Probing Neutrino Decays in Core-Collapse Supernova:

Implications for Mass Ordering and Lifetime

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IP3

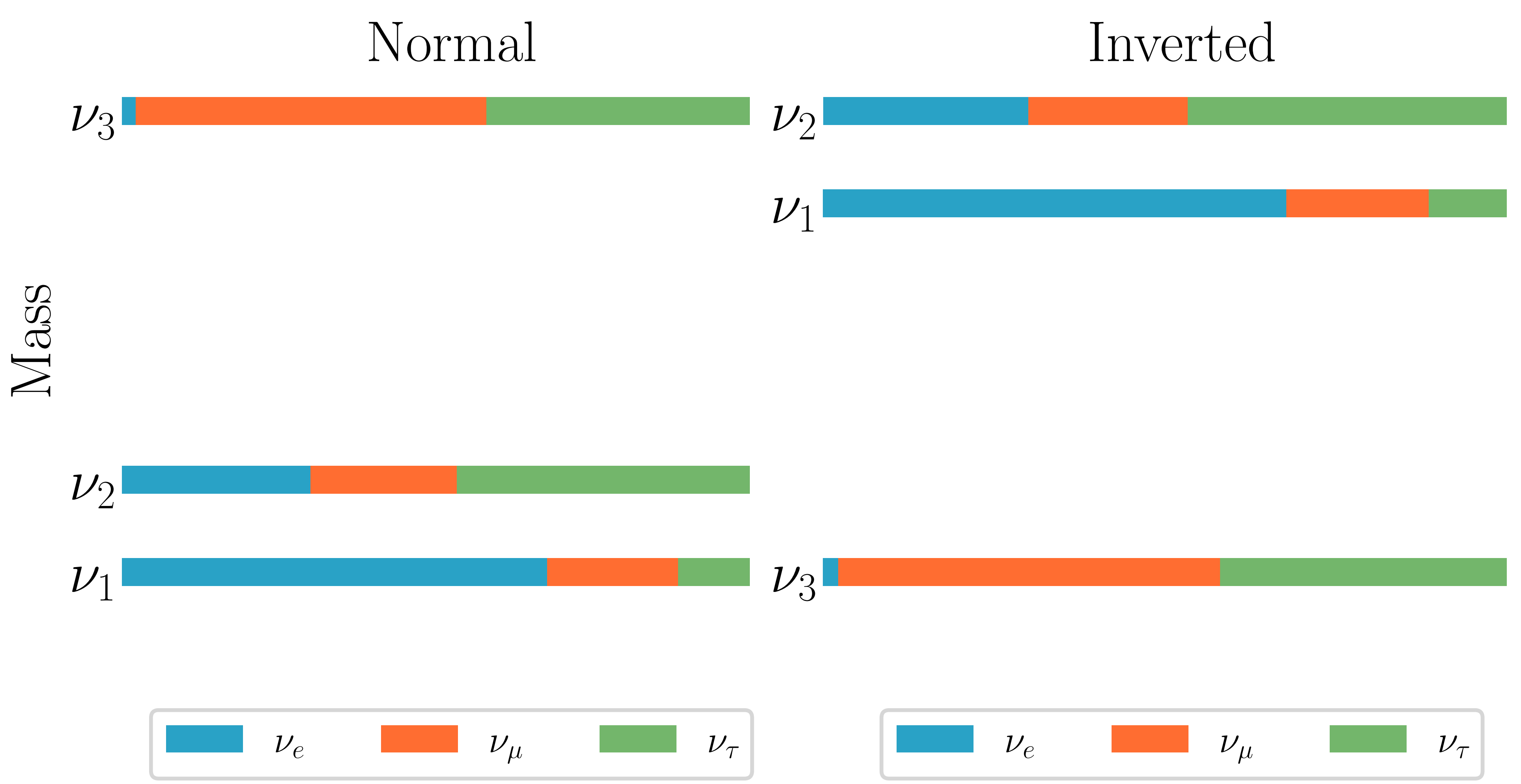
Neutrinos are Massive Particles

Neutrinos are **massive particles** and there is a **hierarchy** between their masses

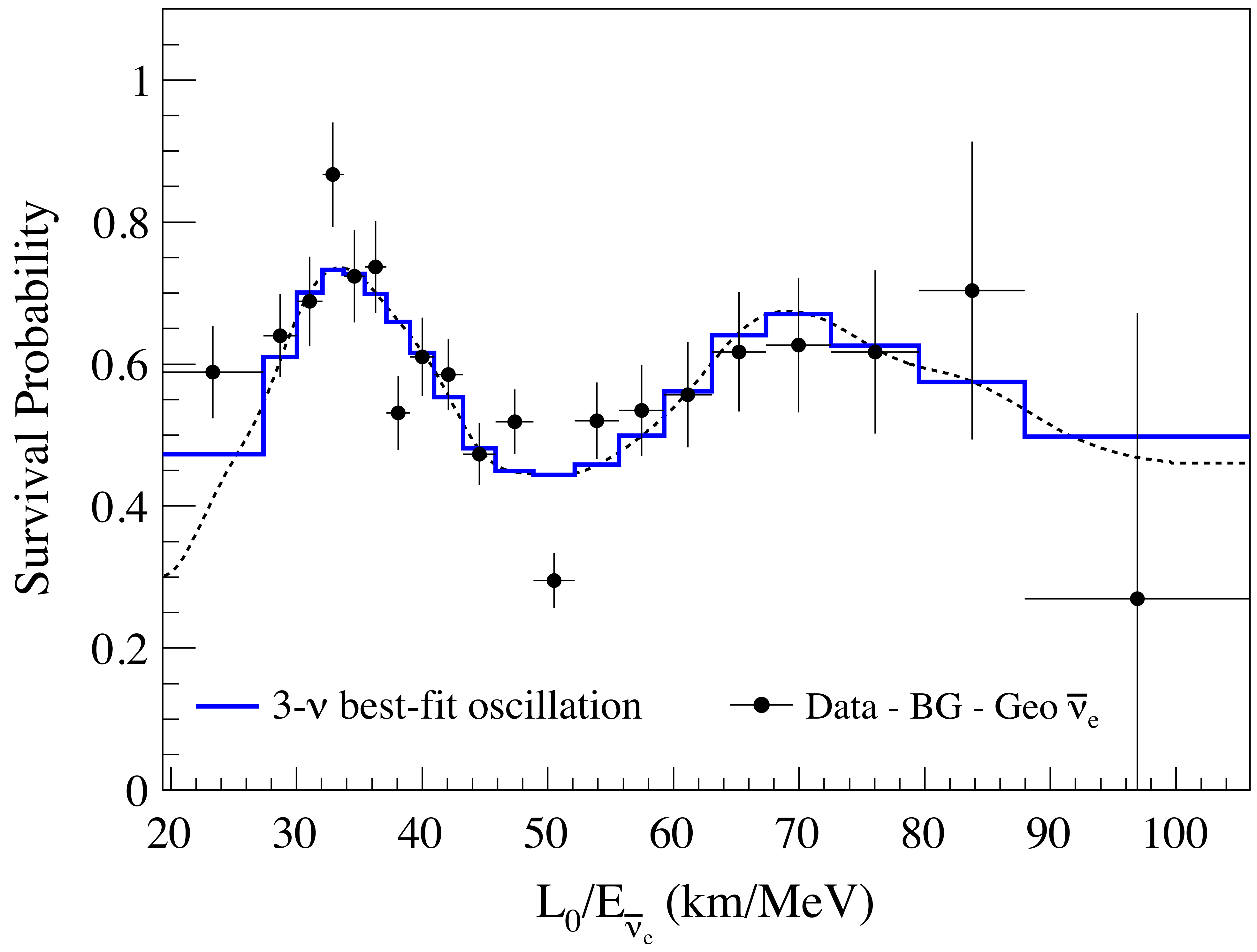
$$\Delta m^2_{21} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$$

$$|\Delta m^2_{31}| \sim 2.5 \times 10^{-3} \mathrm{eV}^2$$

Two possible orderings



Flavor oscillations are the only evidence of neutrinos masses



A. Gando et al. (KamLAND) PRD 88 (2013)

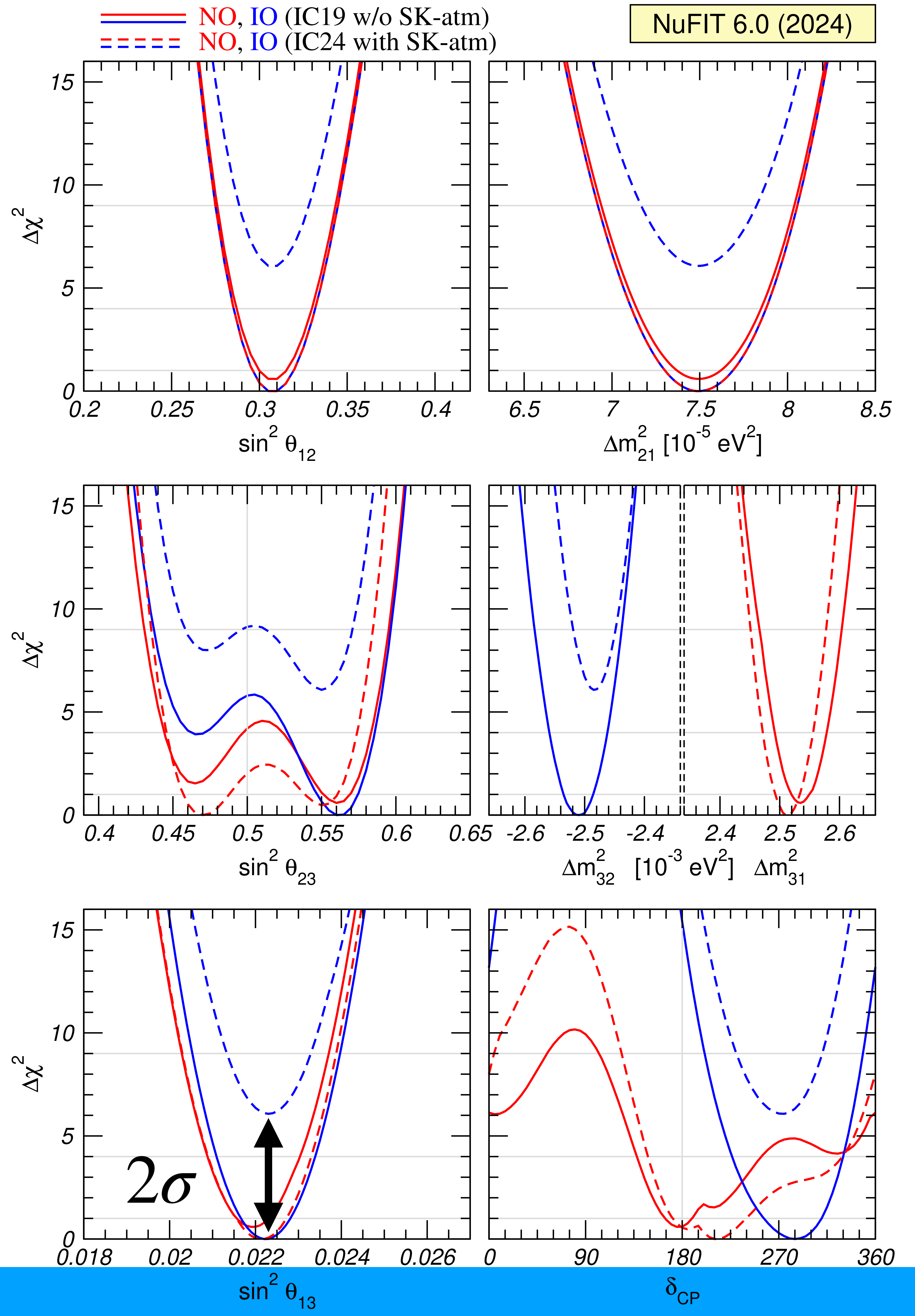
3ν mixing

Global analysis shows that in the 3ν scenario, most of the parameters are known with a good precision

- Small preference for **higher octant** of θ_{23}

- Almost the **entire region of δ_{cp} is allowed** to 3σ.

- There is almost no preference for the **mass ordering**.

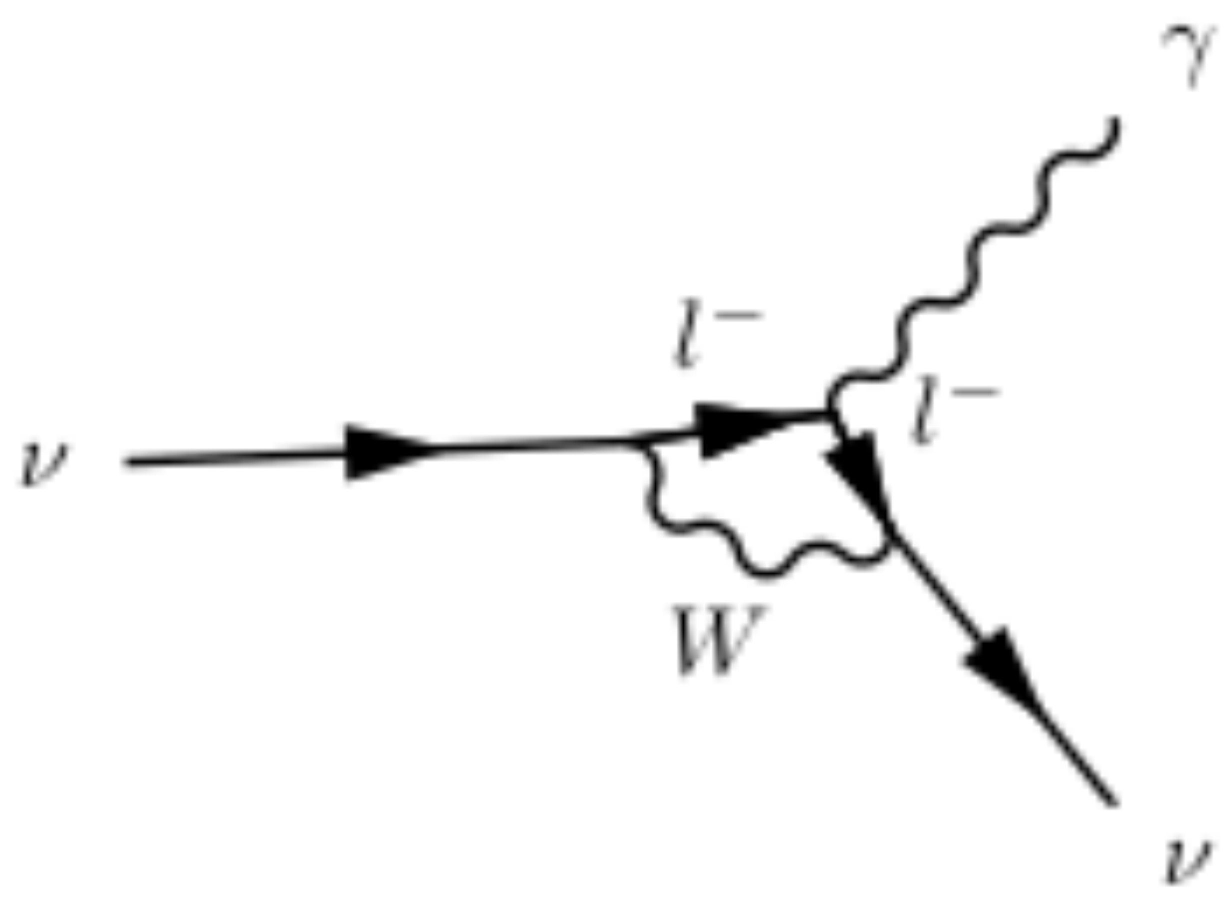


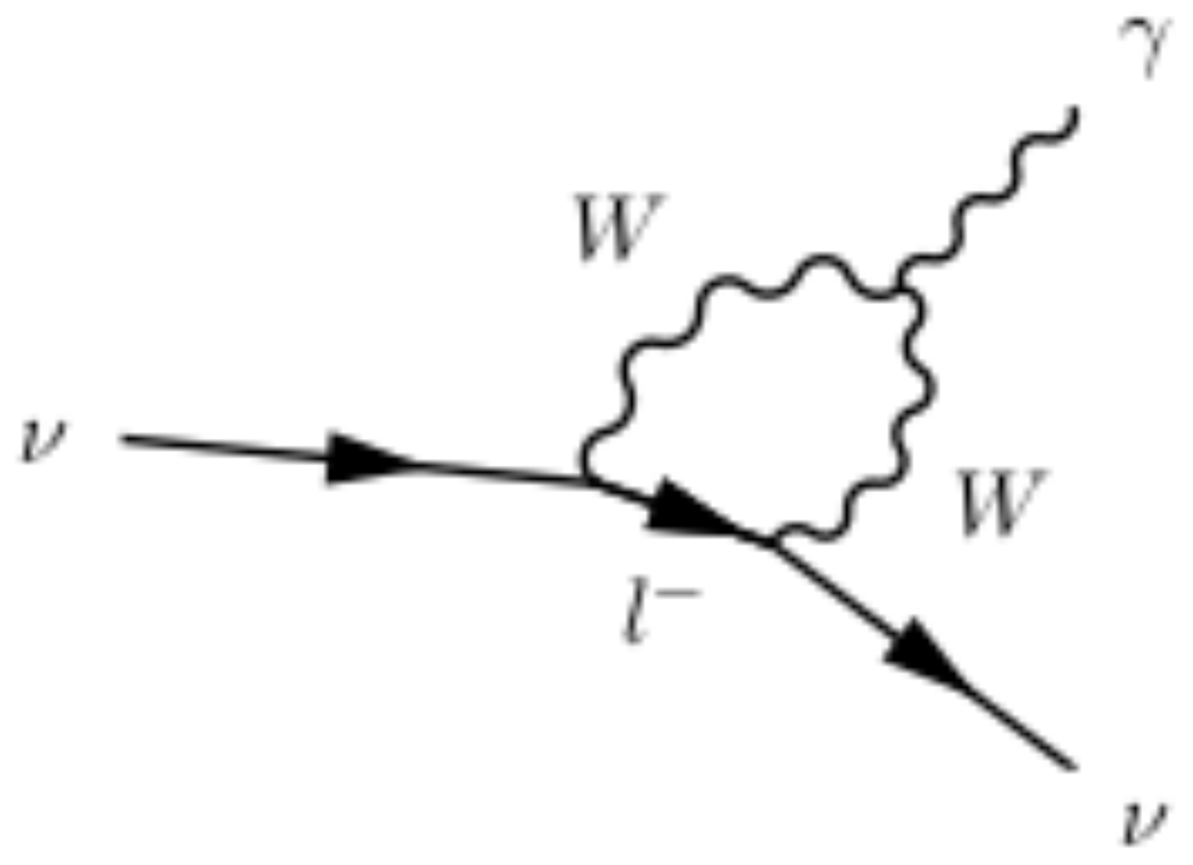
Neutrino Lifetime

Considering **SM** interactions, the neutrino lifetime **exceeds** the age of the universe.

$$\tau \sim 10^{45}\text{sec}$$

Pakvasa and Valle (2003),
Pal and Wolfenstein PRD 25 (1982)
Marciano and Sanda, PLB 67 (1977)





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New interactions among neutrinos can result in a shorter lifetime

In this talk, we will explore interactions with a **scalar**

Gelmini and Roncadelli PLB 99 (1981),
Chikashige, Mohapatra and Peccei (1980),
Bertolini and Santamaria NPB 310 (1988)
Santamaria and Valle PLB 195 (1987)

Neutrino Scalar Interaction

In the case that neutrinos are **Dirac particles**

$$\mathscr{L}_{Dir} \supset \frac{\tilde{g}_{ij}}{\Lambda}(L_i H)\nu_j^c \varphi_0 + \mathrm{h.c.} \supset g_{ij}\nu_i \nu_j^c \varphi_0 + \mathrm{h.c.}$$

Assuming normal ordering, this interaction can result in **two possible decays channels**

$$\nu_{3L} \to \nu_{1L} + \varphi_0 \qquad \nu_{3L} \to \nu_{1R} + \varphi_0$$

- The scalar carries no lepton number ($\varphi \equiv \varphi_0$)

Neutrino Scalar Interaction

In the case that neutrinos are **Dirac particles**

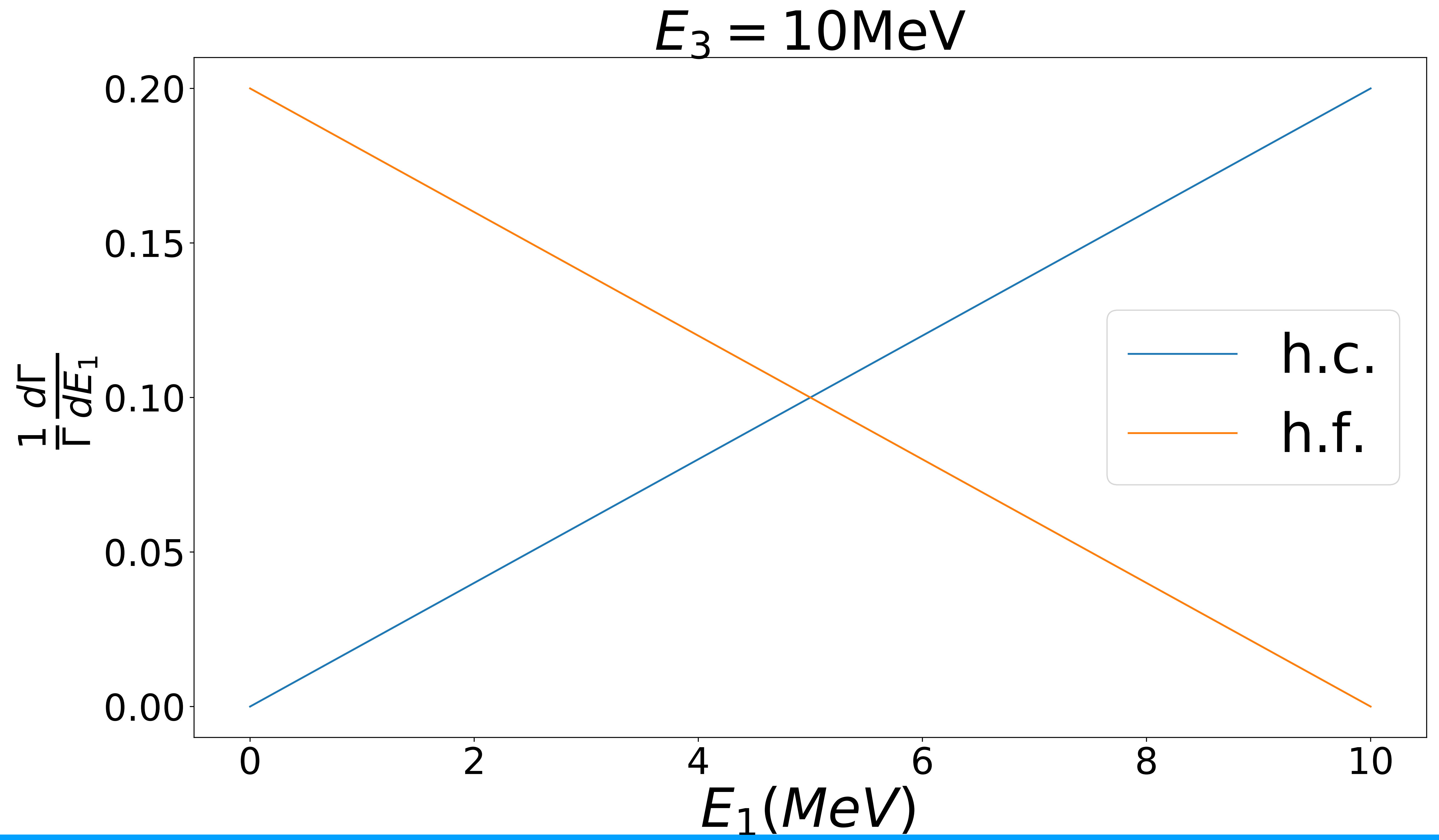
h.c. : $\nu_{3L} \to \nu_{1L} + \varphi_0$

h.f. : $\nu_{3L} \to \nu_{1R} + \varphi_0$

$$\mathscr{L}_{Dir} \supset \frac{\tilde{g}_{ij}}{\Lambda}(L_i H)\nu_j^c \varphi_0 + \mathrm{h.c.} \supset g_{ij}\nu_i \nu_j^c \varphi_0 + \mathrm{h.c.}$$

The decay width is

$$\Gamma = \frac{g^2 m_3^2}{64\pi E_3}$$



Neutrino Scalar Interaction

Decay effects are visible for $\Gamma \times L \geq 1$

The **couplings** that can be explored with **supernova** neutrinos are

$$|g| \gtrsim 2.3 \times 10^{-9} \left(\frac{E_3}{10\ \mathrm{MeV}}\right)^{1/2} \left(\frac{10\ \mathrm{kpc}}{L}\right)^{1/2} \left(\frac{0.5\,\mathrm{eV}}{m_3}\right)$$

The couplings translate to neutrino **lifetimes** as

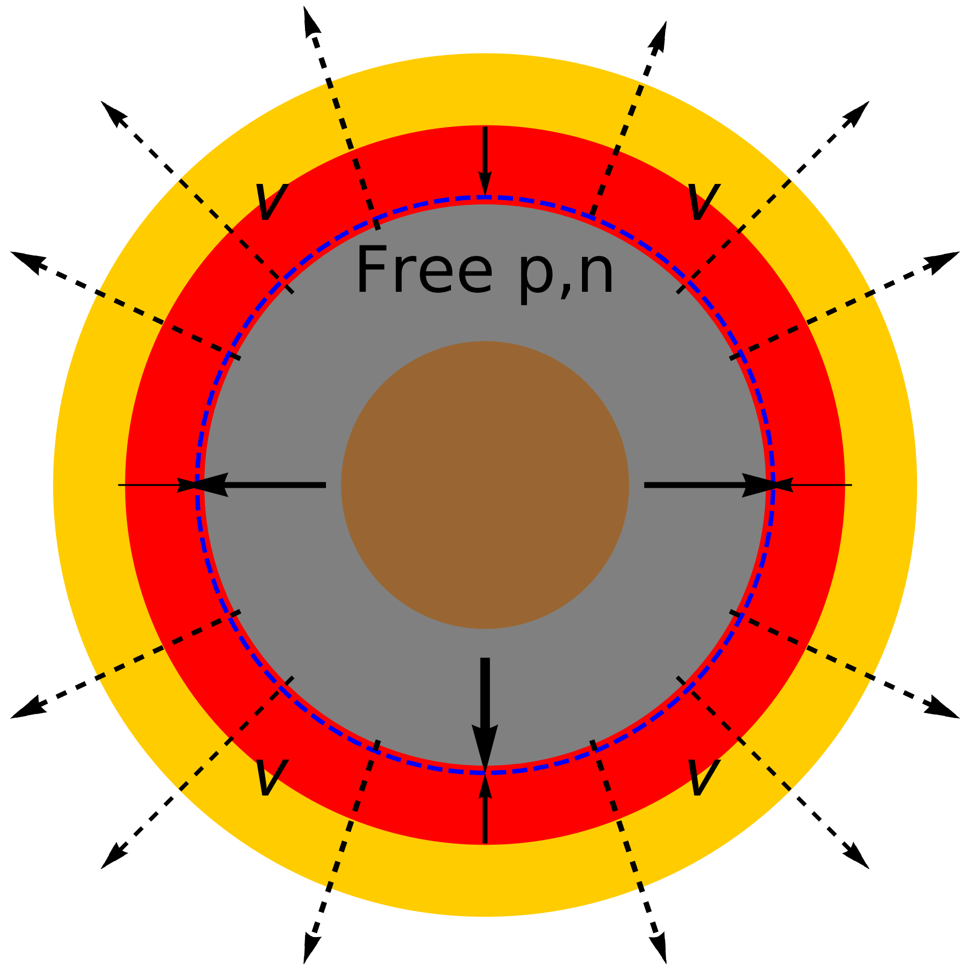
$$\frac{\tau}{m} \lesssim 10^5\ \mathrm{s/eV} \left(\frac{L}{10\ \mathrm{kpc}}\right) \left(\frac{10\ \mathrm{MeV}}{E}\right)$$

Bounds on Neutrinos Lifetimes

See: Maria Cristina Volpe's Talk
Pilar Ivañez Ballesteros's Talk

- Atmospheric neutrinos: $\tau_3/m_3 \geq 1.92 \times 10^{-10} s/\text{eV}$ — Gonzalez-Garcia and Maltoni PLB 663 (2008), Gomes, Gomes and Peres PLB 740 (2014)
- Solar neutrinos (SNO): $\tau_2/m_2 \geq 1.92 \times 10^{-3} s/\text{eV}$ — Aharmim et al. (SNO) PRD 99 (2019)
- High energy astrophysical sources: $\tau/m \geq 10^2 s/\text{eV}$ — Valera, Fiorillo, Esteban and Bustamante, PRD 110 (2024)
- SN1987A $\tau_\nu/m > 10^5 \text{s/eV}$ — Ivañez-Ballesteros and Volpe, PLB 847 (2023)
- CMB data: $\tau_\nu > 4 \times 10^8 \text{s}(\text{m}_\nu/0.005\text{eV})^3$ — Escudero and Fairbairn PRD 10 (2019)
- SN1987A cooling $\tau_\nu/m > 3 \times 10^1 \text{s/eV}$ — Kachelriess, Tomas and Valle, PRD 62 (2001)

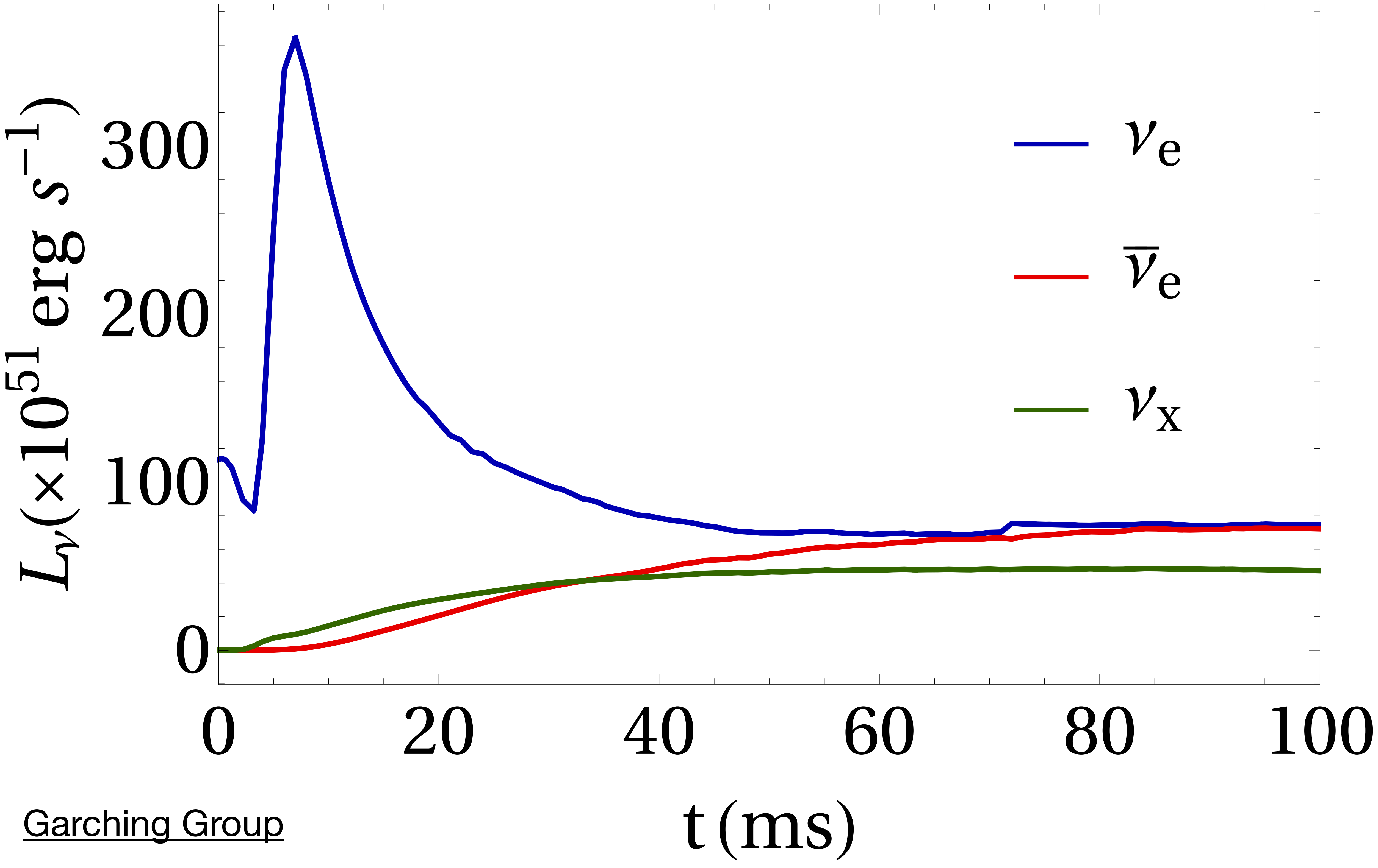
Neutronization Burst



A **large flux of** ν_e is expected in the first 25ms after the core bounces the shock wave

$$f_{\nu_e}(E,t) = \frac{1}{4\pi R^2} |\mathrm{U}_{eh}|^2 \frac{L_\nu(t)}{\langle E_\nu \rangle} \phi(E)$$

The energy distribution follows "alpha-fit" model



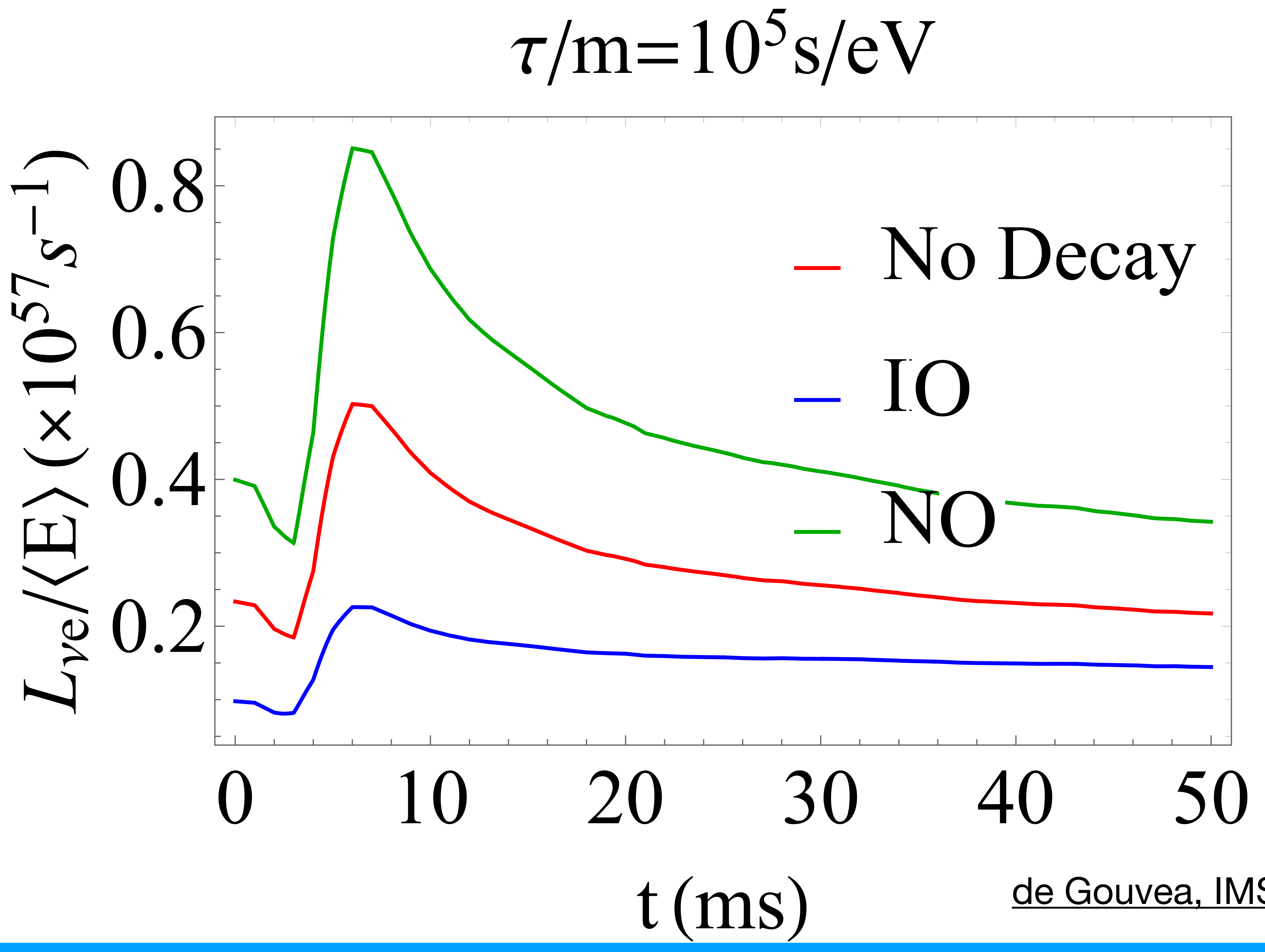
Garching Group

Neutronization Burst

If neutrinos **decay** on their way to Earth, the flux will be **enhanced/suppressed** depending on the mass ordering.

For NH: $|U_{e1}^2|/|U_{e3}^2| \sim 30$

For IH: $|U_{e3}^2|/|U_{e2}^2| \sim 0.07$



$$|U|_{3\sigma}^{\text{IC19 w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix}$$

NuFIT 6.0 (2024)

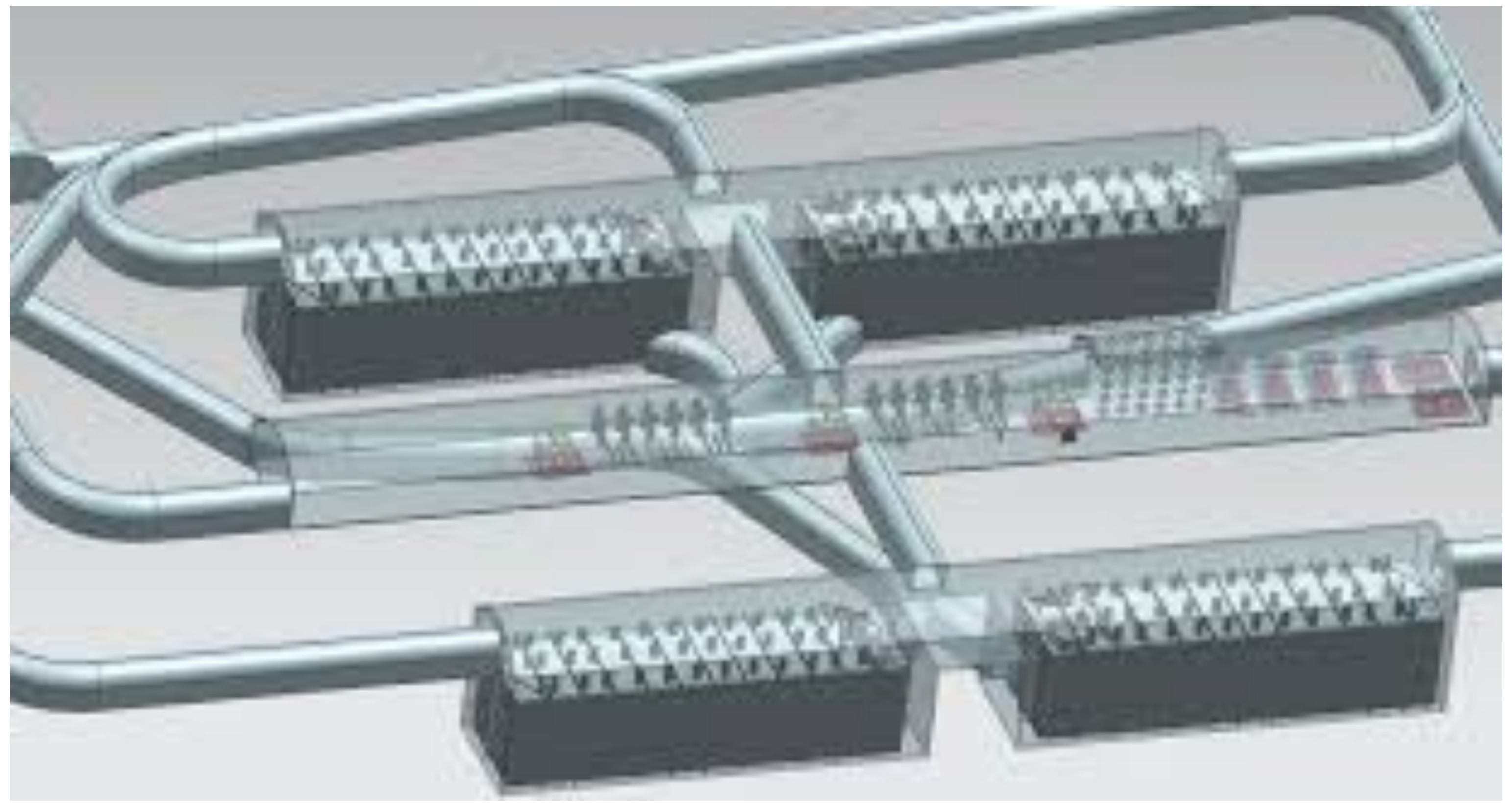
de Gouvea, IMS, Sen, PRD 101 (2019)

DUNE

The **next generation** of experiments will measure the supernova neutrino flux with **high precision**

LArTPC detectors are mainly sensitive to the ν_e **component** of the flux

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



We consider:

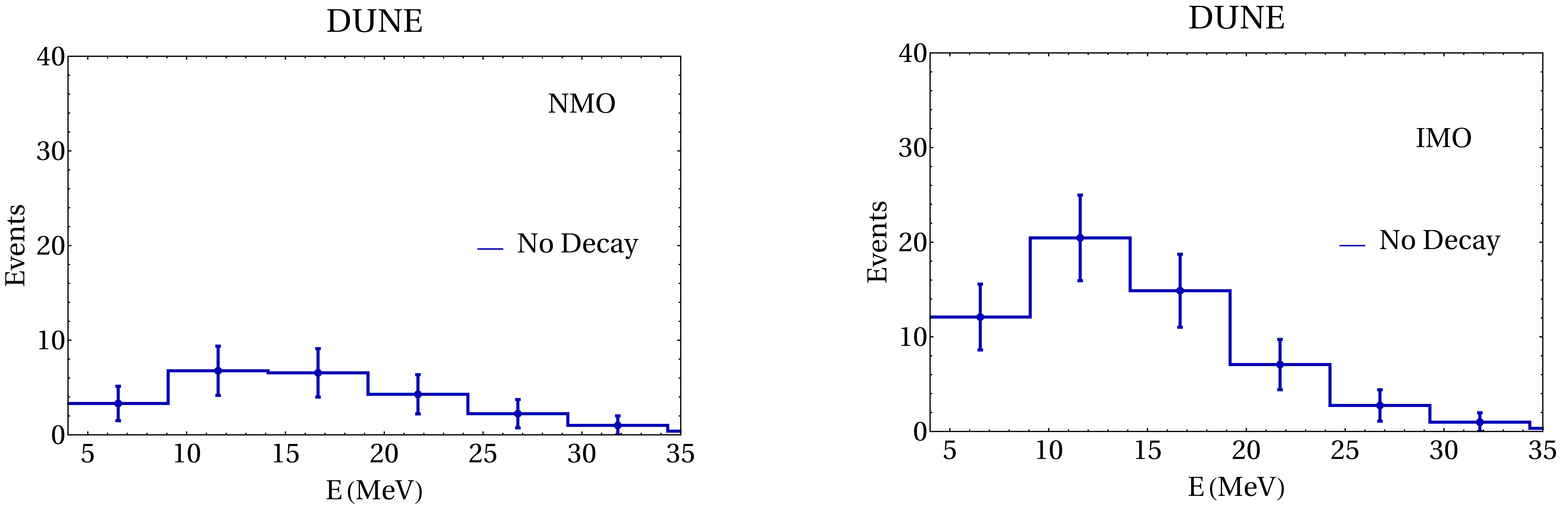
- 40 kton of LAr
- Energy threshold of 4 MeV
- Energy resolution similar to ICARUS
- Time bins of 5ms

$$\sigma(E) = 0.11\sqrt{E/MeV} + 0.2(E/MeV)$$

ICARUS (hep-ex/0311040)

Mass Ordering

Knowing the expected number of neutrinos, the **neutronization burst** can be used to determine the **mass ordering**

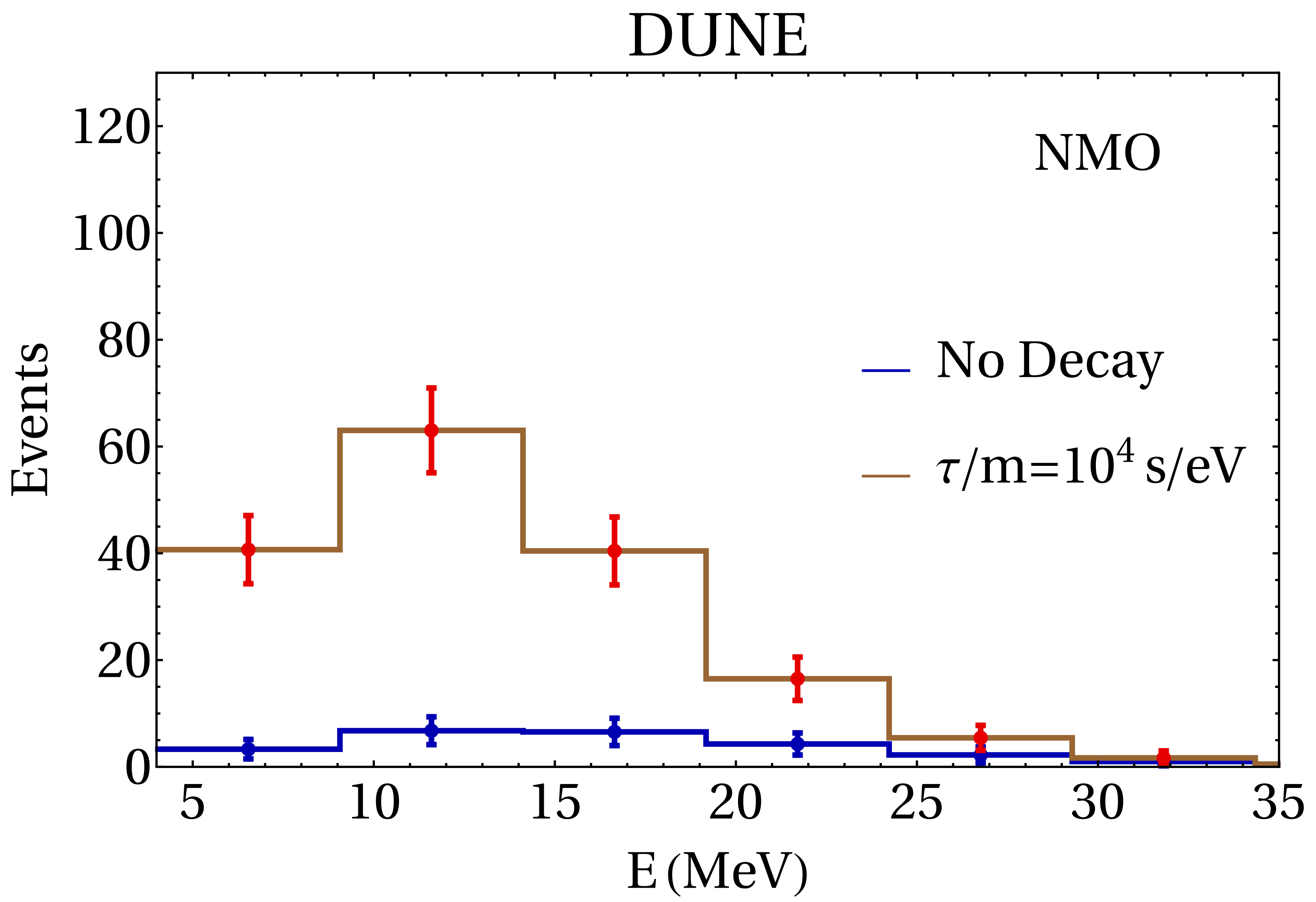


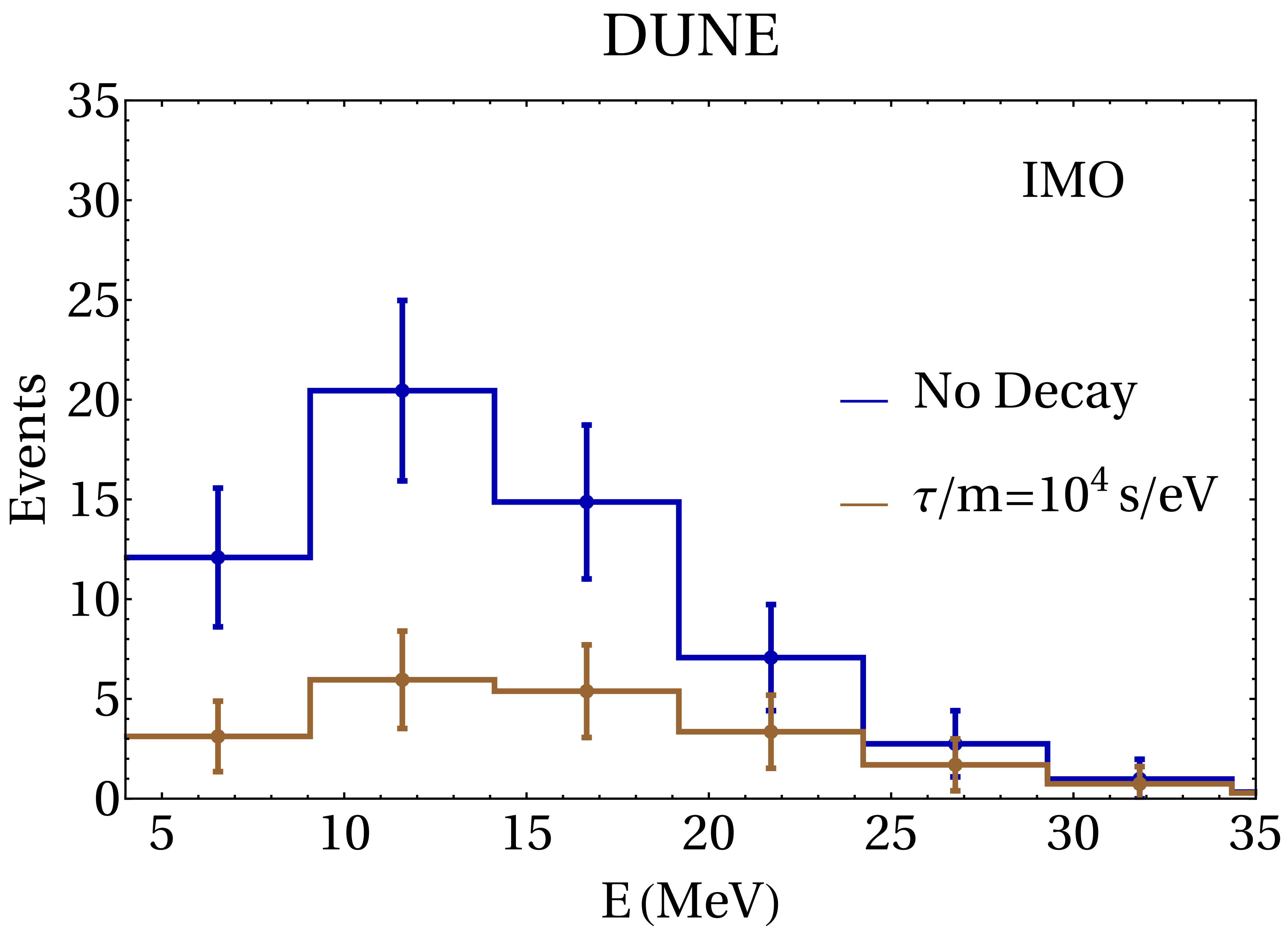
There is also a difference in the time distribution of the events

de Gouvea, IMS, Sen, PRD 101 (2019)

Mass Ordering

If neutrinos **decay**, the event distribution is modified, **mimicking** the event distribution of the **wrong mass ordering**





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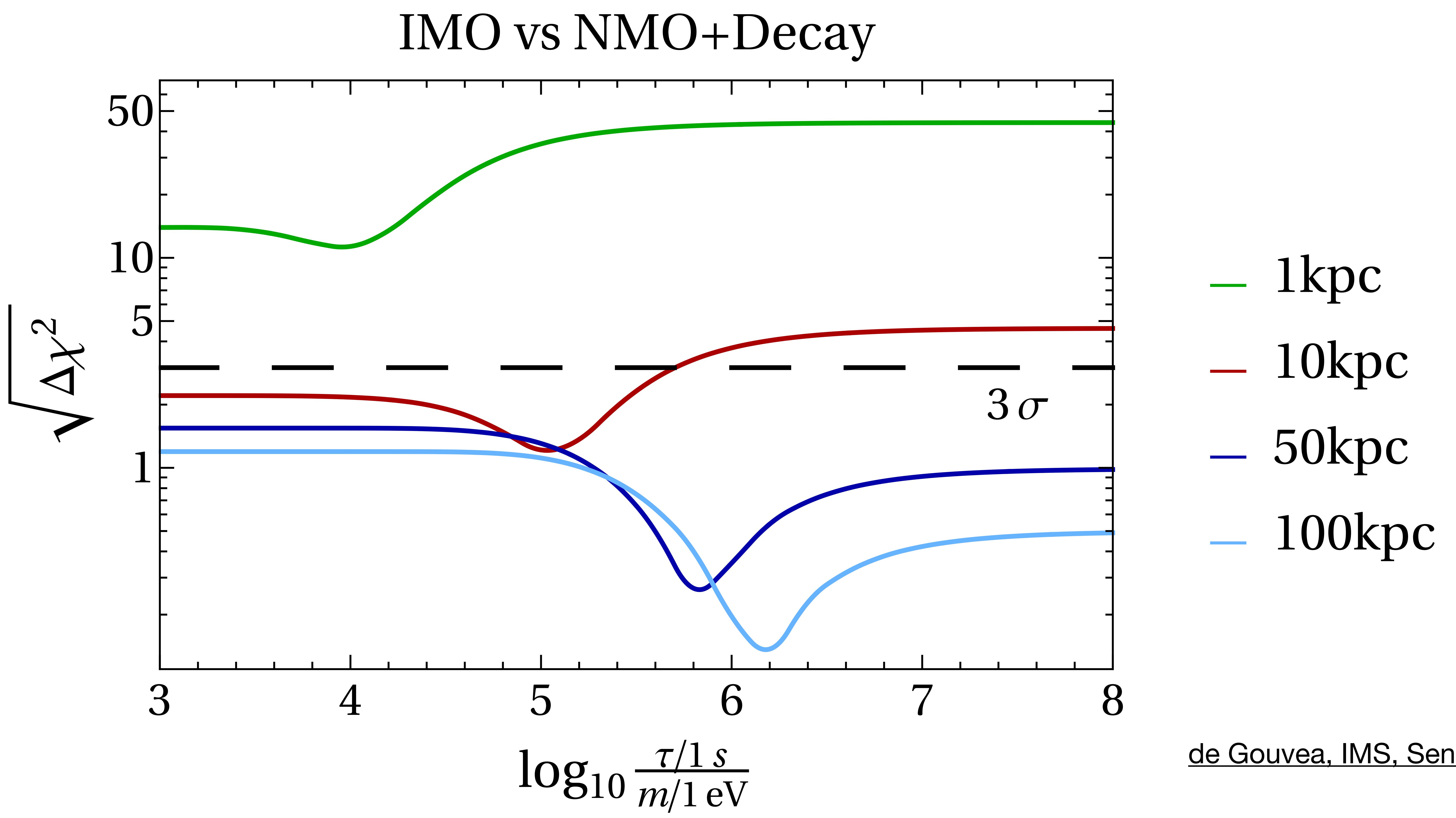
Mass Ordering

The **sensitivity** to the mass ordering **decreases** if the neutrinos decay by the time neutrinos reach the Earth



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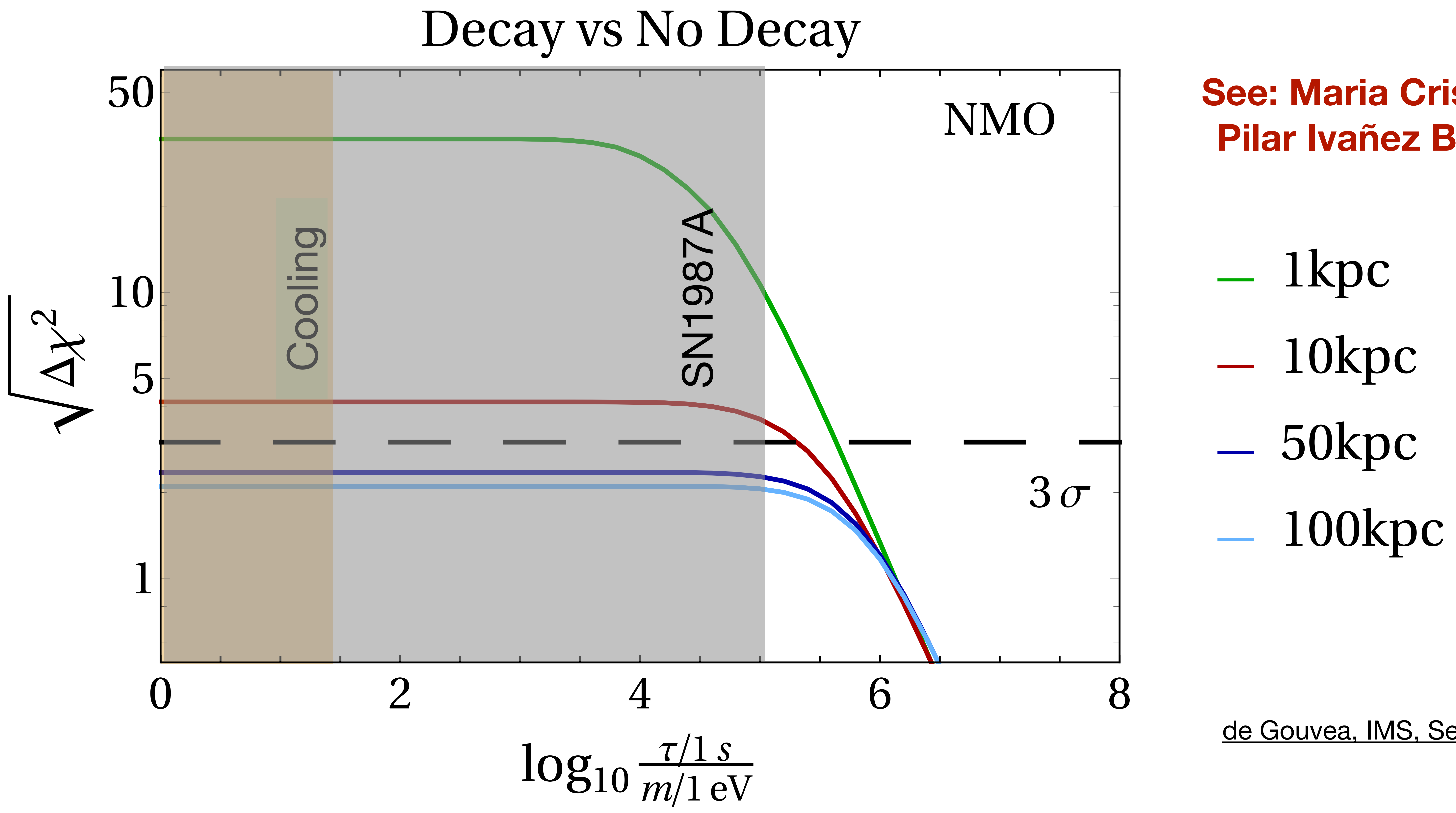
Neutrino Lifetime

Assuming the mass ordering is known, we can explore the **sensitivity to the neutrino lifetime**



See: Maria Cristina Volpe's Talk
Pilar Ivañez Ballesteros's Talk

de Gouvea, IMS, Sen, PRD 101 (2019)

Majorana Neutrinos

If neutrinos are **Majorana** particles, both decay products will be **observable**

$$\mathscr{L}_{Maj} \supset \frac{\tilde{f}_{ij}}{2\Lambda^2}(L_iH)(L_jH)\varphi + \mathrm{h.c.} \supset \frac{f_{ij}}{2}(\nu_L)_i(\nu_L)_j\varphi + \mathrm{h.c.}$$

In this case, the decay width is given by

$$\nu_{3_L} \to \nu_{1_L} + \varphi$$

$$\nu_{3_L} \to \overline{\nu}_{1_R} + \varphi$$

$$\Gamma = 2 \times \frac{f^2 m_3^2}{64\pi E_3}$$

Experiments that can **observe the** $\overline{\nu}_e$ of the flux are very sensitive to this scenario

Hyper-Kamiokande

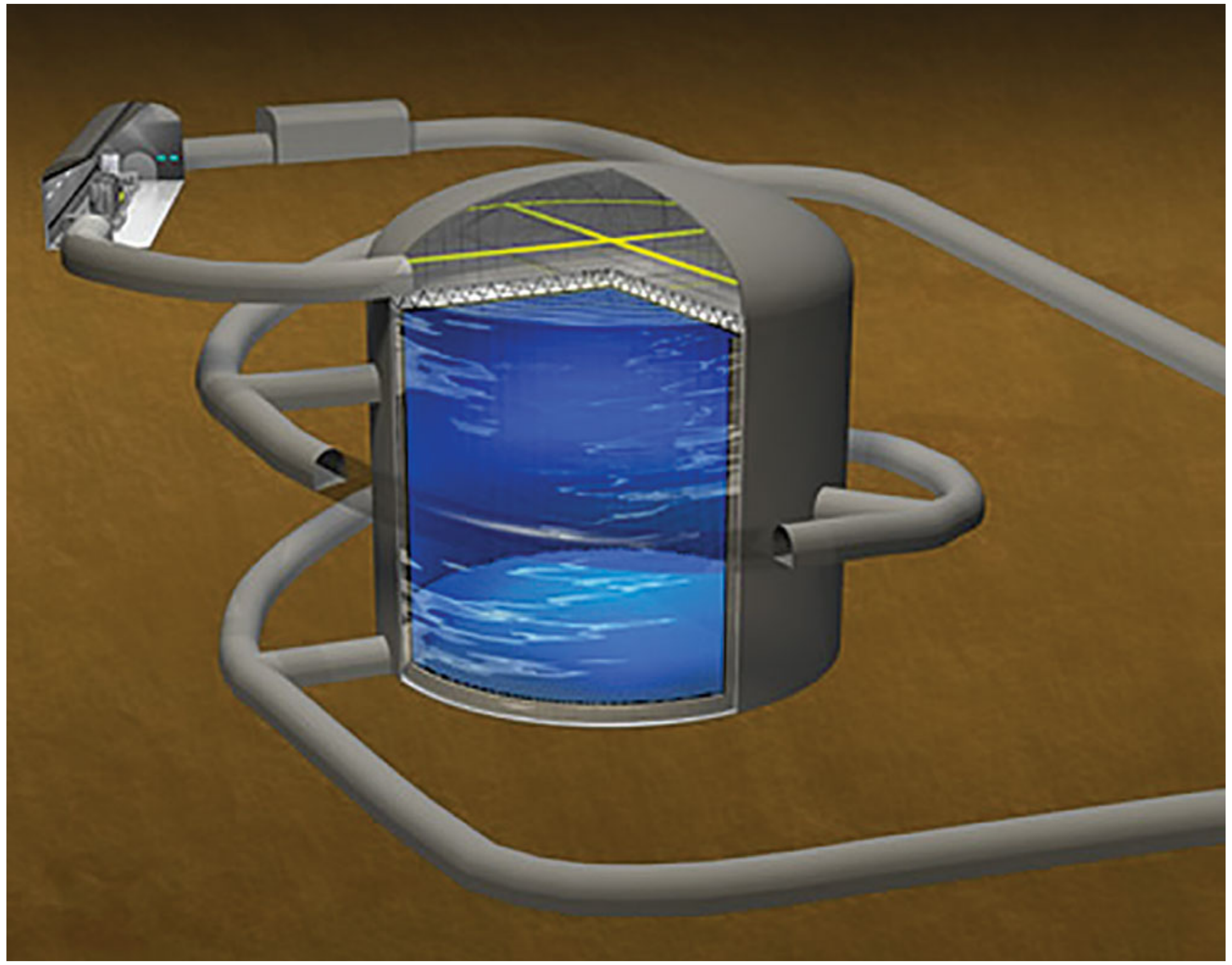
HyperK can detect $\overline{\nu_e}$ via Inverse Beta Decay

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

We consider:

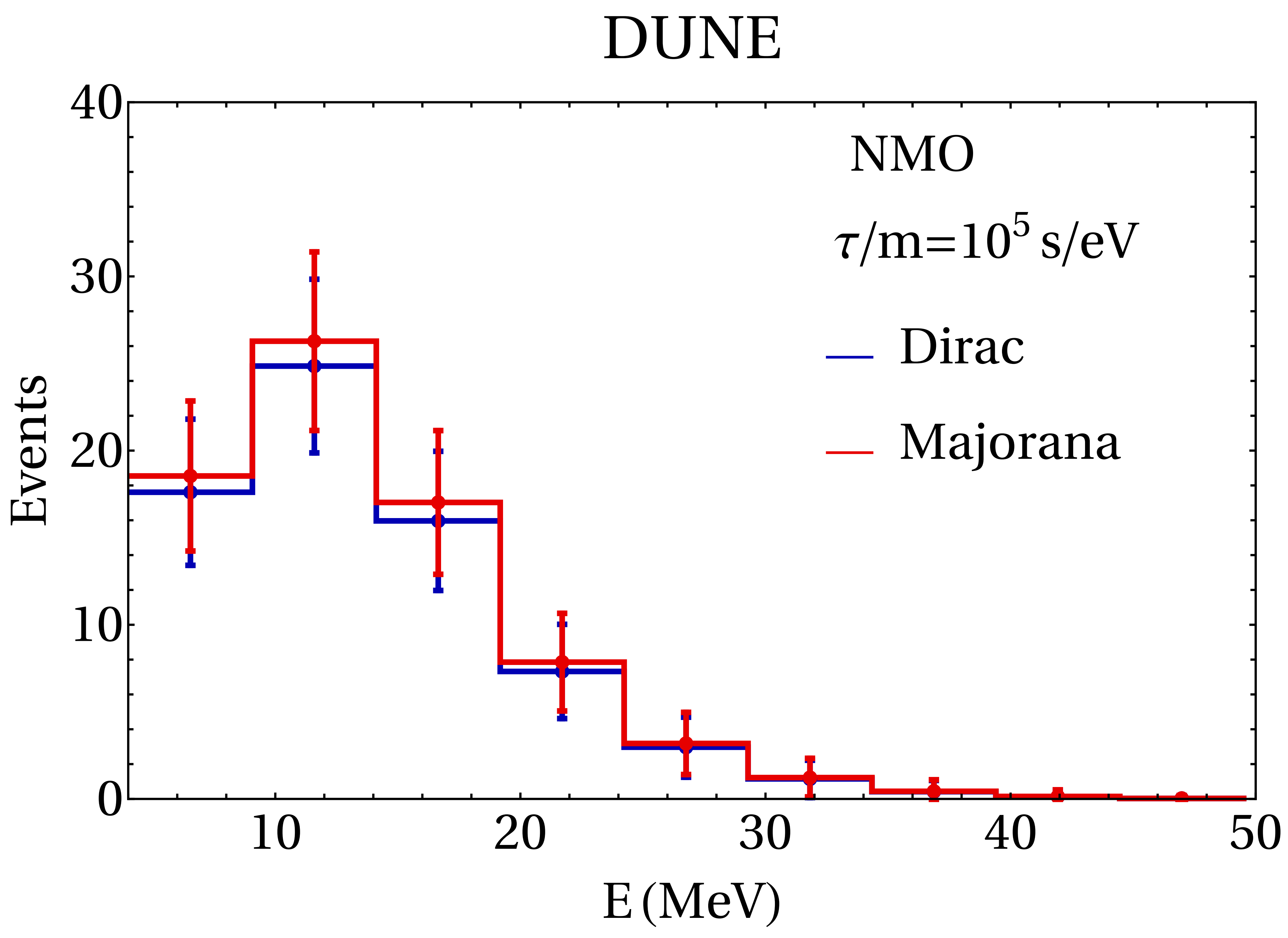
- Similar energy resolution as in SuperK
- Energy Threshold of 3MeV
- Time bins of 5ms

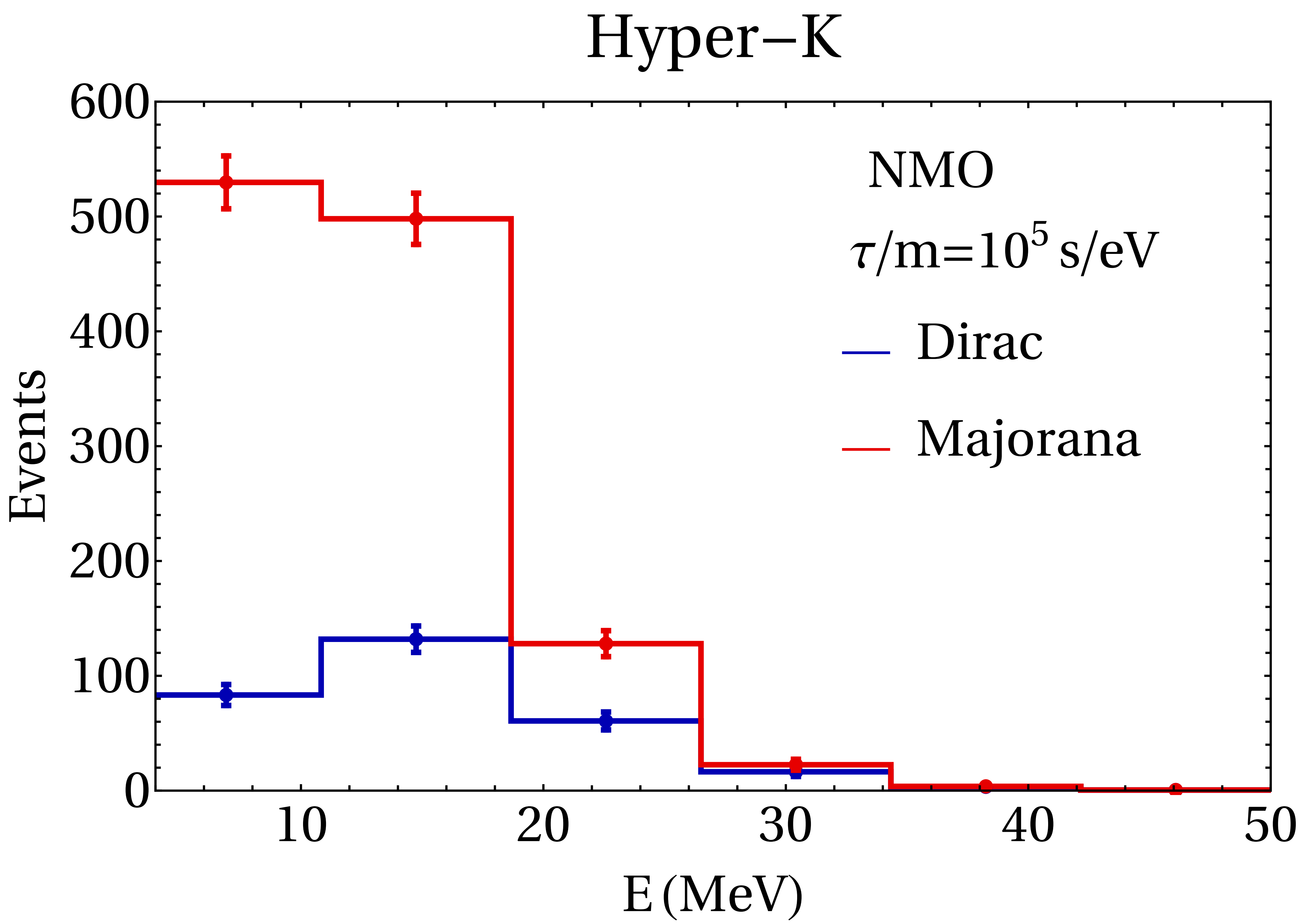
$$\sigma_E = 0.6\sqrt{E/\mathrm{MeV}}$$



Dirac vs Majorana

In the presence of a **coupling with a scalar**, the Dirac or Majorana nature of neutrinos will leave a different signature in the event distribution





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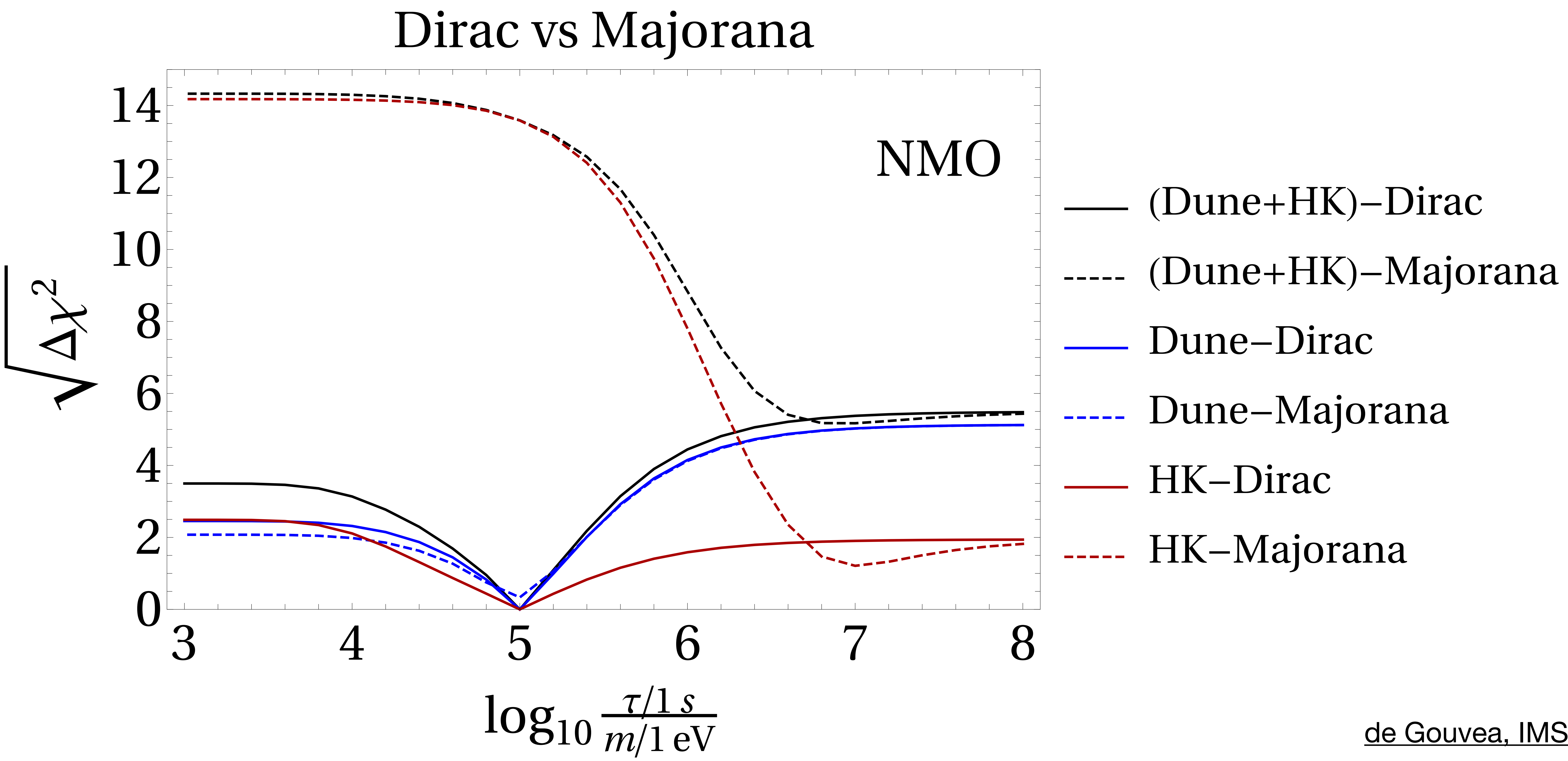
Dirac vs Majorana

It is possible to **distinguish** between Dirac or Majorana in case of a **neutrino decay**



de Gouvea, IMS, Sen, PRD 101 (2019)

Conclusions

- The neutrinos emitted during the neutronization burst can be used to search for BSM

- Neutrinos from SN allow us to explore lifetimes of the order of $\tau/\mathrm{m} \leq 10^5$s/eV. HK can probe lifetimes of $\tau/\mathrm{m} \leq 10^6$s/eV

- The wrong mass ordering, combined with neutrino decay, can mimic the true mass ordering measurement.

- Combining DUNE and HK could make it possible to resolve between Dirac and Majorana in the case of decay.

¡Gracias!

Mass Ordering

Neutrino decay modifies the **time distribution**, leading to a mimicking of the mass orderings