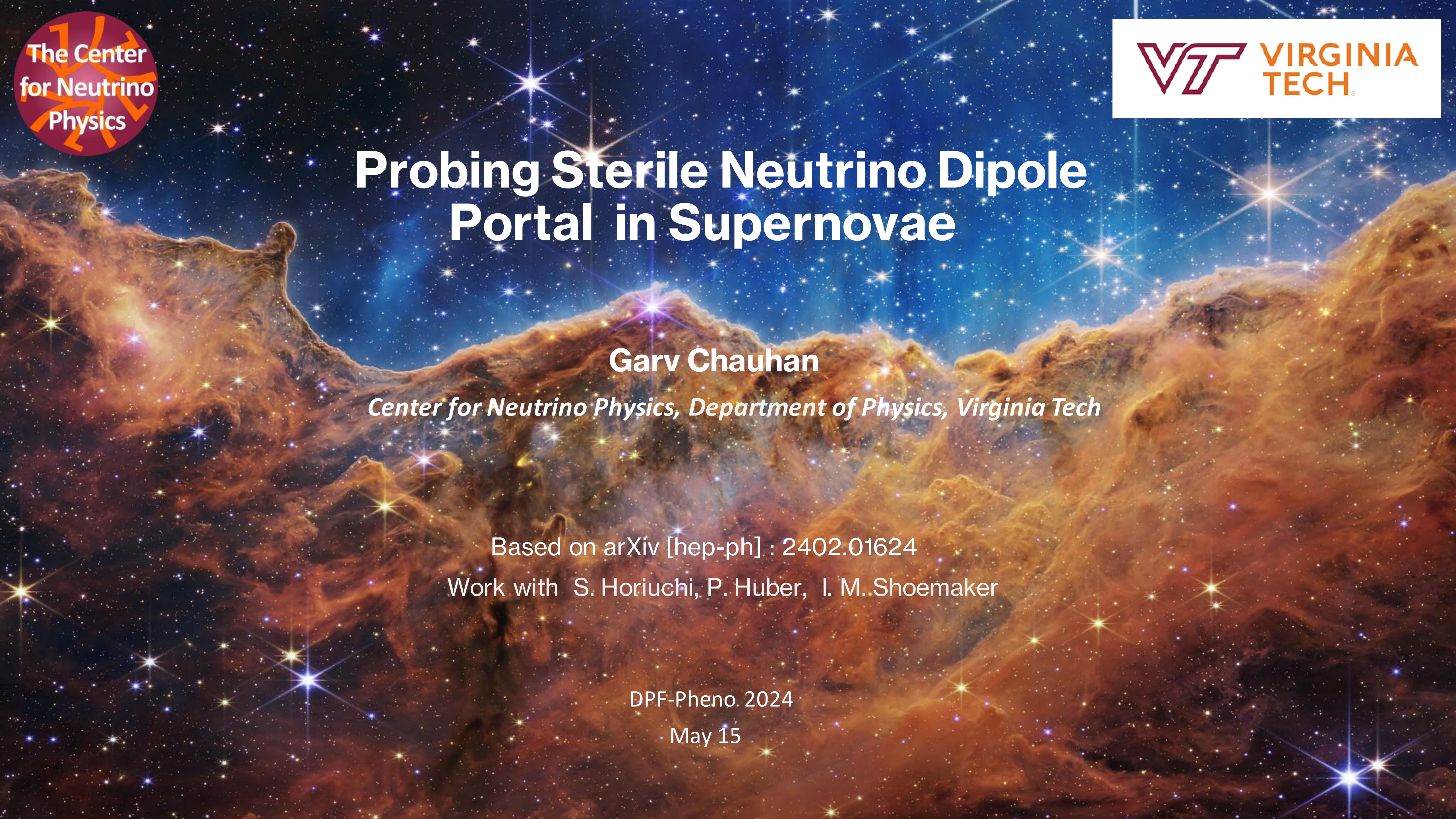

# Probing Sterile Neutrino Dipole Portal in Supernovae

**Garv Chauhan**

*Center for Neutrino Physics, Department of Physics, Virginia Tech*

Based on arXiv [hep-ph] : 2402.01624

Work with S. Horiuchi, P. Huber, I. M. Shoemaker

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May 15

# 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 - $\nu$ masses, dark matter and matter-antimatter asymmetry ($\eta_B$)

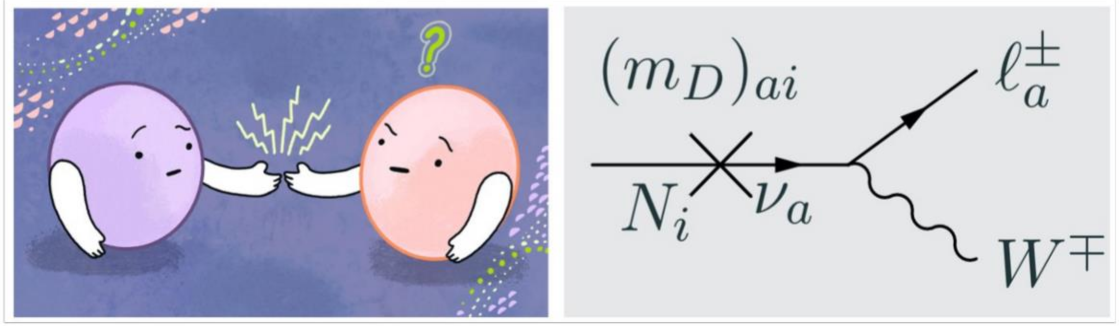
# Sterile Neutrinos

- 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,

$$m_\nu \simeq m_D \, M_N^{-1} \, m_D^T$$



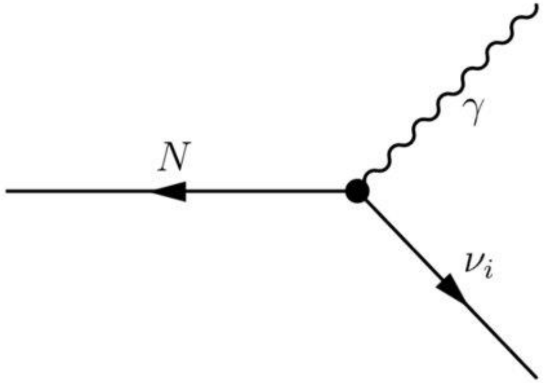
- This also leads to tiny magnetic dipole moment for neutrinos in SM.

# Dipole Portal

- Sterile neutrinos might couple to SM through higher dimensional operator. ( see [0904.3244], [1707.08573], [2007.15563] )
- In these case, large magnetic dipole moment can be generated.
- After EWSB, the lagrangian takes the following form

$$\mathcal{L} \supset i\bar{N}\partial\!\!\!/ N + \sum_{\alpha} d_{\alpha}\bar{N}\sigma_{\mu\nu}\nu^{\alpha}F^{\mu\nu} - \frac{M_N}{2}\bar{N}^c N + h.c.$$

- We will be assuming flavor independent dipole portal coupling.

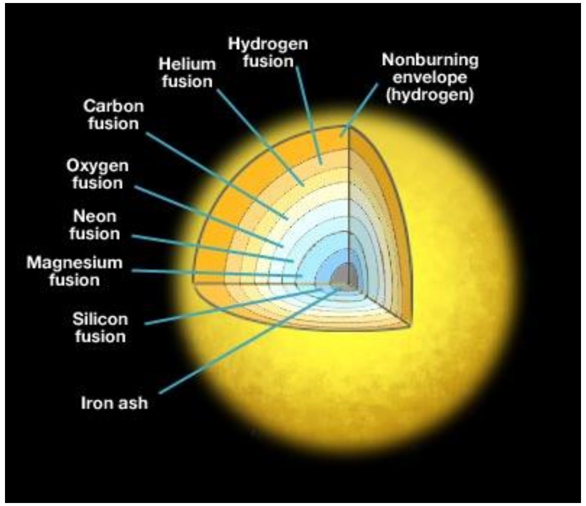


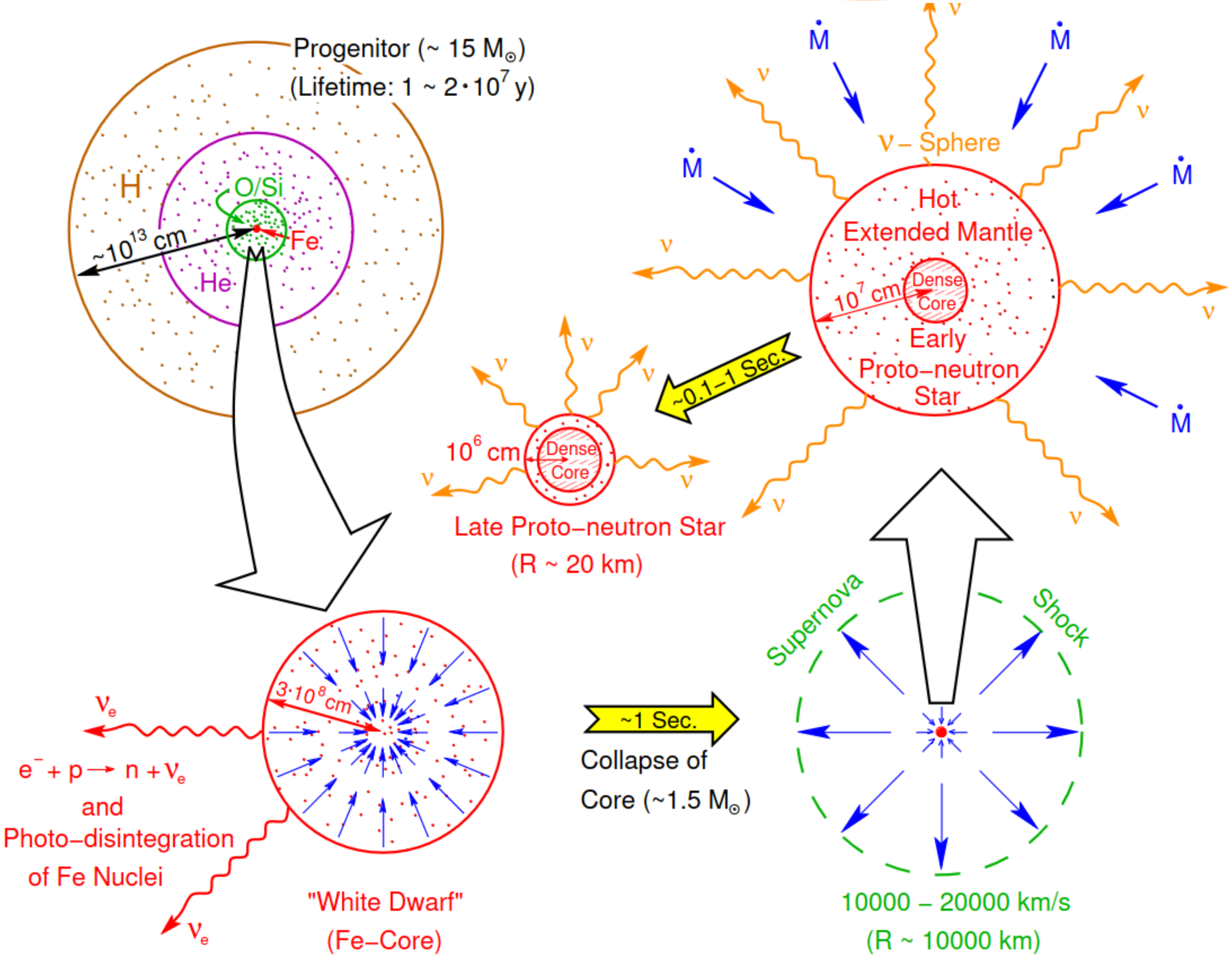
# Supernova : $\nu$ factory

- 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!*

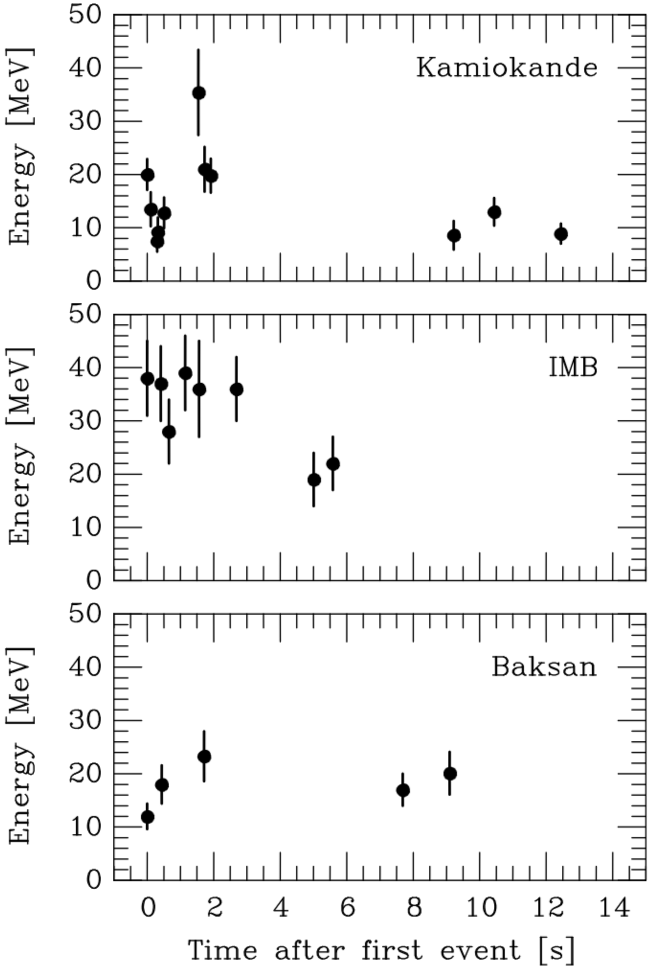




[Burrows, 1990b]

# 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 produced through dipole interaction.



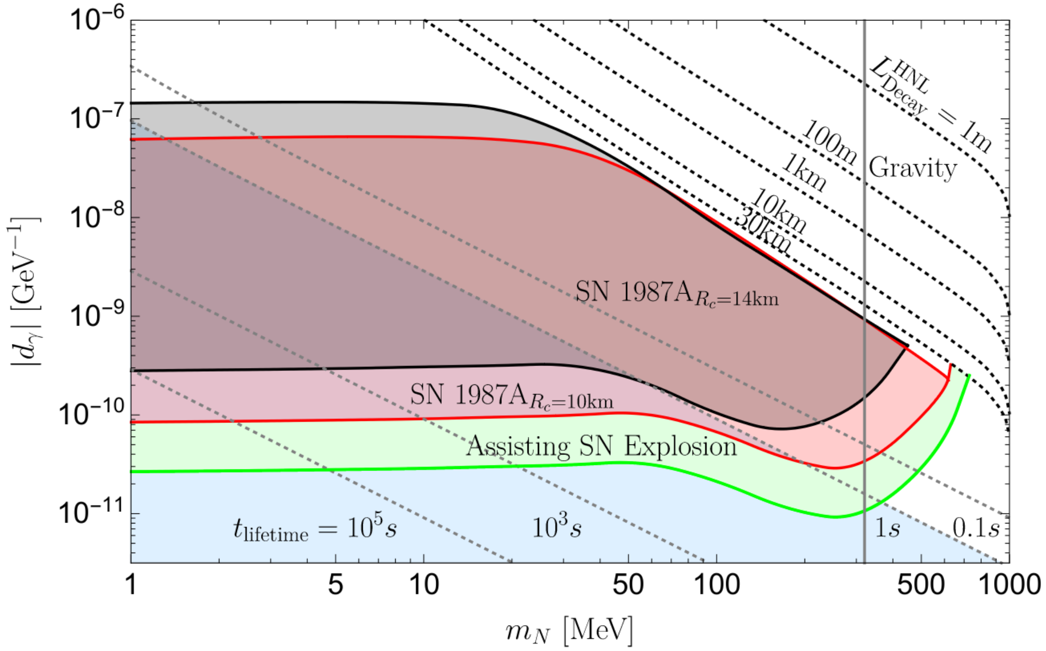
[Janka 1702.08713, Raffelt ]

# Energy Loss SN1987A

- Observations constrain energy-loss rate per unit mass → total luminosity → bounds on dipole moment

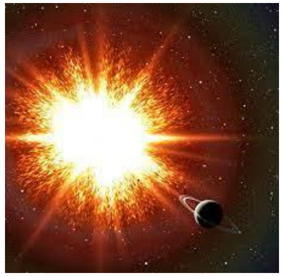
$$L_s = \varepsilon_s \times 1\, M_\odot \simeq 2 \times 10^{52}\ \mathrm{erg/s}$$

- Raffelt Criterion : Bound applied locally for sterile neutrino production at a characteristic radius.
- Integrated Luminosity Criterion : Bound on the total energy carried away by all sterile neutrinos produced at all radii

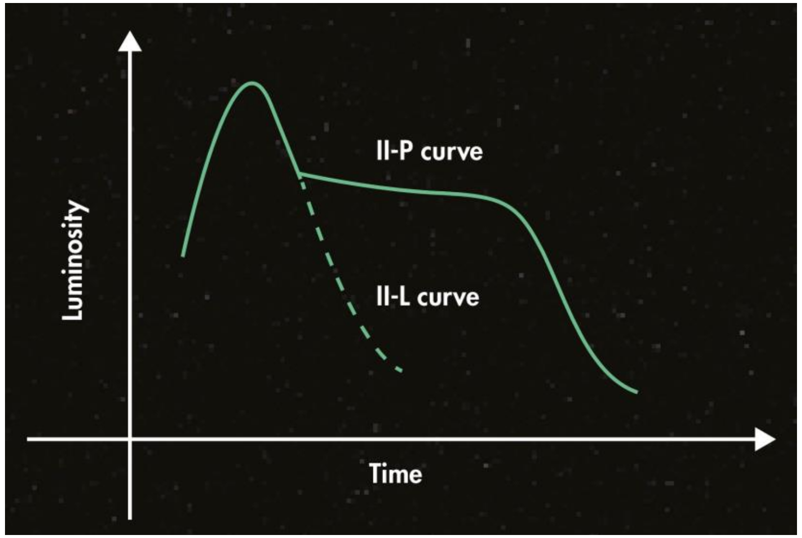


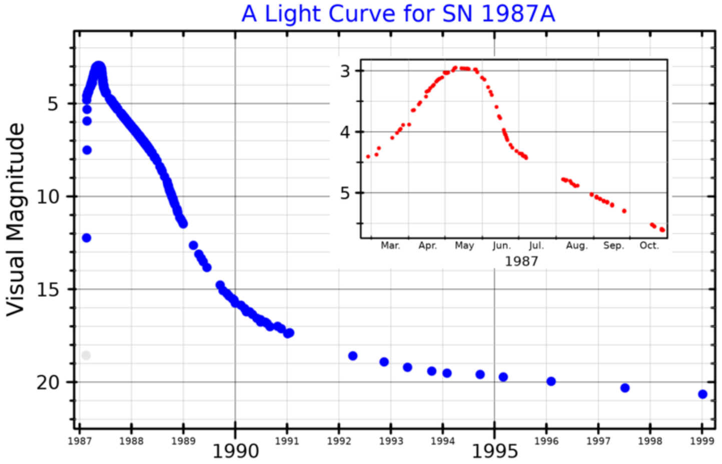
Magill, Plestid, Pospelov, Tsai ( arXiv : 1803.03262 )

# Low-energy SN : IIP or not IIP



- Separate class of core-collapse SN with low-explosion energies : underluminous SN 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.
- Therefore, the explosion energy can be inferred given the spectrum and the light curves.





# Low-energy SN

- (Pejcha et. al. ,Muller et. al.) used fitting formulae and statistical inference along with quantifying the uncertainties, to infer the most likely explosion energy.

- The inferred explosion energy ranges from

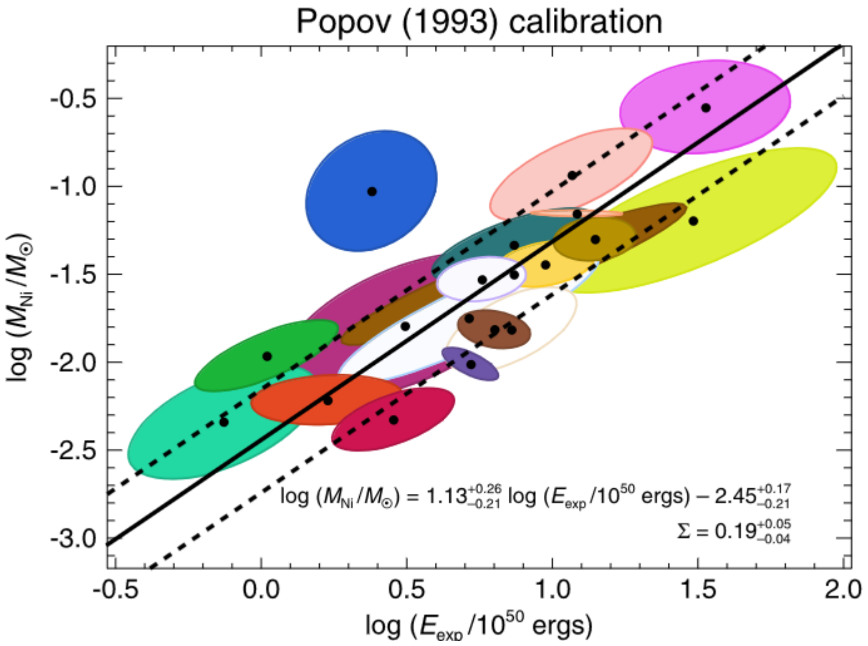
$$E_{obs} \sim (7.4 \times 10^{49} - 4 \times 10^{51})\ \text{erg}.$$

- These reconstructed energies are in good agreement with expectations from the simulated low-energy SN.

- 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)



| Name | $\epsilon = \log_{10}(E_{\rm obs}/10^{51})$ | $\sigma_\epsilon$ |
|---|---|---|
| SN 2001dc | -1.13 | 0.33 |
| SN 2013am | -0.98 | 0.25 |
| SN 1980K | -0.77 | 0.27 |
| SN 1995ad | -0.62 | 0.23 |
| SN 2005cs | -0.55 | 0.21 |
| SN 2009js | -0.51 | 0.43 |

Muller,Prieto,Pejcha,Clocchiatti Astrophys.J. 841 (2017),
Murphy,Mabanta,Dolence MNRAS 489(2019)

# 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)

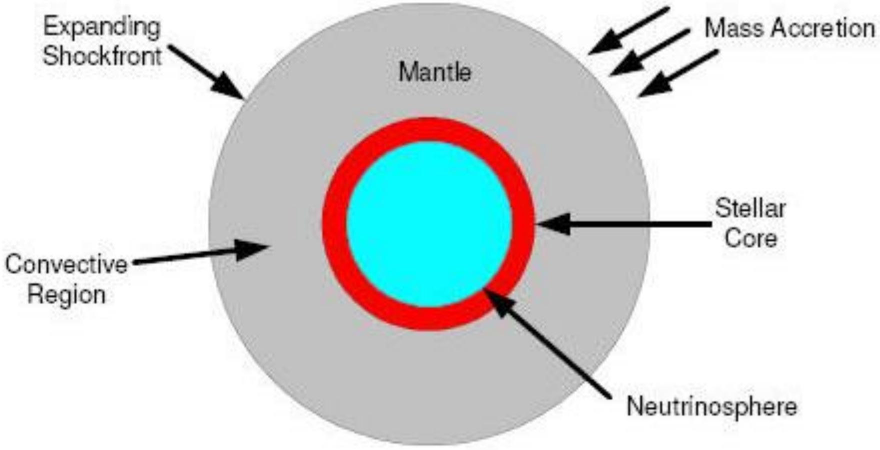
# Energy Loss/Deposition

- The sterile neutrino produced in SN core, decays outside the core but inside the mantle region, depositing energy into the SN envelope.

$$E_{\mathrm{dep/cool}} = \eta_{\mathrm{lapse}}^2 \int dt \int_0^{R_{\mathrm{core}}} dr \int_{M_N}^{\infty} dE_N \frac{dL_N(r, E_N, t)}{dr\, dE_N} \Theta\left(E_N - \frac{M_N}{\eta_{\mathrm{lapse}}}\right) \times P_{\mathrm{cool/dep}}(r)$$

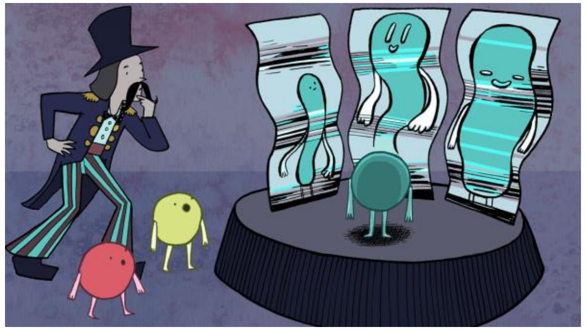
$$P_{\mathrm{cool}}^{\mathrm{SN1987A}}(r) = \exp\left[-\int_r^{R_{\mathrm{far}}} \Gamma_{abs}(r')\, \mathrm{d}r'\right]$$

$$P_{\mathrm{dep}}^{\mathrm{SNIIP}}(r) = \exp\left[-\int_r^{R_{\mathrm{core}}} \Gamma_{abs}(r')\, \mathrm{d}r'\right]\left(1 - \exp\left[-\int_{R_{\mathrm{core}}}^{R_{\mathrm{env}}} \Gamma_{abs}(r')\, \mathrm{d}r'\right]\right)$$



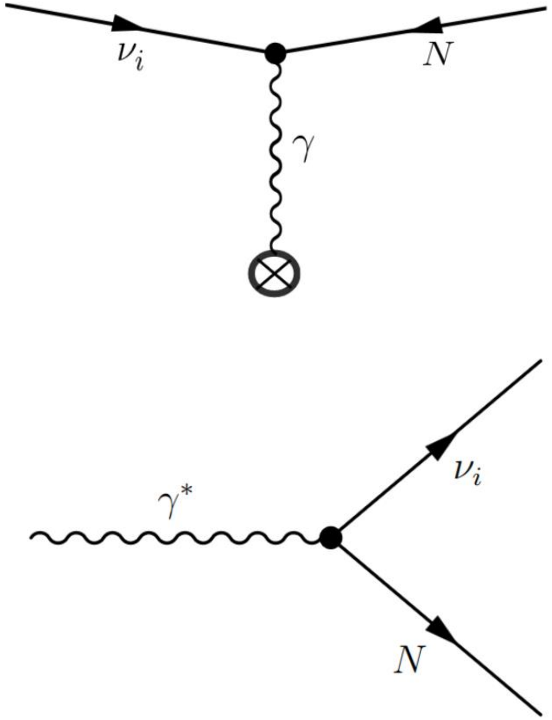
GC, Huber, Horiuchi, Shoemaker (arXiv:2402.01624)

# Dipole Portal : production

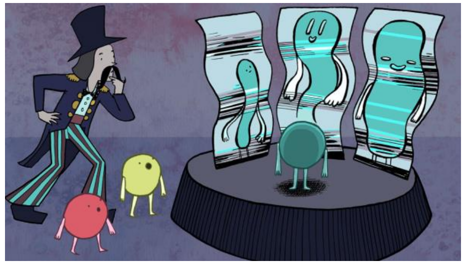


- The following processes are involved in the production :

$$
\begin{aligned}
\nu + e^{\pm} &\to N + e^{\pm}, \\
\nu + \mu^{\pm} &\to N + \mu^{\pm}, \\
\nu + p &\to N + p, \\
e^{+} + e^{-} &\to \bar{\nu} + N, \\
\mu^{+} + \mu^{-} &\to \bar{\nu} + N, \\
\nu + \gamma &\to N \\
\gamma^{*} &\to N + \bar{\nu}.
\end{aligned}
$$



# Dipole Portal : Proton Primakoff



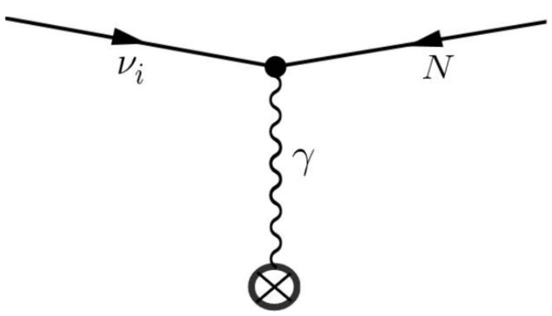
- Due to forward scattering, there is a singularity in the t-channel processes.

$$|\mathcal{M}|^2 = \frac{4\, d^2\, e^2}{q^4} \left[8\,(p_1.p_2)(p_2.p_3)(p_1.p_2 - p_2.p_3) \;-\; 2\, M_N^2 (p_1.p_2 - p_2.p_3)(p_1.p_2 + p_2.p_3 + m_f^2) \;+\; M_N^4 (p_1.p_2 - p_2.p_3 - m_f^2)\right]$$

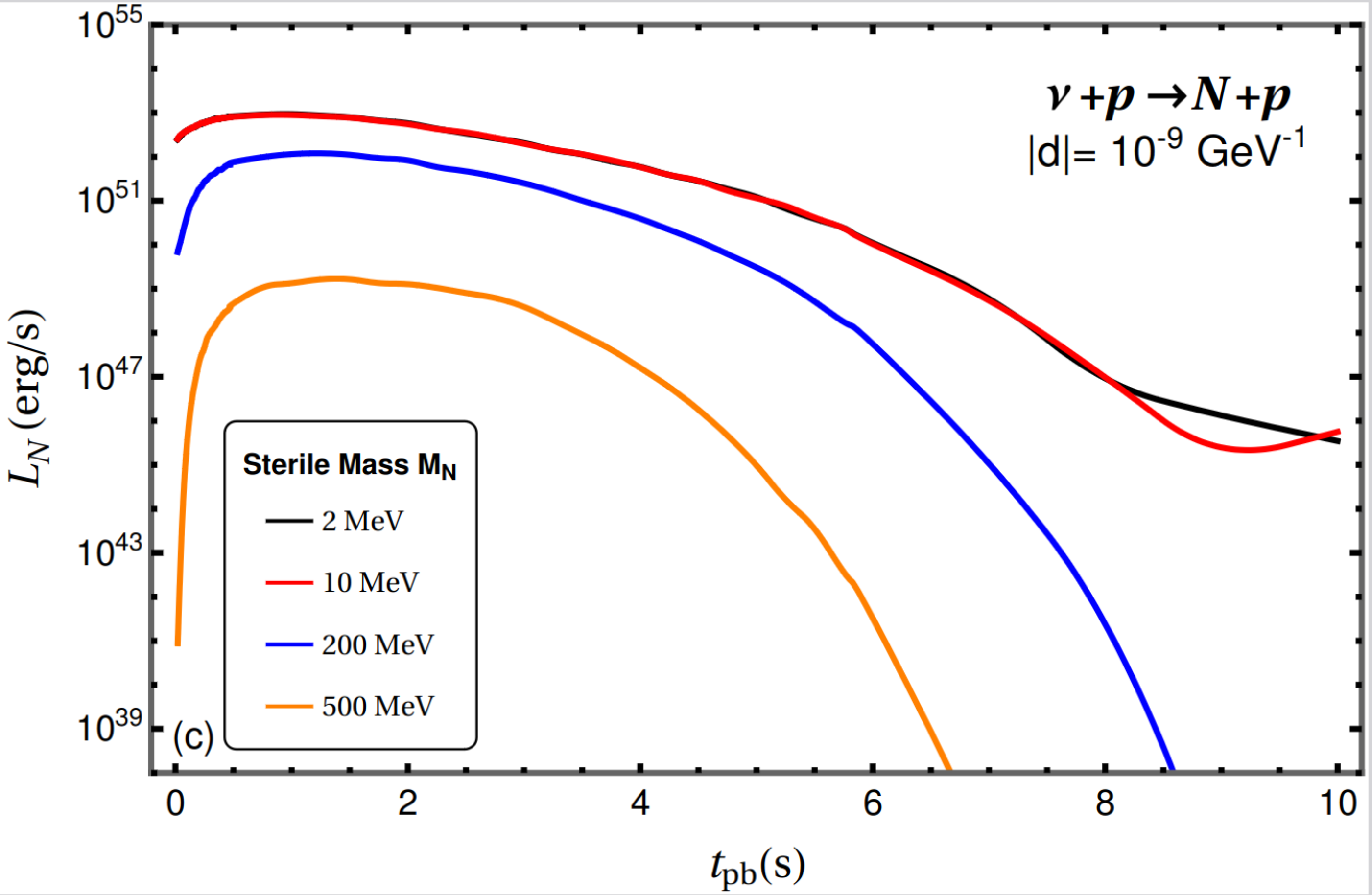
GC, Huber, Horiuchi, Shoemaker (arXiv:2402.01624)

$$\omega_{\mathrm{P}}^2 = \frac{4\alpha}{3\pi}\left(\mu_e^2 + \frac{\pi^2 T^2}{3}\right) + \frac{4\pi\alpha\, n_p}{m_p}$$

$$k_{\mathrm{S}}^2 = \frac{4\pi\alpha}{T} n_p + \frac{4\alpha}{\pi}\left(\mu_e^2 + \frac{\pi^2 T^2}{3}\right)$$



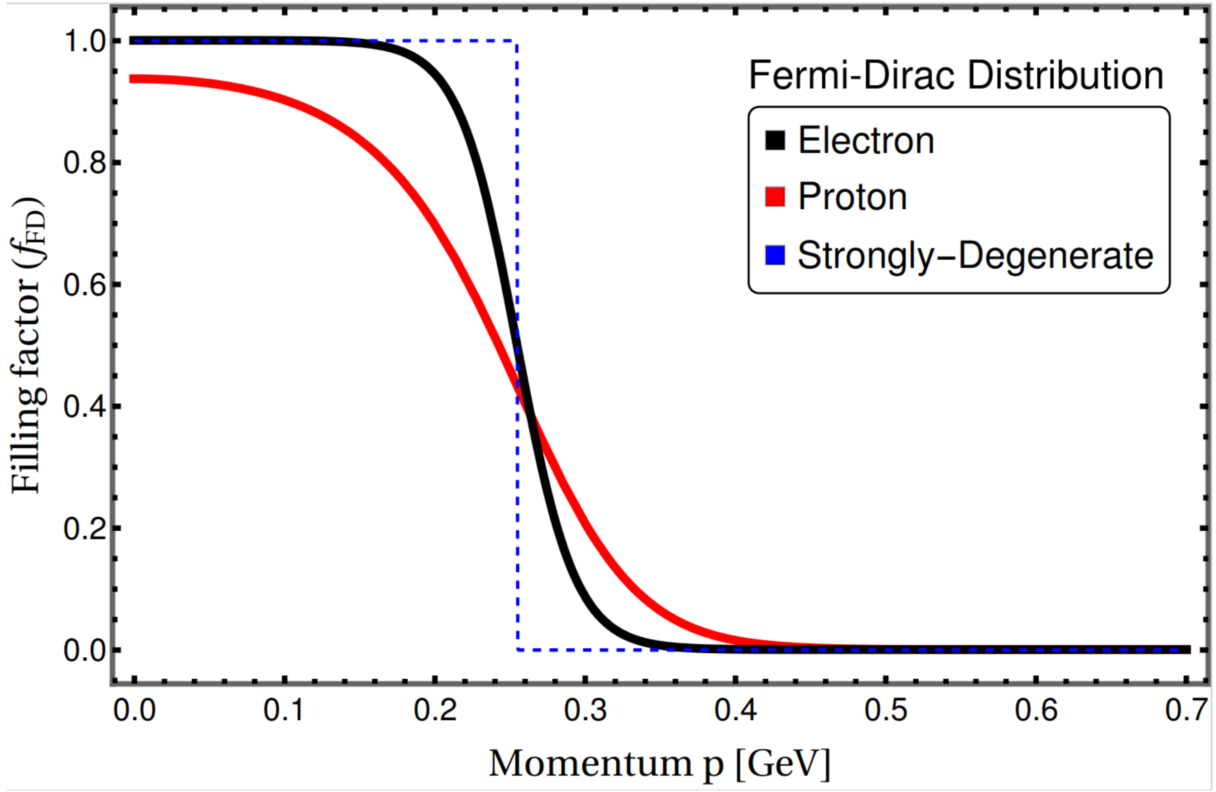
# Dipole Portal : Proton Primakoff



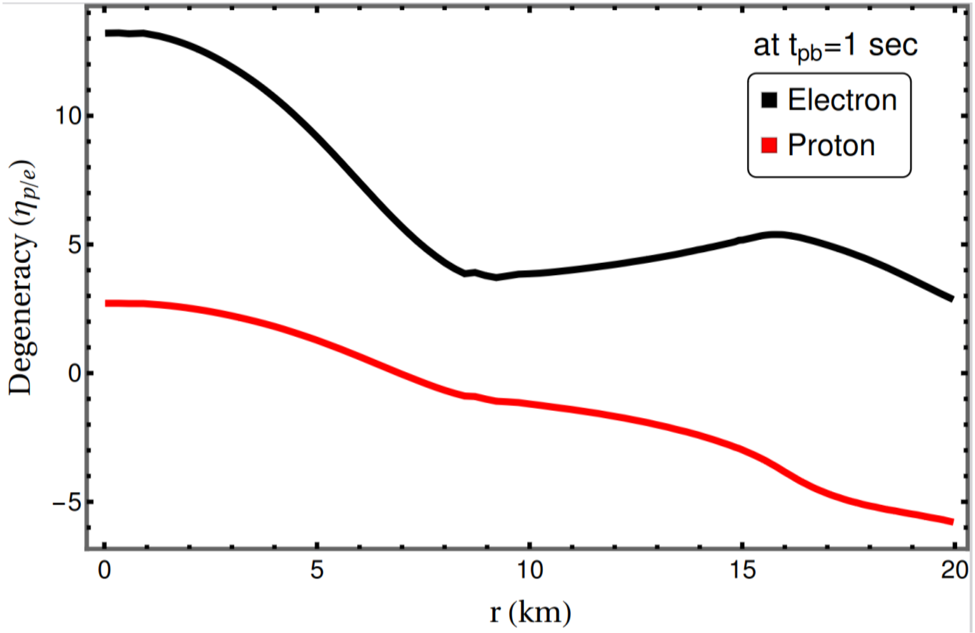
GC, Huber, Horiuchi, Shoemaker (arXiv:2402.01624)

# Dipole Portal : Proton Primakoff

- Contrary to previous literature, we find proton mode to be the most dominant. An order of magnitude stronger than scattering off electron.

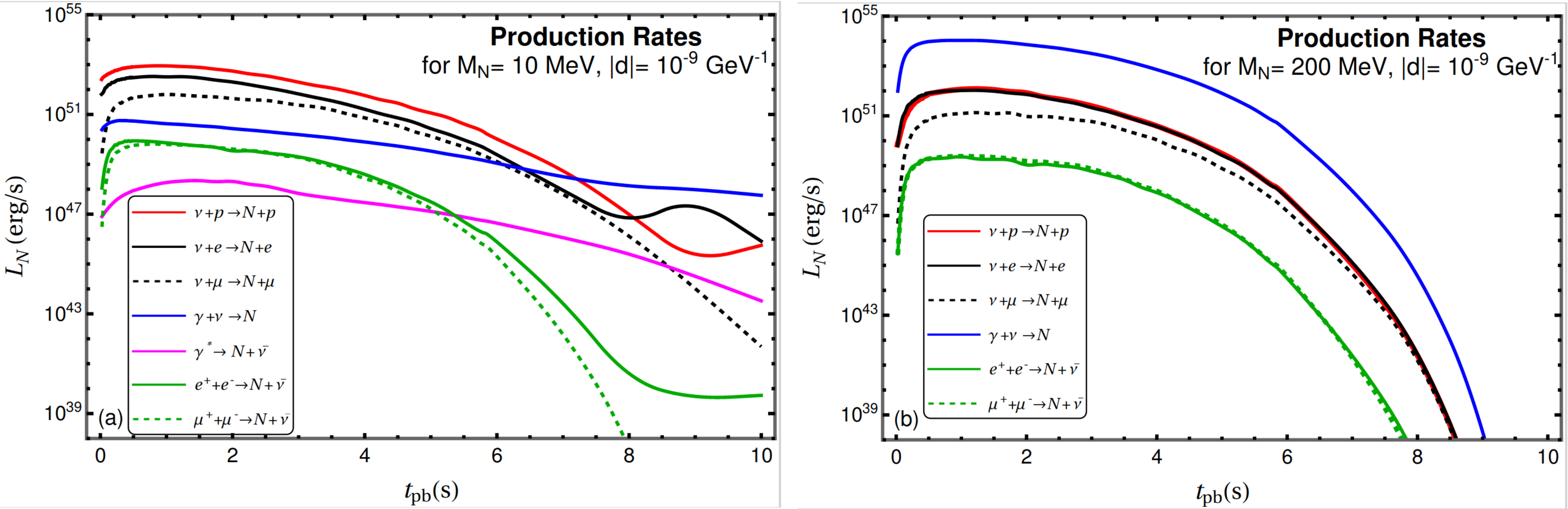


$$\eta_l = \frac{\mu_l - m_l}{T} .$$



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

# Dipole Portal : Production rates



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

# Dipole Portal : decay

- The following processes are involved in the decay :

$$
\begin{aligned}
N + e^{\pm} &\to \nu + e^{\pm}, \\
N + \mu^{\pm} &\to \nu + \mu^{\pm}, \\
N + p &\to \nu + p, \\
N &\to \nu + \gamma.
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{abs} = & \frac{1}{2p_N} \int d^3\tilde{p_2} d^3\tilde{p_3} d^3\tilde{p_4}\, \tilde{\Lambda}(f_2, f_3, f_4) \times \\
& |M|^2_{12\to 34}\, \delta^4(p_N + p_2 - p_3 - p_4)(2\pi)^4
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{N\to\nu+\gamma} = \frac{d^2\, M_N^4}{16\pi p_N^2} \int_{P^-}^{P^+} & dp_\gamma\, (1 + f_\gamma(p_\gamma)) \\
& \times \left[1 - f_\nu\left(\sqrt{p_N^2 + M_N^2} - p_\gamma\right)\right]
\end{aligned}
$$

# Dipole Portal : Integrated luminosity

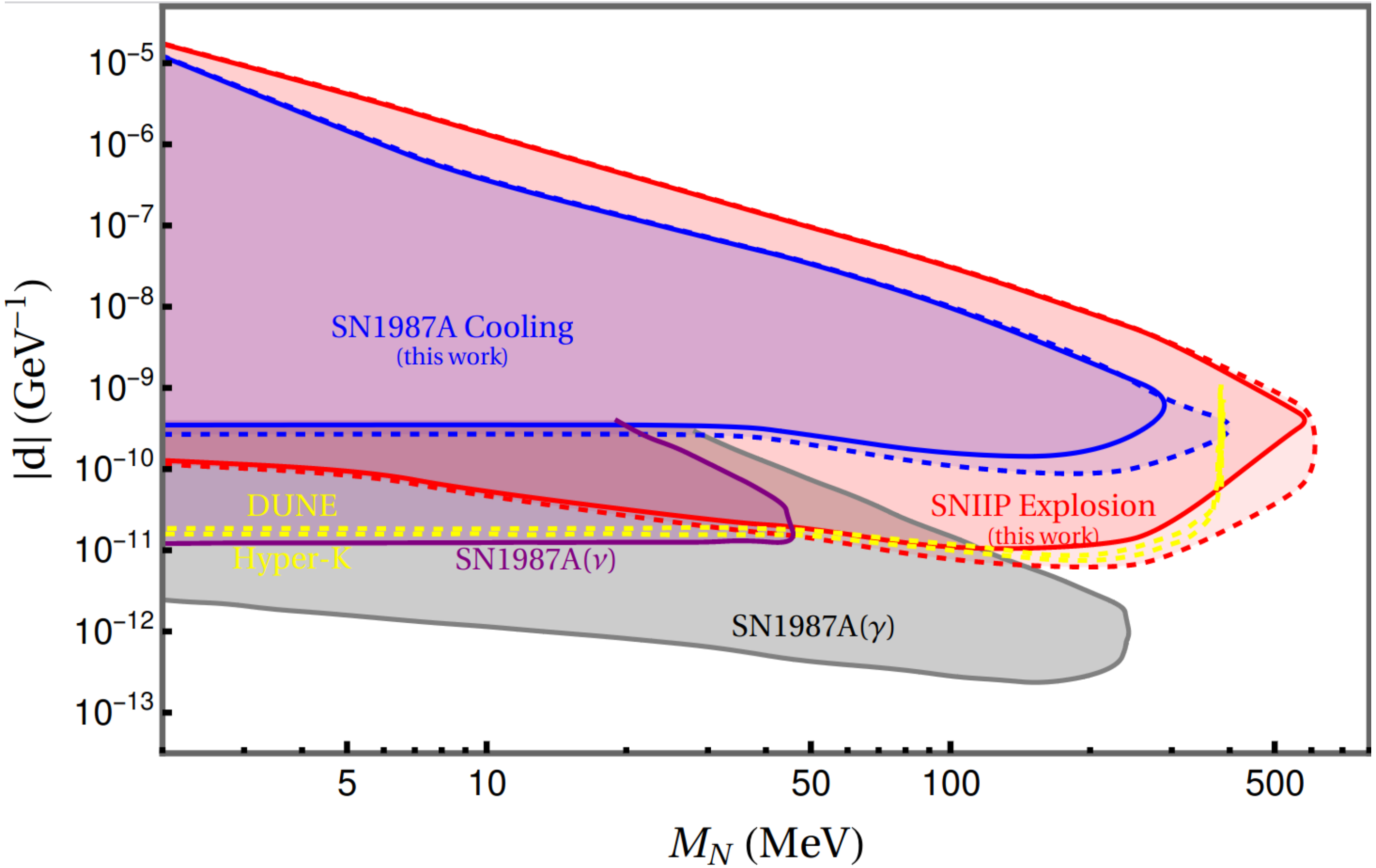


Figure from GC, Huber, Horiuchi, Shoemaker (arXiv : 2402.01624)

Previous constraints from Brdar, Gouvêa, Li, Machado (arXiv : 2302.10965)

# Summary

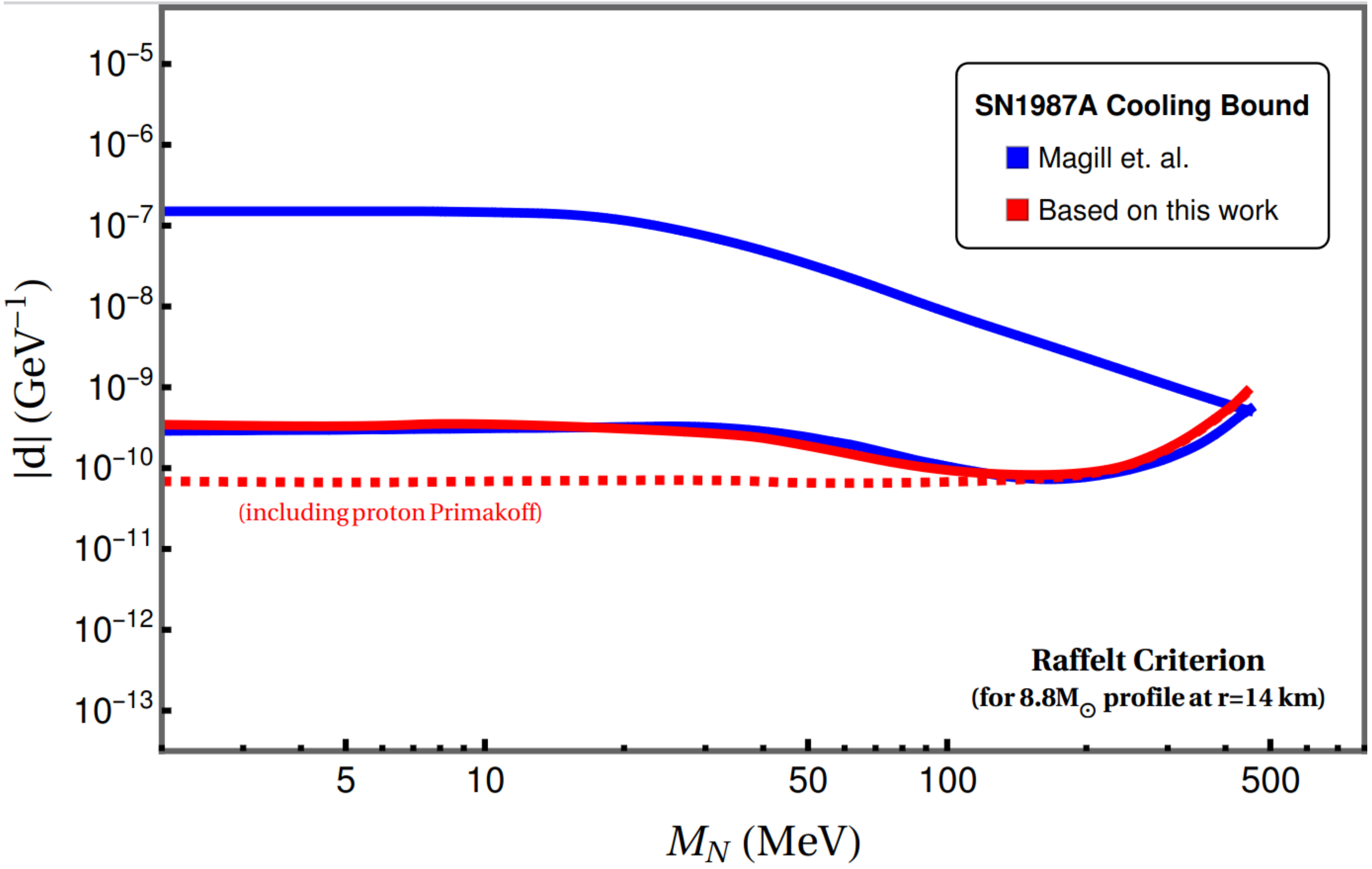
- Usually energy loss argument from the observations of SN198A is used to constrain new physics.
- Sterile neutrinos produced in core-collapse SNe can also deposit energy through their decays inside the SN envelope.
- This energy deposition constrained from the observed SN IIP population

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

- For dipole portal, we find that underluminous SNIIP can help constrain the transition magnetic dipole moment by an order of magnitude than cooling bound.
- We find degeneracy effects for proton as stated previously in literature are absent and can help place even stronger bounds!
- Thus, SN physics can continue to be a powerful tool to test new physics beyond SN1987A!

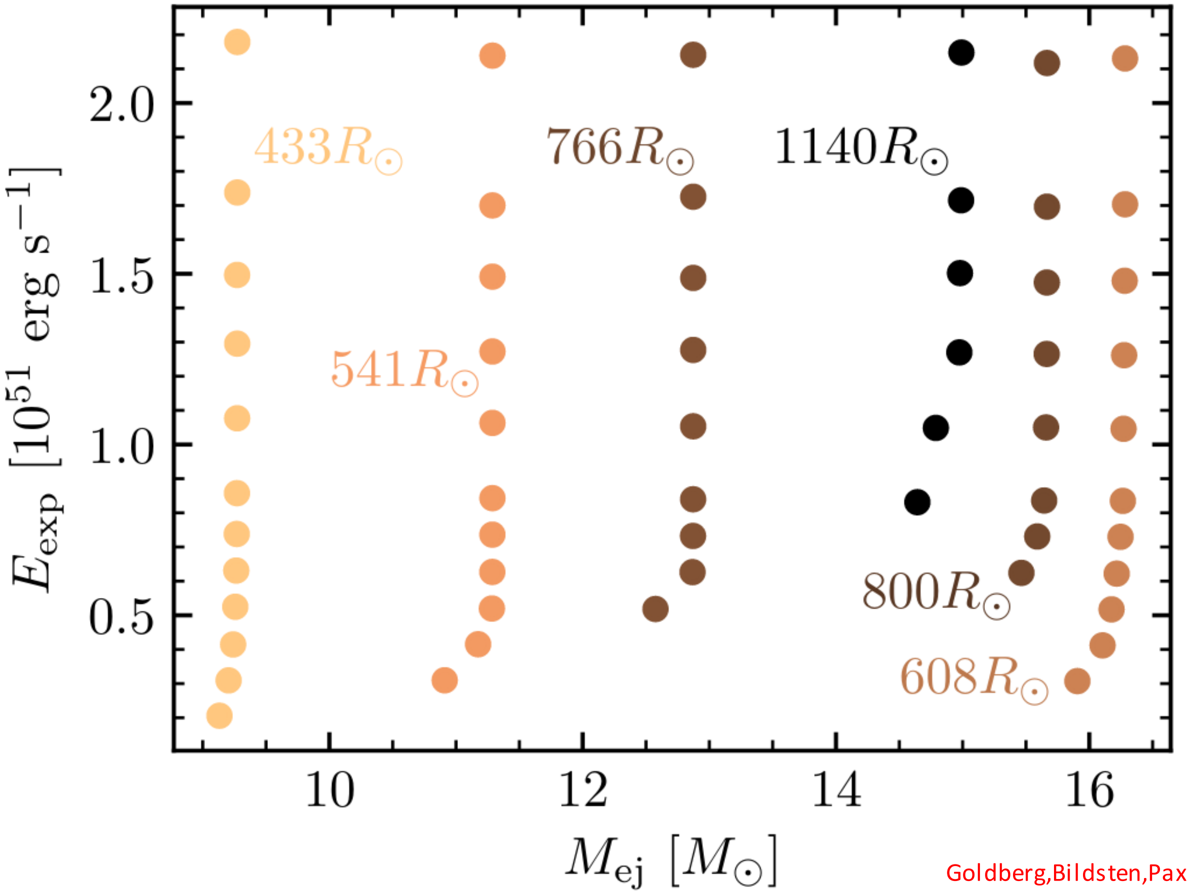
Thank you !

# Dipole Portal : Raffelt criterion



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

# Ejecta Mass and Explosion Energies



Goldberg,Bildsten,Paxton Astrophys.J 841(2017)