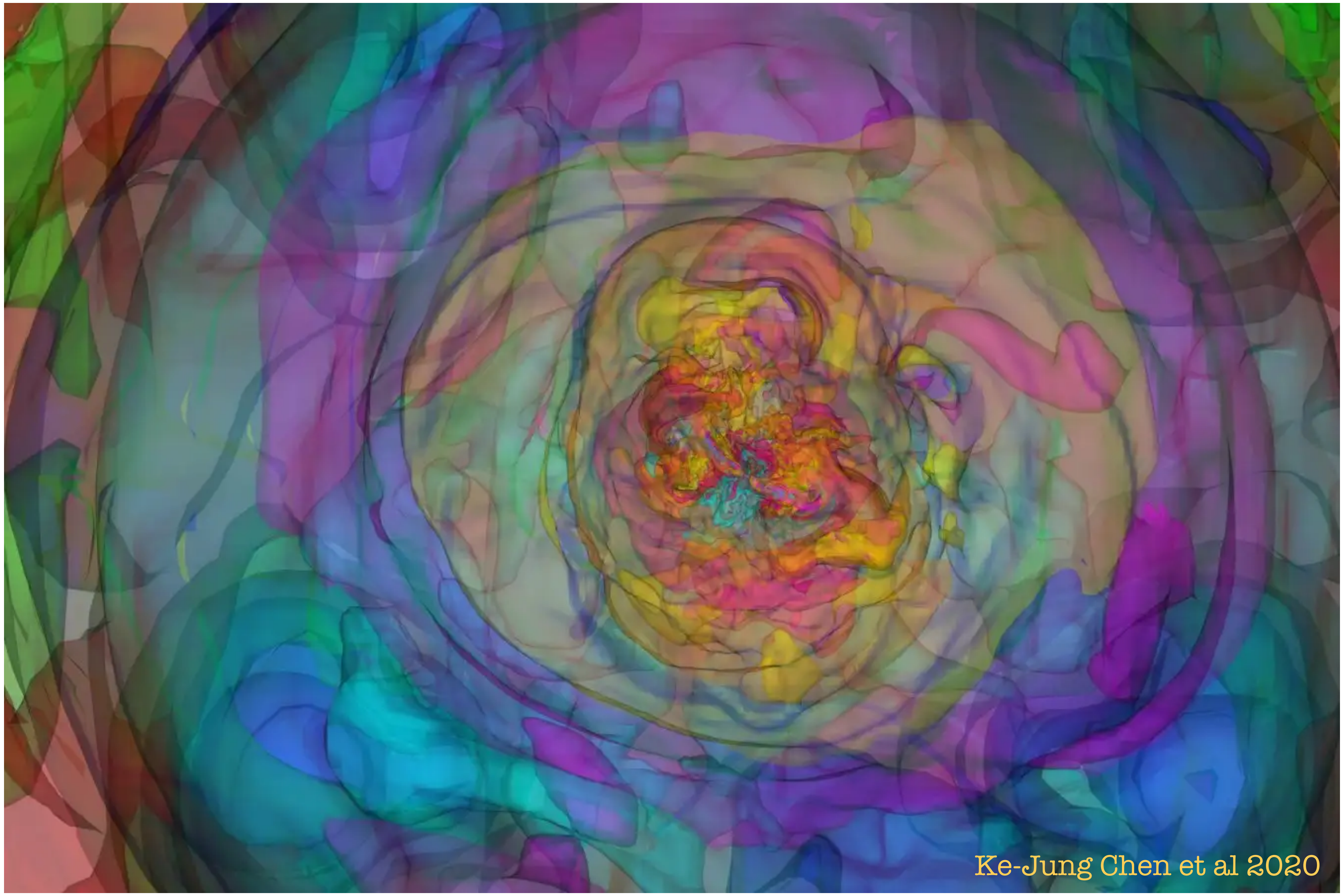
# Constraints on new physics from core collapse supernovae


Ke-Jung Chen et al 2020

Pasquale Dario Serpico (Annecy, France)

UNDARK kickoff meeting,
8-11/10/2014, IAC - La Laguna, Tenerife

Funded by
the European Union

# Plan

I. Generalities on core-collapse SNae

II. How to constrain new physics?

III. Example: massive (MeV-GeV) sterile $\nu$'s

Original results mostly based on P. Carenza et al Phys.Rev.D 109 (2024) 6, 063010

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***Disclaimer on parts I-II:***

Given the scope of the meeting and the diverse audience, I will provide a basic review of the key physics to trigger general interest

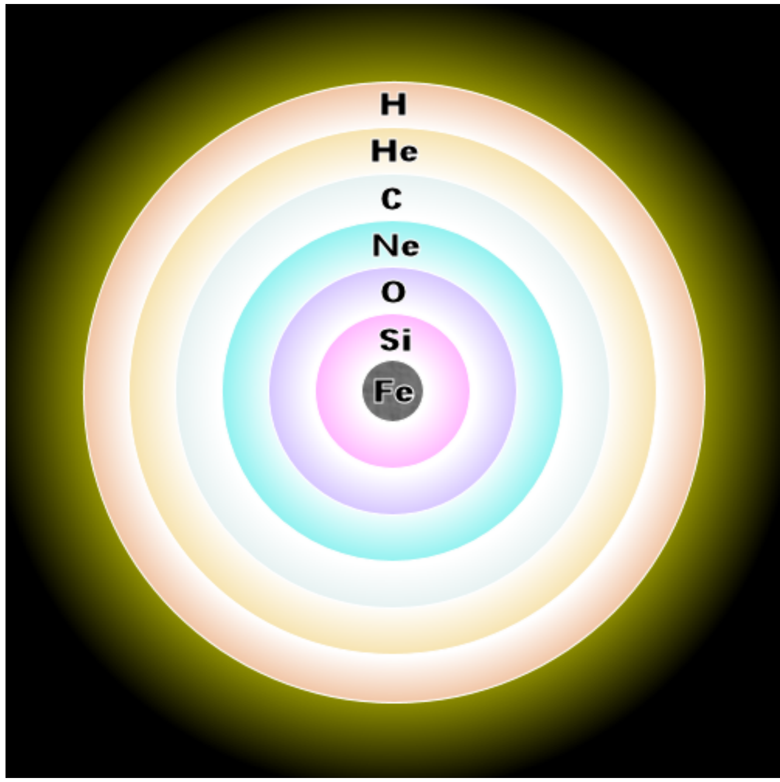
I will not provide reviews of alternatives or controversies, nor give an exhaustive bibliography.

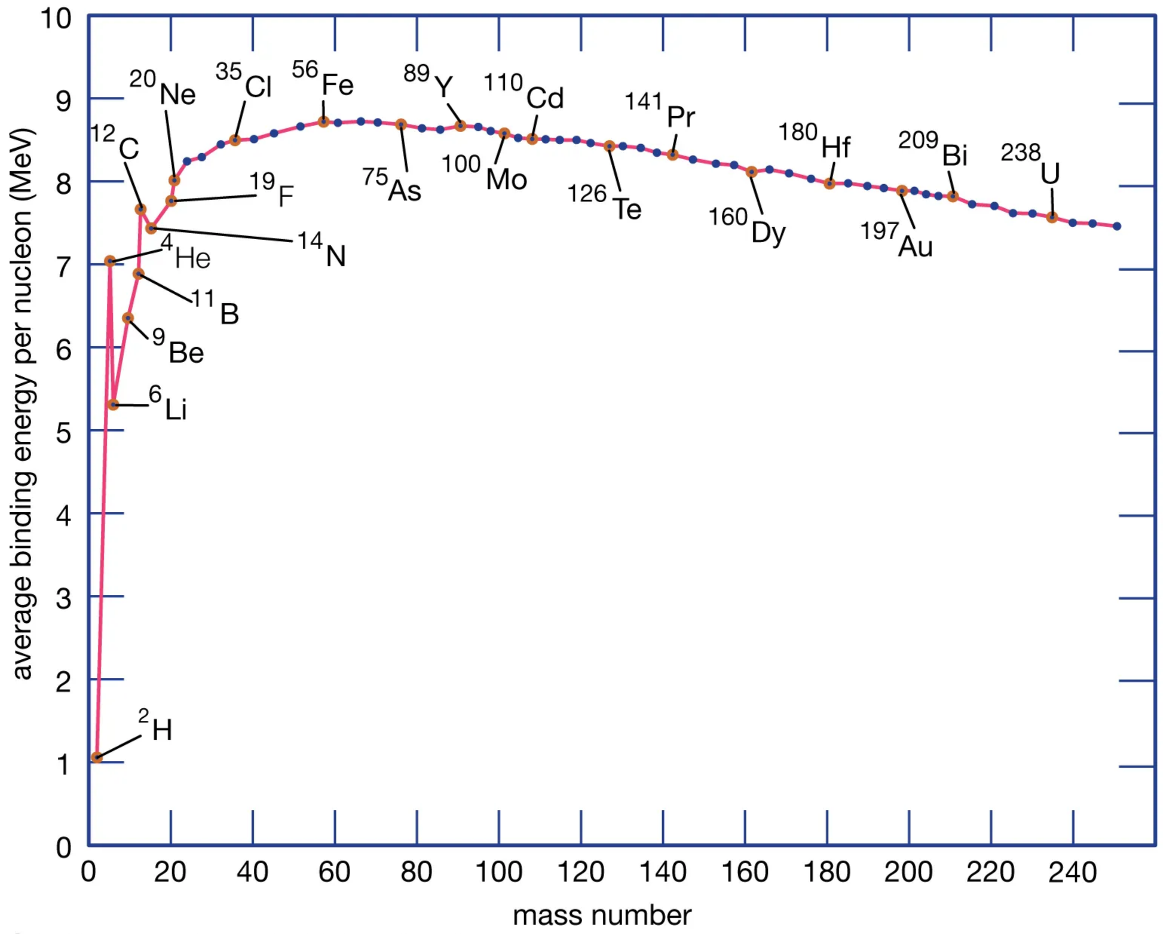
I apologise in advance to experts!

# I. Generalities on (core collapse) SNae

# Stellar collapse & SN explosion

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





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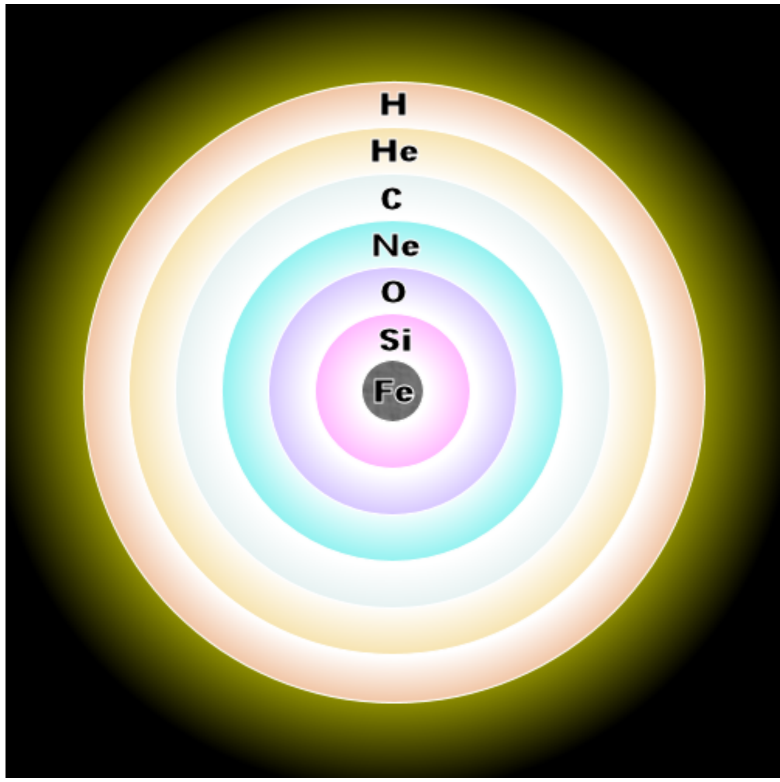
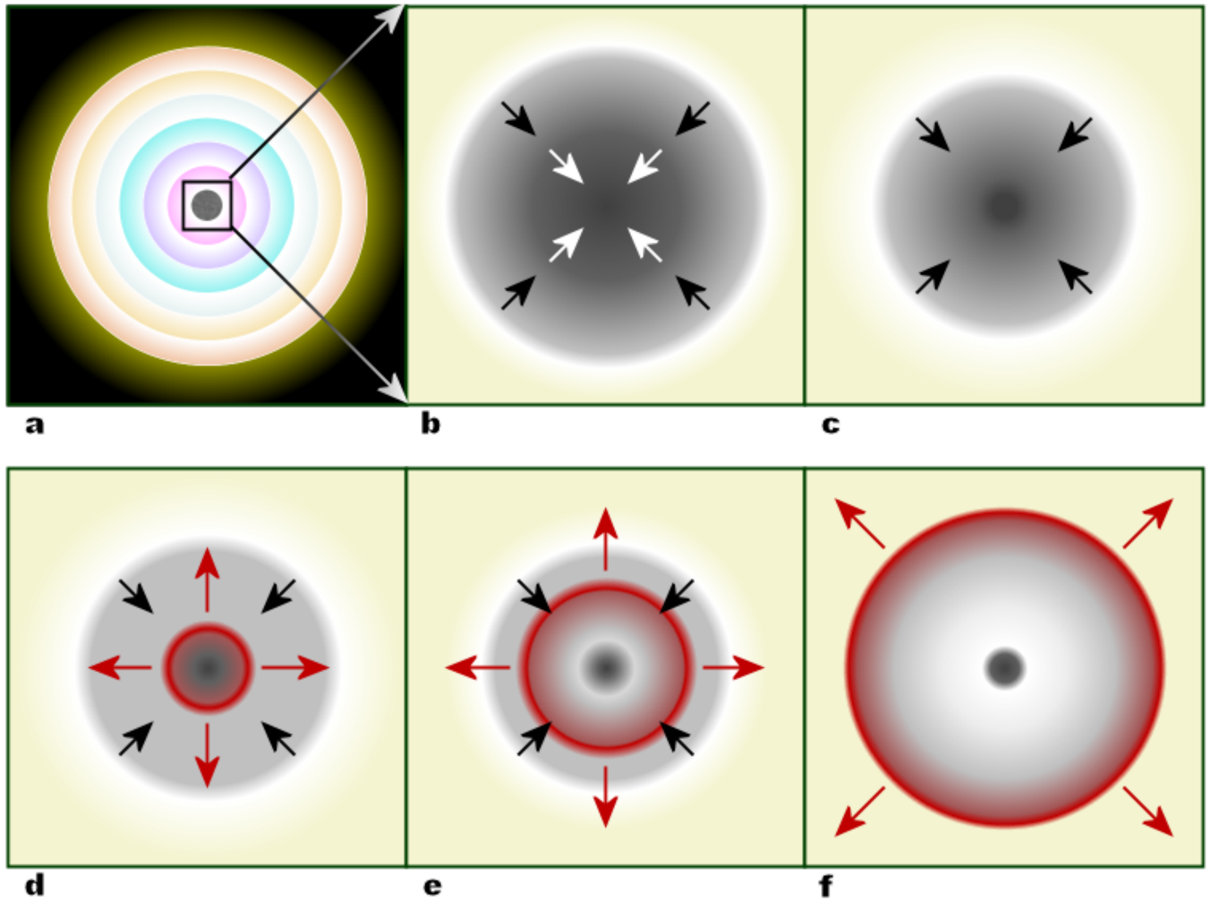
# Stellar collapse & SN explosion

- 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)





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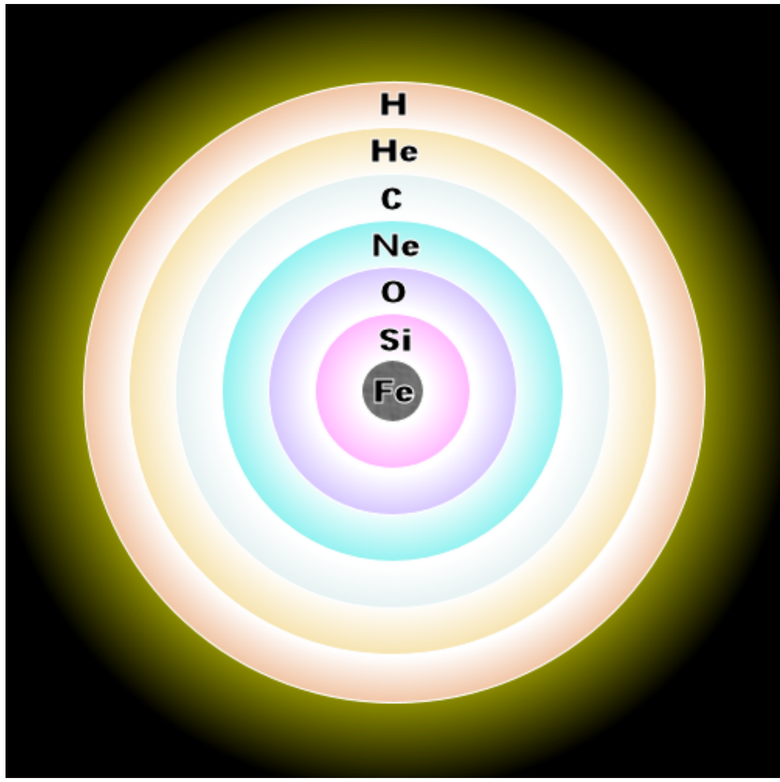
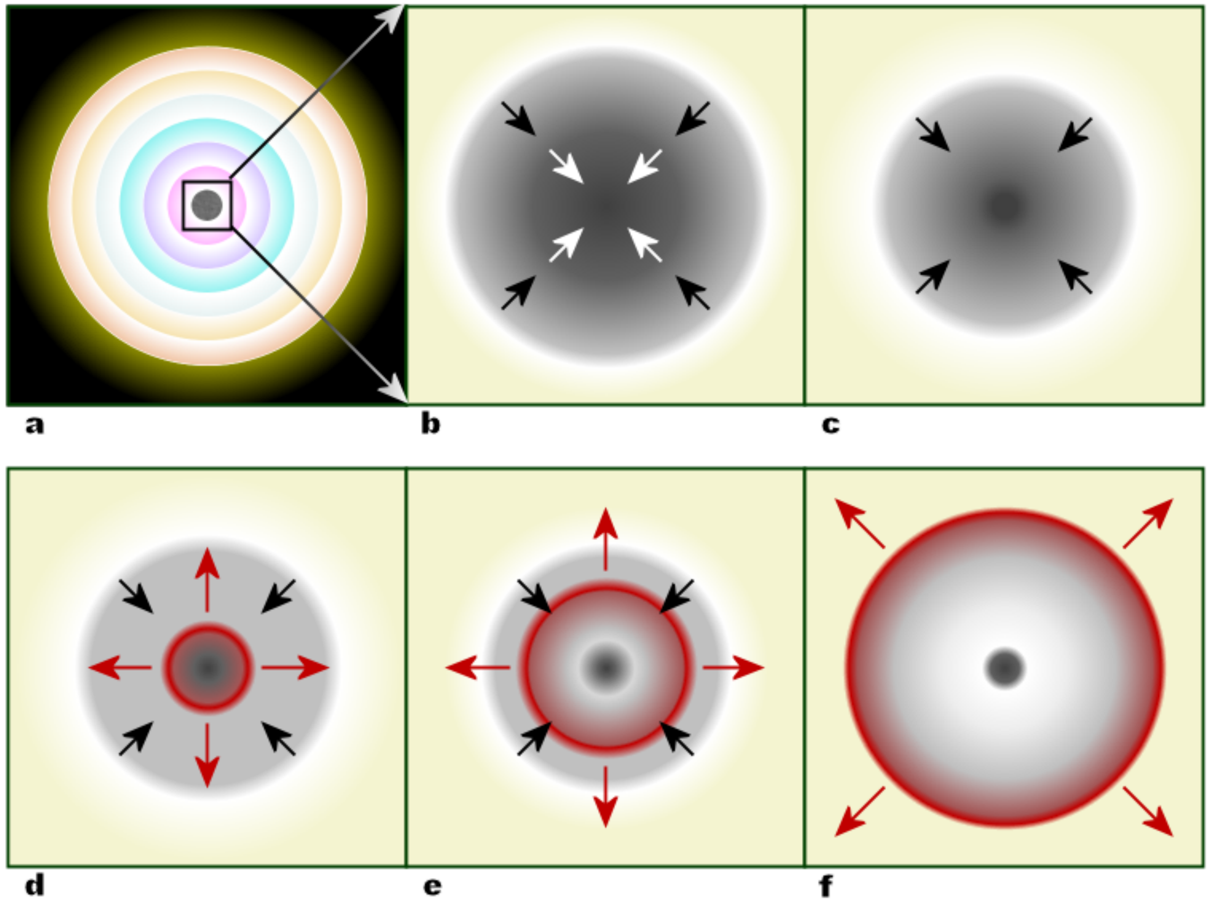




**What's next?**
**Neutrinos to the rescue!**

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!

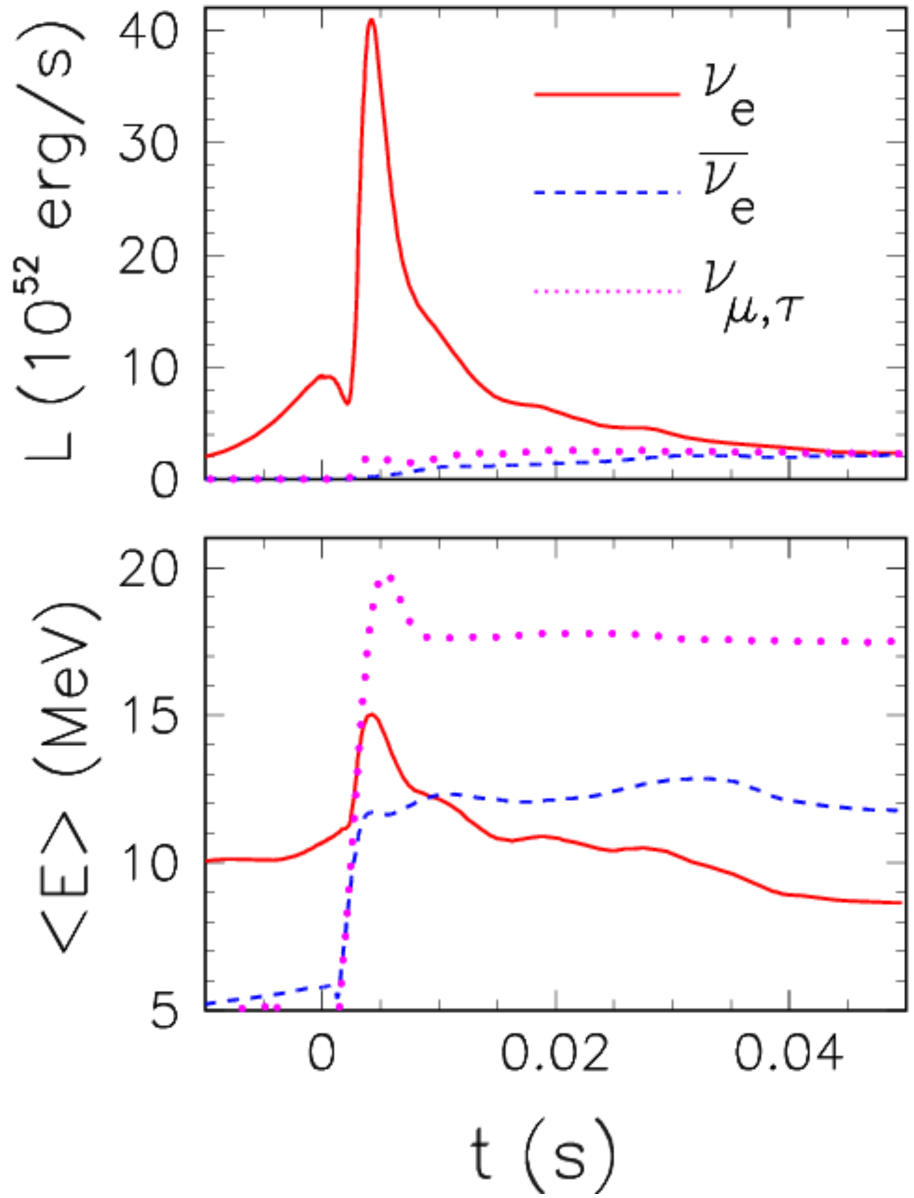
*Delayed ν-heating (Bethe & Wilson '85)*

# Three phases of neutrino emission

Figures adapted from Fischer et al., 0908.1871, 10. 8 $M_\odot$ progenitor mass
(spherical symmetry with Boltzmnann $\nu$ transport)

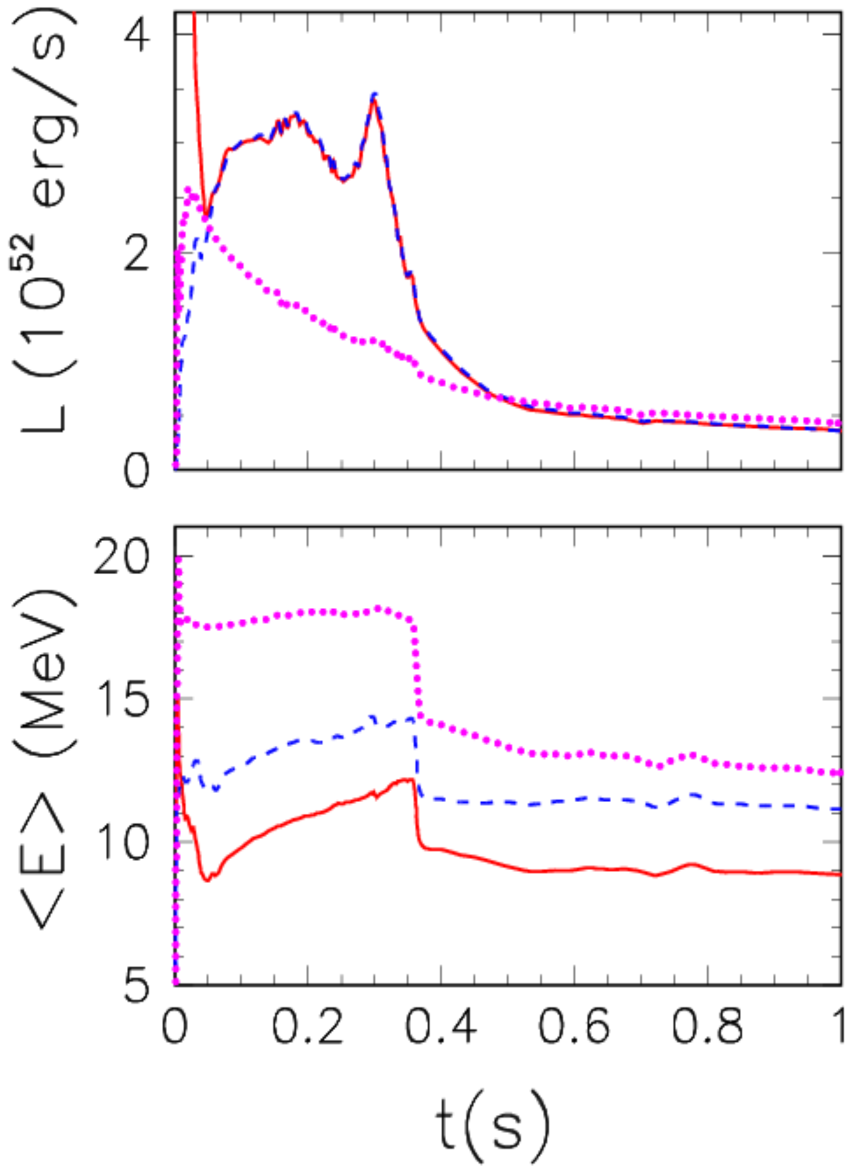
### Neutronization Burst

- **Shock breakout**
- **De-leptonization ($e+p\rightarrow n+\nu_e$) of outer core layers**



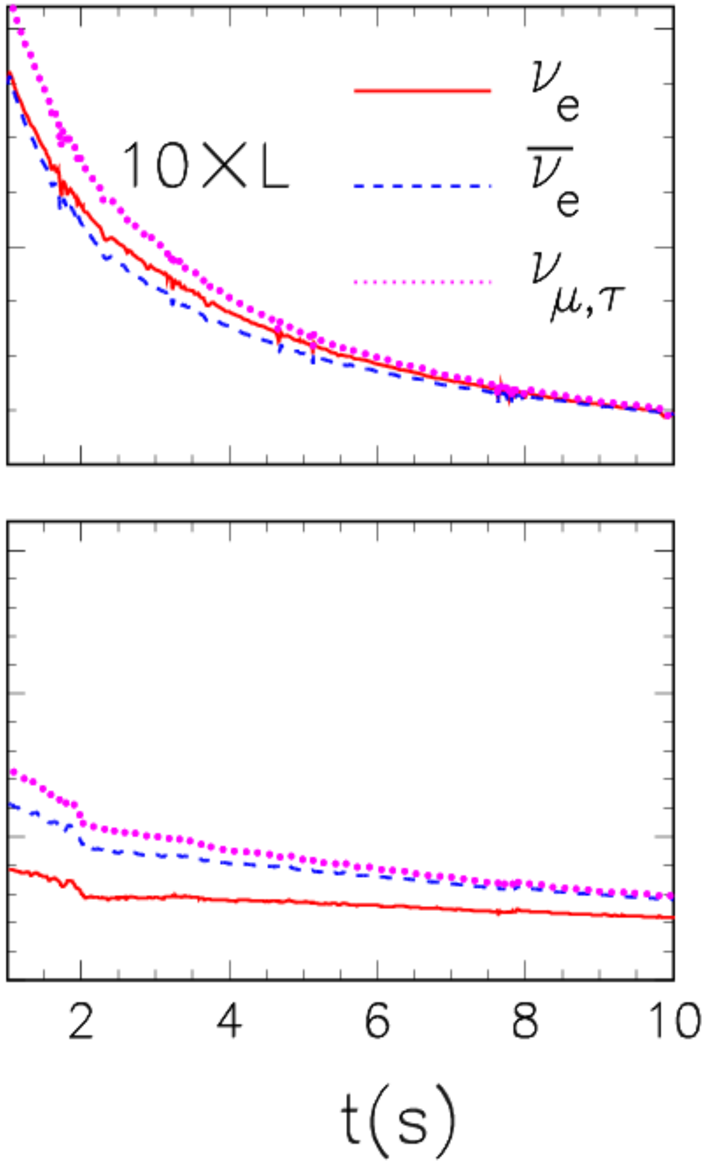
### Accretion

- **Shock stalls ~ 150 km**
- **$\nu$ powered by infalling matter**



### Cooling

- **Cooling on $\nu$ diffusion time scale**



# Emission timescale

Neutrinos are trapped in the core, emitted "diffusively", i.e.

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$$\boxed{t_{\mathrm{diff}} \sim 1\,\mathrm{s}\left(\frac{R}{10\,\mathrm{km}}\right)^2\left(\frac{E}{100\,\mathrm{MeV}}\right)^2}$$

Nuclear densities and weak interactions determine the scale!

# Energy scale set by gravity

**Gravitational binding energy**
(Collapse to a NS,
M~1.5 M⊙, R~15 km)

$$|U| \simeq \frac{3}{5}\frac{GM^2}{R} \sim 0.15 M_\odot c^2 \sim \text{few} \times 10^{53}\,\text{erg}$$

**Virial theorem**
(self-gravitating system)

$$\langle E_{\text{kin}} \rangle = -\frac{1}{2}\langle \Phi_{\text{grav}} \rangle$$

For a nucleon at the proto-neutron star

$$\langle \Phi_{\text{grav}} \rangle \simeq -\frac{3}{2}\frac{G_{\text{N}} M\, m_N}{R} \simeq -200\,\text{MeV}$$

hence

$$E_\nu \lesssim 100\,\text{MeV}$$

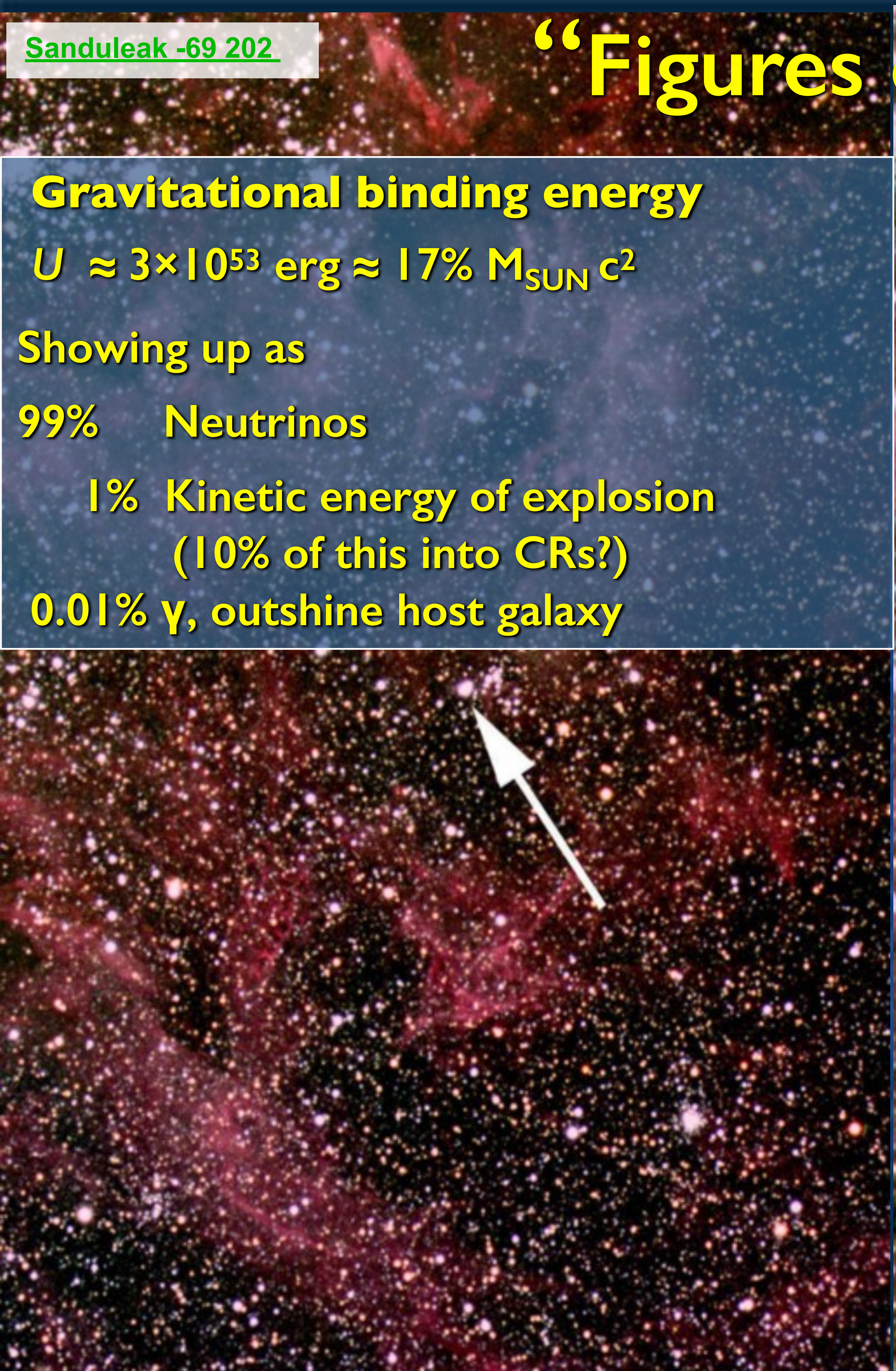
(Note: *E*-losses while diffusing)

# “Figures of merit”

Sanduleak -69 202

Supernova 1987A 23/02/1987

# “Figures of merit”



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**Gravitational binding energy**

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

Showing up as

99% Neutrinos

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

0.01% γ, outshine host galaxy

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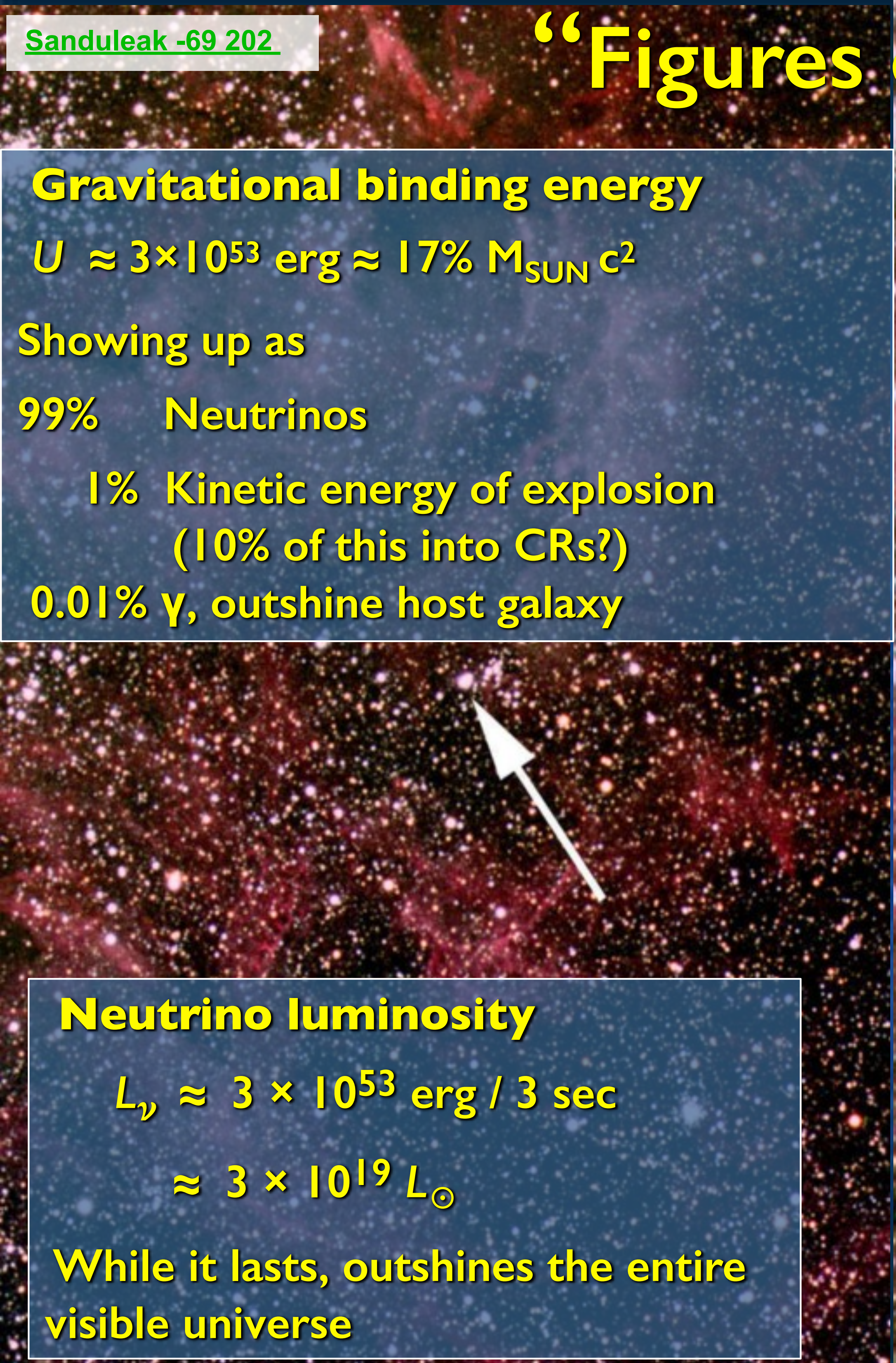

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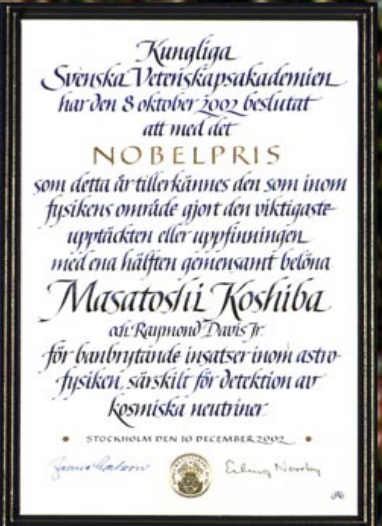
## Rate

Only ~2 collapses/century in the Milky Way (but timescale comparable with large XXIth century accelerator projects...)

2002 Nobel Prize



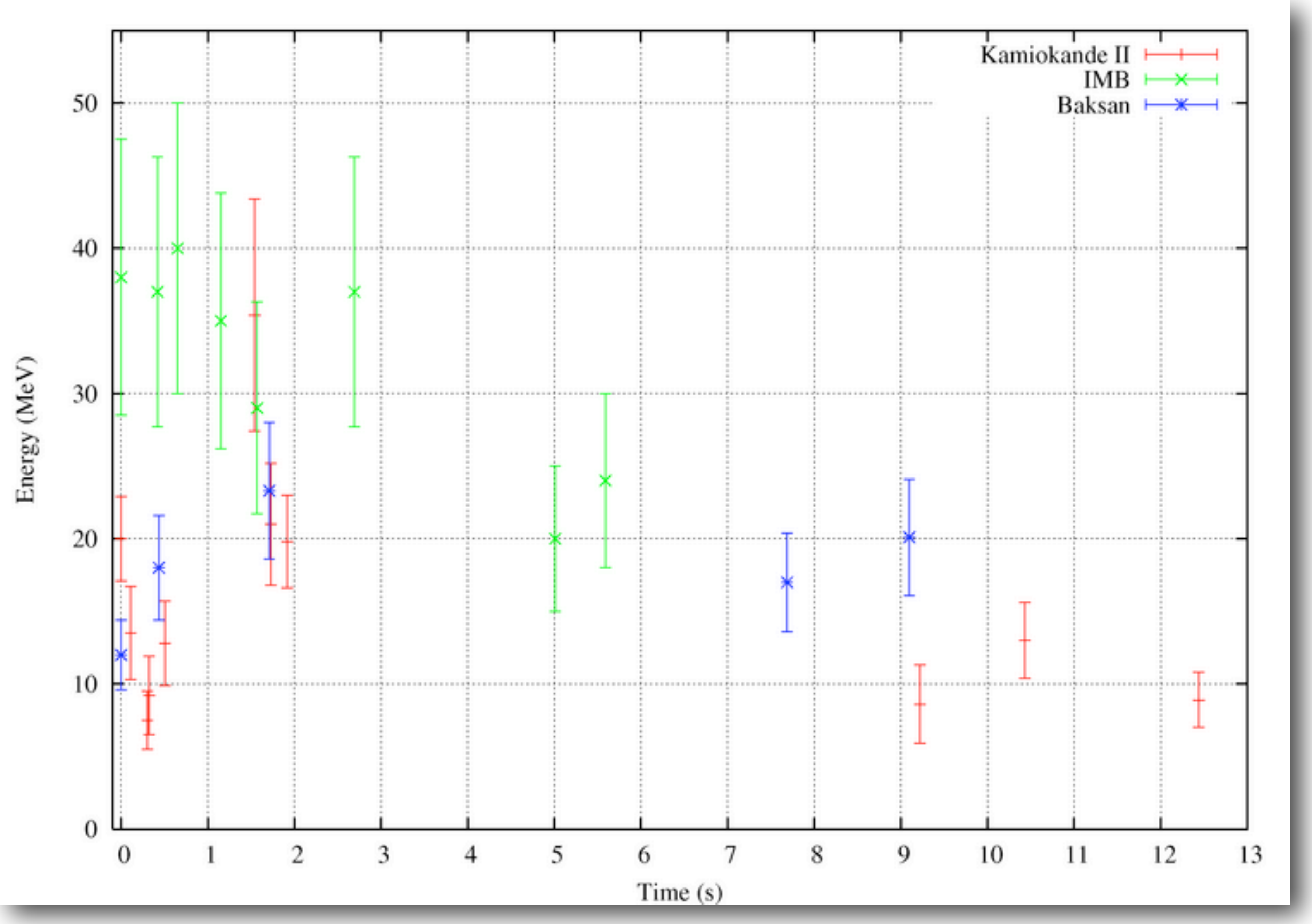
Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2002 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
upptäckten eller uppfinningen
med ena hälften gemensamt belöna
Masatoshi Koshiba
och Raymond Davis Jr.
för banbrytande insatser inom astro-
fysiken, särskilt för detektion av
kosmiska neutriner

STOCKHOLM DEN 10 DECEMBER 2002

Erling Norrby

# 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



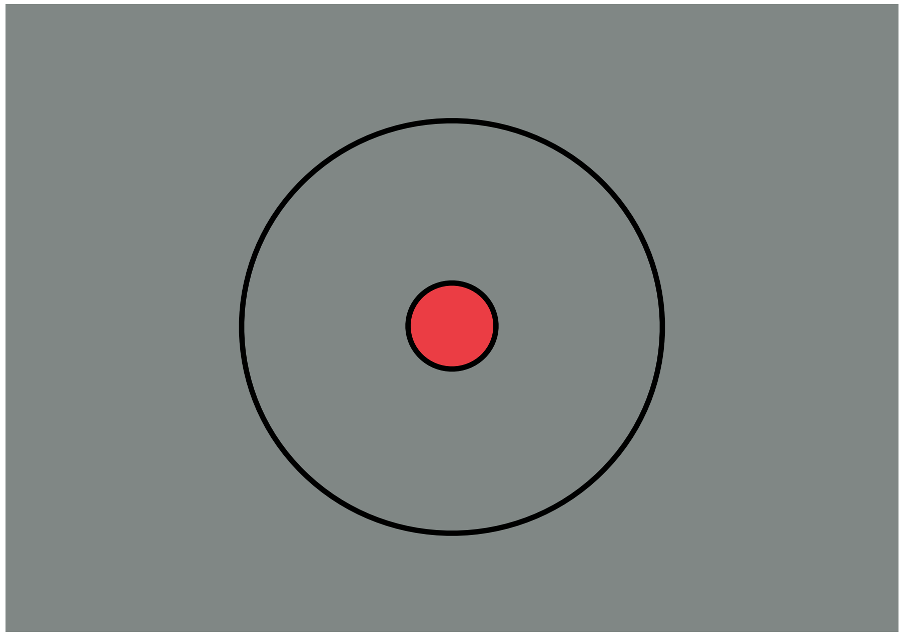
No hint for extra *E*-loss channels; future high-statistics signal (SK, HK, IC…): Room for surprises?

# II. Constraints to new physics: Why/how?

*(Each can be turned into a signature…)*

# Cannot cool too fast : signal duration

**Cooling time ~ *U*/*L***
If extra cooling source beyond known $\nu$'s,
*L* increases, the signal shortens



*Ideal coolant (best constraints):* particles *copiously produced* in the core, but *freely escaping* (do not pay the diffusive price to stream out)

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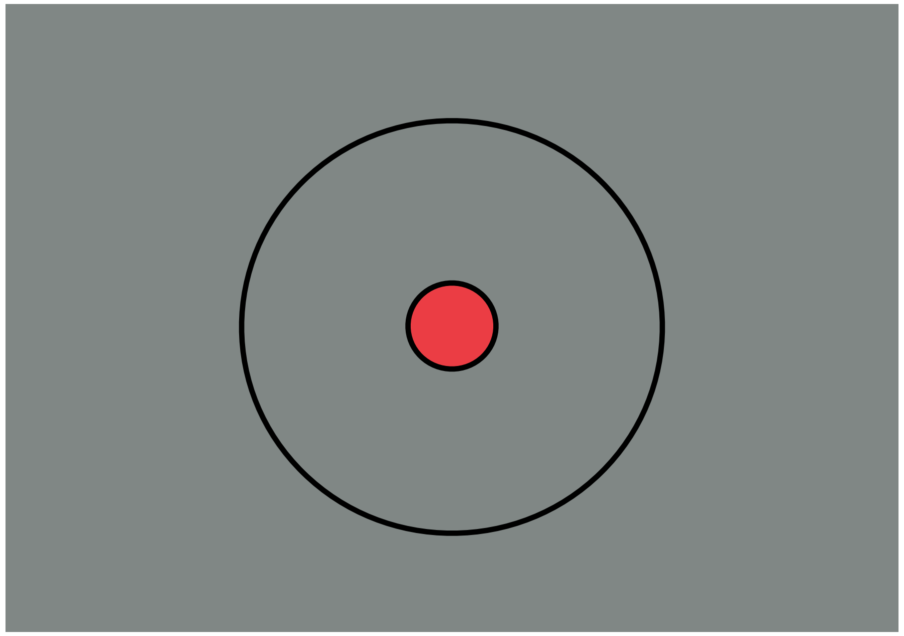

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$L_x \lesssim$ (fudge factor) $L_\nu$

Rough constraint on exotics imposed by SN1987A & validated by simulations

Translates into luminosity/unit mass= **emissivity** $\lesssim 10^{19}$ ergs $g^{-1}\,s^{-1}$ *(Raffelt criterion)*

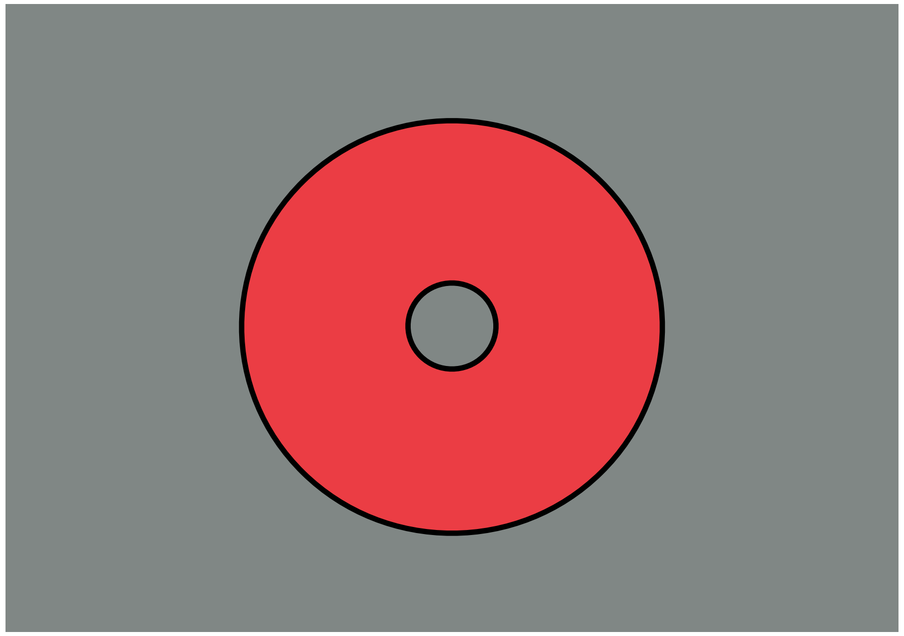
$L_x$ depends on (high) powers of coupling, hence little dependence on fudge factor.

# Explosion cannot be too energetic

If

**Core radius< $\lambda_x$ (mean-free-path) <Stellar Radius**

can raise the deposited energy, leading to too energetic explosions, compared to the weakest ones observed.



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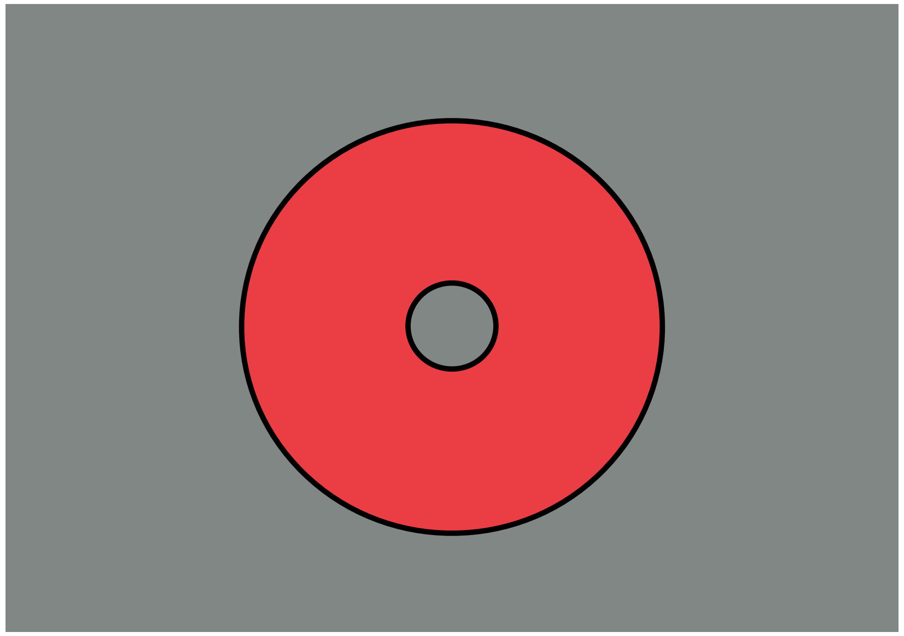


Current studies suggest the bound into energy released in e.m. form at the level of

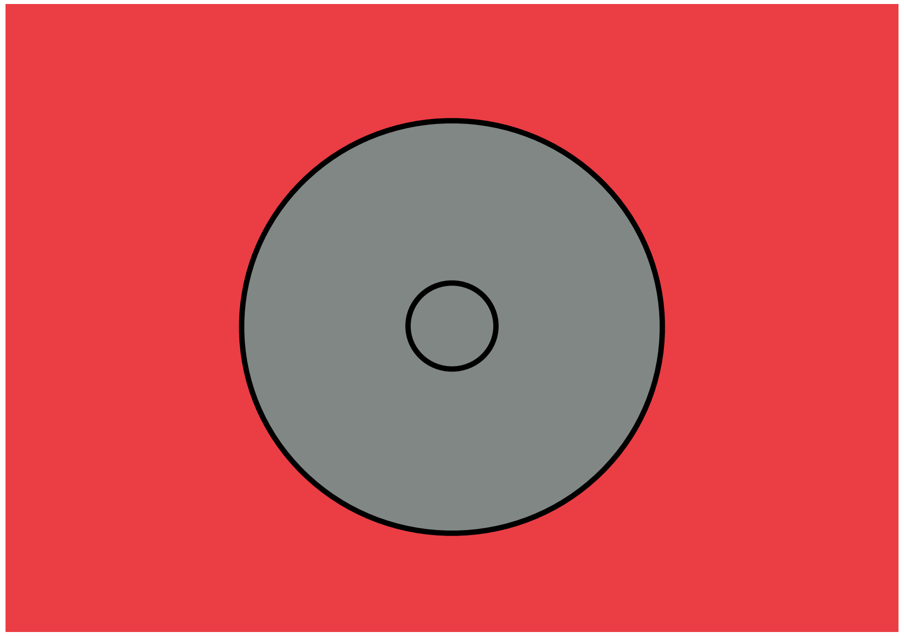
$E<E_{vis} \sim 10^{50}\text{-}10^{51}$ erg

(Typically applied to *decaying particles*, or to scattering mfp with electrons/baryons)

# $\nu$ & $\gamma$ emission can't exceed measurements

The emission 'outside the star', in photons (soft gammas) or neutrinos should be consistent with upper limits / detected spectra

Can be applied to SN1987A, to SNe in the Milky Way, or to SN all over universe



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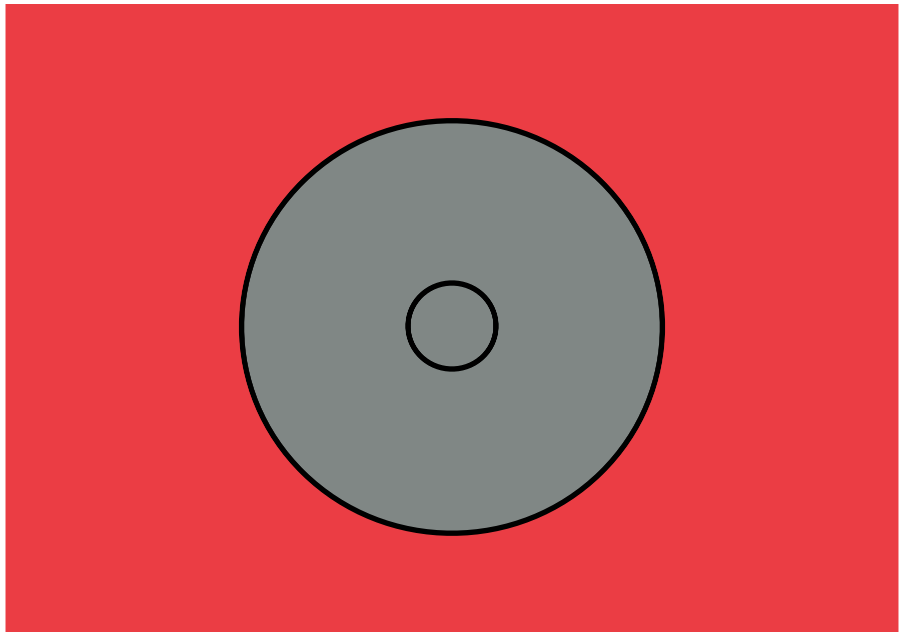
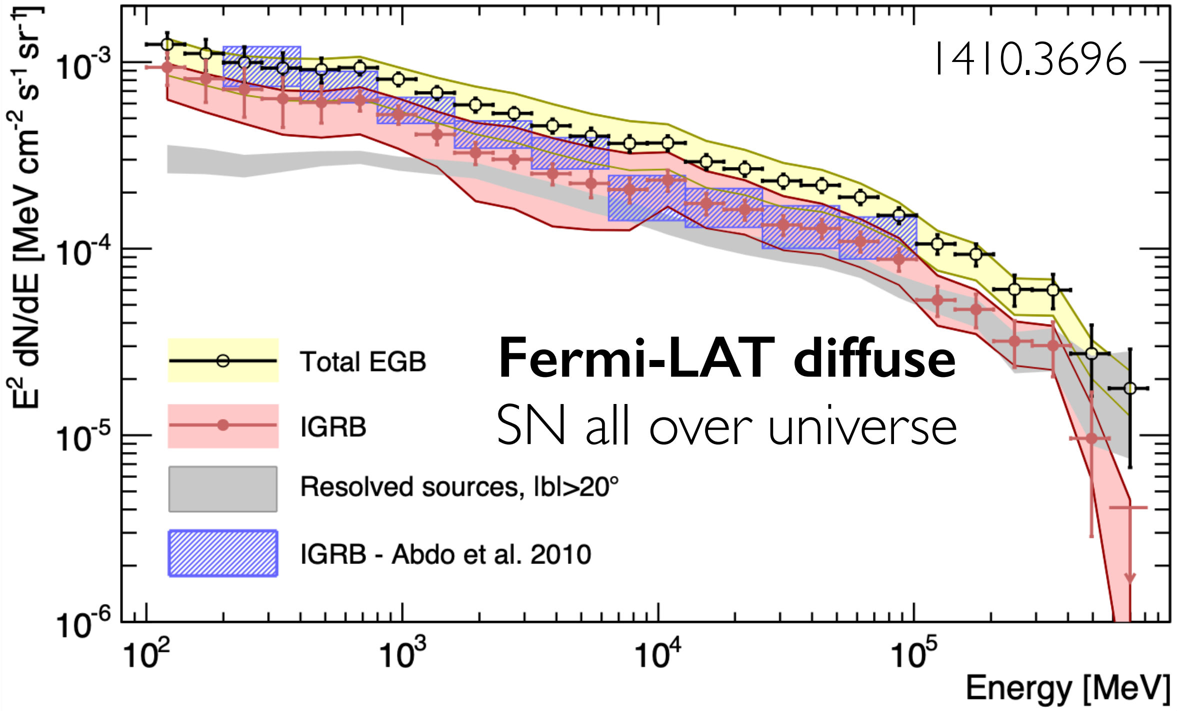


**NASA Solar Maximum Mission**

no photons above background @ 25 < E (MeV)<100 for 232.2 s after the first SN1987A $\boldsymbol{\nu}$ arrival.

$\Phi_\gamma \lesssim 1.38\ \mathrm{cm}^{-2}$



**Fermi-LAT diffuse**

SN all over universe

X-ray / soft-gamma (XMM-Newton, Integral…): emitted positrons, eventually annihilating, contribute to a diffusion-established steady-state Galactic signal

# Which particle physics models/parameters?

**Mostly those involving light** (sub-GeV, kinematically accessible) **and weakly coupled** (to escape the core, interact little/decay sufficiently far) **states**

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**Often of the "portal" type** (renormalisable operators extending the SM)

$\epsilon F'_{\mu\nu} F_Y^{\mu\nu} \subset \mathcal{L}_V$ **Vector coupled to hypercharge**

$\epsilon S^2 |H|^2 \subset \mathcal{L}_S$ **Neutral singlet scalar**

$\epsilon (L\,H) N \subset \mathcal{L}_N$ **Neutral singlet fermion**
(Typically with flavour structure)

[dim 5, NR] $\frac{a}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu} \subset \mathcal{L}_a$ **Neutral (pseudo)scalar**

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**Or violation of symmetries, like L-violation; typically not as competitive;**
see Kolb, Tubbs and Dicus, ApJL 255 (1982), L57 or Lychkovskiy, Blinnikov, and Vysotsky 1010.0883

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

Working in mixing the 2-flavour limit,

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

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

for small mixing

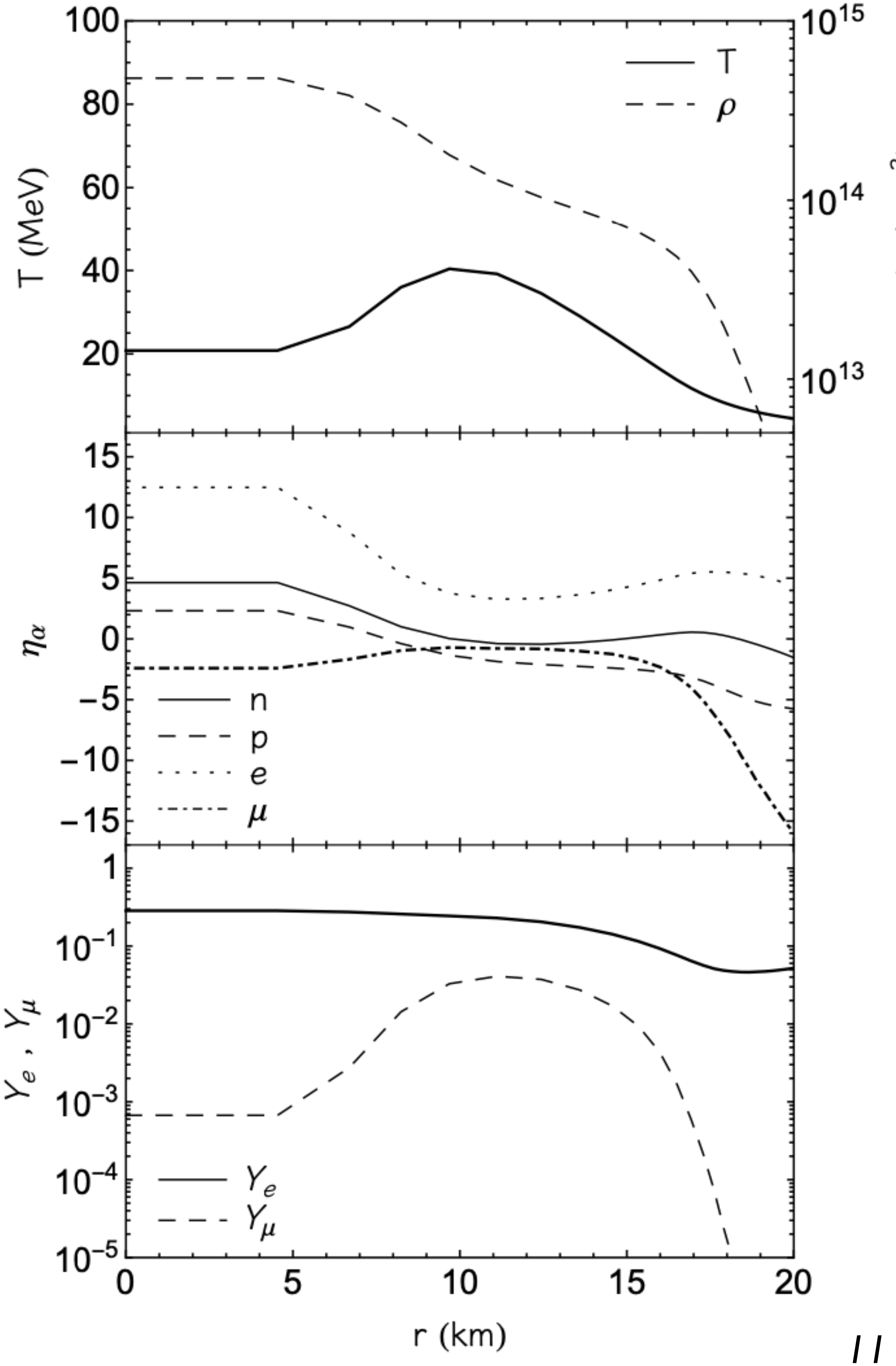
when one can loosely identify $\nu_4 \sim \nu_s$

# The Supernova model

- **Focus on the cooling phase of a *18 $M_\odot$* SN progenitor** (1D spherical symmetry; GR hydro model, based on the AGILE BOLTZTRAN code)
- **FD distributions assumed for the active leptons** (note degenerate e, mildly degenerate *n,p*!)
- **Mean field treatment for nucleon distributions**
- **Inclusion of $\mu$'s** (non-vanishing bckg density)

$$\eta_i = \frac{\mu_i - m_i}{T}$$

$$Y_e = \frac{n_e m_p}{\rho} \to \frac{Z}{A}$$



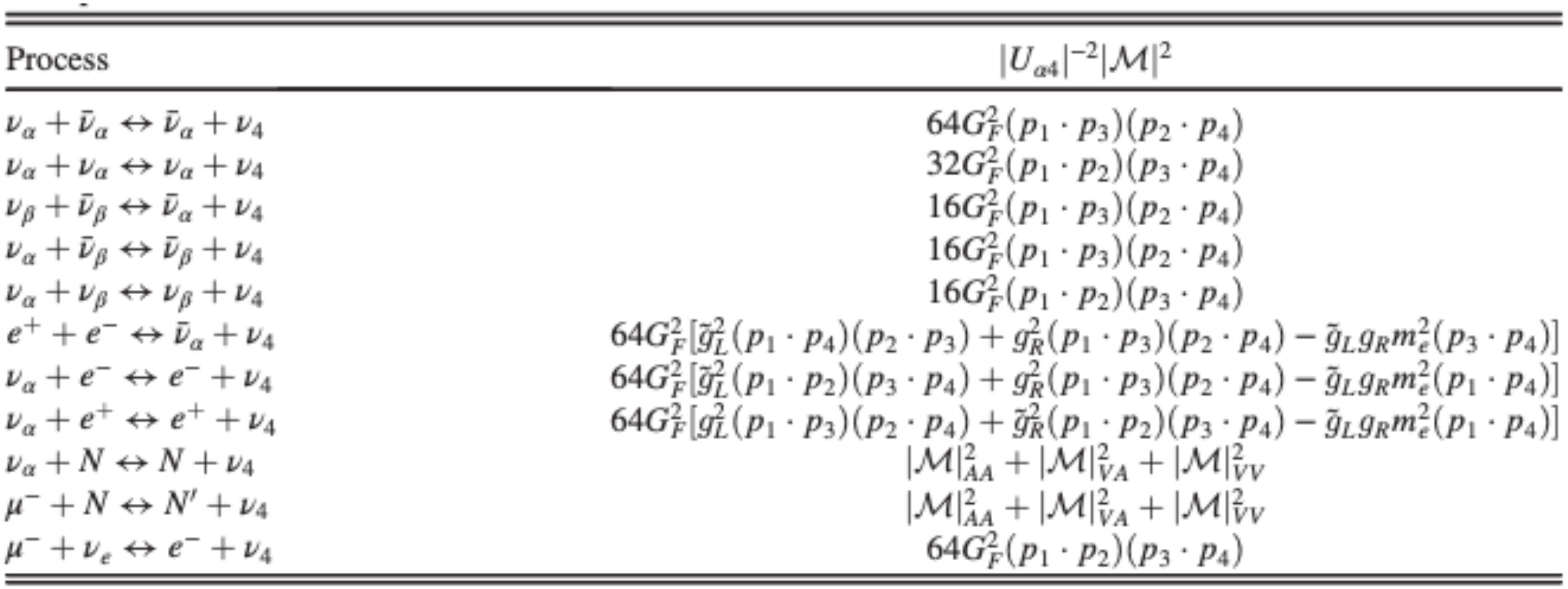
# Sterile neutrino production

- ‘Perturbative’ approach: reference SN solution used as background for the collisional (not oscillation, negligible!) production of sterile neutrinos.

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

$$\mathcal{C}_{\rm coll} = \frac{1}{2E_s}\int d^3\hat{p}_2 d^3\hat{p}_3 d^3\hat{p}_4 \Lambda(f_s, f_2, f_3, f_4) S|M|^2_{12\to 34}\delta^4(p_s + p_2 - p_3 - p_4)(2\pi)^4$$

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



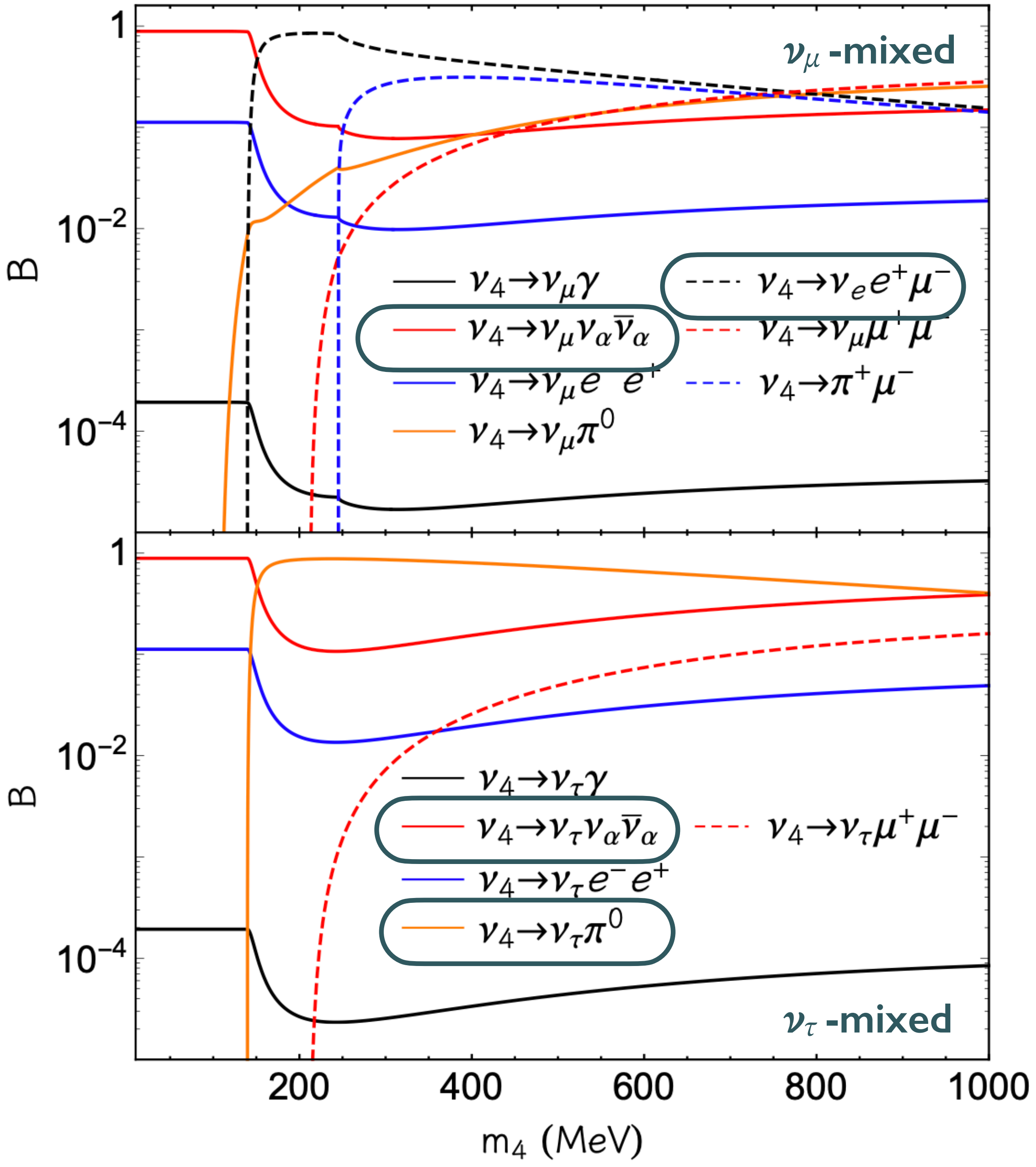
| Process | $\lvert U_{\alpha 4}\rvert^{-2}\lvert\mathcal{M}\rvert^2$ |
|---|---|
| $\nu_\alpha + \bar{\nu}_\alpha \leftrightarrow \bar{\nu}_\alpha + \nu_4$ | $64G_F^2(p_1\cdot p_3)(p_2\cdot p_4)$ |
| $\nu_\alpha + \nu_\alpha \leftrightarrow \nu_\alpha + \nu_4$ | $32G_F^2(p_1\cdot p_2)(p_3\cdot p_4)$ |
| $\nu_\beta + \bar{\nu}_\beta \leftrightarrow \bar{\nu}_\alpha + \nu_4$ | $16G_F^2(p_1\cdot p_3)(p_2\cdot p_4)$ |
| $\nu_\alpha + \bar{\nu}_\beta \leftrightarrow \bar{\nu}_\beta + \nu_4$ | $16G_F^2(p_1\cdot p_3)(p_2\cdot p_4)$ |
| $\nu_\alpha + \nu_\beta \leftrightarrow \nu_\beta + \nu_4$ | $16G_F^2(p_1\cdot p_2)(p_3\cdot p_4)$ |
| $e^+ + e^- \leftrightarrow \bar{\nu}_\alpha + \nu_4$ | $64G_F^2[\tilde{g}_L^2(p_1\cdot p_4)(p_2\cdot p_3) + g_R^2(p_1\cdot p_3)(p_2\cdot p_4) - \tilde{g}_L g_R m_e^2(p_3\cdot p_4)]$ |
| $\nu_\alpha + e^- \leftrightarrow e^- + \nu_4$ | $64G_F^2[\tilde{g}_L^2(p_1\cdot p_2)(p_3\cdot p_4) + g_R^2(p_1\cdot p_3)(p_2\cdot p_4) - \tilde{g}_L g_R m_e^2(p_1\cdot p_4)]$ |
| $\nu_\alpha + e^+ \leftrightarrow e^+ + \nu_4$ | $64G_F^2[g_L^2(p_1\cdot p_3)(p_2\cdot p_4) + \tilde{g}_R^2(p_1\cdot p_2)(p_3\cdot p_4) - \tilde{g}_L g_R m_e^2(p_1\cdot p_4)]$ |
| $\nu_\alpha + N \leftrightarrow N + \nu_4$ | $\lvert\mathcal{M}\rvert^2_{AA} + \lvert\mathcal{M}\rvert^2_{VA} + \lvert\mathcal{M}\rvert^2_{VV}$ |
| $\mu^- + N \leftrightarrow N' + \nu_4$ | $\lvert\mathcal{M}\rvert^2_{AA} + \lvert\mathcal{M}\rvert^2_{VA} + \lvert\mathcal{M}\rvert^2_{VV}$ |
| $\mu^- + \nu_e \leftrightarrow e^- + \nu_4$ | $64G_F^2(p_1\cdot p_2)(p_3\cdot p_4)$ |

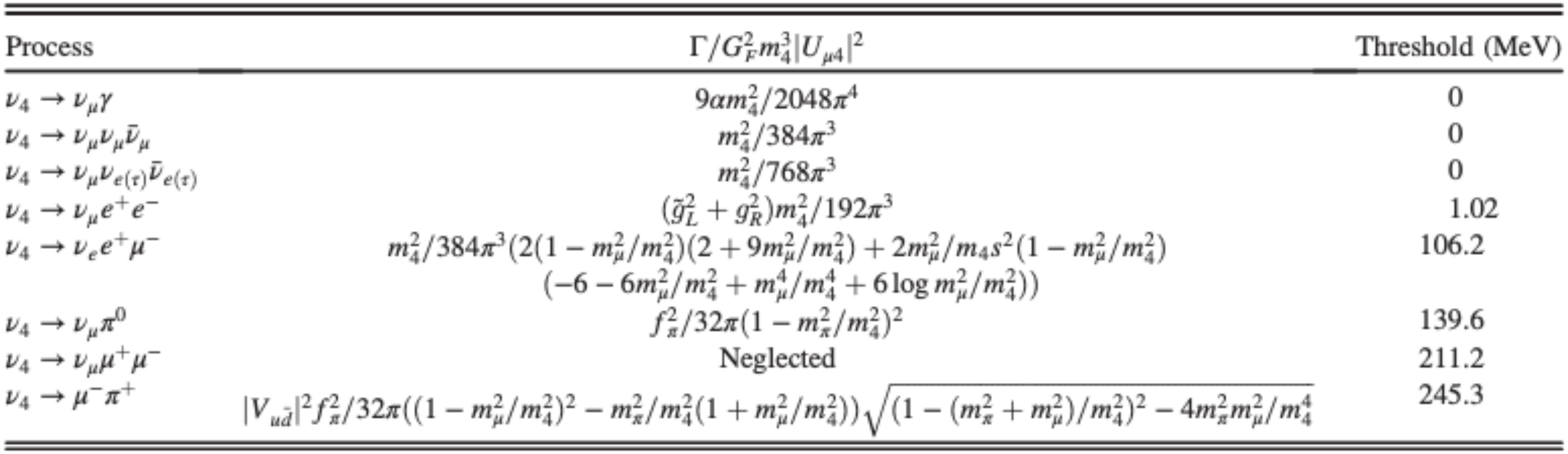
- sterile $\nu$ assumed to free stream and thus $f_s \to 0$ in $\Lambda$

- No feedback, but space & time-dependent calculation

# Sterile neutrino decays

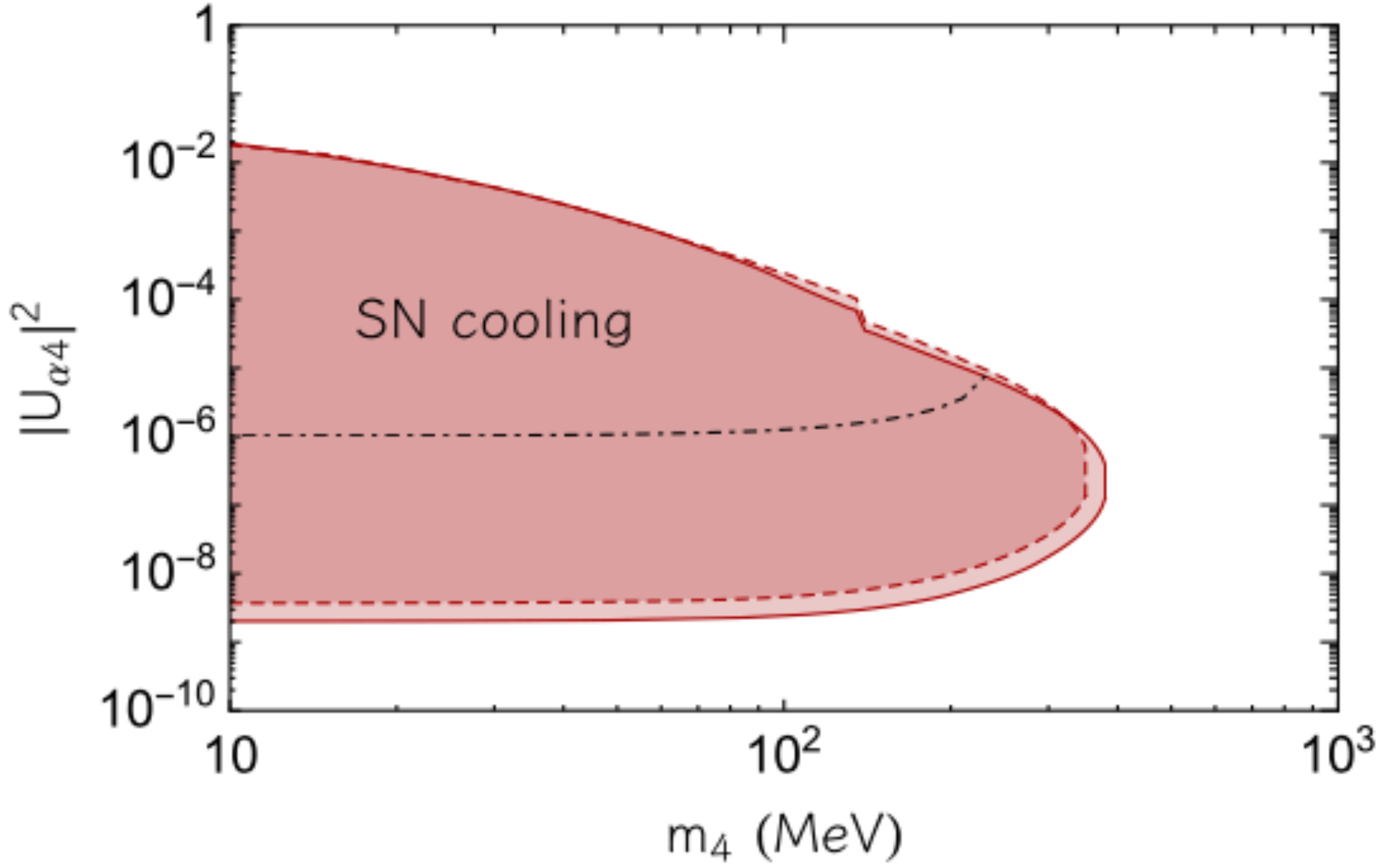
- For *E*-release and out-of-SN signals, crucial to take into account decays
- Significantly different lifetimes and b.r.'s above vs. below the $\mu$,$\boldsymbol{\pi}$ masses; flavour also matters

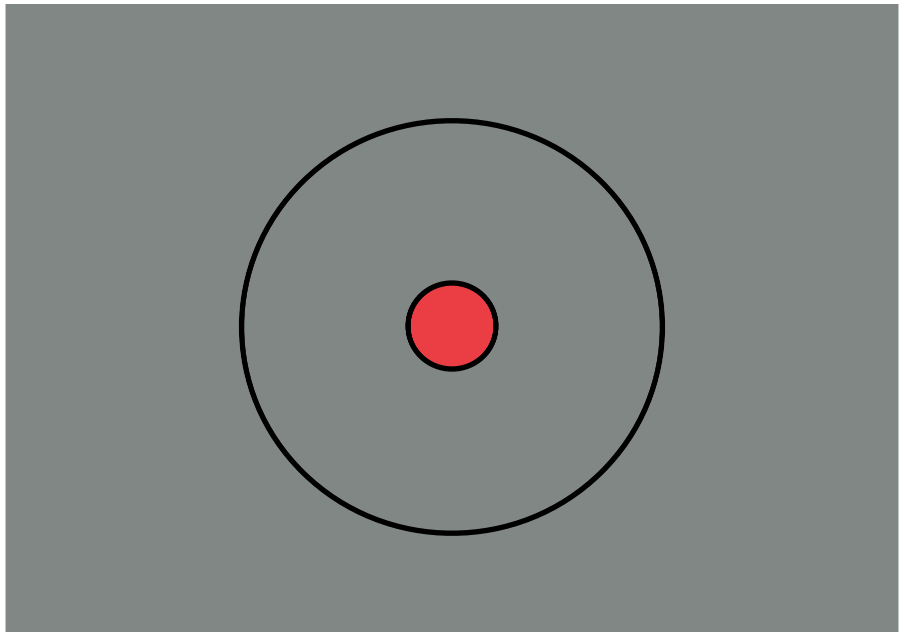




| Process | $\Gamma/G_F^2 m_4^3 \lvert U_{\mu 4}\rvert^2$ | Threshold (MeV) |
|---|---|---|
| $\nu_4 \to \nu_\mu \gamma$ | $9\alpha m_4^2/2048\pi^4$ | 0 |
| $\nu_4 \to \nu_\mu \nu_\mu \bar{\nu}_\mu$ | $m_4^2/384\pi^3$ | 0 |
| $\nu_4 \to \nu_\mu \nu_{e(\tau)} \bar{\nu}_{e(\tau)}$ | $m_4^2/768\pi^3$ | 0 |
| $\nu_4 \to \nu_\mu e^+ e^-$ | $(\tilde{g}_L^2 + g_R^2) m_4^2/192\pi^3$ | 1.02 |
| $\nu_4 \to \nu_e e^+ \mu^-$ | $m_4^2/384\pi^3(2(1 - m_\mu^2/m_4^2)(2 + 9m_\mu^2/m_4^2) + 2m_\mu^2/m_4 s^2(1 - m_\mu^2/m_4^2)$ <br> $(-6 - 6m_\mu^2/m_4^2 + m_\mu^4/m_4^4 + 6\log m_\mu^2/m_4^2))$ | 106.2 |
| $\nu_4 \to \nu_\mu \pi^0$ | $f_\pi^2/32\pi(1 - m_\pi^2/m_4^2)^2$ | 139.6 |
| $\nu_4 \to \nu_\mu \mu^+ \mu^-$ | Neglected | 211.2 |
| $\nu_4 \to \mu^- \pi^+$ | $\lvert V_{u\bar{d}}\rvert^2 f_\pi^2/32\pi((1 - m_\mu^2/m_4^2)^2 - m_\pi^2/m_4^2(1 + m_\mu^2/m_4^2))\sqrt{(1 - (m_\pi^2 + m_\mu^2)/m_4^2)^2 - 4m_\pi^2 m_\mu^2/m_4^4}$ | 245.3 |

# Constraints from cooling & explosion energy

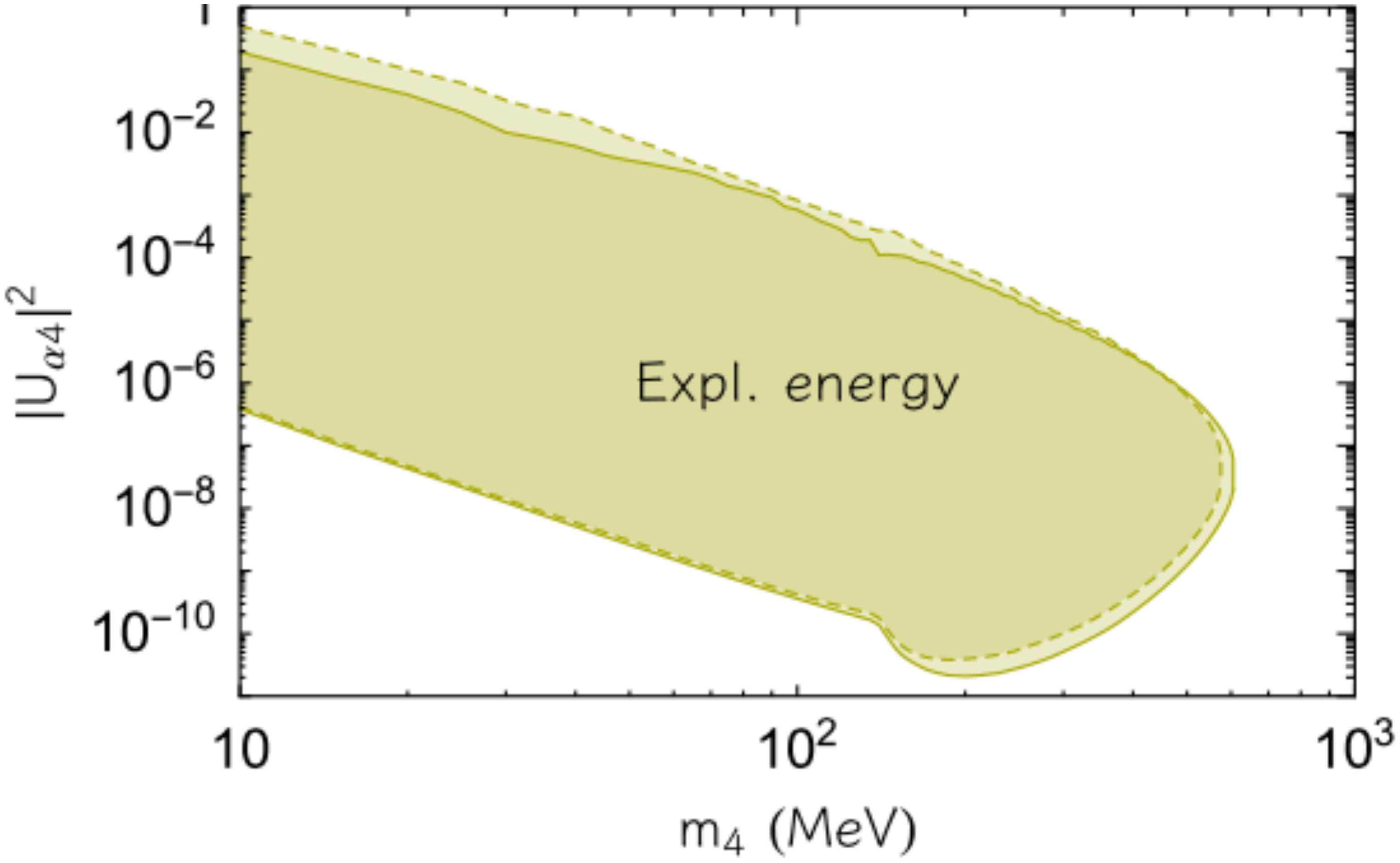


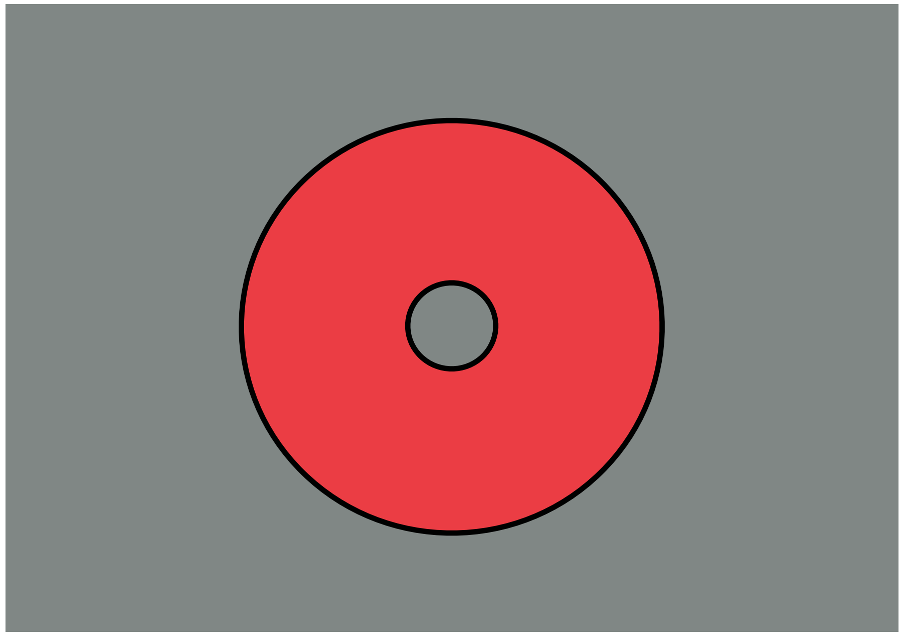


Solid : $\nu_\mu$ -mixed

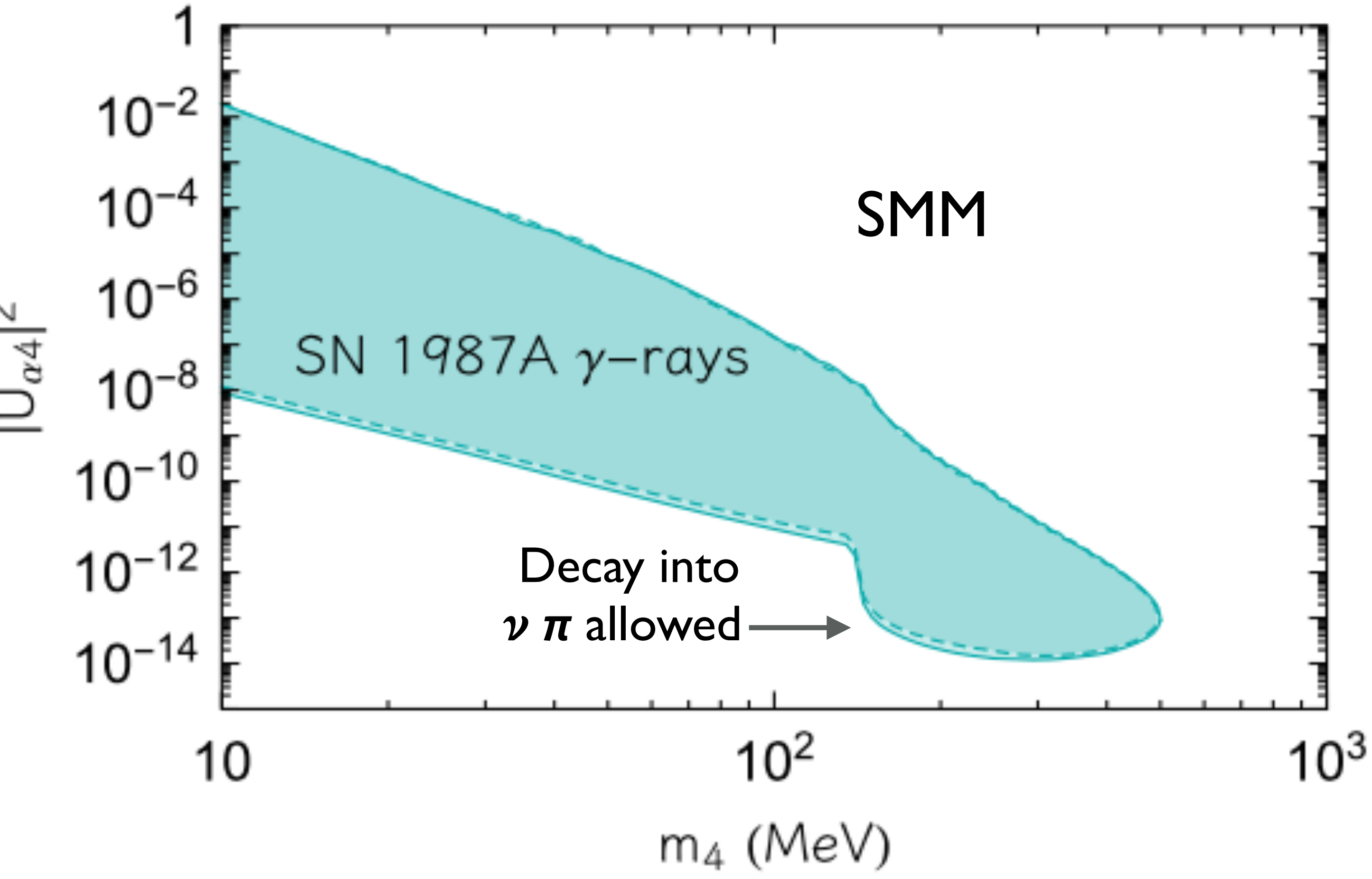
Dashed : $\nu_\tau$ -mixed

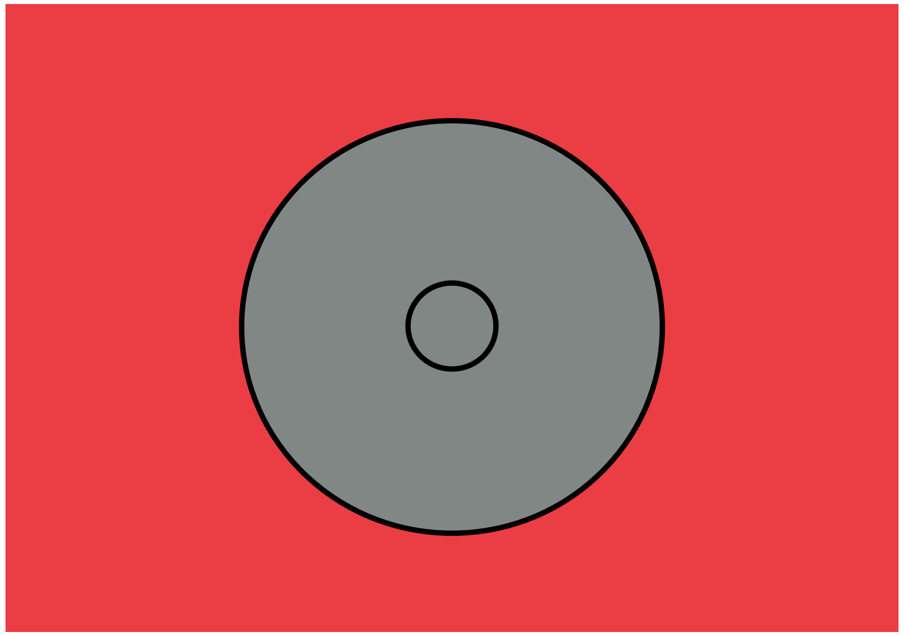
Dot-dashed : NC scattering with $p,n$ neglected

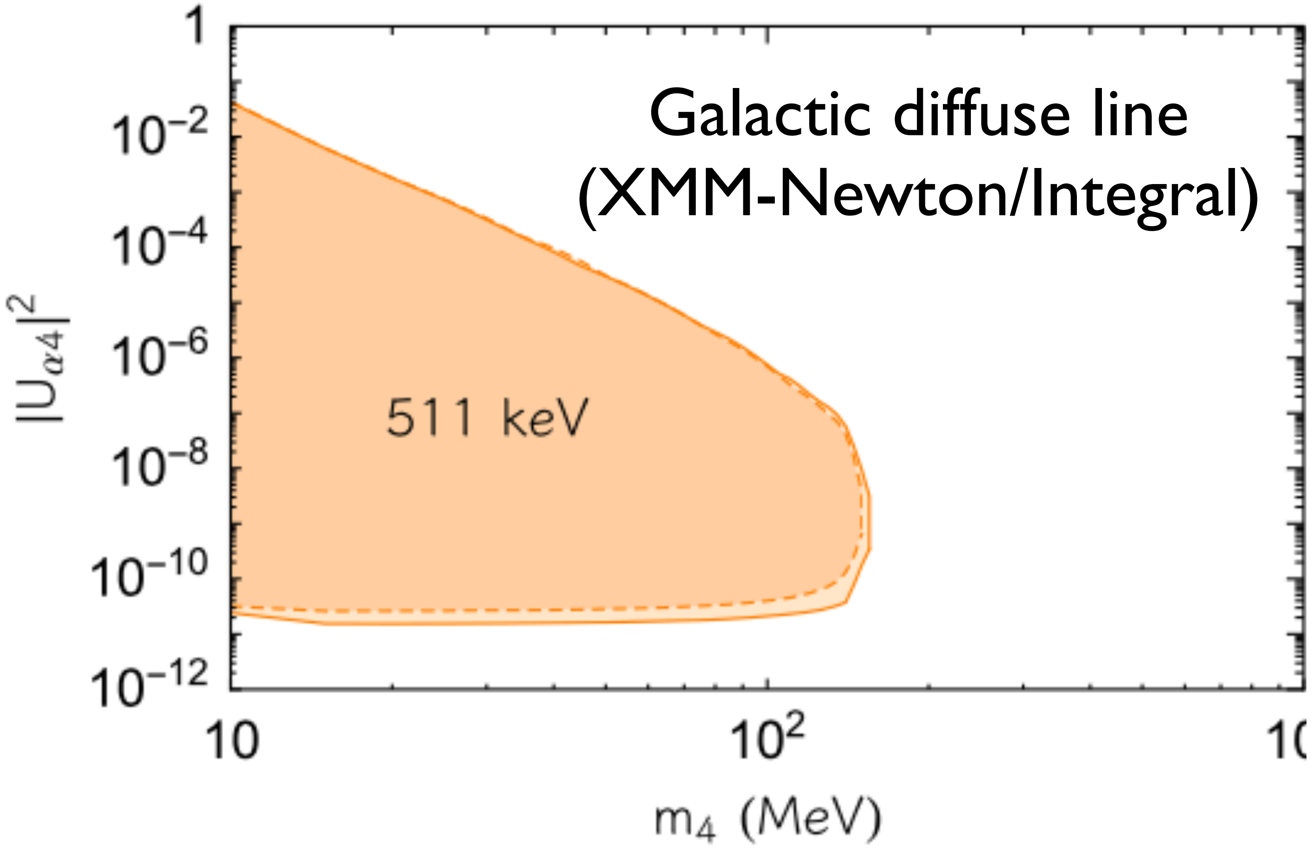


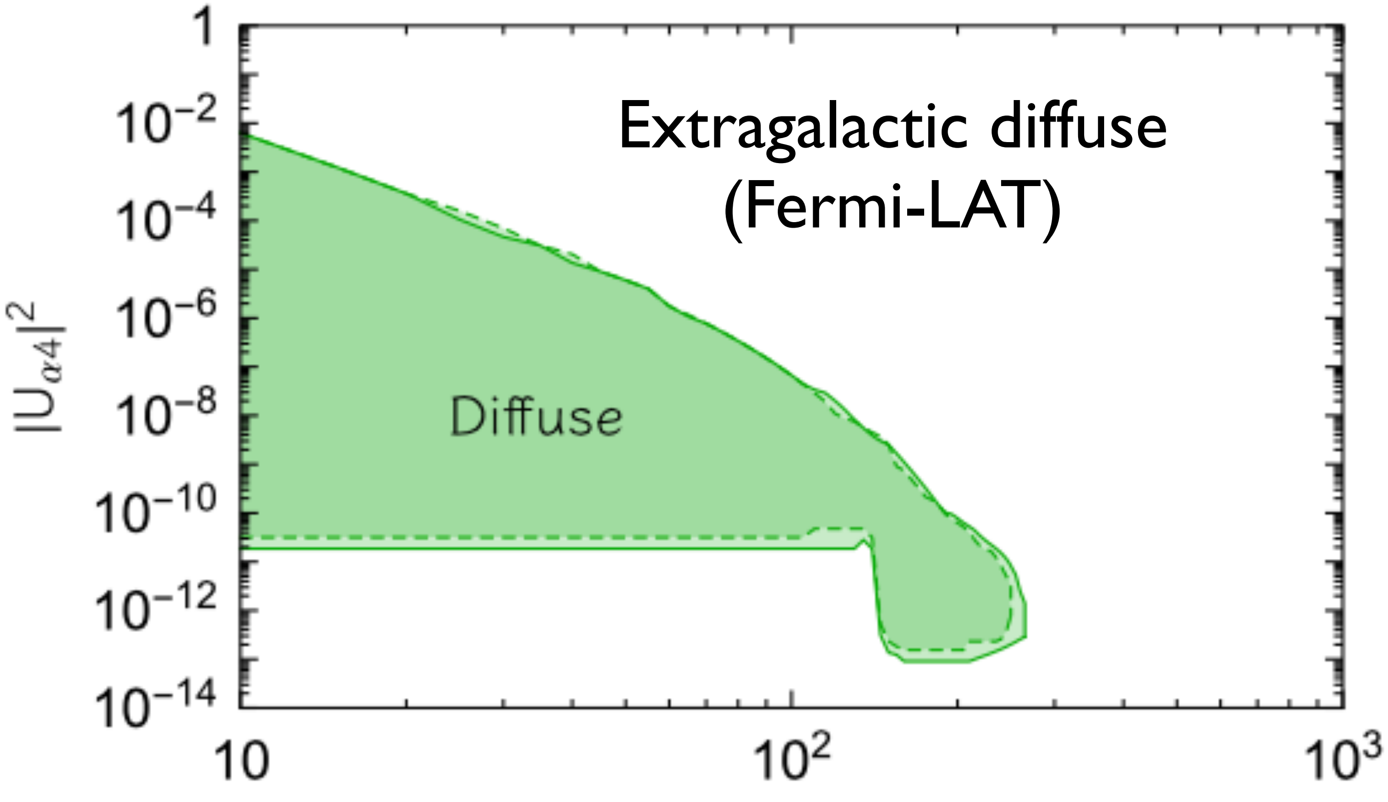


# Constraints from lack of photon appearance


SMM

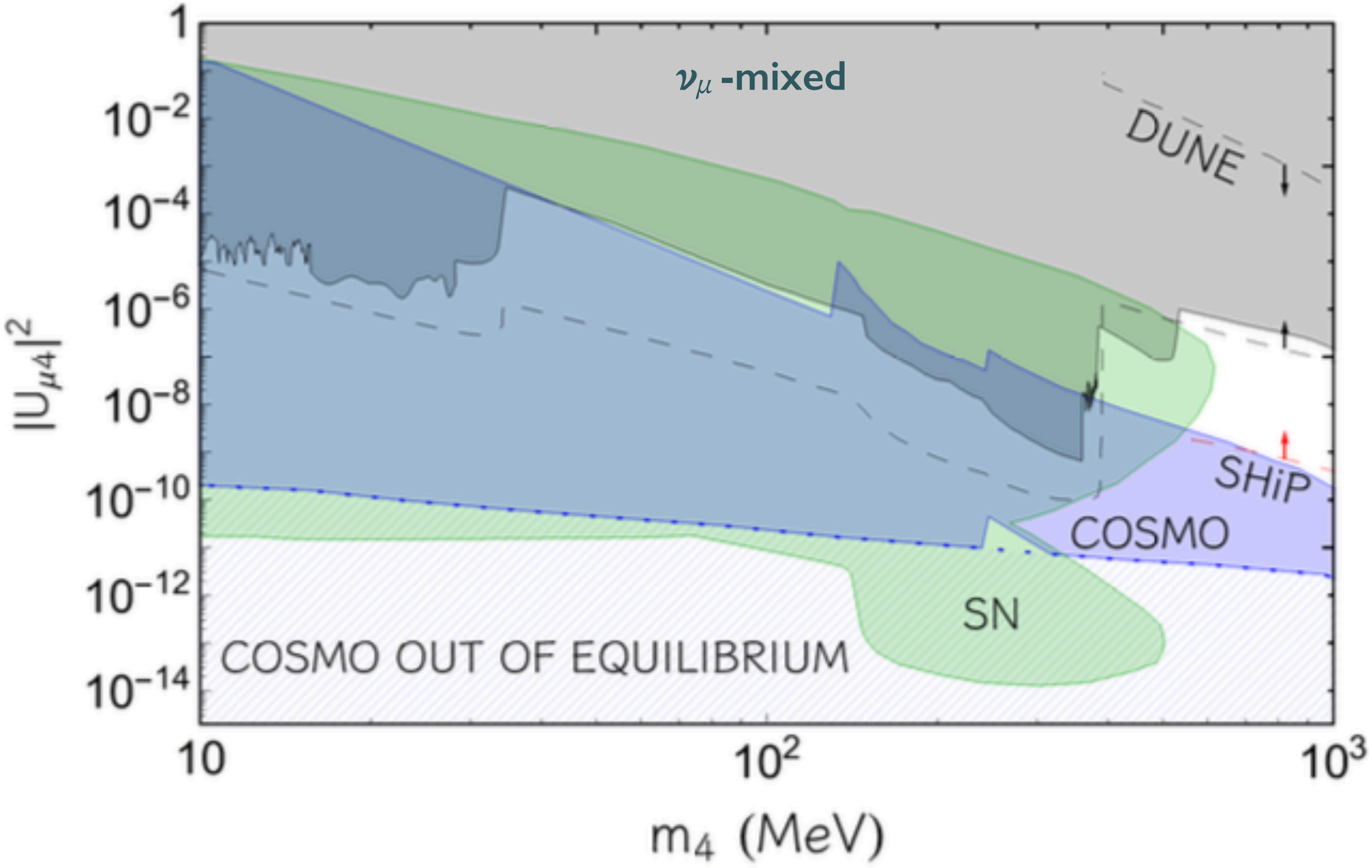


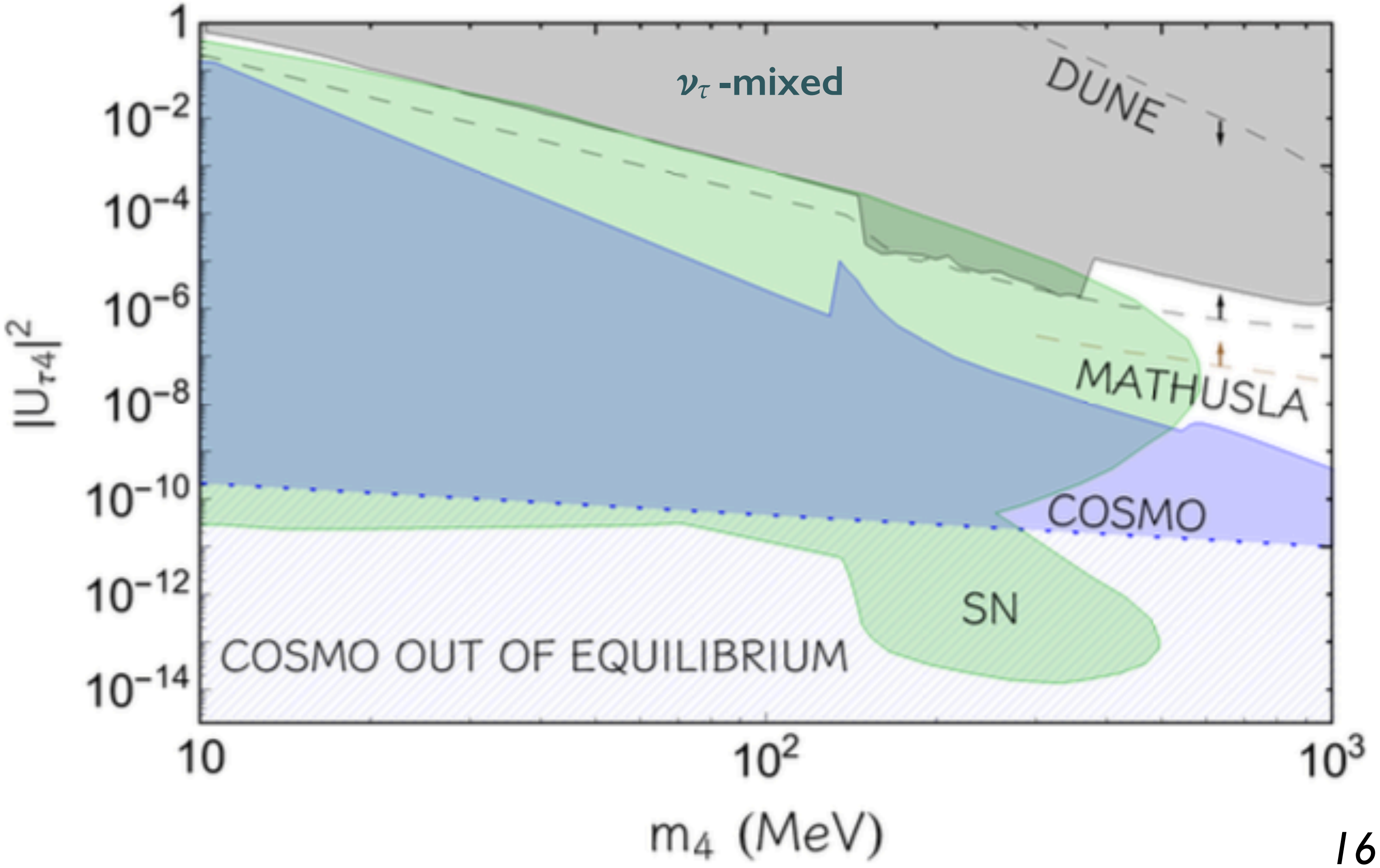

Galactic diffuse line
(XMM-Newton/Integral)


Extragalactic diffuse
(Fermi-LAT)

# Synoptic view of bounds/forecasts

- Nice complementarity astro vs. cosmo vs. colliders!

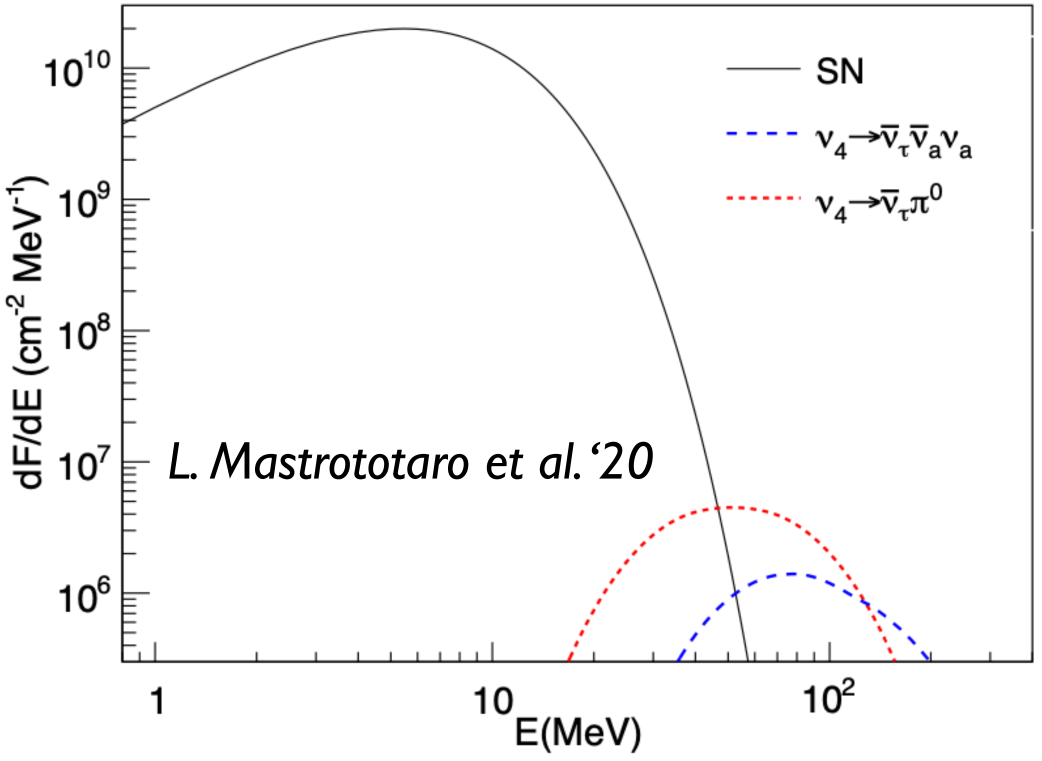




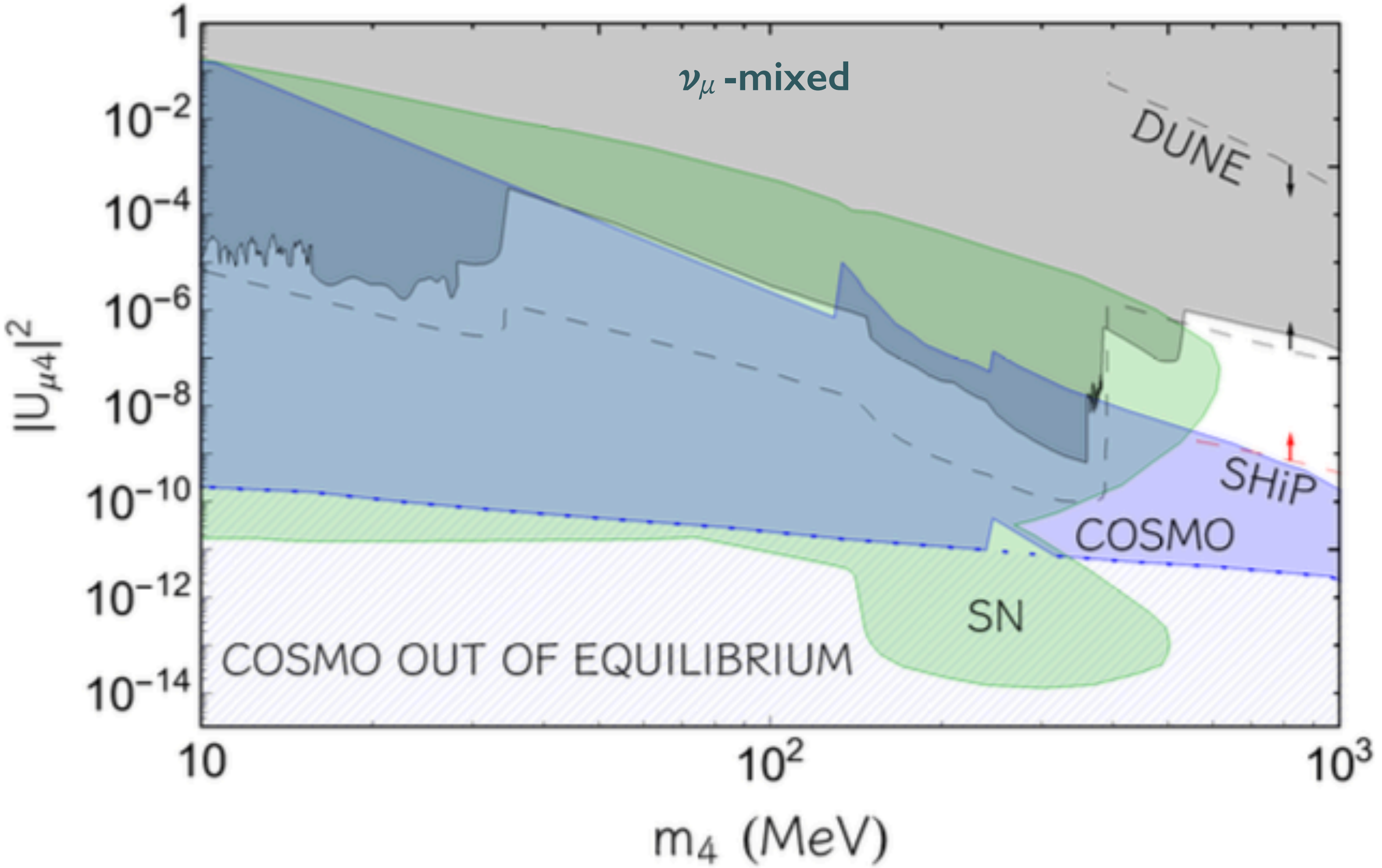
# Synoptic view of bounds/forecasts

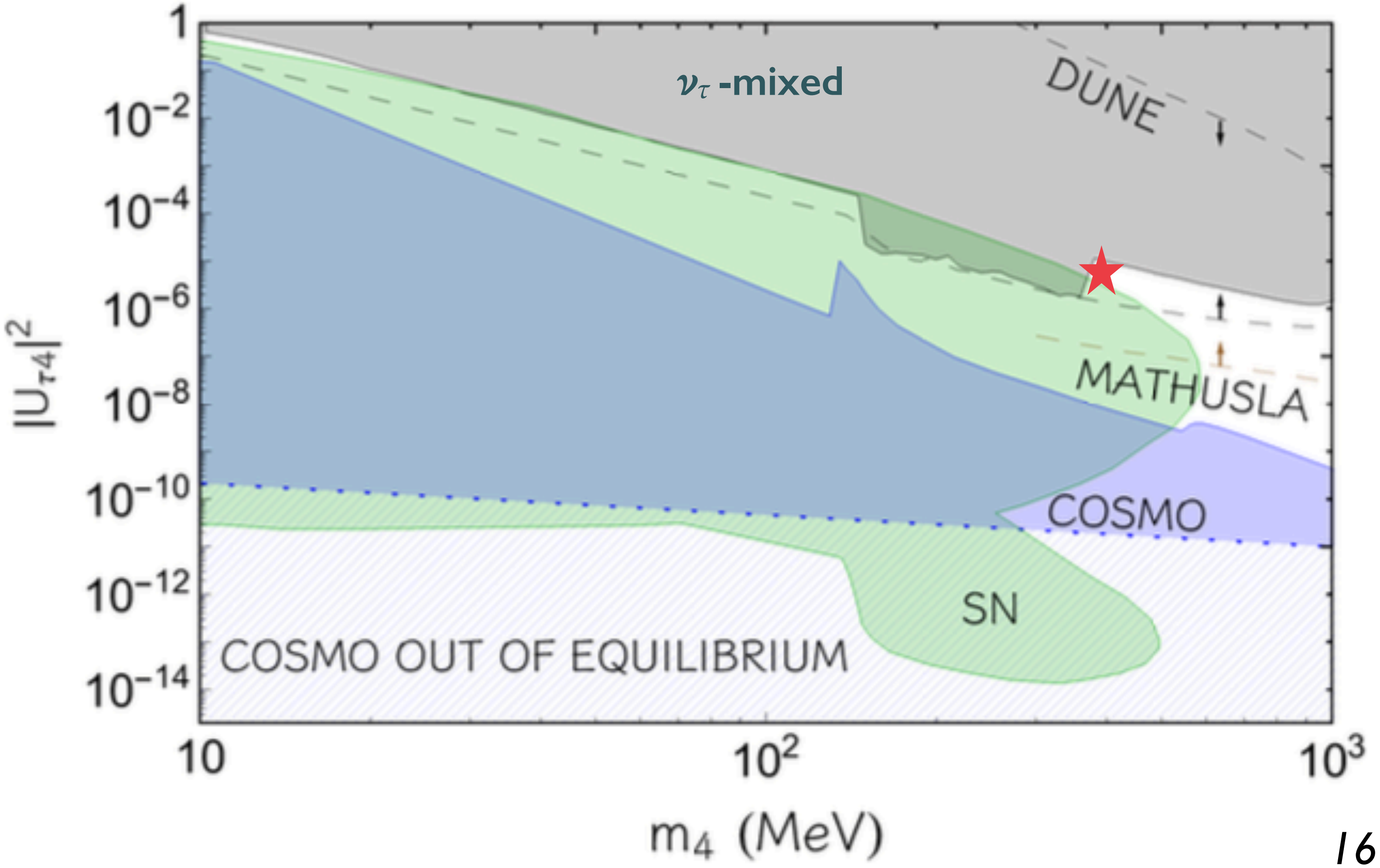
- Nice complementarity astro vs. cosmo vs. colliders!

- Still room for discoveries with spectacular signatures!



*L. Mastrototaro et al.'20*



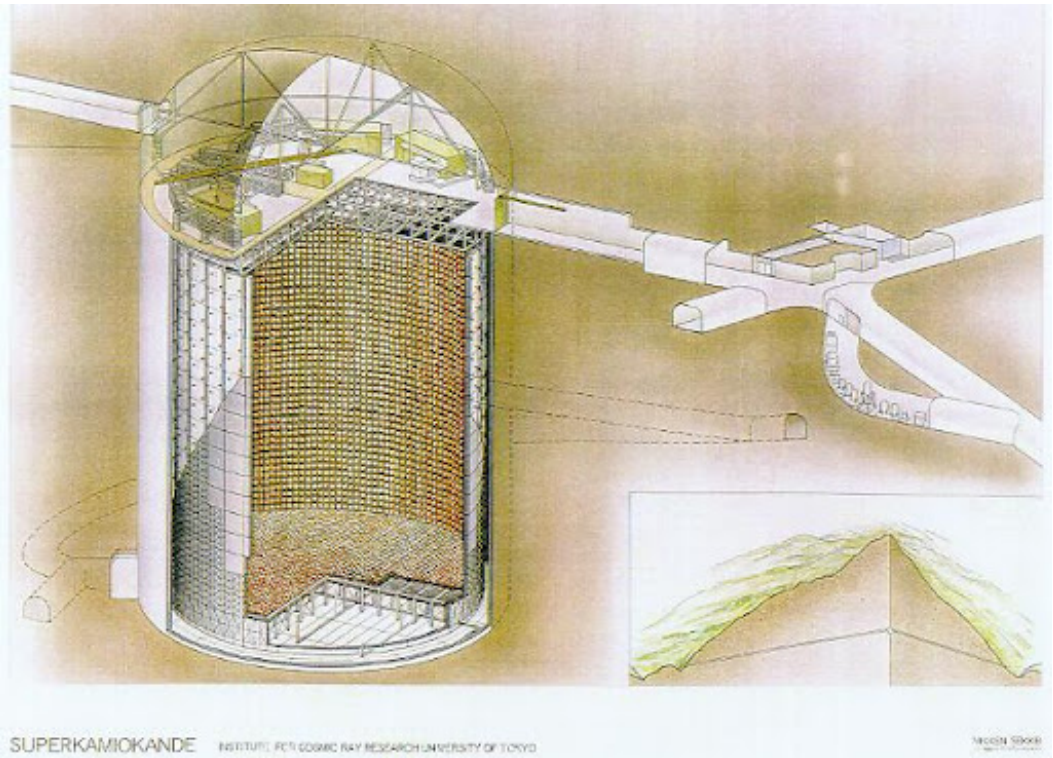


# Expectations in SK (just $\bar{\nu}_e+p\rightarrow n+e^+$)

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

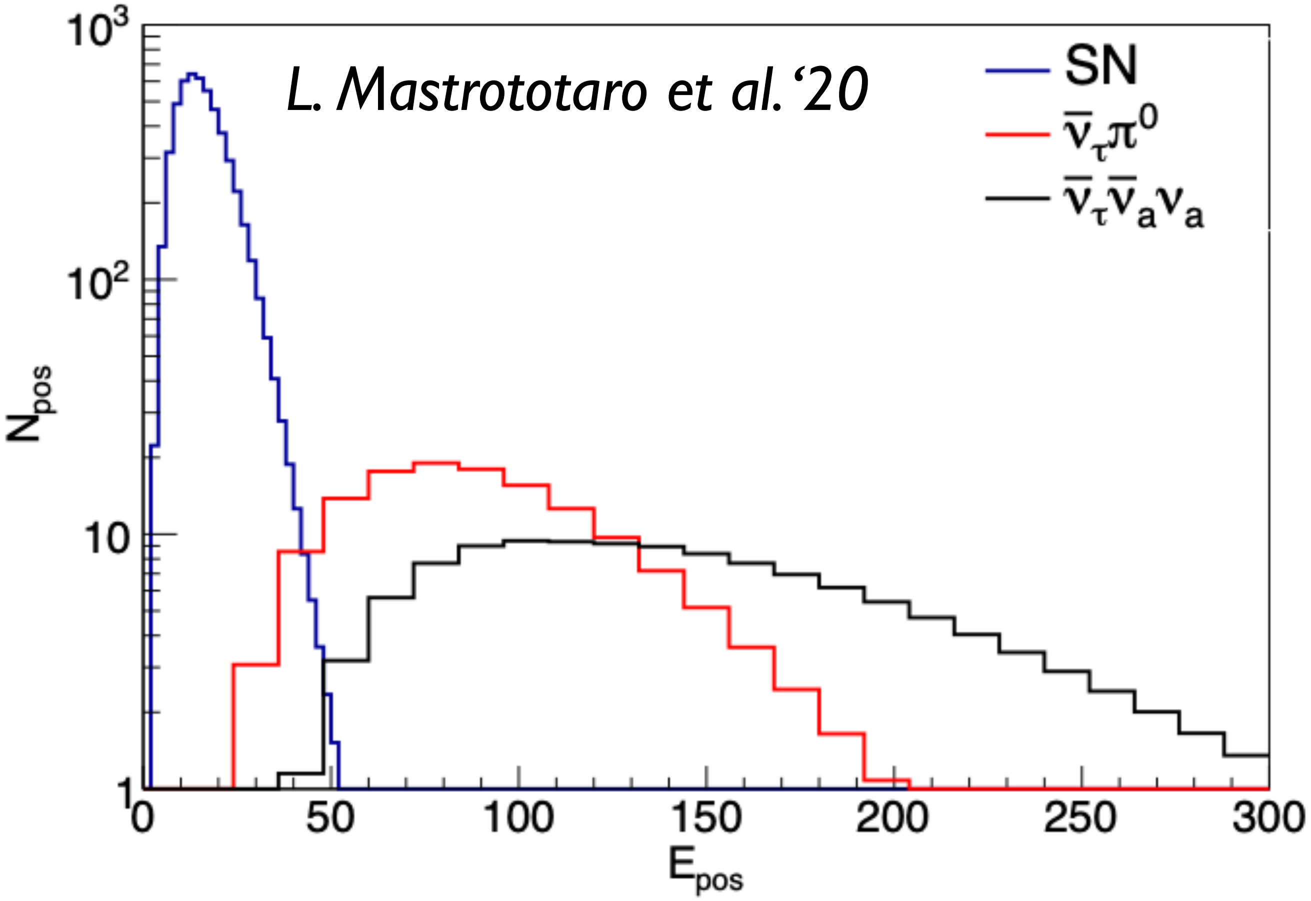
| Channel | Number of events | |
|---|---|---|
| | NH | IH |
| SN $\bar{\nu}_e$ | 5280 | 5640 |
| $\nu_4 \to \pi^0\bar{\nu}_\tau$ | 141 | 470 |
| $\nu_4 \to \nu_\tau\nu_a\bar{\nu}_a$ | 115 | 182 |

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



**most distinctive signature:**
**Spectral bump(s) at $E_{pos}$>50 MeV**

Improved perspectives at next generation detectors and combining more channels.


L. Mastrototaro et al. '20

# Conclusions

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- Principles and observables with sensitivity to BSM physics (and ‘type’)
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  (Similar range could also lead to energetic bump in a future CC SN signal)
- **If mixing with $\nu_\tau$, DUNE could definitely probe masses down to ~10 MeV at large mixings**
  (overlap between SN and laboratory experiments is minimal or absent)