Neutrino nonradiative decay and the diffuse supernova neutrino background

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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
   - Supernova Rate (SNR)

2. **NEUTRINO NON-RADIATIVE 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

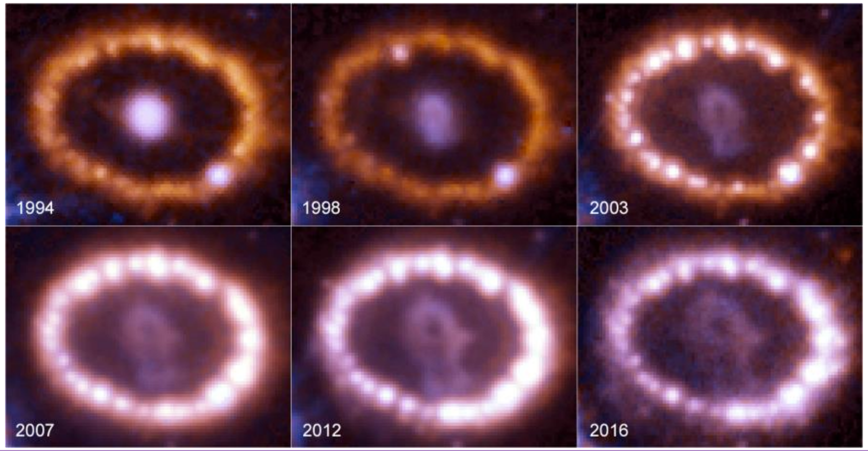
Massive Star ($M > 8\ M_\odot$) → Core Collapse → Neutron Star (NS) / Black Hole (BH)

- 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 <u>all past CCSNe in the observable Universe</u>.

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

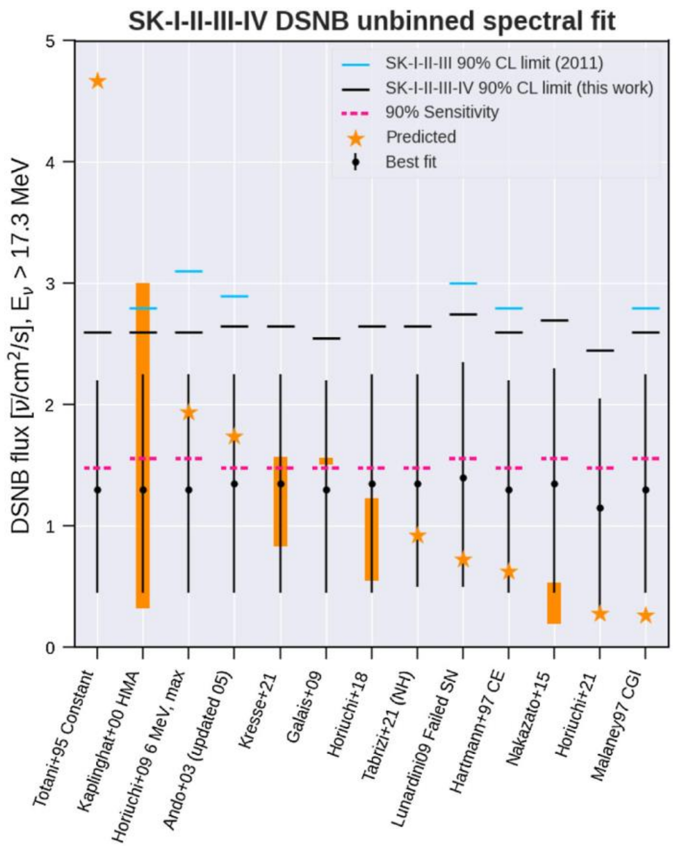
  [Aharmin *et al.*, 2006]

- 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]



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]

The Diffuse Supernova Neutrino Background (DSNB)

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

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

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

- DSNB flux depends on:
  - ❑ **Cosmology** $\longrightarrow H(z)$
  - ❑ **Astrophysics** $\longrightarrow$ Supernova rate R_{SN} $\propto$ Star Formation Rate (SFR)
  - ❑ **Neutrino properties** $\longrightarrow$ Mass ordering, matter effects (MSW), new properties…

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.

DSNB flux without decay

PROGENITOR DEPENDENCE AND SUPERNOVA RATE (SNR)

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

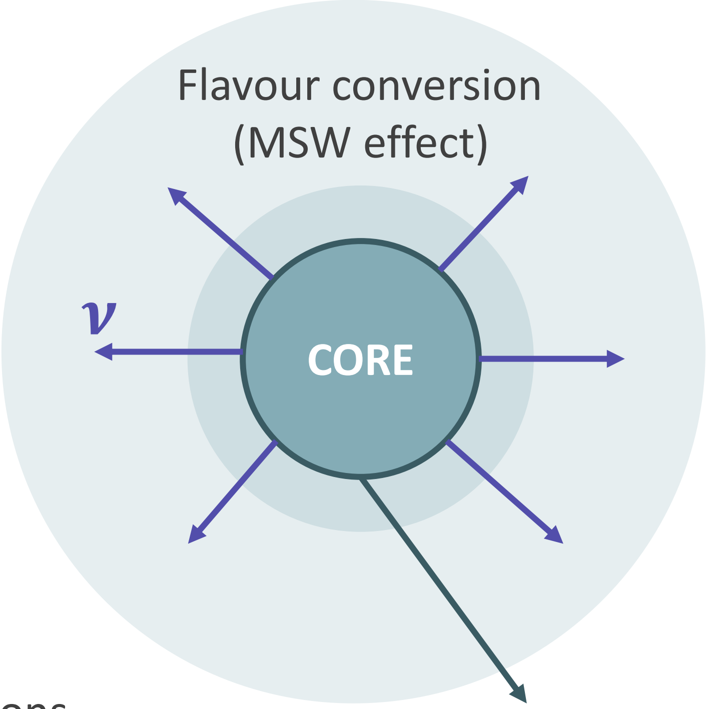
- Neutrino flux at the neutrinosphere can be parametrised by: [Keil *et al.*, 2003]

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

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, 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)

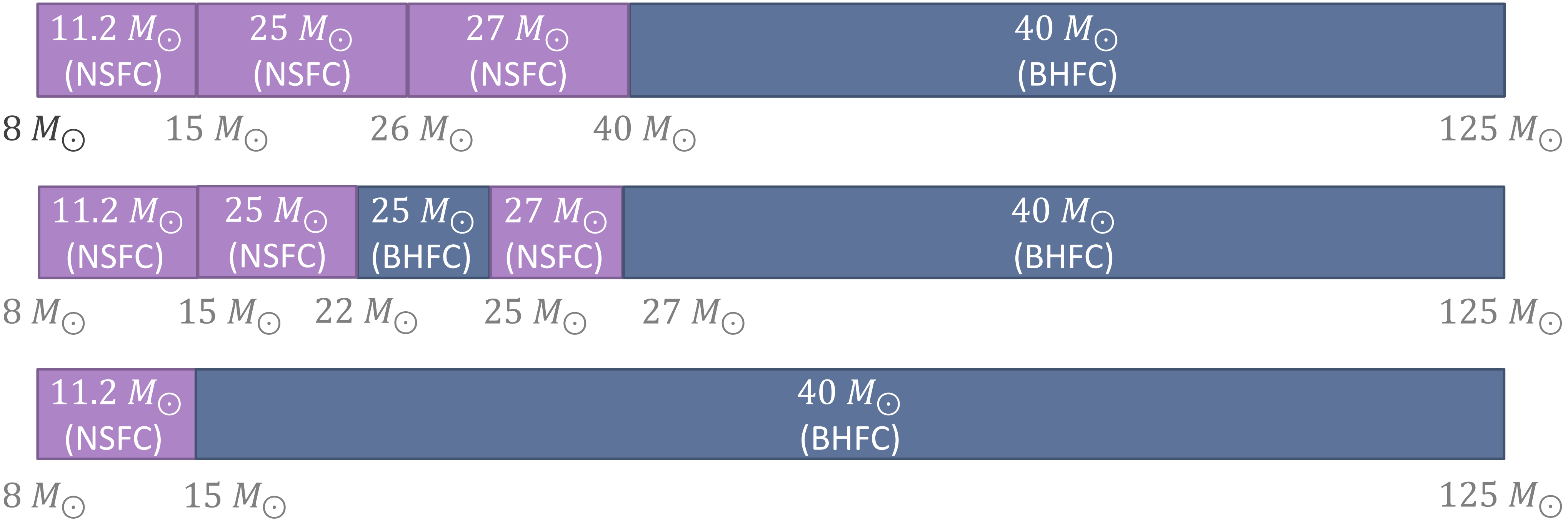
Contribution from Black Hole-Forming Collapses

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

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

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

- $f_{BH} = 0.09$
- $f_{BH} = 0.21$
  (Fiducial case)
- $f_{BH} = 0.41$



[Priya and Lunardini, 2017], [Møller et al., 2018] , [PIB and Volpe, 2023]

The Supernova Rate, $\dot{R}_{SN}(z, M)$

Supernova Rate (SNR) differential in progenitor mass:

$$\dot{R}_{SN}(z, M) = \dot{\rho}_*(z) \frac{\phi(M)}{\int_{0.5M_\odot}^{125M_\odot} M\,\phi(M)dM}$$

- $\dot{\rho}_*(z)$ is the Star Formation Rate
- $\phi(M) \sim M^\chi$ is the Salpeter Initial Mass Function (IMF) with $\chi = -2.35$ for $M \geq 0.5\ M_\odot$

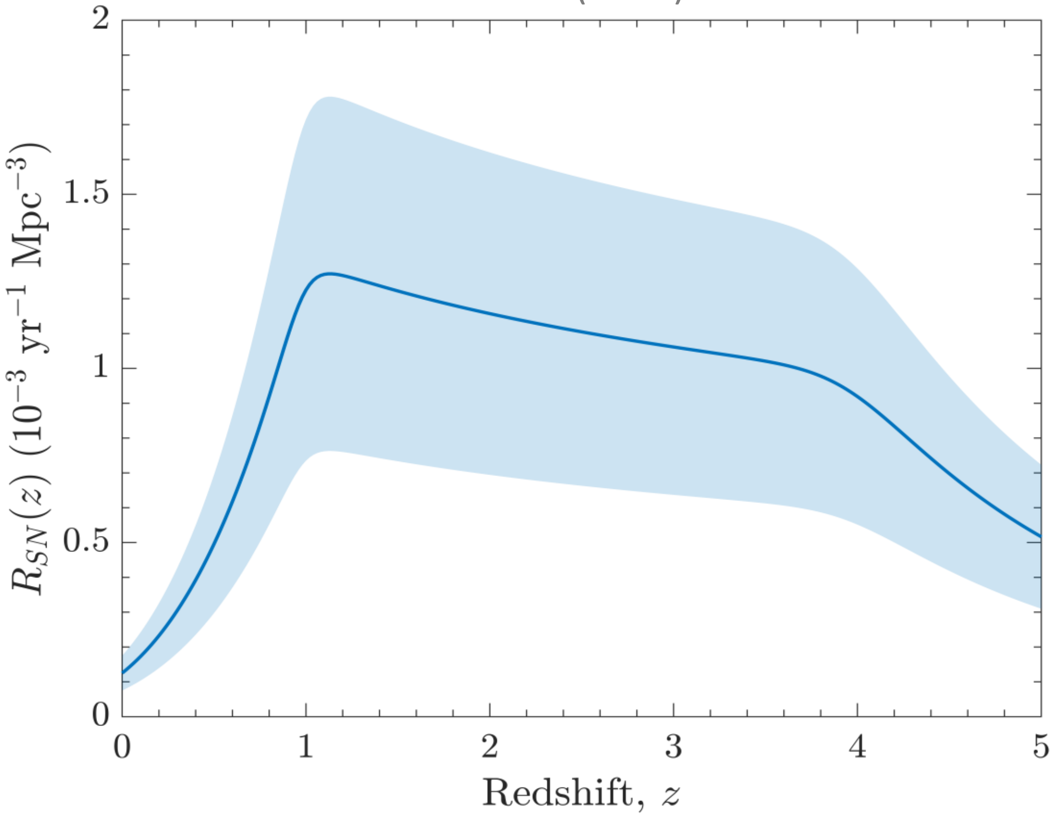
  $\phi(M)dM$ = number of stars in the interval $[M, dM]$

SNR normalisation is:

$$R_{SN}(0) = \int_{8M_\odot}^{125M_\odot} \dot{R}_{SN}(0, M)\, dM$$

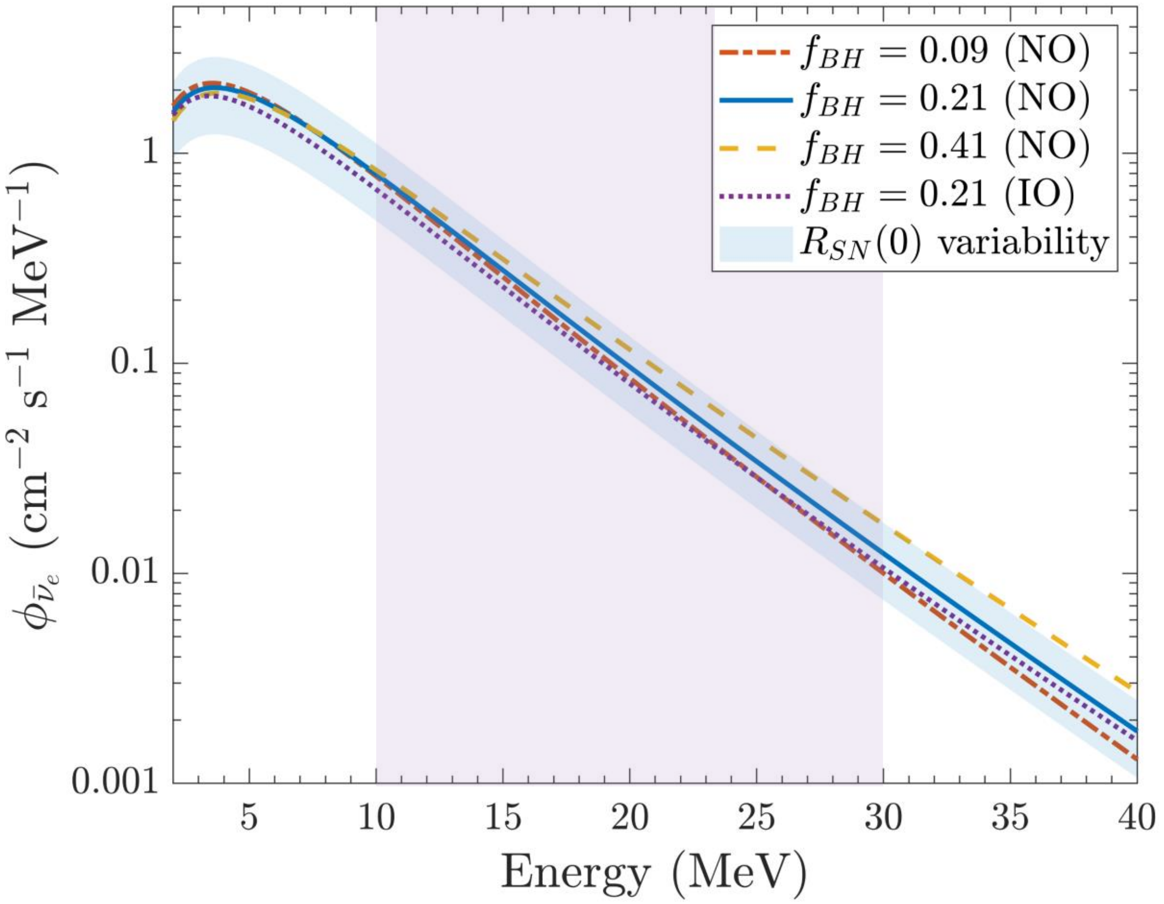
$$= (1.25 \pm 0.5) \times 10^{-4}\ \text{yr}^{-1}\text{Mpc}^{-3} \Longrightarrow$$

Supernova rate used in our work taking the SFR described in Yuksel *et al*. (2008).



In the figure, the band indicates the **uncertainty of the SNR normalisation** → impact DSNB normalisation

DSNB flux on Earth in absence of $\boldsymbol{\nu}$ 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.

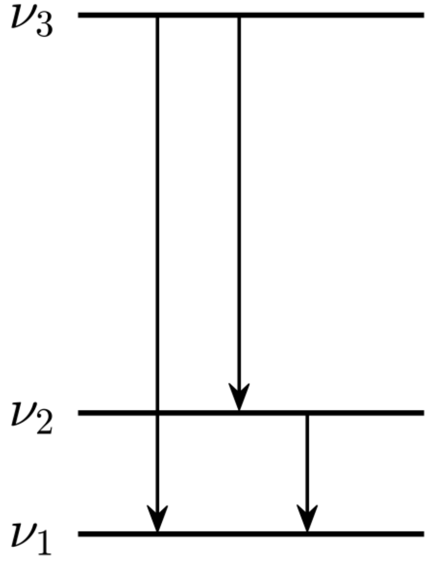
$$\phi_\nu(E) = \int_0^{z_{max}} \frac{dz}{H(z)} \int_{8\,M_\odot}^{125\,M_\odot} dM\, \dot{R}_{SN}(z, M) F_\nu(E', M)$$

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

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
$\bar{\boldsymbol{\nu}}_{\boldsymbol{e}}$ ($E_\nu > 17.3$ MeV)	0.77 ± 0.30 [1.02 ± 0.41]	0.63 ± 0.25 [0.75 ± 0.3]	2.6 (SK) [Abe *et al.*, 2021]
$\boldsymbol{\nu}_{\boldsymbol{e}}$ ($22.9 < E < 36.9$ MeV)	0.20 ± 0.08 [0.24 ± 0.09]	0.18 ± 0.08 [0.23 ± 0.09]	19 (SNO) [Aharmin *et al.*, 2006]

Neutrino decay



Previous studies:

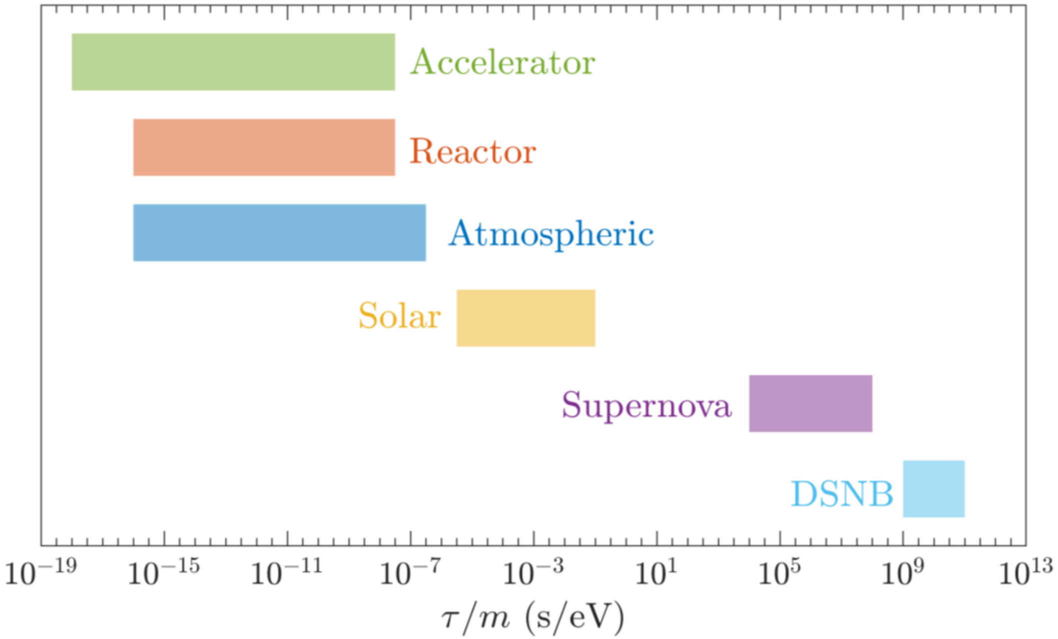
- **Fogli et al. (2004):** three-flavour decay but without detailed astrophysical ingredients
  - e.g.: progenitor dependence and normalisation uncertainty
- **de Gouvêa et al. (2020), Tabrizi and Horiuchi (2021):** two-flavour approximation and only considered one mass pattern (NO).

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



DSNB has unique sensitivity to this decay in the range:

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

Sensitivities to the lifetime-to-mass ratio, τ/m, of different neutrino experiments.
Figure adapted from Fig. 1 of Picoreti *et al.* (2022).

DSNB flux in the presence of decay

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

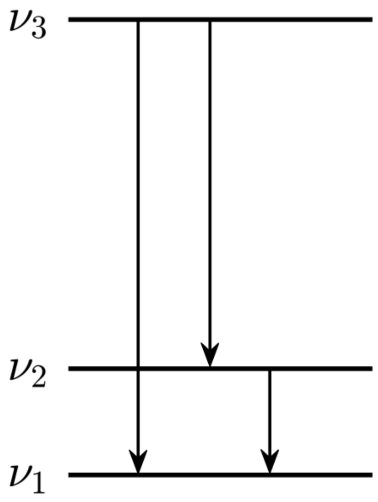
[Fogli *et al.*, 2004]

ν_i flux from core-collapses — decay of ν_j into ν_i

$$\phi_{\nu_i}(E,z) = \frac{1}{1+z}\int_z^{z_{max}} \frac{dz'}{H(z')}\left[R_{SN}(z')F_{\nu_i}\left(E\frac{1+z'}{1+z}\right) + \sum_{m_j>m_i} q_{ji}\left(E\frac{1+z'}{1+z}, z'\right)\right]$$

$$\times\, e^{-m_i\Gamma_i[\xi(z')+\xi(z)](1+z)/E}$$

ν_i decay into lighter neutrinos



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

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

Mass patterns: two extreme cases

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

Quasi-degenerate (QD) masses

$$\boldsymbol{m_j \simeq m_i \gg \Delta m}$$

- $\psi_{\nu_j \to \nu_i}(E_j, E_i) = \delta(E_j - E_i)$
- $\psi_{\nu_j \to \bar{\nu}_i}(E_j, E_i) = 0$

Strongly Hierarchical (SH) masses

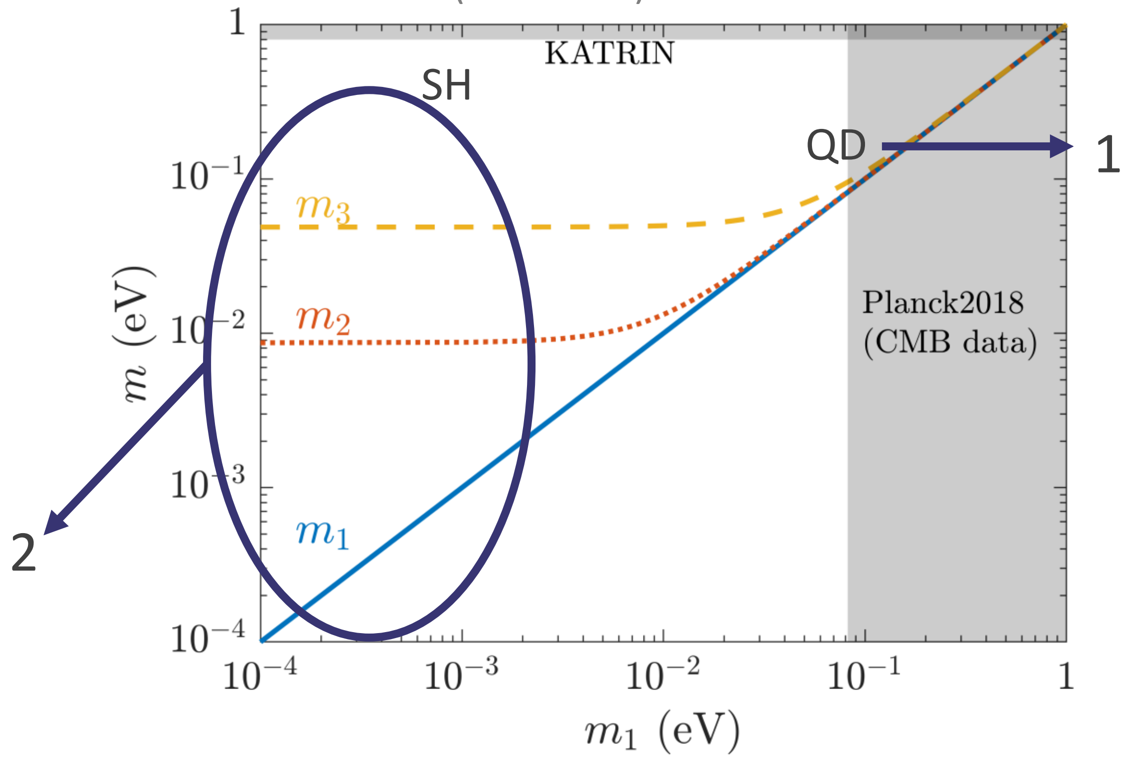
$$\boldsymbol{m_j \gg m_i \simeq 0}$$

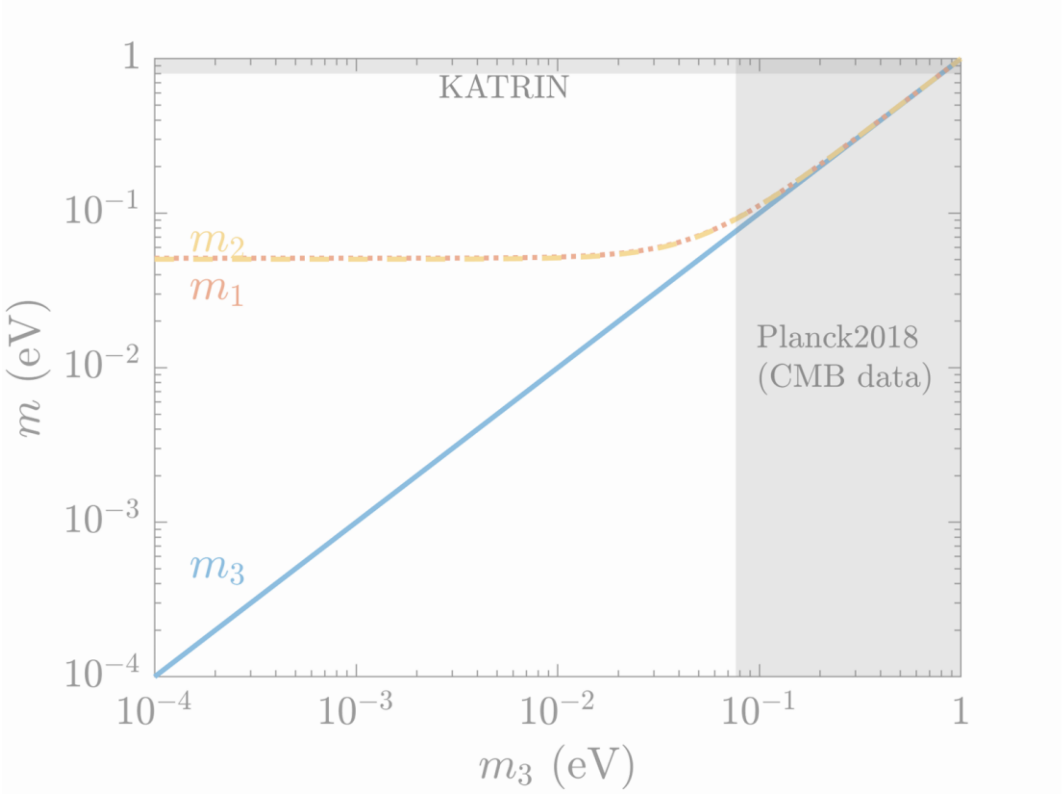
- $\psi_{\nu_j \to \nu_i}(E_j, E_i) = \frac{2E_i}{E_j^2}$
- $\psi_{\nu_j \to \bar{\nu}_i}(E_j, E_i) = \frac{2}{E_j}\left(1 - \frac{E_i}{E_j}\right)$

* $\psi_{\nu_j \to \nu_i}(E_j, E_i) = \text{Prob}[\nu_j(E_j) \to \nu_i(E_i)]$

Mass patterns

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





NORMAL ORDERING:

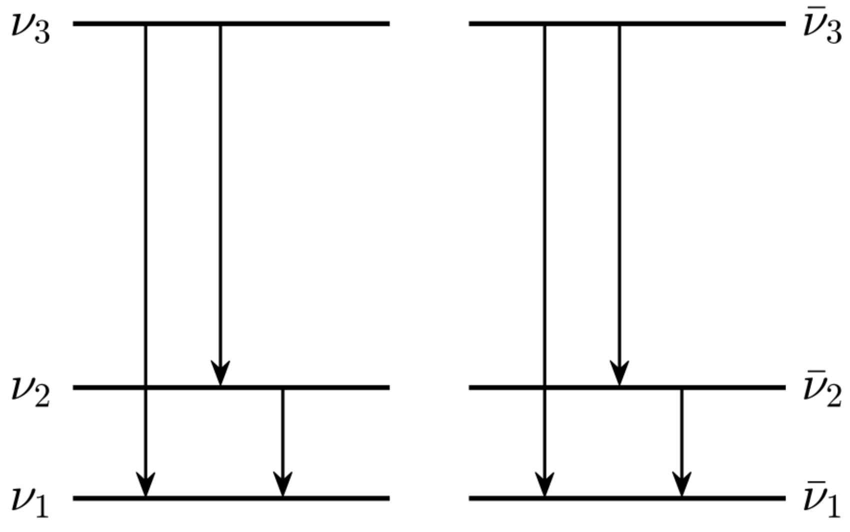
1. **QD** $\Longrightarrow m_1 \simeq m_2 \simeq m_3 \gg \Delta m_{ij}$
2. **SH** $\Longrightarrow m_3 \gg m_2 \gg m_1 \simeq 0$

INVERTED ORDERING:

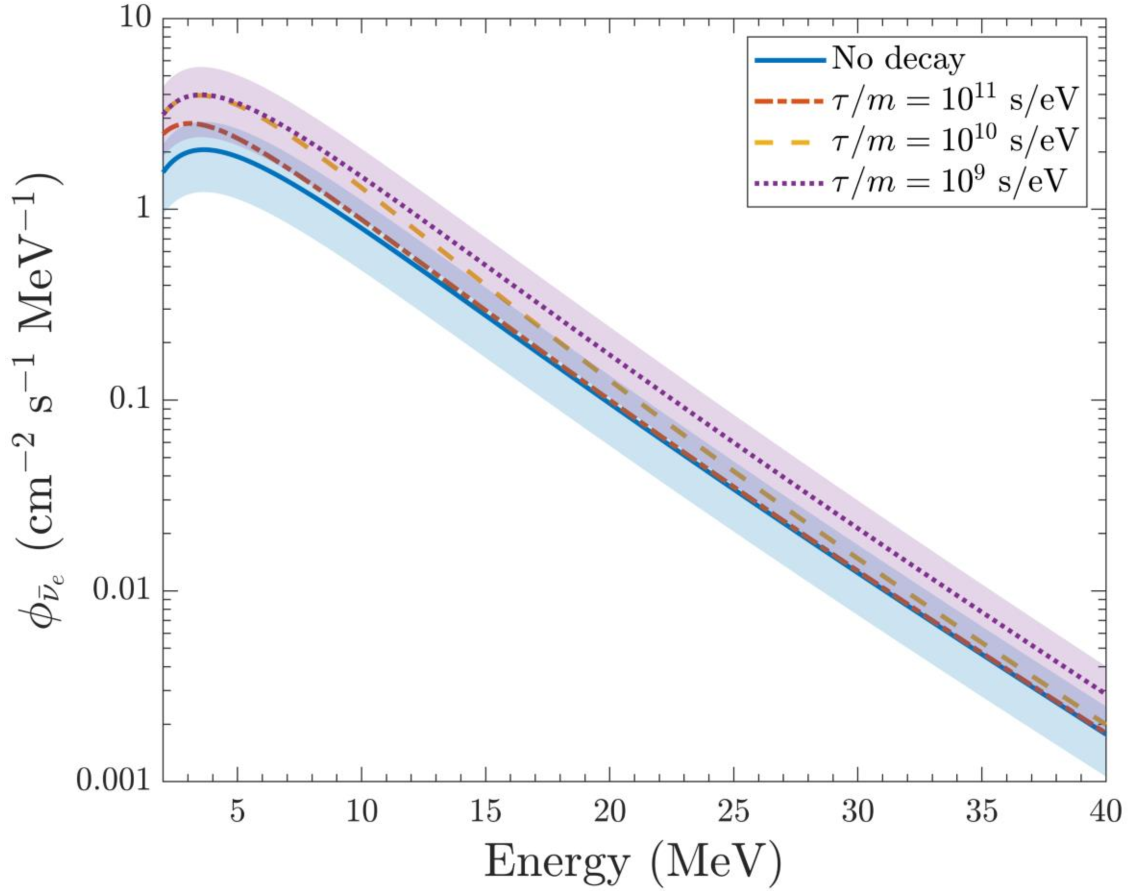
- QD $\Longrightarrow m_1 \simeq m_2 \gg \Delta m_{21}$
- SH $\Longrightarrow m_{1,2} \gg m_3 \simeq 0$

DSNB flux with $\boldsymbol{\nu}$ decay: results for NO, QD case

Decay pattern for NO and QD masses.



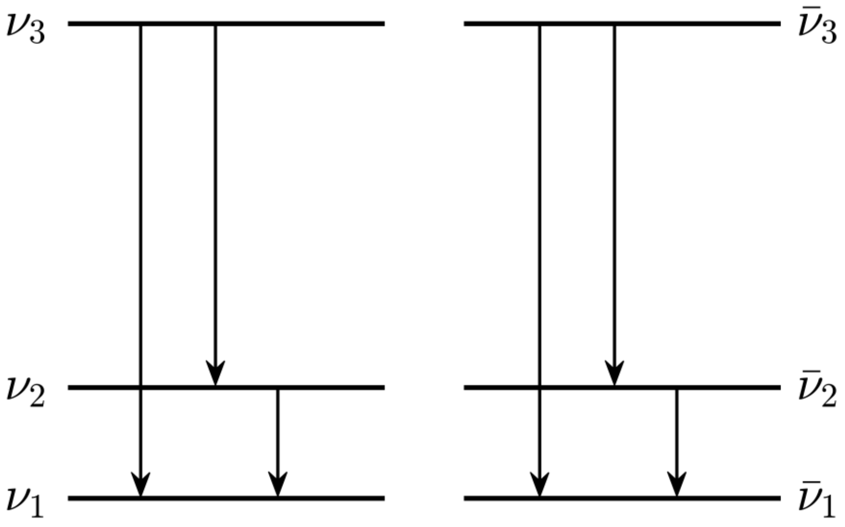
- $\boldsymbol{\tau_3/m_3 = \tau_2/m_2 = \tau/m}$
- $B(\nu_3 \to \nu_2) = B(\nu_3 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_1) = 1$



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.

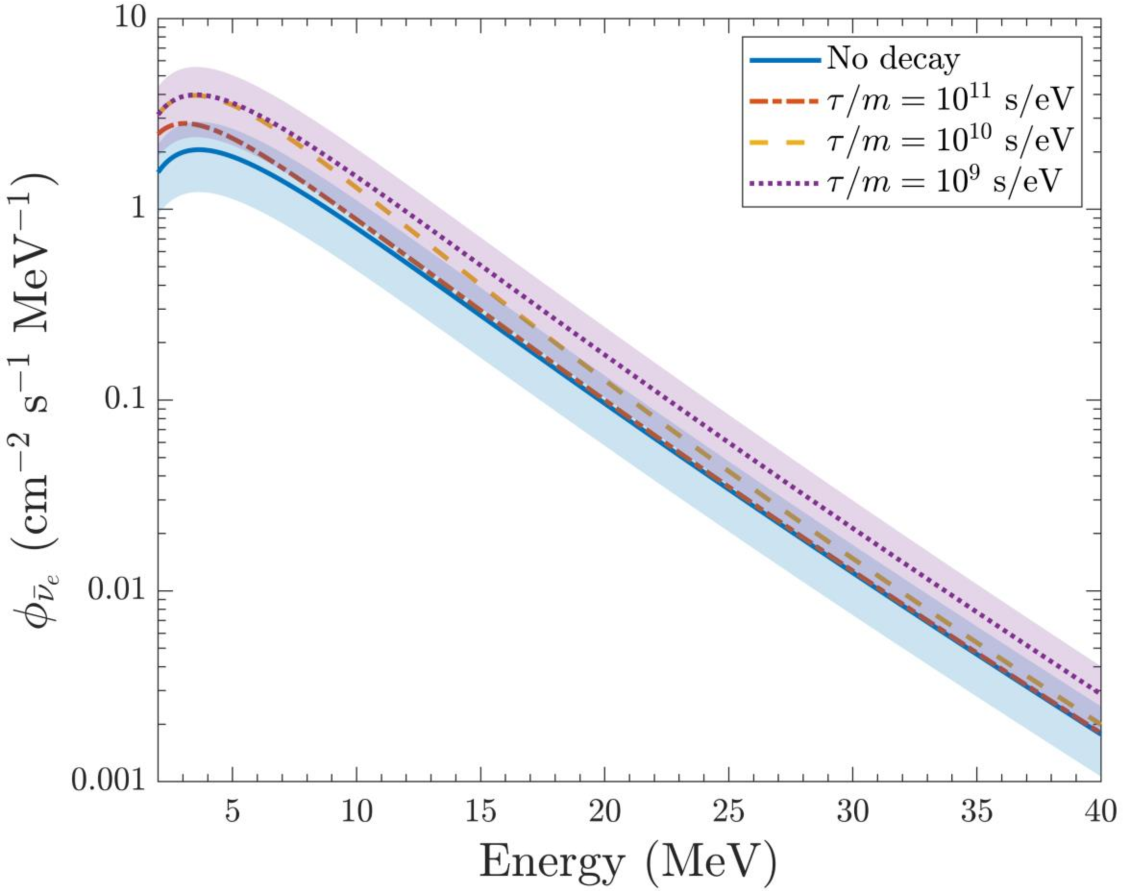
DSNB flux with $\boldsymbol{\nu}$ decay: results for NO, QD case

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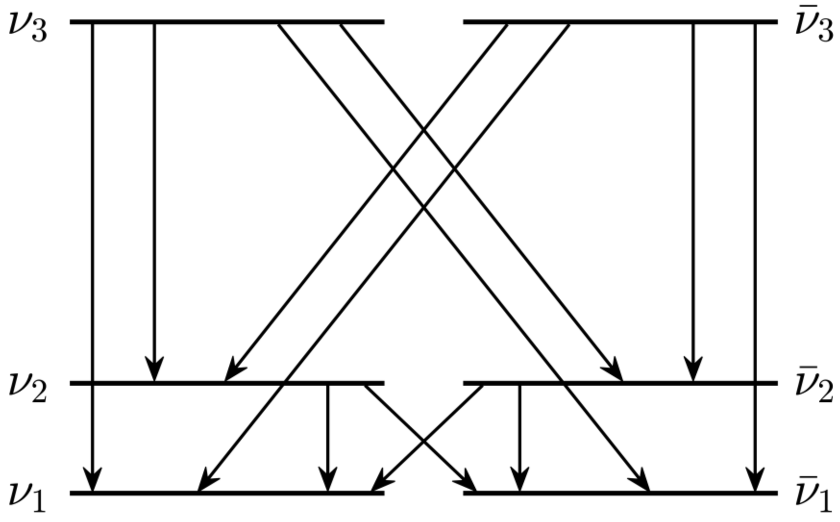
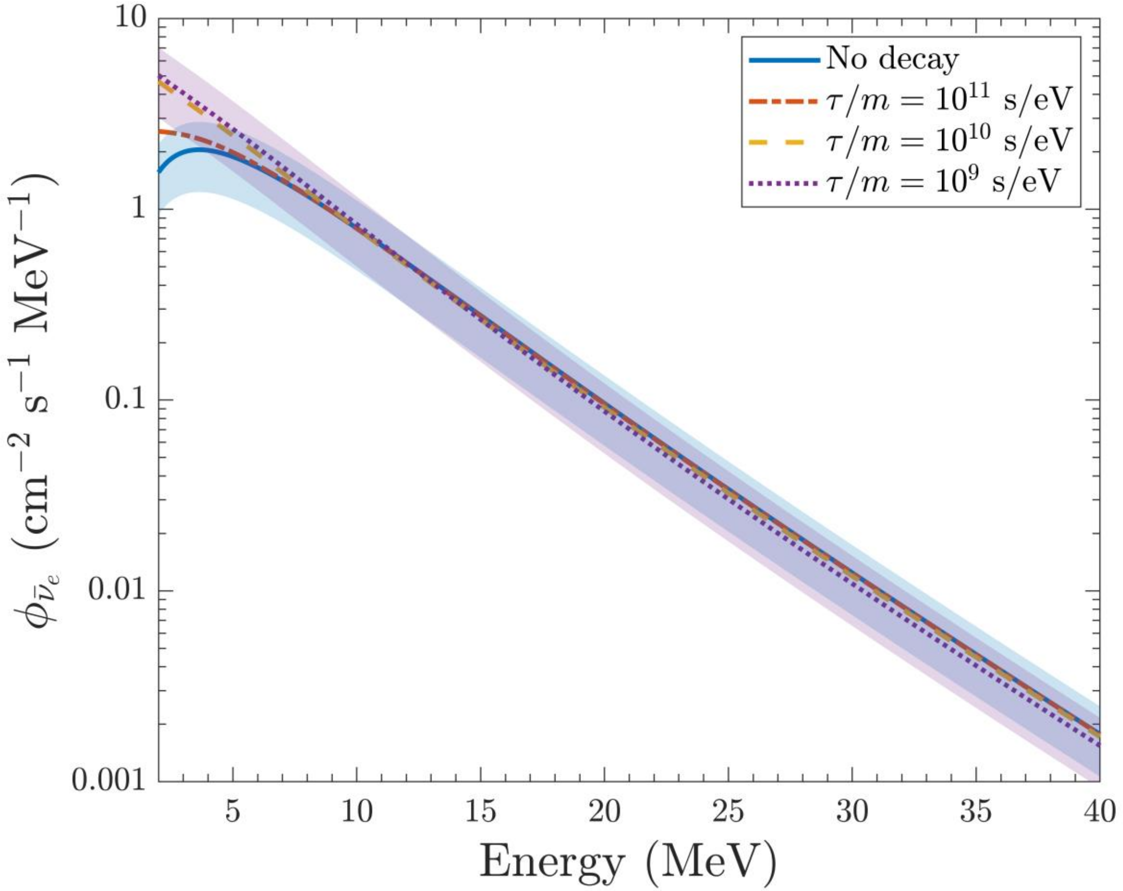
DSNB flux with ν decay: results for NO, SH case

Decay pattern for NO and SH masses.



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



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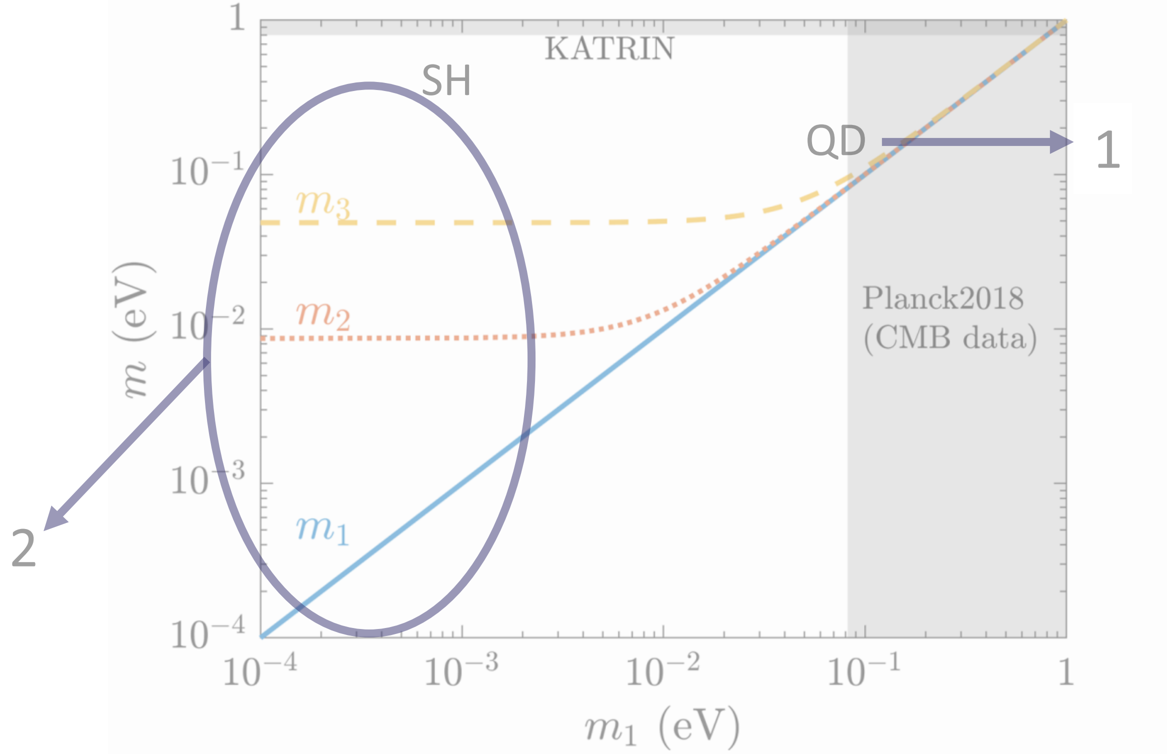
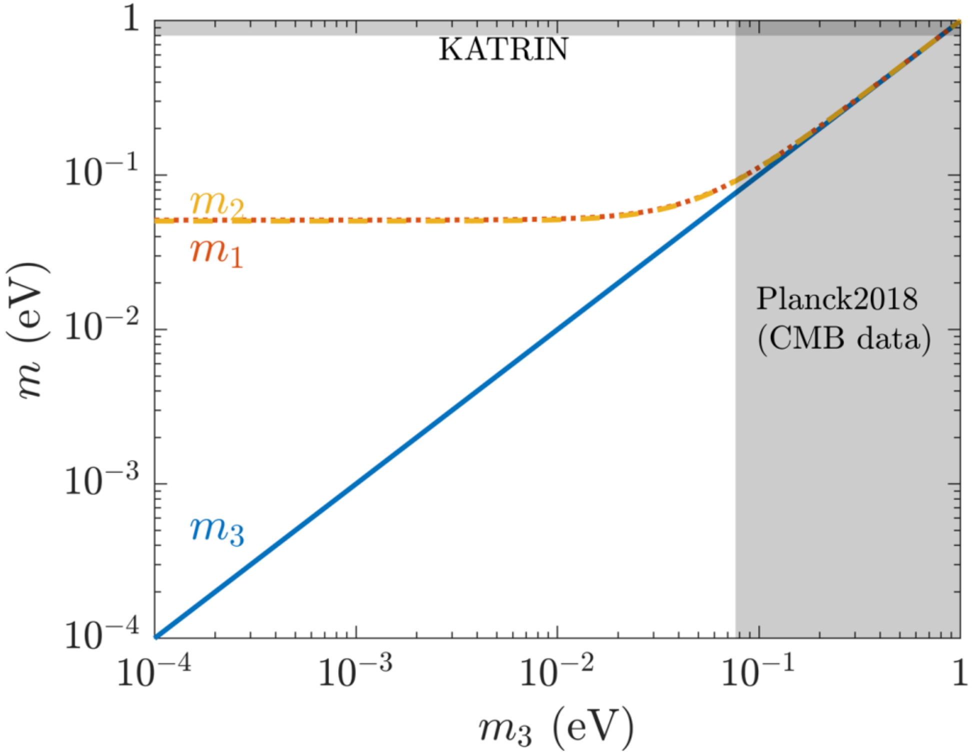
Mass patterns

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





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INVERTED ORDERING:

- **QD** $\Longrightarrow m_1 \simeq m_2 \gg \Delta m_{21}$
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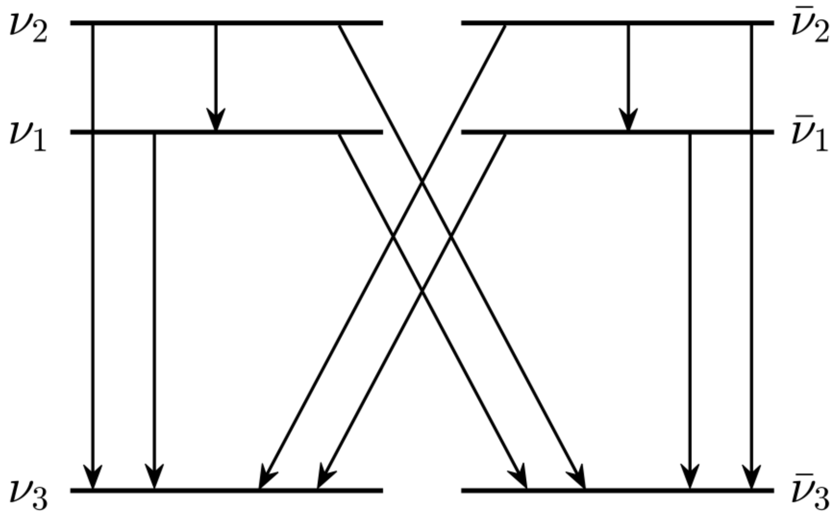
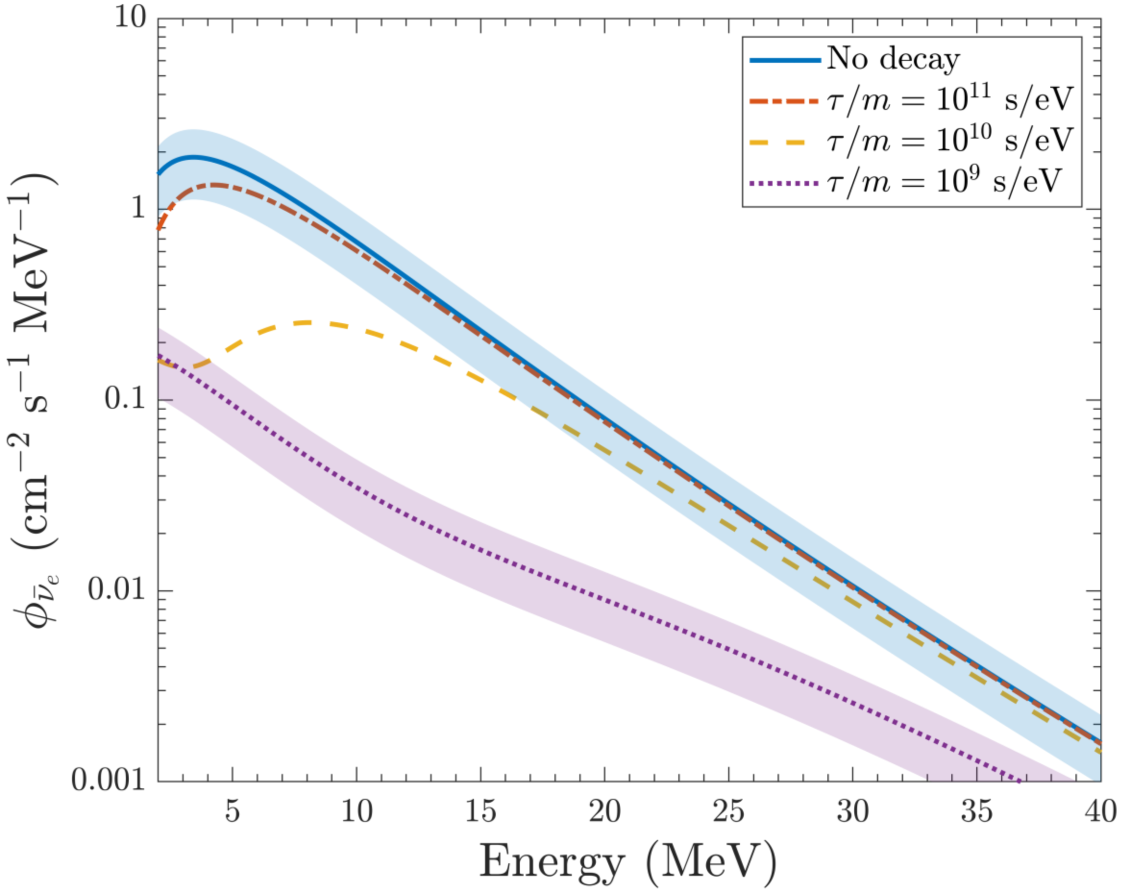
DSNB flux with ν decay: results for IO case

Decay pattern for IO.



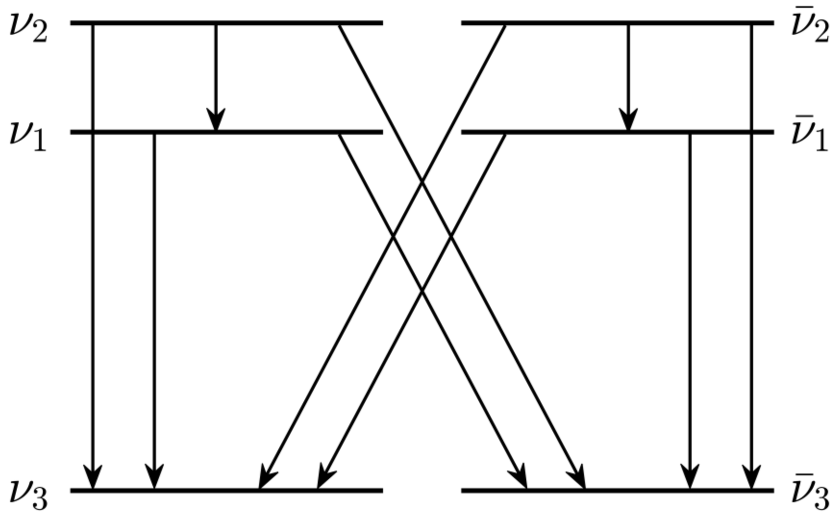
- $\tau_1/m_1 = \tau_2/m_2 = \tau/m$
- $B(\nu_2 \to \nu_1) = \frac{1}{2}$
- $B(\nu_2 \to \nu_3) = B(\nu_2 \to \bar{\nu}_3) = \frac{1}{4}$
- $B(\nu_1 \to \nu_3) = B(\nu_1 \to \bar{\nu}_3) = \frac{1}{2}$



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 $\boldsymbol{\nu}$ decay: results for IO case

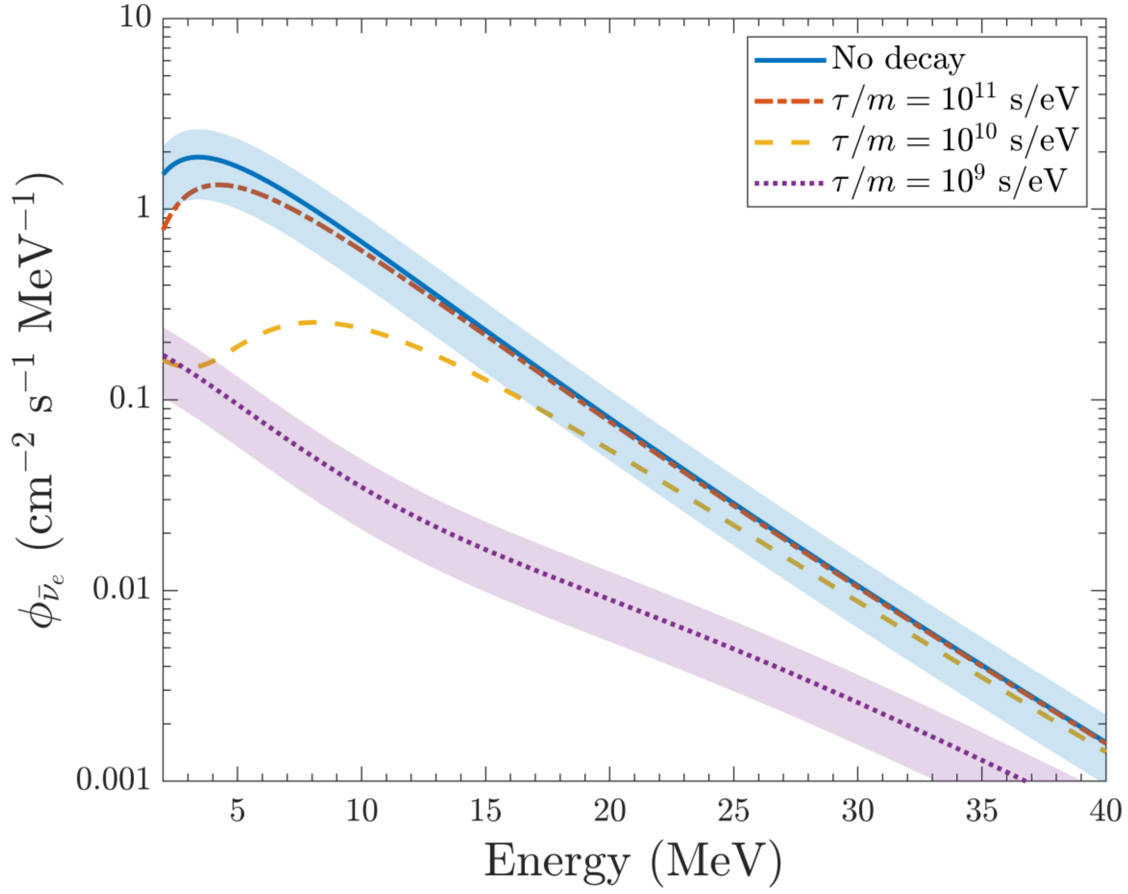
Decay pattern for IO.



<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.

Predictions of the DSNB with/without decay

Detection of the DSNB

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

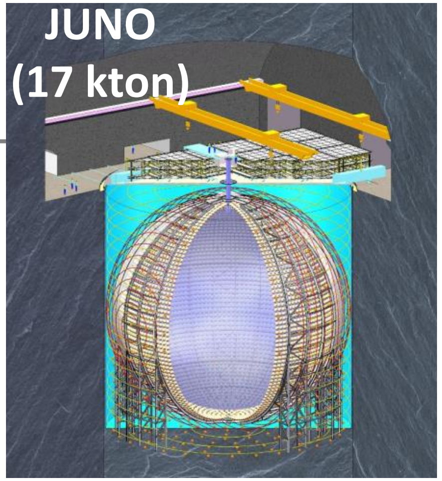
$$\bar{\nu}_e + p \rightarrow n + e^+$$

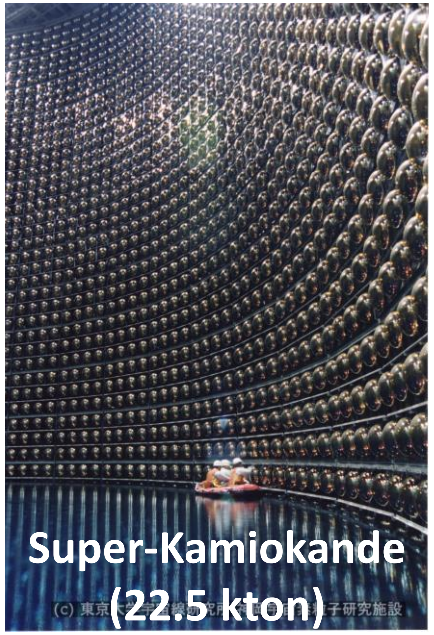
  - **Super-Kamiokande + Gd, Hyper-Kamiokande, JUNO**
  - Backgrounds: reactor $\bar{\nu}_e$ (low energies) and atmospheric ν (high energies)

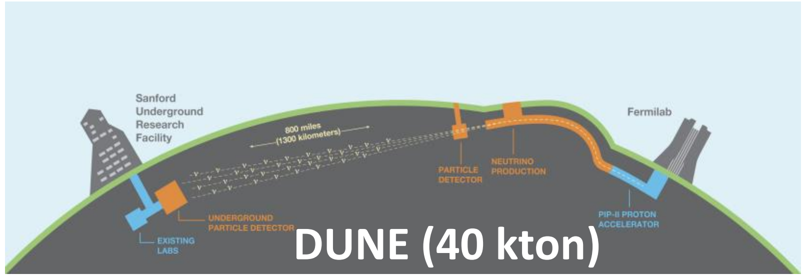
- Detection of ν_e flux → **neutrino absorption in ^{40}Ar**

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

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



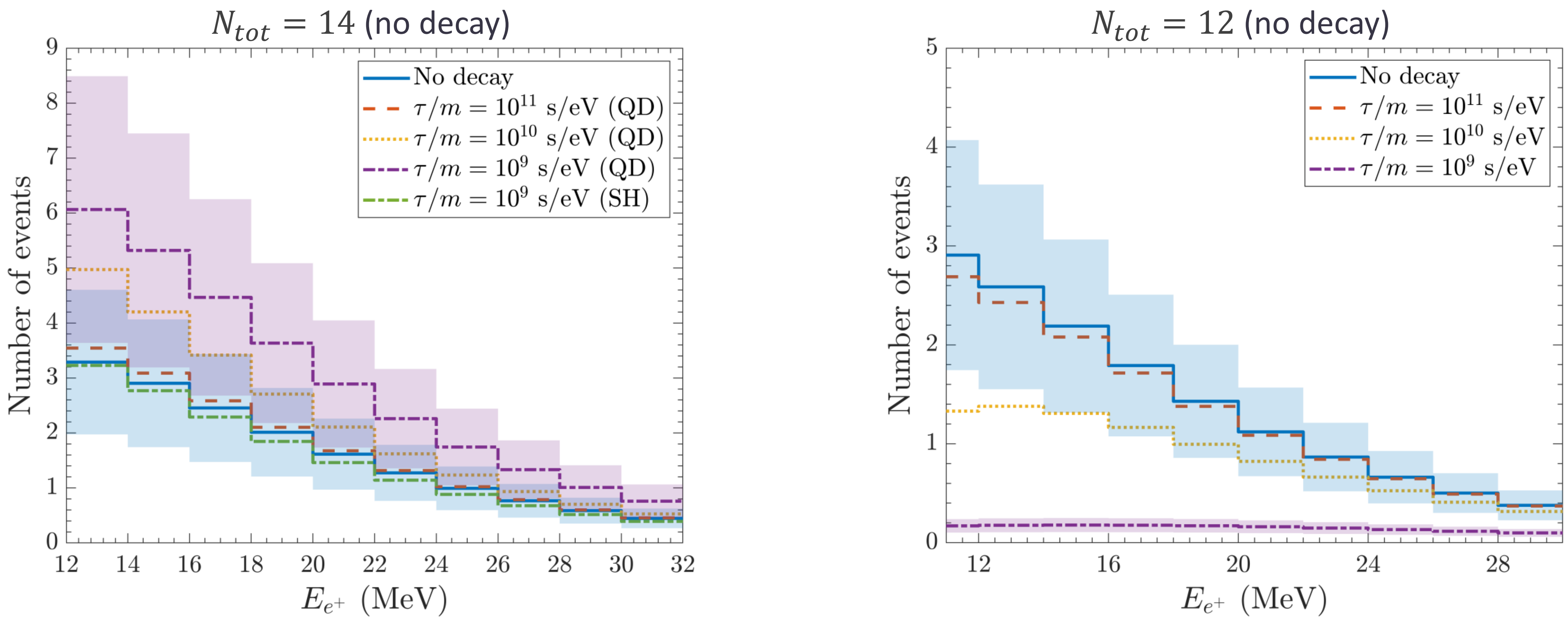




Events at SK-Gd

<u>Fiducial Volume</u>: 22.5 kton
<u>Gd concentration</u>:
0.01% (Phase I), 0.03% (Phase II), 0.1% (Phase III)

NORMAL ORDERING: **INVERTED ORDERING:**



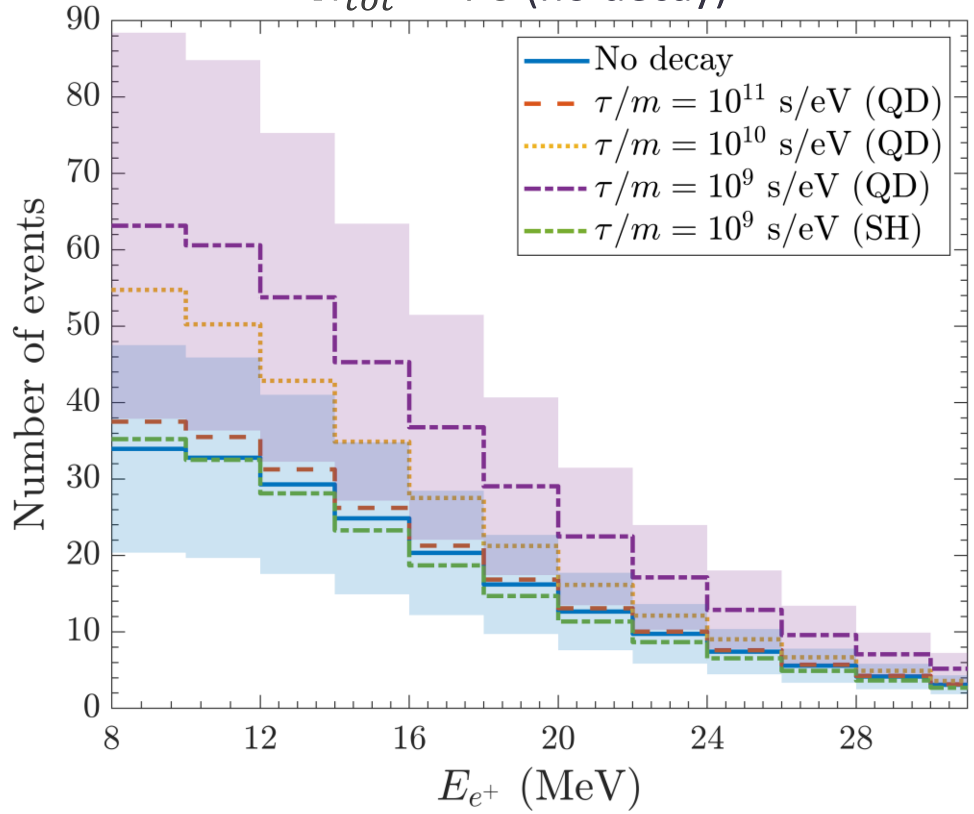
Expected number of events after **10 years of exposure at SK-Gd**. The experimental window is $\mathbf{12.8 \leq E_\nu \leq 30.8}$ **MeV**. The bands represent the uncertainty of the SNR normalisation.

Events at Hyper-Kamiokande + Gd

Fiducial Volume: 187 kton

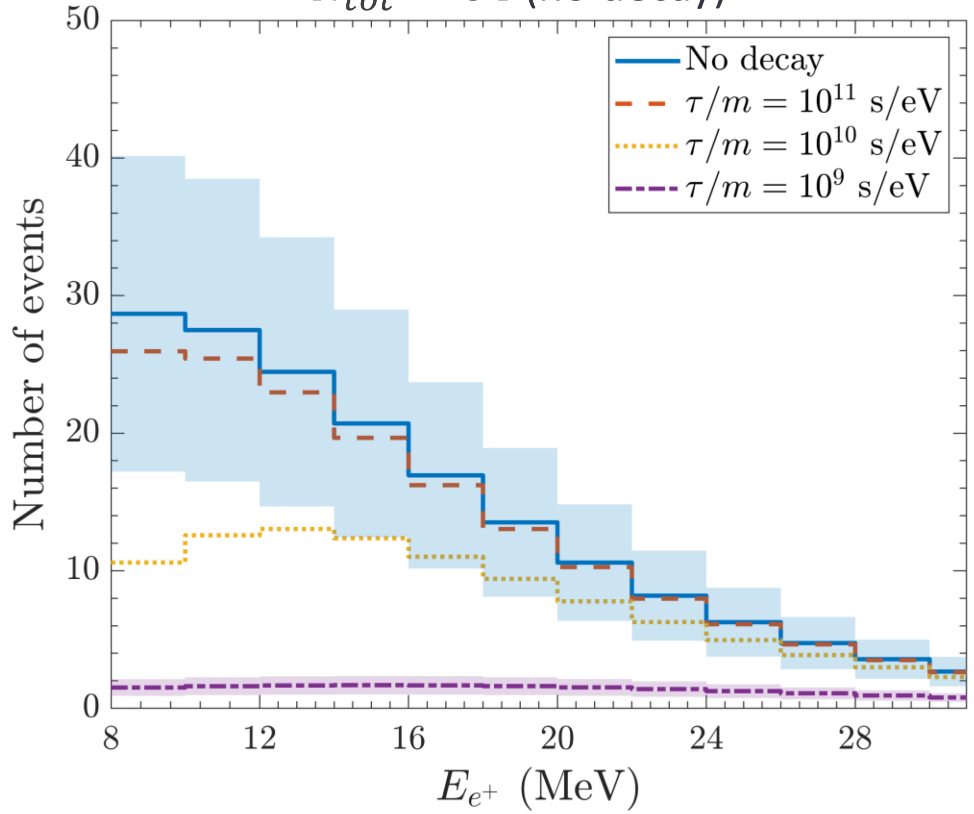
NORMAL ORDERING:

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



INVERTED ORDERING:

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



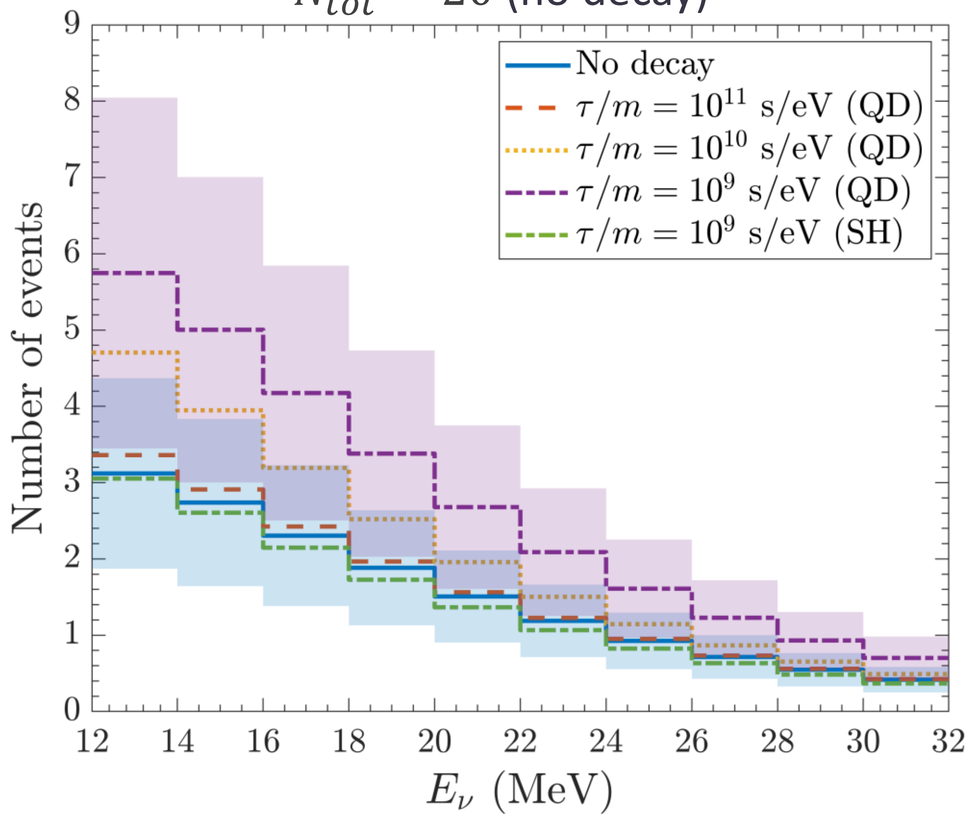
Expected number of events after **20 years of exposure at HK-Gd**. The experimental window is $\mathbf{17.3 \leq E_\nu \leq 31.3}$ **MeV**. The bands represent the uncertainty of the SNR normalisation.

Events at JUNO

Fiducial Volume: 17 kton

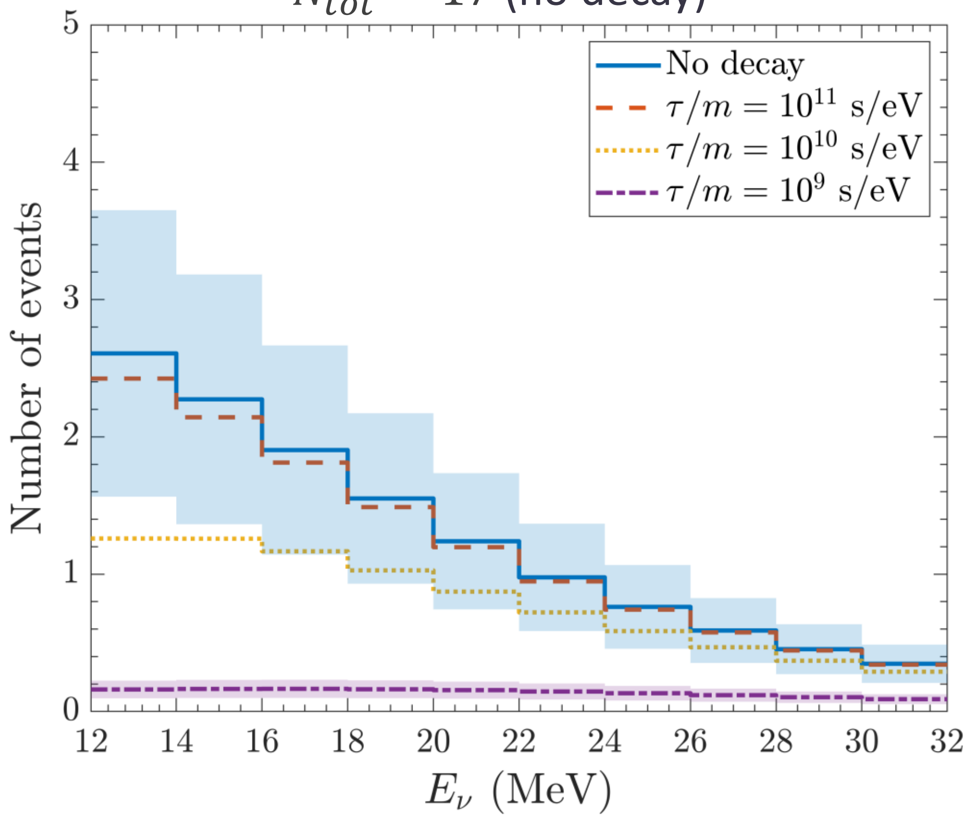
NORMAL ORDERING:

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



INVERTED ORDERING:

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



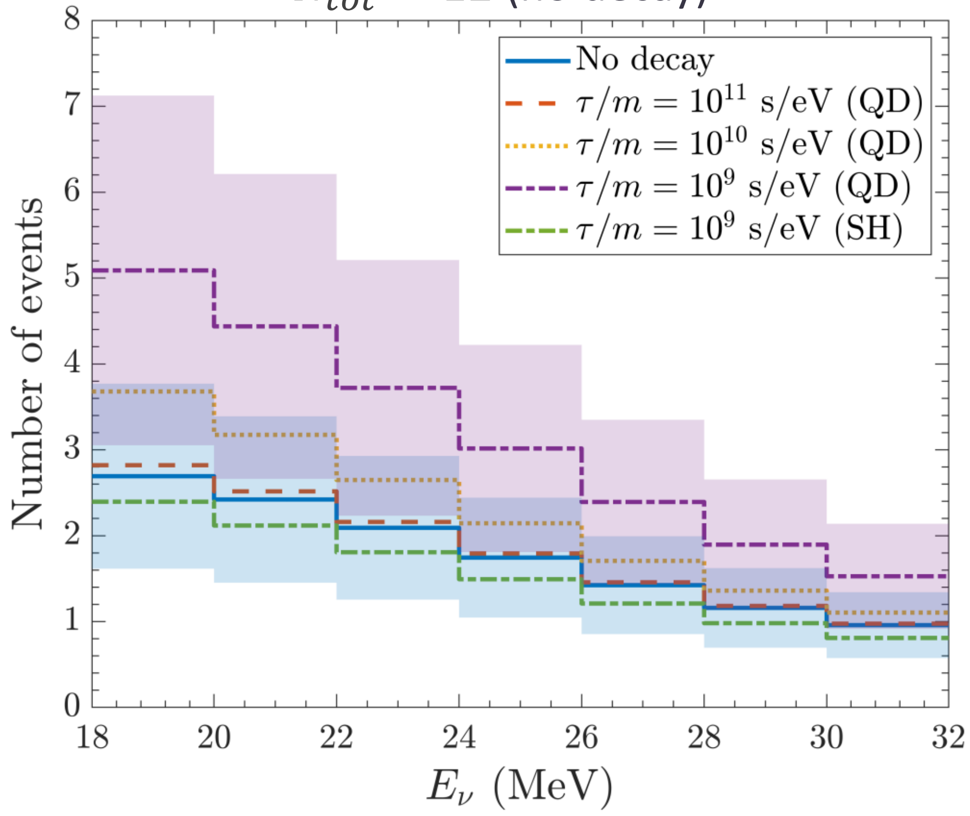
Expected number of events after **20 years of exposure at JUNO**. The experimental window is $\mathbf{11.3 \leq E_\nu \leq 33.3}$ **MeV**. The bands represent the uncertainty of the SNR normalisation.

Events at DUNE

<u>Fiducial Volume</u>: 40 kton

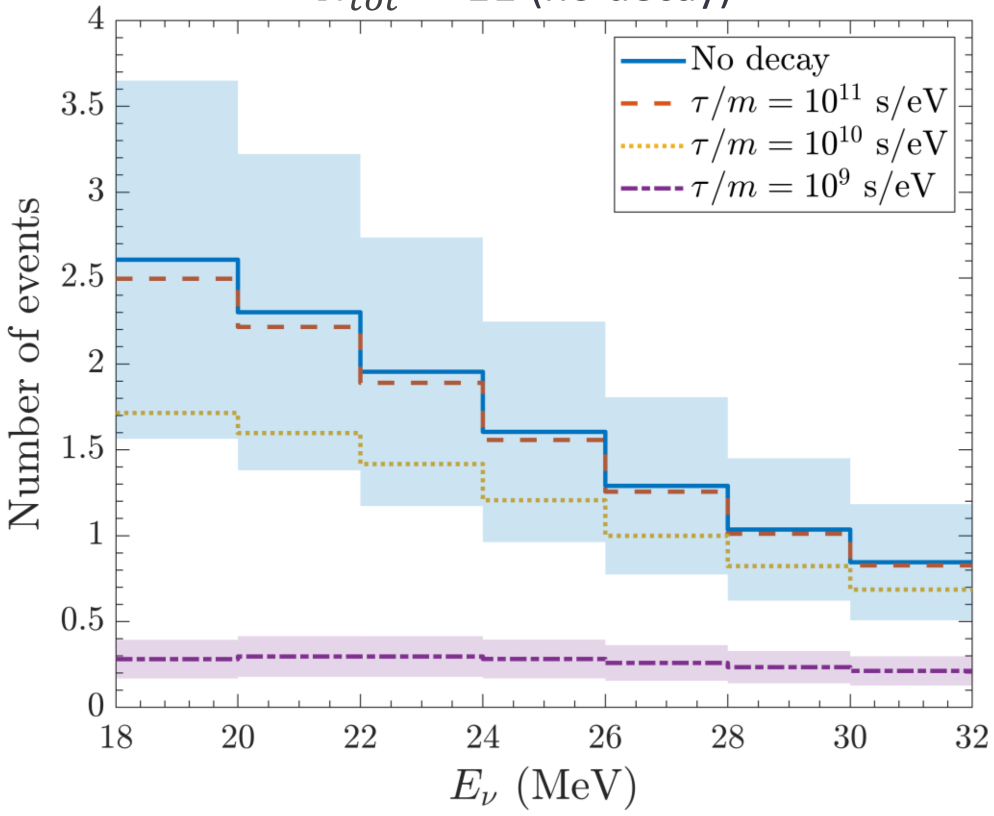
NORMAL ORDERING:

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



INVERTED ORDERING:

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



Expected number of events after **20 years of exposure at DUNE**. The experimental window is $\mathbf{19 \leq E_\nu \leq 31}$ **MeV**. The bands represent the uncertainty of the SNR normalisation.

Main results and conclusions

First investigation of non-radiative 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

Thank you for your attention

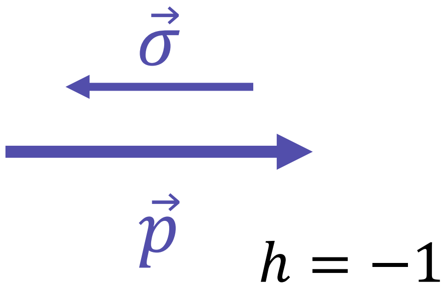
BACK UP SLIDES

QD case: why ν cannot decay into $\bar{\nu}$?

INITIAL STATE:

$$\nu_h \to \nu_{h_L} = \nu_{h(-)} + \mathcal{O}\left({}^{m}/_{E}\right)\ \nu_{h(+)}$$

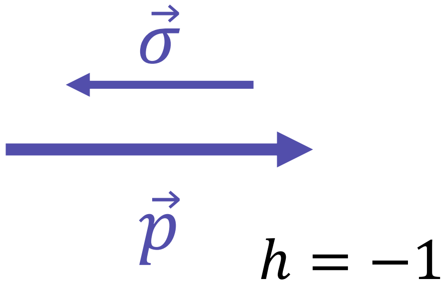
ν_h:



FINAL STATE:

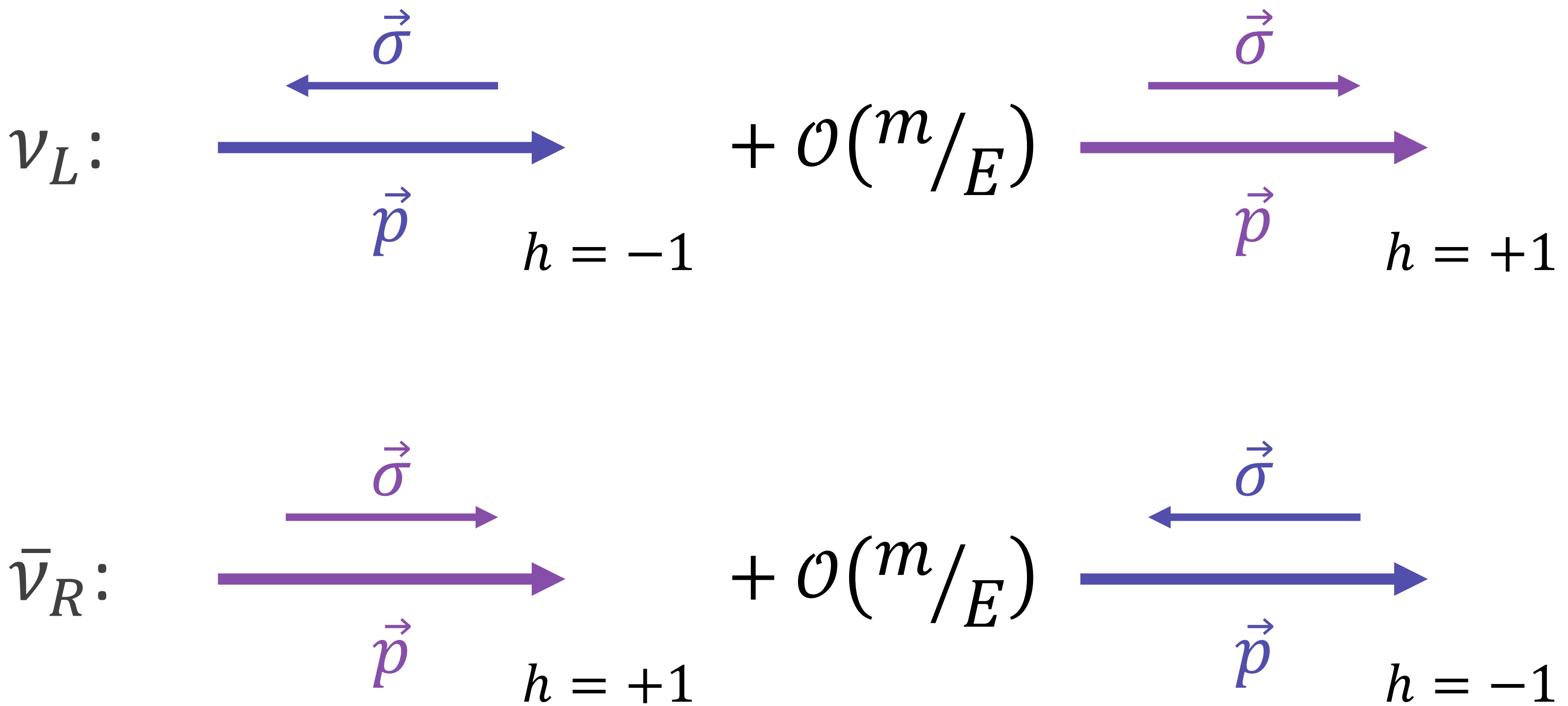
$$\nu_l\ (\bar{\nu}_l) + X$$

- Since $m_h \simeq m_l \Longrightarrow \nu_l\ (\bar{\nu}_l)$ emitted in the forward direction
- Daughter neutrino:

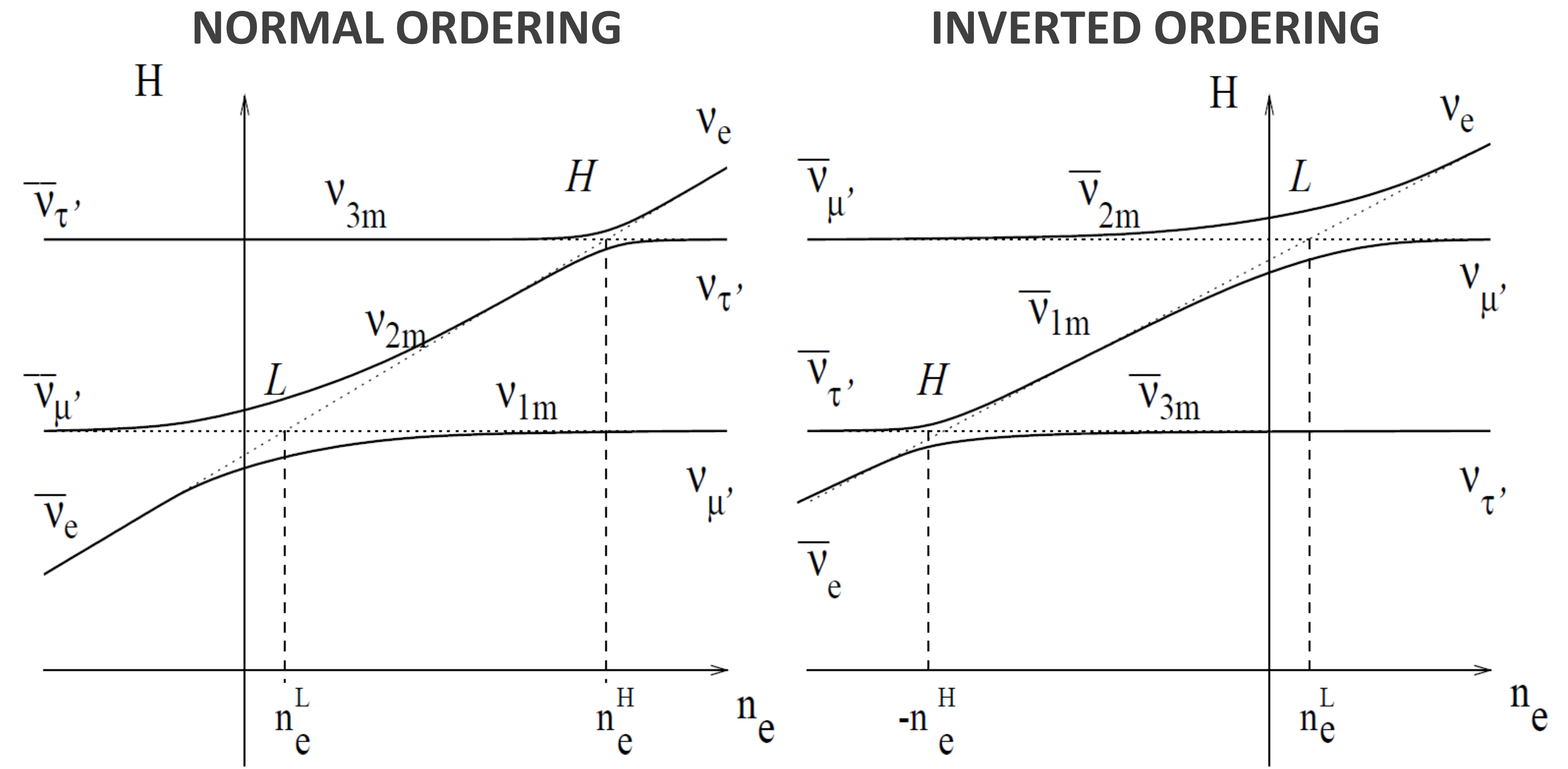


$$\begin{cases} \nu_l \to \nu_{l_L} = \nu_{h(-)} + \mathcal{O}\left({}^{m}/_{E}\right)\ \nu_{h(+)} \\ \bar{\nu}_l \to \bar{\nu}_{l_R} = \nu_{h(+)} + \mathcal{O}\left({}^{m}/_{E}\right)\ \nu_{h(-)} \end{cases}$$

Neutrinos: chirality and helicity



MSW effect:



Level crossing diagrams. Solid lines represent the eigenvalues of the effective Hamiltonian as function of the electron number density. Figure taken from Dighe and Smirnov (1999).

Number of events

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

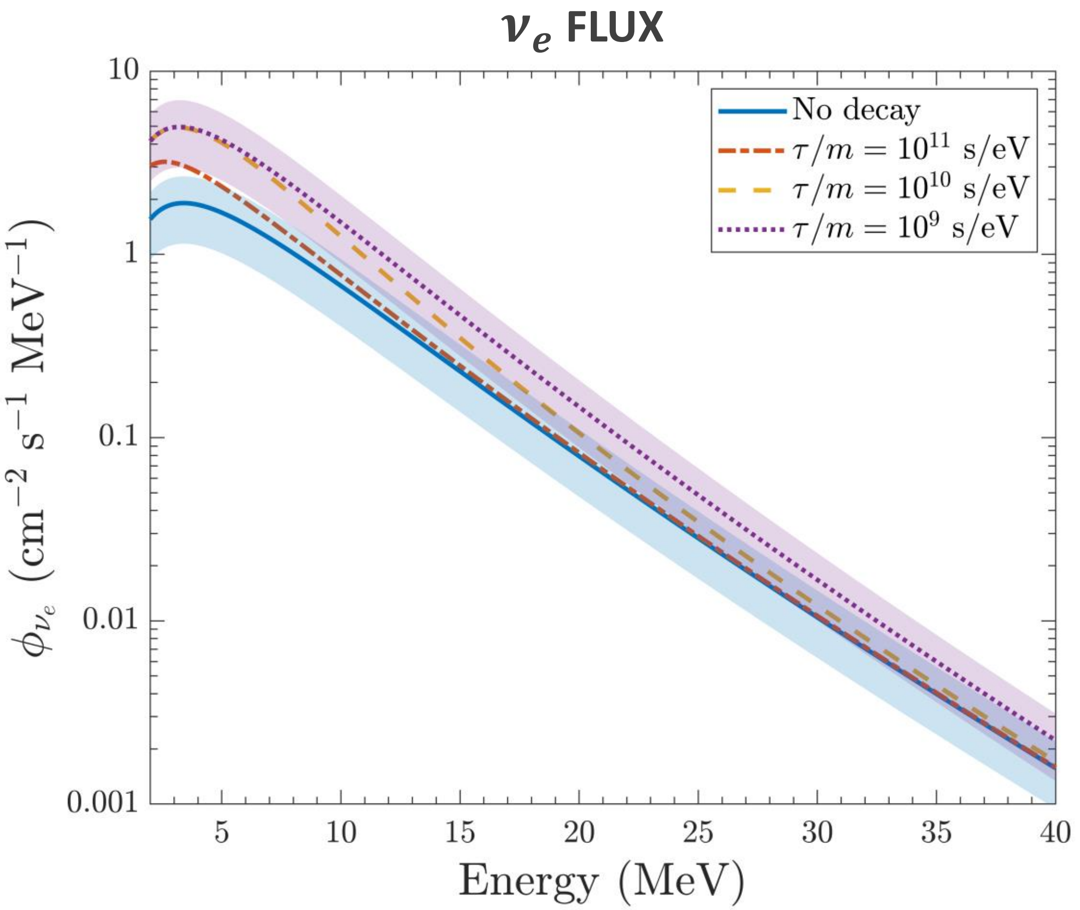
Properties of the experiments considered and total number of events in the absence of decay in NO (IO).

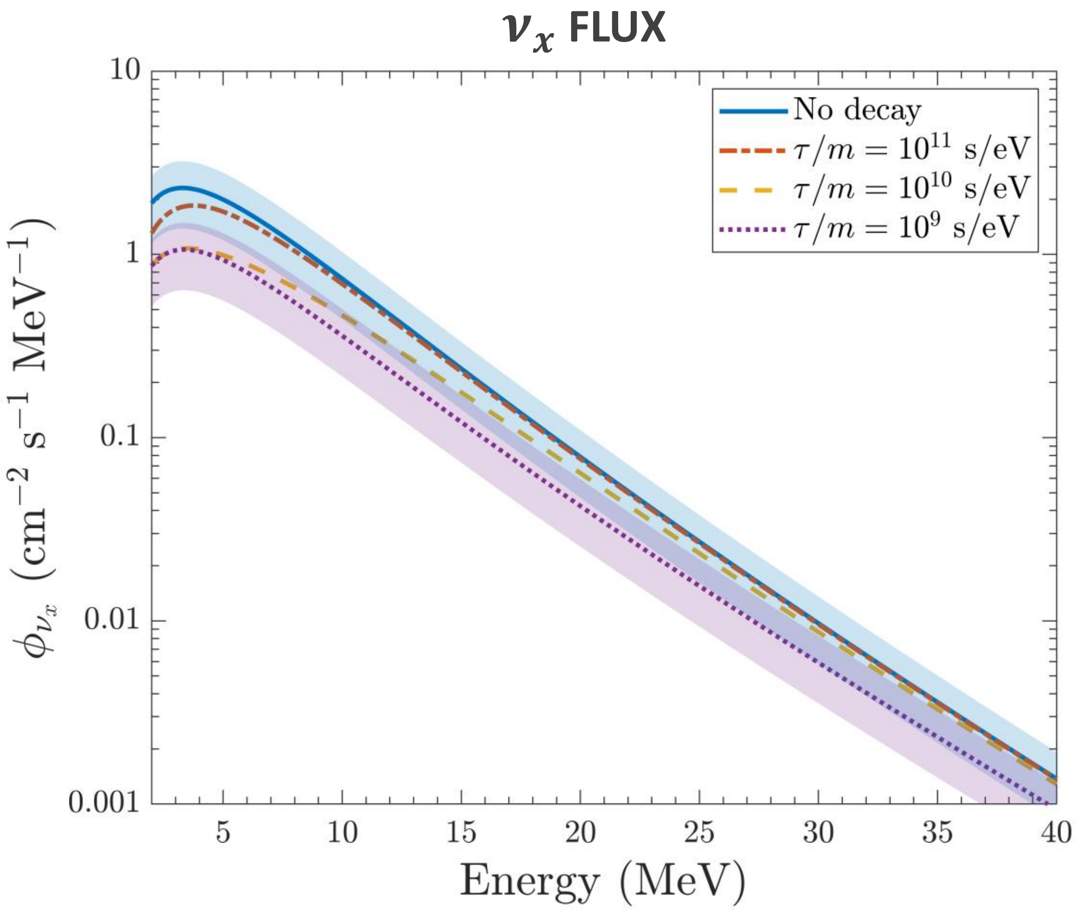
	N_t (10^{33})	ϵ (%)	Time (years)	DSNB window (MeV)	DSNB events
SK-Gd	1.5	57.5	2	(12.8, 30.8)	2 (2) $\bar{\nu}_e$
SK-Gd	1.5	73.75	8	(12.8, 30.8)	12 (10) $\bar{\nu}_e$
HK	12.5	25	20	(17.3, 31.3)	48 (40) $\bar{\nu}_e$
HK-Gd	12.5	40	20	(17.3, 31.3)	76 (64) $\bar{\nu}_e$
JUNO	1.21	50	20	(11.3, 33.3)	20 (17)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

Experiment	Number of events: 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 $\nu_e - ^{40}$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

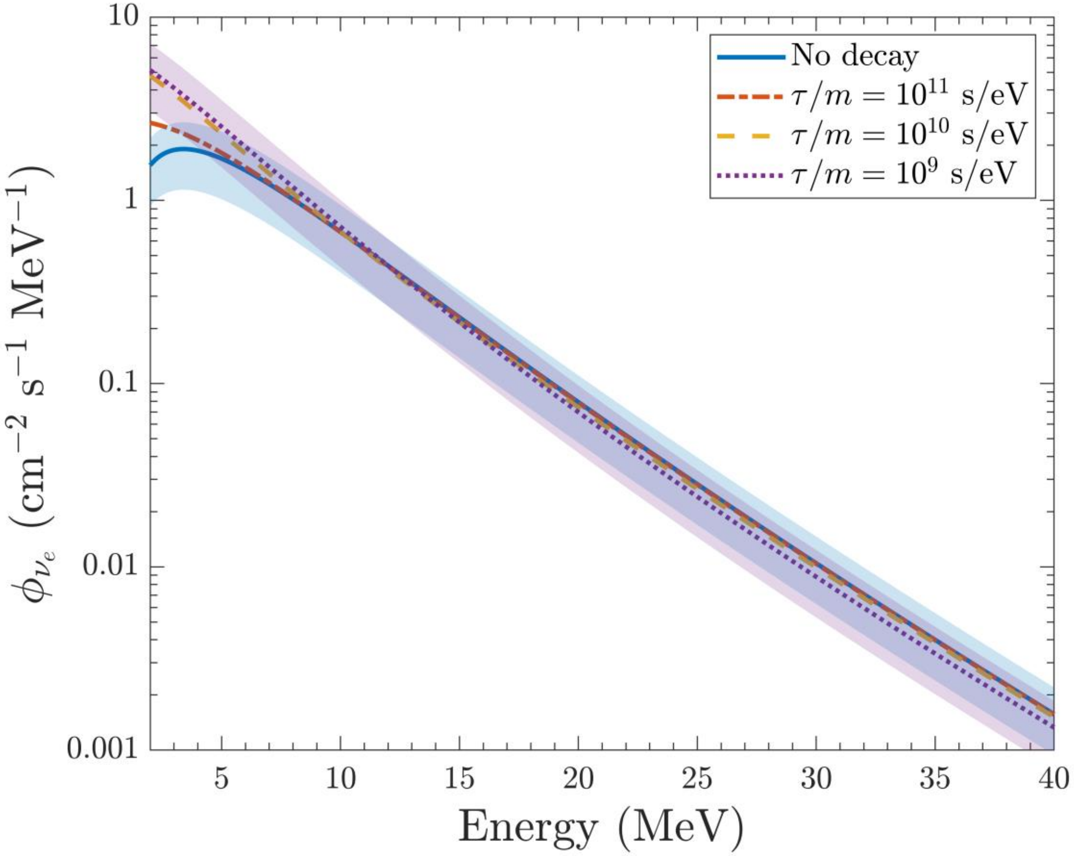




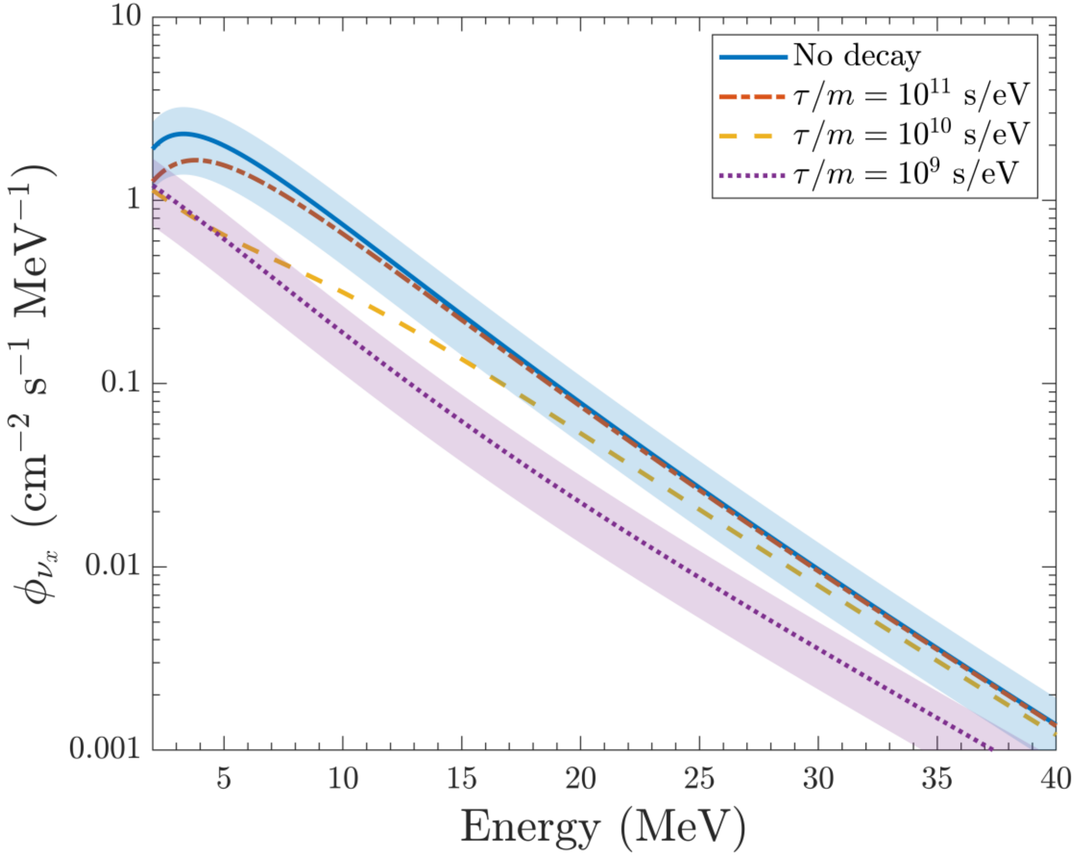
DSNB ν_e and ν_x flux on Earth for a decay scenario with NO and QD masses.
We consider the fiducial case, $f_{BH} = 0.21$. The bands show the uncertainty of the SNR normalisation.

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

ν_e FLUX

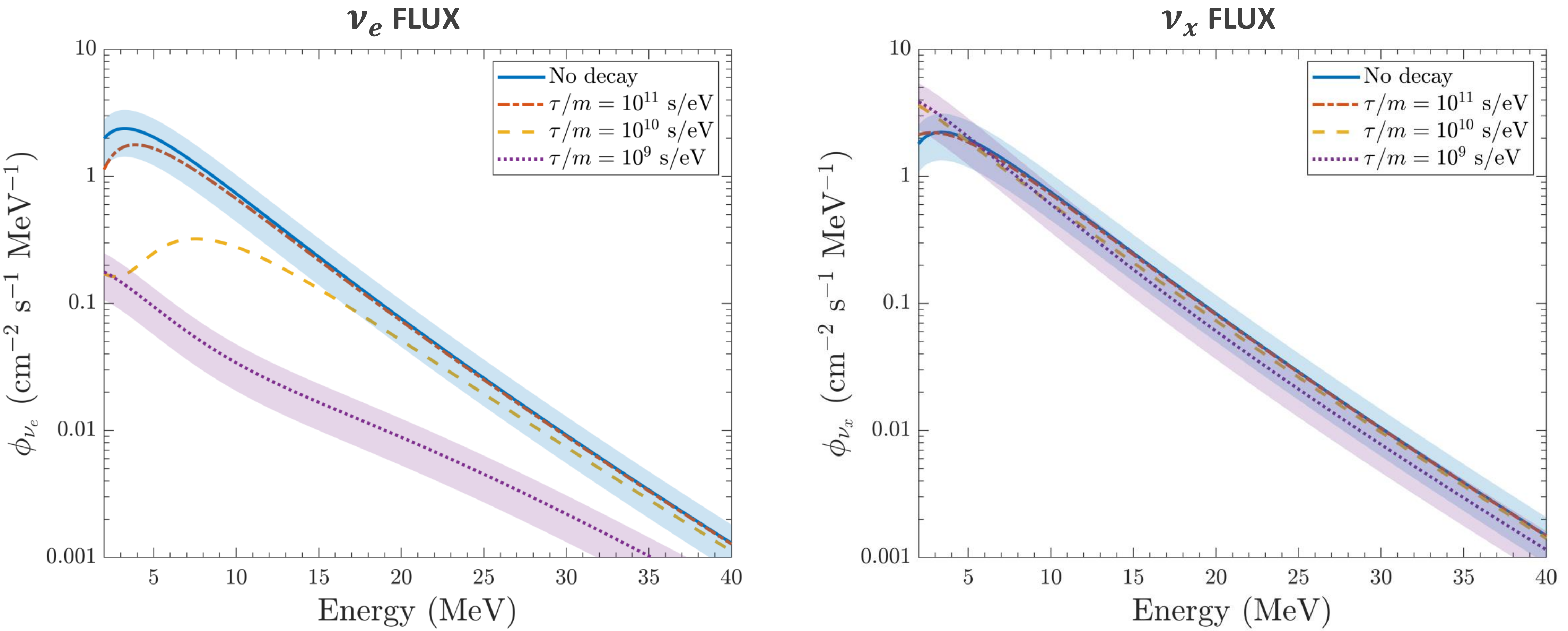


ν_x FLUX



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



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.