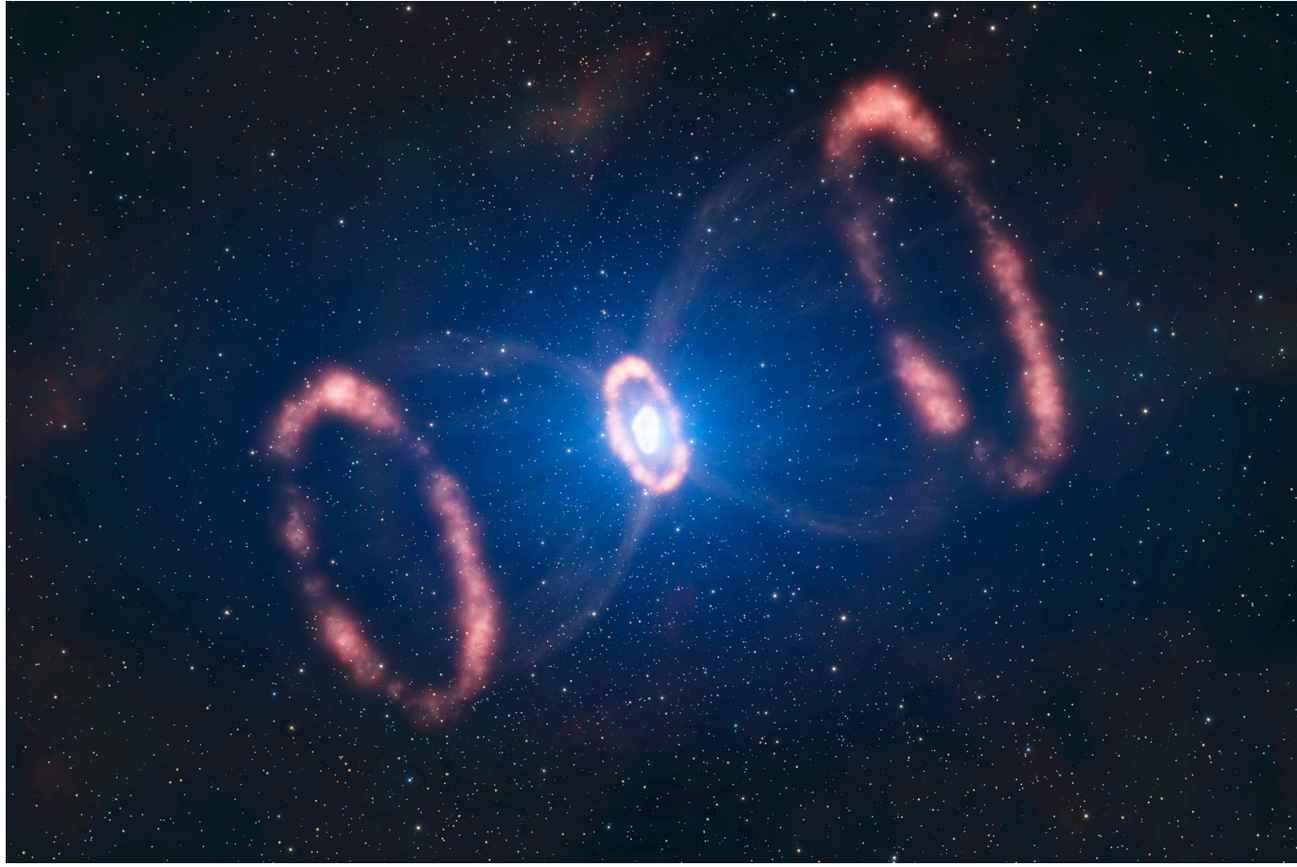
A search for Pseudo-Dirac neutrinos in the Cosmos



Yuber F. Perez-Gonzalez

Neutrinos en Colombia
July 29th, 2021

Fermilab
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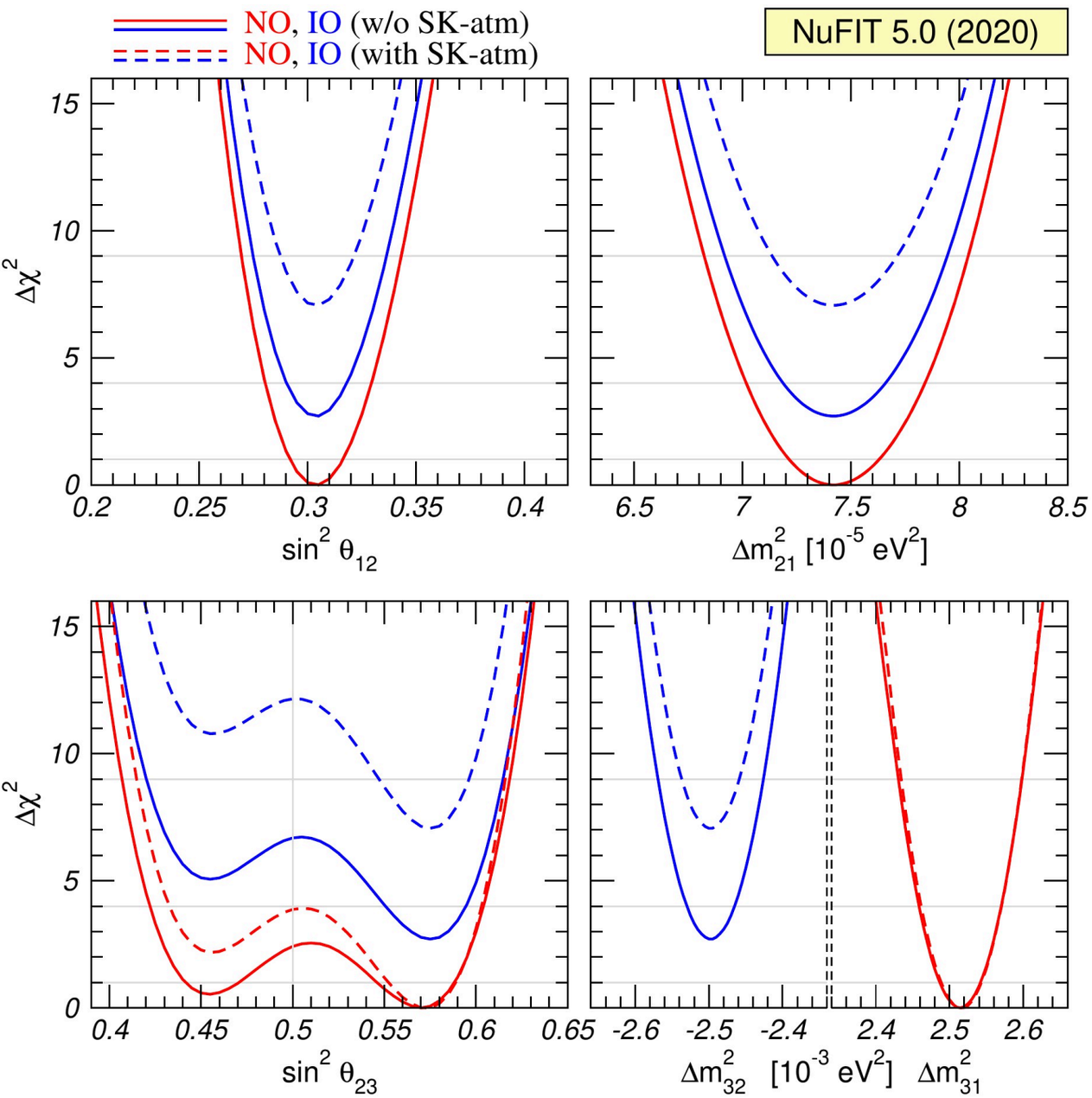
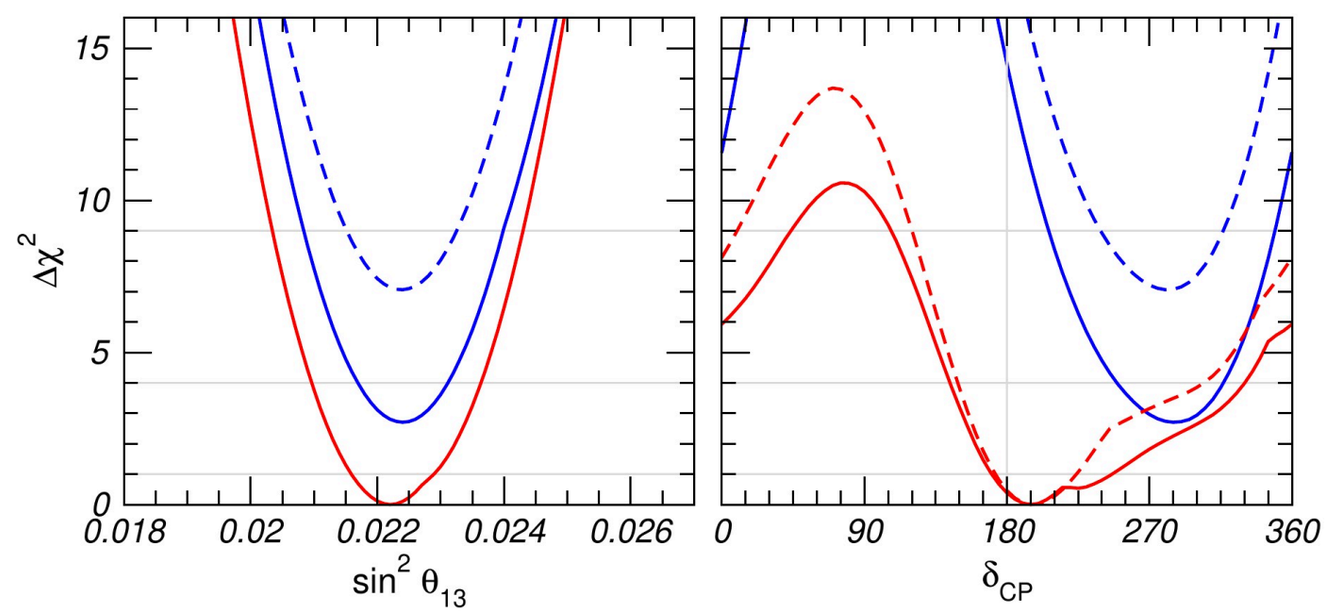
COLEGIO DE FISICA FUNDAMENTAL E INTERDISCIPLINARIA DE LAS AMERICAS
Northwestern

What do we know about neutrino masses and mixing?





Other global fits

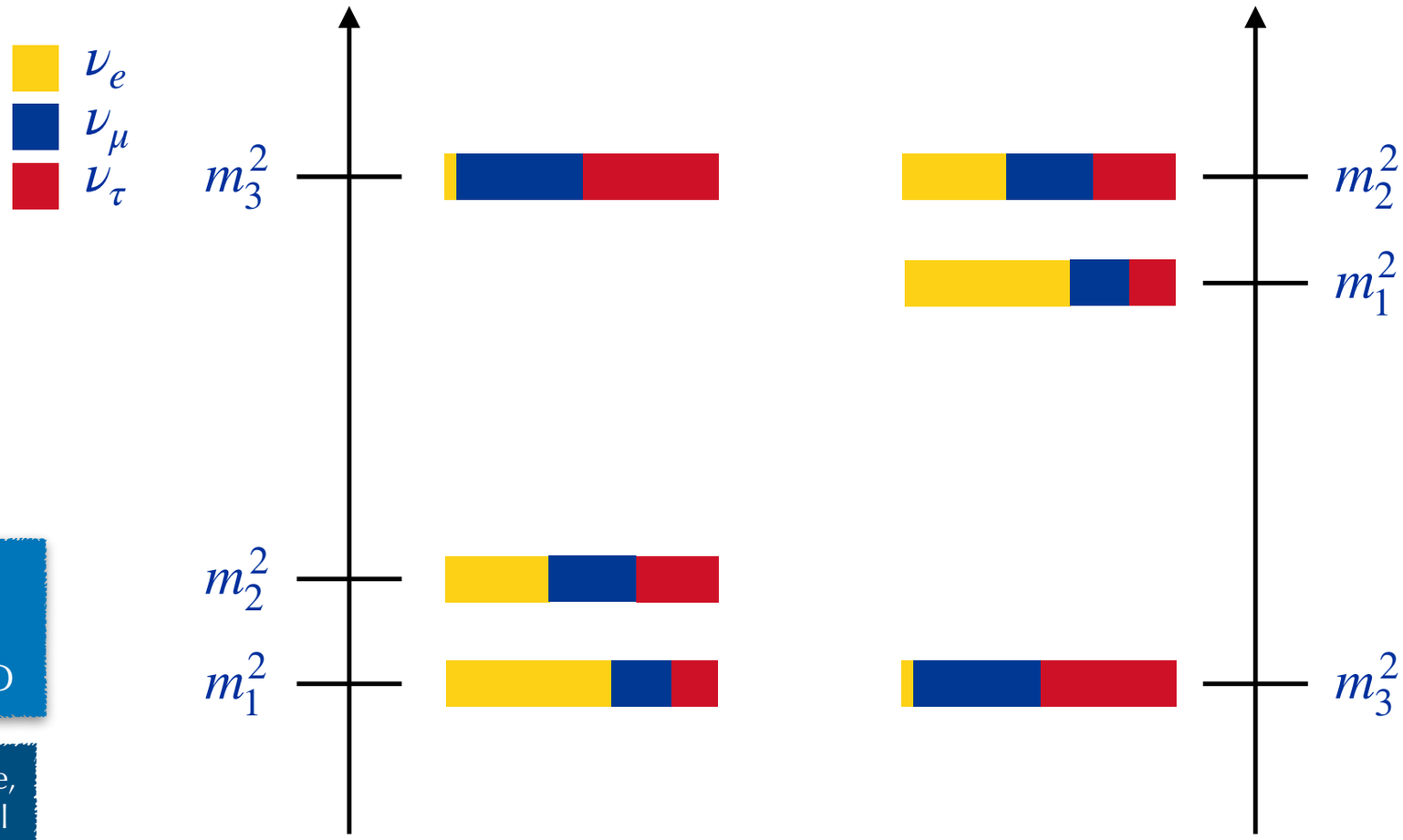
Valencia group
2006.11237

See M. Tortola's talk tomorrow

Bari group
2003.08511

NuFit
JHEP 09 (2020) 178

What do not we know about neutrino masses and mixing?



$$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$$

Normal Ordering

Inverted Ordering

T2K →NO
NOvA → NO
T2K + NOvA → IO

Kelly, Machado, Parke, YFPG, and Z-Funchal
2007.08526

- CP phase - CP violation
- Absolute mass values
- Dirac vs Majorana nature

Nightmare scenario: Neutrinos are Majorana but effectively act as Dirac → Pseudo-Dirac*

*We prefer to use "pseudo" instead of quasi, just by historical reasons 🙂

Pseudo-Dirac Neutrinos

Let's consider the Dirac+Majorana Lagrangian

$$\mathscr{L}_Y = -Y\overline{L}\tilde{H}N_R + \frac{1}{2}\overline{N^c}M_R N + \text{h.c.}$$

$$M = \begin{pmatrix} 0_3 & \underbrace{Yv/\sqrt{2}}_{M_D} \\ Yv/\sqrt{2} & M_R \end{pmatrix}$$

- $M_R = 0 \rightarrow$ Dirac neutrinos
- $M_R \gg M_D \rightarrow$ Usual type I seesaw
- $M_R \ll M_D \rightarrow$ PseudoDirac neutrinos

PMNS matrix

$$\nu_{\beta L} = \frac{U_{\beta k}}{\sqrt{2}}(\nu_{ks} + i\,\nu_{ka})$$

Mass eigenstates

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

$\delta m^2 \rightarrow$ tiny but non-zero mass difference, equal for all eigenstates

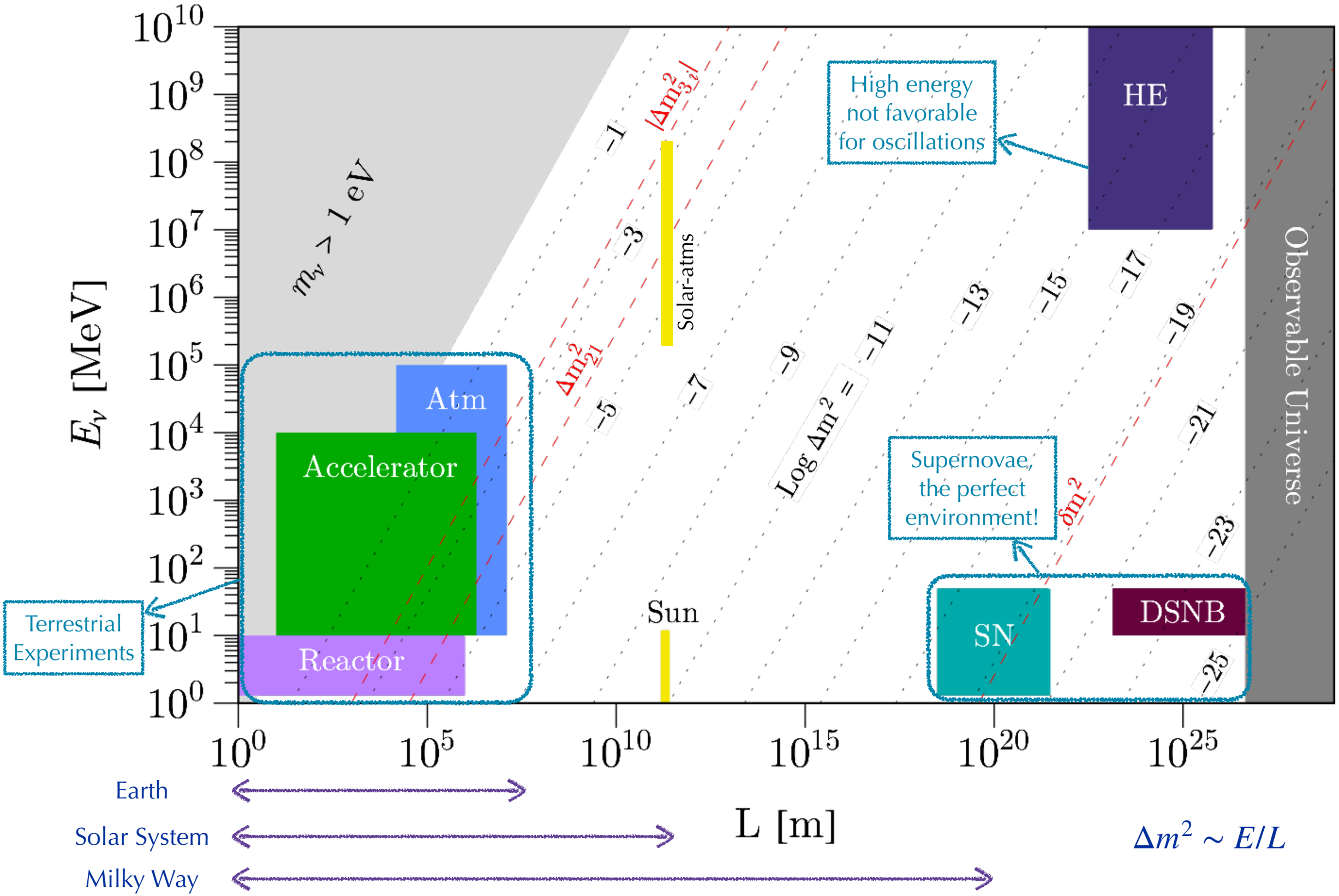
Flavor neutrinos are a ~50-50 combination of two states

Tiny mass difference could lead to oscillations!

See C. Sheng talk

Pseudo-Dirac Neutrinos

Vacuum Oscillations



Pseudo-Dirac Neutrinos

$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m^2$$
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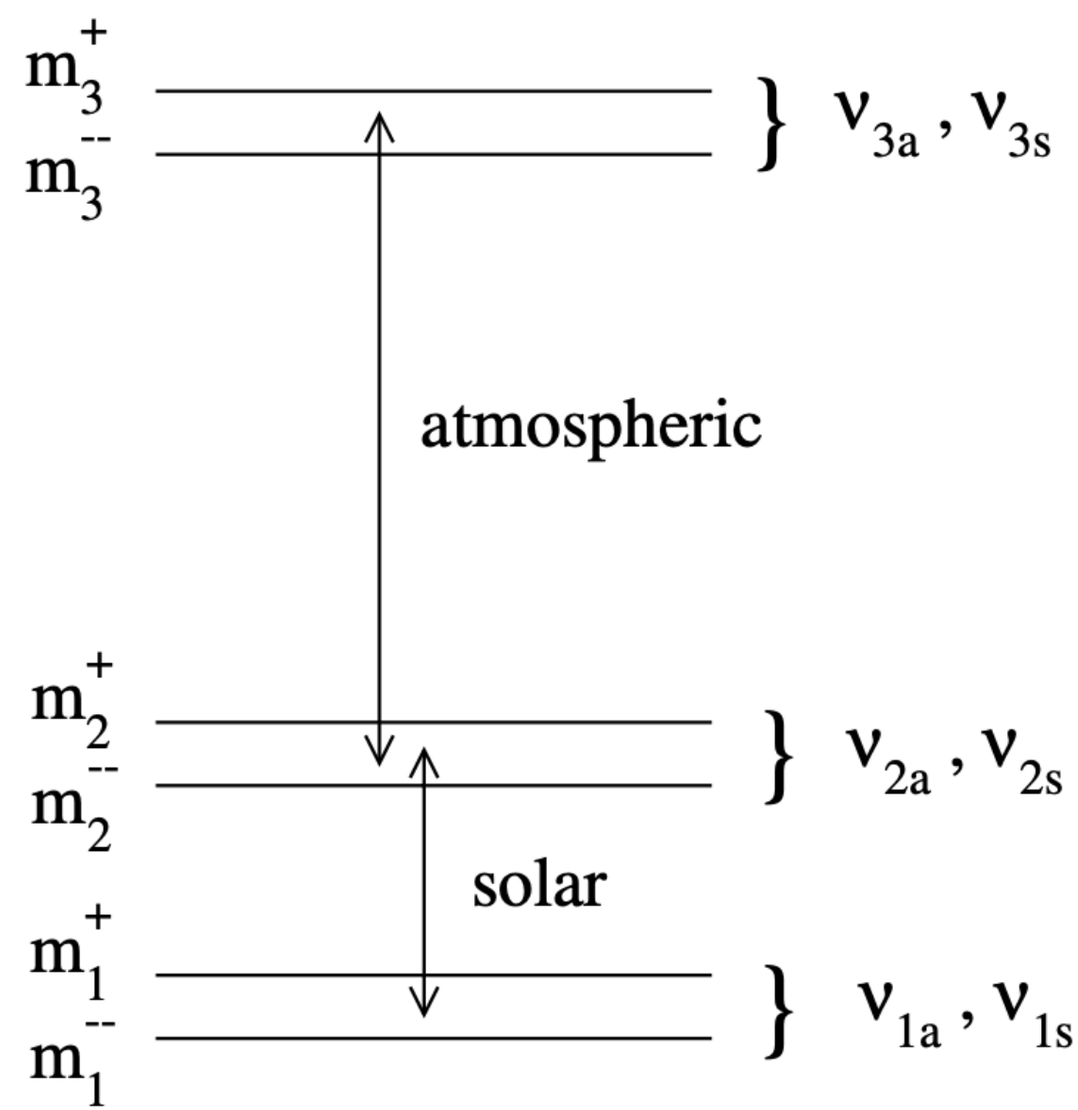
Limits on δm_k^2

- Solar neutrinos $\delta m^2 \lesssim 10^{-12}$ eV^2
  - de Gouvêa et.al. 0906.1611, Donini et.al. 1106.0064
- Atms neutrinos $\delta m^2 \lesssim 10^{-4}$ eV^2
  - Beacom et.al. 0307151
- HE neutrinos
  10^{-18} eV$^2 \lesssim \delta m^2 \lesssim 10^{-12}$ eV^2
  - Beacom et al 0307151, Esmaili 0909.5410, Esmaili and Farzan 1208.6012
- JUNO & DUNE
  - Anamiati, De Romeri, Hirsch, Ternes, and Tortola, 1907.00980

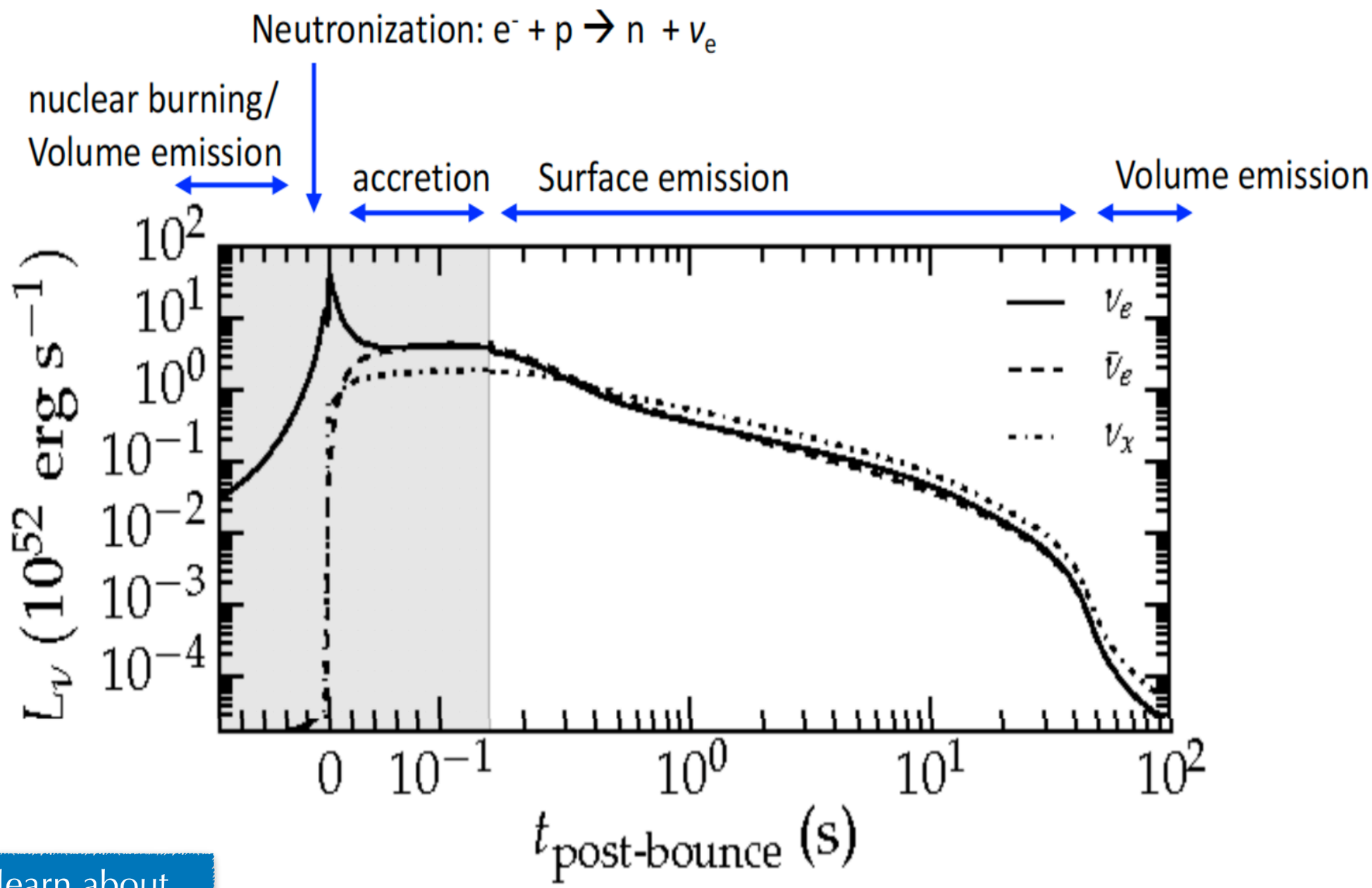


Beacom et.al. 0307151

What about SN?

Core-collapse Supernovae

- MeV neutrinos are emitted

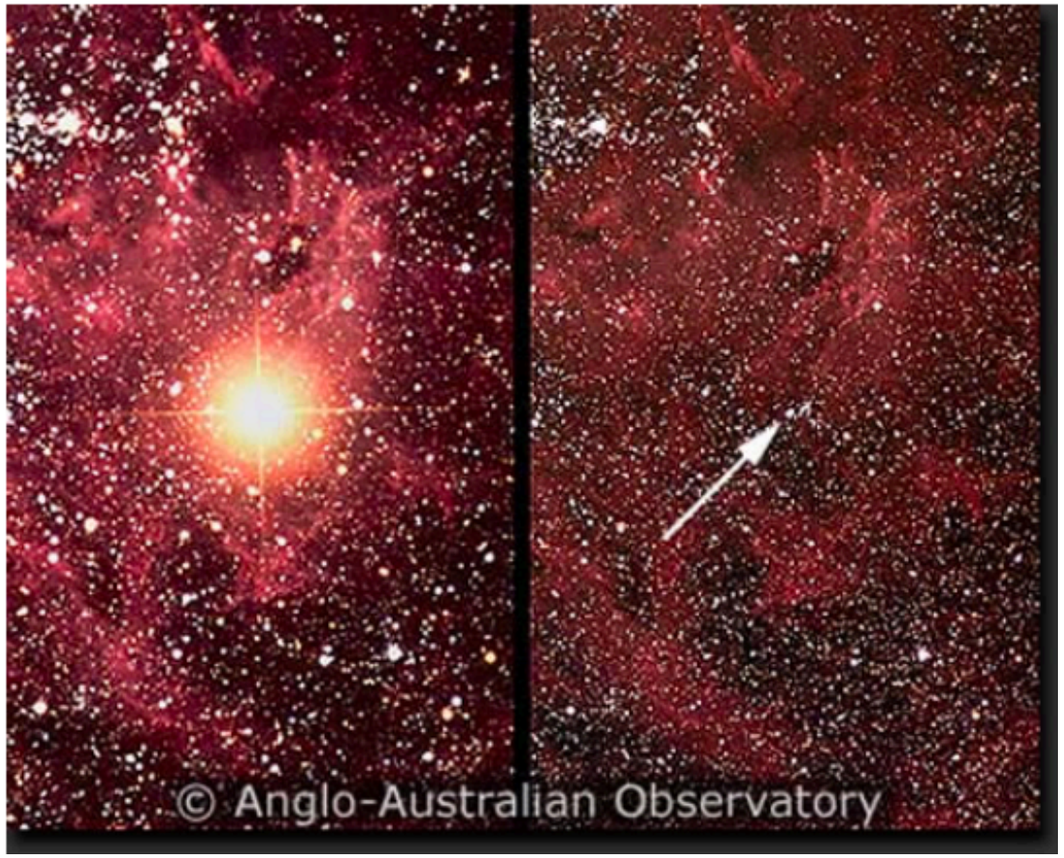


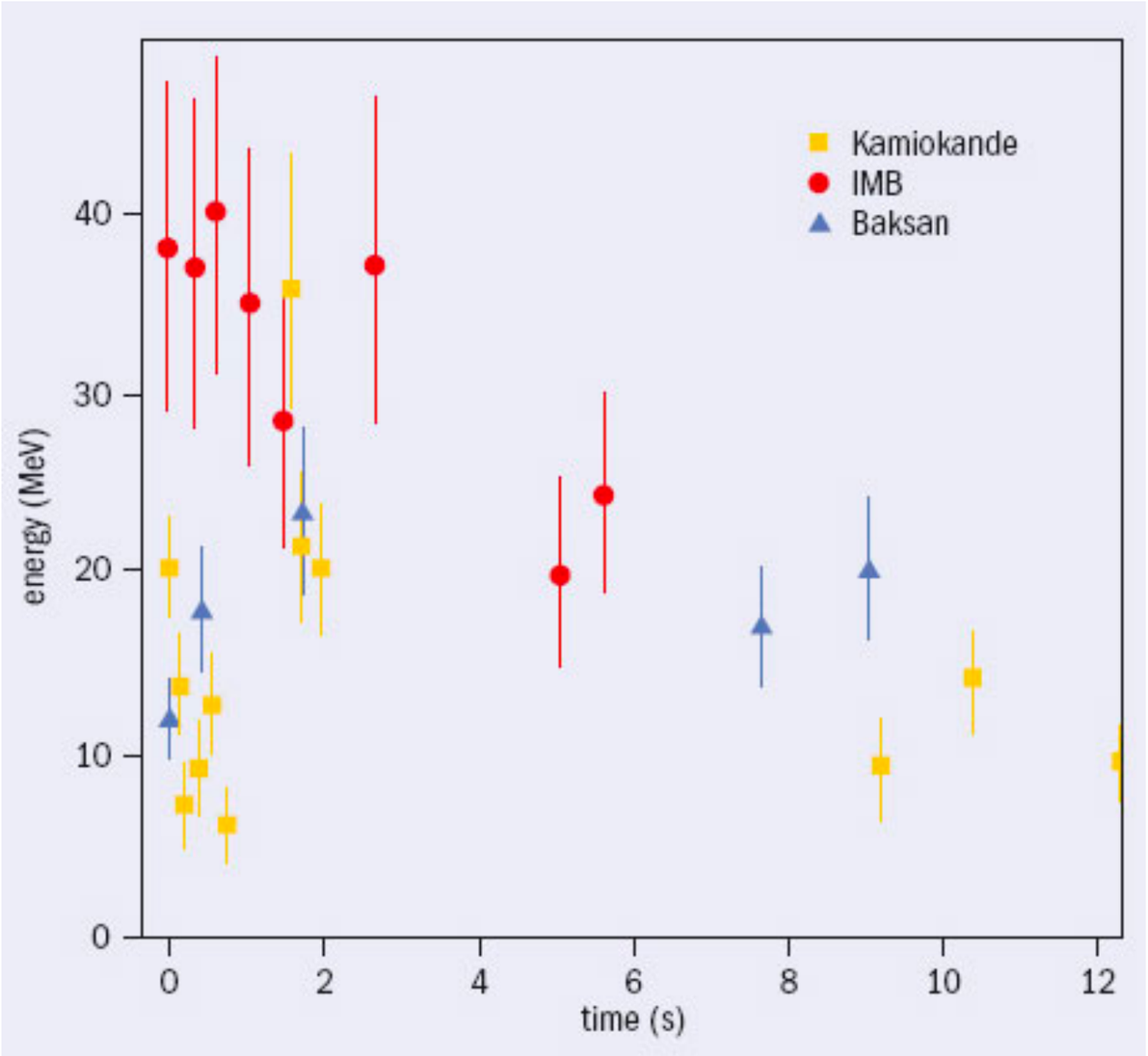
We could learn about mass ordering, δ_{CP}…

Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

SN1987A

- A SN was observed on the large Magellanic cloud
- A burst of neutrinos were detected hours before the light reached the Earth





Masayuki Nakahata, CERN courrier

Pseudo-Dirac Neutrinos → SNe

Baselines that can be of astrophysical order

Vacuum Oscillations:

Active survival probability

$$P(\nu_\beta \to \nu_\gamma) = P_{aa}(E_\nu; L, \delta m^2) \sum_k \left|U_{\beta k}\right|^2 \left|U_{\gamma k}\right|^2$$

Active survival probability

Decoherence

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

Oscillation and decoherence lengths

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

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

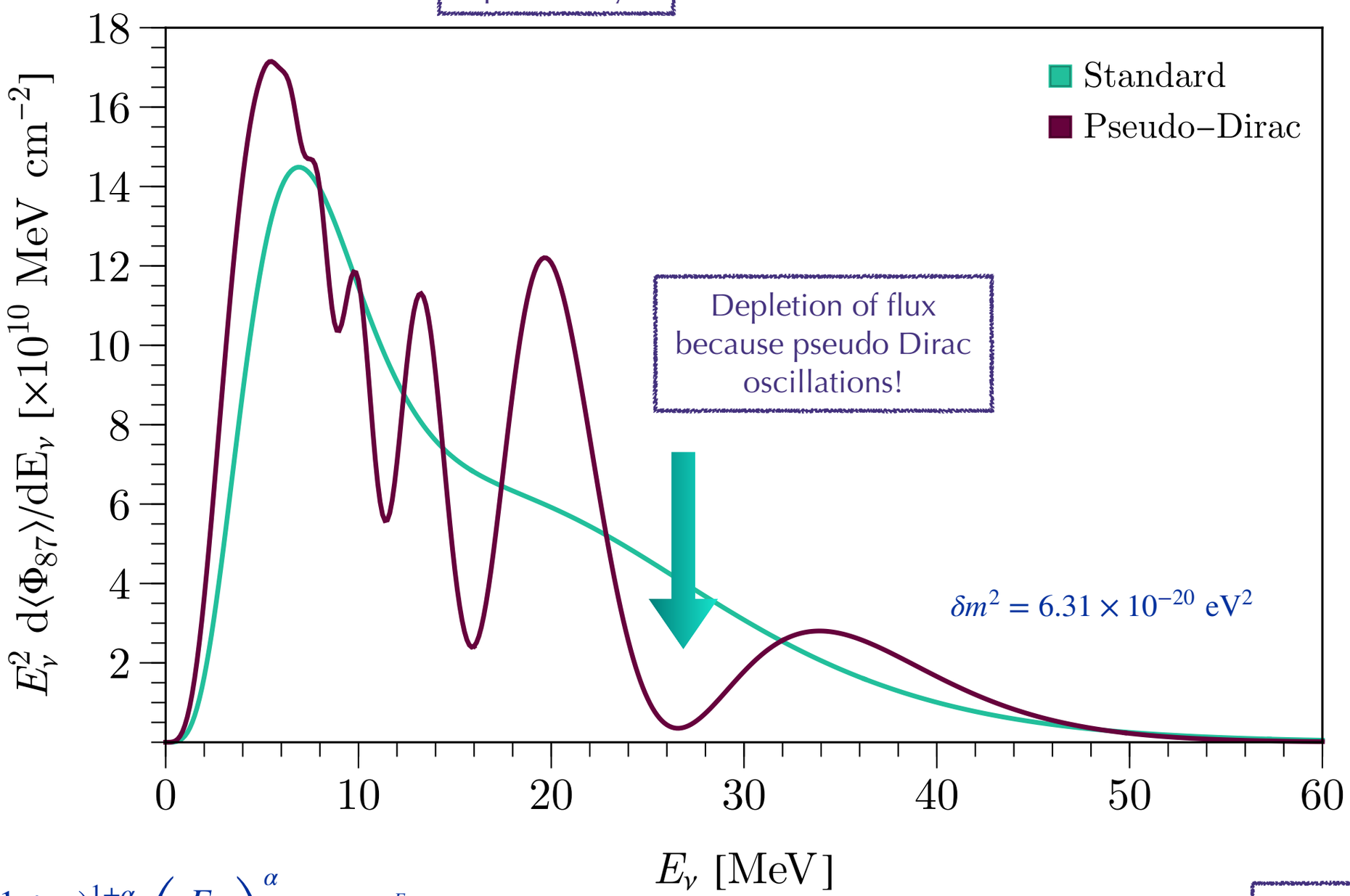
Let's describe the incoming $\overline{\nu}_e$ flux as

$$\frac{d\Phi_{87}}{dE_\nu} = \frac{\mathscr{E}_{\rm tot}}{4\pi d^2} P_{aa} \left[\bar{p}\frac{\phi_e}{E_{0e}} + (1-\bar{p})\frac{\phi_x}{E_{0x}} \right]$$

Active survival probability

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

MSW effect



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

Alpha-fit parametrization

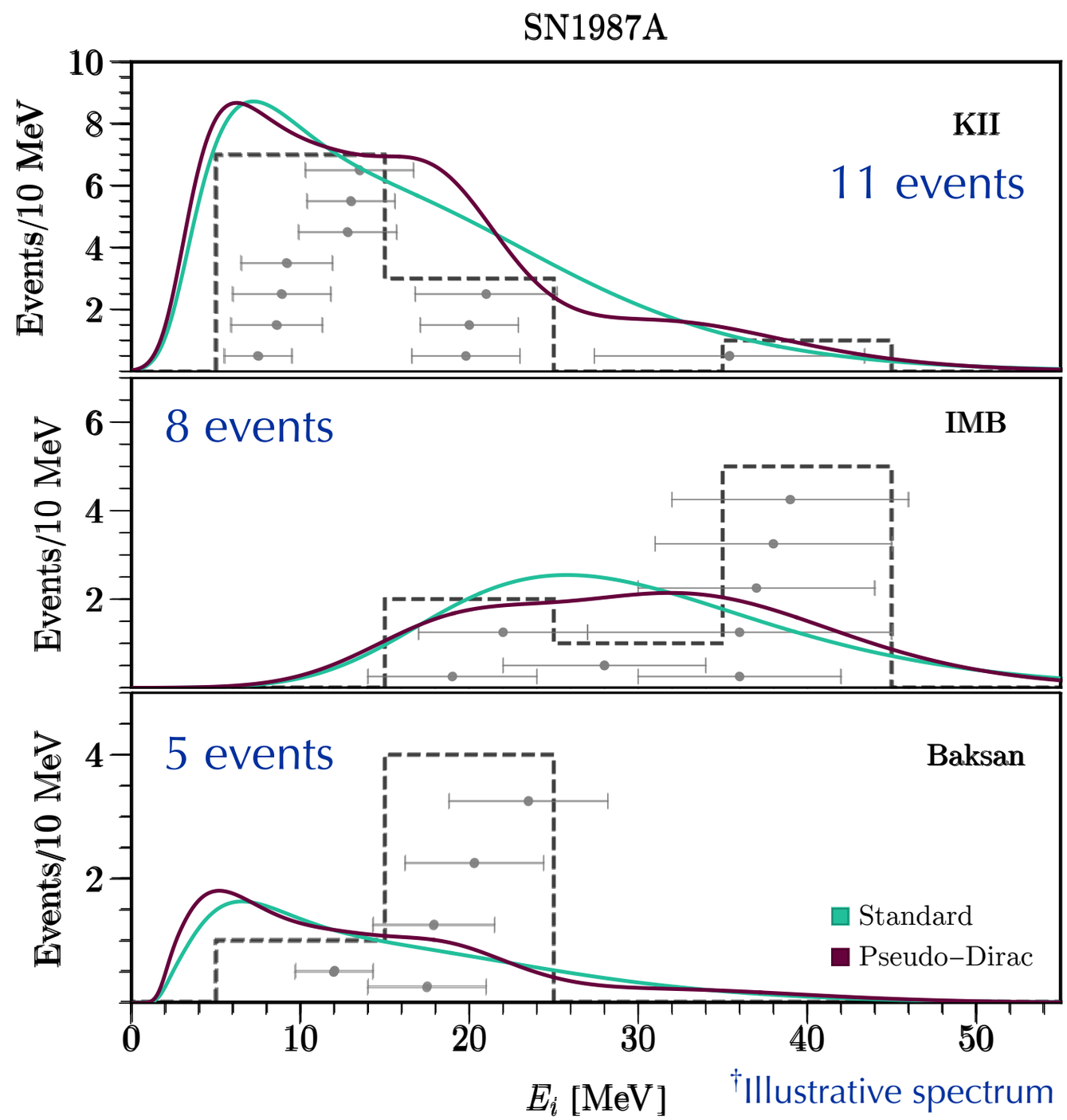
$\alpha = 2.3$

We follow the standard treatment of the SN1987A data*

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

We find a ***mild*** preference for pseudo-Dirac oscillations

Experiment(s)	$\mathcal{E}_{\rm tot}$	E_{0e}	E_{0x}	δm^2	$\Delta\chi^2_{\rm NoOsc}$
KII	2.2	4.24	10.96	6.31	1.1
IMB	3.2	1.36	12.86	6.03	1.7
Baksan	15.7	4.28	8.03	3.16	1.7
Joint Fit	2.7	4.00	12.61	6.31	2.9



†Illustrative spectrum

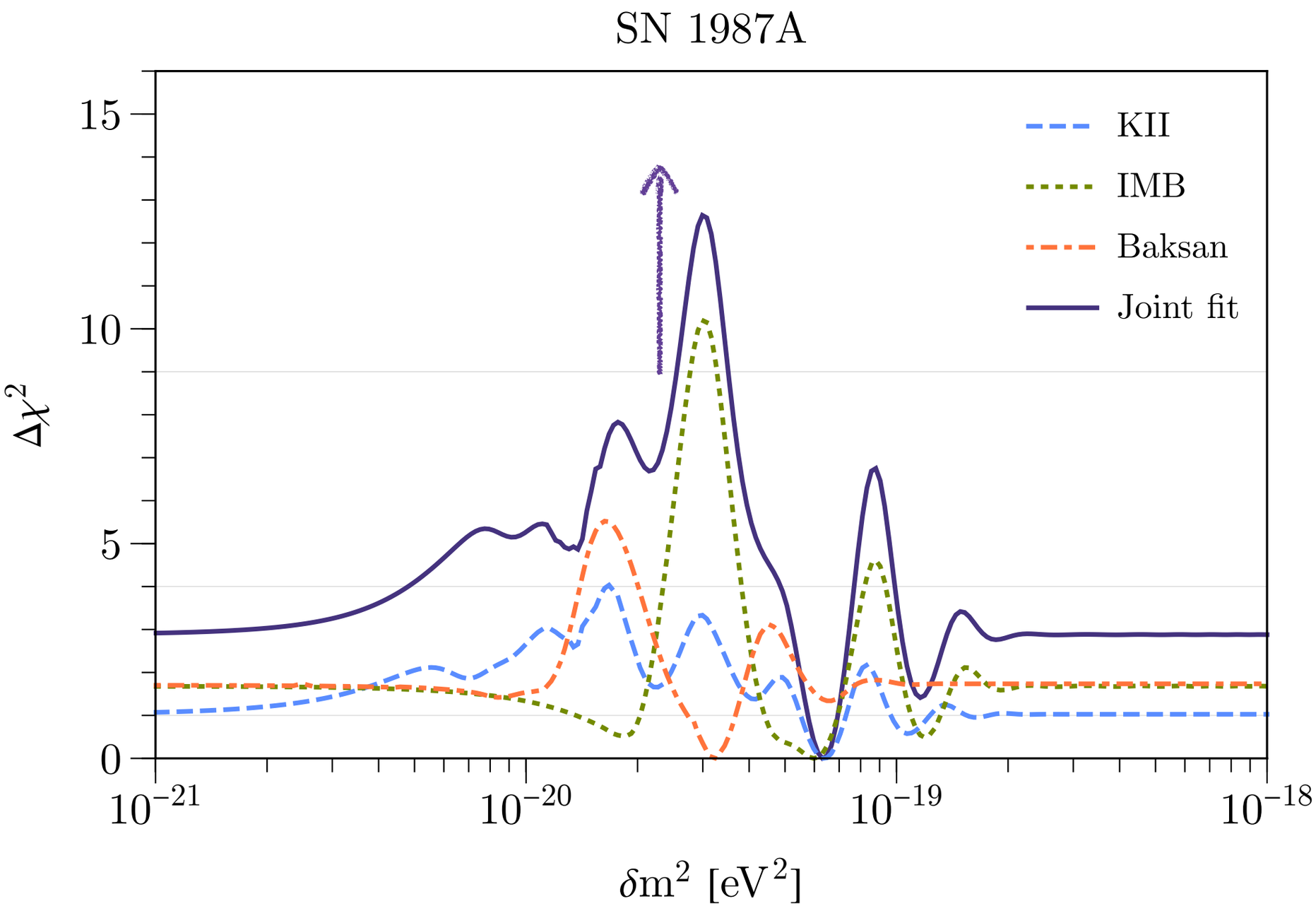
F. Vissani, arXiv:1409.4710

* Assumptions:

- We don't add any prior on SN properties
- Events are due to IBD
- Add expected backgrounds in all experiments

We exclude with $\Delta\chi^2 > 9$ a region on the mass differences

Non trivial synergy between the experiments



Martinez-Soler, YFPG, Sen, 2105.12736

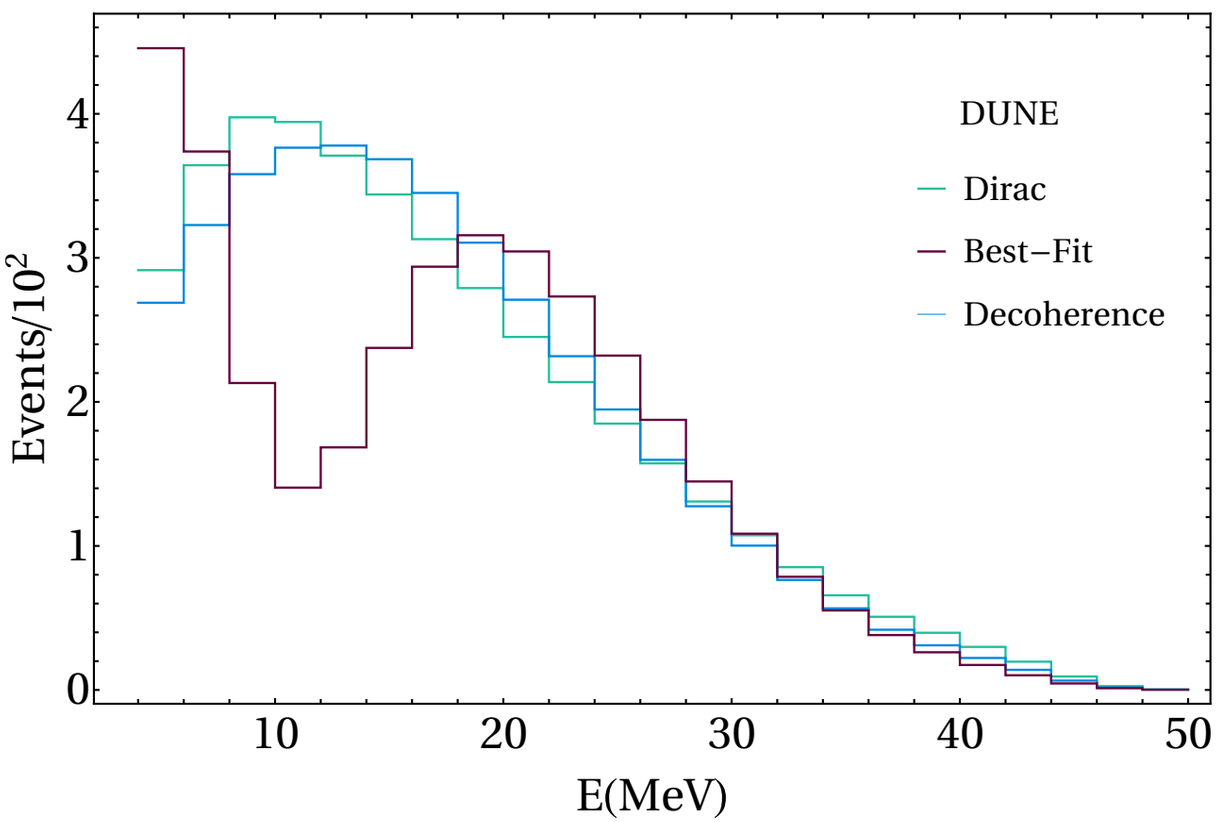
$$2.55 \times 10^{-20}\ \mathrm{eV}^2 \lesssim \delta m^2 \lesssim 3.0 \times 10^{-20}\ \mathrm{eV}^2$$

Future…

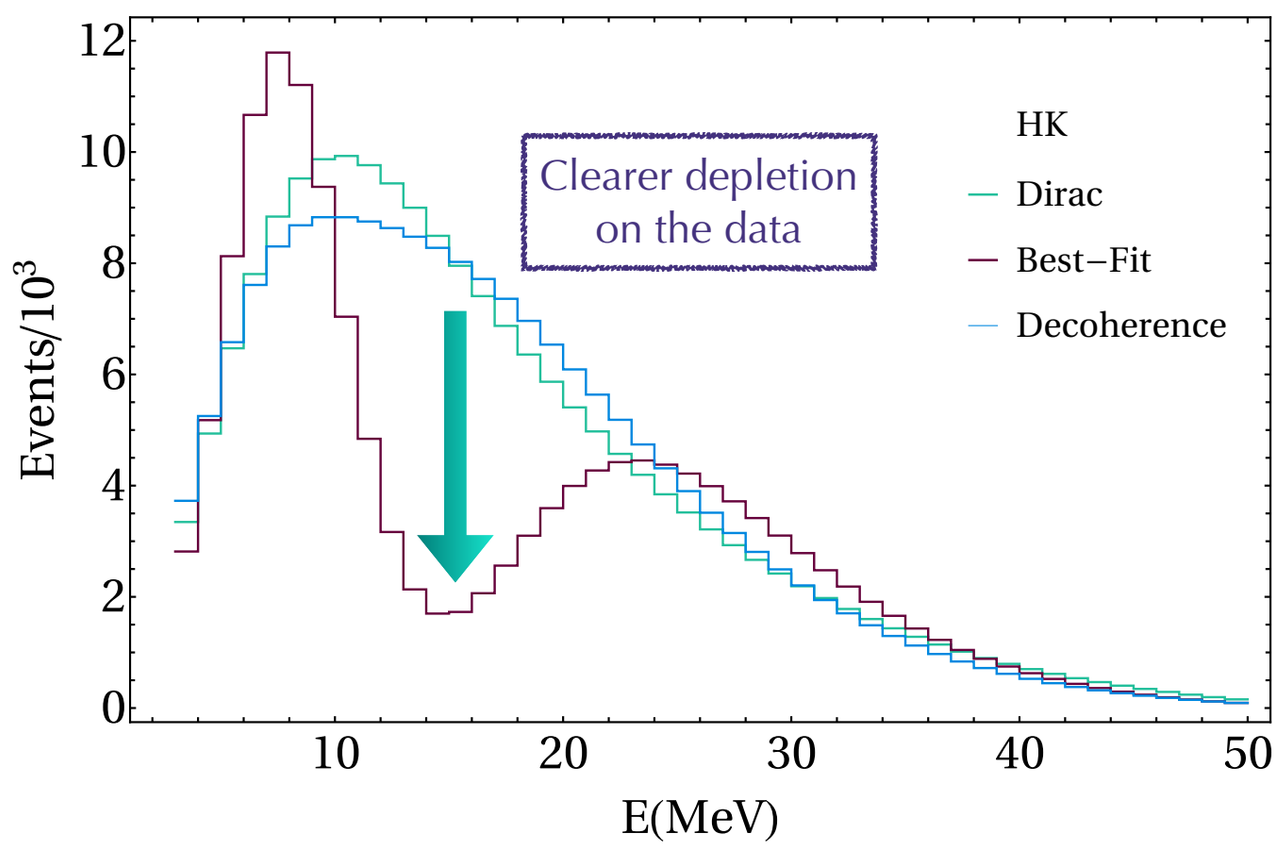
SN1987A data is great, but we need more data!

For a galactic SN (10 kpc)

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



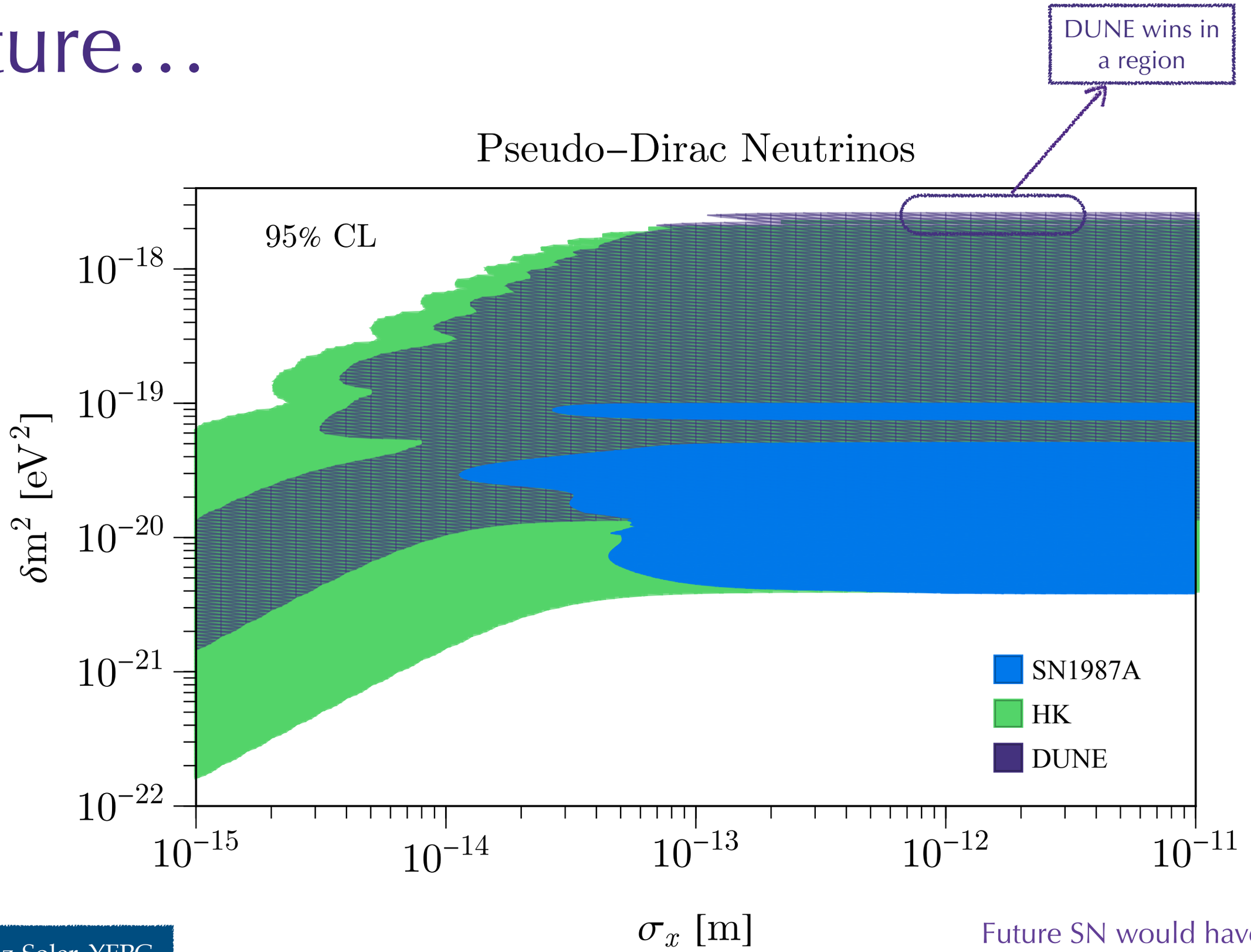
$\overline{\nu_e} + p \rightarrow e^+ + n$



Martinez-Soler, YFPG, Sen, 2105.12736

Alpha-fit parametrization

Future…



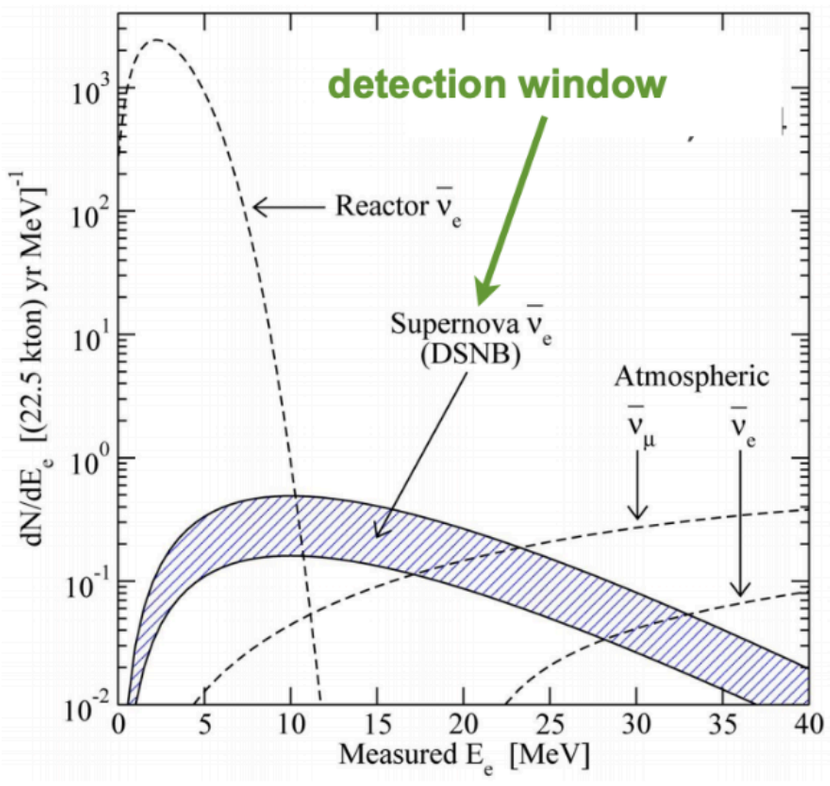
Martinez-Soler, YFPG, Sen, 2105.12736

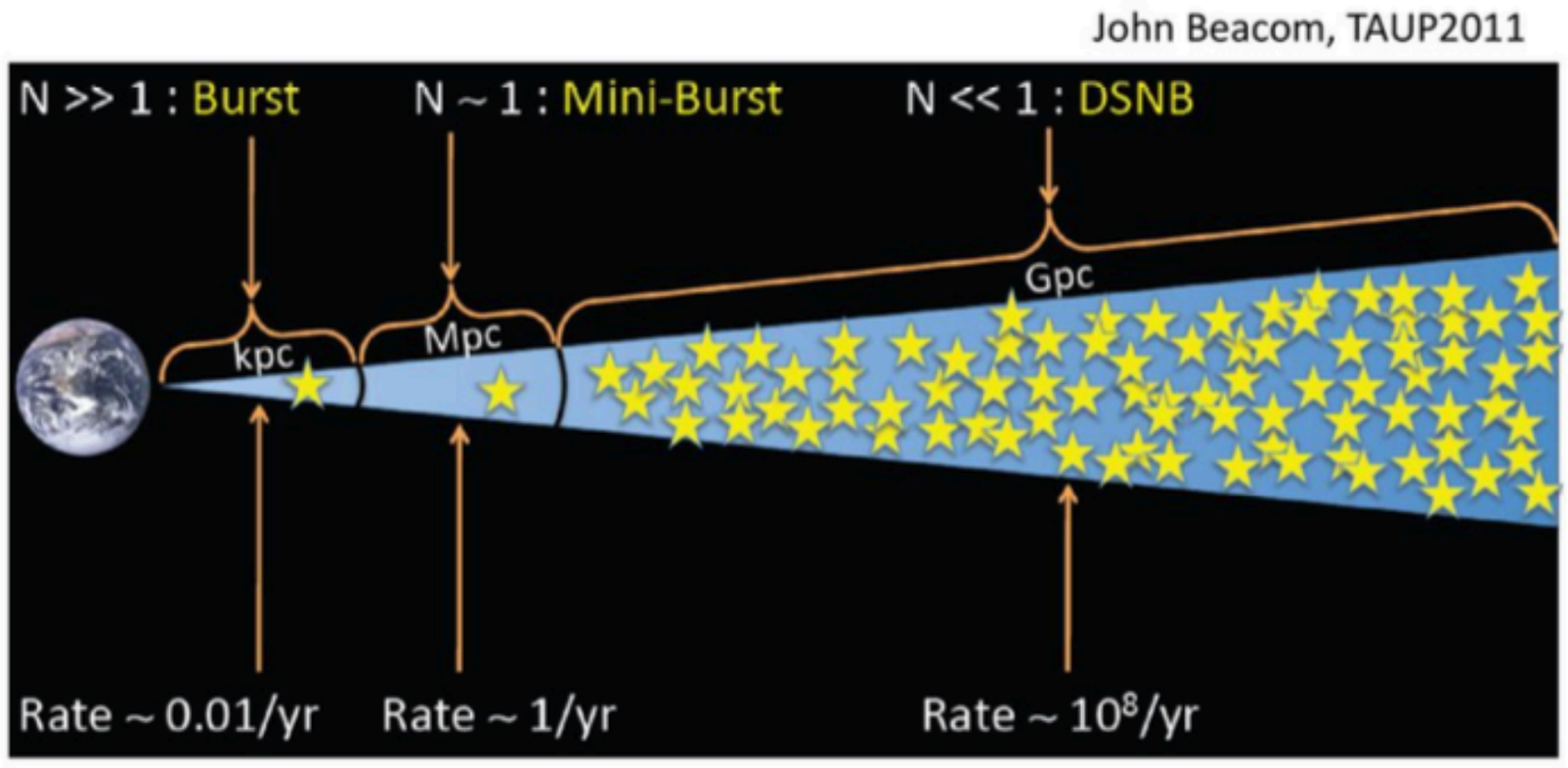
Future SN would have an ***enormous*** number of events in exp. like DUNE or HK

Diffuse Supernova Neutrino Background

- Galactic SNe are rare, 3 per century
- Future SNe could make our detectors "shine like a Christmas tree" —> O(10k) events!
- When will the next galactic SN be?

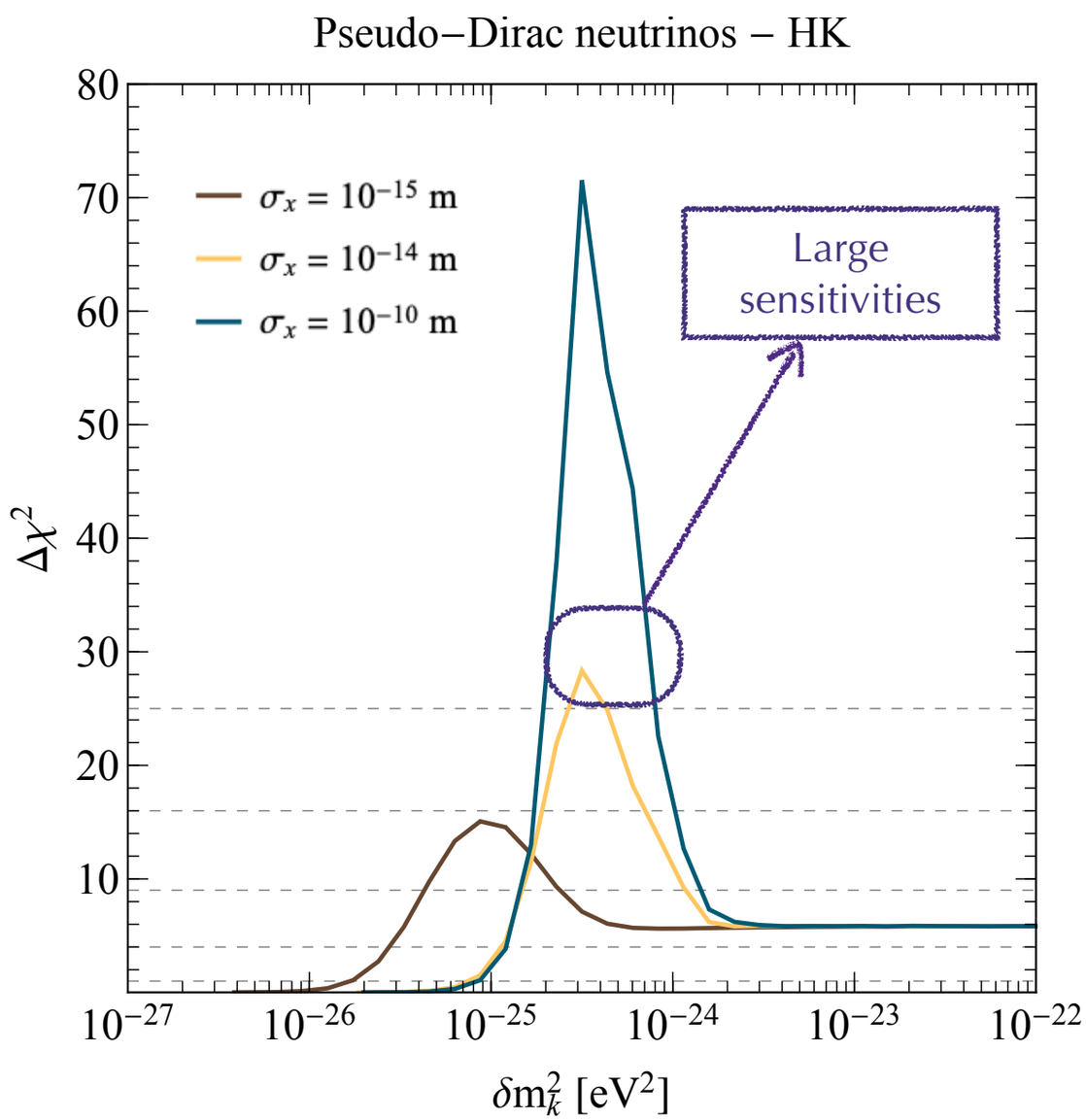
- Instead, we could look at *all* the SNe that have exploded in the Universe
- This should create a diffuse (isotropic and time independent) neutrino flux

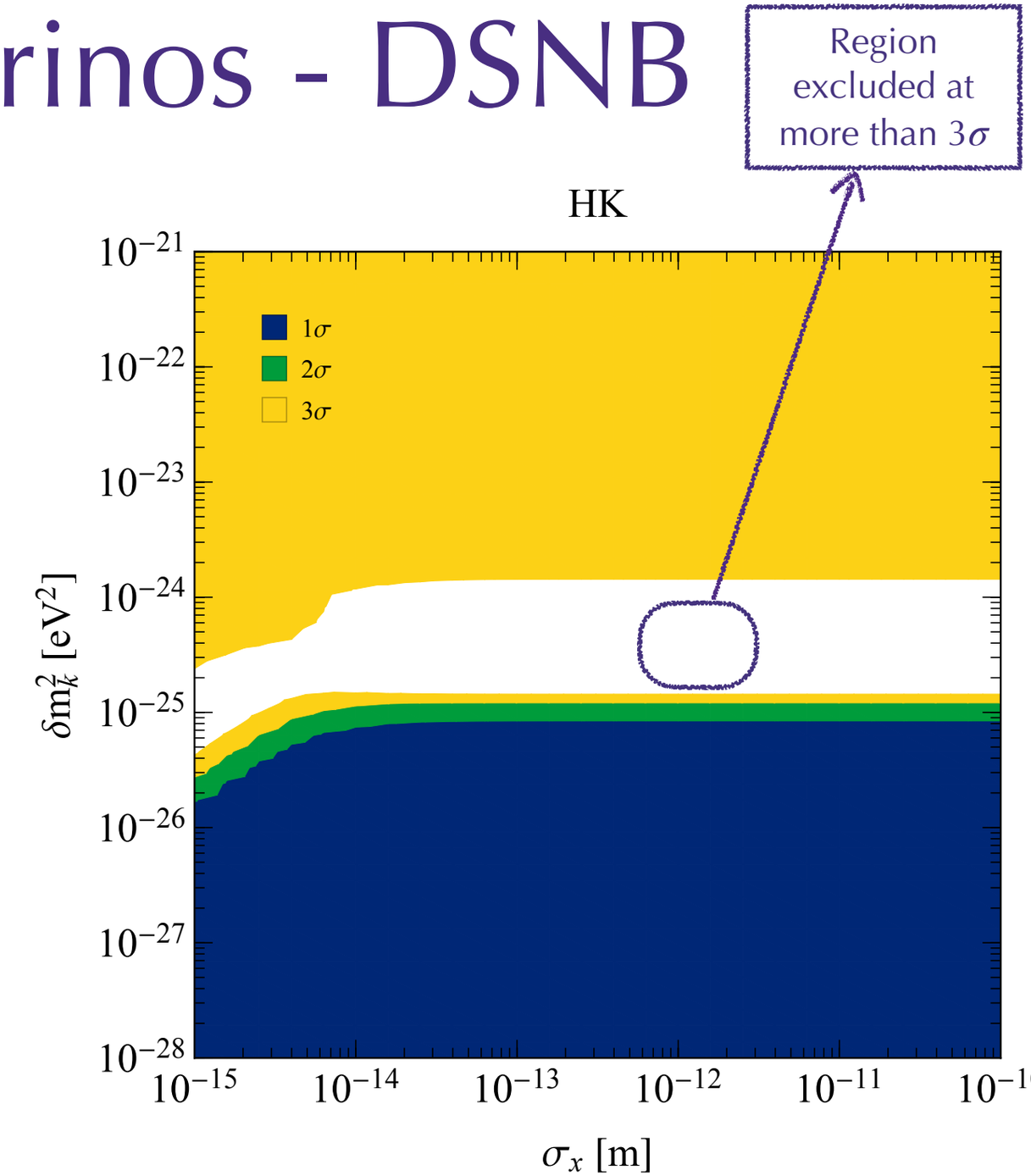




Beacom, Ann.Rev.Nuc.Phys.Sc.2010
Lunardini, Astropart. Phys2016

Pseudo-Dirac Neutrinos - DSNB





$$L_{\rm osc} = \frac{4\pi E}{\delta m_k^2} \approx 8.03 \text{ Gpc} \left(\frac{E}{10 \text{ MeV}}\right)\left(\frac{10^{-25} \text{ eV}^2}{\delta m_k^2}\right)$$

$$L_{\rm coh} = \frac{4\sqrt{2}E^2}{|\,\delta m_k^2\,|}\sigma_x \approx 180 \text{ Gpc} \left(\frac{E}{10 \text{ MeV}}\right)^2\left(\frac{10^{-25} \text{ eV}^2}{\delta m_k^2}\right)\left(\frac{\sigma_x}{10^{-12} \text{ m}}\right)$$

de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Conclusions

- Pseudo-Dirac neutrinos are a real possibility but a nightmare scenario: they are truly Majorana but behave in almost all phenomena as Dirac (no neutrinoless double beta decay)

- Nevertheless, the existence of a tiny mass splitting could lead to observable oscillations between active and sterile states

- To test the smallest possible mass differences we need low energy neutrinos that have travelled the longest $\longrightarrow$ SN neutrinos are the best candidate!

- By looking at the SN1987A data, we found a **mild** preference for a non-zero mass splitting, $\delta m^2 = 6.31 \times 10^{-20}\ \mathrm{eV}^2$. Also, and <u>*more importantly*</u>, we have able to exclude the tiniest mass differences explored so far.

- A future galactic SN would certainly shed more light into this.

- Measuring the DSNB would allow for testing even more smaller mass differences

¡Gracias!