Sterile Neutrinos and Beyond the Three Flavours Overview

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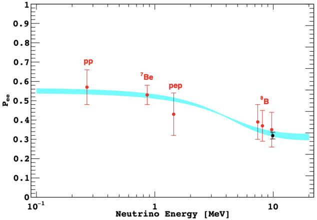
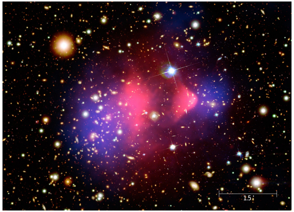
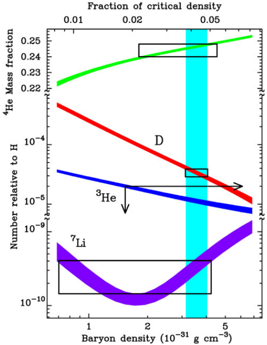
Introduction

Puzzles established experimentally that cannot be explained by the Standard Model

- Origin of neutrino mass, for explaining neutrino oscillation phenomena
- Nature of dark matter, to account for missing mass throughout the universe.
- Origin of the cosmic matter-anti-matter asymmetry.







Introduction

Sterile neutrinos may be the new physics behind all these ppuzzles.

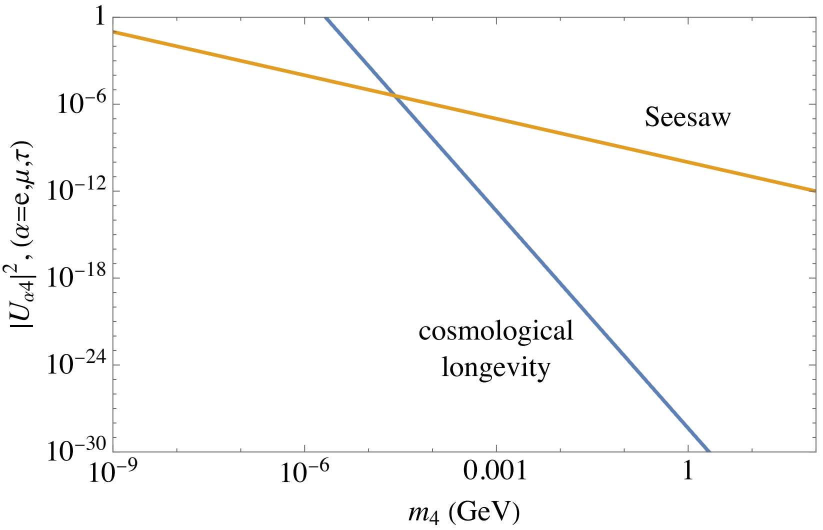
Simple extension to the Standard Model with gauge singlet fermion N

$$\mathcal{L}_{\mathrm{SM}} + \bar{\mathrm{N}}\gamma^{\mu}\partial_{\mu}\mathrm{N} + \mathrm{y}\bar{\mathrm{L}}\mathrm{H}\mathrm{N} + \mathrm{h.c.} - (\text{mass term})$$

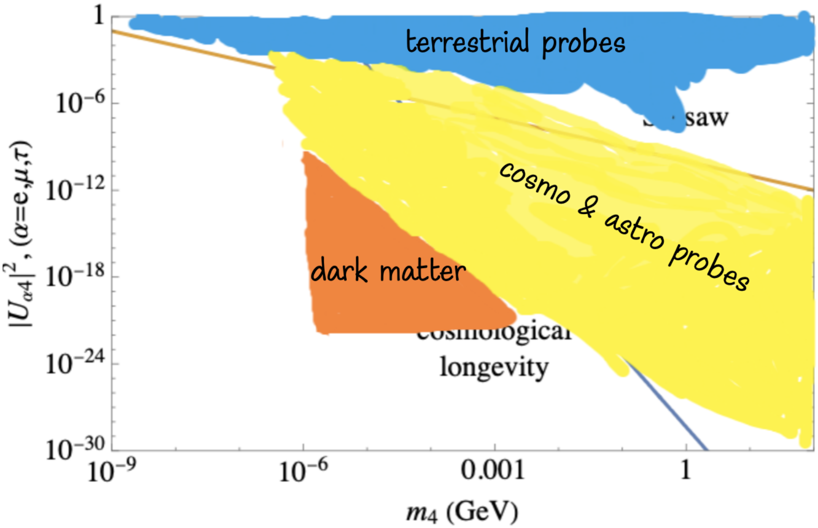
Mixing between active and sterile neutrino is generated by the Higgs condensate.

In the minimal setup, interactions of N with other SM particles always occur through this mixing.

Sketched Parameter Space



Sketched Parameter Space



Type-I Seesaw Mechanism

Active neutrino mass generation

$$\frac{1}{2}\begin{pmatrix}\bar{\nu} & \bar{\mathrm{N}}\end{pmatrix}\begin{pmatrix}0 & \mathrm{yv} \\ \mathrm{y^T v} & \mathrm{M_N}\end{pmatrix}\begin{pmatrix}\nu^{\mathrm{c}} \\ \mathrm{N^c}\end{pmatrix} + h.c.$$

This leads to

$$\mathrm{m}_{1,2,3} = -\frac{\mathrm{y^T y v^2}}{\mathrm{M_N^2}}\ , \quad \mathrm{m}_{4,5,\ldots} \simeq \mathrm{M_N}\ , \quad |\mathrm{U}|^2 \simeq \left(\frac{\mathrm{yv}}{\mathrm{M_N}}\right)^2 \simeq \frac{\mathrm{m}_\nu}{\mathrm{M_N}}$$

It is generically expected that the value of $|\mathrm{U}|^2$ is tied to m_4, if the light neutrino masses are used to explain solar and atmospheric neutrino mass differences.

This is indeed true for one-generation case, however ...

Mass & Mixing Maybe Uncorrelated

Consider a two-generation example

$$\frac{1}{2}\begin{pmatrix}\bar{\nu}_e & \bar{\nu}_\mu & \bar{N}_e & \bar{N}_\mu\end{pmatrix}\begin{pmatrix}0 & 0 & yv & iyv \\ 0 & 0 & yv & iyv \\ yv & yv & M_N & 0 \\ iyv & iyv & 0 & M_N\end{pmatrix}\begin{pmatrix}\nu_e^c \\ \nu_\mu^c \\ N_e^c \\ N_\mu^c\end{pmatrix} + h.c.$$

This matrix has rank 2. It makes zero contribution to light neutrino mass. However, there can be substantial mixing

$$|U|^2 \simeq \left(\frac{yv}{M_N}\right)^2 \gg \frac{m_\nu}{m_4}$$

This is an example where the active-sterile neutrino mixing is uncorrelated to light neutrino mass. In general, this freedom can be parametrized by an orthogonal matrix.

Casas, Ibarra, hep-ph/0103065, NPB; Kersten, Smirnov, 0705.3221, PRD

Connection to Lepton Number Violation

A consequence of the type-I seesaw mechanism is the Majorana neutrino mass that violates lepton number by two units, leading to important predictions for neutrinoless doublet beta decay signal.

However, active-sterile neutrino mixing may also be generated in the Dirac neutrino mass scenario, no LNV.

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} yv & y'v \\ 0 & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix} + h.c.$$

$$\Rightarrow m_{1,2,3} = yv \ , \quad |U|^2 \simeq \left(\frac{y'v}{M_N} \right)^2$$

Disentangling sterile neutrino mass and mixing motivates a broader search program.

Terrestrial Probes

High-energy colliders ($m_4 > \text{GeV}$)

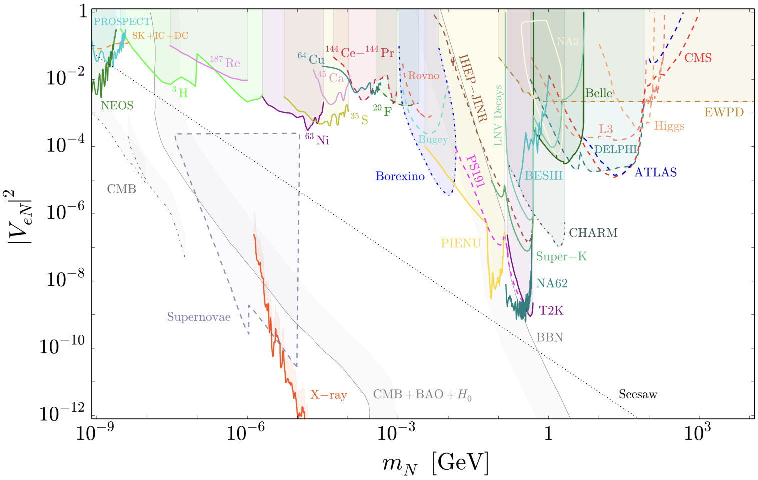
- For sterile neutrino above W/Z masses, precision EW observables give the leading constraint, e.g., lepton universality, invisible Z decay width.
- Sterile neutrino lighter than the W boson are most strongly constrained by ATLAS and CMS, using the $pp \to W \to \ell N$, $N \to \ell\ell\nu$ channel.
- At e^+e^- colliders, the search channel is $e^+e^- \to \nu N$, $N \to \ell jj$. Substantial improvement with a future Z factory (e.g. FCC-ee).

Low-energy measurements ($\text{MeV} < m_4 < \text{GeV}$)

- PIENU: $\pi \to eN$ leads to extra peak in electron spectrum.
- NA62: $K \to \ell N$ leads to extra missing mass distribution.
- Beam dump experiments: (present) CHARM, P191, T2K ; (future) DUNE, SHiP, MATHUSLA ...

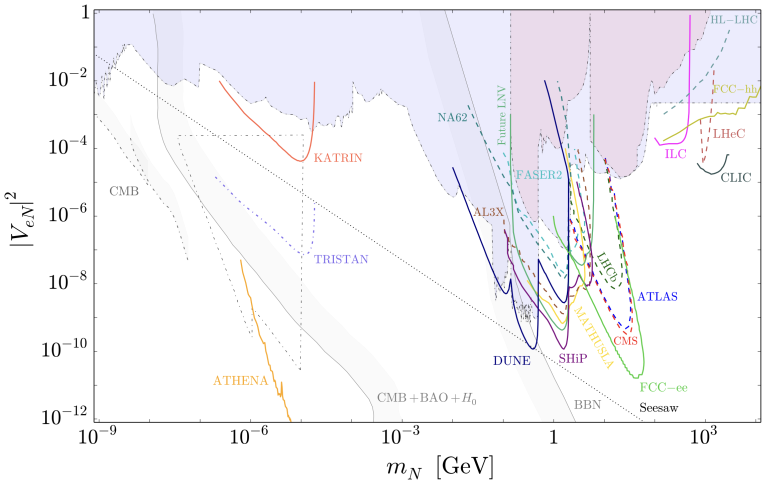
Beta decays ($m_4 < \text{MeV}$)

$\nu_e - N$ Mixing



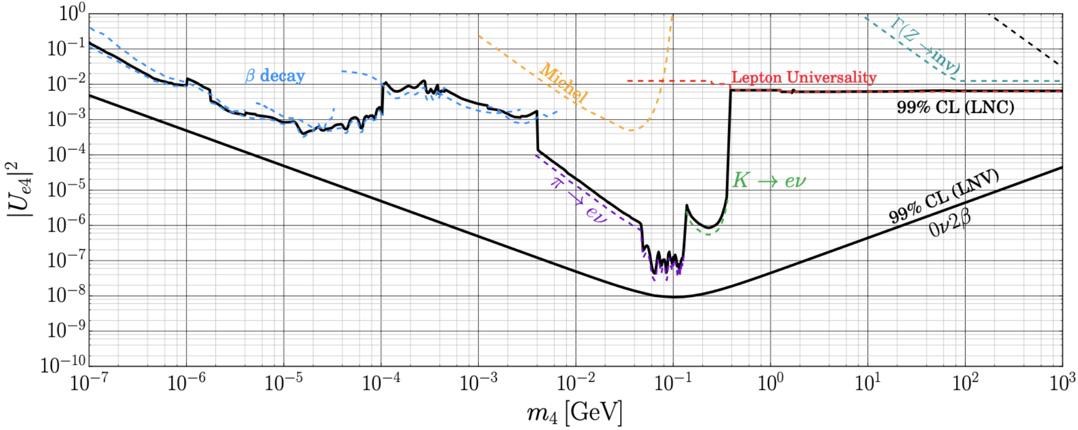
Bolton, Deppisch, Dev, 1912.03058, JHEP

$\nu_e - N$ Mixing (Future)



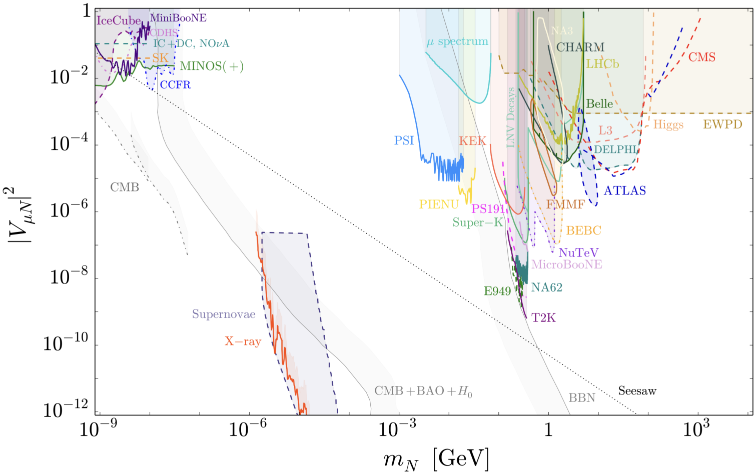
Bolton, Deppisch, Dev, 1912.03058, JHEP

Including Neutrinoless Double-beta Decay

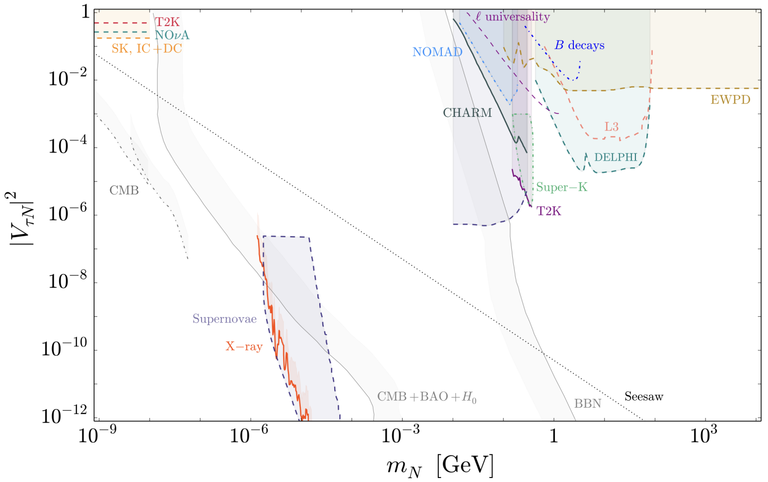


Atre, Han, Pascoli, Zhang, 0901.3589, JHEP; de Gouvêa, Kobach, 1511.00683, PRD

$\nu_\mu - $ N Mixing



$\nu_\tau - \mathrm{N}$ Mixing



Sterile Neutrino in Early Universe

Weak interaction with the thermal plasma sources a potential for active neutrinos, modifies the effective active-sterile neutrino mixing

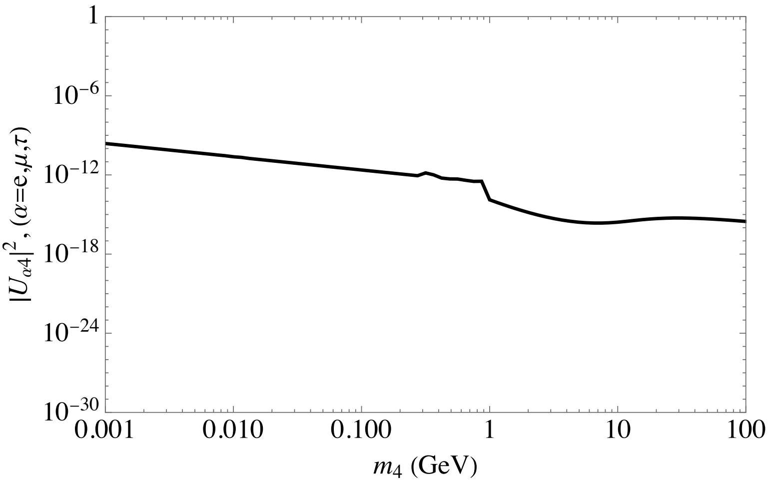
$$\sin^2(2\theta_{\rm eff}) = \frac{\Delta^2 \sin^2(2\theta)}{\Delta^2 \sin^2(2\theta) + (\Delta\cos(2\theta) - \mathrm{V})^2 + (\Gamma/2)^2}\ , \quad \sin^2\theta \simeq |\mathrm{U}|^2$$

In the absence of large lepton number asymmetry, $\Gamma \sim \mathrm{G_F^2 T^4 E}$, $\mathrm{V} \sim \mathrm{G_F T^4 E / M_W^2}$, and $\Delta \simeq \mathrm{m_4^2/(2E)}$.

`Wolfenstein, 1978, PRD; Notzold, Raffelt, 1988, NPB`

- For sufficiently large $|\mathrm{U}|^2$, sterile neutrino was in thermal equilibrium at early times. Freezes out (at $\mathrm{T} > \mathrm{MeV}$) determines its subsequent population.
- For smaller $|\mathrm{U}|^2$, sterile neutrino never in equilibrium. Its population depends on the initial condition. Minimal assumption often made in the literature: zero initial population + freeze in mechanism.

Thermalization Boundary



Yu-Ming Chen, YZ, 2410.07343, PRD

Effects on Big-Bang Nucleosynthesis

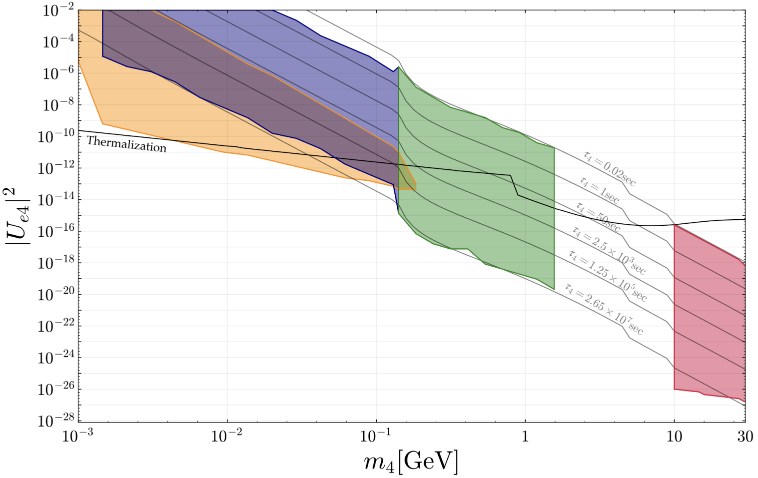
With a lifetime longer than 1 second, sterile neutrino can impact BBN in a number of ways.

- Temporary matter domination before the decay of sterile neutrino.
- pn **conversion by neutrinos/mesons:** $\mathrm{N} \to \ell \nu_{\mathrm{e}} \bar{\nu}_{\mathrm{e}}$ followed by $\nu_{\mathrm{e}} + \mathrm{n} \to \mathrm{p} + \mathrm{e}$. $\mathrm{N} \to \ell\pi$ followed by $\pi^- + \mathrm{p} \to \pi^0 + \mathrm{n}$. Similar for charged K mesons.
- **Hadrodissociation by mesons:** $\mathrm{N} \to \ell\pi, \mathrm{K}$ followed by $\mathrm{K}^- + {}^4\mathrm{He} \to \mathrm{N} + \mathrm{X}$, $(\mathrm{N} = {}^3\mathrm{He}, \mathrm{T}, \mathrm{D}, \mathrm{n}, \mathrm{p})$, and $\pi^- + {}^4\mathrm{He} \to \mathrm{N} + \mathrm{X}$, $\mathrm{X} = \mathrm{T}, \mathrm{D}, \mathrm{p}$.
- Baryon injection effect important for $\mathrm{m}_4 \gg \mathrm{GeV}$.

In a recent work, we explore a wide range of sterile neutrino parameter space, taking into account of freeze out/in mechanisms. The impact of the above processes are taken into account by modifying a public code PRyMordial (recently developed by Burns, Tait, Valli, `2307.07061, EPJC`).

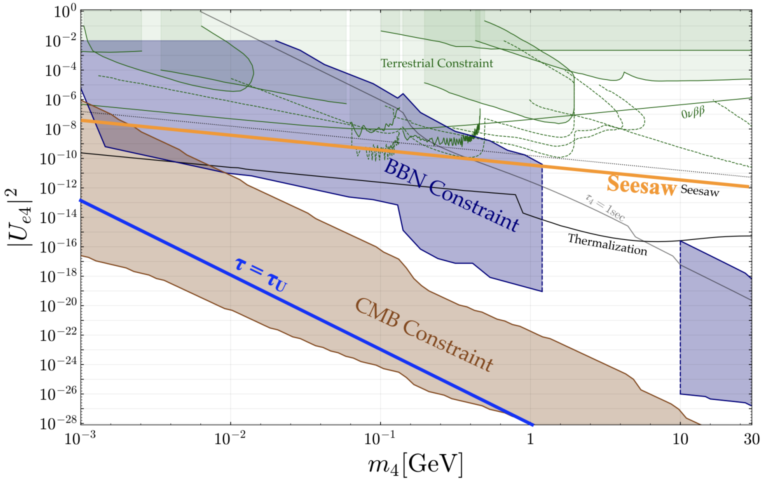
`Yu-Ming Chen, YZ, 2410.07343, PRD`

BBN Constraint



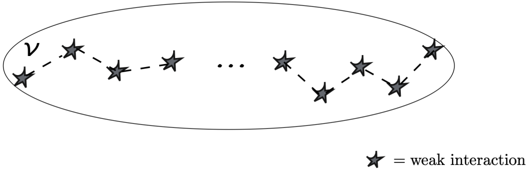
Yu-Ming Chen, YZ, 2410.07343, PRD

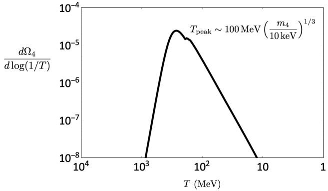
Compare with Other Constraints



Yu-Ming Chen, YZ, 2410.07343, PRD

Sterile Neutrino as Dark Matter





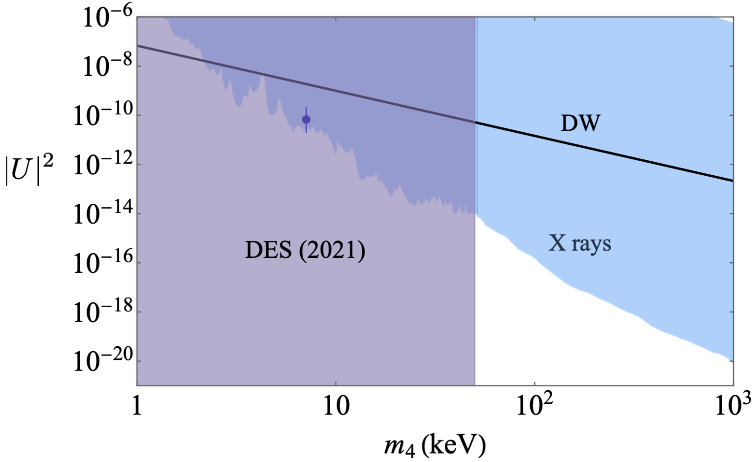
Production of sterile neutrino dark matter via active-sterile oscillation in the early universe. Prior to decoupling, active neutrinos interact frequently with the thermal plasma – many oscillation baselines. Parametrical dependence:

$$\Omega_4 \propto \int \frac{\mathrm{dT}}{\mathrm{T}} \left(\frac{\Gamma}{\mathrm{H}}\right) \sin^2 \theta_{\rm eff}$$

Sterile neutrino is a warm dark matter candidate, and has served as a popular benchmark for various cosmological and astrophysical studies.

Dodelson, Widrow, hep-ph/9303287, PRL

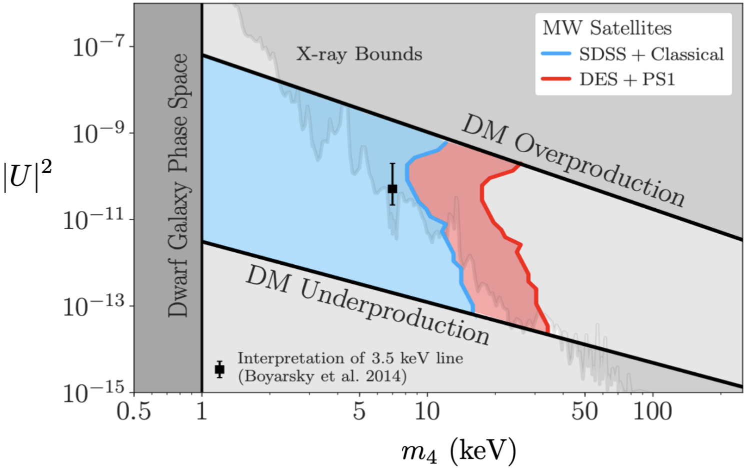
Dodelson-Widrow Mechanism Excluded



DES collaboration, 2008.00022, PRL

Boyarsky, Malyshev, Neronov, Ruchayskiy, 0710.4922, MNRAS

Shi-Fuller Mechanism Also Excluded



Shi Fuller, astro-ph/9810076, PRL

How to Save Sterile Neutrino Dark Matter?

Goal: still resort to oscillation mechanism for the dark matter relic density, which is given by the product of oscillation baselines $\sim \Gamma/\mathrm{H}$ and the oscillation probability per baseline $\sim |\mathrm{U}|^2$.

Challenge: X-ray search sets a strong constraint on $|\mathrm{U}|^2$.

Solution: Crank up Γ/H to compensate for the smallness of $|\mathrm{U}|^2$. Introduce novel interactions to active neutrinos that are stronger than $\mathrm{G_F}$. New physics had better be electric neutral in order not to worsen the X-ray limit.

The Self-interacting Neutrino Idea

Add a gauge singlet scalar ϕ to the Standard Model and a higher dimensional operator

$$\frac{1}{\Lambda^2}(\bar{\mathrm{L}}\mathrm{i}\sigma_2\mathrm{H}^*)(\mathrm{H}^\dagger\mathrm{i}\sigma_2\mathrm{L}^\mathrm{c})\phi + \mathrm{h.c.} \to \lambda\bar{\nu}\nu^\mathrm{c}\phi + \mathrm{h.c.}$$

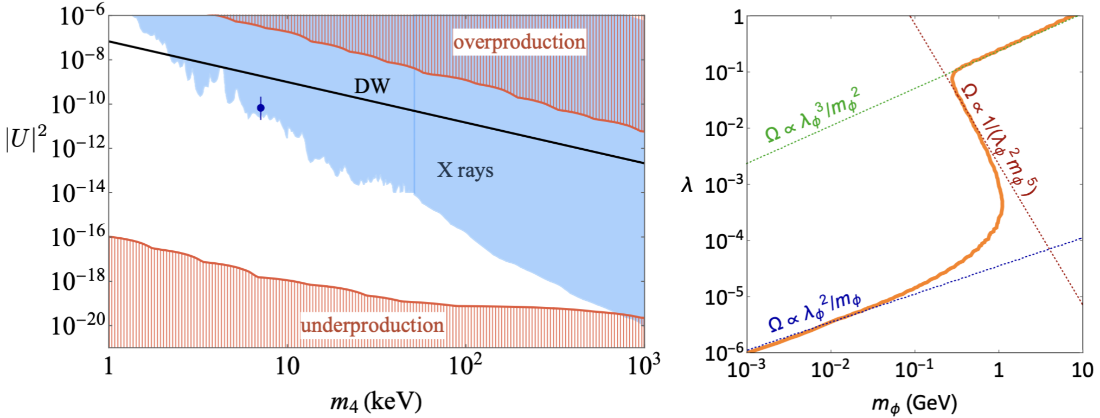
In addition to regular weak interactions, the active neutrinos can also participate in self-interaction by scattering with themselves.

Self-interaction has a higher interaction rate if ϕ mass lies below the electroweak scale.

In the early universe, creates more baselines for active-sterile neutrino oscillation for building up dark matter relic density.

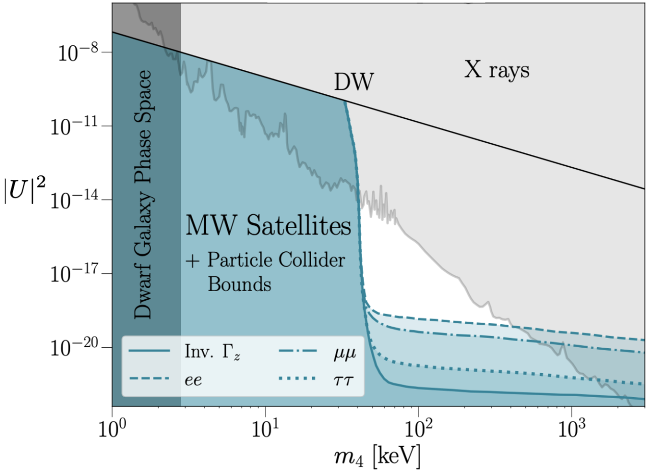
`de Gouvêa, Sen, Tangarife, YZ, 1910.04901, PRL`

Open Up Parameter Space for SνDM



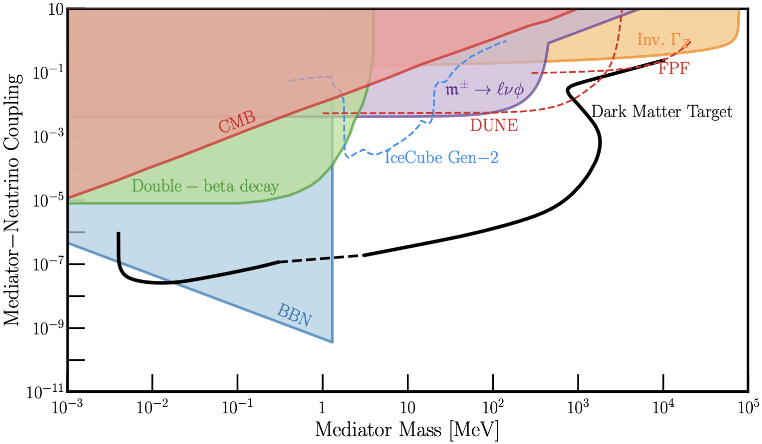
de Gouvêa, Sen, Tangarife, YZ, 1910.04901, PRL

Consistent with Small Scale Structure Observation



An, Gluscevic, Nadler, YZ, 2301.08299, APJL

Rich Opportunities for Future Tests



Blinov, Bustamante, Kelly, YZ, et al, 2203.01955, PDU

Conclusion

Sterile neutrinos are a well-motivated new physics candidate – can be used to address several puzzles that the Standard Model cannot explain.

In the simplest incarnation, sterile neutrino mixes with active neutrinos. This leads to a number of complementary ways to probe its existence using terrestrial and cosmological experiments.

Not covered in this talk:

- Sterile neutrino may be part of a unified theory, where the high-scale physics could modify its story in the early universe, as well as the experimental search prospects.
- Baryogenesis/leptogenesis.

Thanks!