Supernova neutrinos and neutrino nonradiative decay

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Outline

1. Supernova neutrinos

2. Neutrino non-radiative decay

3. Results:
   - SN1987A [P.I.B. and Volpe, PLB847 (2023) 138252]
   - DSNB [P.I.B. and Volpe, PRD107 (2023) 023017]

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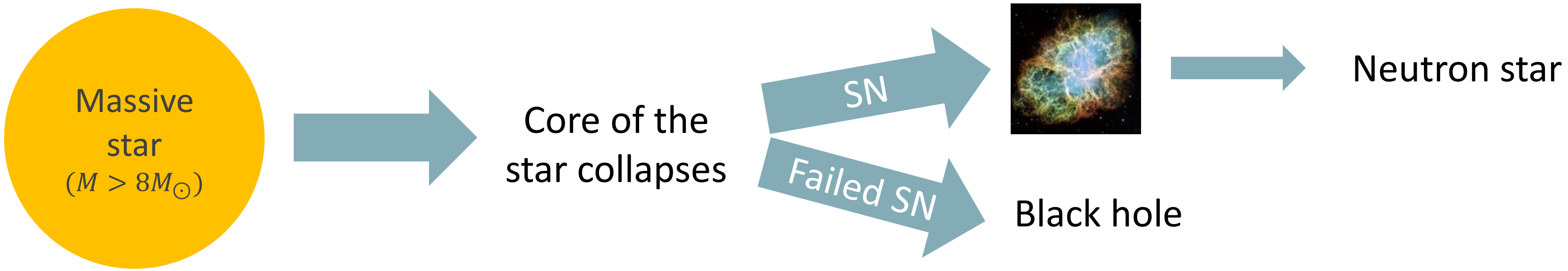
1 **Supernova neutrinos**

2 Neutrino non-radiative decay

3 Results:

- SN1987A
- DSNB

Supernova neutrinos



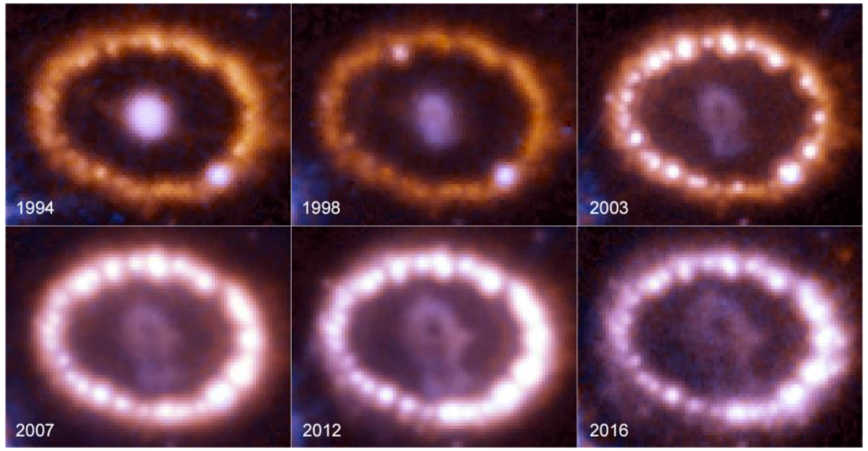
- **Powerful source of neutrinos**: $\sim 10^{53}$ erg emitted in all flavours (99% of gravitational binding energy!)

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

- We are sensitive to galactic supernova, BUT these are **rare events** (1-3 per century)

- Only detection was **SN1987A** (50 kpc away)

  ↳ 24 events detected by Kamiokande-II, IMB and Baksan
  [Hirata *et al.*, 1987] [Bionta *et al.*, 1987] [Alekseyev *et al.*, 1988]



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

The Diffuse Supernova Neutrino Background (DSNB)

DSNB: all neutrinos and antineutrinos emitted by all past core-collapses in the observable Universe.

Current upper limits for the DSNB flux:

- SK I-IV data: $2.6\ \bar{\nu}_e\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ (\mathrm{E}_\nu > 17.3\ \mathrm{MeV})$

  [Abe *et al.*, 2021]

- SNO data: $19\ \nu_e\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ (\mathrm{E}_\nu \in [22.9, 36.9]\ \mathrm{MeV})$

  [Aharmin *et al.*, 2020]

- SK data: $10^3\ \nu_x\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ (\mathrm{E}_\nu > 19.3\ \mathrm{MeV})$

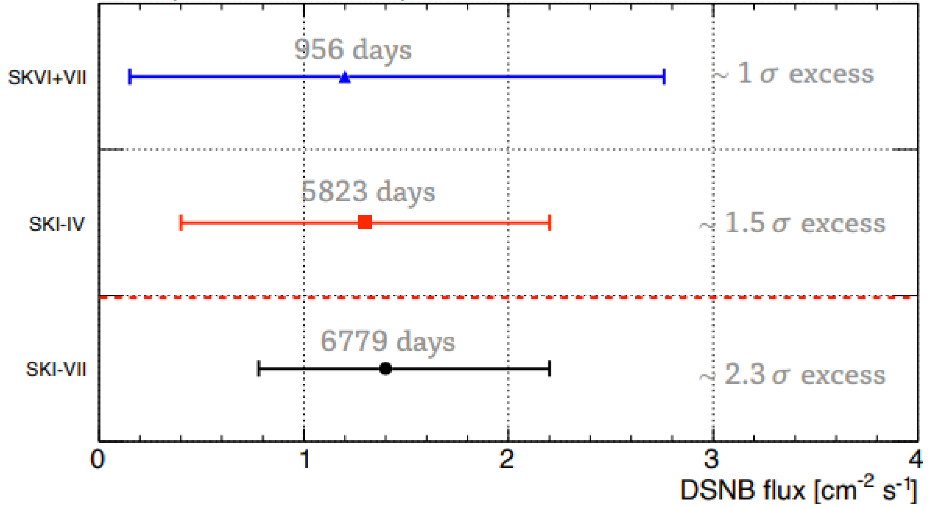
  [Lunardini and Peres, 2008]

Improve sensitivity

Dark Matter detectors: $10\ \nu_x\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

[Suliga *et al.*, 2022]

[Masayuki Harada's presentation at Neutrino 2024]

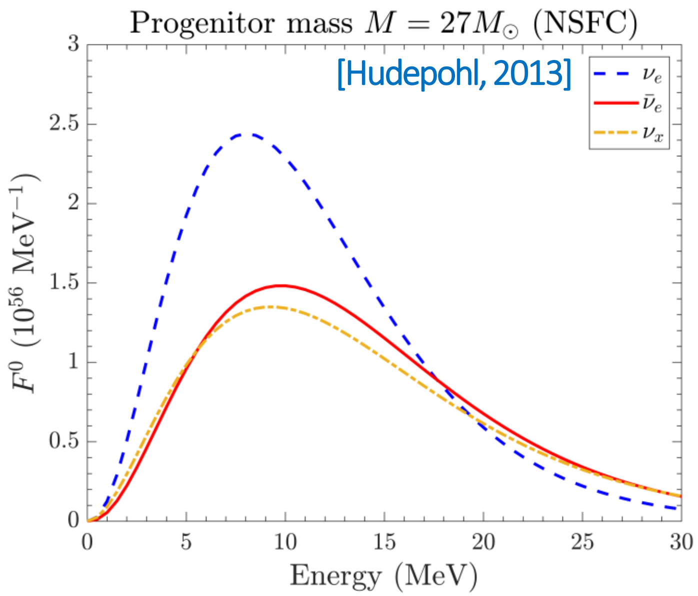


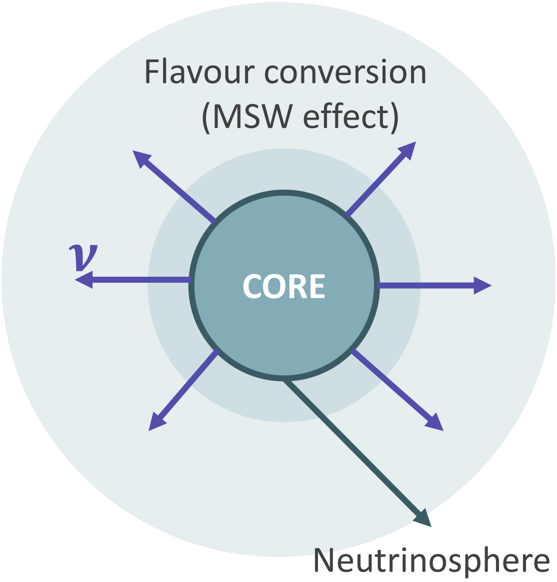
Latest SK results for the DSNB search considering phases I-VII.

See **Thomas Mueller's** presentation on **Monday 8th July**

Neutrino emission from a single collapse: $F_\nu(E, M)$

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





- Flavour effects inside supernova:
  - Still under study: shock wave effects, ν–ν interactions… see e.g. the review Volpe (2023)
  - We considered only the **Mikheev-Smirnov-Wolfenstein (MSW) effect**: describes the flavour transformations due to the ν-matter interactions.

We have assumed to be adiabatic $\to F_{\bar{\nu}_l} = F^0_{\bar{\nu}_e}\,;\; F_{\bar{\nu}_i} = F_{\bar{\nu}_h} = F^0_{\nu_x}$

[Wolfenstein, 1978]
[Mikheev and Smirnov, 1986]

DSNB flux

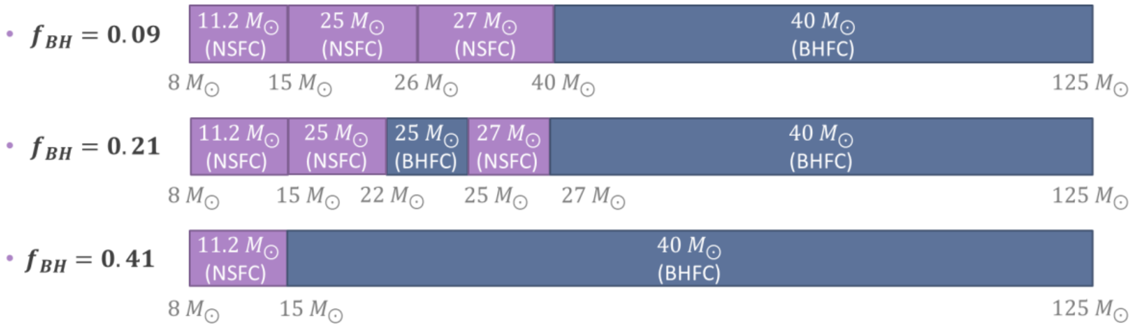
see e.g. [Beacom, 2010], [Priya and Lunardini, 2017], [Møller *et al.*, 2018], [de Gouvêa *et al.*, 2020], …

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

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]

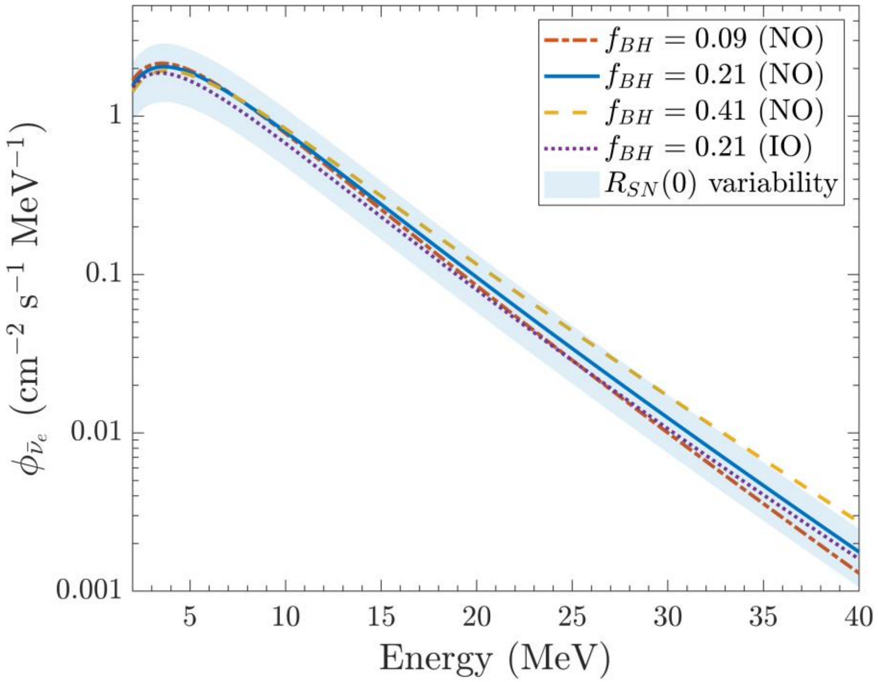
DSNB flux

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 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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)



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.

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

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1 Supernova neutrinos

2 **Neutrino non-radiative decay**

3 Results:
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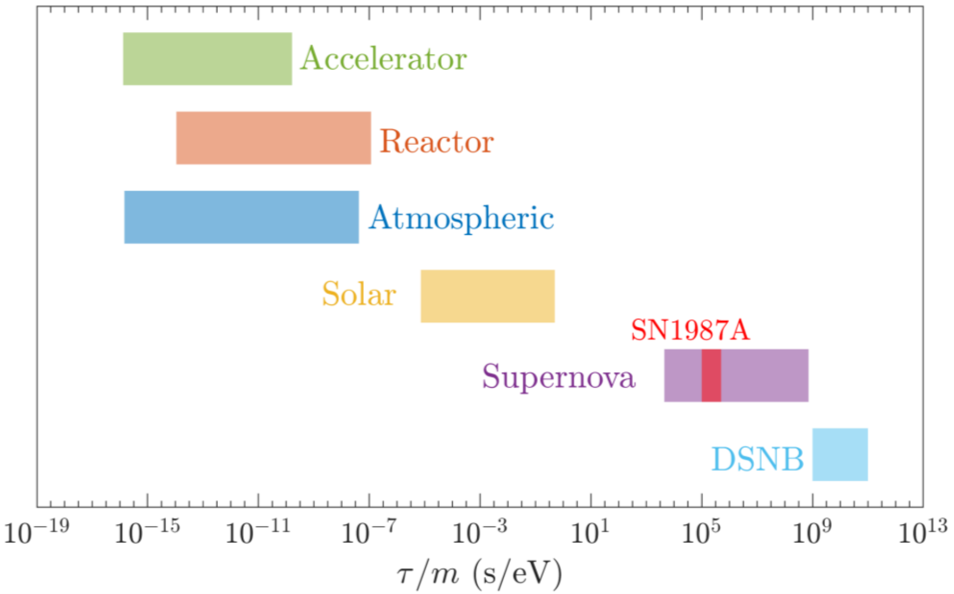
- DSNB

Neutrino nonradiative decay

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

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: $\exp\left(-\frac{m_i\, L}{\tau_i\, E}\right)$



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

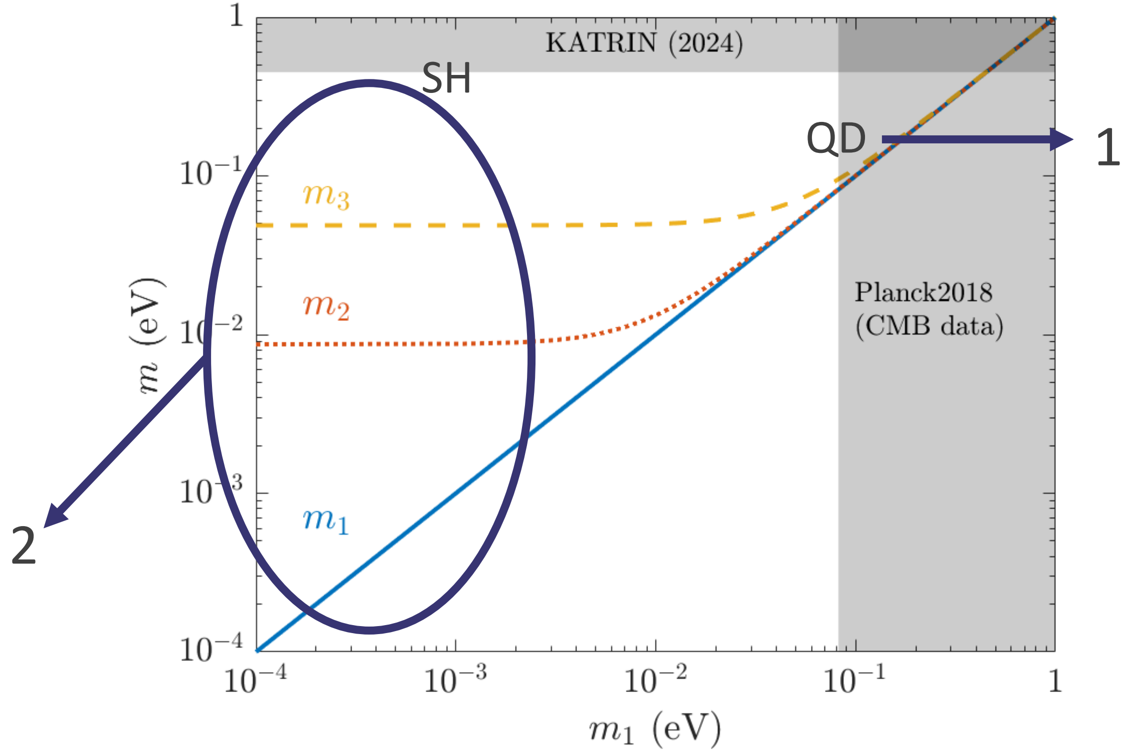
DSNB has unique sensitivity to this decay in the range:

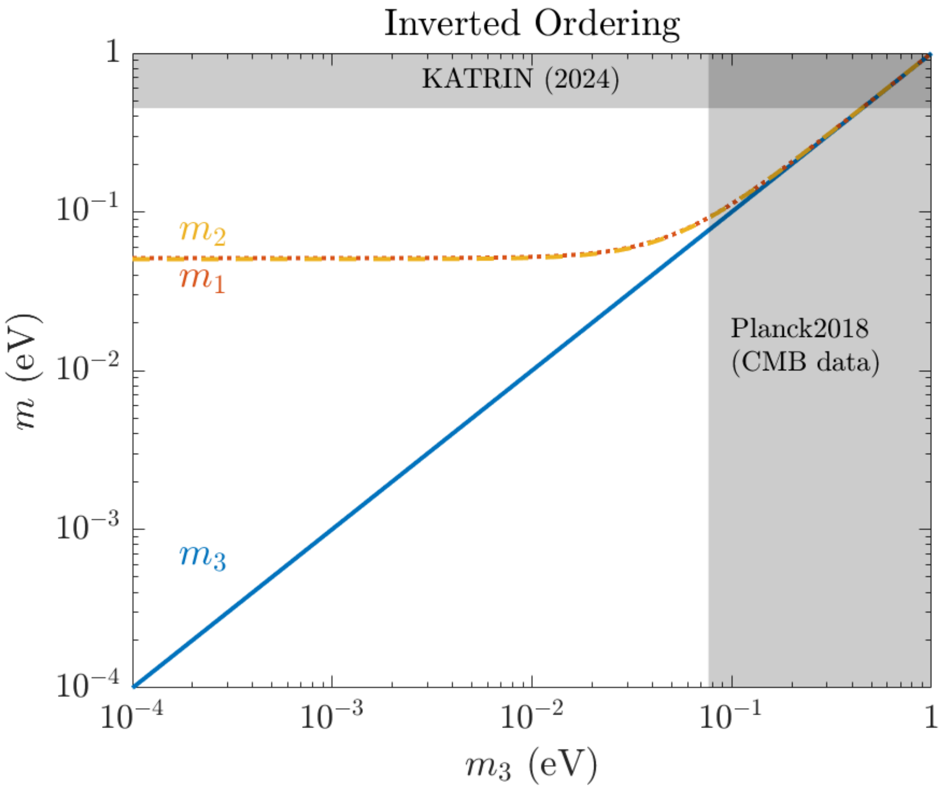
$$\frac{\tau}{m} \in \left[10^{9} - 10^{11}\right]\ \mathrm{s/eV}$$

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

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:

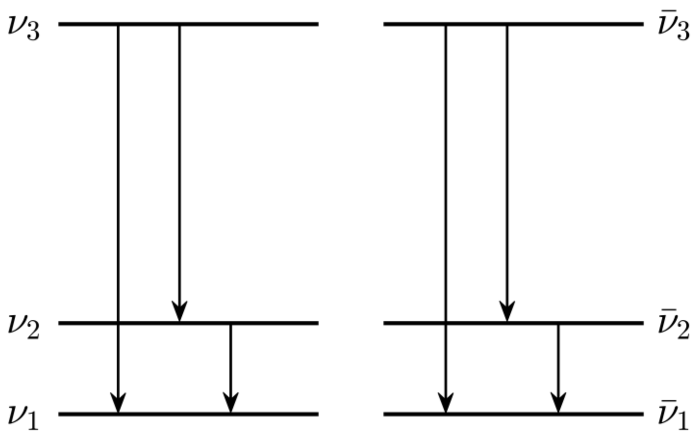
1. **QD** $\Longrightarrow m_1 \simeq m_2 \simeq m_3 \gg \Delta m_{ij}$
2. **SH** $\Longrightarrow m_3 \gg m_2 \gg m_1 \simeq 0$

INVERTED ORDERING:

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

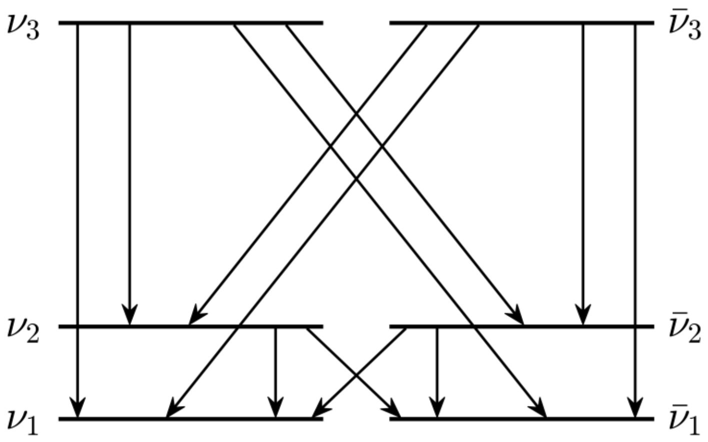
Decay patterns

NO and QD masses.



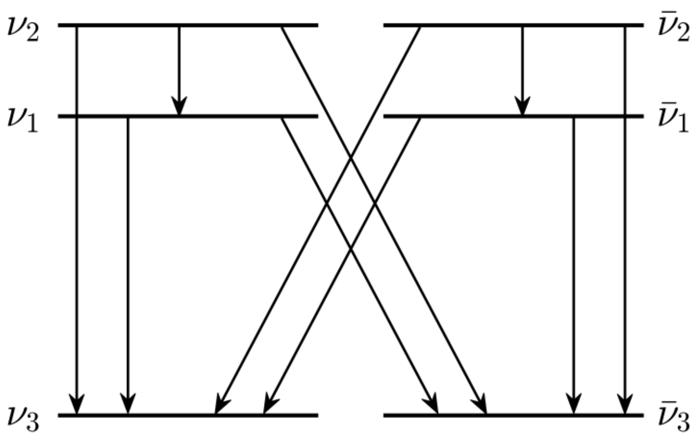
- $\boldsymbol{\tau_3/m_3 = \tau_2/m_2 = \tau/m}$
- $B(\nu_3 \to \nu_2) = B(\nu_3 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_1) = 1$

NO and SH masses.



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

IO



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

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3 **Results:**
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- **DSNB**

Limits on τ/m from SN1987A data

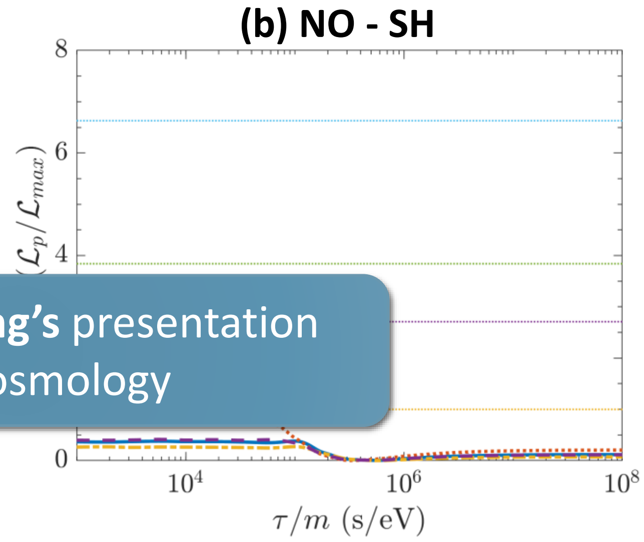
[P.I.B. and Volpe, PLB847 (2023) 138252]

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

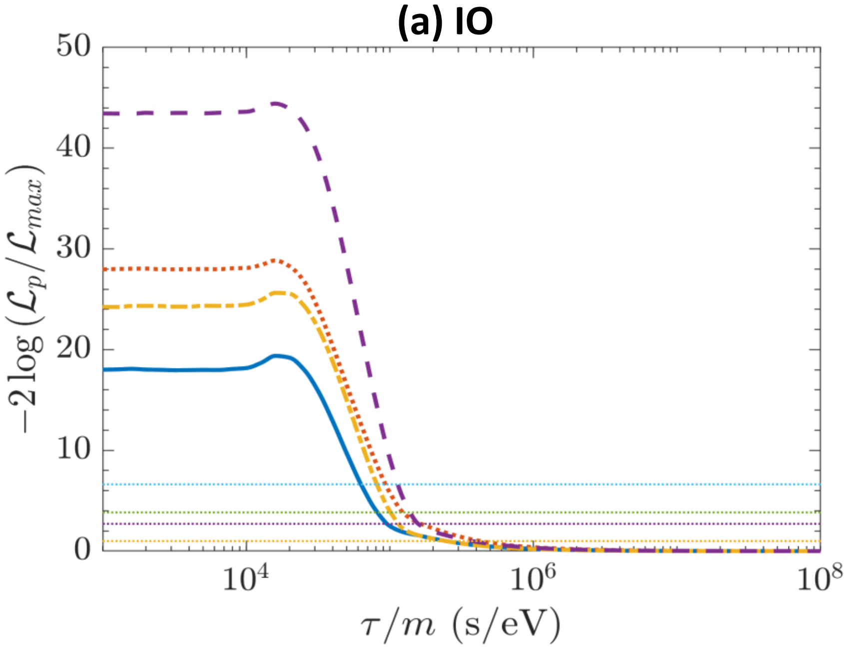
→ Parameters considered: $L_{\nu_\alpha}, \langle E_{\nu_\alpha} \rangle$ with $\nu_\alpha = \nu_e, \bar{\nu}_e, \nu_x$ and $^{\tau}/_{m}$

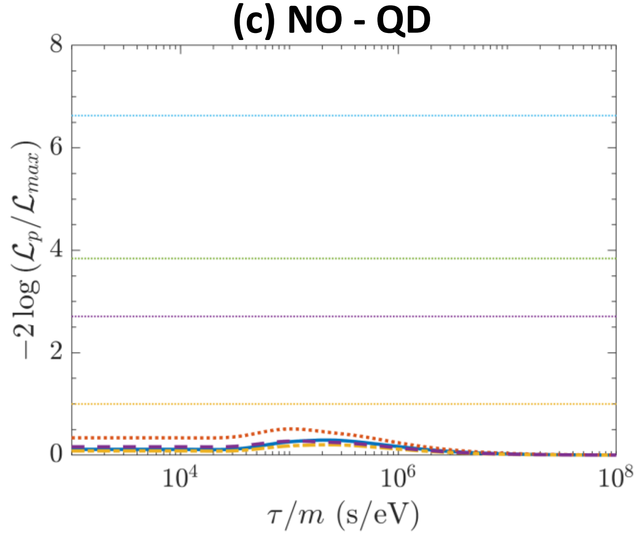
- Normal ordering: no sensitivity
- Inverted ordering: $\frac{\tau}{m} \geq 1.2 \times 10^5$ s/eV at 90% CL.

See **Yvonne Wong's** presentation for limits from cosmology



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.





How can we detect the DSNB?

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

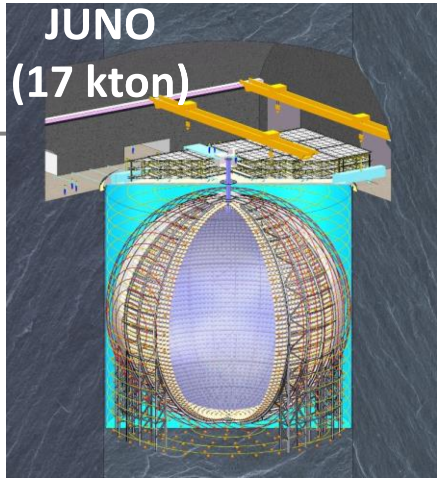
$$\bar{\nu}_e + p \rightarrow n + e^{+}$$

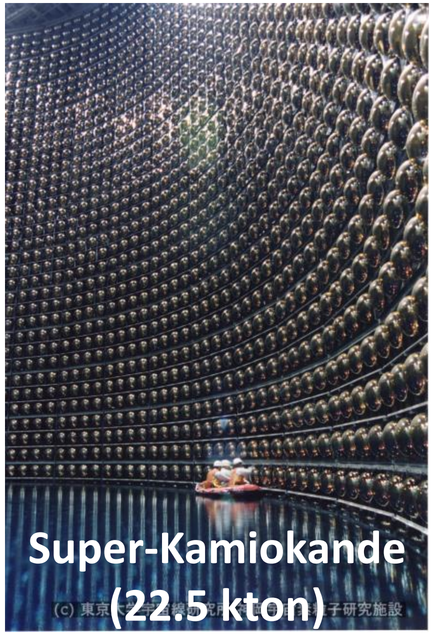
  - **Super-Kamiokande + Gd, Hyper-Kamiokande, JUNO**
  - Backgrounds: reactor $\bar{\nu}_e$ (low energies) and atmospheric ν (high energies)

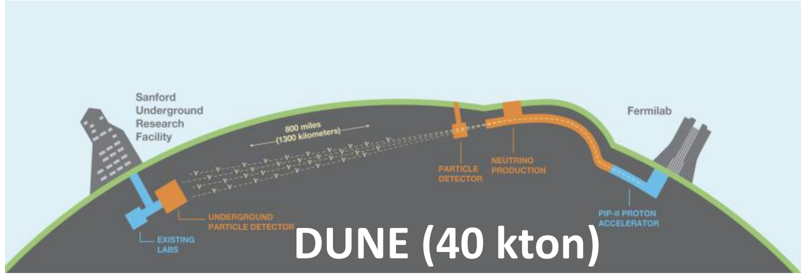
- Detection of ν_e flux → **neutrino absorption in ^{40}Ar**

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

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







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.

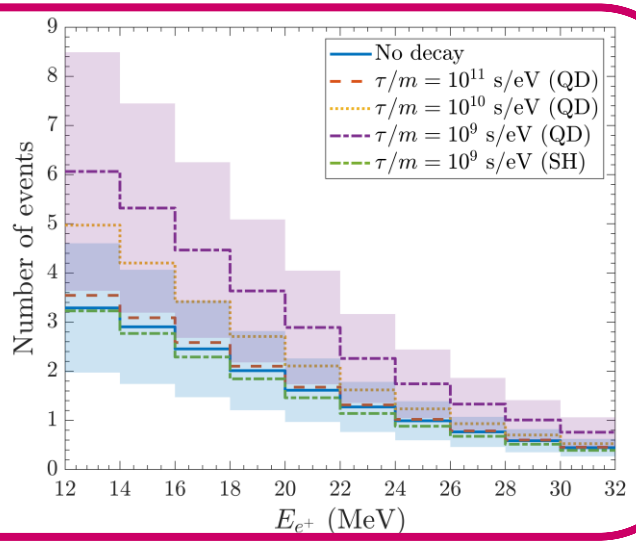
[P.I.B. and Volpe, PRD107 (2023) 023017]

SK-Gd:

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

Exposure time: 10 years

Energy window:
$12.8 \leq E_\nu \leq 30.8$ MeV

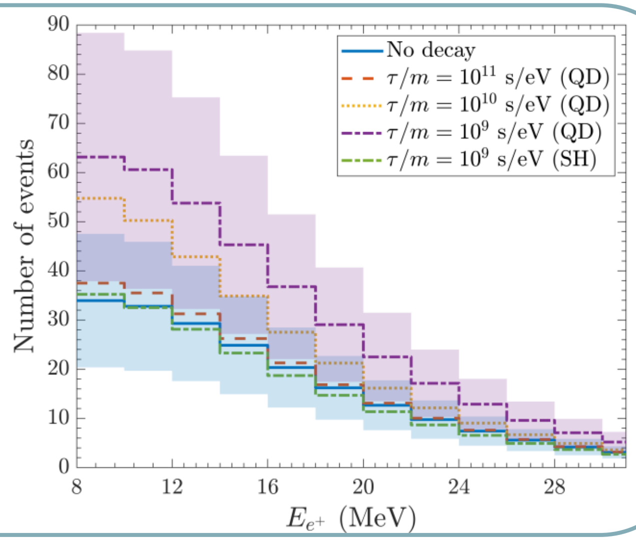


HK-Gd:

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

Exposure time: 20 years

Energy window:
$17.3 \leq E_\nu \leq 31.3$ MeV

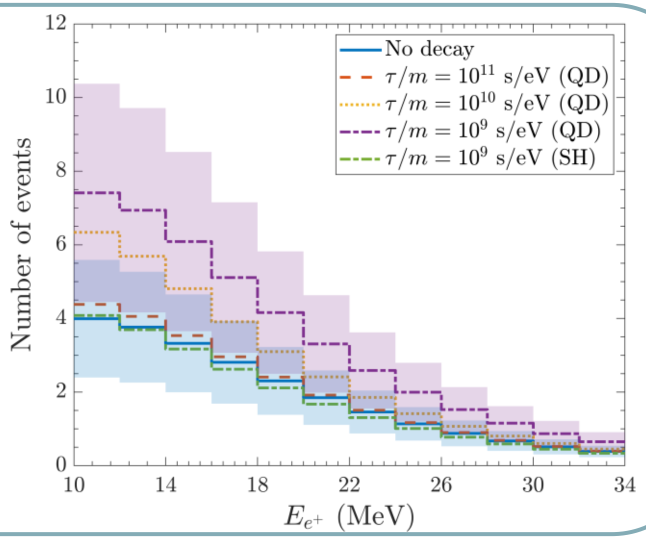


JUNO:

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

Exposure time: 20 years

Energy window:
$11.3 \leq E_\nu \leq 33.3$ MeV

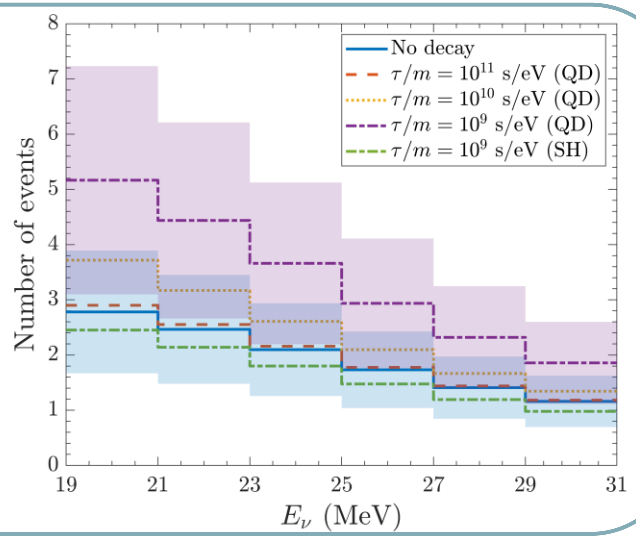


DUNE:

$N_{tot} = 12$ (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]

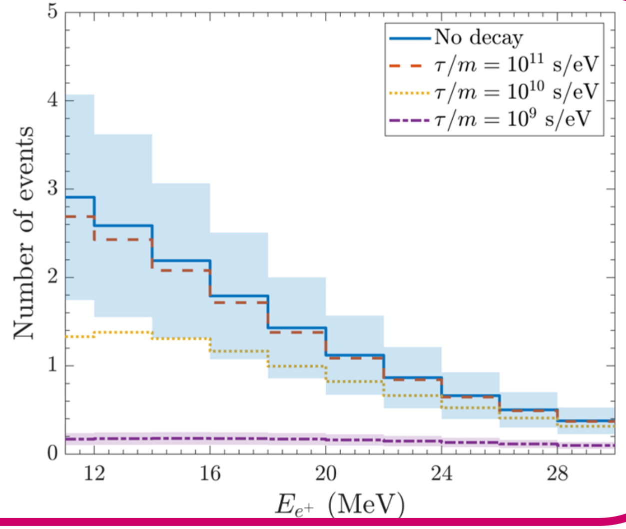
SK-Gd:

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

Exposure time: 10 years

Energy window:

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



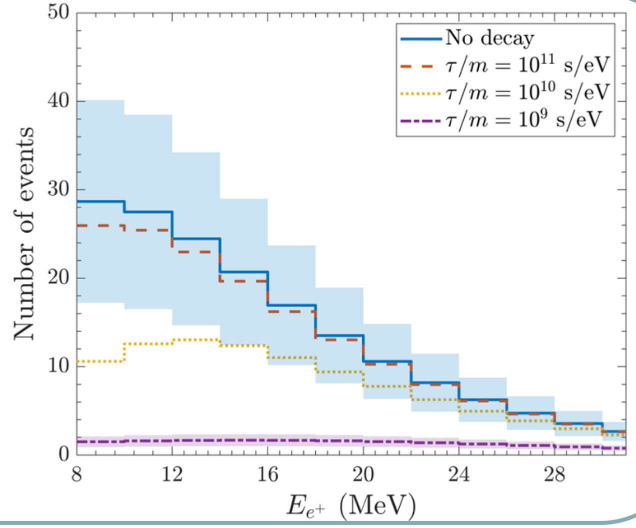
HK-Gd:

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

Exposure time: 20 years

Energy window:

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



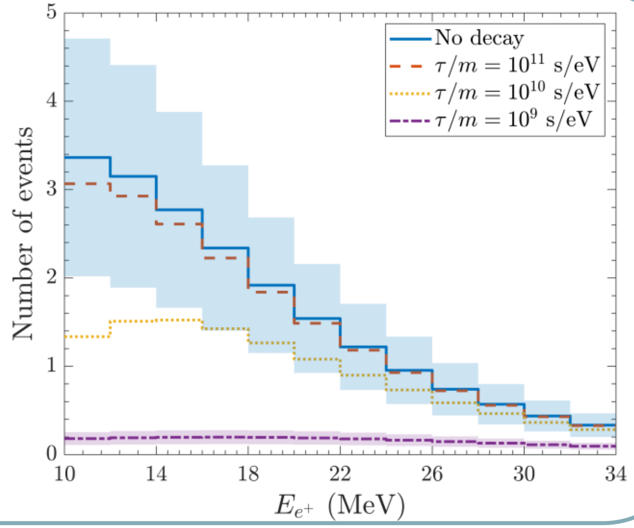
JUNO:

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

Exposure time: 20 years

Energy window:

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



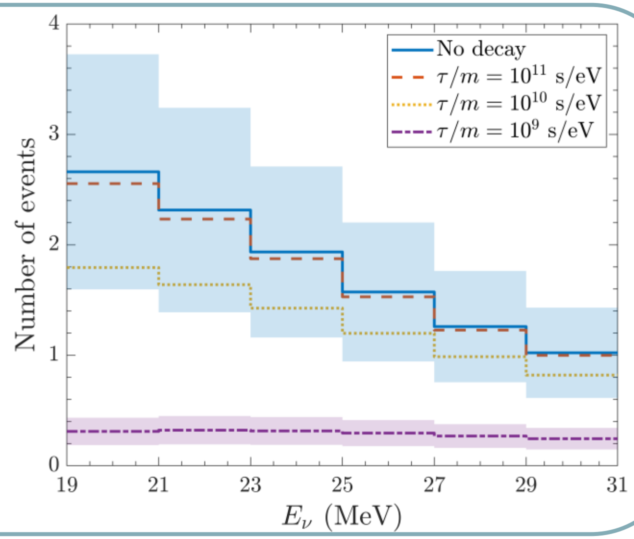
DUNE:

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

Exposure time: 20 years

Energy window:

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



Main results and conclusions

Investigation of neutrino nonradiative decay and its effects on supernova neutrinos using a 3ν framework and considering both NO and IO.

SN1987A: 7D likelihood analysis of the data to obtain limits on τ/m

DSNB: for the first time 3ν framework **+** dependence on the SN progenitors and uncertainty from the SN rate.
Prediction for the number of events at different experiments: **SK-Gd, HK, JUNO and DUNE**

MAIN RESULTS:

SN1987A

- Normal Ordering: **no sensitivity** to neutrino nonradiative decay
- Inverted Ordering: $\frac{\tau}{m} \geq \mathbf{1.2 \times 10^5}$ **s/eV** at 90% CL

DSNB: Normal Ordering

- SH masses: **degeneracy** between the number of events in the case of decay and no decay
- QD masses: **enhancement** of the ν_e and $\bar{\nu}_e$ flux and number of events in the presence of decay

DSNB: Inverted Ordering

- The ν_e and $\bar{\nu}_e$ fluxes and number of events with decay **suppressed** with respect to the case of no decay.

P. Iváñez-Ballesteros and M.C. Volpe, PRD107 (2023) 023017, arXiv:2209.12465
P. Iváñez-Ballesteros and M.C. Volpe, PLB847 (2023) 138252, arXiv:2307.03549