Neutrino Interactions at DUNE

Sudip Jana

Harish-Chandra Research Institute

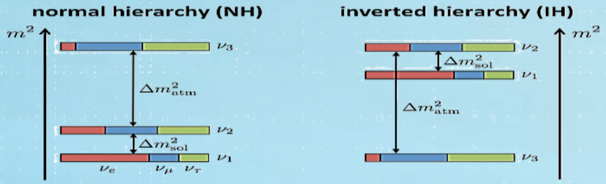
DUNE-India Meeting 2025

TIFR, Mumbai, India

June 6, 2025

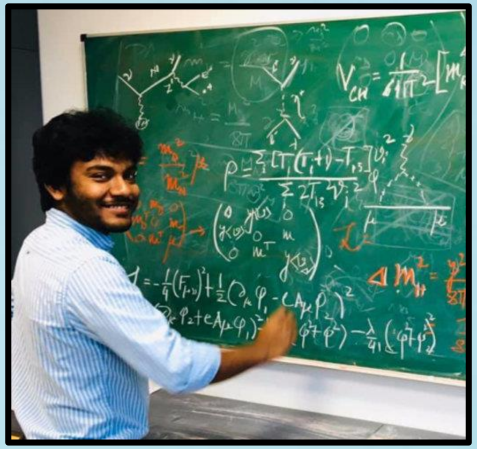
Neutrino @ HRI

1. *How do neutrinos get mass?*
2. *Nature of neutrinos (Dirac or Majorana?)*
3. *Neutrino Mass ordering (Normal or Inverted?)*



4. *Probing neutrino mass messengers at facilities such as DUNE*
5. *New interactions of Neutrinos with matter and its implications*
6. *Electromagnetic properties of neutrinos*
7. *Investigating experimental anomalies such as MiniBooNE, LSND……*

Prof. Raj Gandhi

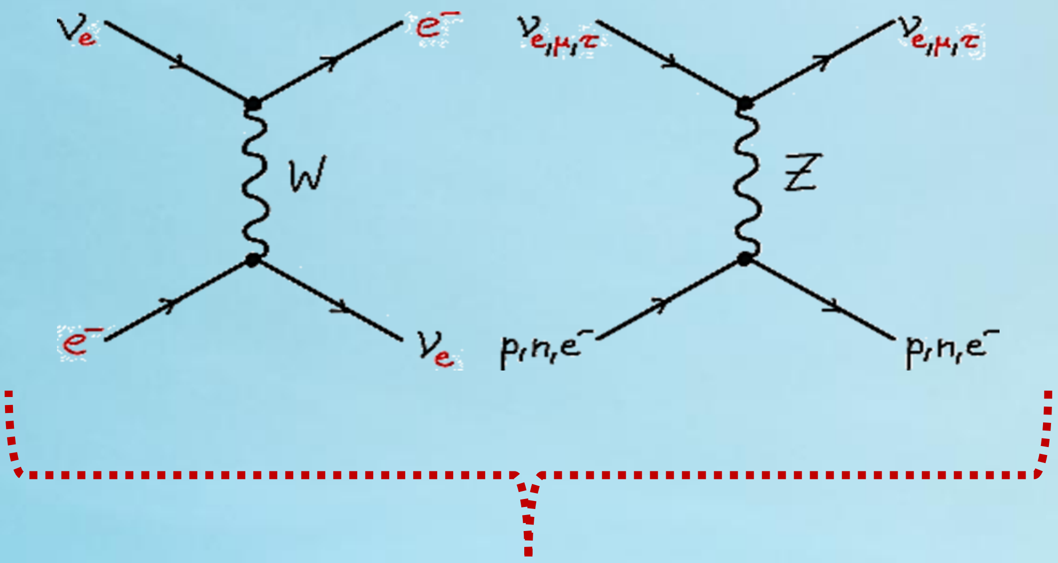


Dr. Sudip Jana

Other Members

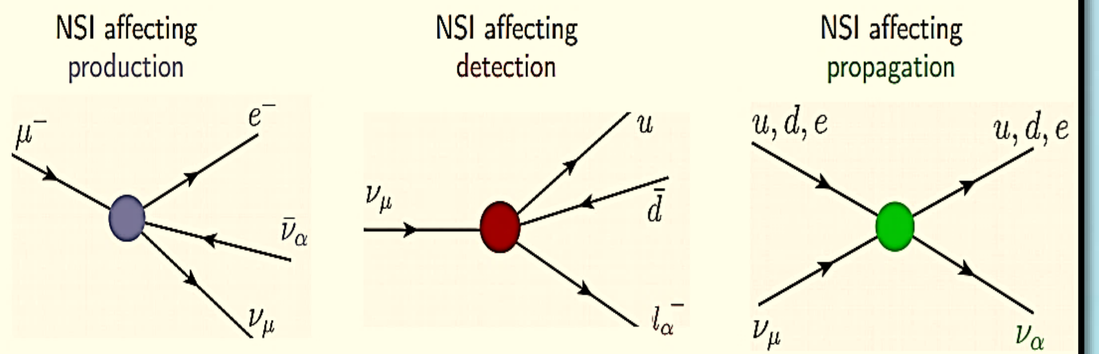
4 Faculty members
6 PhD Students
3 Postdocs (+ 2 incoming)
7 Master's Thesis Students

Non-Standard Interactions of Neutrinos



Standard Interactions of Neutrinos

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6}} + \ldots$$



$\varepsilon^{e\mu,P}_{\mu\alpha}\,(\bar{e}\gamma^\rho P\mu)\,(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$ $\varepsilon^{ud,P}_{\mu\alpha}\,(\bar{d}\gamma^\rho Pu)\,(\bar{\nu}_\mu\gamma_\rho P_L l_\alpha)$ $\varepsilon^{f,P}_{\mu\alpha}\,(\bar{f}\gamma^\rho Pf)\,(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$

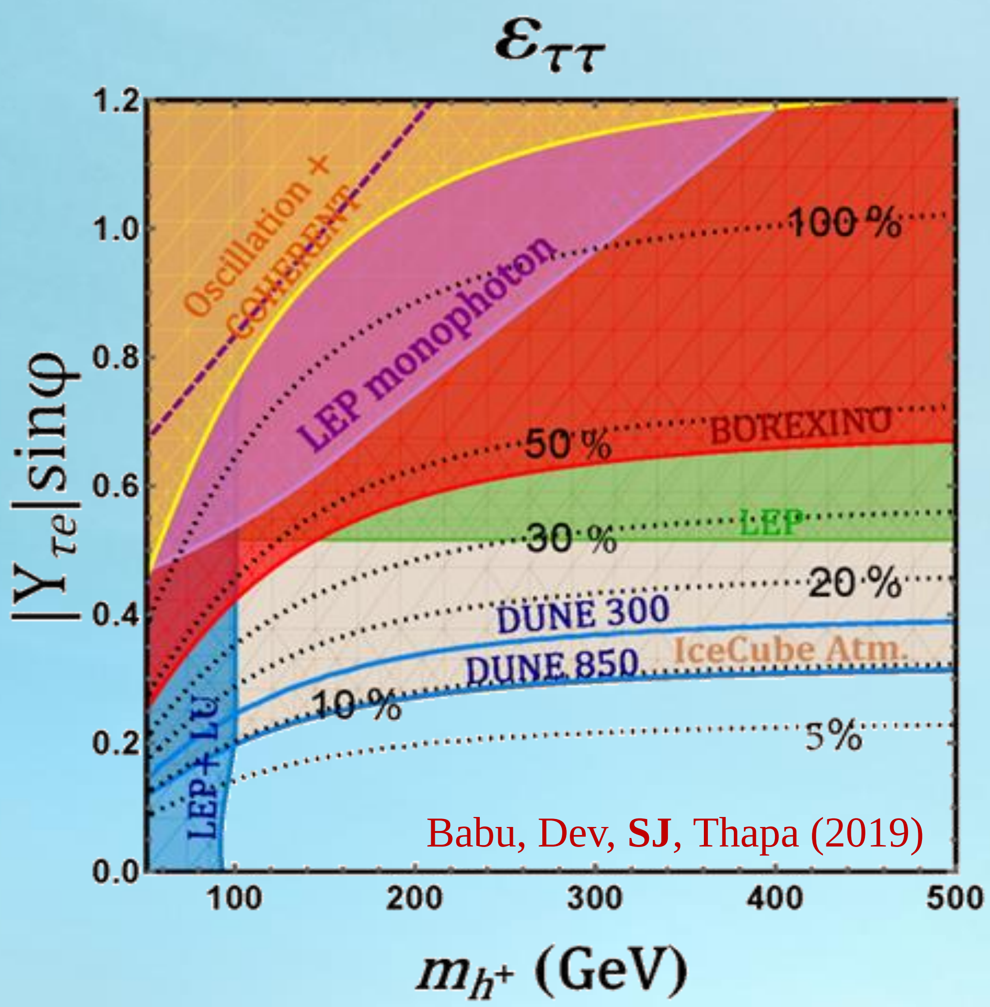
$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu Pf)$$

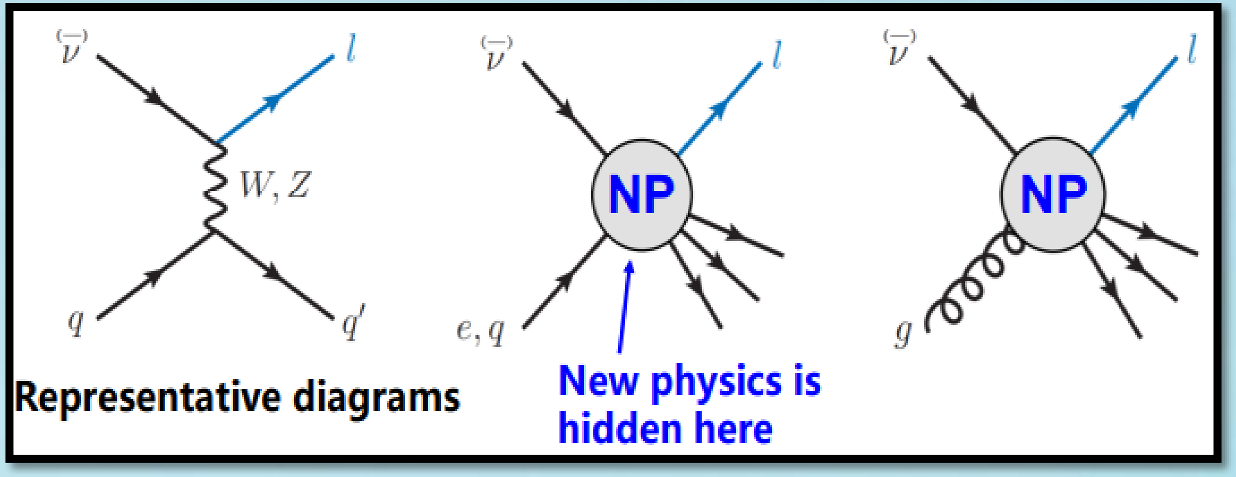
$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}\gamma_\mu Pf')$$

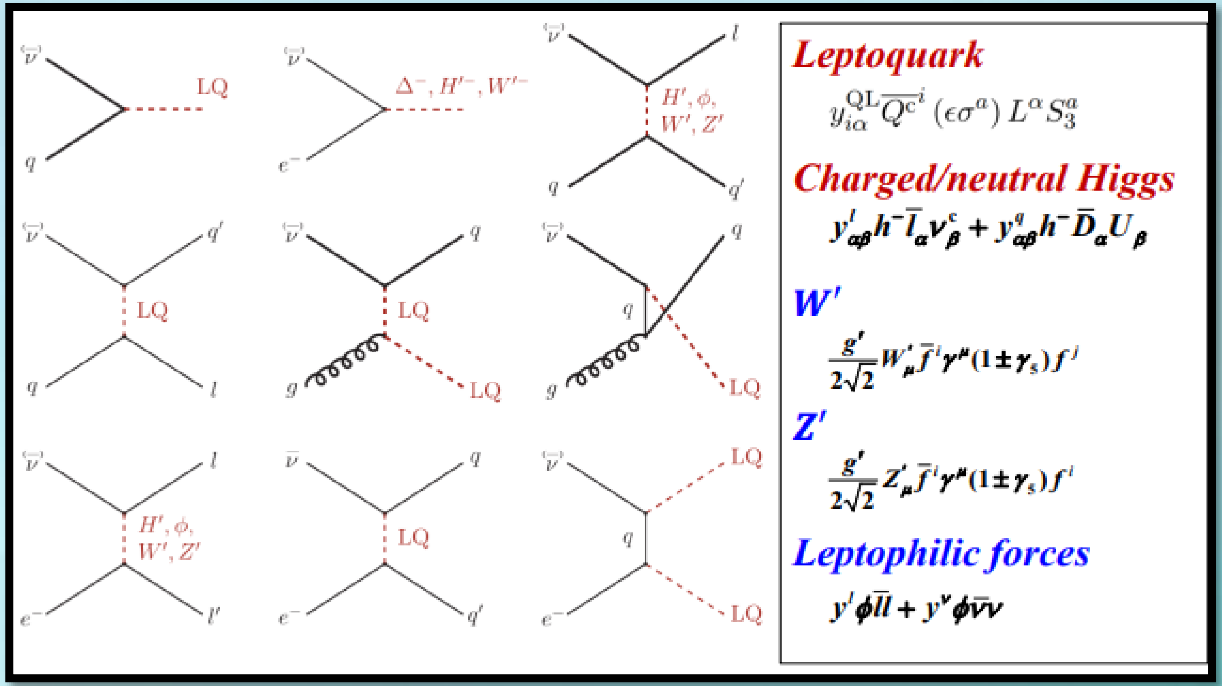
Wolfenstein (1978)

- *NSI: unknown couplings involving neutrinos.*
- *NSI effects: neutrino production, propagation through matter, and the detection processes.*
- *It can affect mass ordering and CP violation.*

Non-Standard Interactions of Neutrinos

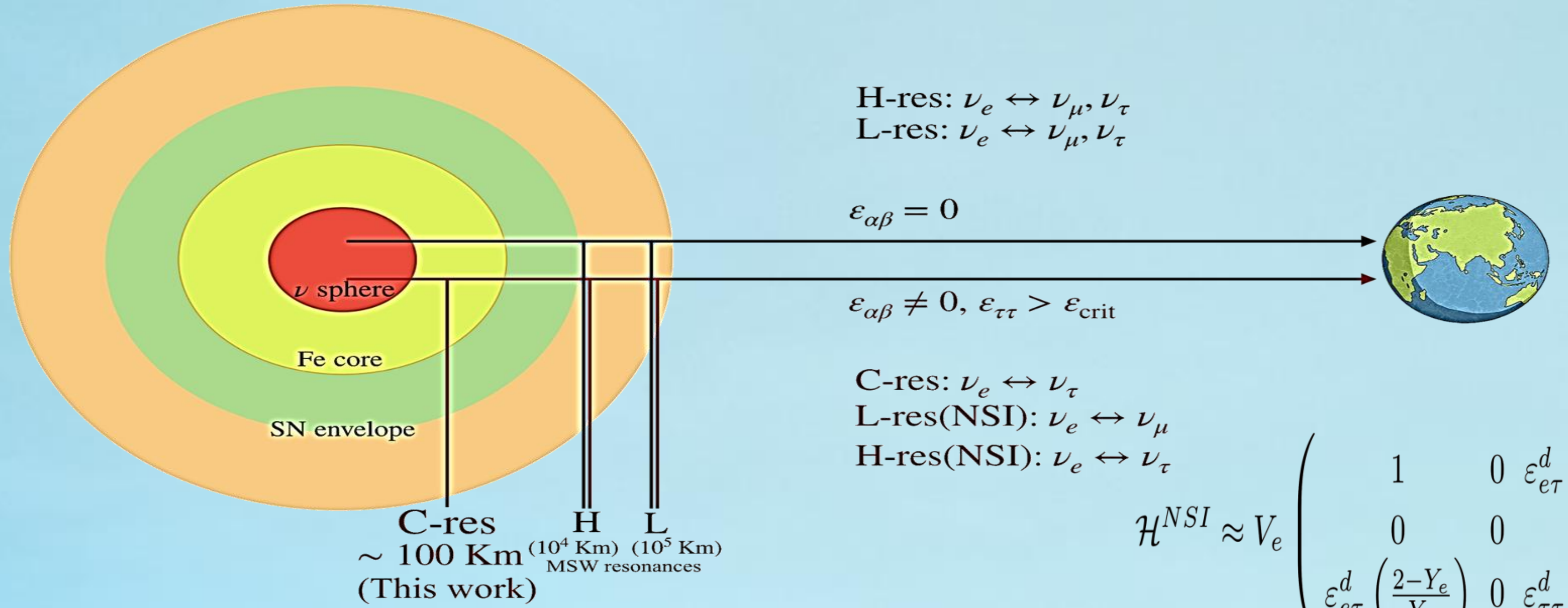




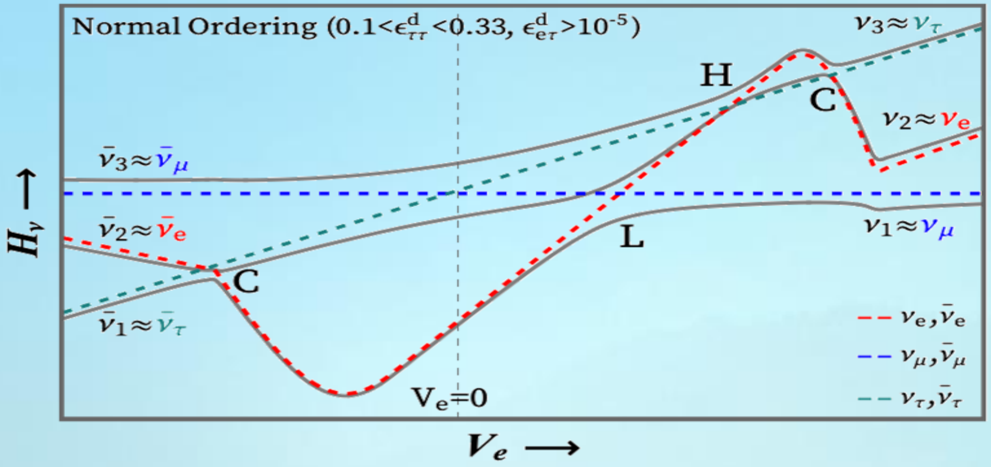


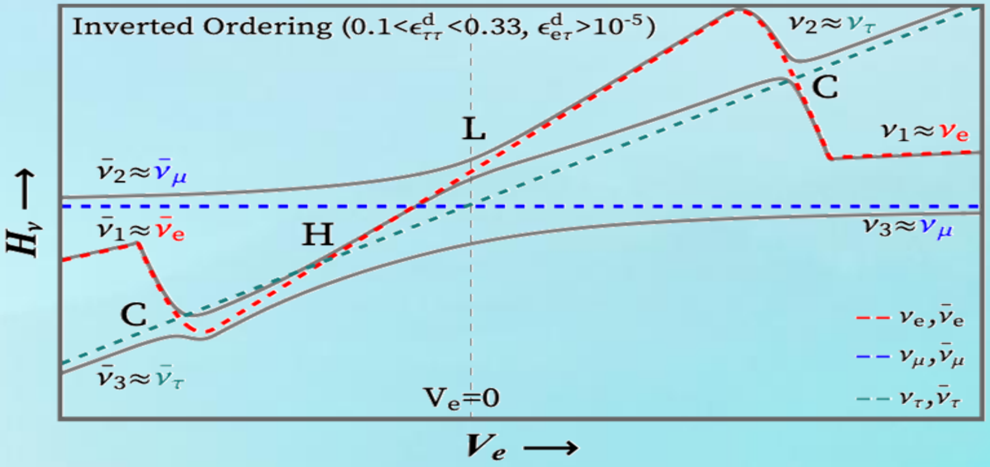
Projected ***DUNE*** *sensitivity:* ***14% (9.5%)*** *for* $\varepsilon_{\tau\tau}$
for an exposure of 300 kt·MW·yr (and 850 kt·MW·yr)

Simplified Picture of Flavor Conversions due to NSI

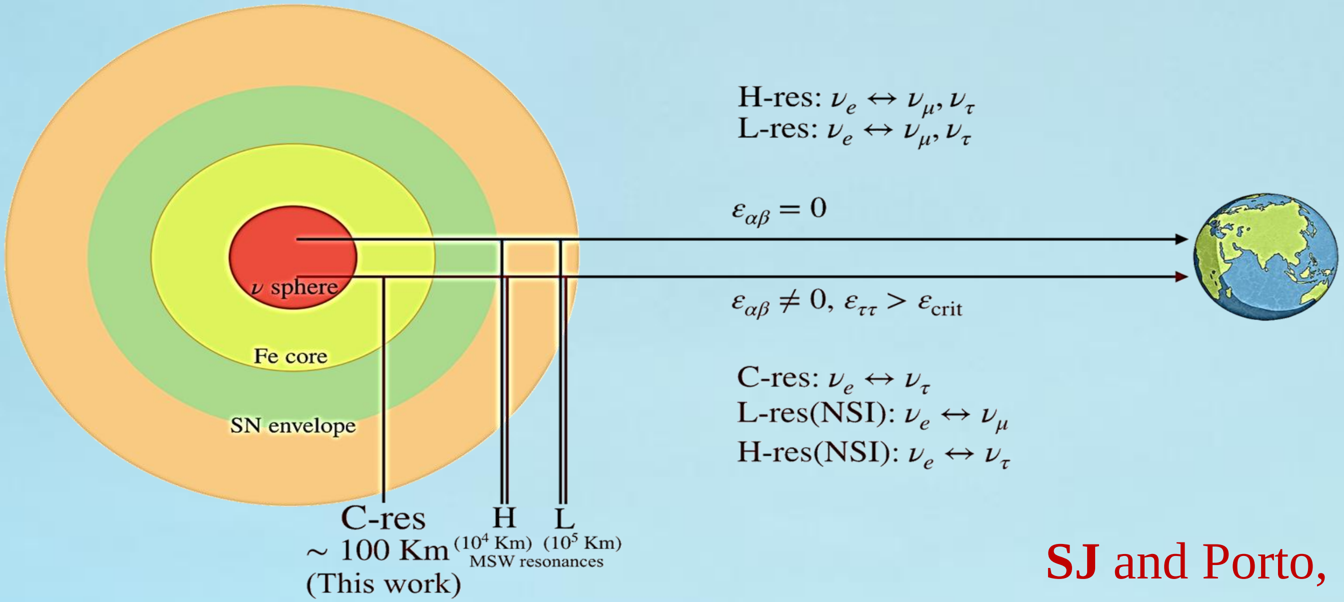


$$\mathcal{H}^{NSI} \approx V_e \begin{pmatrix} 1 & 0 & \varepsilon^d_{e\tau}\left(\frac{2-Y_e}{Y_e}\right) \\ 0 & 0 & 0 \\ \varepsilon^d_{e\tau}\left(\frac{2-Y_e}{Y_e}\right) & 0 & \varepsilon^d_{\tau\tau}\left(\frac{2-Y_e}{Y_e}\right) \end{pmatrix}$$

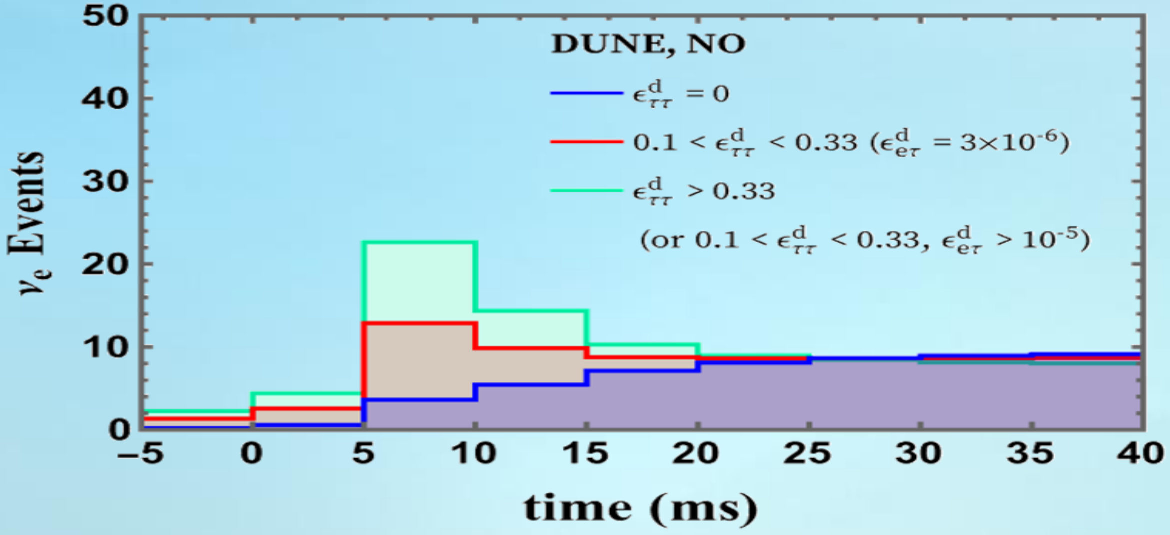


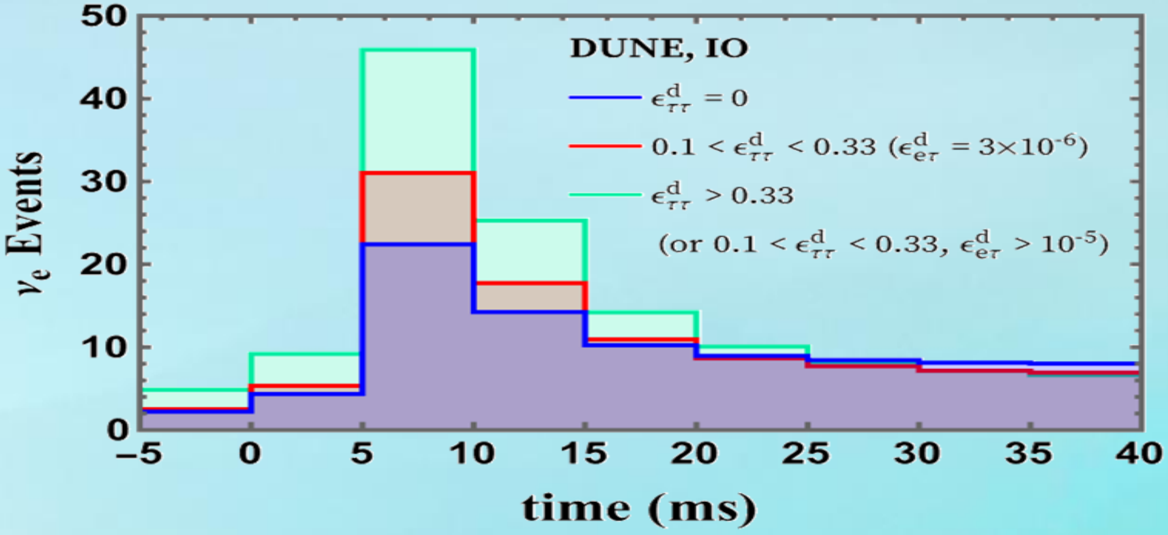


Non-Standard Interactions of Supernova Neutrinos and Mass Ordering Ambiguity at DUNE



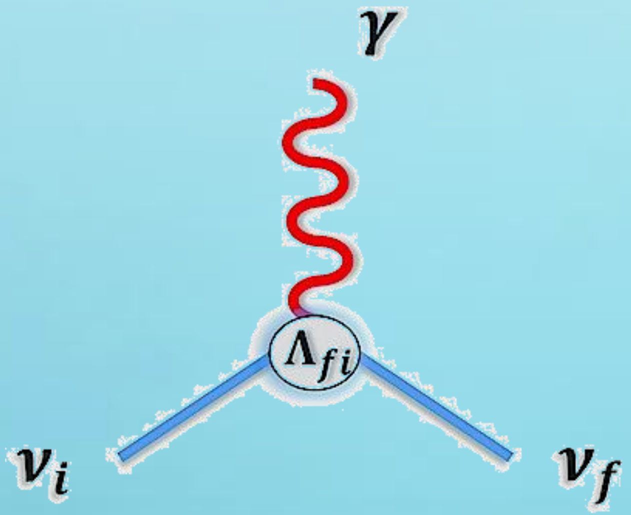
SJ and Porto, arXiv:2403:14762

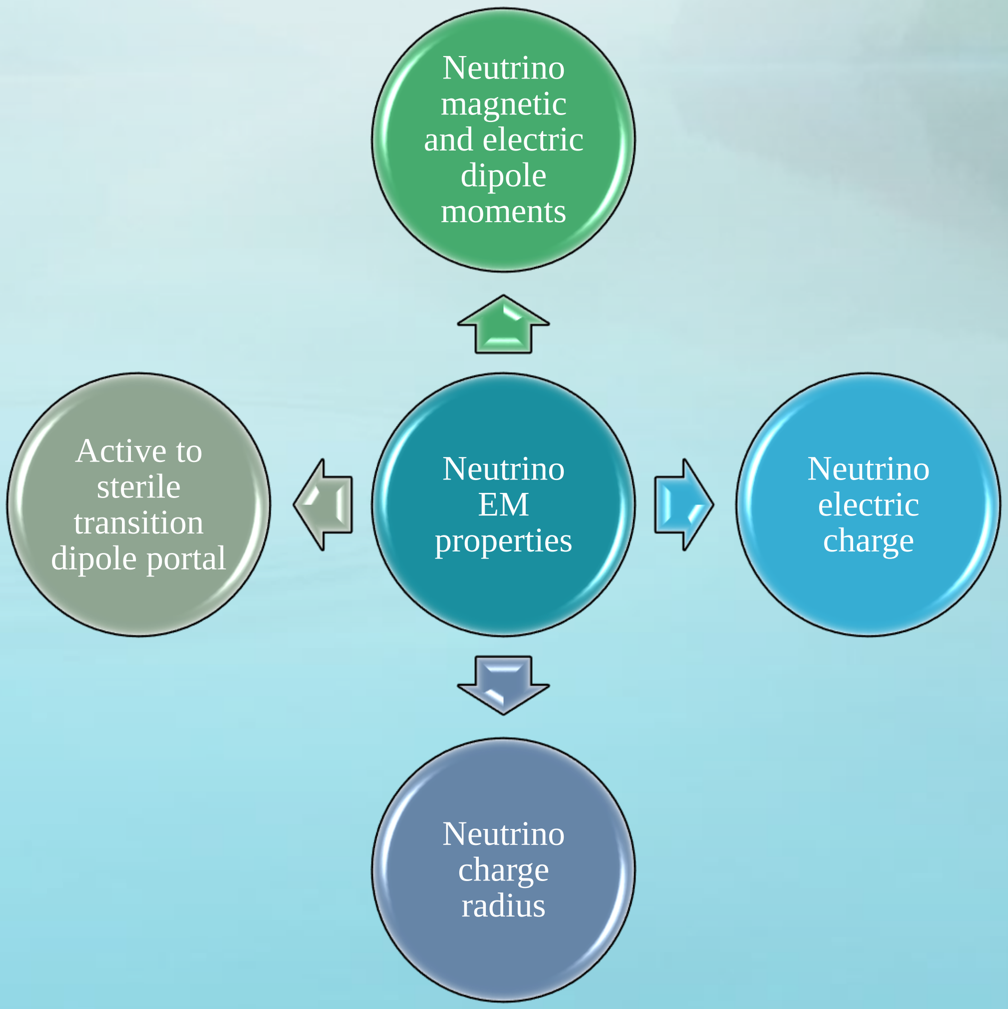




Electromagnetic Interactions of Neutrinos

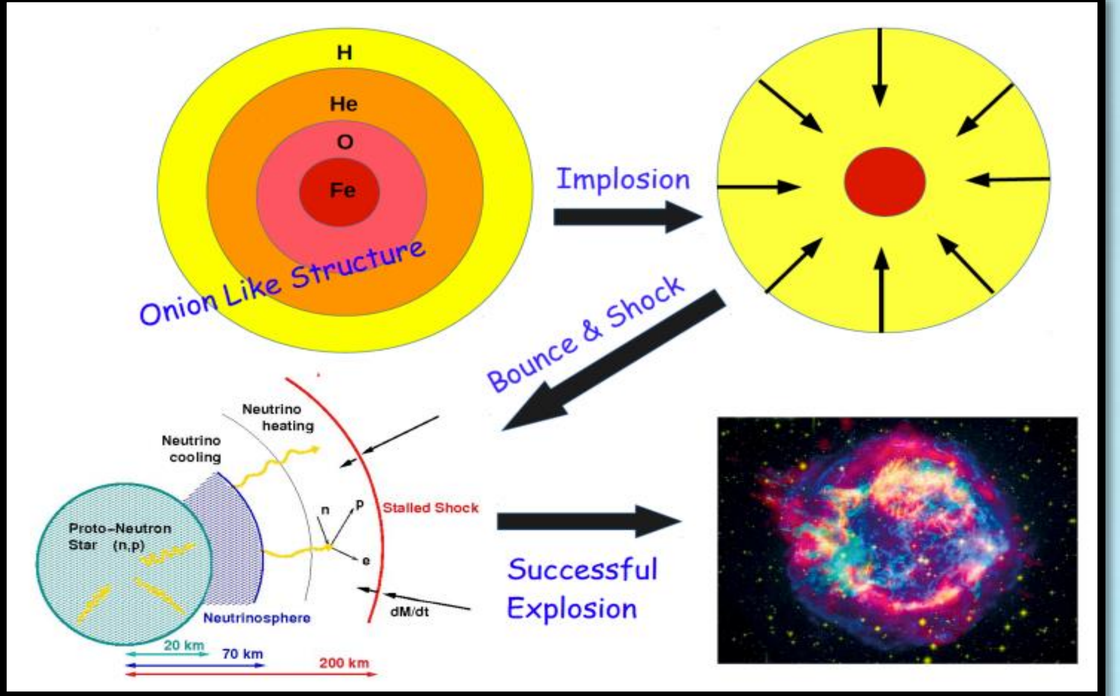
- *In the Standard Model, neutrinos do not have direct coupling to photons.*
- *Quantum loop corrections can induce electromagnetic properties of neutrino.*
- *Study of neutrino electromagnetic interactions may shed light on the underlying theory.*

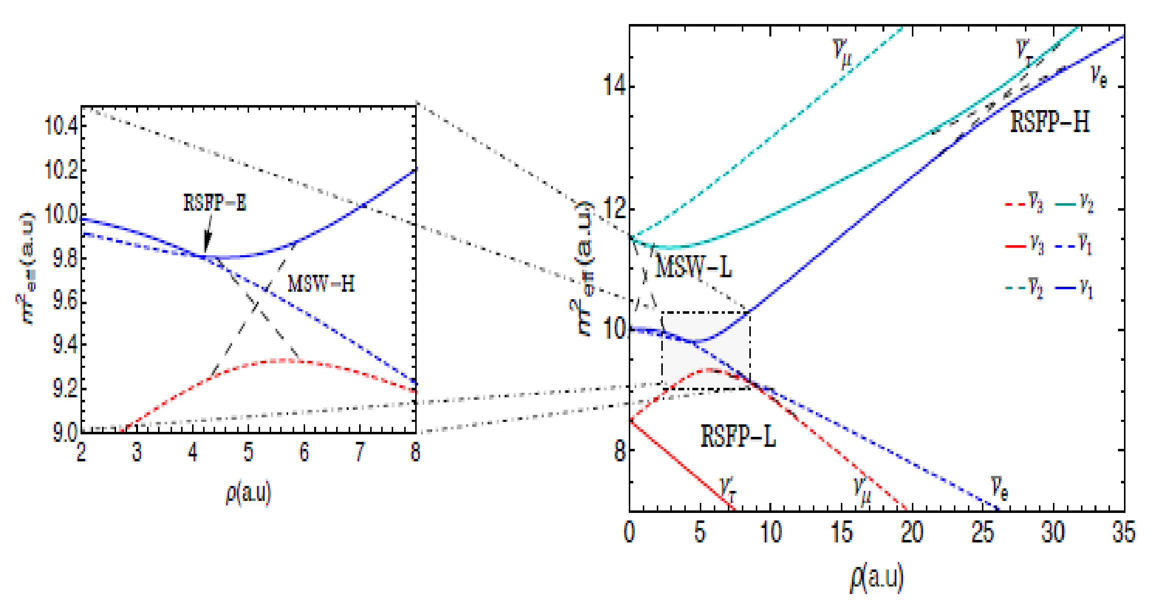




Exploiting a future galactic supernova to probe neutrino magnetic moments

Porto-Silva, **SJ**, Sen (2022)



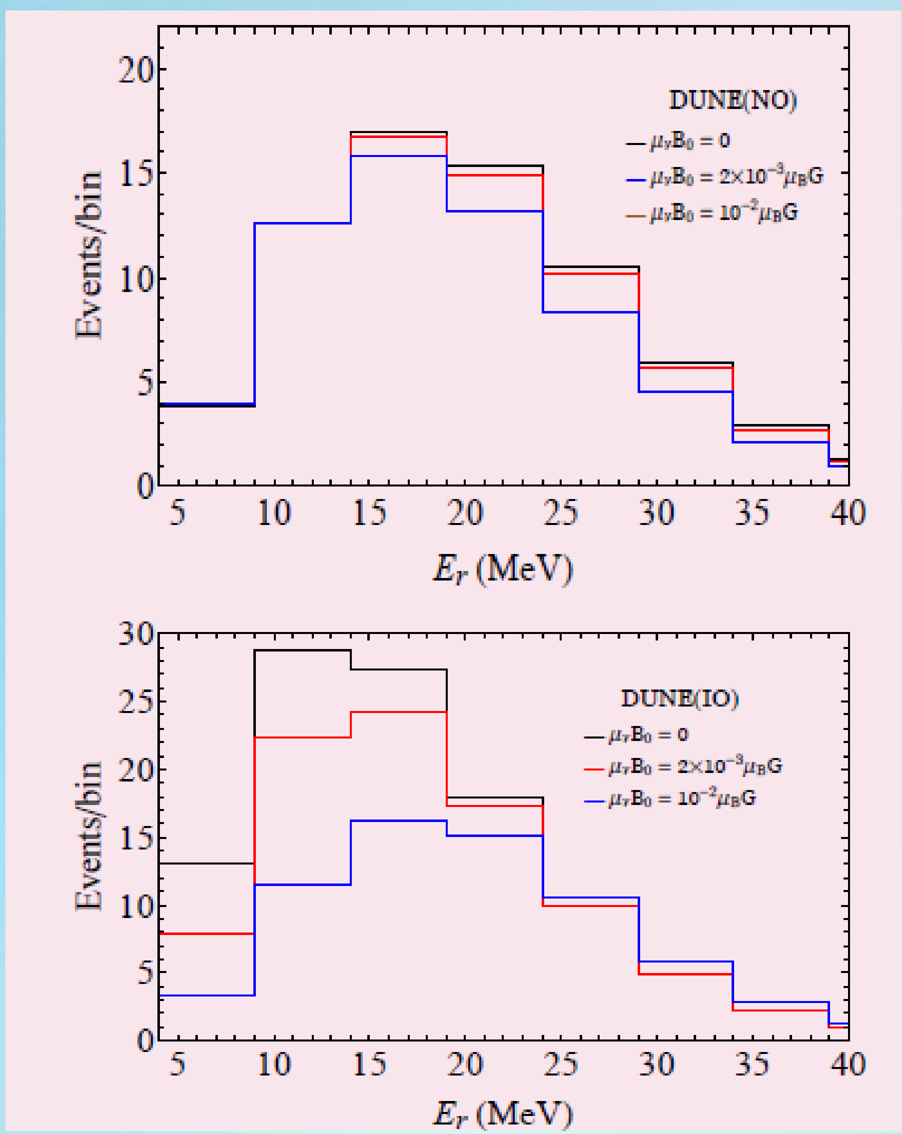


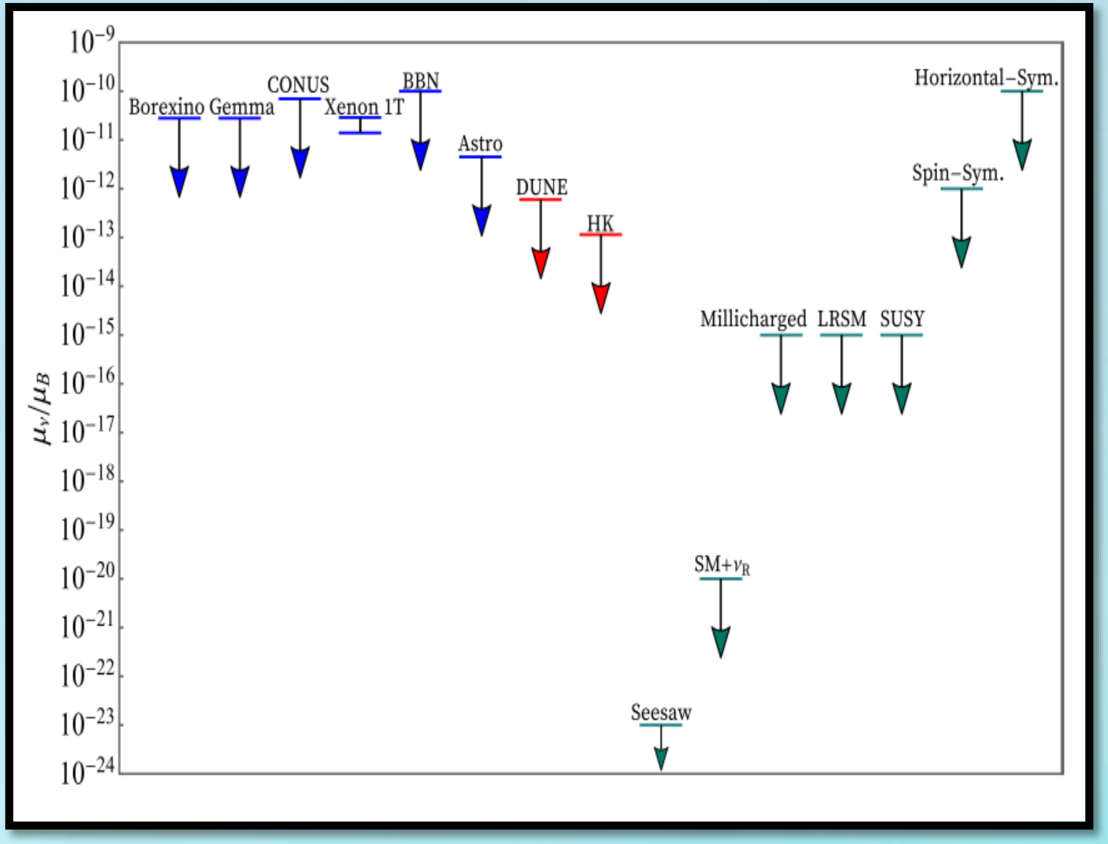
- Neutrino evolution equation: $$i\frac{d}{dr}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix} = \begin{pmatrix}H_\nu & B_\perp M\\ -B_\perp M & H_{\bar{\nu}}\end{pmatrix}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}$$
- Neutrino Hamiltonian in matter: $$H_\nu = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}V_{\nu_e} & 0 & 0\\ 0 & V_{\nu_\mu} & 0\\ 0 & 0 & V_{\nu_\tau}\end{pmatrix}$$

Akhmedov and T. Fukuyama (2003), Ando and Sato (2003)

Resonance Condition: $$\frac{\Delta m^2_{21}}{2E_\nu}\cos 2\theta_{12} + \bar{V}_\mu - V_e = 0$$

Neutrino magnetic moments at DUNE





Porto-Silva, **SJ**, Sen (JCAP 2022)

Dirac neutrino magnetic moments in Sne?

$$\boxed{i\frac{d}{dr}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix} = \begin{bmatrix}V_e & \mu_\nu B(r)\\ \mu_\nu B(r) & 0\end{bmatrix}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix}}$$

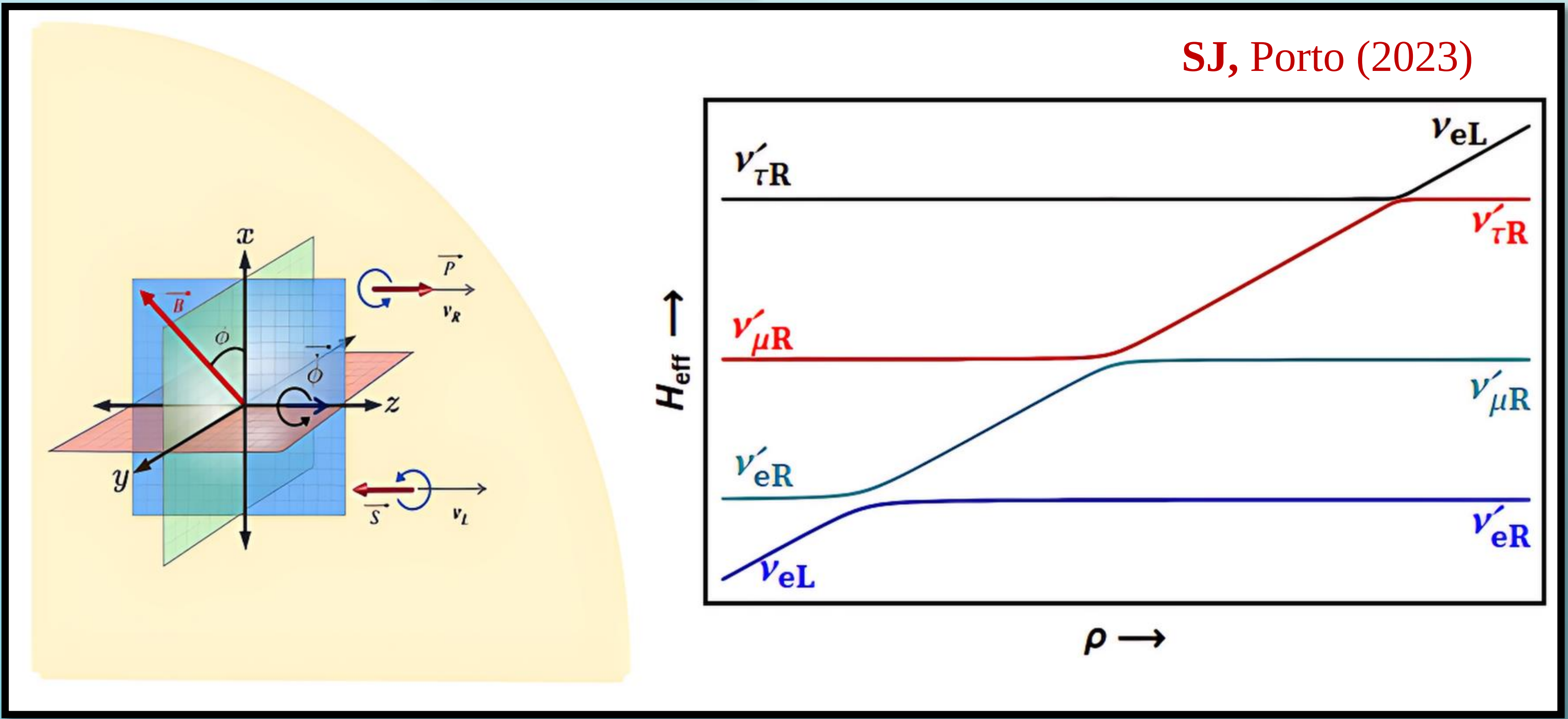
But $V_e \neq 0$ "Always"

SN neutrino flavor conversion was thought to be insensitive to Dirac Magnetic Moments.

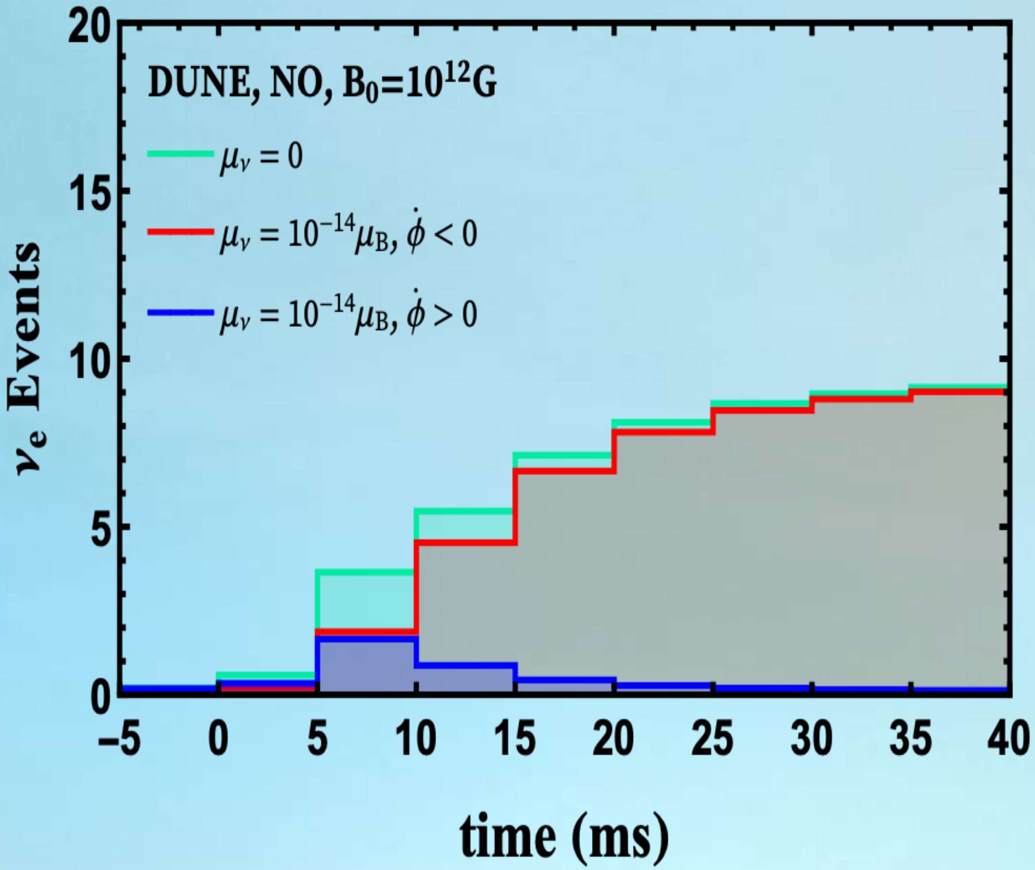
Dirac neutrino magnetic moments in Sne?

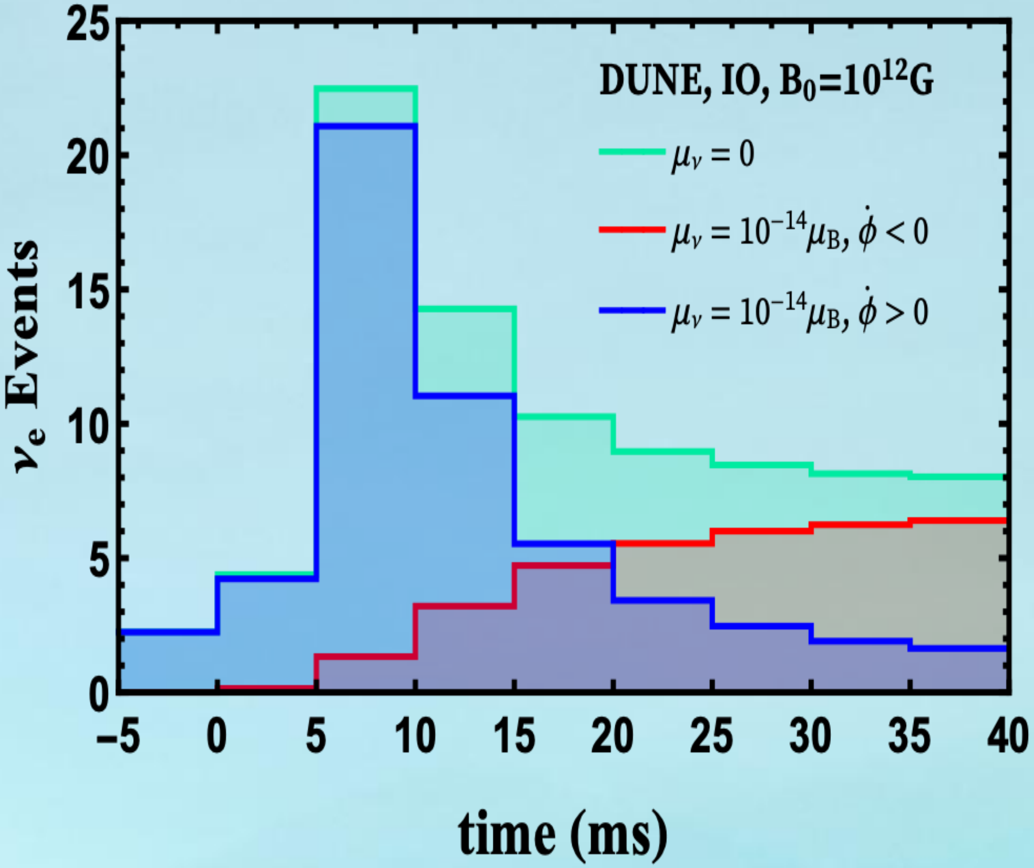
$$i\frac{d}{dr}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix} = \begin{bmatrix} V_e + \dot{\phi}/2 & \mu_\nu B(r) \\ \mu_\nu B(r) & -\dot{\phi}/2 \end{bmatrix}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix}$$

$$V_e + \dot{\phi} = 0$$ **(Resonance Condition)**

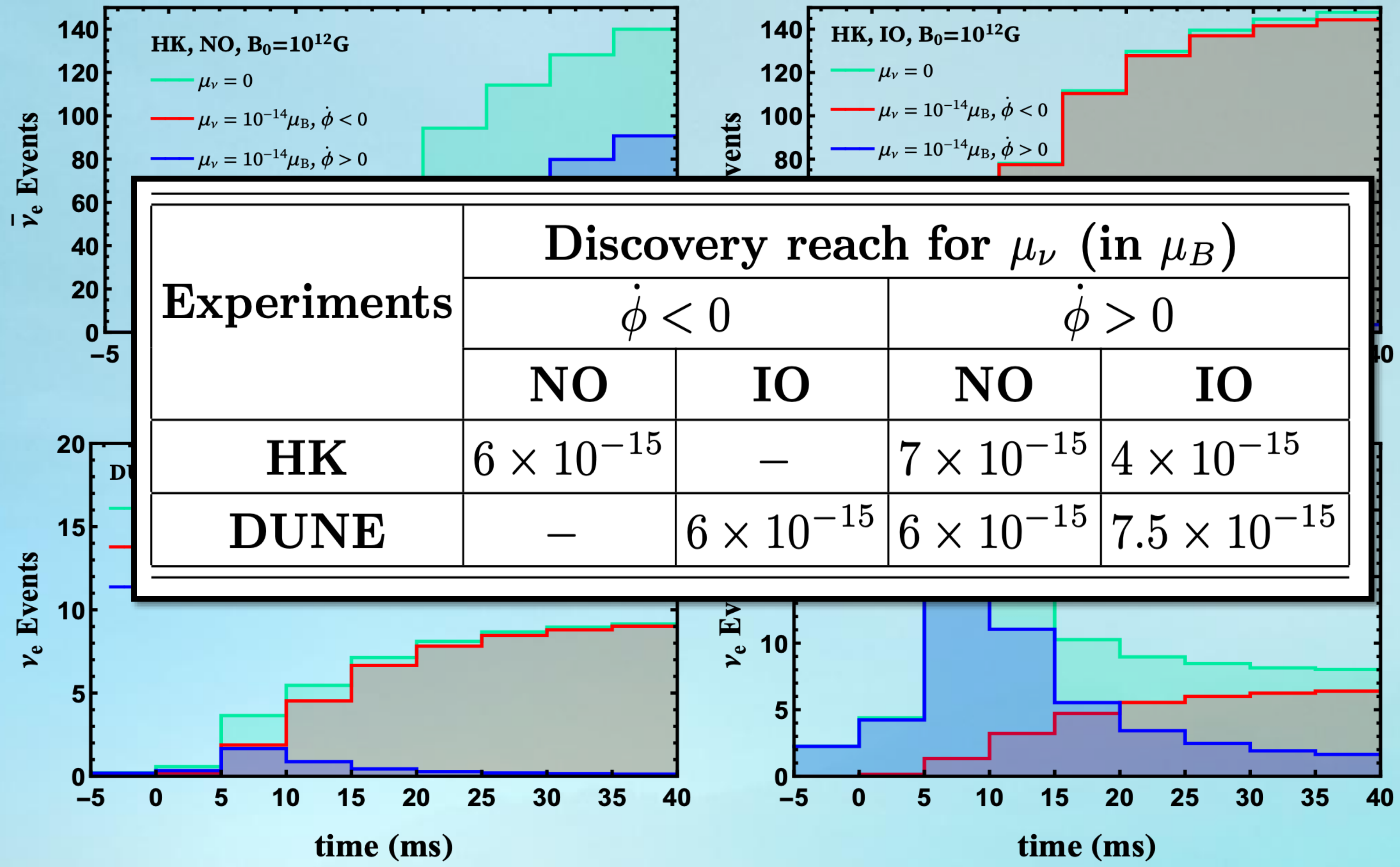


Neutrino spectra at DUNE



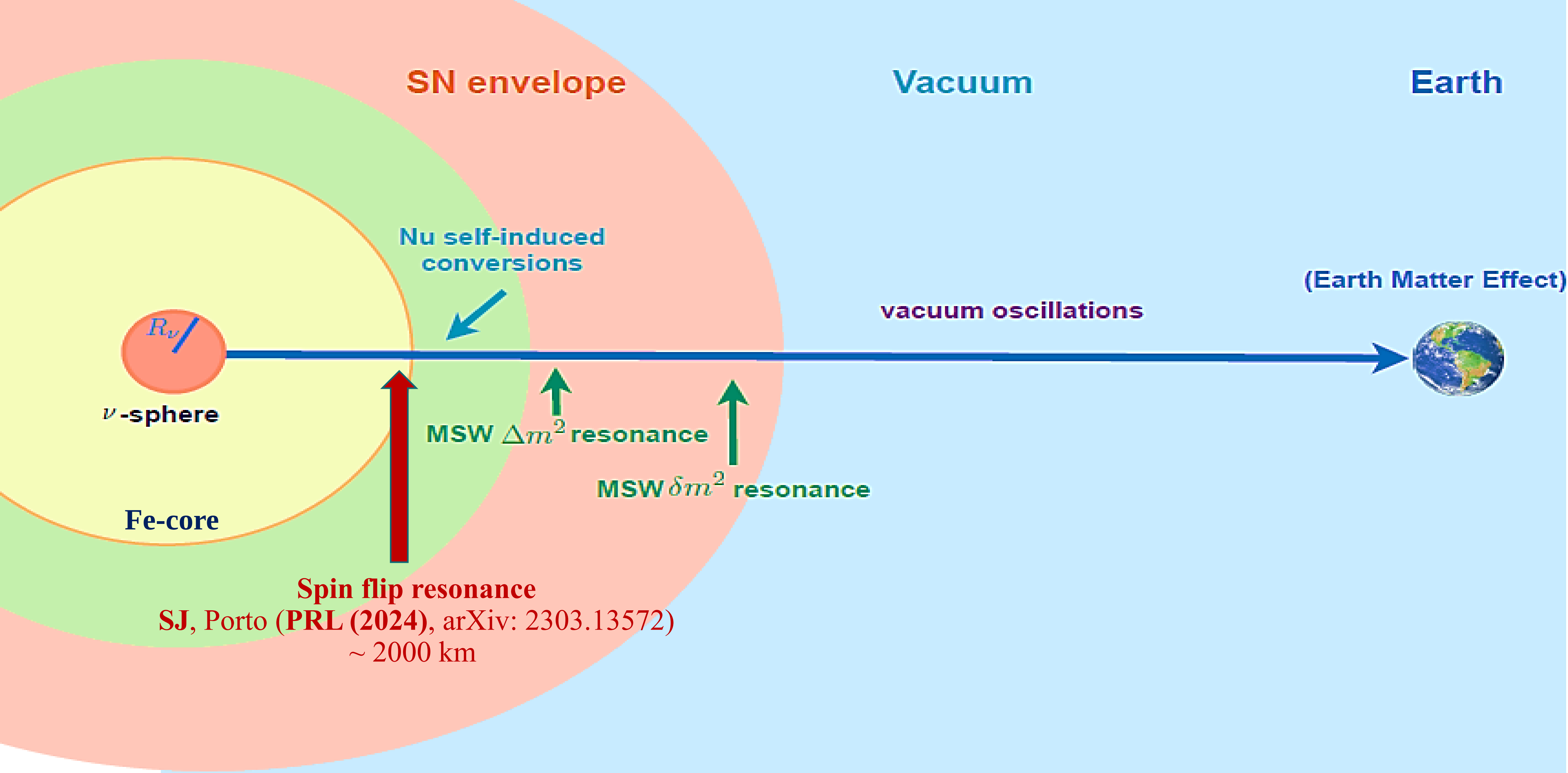


Neutrino spectra at DUNE and HK



Experiments	Discovery reach for μ_ν (in μ_B)			
	$\dot{\phi} < 0$		$\dot{\phi} > 0$	
	NO	IO	NO	IO
HK	6×10^{-15}	–	7×10^{-15}	4×10^{-15}
DUNE	–	6×10^{-15}	6×10^{-15}	7.5×10^{-15}

Simplified Picture of Flavor Conversions



Future Directions at DUNE

Near Detector Searches

Take advantage of high beam power

- Axion-like Particles (ALP)
- Low mass Dark Matter (LDM)
- Heavy Neutral Leptons (HNL)
- Dark Photon
- Neutrino Trident
- Milli-charge Particles (mCP)
- And many many more…

Far Detector Searches

Take advantage of ND, large VA FD & long baseline

- Sterile neutrino searches
- Non-standard Interactions, Non-Unitarity, CPT violation
- Large Extra Dimensions (LED)
- Boosted Dark Matter (BDM) & Inelastic Boosted Dark Matter (iBDM)
- And many many more…

BSM Process	Selected signatures	Background
ALP	Scattering: γ+e, γ+N (n) Decay in flight : $\gamma\gamma$	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
LDM	$\chi e^- \rightarrow \chi e^-$, $\chi N \rightarrow \chi' N \rightarrow \chi e^- e^- N$, $\chi N \rightarrow \chi' N \rightarrow \chi\gamma N$,	NC w/ π^0, ν_e CC, QE, RES
mCP	Multiple e$^-$ scatterings	ν_e CC w/ π^0
Dark Photon	$A \rightarrow e^- e^+$, $\mu^- \mu^+$, many more	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \rightarrow \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu\gamma$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \rightarrow \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$	$\nu_\mu N \rightarrow \nu_\mu \pi N'$ (ν CC)
BDM/ iBDM	$\chi N \rightarrow e^+ e^- e^- N$, $\chi N \rightarrow e^- N$, $\chi N \rightarrow nN$	ν coherent, NC w/ π^0, ν_e CC
Many more	Many many more	

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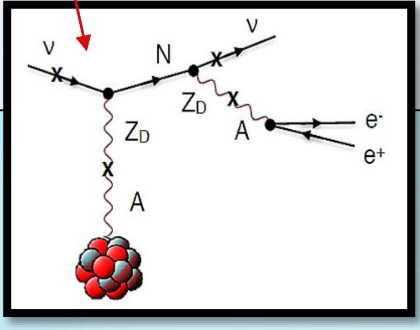

Bertuzzo, **SJ**, Machado, Z. Funchal (PRL’ 2018)

BSM Process	Selected signatures	Background
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mCP	Multiple e$^-$ scatterings	ν_e CC w/ π^0
Dark Photon	$A \to e^- e^+$, $\mu^- \mu^+$, many more	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu\gamma$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$	$\nu_\mu N \to \nu_\mu \pi N'$ (ν CC)
BDM/ iBDM	$\chi N \to e^+ e^- e N$, $\chi N \to e^- N$, $\chi N \to nN$	ν coherent, NC w/ π^0, ν_e CC
Many more	Many many more	

Take Home Messages…

- ***DUNE is a powerful, multi-purpose ν experiment for exploring rich new physics.***
- ***DUNE compliments the Energy Frontier experiments on BSM physics.***
- ***Key open questions in neutrino physics demand new physics — DUNE can help answer them.***


Thank you!