High energy neutrinos as probes of soft lepton number violation

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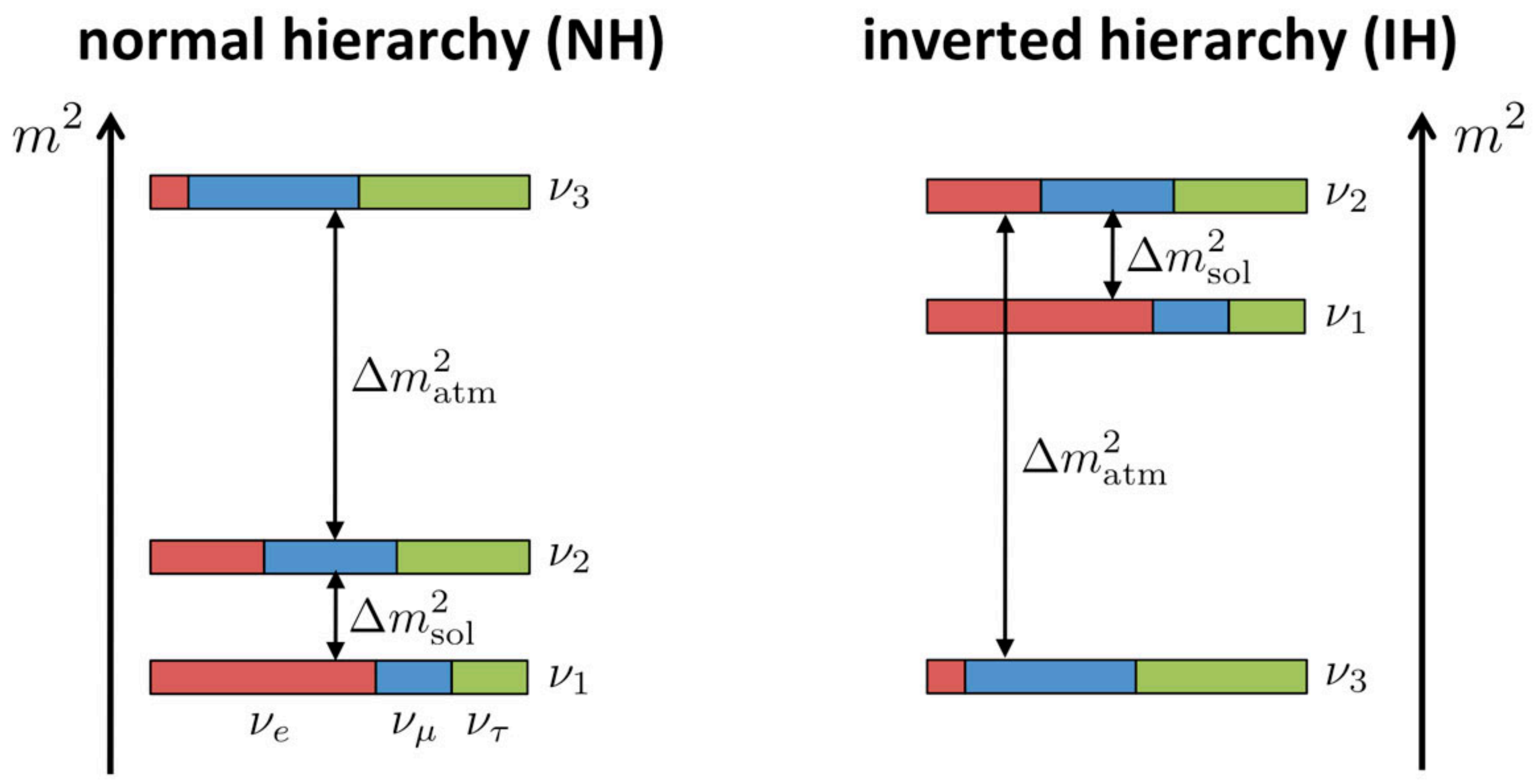
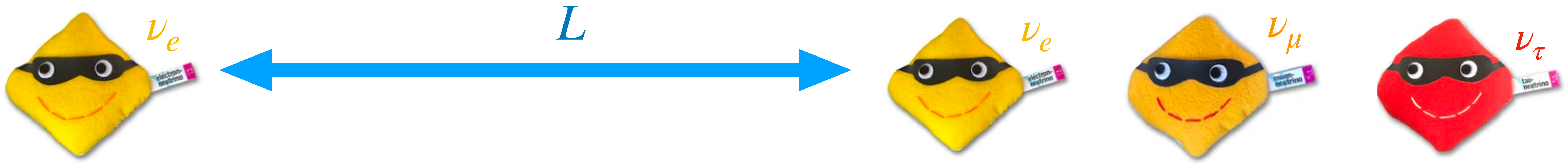
Neutrino oscillations

- 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,

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

$\not{L}$

- 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.

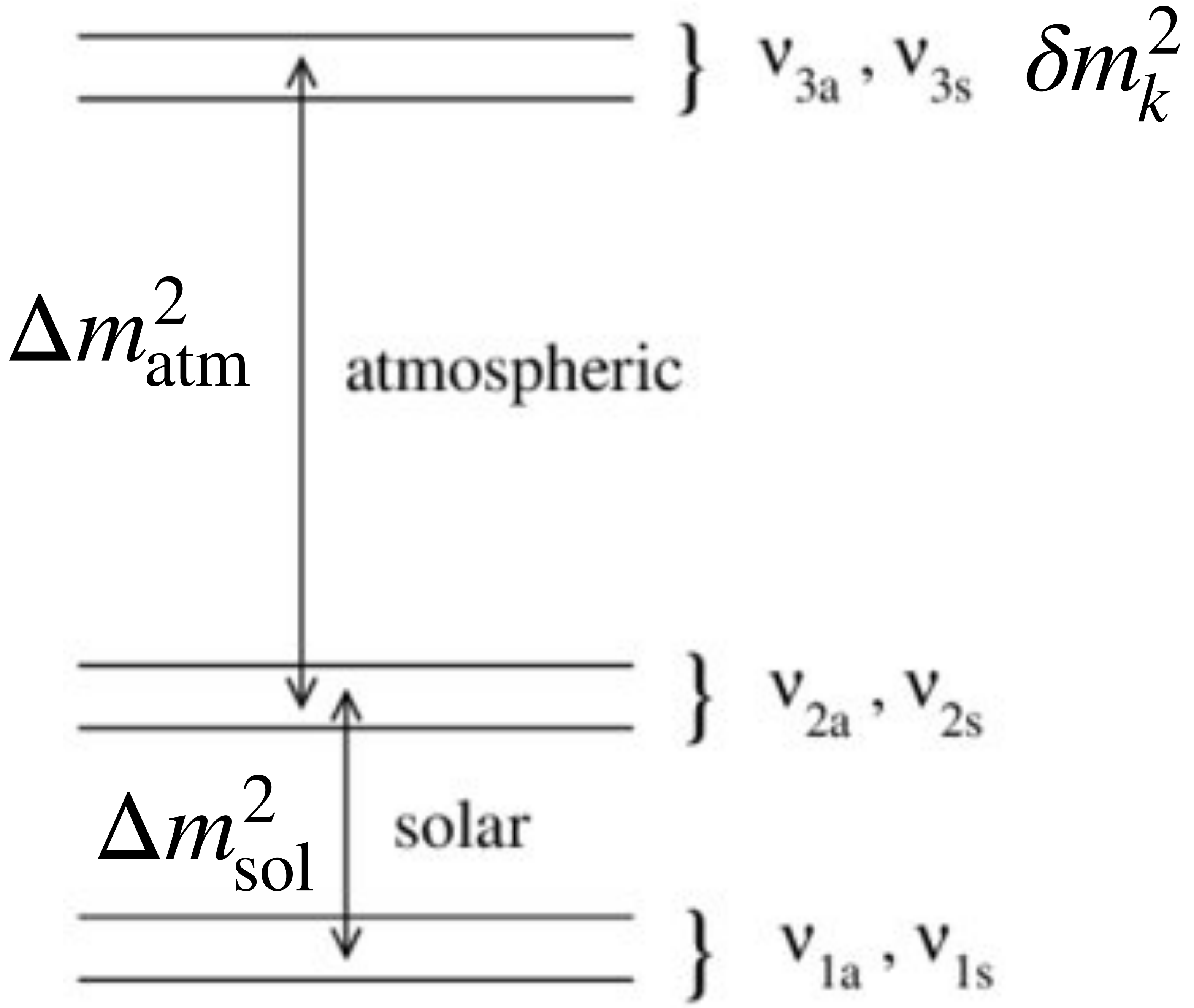
Wolfenstein, NPB 1981
Valle, PRD 1983

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

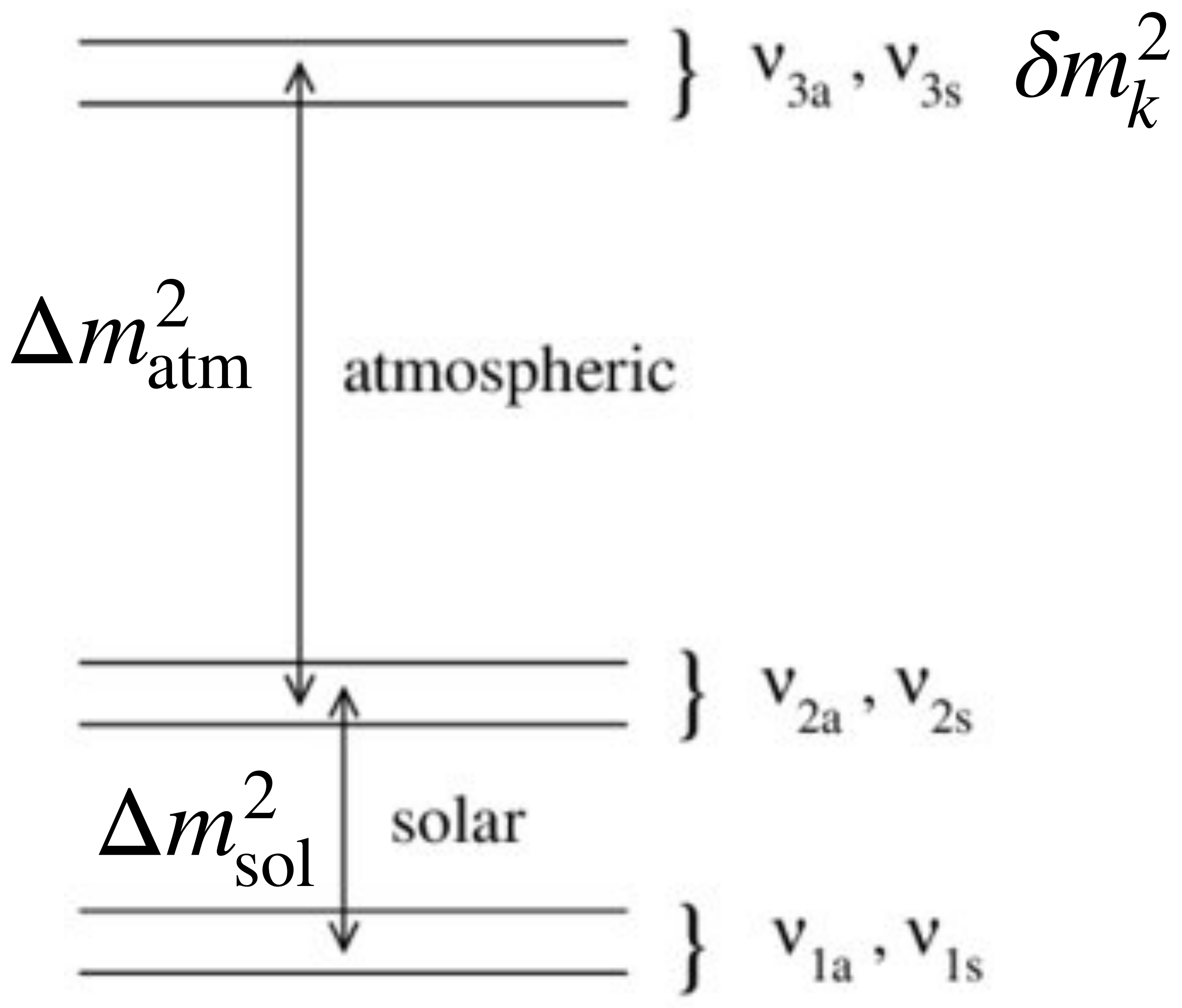
- δm_k^2 will lead to oscillations at very large distances, $L \propto 1/\delta m^2$

- Flavor oscillation probability induced by Δm^2_{sol} and Δm^2_{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

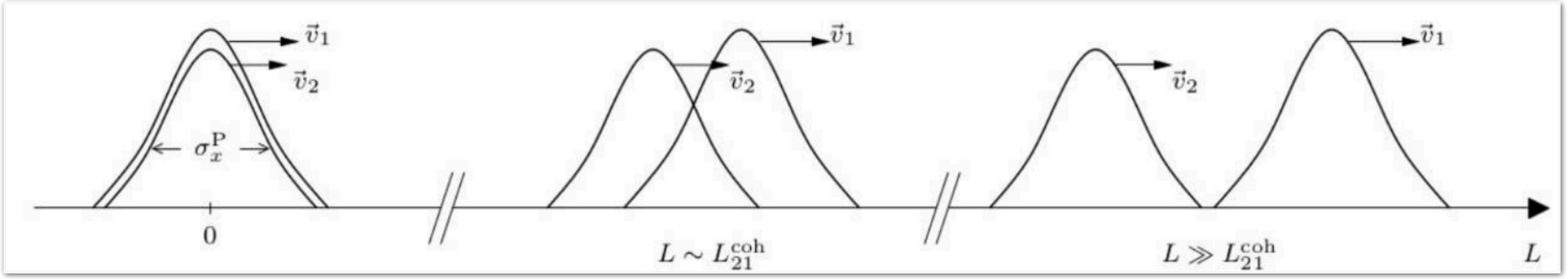
$$P_{aa}(z,E) = \frac{1}{2}\left(1 + e^{-\left(\frac{L(z)}{L_{\text{coh}}}\right)^2} \cos\left(2\pi \frac{L(z)}{L_{\text{osc}}}\right)\right)$$



Oscillations due to small δm^2

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

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



Giunti and Kim, Fundamentals of neutrino physics

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

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	$1.7(0.07) \times 10^{-5}$	$2.3(0.09) \times 10^{-5}$	$6.0(2.2) \times 10^{-5}$

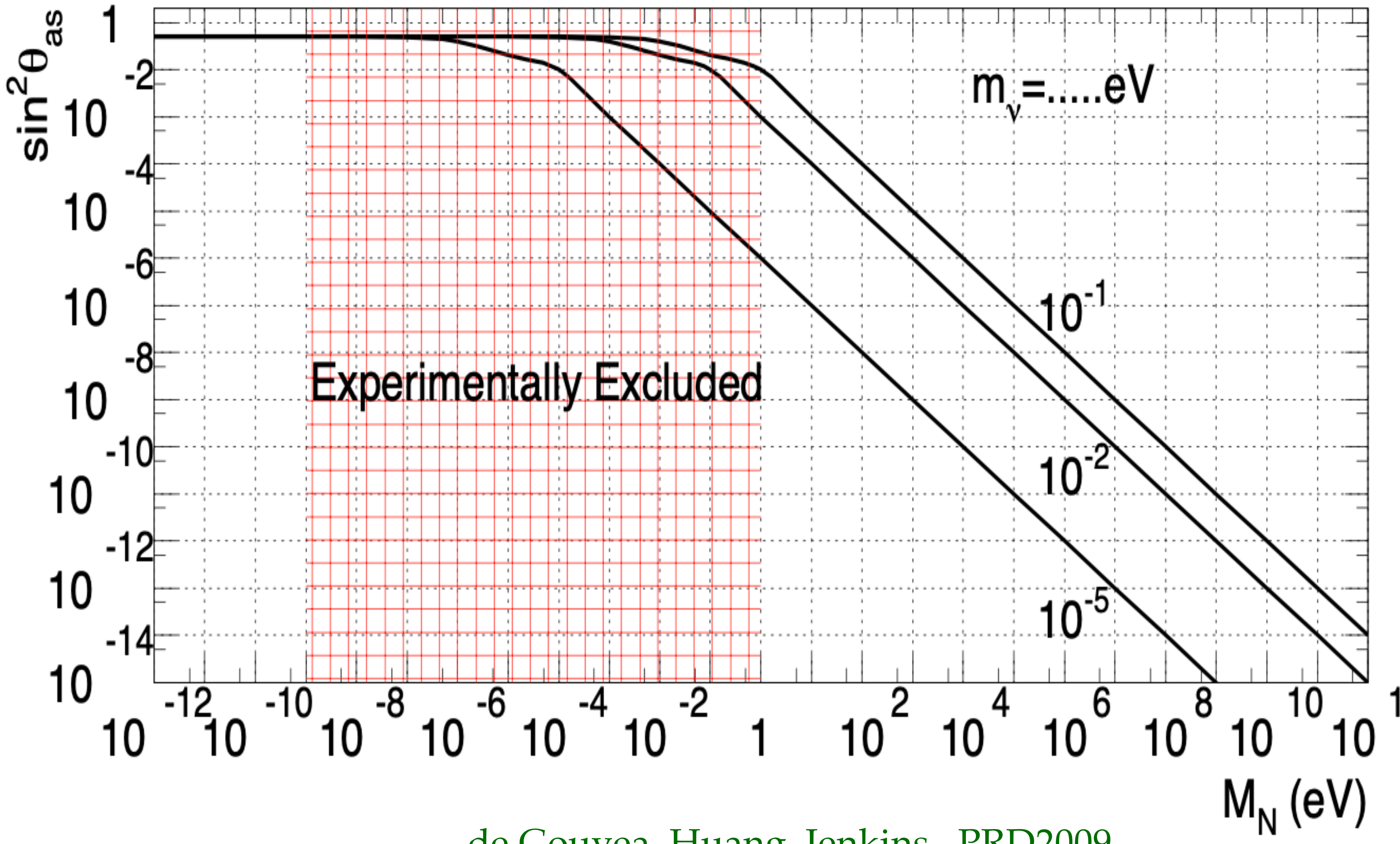
Table 1: 95 % upper limits on ε_i^2 derived from different experimental data sets. Two numbers are given for each case; the first one is the limit obtained marginalizing over two standard oscillation parameters (see text), the second (in brackets) is the limit obtained for the best fit point value of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

Bounds:

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

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

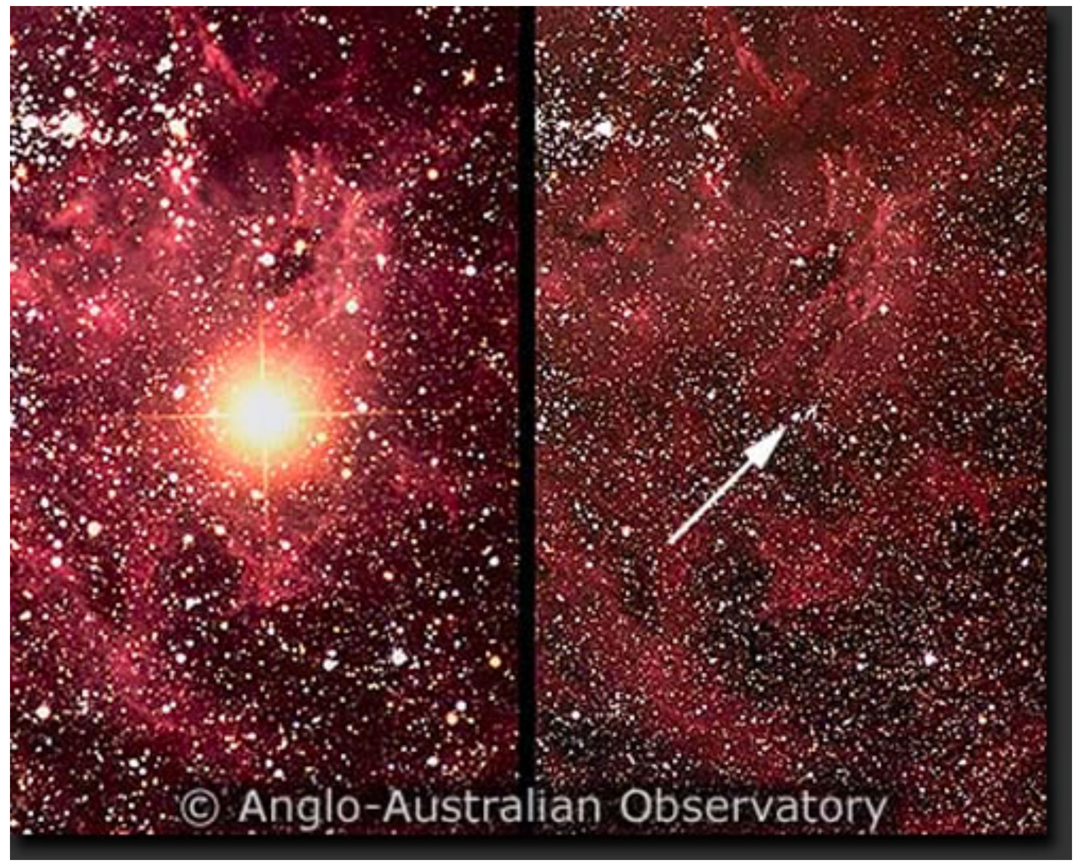
3. High energy astrophysical neutrinos $10^{-18}\,\mathrm{eV}^2 < \delta m^2 < 10^{-12}\,\mathrm{eV}^2$



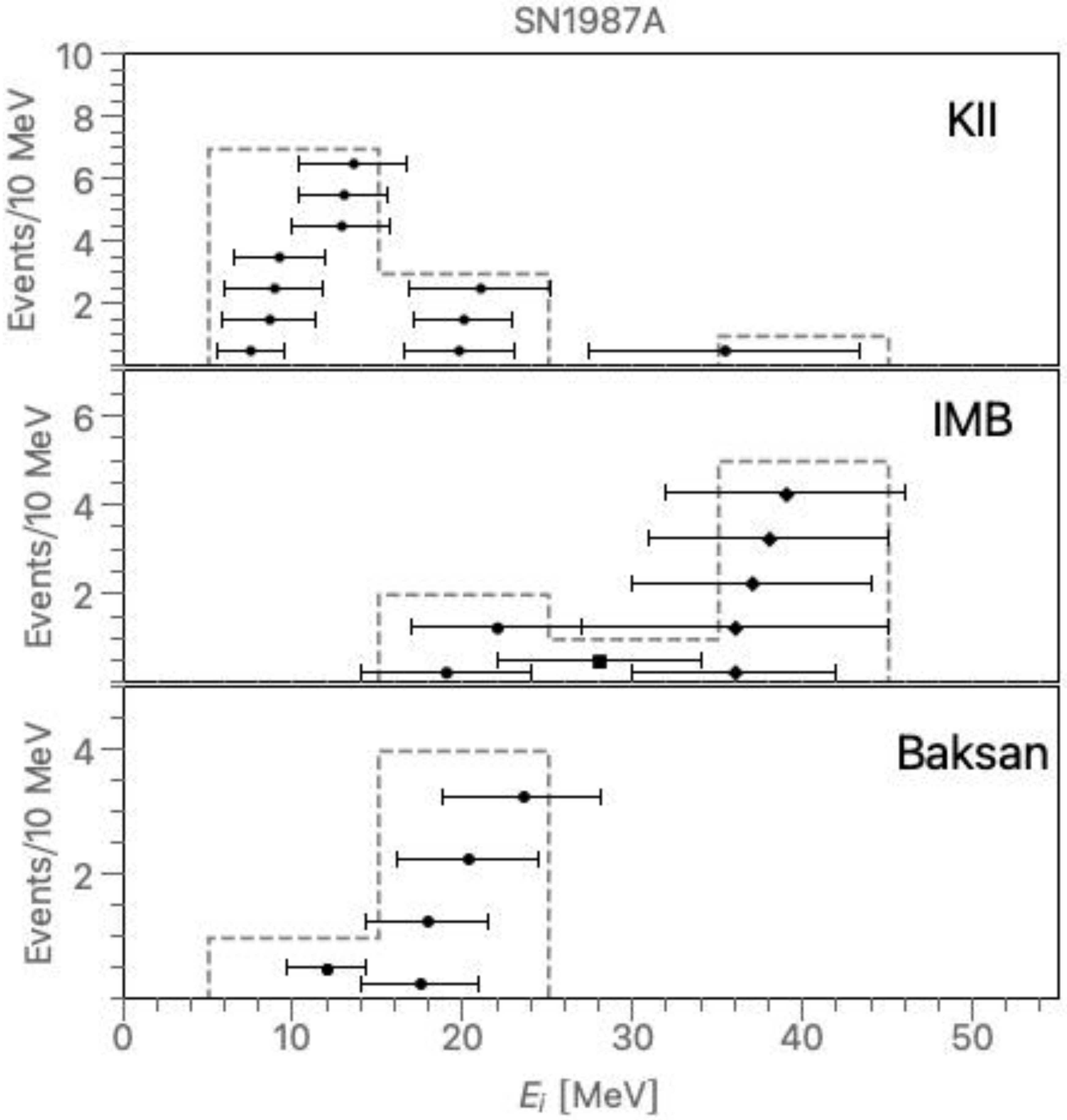
de Gouvea, Huang, Jenkins, PRD2009

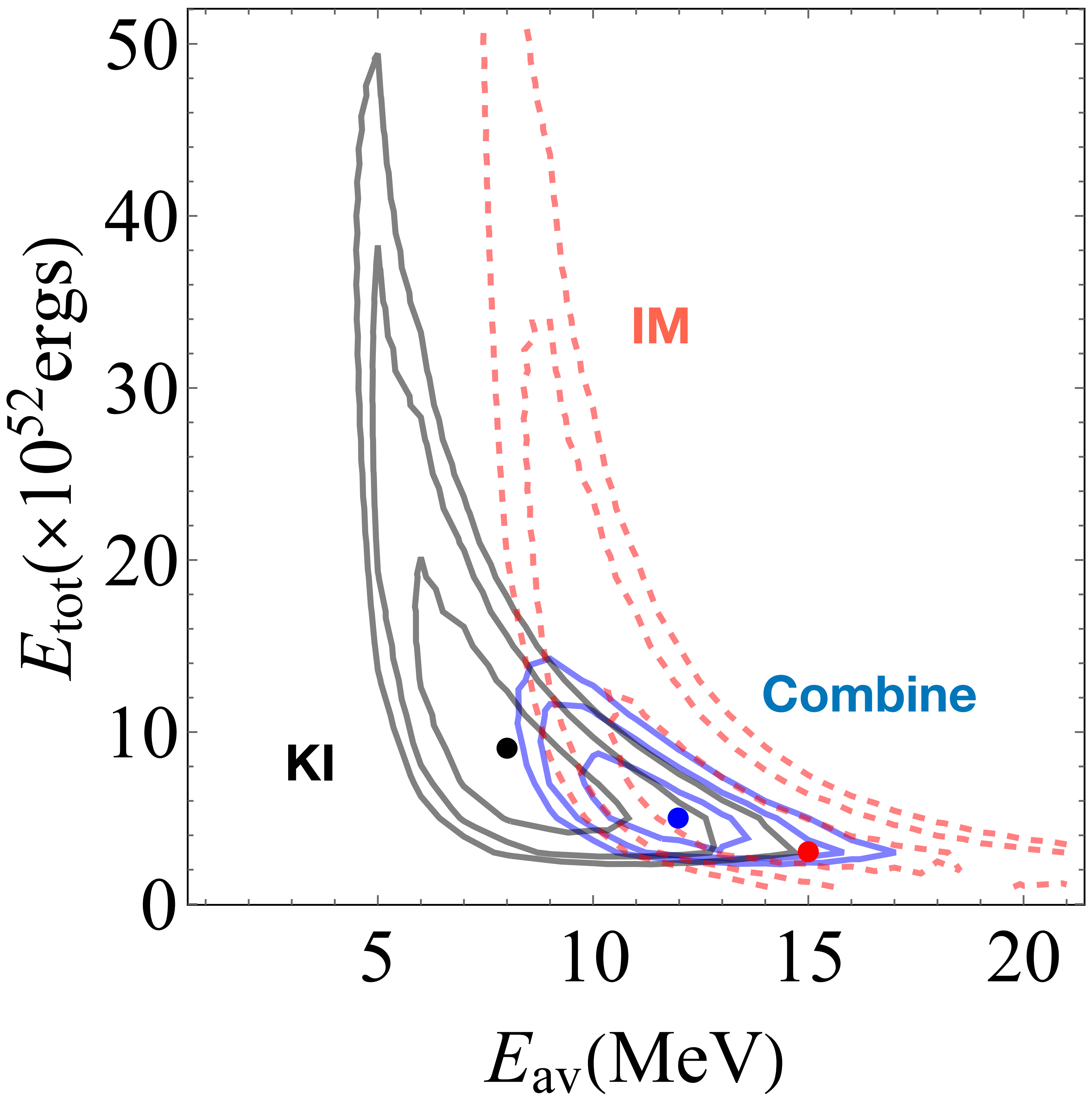
What other sources can we consider?

1. SN1987A



Large Magellanic Cloud
50 kpc away



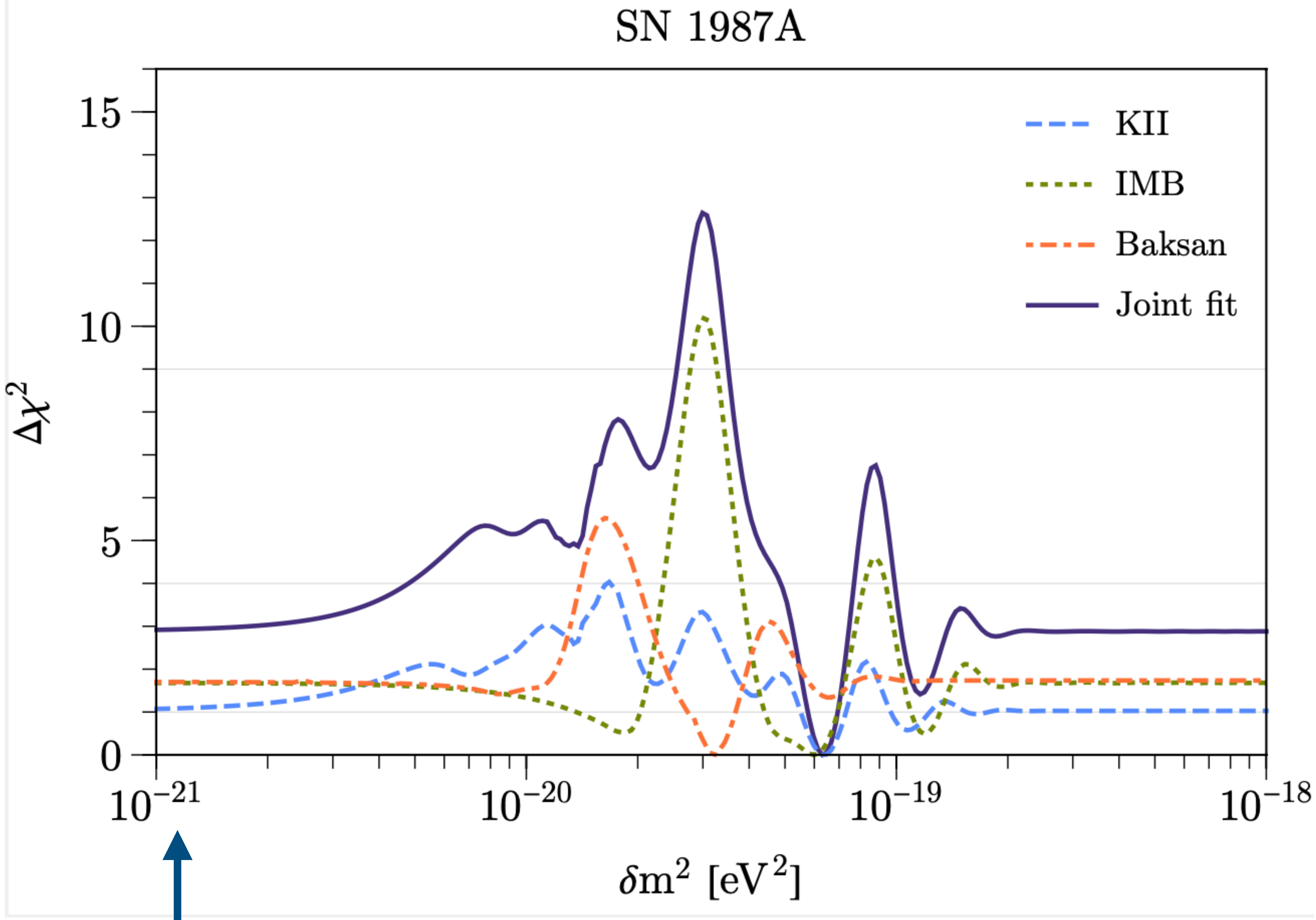


Slight tension between IMB and KII data?

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

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

1. SN1987A



No Oscillations

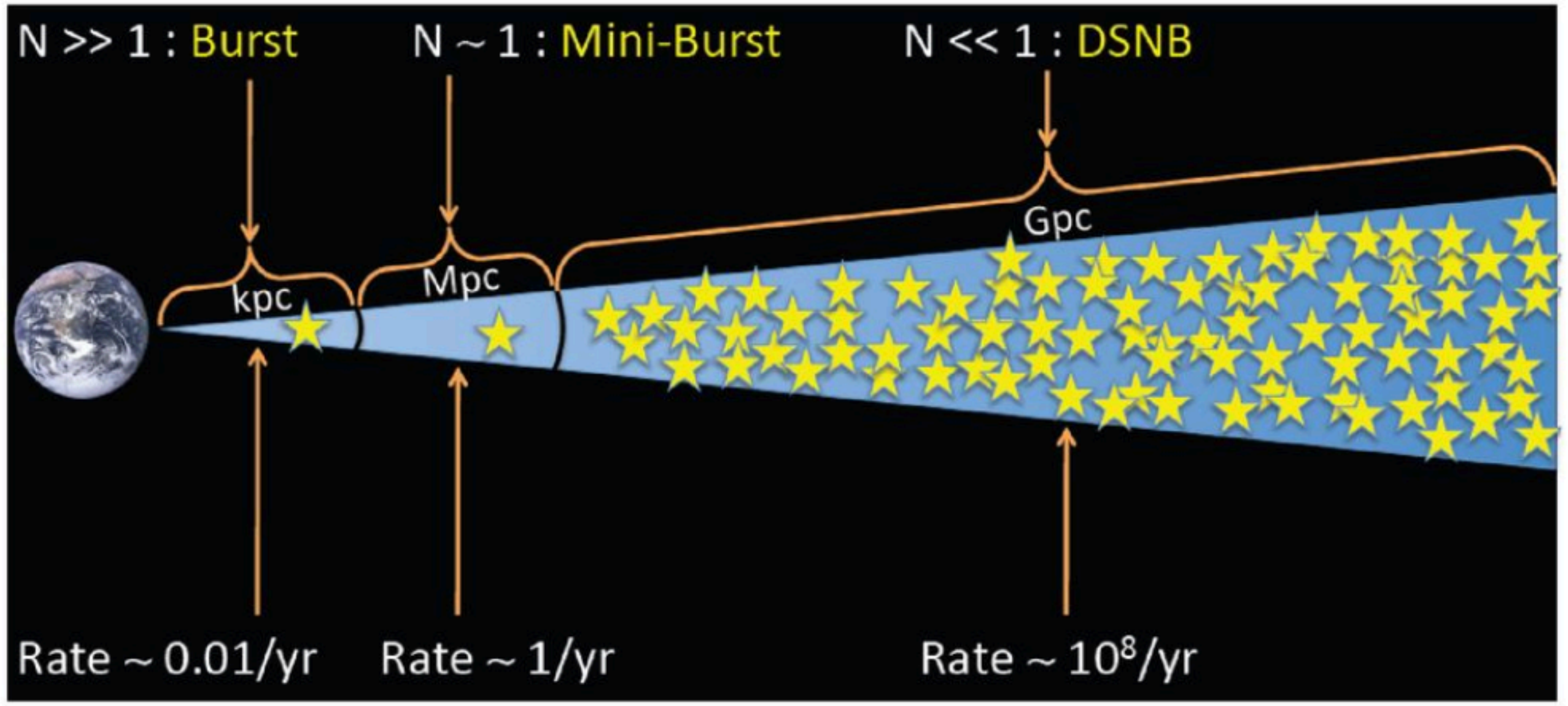
- Slight preference for the PD possibility, $\Delta\chi^2 \sim 3$
- Exclude $\delta m^2 \sim [2.5, 3.] \times 10^{-20}\text{eV}^2$ with $\Delta\chi^2 > 9$

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

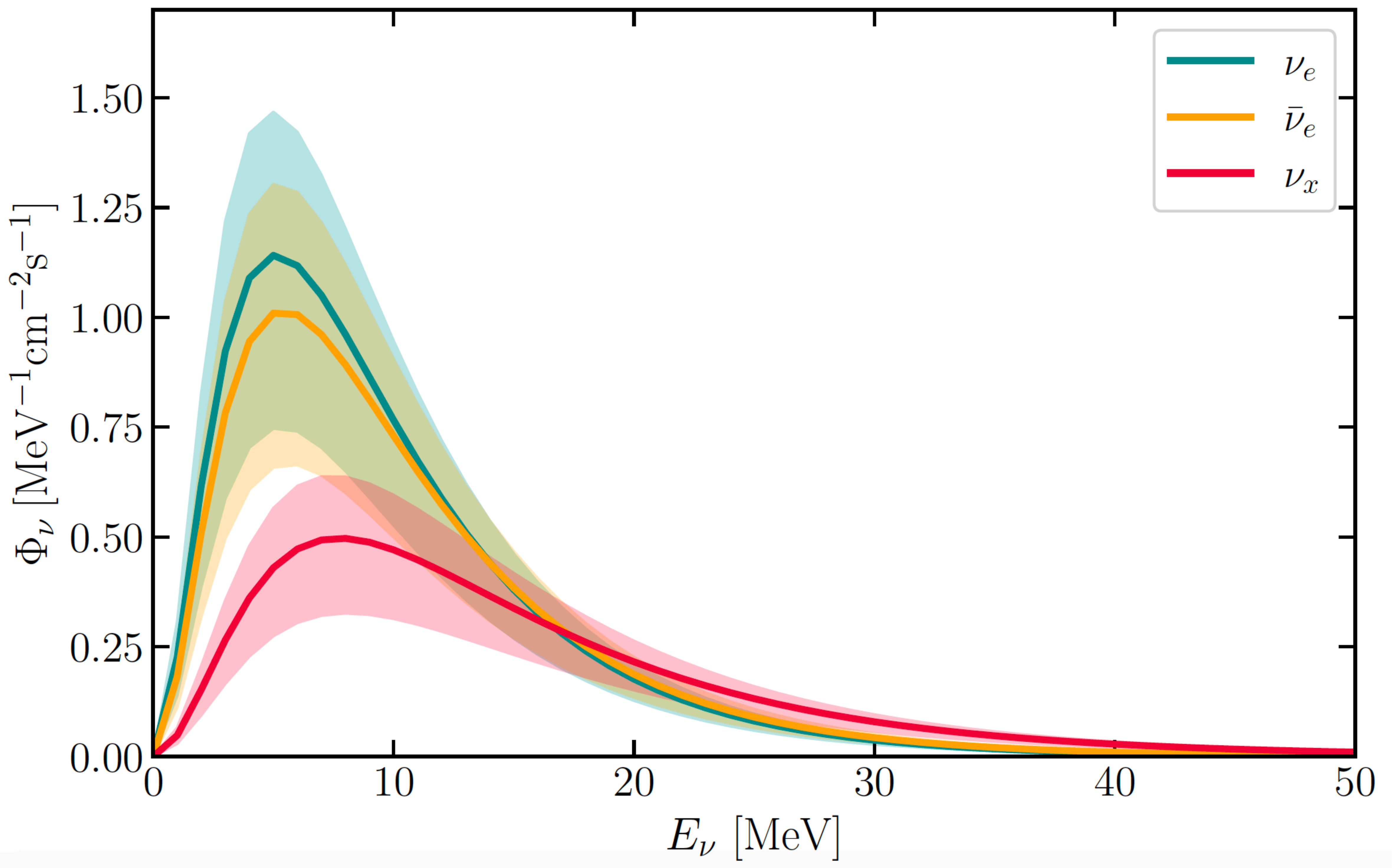
$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \sim 20\,\text{kpc}\left(\frac{E_\nu}{25\text{MeV}}\right)\left(\frac{10^{-19}\text{eV}^2}{\delta m^2}\right)$$

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)

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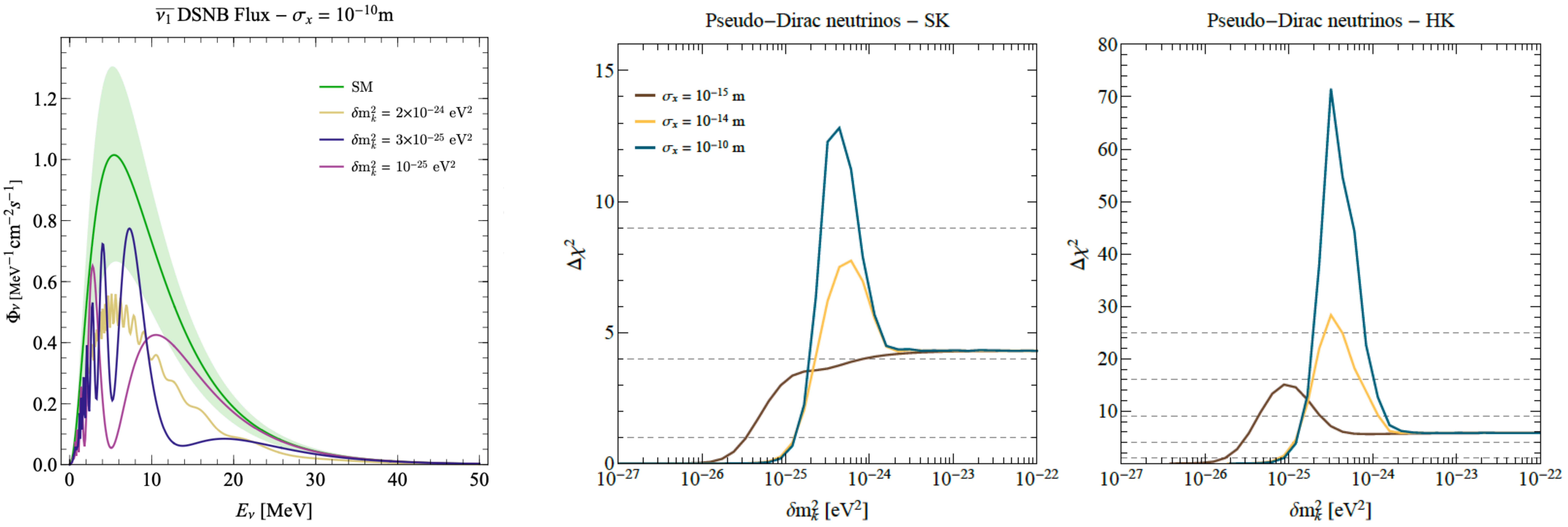

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de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

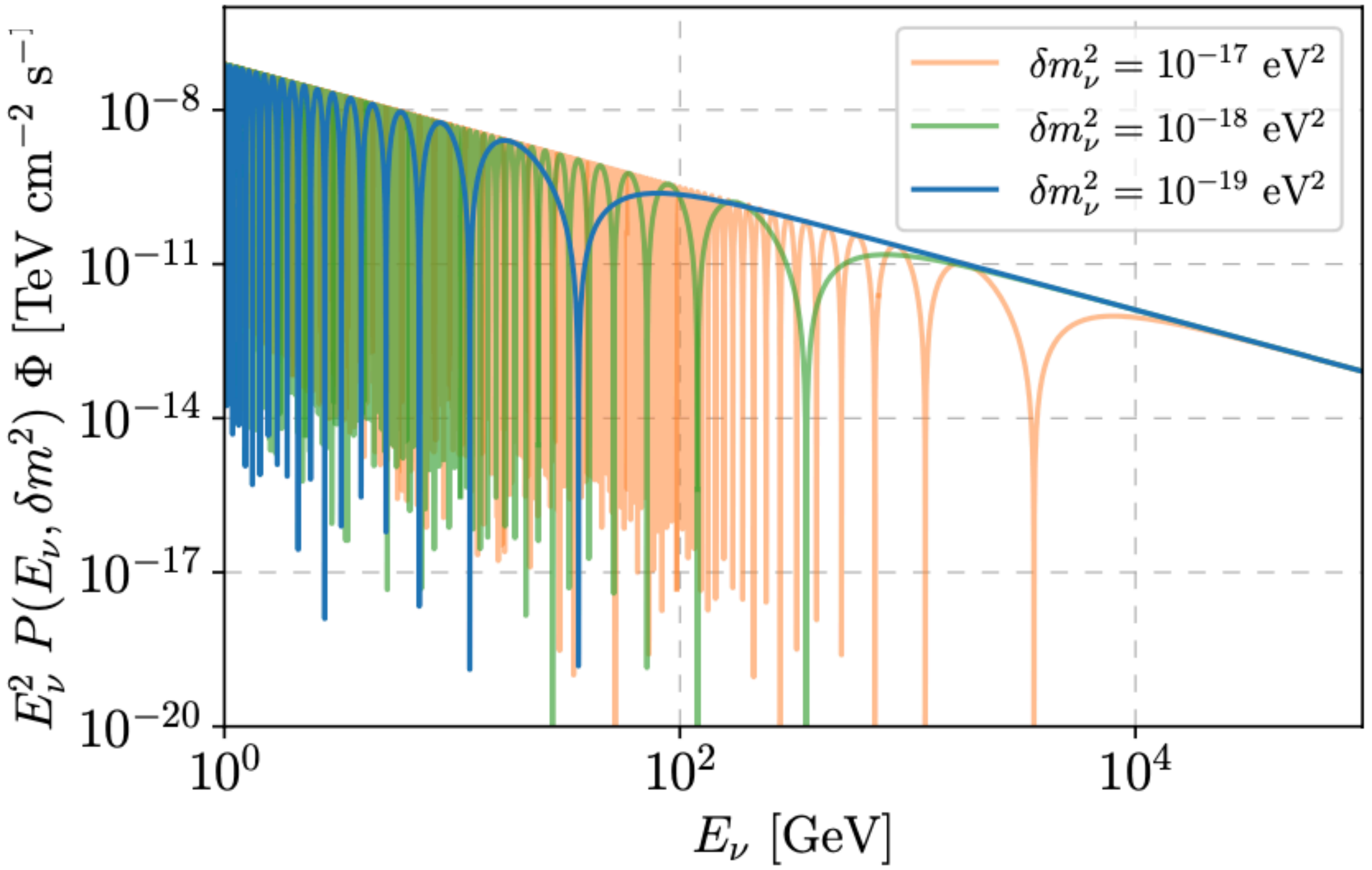
DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,{\rm eV}^2)$ with a high significance.

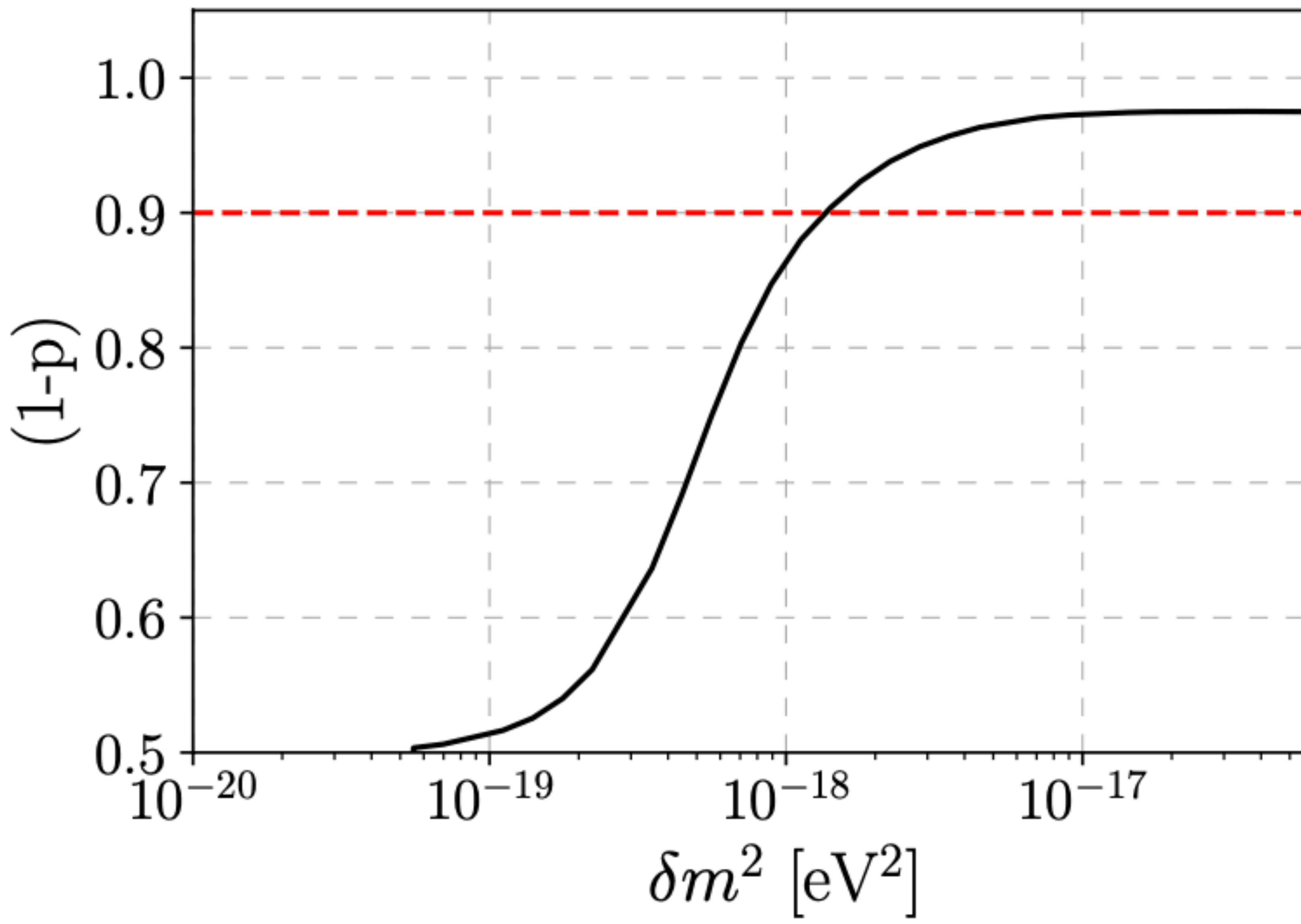
3. NGC 1068

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†





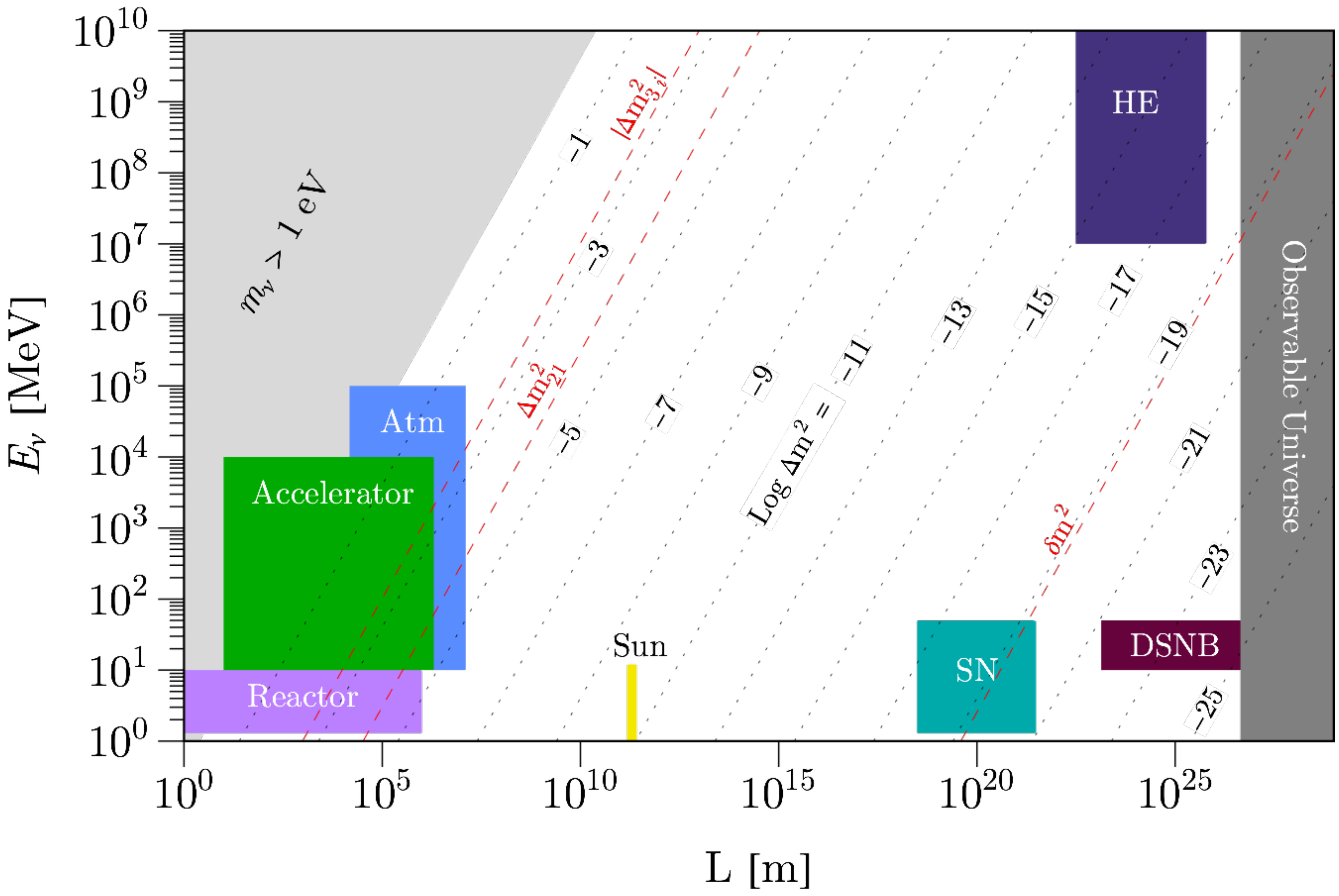
Rink, **MS** (2023)

$$L_{\rm osc} = \sim 15\,{\rm Mpc}\left(\frac{E_\nu}{1\,{\rm TeV}}\right)\left(\frac{10^{-18}{\rm eV}^2}{\delta m^2}\right)$$

TeV neutrinos from Gpc sensitive to $\delta m^2 \sim \mathcal{O}(10^{-18}\,{\rm eV}^2)$

Final thoughts

Neutrinos from far-away sources are strong probes of soft lepton-number violation.



Thank you!

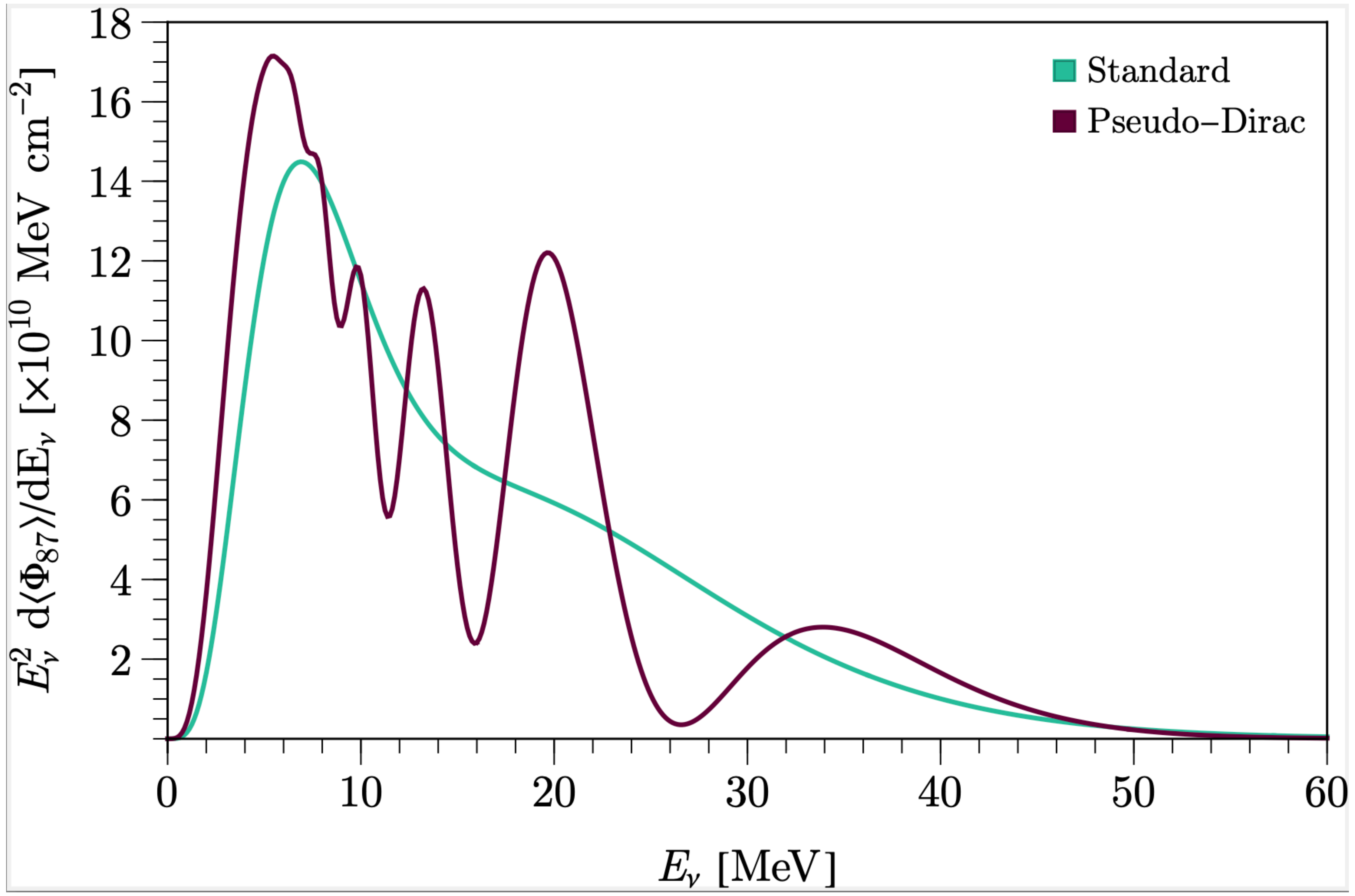
SN flux, processed by PD probability

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

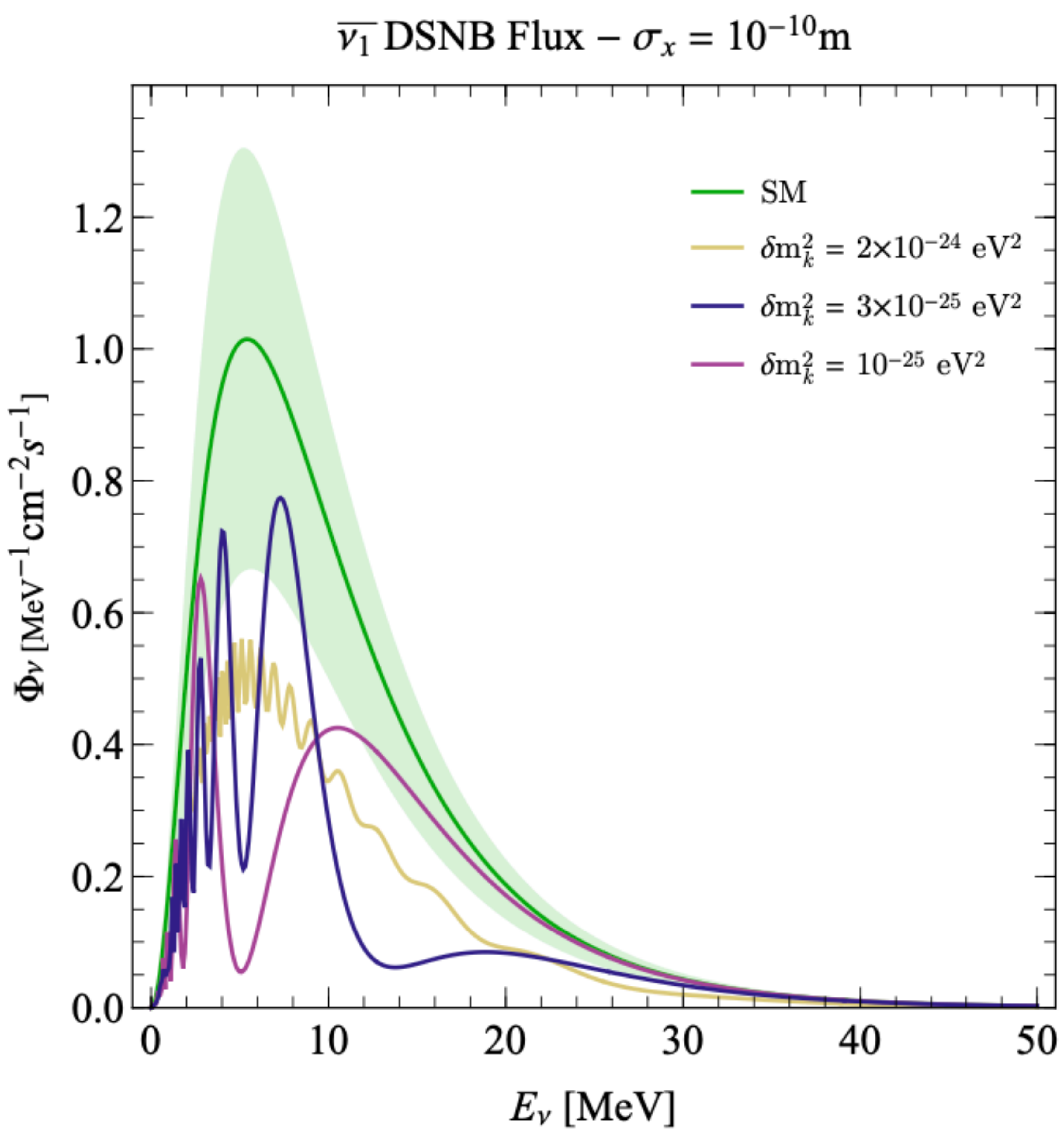
$$L_{\rm coh} = \frac{4\sqrt{2}E_\nu}{|\,\delta m^2\,|}(E_\nu\sigma_x) \sim 114\,{\rm kpc}\left(\frac{E_\nu}{25{\rm MeV}}\right)^2\left(\frac{10^{-19}{\rm eV}^2}{\delta m^2}\right)\left(\frac{\sigma_x}{10^{-13}{\rm m}}\right),$$

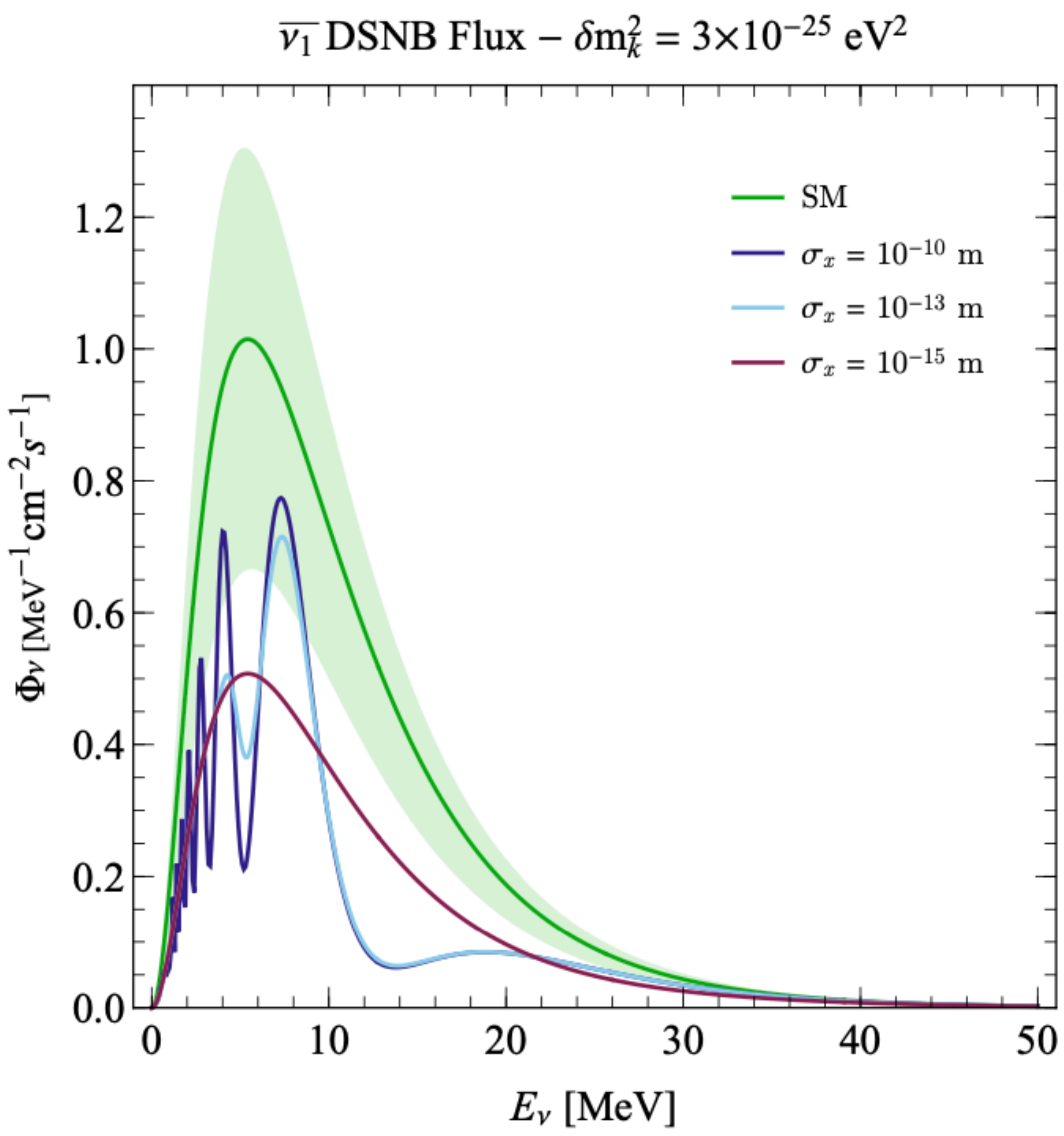
Oscillations due to δm^2

Decoherence due to δm^2 and σ_x



DSNB: Oscillations due to pseudo-Dirac nature

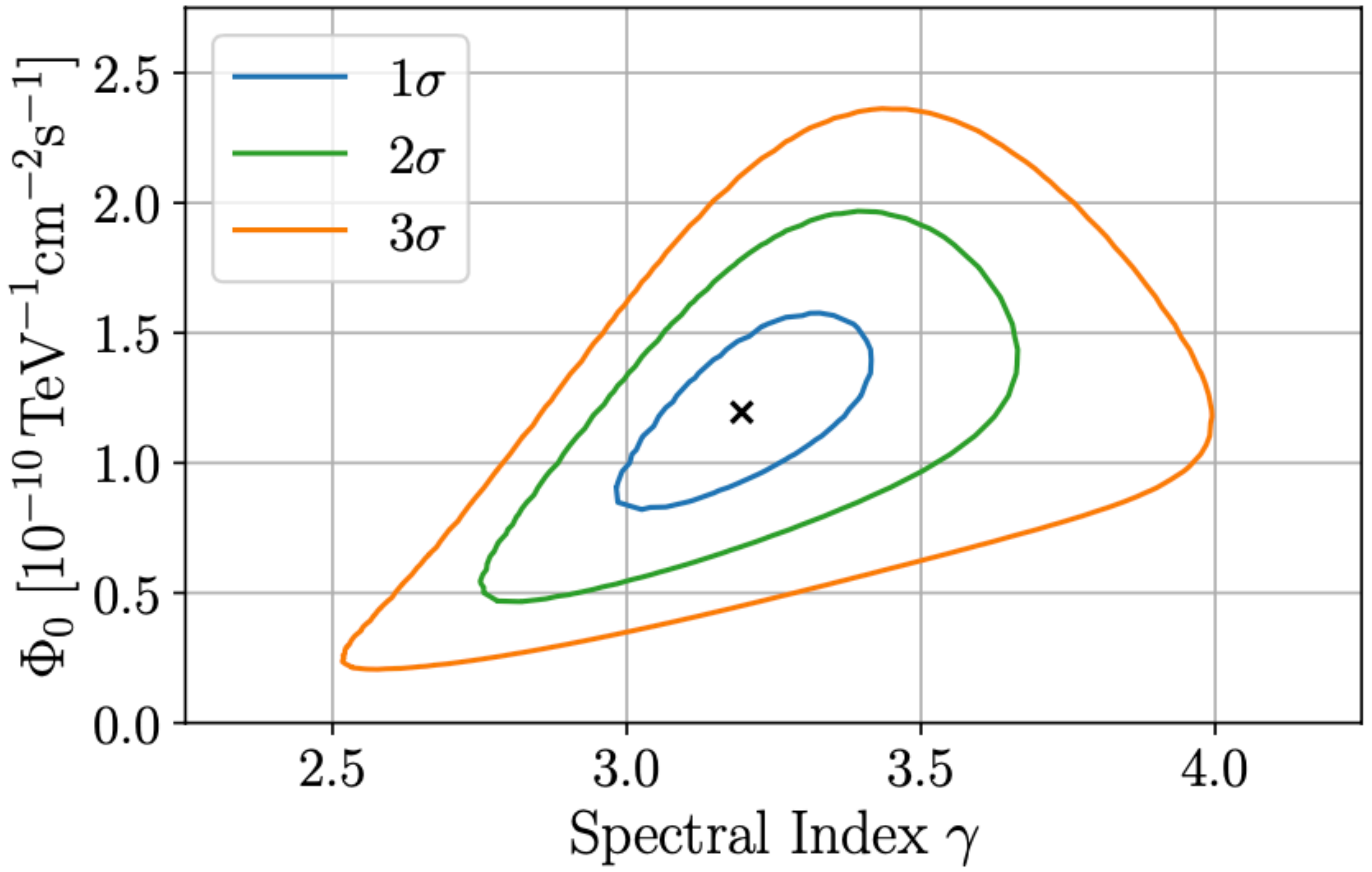


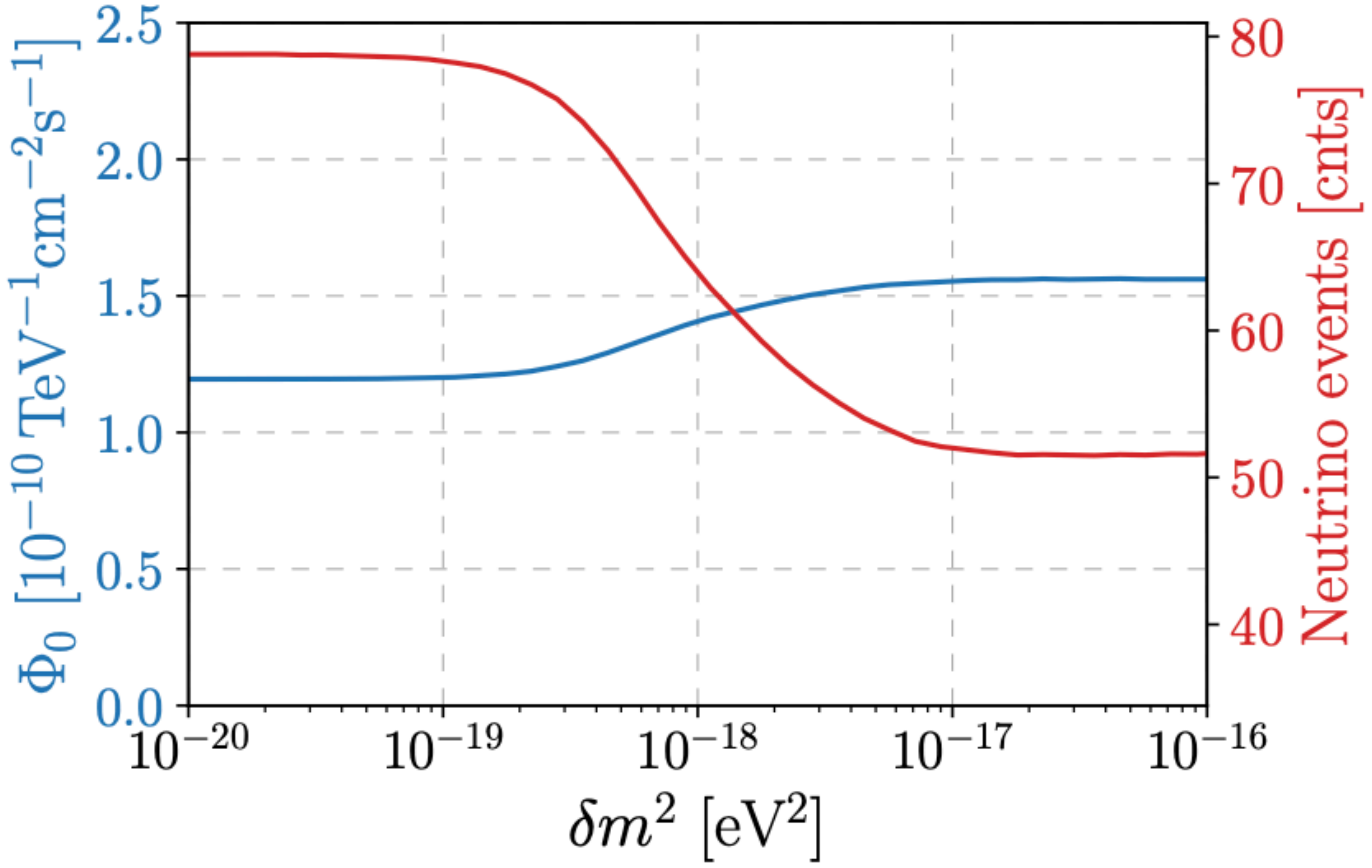


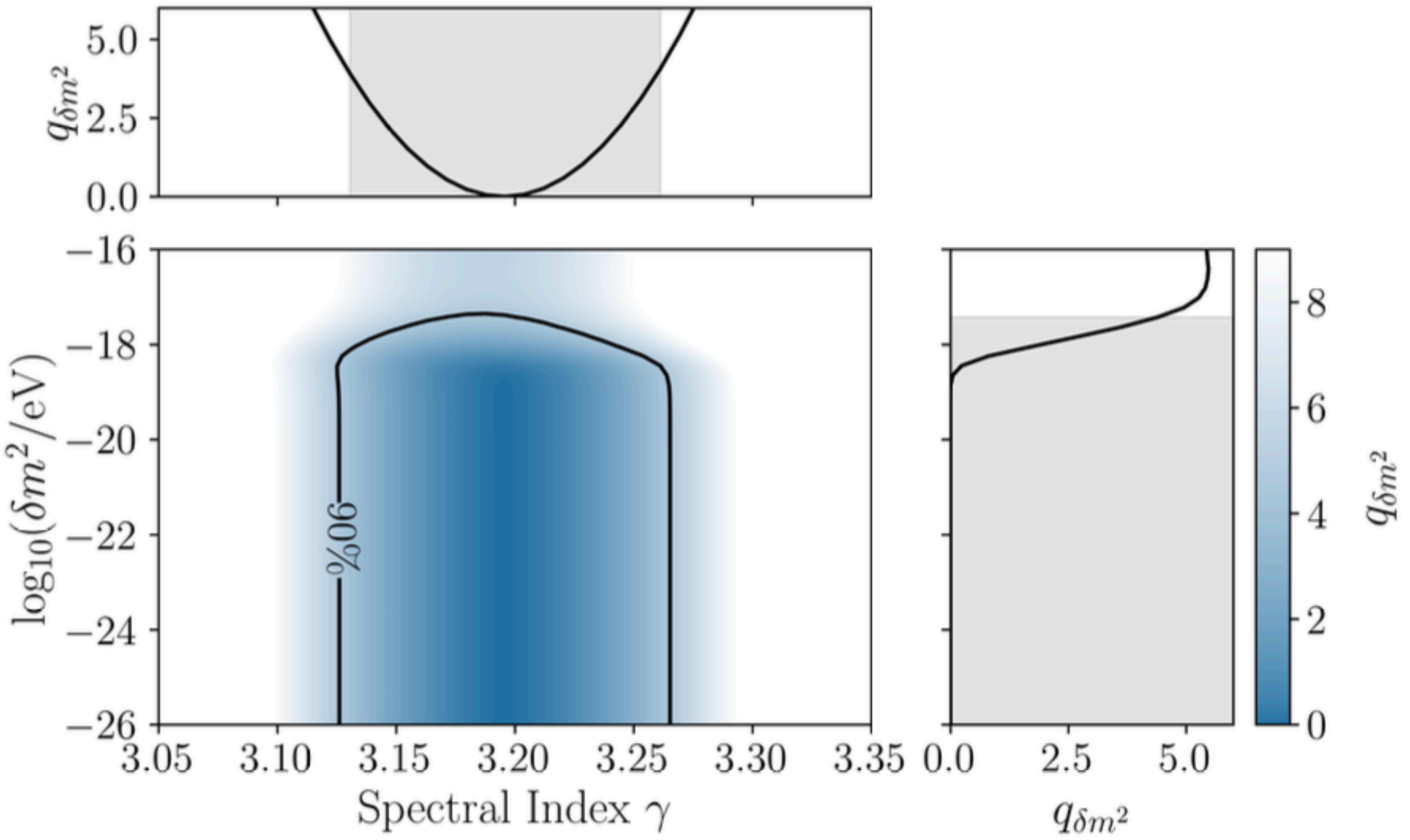
Increasing δm^2 reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

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

Icecube: Oscillations due to pseudo-Dirac nature







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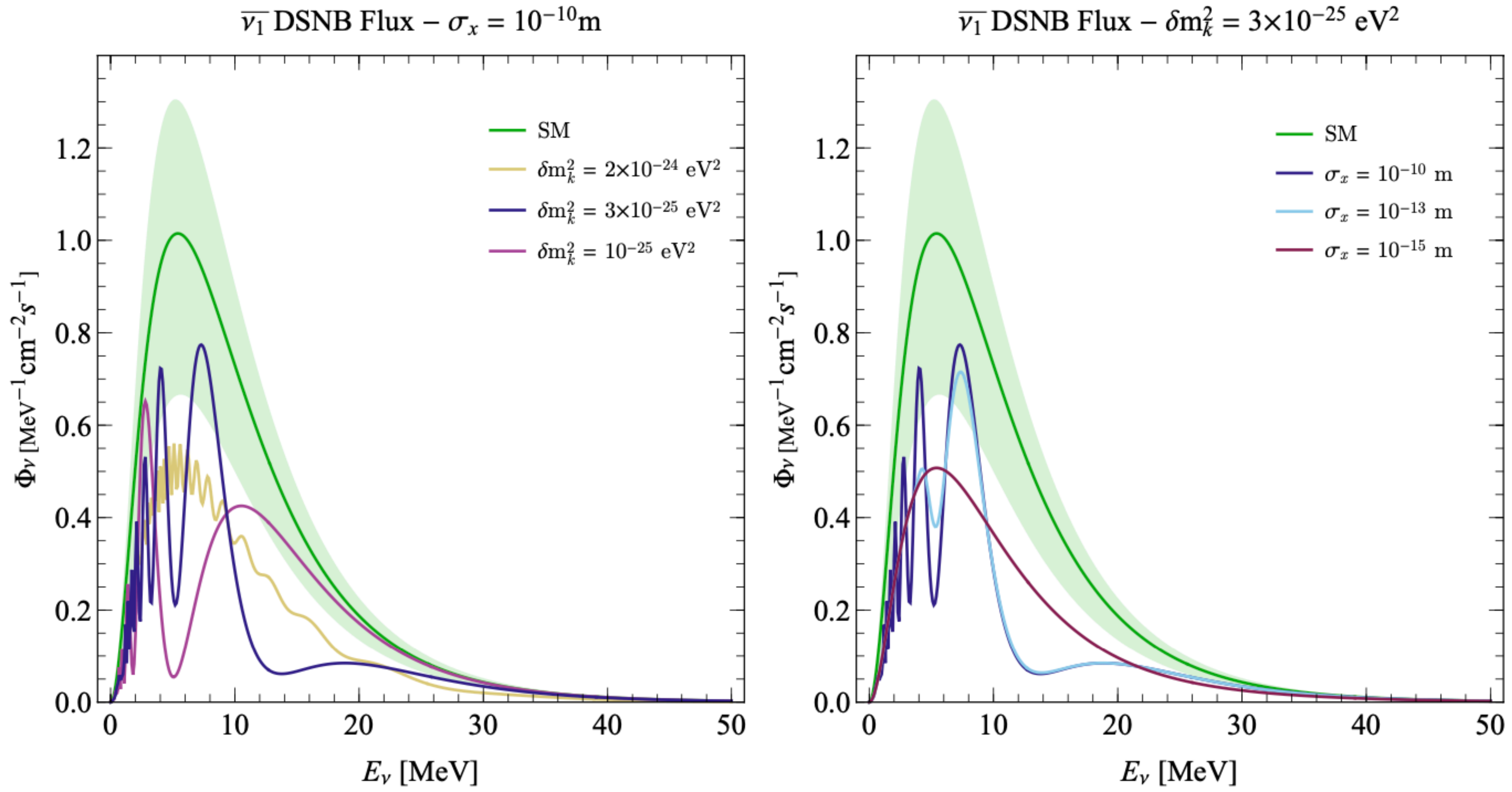

Increasing δm^2 reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

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