}\dot{h} + \frac{8}{15}\dot{\eta} - (1-3c_{\text{vis}}^2) \left(\frac{8}{15}\theta_\nu + \frac{4}{15}\dot{h} + \frac{8}{15}\dot{\eta} \right).\end{aligned}$$



[M.Gerbino et al., 2014]

$$\begin{aligned} \left(\frac{\partial f}{\partial \tau} \right)_{ij \leftrightarrow kl}^{(0)} &= \frac{g_j g_k g_l}{2|q|(2\pi)^5} \int \frac{d^3 \vec{q}'}{2|\vec{q}'|} \int \frac{d^3 \vec{l}'}{2|\vec{l}'|} \int \frac{d^3 \vec{l}}{2|\vec{l}|} \delta_D^4(q + l - q' - l') \\ &\quad \times |\mathcal{M}_{ij \leftrightarrow kl}|^2 \left(f_k^0(|\vec{q}'|, \tau) f_l^0(|\vec{l}'|, \tau) - f_i^0(|\vec{q}'|, \tau) f_j^0(|\vec{l}'|, \tau) \right) . \\ \left(\frac{\partial f}{\partial \tau} \right)_{ij \leftrightarrow kl}^{(1)} &= \frac{g_j g_k g_l}{2|q|(2\pi)^5} \int \frac{d^3 \vec{q}'}{2|\vec{q}'|} \int \frac{d^3 \vec{l}'}{2|\vec{l}'|} \int \frac{d^3 \vec{l}}{2|\vec{l}|} \delta_D^4(q + l - q' - l') \\ &\quad \times |\mathcal{M}_{ij \leftrightarrow kl}|^2 \left(f_k^0(|\vec{q}'|, \tau) F_l(\vec{k}, \vec{l}', \tau) + f_l^0(|\vec{l}'|, \tau) F_k(\vec{k}, \vec{q}', \tau) \right. \\ &\quad \left. - f_i^0(|\vec{q}'|, \tau) F_j(\vec{k}, \vec{l}', \tau) - f_j^0(|\vec{l}'|, \tau) F_i(\vec{k}, \vec{q}', \tau) \right) , \end{aligned}$$



[Oldengott et al., 2017]

Results [Λ CDM] models

Most relevant parameters for the considered models (PlanckTT):

| Parameter | Λ CDM | S Λ CDM_GX0 | S Λ CDM | S Λ CDM_Broad | S Λ CDM_Narrow |
|--------------------|-----------------------|-----------------------|---------------------------------|------------------------------|---------------------------------|
| $\Omega_b h^2$ | 0.02222 ± 0.00023 | 0.02177 ± 0.00024 | 0.02172 ± 0.00025 | 0.02167 ± 0.00025 | $0.02166^{+0.00024}_{-0.00024}$ |
| $\Omega_c h^2$ | 0.1197 ± 0.0021 | 0.1167 ± 0.0022 | 0.1171 ± 0.0023 | 0.1165 ± 0.0022 | 0.1160 ± 0.0021 |
| $100\theta_{MC}$ | 1.04085 ± 0.00047 | 1.04103 ± 0.00050 | $1.04323^{+0.00091}_{-0.00073}$ | 1.04319 ± 0.00074 | $1.04307^{+0.0010}_{-0.00077}$ |
| τ | 0.078 ± 0.019 | 0.070 ± 0.018 | 0.065 ± 0.018 | 0.067 ± 0.018 | 0.066 ± 0.018 |
| n_s | 0.9655 ± 0.0061 | 0.9448 ± 0.0070 | 0.9284 ± 0.0088 | $0.9191^{+0.0076}_{-0.0078}$ | $0.9161^{+0.0081}_{-0.0072}$ |
| $\ln(10^{10} A_s)$ | 3.089 ± 0.036 | 3.063 ± 0.035 | 3.023 ± 0.038 | 3.027 ± 0.037 | 3.028 ± 0.036 |
| G_X/G_F | — | 10^8 | $< 2.8 \times 10^{10}$ | $< 2.9 \times 10^{10}$ | $< 4.0 \times 10^{10}$ |
| m_s | — | < 0.82 | < 0.82 | $[0.93, 1.30]$ | 1.27 ± 0.028 |
| H_0 | 67.31 ± 0.95 | $62.2^{+2.0}_{-1.7}$ | $62.6^{+1.8}_{-1.8}$ | 59.56 ± 0.88 | $58.91^{+0.82}_{-0.79}$ |

Goodness of fit:

| Parameter | Λ CDM | S Λ CDM_GX0 | S Λ CDM | S Λ CDM_Broad | S Λ CDM_Narrow |
|-----------------------|---------------|---------------------|-----------------|-----------------------|------------------------|
| χ^2_{min} | 11265.1 | 11272.8 | 11269.0 | 11275.2 | 11277.6 |

Results [Λ CDM] models

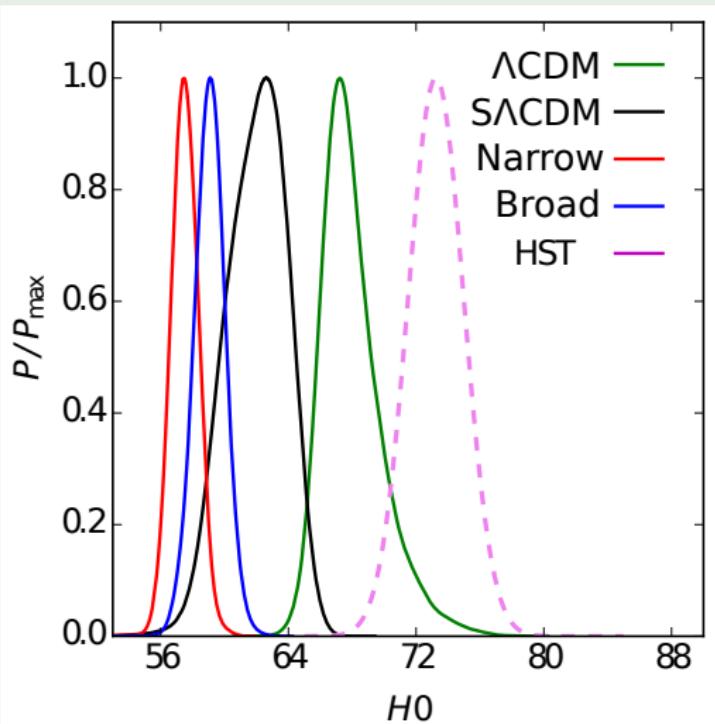
Most relevant H_0 problem

| Parameter |
|--------------------|
| $\Omega_b h^2$ |
| $\Omega_c h^2$ |
| $100\theta_{MC}$ |
| τ |
| n_s |
| $\ln(10^{10} A_s)$ |
| G_X/G_F |
| m_s |
| H_0 |

Goodness of fit

Parameter

$$\chi^2_{\min}$$



| CDM_Narrow |
|-------------------------------|
| $02166^{+0.00024}_{-0.00024}$ |
| 160 ± 0.0021 |
| $04307^{+0.0010}_{-0.00077}$ |
| 066 ± 0.018 |
| $.9161^{+0.0081}_{-0.0072}$ |
| 028 ± 0.036 |
| $< 4.0 \times 10^{10}$ |
| $.27 \pm 0.028$ |
| $58.91^{+0.82}_{-0.79}$ |

M_Narrow

$$277.6$$