Sterile Neutrinos from Supernovae at Gamma ray Telescopes

Garv Chauhan

Center for Neutrino Physics, Department of Physics, Virginia Tech

Work with R. Andrew Gustafson, Ian M. Shoemaker

Based on arXiv [hep-ph] : 2410.abcde

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Neutrino Masses

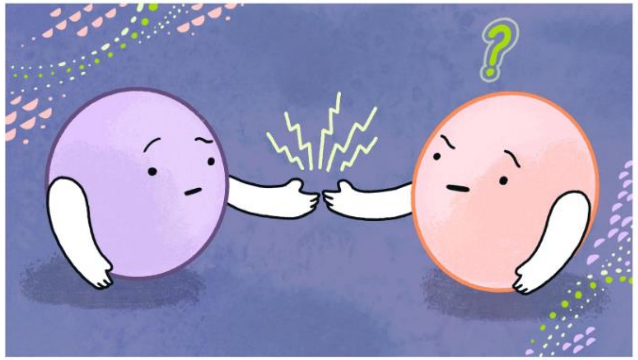
- The discovery of neutrino oscillations implies non-zero neutrino masses.
- Monumental progress to understand neutrino mixing paradigm but yet to understand the neutrino mass mechanism.
- The minimal scenario includes the introduction of right-handed neutrinos (RHN).
- RHNs are motivated BSM candidates - ν masses, dark matter and matter-antimatter asymmetry (η_B)

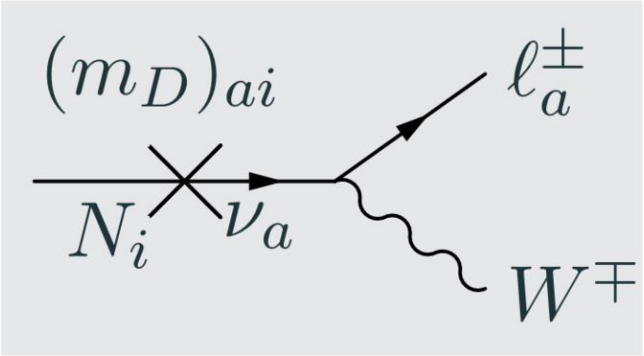
Sterile Neutrinos

- Add SM-singlet heavy Majorana neutrinos.

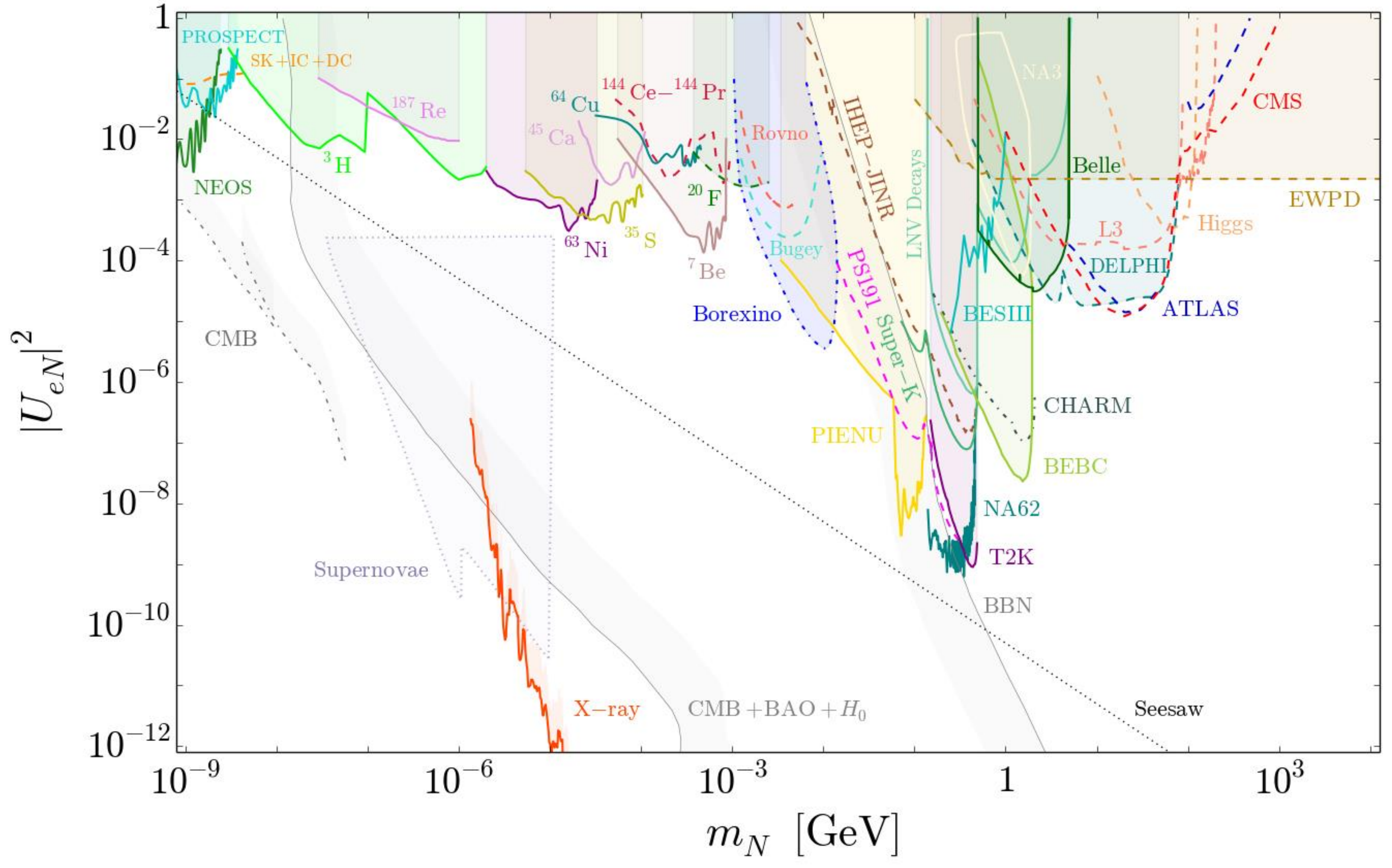
$$-\mathcal{L} \supset Y_D \bar{L}_l \tilde{H} N + \frac{1}{2} \bar{N}^c M_N N + h.c.$$

- For small mixing $M_N^{-1}\, m_D \ll 1$, $m_\nu \simeq m_D\, M_N^{-1}\, m_D^T$, where $m_D = v_{ew}\, Y_D$.

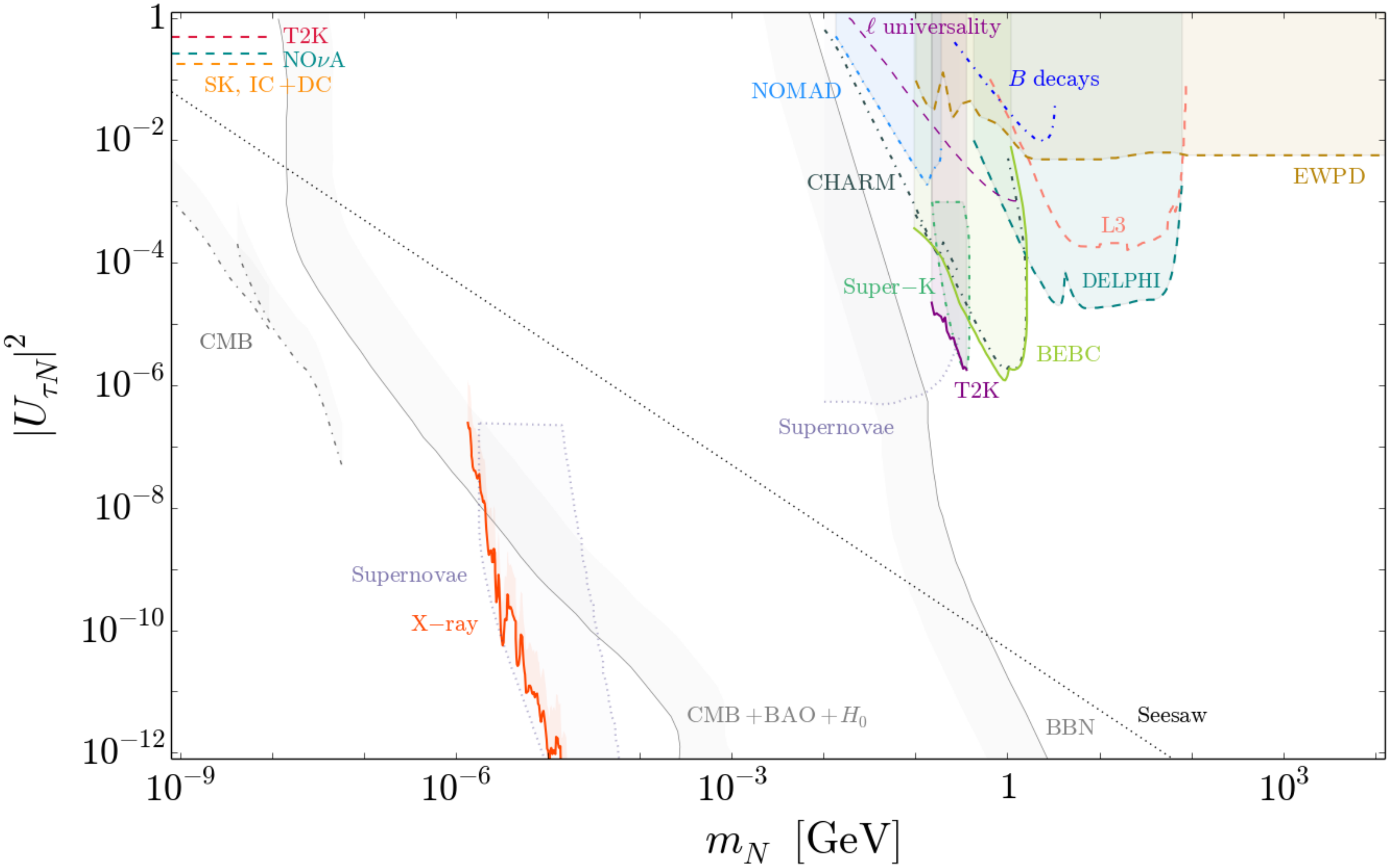




- What values of masses and mixing angles can be probed by direct experiments, cosmology and astrophysics ?



[Bolton, Deppisch, Dev (JHEP ’20)][Atre, Han, Pascoli, Zhang (JHEP ’09); Deppisch, Dev, Pilaftsis (NJP ’15); de Gouvêa, Kobach (PRD ’16); Drewes, Garbrecht (NPB ’17)]



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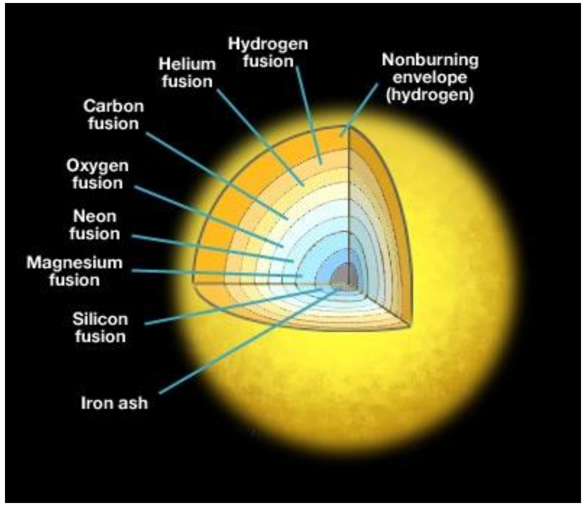
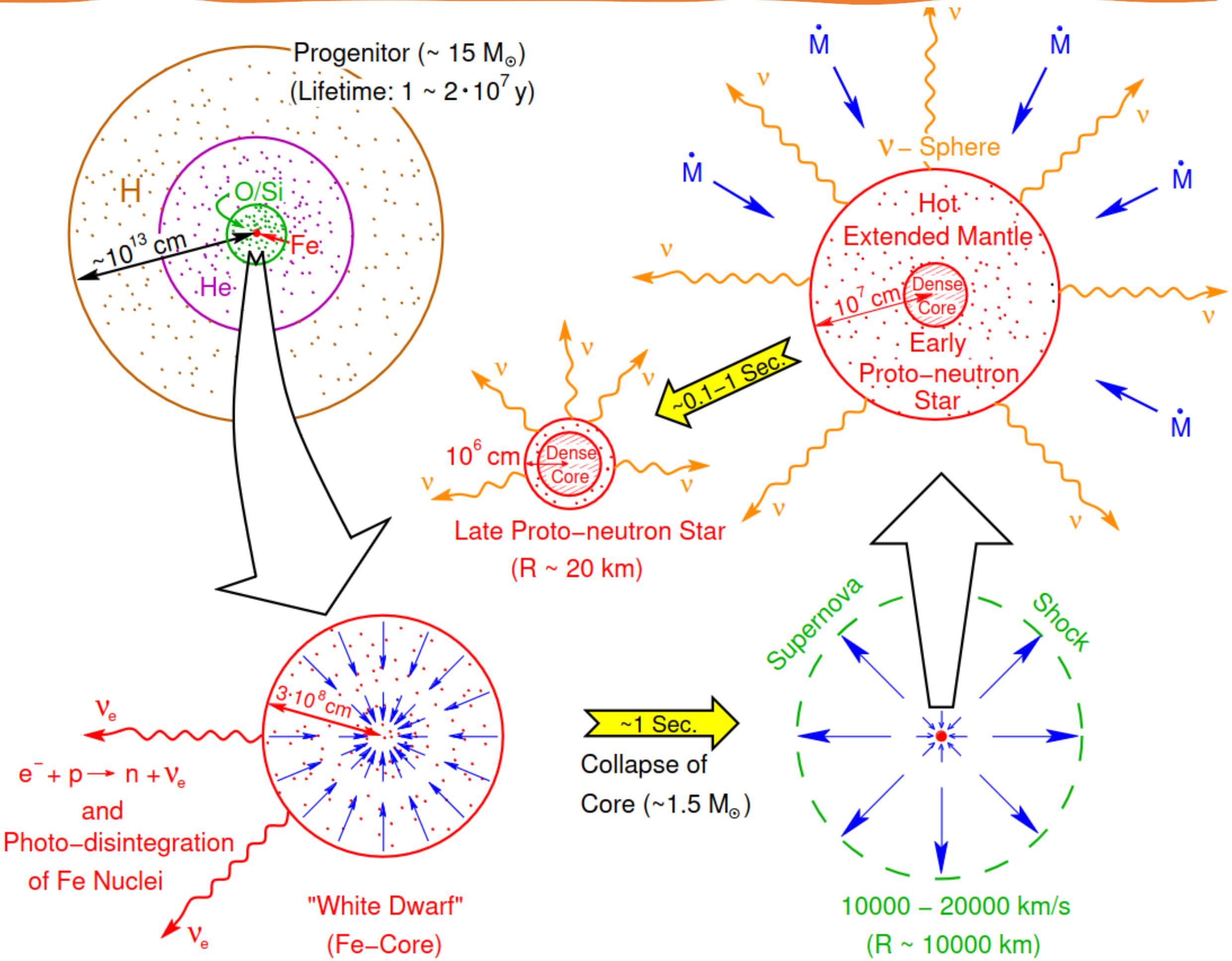
Supernova : ν factory

- Core-collapse supernovae represent the most powerful sources of neutrinos in the Universe.
- during the explosion, $\mathcal{O}(10^{58})$ (anti)neutrinos of all the flavors are emitted with average E ~ 15 MeV.
- Probe fundamental properties of neutrinos and even *emission of exotic BSM particles!*



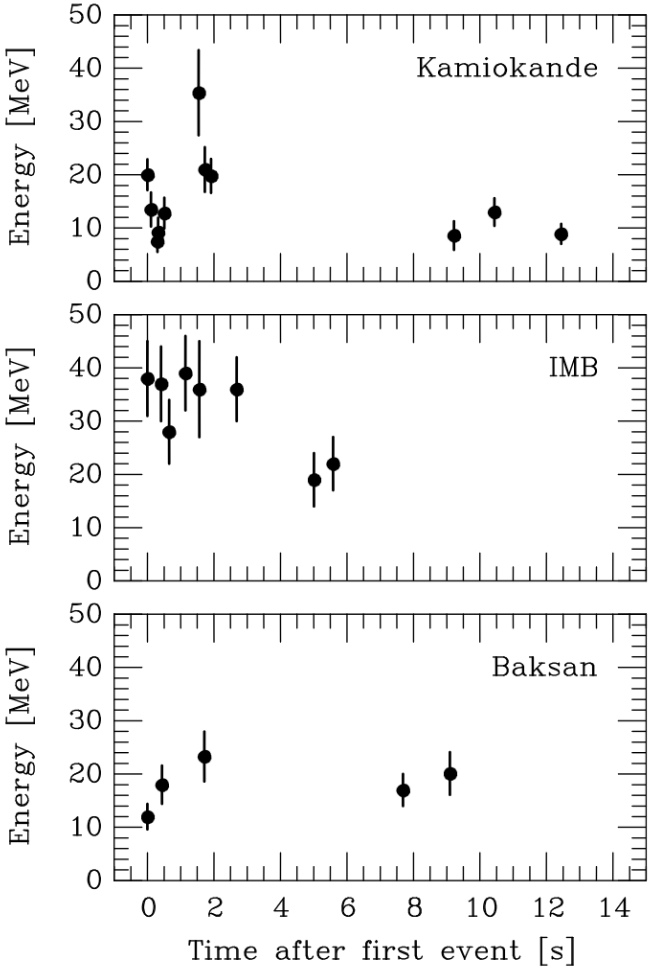


[Burrows, 1990b]

Energy Loss SN1987A

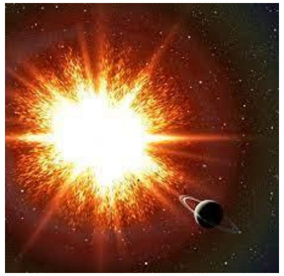
- SN 1987A neutrino signal ~ 10 s, as expected from standard SN cooling scenario
- Light BSM particles produced in the SN core would constitute a novel channel of energy loss, shortening the duration of the neutrino burst.
- Excluding an additional energy drain can constrain sterile states mixing with the active ones.
- Observations constrain energy-loss rate per unit mass → total luminosity → bounds on active-sterile mixing

$$L_s = \varepsilon_s \times 1\, M_\odot \simeq 2 \times 10^{52}\ \mathrm{erg/s}$$

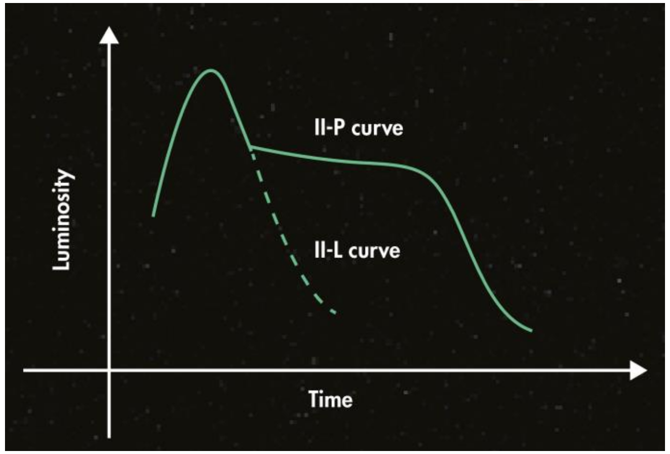


[Janka 1702.08713, Raffelt]

Low-energy SN : IIP or not IIP

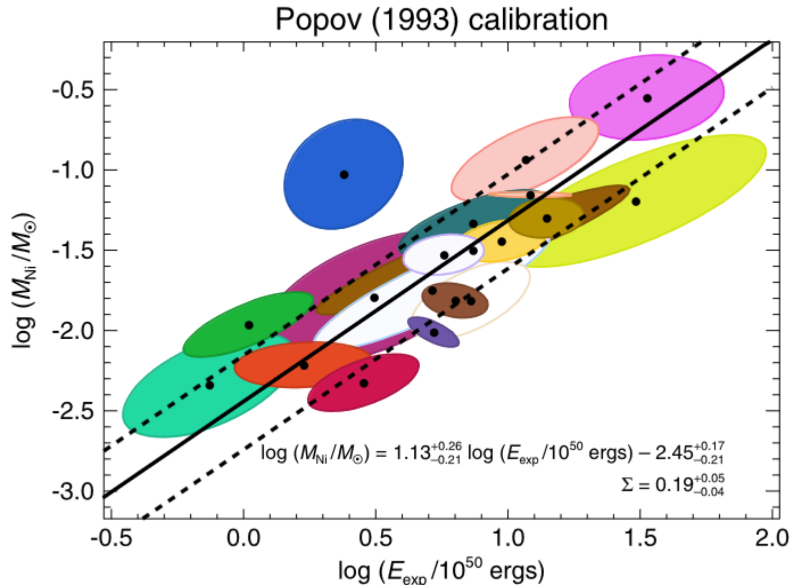


- Based on the presence of characteristic *plateau* shape in their light curves , are termed SN IIP.



- The brightness and duration of the plateau is determined mainly by the explosion energy, ejecta mass, nickel mass and progenitor radius.

- The reconstructed energies from observed SN are in good agreement with expectations from the simulated low-energy SN.
  Muller,Prieto,Pejcha,Clocchiatti Astrophys.J. 841 (2017),
  Murphy,Mabanta,Dolence MNRAS 489(2019)

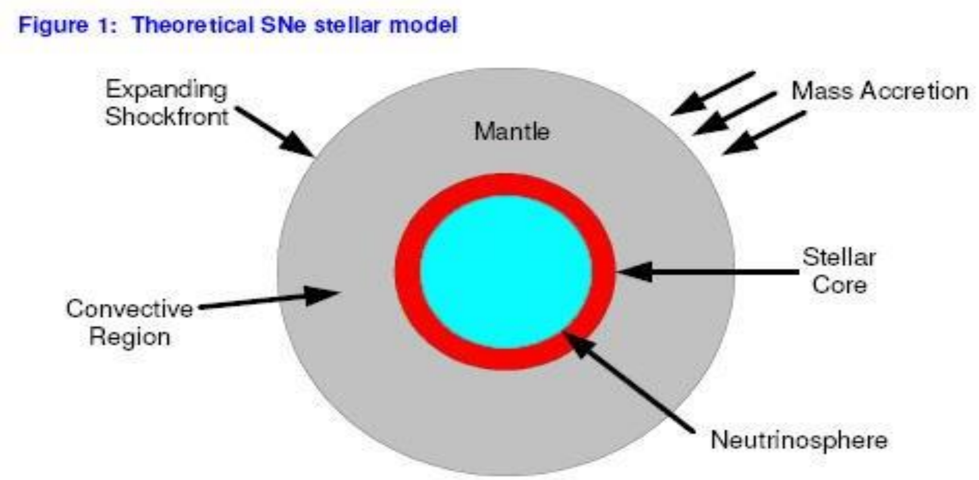


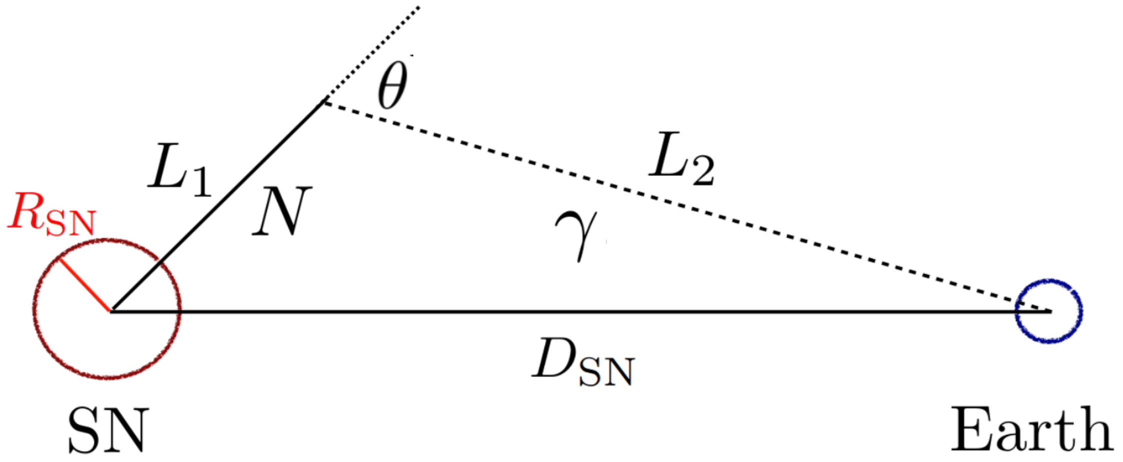
- But the sterile neutrinos produced in the core can deposit energies of a similar magnitude, and hence can be constrained from the observations of these low-energy SN

$$E_{dep} \leq 10^{50} \text{ erg.}$$

Caputo, Janka, Raffelt, Vitagliano PRL 128(2022)   GC, Huber, Horiuchi, Shoemaker (2023)
Carenza, Lucente, Mastrototaro, Mirizzi, Serpico (2023)

Photons from Decay





Oberauer, Hagner,Raffelt, Rieger (!993)

Sterile neutrino production

- We assume that the sterile mixes dominantly with one flavor i.e ν_τ.

$$\nu_a = \cos\theta\ \nu_1 + \sin\theta\ \nu_2\,,$$

$$\nu_s = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2\,,$$

- In a SN core, sterile neutrino can be produced by electron and neutrino pair annihilation, the inelastic scattering of (anti-) neutrinos and scattering of neutrinos with nucleons.

- Contrary to previous literature, the neutrino scattering off of neutrons is the most dominant as shown by Carenza et.al. (2023).

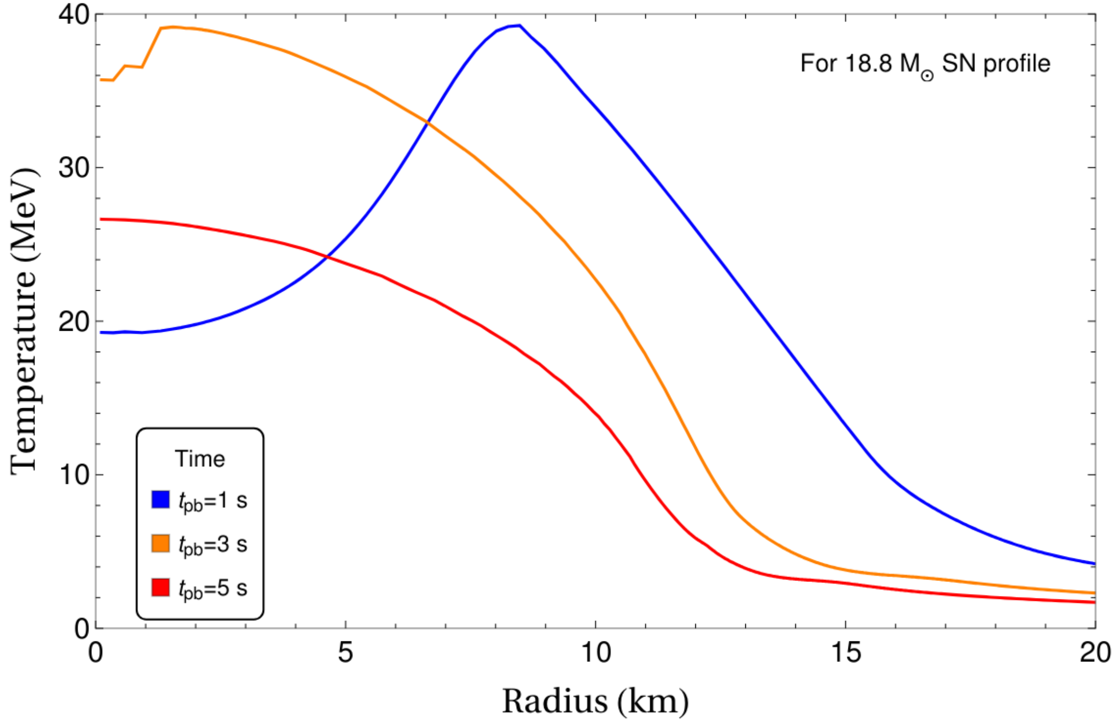
Process
$\nu_\alpha + \bar{\nu}_\alpha \leftrightarrow \bar{\nu}_\alpha + \nu_4$
$\nu_\alpha + \nu_\alpha \leftrightarrow \nu_\alpha + \nu_4$
$\nu_\beta + \bar{\nu}_\beta \leftrightarrow \bar{\nu}_\alpha + \nu_4$
$\nu_\alpha + \bar{\nu}_\beta \leftrightarrow \bar{\nu}_\beta + \nu_4$
$\nu_\alpha + \nu_\beta \leftrightarrow \nu_\beta + \nu_4$
$e^+ + e^- \leftrightarrow \bar{\nu}_\alpha + \nu_4$
$\nu_\alpha + e^- \leftrightarrow e^- + \nu_4$
$\nu_\alpha + e^+ \leftrightarrow e^+ + \nu_4$
$\nu_\alpha + N \leftrightarrow N + \nu_4$

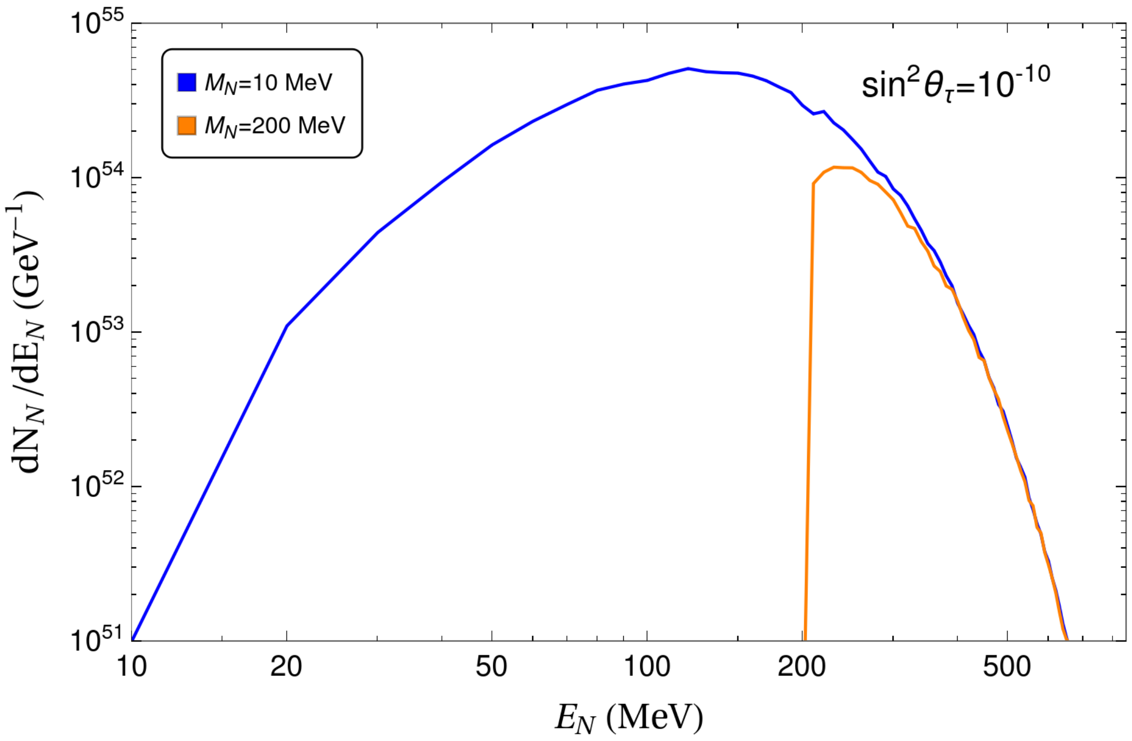
Fuller,Kusenko,Petraki PLB 670(2009)

Carenza, Lucente, Mastrototaro, Mirizzi, Serpico (2023)

Production rates

GC, Huber, Horiuchi, Shoemaker (arXiv : 2402.01624)





- For reference model, we use Garching group's SFHo-18.8 muonic model.

Peak Temps. : 30-40 MeV
Final NS mass : 1.351 solar mass

Boltzmann Transport

- The evolution of sterile neutrino abundances is governed by the Boltzmann transport equation.
- Assuming the medium is homogeneous and isotropic. This implies that the change in phase-space density will only be affected by the scatterings/pair-annihilation processes in the SN core.

$$\frac{\partial f_s}{\partial t} = \mathcal{C}_{coll}(f_s)$$

$$\mathcal{C}_{coll} = \frac{1}{2E_s} \int d^3\tilde{p_2} d^3\tilde{p_3} d^3\tilde{p_4}\, \Lambda(f_s, f_2, f_3, f_4)\ S|M|^2_{12\to 34}\, \delta^4(p_s + p_2 - p_3 - p_4)(2\pi^4)$$

$$\Lambda(f_s, f_2, f_3, f_4) = (1-f_s)(1-f_2)f_3 f_4 - f_s f_2 (1-f_3)(1-f_4)$$

$$\frac{dL_s}{dE_s} = \frac{2E_s}{\pi} \int dr\, r^2 \frac{df_s}{dt} E_s\, p_s$$

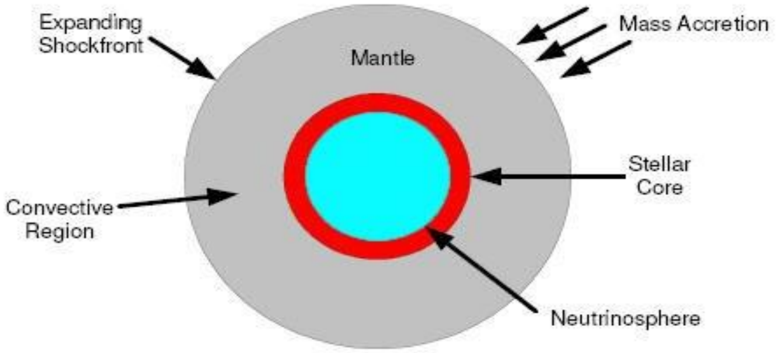
Mastrotaro, Mirizzi, Serpico, Esmaili JCAP 01 (2020)

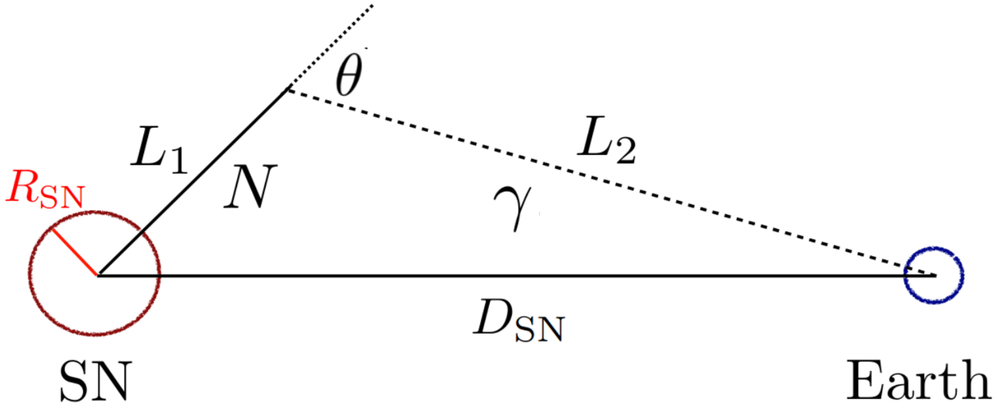
Photons from Decay

- For mass range of interest and mixing only with ν_τ, the charged-current processes are kinematically forbidden.

$$\nu_s \to \nu_\tau \gamma,$$
$$\nu_s \to \nu_\tau \pi^0,$$
$$\nu_s \to \nu_\tau e^+ e^-,$$
$$\nu_s \to \nu_\tau \mu^+ \mu^-,$$
$$\nu_s \to \nu_\tau \nu_x \bar{\nu}_x,$$

Figure 1: Theoretical SNe stellar model





Atre,Han,Pascoli, Zhang JHEP 05(2009), Gorbunov,Shaposhnikov JHEP 10(2007)

Photons Flux at Earth

- The expected gamma ray flux near Earth is given by

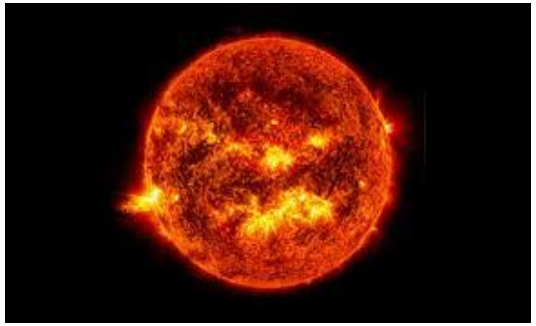
$$\frac{dN_\gamma}{dE_\gamma dt_d} = \int dE_N d\cos\theta_N \frac{B_\gamma}{\tau} f_N\left(\frac{E_\gamma}{\gamma(1+\beta\cos\theta_N)}\right) \times \exp\left(\frac{-\gamma t_d(1+\beta\cos\theta_N)}{\tau}\right)\frac{dN_N}{dE_N}\Theta(x - R_{env})$$

- The distribution function for both processes in the sterile neutrino rest frame are

$$f_{N\to\gamma\nu}(\omega) = \frac{1}{2}\delta(\omega - m_N/2),$$

$$f_{N\to\pi\nu}(\omega) = \frac{2B_{\pi\nu}}{\gamma_\pi\beta_\pi m_\pi}\Theta\left(\omega - \frac{E_\pi(1-\beta_\pi)}{2}\right)\Theta\left(\frac{E_\pi(1+\beta_\pi)}{2} - \omega\right)$$

Solar Maximum Mission (SMM)



- The Gamma-Ray Spectrometer (GRS) was one of two instruments on the Solar Maximum Mission (SMM), that was operating during the SN1987A, observed 1393 events in 25-100 MeV.

- The data analysis showed that no excess of gamma-rays reaching the detector during the SN1987A neutrino burst, consistent with expectations from the galactic diffuse photon flux and other sources.

TABLE II. GRS 3σ upper fluence limits for the two indicated time intervals after the arrival of the first SN 1987A neutrino.

Channel	Energy band [MeV]	Gamma fluence limits [cm^{-2}] 10 s [31]	223.2 s [32]
1	4.1–6.4	0.9	6.11
2	10–25	0.4	1.48
3	25–100	0.6	1.84

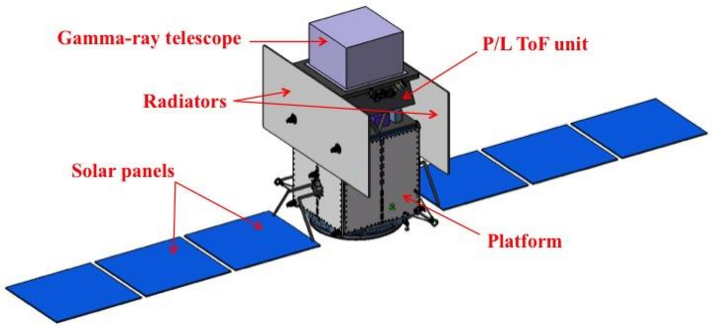
Future Observations

- The sensitivity of current and near-future gamma ray telescopes can help probe the sterile neutrino parameter space further.

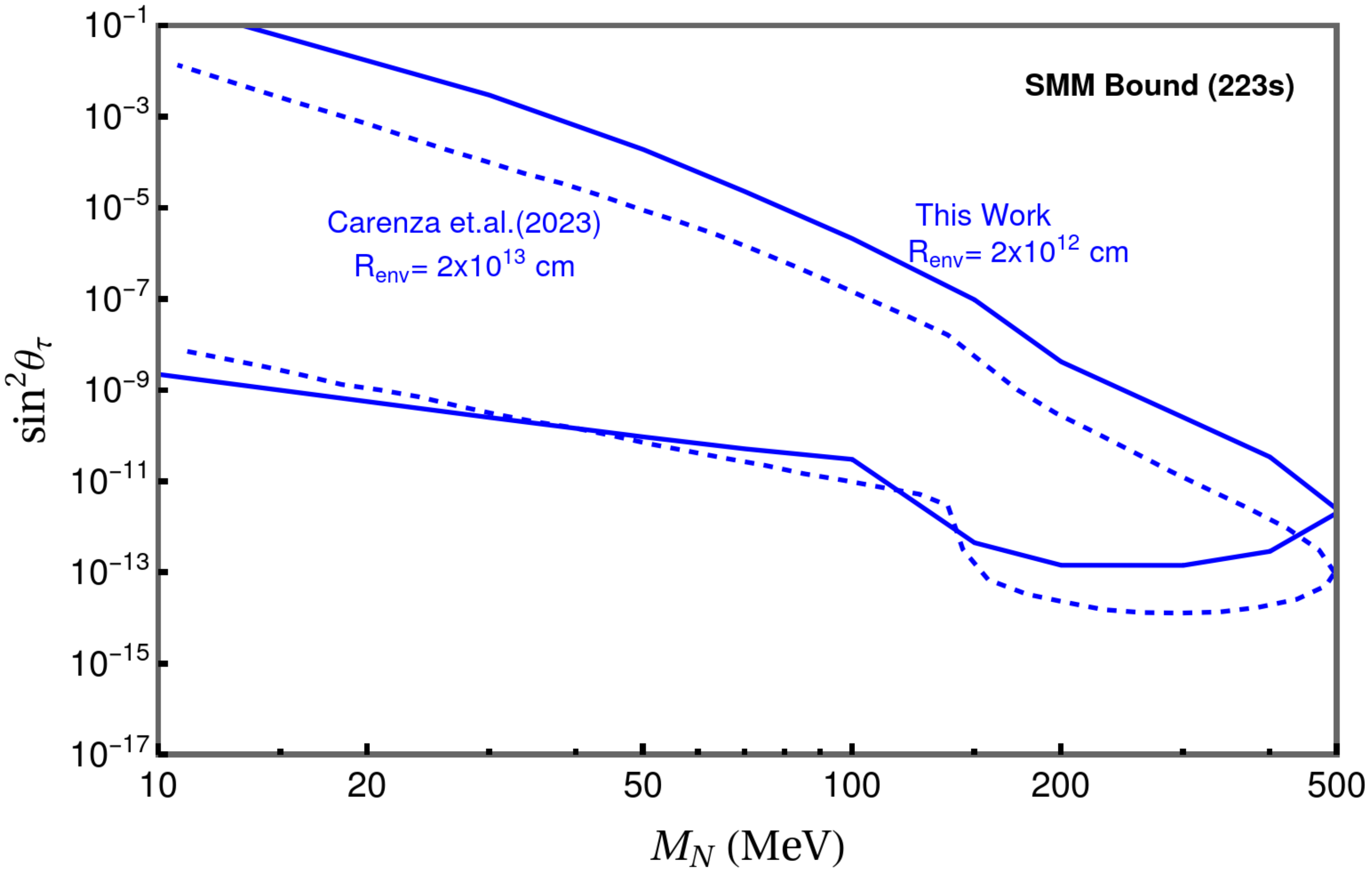
- We study the projections for Fermi-LAT and e-ASTROGAM, assuming a near-galactic SN (10 kpc away).

- Fermi-LAT : 5^0 coverage, effective area 9500 cm^2

- E-ASTROGAM : 1.25^0 coverage, effective area 9025 cm^2

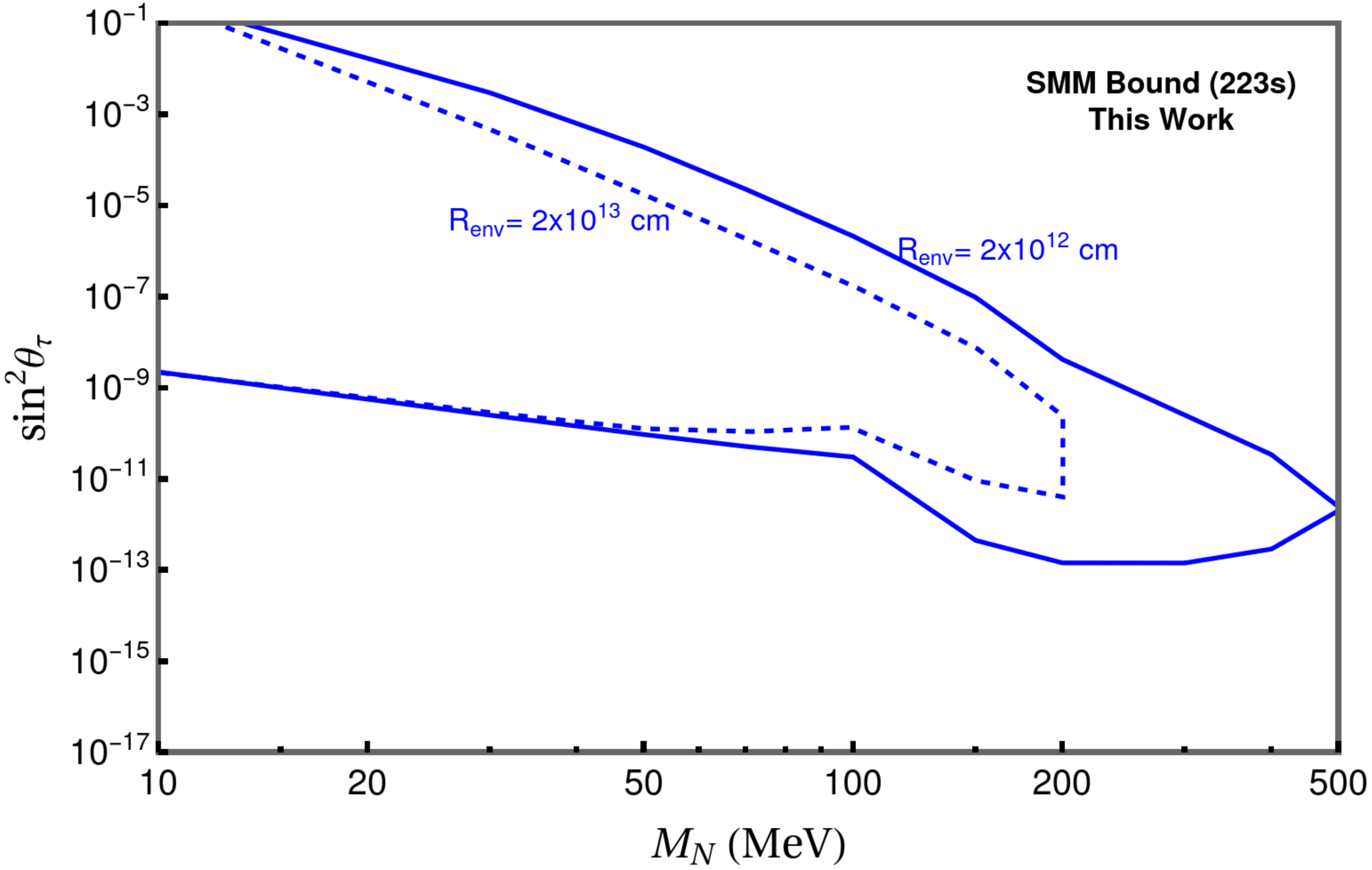


Result: SMM



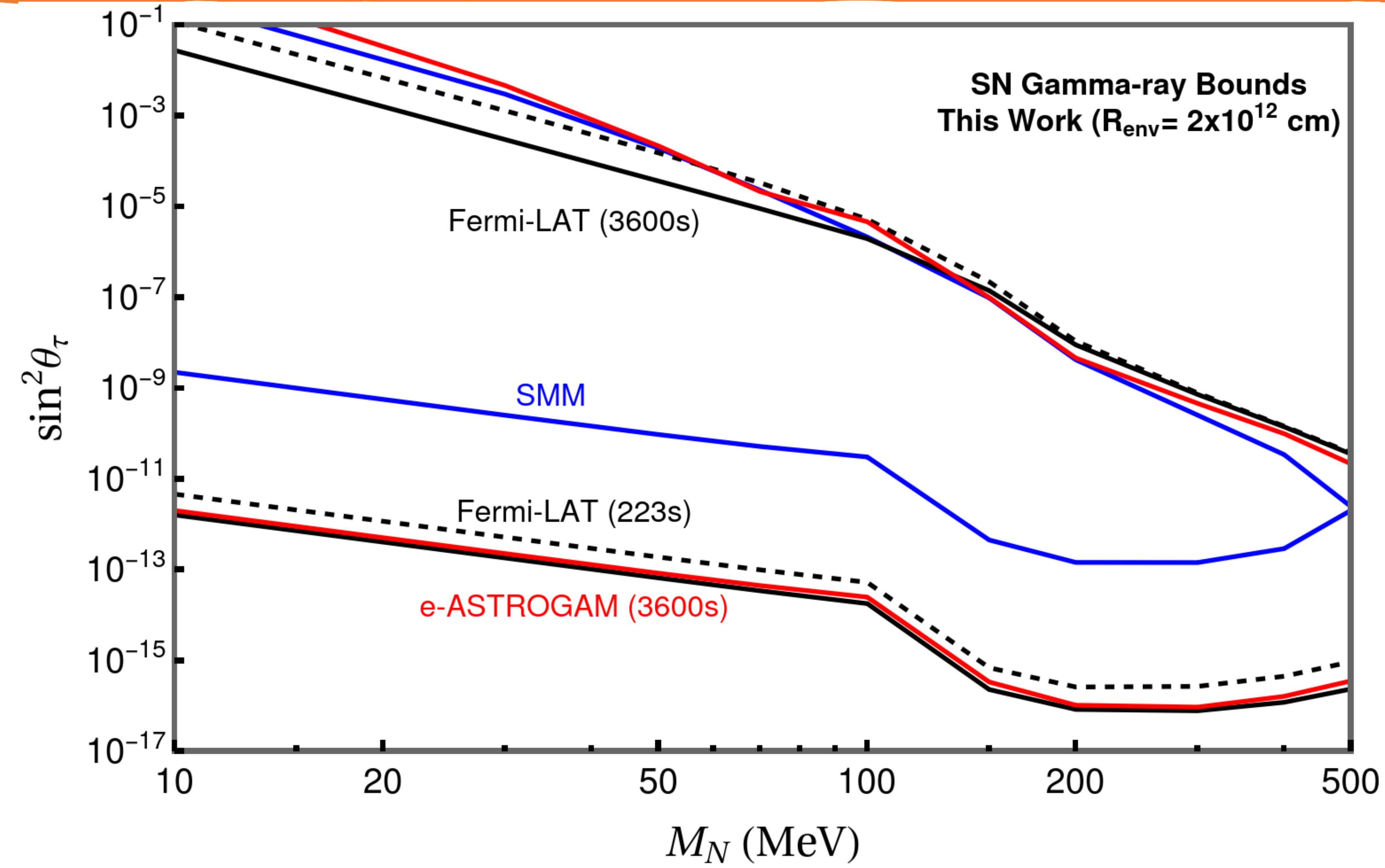
GC, Gustafson, Shoemaker (arXiv : 2410.abcde)

Result: SMM - Radius



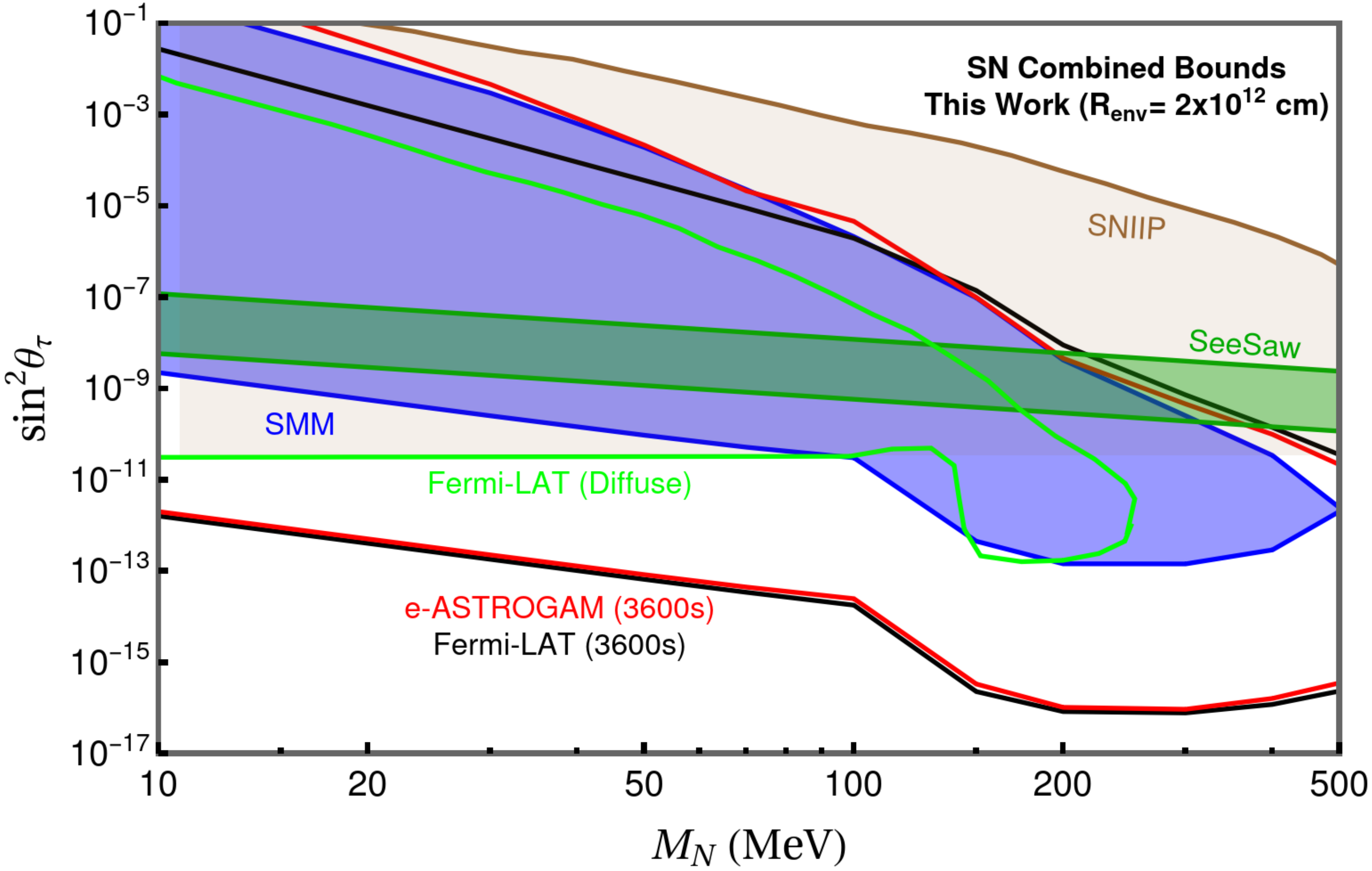
GC, Gustafson, Shoemaker (arXiv : 2410.abcde)

Result : Future Projections



GC, Gustafson, Shoemaker (arXiv : 2410.abcde)

Result : Combined



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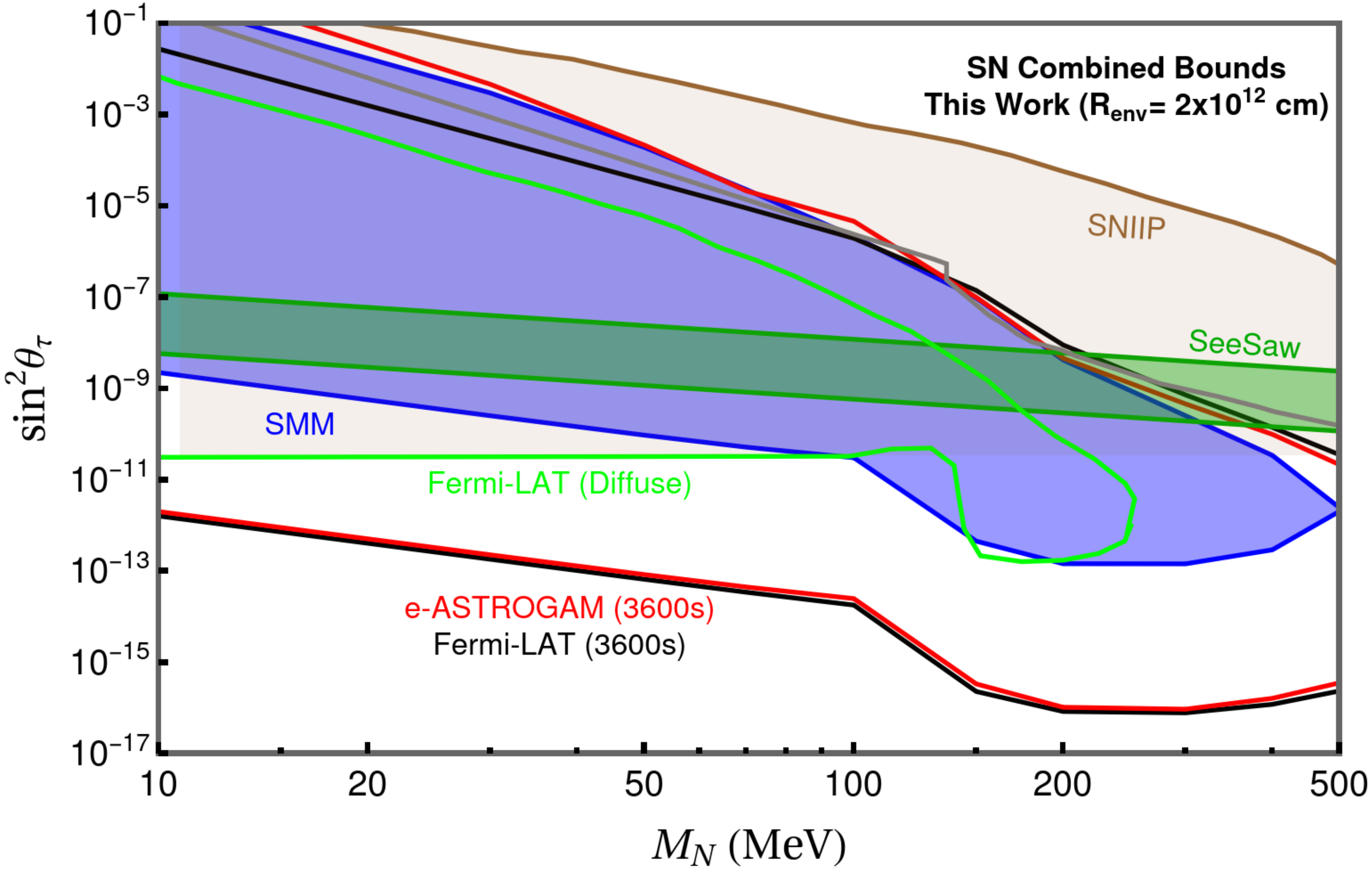
Summary

- The observations of SN198A has been used to constrain new physics, especially sterile neutrinos.
- Sterile neutrinos produced in core-collapse SNe are constrained from cooling or energy deposition through their decays inside the SN envelope.
- The decays outside the envelope into photons and neutrinos can also be used to constrain the parameter space.
- In this talk, we revisit the SMM constraint from SN1987A.
- We also examine the future sensitivity of Fermi-LAT and e-ASTROGAM.
- We find that the future observation of a near-galactic supernova SMM constraint can push bounds by 1-4 orders.
- Thus, SN physics can continue to be a powerful tool to test new physics beyond SN1987A!

Thank you !

Result : Combined with BBN



GC, Gustafson, Shoemaker (arXiv : 2410.abcde)

Pauli Blocking ?

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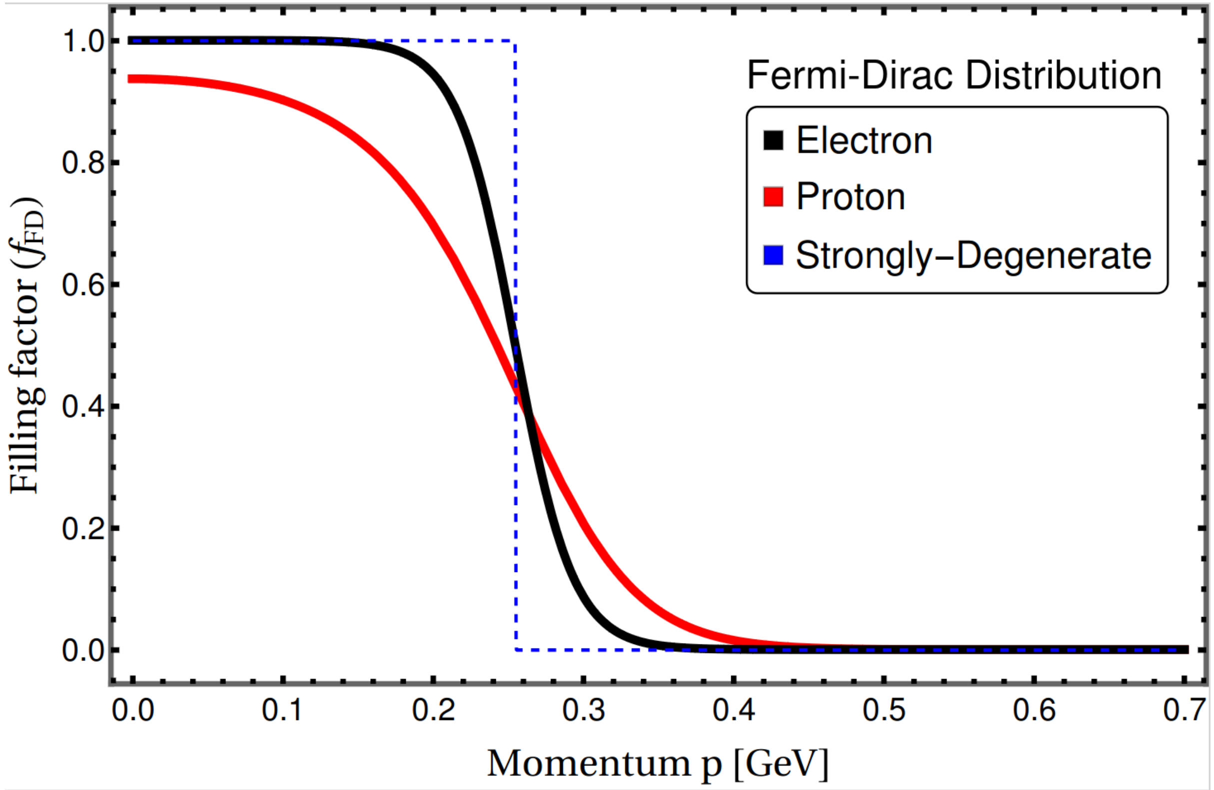
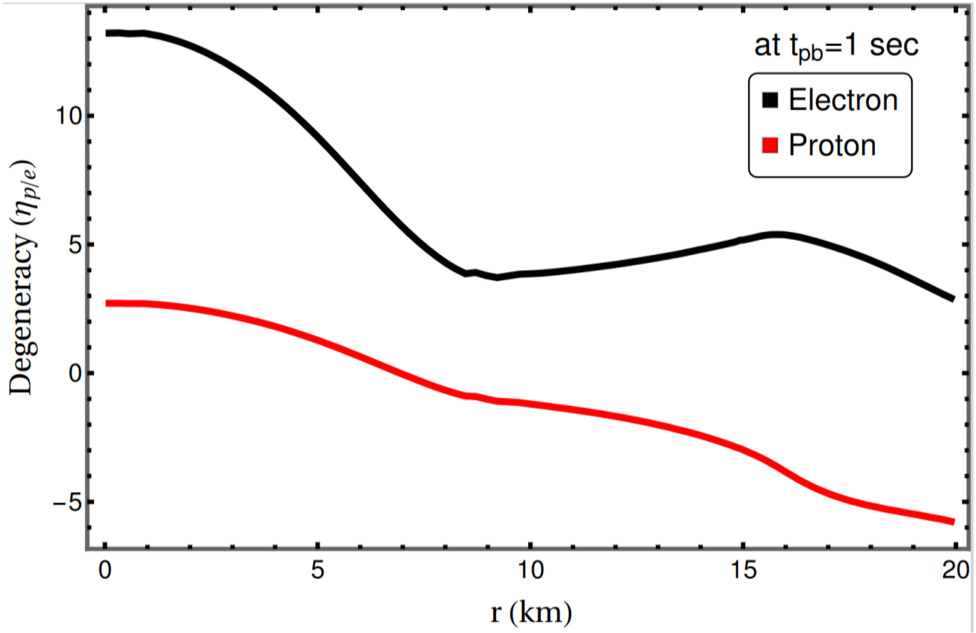


$$\eta_l = \frac{\mu_l - m_l}{T} .$$



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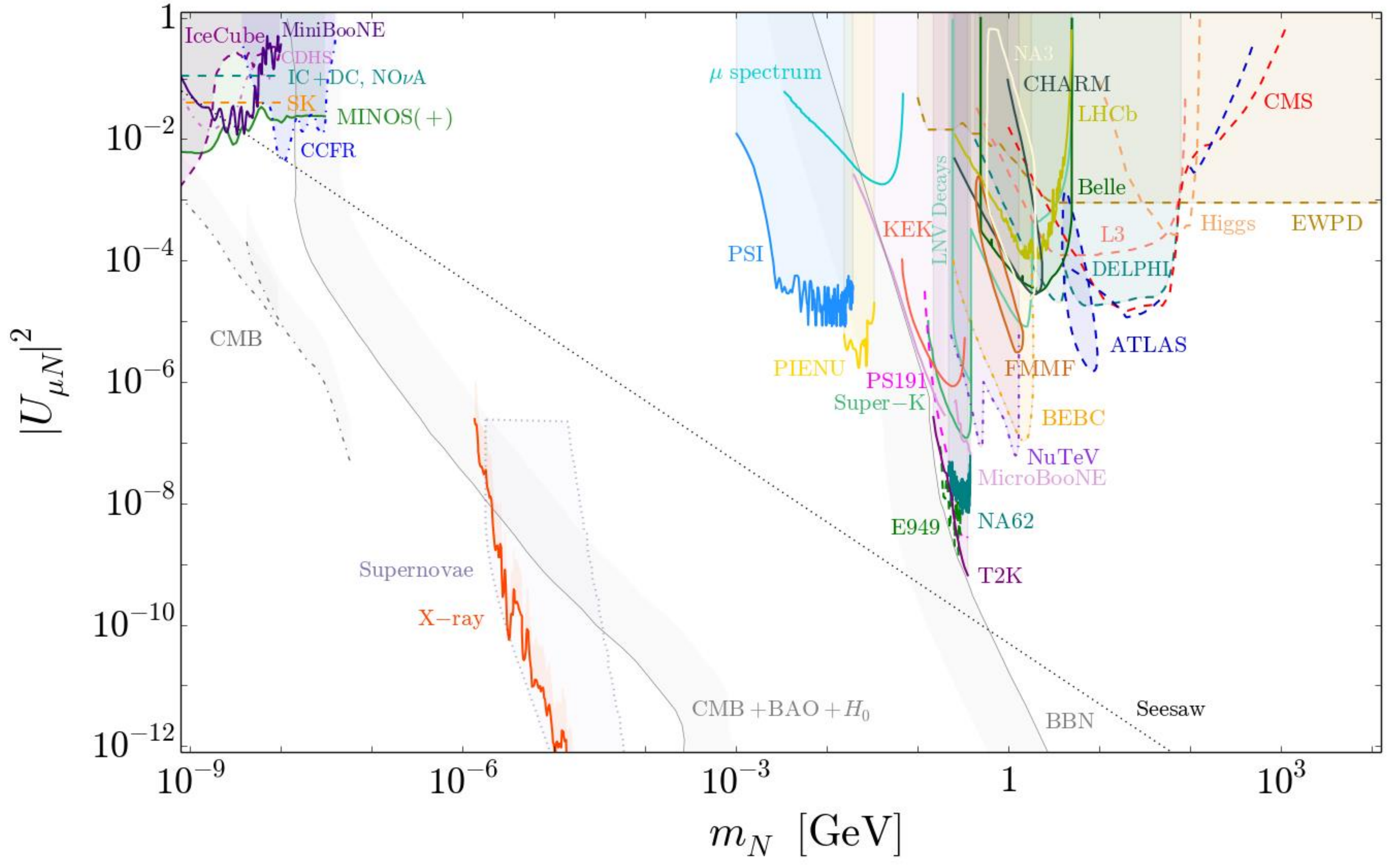

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