# Cosmological Constraints with Self-Interacting Sterile Neutrinos

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## What to Expect

- Tension between sterile neutrinos suggested by short baseline (SBL) anomalies and cosmology
- A gauge boson model to suppress sterile neutrino production before the epoch of neutrino decoupling
- Confronting the model with Big Bang Nucleosynthesis (BBN) data
- Confronting the model with CMB and Baryon Acoustic Oscillation (BAO) data

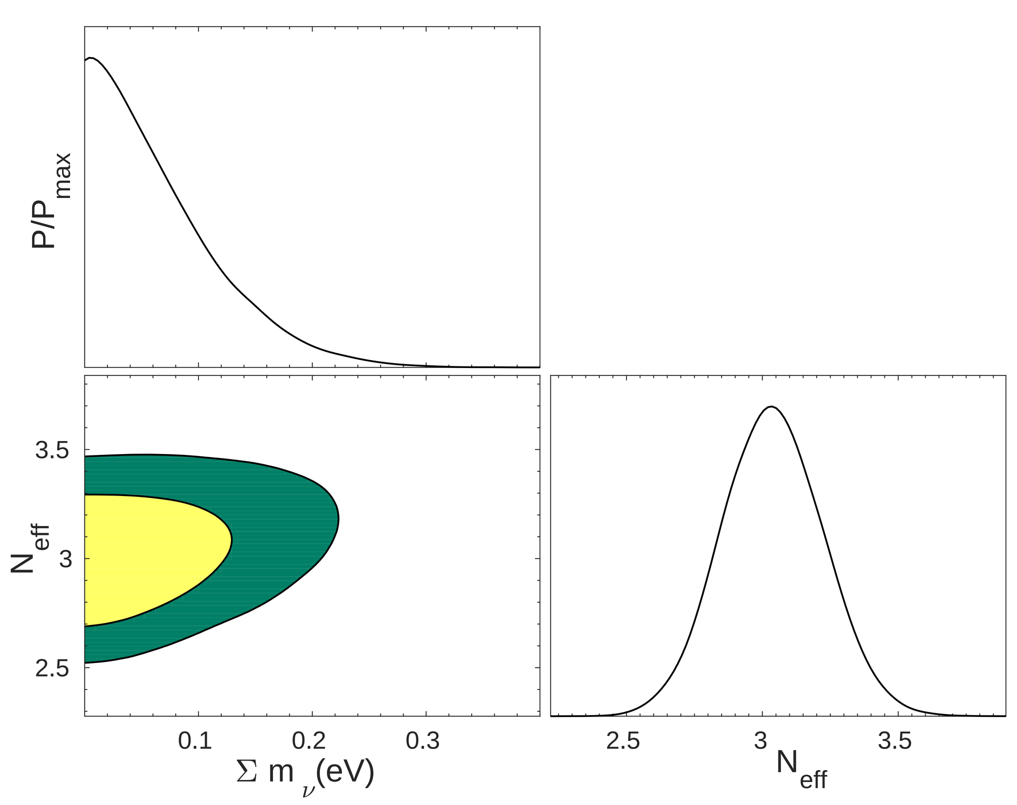
## Introduction

Effects of neutrinos in cosmology:

- Neutrino energy density affects the expansion rate

$$N_{\rm eff} = \frac{\rho_{\rm rel} - \rho_\gamma}{\rho_\nu^*}$$

- Neutrino free-streaming suppresses structure growth at small scales




Planck TT,TE,EE+lowP+lensing+BAO[1]

$\Sigma m_\nu < 0.18$ eV $(2\sigma)$, $N_{\rm eff} = 3.04 \pm 0.18\,(1\sigma)$

Anomalies in short baseline neutrino experiments indicate ∼eV sterile neutrinos (LSND[2]/MiniBooNE, Gallium anomaly, reactor anomaly). For LSND $\bar\nu_\mu \to \bar\nu_e$ oscillation,

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2}{\rm eV^2}\frac{L}{\rm km}\frac{\rm GeV}{E}\right), \; L \sim 30\ {\rm m},$$

$E \lesssim 100$ MeV $\Longrightarrow$ $\Delta m^2 \sim {\rm eV}^2$, $\sin\theta \sim 0.1$ $\Longrightarrow$ $N_{\rm eff} \simeq 4$

## Self-Interacting Model

New mechanism was introduced[3]:

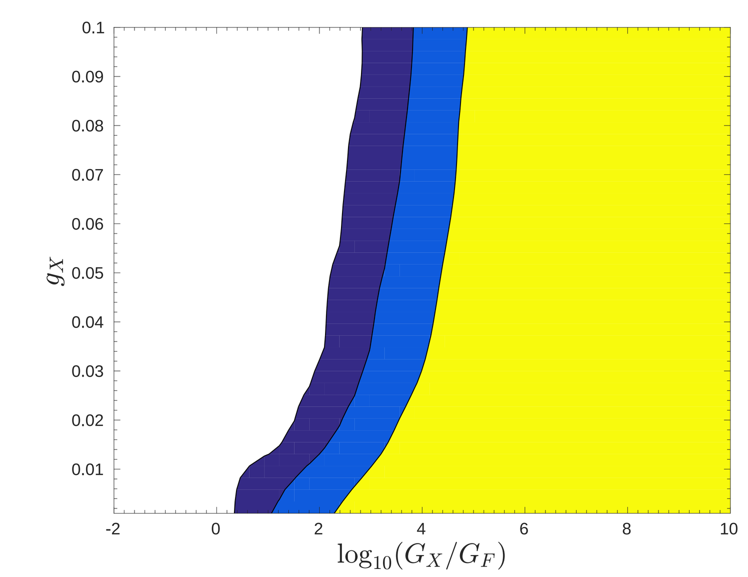
- Sterile neutrino interaction mediated by massive gauge boson: $\mathcal{L} = g_X \bar\nu_s \gamma_\mu \frac{1}{2}(1-\gamma_5)\nu_s X^\mu$
- In case $T_\nu < M_X$, approximate by $4\nu$ effective interaction with $G_X/\sqrt{2} = g_X^2/(8M_X^2)$,

$$\Gamma_X = n_{\nu_s}\langle\sigma v\rangle \simeq G_X^2 T_s^5 \,, V_{\rm eff} = -\frac{8\sqrt{2}G_X\, p\, \varepsilon_s}{3M_X^2}$$

- In-medium mixing angle modified: $\sin^2 2\theta_m = \dfrac{\sin^2 2\theta_0}{(\cos 2\theta_0 + V_{\rm eff}/f_{\rm osc})^2 + \sin^2 2\theta_0}$, $\quad f_{\rm osc} = \dfrac{m_{\rm st}^2}{2E}$

## Results: BBN

- $N_{\rm eff}$ affects expansion rate of the universe
- $\nu_e$ number density affects $n - p$ conversion rate
- Large $G_X$ preferred

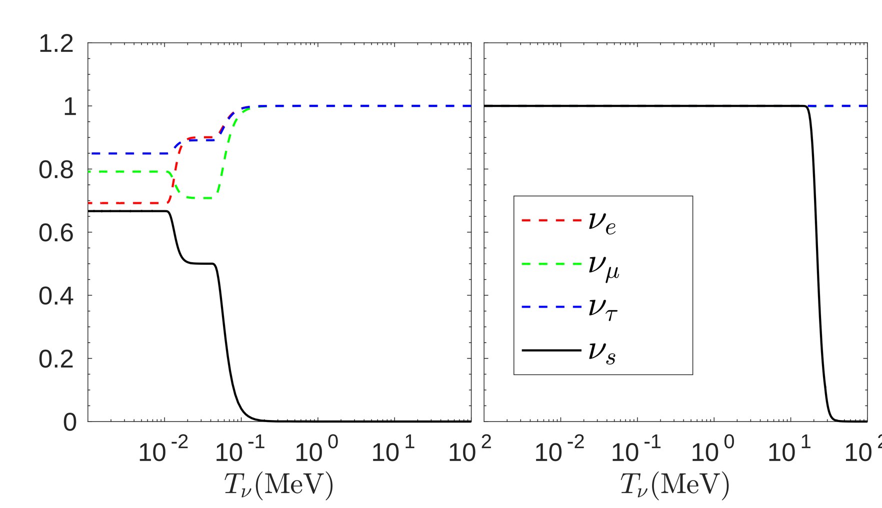



## Sterile Neutrino Production Delayed

If $V_{\rm eff} \gg f_{\rm osc}$ before 1 MeV, $\nu_s$ production delayed, by energy conservation $\longrightarrow N_{\rm eff} \simeq 3.0$.

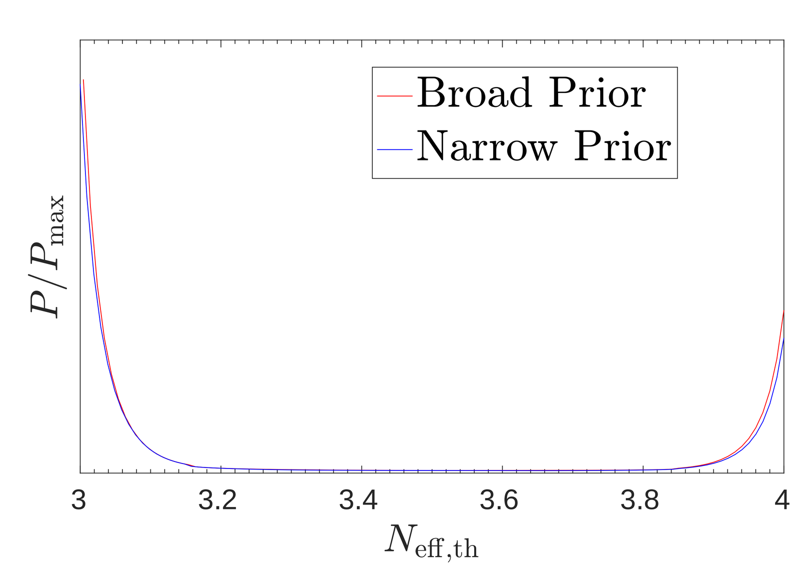
## Exact Solution

Neutrino flavor conversion in the early universe can be described by density matrix $\rho$ whose evolution is governed by quantum kinetic equations[4].




Left: $G_X = 10^{10} G_F$ Right: $G_X = 0$

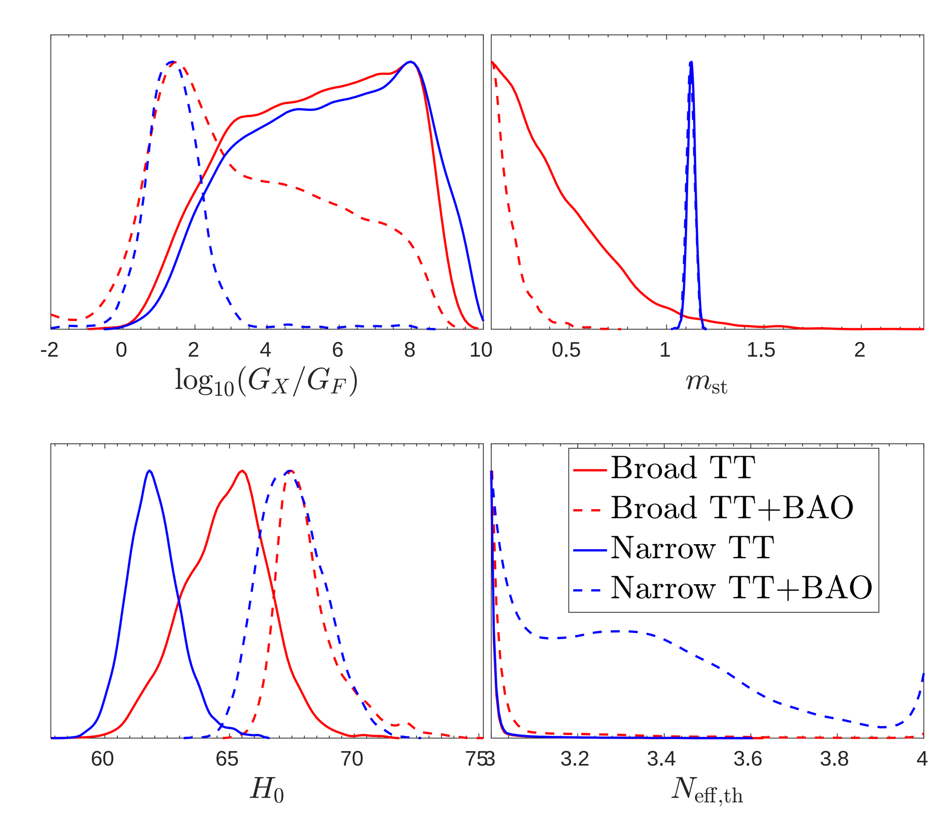
- $G_X \gg G_F$ $\nu_s$ produced after 1MeV $\to N_{\rm eff} \simeq 3$
- $G_X \ll G_F$ $\nu_s$ produced before 1MeV $\to N_{\rm eff} \simeq 4$




## Results: CMB+BAO

Prior parameter range:

| Prior | $\log_{10}(G_X/G_F)$ | $m_{\rm st}$(eV) | $\sin^2\theta_{14}$ |
|---|---|---|---|
| Broad | $[-2,\, 10]$ | $[0.1,\, 3]$ | $[0.003\,,\, 0.3]$ |
| Narrow | $[-2,\, 10]$ | $1.13 \pm 0.02$ | $0.009 \pm 0.003$ |




- Still $m_{\rm st} \sim O$(eV) excluded at more than $2\sigma$
- Large $G_X$ ($N_{\rm eff} \simeq 3$) favored using Planck only
- Large $G_X$ leads to small $H_0$ which is in tension with BAO data

## Analysis

$\chi^2_{\rm min}$ for various models and data combinations[5]:
Free-$\nu_s$: no new interactions.
Int-$\nu_s$: with new Interactions.
BP: broad prior NP: narrow prior

| Data | ΛCDM | Free-$\nu_s$ BP | Free-$\nu_s$ NP | Int-$\nu_s$ BP | Int-$\nu_s$ NP |
|---|---|---|---|---|---|
| TT | 11261.9 | 9.0 | 18.5 | 1.7 | 6.4 |
| TT+BAO | 11266.4 | 7.3 | 32.0 | 1.1 | 22.1 |

- Broad prior: Good fit obtained at $m_{\rm st} \sim 0.1$eV
- Narrow Prior: Better than non-interacting scenario using Planck only, but much worse when including BAO

## Conclusions

We have revisited the scenario with self-interaction among light sterile neutrinos (motivated by the SBL anomalies) mediated by a massive gauge boson proposed to alleviate the tension between $\mathcal{O}$(eV) sterile neutrinos and the cosmological bounds on $m_\nu$ and $N_{\rm eff}$.

- $m_{\rm st} \sim O$(eV) still excluded at more than $2\sigma$
- Large $G_X$ preferred by BBN data and using Planck data only
- Self-interacting model has limited power to reconcile the sterile neutrinos required by the SBL anomalies when considering Planck+BAO data

## References

1. Ade, P. A. R. et al.1502.01589.
2. Aguilar-Arevalo, A. et al.hep-ex/0104049.
3. Dasgupta, Basudeb et al.1310.6337.
4. Forastieri, Francesco et al.1704.00626.
5. Song, Ningqiang et al.1805.08218.

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