New physics with supernova neutrinos @ DUNE

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DUNE-India Meeting 2025

THEP @ IIT Bombay

- I joined IITB as an assistant professor in October 2024. I completed my PhD at TIFR (with Amol Dighe and Basudeb Dasgupta), followed by postdocs at UC Berkeley and Max-Planck Institute for Nuclear Physics, Heidelberg.

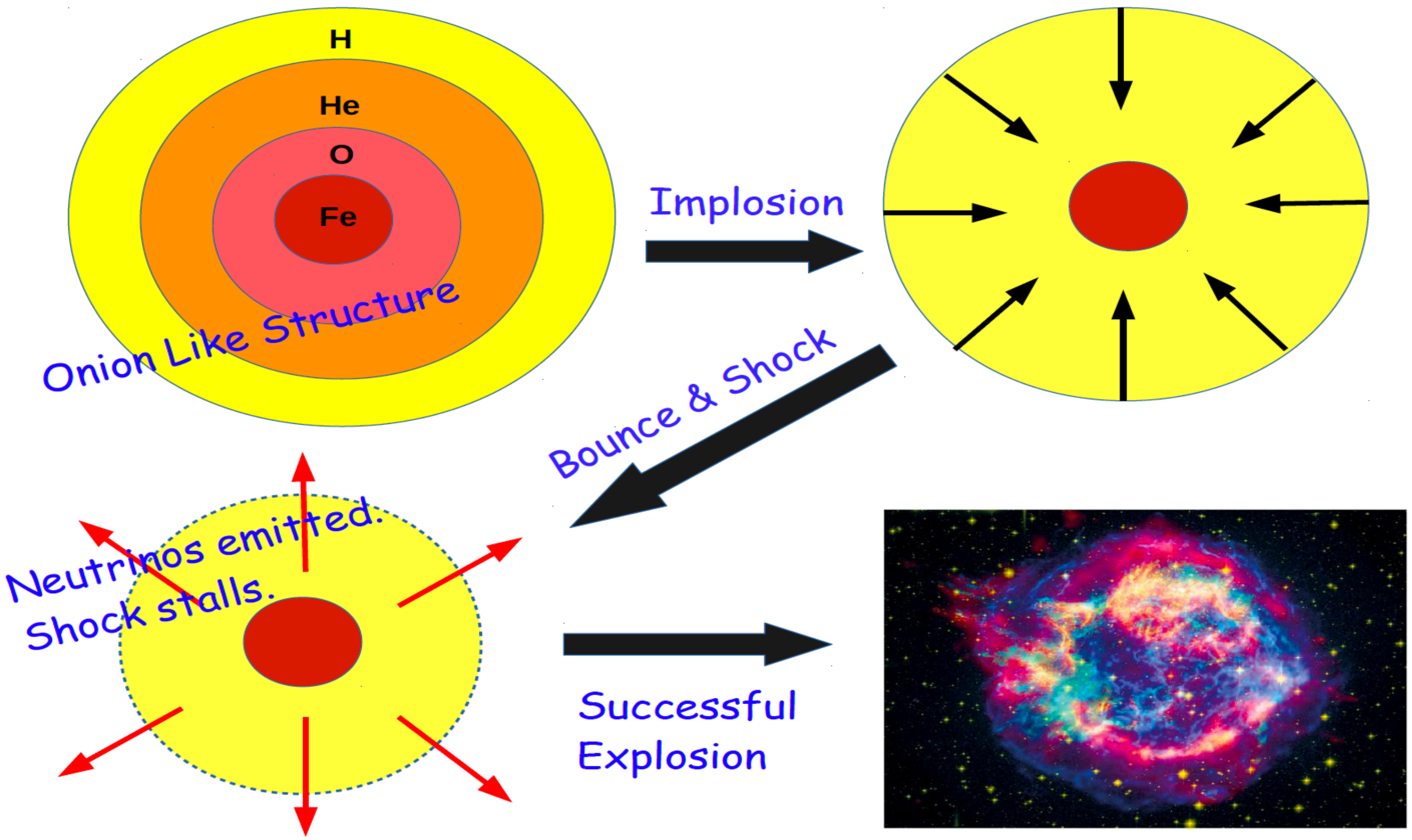
- Work on neutrino and dark sector physics. A large part of my work revolves around SN neutrinos and testing non-standard neutrino properties, which is of relevance to DUNE.

- My group consists of 1 PhD student and 1 postdoc, working on aspects of neutrino physics. Looking to expand further.

- High Energy Theory group consisting of 7 faculty members, 10 PhD students and 5 postdocs.
    1. Elementary Particle physics and physics beyond the Standard Model
    2. Astroparticle physics and early universe cosmology
    3. Mathematical Physics

- Experimental High Energy Physics with 5 members, with active collaborations in ALICE, COMET@JPARC and Astrophysics and Cosmology group with 4 members with active collaboration in LIGO, Astrosat.

A supernova engine



Onion Like Structure

Implosion

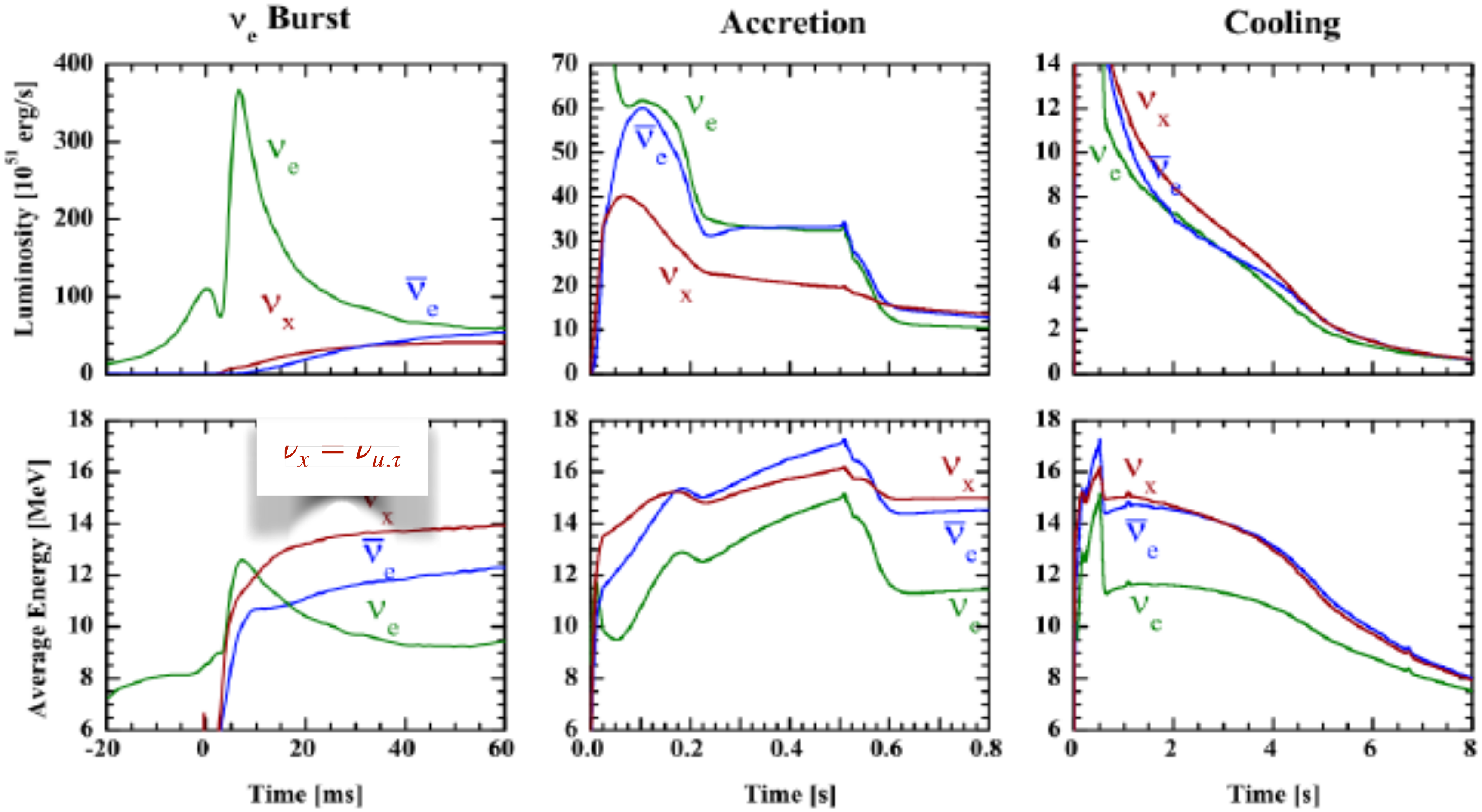
Bounce & Shock

Neutrinos emitted.
Shock stalls.

Successful
Explosion

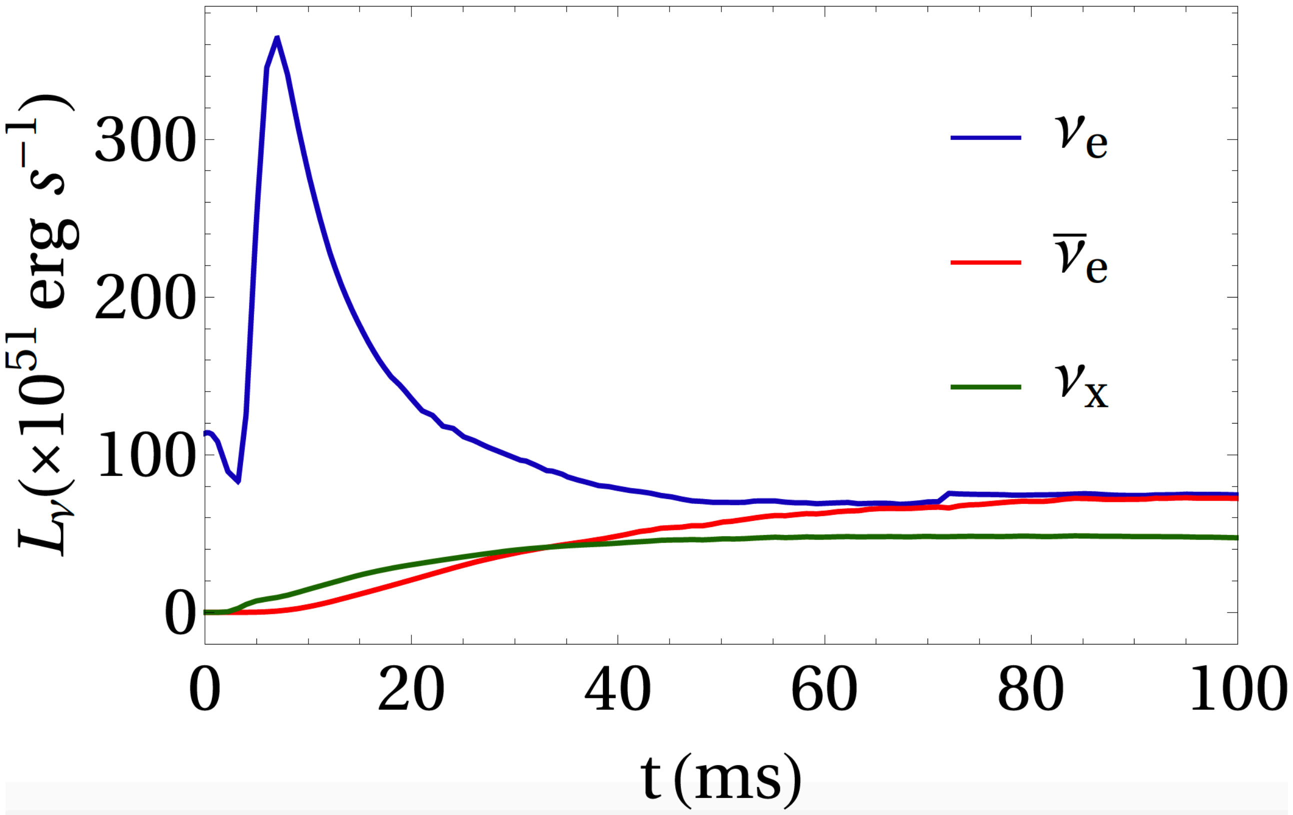
Talk by Basudeb Dasgupta

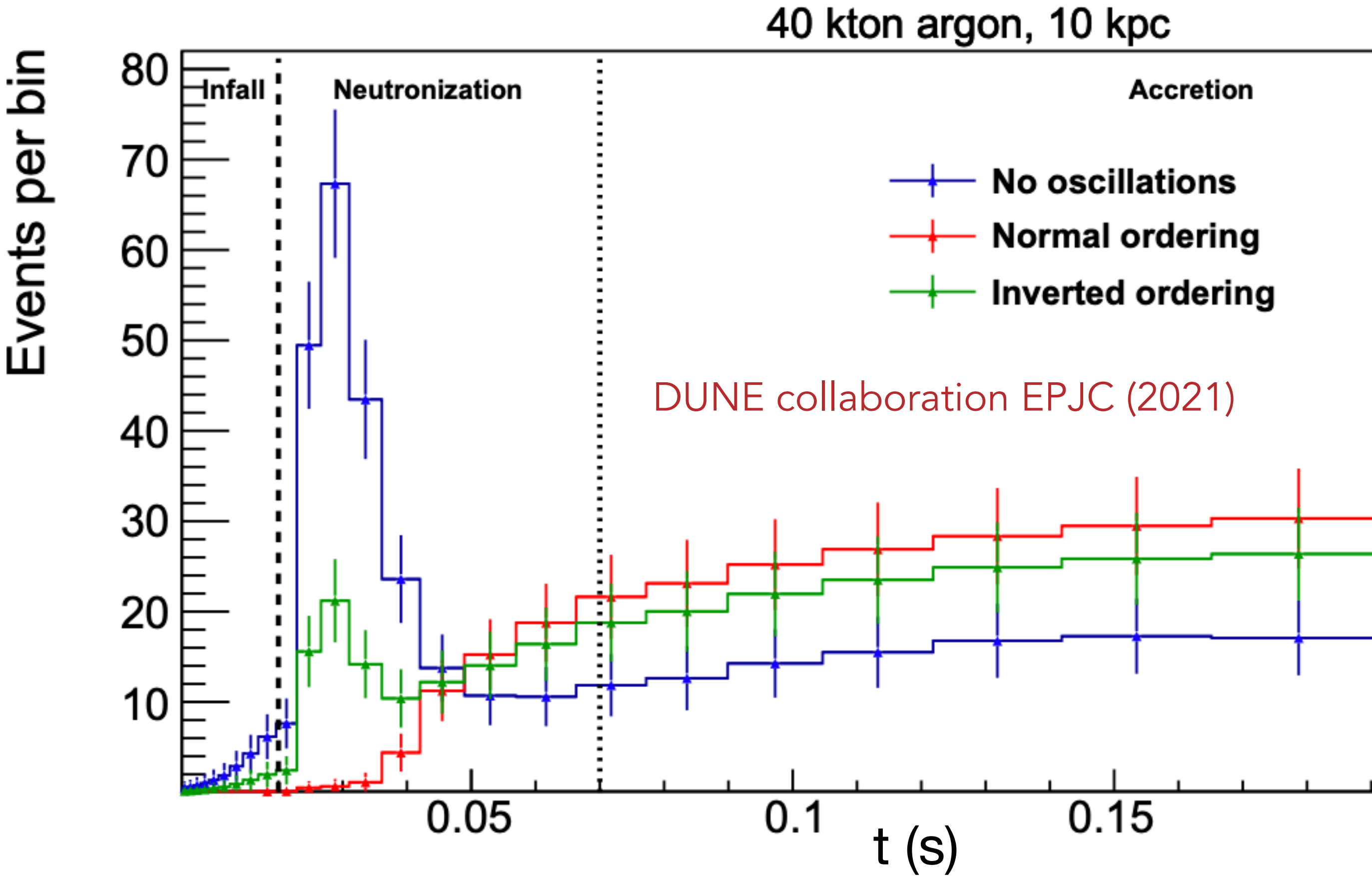
O(10) MeV neutrinos are emitted



Garching simulations

The neutronization burst: a foreward





DUNE collaboration EPJC (2021)

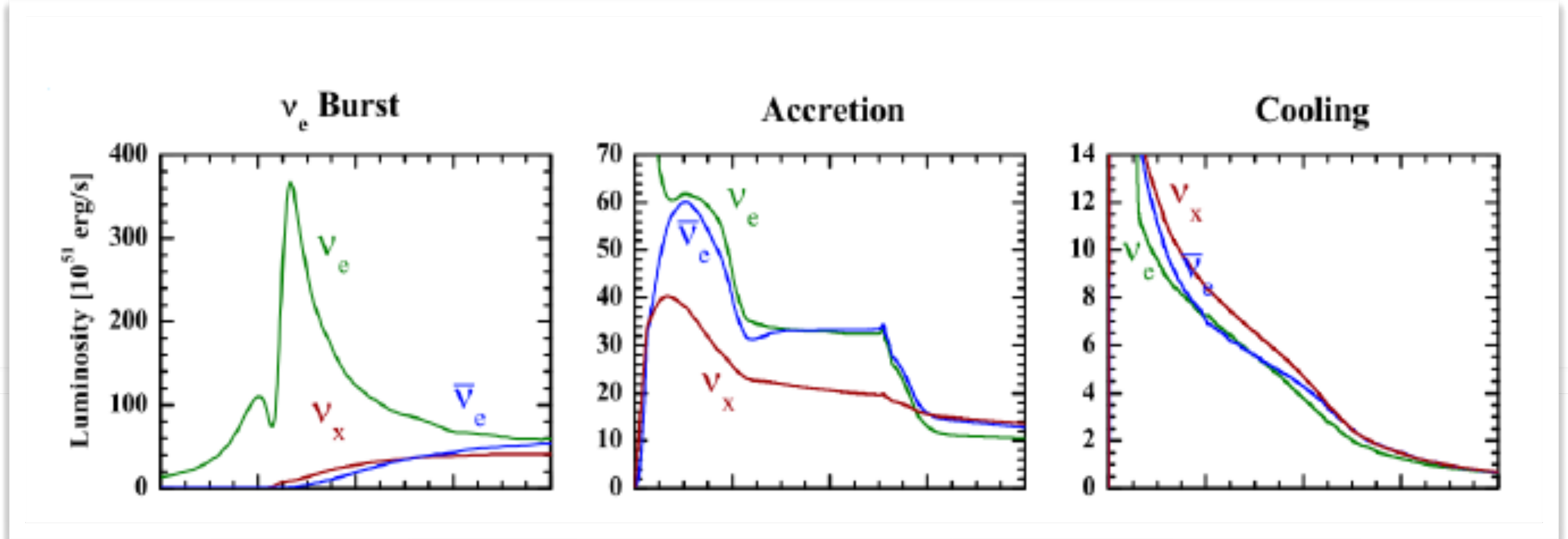
- DUNE will be uniquely sensitive to ν_e component of the SN neutrino flux.
- Large burst of ν_e in the first ~30 ms post bounce. *No collective oscillations within the SM*.
- Independent probe of mass ordering! DUNE will play a major role.

$$L_{\nu_e}(R_E) \simeq |U_{e2}|^2 \, L^0_{\nu_e} = 0.2 \, L^0_{\nu_e} \quad \text{IH}$$

Dighe, Smirnov (PRD 2000)

$$L_{\nu_e}(R_E) \simeq |U_{e3}|^2 \, L^0_{\nu_e} = 0.03 \, L^0_{\nu_e} \quad \text{NH}$$

Category of bounds from SN neutrinos



New Physics can

1. Impact on the neutrino luminosity, and average energy, and duration of neutrino burst

2. Impact on the neutrino spectra/ flux

1. Non-standard self-interactions (NSSI)

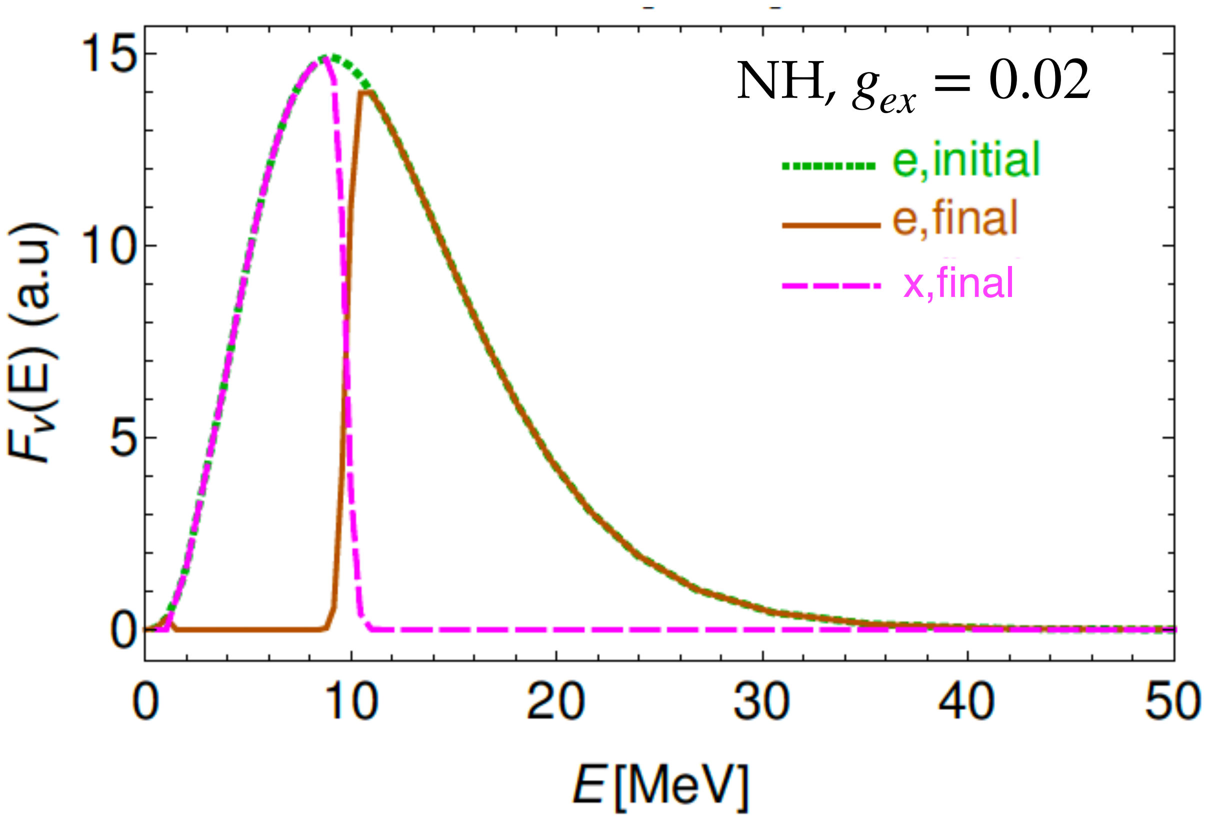
- Testing ground for neutrino NSSI.

Raffelt, Sigl (NPB 1993)
Blennow, Mirizzi, Serpico (PRD 2008)
Das, Dighe, **MS** (JCAP 2017)

- Consider $\mathscr{L} \supset G_F\,(G_{\alpha\beta}\,\bar{\nu}^{\alpha}\,\gamma^{\mu}L\,\nu^{\beta})\,(G_{\eta\delta}\,\bar{\nu}^{\eta}\,\gamma^{\mu}L\,\nu^{\delta})$,

  where most generally, $G = \begin{pmatrix} 1+g_{ee} & g_{ex} \\ g_{ex} & 1+g_{xx} \end{pmatrix}$.

- Flavour violating (g_{ex}) causes collective oscillations even in neutronisation burst with distinct splits.

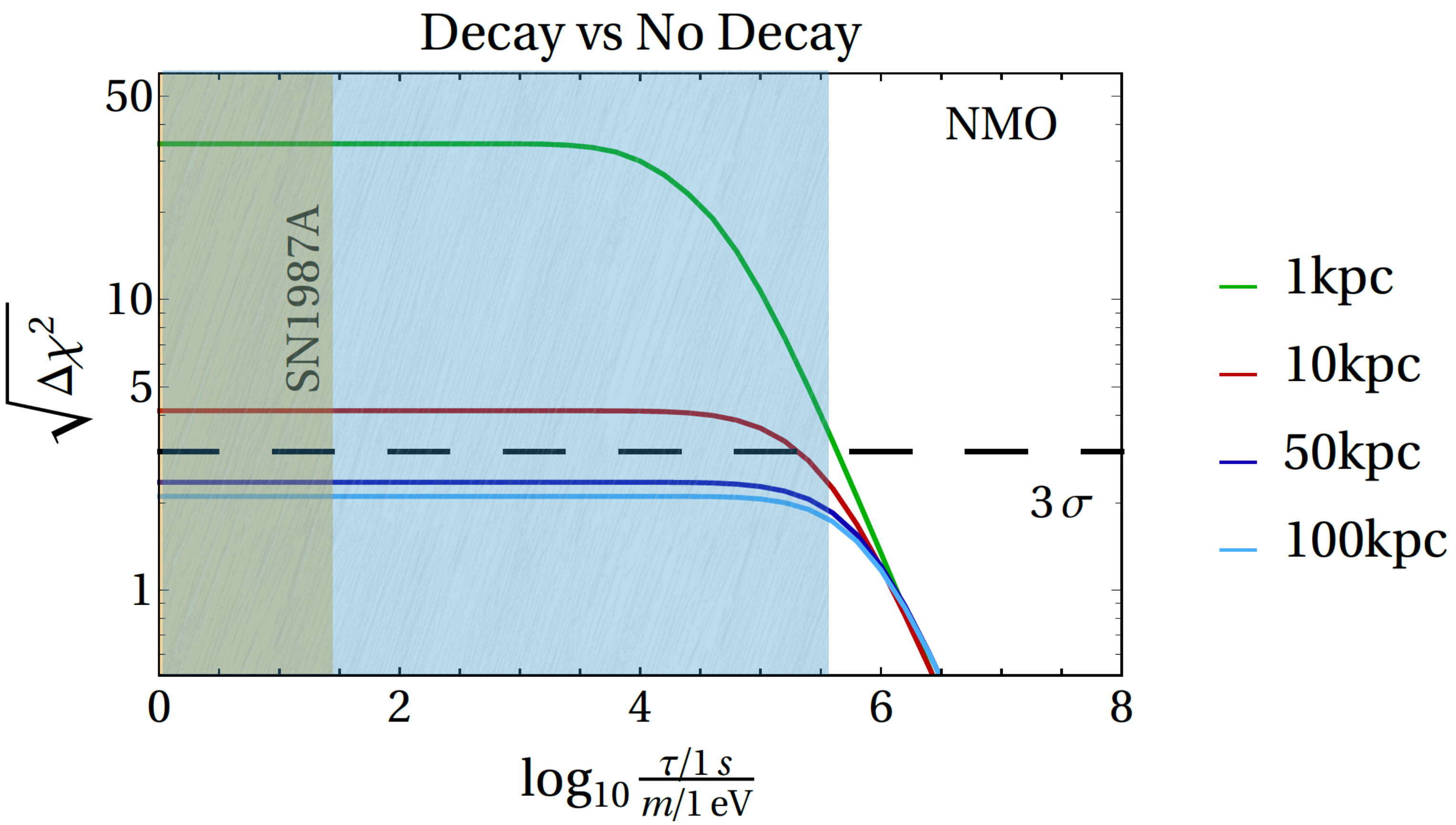


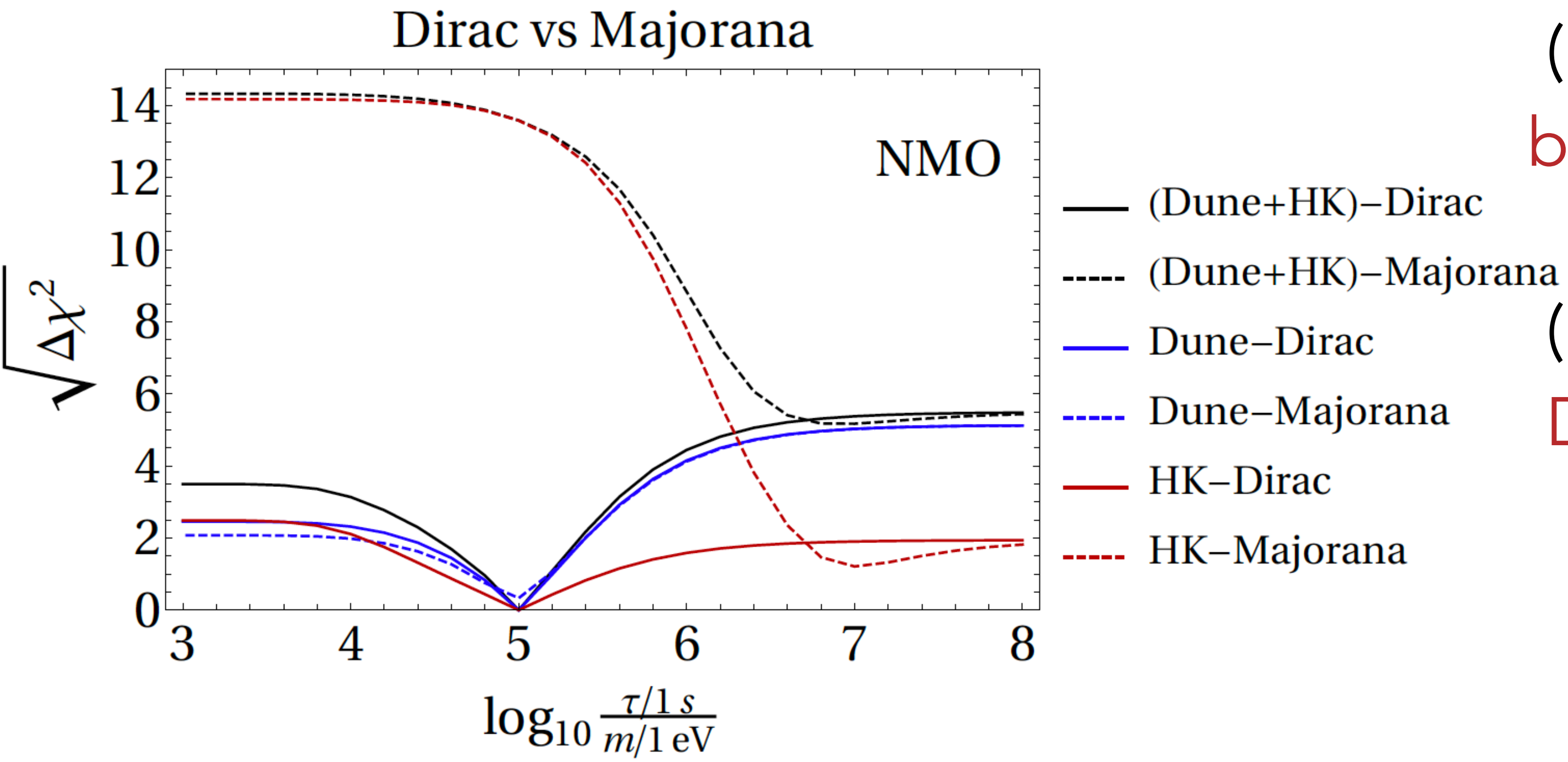
- Stringent bounds on NSSI.

- Can also be used to constrain NSI through new resonances.

Esteban-Pretel, Tomas, Valle, (PRD 2007)

2. New neutrino decay modes





- New physics can mediate faster decay than SM.

$$\mathscr{L} \supset \nu_h \nu_l \phi + \mathrm{H.c.}$$

- Use the neutronization flux to

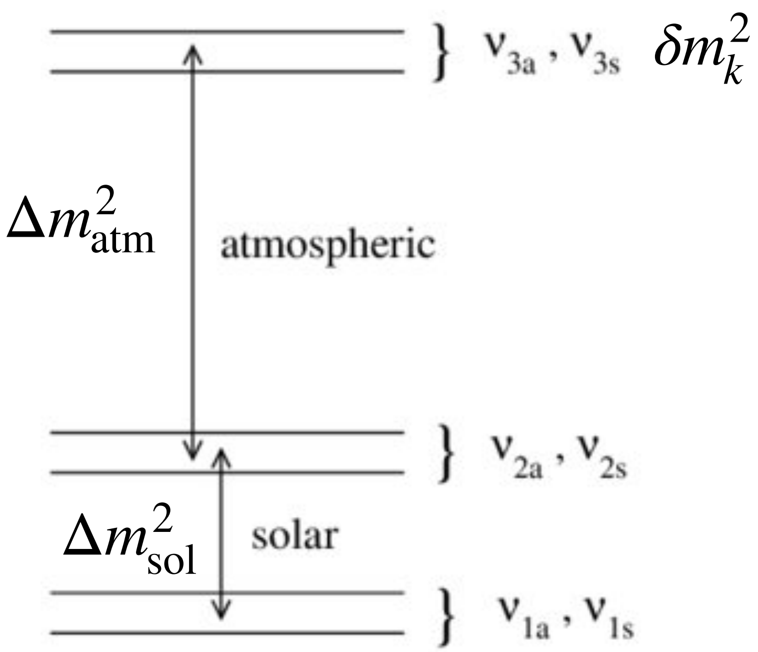
(i) Put some of the tightest bound on this decay.

(ii) Distinguish between decaying Dirac and Majorana nature.

de Gouvea, Martinez-Soler, **MS** (PRD 2019)

3. Pseudo-Dirac neutrinos

- Neutrinos have sub-dominant Majorana mass terms.



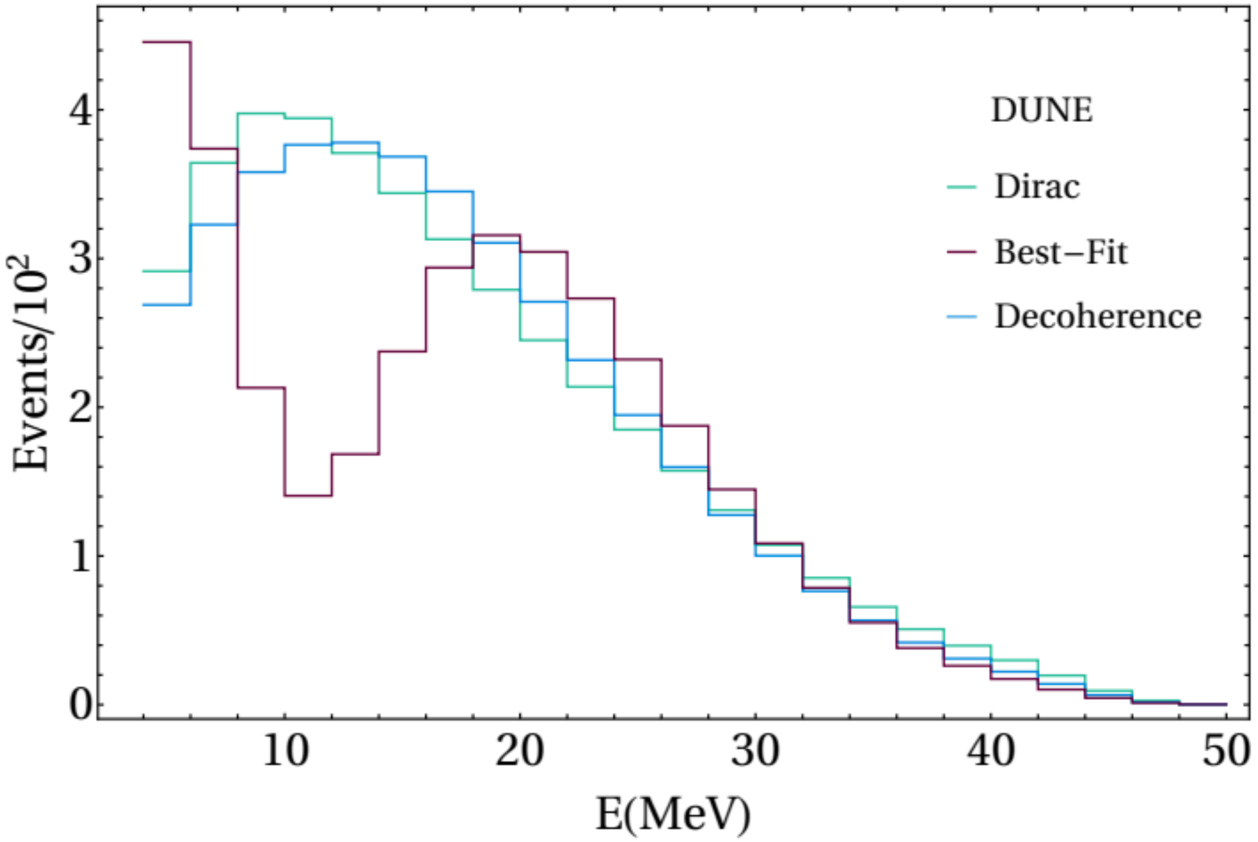
Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

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

- Oscillations driven by the tiny $\delta m^2 \sim m_L m_R$.

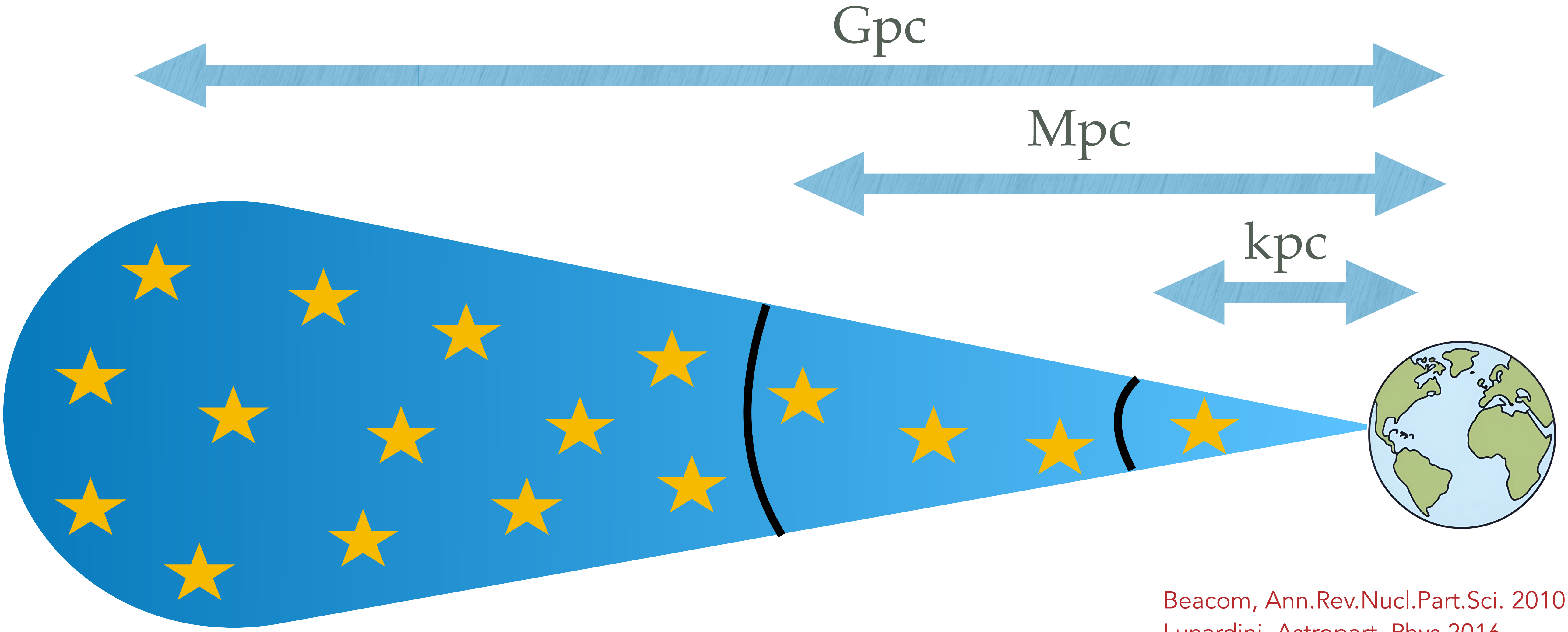
$$L_{\text{osc}} = \frac{4\pi E_\nu}{\delta m^2} \sim 20\,\text{kpc}\left(\frac{E_\nu}{25\text{MeV}}\right)\left(\frac{10^{-19}\text{eV}^2}{\delta m^2}\right)$$

- Constraints on δm^2 from dips in spectra.



Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)

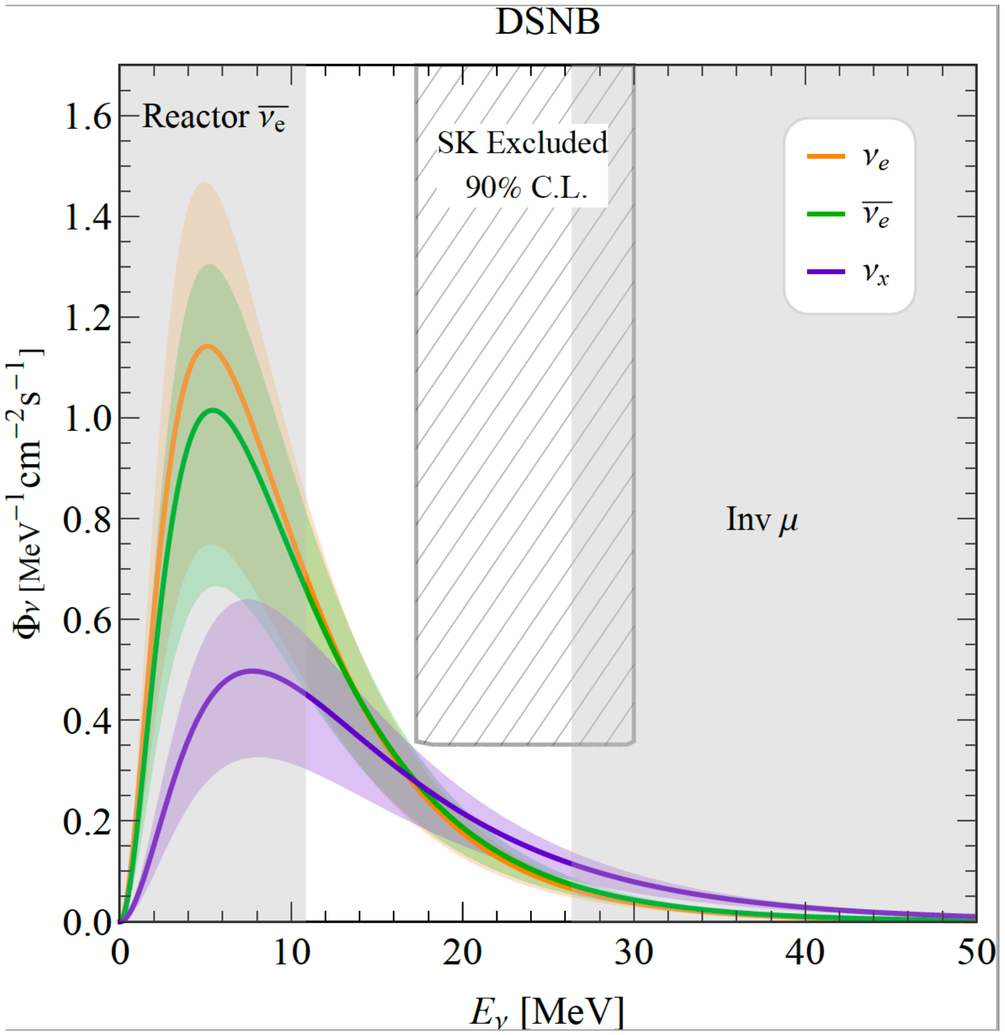
The Diffuse Supernova Neutrino Background

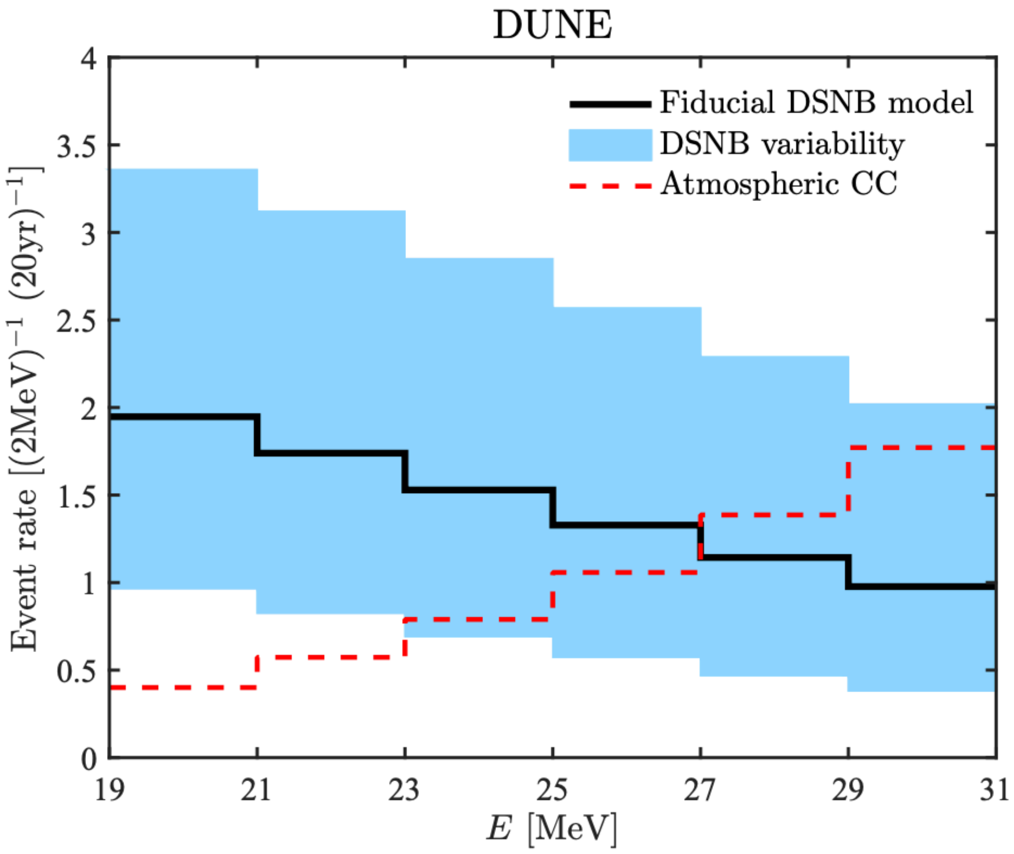


Beacom, Ann.Rev.Nucl.Part.Sci. 2010
Lunardini, Astropart. Phys 2016

- A galactic SN is very rare. Look beyond our galaxy.
- Almost 1 SN going off per second. The neutrino emission produces the DSNB.
- Isotropic flux of O(10) MeV neutrinos - opens up a new frontier in neutrino astronomy.

The DSNB: an omnipresent laboratory





Denton, Moller, Suliga, Tamborra (JCAP 2018)
de Gouvea, Martinez-Soler, Perez-Gonzalez , **MS** (PRD 2020, 2022)
Das, **MS** (PRD 2021)
Das, Herbermann, **MS**, Takhistov (JCAP 2024)
Perez-Gonzalez, **MS**, (PRD 2025)

- Particle physics aspects: neutrino properties, new neutrinophilic particles…
- Astrophysics: Star formation rates,equation of state, nucleosynthesis…
- Cosmology: dark matter physics, distance indicators…

Adds to the multi-messenger aspect.

Future Outlook

- A core-collapse SN is one of the best astrophysical laboratories for fundamental neutrino physics.

- DUNE will be uniquely sensitive to ν_e component of the SN neutrino flux.

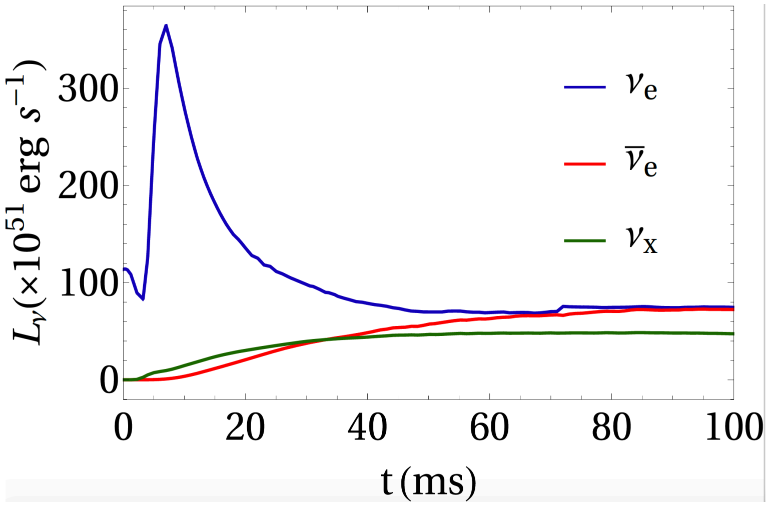
- Till a galactic SN takes place, one can utilize the constant availability of the DSNB to already probe some of these physics.

- Interested in probing neutrino-dark sector interactions using DUNE in the future.

Thank you!

Backup

Neutrino Decay



Normal Ordering

Ando PRD (2004)
de Gouvea, Martinez-Soler, **MS** (PRD 2019)

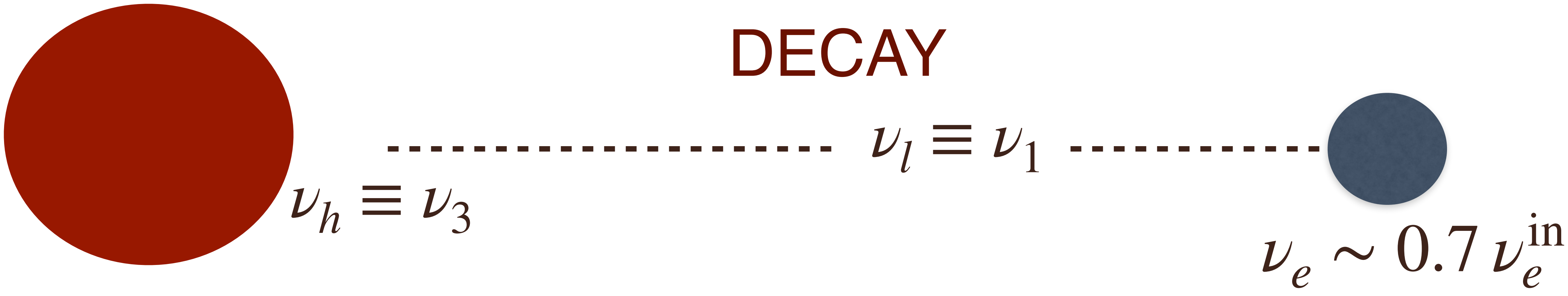
For a detailed theoretical framework of neutrino decay, see Lindner, Ohlsson, Winter, (NPB 2002)

NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim 0.02\,\nu_3$

DECAY



$\nu_h \equiv \nu_3$

$\nu_l \equiv \nu_1$

$\nu_e \sim 0.7\,\nu_e^{\mathrm{in}}$

Enhancement in spectra

Dirac vs Majorana

$$\mathscr{L}_{\mathrm{Dir}} \supset \nu_h \nu_l^c \phi + \mathrm{H.c.}$$

$$\nu_{hL} \to \nu_{lL} + \phi$$

$$\nu_{hL} \to \nu_{lR} + \phi$$

acts as an “inert” neutrino and cannot be observed.

$$\mathscr{L}_{\mathrm{Maj}} \supset \nu_h \nu_l \phi + \mathrm{H.c.}$$

$$\nu_{hL} \to \nu_{lL} + \phi$$

$$\nu_{hL} \to \nu_{lR} + \phi$$

acts as the “antineutrino” - produces an e^+ on interaction—observable

Different signatures in detectors sensitive to ν_e and $\overline{\nu}_e$.

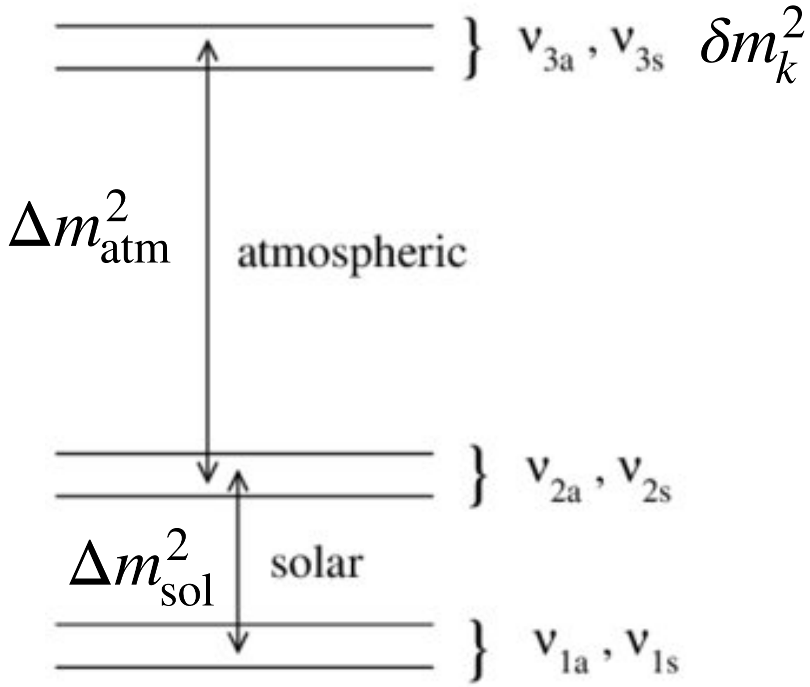
Look at DUNE and HK

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 : $m_{L,R} \ll m_D$



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

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

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

Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)

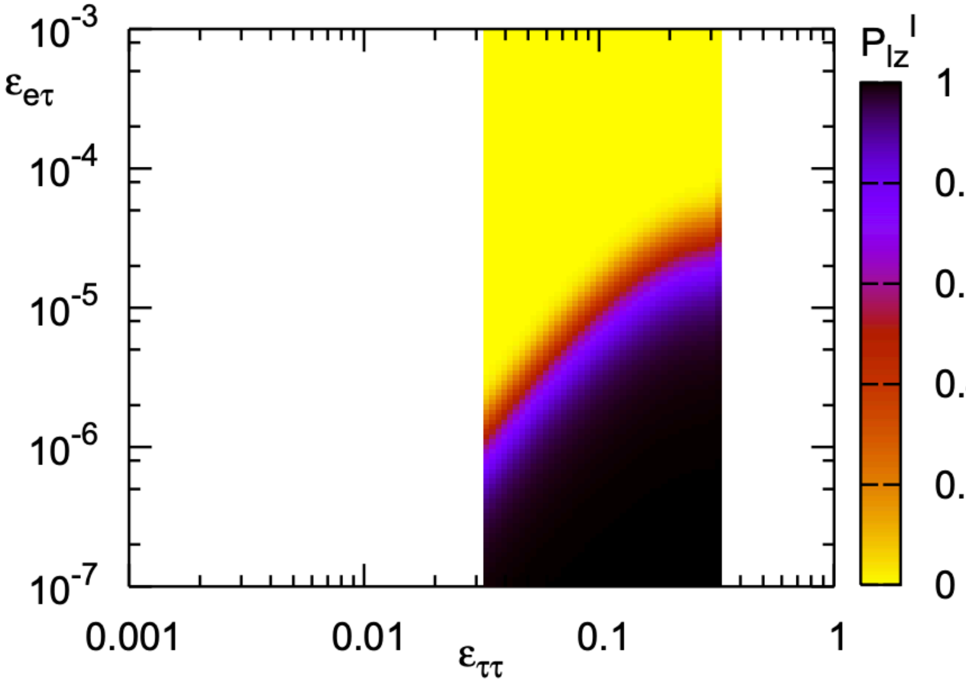
Bounds:

1. Solar neutrinos $\delta m^2 = 10^{-12}\,{\rm eV}^2$
   de Gouvea, Huang, Jenkins (PRD 2009)
2. Atmospheric neutrinos
   $\delta m^2 > 10^{-4}\,{\rm eV}^2$
   Beacom, Bell, et al. (PRL 2004)
3. High energy astrophysical neutrinos
   $10^{-18}\,{\rm eV}^2 < \delta m^2 < 10^{-12}\,{\rm eV}^2$
   Esmaili, Farzan, (JCAP 2012)

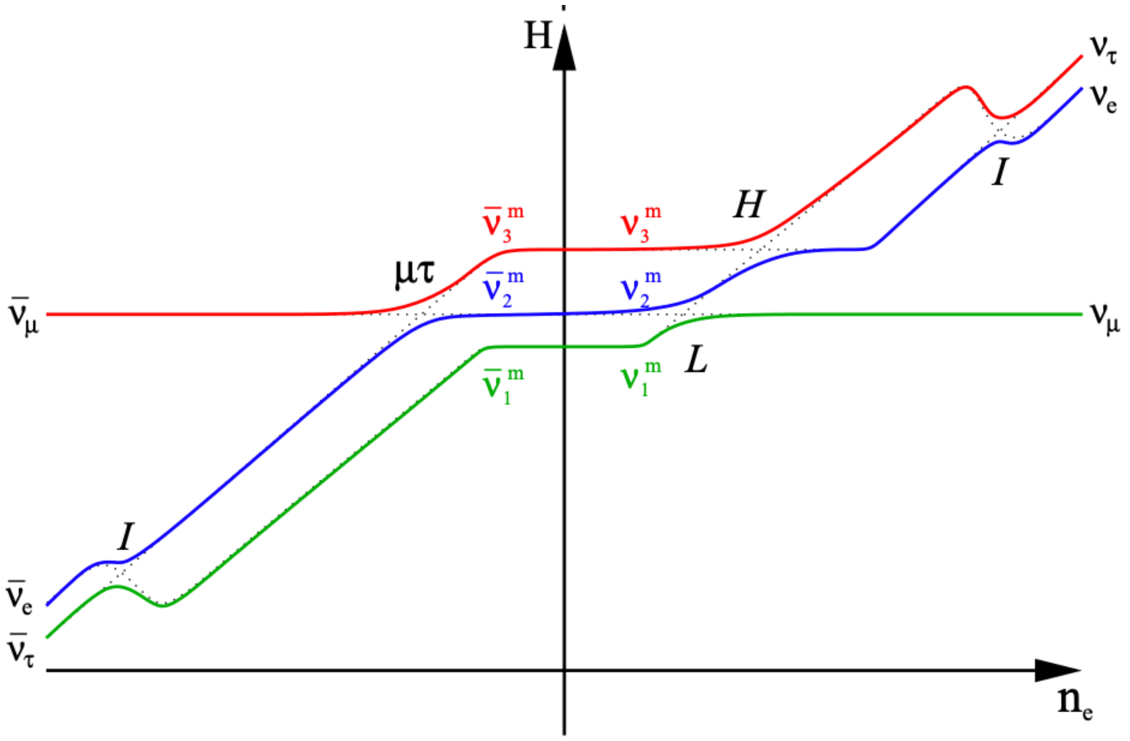
Non-standard interactions

- Presence of NSI can lead to important consequences in dense core
  $$\mathscr{L} \supset \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2}G_F\,(\bar{\nu}^{\alpha}\gamma^{\mu}L\,\nu^{\beta})\,(\bar{f}\gamma_{\mu}Pf)$$
- Extra potential $V = \sqrt{2}G_F N_f\, \varepsilon_{\alpha\beta}^{fP}$
- Leads to an extra resonance ('I' resonance) if $H_{ee} = H_{\mu\mu}, H_{\tau\tau}$. Changes flavor content deep inside the SN.
- Can reduce Y_e during collapse, leading to lower shock energy.

Amanik, Fuller, (PRD 2007)
See also Amanik, Fuller, Grinstein, Astropart. Phys (2005)



Esteban-Pretel, Tomas, Valle, (PRD 2007)



Estimating the DSNB

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)}\, R_{\rm CCSN}(z)\, F_\nu\big(E(1+z)\big)$$

Beacom,
Ann.Rev.Nucl.Part.Sci. 2010
Lunardini, Astropart. Phys
2016

SN Neutrino spectra

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

Cosmological SN rate

$$R_{\rm CCSN}(z) = \dot{\rho}_{\rm SFR}(z) \frac{\int_8^{50} \psi_{\rm IMF}(M)\, dM}{\int_{0.1}^{100} M\psi_{\rm IMF}(M)\, dM}\,.$$

Cosmology

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$$

Other new physics—an incomplete list

- Axions, and axion-like particles. Raffelt, Stars as laboratories for fundamental physics, UCP (1996)
  Jaeckel, Spannowsky, (PLB 2016)
  Lucente, Carenza, Fischer, et al. (JCAP 2020)

  Majorons and other feebly interacting scalars. Kachelreiss, Tomas, Valle, (PRD 2000)
  Farzan (PRD 2000)
  Fiorillo, Raffelt, Vitagliano, 2209.11773

- Neutrino magnetic moment: bounds $\mu_D < 10^{-12}\mu_B$. Barbieri, Mohapata, (PRL 1988)
  Jana, **MS**, Silva (JCAP 2022)

- Radiative decays: $\nu \to \nu'\gamma$, gives a coincident γ-ray flare. Bounds $\tau/m > 10^{15}\,\mathrm{s/eV}$. Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

- Time of flight delay due to neutrinos: $m_\nu < 20\,\mathrm{eV}$. Zatsepin, JETP Lett (1968)
  More precise time measurements narrow it to O(1)eV.
  Hansen, Lindner, Scholer, (PRD 2020)
  Pompa, Capozzi, et al (PRL 2022)

- If ν have millicharge, their path can be bent by galactic B field, causing a time delay, $e_\nu < 10^{-17}e\,(1\mu G/B)$ Barbiellini, Cocconi, Nature (1987)