LOW ENERGY SUPERNOVA BOUNDS ON STERILE NEUTRINOS

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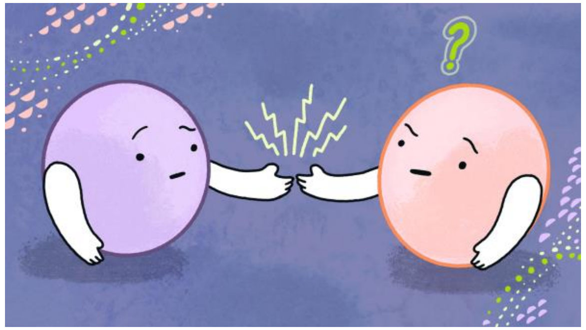
Sterile Neutrino



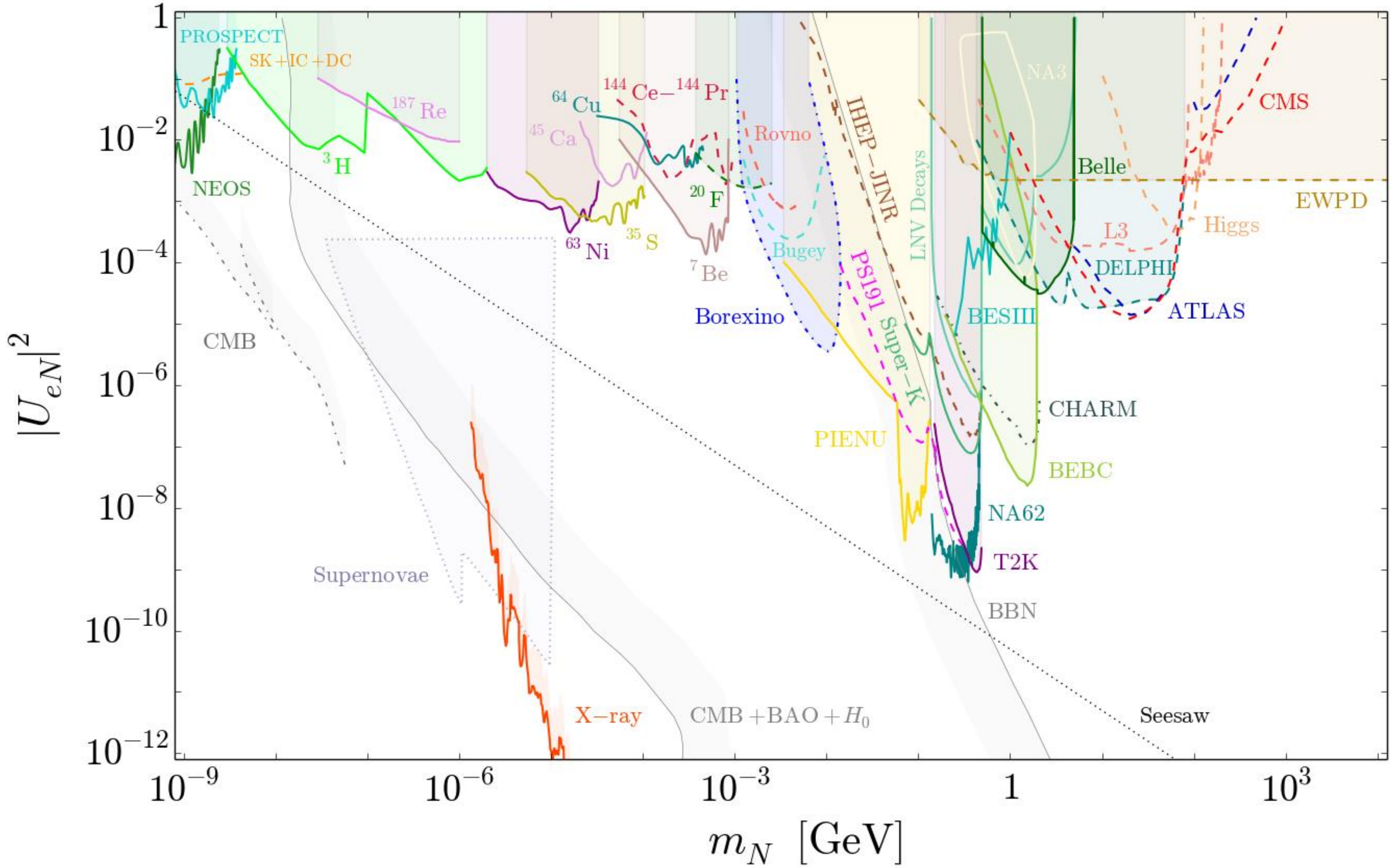
- Motivated class of BSM candidates : neutrino mass mechanisms, dark matter and baryon asymmetry generation.

- Sterile neutrinos have been suggested as solutions of various anomalies in neutrino experiments.

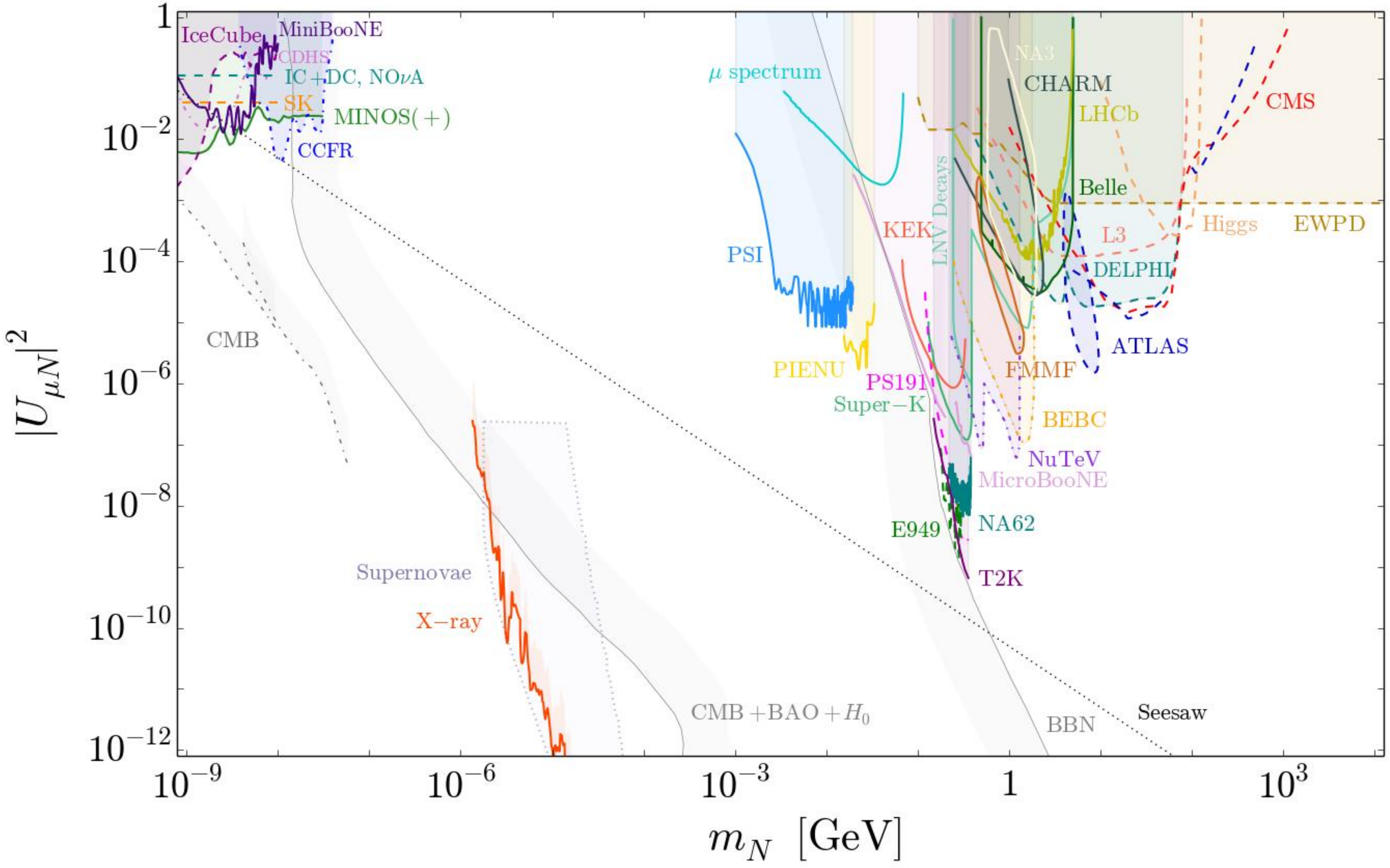
- An interesting question : which values of masses and mixing angles can be excluded by direct experiments, cosmology and astrophysics.

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

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



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



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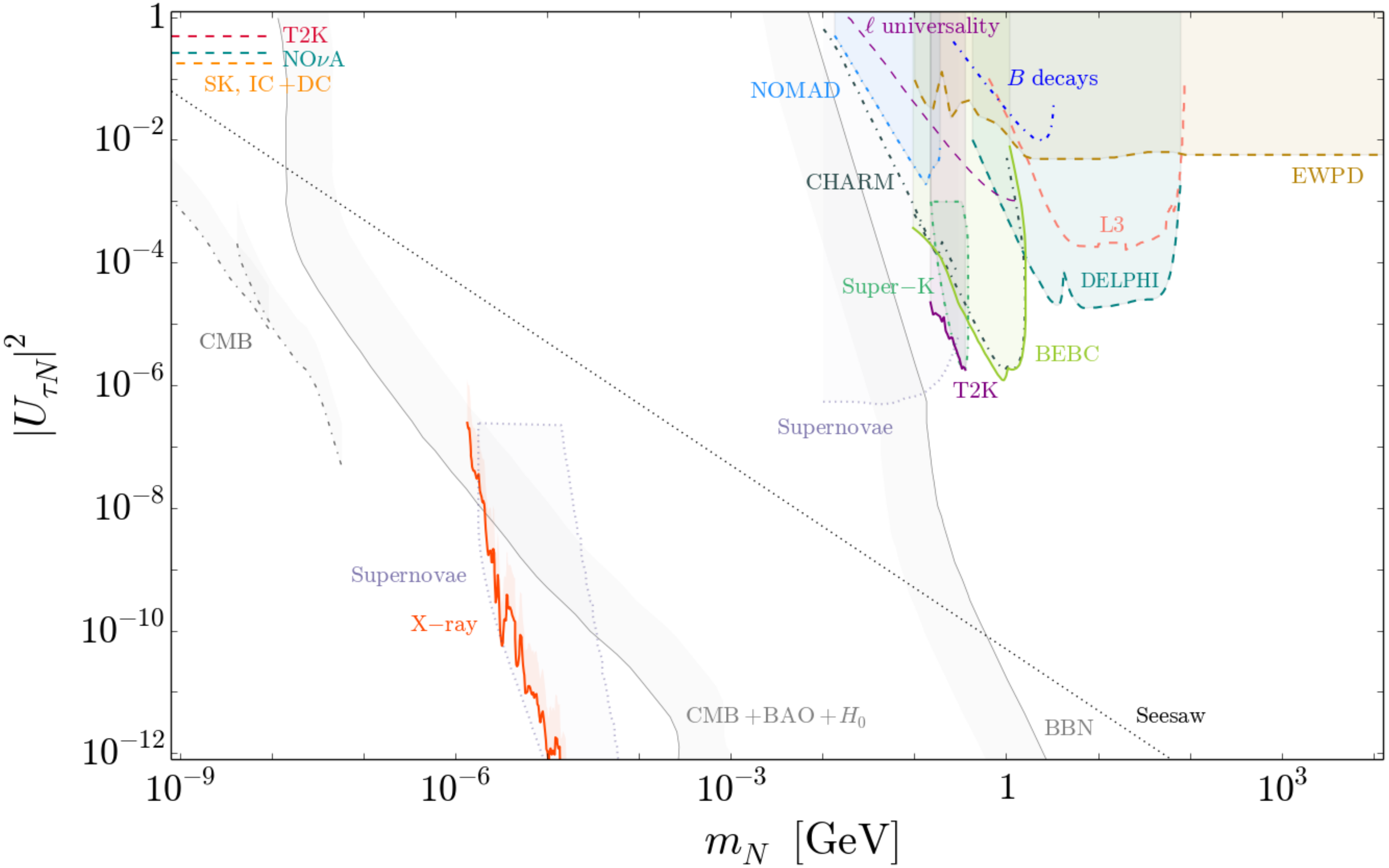

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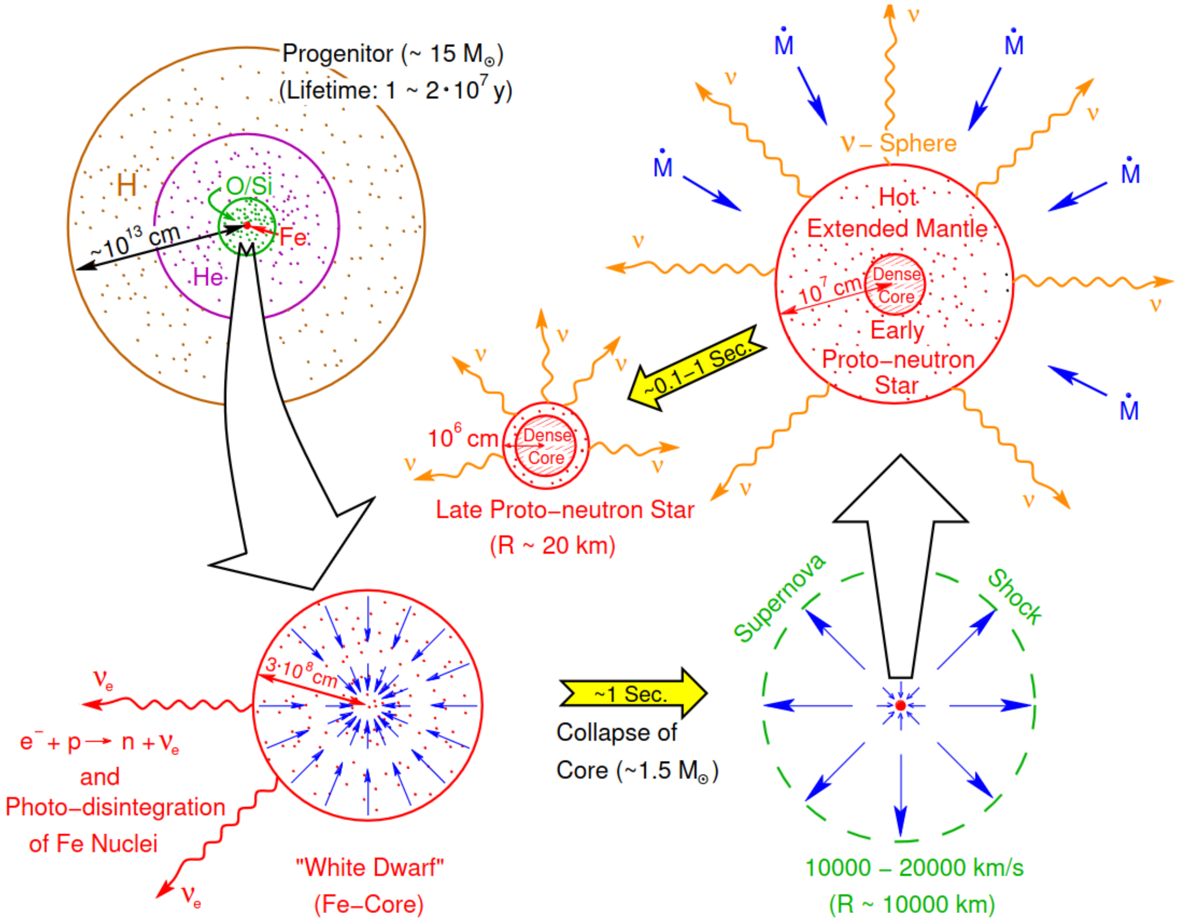
Supernova : ν factory

- 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.
- Can be used to probe fundamental properties of neutrinos and even .....

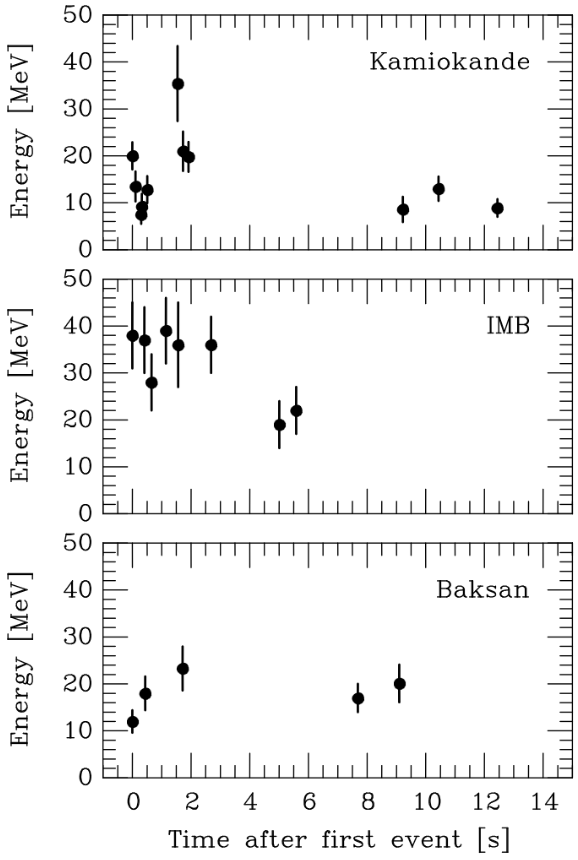
emission of exotic BSM particles!



[Burrows, 1990b]

Energy Loss SN1987A

- Light BSM particles produced in the SN core would constitute a novel channel of energy loss, shortening the duration of the neutrino burst.
- SN 1987A neutrino signal ~ 10 s, as expected from standard SN cooling scenario, excludes an additional energy drain associated with exotic particles
- Constrain sterile states mixing with the active ones.
- typical temperature T ~ 30 MeV in the SN core, heavy sterile neutrinos might still be produced by the mixing with the active ones, suffering only a moderate suppression due to the Boltzmann factor.

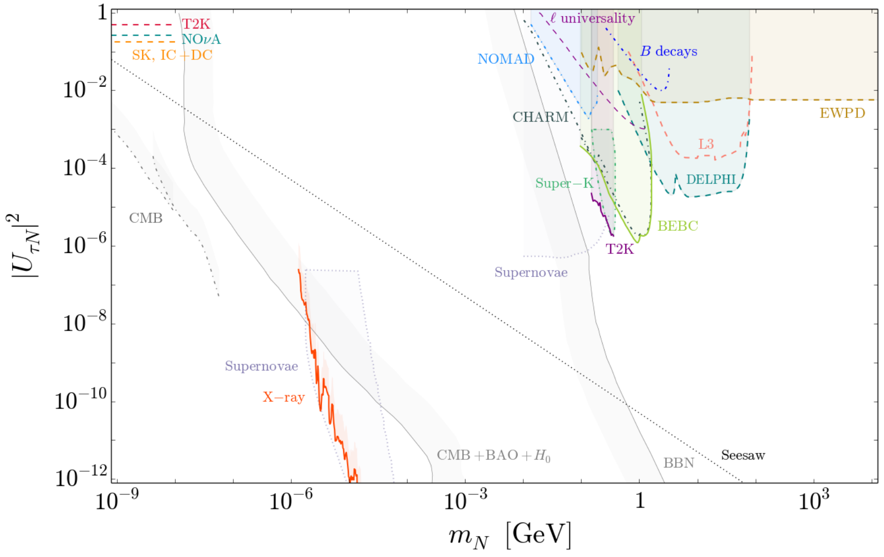


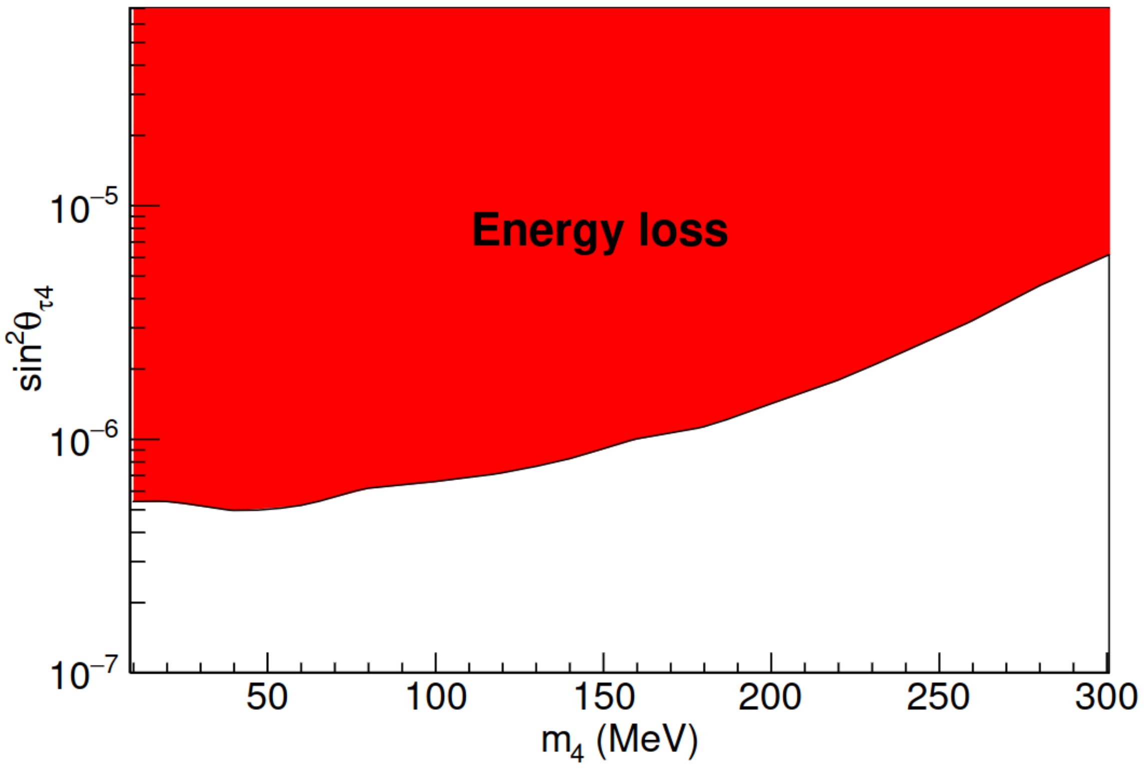
[Janka 1702.08713, Raffelt]

Energy Loss SN1987A

- Observations constrain energy-loss rate per unit mass → total luminosity → bounds on active-sterile mixing

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





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

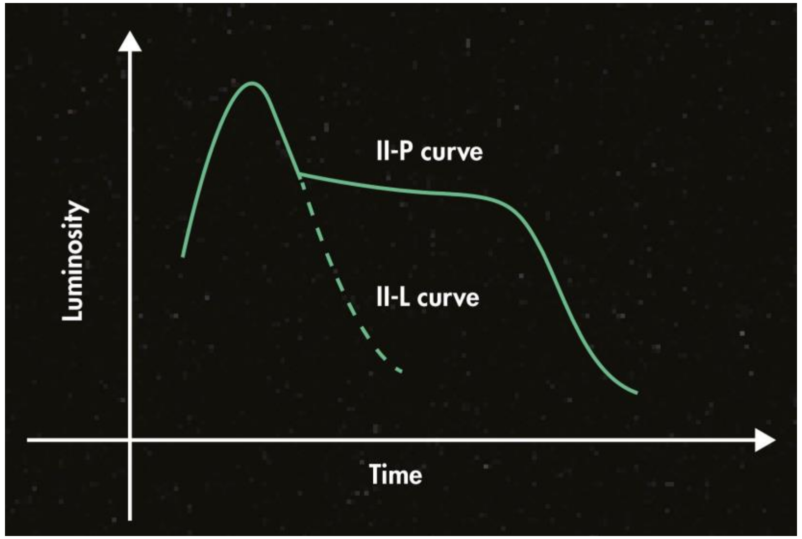
Low-energy SN : IIP or not IIP

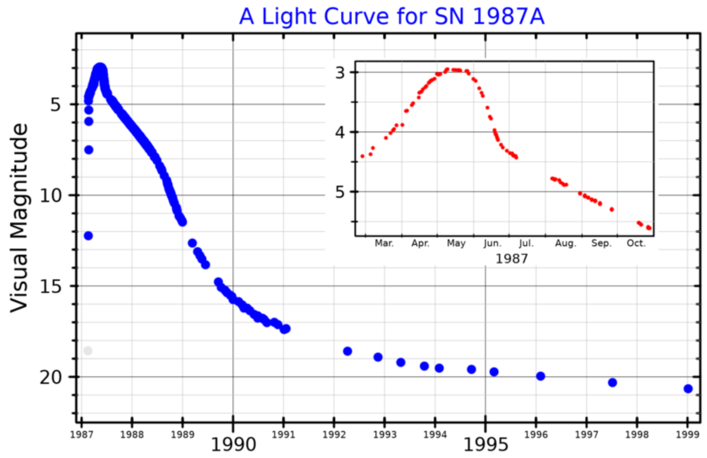
- There is a separate class of core-collapse SN with low-explosion energies : underluminous SN IIP

- 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:2015 ,Muller:2017) use the fitting formulae and statistical inference along with quantifying the uncertainities, to infer the most likely explosion energy.

- The inferred explosion energy ranges from

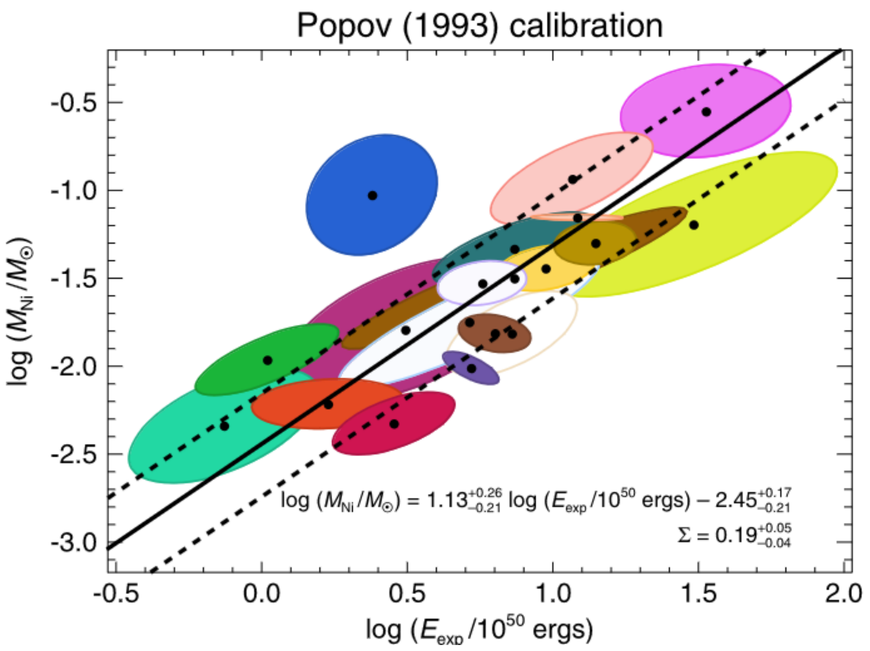
$$E_{obs} \sim (7.4 \times 10^{49} - 4 \times 10^{51})\ \text{erg}.$$

- 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	$\epsilon = \log_{10}(E_{\rm obs}/10^{51})$	σ_ϵ
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)

Sterile neutrino production

- In a SN core, sterile neutrino can be produced by e^+, e^- or neutrino pair annihilation and the inelastic scattering of (anti-) neutrinos.
- But $n, p, e^+, e^-, \nu_e, \bar{\nu}_e$ are degenerate in the hot proto-neutron star core,
- Pauli-blocking will render pair-annihilation and inelastic scattering on the non-degenerate neutrino species, the dominant processes for sterile production.

Process	Amplitude/$(8G_F^2\theta_\tau^2)$
$\nu_\tau + \bar{\nu}_\tau \to \nu_s + \bar{\nu}_\tau$	$4u(u - m_N^2)$
$\nu_\tau + \bar{\nu}_\tau \to \nu_s + \nu_\tau$	$4u(u - m_N^2)$
$\nu_\mu + \bar{\nu}_\mu \to \nu_s + \bar{\nu}_\tau$	$u(u - m_N^2)$
$\nu_\mu + \bar{\nu}_\mu \to \nu_s + \nu_\tau$	$u(u - m_N^2)$
$\nu_\tau + \bar{\nu}_\tau \to \nu_s + \nu_\tau$	$2s(s - m_N^2)$
$\bar{\nu}_\tau + \bar{\nu}_\tau \to \nu_s + \bar{\nu}_\tau$	$2s(s - m_N^2)$
$\nu_\mu + \bar{\nu}_\tau \to \nu_s + \nu_\mu$	$s(s - m_N^2)$
$\bar{\nu}_\mu + \bar{\nu}_\tau \to \nu_s + \bar{\nu}_\mu$	$s(s - m_N^2)$
$\nu_\tau + \bar{\nu}_\mu \to \nu_s + \bar{\nu}_\mu$	$u(u - m_N^2)$
$\nu_\mu + \bar{\nu}_\tau \to \nu_s + \nu_\mu$	$u(u - m_N^2)$

Fuller,Kusenko,Petraki PLB 670(2009)

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.

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

$$\mathcal{C}_{coll} = \frac{1}{2E_s} \int d^3\tilde{p_2} d^3\tilde{p_3} d^3\tilde{p_4}\, \Lambda(f_s, f_2, f_3, f_4)\; S|M|^2_{12\to34}\, \delta^4(p_s + p_2 - p_3 - p_4)(2\pi^4)$$

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

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

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

Energy Deposition

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

$$E_{\text{mantle}} = \int dt \int_0^{R_{\text{core}}} dr \int_{m_s}^{\infty} dE_s \frac{dL_s(r, E_s, t)}{dr\, dE_s} \times \left\{ \exp\left[-\frac{(R_{core} - r)}{L_{decay}}\right] - \exp\left[-\frac{(R_{env} - r)}{L_{decay}}\right] \right\}$$

Caputo, Janka, Raffelt, Vitagliano PRL 128(2022)

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

Peak Temps. : 30-40 MeV
Final NS mass : $1.351\ M_{\odot}$

Mirizzi, Tamborra, Janka, Saviano, Scholberg, Bollig RNC 39(2016),
Bollig,Janka,Lohs,PInedo,Horowitz,Melson PRL 119(2017)

Energy Deposition

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

$$\nu_s \to \nu_\tau \pi^0$$

$$\nu_s \to \nu_\tau e^+ e^-$$

$$\nu_s \to \nu_\tau \mu^+ \mu^-$$

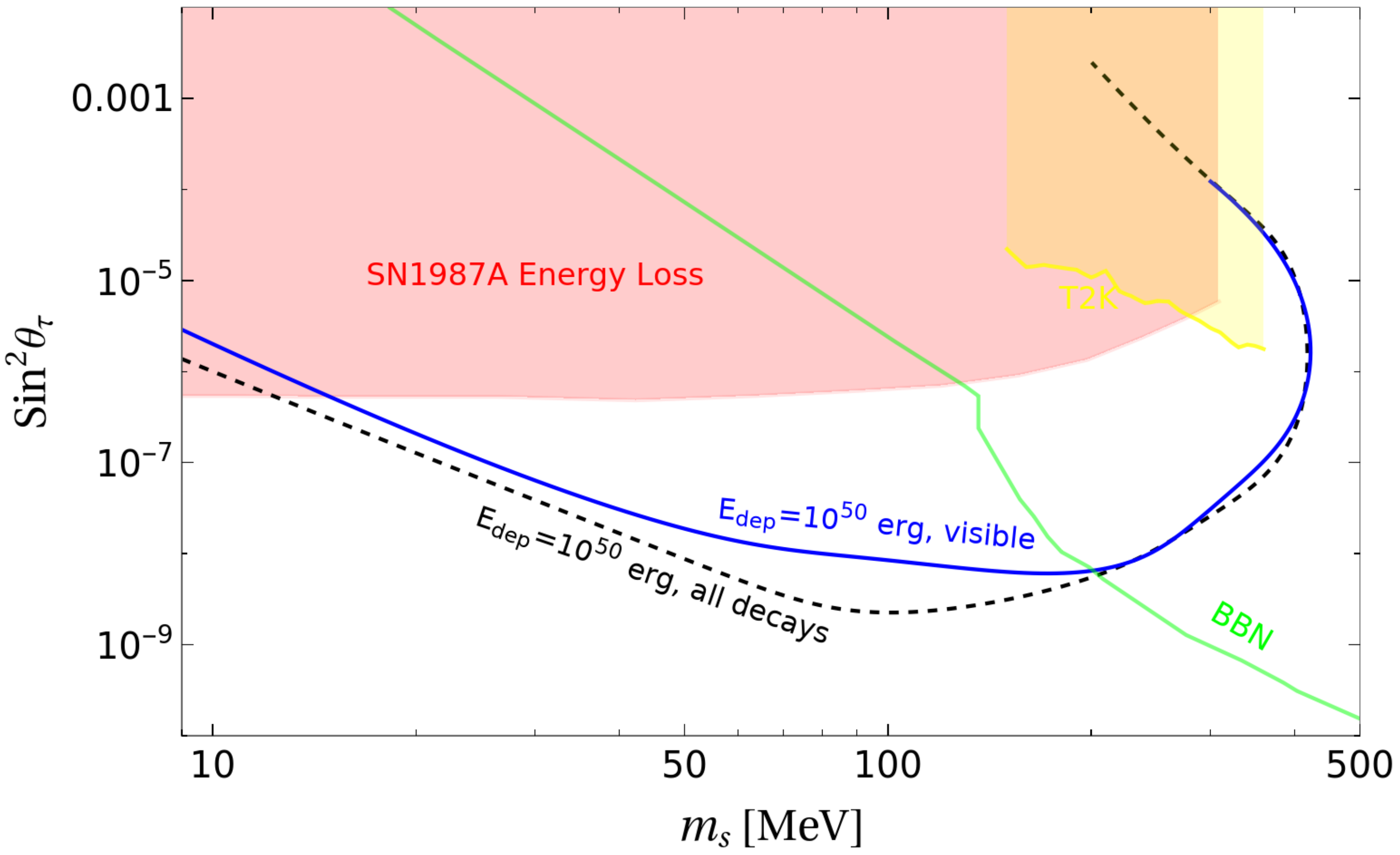
$$\nu_s \to \nu_\tau \nu_x \bar{\nu}_x$$

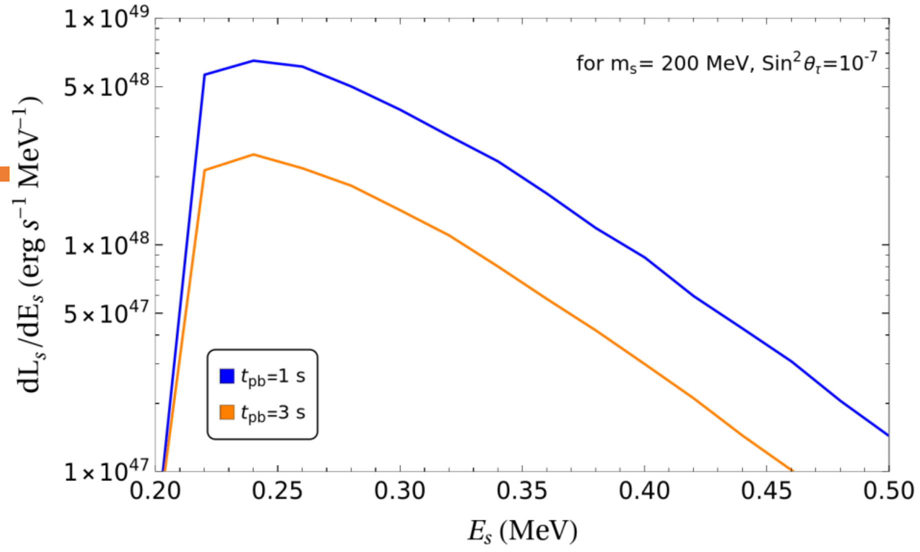
- Only the *visible* decay modes deposit their energy, determined by

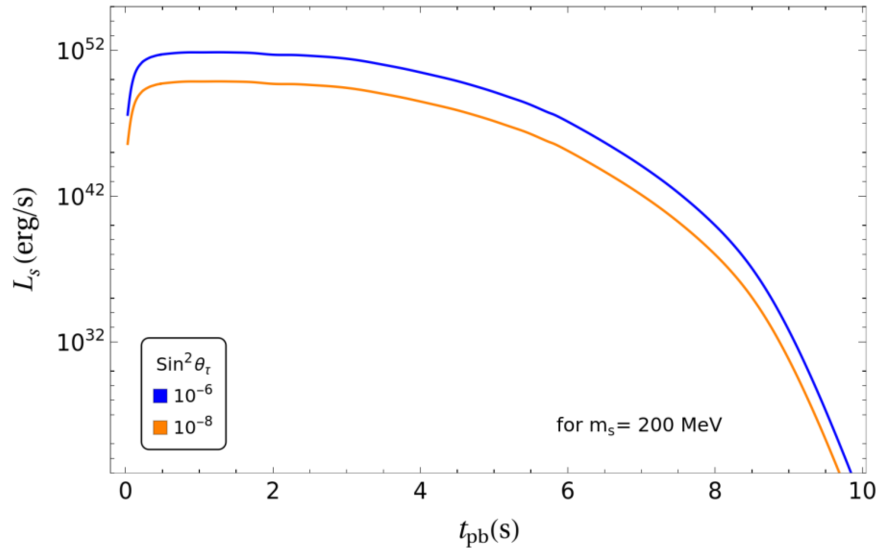
$$BR_{vis} = 1 - \frac{\Gamma(\nu_s \to \nu_\tau \nu_x \bar{\nu}_x)}{\Gamma_{tot}}$$

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

Results







GC, Huber, Horiuchi, Shoemaker (arXiv : 2305.abcde)

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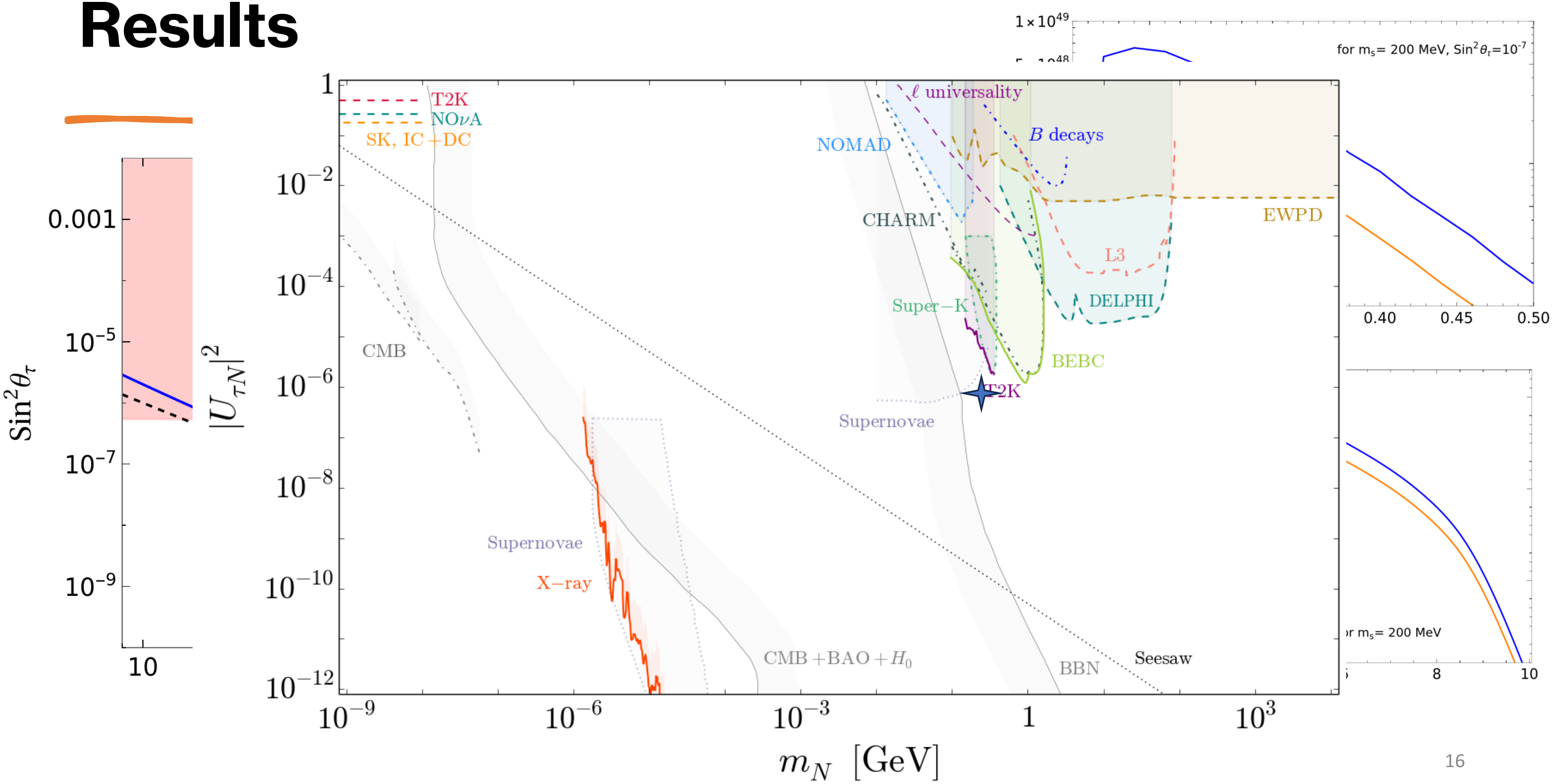

T2K
NOνA
SK, IC+DC
ℓ universality
NOMAD
B decays
CHARM
EWPD
L3
DELPHI
Super−K
BEBC
T2K
Supernovae
CMB
Supernovae
X−ray
CMB+BAO+H_0
BBN
Seesaw
$|U_{\tau N}|^2$
m_N [GeV]
$\sin^2\theta_\tau$
0.001
10^{-5}
10^{-7}
10^{-9}
10
for m_s= 200 MeV, $\sin^2\theta_\tau$=10^{-7}
0.40
0.45
0.50
for m_s= 200 MeV
8
10

Summary

- Sterile neutrinos can be produced through mixing with active neutrinos in the hot and dense core of a collapsing supernova (SN).

- We discuss a novel bound from energy deposition through the decays of sterile neutrinos inside the SN envelope.

- Using observed SN IIP population with low-ejecta velocities, this energy deposition is constrained

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

- for masses 10-400 MeV stringent constraints on tau mixing, 2-3 orders of magnitude lower than those from current constraints