Searching for Pseudo-Dirac Neutrinos in Supernovas

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arXiv:2105.12736

AstroDark-2021

December 8th, 2021

Neutrino masses

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Let's consider a generic mass term

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

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

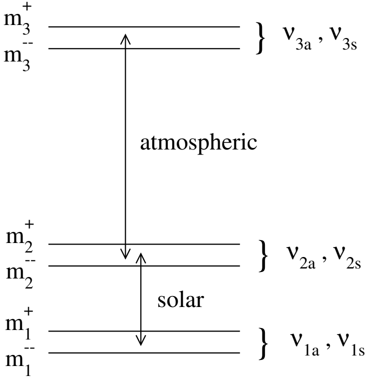
$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_{js} + i\,\nu_{ja})$$

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)]

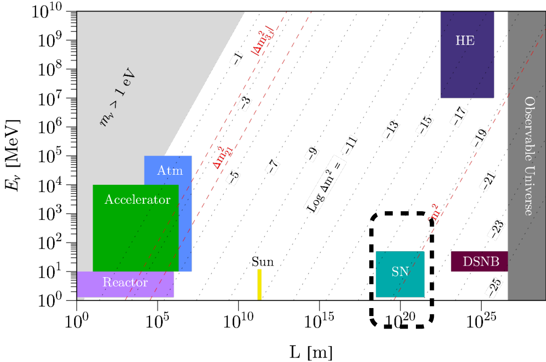
- Atmospheric neutrinos: $\delta m_k^2 \leq 10^{-4}\text{eV}^2$

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

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

- DSNB: $10^{-25}\text{eV}^{-2} \leq \delta m_k^2 \leq 10^{-23}\text{eV}^2$

[de Gouvea, IMS, Perez-Gonzalez and Sen (2007.13748)]



Neutrino spectrum from a SN

See Mori's talk

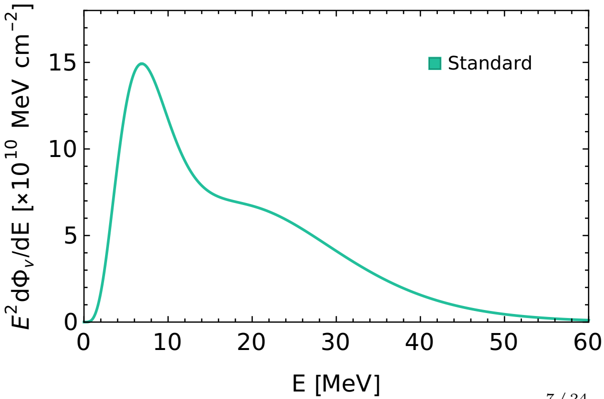
The time-integrated neutrino spectra from a SN can be parameterized by the alpha-fit

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

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

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

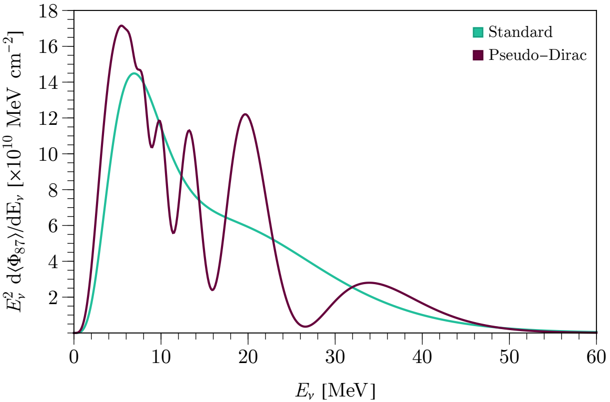
$\overline{p} = |U_{e1}|^2$



Neutrino spectrum from a SN

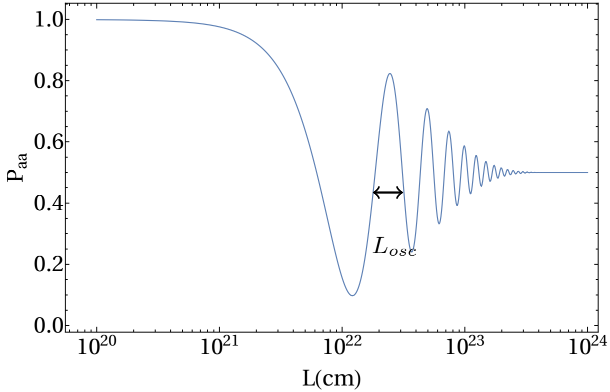
If neutrinos are pseudo-Dirac particles, the fluence at the Earth

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



Neutrino spectrum from a SN

$$P_{aa} = \frac{1}{2}\left(1 + e^{-\left(\frac{L}{L_{\rm coh}}\right)^2}\cos\left(\frac{2\pi L}{L_{\rm osc}}\right)\right)$$



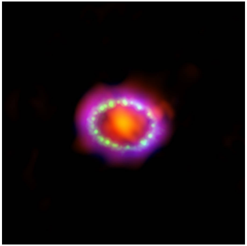
$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \approx 20 \text{ kpc}\left(\frac{E_\nu}{25 \text{ MeV}}\right)\left(\frac{10^{-19}\text{ eV}^2}{\delta m^2}\right)$$

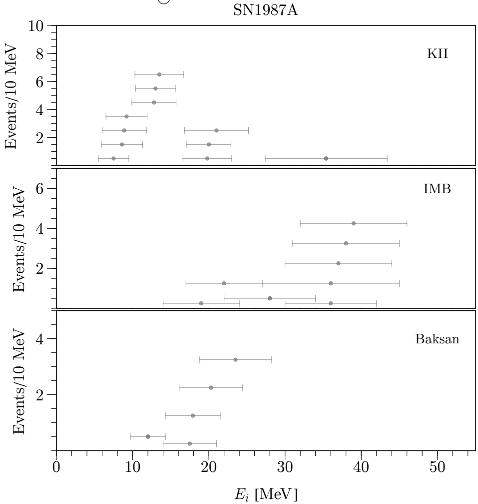
$$L_{\rm coh} = \frac{4\sqrt{2}E_\nu}{|\delta m^2|}(E_\nu\sigma_x) \approx 114 \text{ kpc}\left(\frac{E_\nu}{25 \text{ MeV}}\right)^2\left(\frac{10^{-19}\text{ eV}^2}{\delta m^2}\right)\left(\frac{\sigma_x}{10^{-13}\text{ m}}\right),$$

SN1987A

Several neutrino detectors observed the SN1987A

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





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

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

SN1987A: Analysis

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

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

Background spectrum

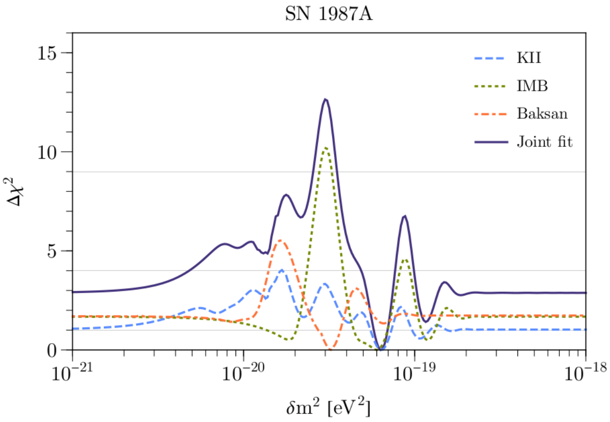
The detector response is given by

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

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

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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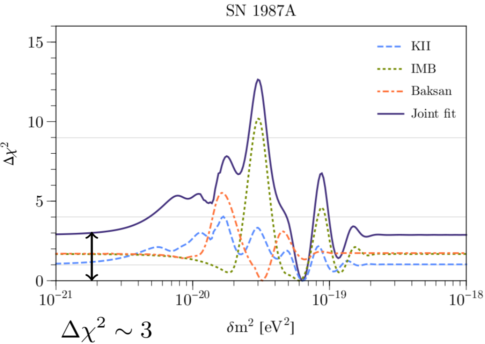
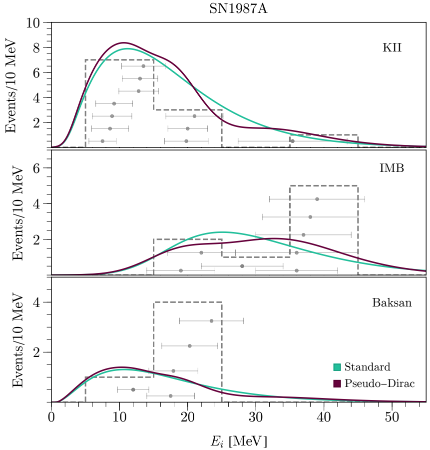


$\Delta\chi^2 \sim 3$



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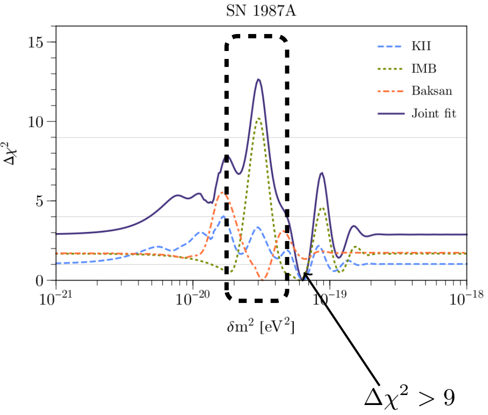
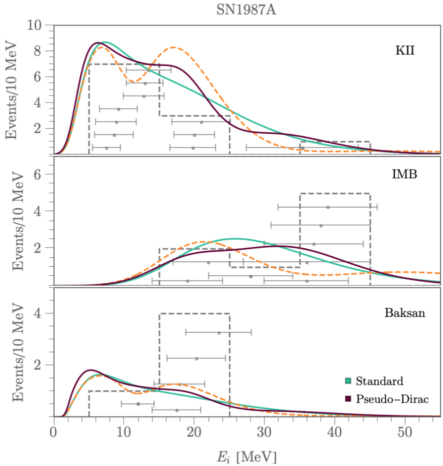
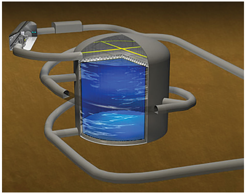




Future sensitivity



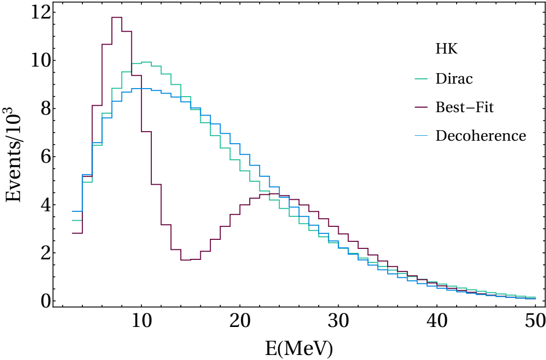
Hyper-K is sensitive to $\overline{\nu}_e$ via IBD

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

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

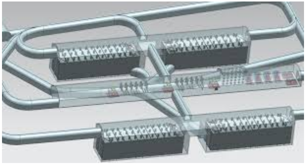
$$\sigma_E = 0.6\sqrt{E/\mathrm{MeV}}$$

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



[Hyper-Kamiokande (arXiv:1805.04163)]

Future sensitivity



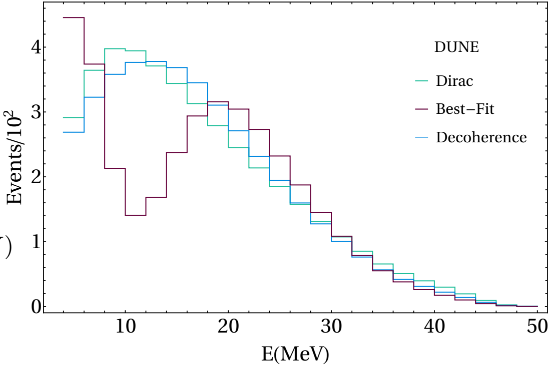
DUNE is sensitive to ν_e

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

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

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

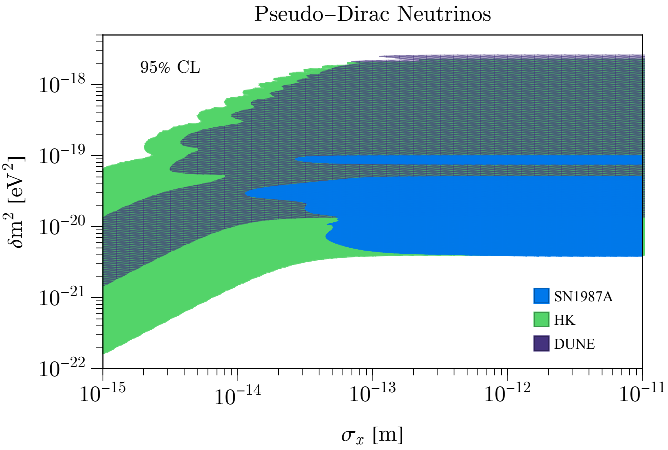
- Bin size of 2 MeV.



[ICARUS (hep-ex/0311040)]

Future sensitivity

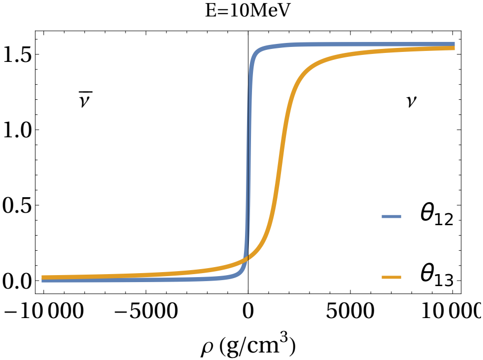
The **next generation** of experiments will be able to explore a large fraction of the pseudo-Dirac scenario.

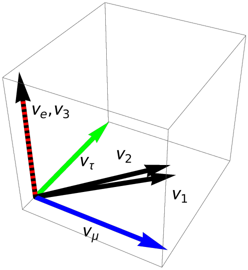


Conclusion

- In this work, we search for signals of **pseudo-Dirac** neutrinos on the **supernova** neutrino flux.
- Analysis of **SN1987A**:
  - Mild preference for pseudo-Dirac neutrinos
  - Exclude $2.55 \times 10^{-20}\text{eV}^2 \leq \delta m^2 \leq 3 \times 10^{-20}$ at $\Delta\chi^2 \geq 9$.
- The **next generation of experiments** will be able to explore this scenario with large precision.

Back up: Neutrino spectrum from the SN



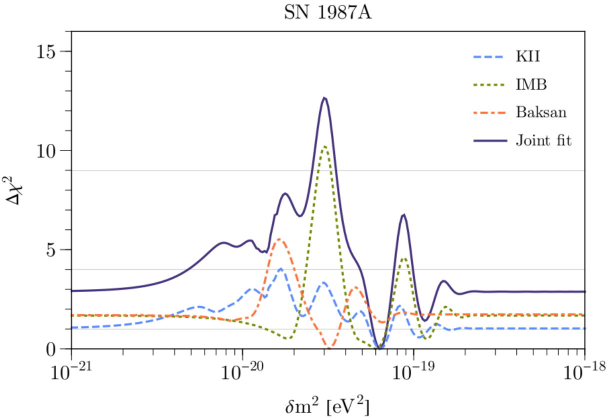


[Denton, Minakata, Parke ('16)]

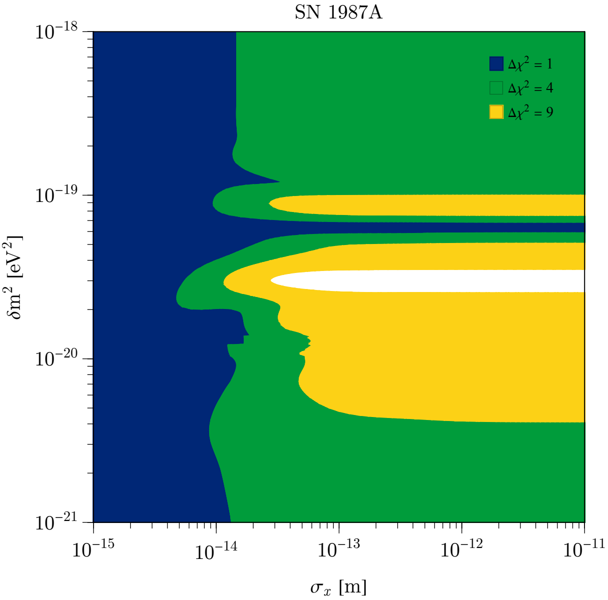
Back up: SN1987A Result

Experiment(s)	$\mathcal{E}_{\text{tot}}$	E_{0e}	E_{0x}	δm^2
KII	2.2	4.24	10.96	6.31
IMB	3.2	1.36	12.86	6.03
Baksan	15.7	4.28	8.03	3.16
Joint Fit	2.7	4.00	12.61	6.31

Best-Fit values of the flux parameteres



Back up: SN1987A Result



Backup: Pseudo-Dirac neutrinos

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

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

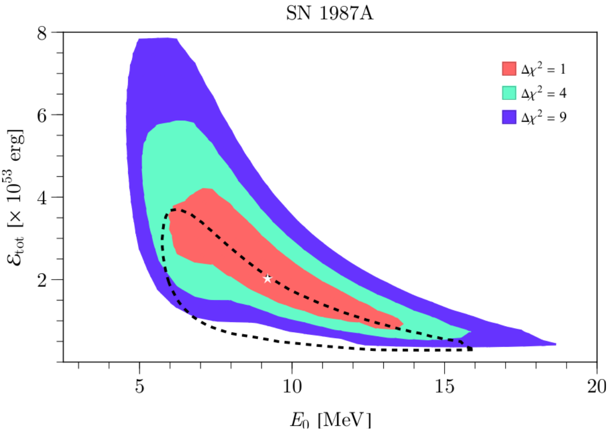
- U is the 3×3 lepton mixing matrix
- U_R mixing of the sterile sector
- $\varphi = \mathrm{diag}(e^{-i\phi_1}, e^{-i\phi_2}, e^{-i\phi_3})$ asociated to $U_R^t M_R U_R$

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

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

Backup: pseudo-Dirac vs standard mixing scenario

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



Backup: Dependence on α

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