MeV-Scale Sterile Neutrino Dark Matter and Future Detection

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S. Fujisawa, T. Hayashi, S. Matsumoto, Y. Watanabe,
"Detecting Sterile Neutrino Dark Matter at MeV Gamma-Ray Observatories"
JHEP 01 (2026) 097, arXiv: 2508.08695 [hep-ph]

Motivation for Sterile Neutrino Dark Matter

<u>What is dark matter made of ?</u>

WIMP ? Axion ? Primordial Black hole ?

<u>Unsolved problems in particle physics</u>

- Nature of dark matter
- Origin of neutrino masses
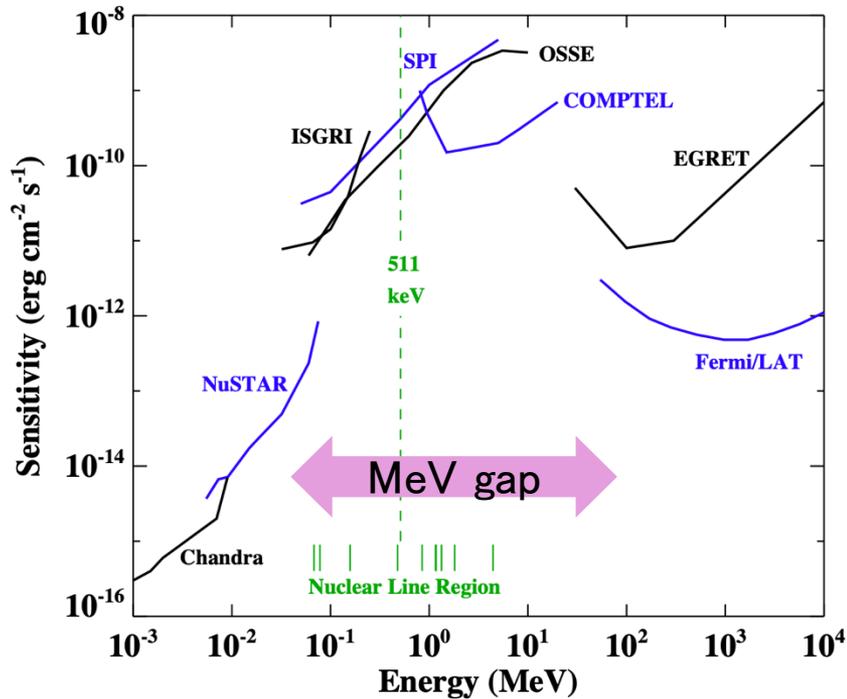- Origin of the baryon asymmetry

We need physics beyond the SM

<u>Three generations of right-handed neutrinos</u>

- The lightest one → **Sterile neutrino DM !**
- Two heavy right-handed neutrinos
  - Seesaw mechanism
  - Leptogenesis

"MeV–Gap" and Motivation for MeV–Scale Dark Matter

Next generation MeV gamma–ray observation COSI

Source: Tomsick et al., PoS ICRC2023

Photo–absorption

Compton scattering

e^+e^- pair creation
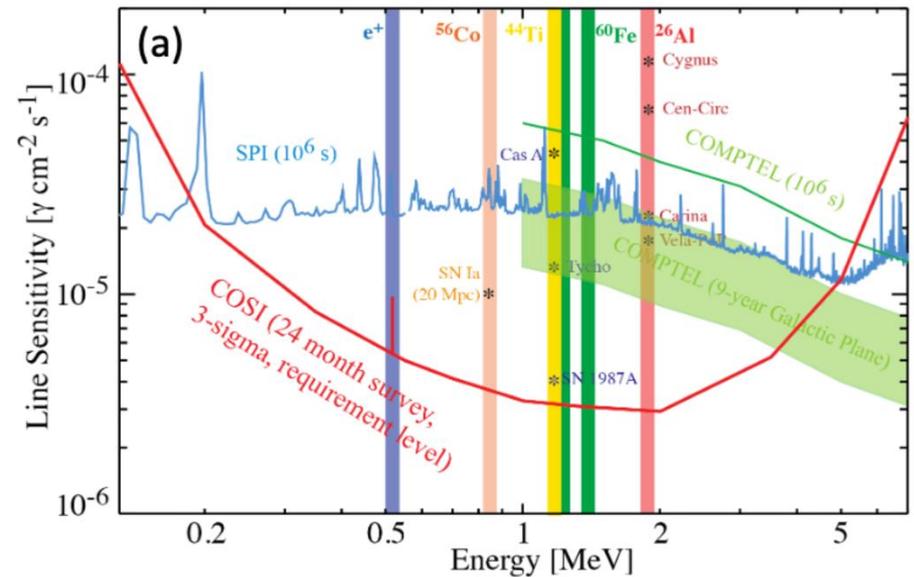
From slides: Tomsick, LBNL instrumentation colloquium

Model and Setup

<u>Standard Model extended by a $U(1)_{B-L}$ gauge symmetry</u>

- Gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

- Fields:
  - Standard Model particles
  - $U(1)_{B-L}$ gauge boson $\boldsymbol{Z'}$
  - Complex scalar field ("Higgs" field) $\boldsymbol{\Phi}$
  - <u>Three generations</u> of right-handed neutrinos $\boldsymbol{N_I}$ $(\boldsymbol{I = 1, 2, 3})$

- Quantum numbers

	$\boldsymbol{Q_i}$	$\boldsymbol{U_{i,}}$	$\boldsymbol{D_i}$	$\boldsymbol{L_i}$	$\boldsymbol{E_i}$	$\boldsymbol{H}$	$\boldsymbol{\Phi}$	$\boldsymbol{N_I}$
$U(1)_{B-L}$	1/3	1/3	1/3	-1	-1	0	2	-1

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin}[Z', N_I, \Phi] + \mathcal{L}_{B-L}[SM]$$
$$+ \mathcal{L}_{Yukawa}[N_I, \Phi] + \mathcal{L}_{Yukawa}[L, N_I, H] - V[\Phi, H]$$

Effective Lagrangian

Hierarchy of mass scales
$$m_{N_2,N_3,Z',\phi} \gg m_{W,Z} \gg m_{N_1} = \mathcal{O}(\text{MeV})$$

SSB of the $U(1)_{B-L}$ gauge symmetry : $\langle \Phi \rangle = v_\Phi/\sqrt{2}$

- Effective theory at energies well below v_Φ

  ➡️
  - N_I, Z', ϕ acquire masses
  - Weinberg operator
  - Four-Fermi interaction from $Z' \rightarrow$ Production mechanism

$N_{2,3}, Z', \phi$

SSB of the $SU(2)_L \times U(1)_Y$ gauge symmetry : $\langle H \rangle = v_{EW}/\sqrt{2}$ W, Z, h

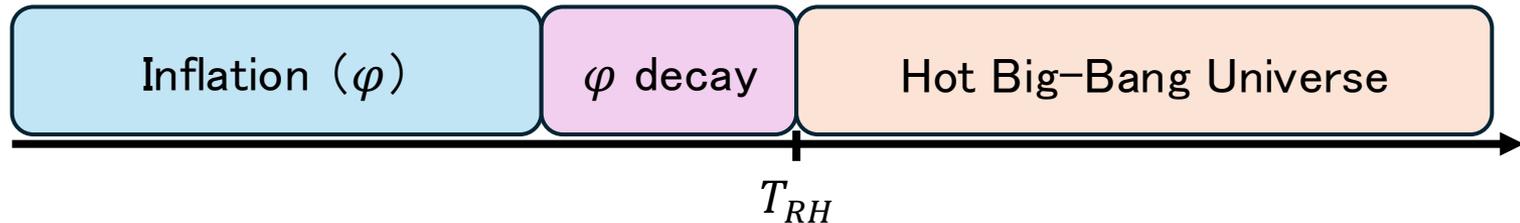- Effective theory at energies well below v_{EW}

  ➡️
  - ν_i acquire masses (Seesaw mechanism)
  - Mixing between N_1 and ν_i (Mixing angle Θ_{i1})
  - Four-Fermi interaction from $W, Z \rightarrow$ DM Decay

$N_1, e^\pm, \nu_i$

Sterile Neutrino Dark Matter

Can we explain the DM abundance $\Omega_{DM} h^2 \cong 0.12$?

- Production mechanism : (UV) Freeze-in mechanism

Inflation (φ)	φ decay	Hot Big-Bang Universe

T_{RH}

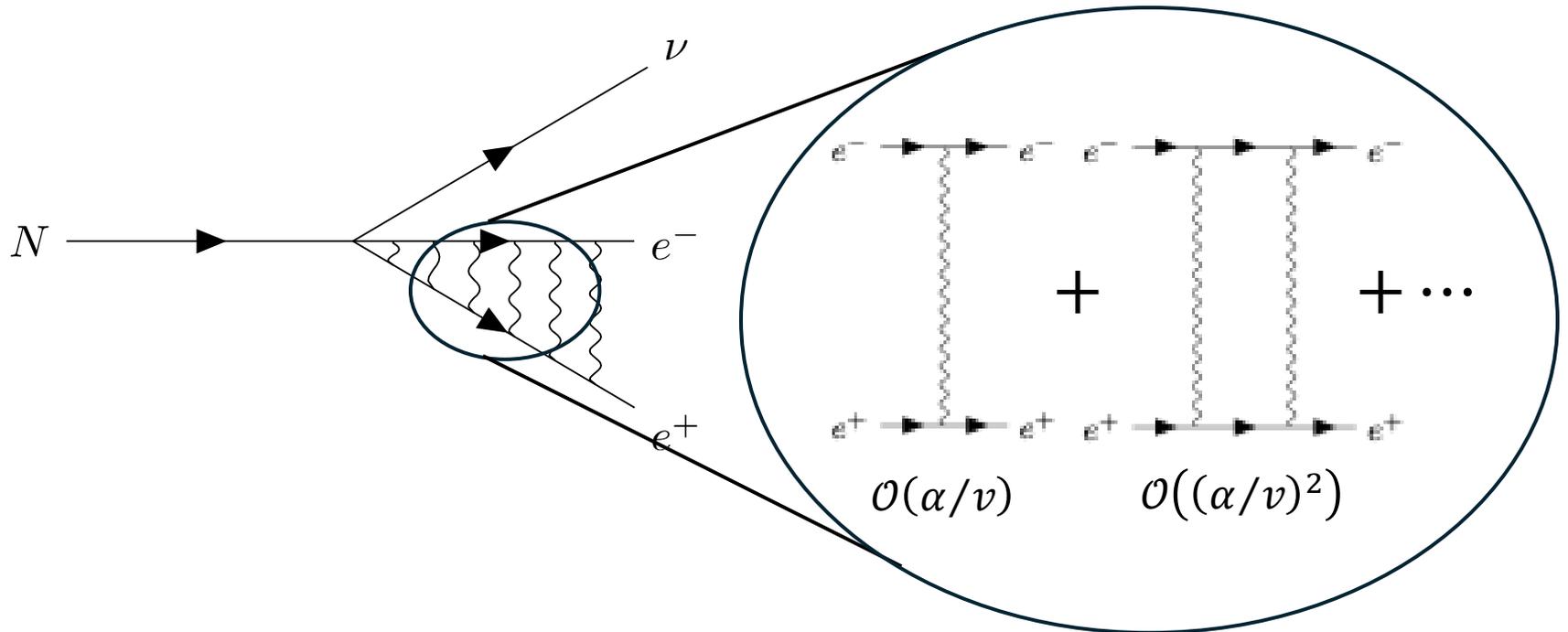- Dominant channel: $f\bar{f} \to NN$

- From the Boltzmann and Friedmann equations

$$\to \Omega_N h^2 = 0.11 \times \left(\frac{m_N}{1\ \text{MeV}}\right) \times \left(\frac{T_{RH}}{10^{14}\ \text{GeV}}\right)^3 \times \left(\frac{10^{16}\ \text{GeV}}{v_\Phi}\right)^4$$

Can produce a sufficient abundance, given the reheating temperature T_{RH} and the new-physics scale v_Φ for successful seesaw and leptogenesis !
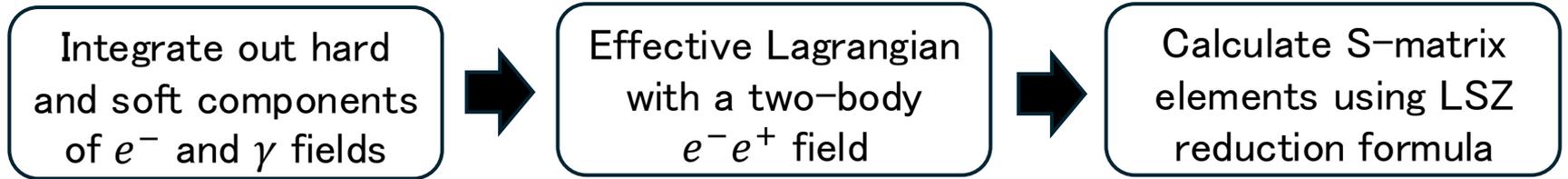
Sommerfeld Enhancement

- As $m_N \to 2m_e$, a strong long-range Coulomb interaction acts between the e^- and e^+ produced in $N \to e^- e^+ \nu$


- Perturbation theory breaks down near the $e^- e^+$ threshold $(v \to 0)$

Potential Non-Relativistic Lagrangian Method

| Integrate out hard and soft components of e^- and γ fields | ➤ | Effective Lagrangian with a two-body $e^- e^+$ field | ➤ | Calculate S-matrix elements using LSZ reduction formula |

Results of Sommerfeld enhancement

- $\mathcal{O}(10)\%$ degeneracy $m_N \cong 2m_e \rightarrow \mathcal{O}(10\%)$ enhancement of the decay width
- $\mathcal{O}(0.1)\%$ degeneracy $m_N \cong 2m_e \rightarrow \mathcal{O}(100\%)$ enhancement of the decay width
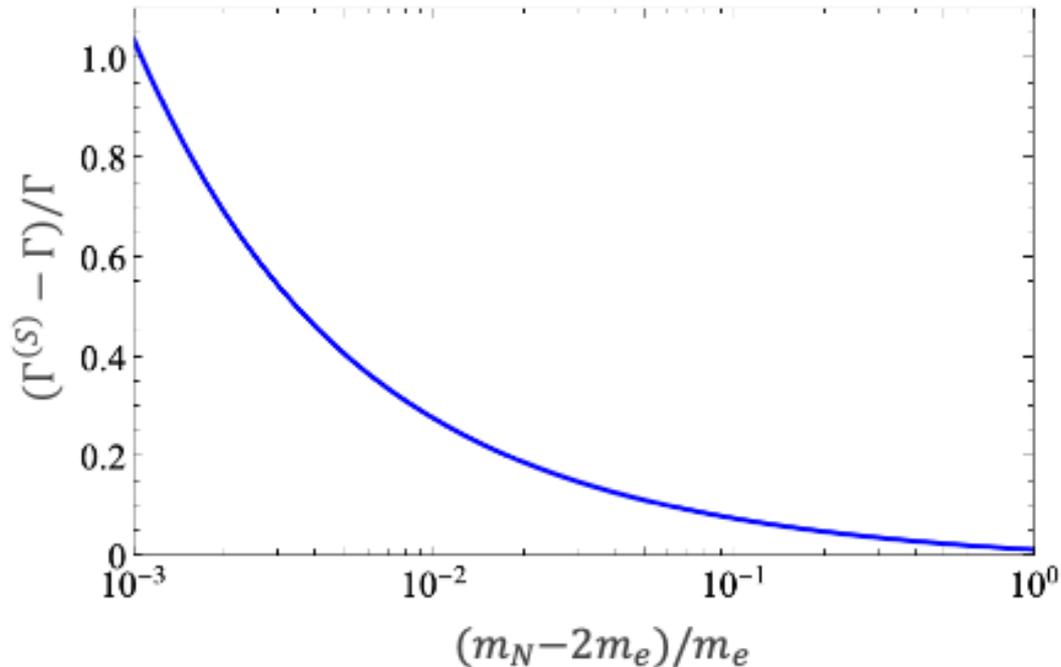
Summary of current constraints

Constraints on mixing angle Θ

Assumption: the mixing angle is flavor-independent

$$\Theta \equiv \Theta_{11} = \Theta_{21} = \Theta_{31}$$

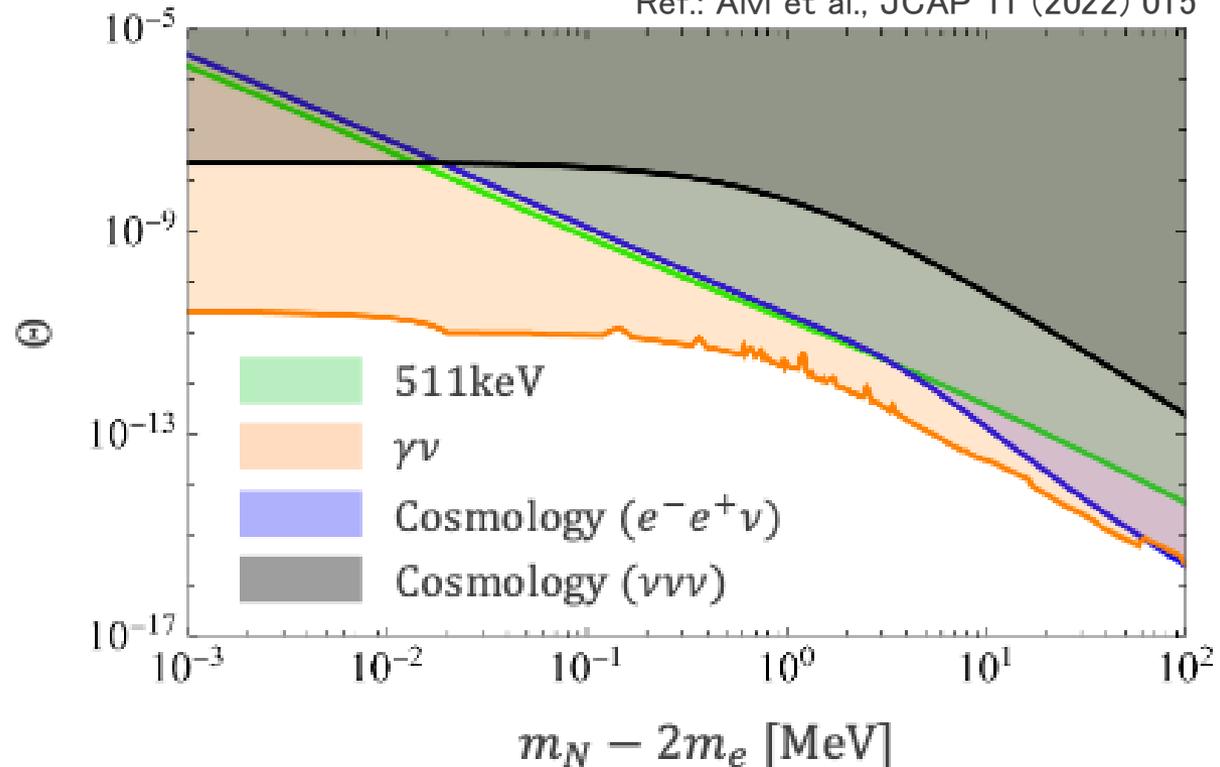Data from: Slatyer and Wu, Phys. Rev. D 95, 023010 (2017);
Siegert et al., Astron. Astrophys. 586, A84 (2016)
Essig+ (JHEP 2013); Laha+ (PRD 2020); Fischer+ (MNRAS 2023)
Ref.: Alvi et al., JCAP 11 (2022) 015

Decay channel of MeV sterile neutrino

- $N \to \nu\nu\nu$

  $\to$ Cosmology

- $N \to e^- e^+ \nu$

  $\to$ CMB and 511 keV

- $N \to \gamma\nu$

  $\to$ γ-ray observation

511keV

$\gamma\nu$

Cosmology $(e^- e^+ \nu)$

Cosmology $(\nu\nu\nu)$

$m_N - 2m_e$ [MeV]

Outline of COSI

Compton Spectrometer and Imager (COSI)

- Scheduled for launch in 2027 (2-years mission)

- High sensitivity to γ-ray line signal in the $0.2 \sim 5$ MeV range

- High energy resolution : 6.0 keV (0.511 MeV), 9.0 keV (1.157 MeV)

- Employs a Compton camera

Source: Tomsick et al., PoS ICRC2023
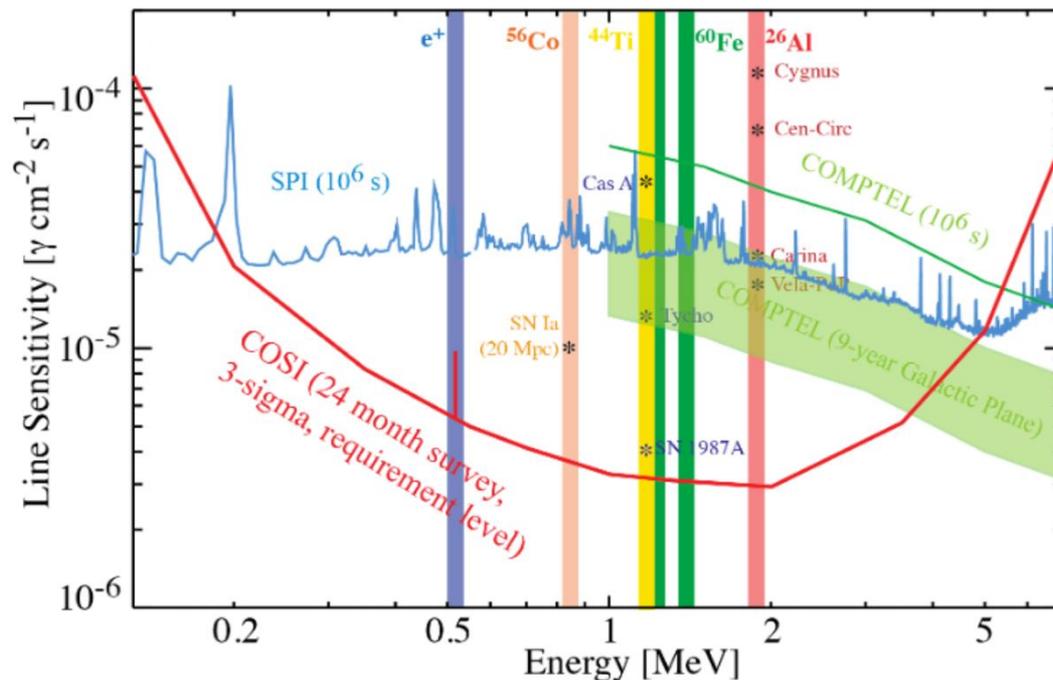
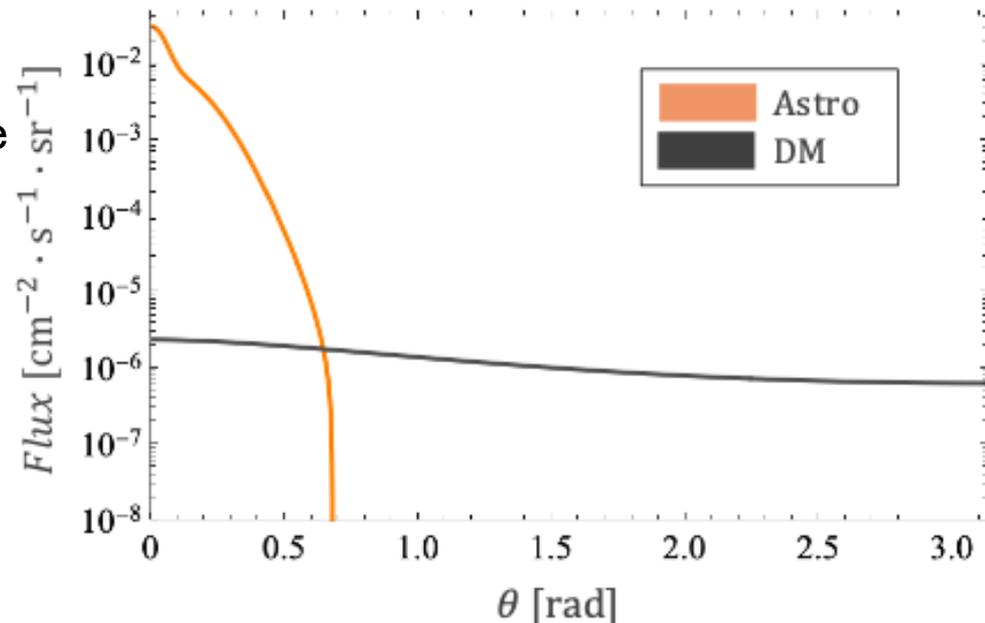# Future Detection of MeV Sterile Neutrino Dark Matter

$\underline{N \to \gamma\nu}$

- Region of Interest (ROI): within 10° of the Galactic Center
- Sensitivity estimate based on publicly available COSI performance data

$\underline{e^+ \to Ps \to 2\gamma \ (511 \ \mathrm{keV})}$

- Sensitivity estimate based on publicly available COSI performance data
- The 511 keV line has already been observed from the bulge
- The Decaying DM contribution is small in the bulge region

⬇

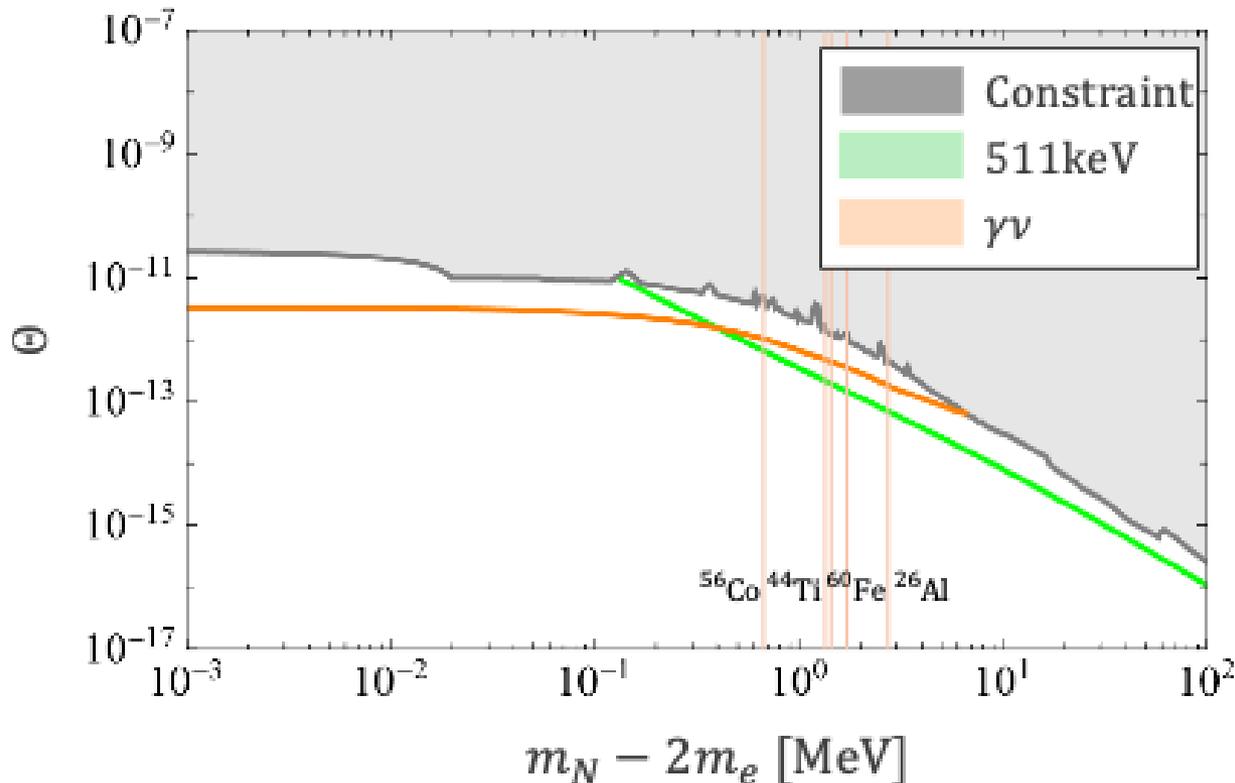Look outside the bulge !

Data: Skinner et al. (PoS INTEGRAL2014)

Future Detection of MeV Sterile Neutrino Dark Matter

Sensitivity to sterile neutrino dark matter with COSI

- COSI can probe new parameter space
- For $m_N - 2m_e \sim 0.1 \sim 10$ MeV, there is a parameter region where both the monochromatic $\gamma\nu$ line and the 511 keV line are observable

Summary

- Extending the SM with right-handed neutrinos is well motivated, as it can explain neutrino masses, the baryon asymmetry, and dark matter

- Due to Sommerfeld effect, the decay width near the e^-e^+ threshold is enhanced relative to perturbative result

- This enhancement can impact indirect-detection signals, since future observations are expected to have high-sensitivity in this region

- COSI can observe γ-ray line spectra in the $0.2\sim5$ MeV range with higher sensitivity and better energy resolution than the previous MeV γ-ray experiments

- Therefore, COSI is expected to probe new parameter in the sterile-active mixing angle

Future Detection of MeV Sterile Neutrino Dark Matter

Definition of the ROI

- Compton data space: apparent incident direction (θ_a, ϕ_a) and scattering angle ψ

- ROI for the 511 keV signal: outside the region with radius $\theta \equiv \theta_0 + \psi$

   (θ_0 is defined by $d\mathcal{F}_{ast}/d\Omega\,(\theta_0) = d\mathcal{F}_{DM}/d\Omega\,(\theta_0)$)