Looking for BSM signals with neutrinos from supernovas

Iván Martínez Soler

Based on: Phys.Rev.D101 (2020) no.4, 043013 (1910.01127)
Phys.Rev.D 102 (2020) 123012 (2007.13748)
and 2105.12736

HET seminar at BNL

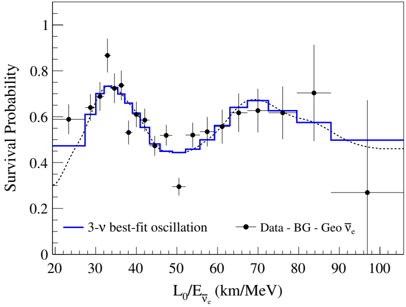
September 2nd, 2021

Fermilab

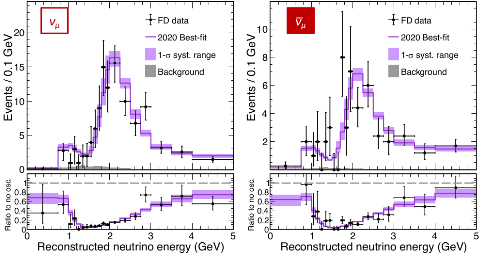
Northwestern University

Neutrinos are massive particles

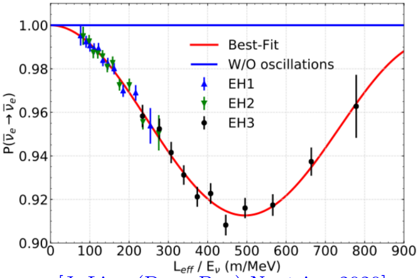
[Gando A., et al. (KamLAND) Phys.Rev.D 88 (2013) 3]



The observation of **neutrino flavor oscillations** shows that neutrinos are **massive particles**.



[A. Himmel (NOvA) Neutrino 2020]



[J. Ling (Daya Bay) Neutrino 2020]

Pseudo-Dirac neutrinos

One of the fundamental questions in neutrino physics is the **origin of the neutrino mass**

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Let's consider a generic mass term

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$$\Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

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- Dirac neutrinos ($M_R = 0$)
- See-saw scenario $M_R >> M_D$
- **Pseudo-Dirac** $M_R << M_D$

Pseudo-Dirac neutrinos

The mass squared matrix $MM^\dagger$ can be diagonalized by

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} U & 0 \\ 0 & U_R \end{pmatrix} \cdot \begin{pmatrix} 1_3 & i \cdot 1_3 \\ \varphi & -i\varphi \end{pmatrix}$$

- U is the 3×3 lepton mixing matrix
- U_R mixing of the sterile sector
- $\varphi = \mathrm{diag}(e^{-i\phi_1}, e^{-i\phi_2}, e^{-i\phi_3})$ asociated to $U_R^t M_R U_R$

The active neutrinos can be written as a supperposition of the two mass eigenstates

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_{js} + i\, \nu_{ja})$$

Pseudo-Dirac neutrinos

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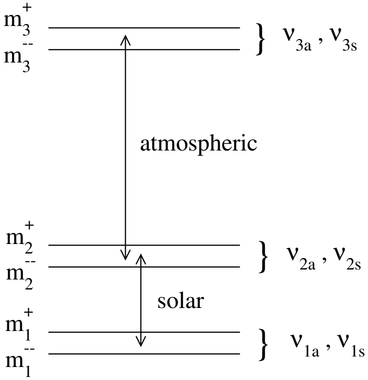
The masses are given by

$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$
$$m_{ka}^2 = m_k^2 - \frac{1}{2}\delta m_k^2$$

$$\delta m^2 \sim M_D M_R$$



[Beacom, Bell, Hooper, Learned, Pakvasa and Weiler (0307151)

Pseudo-Dirac neutrinos

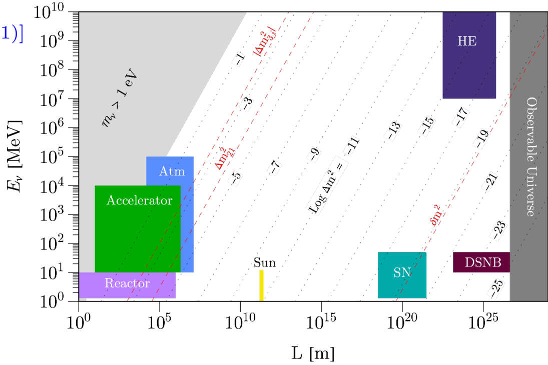
Limits on δm_k^2

- Solar neutrinos: $\delta m_k^2 \leq 10^{-12}\text{eV}^2$

[de Gouvea, Huang and Jenkins (0906.1611)]

- Atmospheric neutrinos: $\delta m_k^2 \leq 10^{-4}\text{eV}^2$

- Hig-energy astrophysical neutrinos: $10^{-18}\text{eV}^{-2} \leq \delta m_k^2 \leq 10^{-12}\text{eV}^2$



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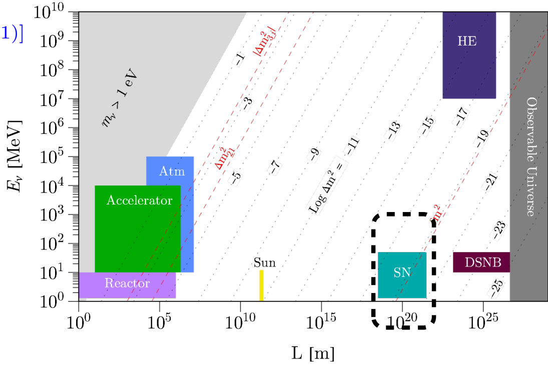
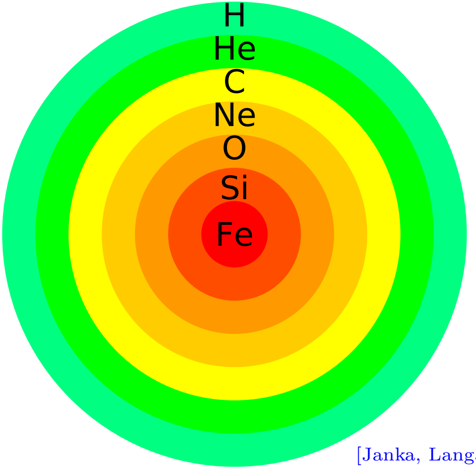


[Beacom, Bell, Hooper, Learned, Pakvasa and Weiler (0307151)]

Core-collapse supernova

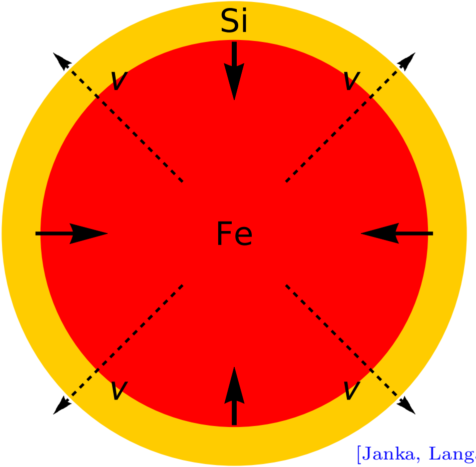
At the end of a massive star $M > 8M_{\odot}$



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

Core-collapse supernova

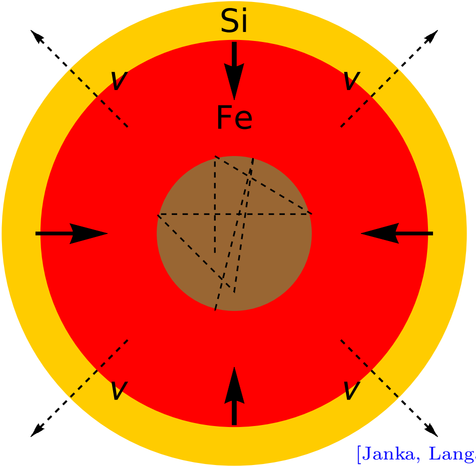
For $M_c \sim 1.44 M_\odot$, the electron pressure cannot stabilize the core



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

Core-collapse supernova

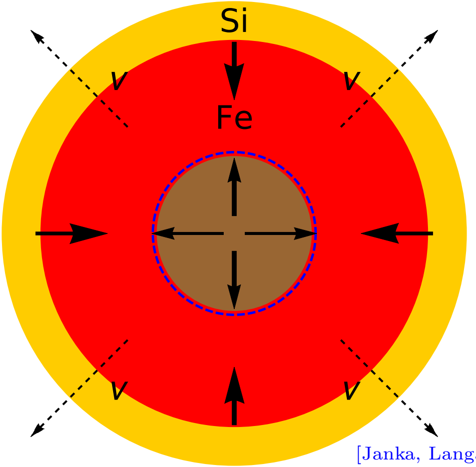
For densities $\rho \sim 10^{12}\text{g/cm}^3$ neutrinos become trapped in the core.



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

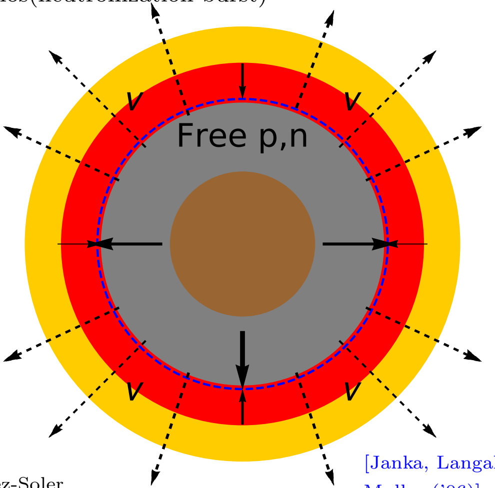
Core-collapse supernova

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)]

- 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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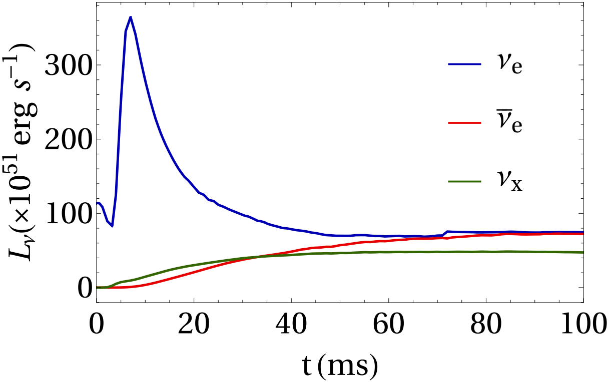
In a supernova, a large flux of neutrinos is emitted.



Neutrino spectrum from a SN

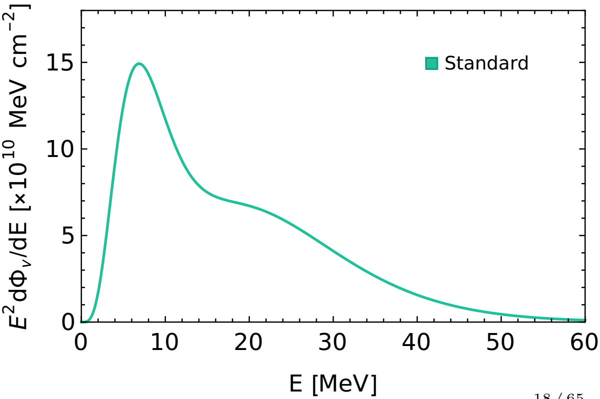
The energy neutrino spectra from a SN can be parameterized by the alpha-fit

$$\phi_\beta(E) = \frac{1}{E_{0\beta}} \frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)} \left(\frac{E}{E_{0\beta}}\right)^\alpha e^{-(\alpha+1)\frac{E}{E_{0\beta}}}$$

The $\overline{\nu}_e$ fluence at the Earth (standard case)

$$\frac{d\Phi_e}{dE} = \frac{E_{tot}}{4\pi d^2}\left(\overline{p}\frac{\phi_e}{E_{0e}} + (1-\overline{p})\frac{\phi_x}{E_{0x}}\right)$$

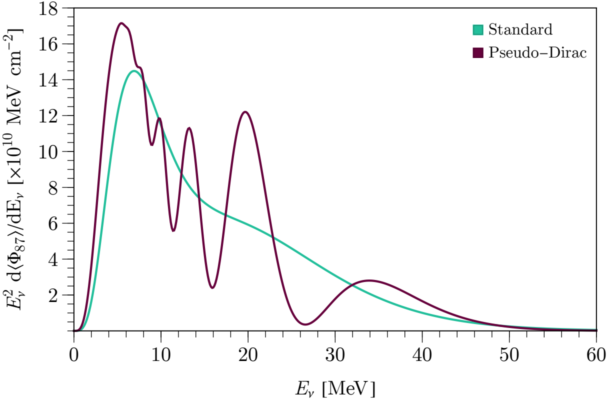
$\overline{p} = |U_{e1}|^2$



Neutrino spectrum from a SN

If neutrinos are pseudo-Dirac particles, the fluence at the Earth

$$\frac{d\Phi_e}{dE} = \frac{E_{tot} P_{aa}}{4\pi d^2} \left(\overline{p} \frac{\phi_e}{E_{0e}} + (1 - \overline{p}) \frac{\phi_x}{E_{0x}} \right) \qquad P_{aa} = \frac{1}{2} \left(1 + e^{-\left(\frac{L}{L_{\rm coh}}\right)^2} \cos\left(\frac{2\pi L}{L_{\rm osc}} \right) \right)$$



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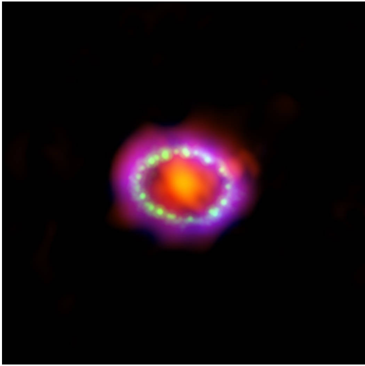
$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \approx 20 \text{ kpc} \left(\frac{E_\nu}{25 \text{ MeV}} \right) \left(\frac{10^{-19} \text{ eV}^2}{\delta m^2} \right)$$

$$L_{\rm coh} = \frac{4\sqrt{2} E_\nu}{|\delta m^2|} (E_\nu \sigma_x) \approx 114 \text{ kpc} \left(\frac{E_\nu}{25 \text{ MeV}} \right)^2 \left(\frac{10^{-19} \text{ eV}^2}{\delta m^2} \right) \left(\frac{\sigma_x}{10^{-13} \text{ m}} \right),$$

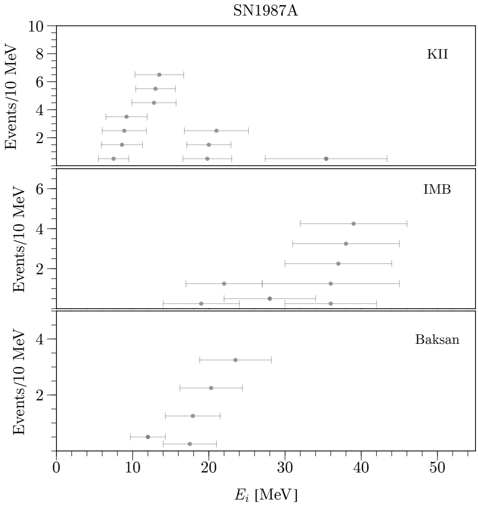
SN1987A

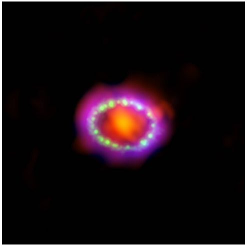


- Type II supernova
- ~ 50 kpc (Large Magellanic Cloud)
- $\sim 20 M_{\odot}$

SN1987A

Several neutrino detectors observed the SN1987A





- It was detected the $\overline{\nu}_e$ component of the flux
- Detection happened via IBD

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

SN1987A: Analysis

Due to the small number of events, we used an unbinned likelihood

$$\mathscr{L} = e^{-N_{\rm tot}} \prod_{i}^{N_{\rm obs}} dE_i \left[\frac{dS}{dE_i} + \frac{dB}{dE_i} \right]$$

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The detector response is given by

$$\frac{dS}{dE_i} = N_{tgt} \int dE_e dE_\nu \eta(E_e) G(E_e - E_i, \sigma(E_e)) \frac{d\sigma_{IBD}}{dE_e} \frac{d\Phi_e}{dE_\nu}$$

- $\eta(E_e)$: detector effiency
- $G(E_e - E_i, \sigma(E_e))$: Gaussian uncertainty in the reconstruction of the electron energy

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Background spectrum

The detector response is given by

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- $\eta(E_e)$: detector effiency
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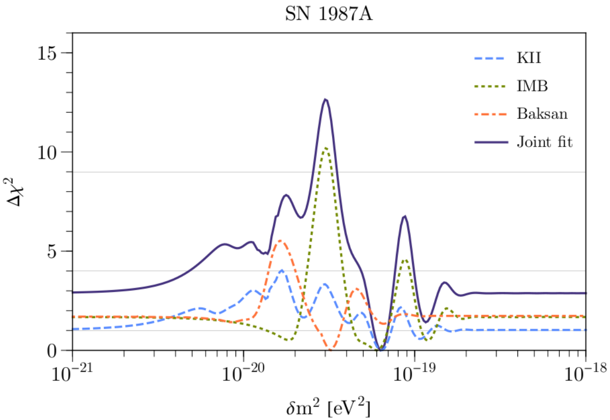
SN1987A: Result

SN1987A allows the exploration of $\delta m^2 \sim 10^{-20}\text{eV}^2$ for the first time.



In the analysis:

- $\sigma_x = 10^{-13}$m and $\alpha = 2.3$ are fixed
- E_{tot}, $E_{0,e}$ and $E_{0,x}$ are free parameters

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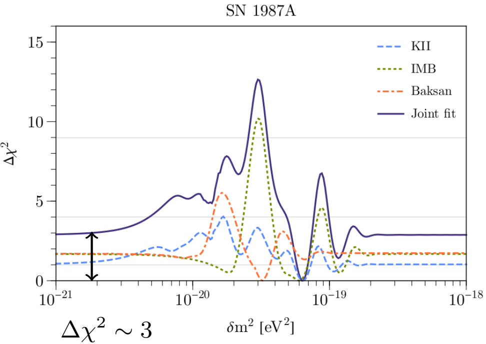

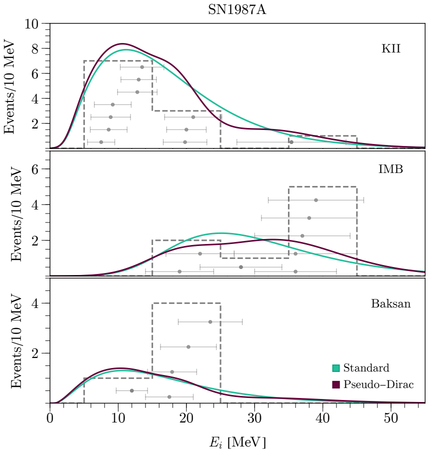

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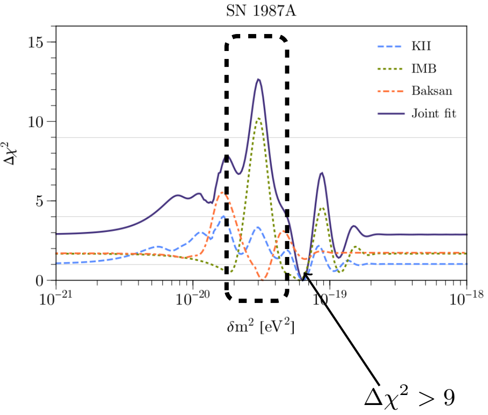
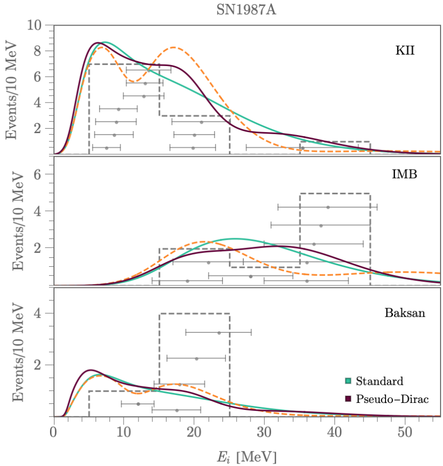
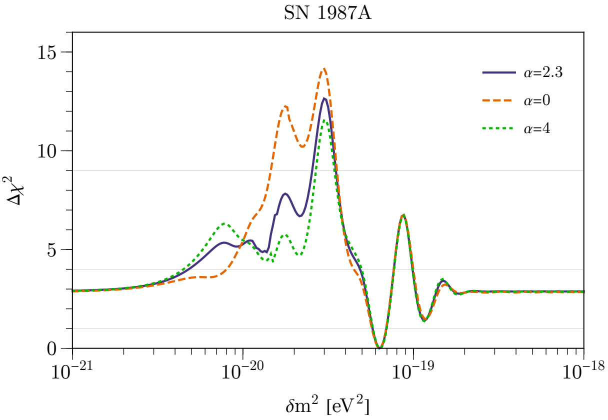




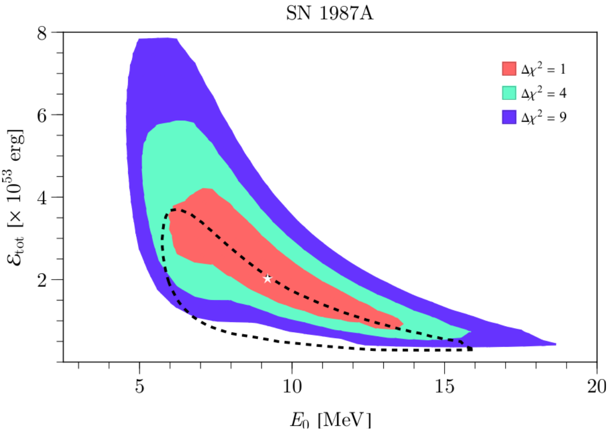
SN1987A: Result

There is not a strong dependence on the pinching parameter (α)

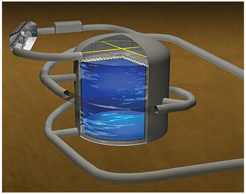


SN1987A: Result

The flux parameter in the standard and the pseudo-Dirac scenario are compatibles



Pseudo-Dirac: Future sensitivity



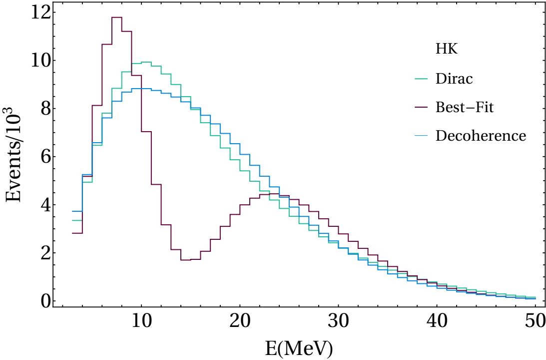
Hyper-K is sensitive to $\overline{\nu}_e$ via IBD

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

- Fiducial volume: 187 ktons
- The same energy resolution as Super-K for solar neutrinos

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

- Energy threshold of 3 MeV.
- Bin width is 1 MeV.



[Hyper-Kamiokande (arXiv:1805.04163)]

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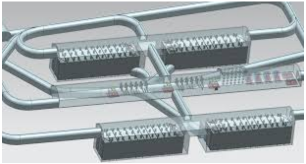


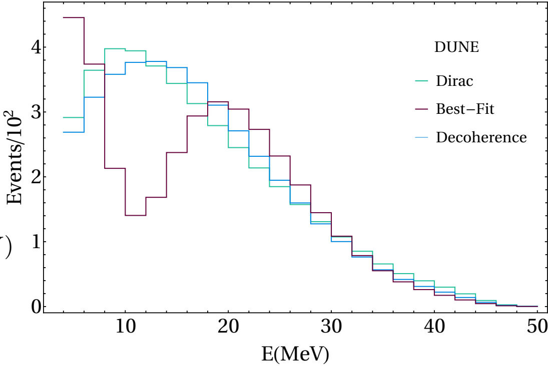
DUNE is sensitive to ν_e

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

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

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

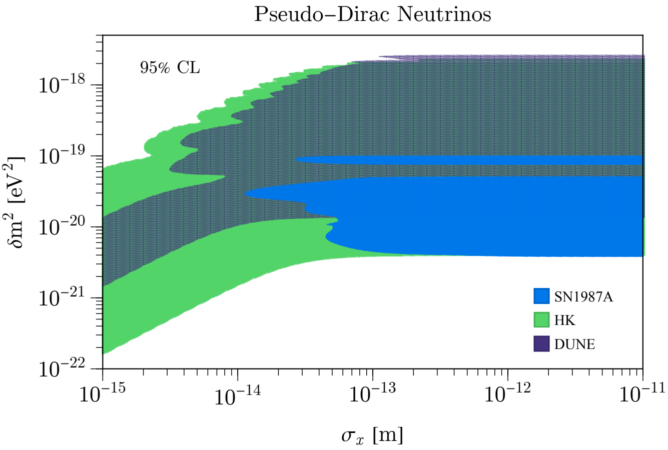
- Bin size of 2 MeV.



[ICARUS (hep-ex/0311040)]

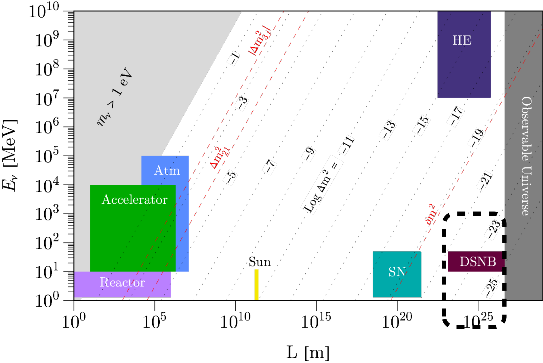
Pseudo-Dirac: Future sensitivity

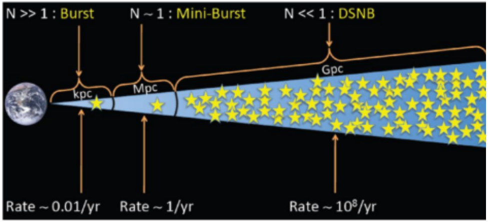
The **next generation** of experiments will be able to explore a large fraction of the pseudo-Dirac scenario.



DSNB neutrinos

- CCNe are very rare events
- **DSNB** is a continous source of astrophysical neutrinos
  - All the past CCSN in the observable universe.
  - Isotropic and time independent





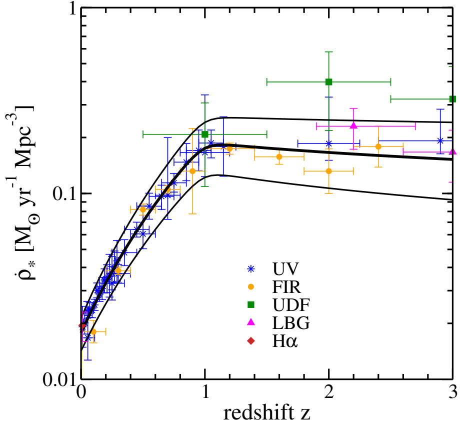
[Beacom TAUP 2011]

DSNB Flux

The rate of the CCSN is given by

$$R_{\mathrm{CCSN}}(z) = \dot{\rho}_*(z)\,\frac{\int_8^{50}\psi(M)\,dM}{\int_{0.1}^{100}M\psi(M)\,dM}$$

$$\psi \sim M^{-2.35}$$



Fit of the co-moving SFR

$$\dot{\rho}_*(z) = \dot{\rho}_0\left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B}\right)^{-10\,\beta} + \left(\frac{1+z}{C}\right)^{-10\,\gamma}\right]^{-1/10}$$

[Horiuchi, Beacom, Qwek (2009)]

$$\begin{aligned} B &= (1+z_1)^{1-\alpha/\beta} \\ C &= (1+z_1)^{(\beta-\alpha)/\gamma}(1+z_2)^{1-\beta/\gamma} \end{aligned}$$

DSNB Flux

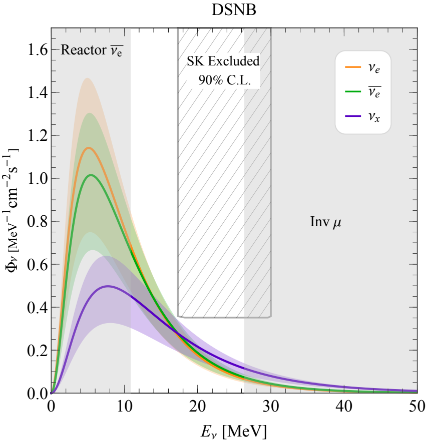
The diffuse neutrino flux is given by

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z) F_\nu(E')$$

The neutrino energy spectra is consider as a Fermi-Dirac distribution

$$F_\nu(E) = \frac{E_\nu^{\mathrm{tot}}}{6} \frac{120}{7\pi^4} \frac{E_\nu^2}{T_\nu^4} \frac{1}{e^{E_\nu/T_\nu} + 1}$$

$$T_{\nu_e} < T_{\overline{\nu}_e} < T_{\nu_x}$$



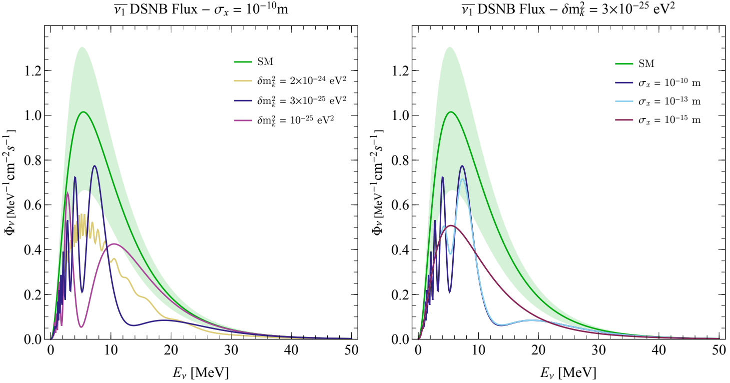
The hubble is given by

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1 - \Omega_m - \Omega_\Lambda)(1+z)^2}$$

Pseudo-Dirac neutrinos: DSNB

The DSNB allow to explore Gpc distances

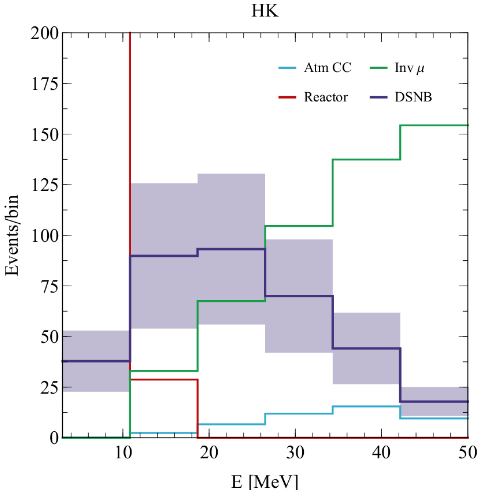
- Explore tiny δm_k^2
- Decoherence effects are important



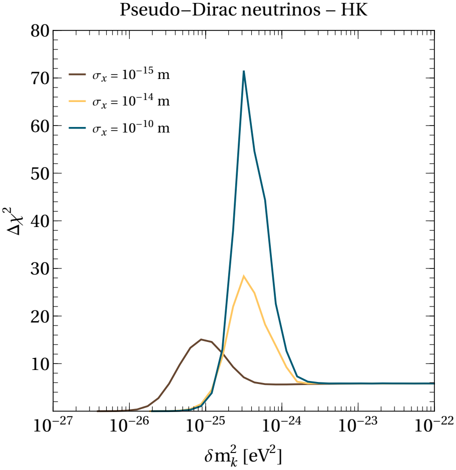
Detection of DSNB

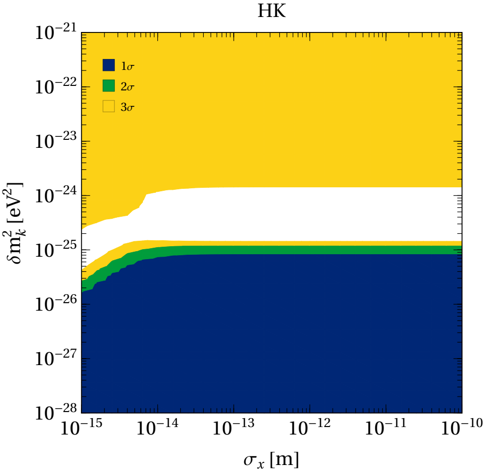
Expected number of events for a Water dopped with gadolinium detector (**GADZOOKS**):

- Main detection channel IBD
- Highly affected by the background
  - $E_\nu < 10$ MeV: $\overline{\nu}_e$ from reactors.
  - $E_\nu > 10$ MeV: muon-spallation, $\overline{\nu}_e$ from the atmosphere, invisible muon decays, neutral currents.
- Neutron tagging to reduce the background



Pseudo-Dirac neutrinos: DSNB





Neutrino decay

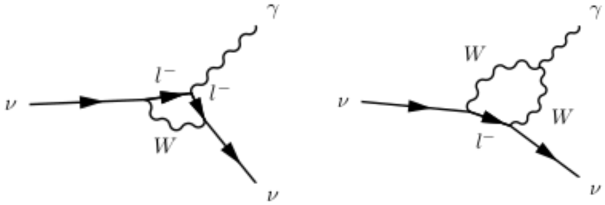
The discovery that the neutrinos have a non-zero mass lead to question other properties like its **lifetime**

Neutrino decay

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)]



Neutrino decay

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

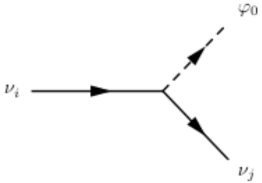
[Pakvasa and Valle ('03), Pal and Wolfenstein ('82), Petcov, Marciano and Sanda ('77)]

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 $g_{ij} = g_{ji}$.

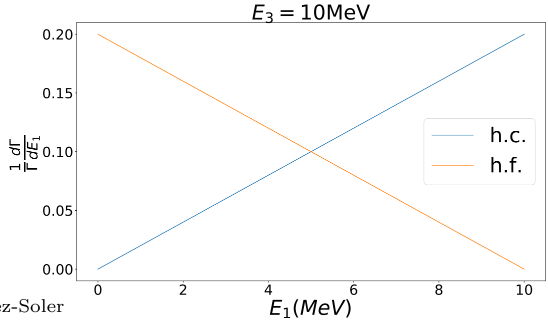
Neutrino decaying into a scalar

The decay width is

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

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

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



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

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

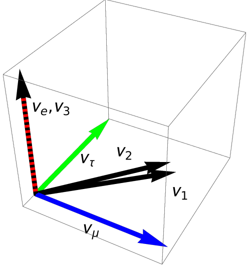
We can translate that limit on the lifetime that can be explored with supernova neutrinos

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

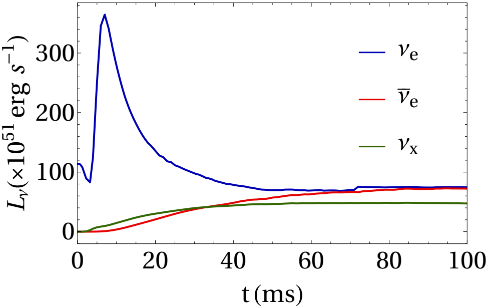
Bounds on neutrinos lifetime

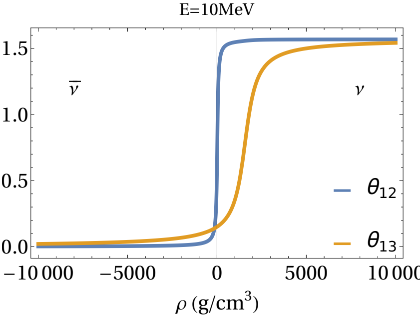
- Bound from solar ν $\tau_2/m_2 \geq 10^{-3} s/\text{eV}$ and $\tau_1/m_1 \geq 10^{-4} s/\text{eV}$
  [SNO (1812.01088)
  Berryman, de Gouvea, Hernandez (1411.0308)]
- Bound from atmospheric data $\tau_3/m_3 \geq \times 10^{-10} s/\text{eV}$
  [Gonzalez-Garcia and Maltoni (0802.3699)
  Gomes, Gomes and Peres (1407.5640)]
- Bounds from CMB data $\tau_\nu > 4 \times 10^{8}\text{s}(\text{m}_\nu/0.005\text{eV})^3$
  [Escudero and Fairbairn (1907.05425)
  Chacko, Dev, Du, Poulin and Tsai (1909.05275)]
- Bounds from SN1987A (Majoron) $\tau_\nu/m_3 > 3 \times 10^{1}\text{s}/\text{eV}$
  [Kachelriess, Tomas and Valle (0001039)
  Farzan ('02)]

Neutrino decay: Supernova neutrino flux



The ν_e produced inside a supernova coincides with the **heavy neutrino state**

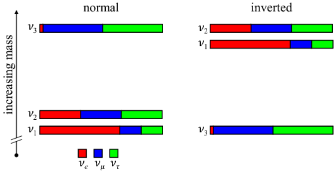




[Denton, Minakata, Parke ('16)]

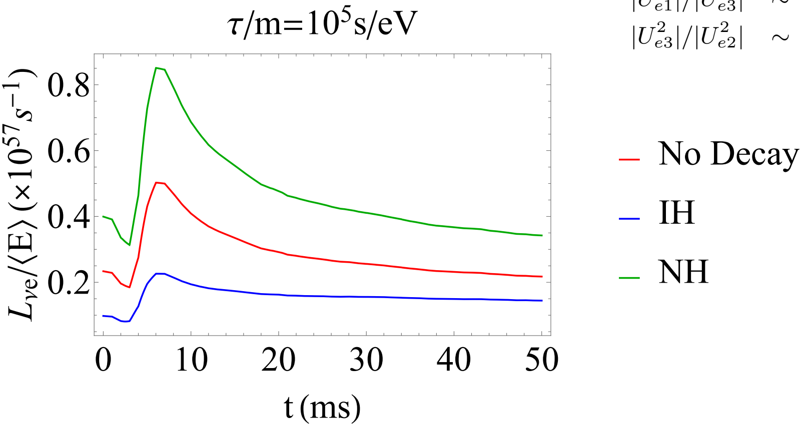
Neutrino decay: Supernova neutrino flux

If neutrinos decay...



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

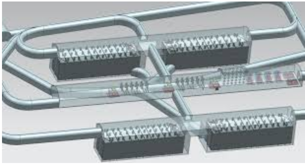
Out[∘]=

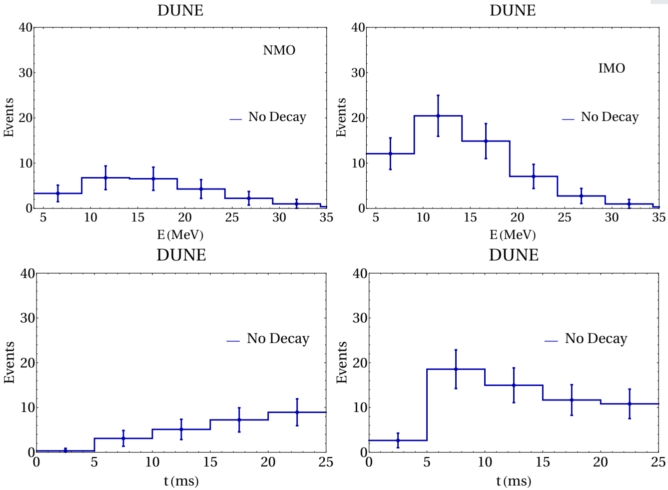


Neutrino decay: Mass ordering

The ν_e distribution expected in DUNE is

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

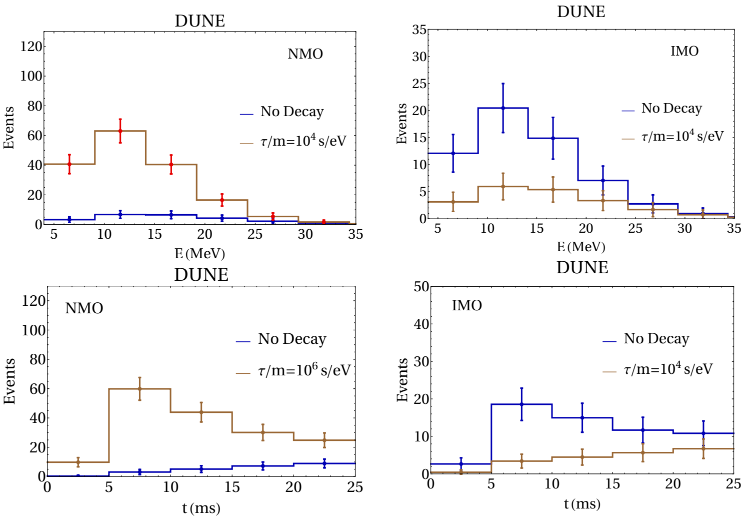




$$|U_{e3}^2|/|U_{e2}^2| \sim 0.07$$

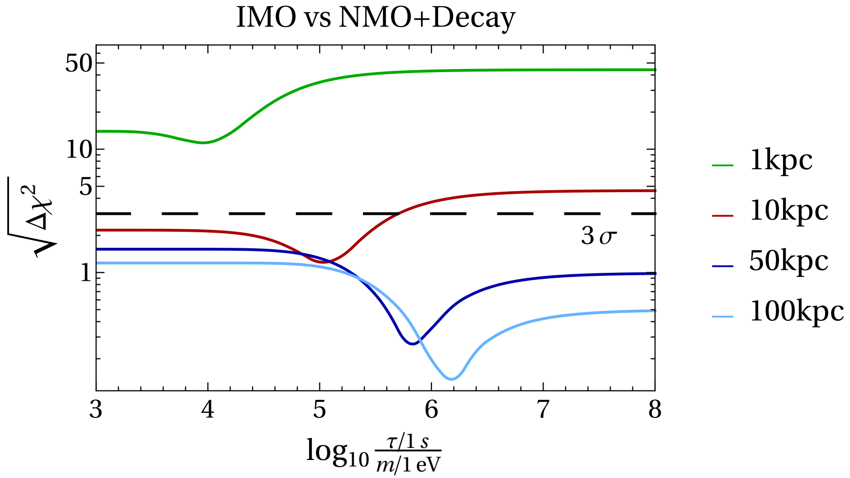
Neutrino decay: Mass ordering

If the **neutrinos decay**, the number of events **increase (decrease) for NMO (IMO)**



Neutrino decay: Mass ordering

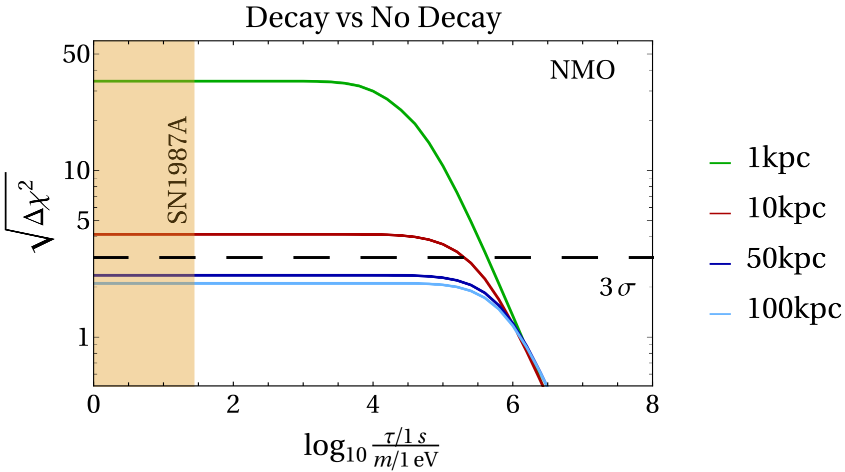
The sensitivity to the **mass ordering is reduced** if the neutrino decay



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

Neutrino lifetime

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



Neutrino decay: Majorana particles

If neutrinos are Majorana particles...

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

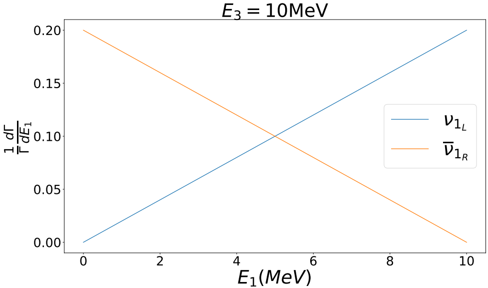
$$\nu_{3_L} \to \nu_{1_L} + \varphi \qquad\qquad \nu_{3_L} \to \overline{\nu}_{1_R} + \varphi$$

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

Neutrino decay: Majorana particles

If neutrinos are Majorana particles

The decay width



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

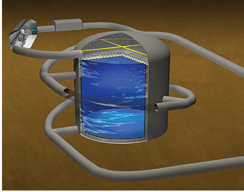
$$\frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2E_1}{E_3^2} \qquad \text{for } \nu_{3_L} \to \nu_{1_L} + \varphi$$

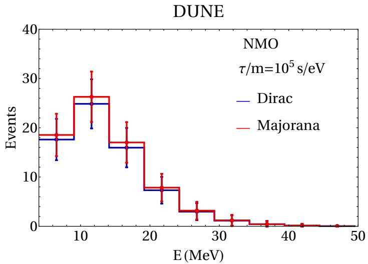
$$\frac{1}{\Gamma}\frac{d\,\Gamma}{d\,E_1} = \frac{2}{E_3}\left(1 - \frac{E_1}{E_3}\right) \qquad \text{for } \nu_{3_L} \to \overline{\nu}_{1_R} + \varphi\ ,$$

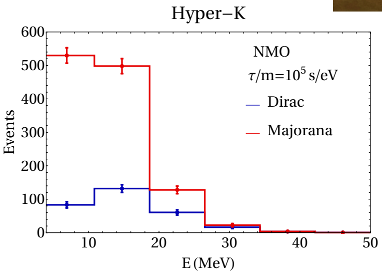
To see the effects of decays in Majorana neutrinos we need a detector that measures $\overline{\nu}_e$

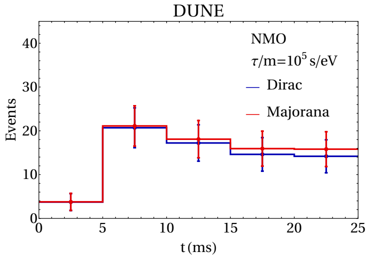
Dirac vs Majorana

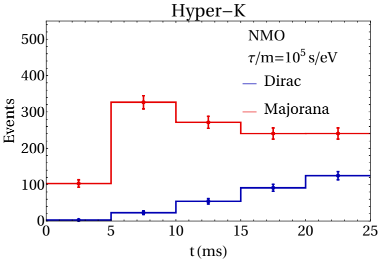
If the neutrino decay, **Hyper-K** would be able to differenciate between **Dirac or Majorana** neutrinos

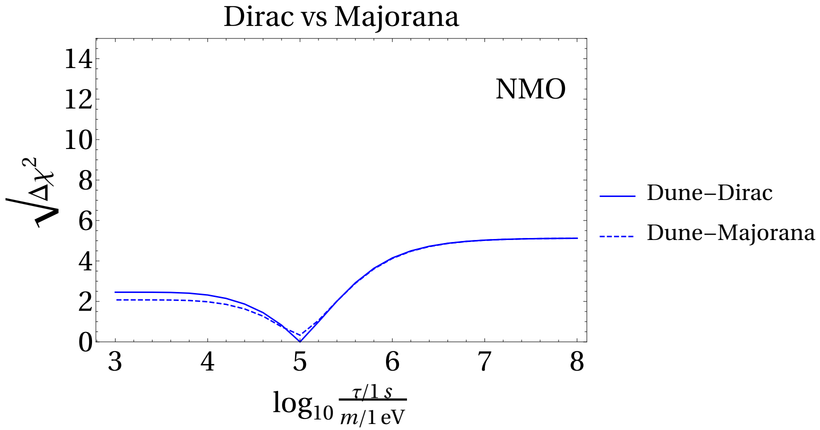




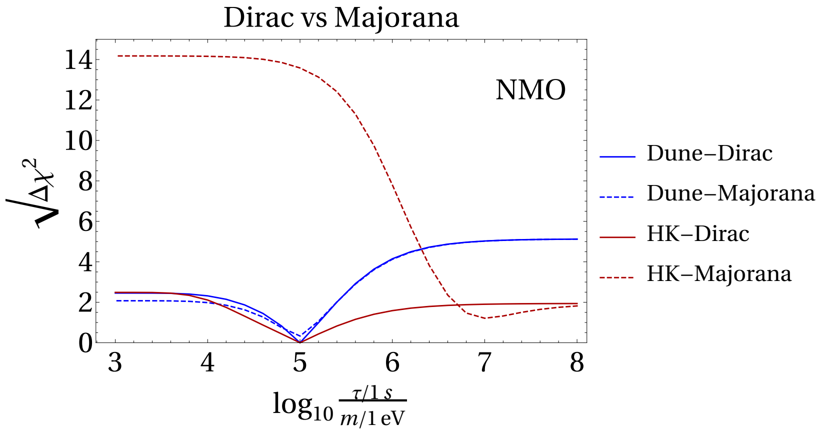




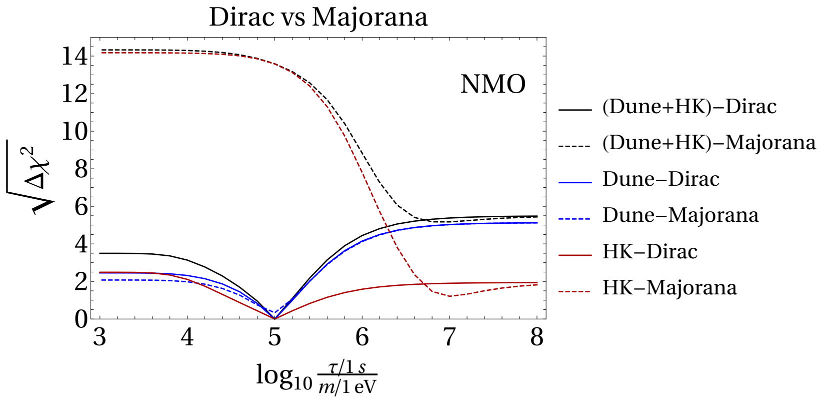




$\tau_3/m_3 = (1.0^{+0.6}_{-0.4}) \times 10^5$ s/eV (one sigma)


Dirac vs Majorana
NMO
14
12
10
8
6
4
2
0
3
4
5
6
7
8
$\sqrt{\Delta\chi^2}$
$\log_{10}\frac{\tau/1\,s}{m/1\,\mathrm{eV}}$
Dune−Dirac
Dune−Majorana
HK−Dirac
HK−Majorana

Dirac vs Majorana



Conclusion

We studied the impact of two BSM scenarios in neutrinos from SN:
Neutrino decay and **pseudo-Dirac fermions**

Pseudo-Dirac neutrinos:

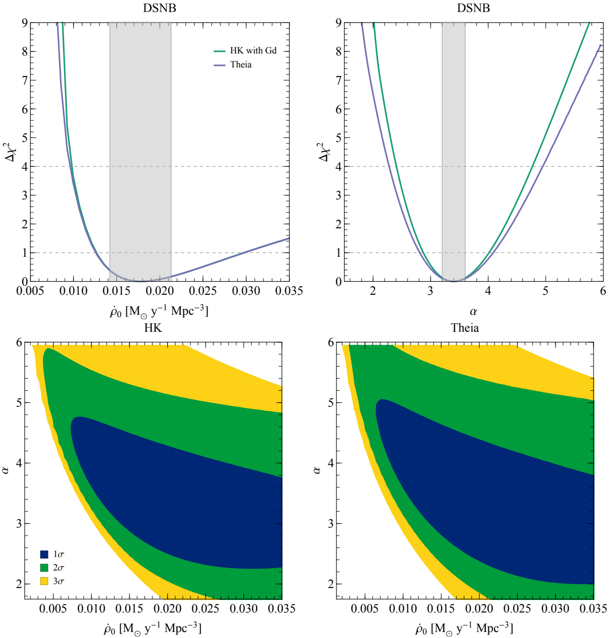
- **Analysis of SN1987A:**
  - Mild preference for pseudo-Dirac neutrinos.
  - Exclusion of $2.55 \times 10^{-20}\text{eV}^2 \leq \delta m^2 \leq 3 \times 10^{-20}\text{eV}^2$ at $\Delta \geq 9$.
- The **next generation of experiments** will be able to explore this scenario by the detection of **CCSN or DSNB**

Neutrino decay:

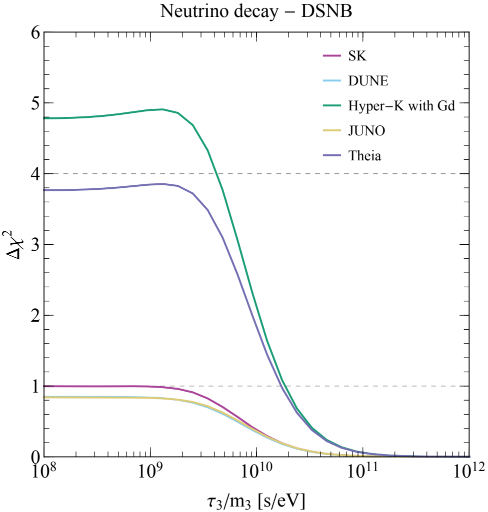
- Neutrinos from SN allow to **explore lifetimes on the order of** $\tau/m \leq 10^6$ **s/eV**. HK can probe lifetimes $\tau/m \leq 10^7$ s/eV.
- Neutrino decay can **reduce the sensitivity to the neutrino mass ordering**.
- Combining DUNE and HK would be possible to distinguish a decaying Dirac neutrino from a Majorana neutrino.

Thanks!

Backup: Measuring the SFR with neutrinos



Neutrino decay with the DSNB



$$\frac{\tau}{m} \lesssim 10^{10}\ \mathrm{s/eV} \left(\frac{L}{1\ \mathrm{Gpc}}\right) \left(\frac{10\ \mathrm{MeV}}{E}\right)$$