BSM Searches and Supernovae

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In collaboration with: André de Gouvêa, Yuber Perez-Gonzalez and Manibrata Sen

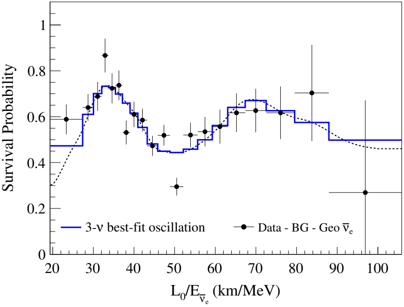
Interdisciplinary Developments in Neutrino Physics

March 30, 2022

Based on: Phys.Rev.D 102 (2020) 123012 (2007.13748) and 2105.12736

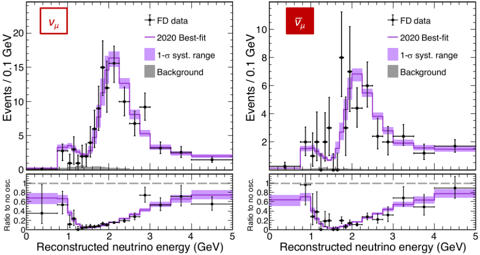
Neutrinos are massive particles

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

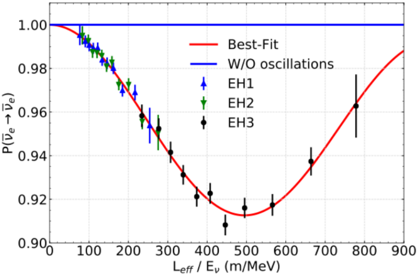


The observation of **neutrino flavor oscillations** shows that neutrinos are **massive particles**.

See Callum, Zoya, Leigh, Michael, Karsten... Talk



[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**

Pseudo-Dirac neutrinos

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Let's consider a generic mass term

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\Psi_L^t C M \Psi_L \qquad \Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

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

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- **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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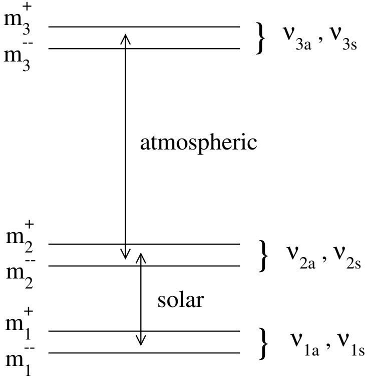
The masses are given by

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

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

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



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

Pseudo-Dirac neutrinos

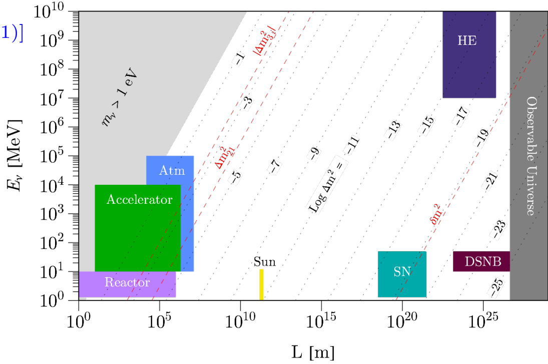
Limits on δm_k^2

- 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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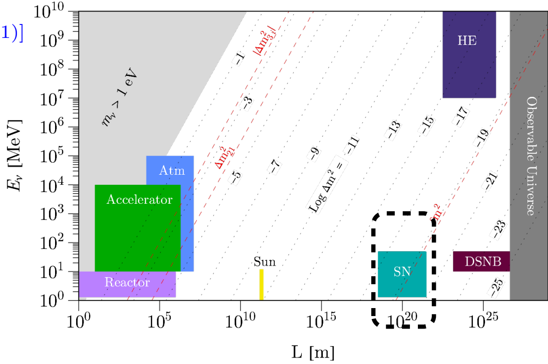

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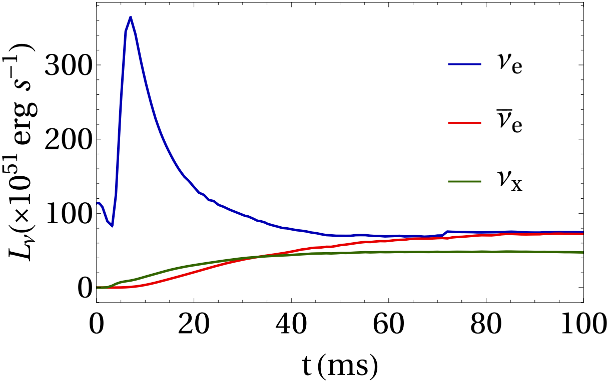
Neutrino spectrum from the SN

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



See George Fuller's Talk

Neutrino spectrum from a SN

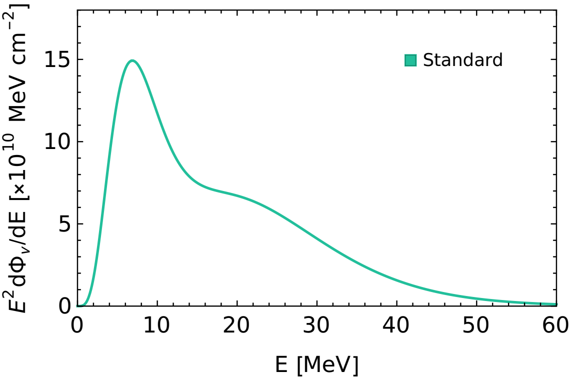
The energy neutrino spectra from a SN can be parameterized by the alpha-fit

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

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

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

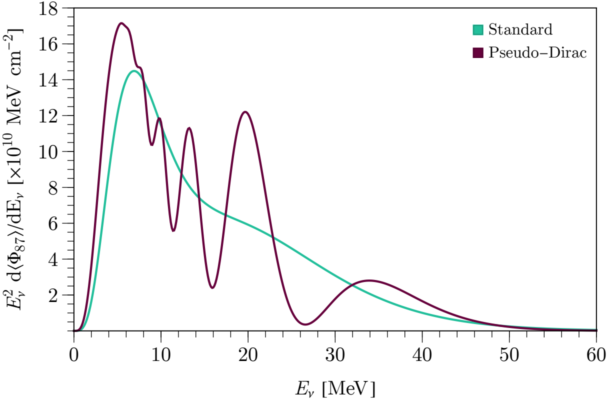
$\overline{p} = |U_{e1}|^2$



Neutrino spectrum from a SN

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

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



Neutrino spectrum from a SN

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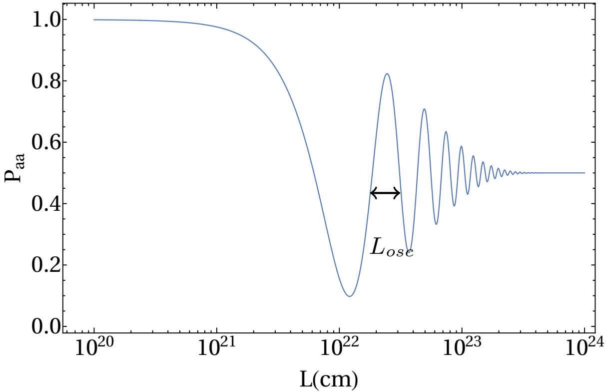
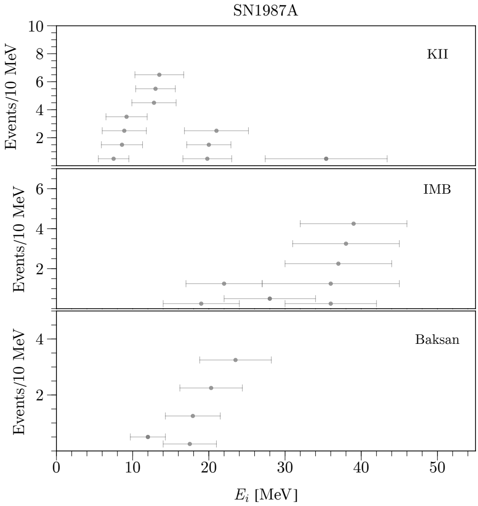
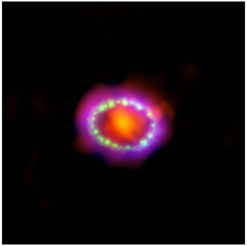


$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \qquad L_{\rm coh} = \frac{4\sqrt{2}E_\nu}{|\delta m^2|}(E_\nu \sigma_x)$$

SN1987A

Several neutrino detectors observed the SN1987A





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

SN1987A: Analysis

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

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

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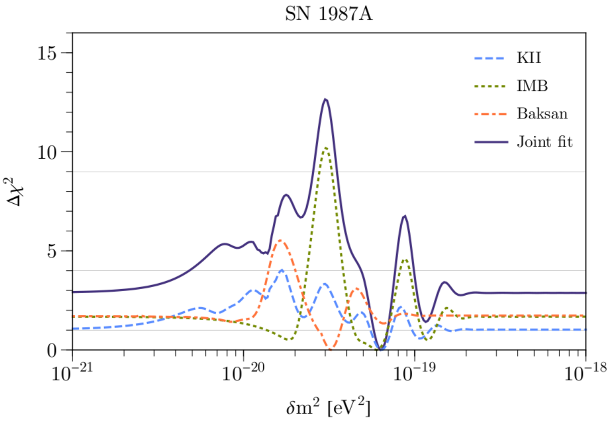
- $\eta(E_e)$: detector effiency
- $G(E_e - E_i, \sigma(E_e))$: Gaussian uncertainty in the reconstruction of the electron energy

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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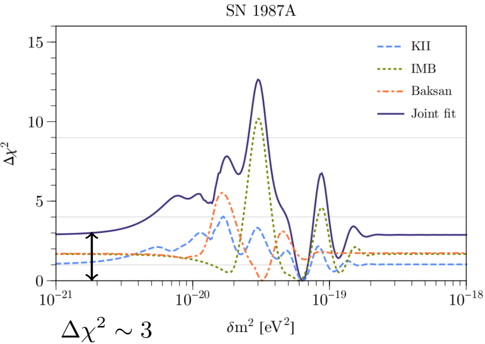
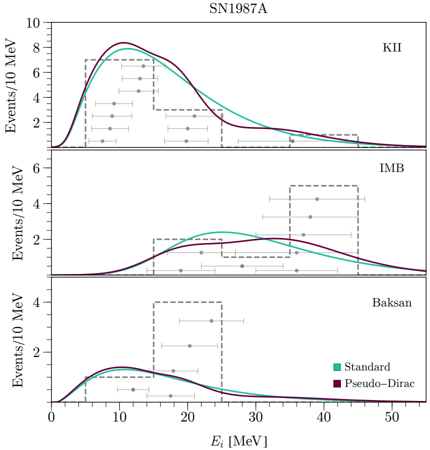


$\Delta\chi^2 \sim 3$



SN1987A: Result

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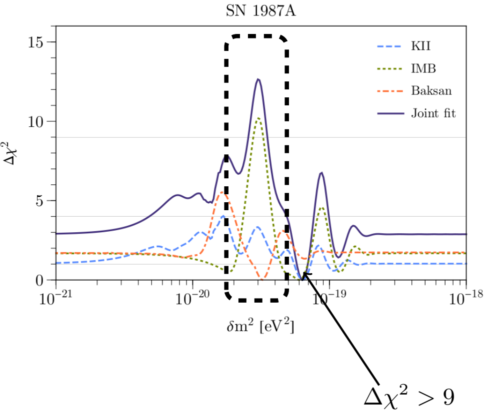
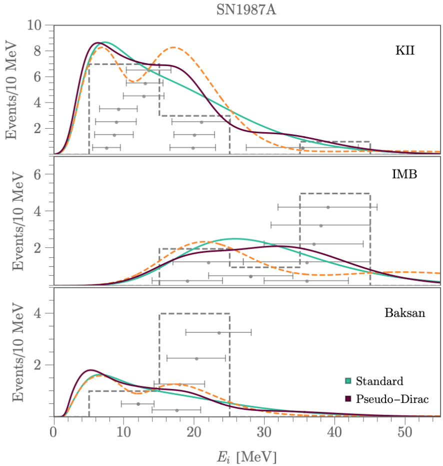
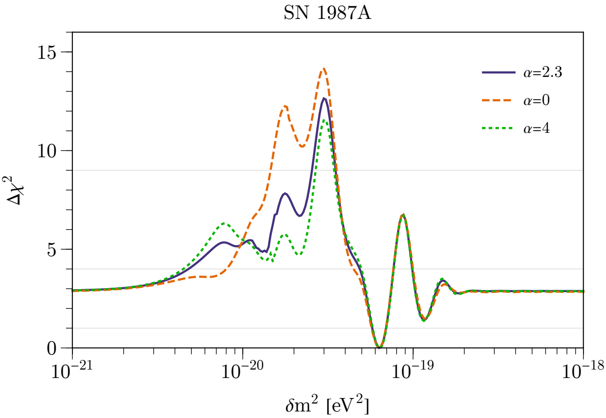




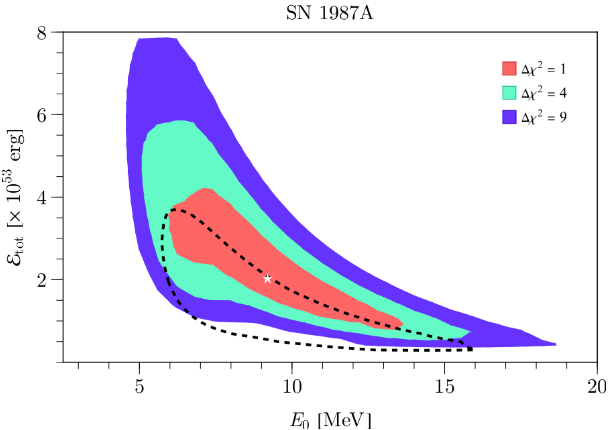
SN1987A: Result

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



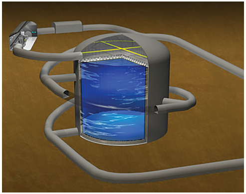
SN1987A: Result

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



Pseudo-Dirac: Future sensitivity

See Michael Smy's Talk



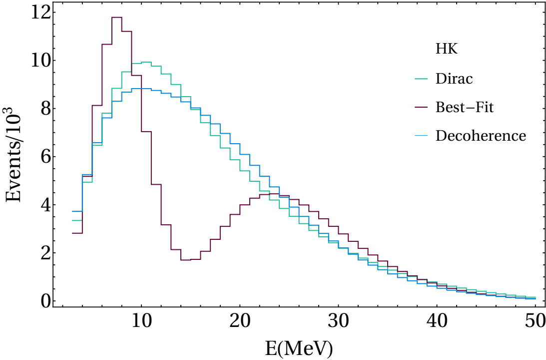
Hyper-K is sensitive to $\overline{\nu}_e$ via IBD

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

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

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

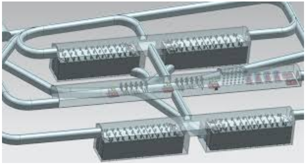
- Energy threshold of 3 MeV.
- Bin width is 1 MeV.



[Hyper-Kamiokande (arXiv:1805.04163)]

Pseudo-Dirac: Future sensitivity

See Leigh Whitehead's Talk



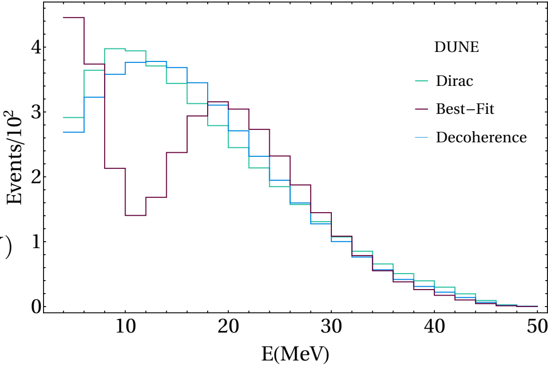
DUNE is sensitive to ν_e

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

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

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

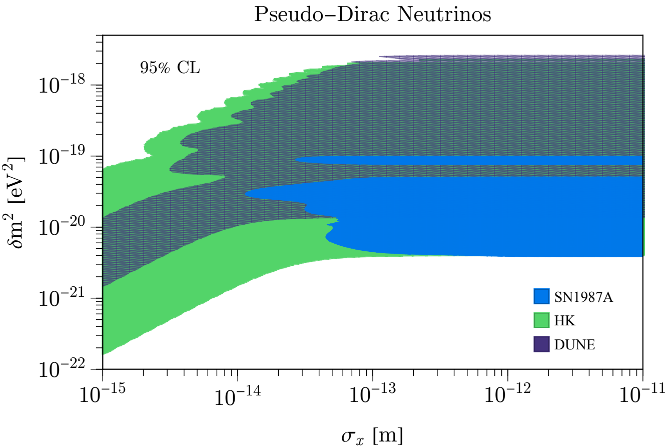
- Bin size of 2 MeV.



[ICARUS (hep-ex/0311040)]

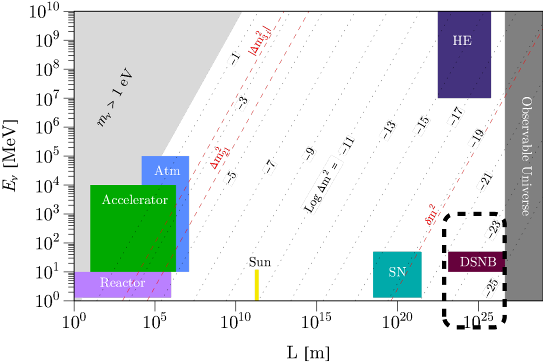
Pseudo-Dirac: Future sensitivity

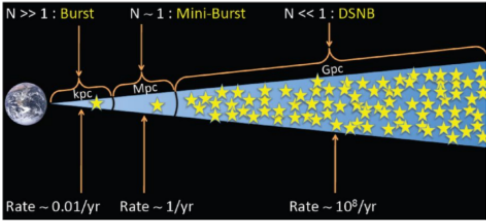
The **next generation** of experiments will be able to explore a large fraction of the pseudo-Dirac scenario.



DSNB neutrinos

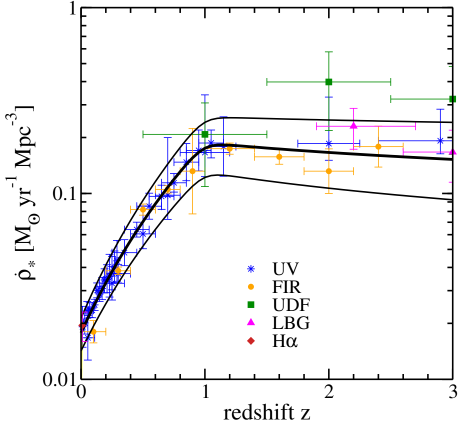
- CCNe are very rare events
- **DSNB** is a continous source of astrophysical neutrinos
  - All the past CCSN in the observable universe.
  - Isotropic and time independent





[Beacom TAUP 2011]

DSNB Flux



The rate of the CCSN is given by

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

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

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)]

$$B = (1+z_1)^{1-\alpha/\beta}$$

$$C = (1+z_1)^{(\beta-\alpha)/\gamma}(1+z_2)^{1-\beta/\gamma}$$

DSNB Flux

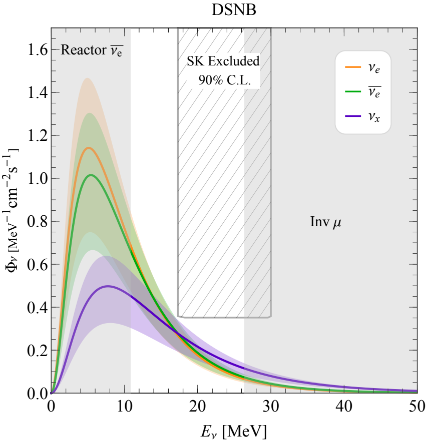
The diffuse neutrino flux is given by

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

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

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

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



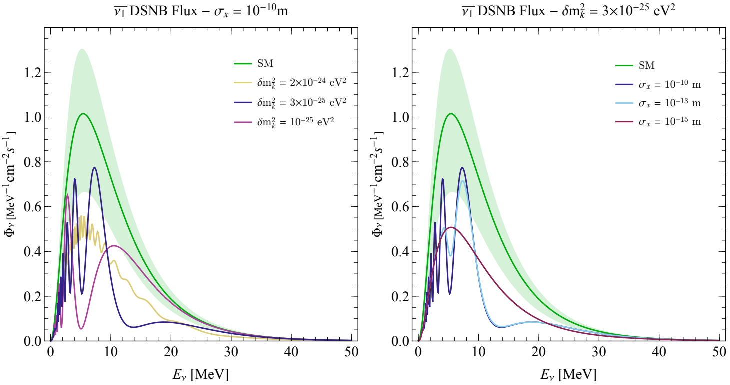
The hubble is given by

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

Pseudo-Dirac neutrinos: DSNB

The DSNB allow to explore Gpc distances

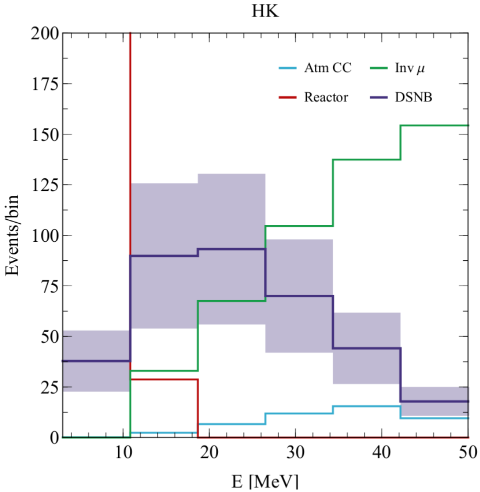
- Explore tiny δm_k^2
- Decoherence effects are important



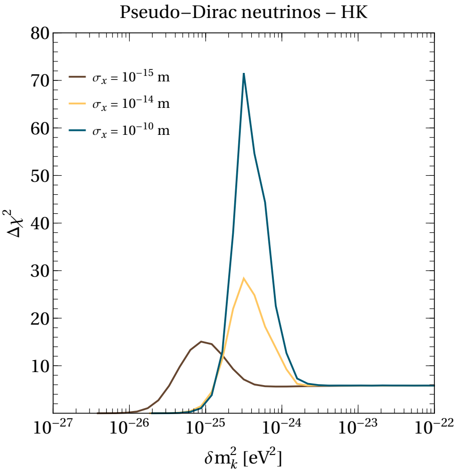
Detection of DSNB

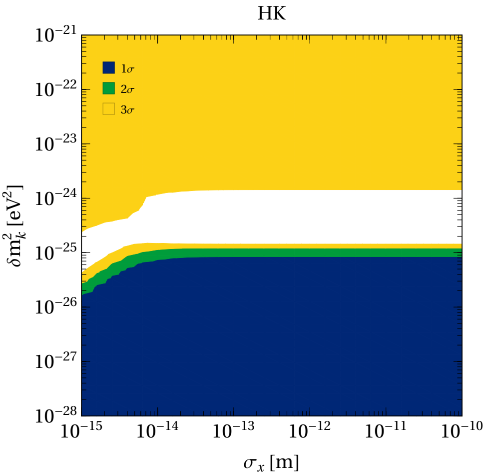
Expected number of events for a Water dopped with gadolinium detector (**GADZOOKS**):

- 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



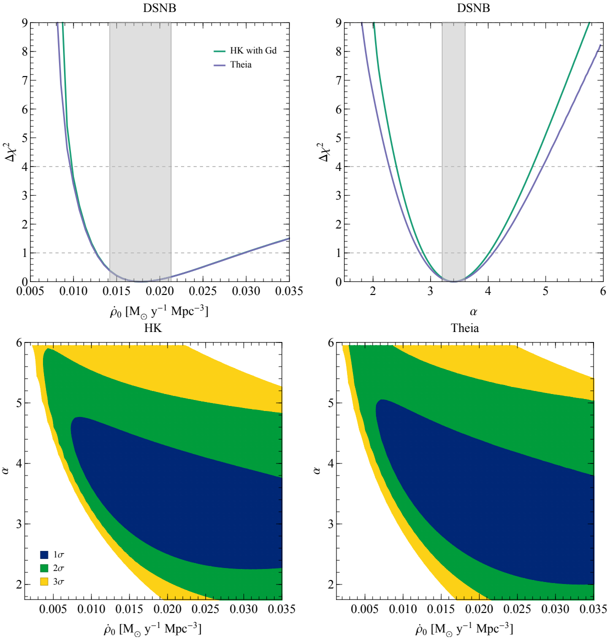


Conclusion

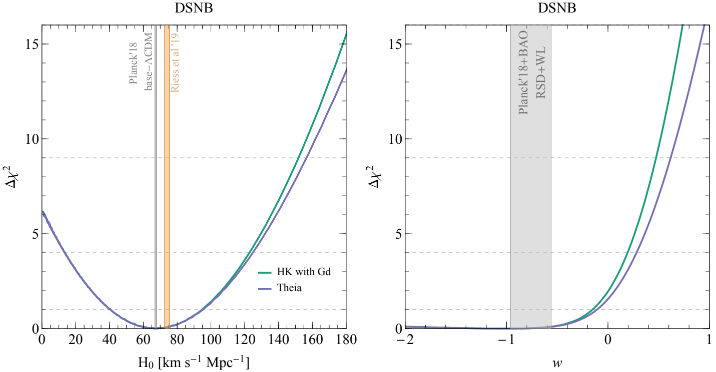
- If neutrinos are **pseudo-Dirac fermions** we can try to observe the effect in the flux from SN.
- In particular, we considered the **SN1987A**
- Exclusion of $2.55 \times 10^{-20}\text{eV}^2 \leq \delta m^2 \leq 3 \times 10^{-20}\text{eV}^2$ at $\Delta\chi^2 \geq 9$.
- Future experiments will explore this scenario with a better sensitivity.
- New sources will be availabel to future experiments: **DSNB**
- The large distance covered by the DSNB will allow us to explore $\delta m^2 \sim 10^{-25}\text{eV}^2$

Thanks!

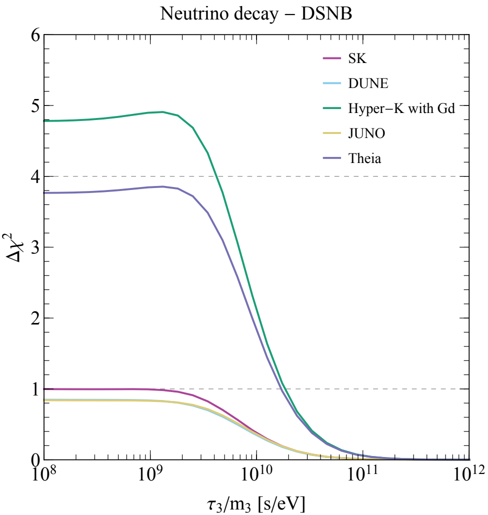
Backup: Measuring the SFR with neutrinos



Backup: Measuring H_0 and ω with neutrinos



Backup: Neutrino decay with the DSNB



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

Backup: Neutrino lifetime