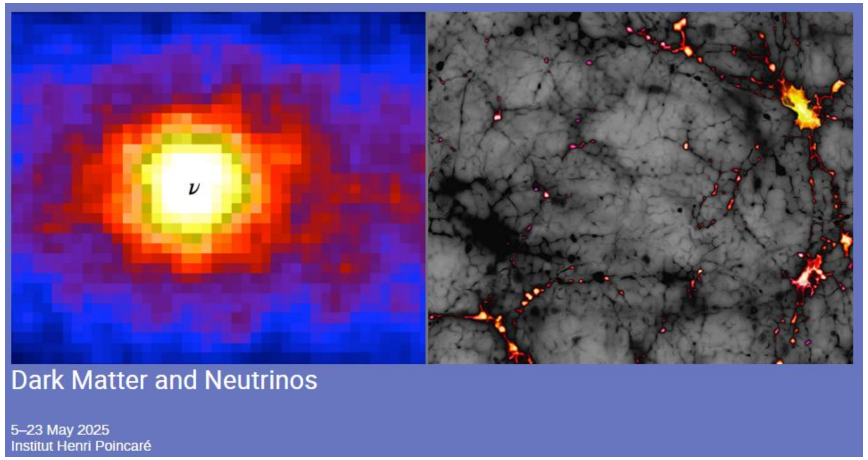


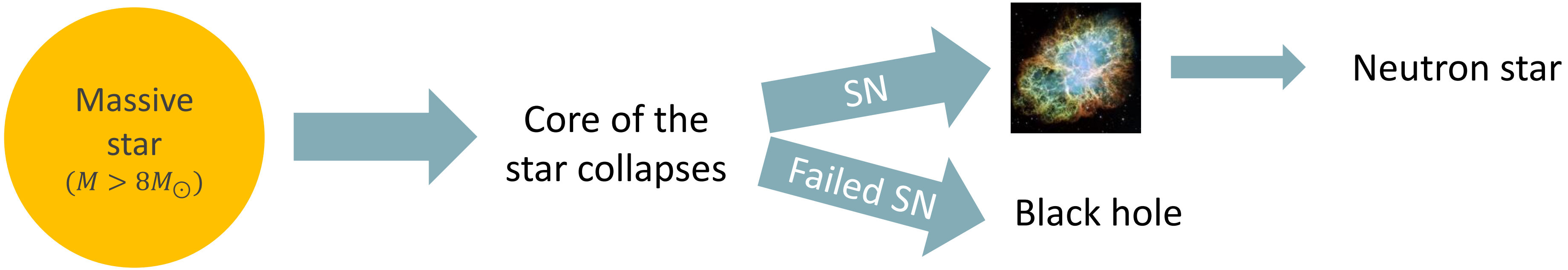
Probing neutrino decay in matter with supernova neutrinos

PILAR IVÁÑEZ BALLESTEROS (she/her)

PhD supervisor: DR. M. C. VOLPE

APC – UNIVERSITÉ PARIS CITÉ

Supernova neutrinos

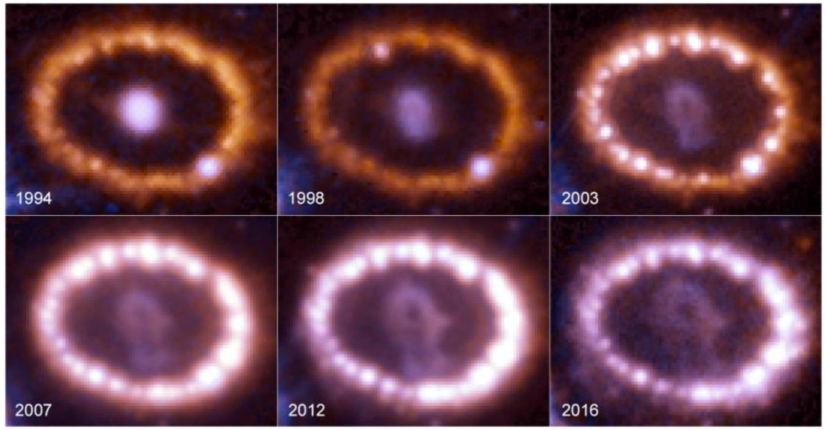


- **Powerful source of neutrinos**: $\sim 10^{53}$ erg emitted in all flavours (99% of gravitational binding energy!)

  ➡ interesting information can be obtained if we detect these neutrinos!

- We are sensitive to galactic supernova, BUT these are <u>rare events</u> (1-3 per century)

- Only detection was **SN1987A** (50 kpc away)
  - ↳ <u>24 $\bar{\nu}_e$ events</u> detected by Kamiokande-II, IMB, and Baksan
    [Hirata *et al*., 1987] [Bionta *et al*., 1987] [Alekseyev *et al*., 1988]
  - ↳ Total energy associated to $\bar{\nu}_e$ events: $\sim \mathbf{5 \times 10^{52} erg}$
  - ↳ Confirmed our broad understanding of gravitational collapse

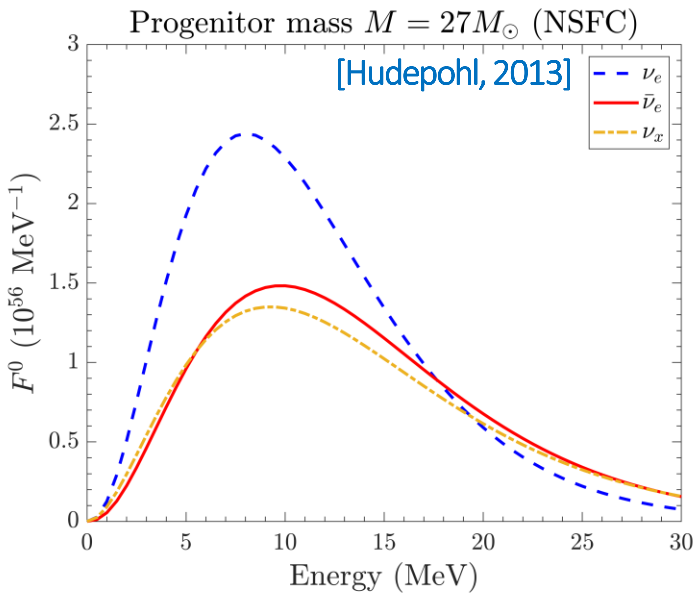


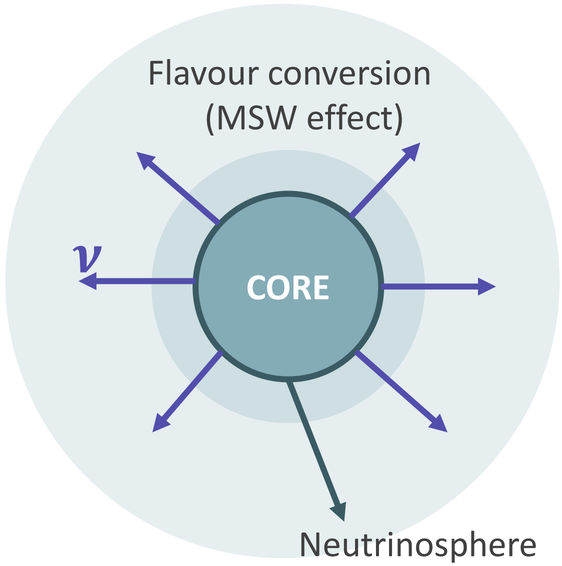
Evolution of SN 1987A. Hubble Space Telescope
https://www.esa.int/About_Us/ESAC/The_evolution_of_SN_1987A

❖ **Diffuse Supernova Neutrino Background** (DSNB):
flux of all neutrinos and antineutrinos emitted by past supernovae

Standard neutrino emission from a single collapse

- Emission depends on: outcome of the collapse, progenitor characteristics…
- Flux at the neutrinosphere, $\phi^0_{\nu_\alpha}$:
  - It can be parametrised by a **power-law distribution**: $\mathcal{L}_{\nu_\alpha}$, $\langle E_{\nu_\alpha}\rangle$, α_{ν_α} [Keil *et al.*, 2003]
  - Luminosity of $\mathcal{L}_{\nu_\alpha} \sim 10^{52}$ erg
  - $\langle E_{\nu_\alpha}\rangle$: average energy $(\sim 9-18\ \mathrm{MeV}) \rightarrow \langle E_{\nu_e}\rangle < \langle E_{\overline{\nu}_e}\rangle < \langle E_{\nu_x}\rangle$
  - $\alpha_{\nu_\alpha} \sim 2-3$

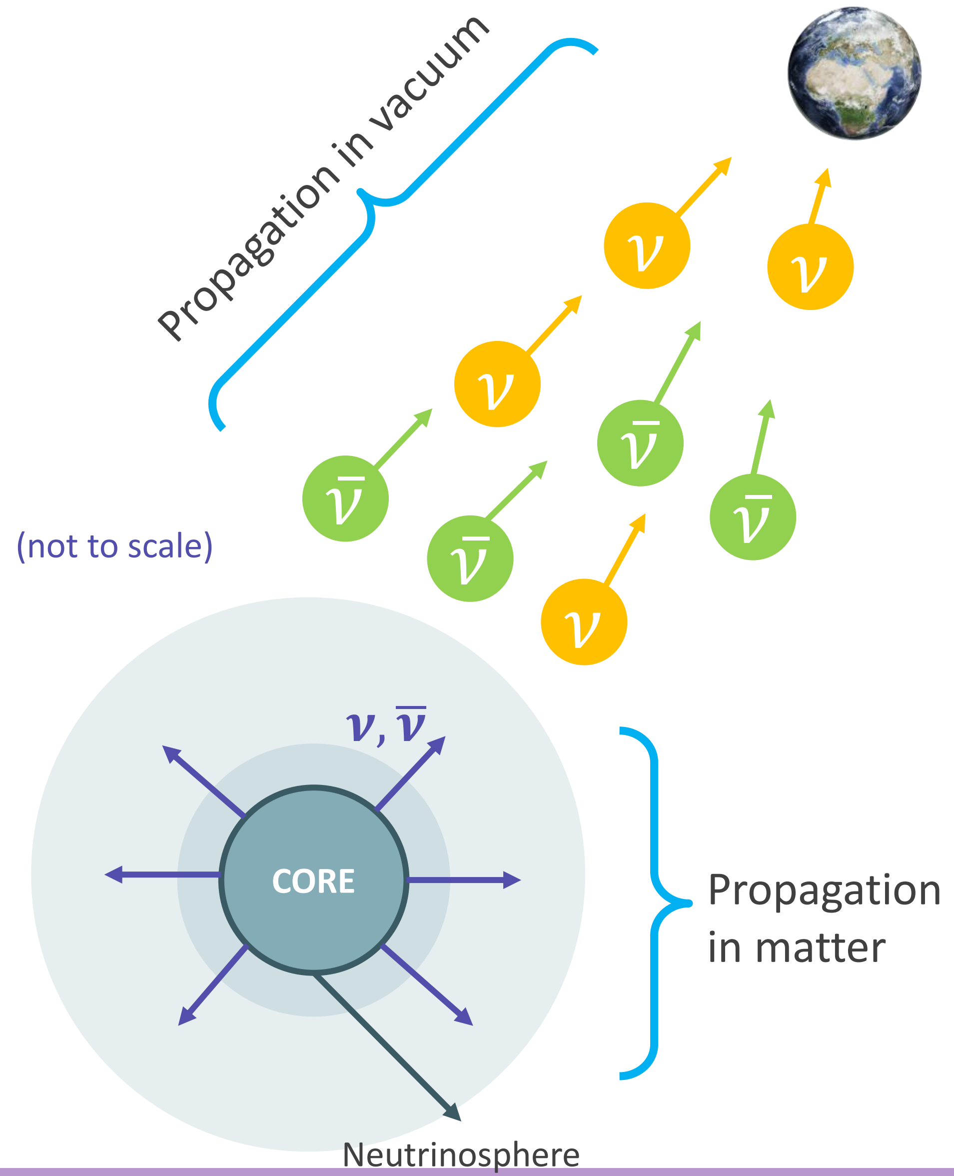




- Flavour effects inside supernova:
  - **Mikheev-Smirnov-Wolfenstein (MSW) effect**: describes the **flavour transformations** due to the ν-matter interactions. [Wolfenstein, 1978] [Mikheev and Smirnov, 1986]

    MSW effect inside SN is assumed to be adiabatic $\rightarrow \phi_{\overline{\nu}_l} = \phi^0_{\overline{\nu}_e}$; $\phi_{\overline{\nu}_i} = \phi_{\overline{\nu}_h} = \phi^0_{\nu_x}$
  - Other effects still under study: shock wave effects, $\nu-\nu$ interactions…
    see e.g. the review Volpe (2024)

How does neutrino decay affect this picture?



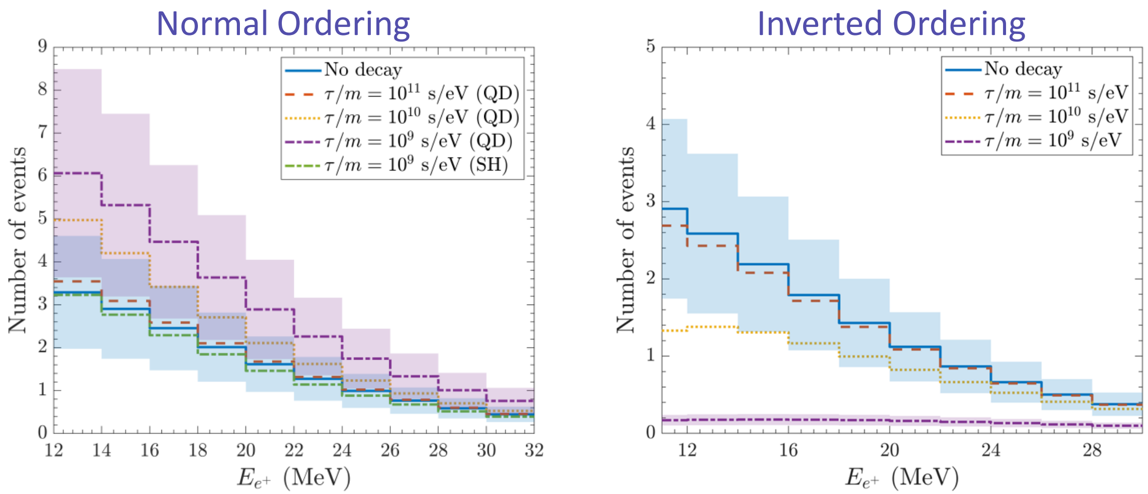
Two possibilities for neutrino decay:

1. Neutrino nonradiative decay **in vacuum**

$$\nu_j \longrightarrow \nu_i \, (\bar{\nu}_i) + X$$

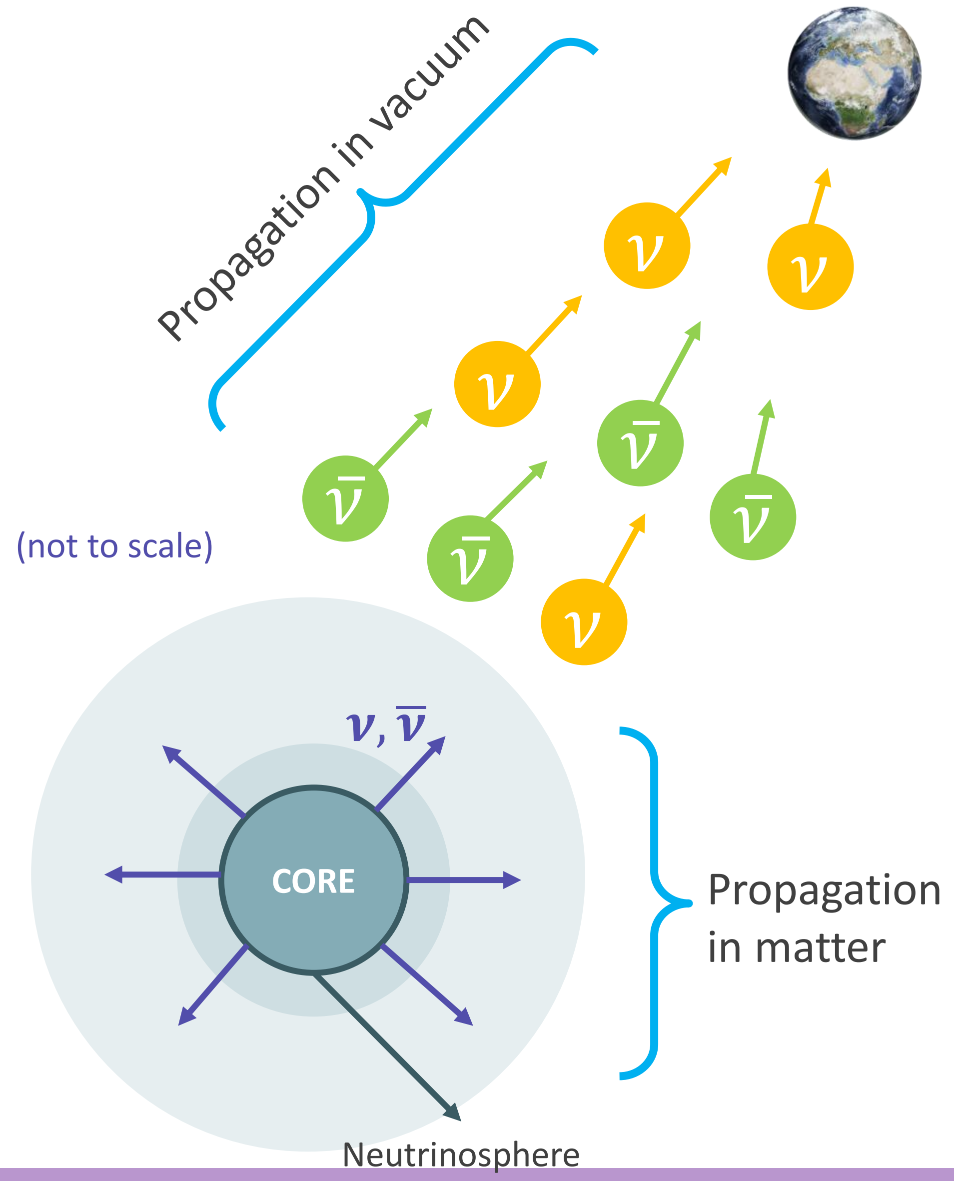
- SN1987A data $\Longrightarrow \frac{\tau}{m} \geq 1.2 \times 10^5$ s/eV at 90% CL (IO) [P.I.B. and Volpe, PRD107 (2023) 023017]
- DSNB: unique sensitivity in the range: $\frac{\tau}{m} \in \left[10^9 - 10^{11}\right]$ s/eV

Number of events in SK+Gd (20 years)



[P.I.B. and Volpe, PRD107 (2023) 023017]

How does neutrino decay affect this picture?



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2. Neutrino decay **in matter:**
   - Neutrino decay to Majorons inside supernova

Neutrino decay to Majorons in supernovae

We consider interactions between neutrinos and massless Majorons, J:

$$\mathcal{L} \propto \sum_{i,j} g_{ij} \bar{\nu}_i \gamma_5 \nu_j J$$

- Coupling matrix diagonal in mass basis: $\boldsymbol{g_{ij} \propto m_i \delta_{ij}}$ [Schechter and Valle, 1982]
- Interactions of neutrinos with the medium: $V_{\nu_e} = V_{CC} + V_{NC}, \quad V_{\nu_x} = V_{NC}$

$$V_{CC} = \sqrt{2} G_F n_B (Y_e + Y_{\nu_e}) \text{ and } V_{NC} = \sqrt{2} G_F n_B \left(-\frac{1}{2} Y_N + Y_{\nu_e}\right)$$

- $\tilde{g}_{ij}$**: non-diagonal:**

  Processes like $\nu^{\pm} \to \nu^{\mp} + J$ are allowed and can affect the neutrino emission

Limits on coupling of neutrinos and massless Majorons from SNe: see e.g. [Choi *et al.*, 1988], [Berezhiani and Smirnov, 1989], [Farzan, 2003], ...

- Energy-loss argument: $\mathcal{L}_J < 5 \times 10^{52} \mathrm{erg/s} \to 3 \times 10^{-7} \lesssim g_{\alpha\beta} \lesssim 2 \times 10^{-5}$ excluded
- Deleptonization argument: $Y_L(t_{\mathrm{bounce}}) \geq 0.375 \to g_{ee} \lesssim 2 \times 10^{-6}$

[Kachelriess *et al.*, 2000]

Neutrino decay to Majorons in supernovae

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Limits on coupli ... mirnov, 1989], [Farzan, 2003], ...

- Energy-loss
- Deleptonizat ... et al., 2000]

CAN WE OBTAIN INFORMATION ON THE NEUTRINO-MAJORON COUPLINGS USING A **LIKELIHOOD ANALYSIS** OF SN1987A DATA?

Decay of (anti)neutrinos

Hamiltonian: $H_{\text{tot}} = \underbrace{H_0}_{\text{vacuum}} + \underbrace{\sum_{i,j} \bar{\nu}_i V_{ij} \nu_j}_{\text{medium}} + \underbrace{g_{ij} \bar{\nu}_i \gamma_5 \nu_j J}_{\text{interaction}}$

[Kachelriess *et al.*, 2000]
[P.I.B. and Volpe, arXiv:2410.11517]

Coupling matrix in matter, $\tilde{g}_{ij}$, is non-diagonal and $\tilde{g}_{ij} \approx g_{\alpha'\beta'}$ **at very high densities**

- Decay rate for $\nu_\alpha^\pm \to \nu_\beta^\mp + J$ (helicity flipping)

$$\Gamma_{\alpha\beta} = \frac{g_{\alpha\beta}^2}{16\pi}(V_\alpha - V_\beta)$$

Decay is **only allowed for $V_\alpha - V_\beta > 0$**

→ for the profiles* we considered, only **satisfied by $\bar{\nu}$ decay**: $\bar{\nu}_\alpha \to \nu_\beta + J$

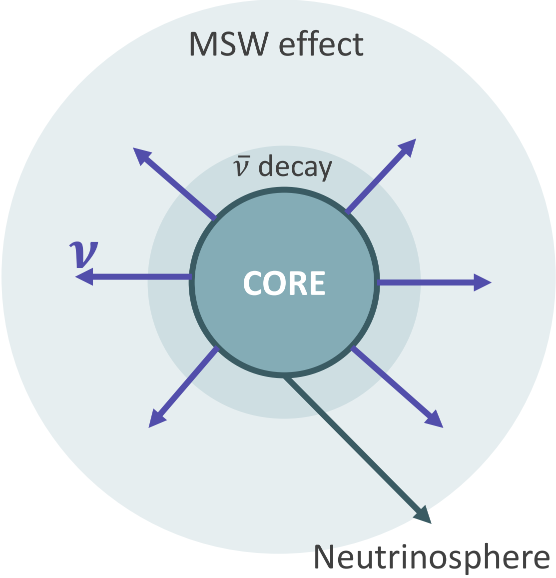
- Survival probability: (in general, a function of time and energy)

$$N_{\bar{\nu}_\alpha}(E, t) = \exp\left\{ - \int_{R_{E,\bar{\nu}_\alpha}(t)}^{R_{T,\bar{\nu}_\alpha}(t)} \frac{dr'}{v(E, r', t)} \Gamma_{\bar{\nu}_\alpha}(r', t) - \int_{R_{T,\bar{\nu}_\alpha}(t)}^{\infty} dr' \Gamma_{\bar{\nu}_\alpha}(r', t) \right\}$$

$R_{E,\bar{\nu}_\alpha}$ and $R_{T,\bar{\nu}_\alpha}$ are the energy- and transport-spheres

- $\bar{\nu}_\alpha$ fluxes after decay:

$$\phi_{\bar{\nu}_\alpha}^{d}(E, t) = N_{\bar{\nu}_\alpha}(E, t)\phi_{\bar{\nu}_\alpha}^{0}(E, t)$$



*We used SN profiles and fluxes from the 1D simulations by the Garching group. https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html These models agree well with SN1987A data. [Fiorillo *et al.* (2023)]

Limits to $\boldsymbol{\nu}$-Majoron coupling

- **2D unbinned likelihood analysis** of SN1987A time-independent data:

g_{11}, m_1 **(NO):**

$$g_{22} = g_{11}\sqrt{1+\frac{\Delta m_{21}^2}{m_1^2}}$$

$$g_{33} = g_{11}\sqrt{1+\frac{\Delta m_{31}^2}{m_1^2}}$$

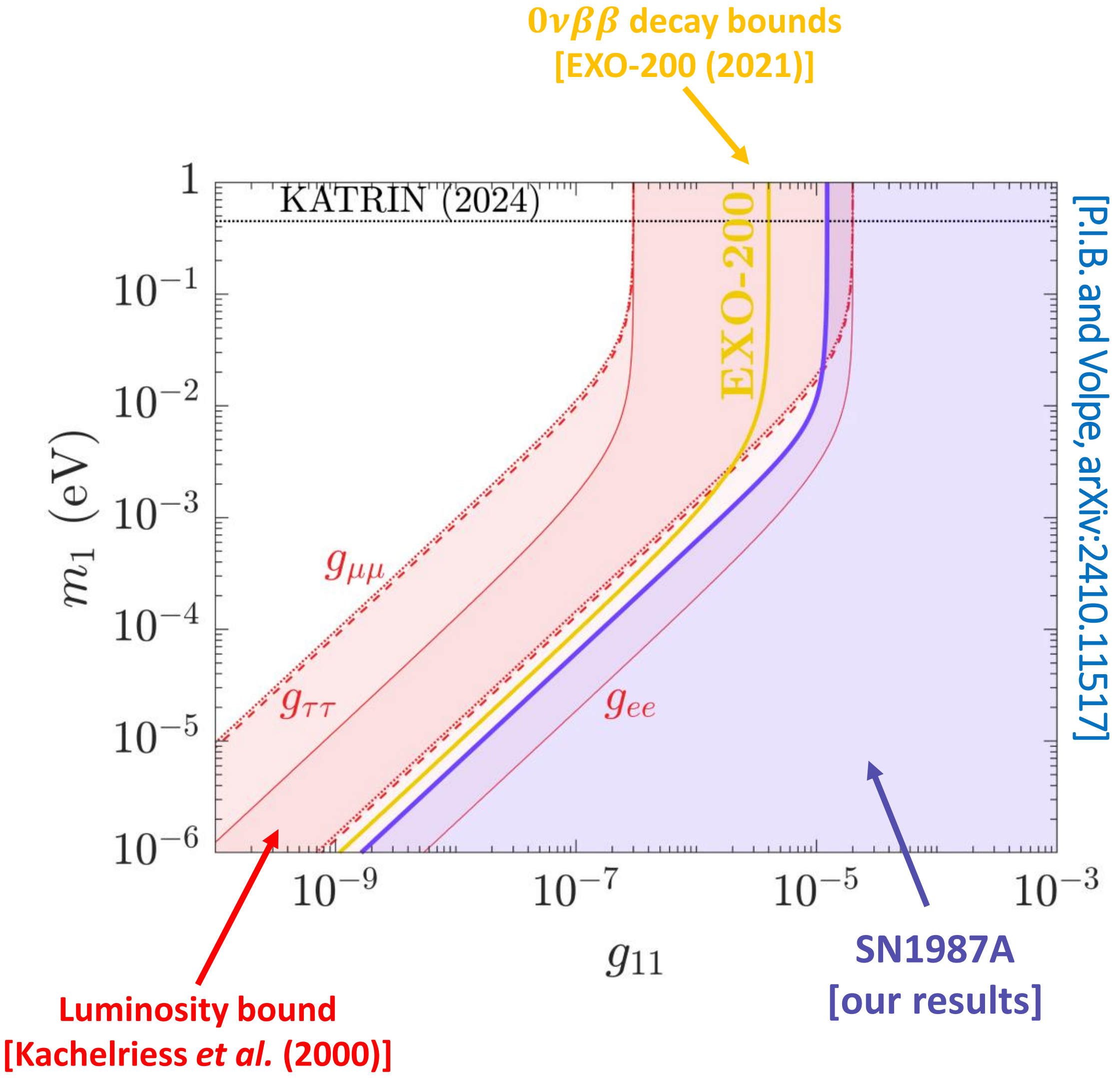
Using profiles and fluxes from the model **1.44SFHx**
https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html
[Fiorillo *et al.* (2023)]

- Luminosity bound: $\mathcal{L}_J < 5\times10^{52}$ erg/s

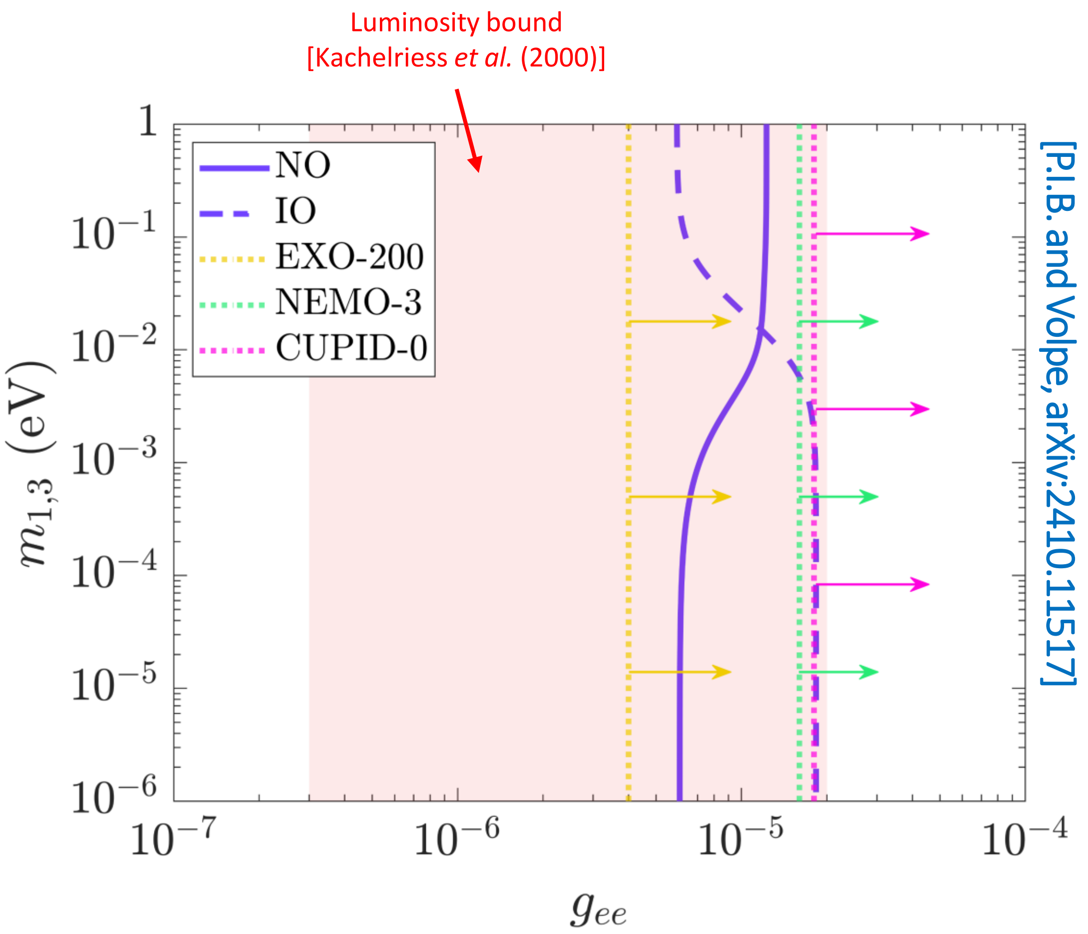
$$3\times10^{-7} \lesssim g_{\alpha\alpha} \lesssim 2\times10^{-5}\ \text{(exclusion)}$$

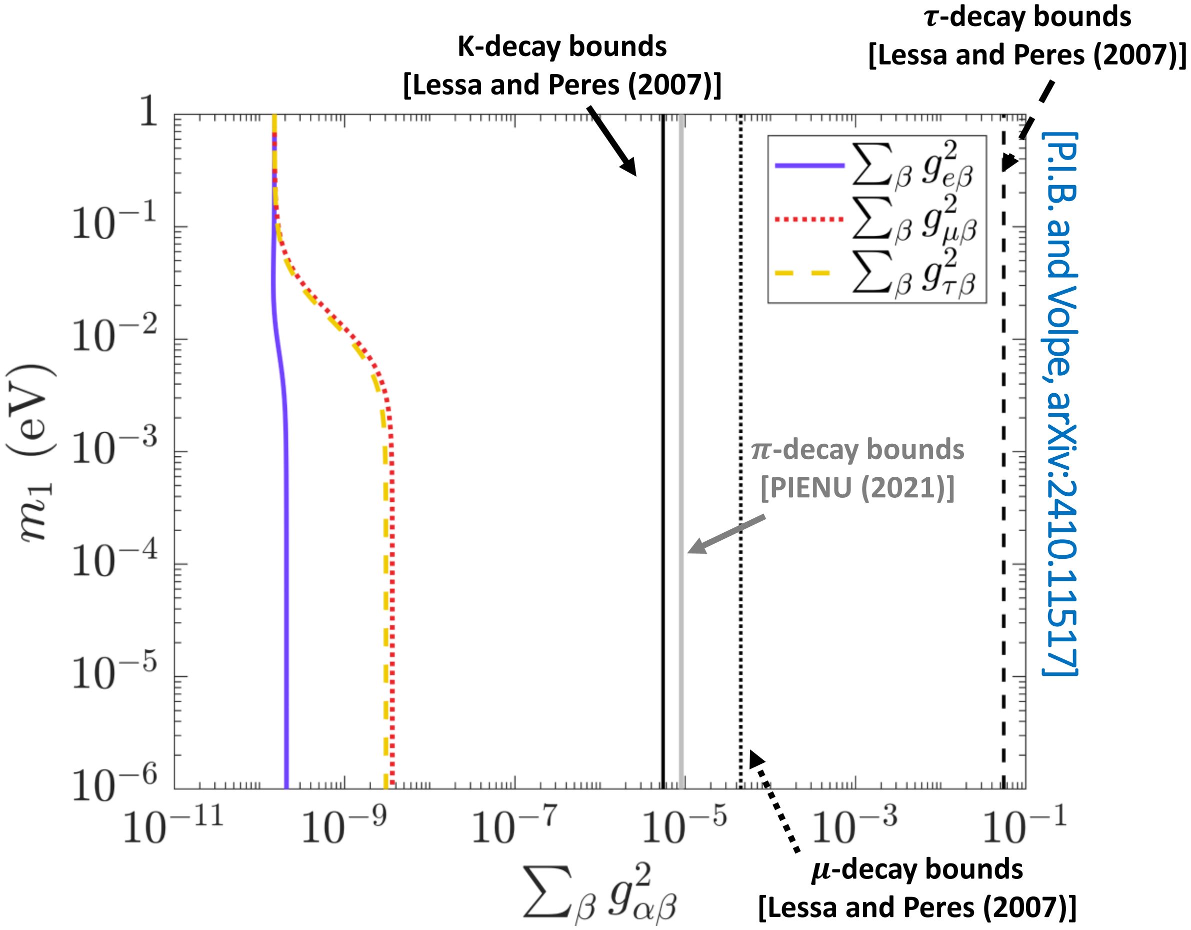
- $0\nu\beta\beta$ bounds only on g_{ee}:

$$\text{EXO-200: } g_{ee} < (0.4-0.9)\times10^{-5}$$



Limits to ν-Majoron coupling: flavour basis





Main results and conclusions

The supernova neutrino signal can be affected by neutrino decay in vacuum or matter.

- **Neutrino decay to Majorons** enhanced by **matter effects**
- First likelihood analysis of SN1987A data to obtain limits on couplings between neutrino and massless Majorons
  - Competitive with limits from $0\nu\beta\beta$ decay experiments
  - Improving 4-7 orders of magnitude the limits from meson and lepton decays

P. Iváñez-Ballesteros and M.C. Volpe, arXiv:2410.11517

Thank you! :)

BACK UP SLIDES

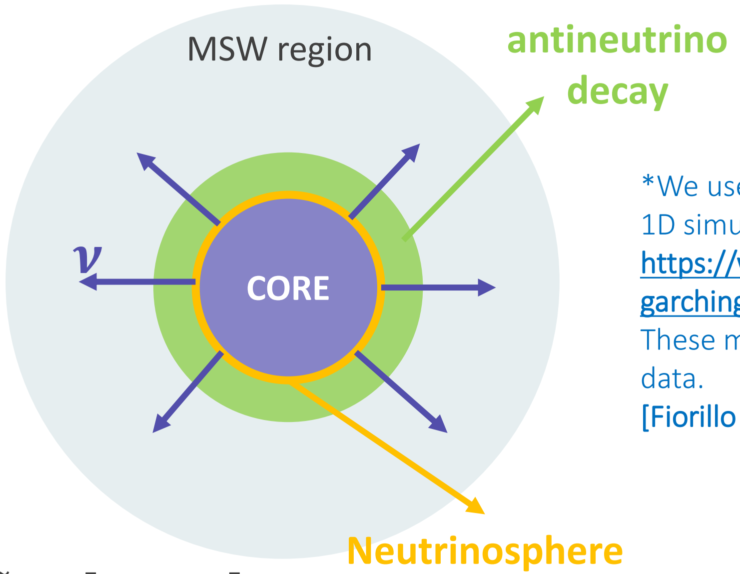
Antineutrino decay in matter: implementation

1. **Flux at the neutrinosphere:** $\phi^0_{\bar{\nu}_\alpha}(E,t)$
2. **Antineutrino decay**:
   - Decay only allowed for $\bar{\nu} \to \nu + J$ *
   - Survival probability: $N_{\bar{\nu}_\alpha}(E,t)$
3. **Flux after decay:** $\phi^d_{\bar{\nu}_\alpha}(E,t)$
   1. Supernova evolution split into 6 intervals
   2. Choose representative time-point for each interval: $\tilde{t}_i \in [t_{i-1}, t_i]$
   3. Calculate survival probability at those times: $\boldsymbol{N^i_{\bar{\nu}_\alpha}(E) = N_{\bar{\nu}_\alpha}(E, \tilde{t}_i)}$
   4. Decayed antineutrino flux at time $t \in [t_{i-1}, t_i]$ with $i = 1, \dots, 6$

$$\boldsymbol{\phi^d_{\bar{\nu}_\alpha}(E,t) = N^i_{\bar{\nu}_\alpha}(E)\phi^0_{\bar{\nu}_\alpha}(E,t)}$$

4. **Flux at the surface of the SN**:

$$\phi_{\bar{\nu}_1} = \phi^d_{\bar{\nu}_{e'}}, \quad \phi_{\bar{\nu}_2} = \phi^d_{\bar{\nu}_{\mu'}}, \quad \phi_{\bar{\nu}_3} = \phi^d_{\bar{\nu}_{\tau'}} \quad \text{(NO)}$$
$$\phi_{\bar{\nu}_1} = \phi^d_{\bar{\nu}_{\tau'}}, \quad \phi_{\bar{\nu}_2} = \phi^d_{\bar{\nu}_{\mu'}}, \quad \phi_{\bar{\nu}_3} = \phi^d_{\bar{\nu}_e} \quad \text{(IO)}$$



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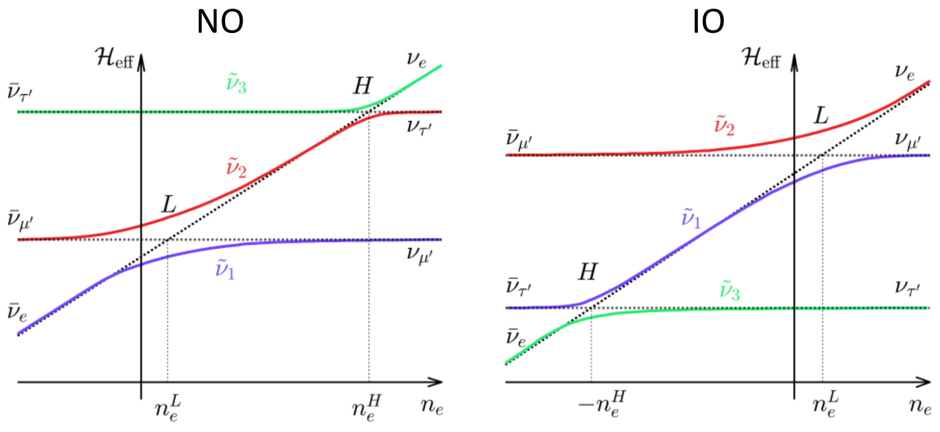
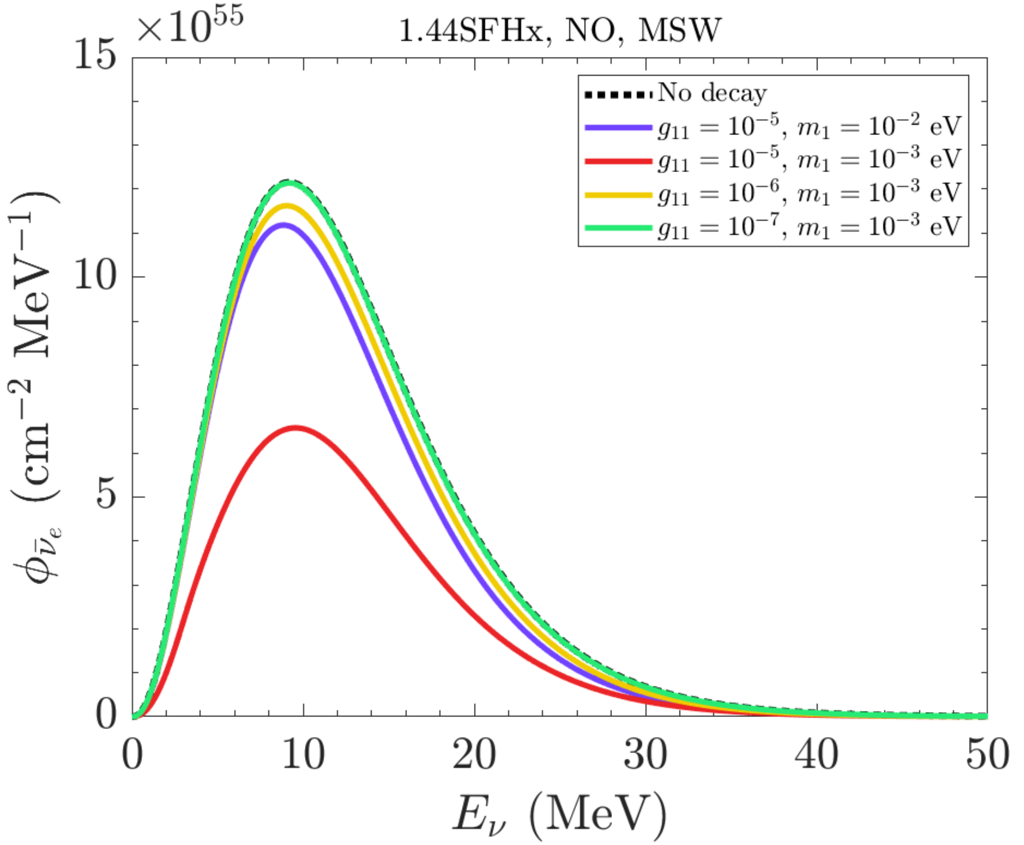
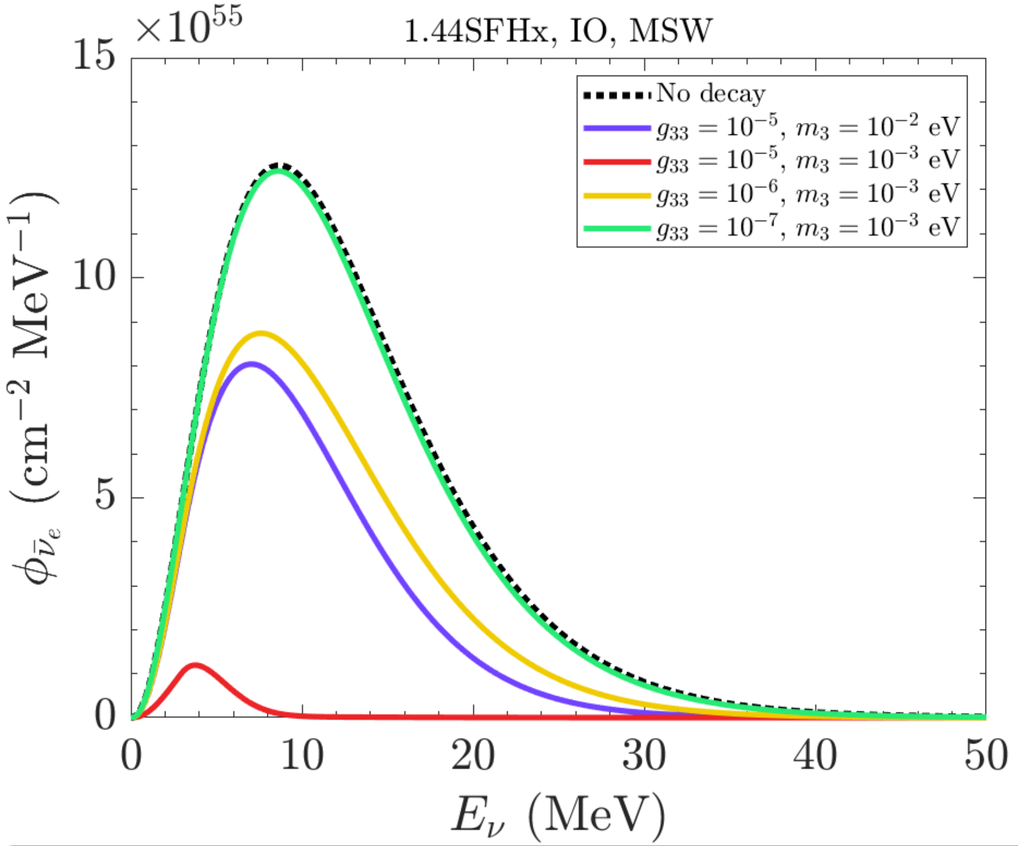


Neutrino fluences in the presence of ν-Majoron interactions

Using profiles and fluxes from the model **1.44SFHx**

https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html [Fiorillo *et al.* (2023)]

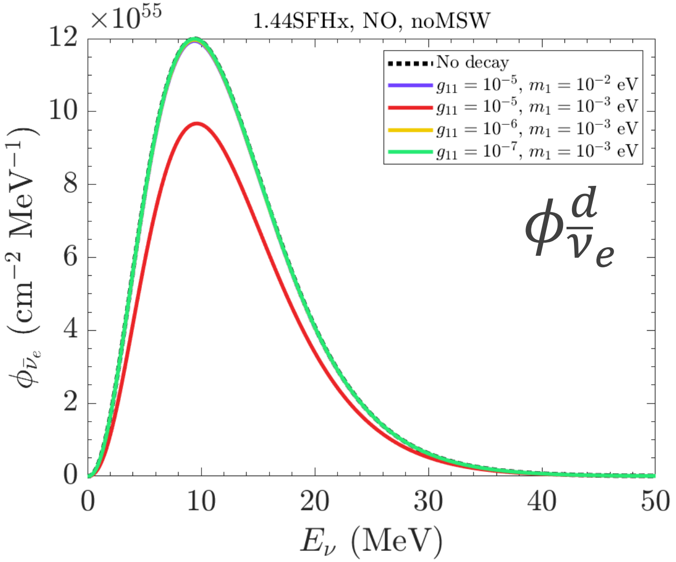


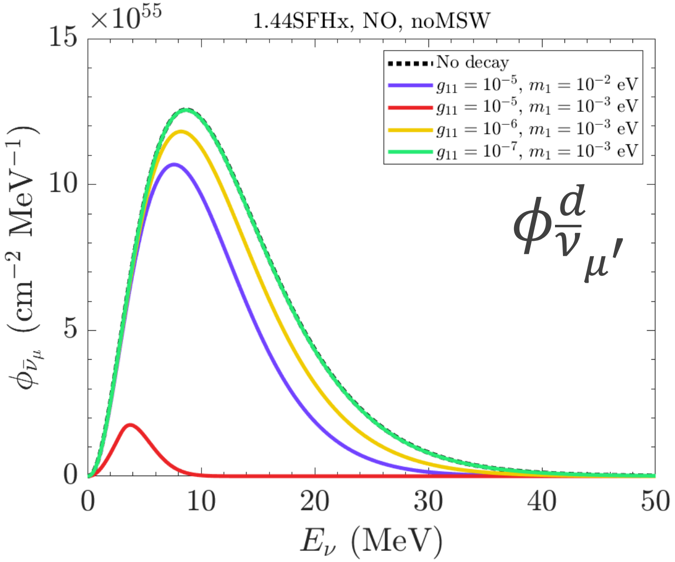


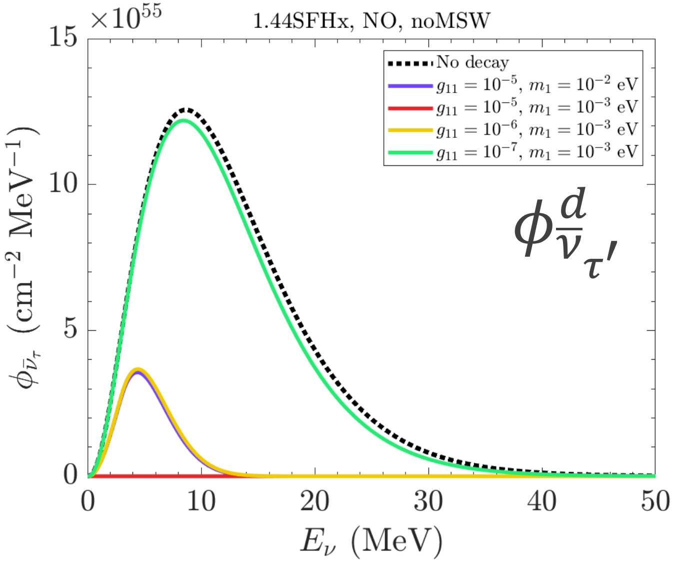
$$g_{22} = \boldsymbol{g_{11}}\sqrt{1+\frac{\Delta m_{21}^2}{\boldsymbol{m_1^2}}}, \qquad g_{33} = \boldsymbol{g_{11}}\sqrt{1+\frac{\Delta m_{31}^2}{\boldsymbol{m_1^2}}}$$

$$g_{11} = \boldsymbol{g_{33}}\sqrt{1+\frac{|\Delta m_{31}^2|}{\boldsymbol{m_3^2}}}, \qquad g_{22} = \boldsymbol{g_{33}}\sqrt{1+\frac{|\Delta m_{32}^2|}{\boldsymbol{m_3^2}}}$$

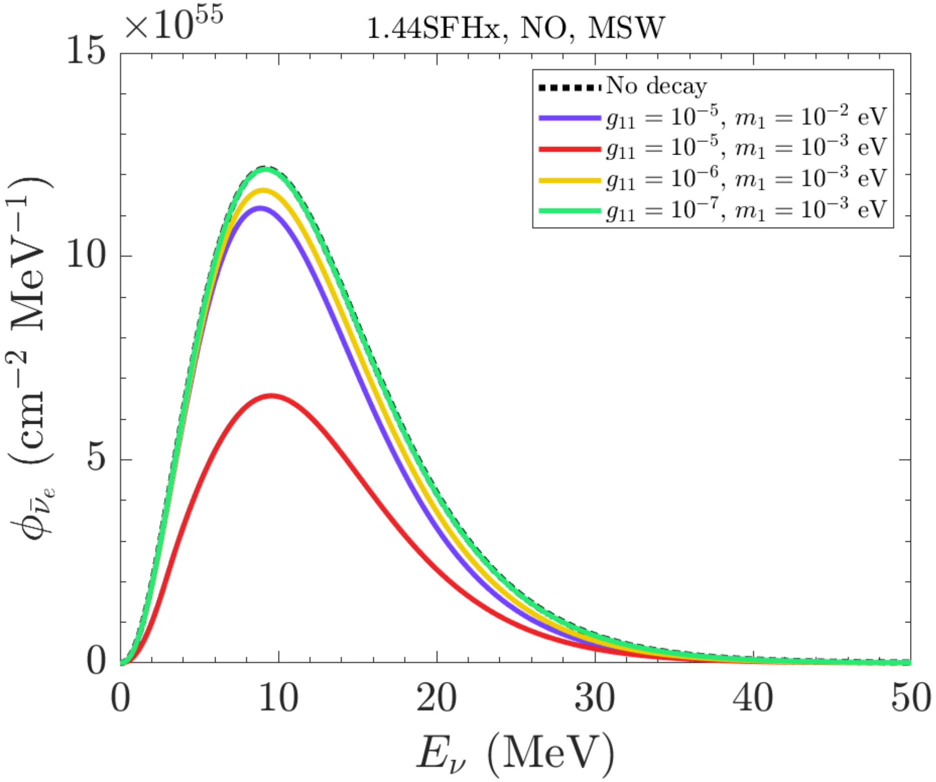
Neutrino fluences in the presence of $\boldsymbol{\nu - J}$ interactions: NO



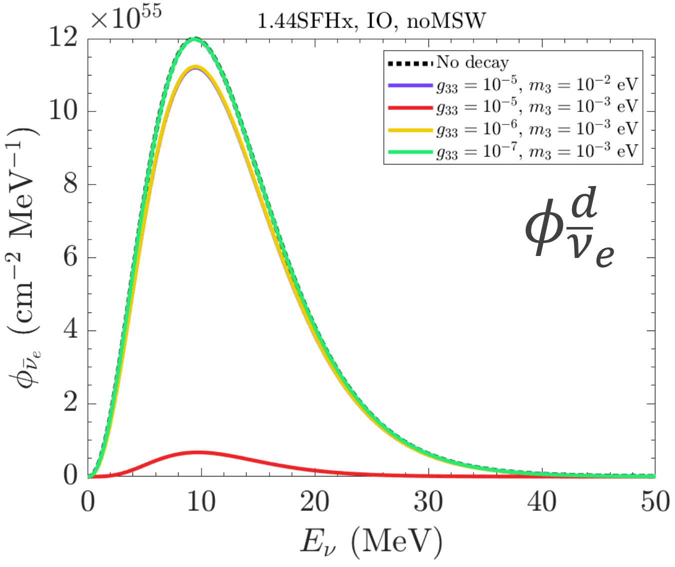


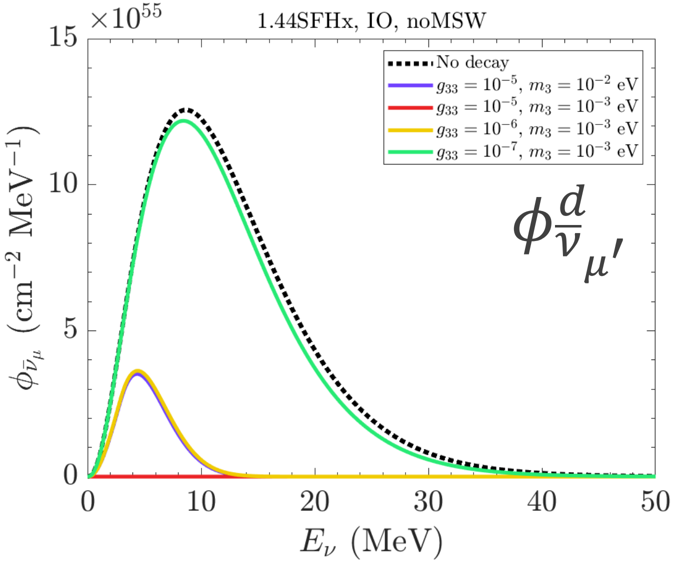


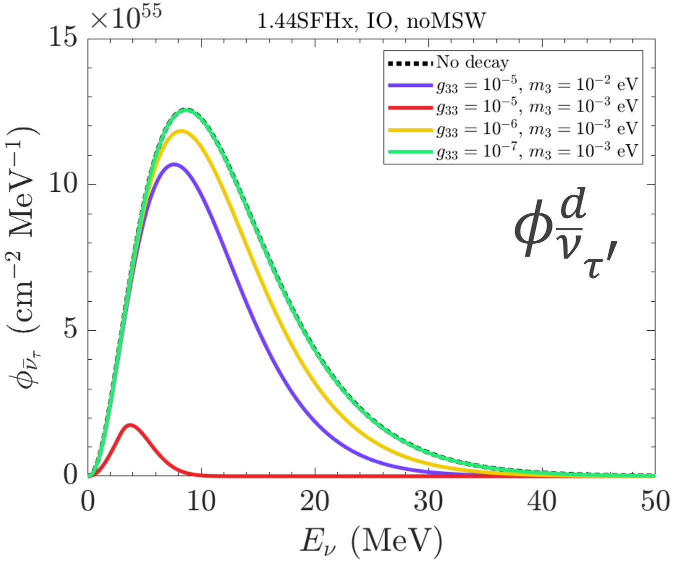
$$\phi_{\bar{\nu}_e} = |U_{e1}|^2 \phi^d_{\bar{\nu}_e} + |U_{e2}|^2 \phi^d_{\bar{\nu}_{\mu'}} + |U_{e3}|^2 \phi^d_{\bar{\nu}_{\tau'}}$$



Neutrino fluences in the presence of $\boldsymbol{\nu - J}$ interactions: IO







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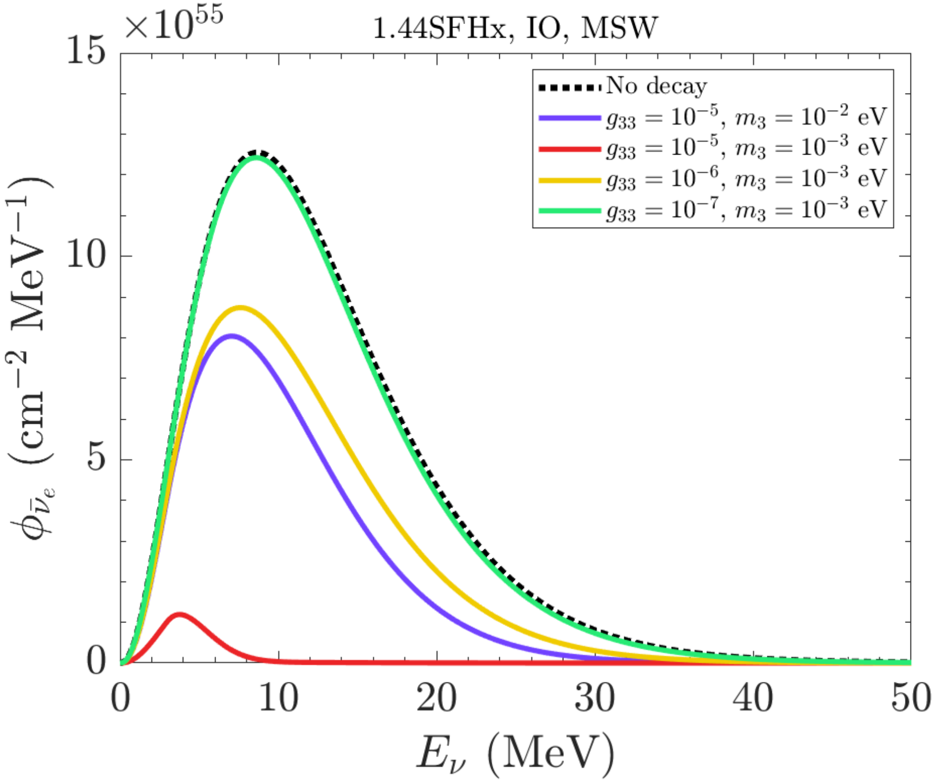


Statistical analysis of SN1987A data (I)

[Vissani, 2015]
[P.I.B. and Volpe, PLB 2023]

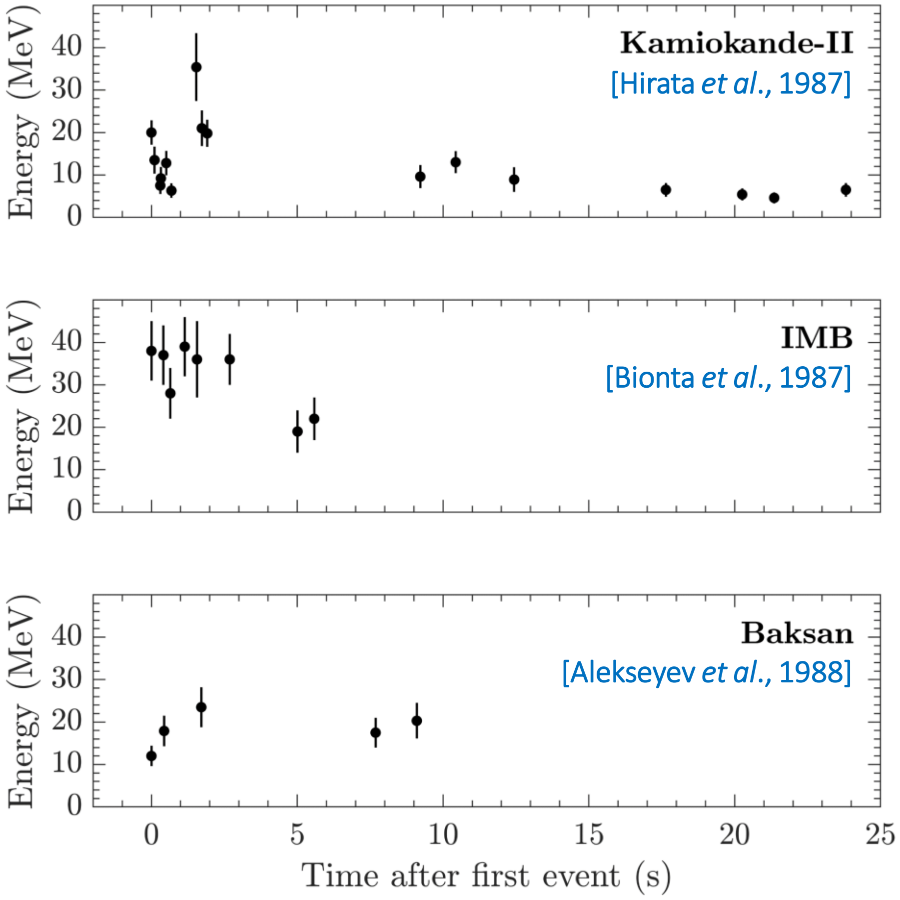
Since data available is limited, we use unbinned likelihood:

$$\mathcal{L}(\boldsymbol{x}) = e^{-N_{tot}(\boldsymbol{x})} \times \prod_{i=1}^{N_{obs}} dN_i(\boldsymbol{x})$$

- $\boldsymbol{N_{obs}}$: number of observed events
- $\boldsymbol{dN_i}$: expected number of events around the observed energy E_i

$$dN_i = dE\left[\frac{dS}{dE_i} + \frac{dB}{dE_i}\right]$$

- $\boldsymbol{N_{tot}}$: total number of expected events
- $\boldsymbol{x}$**:** model parameters:
  - Decay in matter $\longrightarrow$ g_{ii}, m_i ($i = 1$ in NO, $i = 3$ in IO)
  - Decay in vacuum $\longrightarrow$ τ/m, $\overrightarrow{L_\nu}$, $\overrightarrow{\langle E_\nu \rangle}$



Statistical analysis of SN1987A data (II)

[Vissani, 2015]
[P.I.B. and Volpe, PLB 2023]

Main detection channel Inverse Beta Decay:

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

- True positron spectrum:

$$\frac{dS_e}{dE_e} \approx N_p F_{\bar{\nu}_e}(E_\nu)\sigma_{IBD}(E_\nu)J(E_\nu)$$

$$J(E_\nu) = \frac{\left(1 + {E_\nu}/{m_p}\right)^2}{1 + {\Delta_{np}}/{m_p}}, (\Delta_{np} = m_n - m_p = 1.293 \text{ MeV})$$

- Observed positron spectrum:

$$\frac{dS}{dE_i} = \int_0^\infty \eta(E_e) G\big(E_e - E_i, \sigma(E_e)\big) \frac{dS_e}{dE_e}\, dE_e$$

- $\eta(E_e)$: intrinsic efficiency function (depends on the detector)
- $G\big(E_e - E_i, \sigma(E_e)\big)$: smearing function (assumed to be Gaussian)
- $\sigma(E_e) = \sigma_{stat} \times \left(\frac{E_e}{10 \text{ MeV}}\right)^{1/2} + \sigma_{syst} \times \left(\frac{E_e}{10 \text{ MeV}}\right)$

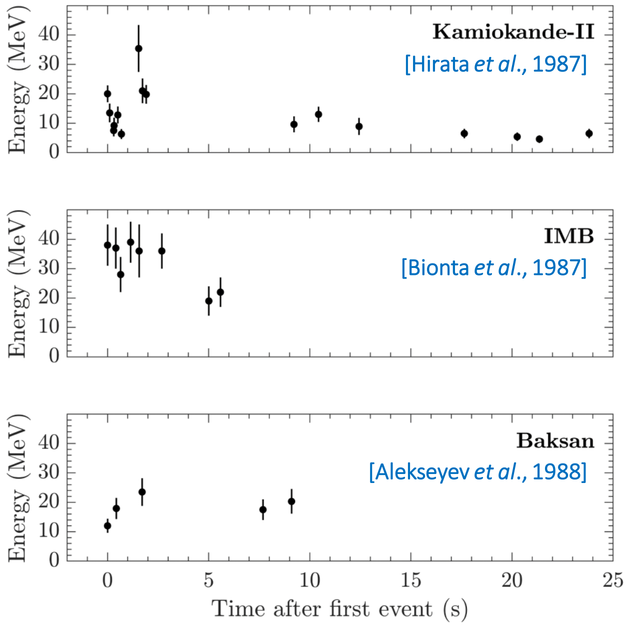


Table 1
Properties of the experiments (first column) that detected the neutrinos from SN1987A. The table shows the number of target protons (second column) and the two coefficients defining the uncertainty function $\sigma(E_e)$ (third and fourth columns). The last column gives the total background B_{tot} (see text). (From [52].)

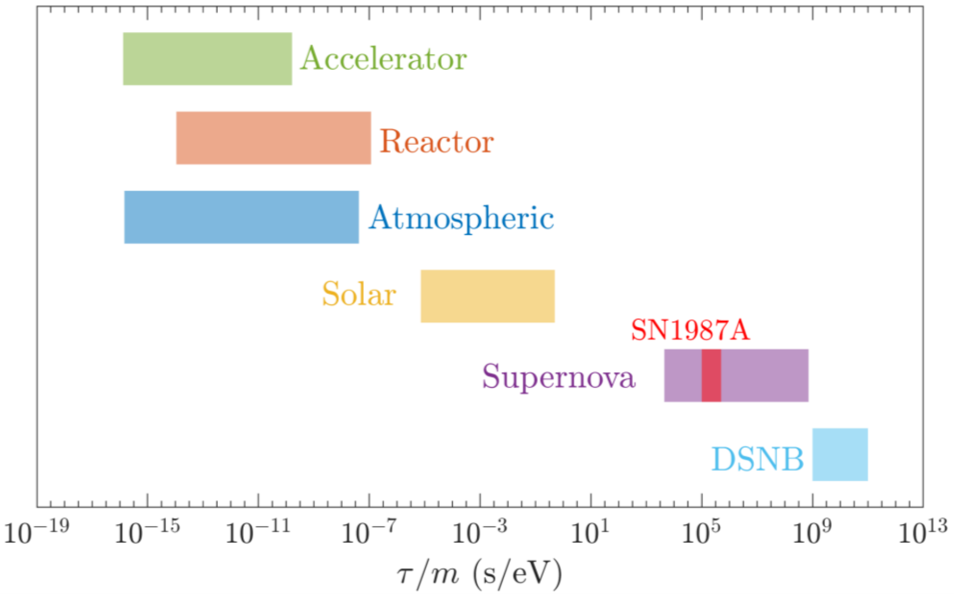
	N_p	σ_{stat} [MeV]	σ_{syst} [MeV]	B_{tot}
Kamiokande-II	1.4×10^{32}	1.27	1.0	0.55
IMB	4.6×10^{32}	3.0	0.4	0.01
Baksan	0.2×10^{32}	0.0	2.0	1.0

Neutrino nonradiative decay in vacuum

$$\boxed{\boldsymbol{\nu_j \longrightarrow \nu_i\ (\bar{\nu}_i) + X}}$$

where $m_j > m_i$ and X is a very light (pseudo)scalar particle (e.g. Majoron).

Neutrino fluxes deplete over a distance L due to decay by a factor: $\mathbf{exp}\left(-\frac{m_i\,L}{\tau_i\,E}\right)$



Sensitivities to the lifetime-to-mass ratio, τ/m, for different experiments. Figure taken from P.I.B. and Volpe, PLB 2023.

DSNB has unique sensitivity to this decay in the range:

$$\frac{\tau}{m} \in \left[10^9 - 10^{11}\right]\ \mathrm{s/eV}$$

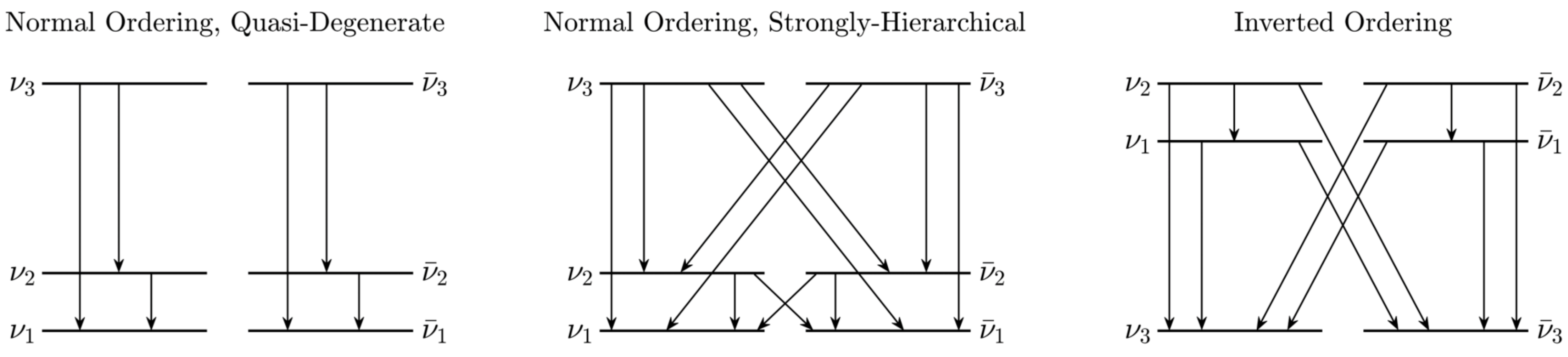
[Ando, 2003], [Fogli *et al.*, 2004], [de Gouvêa *et al.*, 2020], [Tabrizi and Horiuchi, 2021]

Neutrino nonradiative decay in vacuum

- Two body nonradiative decay: $\nu_j \longrightarrow \nu_i\ (\bar{\nu}_i) + X$
- Flux on Earth is obtained by solving:

$$\frac{dF_{\nu_i}}{dr}(E,r) = -\Gamma_i \frac{m}{E} F_{\nu_i}(E,r) + \sum_{m_j > m_i} \int_E^\infty dE' F_{\nu_j}(E',r) \Gamma_{\nu_j \to \nu_i} \frac{m}{E'} \psi_{\nu_j \to \nu_i}(E',E)$$

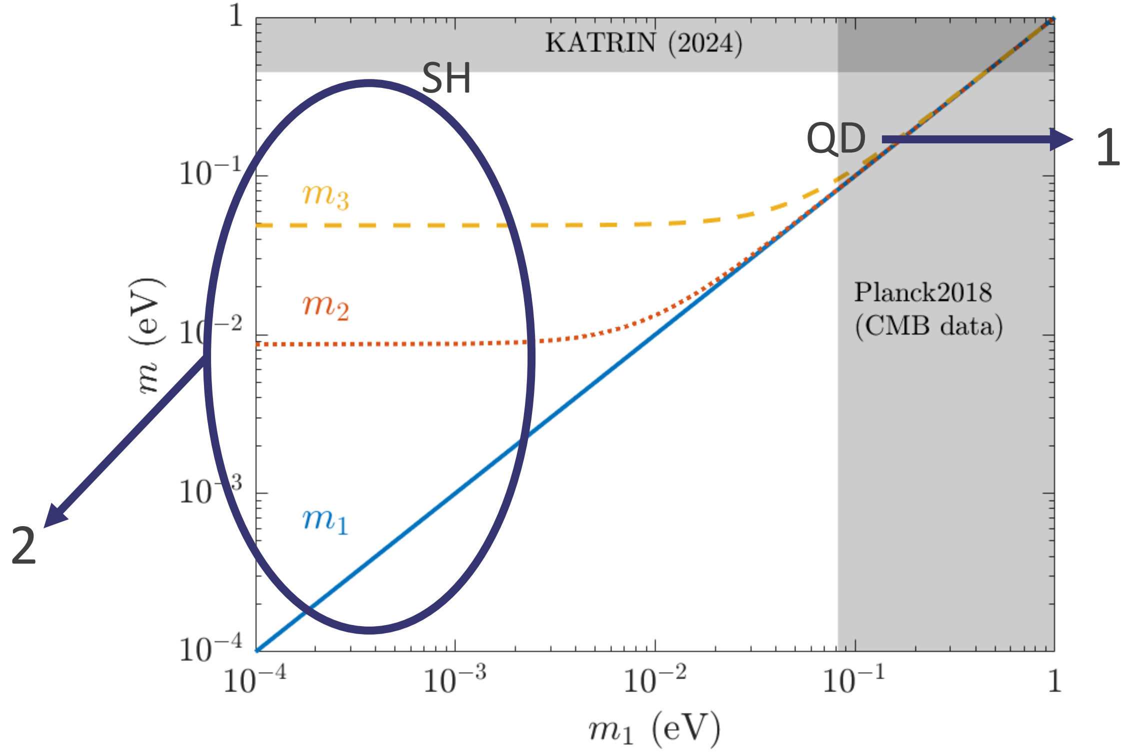
[Ando, 2004]

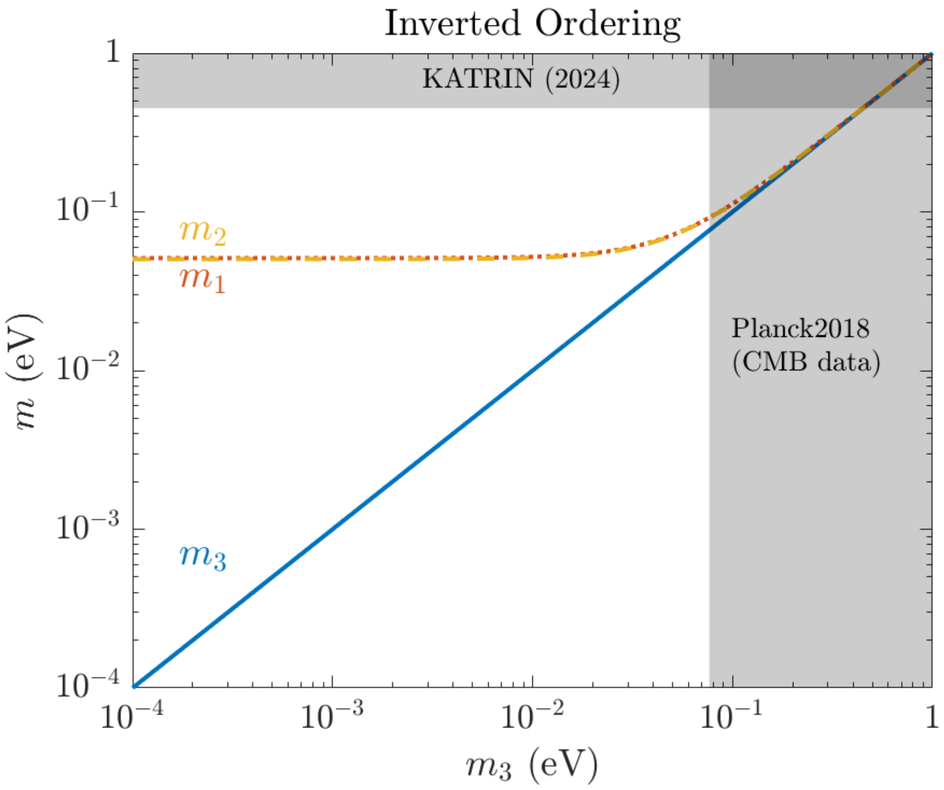


$m_1 \approx m_2 \approx m_3$ $\quad$ $m_1 \ll m_2 \ll m_3$ $\quad$ $m_1 \approx m_2 \gg m_3$

Mass ordering cases

Absolute neutrino masses as a function of the lightest neutrino. The shaded regions are excluded by KATRIN and Planck2018 (CMB data).





NORMAL ORDERING:

1. **QD** $\Longrightarrow m_1 \simeq m_2 \simeq m_3 \gg \Delta m_{ij}$
2. **SH** $\Longrightarrow m_3 \gg m_2 \gg m_1 \simeq 0$

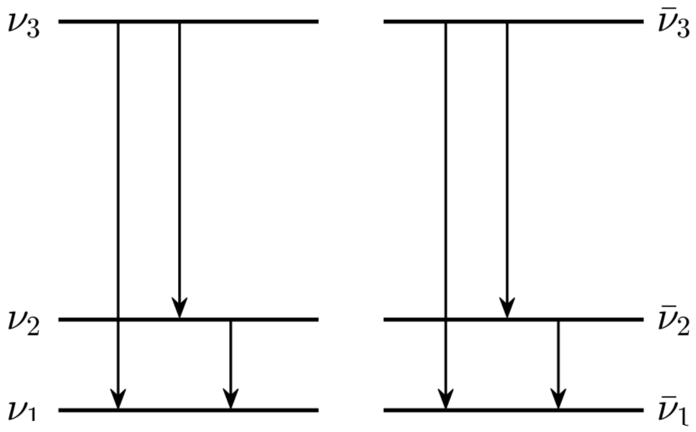
INVERTED ORDERING:

- QD $\Longrightarrow m_1 \simeq m_2 \gg \Delta m_{21}$
- SH $\Longrightarrow m_{1,2} \gg m_3 \simeq 0$

Decay patterns

NO and QD masses.

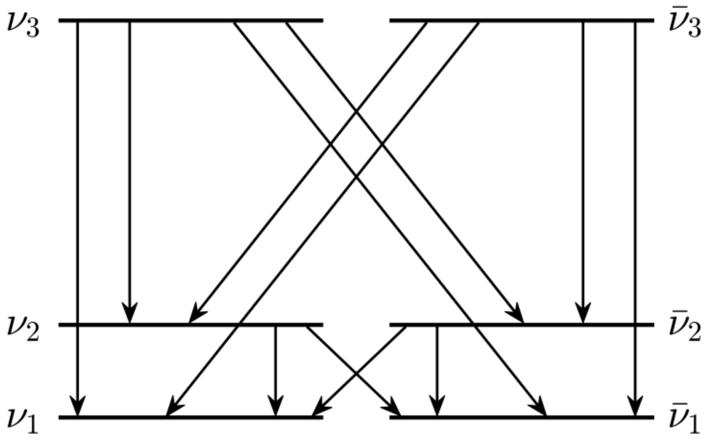
$$m_1 \simeq m_2 \simeq m_3 \gg \Delta m_{ij}$$



- $\boldsymbol{\tau_3/m_3 = \tau_2/m_2 = \tau/m}$
- $B(\nu_3 \to \nu_2) = B(\nu_3 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_1) = 1$

NO and SH masses.

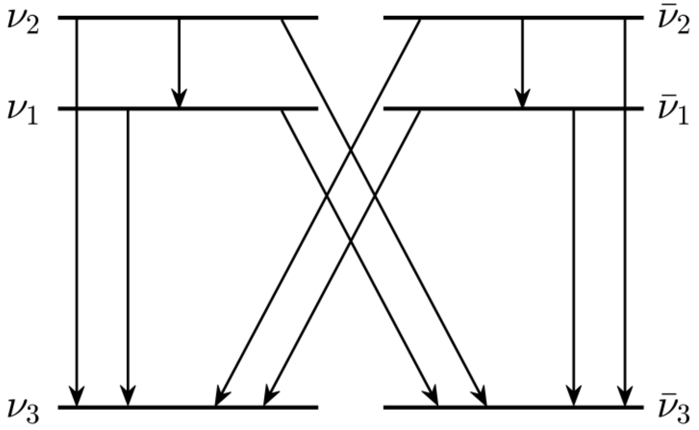
$$m_3 \gg m_2 \gg m_1 \simeq 0$$



- $\boldsymbol{\tau_3/m_3 = \tau_2/m_2 = \tau/m}$
- $B(\nu_3 \to \nu_i) = B(\nu_3 \to \bar{\nu}_i) = \frac{1}{4}$
- $B(\nu_2 \to \nu_1) = B(\nu_2 \to \bar{\nu}_1) = \frac{1}{2}$

IO

$$m_1 \simeq m_2 \gg m_3 \simeq 0$$



- $\boldsymbol{\tau_1/m_1 = \tau_2/m_2 = \tau/m}$
- $B(\nu_2 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_3) = B(\nu_2 \to \bar{\nu}_3) = \frac{1}{4}$
- $B(\nu_1 \to \nu_3) = B(\nu_1 \to \bar{\nu}_3) = \frac{1}{2}$

Neutrino nonradiative decay in vacuum: QD case

[Beacom and Bell, 2002]

Neutrino nonradiative decay:

$$\boldsymbol{\nu_i \longrightarrow \nu_j\ (\bar{\nu}_j) + X}$$

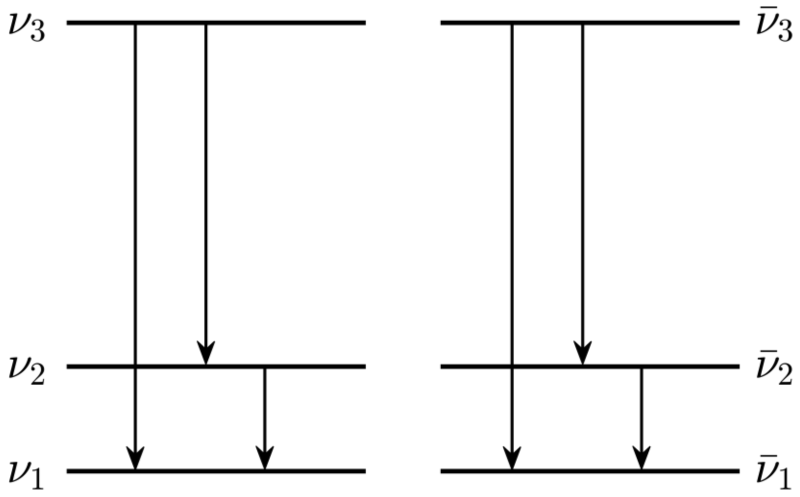
Typical lagrangian:

$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j X + h_{ij}\bar{\nu}_i\gamma_5\nu_j X + h.c.$$

In the limit of **QD masses**, i.e. $\Delta m^2 = m_i^2 - m_j^2 \ll m_j^2 \approx m_i^2$

$$\Gamma_{\nu_i \to \nu_j} = \frac{g^2}{16\pi}\frac{\Delta m^2}{4E_i} + h^2 \times \mathcal{O}\left(\frac{\Delta m^2}{m_i^2}\right)^3$$

$$\boldsymbol{\Gamma_{\nu_i \to \bar{\nu}_j} = \frac{(g^2 + h^2)}{16\pi}\frac{\Delta m^2}{E_i} \times \mathcal{O}\left(\frac{\Delta m^2}{m_i^2}\right)^3}$$



$\Longrightarrow$ helicity flipping decays are suppressed

Limits on τ/m from SN1987A data

[P.I.B. and Volpe, PLB847 (2023) 138252]

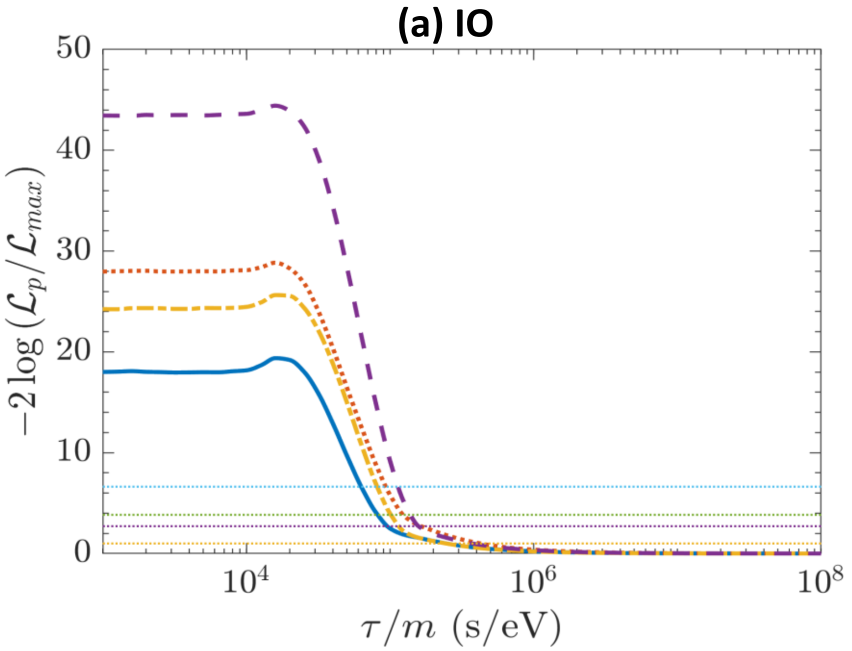
7D likelihood analysis of SN1987A data to obtain $^{\tau}/_{m}$

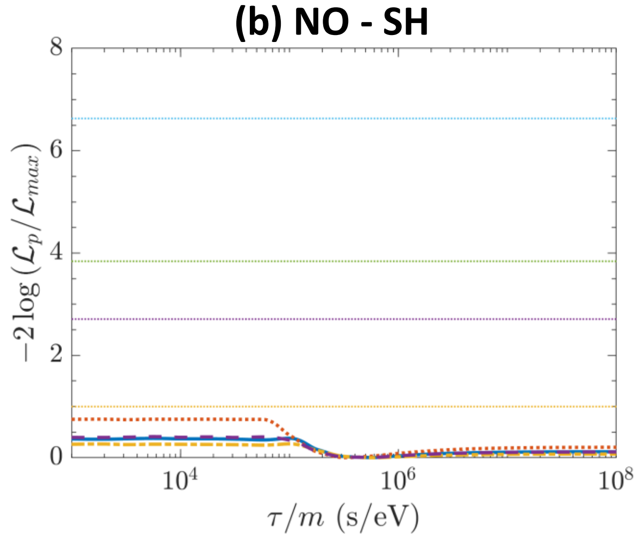
Parameters considered: $L_{\nu_\alpha}, \langle E_{\nu_\alpha} \rangle$ with $\nu_\alpha = \nu_e, \bar{\nu}_e, \nu_x$ and $^{\tau}/_{m}$ (fixed $\alpha = 2.3$)

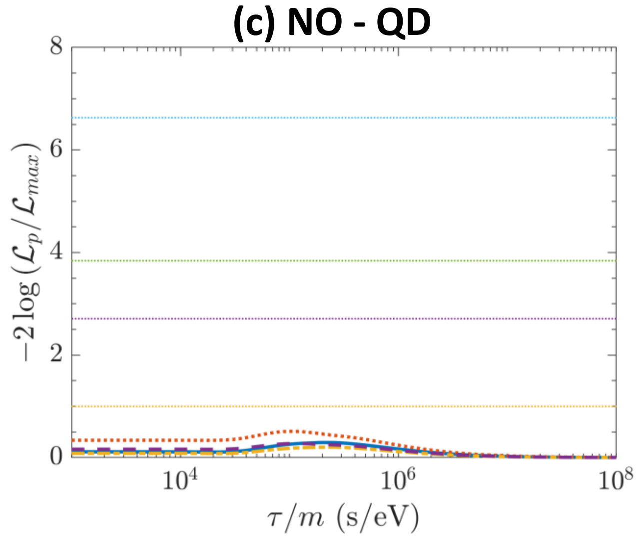
- Normal ordering: no sensitivity
- Inverted ordering: $\frac{\tau}{m} \geq 1.2 \times 10^5$ **s/eV** at 90% CL.

Profile likelihood ratios from the 7D likelihood analysis of SN1987A events: **(a)** inverted ordering, **(b)** normal ordering and strongly hierarchical masses, **(c)** normal ordering and quasidegenerate masses.
The curves correspond to the analysis:

- including Baksan data and background data (dot-dashed line);
- without Baksan data and with background (solid line);
- with Baksan data and without background data (dotted line); and,
- without Baksan data and background data (dashed line).







DSNB flux

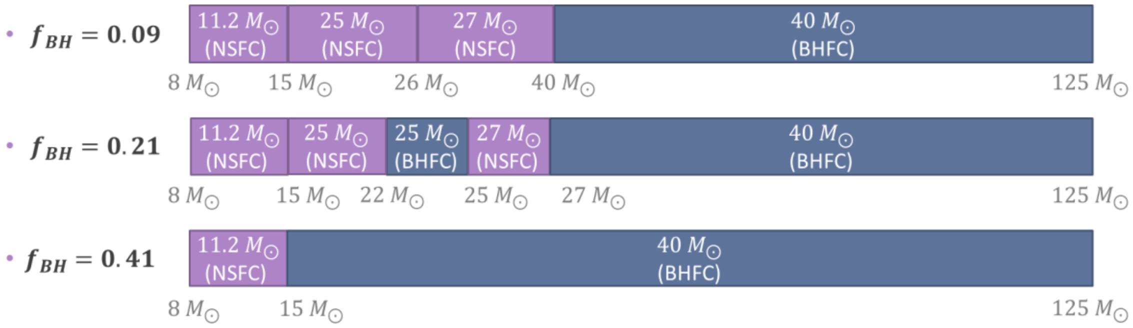
see e.g. [Beacom, 2010], [Priya and Lunardini, 2017], [Møller *et al.*, 2018], [de Gouvêa *et al.*, 2020], …

$$\phi_\nu(E) = \int_0^{z_{max}} \frac{dz}{H(z)} \int_{8\,M_\odot}^{125\,M_\odot} dM\, \dot{R}_{SN}(z,M) F_\nu(E',M) \qquad E' = E(1+z)$$

Hubble parameter:
accounts for Universe expansion. We consider a ΛCDM model.

Supernova rate:
proportional to the star formation rate. The normalization of SNR is one of the largest uncertainties of the DSNB

Neutrino emission from a single collapse:
The emission depends on the outcome of the collapse (NS or BH)



[P.I.B. and Volpe, PRD107 (2023) 023017]

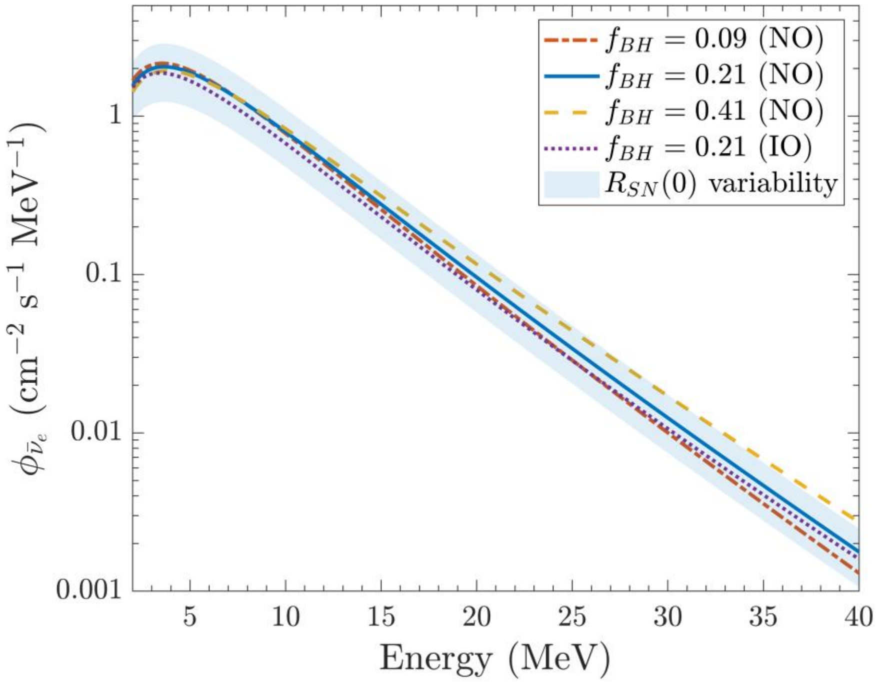
DSNB flux

see e.g. [Beacom, 2010], [Priya and Lunardini, 2017], [Møller *et al.*, 2018], [de Gouvêa *et al.*, 2020], …

$$\phi_\nu(E) = \int_0^{z_{max}} \frac{dz}{H(z)} \int_{8\,M_\odot}^{125\,M_\odot} dM\, \dot{R}_{SN}(z,M) F_\nu(E',M) \qquad E' = E(1+z)$$

Results for the integrated flux in $\mathrm{cm^{-2}s^{-1}}$ for the fiducial case ($f_{BH} = 0.21$) and the most optimistic case ($f_{BH} = 0.41$) in brackets:

	NO	IO	UPPER LIMITS
$\bar{\nu}_e$ ($E_\nu > 17.3$ MeV)	0.77 ± 0.30 $[1.02 \pm 0.41]$	0.63 ± 0.25 $[0.75 \pm 0.3]$	2.6 (SK)
ν_e ($22.9 < E < 36.9$ MeV)	0.20 ± 0.08 $[0.24 \pm 0.09]$	0.18 ± 0.08 $[0.23 \pm 0.09]$	19 (SNO)



[P.I.B. and Volpe, PRD107 (2023) 023017]

Flux of $\bar{\nu}_e$ on Earth for different f_{BH} in absence of decay.
The band shows the uncertainty of the SNR normalisation.
Results obtained using 1D SN simulations from Garching group.

How can we detect the DSNB?

- Detection of $\bar{\nu}_e$ flux → **Inverse Beta Decay** (IBD)

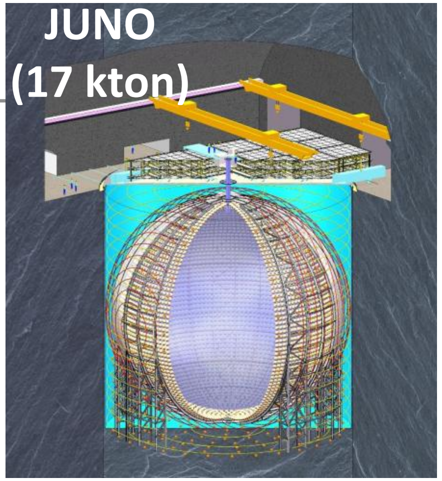
$$\bar{\nu}_e + p \rightarrow n + e^+$$

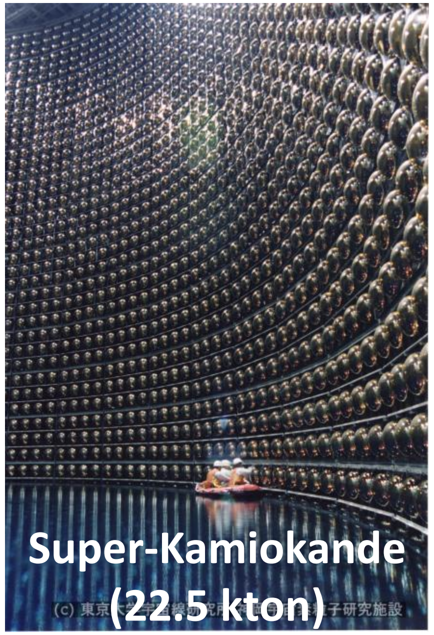
  - **Super-Kamiokande + Gd, Hyper-Kamiokande, JUNO**
  - Backgrounds: reactor $\bar{\nu}_e$ (low energies) and atmospheric ν (high energies)

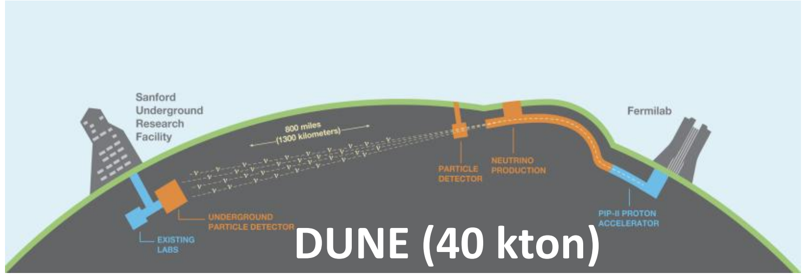
- Detection of ν_e flux → **neutrino absorption in ^{40}Ar**

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

  - **Deep Underground Neutrino Experiment (DUNE)**
  - Backgrounds: solar neutrinos (low energies) and atmospheric ν_e (high energies)







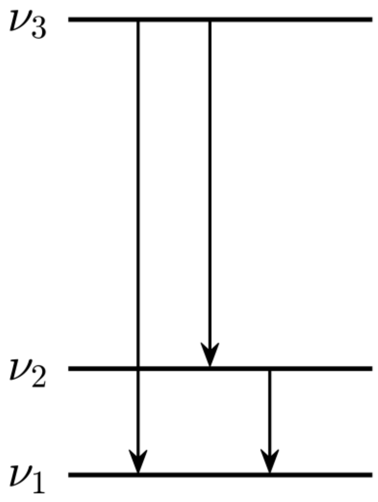
DSNB flux in the presence of decay in vacuum

Solution to the neutrino kinetic equations in the presence of decay:

[Fogli *et al.*, 2004]

$$\phi_{\nu_i}(E,z) = \frac{1}{1+z}\int_z^{z_{max}} \frac{dz'}{H(z')}\Bigg[\overbrace{R_{SN}(z')F_{\nu_i}\left(E\frac{1+z'}{1+z}\right)}^{\nu_i \text{ flux from core-collapses}} + \overbrace{\sum_{m_j>m_i} q_{ji}\left(E\frac{1+z'}{1+z}, z'\right)}^{\text{decay of } \nu_j \text{ into } \nu_i}\Bigg]$$

$$\times \underbrace{e^{-m_i\Gamma_i[\xi(z')+\xi(z)](1+z)/E}}_{\nu_i \text{ decay into lighter neutrinos}}$$



$$_{ji}(E,z) = \int_E^{\infty} dE'\phi_{\nu_j}(E',z)\Gamma_{\nu_j\to\nu_i}\frac{m_j}{E'}\psi_{\nu_j\to\nu_i}(E',E)$$

(z) auxiliary function

$\psi_{\nu_j\to\nu_i}(E',E) = \text{Prob}\left[\nu_j(E')\to\nu_i(E)\right]$

Predictions for the DSNB: Normal Ordering

* Results obtained for our fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

[P.I.B. and Volpe, PRD107 (2023) 023017]

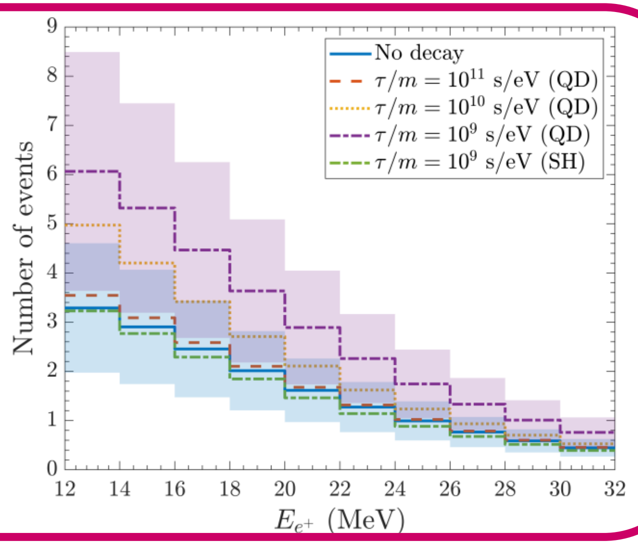
SK-Gd:

$N_{tot} = 14$ (no decay)

Exposure time: 10 years

Energy window:

$12.8 \leq E_\nu \leq 30.8$ MeV



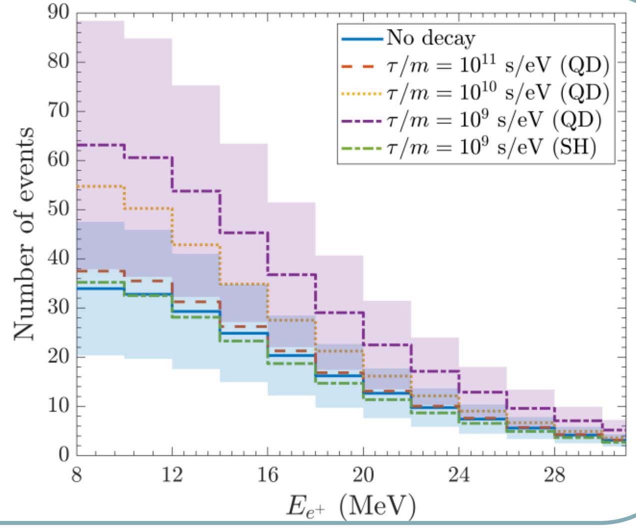
HK-Gd:

$N_{tot} = 76$ (no decay)

Exposure time: 20 years

Energy window:

$17.3 \leq E_\nu \leq 31.3$ MeV



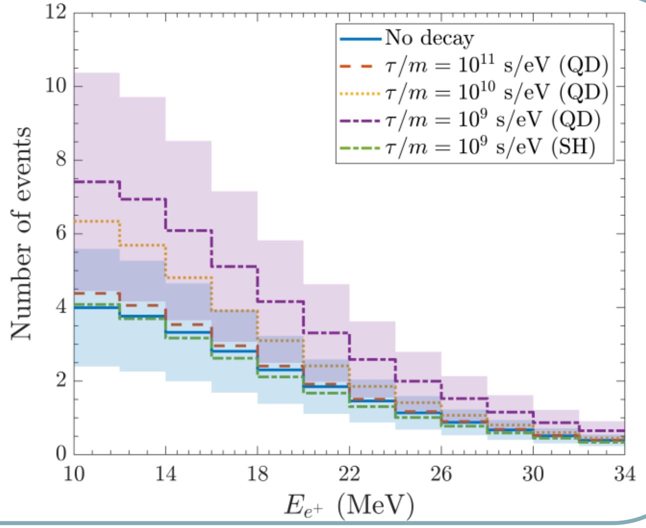
JUNO:

$N_{tot} = 20$ (no decay)

Exposure time: 20 years

Energy window:

$11.3 \leq E_\nu \leq 33.3$ MeV



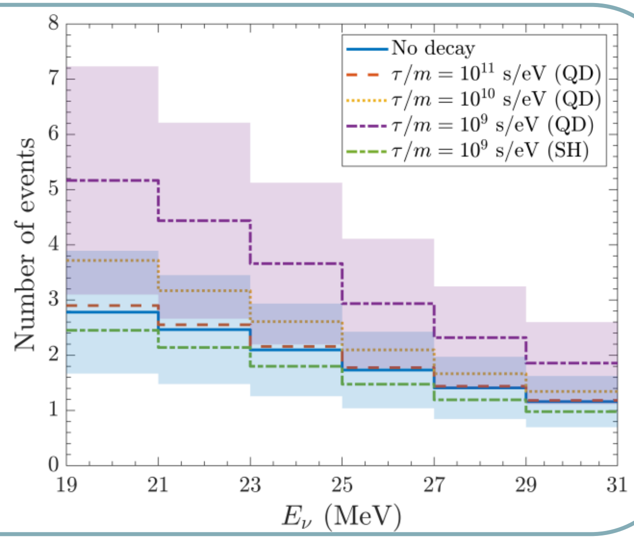
DUNE:

$N_{tot} = 12$ (no decay)

Exposure time: 20 years

Energy window:

$19 \leq E_\nu \leq 31$ MeV



Predictions for the DSNB: Inverted Ordering

* Results obtained for our fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

[P.I.B. and Volpe, PRD107 (2023) 023017]

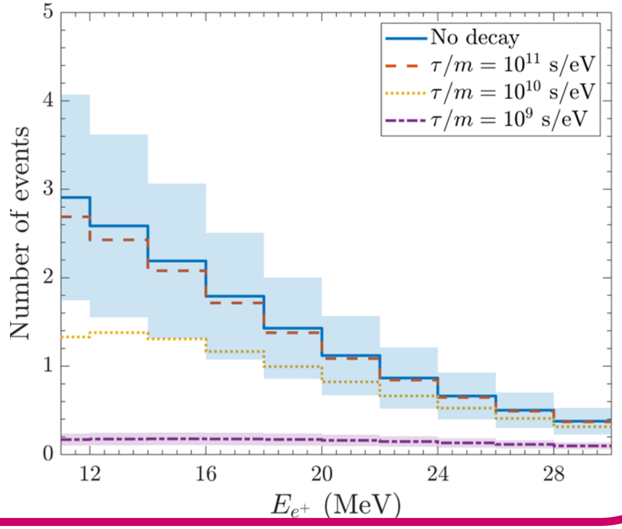
SK-Gd:

$N_{tot} = 12$ (no decay)

Exposure time: 10 years

Energy window:

$12.8 \leq E_\nu \leq 30.8$ MeV



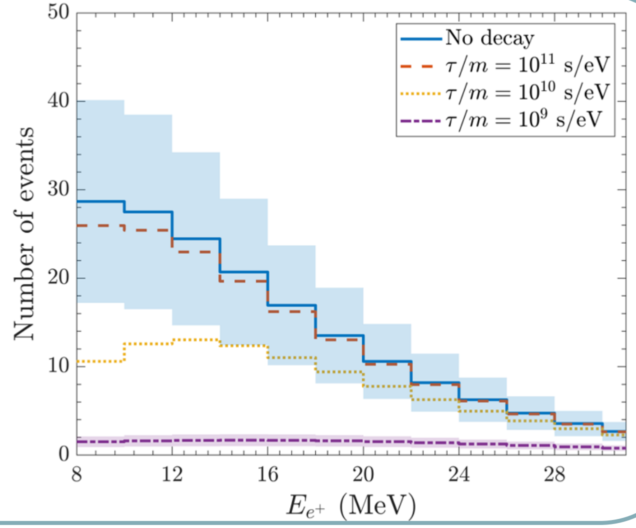
HK-Gd:

$N_{tot} = 64$ (no decay)

Exposure time: 20 years

Energy window:

$17.3 \leq E_\nu \leq 31.3$ MeV



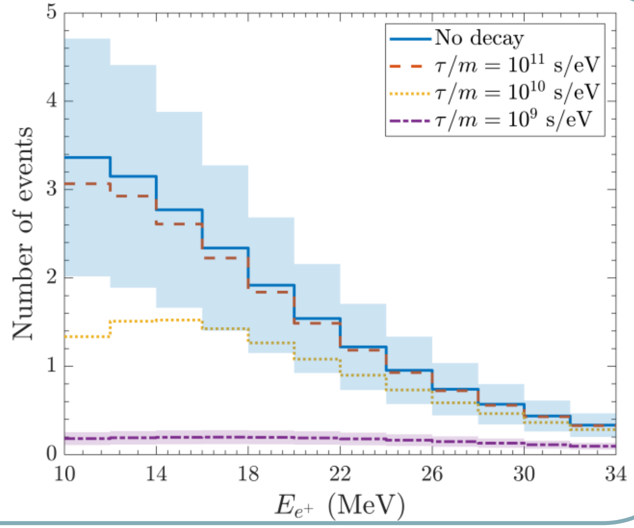
JUNO:

$N_{tot} = 17$ (no decay)

Exposure time: 20 years

Energy window:

$11.3 \leq E_\nu \leq 33.3$ MeV



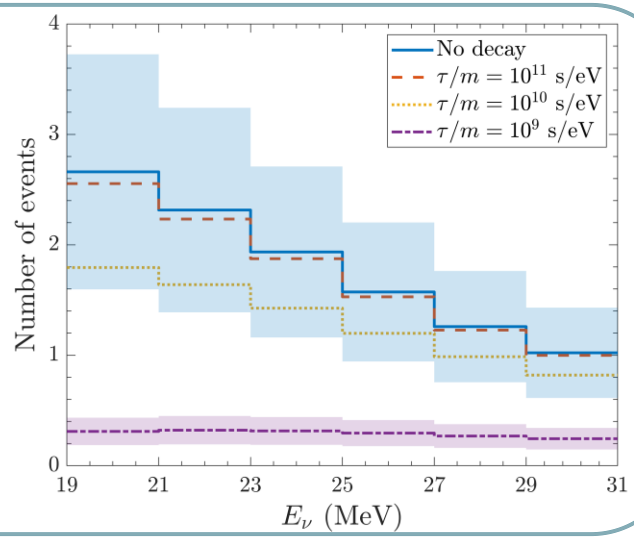
DUNE:

$N_{tot} = 11$ (no decay)

Exposure time: 20 years

Energy window:

$19 \leq E_\nu \leq 31$ MeV



DSNB number of events

$$N_\alpha = \epsilon\, N_t \int \mathrm{d}E_\nu \phi_{\nu_\alpha}(E_\nu)\sigma(E_\nu)$$

Properties of the experiments considered and total number of events in the absence of decay in NO (IO).

	N_t (10^{33})	ϵ (%)	Time (years)	DSNB window (MeV)	DSNB events
SK-Gd	1.5	57.5	2	(12.8, 30.8)	2 (2) $\bar{\nu}_e$
SK-Gd	1.5	73.75	8	(12.8, 30.8)	12 (10) $\bar{\nu}_e$
HK	12.5	25	20	(17.3, 31.3)	48 (40) $\bar{\nu}_e$
HK-Gd	12.5	40	20	(17.3, 31.3)	76 (64) $\bar{\nu}_e$
JUNO	1.21	50	20	(11.3, 33.3)	20 (17) $\bar{\nu}_e$
DUNE	0.602	86	20	(19,31)	12 (11) ν_e

	Number of events			
Experiment	No decay	$(\tau/m)_{\text{long}}$	$(\tau/m)_{\text{medium}}$	$(\tau/m)_{\text{short}}$
SK-Gd (12.8–30.8) 2 + 8 years	2 (2)	2 [2] (2)	3 [2] (1)	4 [2] (0)
	12 (10)	13 [12] (10)	17 [12] (7)	22 [11] (1)
HK (17.3–31.3) 20 years	48 (40)	49 [47] (39)	61 [45] (29)	84 [43] (6)
HK-Gd (17.3–31.3) 20 years	76 (64)	79 [73] (62)	98 [73] (46)	135 [69] (9)
JUNO (11.3–33.3) 20 years	20 (17)	21 [20] (16)	28 [19] (10)	37 [19] (2)
DUNE (19–31) 20 years	12 (11)	12 [11] (10)	15 [11] (8)	20 [10] (2)

Number of events associated with inverse-beta decay in SK-Gd, HK and JUNO as well as with $\nu_e - {}^{40}\mathrm{Ar}$ scattering in DUNE. The predicted number of events are given in the third to fifth columns for the different τ/m considered. The values are given for NO, QD; for NO, SH (in brackets) and for IO (in parenthesis).