# Massive sterile $\nu$'s in supernovae

Motivations from $\nu$ physics & relevant parameter space

Generalities on core-collapse SNae

Sterile $\nu$ in CC SNae: production and signatures

Pasquale Dario Serpico (Annecy, France)

Mostly based on
L. Mastrototaro, A. Mirizzi, PDS and A. Esmaili, JCAP 010 (2020)

18th Rencontres du Vietnam - Neutrino Physics 19/07/2022

# Motivations

The discovery of $\nu$ mass via oscillations requires a SM extension, whose simplest incarnation involves *sterile $\nu$'s*

(SM gauge singlet fermions)

## The Nobel Prize in Physics 2015



Takaaki Kajita

Prize share: 1/2



Arthur B. McDonald

Prize share: 1/2

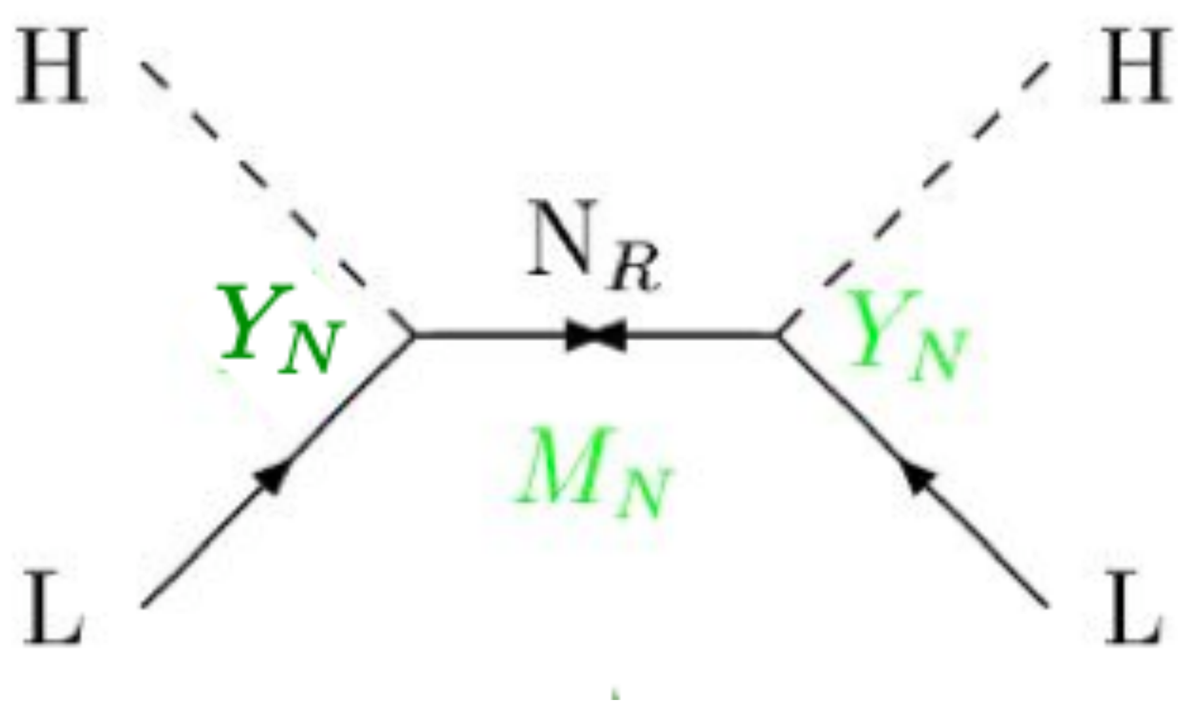
$$\mathcal{L} \ni -Y_{N_{ij}} \bar{N}_i L_j H - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$$

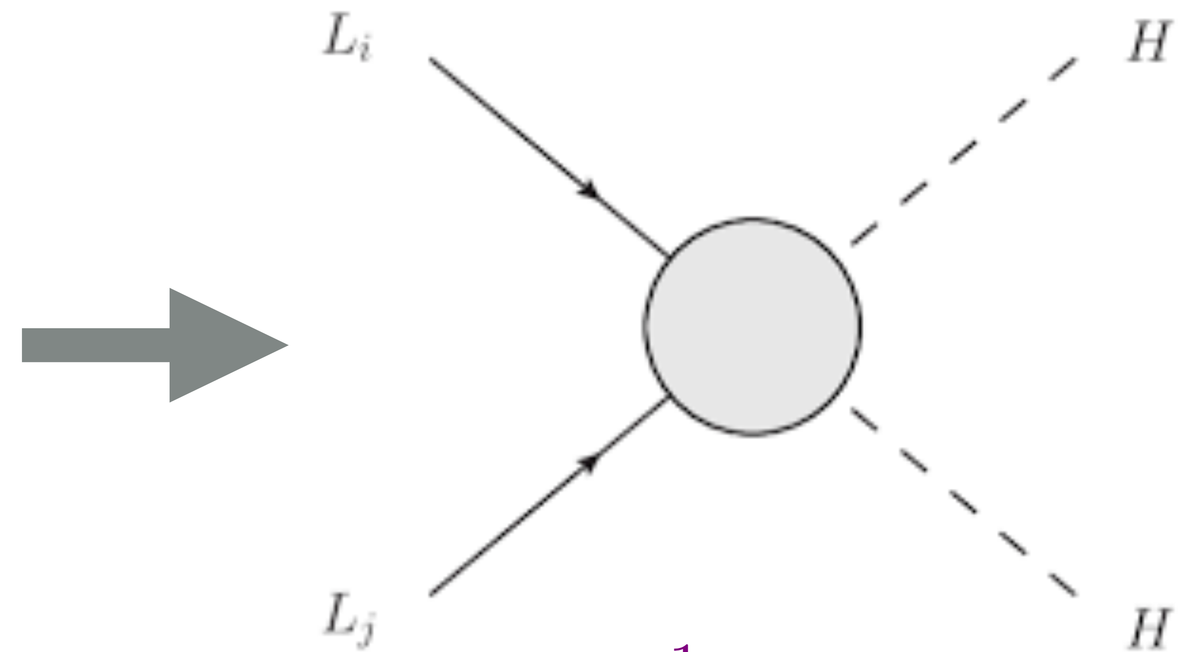
*Yukawa mass term possible*

*Renormalizable extension of SM not prevented by symmetries*

# $\nu$ mass as a remnant of high-scale physics?

Typically interpreted as a 'high-scale phenomenon'




$$\mathcal{L}_5 = \frac{1}{\Lambda}(HL)(HL)$$

*'Weinberg operator'*

Leading to tiny $\nu$ masses via the '**see-saw**' effect (suppressed by high scale $M_N$)

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

# What if it is a low-scale/tiny coupling phenomenon?

- After all, most of the SM Yukawa's are not O(1), but much smaller!
- sterile $\nu$'s could be light enough to be kinematically accessible. At (sub)GeV scale, could implement a leptogenesis model, and the lightest keV-MeV state could also be the dark matter (e.g. *$\nu$MSM Shaposnikov et al, arXiv: hep-ph/0505031)*
- Motivated dedicated accelerator programs *(e.g. SHiP, arXiv:1504.04855)*

Jinst

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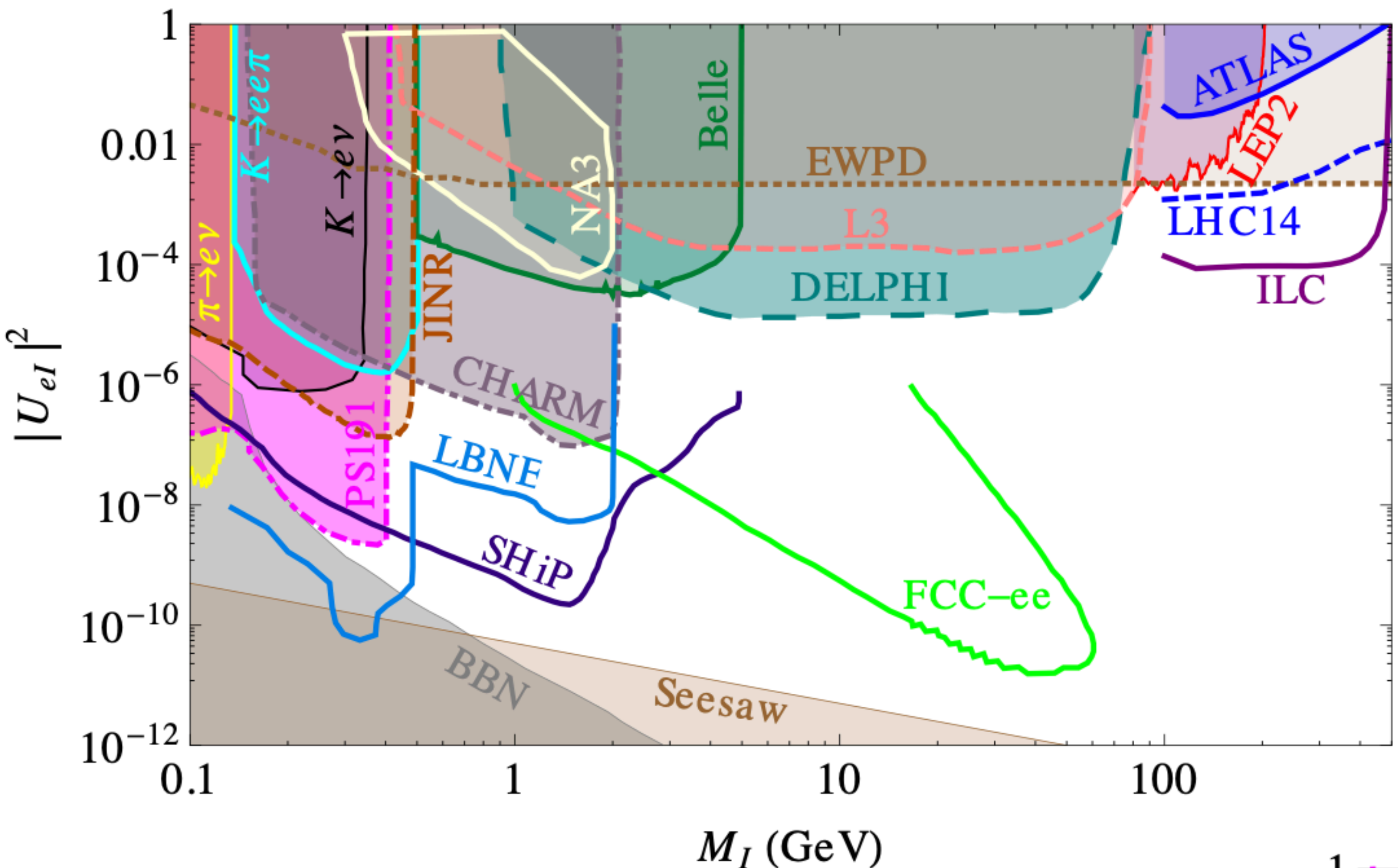
**The experimental facility for the Search for Hidden Particles at the CERN SPS**

**The SHiP collaboration**

*1810.06880*

# Current parameter space of interest




In the 2-flavour limit

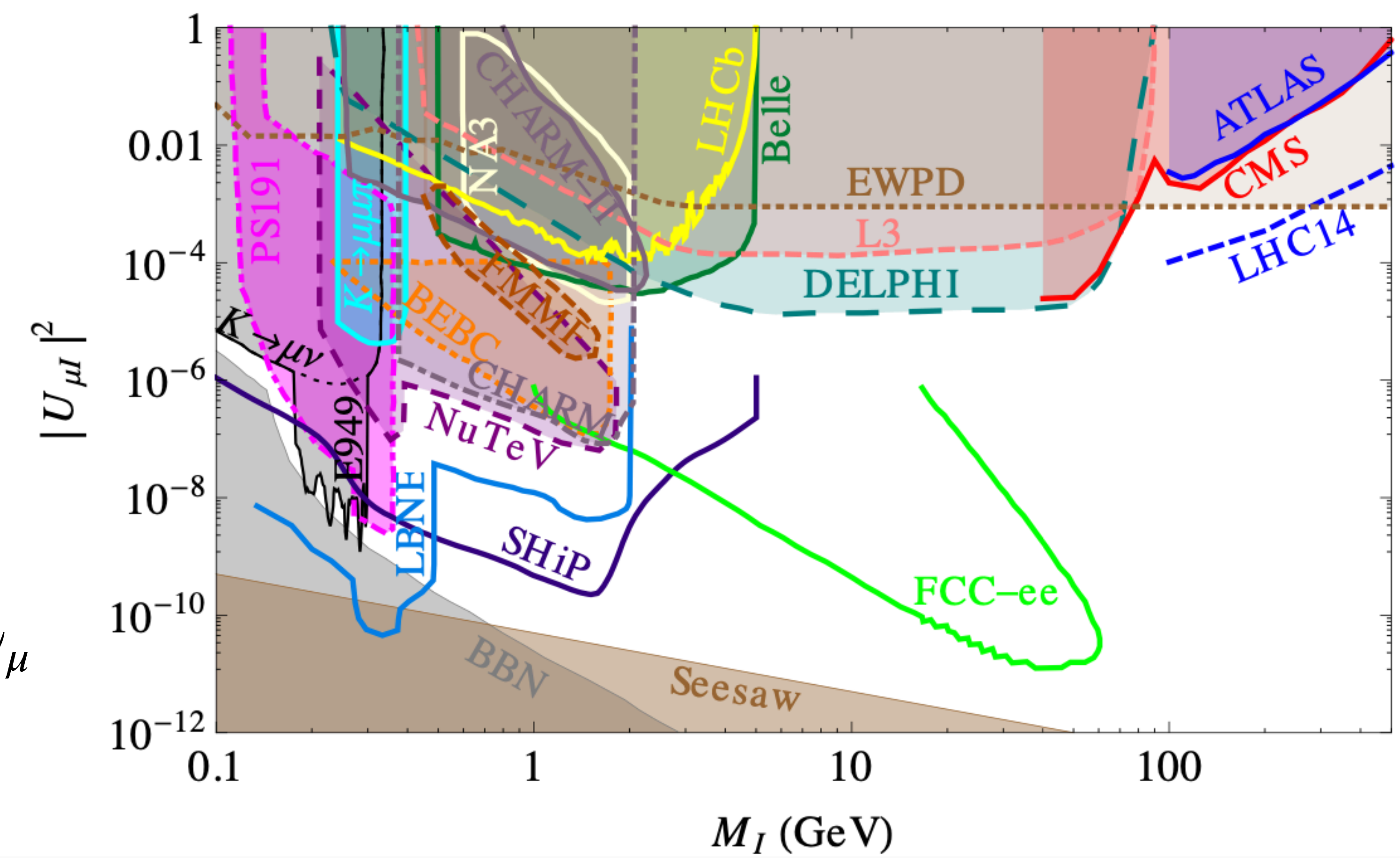
$$\nu_\alpha = \cos\theta_{\alpha s}\nu_\ell + \sin\theta_{\alpha s}\nu_H$$
$$\nu_s = -\sin\theta_{\alpha s}\nu_\ell + \cos\theta_{\alpha s}\nu_H$$

$$|U_{\alpha s}|^2 \simeq \frac{1}{4}\sin^2 2\theta_{\alpha s} \simeq \theta_{\alpha s}^2$$

Loosely, one can identify

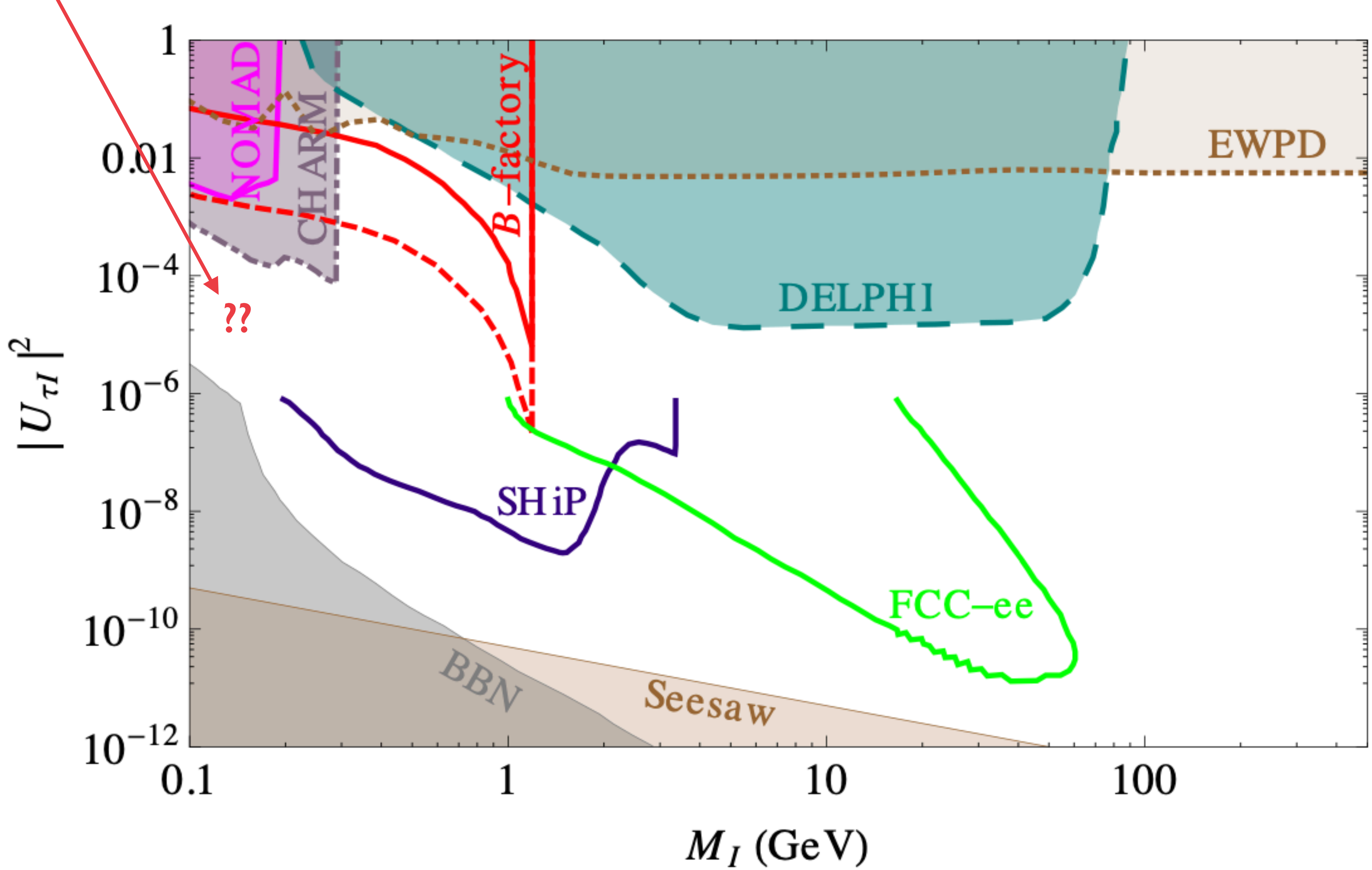
$$\nu_H \sim \nu_s$$

"Light" parameter space largely probed if dominant mixing with $\nu_e$ , $\nu_\mu$

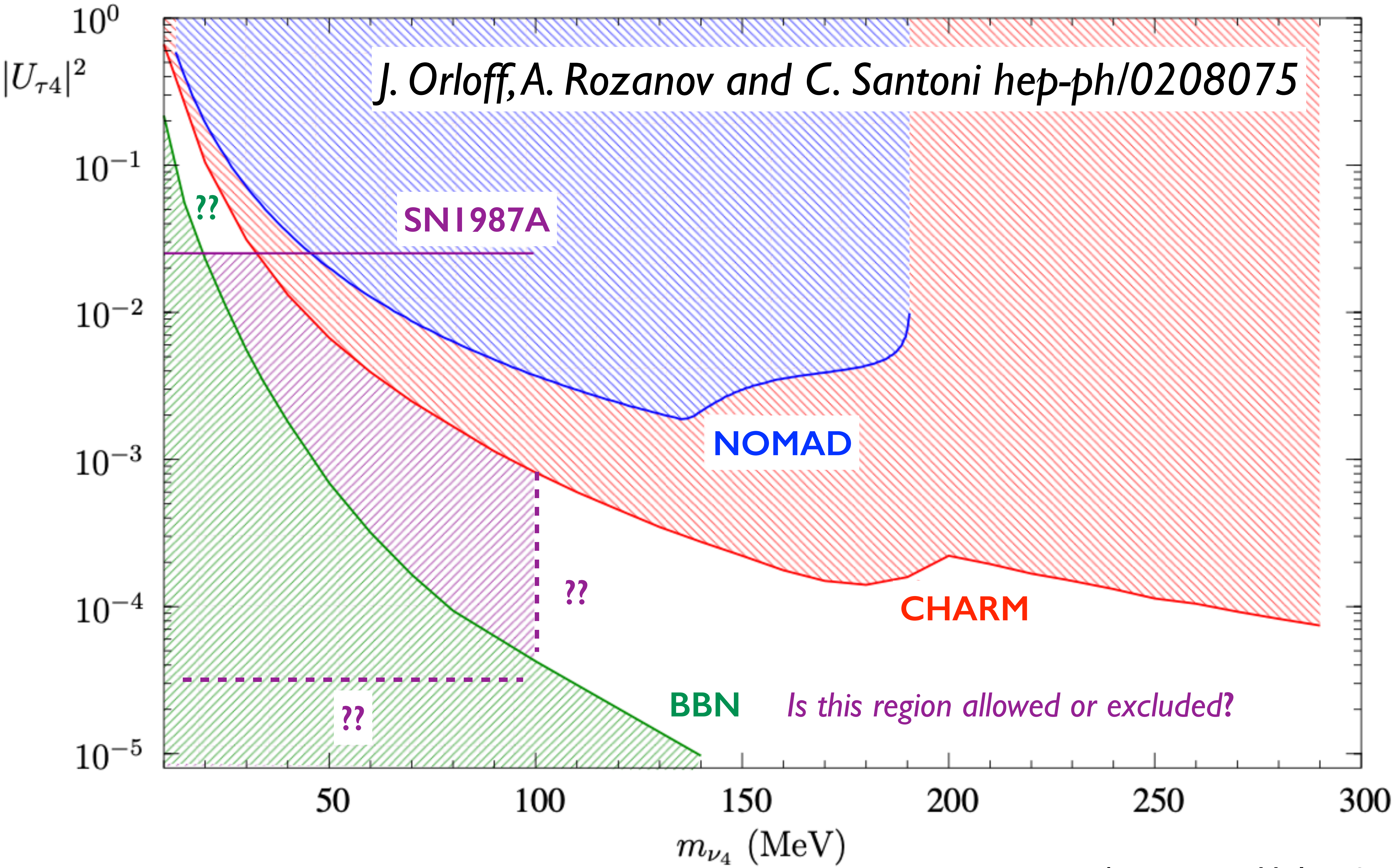


# Why astroparticle probes?

- Sterile state in the O(10-100) MeV mass range (mostly) mixing with $\nu_\tau$ hard to probe in the lab
- Range kinematically accessible ***(collisional, not oscillation production!)*** in supernova cores and in the early universe, which are ~ "flavour-universal" environments
- Some peculiar phenomenology to be studied, chances for serendipitous discoveries



# Zooming in - Region of interest




Assess credibility & update ~20 yr later

*Astroparticle bounds from A.D. Dolgov et al., Nucl. Phys. B 590 (2000) 562*

# II. (Core collapse) SNae

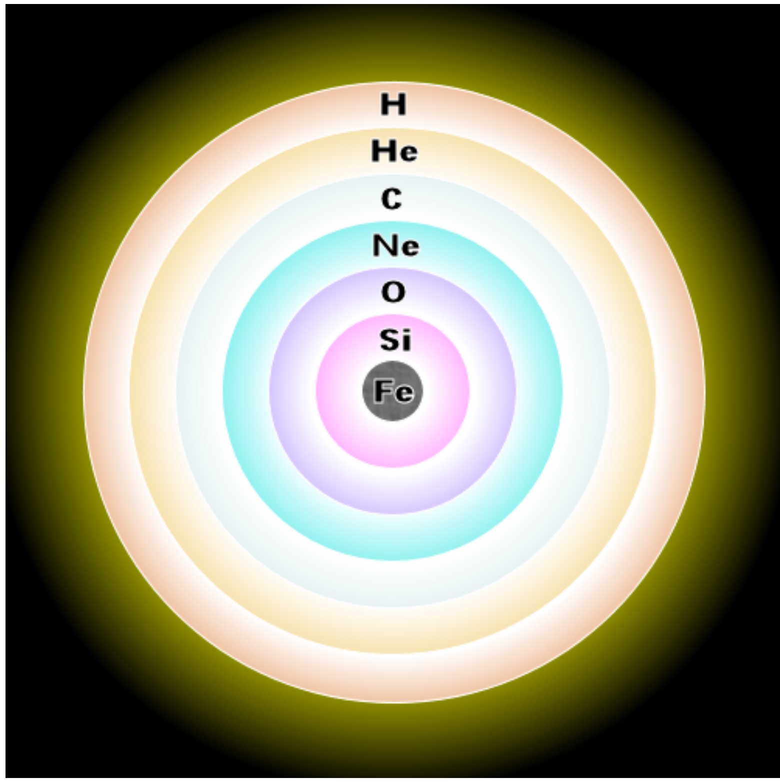
# Stellar collapse & SN explosion

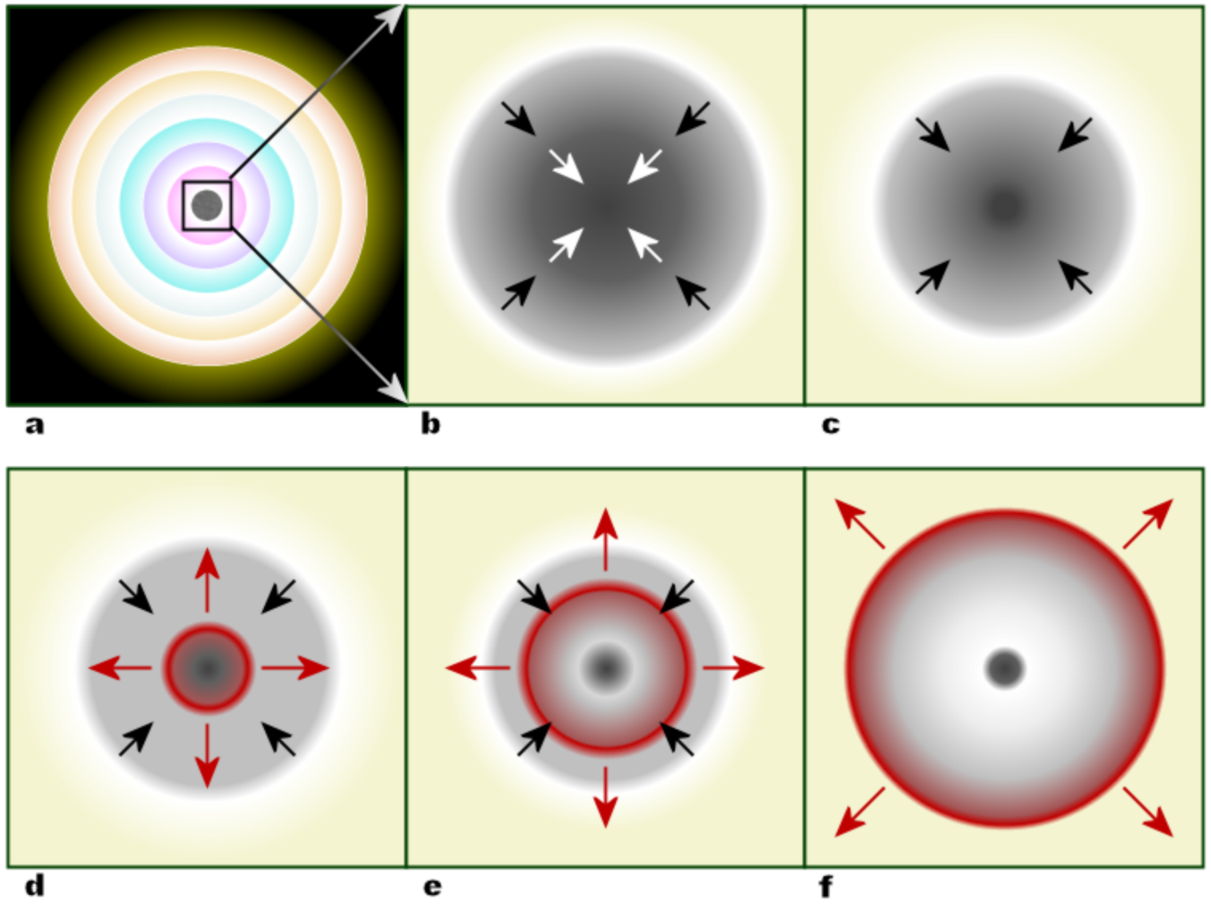
- The core of a massive star cannot sustain equilibrium by thermonuclear fusion beyond A~56 (Ni-Fe)

- The degenerate iron core starts to collapse, halting when nuclear densities are reached (~incompressible).

- A shock wave (SW) propagates outwards.

- The SW energy is mostly dissipated by dissociating the outer layer of iron, and no explosion happens (prompt explosion fails)




**What happens, next?**

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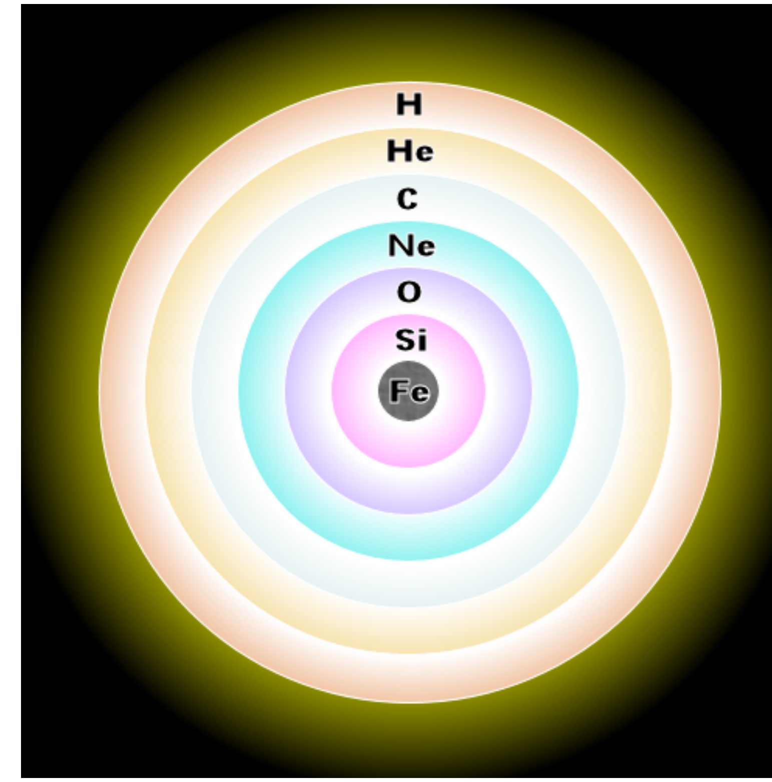
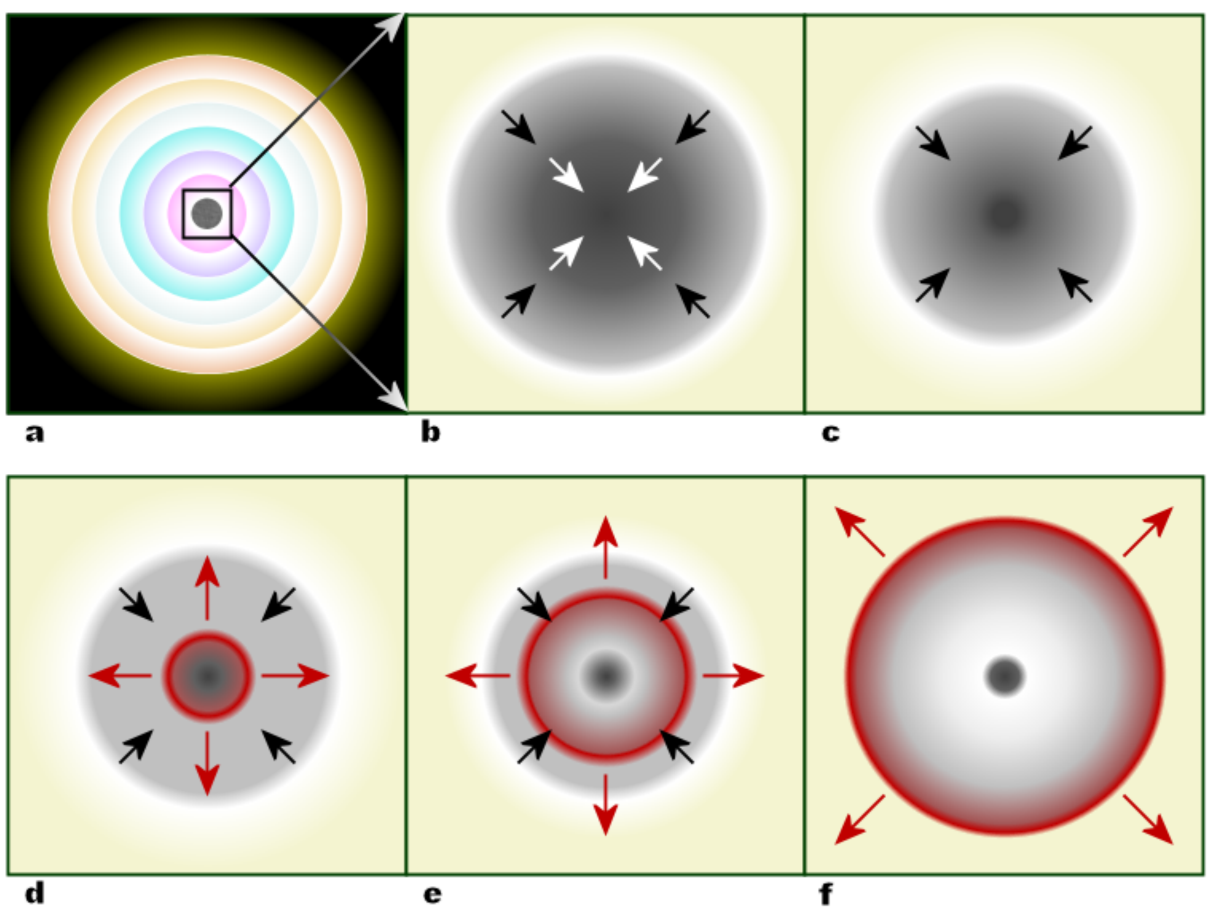



## Neutrinos to the rescue!

The core (now a "T~O(10) MeV" p-n star) dissipates its binding energy into $\nu$'s

$\nu$ heating increases pressure behind shock front, rescuing stalled shock. Eventually ejects star's outer mantle (explosion). While it lasts, $L_\nu$ outshines whole universe!

*Delayed $\nu$-heating (Bethe & Wilson '85)*

# Three phases of neutrino emission

Figures adapted from Fischer et al., arXiv: 0908.1871, 10. 8 $M_{sun}$ progenitor mass (spherically symmetric with Boltzmnann ν transport)

## Neutronization Burst

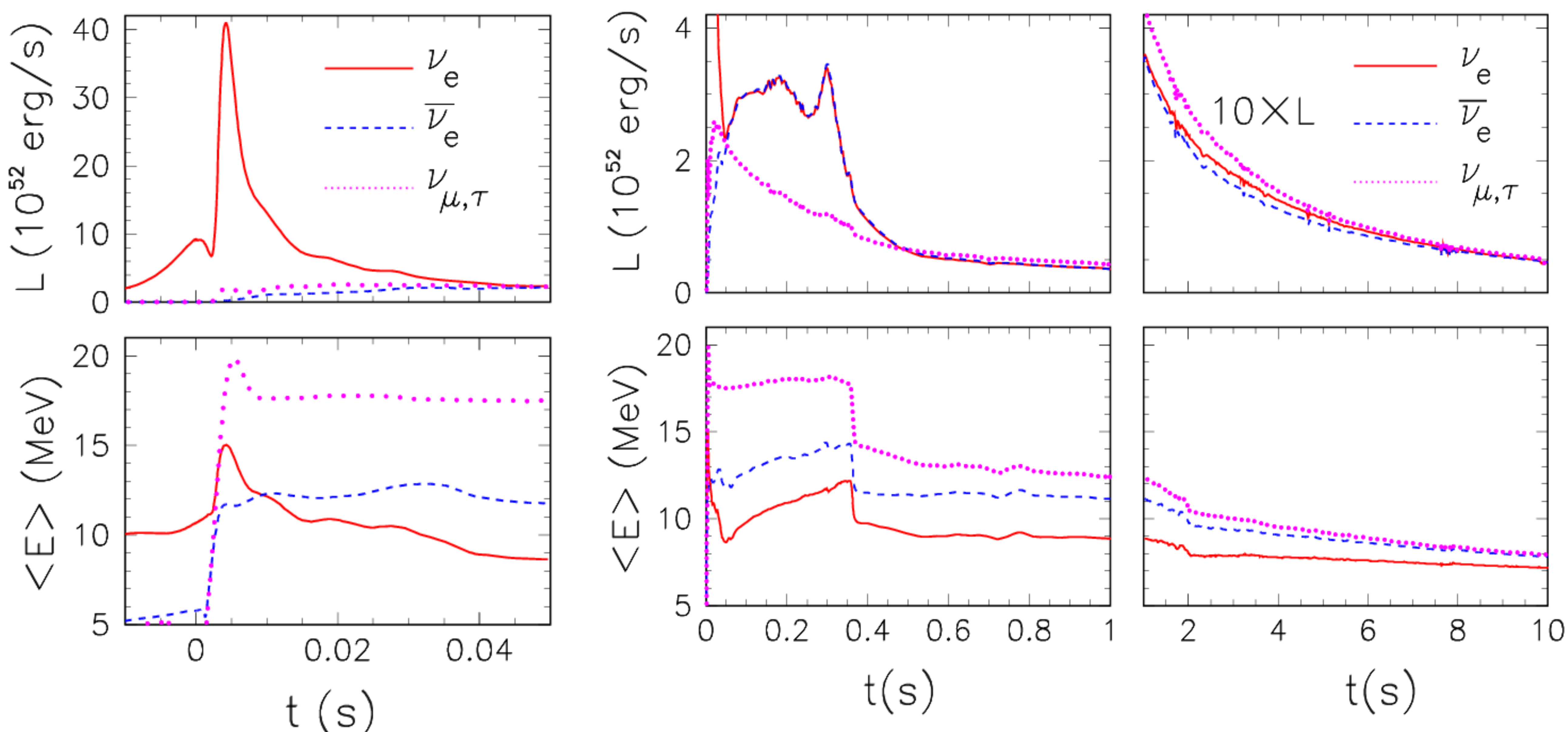
- Shock breakout
- De-leptonization of outer core layers

## Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

## Cooling

- Cooling on ν diffusion time scale



# “Figures of merit”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Supernova 1987A 23/02/1987

**Gravitational binding energy**

**$E_b \approx 3\times10^{53}$ erg $\approx$ 17% $M_{SUN}\,c^2$**

**Showing up as**

**99% Neutrinos**

**1% Kinetic energy of explosion (10% of this into CRs?)**

**0.01% $\gamma$, outshine host galaxy**

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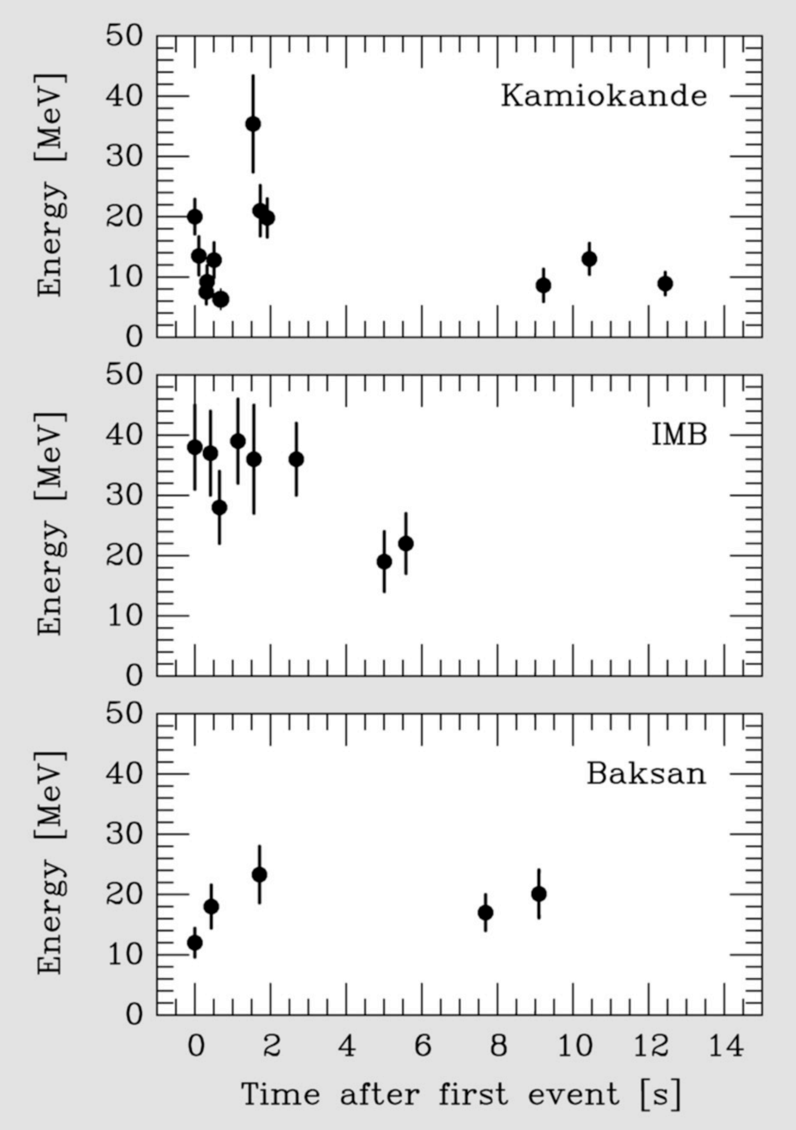


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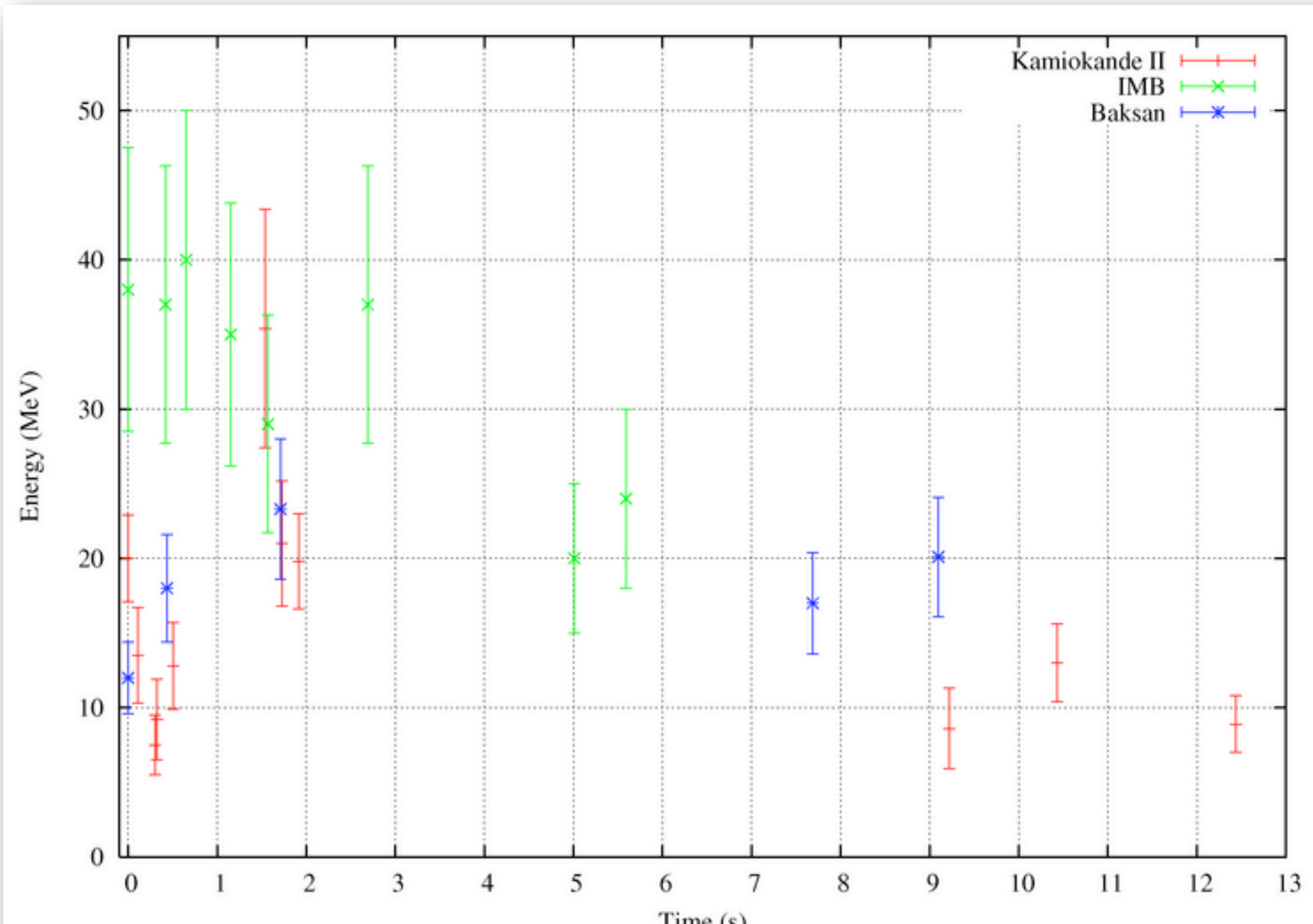
# SN 1987A: Validation of the basic picture of massive star death

Ingredients for "flux-energy-timescale": powered by gravitational collapse, signal from diffusion via weak reactions in medium with nuclear densities




No hint for extra *E*-loss channels; future high-statistics signal (SK, HK, IC…): Room for surprises?

# III. Sterile $\nu$'s in SNae

# Sterile neutrino production in Supernovae

- We focus on the cooling phase of a *18 $M_\odot$* SN progenitor *(T. Fisher, arXiv:1608.05004)*
- We adopt a 'perturbative' approach: take a standard reference SN, and use it as 'background' to the *collisional* ***(not oscillation!)*** production of sterile neutrinos.

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

$$\mathcal{C}_{\rm coll} = \frac{1}{2E_s}\int d^3\hat{p}_2 d^3\hat{p}_3 d^3\hat{p}_4 \Lambda(f_s, f_2, f_3, f_4) S|M|^2_{12\to34}\delta^4(p_s + p_2 - p_3 - p_4)(2\pi)^4$$

- Local thermal distributions assumed for the active $\nu$, sterile $\nu$ assumed to free-stream and thus $f_s \to 0$ in $\Lambda$

$$\Lambda(f_1, f_2, f_3, f_4) = (1-f_1)(1-f_2)f_3 f_4 - f_1 f_2 (1-f_3)(1-f_4)$$

- No feedback, but space & time-dependent calculation

| Process | $S\vert\mathcal{M}\vert^2/(8G_F^2 \sin^2\theta_{\tau 4})$ |
|---|---|
| $\nu_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$ | $4u(u-m_4^2)$ |
| $\nu_\mu + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$ | $u(u-m_4^2)$ |
| $\nu_\tau + \nu_\tau \to \nu_4 + \nu_\tau$ | $2s(s-m_4^2)$ |
| $\bar{\nu}_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau$ | $2s(s-m_4^2)$ |
| $\nu_\mu + \nu_\tau \to \nu_4 + \nu_\mu$ | $s(s-m_4^2)$ |
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# Differential & integral luminosity

- Differential number flux

$$\frac{\mathrm{d}^2 N_s}{\mathrm{d}E_s \mathrm{d}t} = \int \mathrm{d}^3 r \frac{1}{2\pi^2} \frac{\mathrm{d}f_s}{\mathrm{d}t} E_s p_s = \frac{2}{\pi} \int \mathrm{d}r r^2 \frac{\mathrm{d}f_s}{\mathrm{d}t} E_s p_s$$

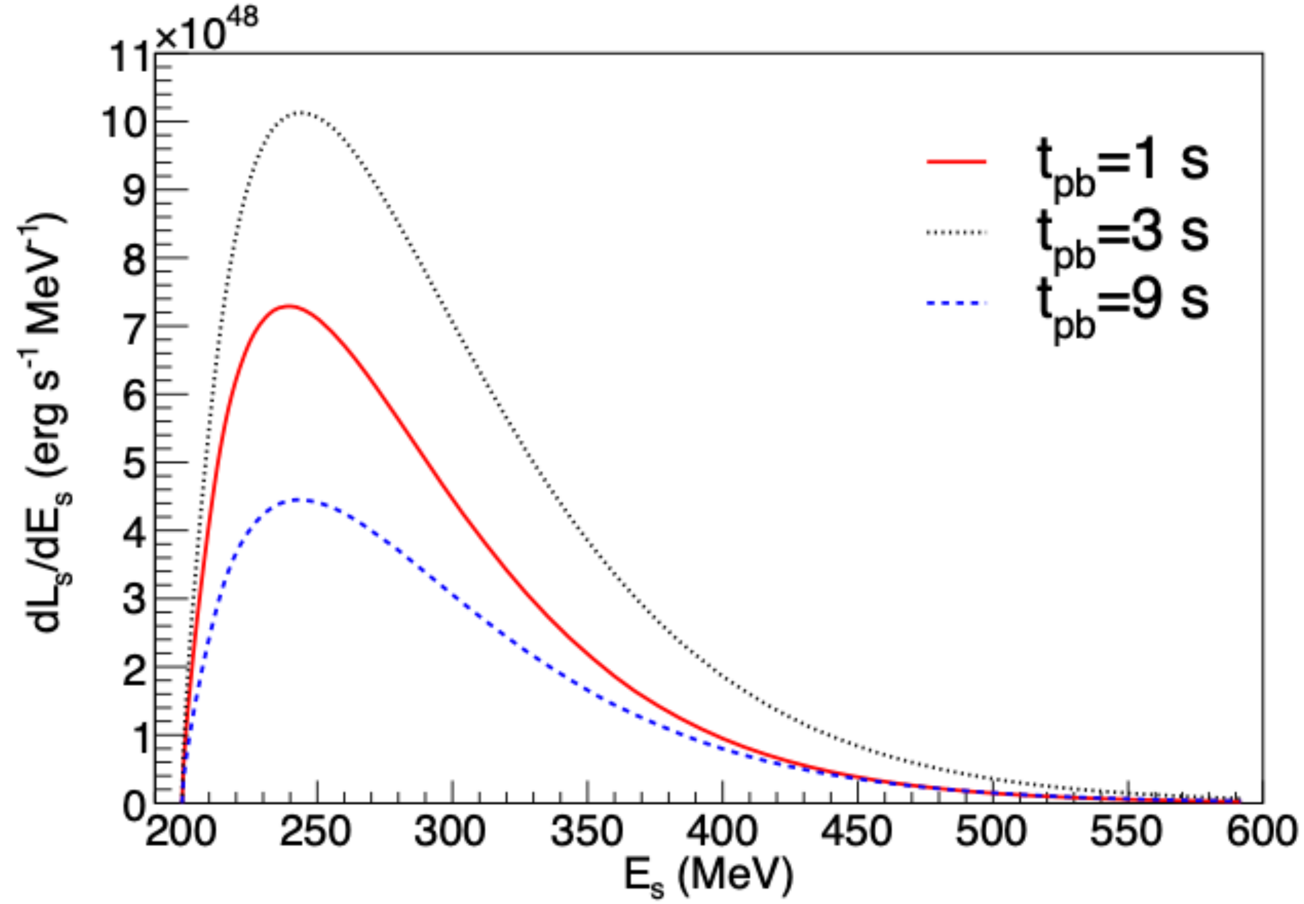
- Differential luminosity

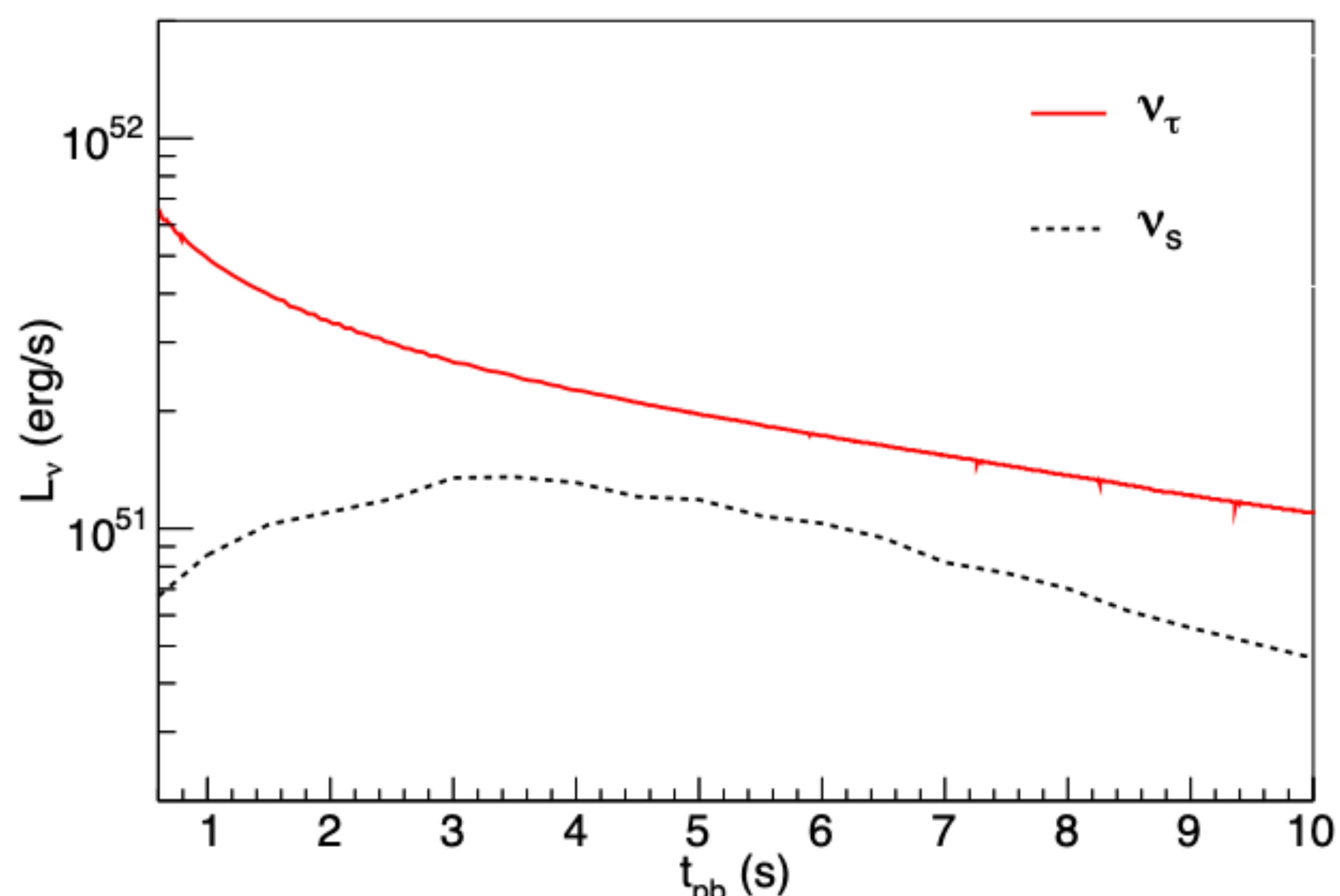
$$\frac{\mathrm{d}L_s}{\mathrm{d}E_s} = E_s \frac{\mathrm{d}^2 N_s}{\mathrm{d}E_s \mathrm{d}t}$$

- Benchmark (unless stated otherwise)

$$m_4 = 200\,\mathrm{MeV}$$
$$\sin^2\theta_{\tau 4} = 10^{-7}$$

- Dominant decays via $\nu \to \nu_\tau \pi^0$, $\nu_\tau \nu_a \nu_a$



# SN1987A 'energy loss bounds'

*Too weakly coupled particles would drain energy too fast for the $\nu$ signal to last O(10)s*

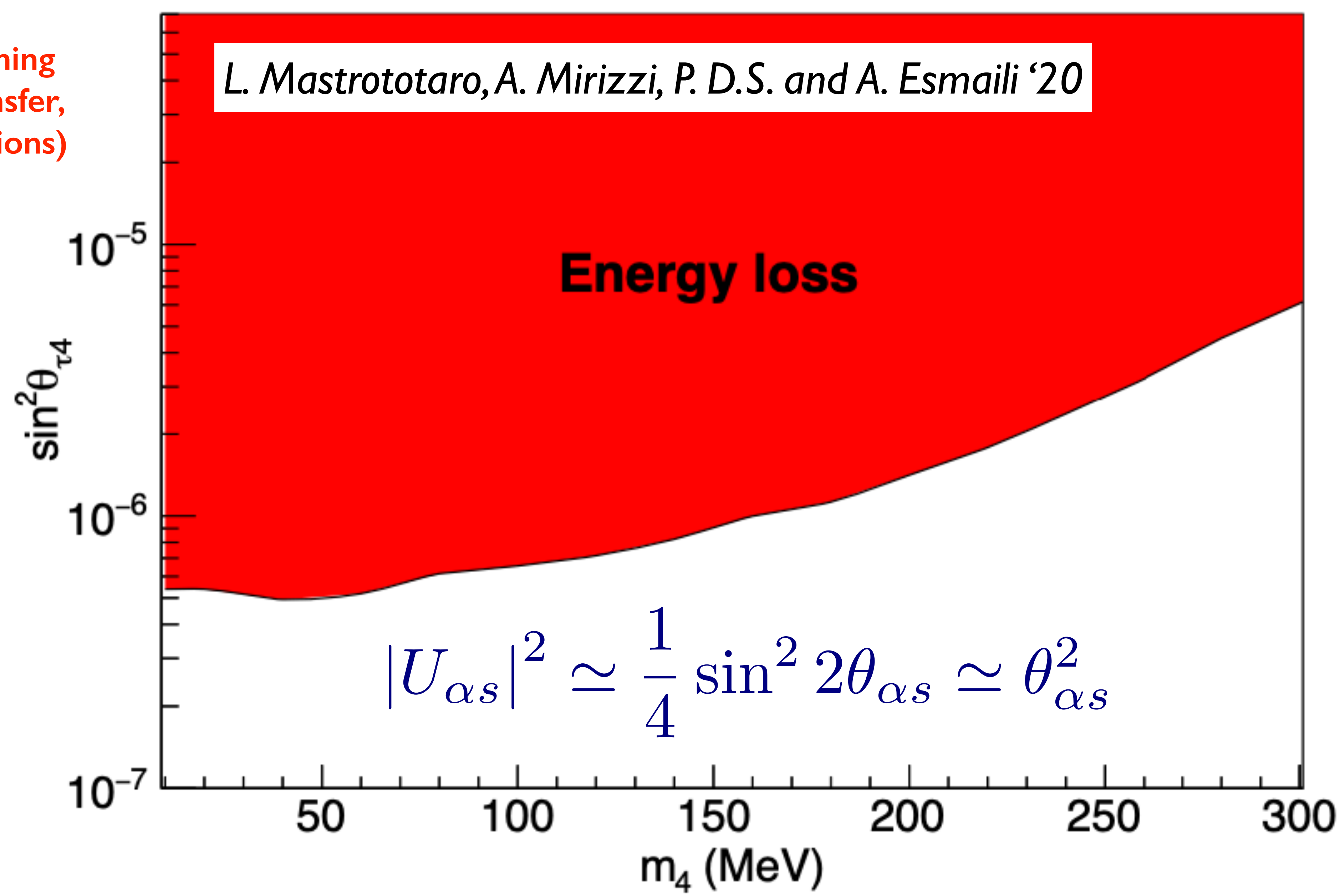
To avoid conflict wit observations, *E*-loss rate per unit mass $\epsilon$ <$10^{19}$ erg/(g s)

*G. G. Raffelt and S. Zhou, Phys. Rev. D 83, 093014 (2011) [arXiv:1102.5124]*

→ $L < \epsilon\, M_{core} \sim 2\text{x}\ 10^{52}$ erg/s

↑

**Not free-streaming anymore (E-transfer, requires simulations)**




→

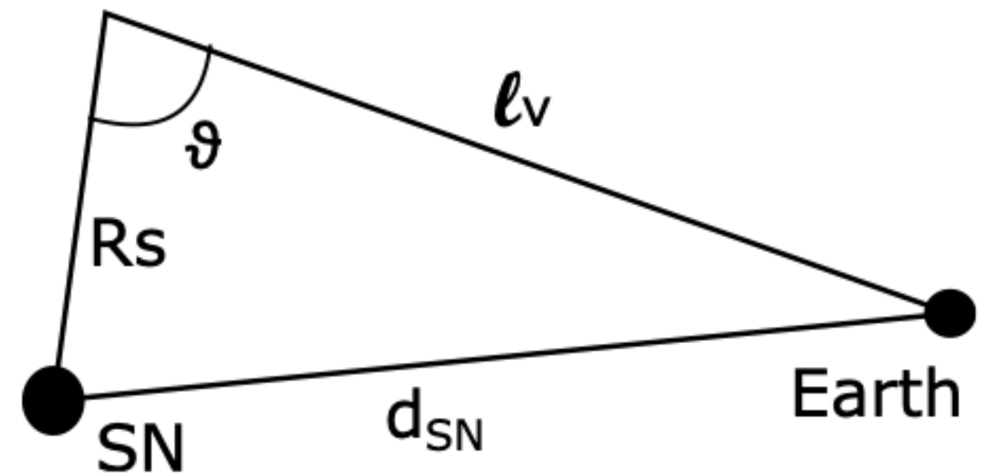
*Multi-pion decay modes,*

**Important gravitational capture**

**(bound disappears)**

# Pheno Consequences

delayed-displaced neutrino decays




$$\tau = \frac{1}{\Gamma_{\rm tot}} = \frac{B_{\pi^0}}{\Gamma_{2\,\rm body}} \simeq \frac{0.016\ {\rm s}}{\left(1 - 0.46\left(\frac{200\ {\rm MeV}}{m_4}\right)^2\right)^2} \times \left(\frac{10^{-7}}{\sin^2\theta_{\tau 4}}\right)^2 \left(\frac{200\ {\rm MeV}}{m_4}\right)^3$$

- Slight alteration of time signal, hard to detect over a signal of several seconds…

$$d = \tau\frac{p_s}{m_4} \simeq \frac{3.6\times 10^3\ {\rm km}}{\left(1 - 0.46\left(\frac{200\ {\rm MeV}}{m_4}\right)^2\right)^2} \times \left(\frac{10^{-7}}{\sin^2\theta_{\tau 4}}\right)^2 \left(\frac{200\ {\rm MeV}}{m_4}\right)^3$$

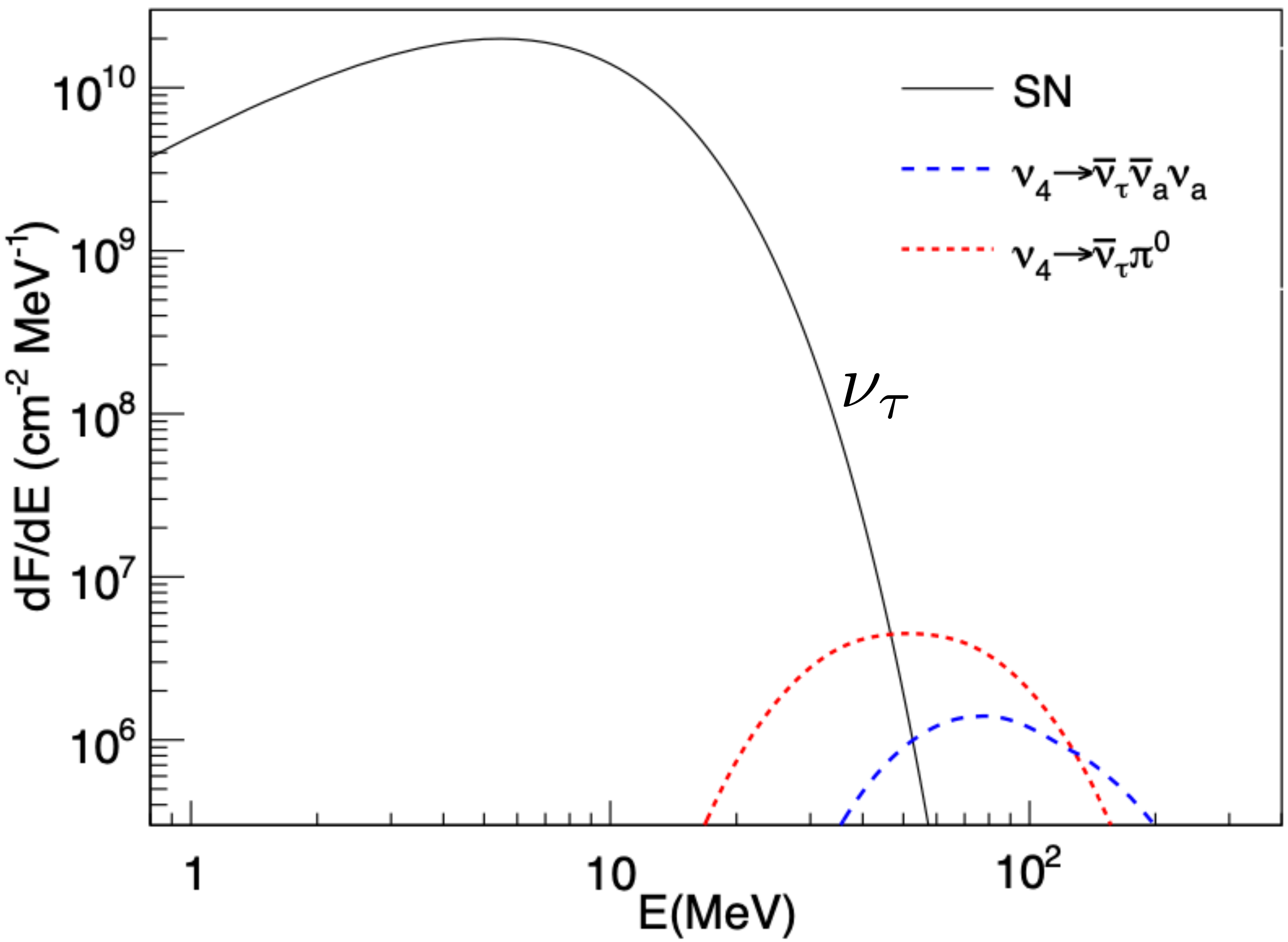
- *E*-release in outer layers could induce peculiar nucleosynthetic pattern

- *E*-release 'at right distance' could trigger explosion!

*G. M. Fuller, A. Kusenko and K. Petraki, Phys. Lett. B 670, 281-284 (2009) [arXiv:0806.4273]*

# Most easily observable signal: Spectrum

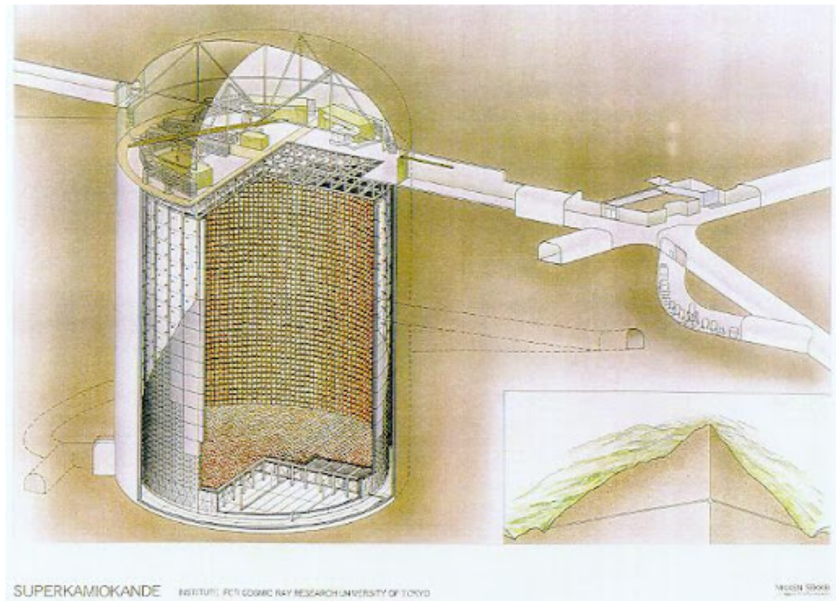
$$\frac{dN_a}{\mathrm{d}E} = B_a \int \mathrm{d}\cos\theta \int_{E_{\min}}^{\infty} \mathrm{d}E_s \, \frac{1}{\gamma(1+\beta\cos\theta)} \frac{\mathrm{d}N_s(0,E_s)}{dE_s} f_a\left(\frac{E}{\gamma(1+\beta\cos\theta)}, \cos\theta\right)$$




- Rather peculiar flavour structure as well (dominated by $\nu_\tau$) but hard to infer

# Expectations in SK (inverse beta decay events)

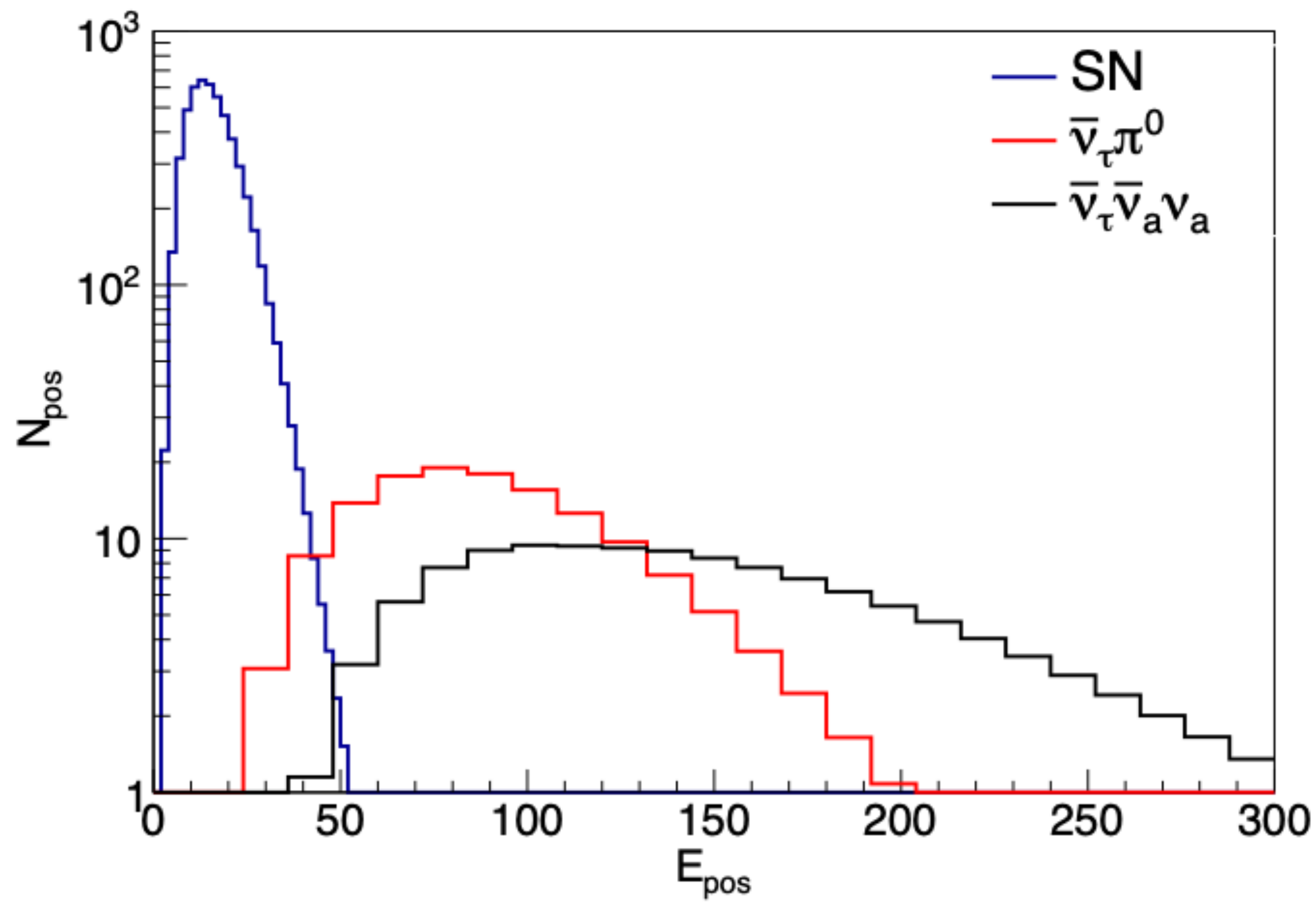
$$F_{\bar{\nu}_e} = \bar{P}_{ee}(E) F^0_{\bar{\nu}_e} + [1 - \bar{P}_{ee}(E)] F^0_{\bar{\nu}_x}(E)$$




| Channel | Number of events NH | IH |
|---|---|---|
| SN $\bar{\nu}_e$ | 5280 | 5640 |
| $\nu_4 \to \pi^0 \bar{\nu}_\tau$ | 141 | 470 |
| $\nu_4 \to \nu_\tau \nu_a \bar{\nu}_a$ | 115 | 182 |

Some dependence on mass hierarchy, but does not change the conclusion

most distinctive and robust signature of the existence of massive sterile $\nu_4$ would be a bump in the energy spectrum at $E_{pos}$ >50 MeV




Most favourable parameter space

$$m \simeq 200 - 300\,\mathrm{MeV}$$
$$\sin^2\theta_{\tau 4} \simeq 10^{-6} - 10^{-7}$$

# Conclusions

- Revisited implications of SNae for massive sterile $\nu$'s (MeV~0.4 GeV range), as motivated in low-scale models of $\nu$ masses
- Most interesting open parameter space is mixing in the $\nu_\tau$ sector. SN bound + possible peculiar signatures (high-*E* bump!) in existing and forthcoming $\nu$ detectors.
- Motivates further studies: peculiar nucleosynthesis patter, peculiar *E*-transfer in the high-mixing regime, exact reach in parameter space for future detectors.

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Cảm ơn