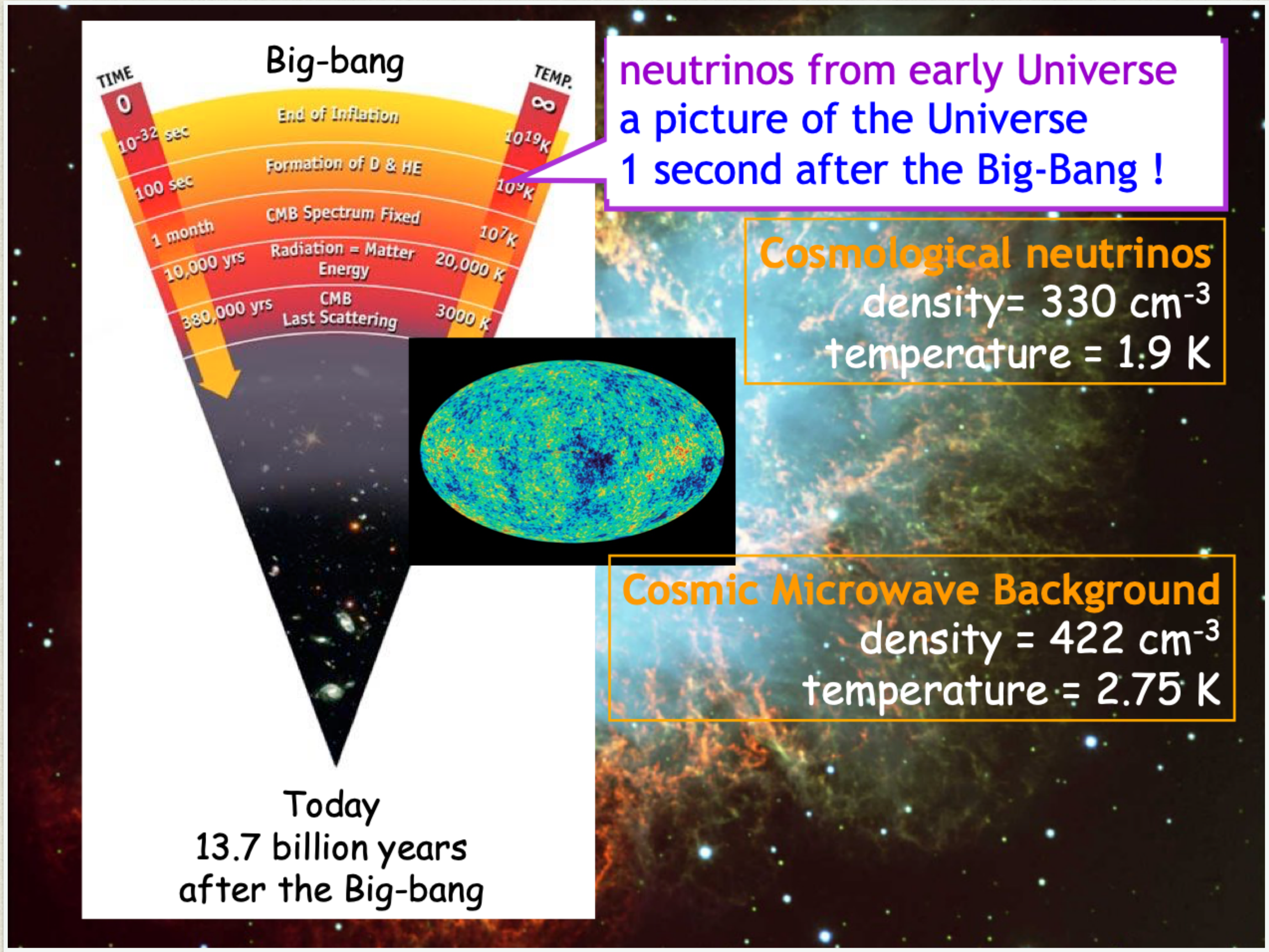
Neutrinos from dense environments, non-radiative neutrino decay and the diffuse supernova neutrino background

Maria Cristina Volpe (CNRS, APC)

Image from ESA/Hubble Space Telescope

OUTLINE

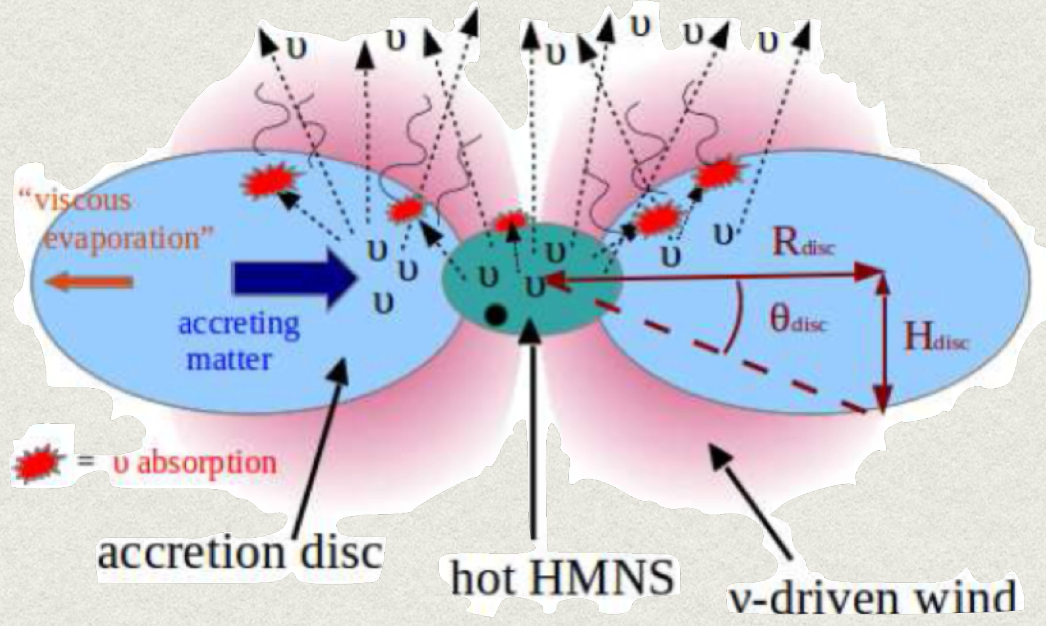
- ★ Introduction
- Neutrino flavor evolution in dense media: Recent developments
- ❄ Neutrino non-radiative decay and the diffuse supernova neutrino background
- ☼ Conclusions



Complex, new flavor conversion phenomena

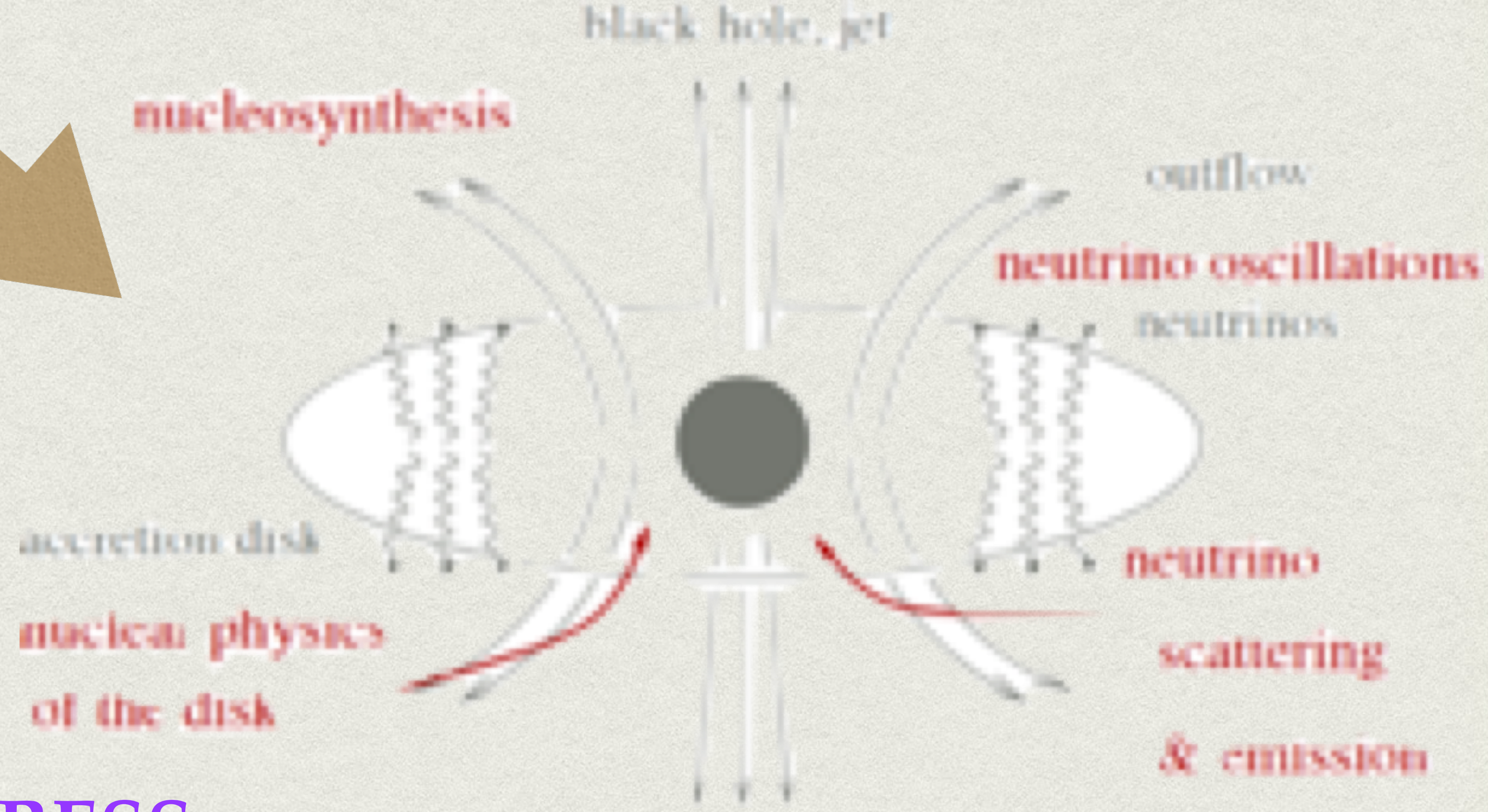
NEUTRINOS FROM DENSE ENVIRONMENTS

BINARY NEUTRON STAR MERGERS

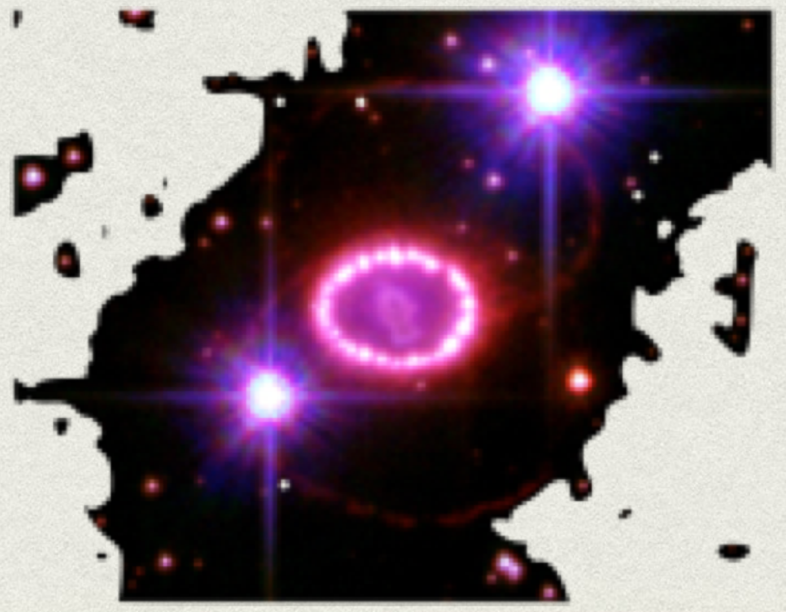


GW170817

ACCRETION DISKS AROUND BLACK HOLES



CORE-COLLAPSE SUPERNOVAE

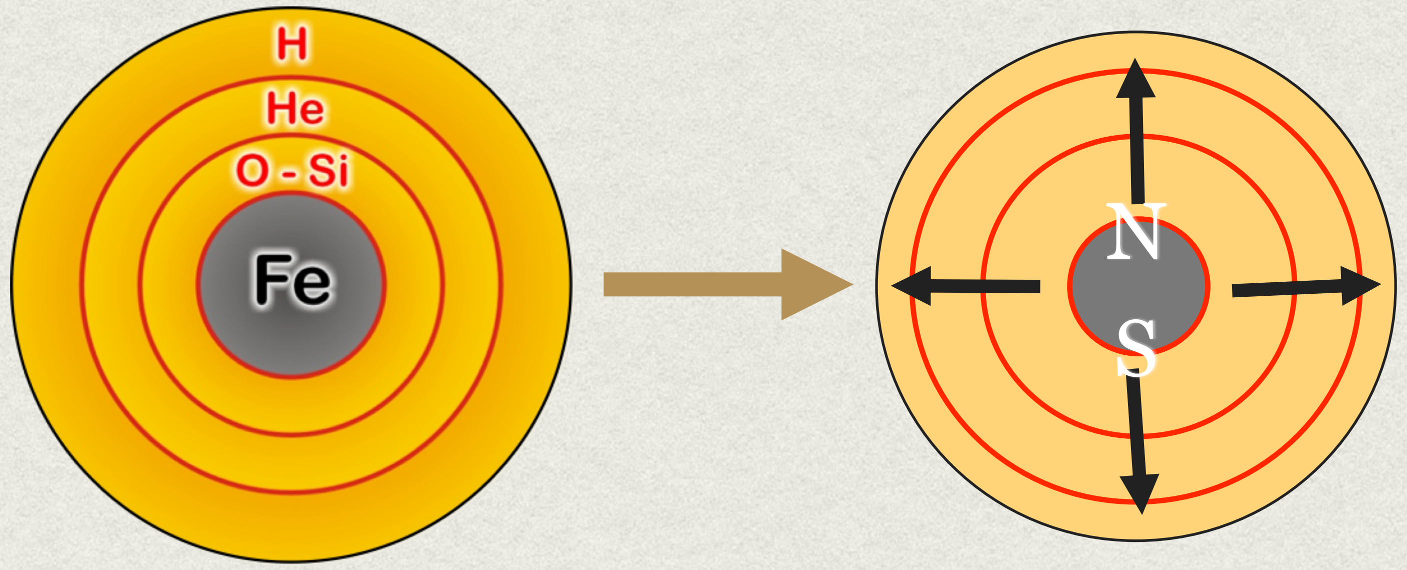


SN1987A

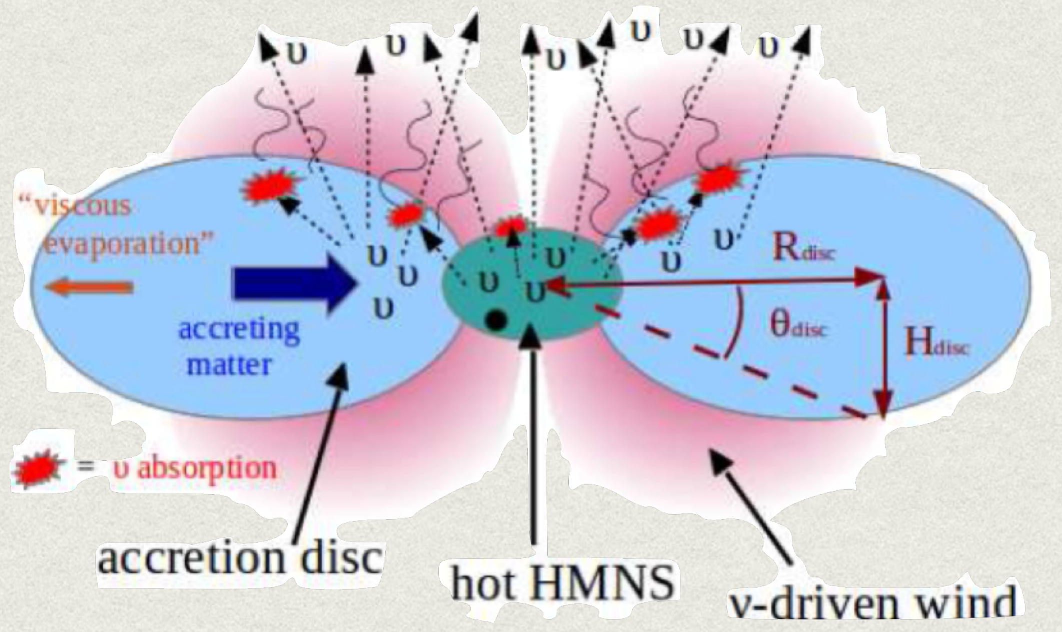
IMPORTANT THEORETICAL PROGRESS

DENSE ENVIRONMENTS

- **« Dense» =** a medium that can reach 10^{10} g/cm^3 and more, 10^{15} - 10^{16} g/cm^3 (limits of matter compressibility), e.g. massive stars called core-collapse supernovae or binary neutron star merger remnants.



core-collapse supernova



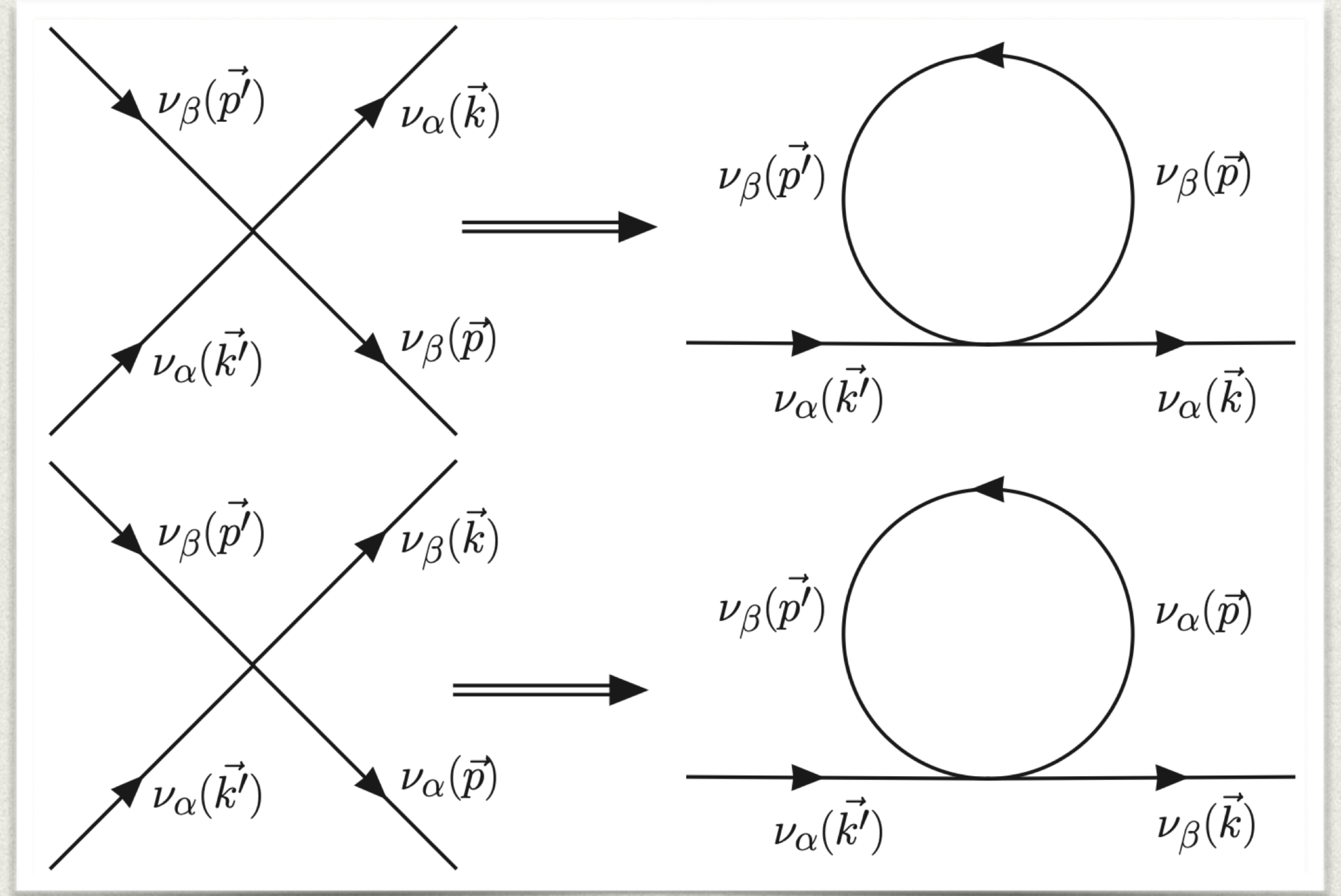
binary neutron-star merger remnant

IN MATTER

DENSE ENVIRONMENTS

- But « dense » also means in neutrinos. In a supernova explosion about 10^{58} neutrinos with an average energy of 10 MeV produced.

➡ These neutrinos interact with each other making the neutrino-neutrino interaction sizable.

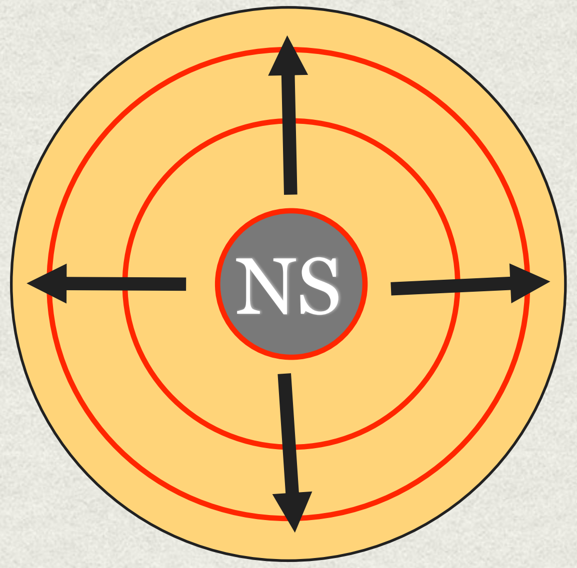


Neutrino-neutrino mean-field potential
-diagonal contribution-

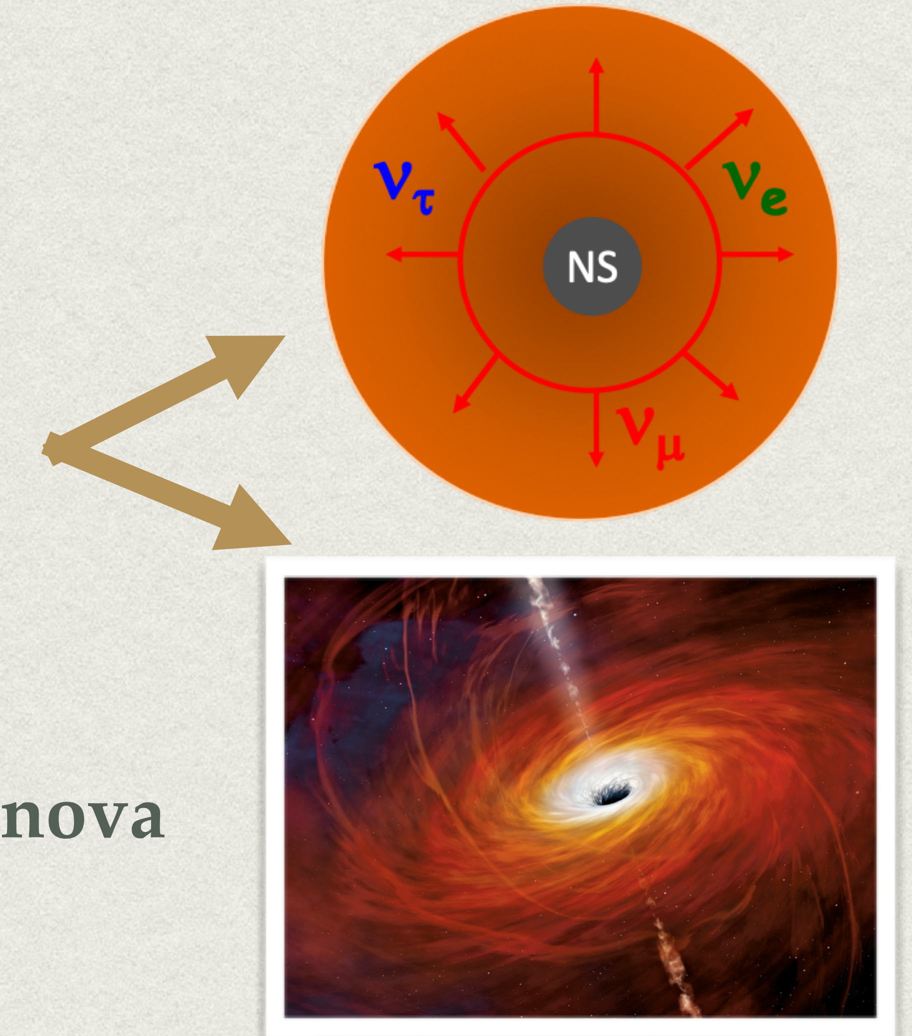
-non-diagonal contribution-

« Neutrino propagation in supernovae is a non-linear many-body problem. »

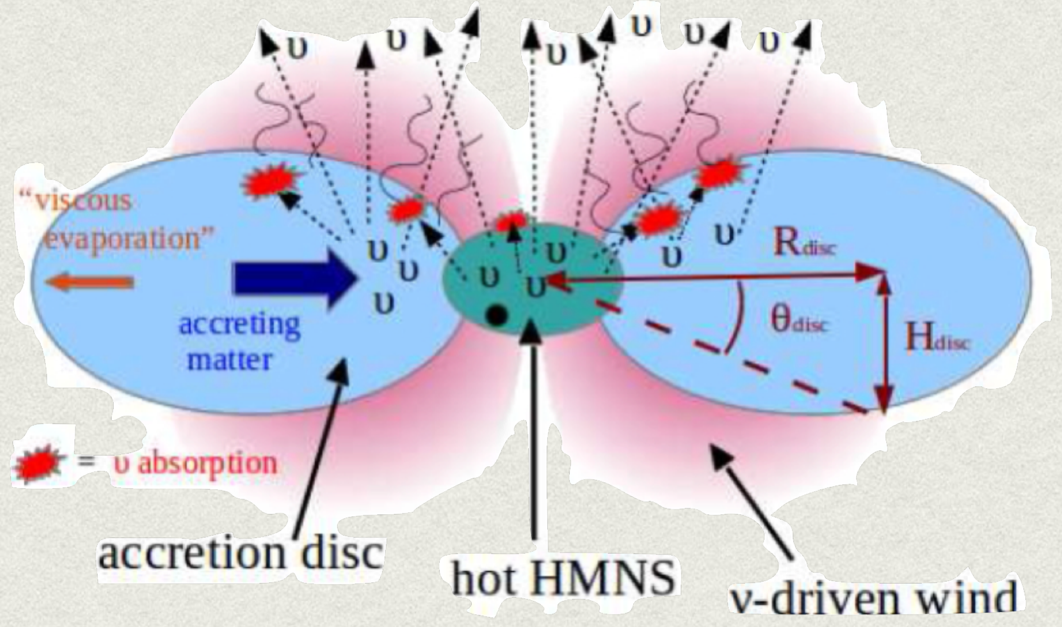
Pantaleone, PLB 1992



core-collapse supernova



neutron-star or black-hole formed



binary neutron-star merger remnant

IN MATTER AND NEUTRINOS

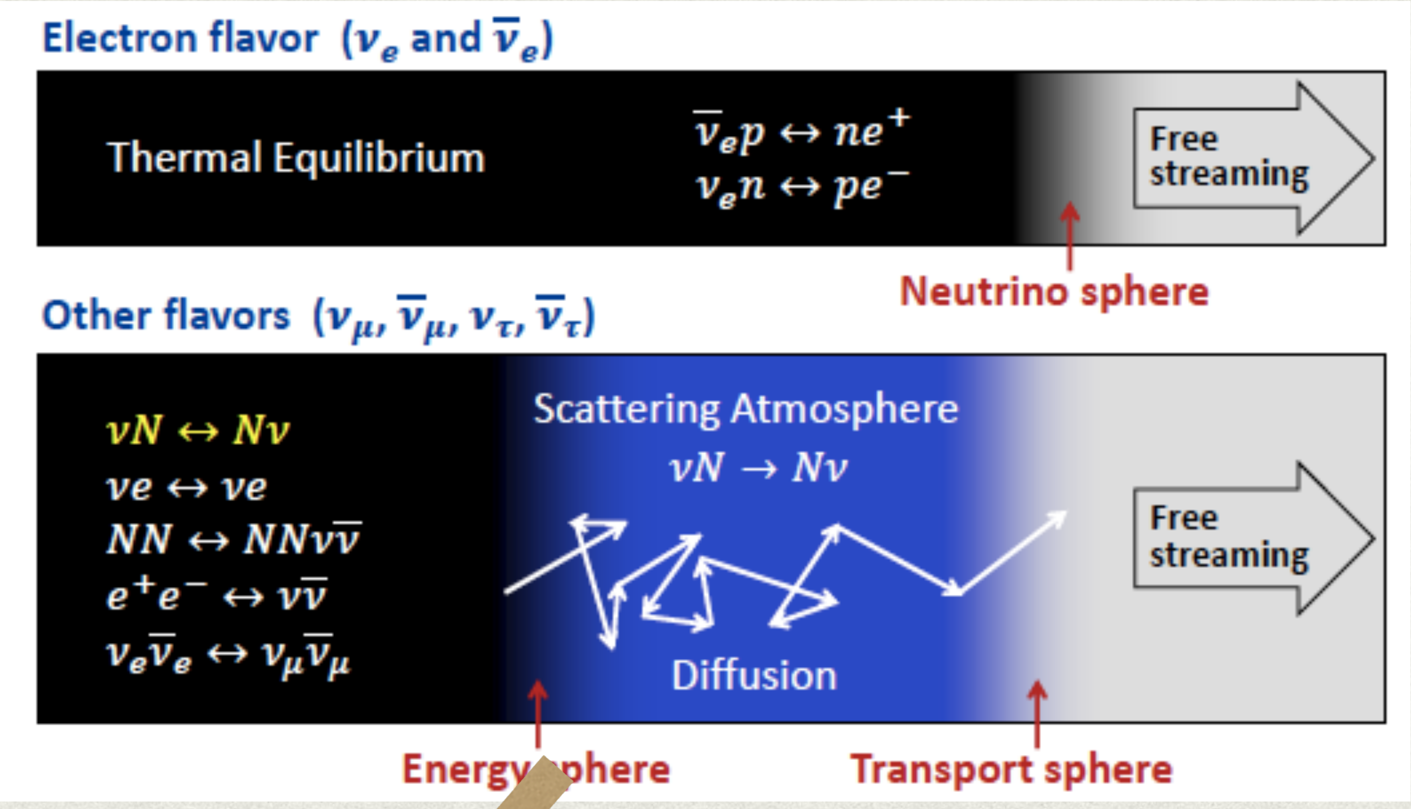
NEUTRINO FLAVOR CONVERSION in DENSE ENVIRONMENTS

- In such environments neutrinos are trapped.
  $E = 10$ MeV
  Typical cross section Density Mean free path $\lambda = \dfrac{1}{\sigma\rho}$

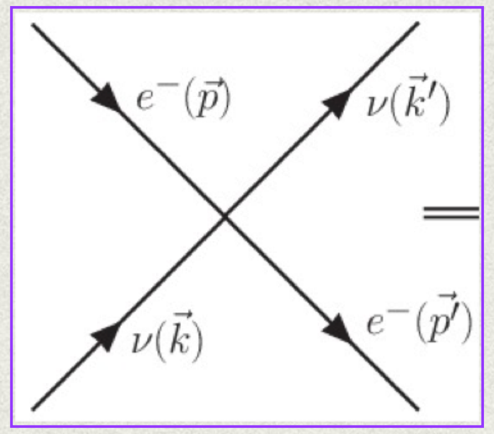
  $\sigma = 6\ 10^{-41}\mathrm{cm}^2$ $\rho = 10^{14}\mathrm{g/cm}^3$ $\lambda \approx \mathrm{m}$

  $\rho = 10^{12}\mathrm{g/cm}^3$ $\lambda \approx$ tens of km

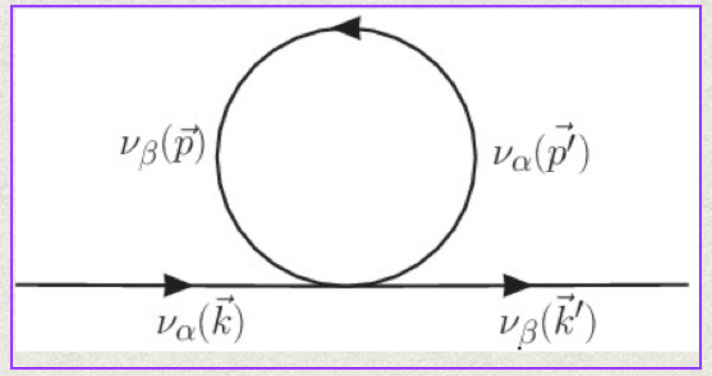
  The region where neutrinos start free-streaming is called the neutrinosphere. It is energy and flavor dependent. In flavor studies, up to 2016 it was always taken as a a sharp boundary.



Raffelt (2012)



collisions dominated
Boltzmann approximation

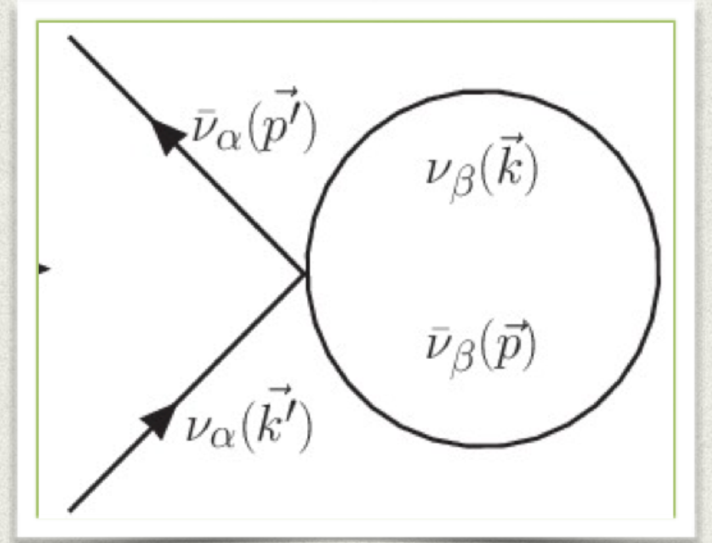


flavor conversion
mean-field approximation

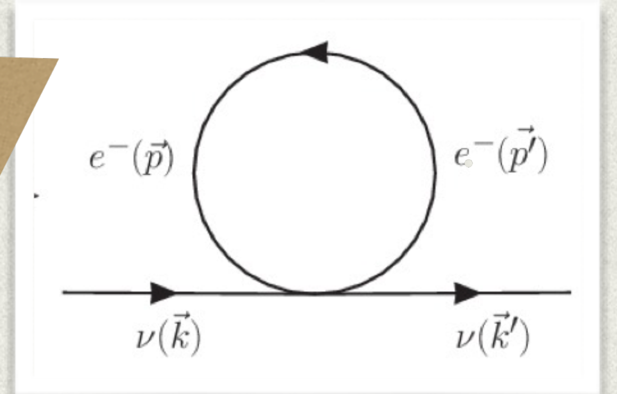
FROM TRAPPED TO **FREE-STREAMING**

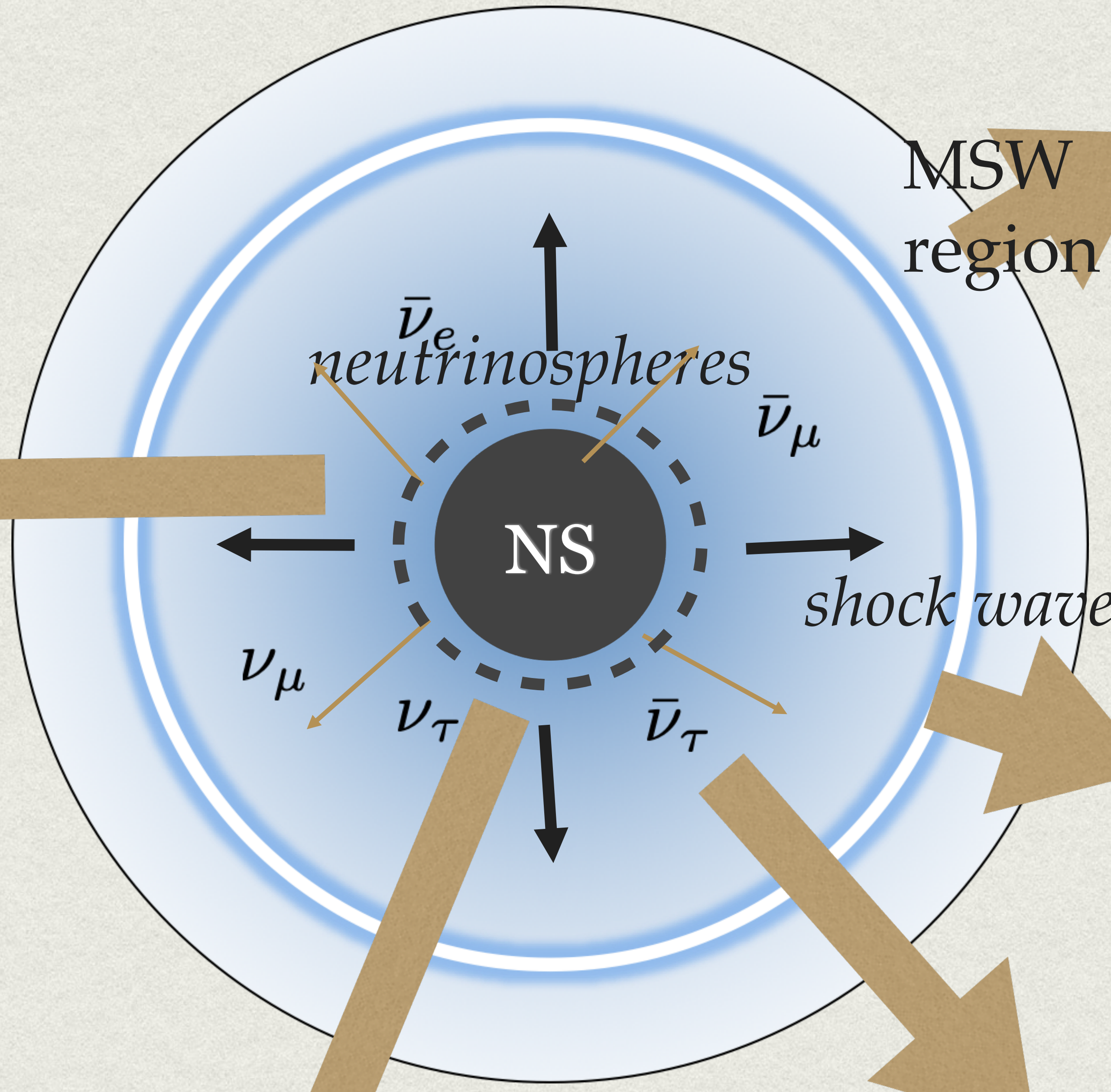
THIS SEPARATION OF SCALES does not hold fully…

FLAVOR CONVERSION EFFECTS IN SUPERNOVAE



MSW effect





Neutrino-neutrino interactions

Pantaleone, PLB287 (1992).
Studied intensively since 2006

→ ***slow* and *fast* modes,** due to the neutrino-neutrino interaction.

Shock wave effects **multiple MSW resonances**

Schirato and Fuller,
hep-ph/0205390

Fast modes have a short scale, of the order of m and can occur behind the shock.

Sawyer PRD 2005, PRL 2016.

Turbulence effects

Loreti et al, PRD 52 (1995)

Collisional instabilities

Johns, PRL 19 (2023)

OCCURS in the FREE-STREAMING regime, and also close to the NEUTRINOSPHERE

FLAVOR CONVERSION EFFECTS IN SUPERNOVAE

✓ A complex many-body problem because of the neutrino-neutrino interaction. It is a 7-dimensional problem - it depends on time, space and momentum.

$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \mathbf{F} \cdot \nabla_{\mathbf{p}})\varrho_{\mathbf{p}} = [\mathcal{H}_{\mathbf{p}}, \varrho_{\mathbf{p}}]$

$\mathcal{H}_{\mathbf{p}} = \mathcal{H}^{f}_{\mathrm{vac,p}} + \mathcal{H}_{\mathrm{mat}} + \mathcal{H}_{\nu\nu,\mathbf{p}} + \mathcal{H}_{\mathrm{NSI}}$ - mean-field Hamiltonian including vacuum, matter terms, neutrino-neutrino and non-standard interactions (if any)

Solved in the early Universe (isotropy, homogeneity). A precise value for Neff = 3.0440 (BBN epoch)

Froustey, Pitrou, Volpe, JCAP 12 (2020)15 —-PDG

✓ **Flavor mechanisms produce neutrino spectral modifications and impact the interactions rates on p/n in the medium— SN explosion, r-process and future supernova observations.**

FLAVOR CONVERSION EFFECTS IN DENSE ENVIRONMENTS

✓ Nuclei are used as targets in supernova detectors (D, O, C, Ar, Fe, Pb, …). Predictions are based on different model — EFT, shell model, RPA and its variants (QRPA, CRPA), … . After 20 years, the COHERENT Collaboration is now measuring again neutrino-nucleus cross sections at SNS. ^{nat}Pb, An et al, 2212.11295 and ^{127}I, 2305.19594

Neutrino-nucleus interactions as a probe to constrain double-beta decay predictions C. Volpe, J. Phys. G. 31 (2005), hep-ph/0501233

M.C. Volpe, «Neutrinos from dense: flavor mechanisms,theoretical approaches, observations, new directions », Review of Modern Physics, arXiv: 2301.11814 — v2 (next week).

NEUTRINO NON-RADIATIVE DECAY

- Since neutrinos are massive they can decay.
  Neutrino non-radiative two-body decay:

$$\nu_i \rightarrow \nu_j + \phi \quad \text{or} \quad \nu_i \rightarrow \bar{\nu}_j + \phi$$

ϕ a massless (pseudo)scalar particle

due to tree-level (pseudo)scalar couplings.

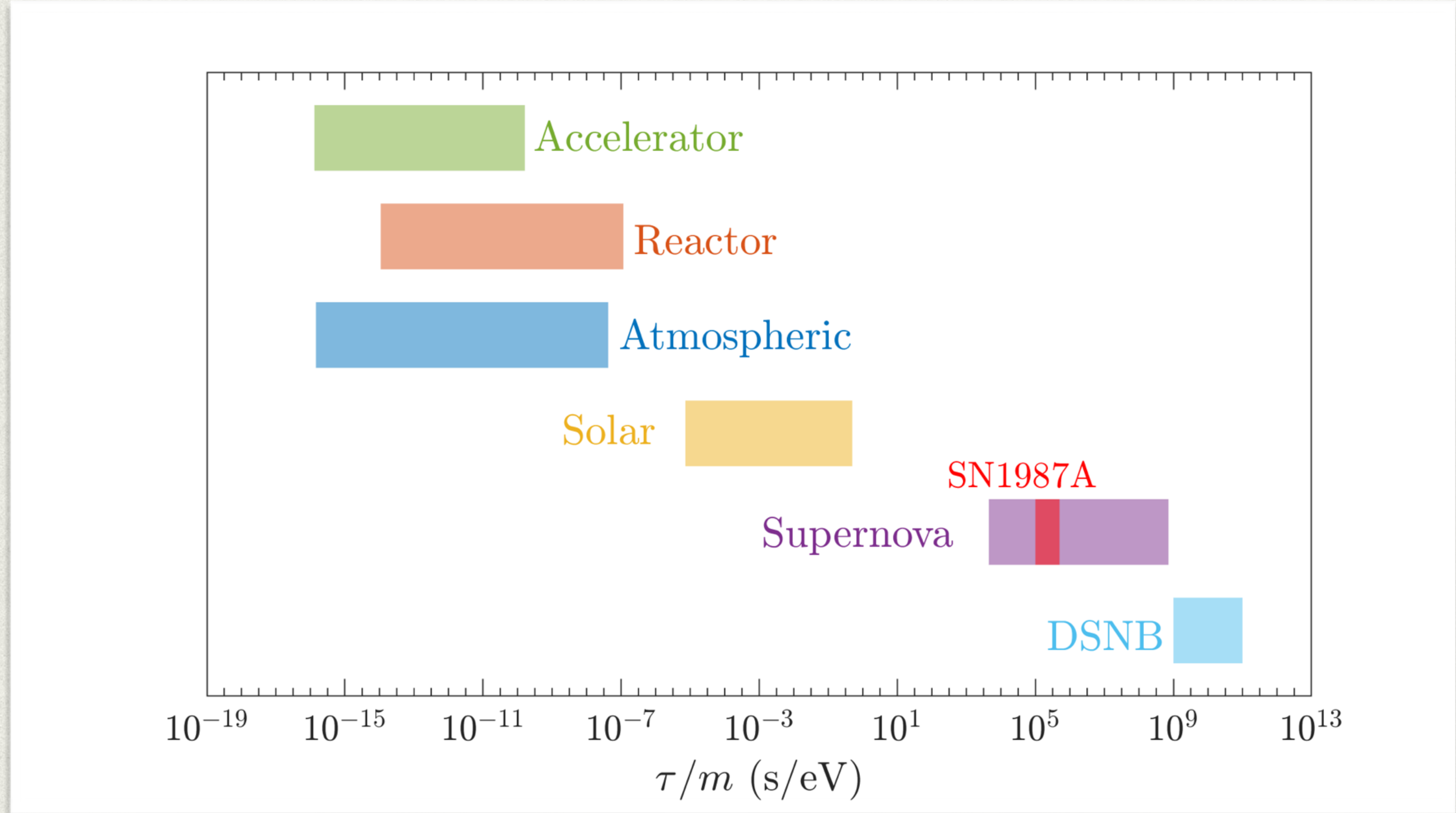
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + H.c. \ ,$$

- The neutrino fluxes get suppressed by the factor

$$\exp\left(-\frac{L}{E} \times \frac{m}{\tau}\right)$$

L - souce-detector distance
E - neutrino energy
m - neutrino mass
τ - lifetime

Sensitivity to non-radiative decay from different neutrino sources

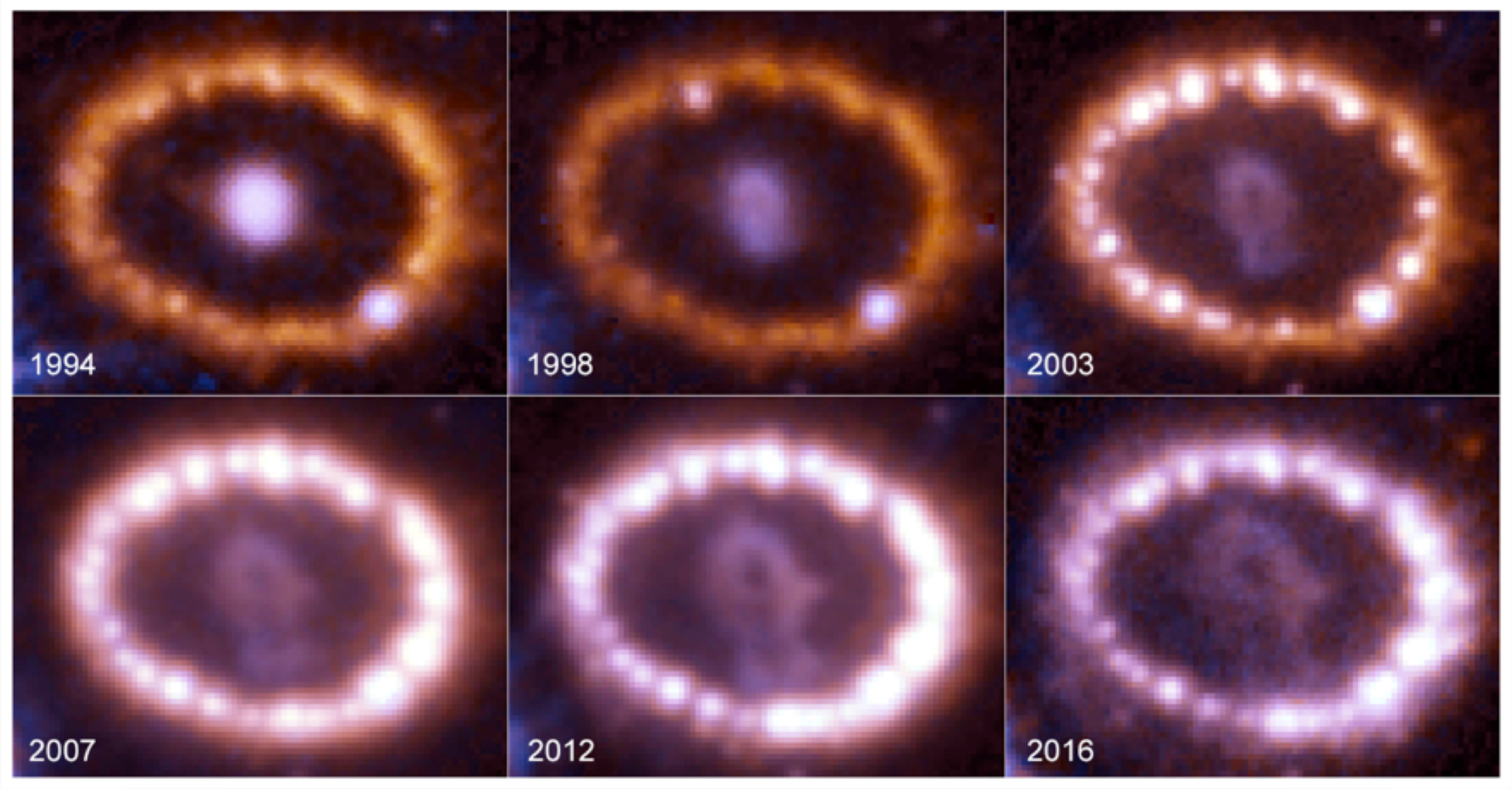


Ivanez-Ballesteros and Volpe, Phys. Lett. B (2023), arXiv: 2307.03549

Unique sensitivity to tau/m from the diffuse supernova neutrino background (DSNB)

SN1987A and neutrinos

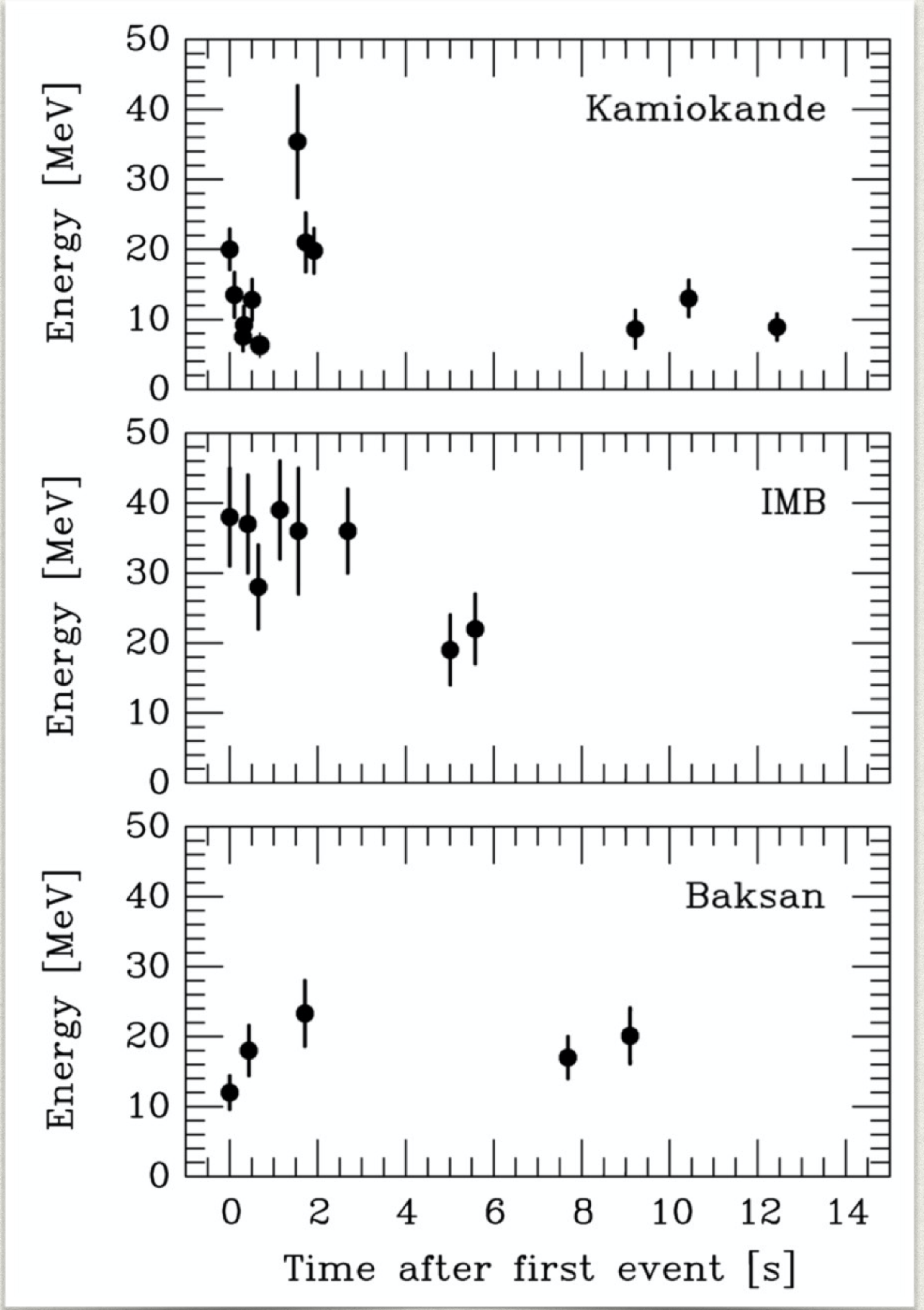
Evolution of the ejecta and of the central object over more than 20 y.



Hubble Space Telescope

First observation of neutrinos from the death of a massive star: 24 events detected.

A wonderful laboratory for particle physics and astrophysics.

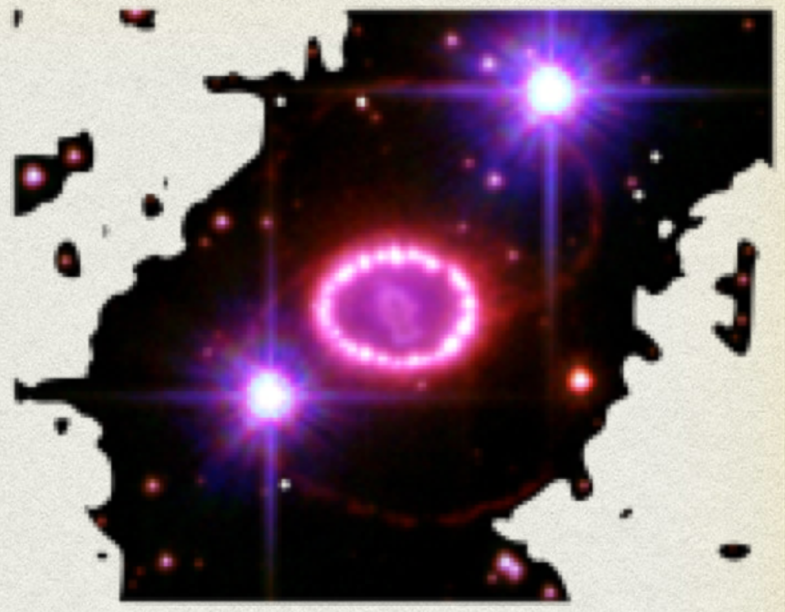


Water Cherenkov detector, 2140 tons

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

Baksan Scintillator Telescope, 200 tons

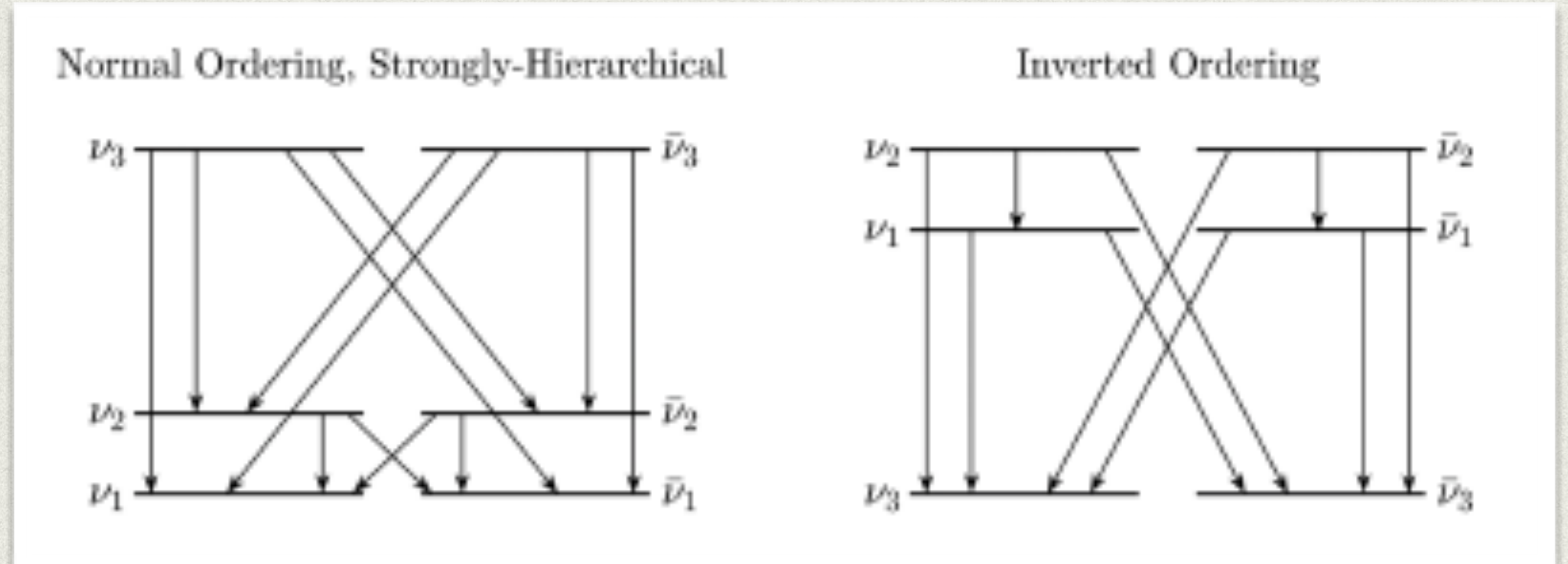
NEUTRINO NON-RADIATIVE DECAY and SN1987A

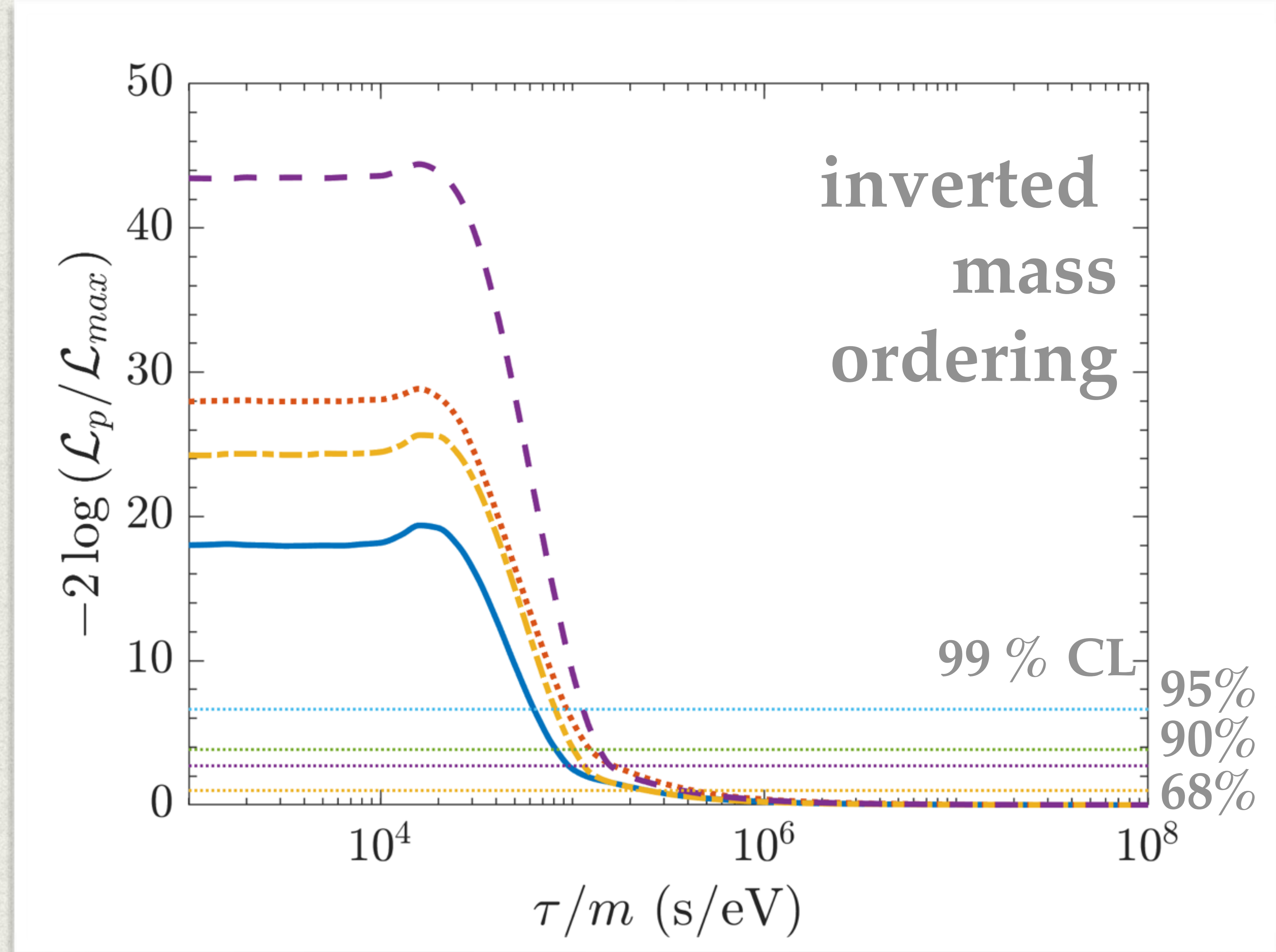


- Previous analysis either do not make a full statistical analysis - Frieman, Haber, Freese, PLB (1988)
  or considered decay in matter. Kachelriess, Tomas, Valle, PRD62 (2000);Farzan, PRD67 (2003)

- Full 3 neutrino framework, three possible decay patterns (NO and SH or QD, IO) .

$$\nu_i \to \nu_j + \phi \quad \text{or} \quad \nu_i \to \bar{\nu}_j + \phi$$

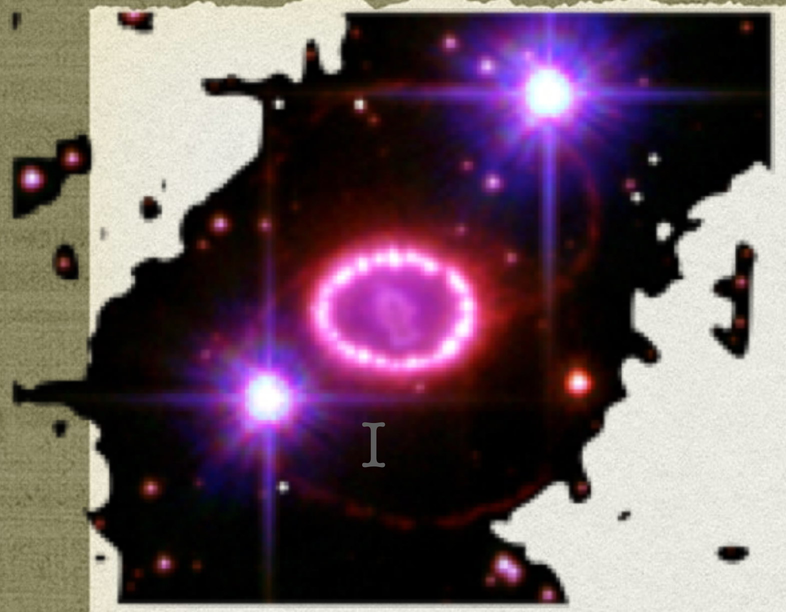




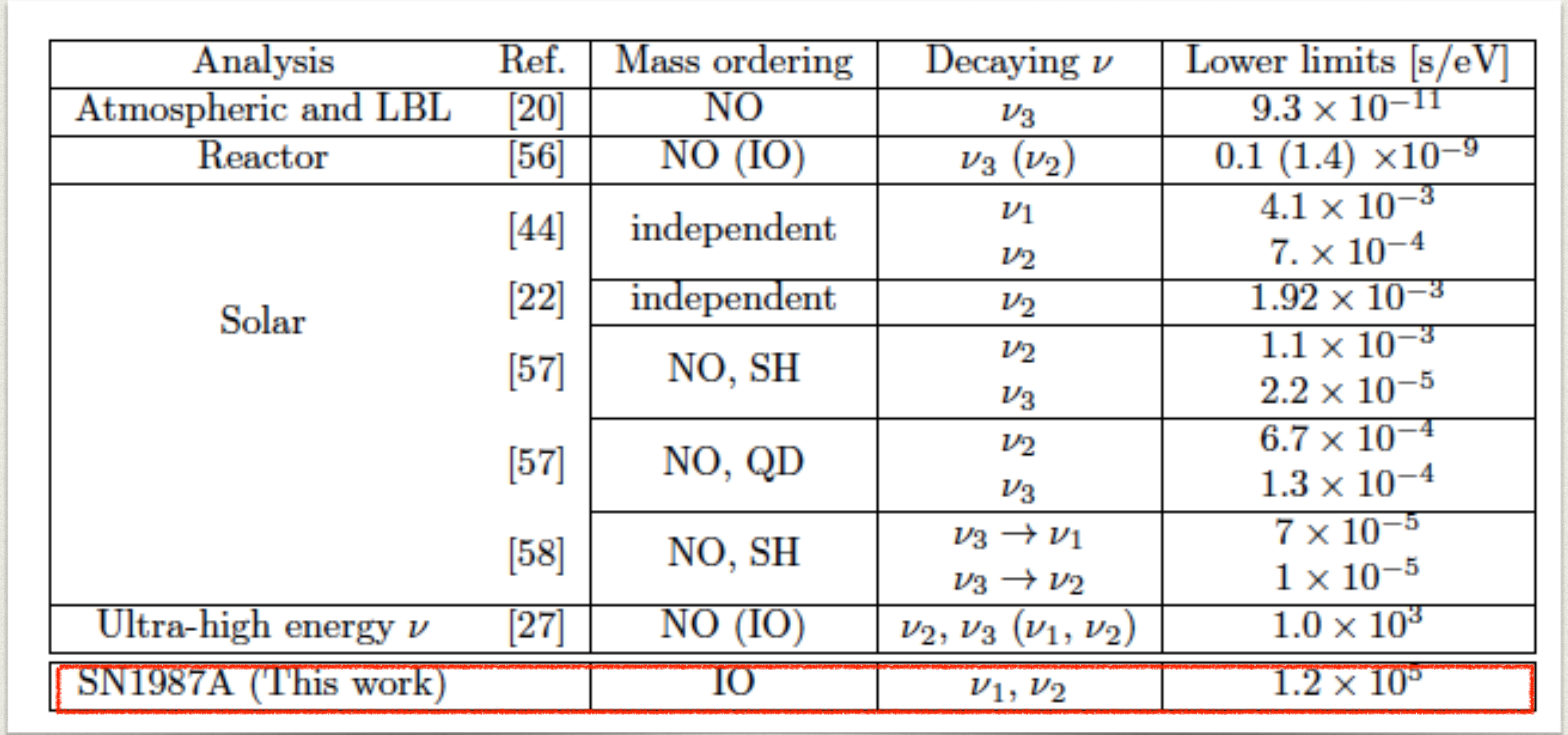
Ivanez-Ballesteros, Volpe, Phys. Lett. B (2023) arXiv:2307.03549

- Solved the transfer equations to determine the events with the neutrino spectral distortion due to neutrino decay.

Likelihood analysis (7D) of the 24 SN1987 neutrino events
in Kamiokande, IMB and Baksan, including non-radiative decay.



NEUTRINO NON-RADIATIVE DECAY and SN1987A

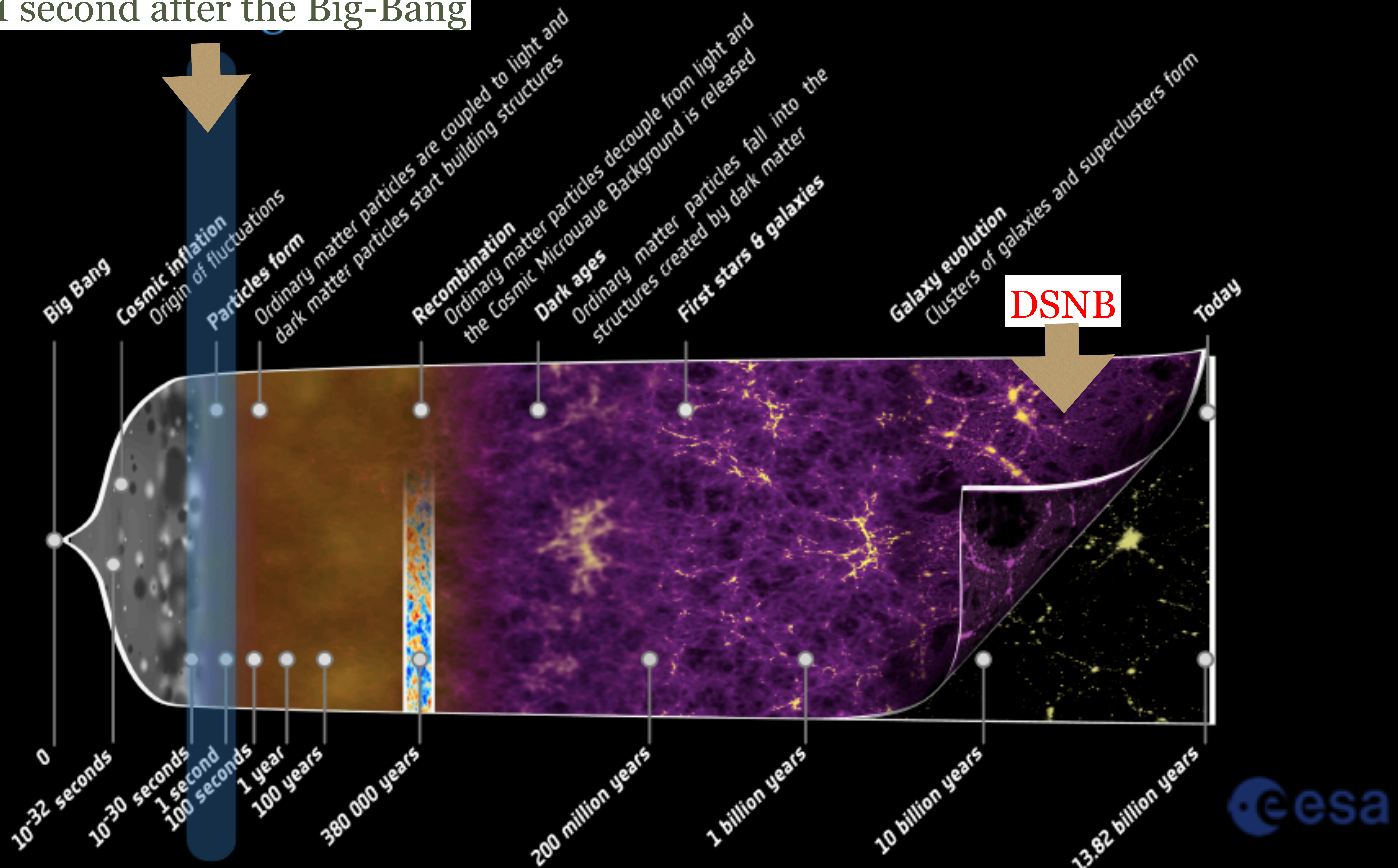


Analysis	Ref.	Mass ordering	Decaying ν	Lower limits [s/eV]	
Atmospheric and LBL	[20]	NO	ν_3	9.3×10^{-11}	99 % CL
Reactor	[56]	NO (IO)	ν_3 (ν_2)	$0.1\ (1.4)\ \times 10^{-9}$	90 % CL
Solar	[44]	independent	ν_1 ν_2	4.1×10^{-3} $7. \times 10^{-4}$	95 % CL
	[22]	independent	ν_2	1.92×10^{-3}	90 % CL
	[57]	NO, SH	ν_2 ν_3	1.1×10^{-3} 2.2×10^{-5}	90 % CL
	[57]	NO, QD	ν_2 ν_3	6.7×10^{-4} 1.3×10^{-4}	90 % CL
	[58]	NO, SH	$\nu_3 \to \nu_1$ $\nu_3 \to \nu_2$	7×10^{-5} 1×10^{-5}	90 % CL
Ultra-high energy ν	[27]	NO (IO)	ν_2, ν_3 (ν_1, ν_2)	1.0×10^{3}	95 % CL
SN1987A (This work)		IO	ν_1, ν_2	1.2×10^{5}	90 % CL

Ivanez-Ballesteros and Volpe, Phys. Lett. B (2023) arXiv:2307.03549

The tightest bound on tau/m, competitive with cosmology for inverted mass ordering

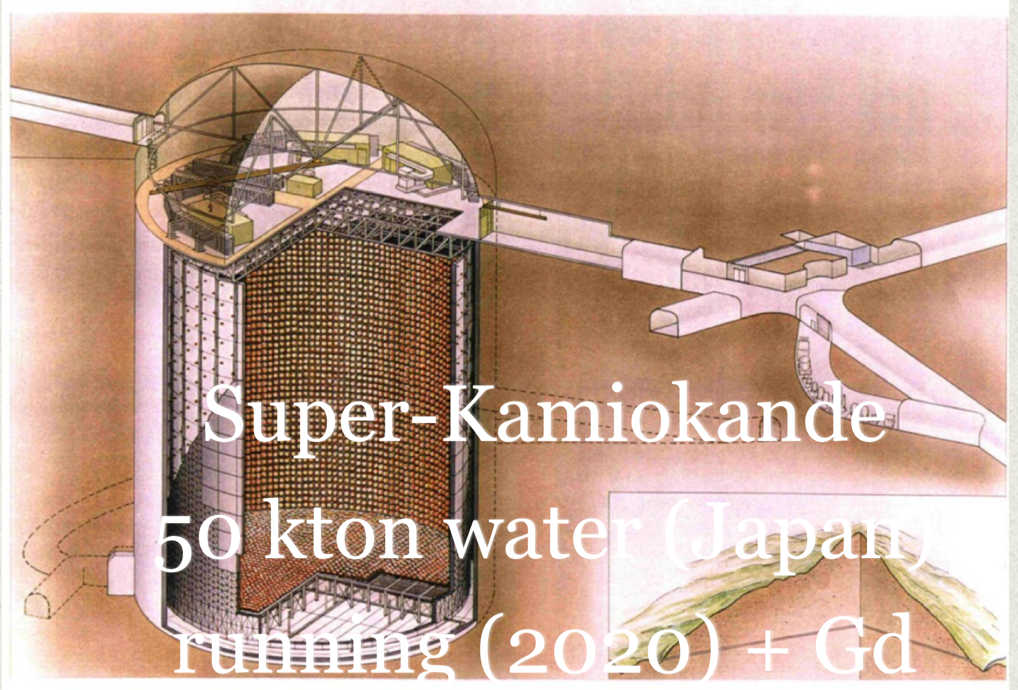
EVOLUTION OF THE UNIVERSE



1 second after the Big-Bang

DSNB

SEARCH FOR THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND (DSNB)

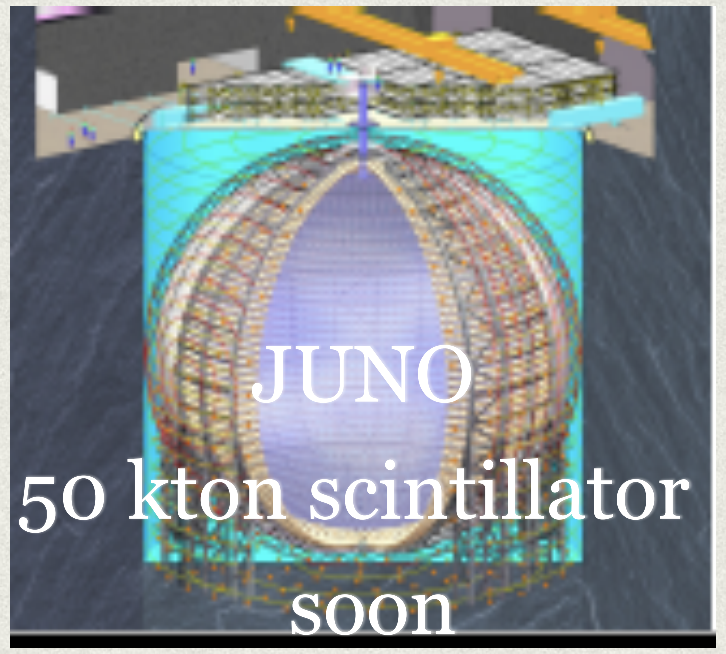


Super-Kamiokande
50 kton water (Japan)
running (2020) + Gd

$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$

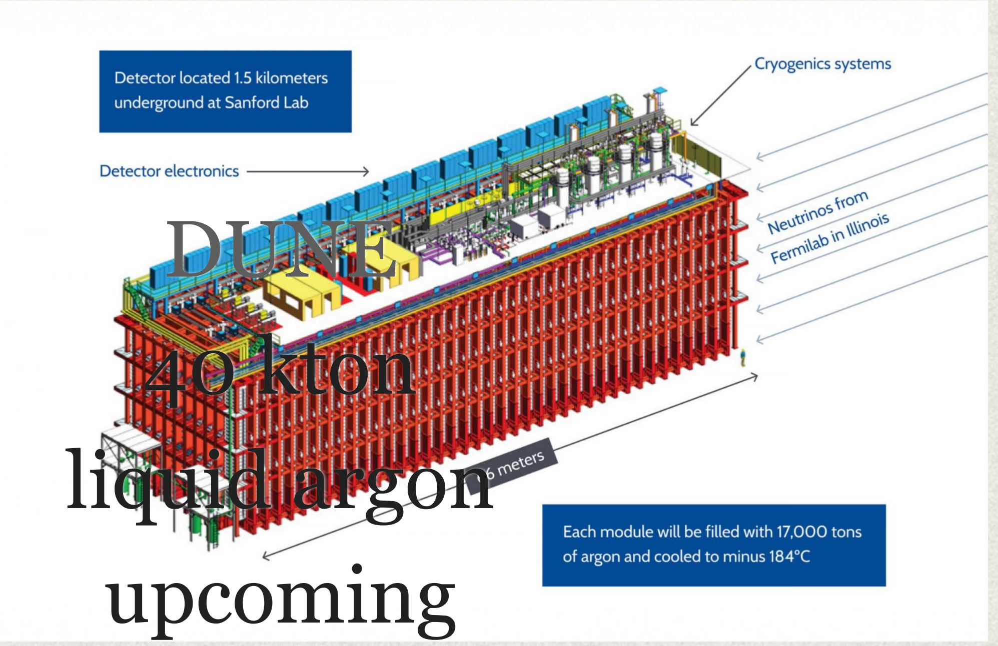
Hyper-Kamiokande
178 kton (FV) water
Starting 2027

$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$



JUNO
50 kton scintillator
soon

$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$



DUNE
40 kton
liquid argon
upcoming

$$\nu_e +^{40} Ar \rightarrow e^- +^{40} K$$

Super-Kamiokande+Gd running since 2020, JUNO, DUNE and Hyper-K upcoming

STATUS on the DSNB SEARCHES

- Flux upper limits from SKI-IV and SNO data

$$2.8 - 3 \quad \bar{\nu}_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu > 17.3 \quad \mathrm{MeV})$$

Abe et al, 2109.11174

$$19 \quad \nu_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu \in [22.9, 36.9] \quad \mathrm{MeV})$$

SNO data, Aharmim et al, Astrophys. J. 2006

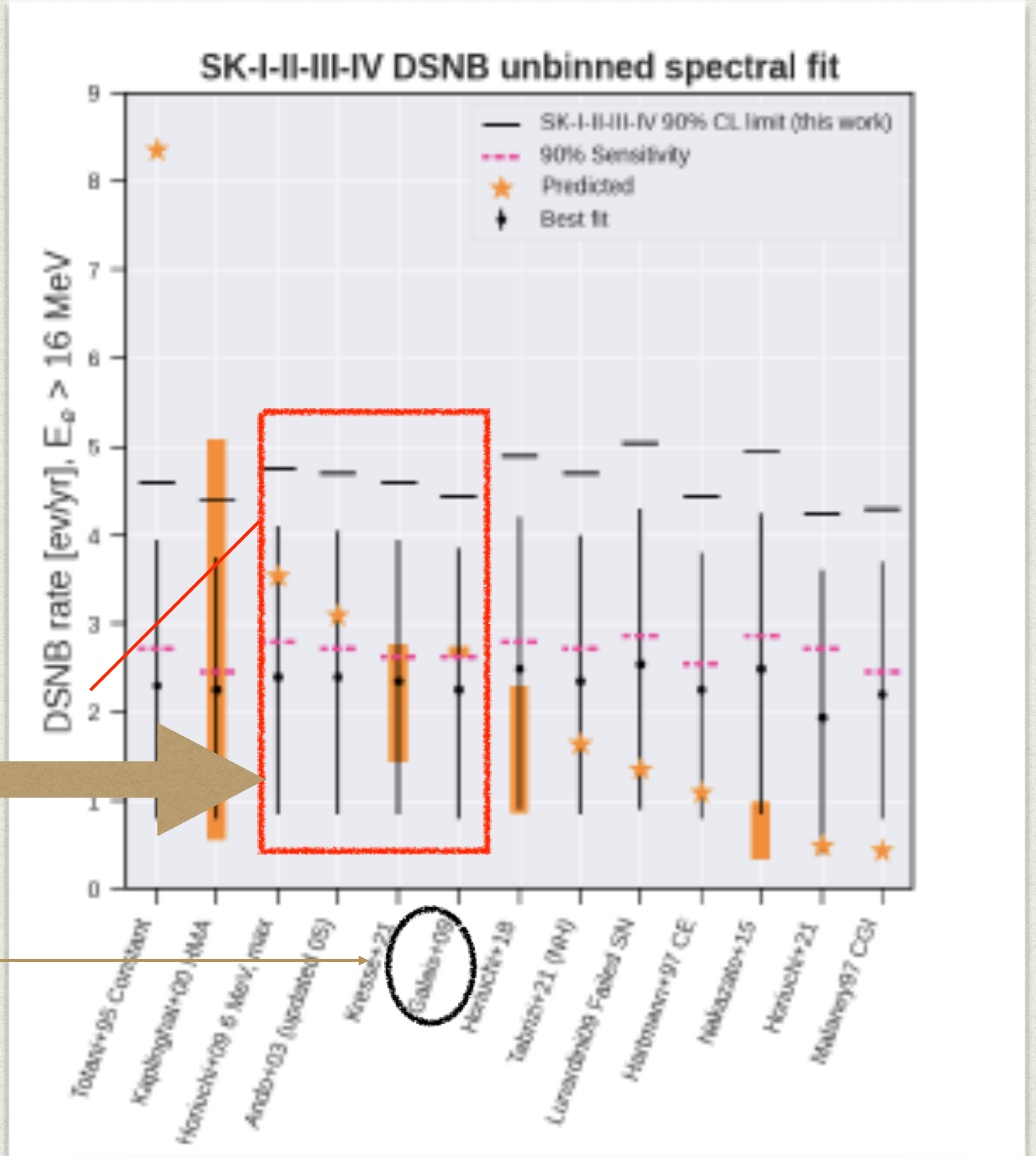
$$10^3 \nu_x \ cm^{-2} s^{-1}$$

Peres and Lunardini,. JCAP 2008

The sensitivity of the combined analysis (90 % C.L.) is on par with 4 predictions.

DSNB predictions including the neutrino-neutrino interactions, shock waves and the MSW effect

EXCESS (1.5 sigma) over BACKGROUND OBSERVED



Expected rates, 90% C.L. upper limits, best fit values (1 sig.) and expected sensitivity from SK-I and SK-IV data

Abe et al, 2109.11174

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- The DSNB flux depends on the evolving core-collapse supernova rate, the neutrino fluxes from a supernova, integrated over time

$$\phi^{\mathrm{DSNB}}_{\nu_\alpha}(E_\nu) = c \int\int \mathrm{dM}\, dz \left|\frac{dt}{dz}\right| \underset{\longleftrightarrow}{R_{\mathrm{SN}}(z,\ \mathrm{M})}\ \underset{\longleftrightarrow}{\phi_{\nu_\alpha,SN}(E'_\nu,\ \mathrm{M})}$$

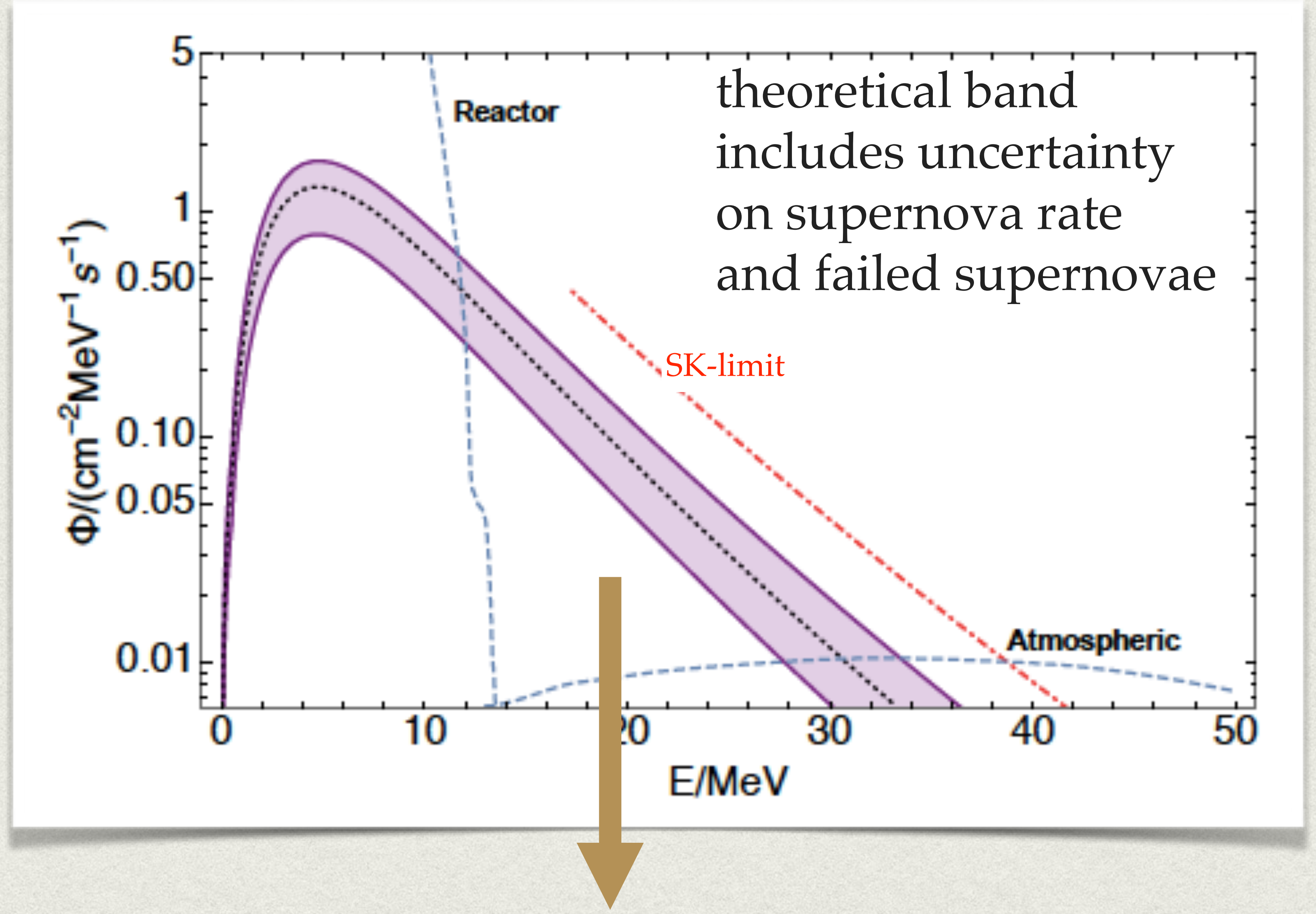
$E'_\nu = E_\nu(1+z)$ redshifted neutrino energies

M mass of the supernova progenitor giving either a neutron star or a black hole

Contribution from failed supernovae (black-hole): hotter energy spectrum determines the relic flux tail.

Lunardini, PRL 2009

The BH fraction is a debated astrophysical input.



theoretical band includes uncertainty on supernova rate and failed supernovae

Priya and Lunardini JCAP 2017

DSNB detection window

- Dependence on the cosmological model ΛCDM

$$\left|\frac{dz}{dt}\right| = H_0(1+z)\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}$$

$\Omega_\Lambda = 0.7 \quad \Omega_m = 0.3$ dark energy, matter cosmic energy densities

$H_0 = 67.4\ \mathrm{km\ s^{-1}Mpc^{-1}}$ Hubble constant

EVOLVING CORE-COLLAPSE SUPERNOVA RATE

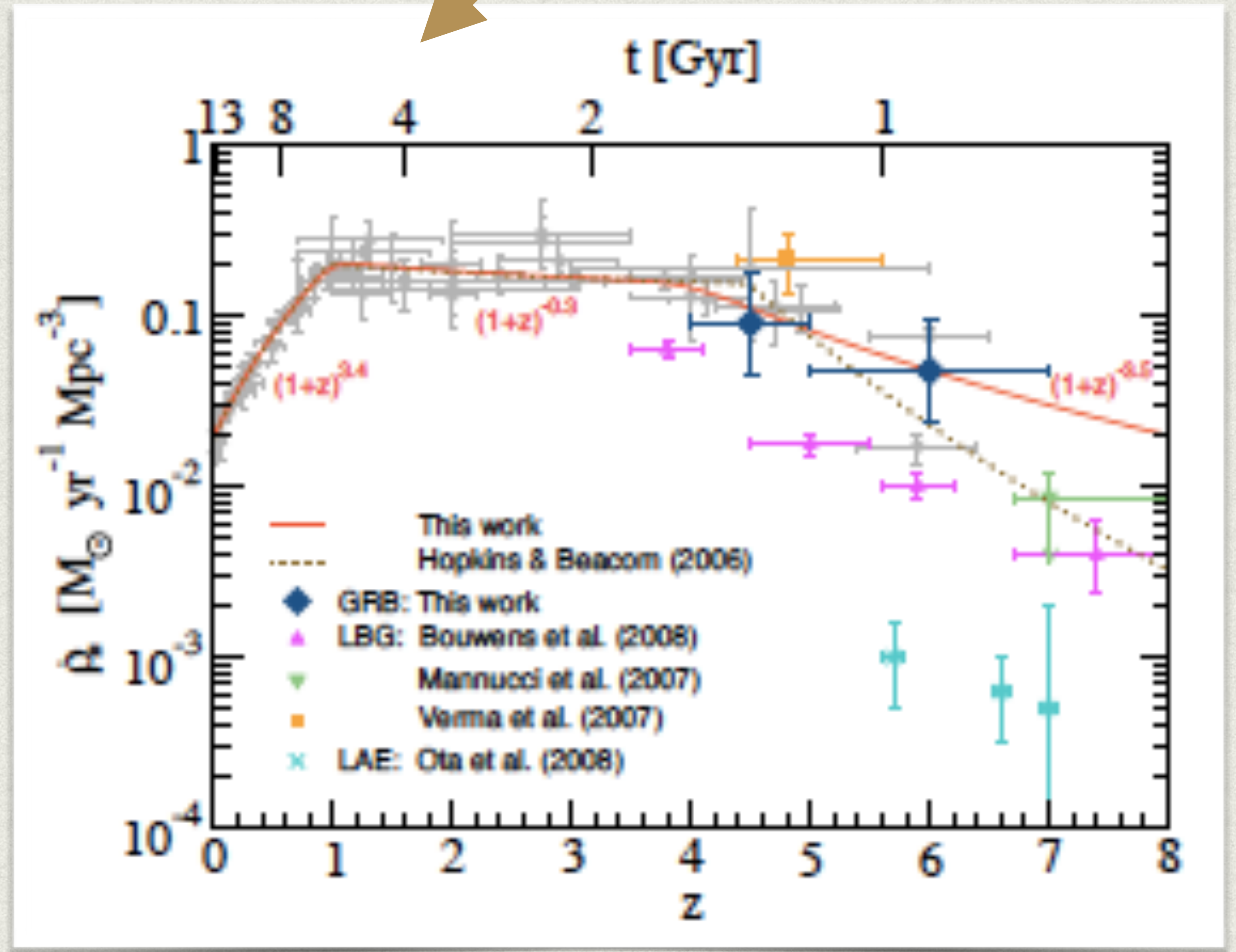
- The cosmic core-collapse supernova rate history can be deduced from the cosmic star formation rate history.

$$R_{\rm SN}(z,{\rm M}) = \dot{\rho}_*(z)\frac{\phi({\rm M})d{\rm M}}{\int_{0.5\ {\rm M}_\odot}^{125\ {\rm M}_\odot}\phi({\rm M}){\rm M}d{\rm M}}$$

- $\phi({\rm M}){\rm dM}$ is the number of stars with progenitor mass $[{\rm M}, {\rm M}+{\rm dM}]$

$$\phi({\rm M}) \sim {\rm M}^\chi \qquad \chi = -2.35 \qquad {\rm M} \geq 0.5{\rm M}_\odot$$

Salpeter Initial Mass Function (IMF)



Yuksel et al, i Astrophys. J(2008)

relevant for the DSNB

below detection threshold

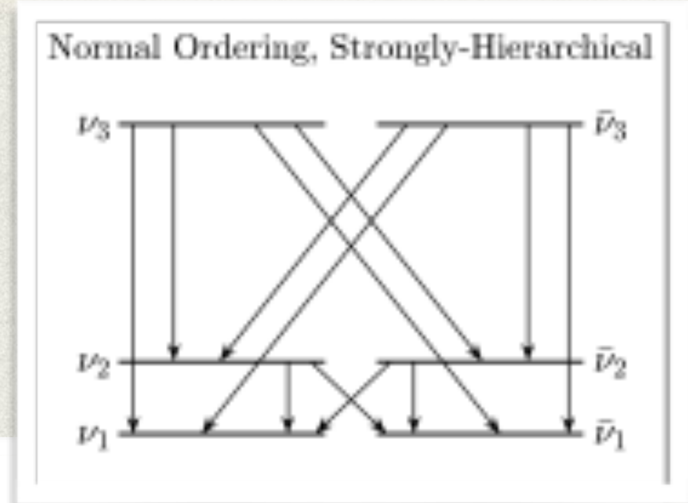
- **Local SN rate uncertain by a factor of 2:**

$$R_{SN}(0) = \int_{8\ {\rm M}_\odot}^{125\ {\rm M}_\odot} R_{\rm SN}(0,{\rm M})d{\rm M}$$

$$= 1.25 \pm 0.5 \times 10^{-4} yr^{-1} Mpc^{-3}$$

ONE of the main UNCERTAINTIES

DSNB and NEUTRINO DECAY



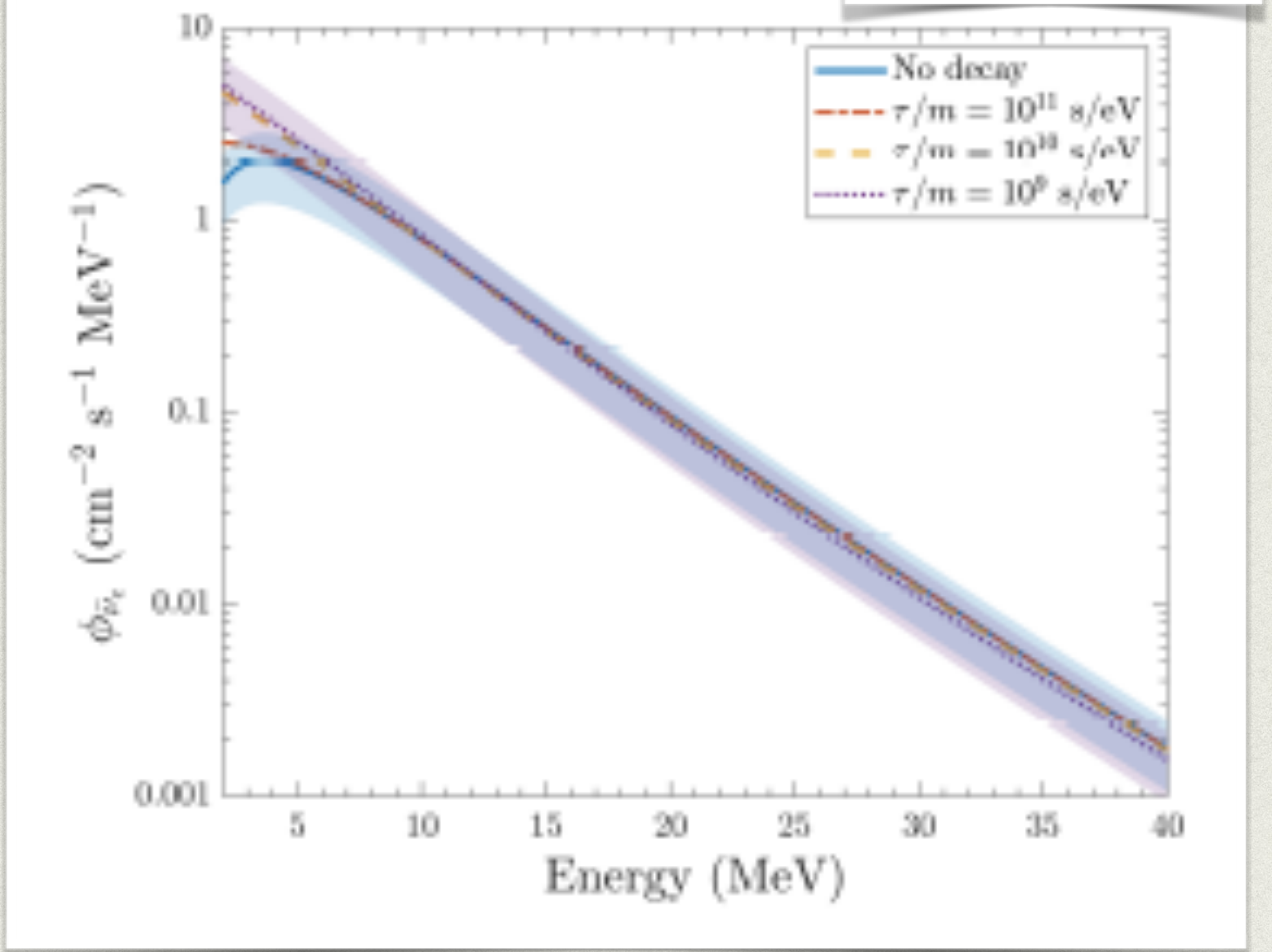
- Previous calculations for $\nu_i \rightarrow \nu_j + \phi$ or $\nu_i \rightarrow \bar{\nu}_j + \phi$

  Ando PLB (2003), Fogli et al PRD (2004), De Gouvea et al, PRD (2020)

- We have implemented for the first time uncertainties on the core-collapse supernova rate and solved the kinetic equations in a full 3nu framework for neutrino non-radiative decay. Considered normal mass ordering (strongly hierarchical or quasi-degenerate mass partterns) and inverted mass ordering.

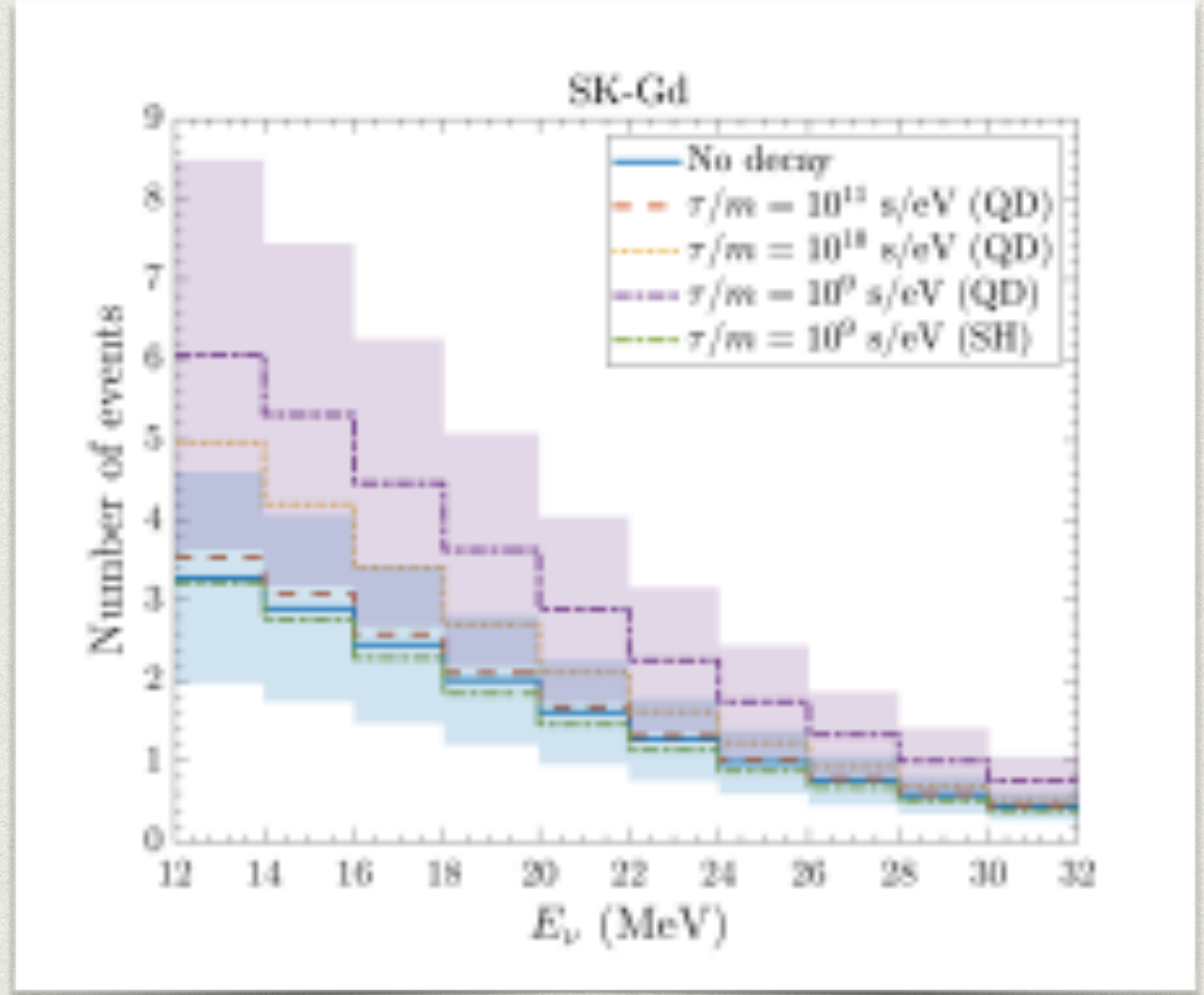
- Performed DSNB predictions for Super-Kamiokande+Gd, JUNO, DUNE and Hyper-Kamiokande, with/without neutrino decay.

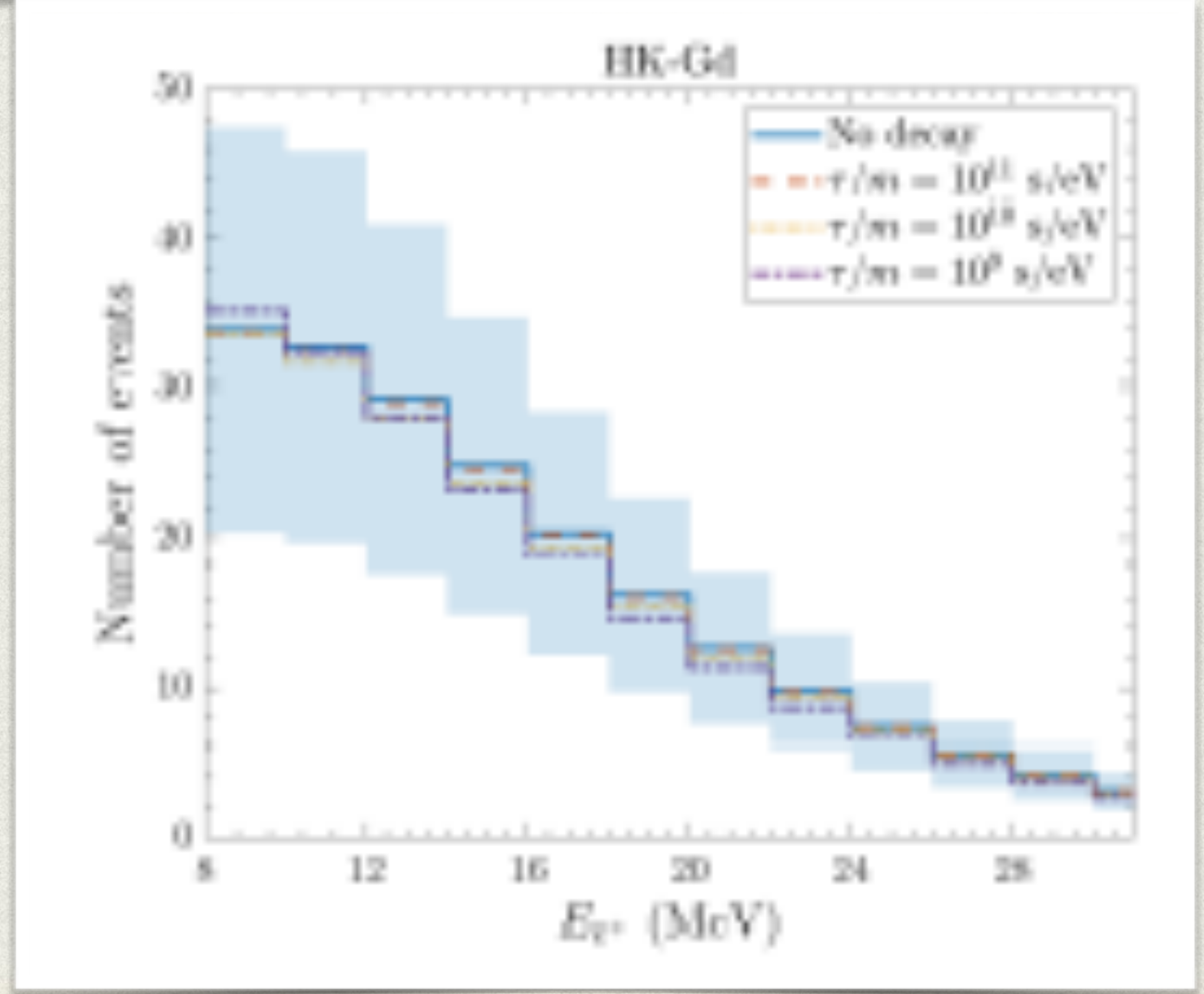
- **Expected DSNB events (no decay) :**
  10 for SK-Gd (10 year), and DUNE (20 years),
  10-40 for JUNO (20 years)
  several hundreds for Hyper-Kamiokande (10-20 years).

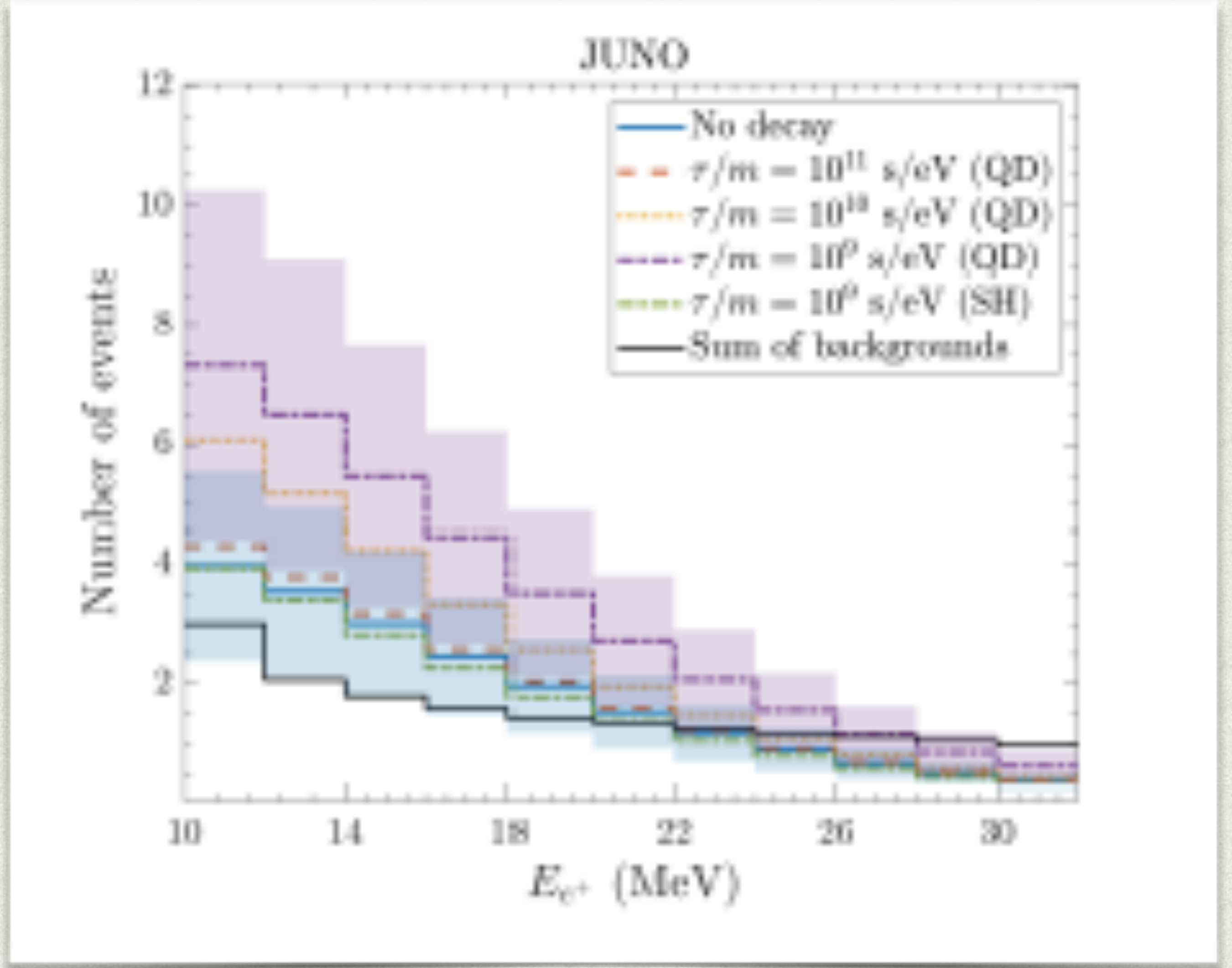


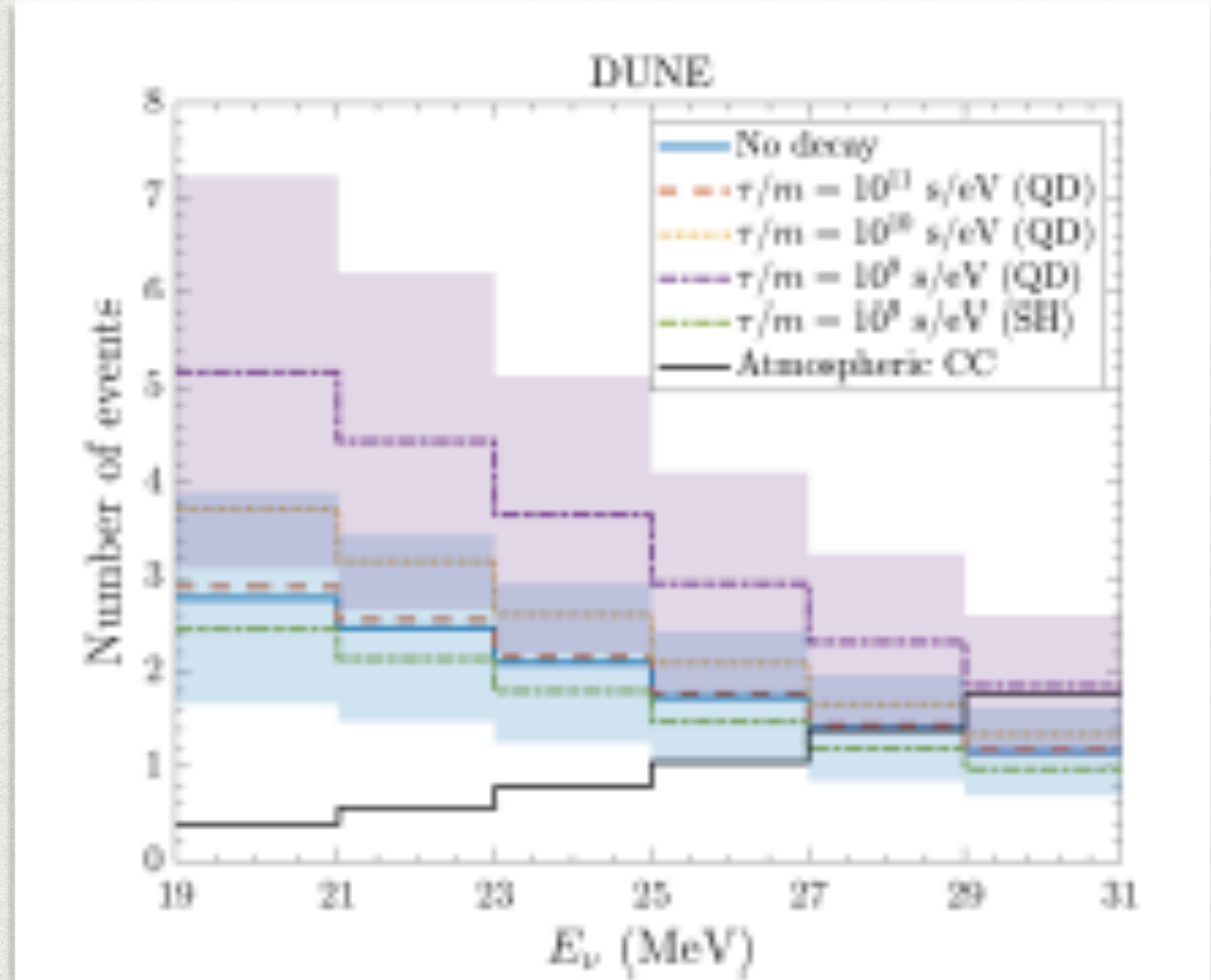
Ivanez-Ballesteros and Volpe,
PRD107 (2023), arXiv:2209.12465

DSNB EVENTS in presence/absence of neutrino decay



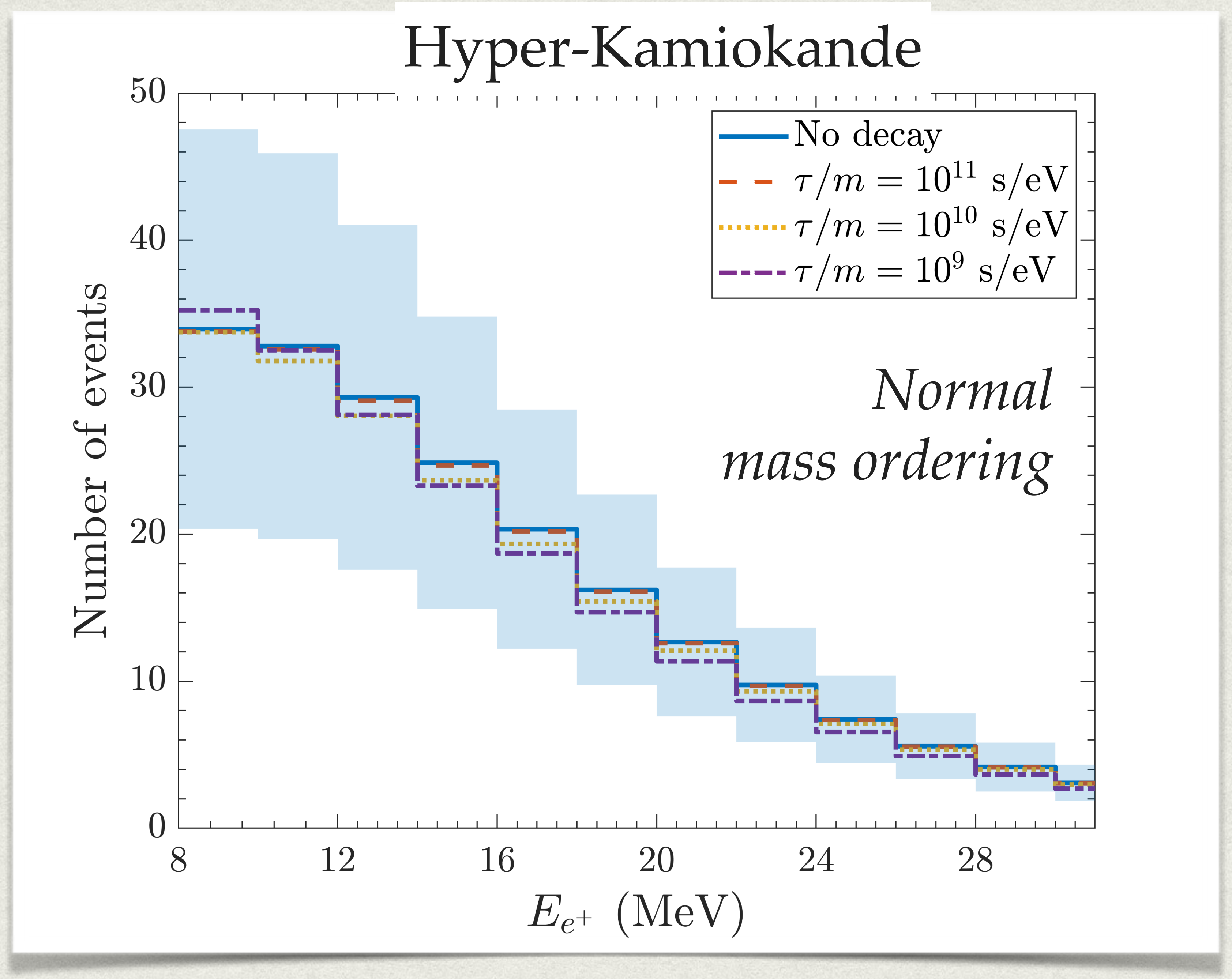


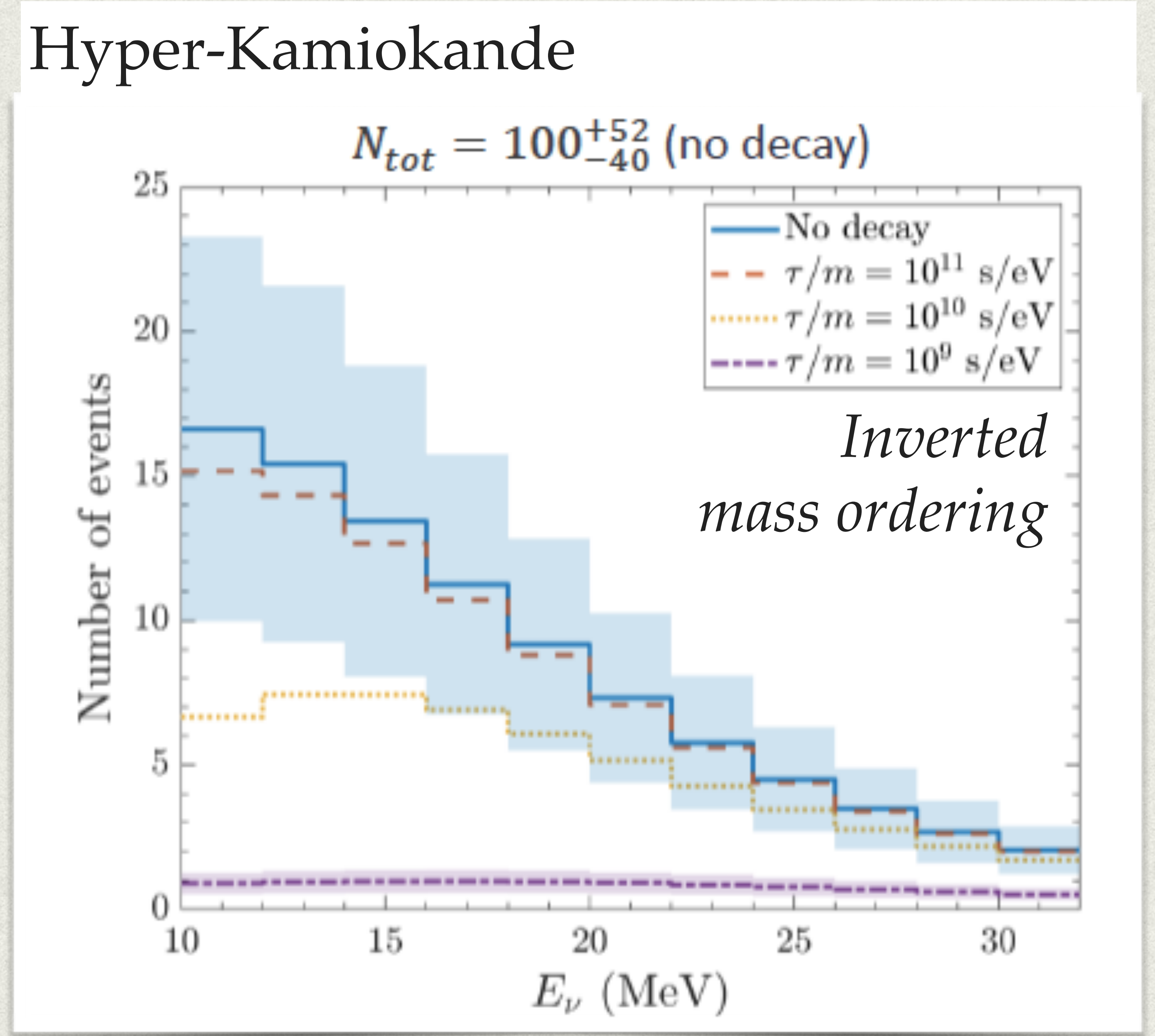




Ivanez-Ballesteros and Volpe,
PRD107 (2023), arXiv:2209.12465

DSNB predictions with/without neutrino decay





Ivanez-Ballesteros and Volpe,
PRD107 (2023), arXiv:2209.12465

If the mass ordering is normal, there are important degeneracies between predictions with and without decay

In case DSNB not observed, it could be due to neutrino non-radiative two-body decay

Conclusions and Perspectives

- **Neutrinos in dense media is a complex weakly interacting many-body system.** A variety of novel flavor mechanisms, beyond the Mikheev-Smirnov-Wolfenstein effect have been discovered in the last two decades which can **impact the supernova explosion dynamics, r-process nucleosynthetic abundances and future observations**.

- Neutrinos from astrophysical environments have unique sensitivities to unknown neutrino properties such as non-radiative neutrino decay. We have extracted a tight limit on tau/m for the mass eigenstates 1 and 2 for inverted mass ordering from SN1987A neutrino events.

- For the DSNB, our predictions with neutrino decay in a full 3nu framework and including astrophysical uncertainties on the core-collapse supernova rate show a significant suppression in inverted mass ordering and important degeneracies in normal mass ordering.

- **The upcoming discovery of the diffuse supernova neutrino background will open a new window in low energy neutrino astronomy.**

« *Une femme jouant de guitare* », Vermeer, 1672