Constraining Pseudo-Dirac neutrinos from a future galactic supernova

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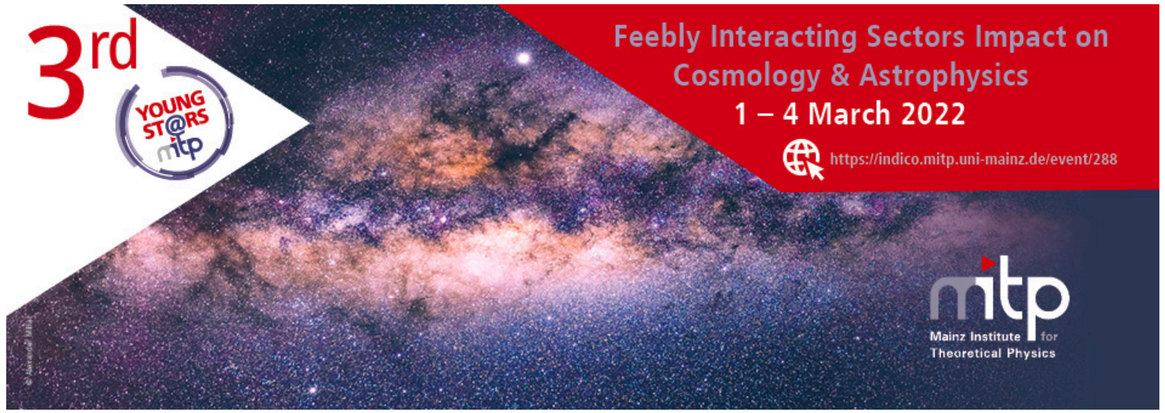
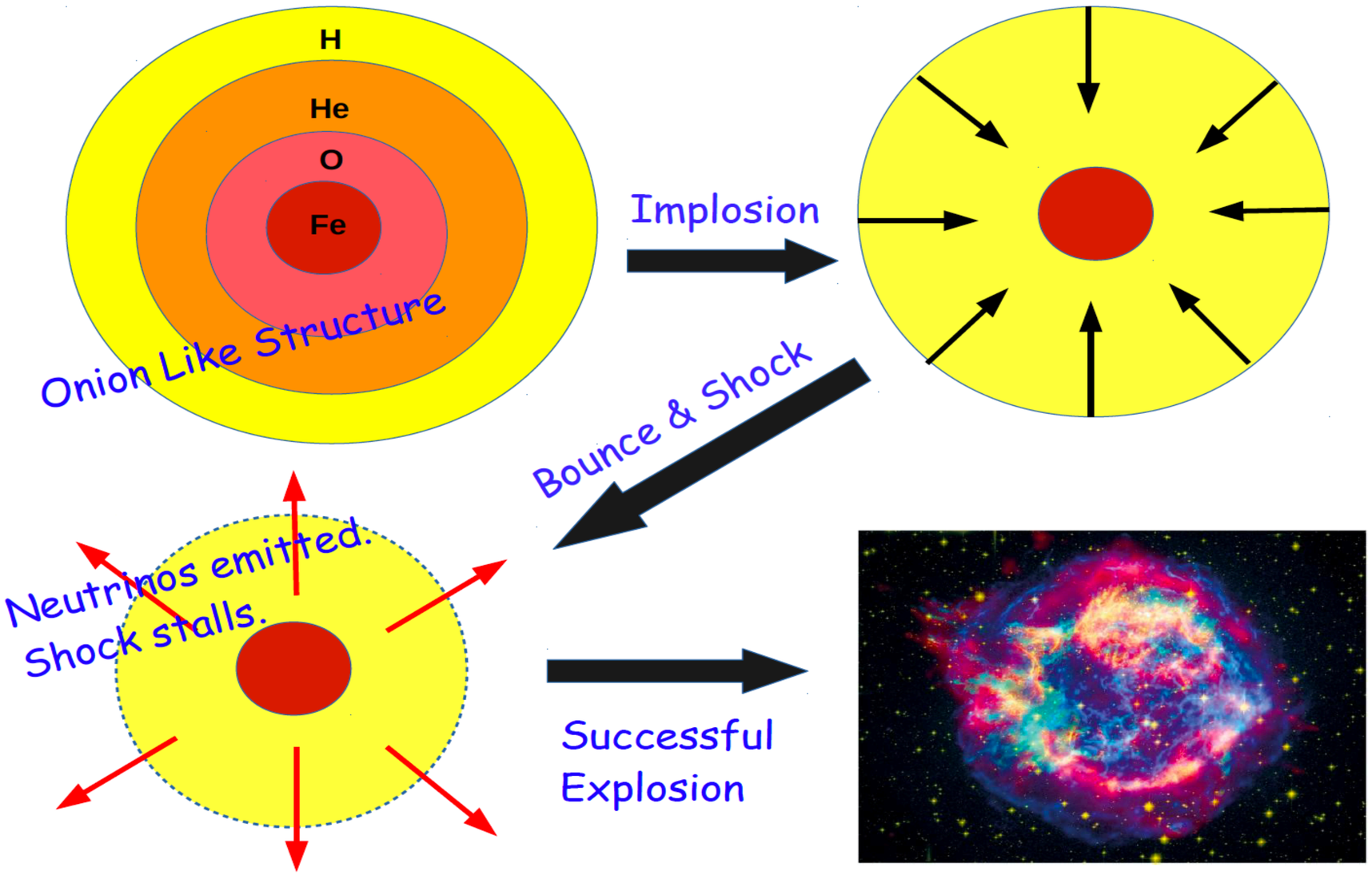
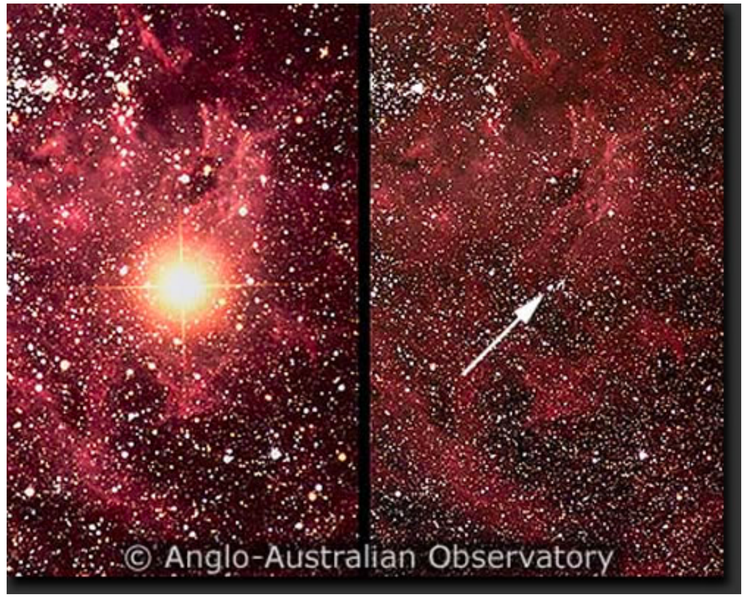


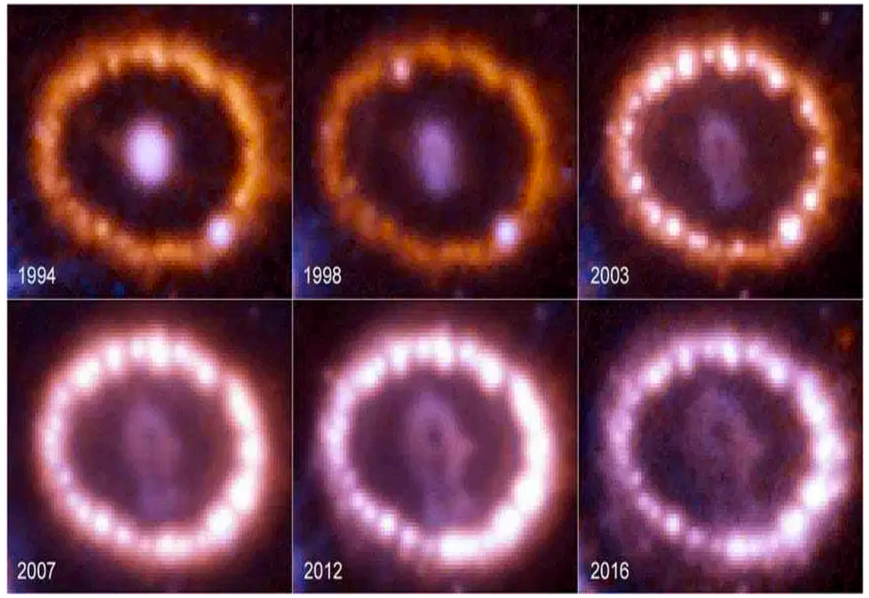
Core-collapse SNe: Mechanism



SN 1987A: the marvel of the last century

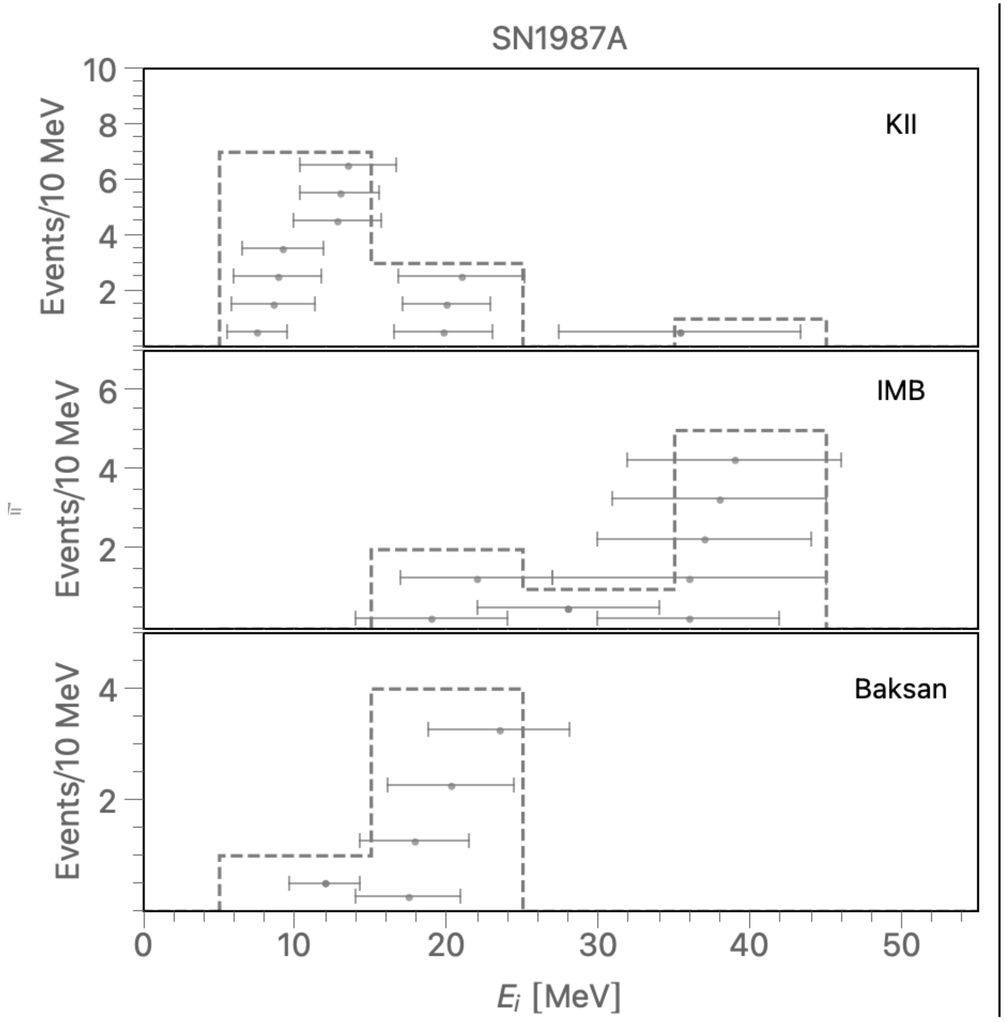
Feb 23, 1987

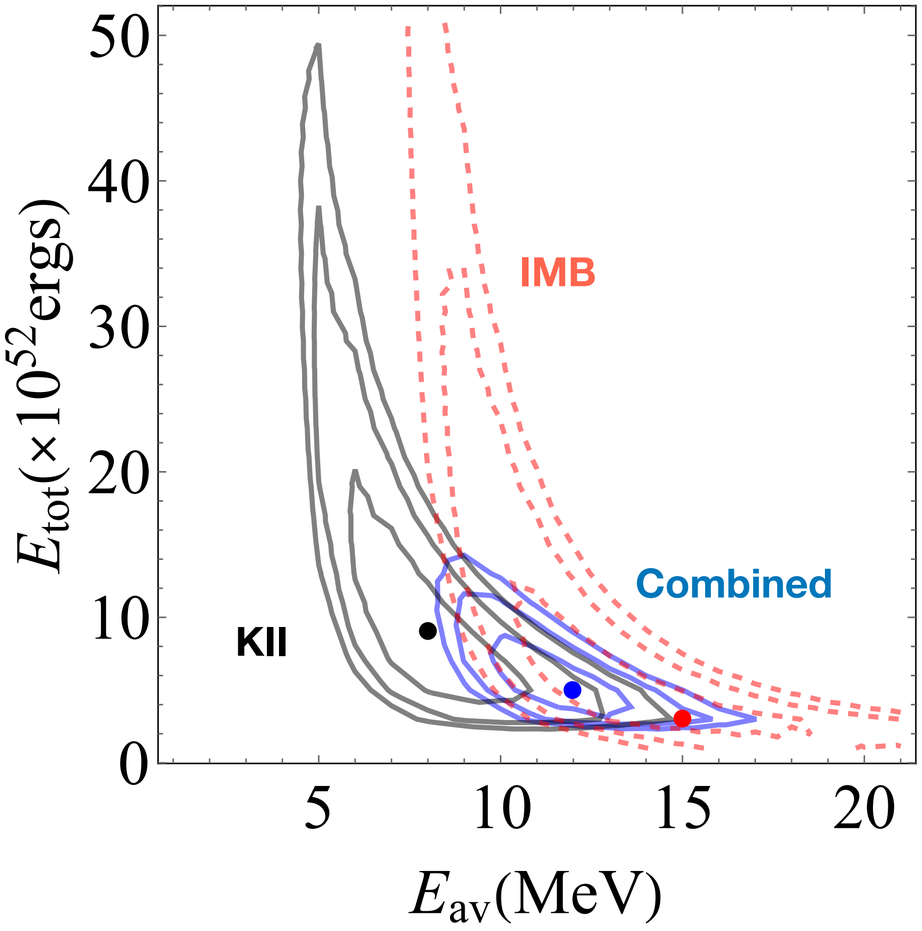




- Took place 168,000 years ago
- In the Large Magellanic Cloud, 50 kpc away. $18M_\odot$ star.

SN 1987A : events



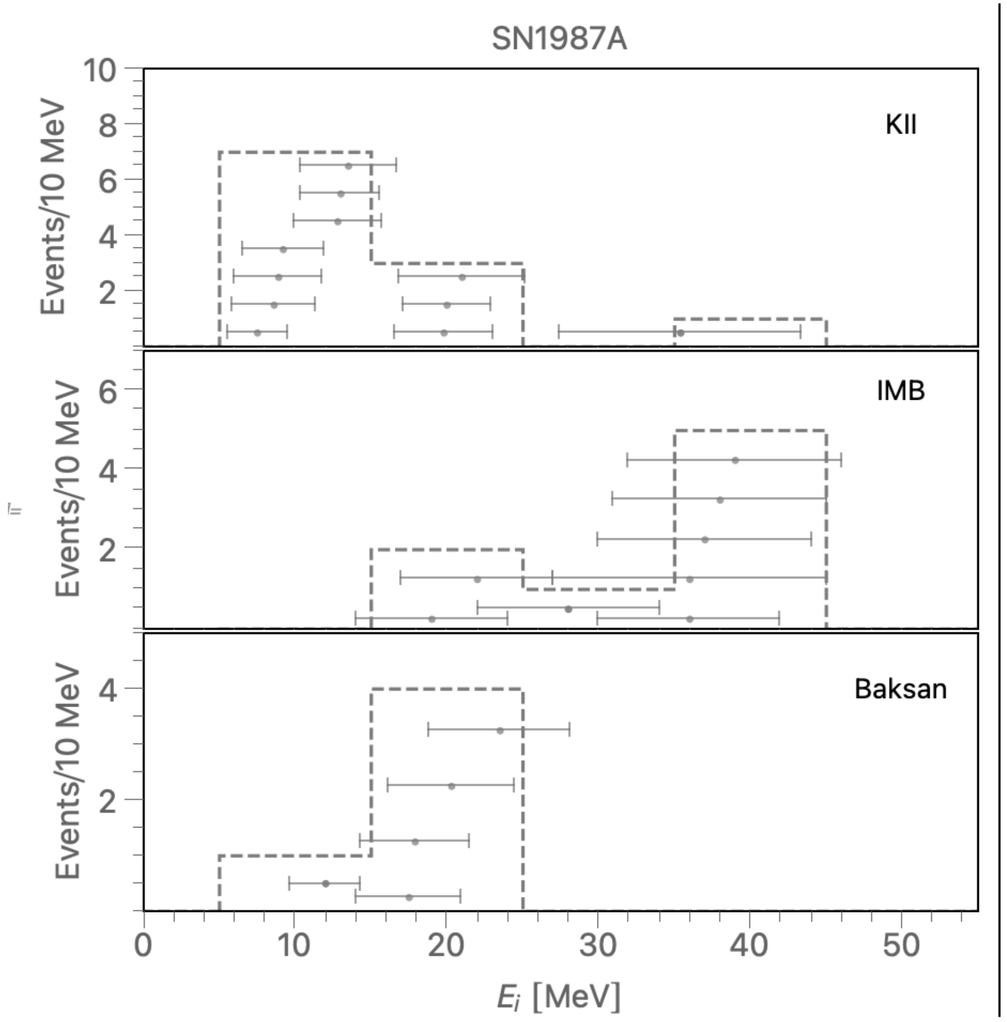


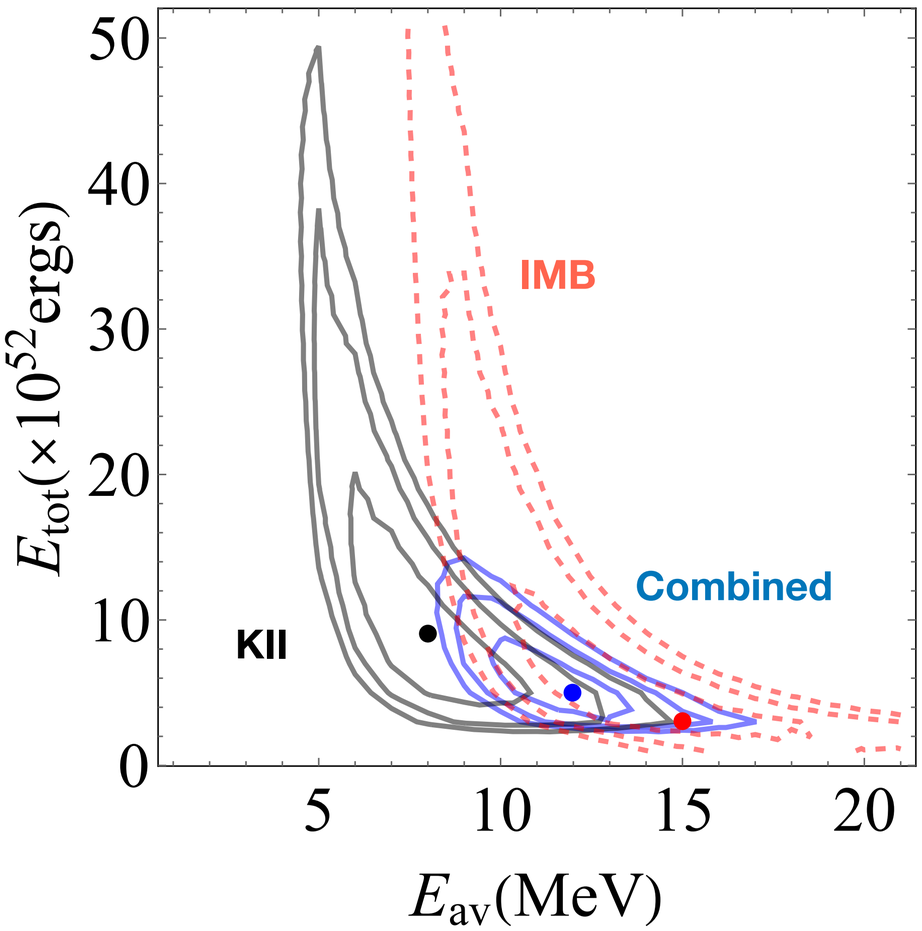
$$d\mathcal{N}_{\bar{\nu}}(E_\nu) = \frac{E_{tot}}{\langle E_{\bar{\nu}}\rangle}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_{\bar{\nu}}\rangle}},$$

Slight tension between IMB and KII data?

See also Mirizzi and Raffelt, PRD 2005, Vissani J.Phys.G (2015)

SN 1987A : events





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Slight tension between IMB and KII data?

Can have theoretical implications: pseudo-Dirac neutrinos?

See also Mirizzi and Raffelt, PRD 2005, Vissani J.Phys.G (2015)

What are pseudo-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. Pseudo-Dirac limit : $m_{L,R} \ll m_D$. Soft lepton-number violation.

- In the P-D limit, mass matrix can be diagonalized by $\mathscr{V} = \begin{pmatrix} U_{\rm PMNS} & 0 \\ 0 & U_R \end{pmatrix} \cdot \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1_3 & i1_3 \\ \varphi & -i\varphi \end{pmatrix}$

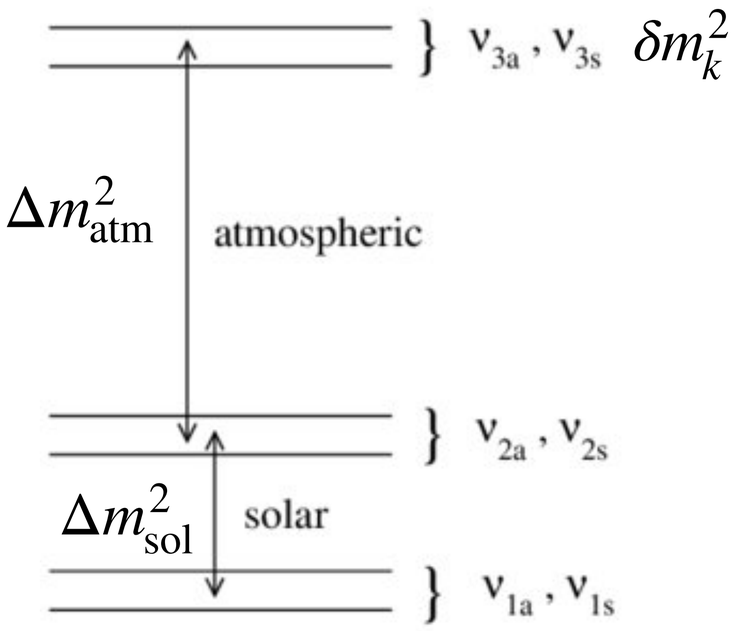
Kobayashi, Lim, PRD2001

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

$$\nu^{\alpha L} = \frac{1}{\sqrt{2}} U^{\alpha j}_{\rm PMNS} (\nu_{js} + i\,\nu_{ja})$$

- Maximally mixed active and sterile states.

Pseudo-Dirac Neutrinos: formalism



Bounds:

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

- Maximally mixed active and sterile states, $\nu^{\alpha L} = \frac{1}{\sqrt{2}} U^{\alpha j}_{\rm PMNS}(\nu_{js} + i\,\nu_{ja})$
- $m^2_{ks,ka} = m^2_k \pm \delta m^2_k/2$, where $\delta m^2 \sim m_D(m_L + m_R)$
- δm^2_k will lead to oscillations at very large distances. Wave-packet separation decoherence also becomes important.

Oscillations due to pseudo-Dirac Neutrinos

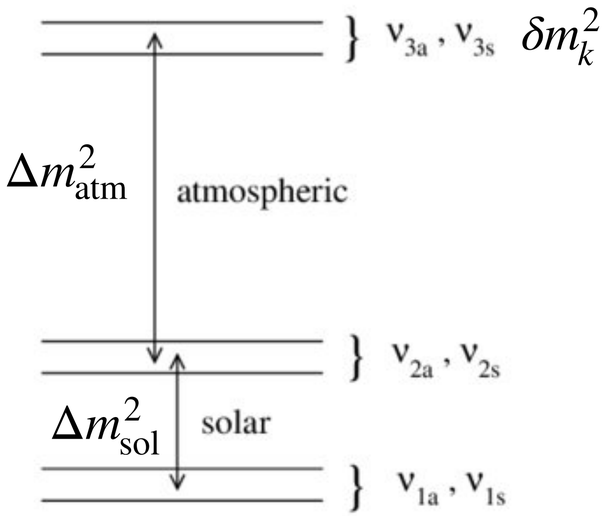
- Flavor oscillation probability induced by $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ over a large distance gets averaged.

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

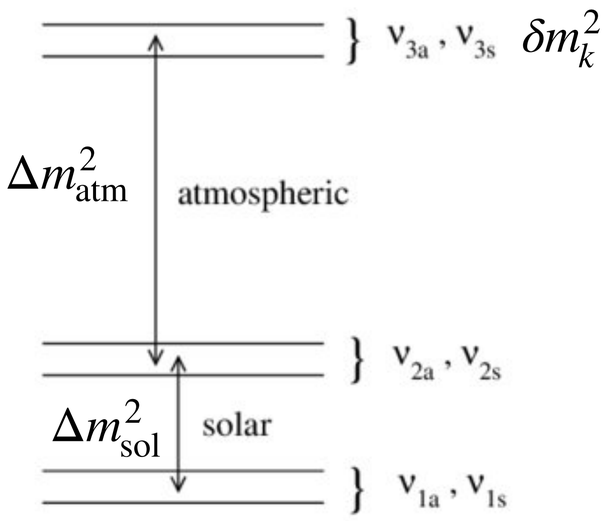
- The active-sterile probability, driven by δm^2_k is

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

- Decoherence important if $L(z) > L_{\rm coh}$



Oscillations due to pseudo-Dirac Neutrinos



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

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

- The active-sterile probability, driven by δm_k^2 is

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

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

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

A smaller σ_x can cause decoherence.

SN flux, processed by PD probability

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

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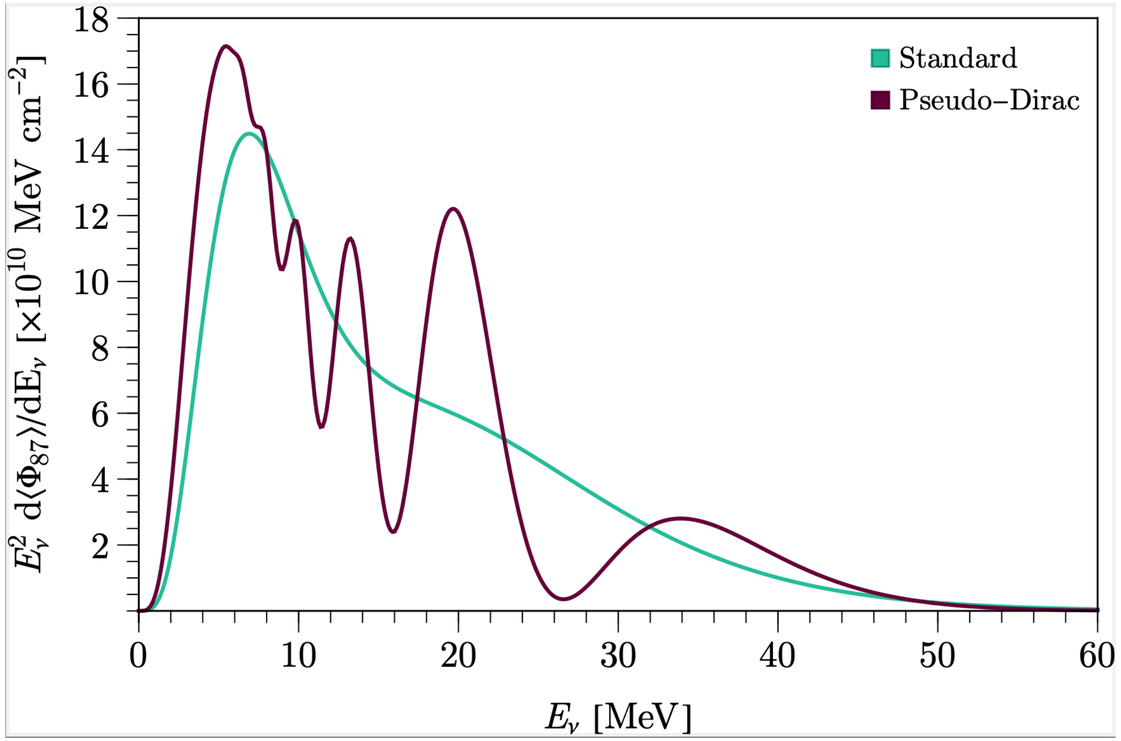
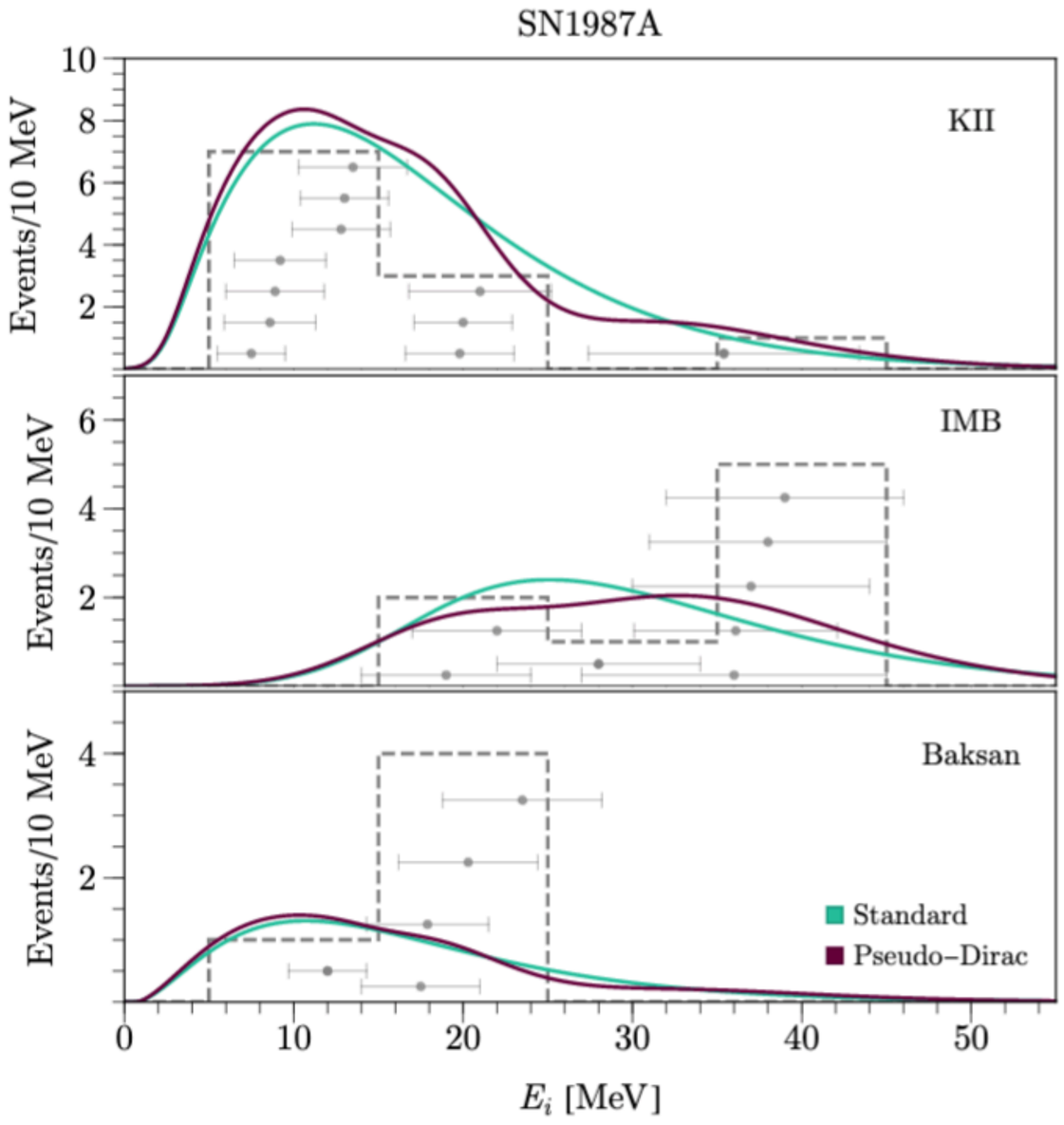
Oscillations due to δm^2

Decoherence due to δm^2 and σ_x

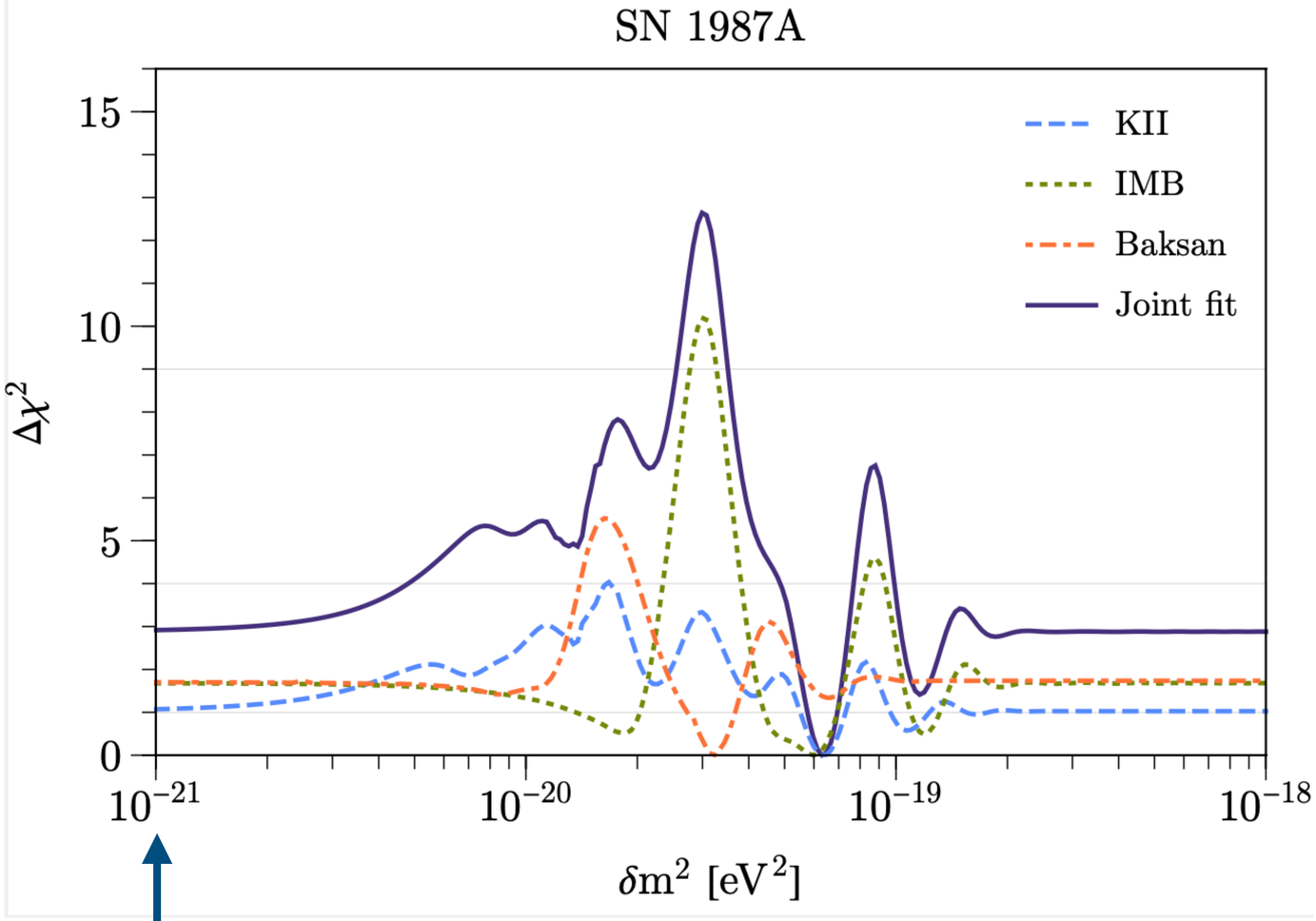


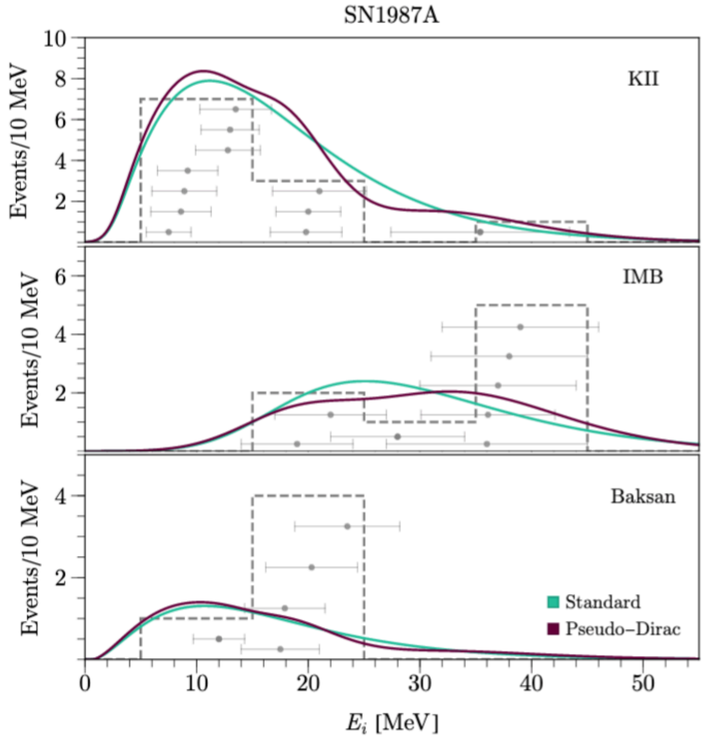
SN1987A data and comparison



A possibly better fit to the data?

SN1987A data and comparison

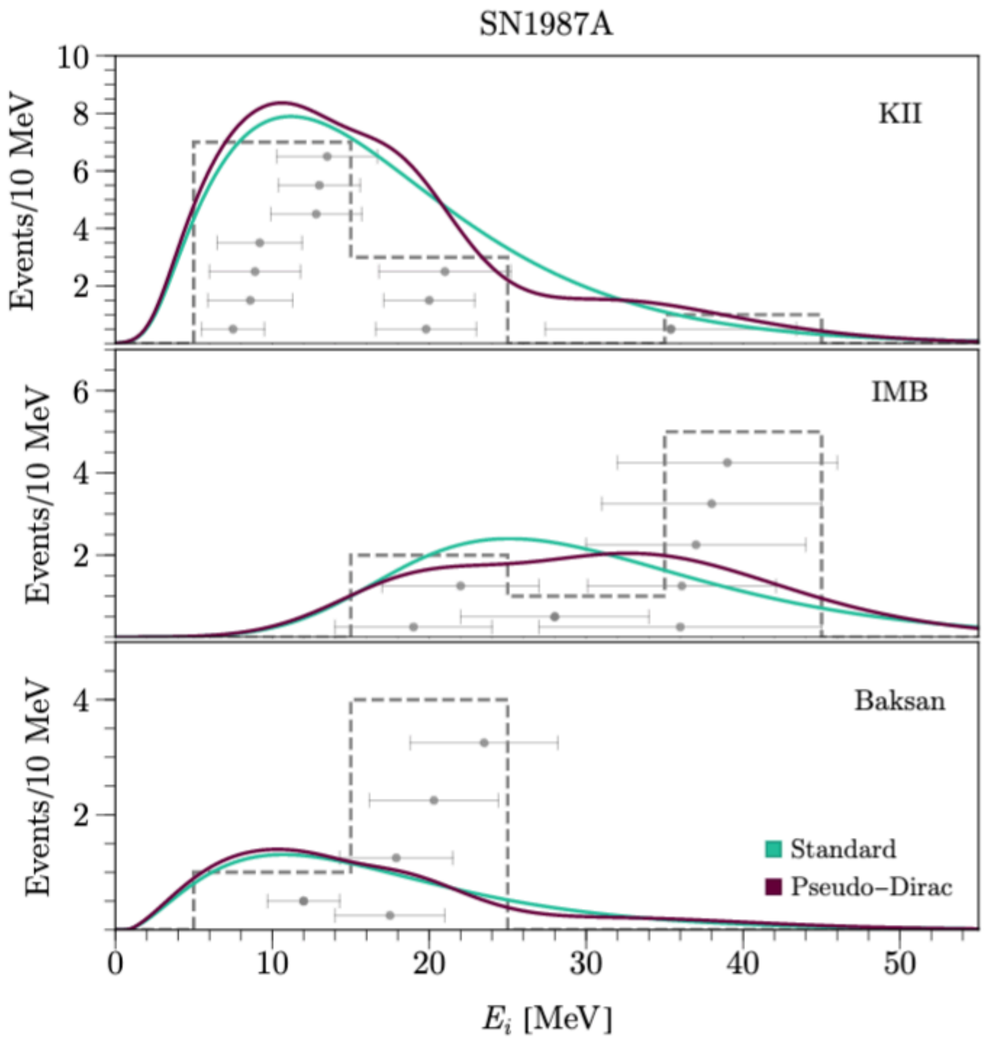


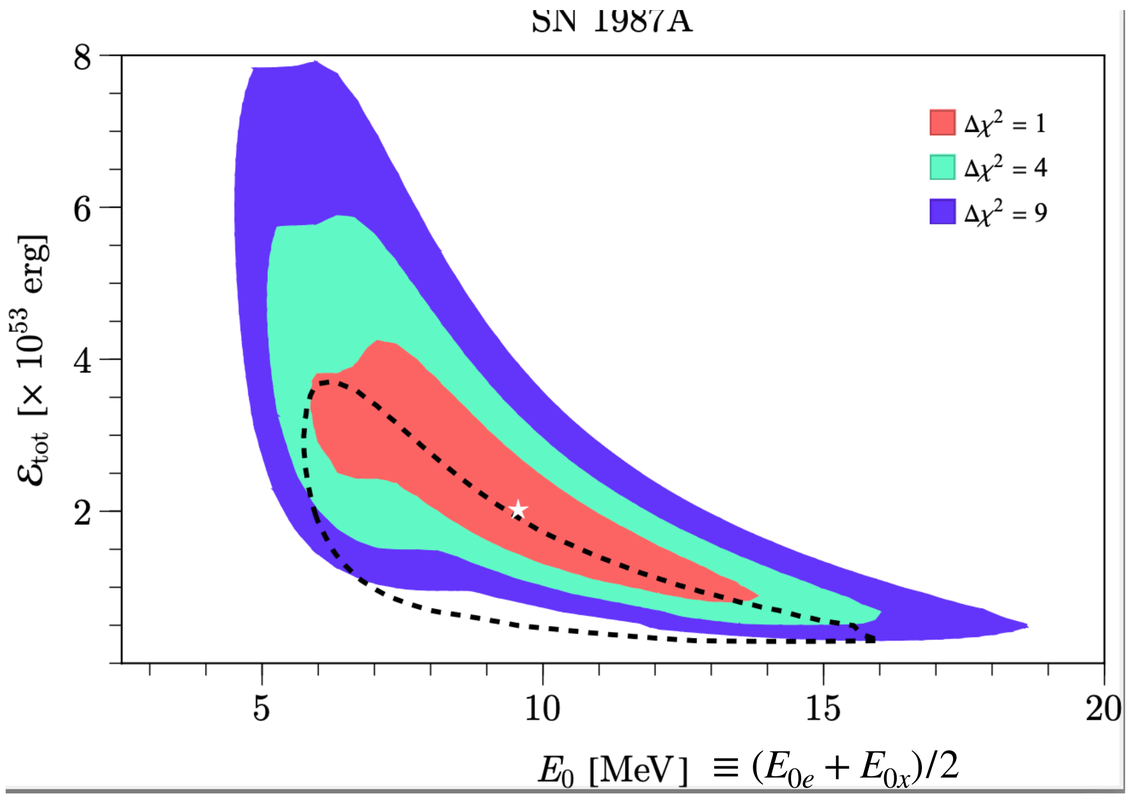


No Oscillations

- 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 $\Delta\chi^2 > 9$

How does it compare to the previous best fit?

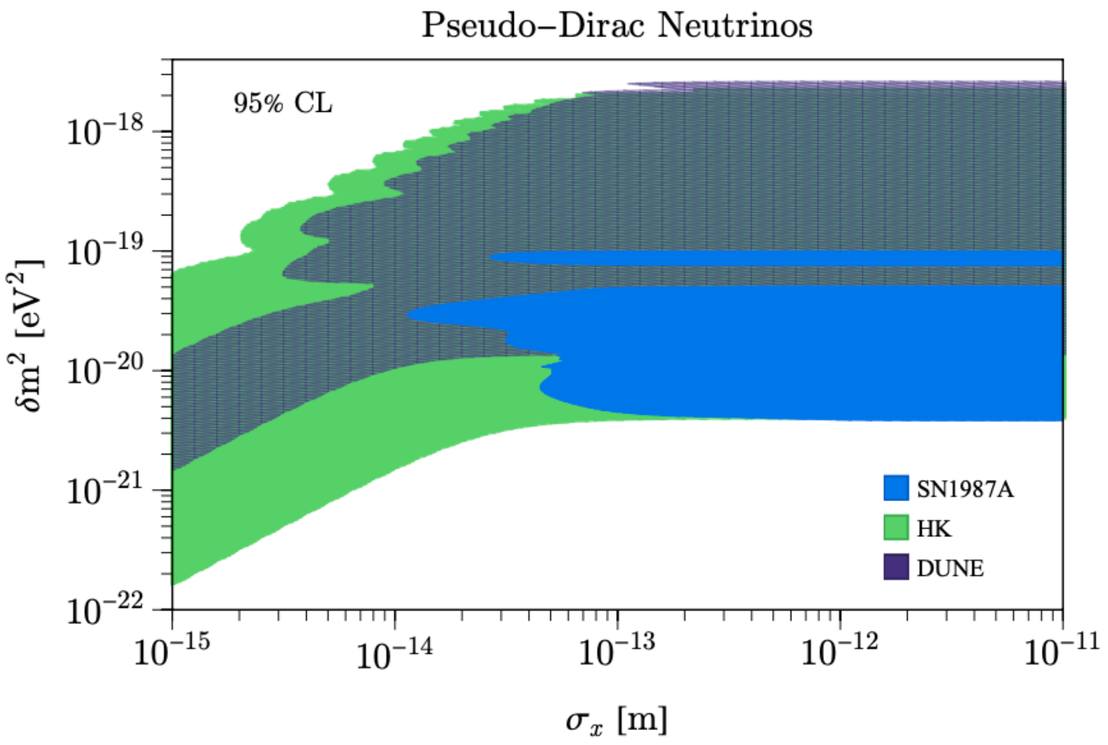




Prefers a slightly larger value of $\epsilon_{\rm tot}$ but otherwise compatible.

Future detectors-sensitivity

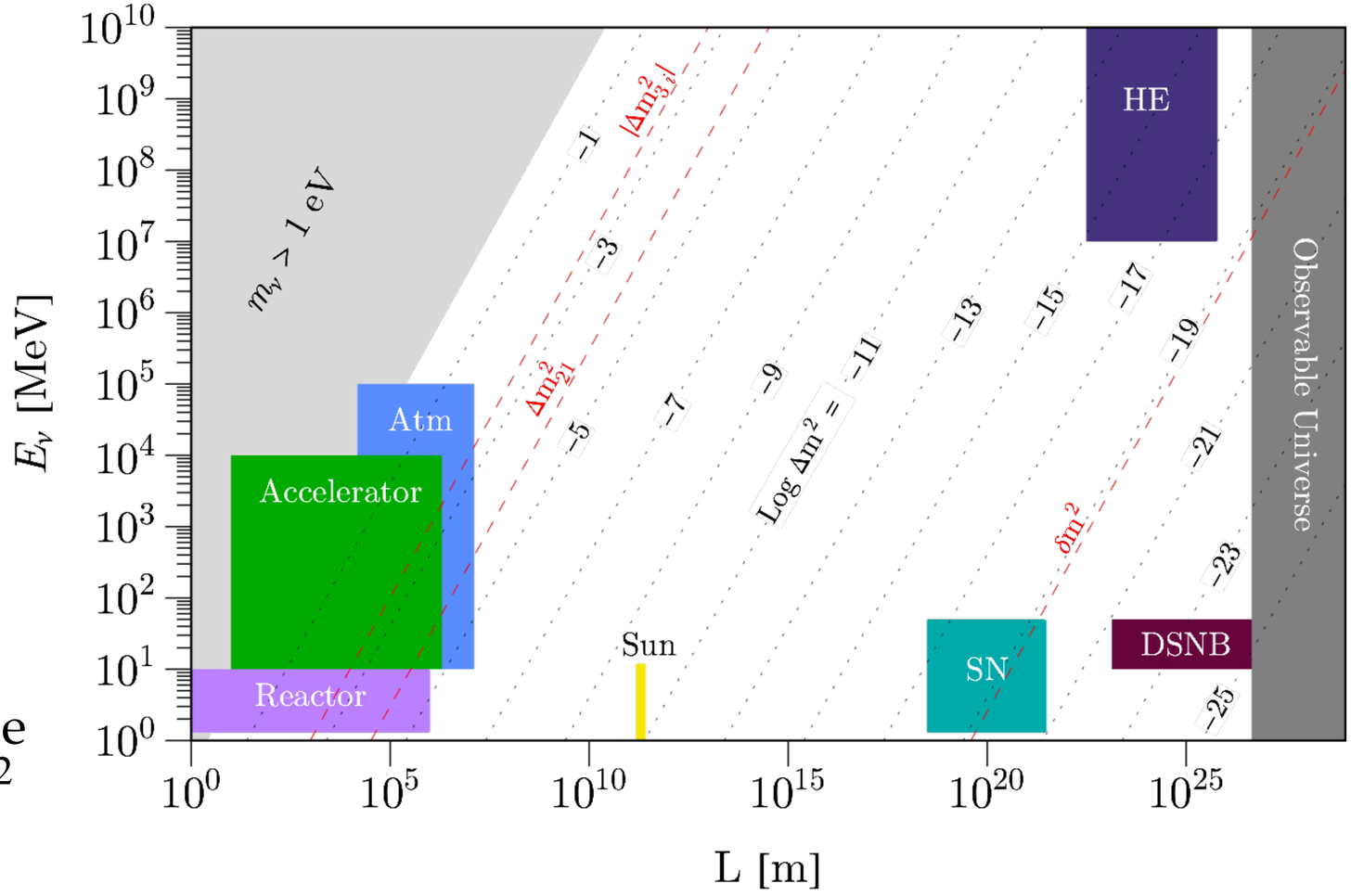
- HK and DUNE can confirm/rule out this scenario with a high confidence.
- Sensitive to lower mass-square differences due to decoherence.
- Non-electron neutrino detectors to play an important role!



Expected sensitivity on $\delta m^2 - \sigma_x$ plane for a SN at 10kpc for DUNE and HK. The exluded region from SN1987a is shown in blue.

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!

SN1987A events

	Relative time [ms]	Energy [MeV]	SN-angle [deg]	Backgr. [Hz/MeV]		Relative time [ms]	Energy [MeV]	SN-angle [deg]	Backgr. [Hz/MeV]
K1	0	20.0±2.9	18±18	1.0E-5	I1	0	38±7	80±10	10^{-5}?
K2	107	13.5±3.2	40±27	5.4E-4	I2	412	37±7	44±15	10^{-5}?
K3	303	7.5±2.0	108±32	2.4E-2	I3	650	28±6	56±20	10^{-5}?
K4	324	9.2±2.7	70±30	2.8E-3	I4	1141	39±7	65±20	10^{-5}?
K5	507	12.8±2.9	135±23	5.3E-4	I5	1562	36±9	33±15	10^{-5}?
K6	686	6.3±1.7	68±77	7.9E-2	I6	2684	36±6	52±10	10^{-5}?
K7	1541	35.4±8.0	32±16	5.0E-6	I7	5010	19±5	42±20	10^{-5}?
K8	1728	21.0±4.2	30±18	1.0E-5	I8	5582	22±5	104±20	10^{-5}?
K9	1915	19.8±3.2	38±22	1.0E-5					
K10	9219	8.6±2.7	122±30	4.2E-3					
K11	10433	13.0±2.6	49±26	4.0E-4					
K12	12439	8.9±2.9	91±39	3.2E-3	B1	0	12.0±2.4	90?	8.4E-4
K13	17641	6.5±1.6	90?	7.3E-2	B2	435	17.9±3.6	90?	1.3E-3
K14	20257	5.4±1.4	90?	5.3E-2	B3	1710	23.5±4.7	90?	1.2E-3
K15	21355	4.6±1.3	90?	1.8E-2	B4	7687	17.5±3.5	90?	1.3E-3
K16	23814	6.5±1.6	90?	7.3E-2	B5	9099	20.3±4.1	90?	1.3E-3

Table 1: *Properties of the events in the neutrino bursts observed in the occasion of SN1987A. The events are indicated by K1, K2... K16 for Kamiokande-II; I1, I2... I8 for IMB; B1, B2 ... B5 for Baksan. The background rate of IMB and some of the angles are unknown; there is no harm (for the analysis) in setting their values as indicated in the table with the question marks.*

Marginalised chi-square

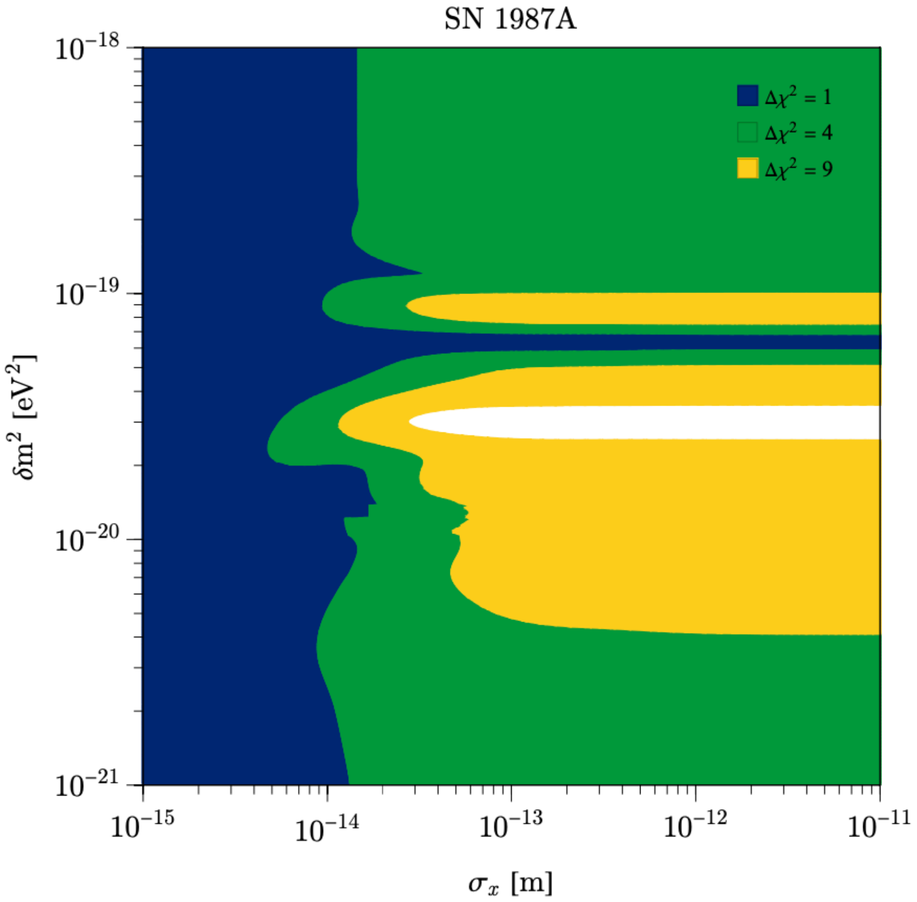


FIG. 3. Marginalized $\Delta\chi^2$ for the joint fit of the three distinct data sets coming from KII, IMB and Baksan in the plane δm^2 vs σ_x. The regions with $\Delta\chi^2 \leq \{1, 4, 9\}$ correspond to the blue, green, and yellow colors respectively. The white region is excluded at more than $\Delta\chi^2 > 9$.

Dependence on α

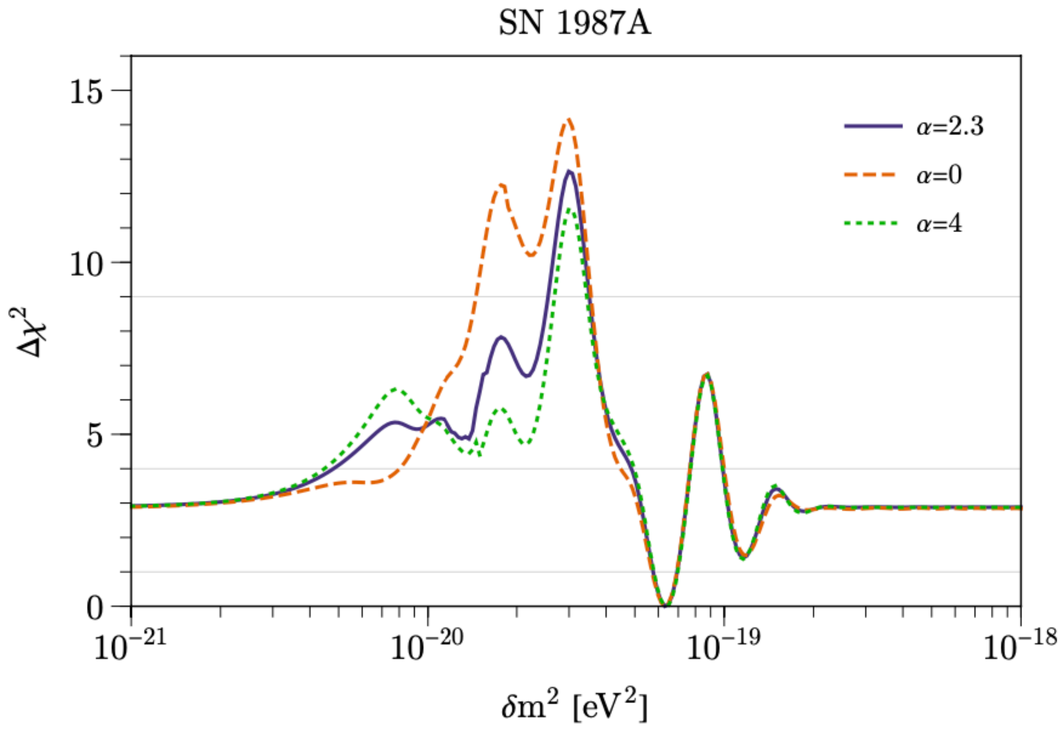


FIG. 2. Marginalized $\Delta\chi^2$ for the joint fit of the three distinct data sets coming from KII, IMB and Baksan as function of δm^2 for different values of the pinching parameter $\alpha = 0$ (orange dashed), 2.3 (purple), and 4 (green dotted).

How good are future detectors?

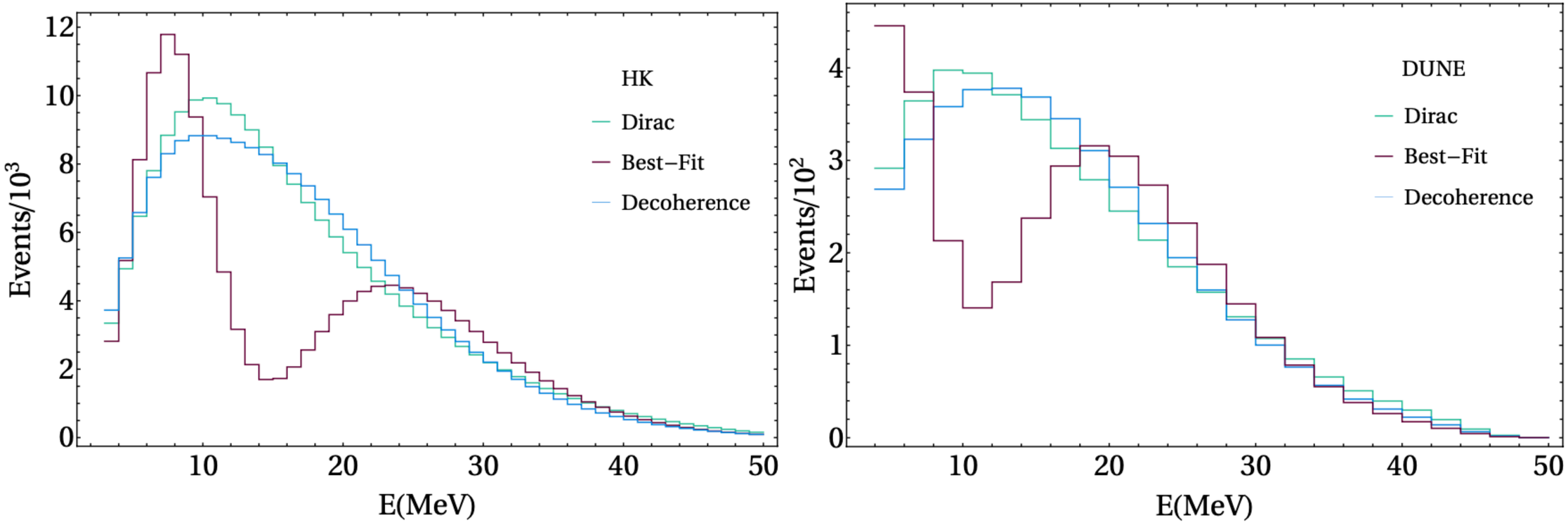


FIG. 8. The Number of events expected in HK (left) and DUNE (right) for a supernova happening at 10kpc. For the supernova luminosity, we assume the best-fit value of the SN1987A. We show the number of events for three different scenarios: neutrinos are Dirac fermions, the best-fit point of the SN1987A 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