Capabilities of neutrino decay on the Supernova Neutronization-Burst Flux

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Based on paper: Andre de Gouvêa, IMS and Manibrata Sen,

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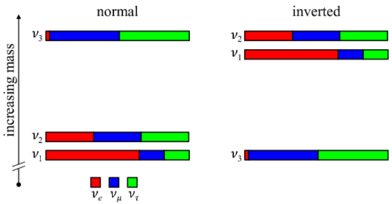
Fermilab

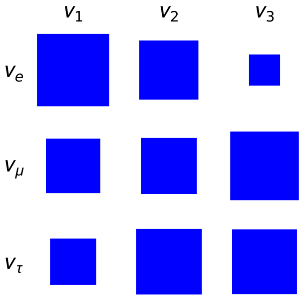
Northwestern University

Introduction

What do we know about the neutrino evolution?

- Two mass splittings ($\Delta m^2_{21} \sim 10^{-5}\mathrm{eV}^2$ and $|\Delta m^2_{31}| \sim 10^{-3}\mathrm{eV}^2$)
  - ν_3 and ν_2 (NMO) are massive
  - ν_2 and ν_1 (IMO) are massive
- Mixing $(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ between ν_α and ν_i



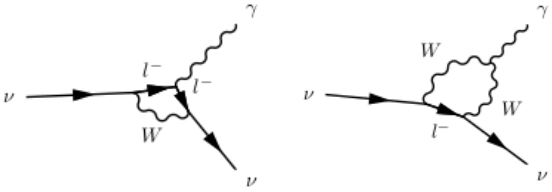


Introduction

Considering SM interactions, the neutrino lifetime is longer than the age of the universe.

$$\Gamma \sim 10^{-45} \text{sec}^{-1}$$

[Pakvasa and Valle ('03), Pal and Wolfenstein ('82), Petcov, Marciano and Sanda ('77)]



Introduction

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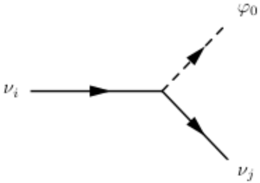
New interactions can lead to shorter lifetimes.

We consider that neutrinos interact with a scalar field φ.

[Gelmini and Roncadelli ('81), Chikashige, Mohapatra and Peccei ('80), Bertolini and Santamaria ('88), Santamaria and Valle ('87)]

Neutrino decaying into a scalar



If neutrinos are Dirac particles...

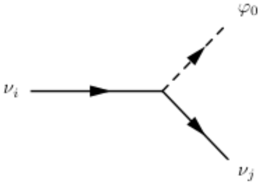
$$\mathcal{L}_{Dir} \supset \frac{\tilde{g}_{ij}}{\Lambda}(L_i H)\nu_j^c \varphi_0 + \text{h.c.} \supset g_{ij}\nu_i \nu_j^c \varphi_0 + \text{h.c.}$$

$$g_{ij} = \frac{\tilde{g}_{ij} v}{\Lambda}$$

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

- The scalar field has lepton number zero $\varphi \equiv \varphi_0$.
- We consider $g_{ij} = g_{ji}$.

Neutrino decaying into a scalar



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The decay width is

$$\Gamma = \frac{g^2 m_3^2}{64\pi E_3} \qquad g^2 = |g_{13}|^2 + |g_{31}|^2$$

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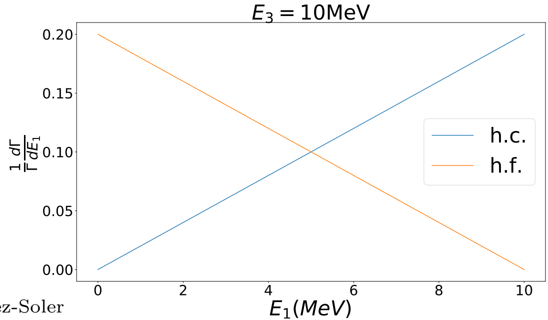
$$\psi_{\text{h.c.}}(E_3, E_1) \equiv \frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2E_1}{E_3^2} \qquad \text{for } \nu_{3_L} \to \nu_{1_L} + \varphi_0$$

$$\psi_{\text{h.f.}}(E_3, E_1) \equiv \frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2}{E_3}\left(1 - \frac{E_1}{E_3}\right) \qquad \text{for } \nu_{3_L} \to \nu_{1_R} + \varphi_0$$



Neutrino decaying into scalar

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

The values of couplings that can be explored with supernova neutrinos

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

We can translate that limit on the lifetime that can be explored with supernova neutrinos

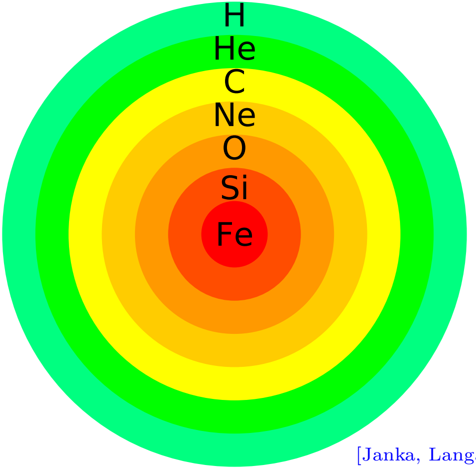
$$\frac{\tau}{m} \lesssim 10^5 \text{ s/eV} \left(\frac{L}{10 \text{ kpc}}\right) \left(\frac{10 \text{ MeV}}{E}\right).$$

Bounds on neutrinos lifetime

- Bound from SNO $\tau_2/m_2 \geq 1.92 \times 10^{-3} s/\mathrm{eV}$
  [SNO (1812.01088)]
- Bound from atmospheric data $\tau_3/m_3 \geq \times 10^{-10} s/\mathrm{eV}$
  [Gonzalez-Garcia and Maltoni ('08), Gomes, Gomes and Peres ('14)]
- Bounds from CMB data $\tau_\nu > 4 \times 10^8 \mathrm{s}(\mathrm{m}_\nu/0.005\mathrm{eV})^3$
  [Escudero and Fairbairn ('19)]
- Bounds from SN1987A $\tau_\nu/m_3 > 3 \times 10^1 \mathrm{s}/\mathrm{eV}$
  [Kachelriess, Tomas and Valle ('00), Farzan ('02)]

Core-collapse supernova

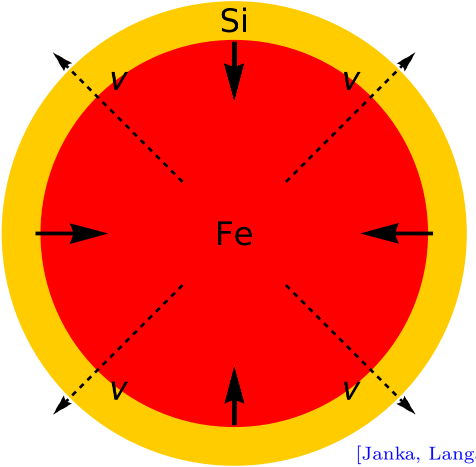
At the end of a massive star $M > 11 M_{\odot}$



[Janka, Langake, Marek, Martínez-Pinedo, Muller ('06)]

Core-collapse supernova

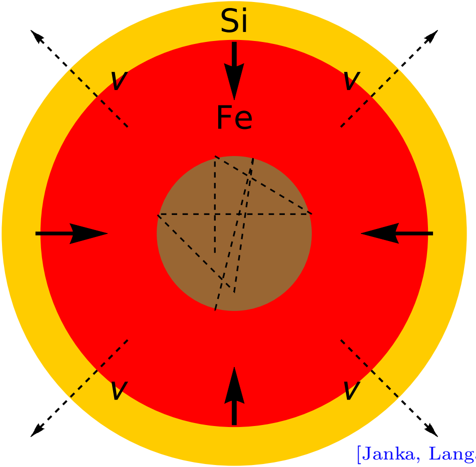
For $M_c \sim 1.44 M_\odot$, the electron pressure cannot stabilize the core



[Janka, Langake, Marek, Martínez-Pinedo, Muller ('06)]

Core-collapse supernova

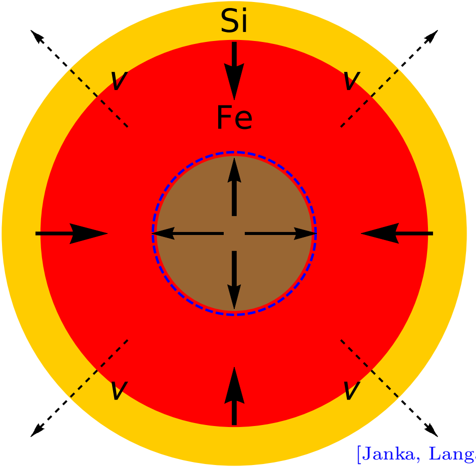
For densities $\rho \sim 10^{12}$g/cm^3 neutrinos become trapped in the core.



[Janka, Langake, Marek, Martínez-Pinedo, Muller ('06)]

Core-collapse supernova

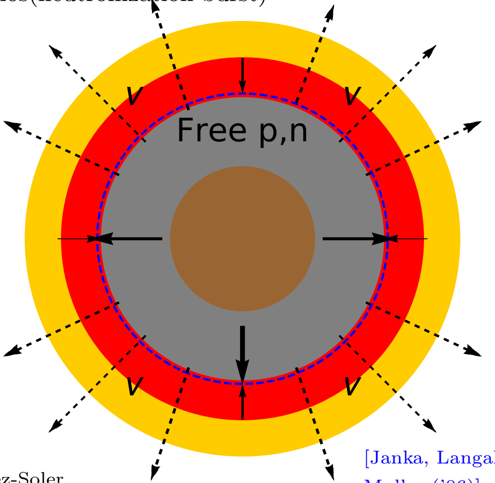
For densities close to the nuclear density ($\rho \sim 10^{14}$g/cm^3) the core bounces and a shock wave is driven to the outer layers.



[Janka, Langake, Marek, Martínez-Pinedo, Muller ('06)]

Core-collapse supernova

- The shock wave disociate the heavy nuclei into nucleons.
- Electrons are captured by free protons producing a large fraction of neutrinos(neutronization burst)



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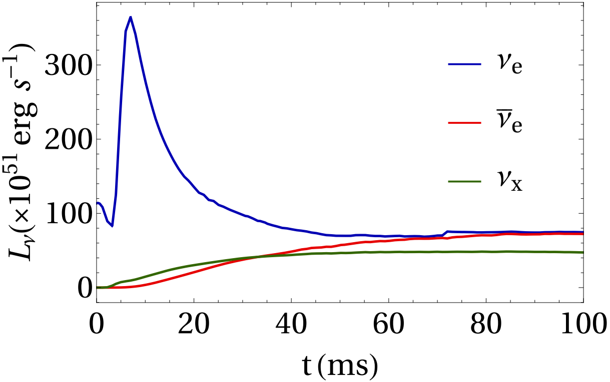
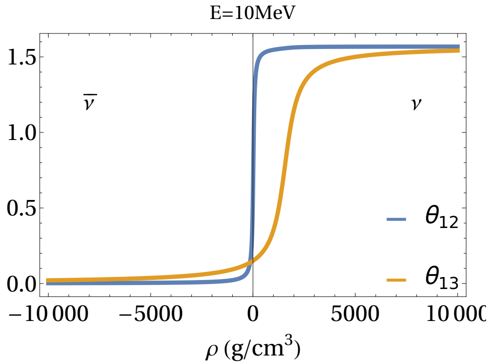
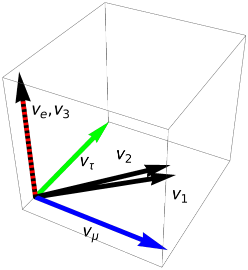
Neutrino spectrum from the SN



Neutrino spectrum from the SN



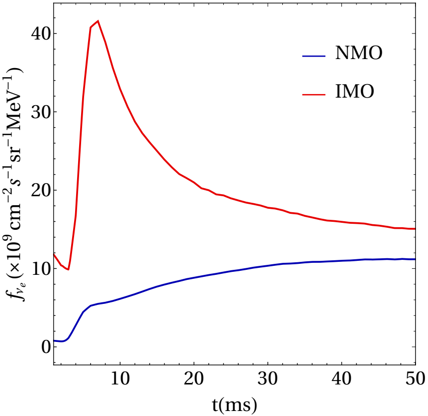


[Denton, Minakata, Parke ('16)]

The flux of neutrinos from a supernova

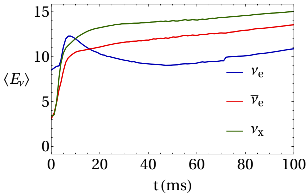
The electron neutrino flux from a supernova at the Earth is

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



Simulation of 25 $M_\odot$ progenitor by the Garching group

The flux of neutrinos from a supernova



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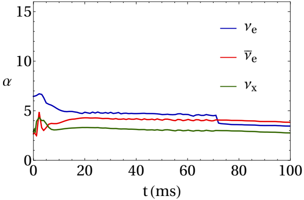
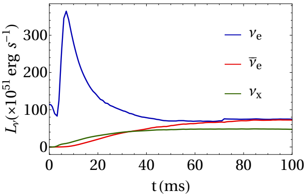


The energy distribution follow the “alpha-fit”

$$\phi(E) = \frac{1}{\langle E_\nu \rangle} \frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)} \left(\frac{E}{\langle E_\nu \rangle} \right)^{\alpha} \exp\left[-(\alpha+1) \frac{E}{\langle E_\nu \rangle} \right]$$



The flux of neutrinos from a supernova

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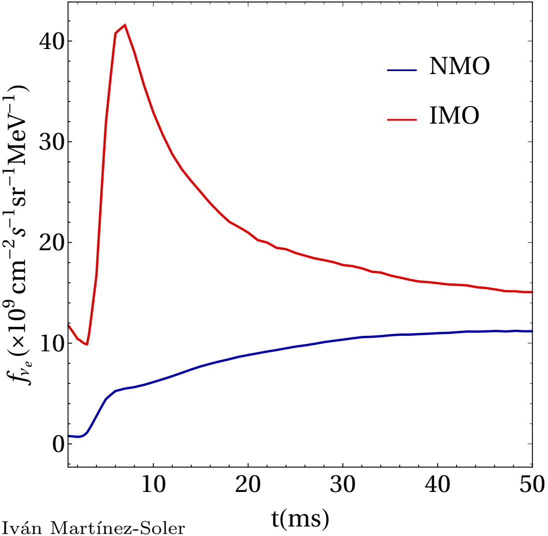


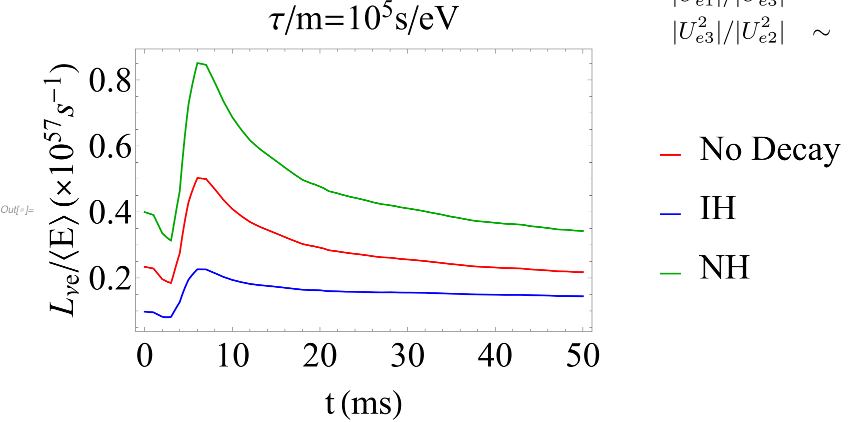
$$|\mathrm{U}_{eh}^{NH}|^2 = |\mathrm{U}_{e3}|^2 \sim 0.022$$
$$|\mathrm{U}_{eh}^{IH}|^2 = |\mathrm{U}_{e2}|^2 \sim 0.3$$

The flux of neutrinos from a supernova

If neutrinos decay...

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

$$|U^2_{e1}|/|U^2_{e3}| \sim 30$$
$$|U^2_{e3}|/|U^2_{e2}| \sim 0.07$$



Simulation details

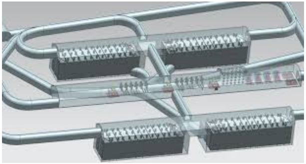
We have focused in the next generation of large neutrino detectors.

The expected number of events at any detector is given by

$$\frac{\mathrm{d}^2 N(E^r,t)}{\mathrm{dt}\,\mathrm{d}E^r} = N_{tg}\int dE^t f_{\nu_\alpha}(E^t,t)\sigma_\alpha(E^t)\epsilon(E^t,E^r)$$

- f_{ν_α} is the neutrino flux at the Earth
- $\sigma_\alpha(E^t)$ is the cross section
- $\epsilon(E^t, E^r)$ correlates the neutrino energy with the energy measured.

Simulation details in DUNE



DUNE is sensitive to ν_e

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

- 40 ktons of liquid argon
- The minimum energy for the neutrino detection of 4 MeV
- The energy resolution consider ($\sim 5\%$ for 10 MeV)

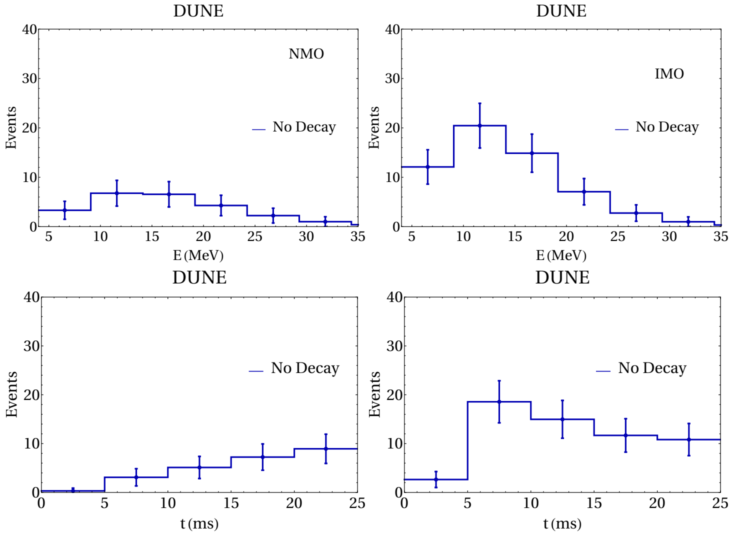
$$\sigma(E) = 0.11\sqrt{E/MeV} + 0.2(E/MeV)$$

[ICARUS (hep-ex/0311040)]

- Bin size of 5 MeV and 5 ms.

Mass ordering

$$|U_{e3}^2|/|U_{e2}^2| \quad \sim \quad 0.07$$



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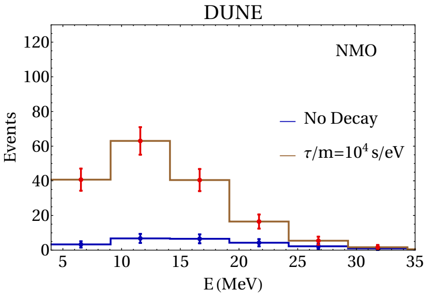

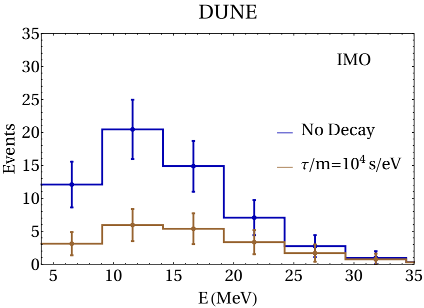

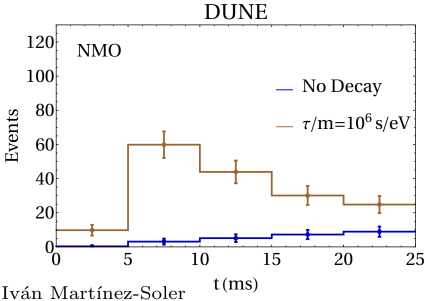

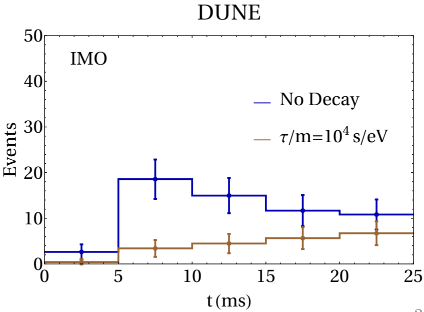

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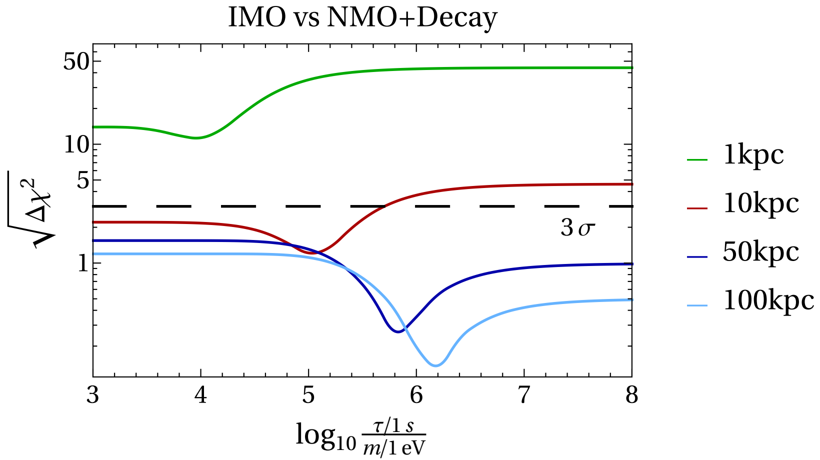

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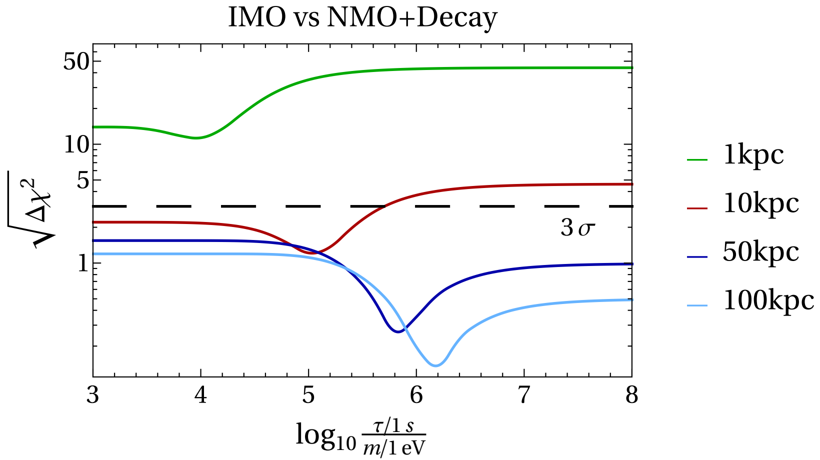


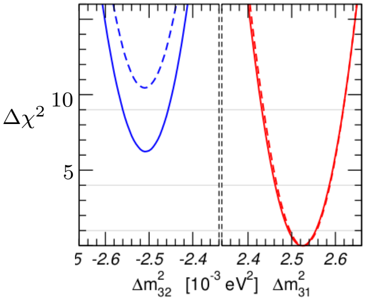
$$\frac{\tau}{m} \lesssim 10^5 \text{ s/eV} \left(\frac{L}{10 \text{ kpc}}\right) \left(\frac{10 \text{ MeV}}{E}\right)$$

Neutrino lifetime

If the ordering is known by the time the supernova happens we can use the supernova data to constrain the neutrino lifetime.

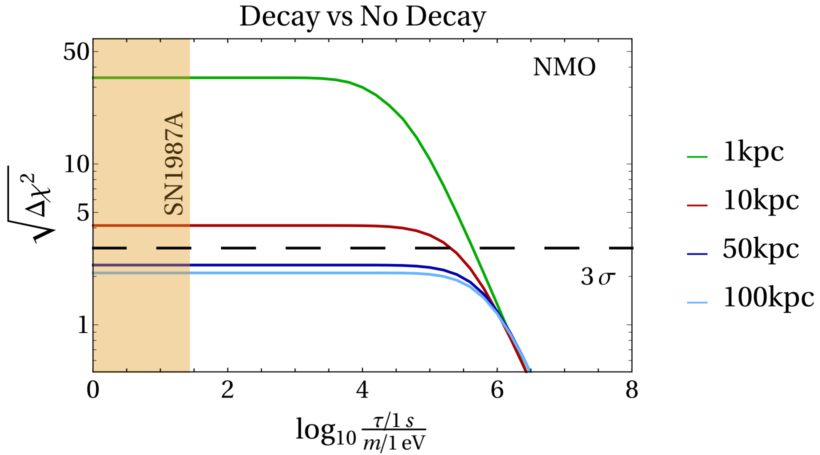
The latest results of global analyses indicate a preference for NMO of 3σ

[Esteban, Gonzalez-Garcia, Hernandez, Maltoni, Schwetz ('18)
Capozzi, Lisi, Marrone and Palazzo ('18)
Salas, Forero, Ternes, Tortola and Valle ('18)]



[NuFIT 4.1 (2019)]

Neutrino lifetime



Majorana neutrinos

If neutrinos are Majorana particles...

$$\mathcal{L}_{Maj} \supset \frac{\tilde{f}_{ij}}{2\Lambda^2}(L_i H)(L_j H)\varphi + \text{h.c.} \supset \frac{f_{ij}}{2}(\nu_L)_i(\nu_L)_j\varphi + \text{h.c.}$$

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

In the limit $m_1/E_1 \to 0$ we can identify the helicity states with the chiral states

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The decay width

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

Majorana neutrinos

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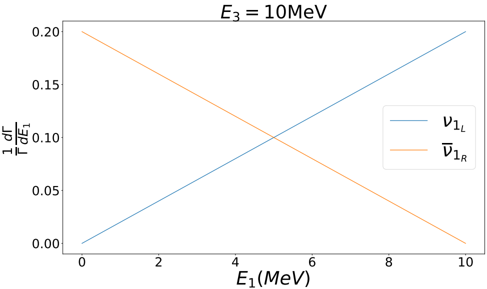
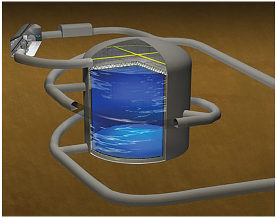


$$\frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2E_1}{E_3^2} \qquad \text{for } \nu_{3_L} \to \nu_{1_L} + \varphi$$

$$\frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2}{E_3}\left(1 - \frac{E_1}{E_3}\right) \qquad \text{for } \nu_{3_L} \to \overline{\nu}_{1_R} + \varphi \ ,$$

To see the effects of decays in Majorana neutrinos we need a detector that measures $\overline{\nu}_e$

Simulation details in Hyper-Kamiokande



HyperK is sensitive to electron-antineutrino via IBD

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

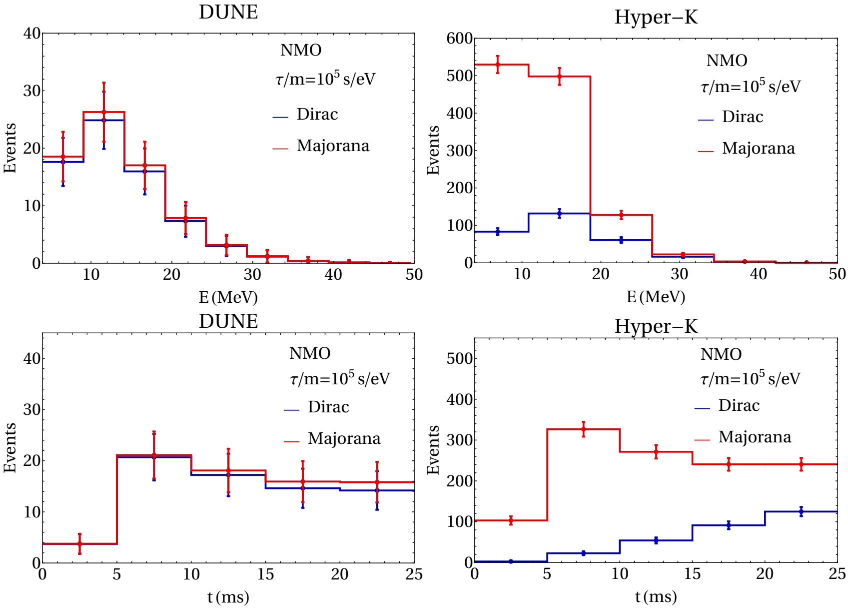
- 2 water tanks of 187 ktons
- The same energy resolution as SuperK (20% for 10 MeV)

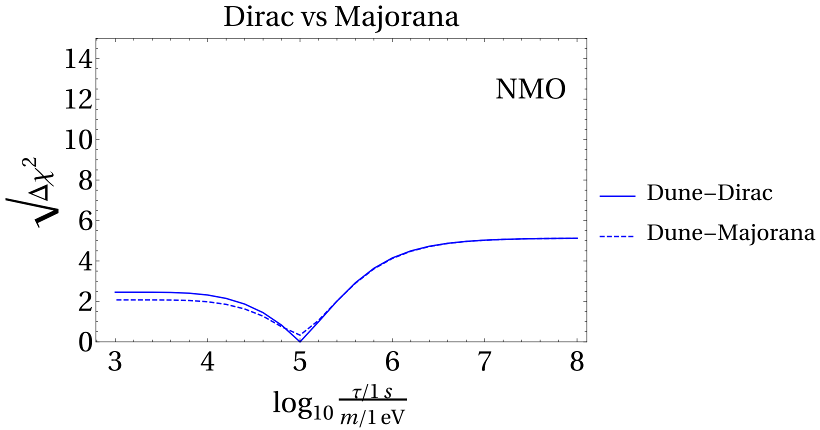
$$\sigma_E = 0.6\sqrt{E/\mathrm{MeV}}$$

[Hyper-Kamiokande (arXiv:1805.04163)]

- Energy threshold of 3 MeV in the prompt energy.
- Bin width is ~ 8 MeV and 5 ms.

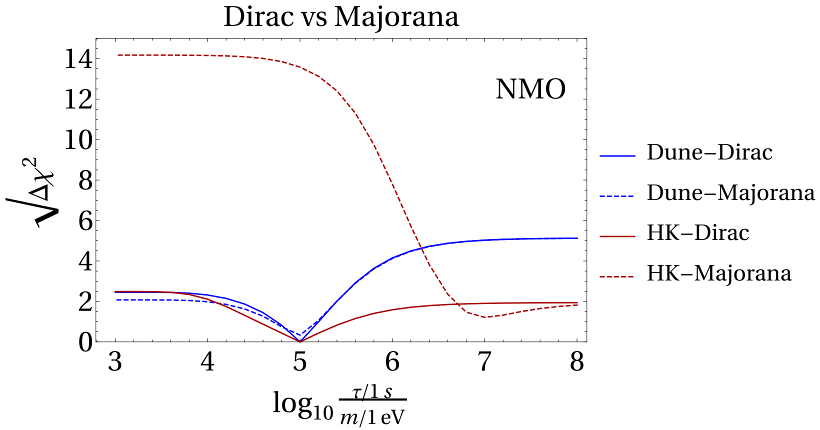
Dirac vs Majorana





$\tau_3/m_3 = (1.0^{+0.6}_{-0.4}) \times 10^5$ s/eV (one sigma)

Dirac vs Majorana



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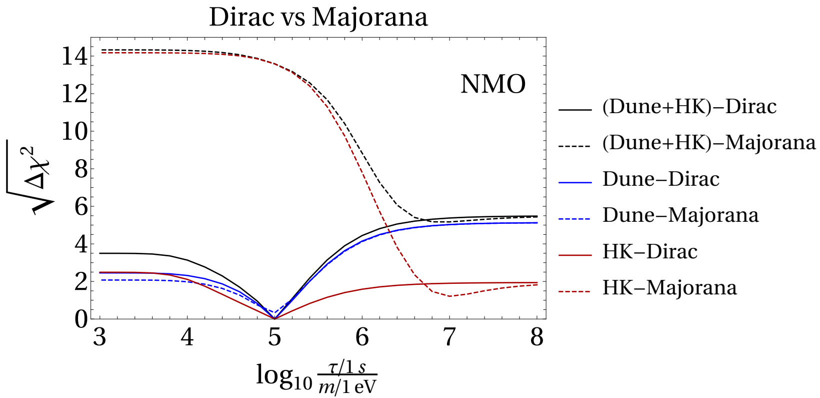

Conclusion

- We study the impact of the decay of the neutrino decay in the neutrinozation-burst flux.
- Neutrinos from SN allow to explore lifetimes of the order of $\tau/m \leq 10^6$ s/eV. HK can probe lifetimes $\tau/m \leq 10^7$ s/eV.
- The event distribution due to a mass ordering can be mimicked by the other mass ordering if the heaviest neutrino decay.
- Combining DUNE and HK would be possible to distinguish a decaying Dirac neutrino from a Majorana neutrino.

Backup: Neutrino decaying into scalar with lepton number 2

If neutrinos are Dirac particles...
$\varphi \equiv \varphi_2$

$$\mathcal{L}_{Dir} \supset \frac{y_{ij}}{2} \nu_i^c \nu_j^c \varphi_2 + \frac{\tilde{h}_{ij}}{2\Lambda^2} (L_i H)(L_j H) \varphi_2^* + \text{h.c}\,,$$

Mediates the decay: $\nu_3 \to \varphi_2 \overline{\nu}_1$

- If $y_{ij} >> h_{ij}$ the helicity of $\overline{\nu}_1$ will be left-handed.
- If $h_{ij} >> y_{ij}$ the helicity of $\overline{\nu}_1$ will be right-handed.