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Neutrino nonradiative decay and the diffuse supernova neutrino background

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APC – UNIVERSITÉ PARIS CITÉ

Outline

P. Iváñez-Ballesteros and M. C. Volpe, Phys. Rev. D 107, 023017 (2023)
arXiv:2209.12465

1. **DSNB FLUX WITHOUT DECAY**:
   - Emission from a single SN
   - Fraction of BH-forming collapses

2. **NEUTRINO NONRADIATIVE DECAY**: three-flavour description
   - Normal Ordering: Quasi-Degenerate (QD) and Strongly Hierarchical (SH) case
   - Inverted Ordering

3. **PREDICTIONS OF THE DSNB WITH/WITHOUT DECAY**
   - SK-Gd, HK, JUNO, DUNE

General context

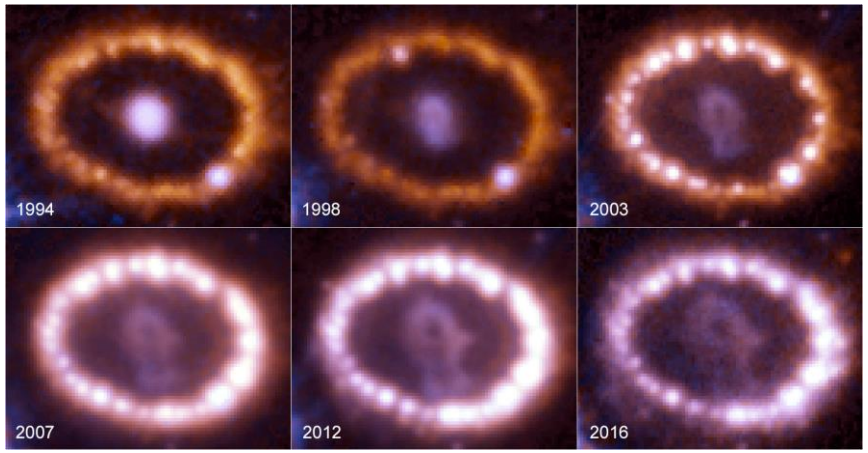
Massive Star ($M > 8\ M_{\odot}$) → Core Collapse → Neutron Star (NS) / Black Hole (BH)

- Most of the gravitational binding energy ($\sim 10^{53}$ erg) released as neutrinos (99 %)
- These neutrinos provide information about the SNe explosion dynamics, neutrino properties, …

Core-Collapse Supernovae (CCSNe) are very rare in our galaxy (1-3 per century)

SN 1987A: first detection of this neutrino burst.

[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)

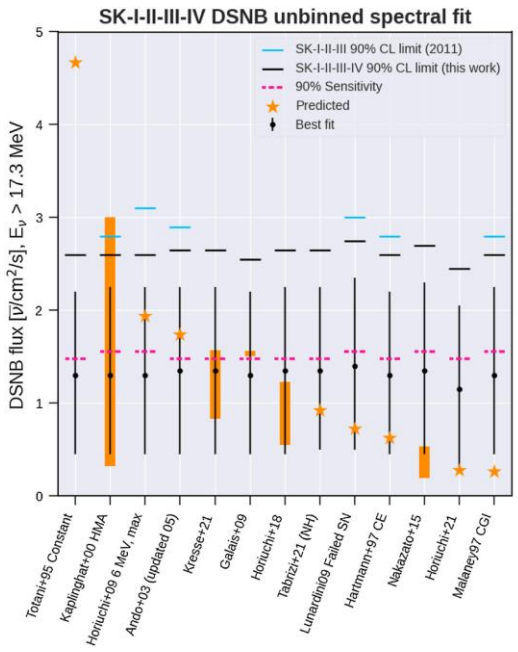
DSNB: all neutrinos and antineutrinos emitted by all past core collapses in the observable Universe.

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

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

$$E' = E(1+z)$$

- DSNB flux depends on:
  - **Cosmology** ⟶ $H(z)$
  - **Astrophysics** ⟶ Supernova rate R_{SN} ∝ Star Formation Rate (SFR)
  - **Neutrino properties** ⟶ mass ordering, matter effects, new properties…



Best-fit values associated to different models, the expected sensitivities for the DSNB fluxes and the 90% CL upper limits for the SK-I-II-III-IV data. [Abe *et al.*, 2021]

GOAL

Investigate what one might learn about neutrino decay through the upcoming observation of the DSNB when considering a detailed astrophysical model in a three-flavour neutrino framework.

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

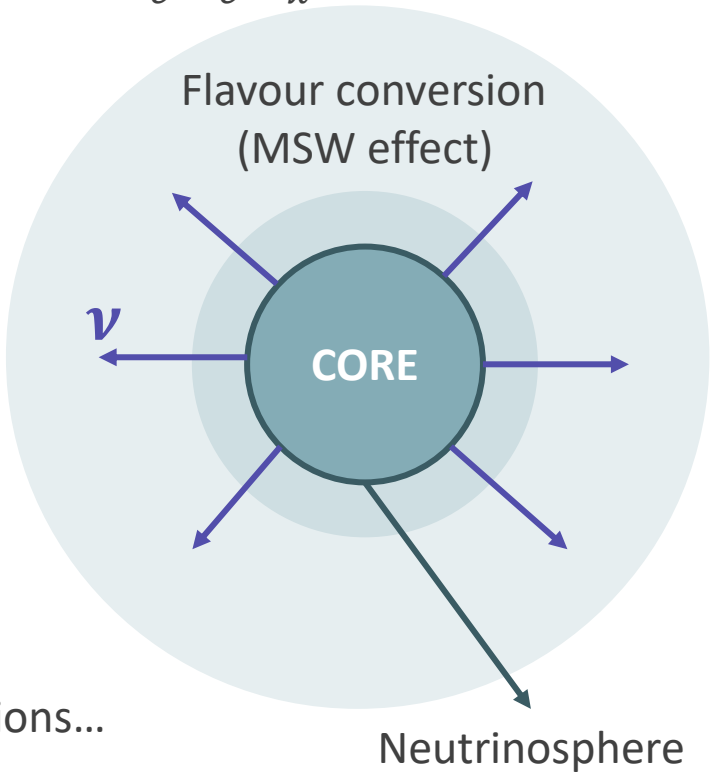
- Neutrino flux at the neutrinosphere can be parametrised by: [Keil *et al.*, 2003]

$$F_\nu^0(E) = \frac{L_\nu}{\langle E_\nu \rangle} \frac{(\alpha_\nu + 1)^{\alpha_\nu + 1}}{\langle E_\nu \rangle \, \Gamma(\alpha_\nu + 1)} \left(\frac{E}{\langle E_\nu \rangle} \right)^{\alpha_\nu} \exp\left[-(\alpha_\nu + 1) \frac{E}{\langle E_\nu \rangle} \right]; \; \nu = \nu_e, \bar{\nu}_e, \nu_x$$

L_ν: luminosity $(\sim 10^{52}\ \mathrm{erg})$

$\langle E_\nu \rangle$: average energy $(\sim 12 - 18\ \mathrm{MeV})$

α_ν: pinching parameter, function of $\langle E_\nu \rangle$ and $\langle E_\nu^2 \rangle$ $(\sim 2 - 3)$



- **Mikheev-Smirnov-Wolfenstein (MSW) effect**: [Wolfenstein, 1978] [Mikheev and Smirnov, 1986]

  Describes the flavour transformations due to the ν-matter interactions.

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

  Flavour conversion in SNe still under study: shock wave effects, $\nu - \nu$ interactions…

  see e.g. the review Volpe (2023)

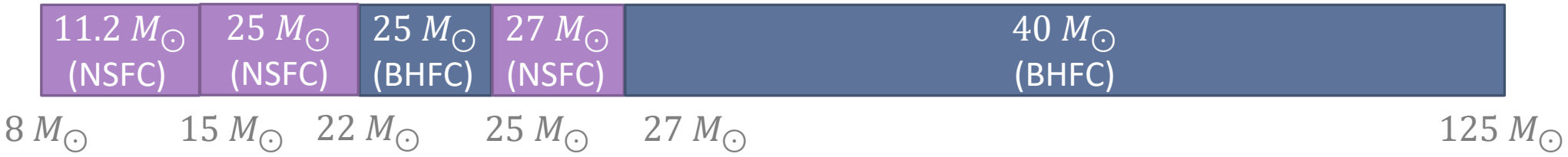
Contribution from Black Hole-Forming Collapses

BH-forming collapses (BHFC) emit a hotter neutrino spectrum than NS-forming collapses (NSFC).

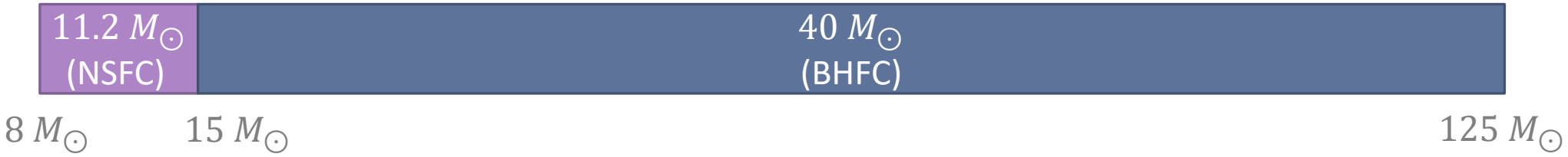
Fraction of BH, f_{BH}: fraction of "failed" collapses, i.e. they end up forming a BH.

- $f_{BH} = 0.09$

- $f_{BH} = 0.21$
  (Fiducial case)



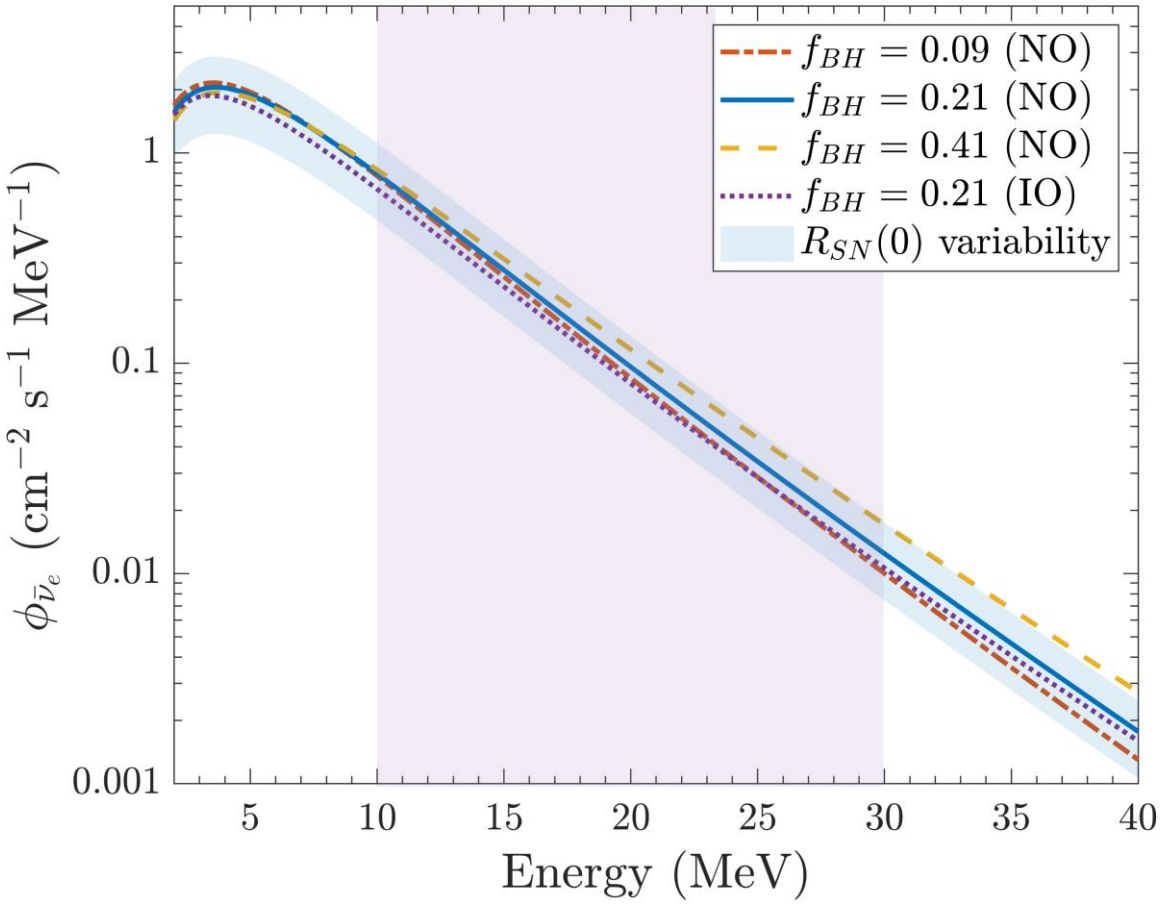
- $f_{BH} = 0.41$



[Priya and Lunardini, 2017], [Møller *et al.*, 2018] , [P.I.B. and Volpe, 2023]

To model the DSNB flux, we used templates from 1D SN simulations from the Garching group. [Hudepohl, 2013]

DSNB flux on Earth in absence of ν decay



Flux of $\bar{\nu}_e$ on Earth for different f_{BH} in absence of decay. The band shows the uncertainty of the SNR normalisation.

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

$$E' = E(1+z)$$

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:

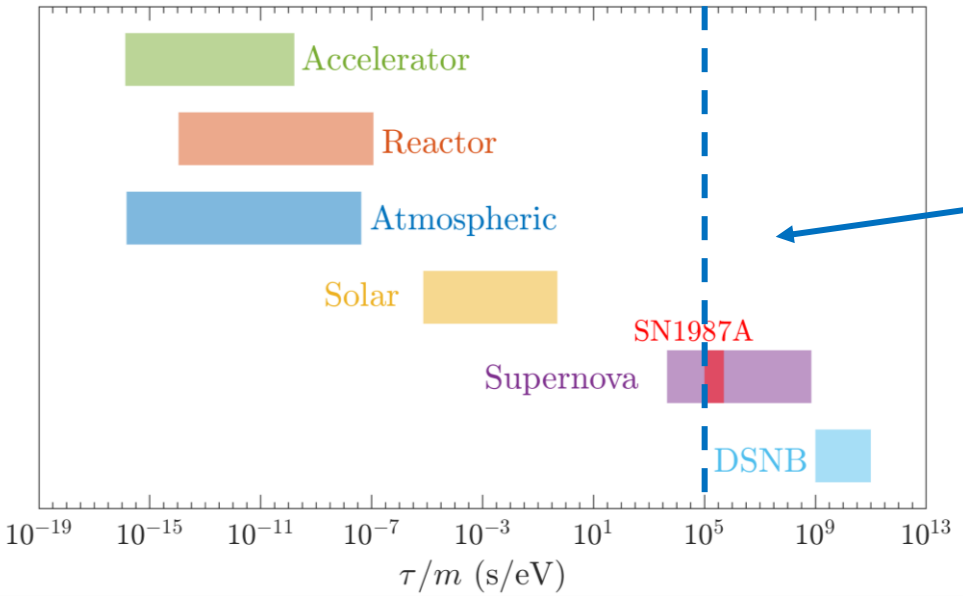
	NO	IO	UPPER LIMITS
$\bar{\nu}_e$ ($E_\nu > 17.3$ MeV)	0.77 ± 0.30 [1.02 ± 0.41]	0.63 ± 0.25 [0.75 ± 0.3]	2.6 (SK) [Abe *et al.*, 2021]
ν_e ($22.9 < E < 36.9$ MeV)	0.20 ± 0.08 [0.24 ± 0.09]	0.18 ± 0.08 [0.23 ± 0.09]	19 (SNO) [Aharmin *et al.*, 2020]

Neutrino nonradiative decay

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

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 (2023).

From SN1987A data, in the case of inverted ordering:

$$\frac{\tau}{m} \geq \mathbf{1.2 \times 10^5\ s/eV} \text{ at } 90\%\ \text{CL}.$$

[P.I.B. and Volpe 2023, arXiv:2307.03549]

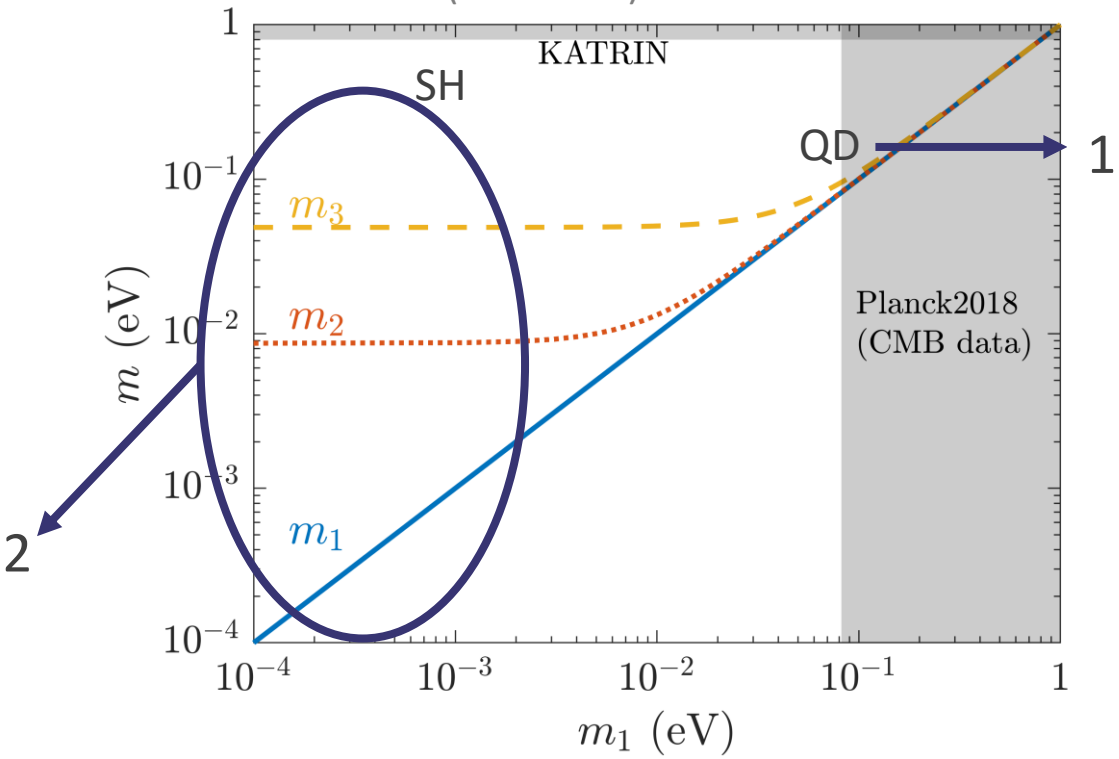
DSNB has unique sensitivity to this decay in the range:

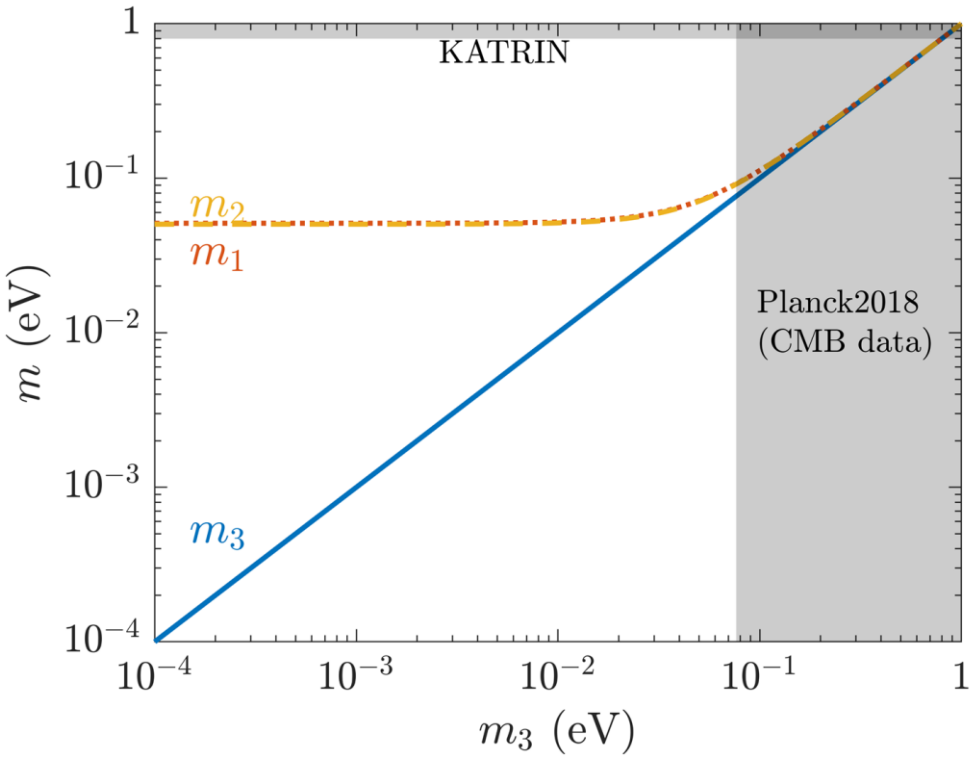
$$\frac{\tau}{m} \in \left[\mathbf{10^9 - 10^{11}}\right]\ \mathbf{s/eV}$$

[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:

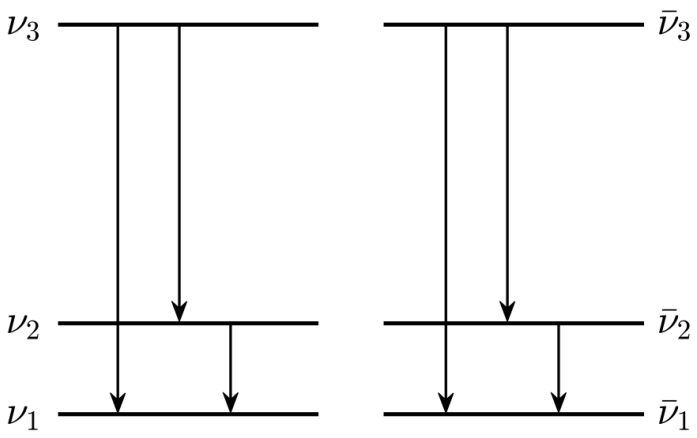
1. **QD** $\Longrightarrow m_1 \simeq m_2 \simeq m_3 \gg \Delta m_{ij}$
2. **SH** $\Longrightarrow m_3 \gg m_2 \gg m_1 \simeq 0$

INVERTED ORDERING:

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

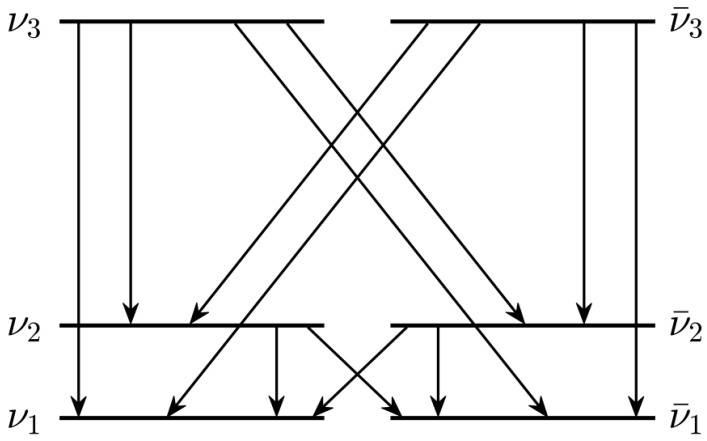
Decay patterns

NO and QD masses.



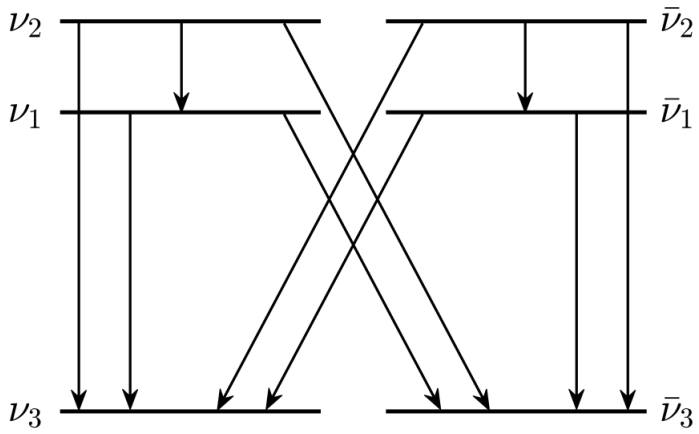
- $\boldsymbol{\tau_3/m_3 = \tau_2/m_2 = \tau/m}$
- $B(\nu_3 \to \nu_2) = B(\nu_3 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_1) = 1$

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



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

Detection of the DSNB

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

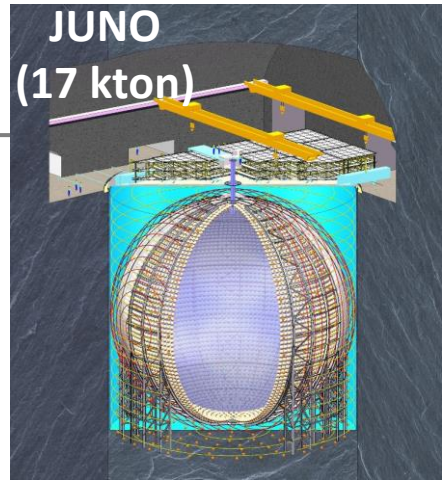
$$\bar{\nu}_e + p \rightarrow n + e^+$$

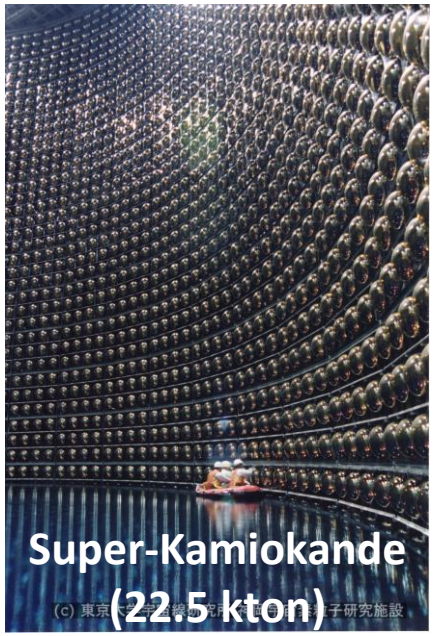
  - **Super-Kamiokande + Gd, Hyper-Kamiokande, JUNO**
  - Backgrounds: reactor $\bar{\nu}_e$ (low energies) and atmospheric ν (high energies)

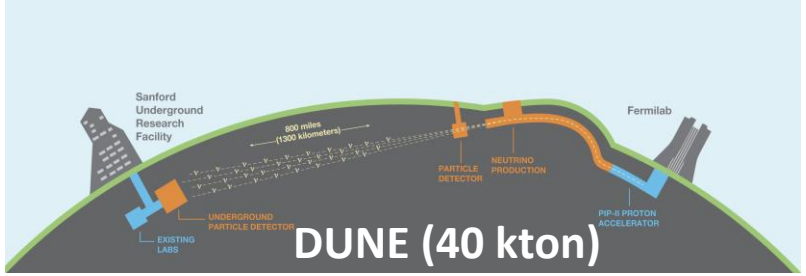
- Detection of ν_e flux → **neutrino absorption in ^{40}Ar**

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

  - **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.

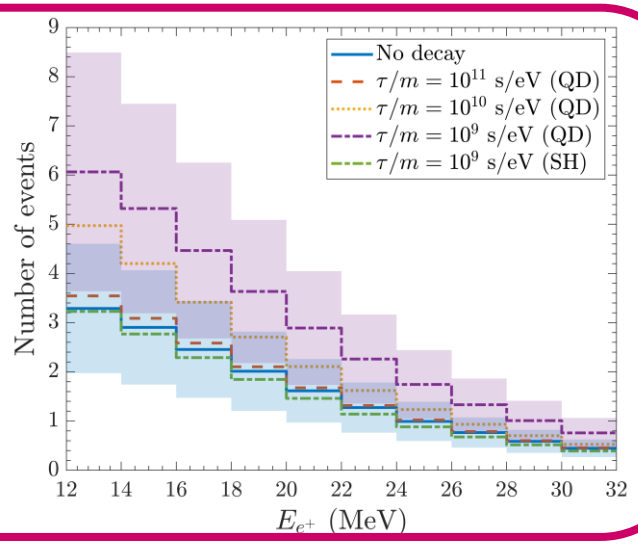
SK-Gd:

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

Exposure time: 10 years

Energy window:

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



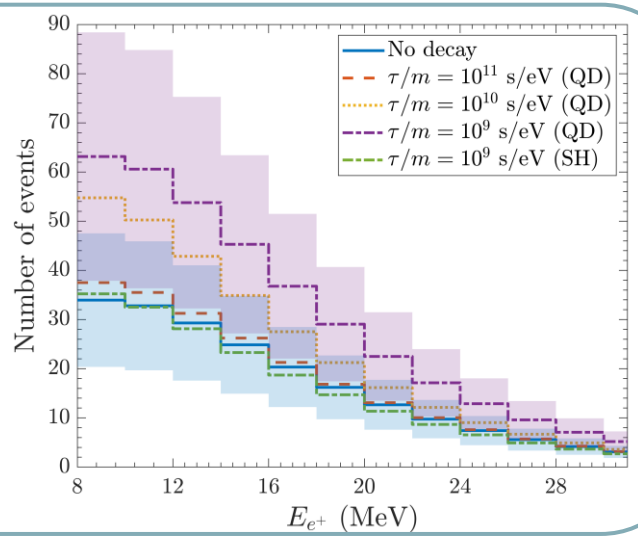
HK-Gd:

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

Exposure time: 20 years

Energy window:

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



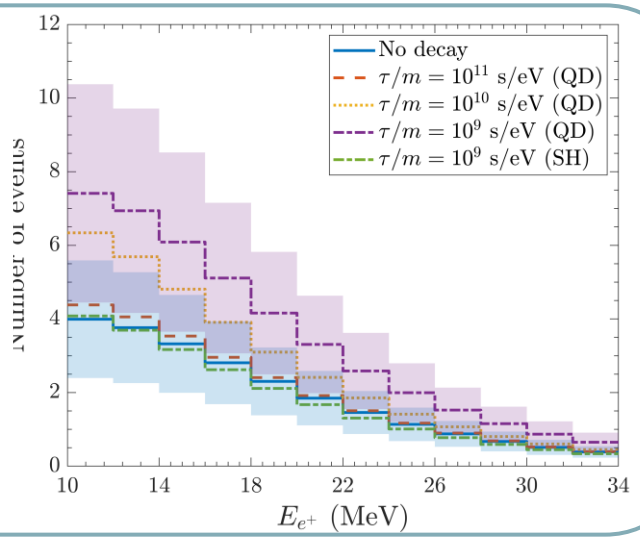
JUNO:

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

Exposure time: 20 years

Energy window:

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



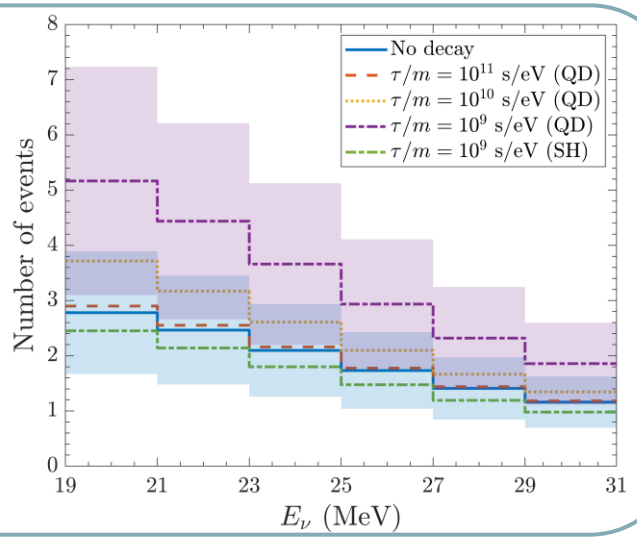
DUNE:

$N_{tot} = 12$ (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.

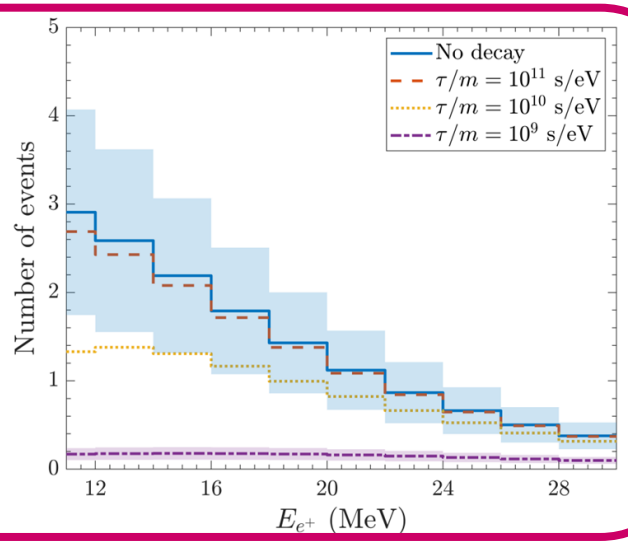
SK-Gd:

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

Exposure time: 10 years

Energy window:

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



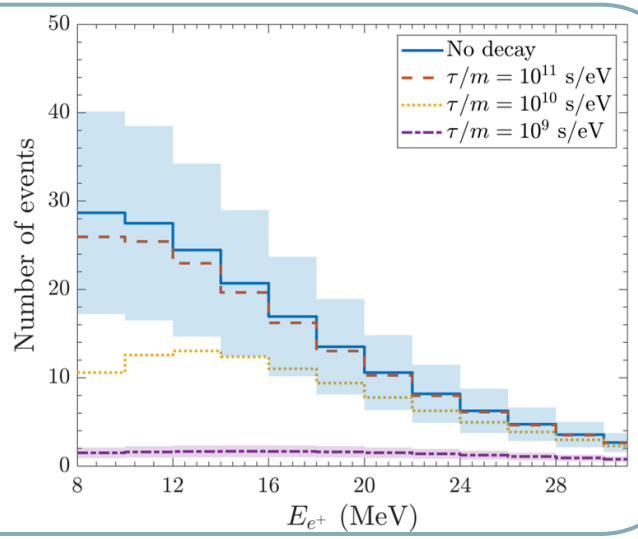
HK-Gd:

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

Exposure time: 20 years

Energy window:

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



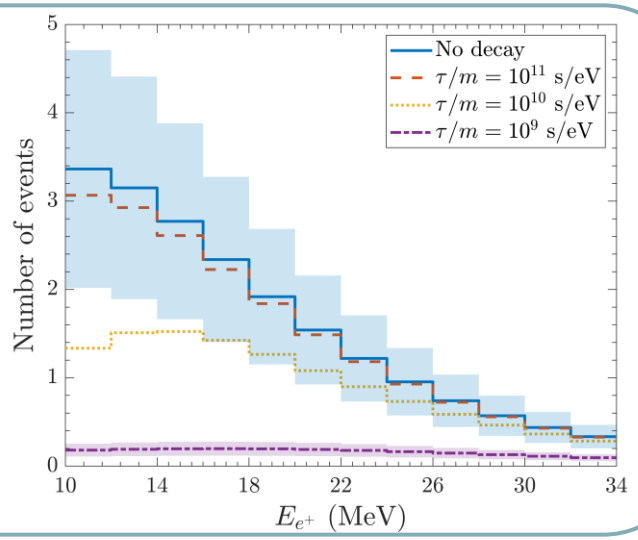
JUNO:

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

Exposure time: 20 years

Energy window:

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



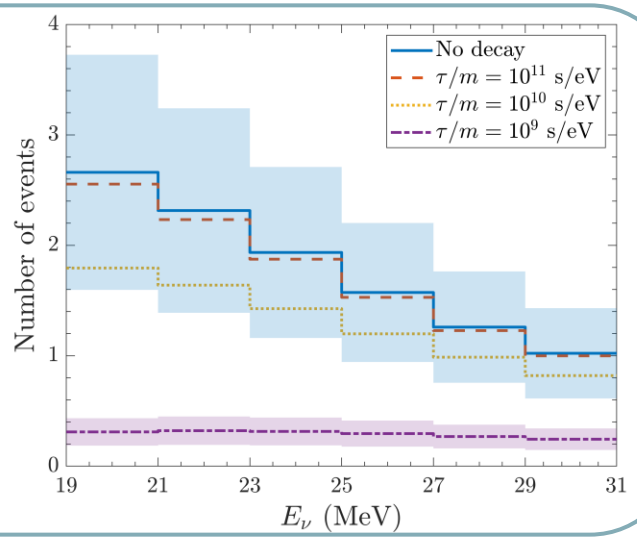
DUNE:

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

Exposure time: 20 years

Energy window:

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



Main results and conclusions

First investigation of nonradiative neutrino decay using a 3ν framework and including the dependence on the SN progenitors and the uncertainty from the SN rate.

Prediction for the number of events at different experiments: **SK-Gd, HK, JUNO and DUNE**

MAIN RESULTS:

NO and SH masses:

- DSNB ν_e and $\bar{\nu}_e$ fluxes with decay degenerate with no decay.

NO and QD masses:

- $\frac{\tau}{m} = 10^{11}$ s/eV: ν_e and $\bar{\nu}_e$ fluxes with decay degenerate with no decay.
- $\frac{\tau}{m} = 10^{9}$ s/eV: enhancement of the ν_e and $\bar{\nu}_e$ fluxes by a factor of 2

IO:

- 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

SN1987A and neutrino nonradiative decay, P. Iváñez-Ballesteros and M.C. Volpe (2023), arXiv:2307.03549

Thank you for your attention

BACK UP SLIDES

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).

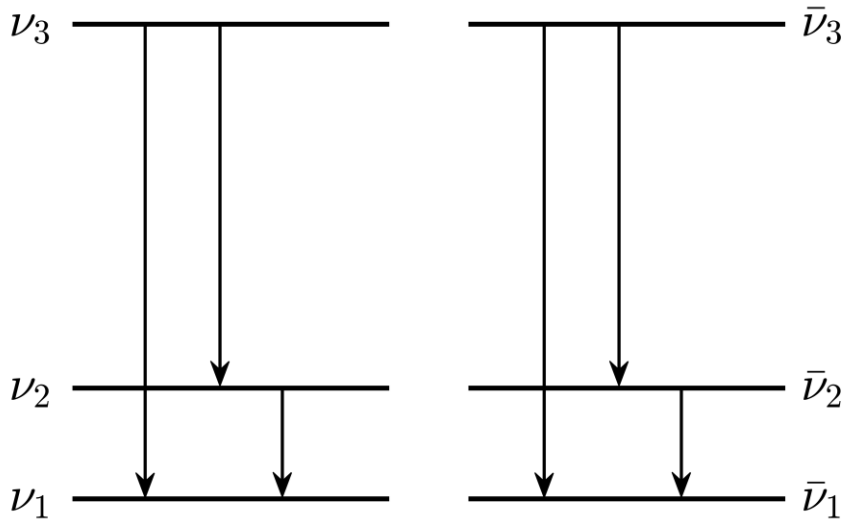
	N_t (10^{33})	ϵ (%)	Time (years)	DSNB window (MeV)	DSNB events
SK-Gd	1.5	57.5	2	(12.8, 30.8)	2 (2) $\bar{\nu}_e$
SK-Gd	1.5	73.75	8	(12.8, 30.8)	12 (10) $\bar{\nu}_e$
HK	12.5	25	20	(17.3, 31.3)	48 (40) $\bar{\nu}_e$
HK-Gd	12.5	40	20	(17.3, 31.3)	76 (64) $\bar{\nu}_e$
JUNO	1.21	50	20	(11.3, 33.3)	20 (17) $\bar{\nu}_e$
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	2	2	3	4
(12.8–30.8)	(2)	[2]	[2]	[2]
2 + 8 years		(2)	(1)	(0)
	12	13	17	22
	(10)	[12]	[12]	[11]
		(10)	(7)	(1)
HK	48	49	61	84
(17.3–31.3)	(40)	[47]	[45]	[43]
20 years		(39)	(29)	(6)
HK-Gd	76	79	98	135
(17.3–31.3)	(64)	[73]	[73]	[69]
20 years		(62)	(46)	(9)
JUNO	20	21	28	37
(11.3–33.3)	(17)	[20]	[19]	[19]
20 years		(16)	(10)	(2)
DUNE	12	12	15	20
(19–31)	(11)	[11]	[11]	[10]
20 years		(10)	(8)	(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).

DSNB flux with ν decay: results for NO, QD case

Decay pattern for NO and QD masses.



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- $B(\nu_3 \to \nu_2) = B(\nu_3 \to \nu_1) = \frac{1}{2}$
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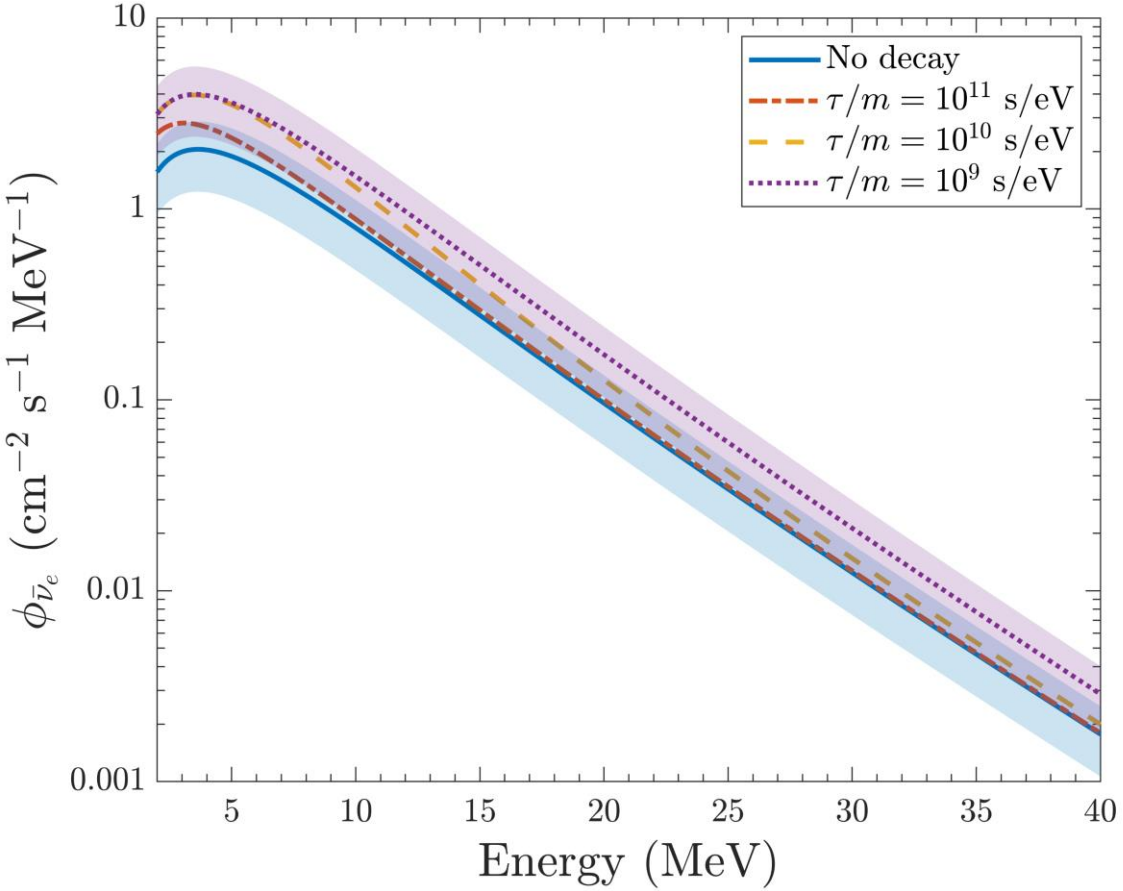
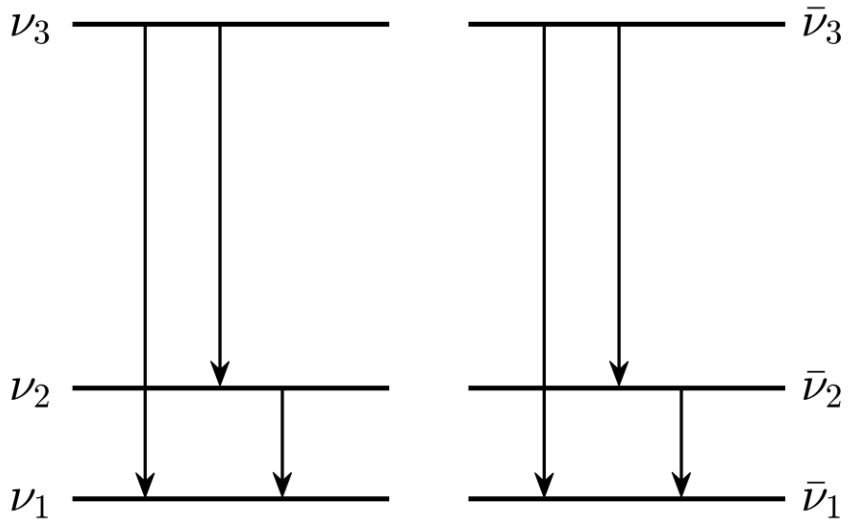


DSNB $\bar{\nu}_e$ flux on Earth for a decay scenario with NO and QD masses.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

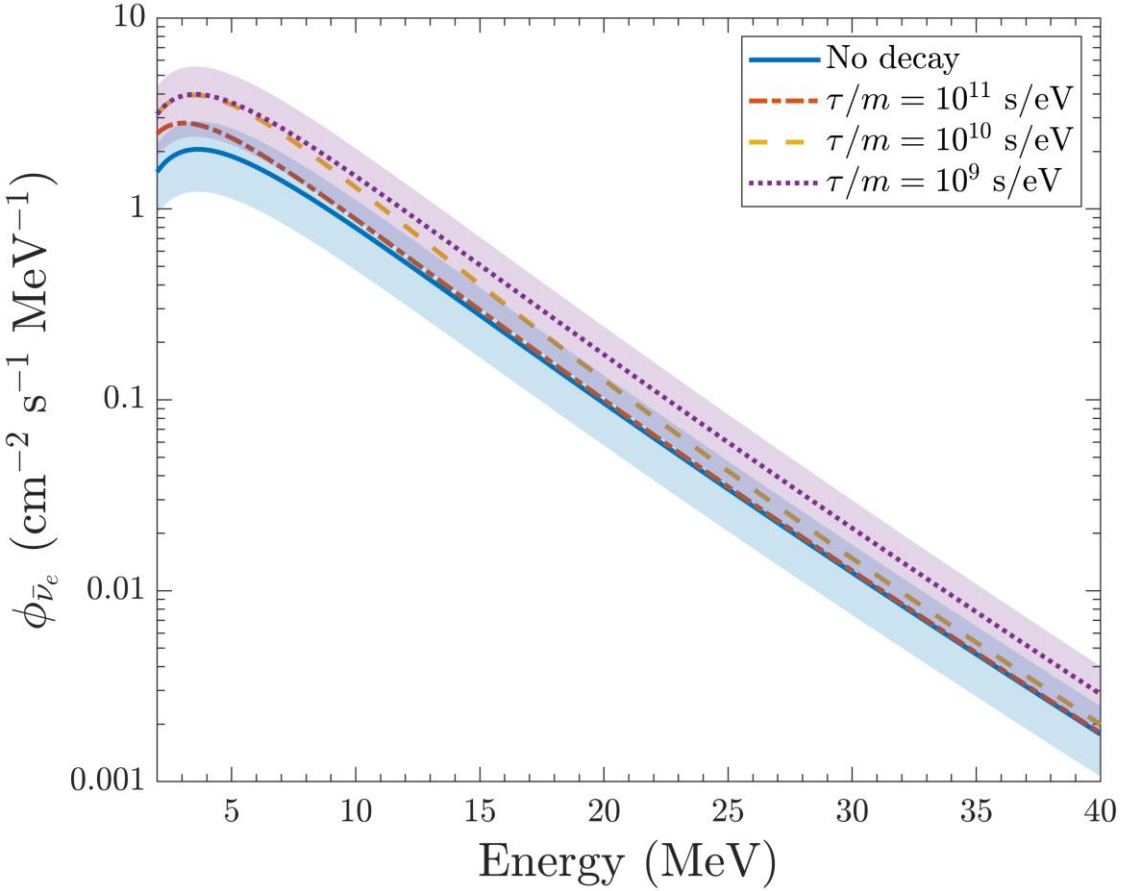
DSNB flux with ν decay: results for NO, QD case

Decay pattern for NO and QD masses.



$$\boldsymbol{\phi_{\bar{\nu}_e} = |U_{e1}|^2 \phi_{\bar{\nu}_1} + |U_{e2}|^2 \phi_{\bar{\nu}_2} + |U_{e3}|^2 \phi_{\bar{\nu}_3}}$$

$$|U_{e1}|^2 \simeq 0.69, |U_{e2}|^2 \simeq 0.29, |U_{e3}|^2 \simeq 0.02$$



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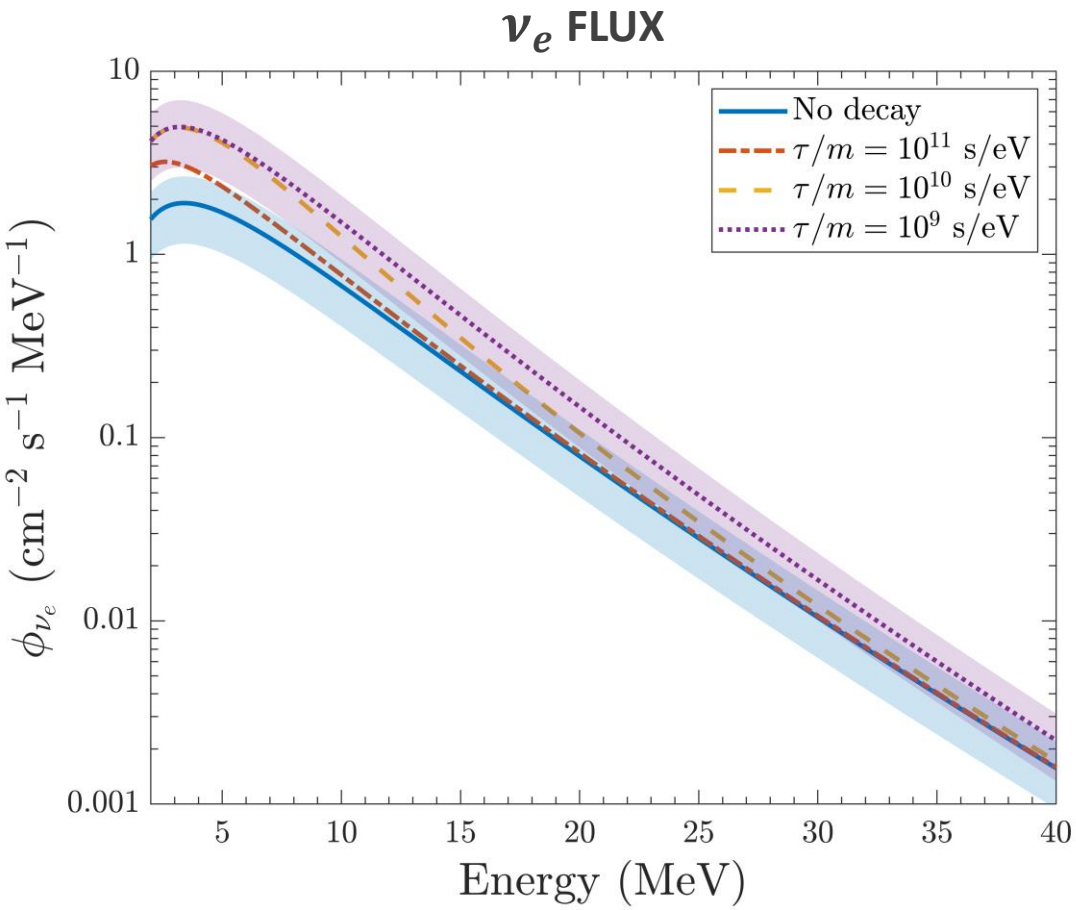
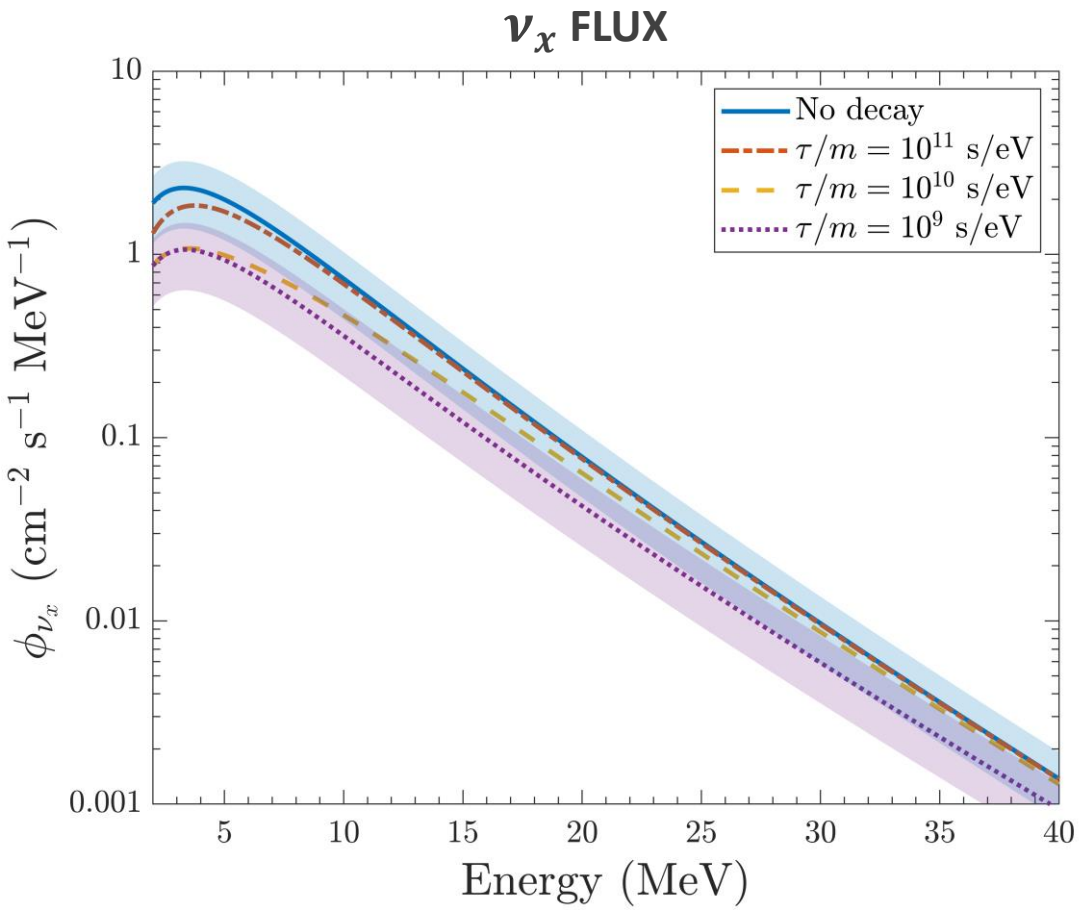
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for NO, QD case

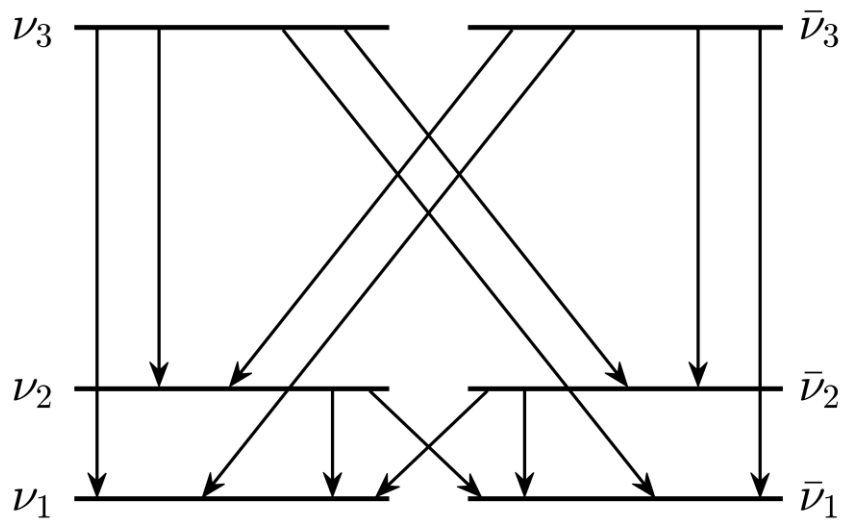




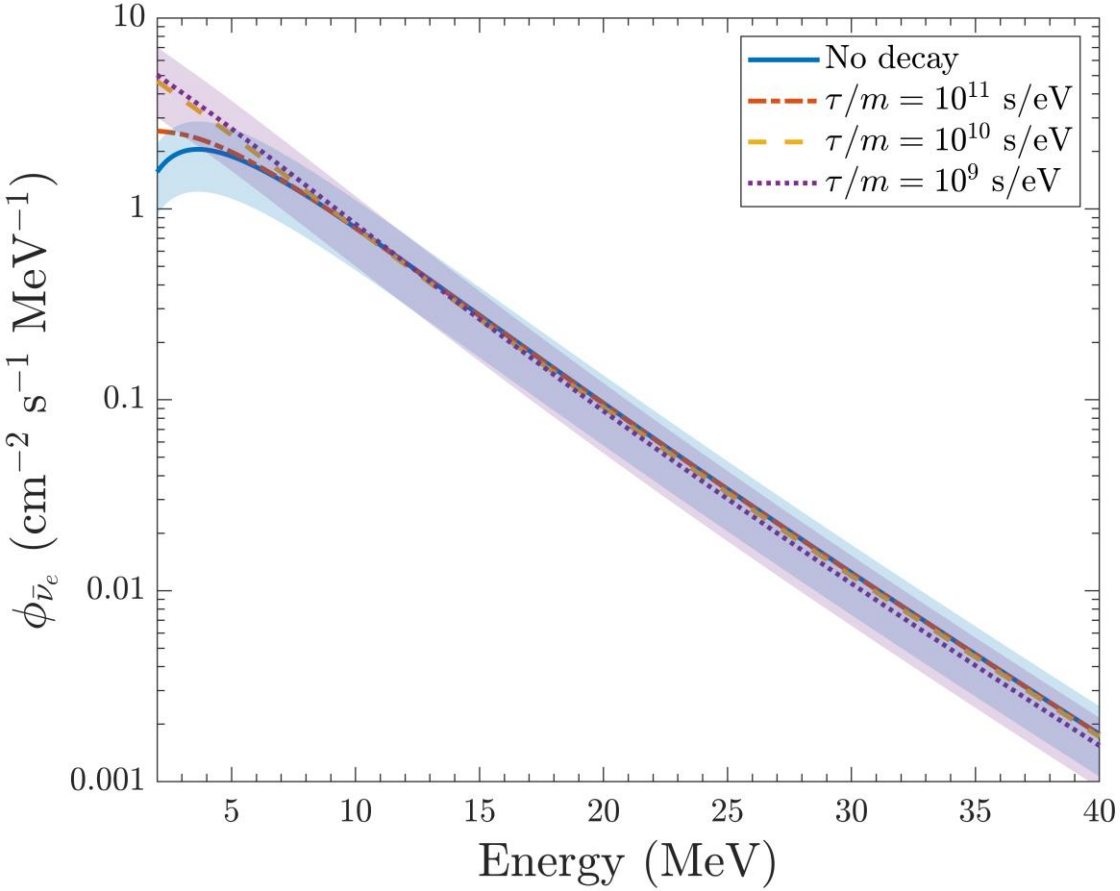
DSNB ν_e and ν_x flux on Earth for a decay scenario with NO and QD masses.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for NO, SH case

Decay pattern for NO and SH masses.

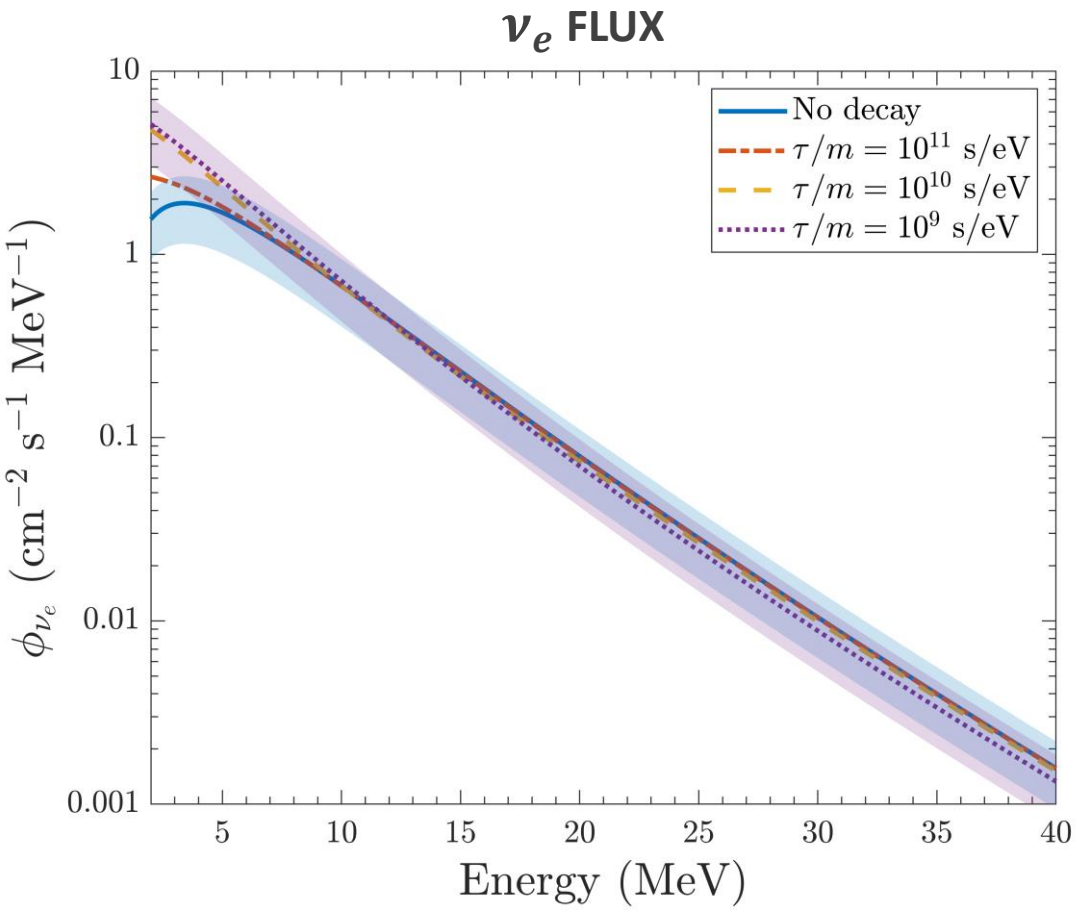


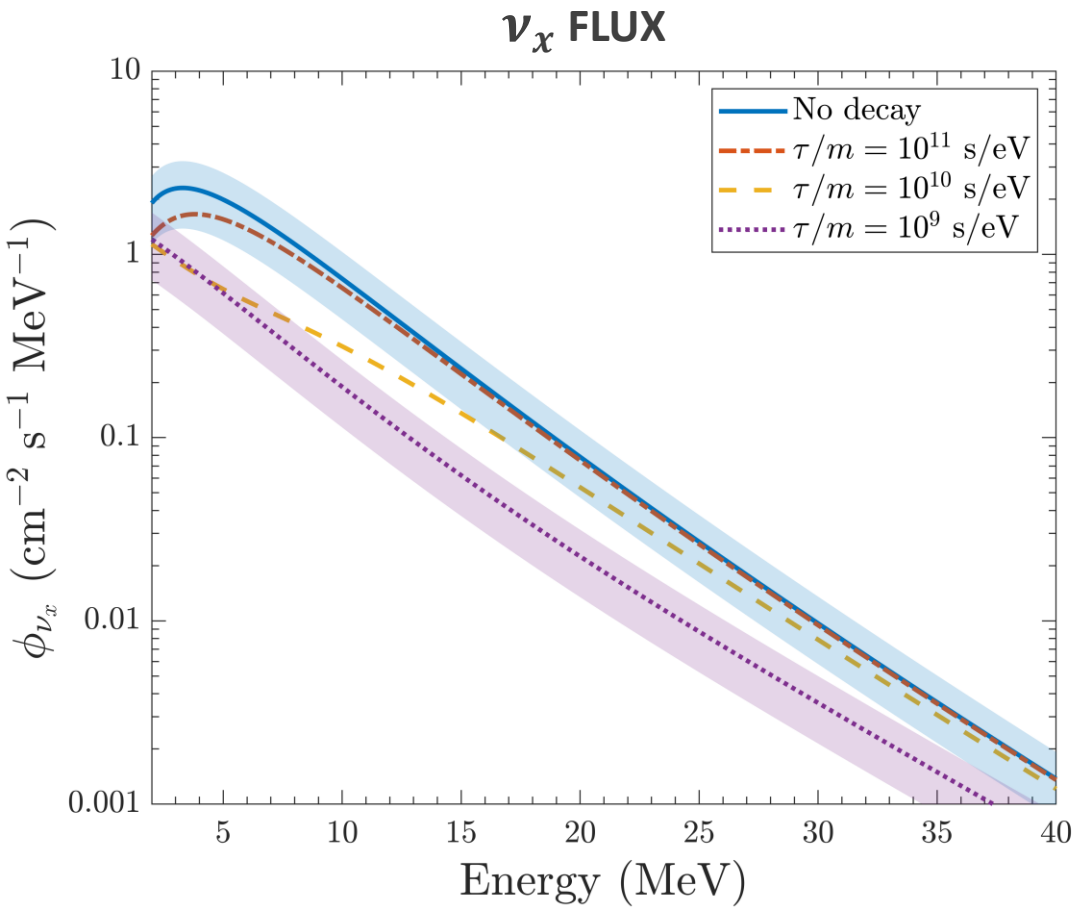
- $\tau_3/m_3 = \tau_2/m_2 = \tau/m$
- $B(\nu_3 \to \nu_i) = B(\nu_3 \to \bar{\nu}_i) = \frac{1}{4}$
- $B(\nu_2 \to \nu_1) = B(\nu_2 \to \bar{\nu}_1) = \frac{1}{2}$



DSNB $\bar{\nu}_e$ flux on Earth for a decay scenario with NO and SH masses. We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for NO, SH case

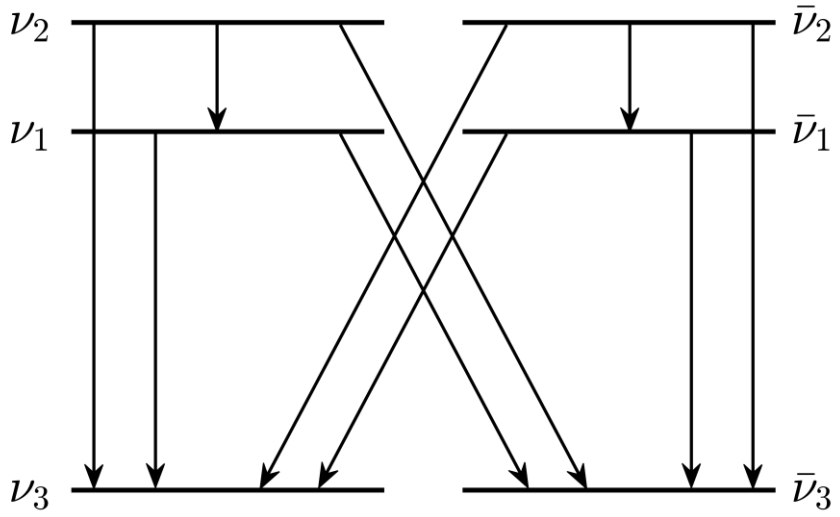




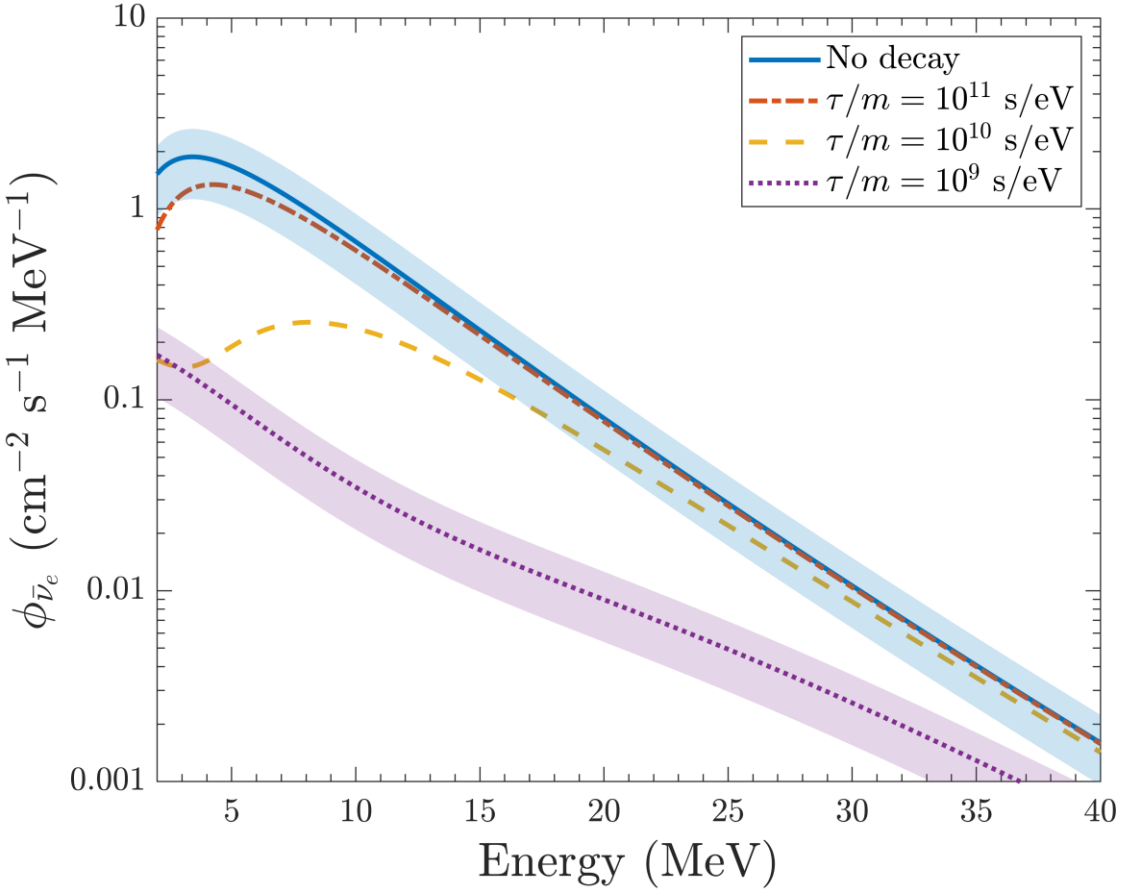
DSNB ν_e and ν_x flux on Earth for a decay scenario with NO and SH masses.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for IO case

Decay pattern for IO.



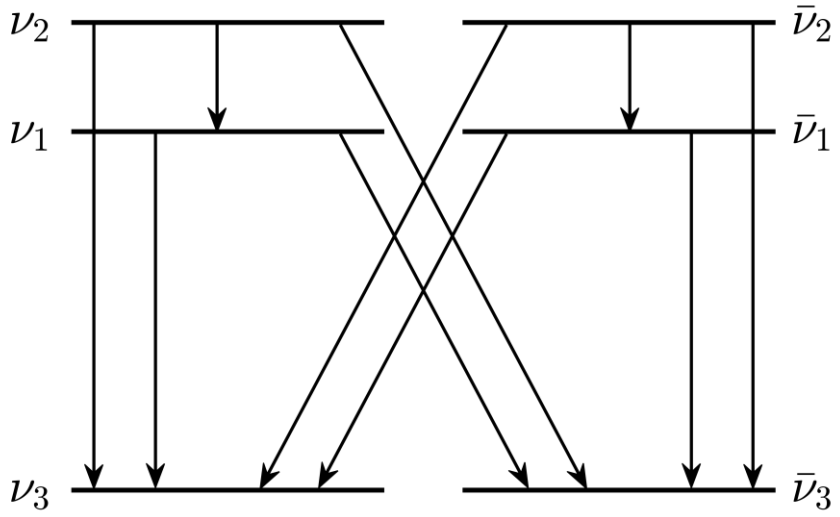
- $\boldsymbol{\tau_1/m_1 = \tau_2/m_2 = \tau/m}$
- $B(\nu_2 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_3) = B(\nu_2 \to \bar{\nu}_3) = \frac{1}{4}$
- $B(\nu_1 \to \nu_3) = B(\nu_1 \to \bar{\nu}_3) = \frac{1}{2}$



DSNB $\bar{\nu}_e$ flux on Earth for a decay scenario with IO.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for IO case

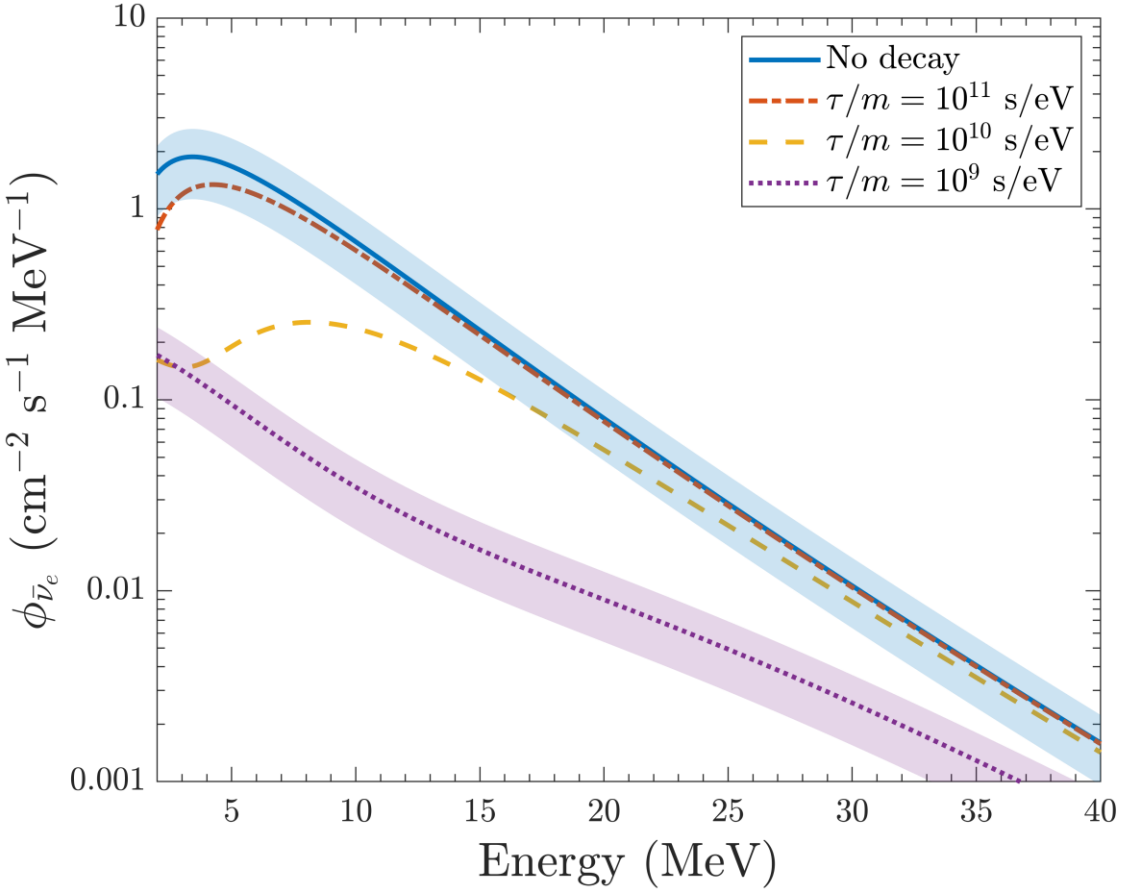
Decay pattern for IO.



<u>Complete decay</u> ($\tau/m = 10^9$ s/eV)

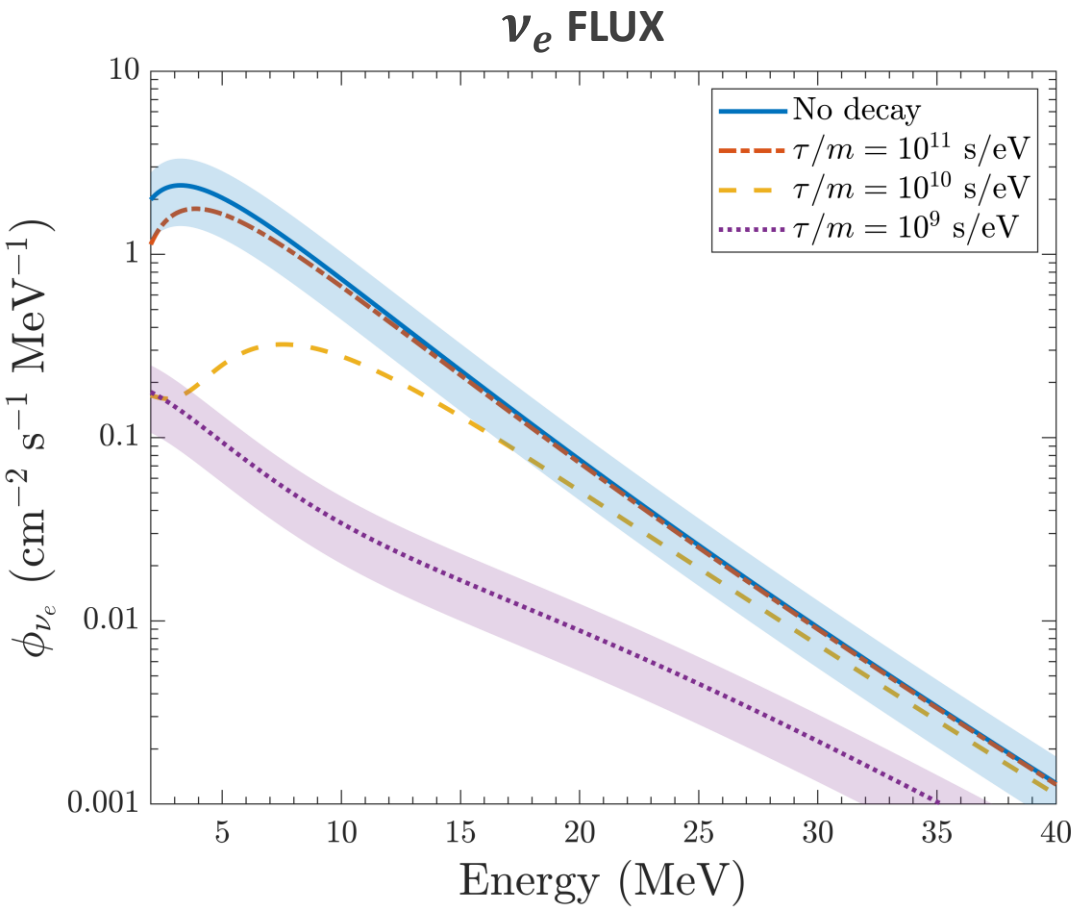
$$\boldsymbol{\phi_{\bar{\nu}_e} \sim |U_{e3}|^2 \phi_{\bar{\nu}_3}}$$

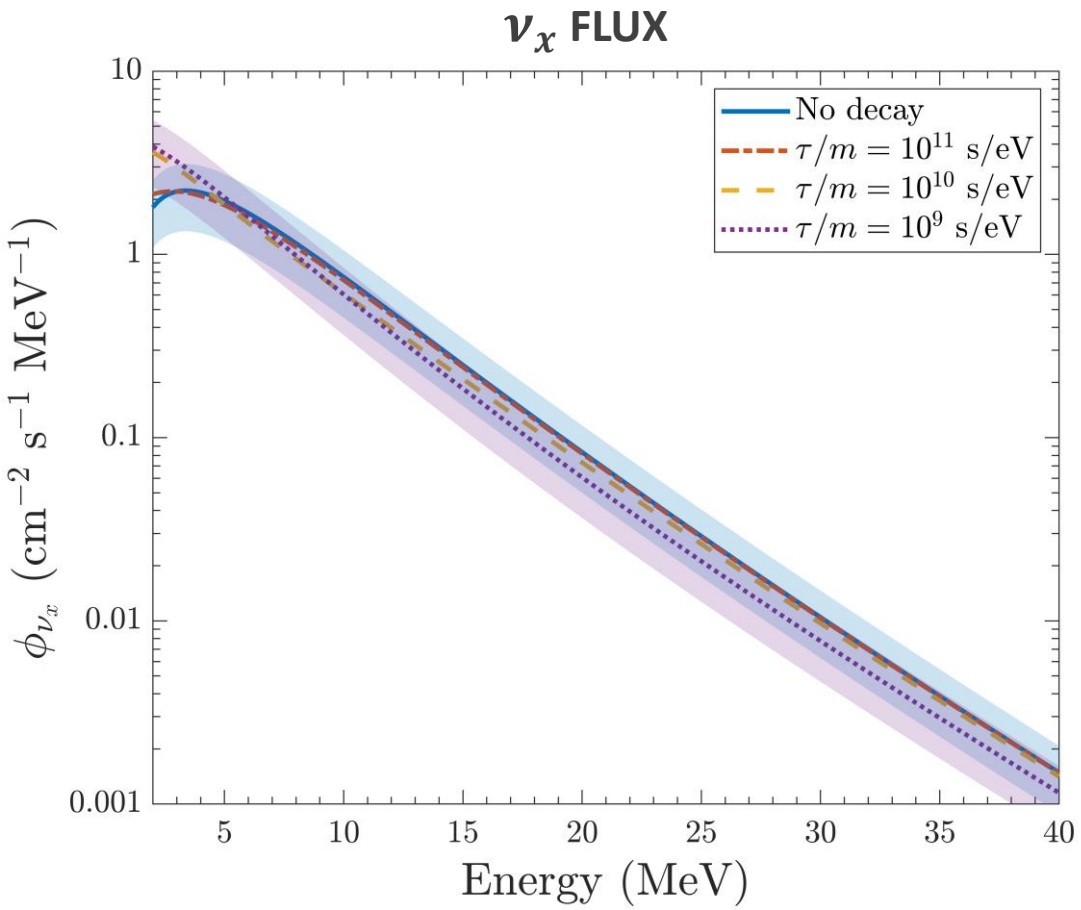
$$|U_{e3}|^2 \simeq 0.02$$



DSNB $\bar{\nu}_e$ flux on Earth for a decay scenario with IO.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

DSNB flux with ν decay: results for IO





DSNB ν_e and ν_x flux on Earth for a decay scenario with IO.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.