Probing pseudo-Dirac neutrinos using supernova neutrinos

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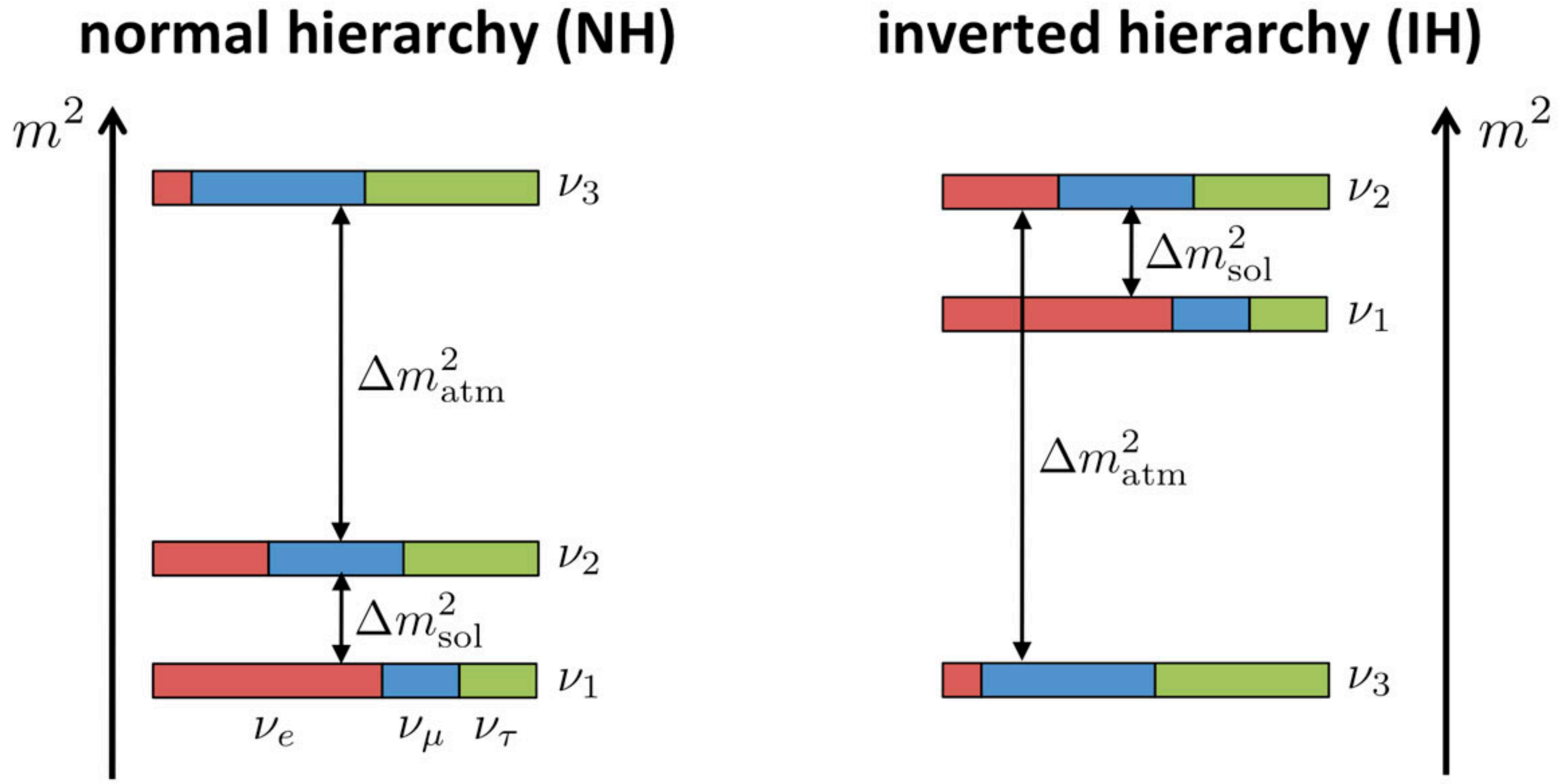
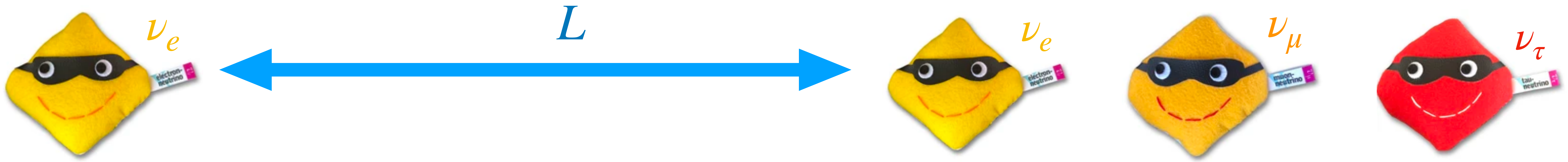
Neutrino oscillations

- Neutrinos interact "weakly" with the rest, as well as with themselves.
- There are 3 active light neutrinos.
- Neutrinos are massive and can change flavor.





$$P_{\nu_a \to \nu_b}(E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$L_{\rm osc} \propto \frac{E}{\Delta m^2}$$

Lepton Number in the Standard Model

- Lepton number is a conserved symmetry in the SM classically. Violated by chiral anomalies.

- New physics leads to lepton-number violation. Might be related to origin of neutrino masses.

- Consider 1 active and 1 sterile neutrino. The Lagrangian,

$$\mathscr{L} = \bar{\nu}_L m_D \nu_R + \frac{1}{2}\overline{\nu_L^C} m_L \nu_L + \frac{1}{2}\overline{\nu_R^C} m_R \nu_R + \mathrm{h.c.}$$

$\cancel{L}$

- The generic mass matrix $\mathscr{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$

Pseudo (Quasi)-Dirac neutrinos

Generic Majorana mass matrix $\mathscr{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}.$

1. Dirac limit: $m_{L,R} = 0$.
   No lepton-number violation.

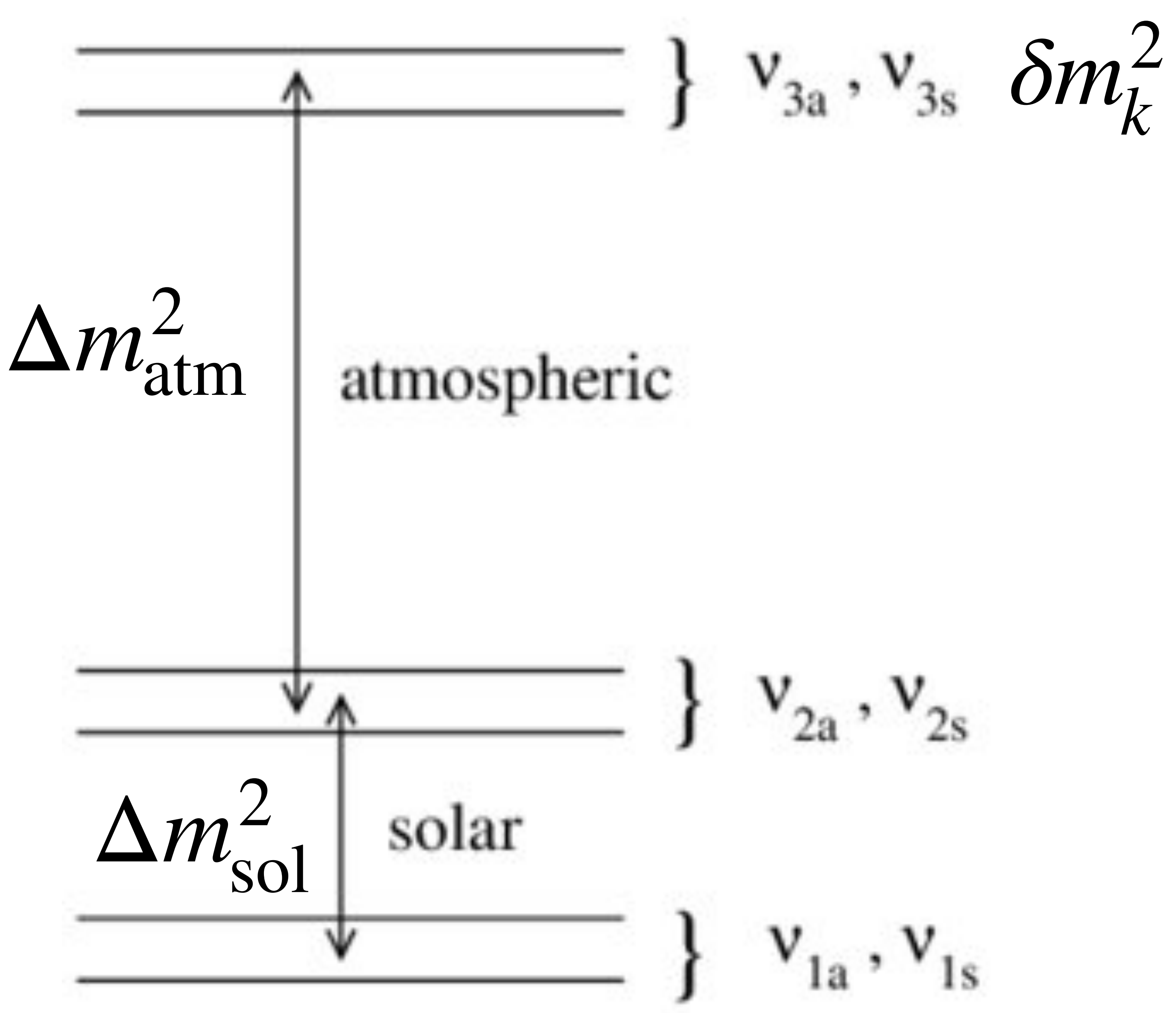
2. Majorana limit : $m_{L,R} \gg m_D$.
   Explicit lepton-number violation.

3. (Quasi) Pseudo-Dirac limit : $m_{L,R} \ll m_D$.
   Soft lepton-number violation.

Wolfenstein, NPB 1981
Valle, PRD 1983

Pseudo-Dirac neutrinos formalism

- 3 pairs of quasi-degenerate states, separated by δm_k^2, which is much smaller than the usual $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$.



$$m^2_{ks,ka} \simeq m_k^2 \pm \delta m_k^2/2, \quad \text{where} \quad \delta m^2 \sim m_D(m_L + m_R)$$

Kobayashi, Lim, PRD2001

- In the P-D limit, under certain approximations, mass matrix can be diagonalized by

$$\mathscr{V} = \begin{pmatrix} U_{\rm PMNS} & 0 \\ 0 & U_R \end{pmatrix} \cdot \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1_3 & i1_3 \\ \varphi & -i\varphi \end{pmatrix}$$

- Further generalizations considered with non-maximal mixings.

Anamiati, Fonseca, Hirsch, PRD2018

Oscillations due to small δm^2

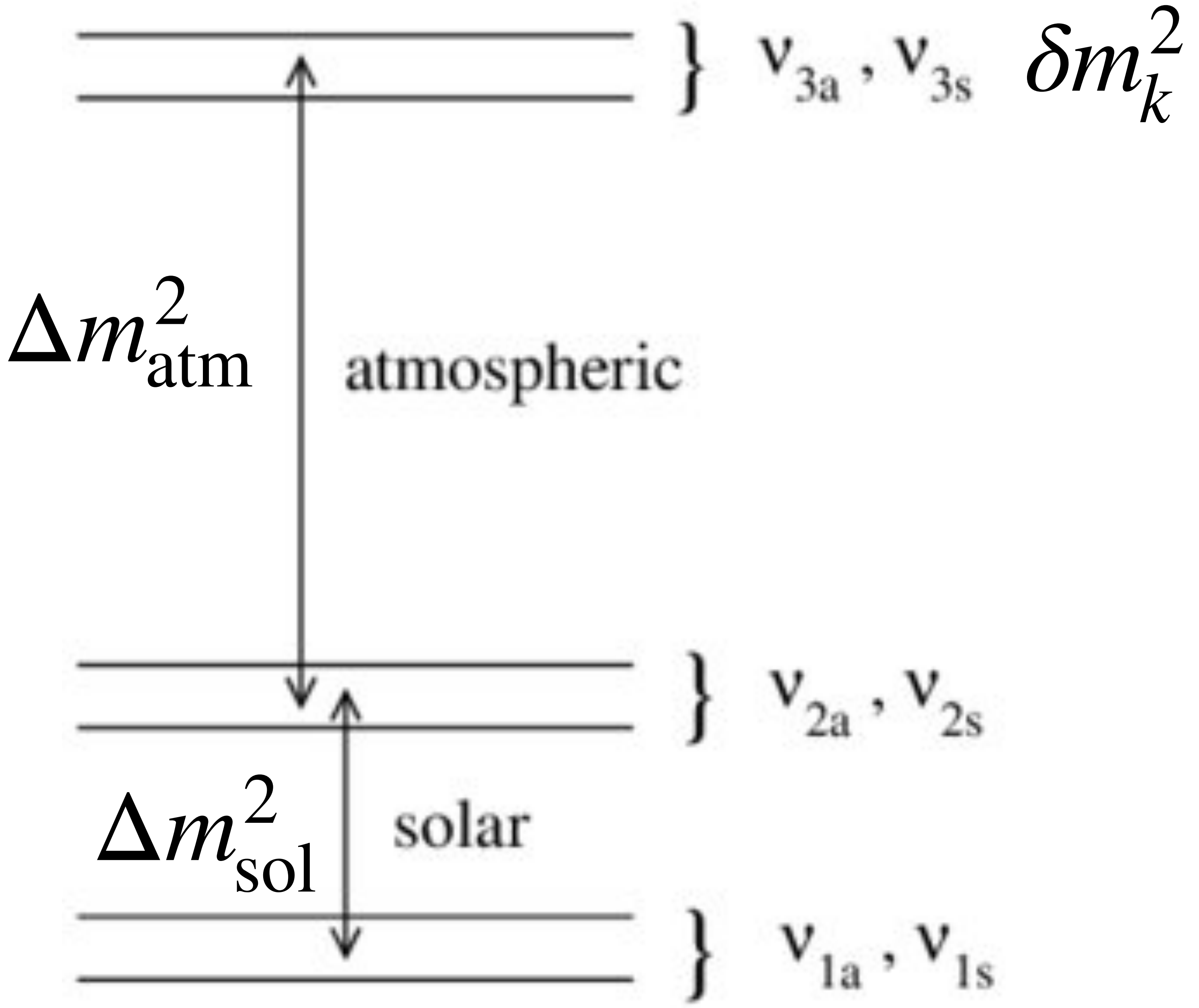
- δm_k^2 will lead to oscillations at very large distances, $L \propto 1/\delta m^2$

- Flavor oscillation probability induced by $\Delta m^2_{\mathrm{sol}}$ and $\Delta m^2_{\mathrm{atm}}$ over a large distance gets averaged.

$$P(\bar{\nu}_\beta \to \bar{\nu}_\gamma) = P_{aa}(z, E) \left| U_{\beta k} \right|^2 \left| U_{\gamma k} \right|^2$$

- Survival probability

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



Oscillations due to small δm^2

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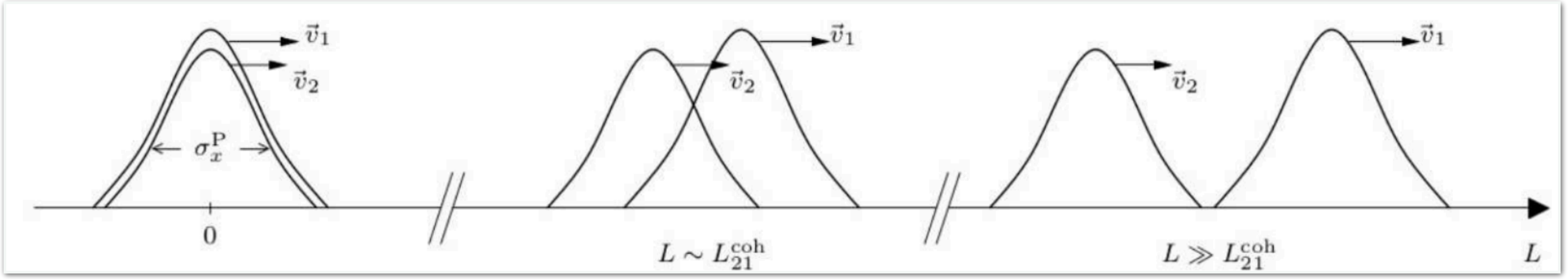
- Wave-packet separation decoherence also becomes important. Decoherence important if $L(z) > L_{\text{coh}}$.



Giunti and Kim, Fundamentals of neutrino physics

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

Width of wavepacket

A smaller σ_x can cause decoherence.

Bounds from neutrino sources

Experiment	ε_1^2 [eV^2]	ε_2^2 [eV^2]	ε_3^2 [eV^2]
KamLAND	$7.7(3.4) \times 10^{-6}$	$1.7(1.0) \times 10^{-5}$	–
Solar + KamLAND	$1.7(1.3) \times 10^{-11}$	$1.7(1.5) \times 10^{-11}$	–
DayaBay + MINOS + T2K	–	$1.5(0.9) \times 10^{-4}$	$1.3(0.074) \times 10^{-3}$
Super-K + DayaBay + MINOS + T2K	–	$1.9(1.8) \times 10^{-5}$	$1.2(1.1) \times 10^{-5}$
JUNO	$1.7(0.07) \times 10^{-5}$	$2.3(0.09) \times 10^{-5}$	$6.0(2.2) \times 10^{-5}$

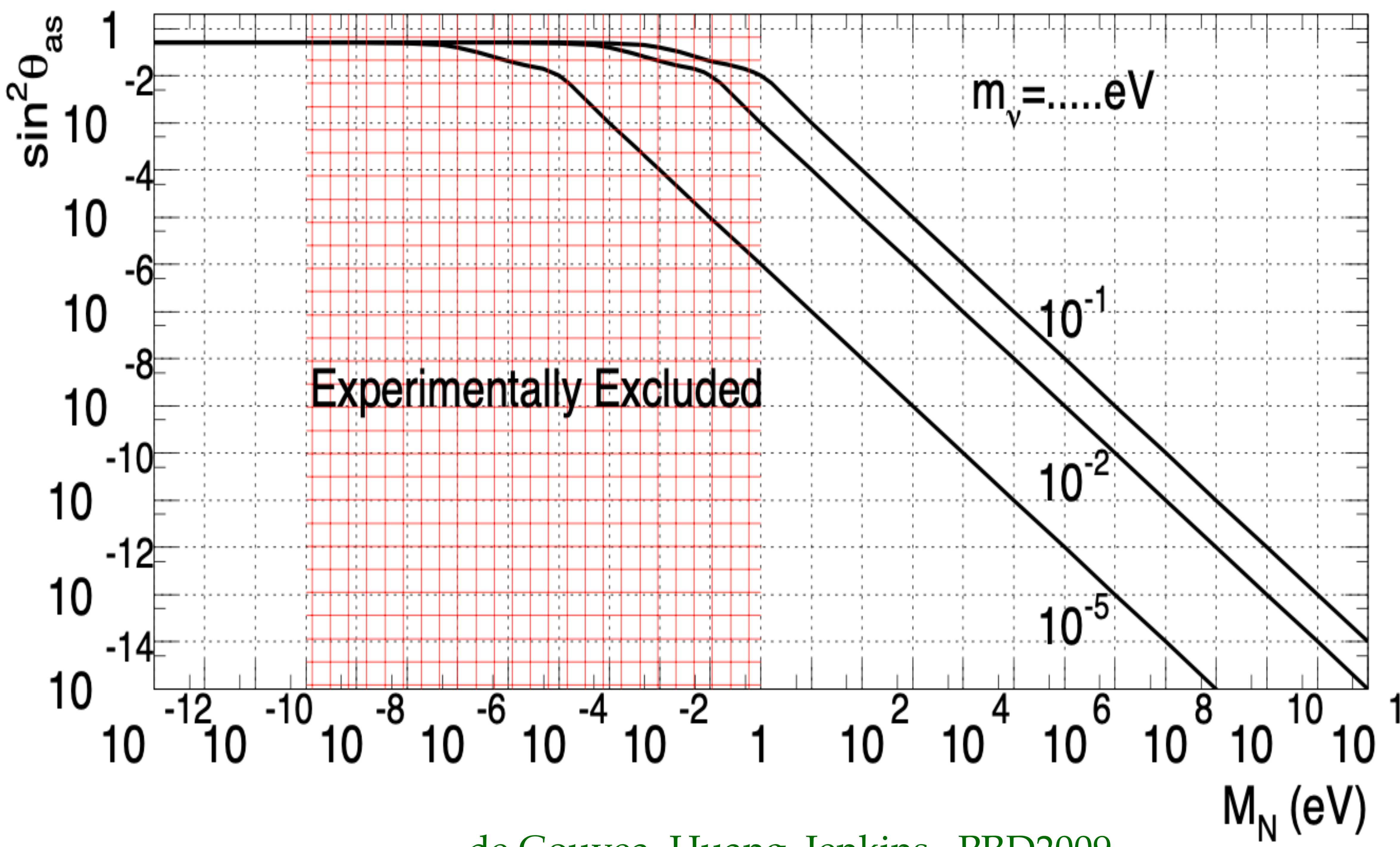
Table 1: 95 % upper limits on ε_i^2 derived from different experimental data sets. Two numbers are given for each case; the first one is the limit obtained marginalizing over two standard oscillation parameters (see text), the second (in brackets) is the limit obtained for the best fit point value of the standard oscillation parameters. For a discussion see text.

Bounds:

1. Solar neutrinos $\delta m^2 < 10^{-12}\,\mathrm{eV}^2$

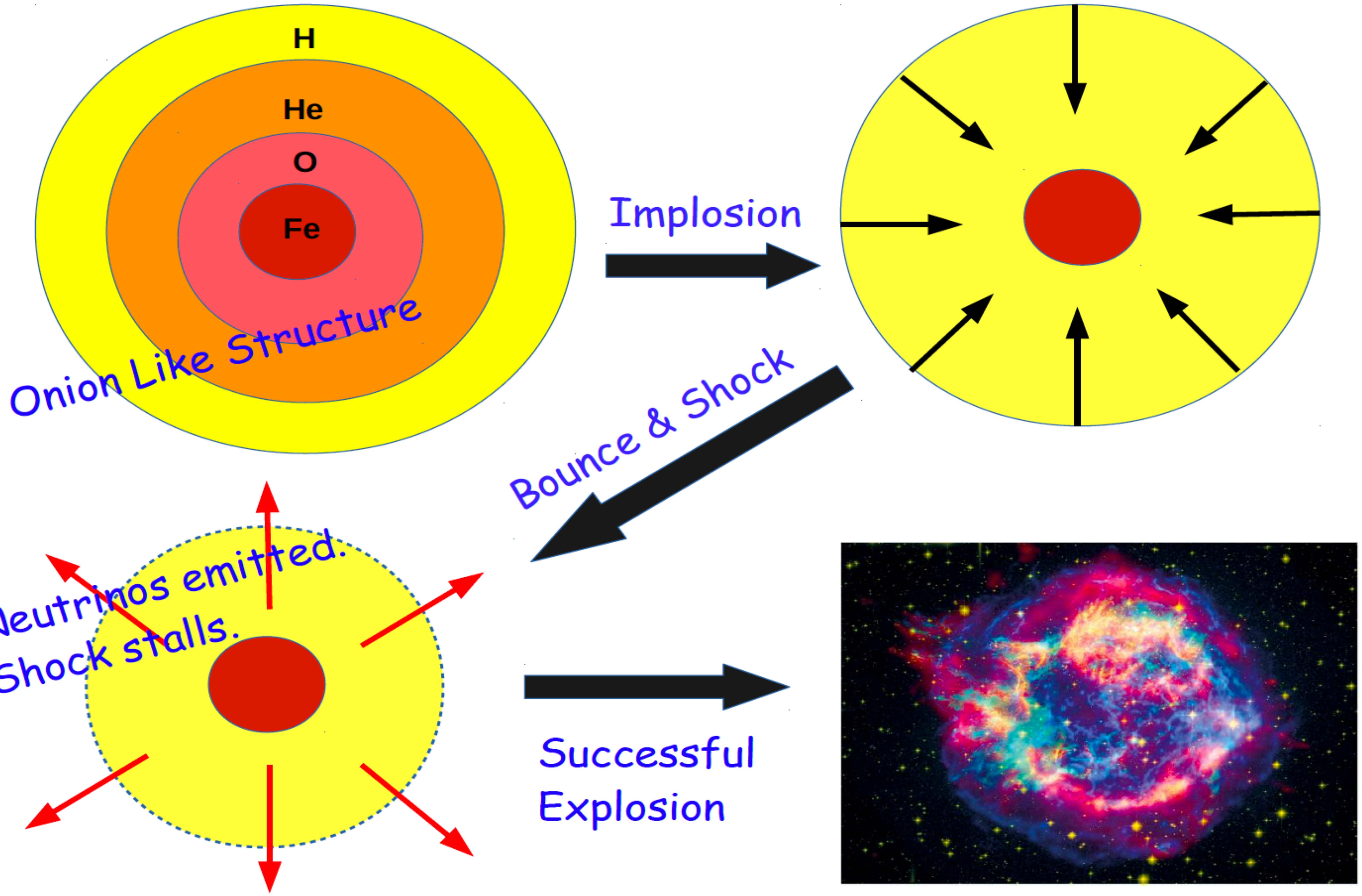
2. Atmospheric neutrinos $\delta m^2 < 10^{-4}\,\mathrm{eV}^2$

3. High energy astrophysical neutrinos $10^{-18}\,\mathrm{eV}^2 < \delta m^2 < 10^{-12}\,\mathrm{eV}^2$



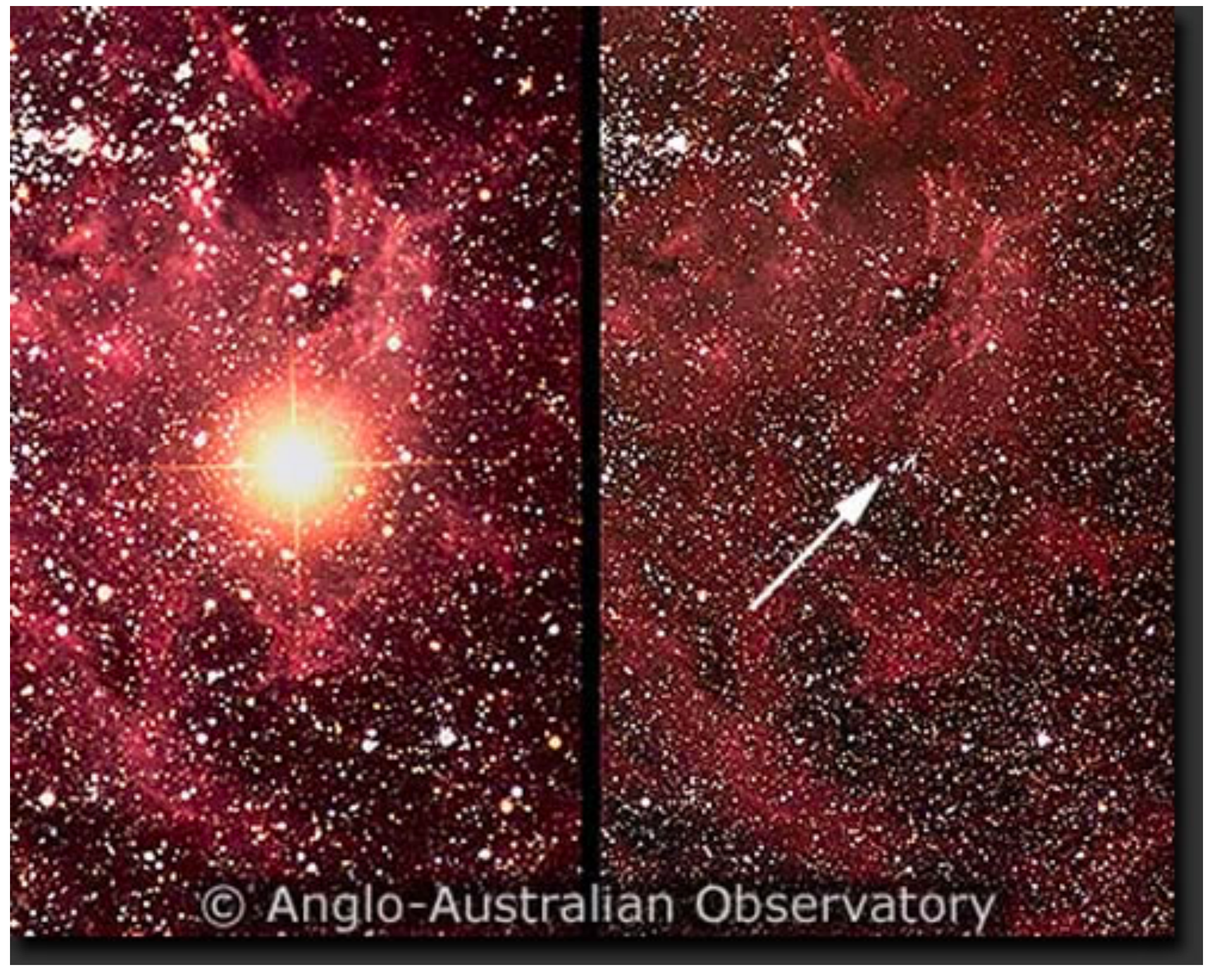
de Gouvea, Huang, Jenkins, PRD2009

1. Core-collapse supernova

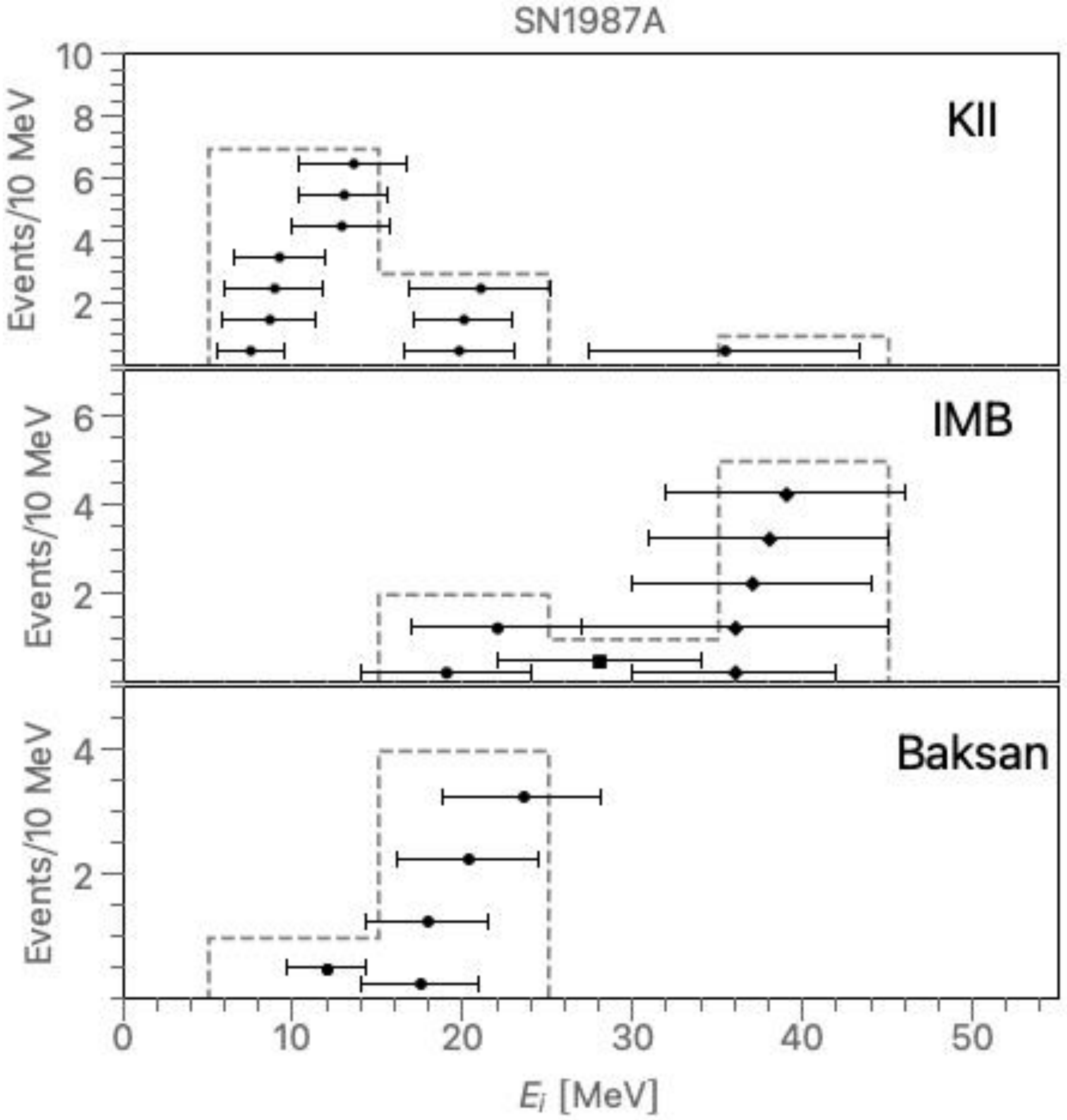


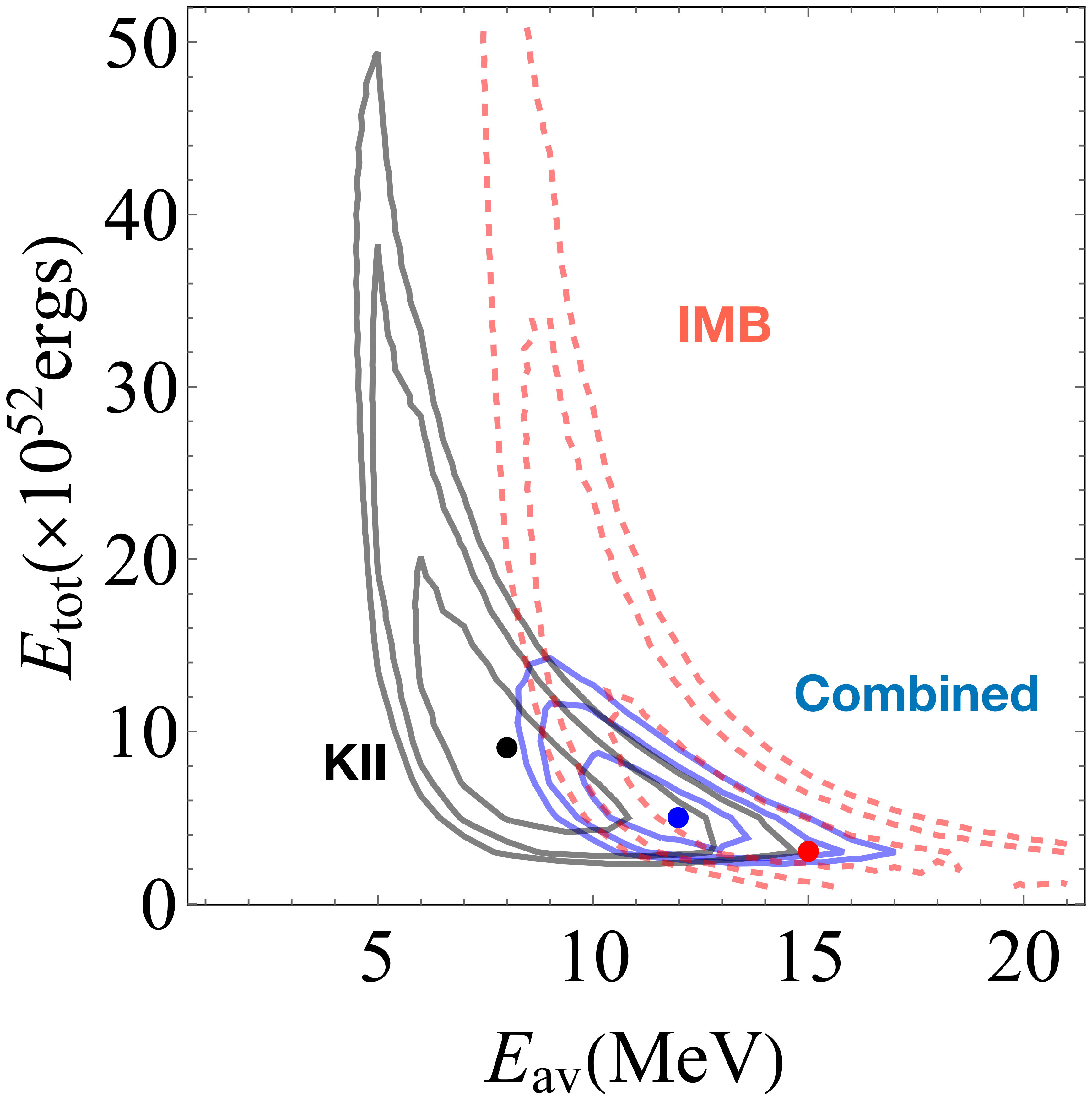
Majority of the energy of the SN is emitted in the form of O(10) MeV neutrinos!!
Excellent laboratories for neutrino physics!

1. SN1987A



Large Magellanic Cloud
50 kpc away





Slight tension between
IMB and KII data?

$$d\mathcal{N}_{\bar{\nu}}(E_\nu) = \frac{E_{\rm tot}}{\langle E_{\bar{\nu}}\rangle}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}},$$

Martinez-Soler, Perez-Gonzalez, **MS**, (PRD 2021)

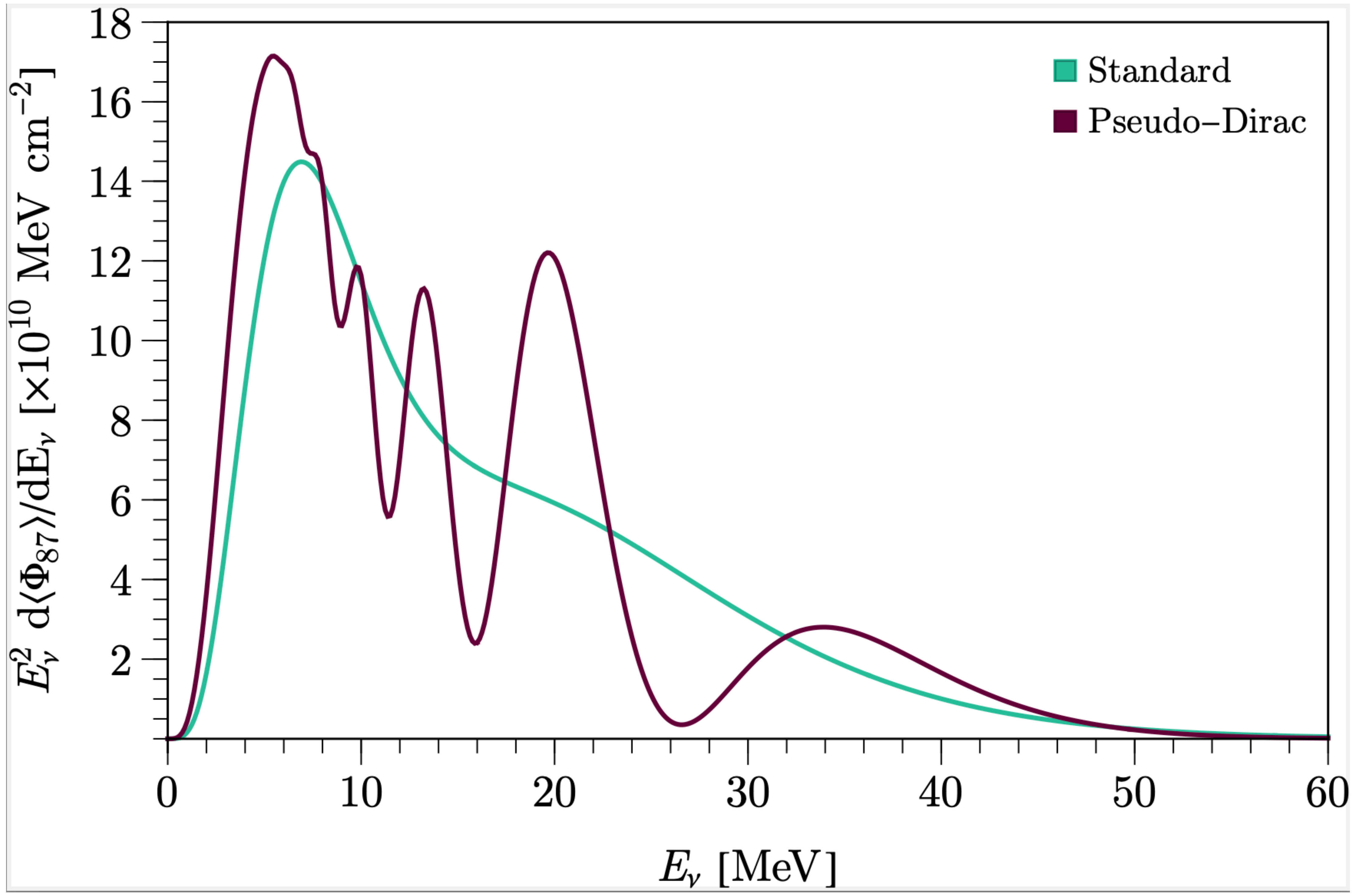
SN spectra due to oscillations

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

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

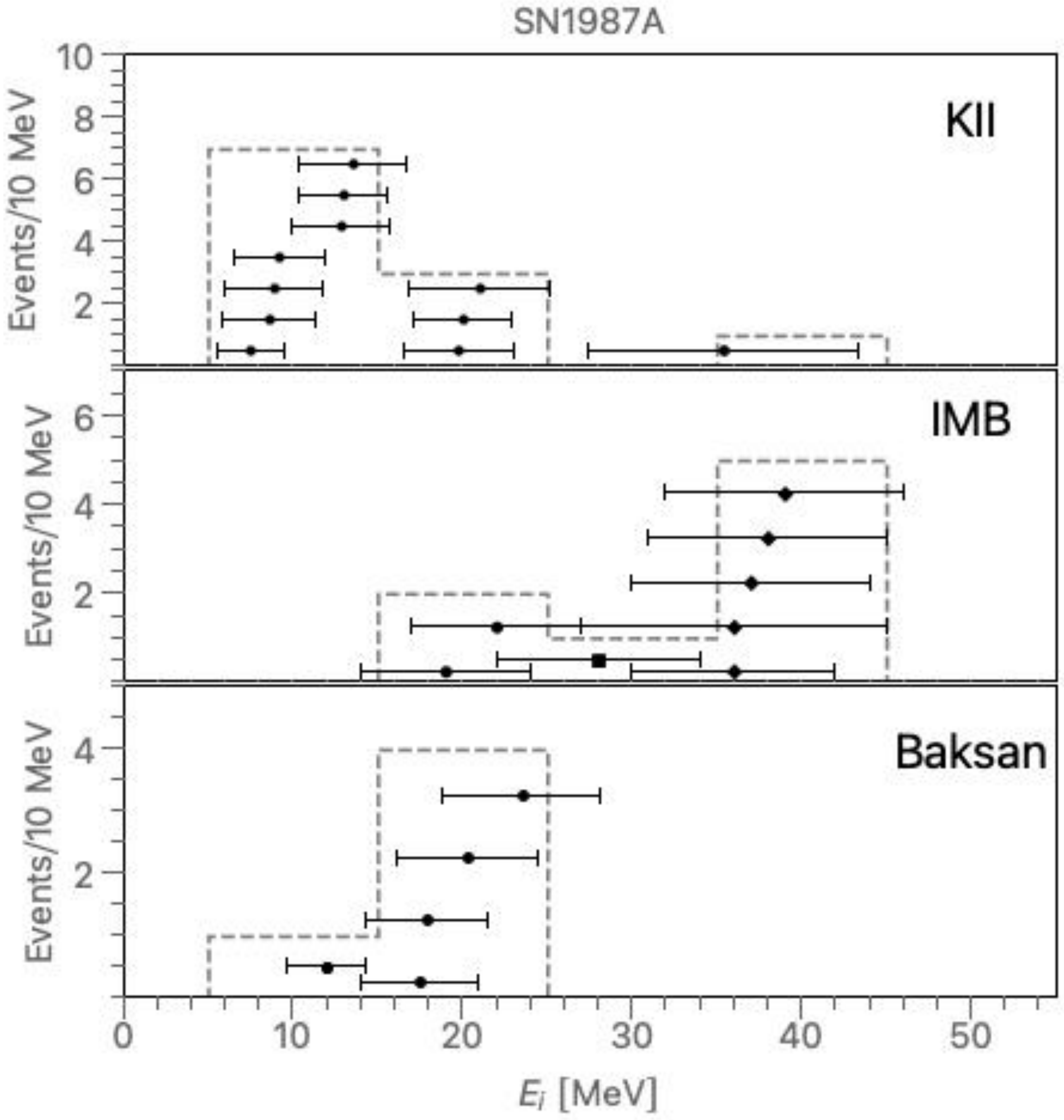
Oscillations due to δm^2

Decoherence due to δm^2 and σ_x



Martinez-Soler, Perez-Gonzalez, **MS**, (PRD 2021)

SN1987A data and comparison



- Fit SN1987A combined data under the pseudo-Dirac hypothesis using an unbinned Likelihood analysis.

- Use the same functional form,

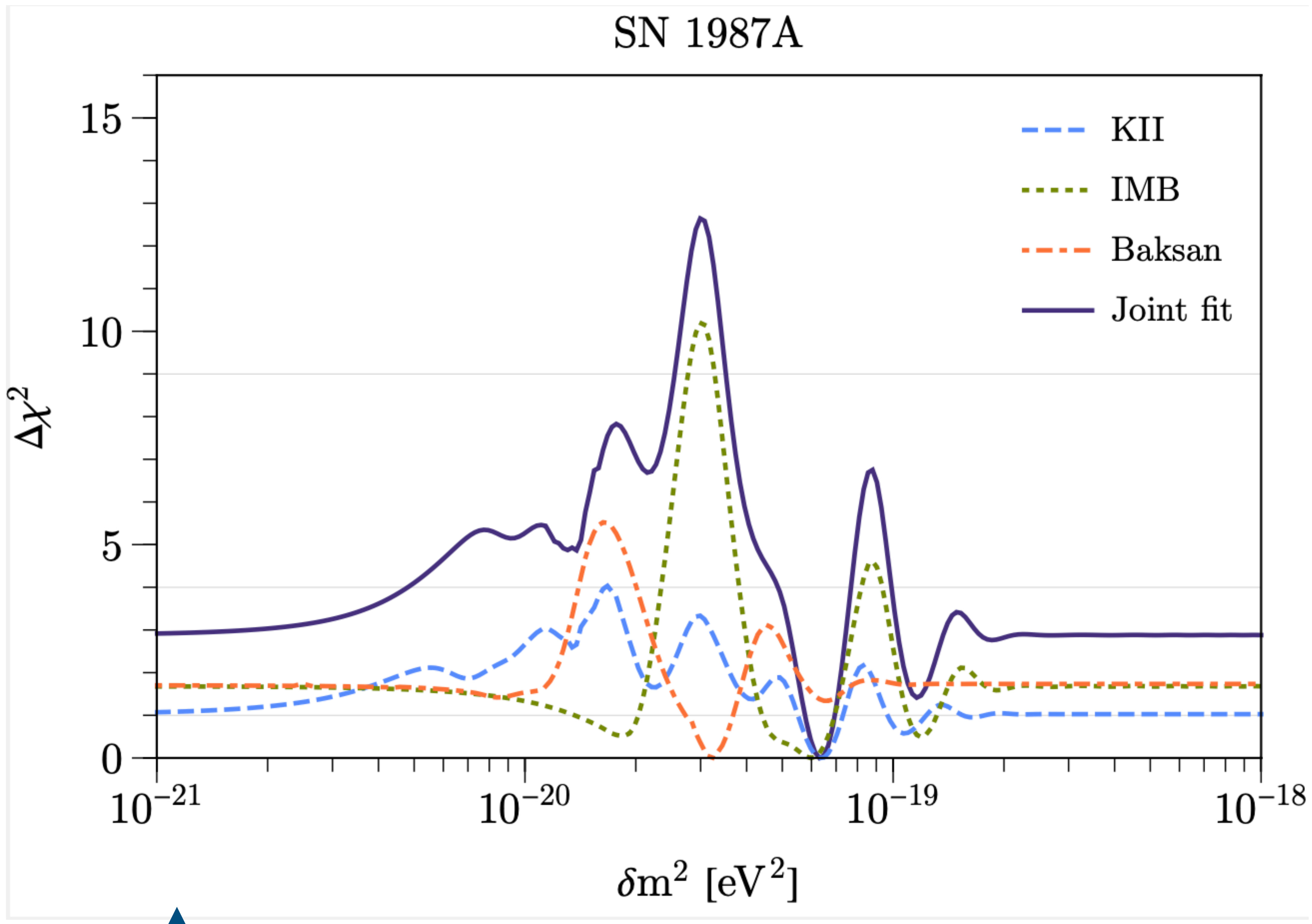
$$d\mathcal{N}_{\bar{\nu}}(E_\nu) = \frac{E_{\rm tot}}{\langle E_{\bar{\nu}}\rangle}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}},$$

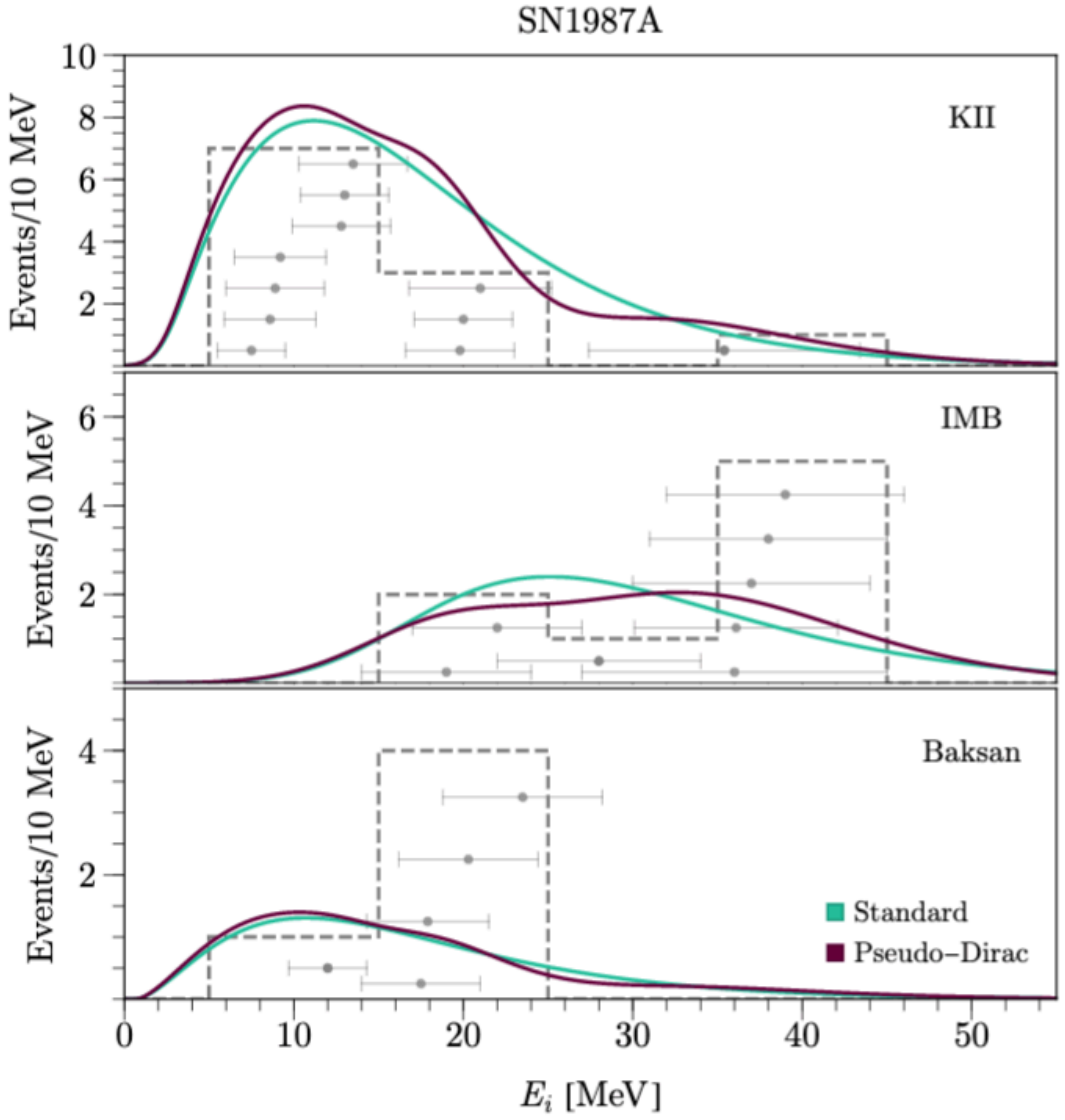
processed by oscillation probability that neutrinos are pseudo-Dirac.

- Parameters varied are $E_{\rm tot}, \langle E_\nu\rangle$, α, and δm^2, which is considered same for all 3 mass eigenstates. The width of the wavepacket is fixed to $\sigma_x = 10^{-13}\,\mathrm{m}$.

Martinez-Soler, Perez-Gonzalez, **MS**, (PRD 2021)

SN1987A data and comparison





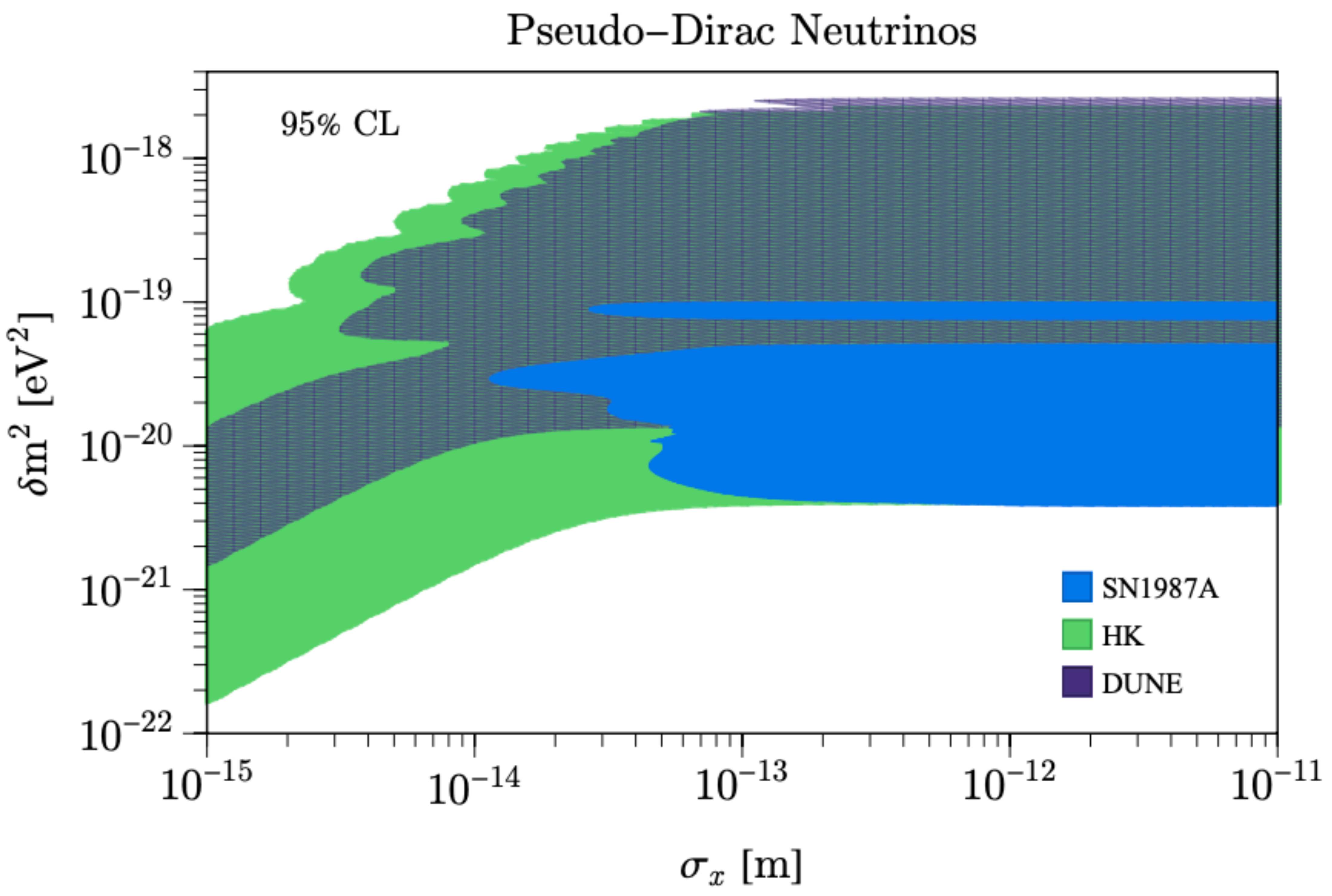
No Oscillations

- Slight preference for the PD possibility, $\Delta\chi^2 \sim 3$!
- Exclude $\delta m^2 \sim [2.5, 3.] \times 10^{-20}\text{eV}^2$ with $\Delta\chi^2 > 9$

Martinez-Soler, Perez-Gonzalez, **MS**, (PRD 2021)

Future detectors: sensitivity

- HK and DUNE can confirm/rule out this scenario with a high confidence.
- Sensitive to lower mass-square differences due to decoherence.
- Non-electron neutrino detectors to play an important role!



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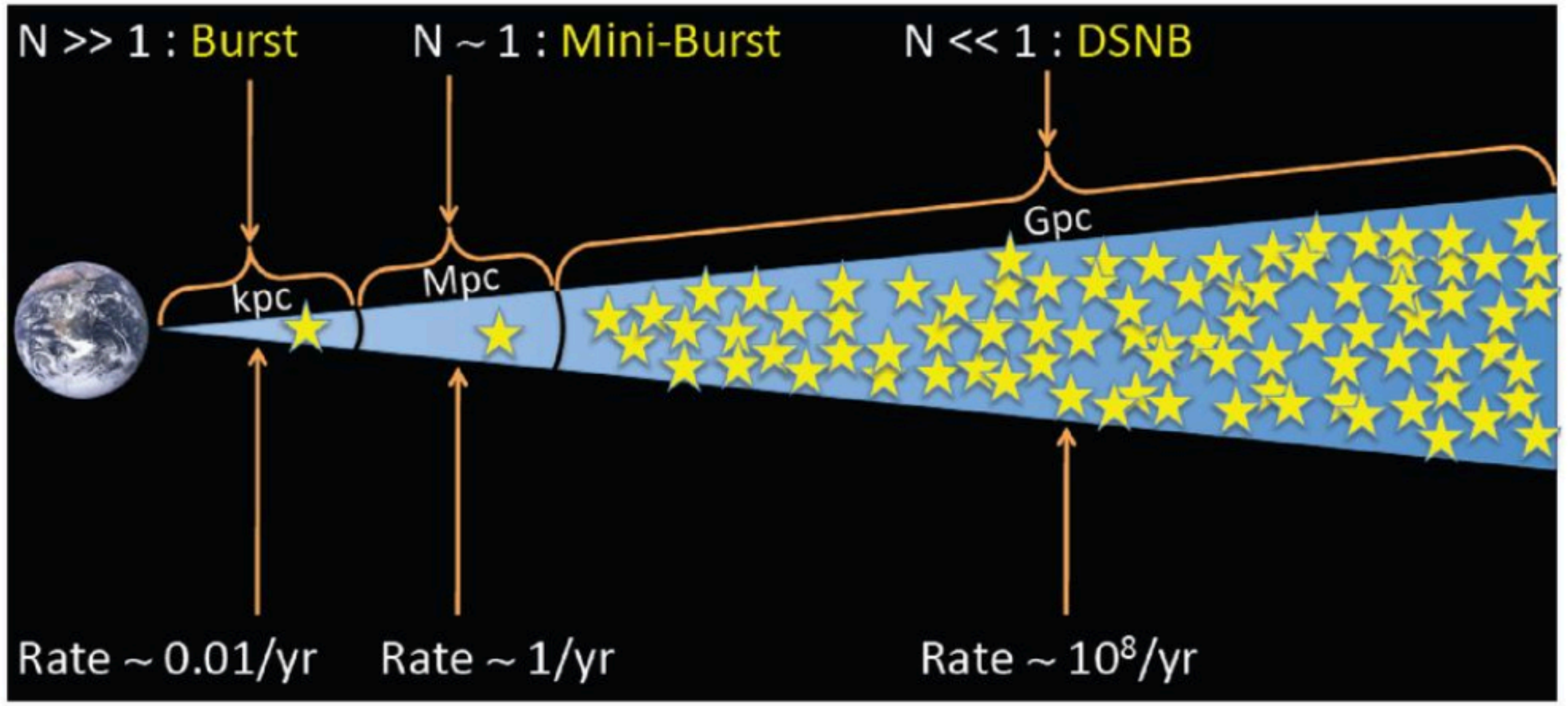
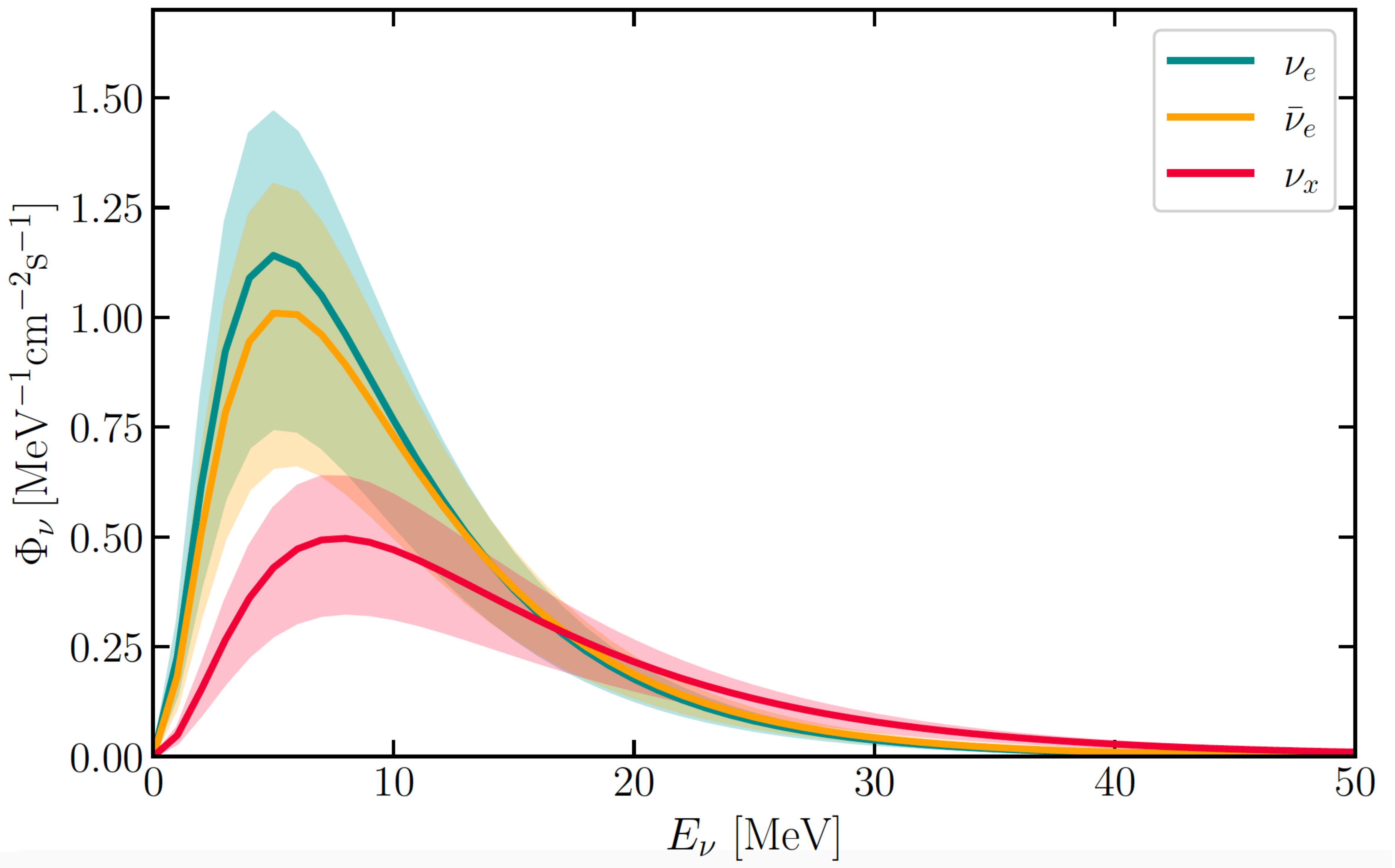
2. DSNB

John Beacom, TAUP2011



DSNB=Diffuse Supernova Neutrino Background

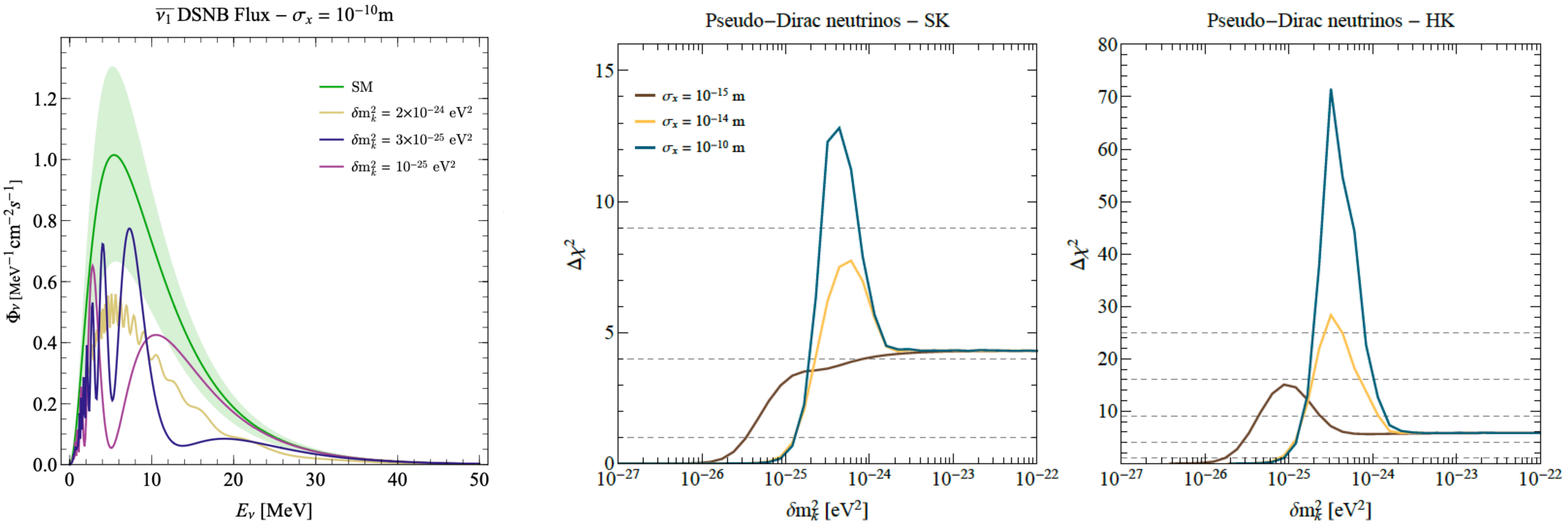


Neutrinos from Gpc distance

$$L_{\rm osc} = \sim 16\,{\rm Gpc}\left(\frac{E_\nu}{20{\rm MeV}}\right)\left(\frac{10^{-25}{\rm eV}^2}{\delta m^2}\right)$$

de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

DSNB sensitivity to pseudo-Dirac neutrinos



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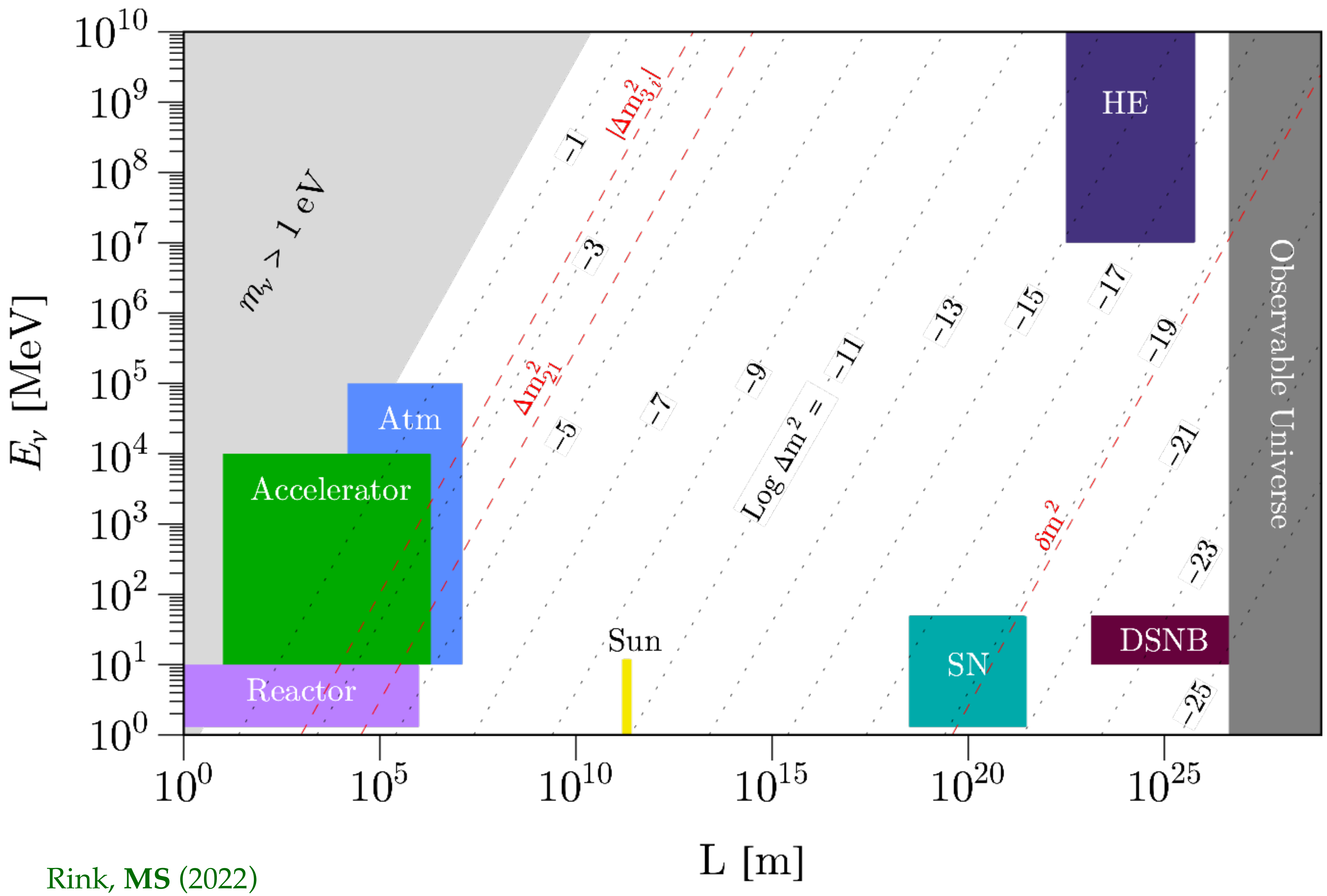
de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,{\rm eV}^2)$ with a high significance.

Final thoughts

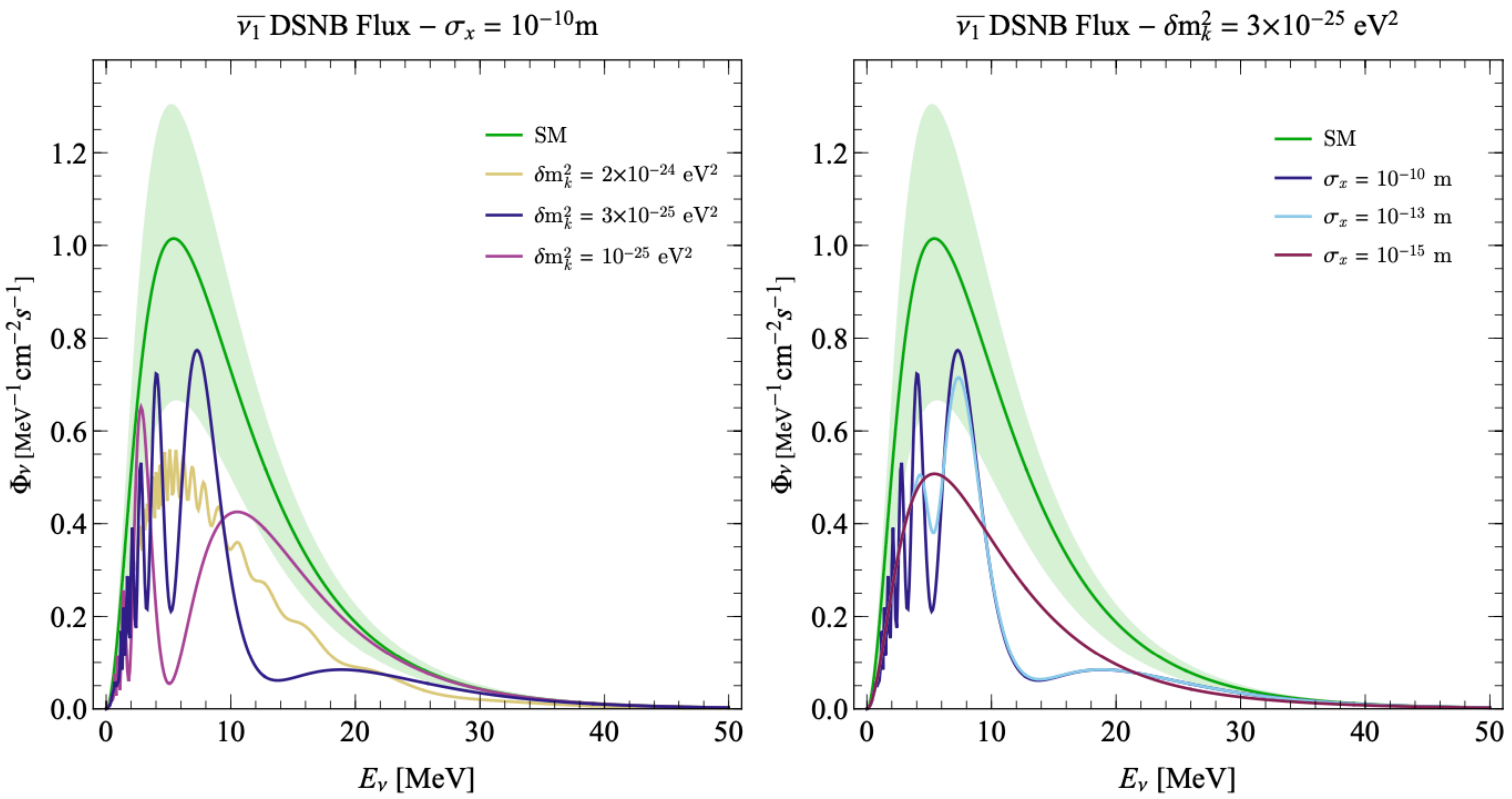


Rink, **MS** (2022)
Perez-Gonzalez, **MS** (2023)

- CCSNe are sensitive to extremely tiny value of δm^2, not otherwise accessible to other experiments.
- Data from SN1987A can already be used to probe $\delta m^2 \sim 10^{-20}\,\mathrm{eV}^2$. In fact, data from SN1987A has a slight preference for a non-zero δm^2.
- Future galactic core-collapse SNe can be used to probe even lower values of δm^2 using DUNE and HK.
- The DSNB opens up a plethora of avenues for neutrino astronomy, next giant leap from the Sun and SN1987A.

Thank you!

DSNB: Oscillations due to pseudo-Dirac nature



Increasing δm^2 reduces L_{osc} and L_{coh}, and causes more oscillations

Decreasing σ_x reduces L_{coh} , and causes more decoherence