Pseudo-Dirac neutrinos and SN1987A

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PHYSICS FRONTIER CENTER
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EuCAPT
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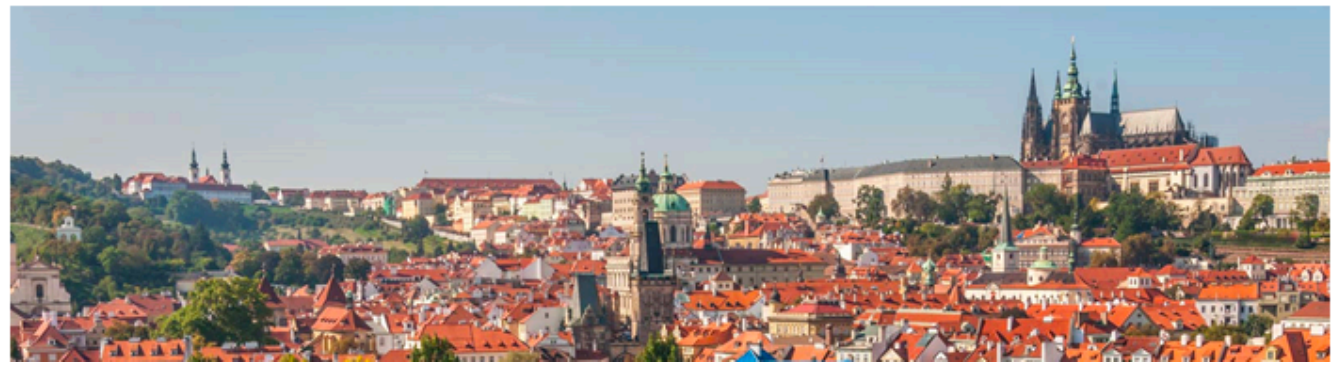
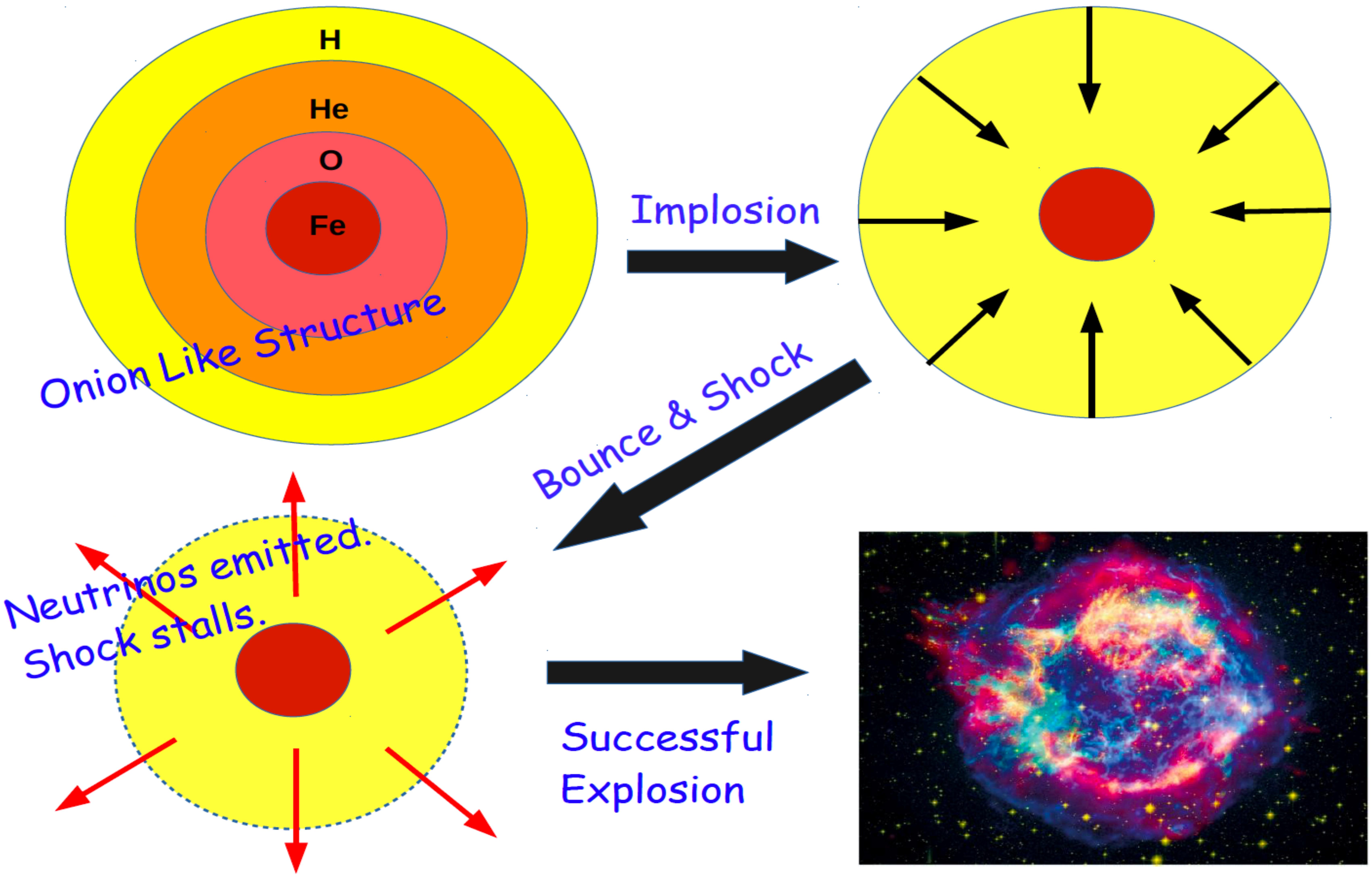
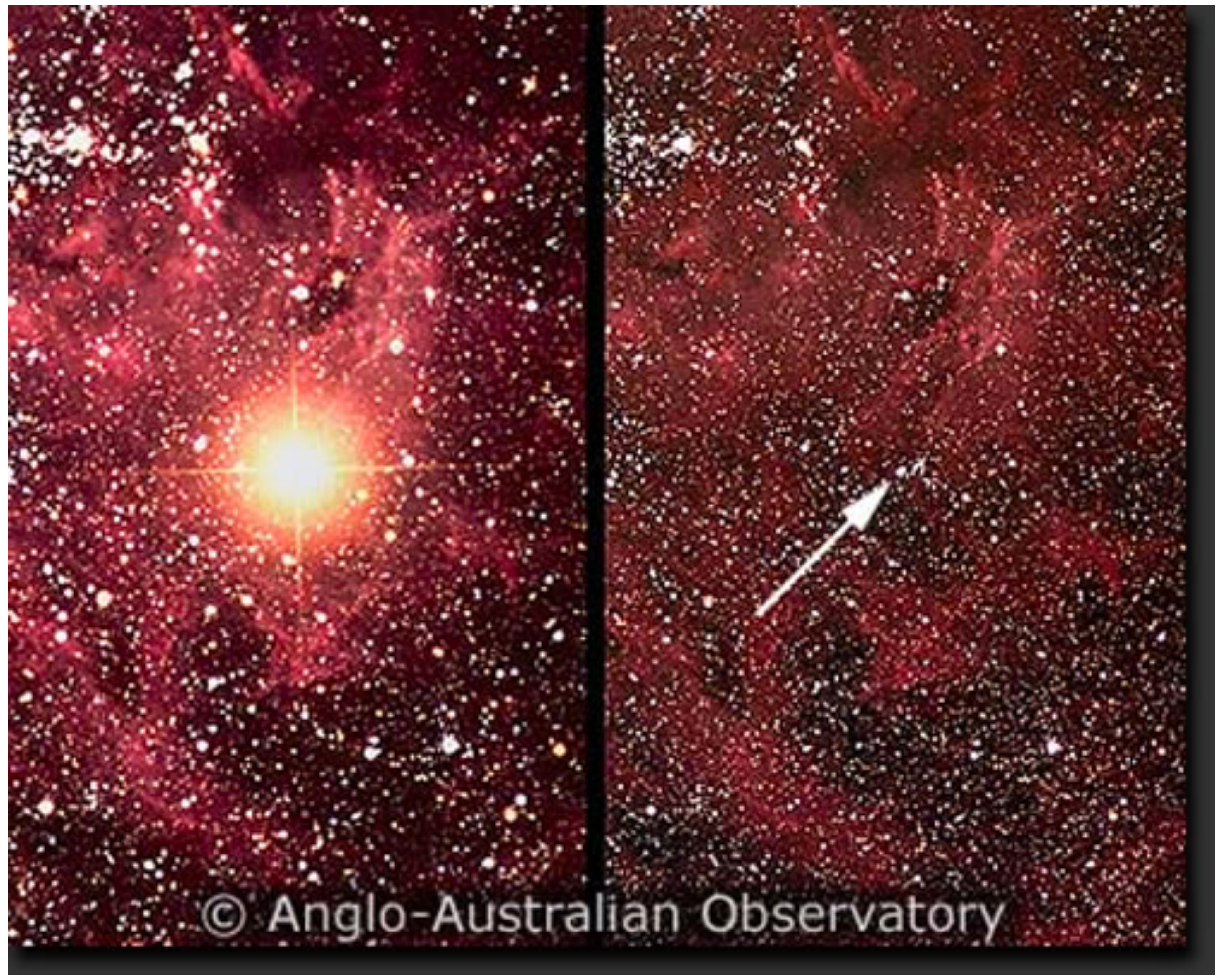


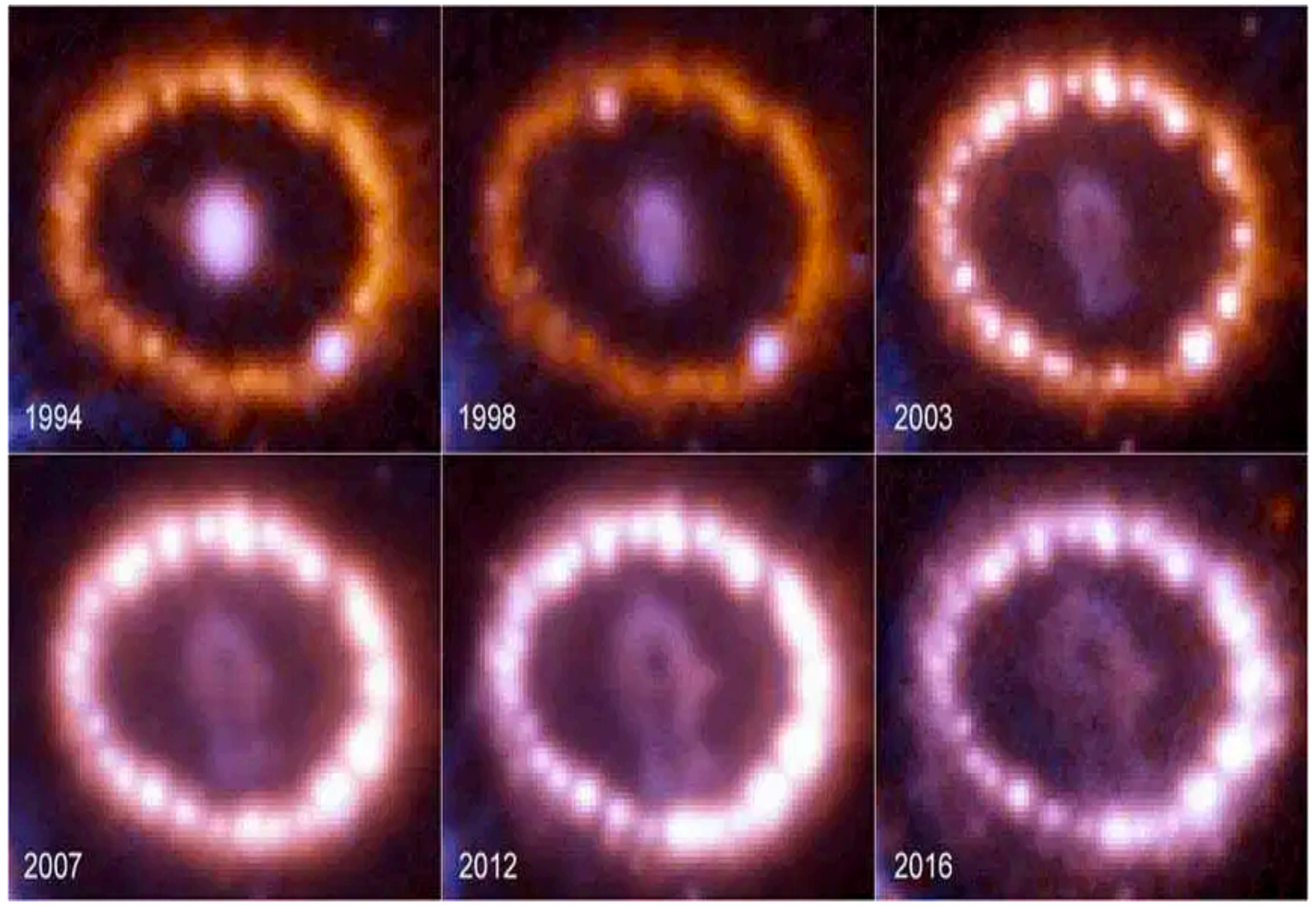
Core-collapse SNe: Mechanism



SN 1987A: the marvel of the last century

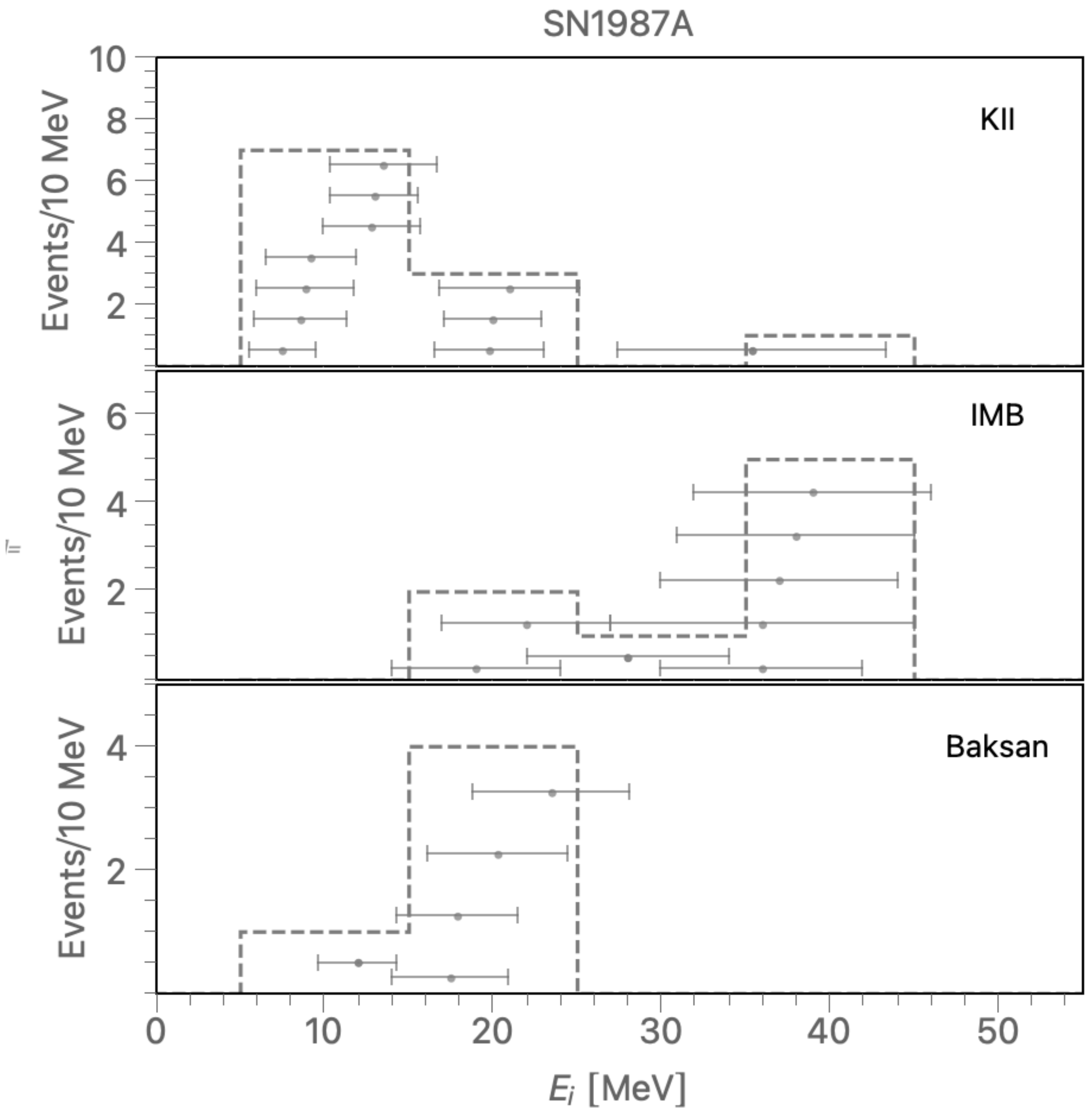
Feb 23, 1987



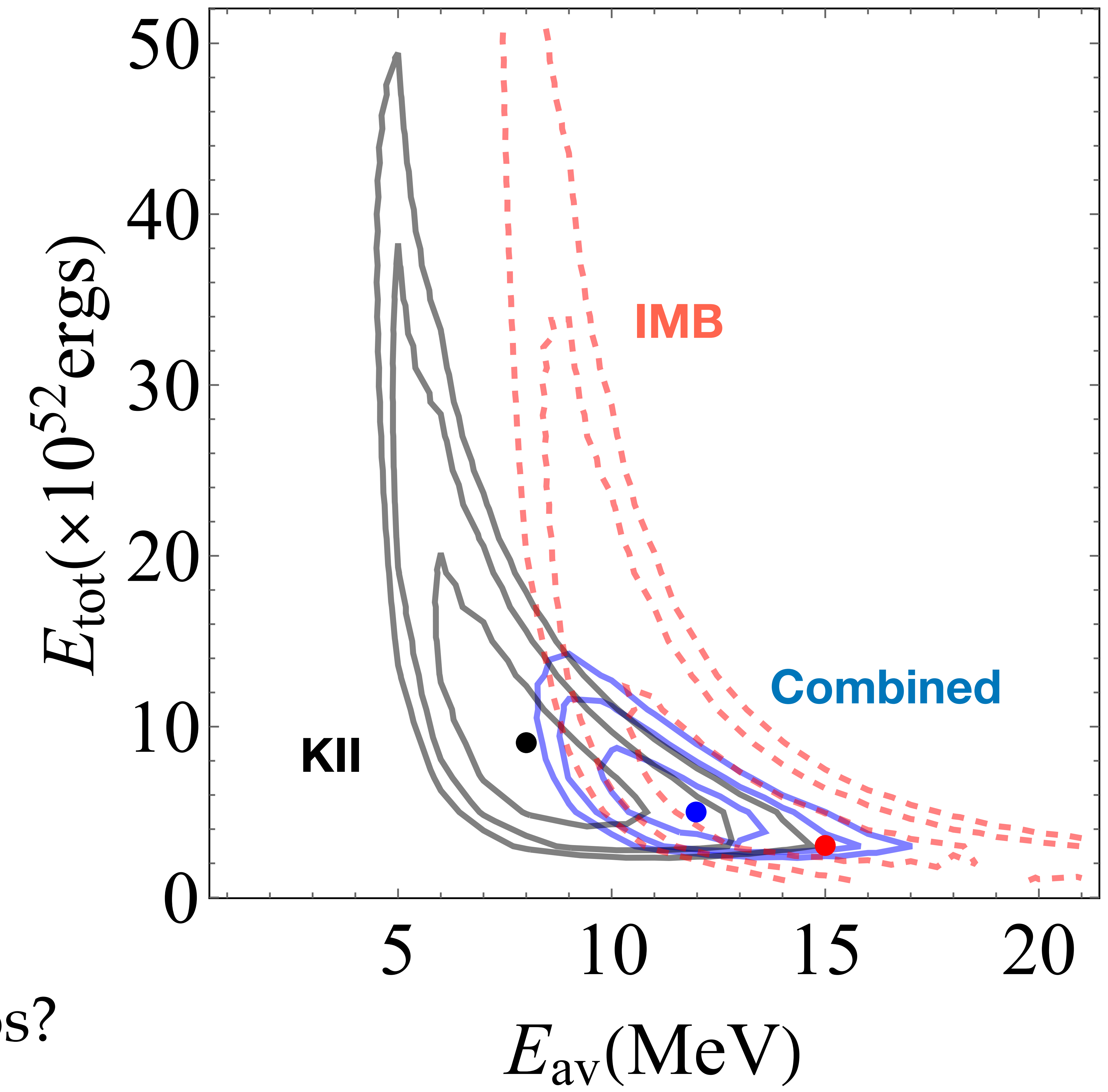


- Took place 168,000 years ago
- In the Large Magellanic Cloud, 50 kpc away. $18M_{\odot}$ star.

SN 1987A : events



$$\phi_{\bar{\nu}}(E_\nu) = \frac{1}{\langle E_{\bar{\nu}}\rangle}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}},$$



Slight tension between IMB and KII data?
Can have theoretical implications: pseudo-Dirac neutrinos?

Pseudo Dirac Neutrinos

- Neutrinos have sub-dominant Majorana mass terms.

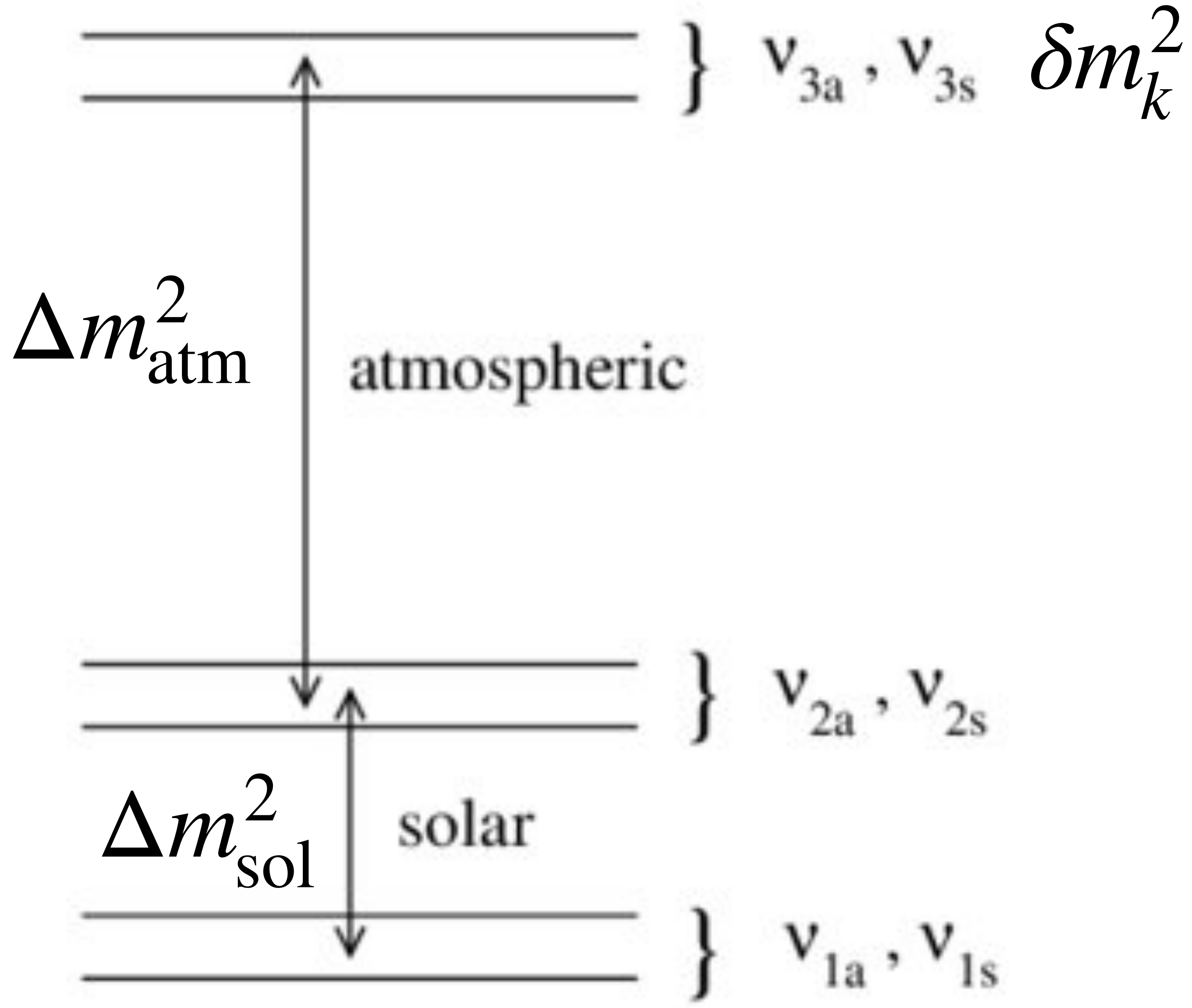
  Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

  Pseudo-Dirac limit : $m_{L,R} \ll m_D$ Kobayashi, Lim, PRD2001

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

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

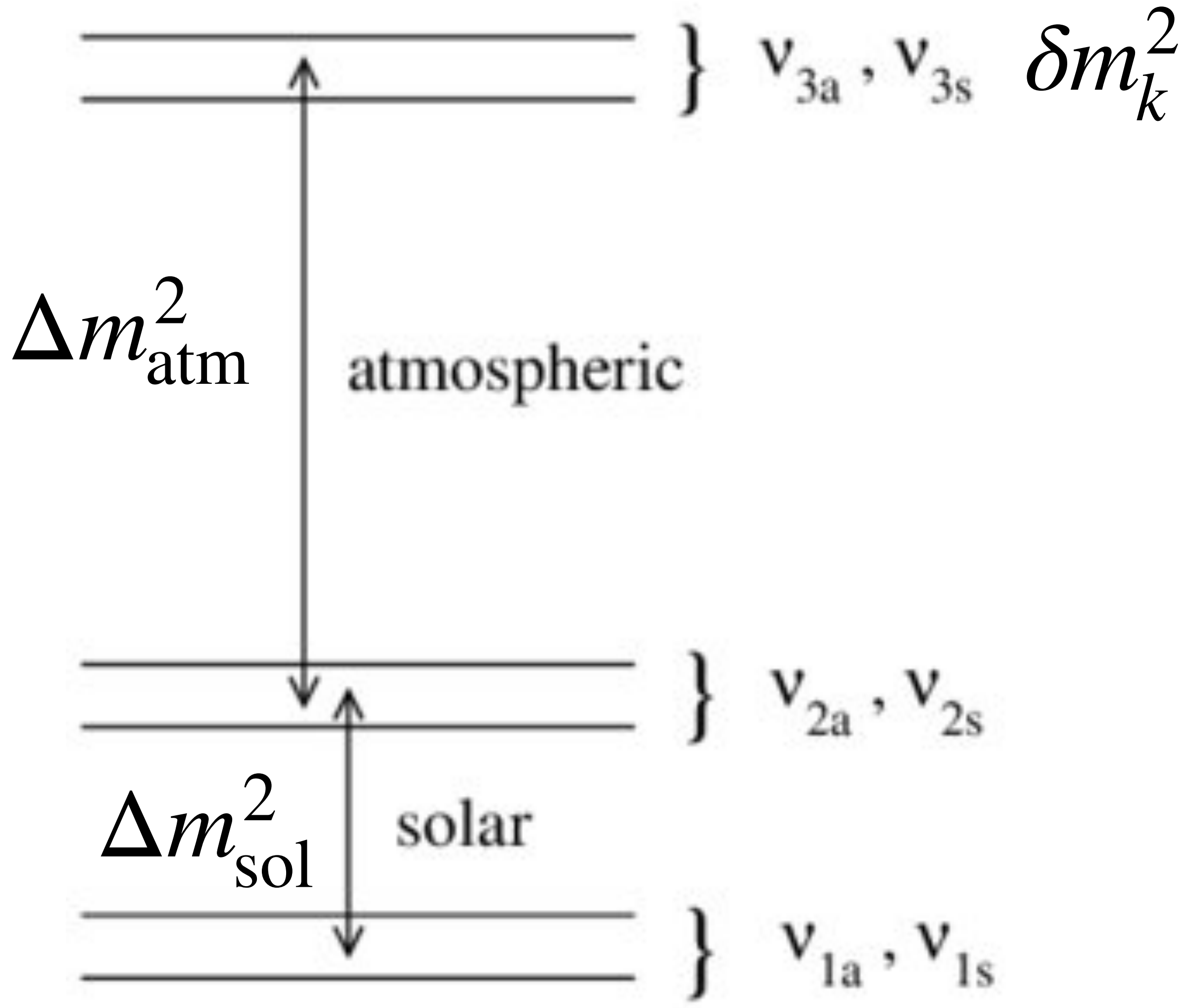
- Maximally mixed active and sterile states. Oscillations driven by this tiny mass.



Bounds:

1. Solar neutrinos $\delta m^2 < 10^{-12}\,{\rm eV}^2$
   de Gouvea, Huang, Jenkins, PRD2009
2. Atmospheric neutrinos $\delta m^2 < 10^{-4}\,{\rm eV}^2$
   Beacom, Bell, et al., PRL2004
3. High energy astrophysical neutrinos $10^{-18}\,{\rm eV}^2 < \delta m^2 < 10^{-12}\,{\rm eV}^2$
   Esmaili, Farzan, JCAP2012

Pseudo Dirac Neutrinos



- δm_k^2 will lead to oscillations at very large distances.
  Wave-packet separation decoherence also becomes important.

- Probability for $\nu_i \to \nu_\beta$

$$P_{i\beta}(z, E) = \frac{1}{2}|U_{\beta i}|^2 \left(1 + e^{-\left(\frac{L(z)}{L_{\rm coh}}\right)^2} \cos\left(\frac{L(z)}{L_{\rm osc}}\right)\right)$$

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

A smaller σ_x can cause decoherence.

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

SN flux, processed by PD probability

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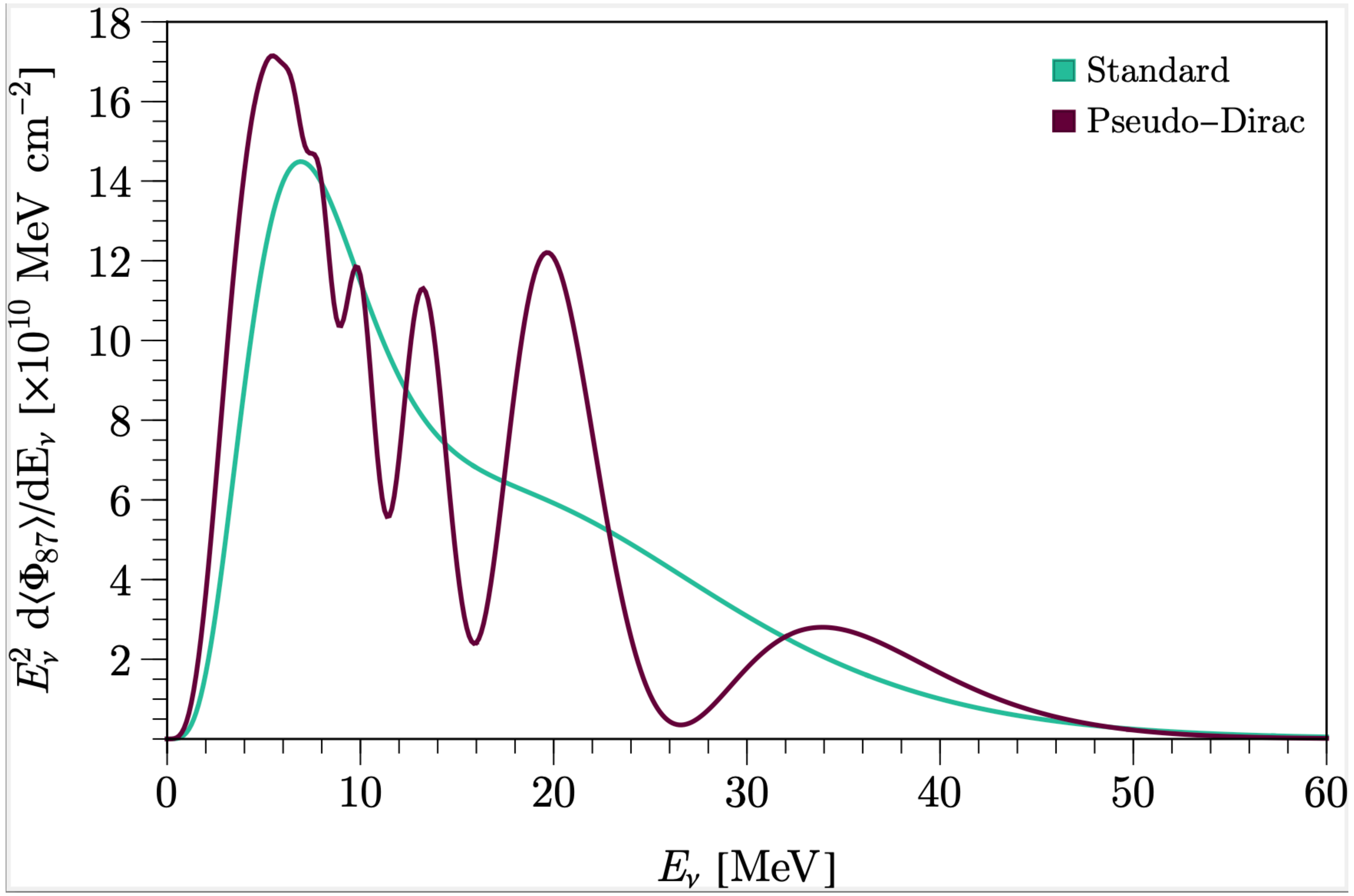
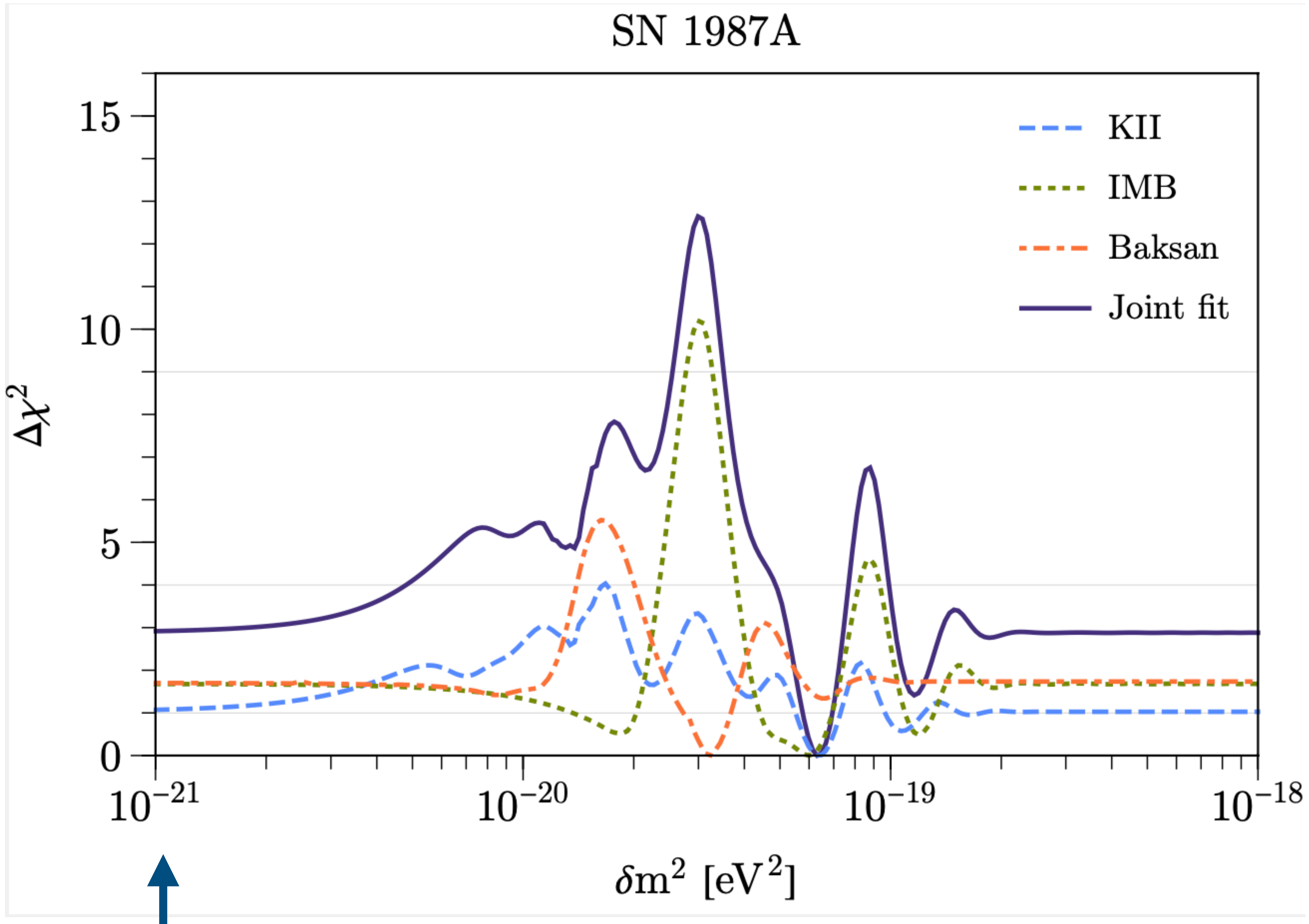
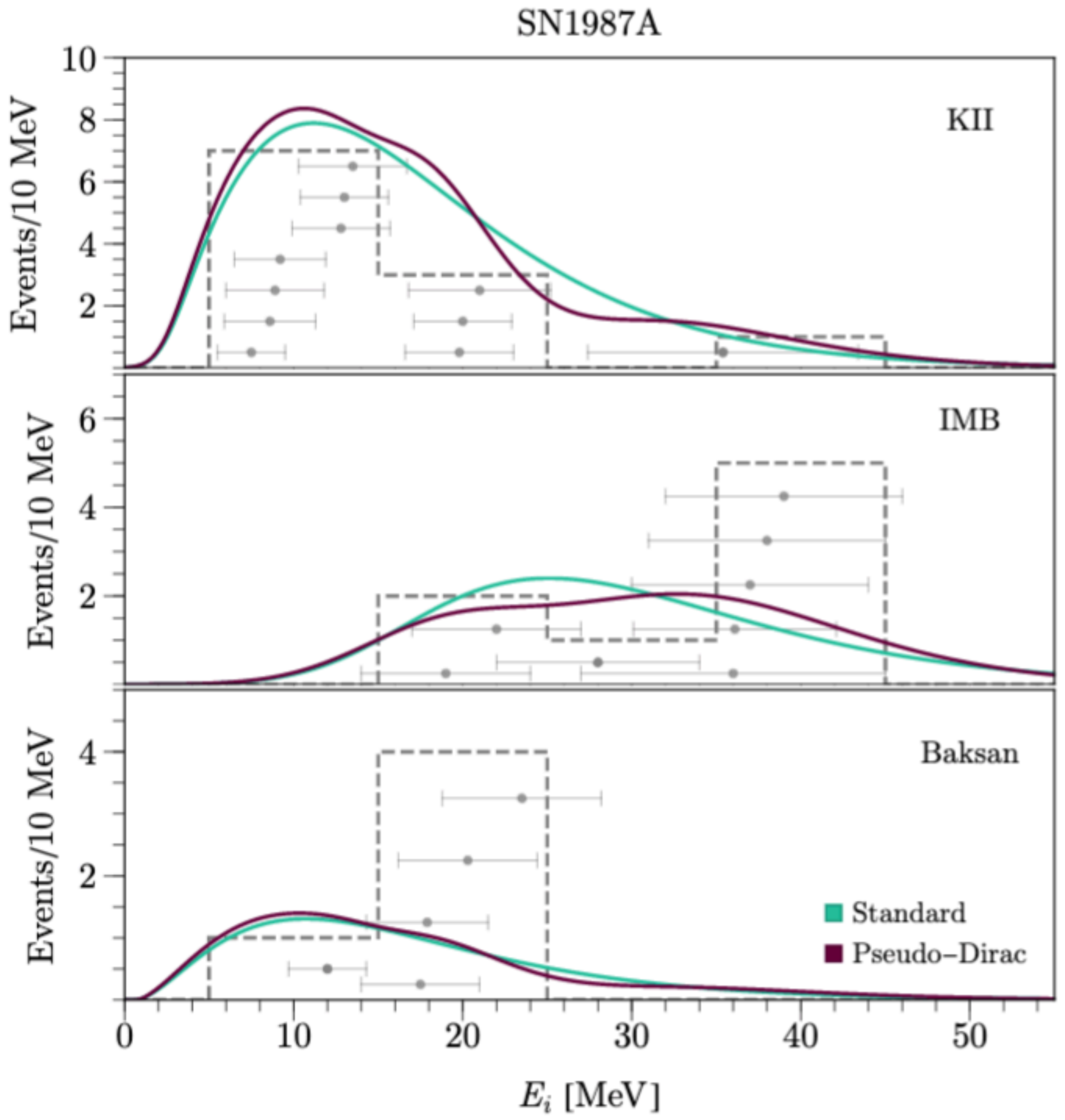
Oscillations due to δm^2



SN1987A data and comparison

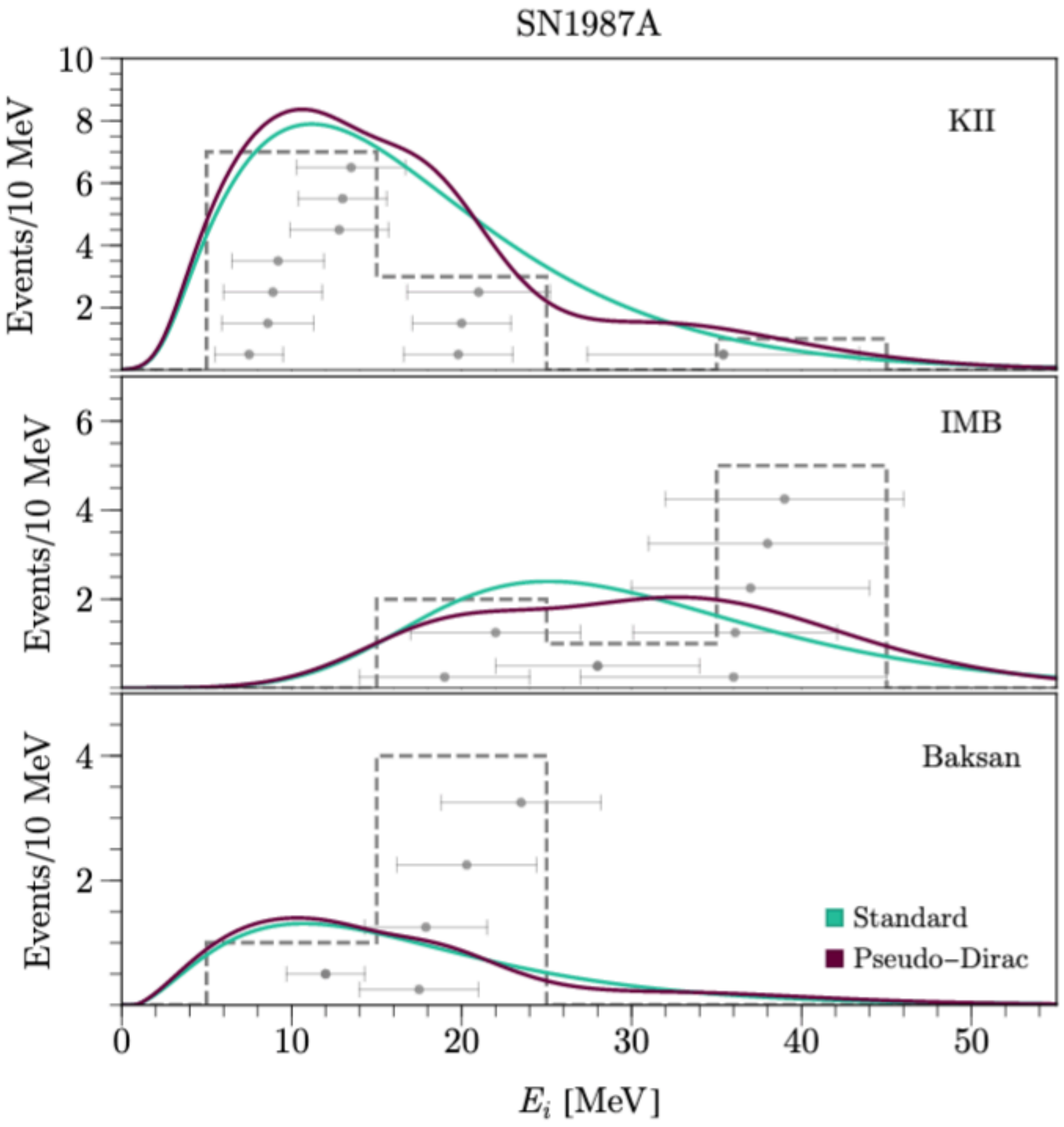


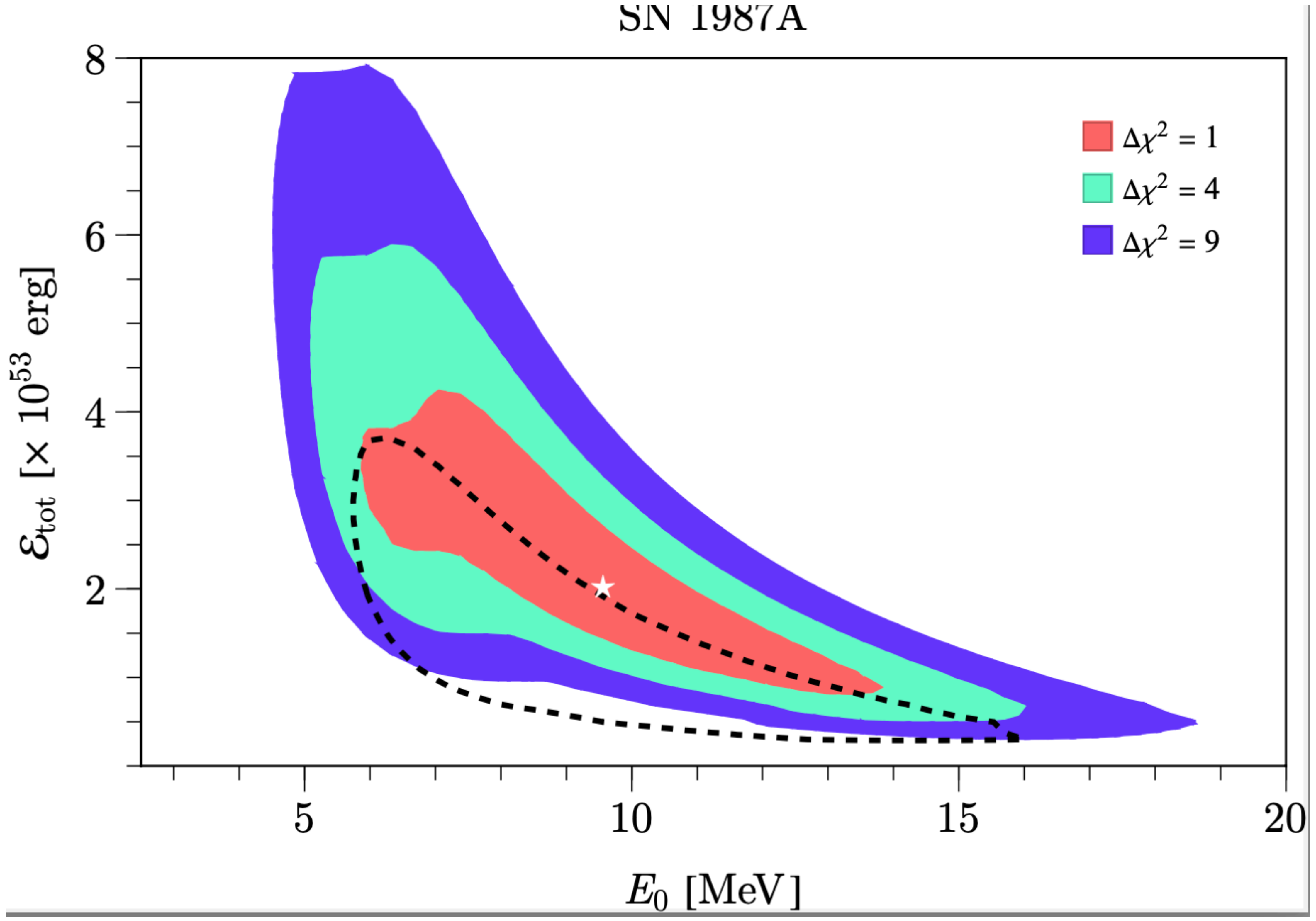


No Oscillations

Slight preference for the PD possibility, $\Delta\chi^2 = 3$!

Why the preference?





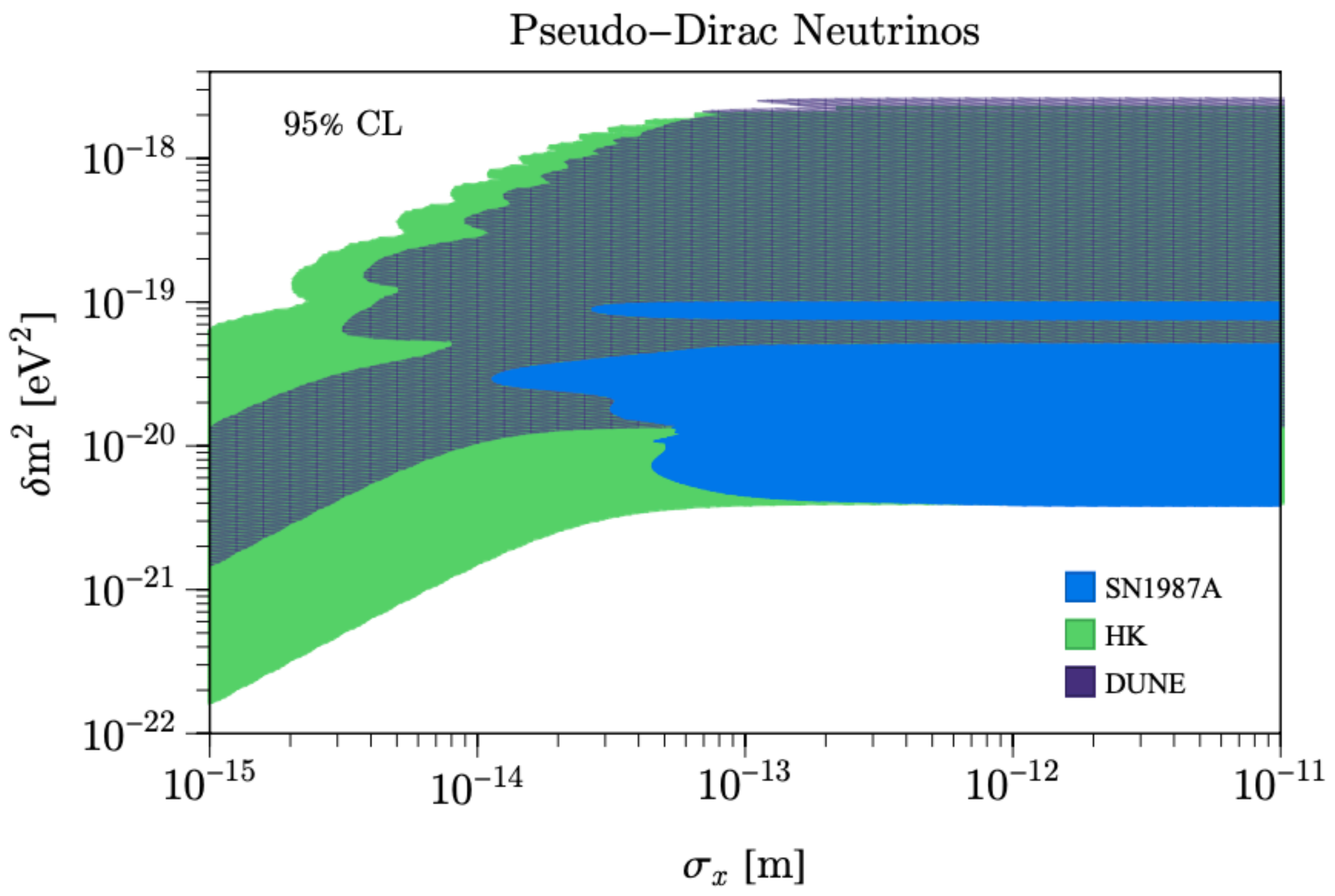
$$\frac{d\Phi_{87}}{dE_\nu} = \frac{\mathcal{E}_{\rm tot}}{4\pi d^2} P_{aa}(E_\nu; d, \delta m^2) \sum_{\beta=e,x} \frac{\bar{p}_{\beta e}}{E_{0\beta}} \phi_\beta(E_\nu)$$

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.

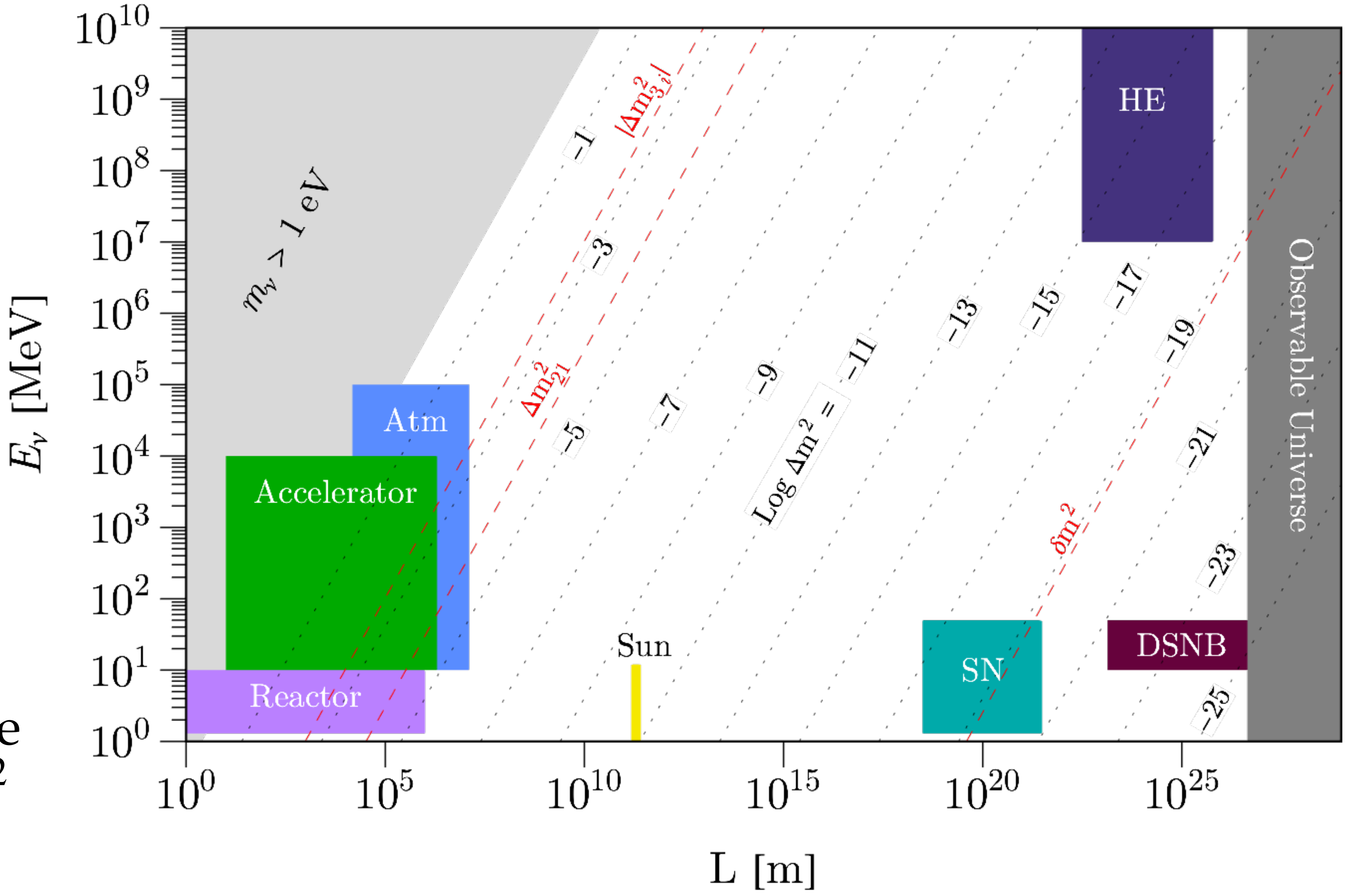
- Non-electron neutrino detectors to play an important role!



SN at 10kpc ~ $\delta m^2 \sim 10^{-20}\,\mathrm{eV}^2$

Final thoughts

- 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.



Thank you!

Backup: Neutrino signals @ DUNE and HK

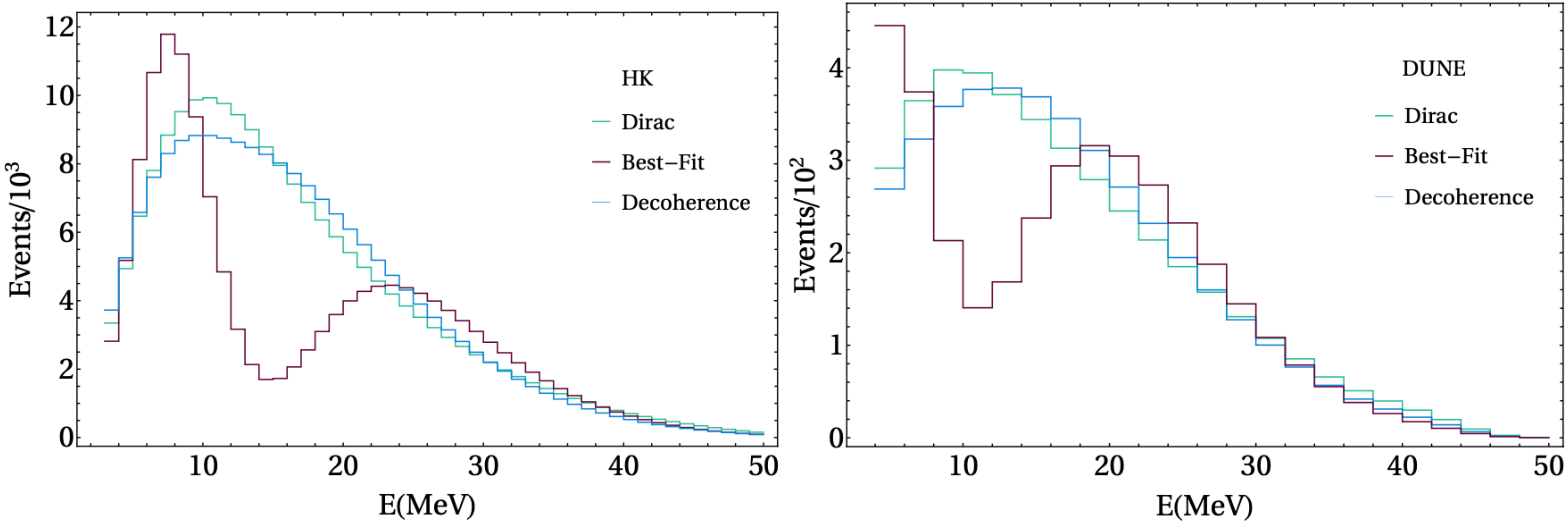


FIG. 8. The Number of events expected in HK (left) and DUNE (right) for a supernova happening at 10kpc. For the supernova luminosity, we assume the best-fit value of the SN1987A. We show the number of events for three different scenarios: neutrinos are Dirac fermions, the best-fit point of the SN1987A analysis, and coherence lengths shorter than 10kpc (Decoherence). In particular, in the last case, we use the following parameters: $\delta m^2 = 5 \times 10^{-21}\mathrm{eV}^2, \sigma_x = 10^{-15}$ m