Extending the Sensitivity of Heavy Sterile Neutrino Searches with Solar Neutrino Experiments

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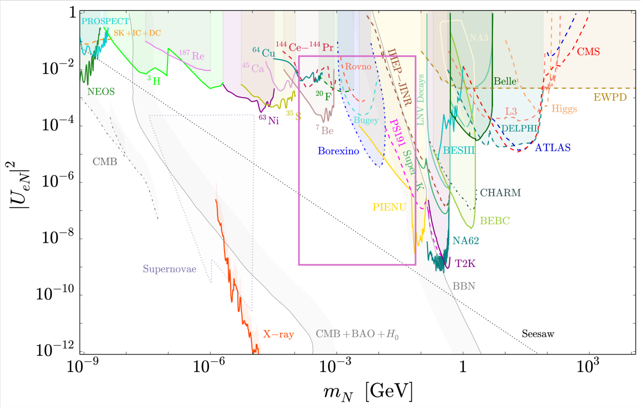
Outline

Introduction

Motivation: MeV-scale sterile neutrinos

- Neutrino oscillations → non-zero masses → physics beyond the SM
- Heavy sterile ν_H suppresses active masses through mixing $|U_{eH}|^2$[6]
- MeV window largely unexplored; current limits from Borexino[4], PIENU[1]



Goal: extend sensitivity of HNL searches with a 500-ton detector (JNE-500)

Physical Process

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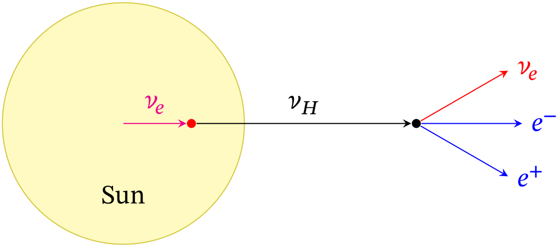


Key ingredients

- Solar neutrino flux → ν_H production rate
- Decay channels and lifetime
- Decayed ν_e and e^+e^- spectrum

Solar neutrino spectrum

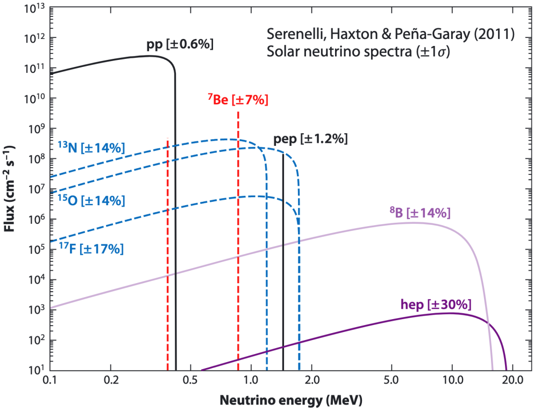


Figure 1: Solar neutrino spectrum[8]

- ^{8}B neutrinos are well-suited for our search, thanks to their high endpoint energy and large flux.

ν_H production from solar ^{8}B neutrino

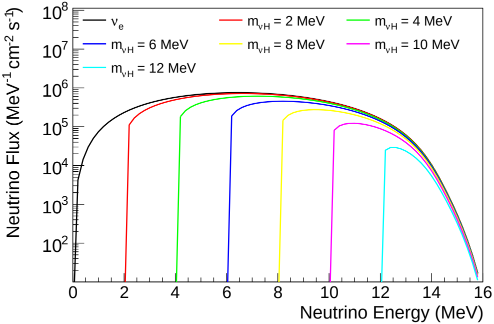


Figure 2: ν_H flux for several m_{ν_H} ($|U_{eH}|^2 = 1.0$), using BS05(OP)[3] ^{8}B neutrino flux for mixing.

ν_H produced via active-sterile mixing in the Sun:

$$\begin{aligned} ^8\mathrm{B} \rightarrow \ & ^8\mathrm{Be}^* + \mathrm{e}^+ + \nu_e \\ \rightarrow \ & ^8\mathrm{Be}^* + \mathrm{e}^+ + \nu_H \end{aligned} \quad (1)$$

Flux scaled by $|U_{eH}|^2$ and phase space:

$$\Phi_{\nu_H} = |U_{eH}|^2 \, \beta(E) \, \Phi_{^8\mathrm{B}} \quad (2)$$

with $\beta(E) = \sqrt{1 - (m_{\nu_H}/E)^2}$.

Decay channels

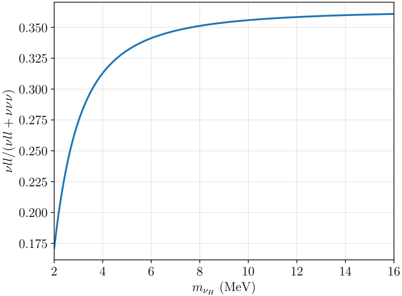
For MeV energy scale ($m_{\nu_H} > 2m_e$), two main decay modes:

- Charged-current: $\nu_H \to e^+e^-\nu_e$ (νll)
- Neutral-current: $\nu_H \to \nu_e\nu_e\bar{\nu}_e$ ($\nu\nu\nu$)

Decay width[7]:

$$\Gamma_{3\nu} = \frac{G_F^2}{192\pi^3} m_{\nu_H}^5 |U_{eH}|^2 \qquad (3)$$

νll width similar, with ratio $\Gamma_{\nu ll}/\Gamma_{3\nu} \approx 0.6$.



Lifetime

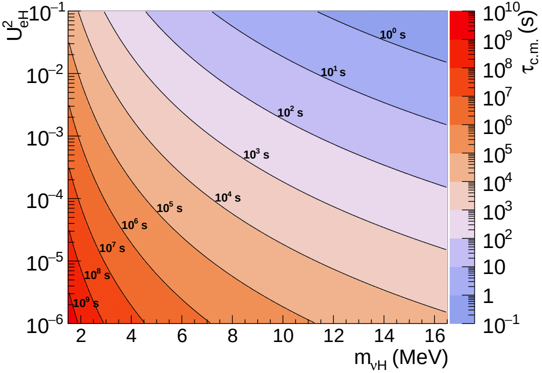
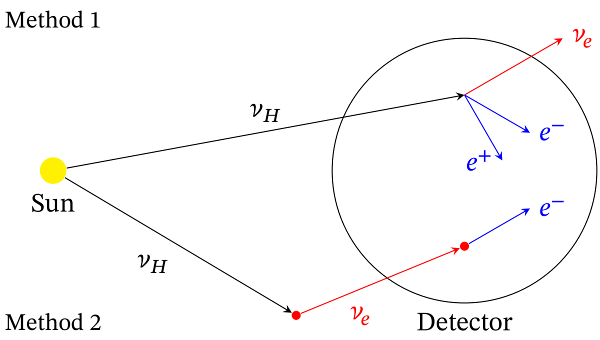


Figure 3: ν_H rest-frame lifetime over $(|U_{eH}|^2, m_{\nu_H})$

$$\tau_{\text{c.m.}} = 1/\Gamma_{\text{total}}$$

- Lower-left: long-lived most ν_H survive to Earth
- Upper-right: short-lived most ν_H decay before Earth

Two detection methods



- Method 1: ν_H decays inside detector → e^+e^- pair
- Method 2: ν_H decays outside detector → detect ν_e from decay

νll decay section

Differential decay width in the ν_H rest frame[10, 4]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E\,\mathrm{d}\cos\theta} = \Gamma_{\text{total}}\left(f_1 + \zeta|\vec{P}|\,f_S\cos\theta\right) \tag{4}$$

- E, θ: ν_e energy and emission angle (rest frame)
- f_1, f_S: kinematic functions of m_{ν_H} and E
- $|\vec{P}| \approx \beta$: ν_H polarization
- $\zeta = +1(-1)$ for $\nu_H(\tilde{\nu}_H)$

By boosting e^+e^- to lab, we can obtain their spectrum.

Method 1: e^+e^- Signal

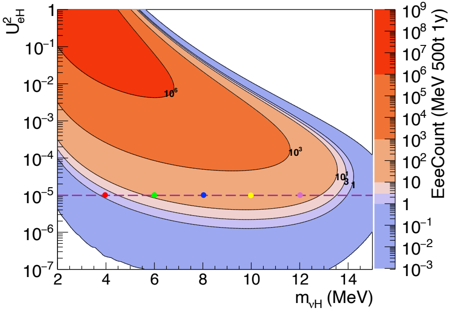


Figure 4: e^+e^- event rate from ν_H decay (500t 1yr, except where noted)

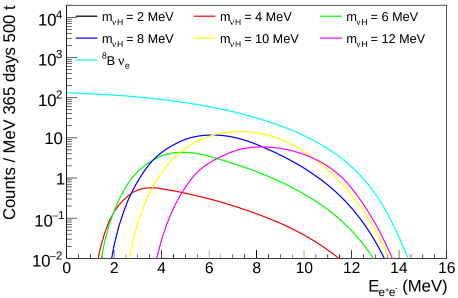


Figure 5: e^+e^- energy spectrum with ^{8}B ES background ($|U_{eH}|^2 = 10^{-5}$)

Background treatment

To give sensitivity, we need background information of the experiment.

For JNE we have:

- Irreducible physics background: e^- from ^{8}B solar ν elastic scattering
- Environmental & cosmogenic backgrounds: ^{208}Tl, ^{11}C, etc.
  Cut by fit window: $4.8 < E_{ee} < 12.8$ MeV[4].

Statistical procedure: profile likelihood ratio test

Binned Poisson likelihood:

$$\mathcal{L}(\mu, \beta) = \prod_i \text{Poisson}(n_i \mid \mu S_i + \beta B_i) \quad (5)$$

- μ: signal strength; β: background flux nuisance parameter
- $\hat{\mu} = 0 \Rightarrow$ Asimov data

Profile likelihood ratio[5]:

$$q(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\beta}}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\beta})} \quad \longrightarrow \quad q_1 = -2 \ln \frac{\mathcal{L}(1, \hat{\hat{\beta}}_1)}{\mathcal{L}(0, \hat{\hat{\beta}}_0)} \quad (6)$$

Exclusion at 90% C.L. for $q_1 > 2.71$.

Sensitivity: e^+e^- energy

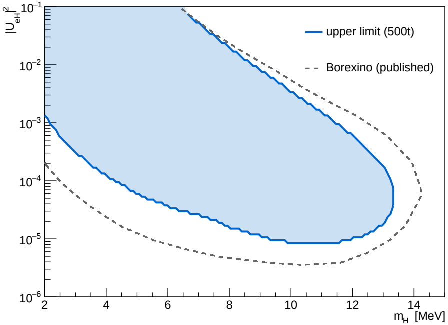


Figure 6: Sensitivity (90% C.L., solid blue: e^+e^- energy)

- Energy-only fit: 0.2 MeV bins, 4.8–12.8 MeV
- Energy smearing: $5\%/\sqrt{E}$
- Dashed gray: Borexino (100t 446d, considering vll branch only)

Separating e^+e^- from single-e^- background

- Signal: $\nu_H \to e^+e^-\nu_e \Rightarrow$ two tracks with opening angle $\theta_{e^+e^-}$
- Background: mainly single e^-
- Ideal directional reconstruction can resolve e^+ and e^- when $\theta_{e^+e^-}$ is large enough

Opening angle distribution

We use MadGraph[2] to generate $\nu_H \to e^+e^-\nu_e$ in rest frame, and then boost these events to lab according to ν_H energy spectrum

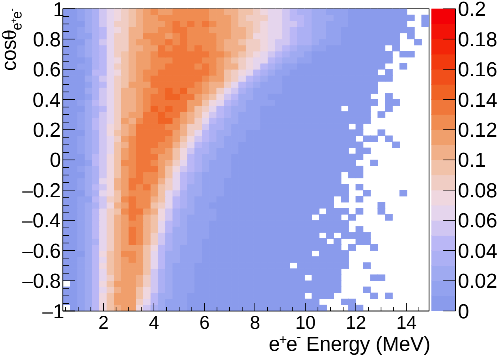


Figure 7: e^+e^- energy vs opening angle $\cos\theta_{e^+e^-}$ distribution in lab ($m_{\nu_H} = 4$ MeV)

- JNE-500 angular resolution[9]: $\sim 25°$ (cosine ~ 0.9, energy dependent)
- Cut: $\cos\theta_{e^+e^-} < 0.9$

Sensitivity: e^+e^- cosine cut

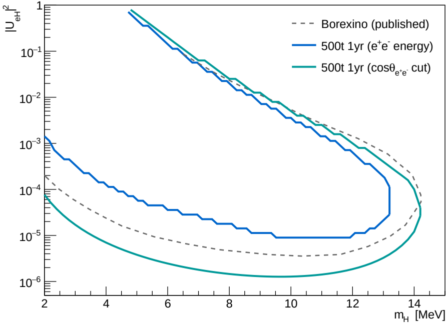


Figure 8: Sensitivity (solid green: e^+e^- cosine cut)

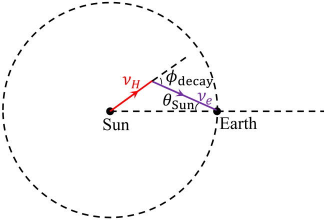
- Improved exclusion
- Energy smearing: $5\%/\sqrt{E}$
- Angular smearing: 25°

Method 2: ν_e–e^- Signal

Concept: detect the decay ν_e

Short-lived ν_H disappears before Earth, but its daughter ν_e keeps energy and directional information.

- ν_e from both $\nu_H \to \nu_e e^+ e^-$ and $\nu_H \to 3\nu_e$ can reach detector
- Signal ν_e has softer energy and non-zero solar angle vs background



Two discriminating variables

❶ ν_e–e^- energy spectrum

❷ Solar angle θ_{Sun} (angle between ν_e–e^- and Sun direction)

ν_e energy spectrum

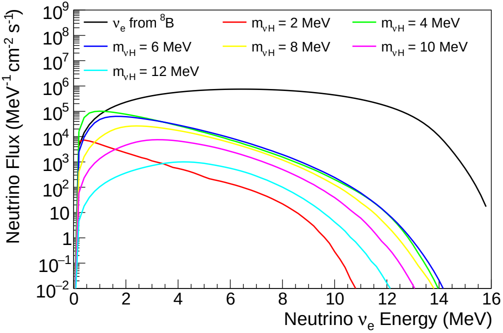


Figure 9: Decay-in-flight ν_e energy spectrum with ^{8}B background

- Signal peaks softer than ^{8}B background
- Good energy resolution critical for separation

ν_e solar angle distribution

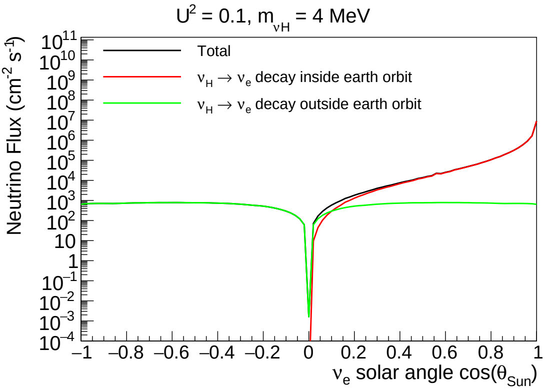


Figure 10: ν_e solar-angle distribution ($|U_{eH}|^2 = 0.1$, $m_{\nu_H} = 4$ MeV)

- Background: always from Sun ($\cos\theta_{\text{Sun}} \approx 1$)
- Signal: tail at large angles from decays in flight

ν_e–e^- elastic scattering

ν_e–e^- ES scattering cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right] \tag{7}$$

where $g_L = \frac{1}{2} + \sin^2\theta_W,\ g_R = \sin^2\theta_W$.

In our simulation:

- Kinematic distributions via integration over recoil e^- phase space
- MSW flavor oscillation effects included in solar propagation
- Output: 2D distribution of scattered e^- in E_e vs $\cos\theta_{\mathrm{Sun}}$

ν_e–e^- signal count

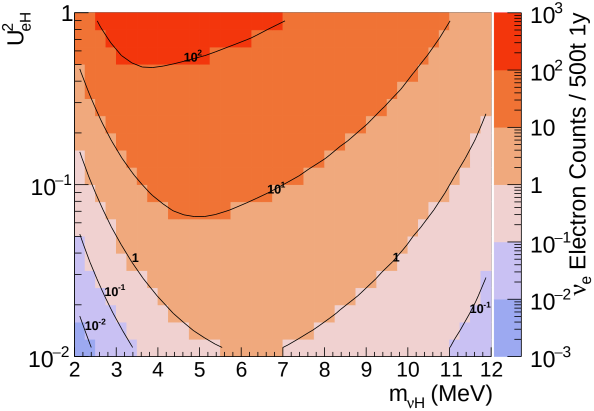


Figure 11: ν_e-e^- scattering event count

- Covers some region where ν_H is short-lived

ν_e–e^- distribution: background vs signal

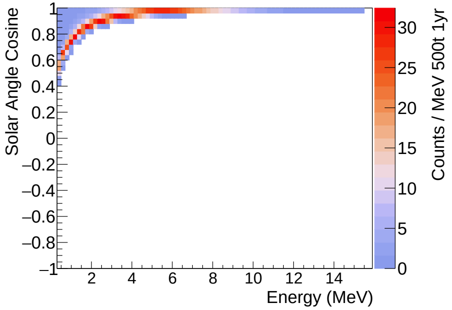


Figure 12: E_e vs $\cos\theta_{\text{Sun}}$ distribution of ν_e–e^- background

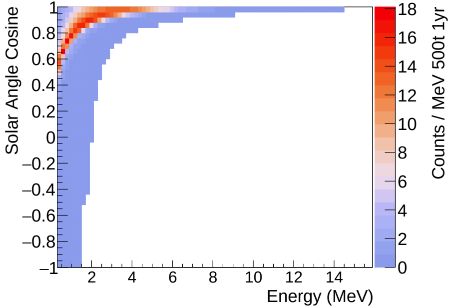


Figure 13: E_e vs $\cos\theta_{\text{Sun}}$ distribution of ν_e–e^- signal ($|U_{eH}|^2 = 10^{-1}, m_{\nu_H} = 4\,\text{MeV}$)

- Signal spans full $\cos\theta_{\text{Sun}}$ range, while background confined to $\cos\theta_{\text{Sun}} > 0.4$
- Signal energy is softer than background

We obtain the sensitivity of method 2 using 2D Poisson likelihood ratio test[5] (same energy and angle smearing as method 1). The two methods are complementary.

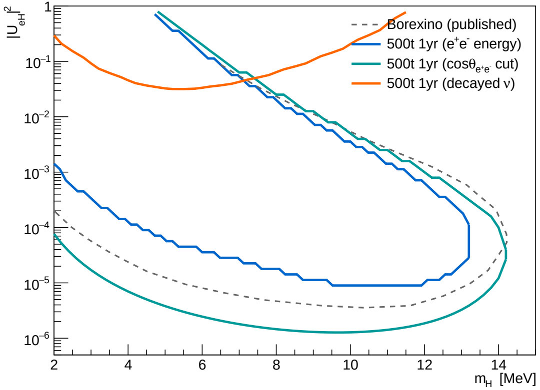


Figure 14: Combined sensitivity (solid orange: ν_e–e^-)

Summary & outlook

Summary & outlook

Summary:

- Two complementary methods for MeV-scale ν_H searches:
  - Method 1: e^+e^- pair from ν_H decay inside detector
  - Method 2: ν_e from ν_H decay before reaching Earth
- A broad MeV HNL region can be probed by combining e^+e^- pair and daughter-neutrino signatures

Outlook:

- Directional information can provide additional background discrimination
- Results motivate solar neutrino experiments (JNE-500) for MeV-scale sterile neutrino searches

Thank you

Any questions?

[1] A. Aguilar-Arevalo et al. **"Improved Search for Heavy Neutrinos in the Decay $\pi \to \mathbf{e}\,\nu$".** In: *Physical Review D* 97.7 (Apr. 2018), p. 072012. ISSN: 2470-0010, 2470-0029. DOI: 10.1103/PhysRevD.97.072012.

[2] J. Alwall et al. **"The Automated Computation of Tree-Level and next-to-Leading Order Differential Cross Sections, and Their Matching to Parton Shower Simulations".** In: *Journal of High Energy Physics* 2014.7 (July 2014), p. 79. ISSN: 1029-8479. DOI: 10.1007/JHEP07(2014)079.

[3] John N. Bahcall, Aldo M. Serenelli, and Sarbani Basu. **"New Solar Opacities, Abundances, Helioseismology, and Neutrino Fluxes".** In: *The Astrophysical Journal* 621.1 (Mar. 2005), pp. L85–L88. ISSN: 0004-637X, 1538-4357. DOI: 10.1086/428929.

[4] G. Bellini et al. **"New Limits on Heavy Sterile Neutrino Mixing in B 8 Decay Obtained with the Borexino Detector".** In: *Physical Review D* 88.7 (Oct. 2013), p. 072010. ISSN: 1550-7998, 1550-2368. DOI: 10.1103/PhysRevD.88.072010.

[5] Glen Cowan et al. **"Asymptotic Formulae for Likelihood-Based Tests of New Physics".** In: *The European Physical Journal C* 71.2 (Feb. 2011), p. 1554. ISSN: 1434-6044, 1434-6052. DOI: 10.1140/epjc/s10052-011-1554-0.

[6] André De Gouvêa. **"Neutrino Mass Models".** In: *Annual Review of Nuclear and Particle Science* 66.1 (Oct. 2016), pp. 197–217. ISSN: 0163-8998, 1545-4134. DOI: 10.1146/annurev-nucl-102115-044600.

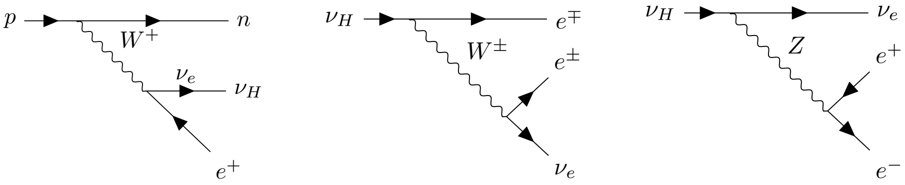
[7] Dmitry Gorbunov and Mikhail Shaposhnikov. **"How to Find Neutral Leptons of the νMSM?"** In: *Journal of High Energy Physics* 2007.10 (Oct. 2007), pp. 015–015. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2007/10/015.

[8] W.C. Haxton, R.G. Hamish Robertson, and Aldo M. Serenelli. **“Solar Neutrinos: Status and Prospects”.** In: *Annual Review of Astronomy and Astrophysics* 51.1 (Aug. 2013), pp. 21–61. ISSN: 0066-4146, 1545-4282. DOI: 10.1146/annurev-astro-081811-125539.

[9] Wentai Luo et al. **“Reconstruction Algorithm for a Novel Cherenkov Scintillation Detector”.** In: *Journal of Instrumentation* 18.02 (Feb. 2023), P02004. ISSN: 1748-0221. DOI: 10.1088/1748-0221/18/02/P02004.

[10] Robert E. Shrock. **“General Theory of Weak Processes Involving Neutrinos. II. Pure Leptonic Decays”.** In: *Physical Review D* 24.5 (Sept. 1981), pp. 1275–1309. ISSN: 0556-2821. DOI: 10.1103/PhysRevD.24.1275.

Feynman diagrams



Production (^{8}B); CC decay $\nu_H \to \nu_e e^+ e^-$; NC decay $\nu_H \to 3\nu_e$.

Decay-in-flight sketches