Electromagnetic Properties of Neutrinos

Sudip Jana

Harish-Chandra Research Institute

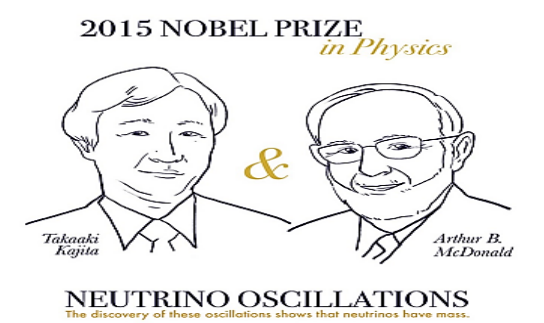
Vikram Discussion on Neutrino Astrophysics
PRL, Ahmedabad, India
March 21, 2025

Current knowledge of neutrino oscillations

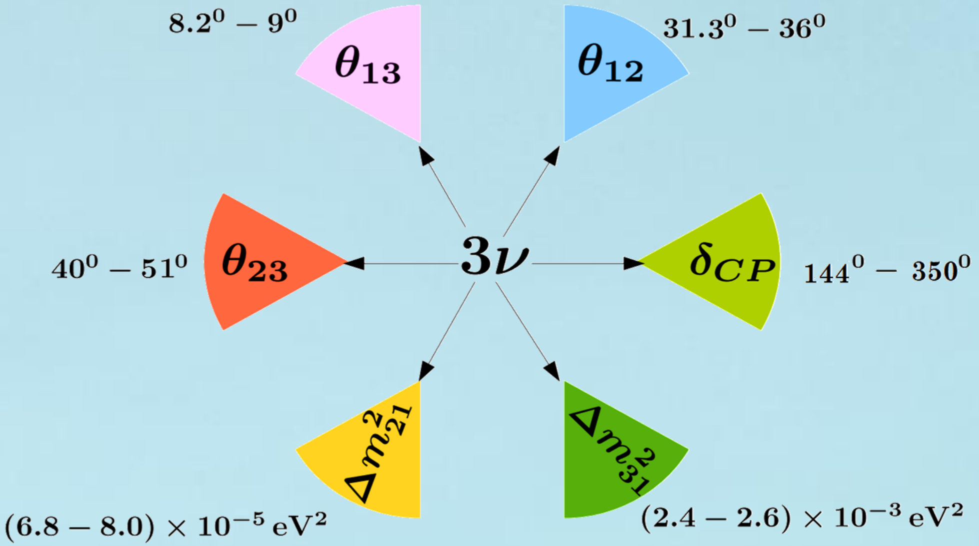
1. Neutrinos in the Standard Model are ***massless.***

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad\qquad m_\nu = 0$$

2. Neutrino flavor ***oscillations*** have been firmly established and it can happen only if neutrinos have ***non-zero masses.***



3. All three ***mixing angles*** and two ***mass splitting*** have been measured with few percent precision.



Sign is unknown

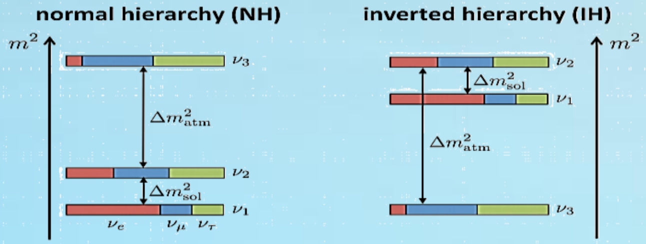
Esteban et al. (2020)
NuFIT 5.1 (2021)

PMNS matrix

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{Flavor eigenstate}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric term}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor term}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \cos\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar term}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{Mass eigenstate}}$$

Neutrino electromagnetic properties & Pressing Questions for Neutrinos

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

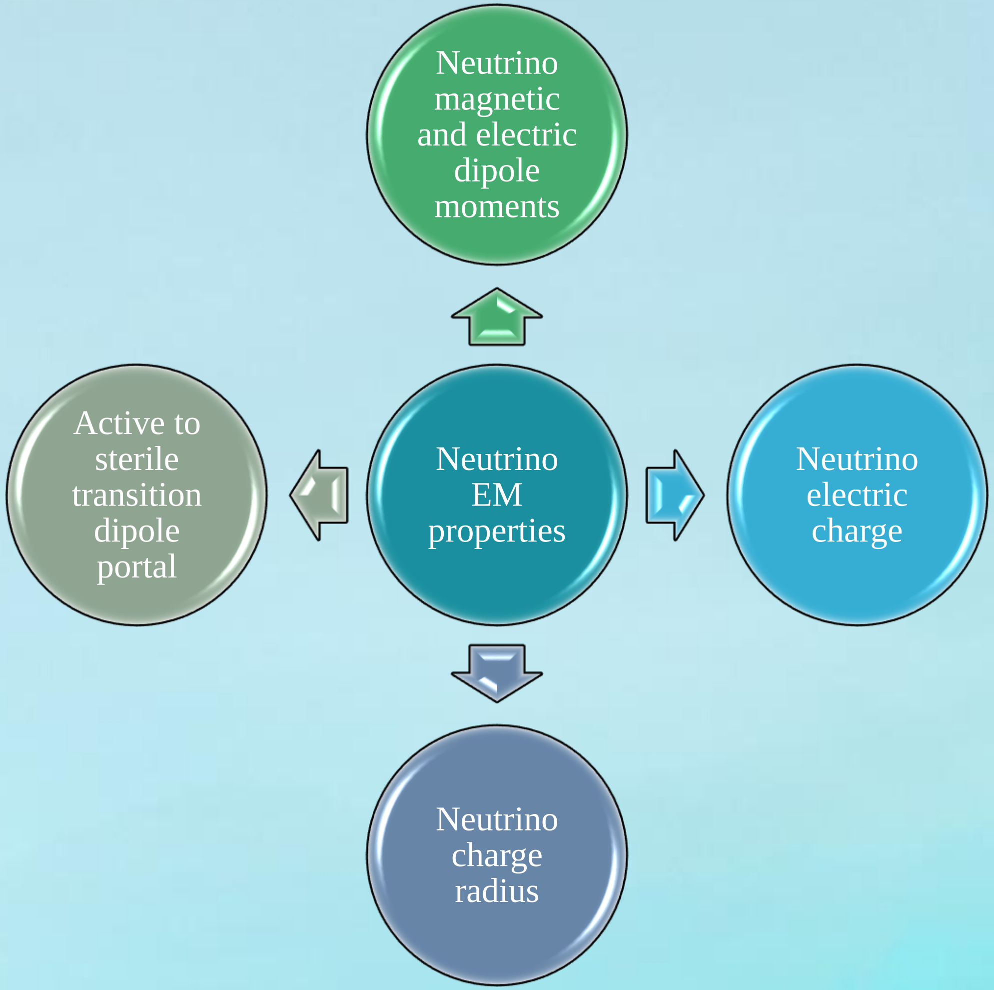


4. ***Correlation between the magnetic moments of charged leptons and neutrinos?***

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$$

5. ***Addressing anomalies***

…..



Neutrino magnetic and electric dipole moments

Active to sterile transition dipole portal

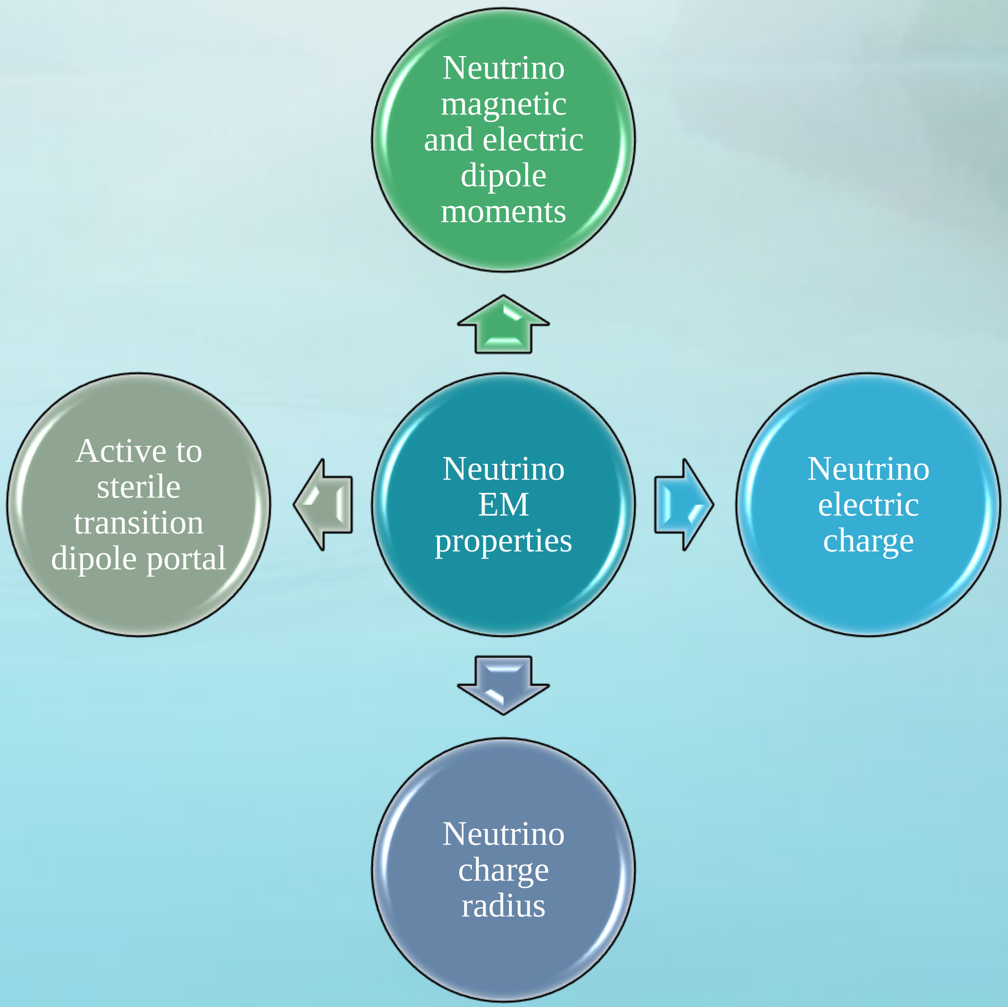
Neutrino EM properties

Neutrino electric charge

Neutrino charge radius

Neutrino electromagnetic properties

- *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.*
- *Anomalous electromagnetic properties of charged leptons and neutrinos can be correlated.*



Neutrino EM properties

Neutrino magnetic and electric dipole moments

Neutrino electric charge

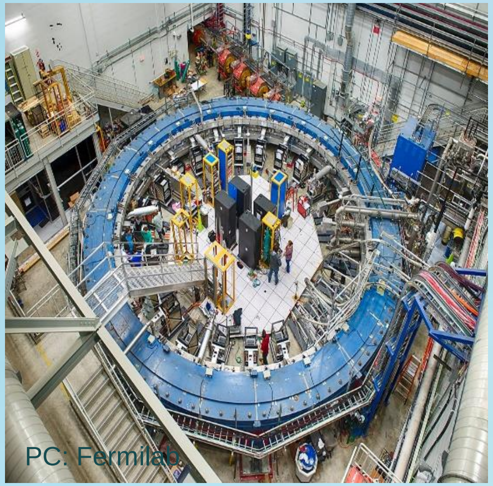
Neutrino charge radius

Active to sterile transition dipole portal

Talk is based on:

1. Babu, **SJ**, Lindner, (JHEP 2020)
2. Babu, **SJ**, Lindner, Vishnu, (JHEP 2021)
3. Ismail, **SJ**, Roshan, (PRD 2021)
4. **SJ**, Porto-Silva, Sen, (JCAP 2022)
5. Huang, **SJ**, Lindner, Rodejohann, (JCAP 2022)
6. **SJ**, Porto (PRL 2024)

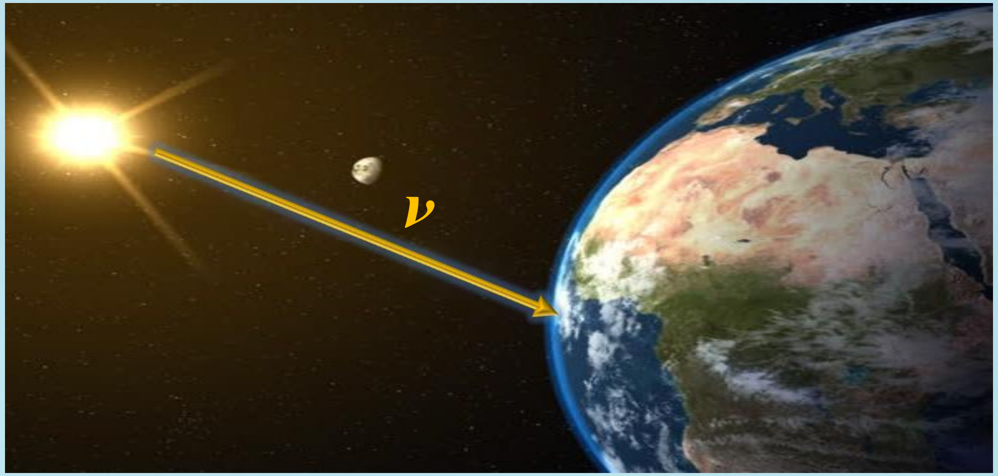
Charged lepton magnetic moments

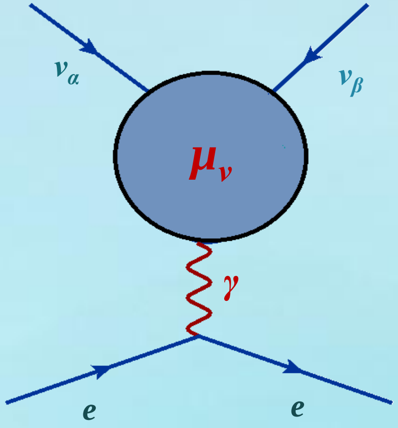


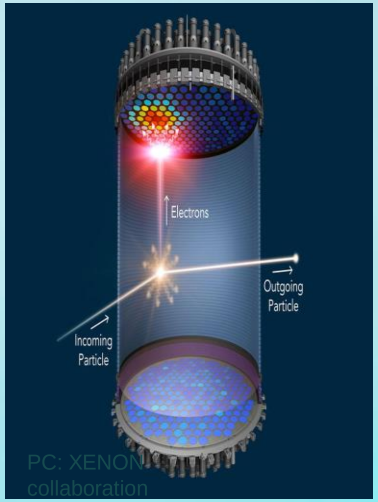
PC: Fermilab

How much do they rotate
on their axes in a powerful magnetic field
as they race around the magnet?

Neutrino magnetic moments

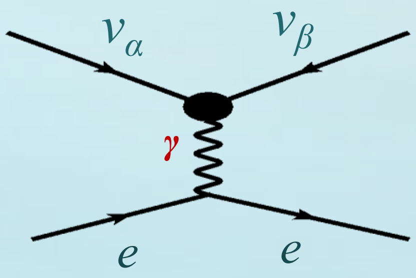






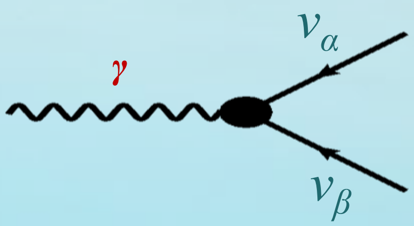
PC: XENON collaboration

Consequences of neutrino magnetic moments



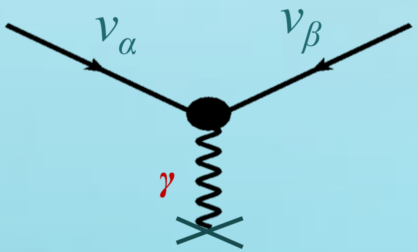
Scattering

$$\left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{tot} = \left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{SM} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{eff}}{\mu_B}\right)^2$$



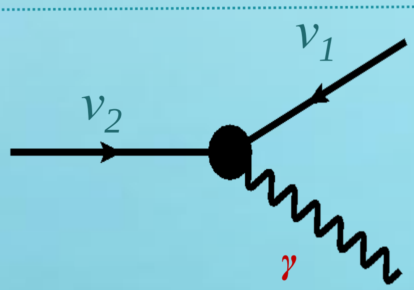
Plasmon decays in stars

$$\Gamma = \frac{\mu_\nu^2}{24\pi}\,\omega_{\mathrm{pl}}^3$$



Spin precision in external B field

$$i\frac{d}{dr}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix} = \begin{pmatrix}0 & B_\perp M\\ -B_\perp M & 0\end{pmatrix}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}$$



Decay or Cherenkov effect

$$\Gamma = \frac{\mu_\nu^2}{8\pi}\left(\frac{m_2^2 - m_1^2}{m_2}\right)^3$$

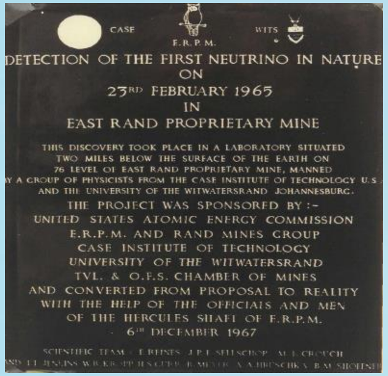
Neutrino magnetic moments: experimental status

- The quest for measuring neutrino magnetic moments was begun <u>even before the discovery of the neutrino</u>.

Frederick Reines

1995 Nobel Prize in Physics

for his co-detection of the neutrino with Clyde Cowan in the neutrino experiment.



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THE PROJECT WAS SPONSORED BY :-
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E.R.P.M. AND RAND MINES GROUP
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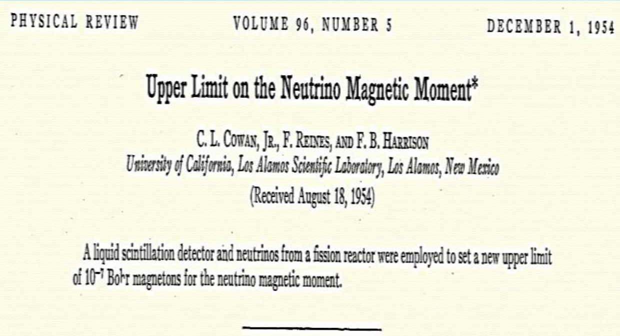

PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

Upper Limit on the Neutrino Magnetic Moment*

C. L. COWAN, JR., F. REINES, AND F. B. HARRISON
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received August 18, 1954)

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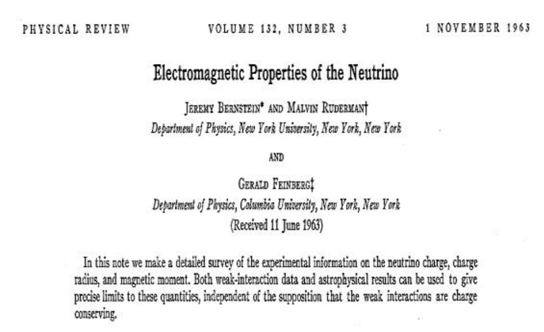

PHYSICAL REVIEW VOLUME 132, NUMBER 3 1 NOVEMBER 1963

Electromagnetic Properties of the Neutrino

JEREMY BERNSTEIN* AND MALVIN RUDERMAN†
Department of Physics, New York University, New York, New York

AND

GERALD FEINBERG‡
Department of Physics, Columbia University, New York, New York
(Received 11 June 1963)

In this note we make a detailed survey of the experimental information on the neutrino charge, charge radius, and magnetic moment. Both weak-interaction data and astrophysical results can be used to give precise limits to these quantities, independent of the supposition that the weak interactions are charge conserving.

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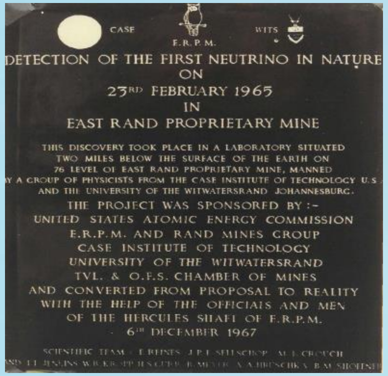

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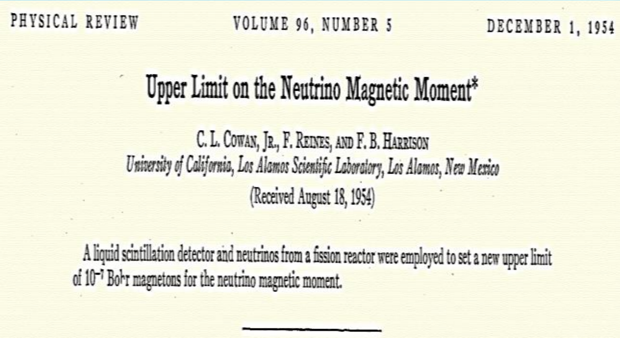

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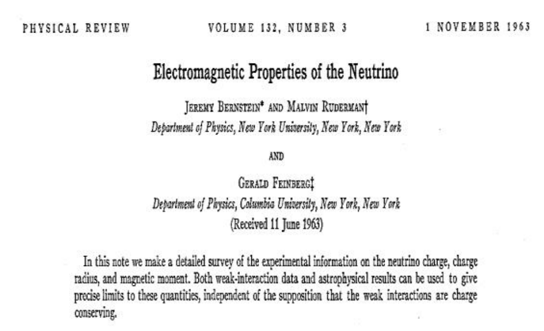

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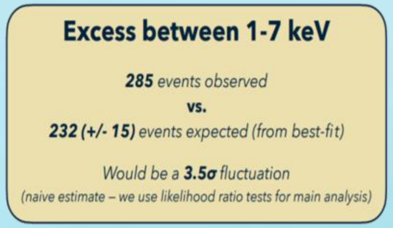
Reactor	KRASNOYARSK (1992):	$\mu_\nu < 2.7 \times 10^{-10}\,\mu_B$
	ROVNO (1993):	$\mu_\nu < 1.9 \times 10^{-10}\,\mu_B$
	MUNU (2005):	$\mu_\nu < 1.2 \times 10^{-10}\,\mu_B$
	TEXONO (2010):	$\mu_\nu < 2.0 \times 10^{-10}\,\mu_B$
	GEMMA (2012):	$\mu_\nu < 2.9 \times 10^{-11}\,\mu_B$
	CONUS (2022):	$\mu_\nu < 7.0 \times 10^{-11}\,\mu_B$
Accelerator	LAPMF (1993):	$\mu_\nu < 7.4 \times 10^{-10}\,\mu_B$
	LSND (2002):	$\mu_\nu < 6.4 \times 10^{-10}\,\mu_B$
Solar	Borexino (2017):	$\mu_\nu < 2.8 \times 10^{-11}\,\mu_B$
	XENONnT (2022):	$\boldsymbol{\mu_\nu < 6.4 \times 10^{-12}\,\mu_B}$

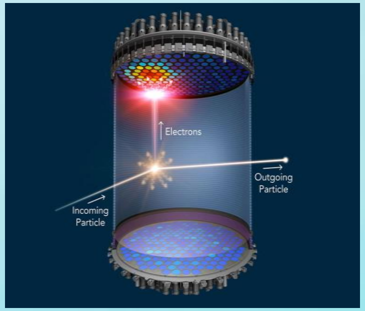


Excess between 1-7 keV

285 events observed
vs.
232 (+/- 15) events expected (from best-fit)

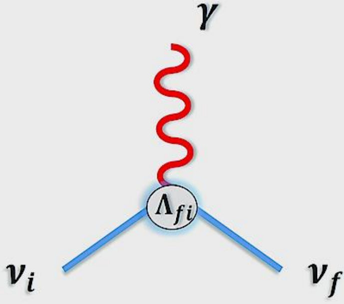
Would be a **3.5σ** fluctuation
(naive estimate – we use likelihood ratio tests for main analysis)

E. Aprile et al. (2020)



XENON Collaboration,

Neutrino Magnetic Moments: from astrophysics and cosmology

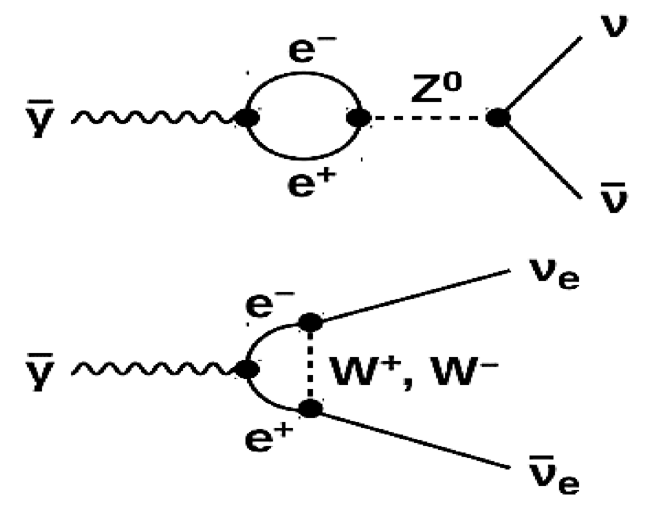


***Photons in the plasma** of stellar environments **can decay** either into $\nu\bar{\nu}$ for the case of Dirac neutrinos or into $\nu_\alpha\nu_\beta$ for the case of Majorana neutrinos.*

*If such decays occur too rapidly, that would **drain energy of the star**, in conflict with standard stellar evolution models.*

*The best limit on μ_ν arises from red giant branch of globular clusters: **$\mu_\nu < 1.5 \times 10^{-12}\ \mu_B$** **Raffelt et al.(2013, 2021), Barbieri and Mohapatra (1988) from SN1987A signal***

*Cosmological limits arising from big bang nucleosynthesis are less severe, of order **$10^{-10}\ \mu_B$**. **Fuller et al. (2015)***



esy: NASA

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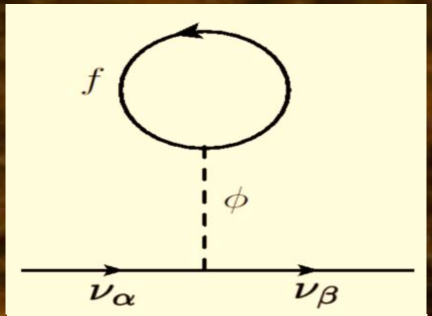
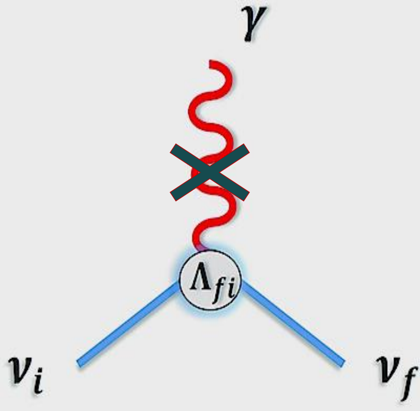
Neutrino Trapping Mechanism

- *Constraints from astrophysics may be evaded if the **plasmon decay to neutrinos is kinematically forbidden**.*



$$\mathcal{L} \supset -\frac{y_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\phi\nu_\beta - y_f\bar{f}\phi f - \frac{m_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\nu_\beta - \frac{m^2_\phi}{2}\phi^2$$



Babu, **SJ**, Lindner (2020)

- ***Medium-dependent mass of the neutrino** in the presence of a light scalar that also couples to ordinary matter in illustrating the mechanism.*

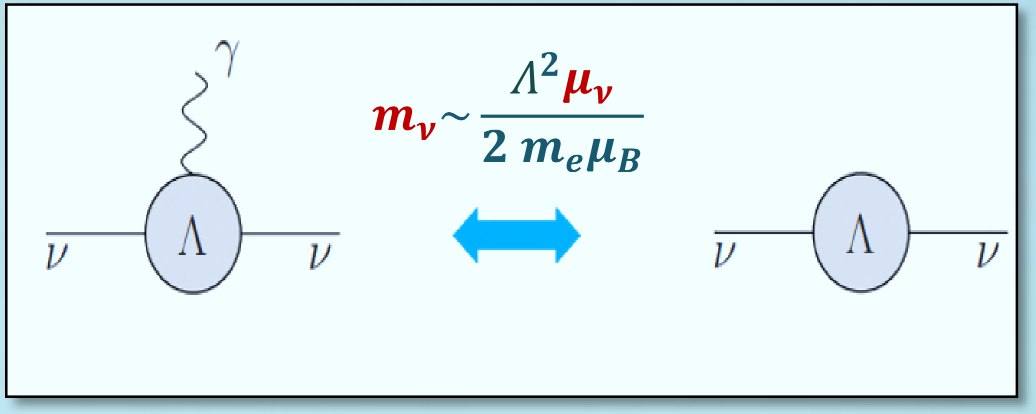
- *For phenomenological implications, see* Parke et al. (2018), Smirnov et al.(2019), Babu et al. (2019)

urtesy: NASA

Neutrino magnetic moment – mass conundrum

- The magnetic moment and the mass operators are both ***chirality flipping***.
- By ***removing the photon line*** from the loop diagram that induces $\boldsymbol{\mu_\nu}$ one would generate a ***neutrino mass*** term.
- In ***absence of additional symmetries*** (and ***without severe fine-tuning***), neutrino masses are several orders of magnitude larger than their measured values, if $\boldsymbol{\mu_\nu \sim 10^{-11} \mu_B}$.

$$m_\nu \sim \frac{\Lambda^2 \mu_\nu}{2\, m_e \mu_B} \sim \mathbf{0.1\ MeV} \text{ for } \Lambda \sim 100\ \text{GeV and } \mu_\nu \sim 10^{-11}\ \mu_B$$



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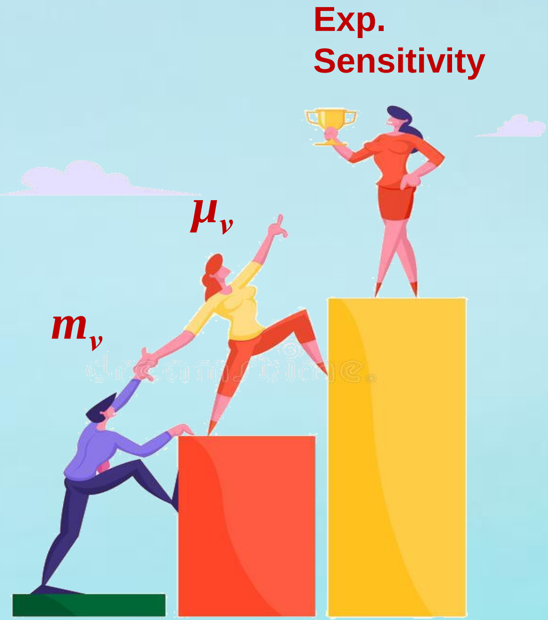


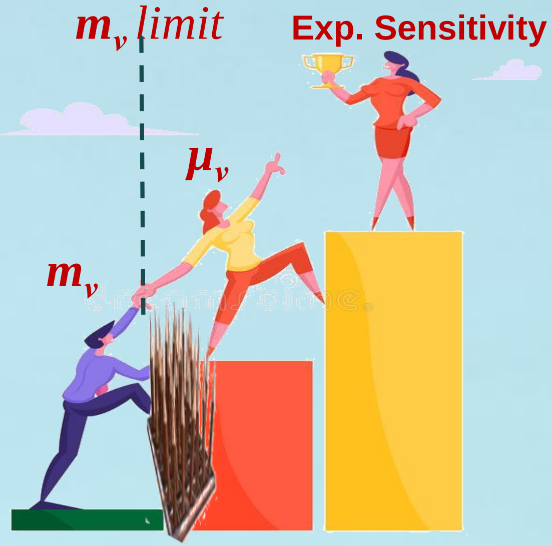
Neutrino magnetic moment – mass conundrum

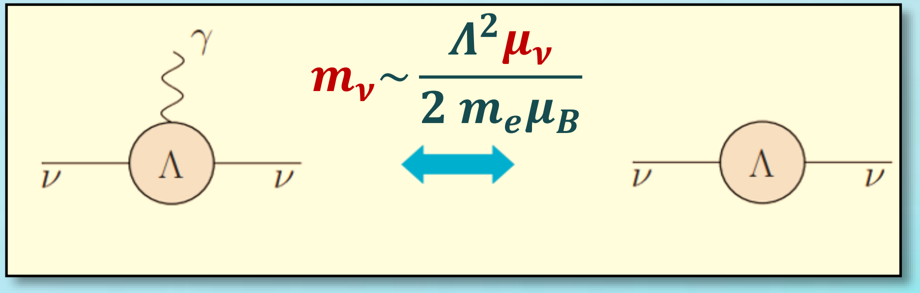
*This conundrum was well recognized **three decades ago** when there was great interest in explaining **the apparent time variation of solar neutrino flux detected by the Chlorine experiment in anti-correlation with the Sun-spot activity**.*

NMM would lead to spin-flip transition inside the solar magnetic field. Such transitions could even undergo a matter enhanced resonance. ***Lim, Marciano (1988), Akhmedov (1988)***

*In the **late 1980's and early 1990's** there were **significant theoretical activities** that addressed the compatibility of a large neutrino magnetic moment with a small mass.*

After that, in the theory side, no interesting developments have been made. These discussions become very relevant today.





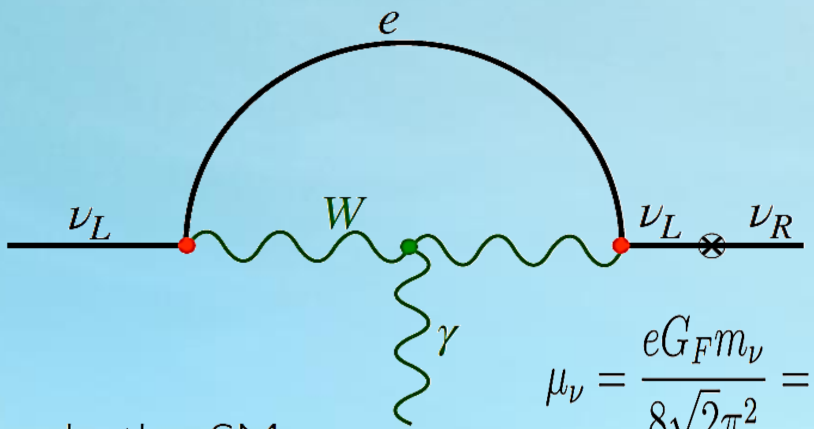
$$m_\nu \sim \frac{\Lambda^2 \mu_\nu}{2\, m_e \mu_B}$$

Neutrino magnetic moments in beyond the Standard Model

SM + ν_R

The magnetic moment and mass operators for the neutrino have the same chiral structure, which for a Dirac neutrino has the form:

$$\mathcal{L} \supset \mu_\nu \bar{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} + m_\nu \bar{\nu}_L \nu_R + \text{H.c.}$$



$$\mu_\nu = \frac{e G_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{0.1\ \text{eV}} \right)$$

In the SM

$$\mu_\nu^{SM} \sim 10^{-20}\ \mu_B$$

K. Fujikawa and R. Shrock (1980)

Bell et al. (2005)

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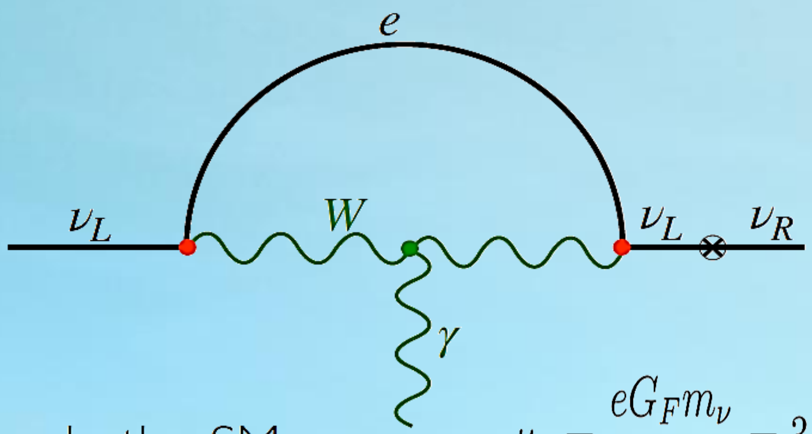

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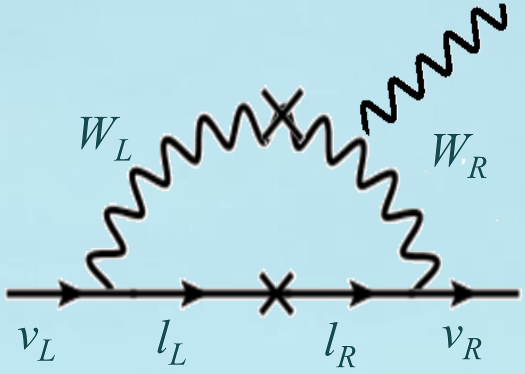
Left-Right Symmetric Model

Right-handed neutrino couples to a W_R gauge boson, which also has mixing with the W boson.



$$\mu_\nu \simeq \frac{G_F m_\ell}{2\sqrt{2}\pi^2} \sin 2\xi$$

Czakon, Gluza, Zralek (1999)
Giunti and A. Studenikin (2014)

This mixing angle is constrained by muon decay asymmetry parameters, $b \to s\gamma$ decay rate, indirect LHC limits leading to a limit $\boldsymbol{\mu_\nu < 10^{-15} \mu_B}$

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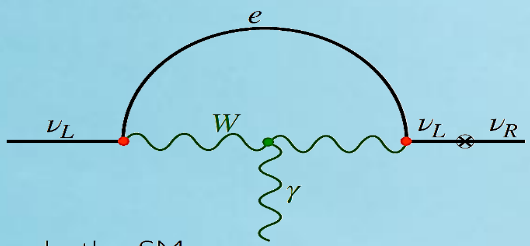

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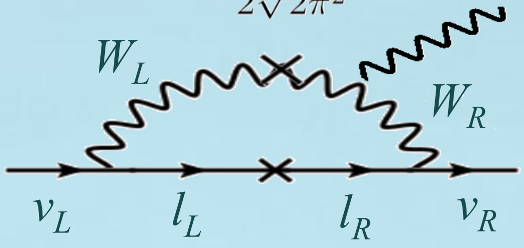
Bell et al. (2005)

Left-Right Symmetric Model

In left-right symmetric models, the right-handed neutrino couples to a W_R gauge boson, which also has mixing with the ***W*** boson:

$$\mu_\nu \simeq \frac{G_F m_\ell}{2\sqrt{2}\pi^2} \sin 2\xi$$



$$\boldsymbol{\mu_\nu < 10^{-15} \mu_B}$$

Czakon, Gluza, Zralek (1999)
Giunti and A. Studenikin (2014)

Supersymmetric theory

In supersymmetric extensions of the SM, lepton number may be violated by R-parity breaking interactions. In such contexts, without relying on additional symmetries, NMM will be (imposing experimental constraints on the SUSY parameters) of the order at most about $10^{-15}\ \mu_B$.

$$\mu_\nu \sim \lambda'^2/(16\pi^2) m_\ell^2 A_\ell / M_{\tilde{\ell}}^4$$

Majorana scenario

If neutrinos are Majorana particles, their transition magnetic moments resulting from Standard Model interactions is given by

$$\mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{\ell=e,\mu,\tau} U_{\ell i}^* U_{\ell j} \frac{m_\ell^2}{m_W^2}$$

At most of order $\boldsymbol{\mu_\nu \sim 10^{-23} \mu_B}$

P. B. Pal and L. Wolfenstein (1982)
For a review, see Giunti and A. Studenikin (2014)

Clearly, these values are well below the sensitivity of current experiments!

Neutrino magnetic moment – mass conundrum

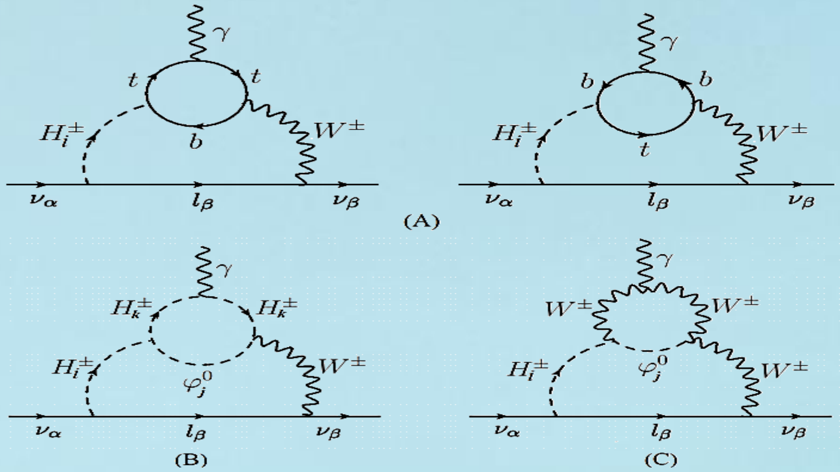
A. Spin Symmetry Mechanism

- *In renormalizable gauge theories there are **no direct couplings** of the type $\gamma W^+ S^-$.*

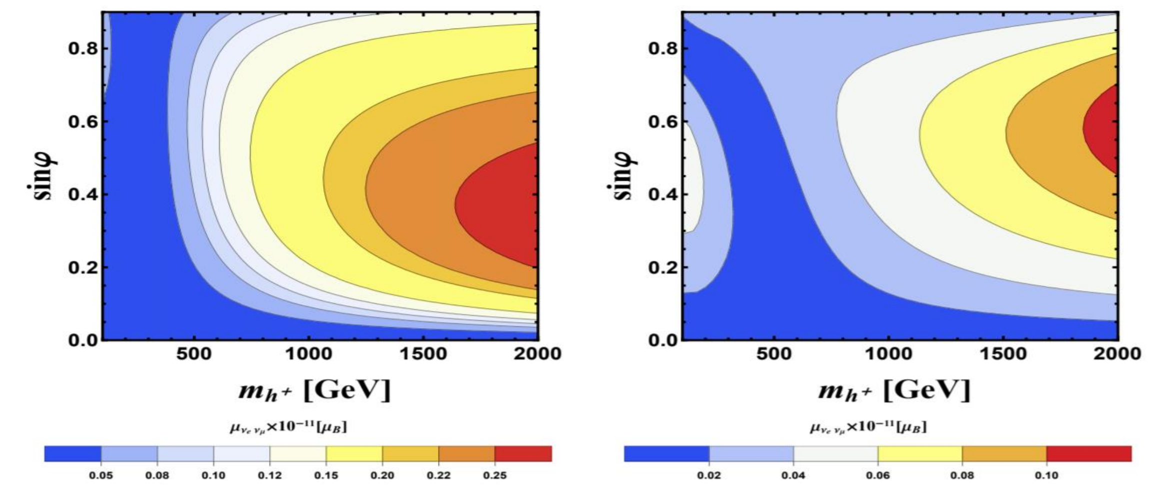
- *As for its contribution to m_ν, for transversely polarized vector bosons, the transition from **spin 1 to spin 0 cannot occur**. Only the longitudianl mode, the Goldstone mode, would contribute to such transitions.*

- *This implies that in the two loop diagram utilizing the $\gamma W^+ S-$ for generating μ_ν, if the photon line is removed, only the longitudinal $W^\pm$ bosons will contribute, leading to a suppression factor of m_l^2/m_W^2 in the neutrino mass.*

Barr, Freire, and Zee (1990), Babu et al. (1992),
Babu, **SJ,** Lindner (2020)



Babu, **SJ,** Lindner (2020)



In this optimized setup, one can achieve neutrino transition magnetic moment as big as $\sim 10^{-12} \mu_B$

B. $SU(2)_H$ Symmetry for Enhanced Neutrino Magnetic Moment

While the neutrino mass operator and the magnetic moment operator both ***are chirality flipping****, there is one important* ***difference in their Lorentz structures****.*

The ***mass operator, being a Lorentz scalar****, is* ***symmetric****, while the magnetic moment, being a* ***Lorentz tensor*** *operator is* ***antisymmetric*** *in the two fermion fields.*

In 1988, Voloshin proposed a new ***$SU(2)_\nu$ symmetry*** *that transforms ν into ν^c.*

A neutrino mass term, being symmetric under this exchange, would then be forbidden by the $SU(2)_\nu$ symmetry, while the magnetic moment operator, $\nu^T C\sigma_{\mu\nu}\nu^c F^{\mu\nu}$ is antisymmetric under the exchange.

1989: ***Barbieri and R. N. Mohapatra*** *pointed out that its hard to implement the* ***Voloshin symmetry*** *since it does not commute with SM.*

$$\mathcal{L}_{\text{mag.}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \sigma_{\mu\nu} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} F^{\mu\nu}$$

$$\mathcal{L}_{\text{mass}} = (\nu_e^T \ \ \nu_\mu^T) C^{-1} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

B. *SU(2)$_H$* Symmetry for Enhanced Neutrino Magnetic Moment

A ***horizontal symmetry acting on the electron and the muon families*** *can serve the same purpose, as such a symmetry commutes with the weak interactions.*

Our simplification is that the symmetry is only ***approximate, broken explicitly by electron and muon masses****.*

The explicit breaking of SU(2)$_H$ by the lepton masses is ***analogous to chiral symmetry breaking in the strong interaction sector by masses of the light quarks****.*

SU(2)$_H$ ***cannot be exact****, as it would imply $m_e = m_\mu$. Explicit but small breaking of SU(2)$_H$, so that realistic electron and muon masses can be generated.*

Leptons of the Standard Model transform under *SU(2)$_L$* × *U(1)$_Y$* × *SU(2)$_H$* as follows:

$$\begin{aligned}
\psi_L &= \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L & (2, -\tfrac{1}{2}, 2) \\
\psi_R &= (e \quad\quad \mu)_R & (1, -1, 2) \\
\psi_{3L} &= \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} & (2, -\tfrac{1}{2}, 1) \\
& \quad\quad \tau_R & (1, -1, 1)
\end{aligned}$$

Higgs sector:

$$\begin{aligned}
\phi_S &= \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} & (2, \tfrac{1}{2}, 1) \\
\Phi &= \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} & (2, \tfrac{1}{2}, 2) \\
\eta &= (\eta_1^+ \quad \eta_2^+) & (1, 1, 2)\ .
\end{aligned}$$

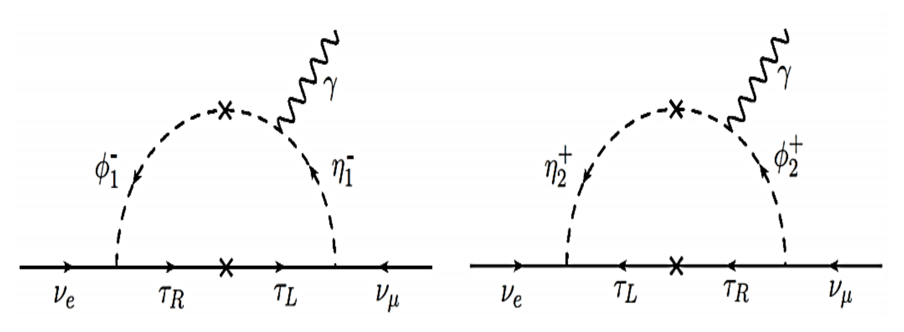
Babu, **SJ,** Lindner (2020)

$$\begin{aligned}
\mathcal{L}_{\text{Yuk}} = {} & h_1 \,\mathrm{Tr}\left(\bar{\psi}_L \phi_S \psi_R\right) + h_2 \bar{\psi}_{3L} \phi_S \tau_R + h_3 \bar{\psi}_{3L} \Phi i \tau_2 \psi_R^T \\
& + f \eta \tau_2 \psi_L^T \tau_2 C \psi_{3L} + f' \,\mathrm{Tr}\left(\bar{\psi}_L \Phi\right) \tau_R + H.c.
\end{aligned}$$

Here *SU(2)$_H$* acts horizontally, while *SU(2)$_L$* acts vertically.

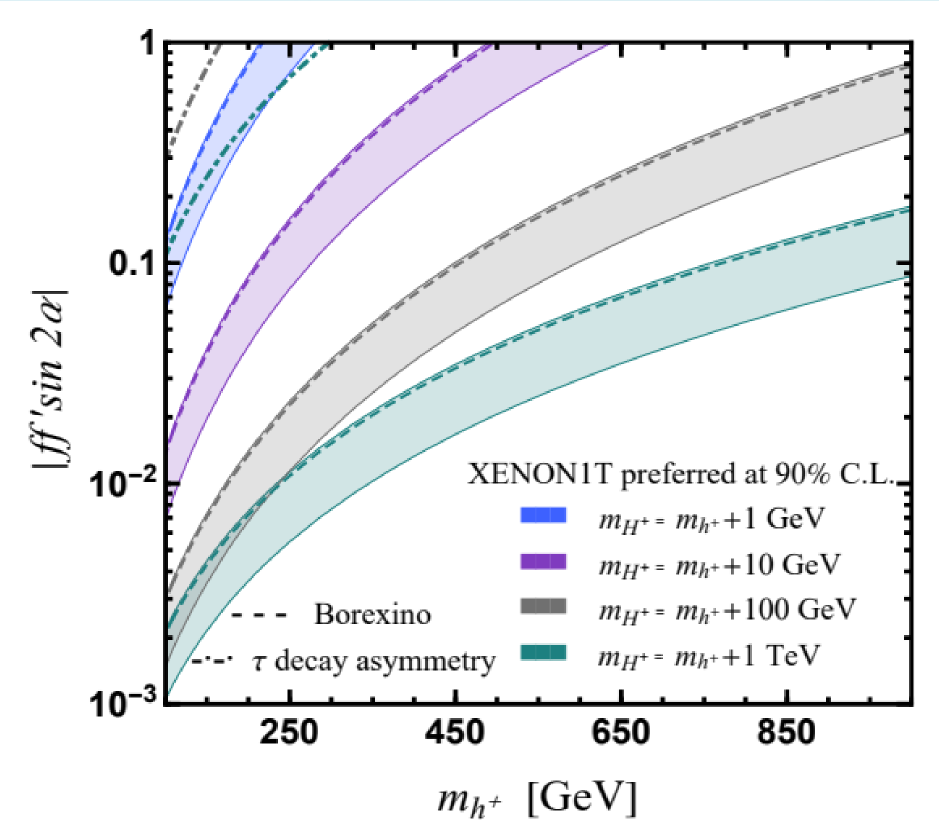
B. *$SU(2)_H$* Symmetry for Enhanced Neutrino Magnetic Moment

- *The Lagrangian of the model* ***does not respect lepton number****. The $SU(2)_H$ limit of the model however respects $L_e - L_\mu$ symmetry. This allows a nonzero transition magnetic moment, while neutrino mass terms are forbidden.*



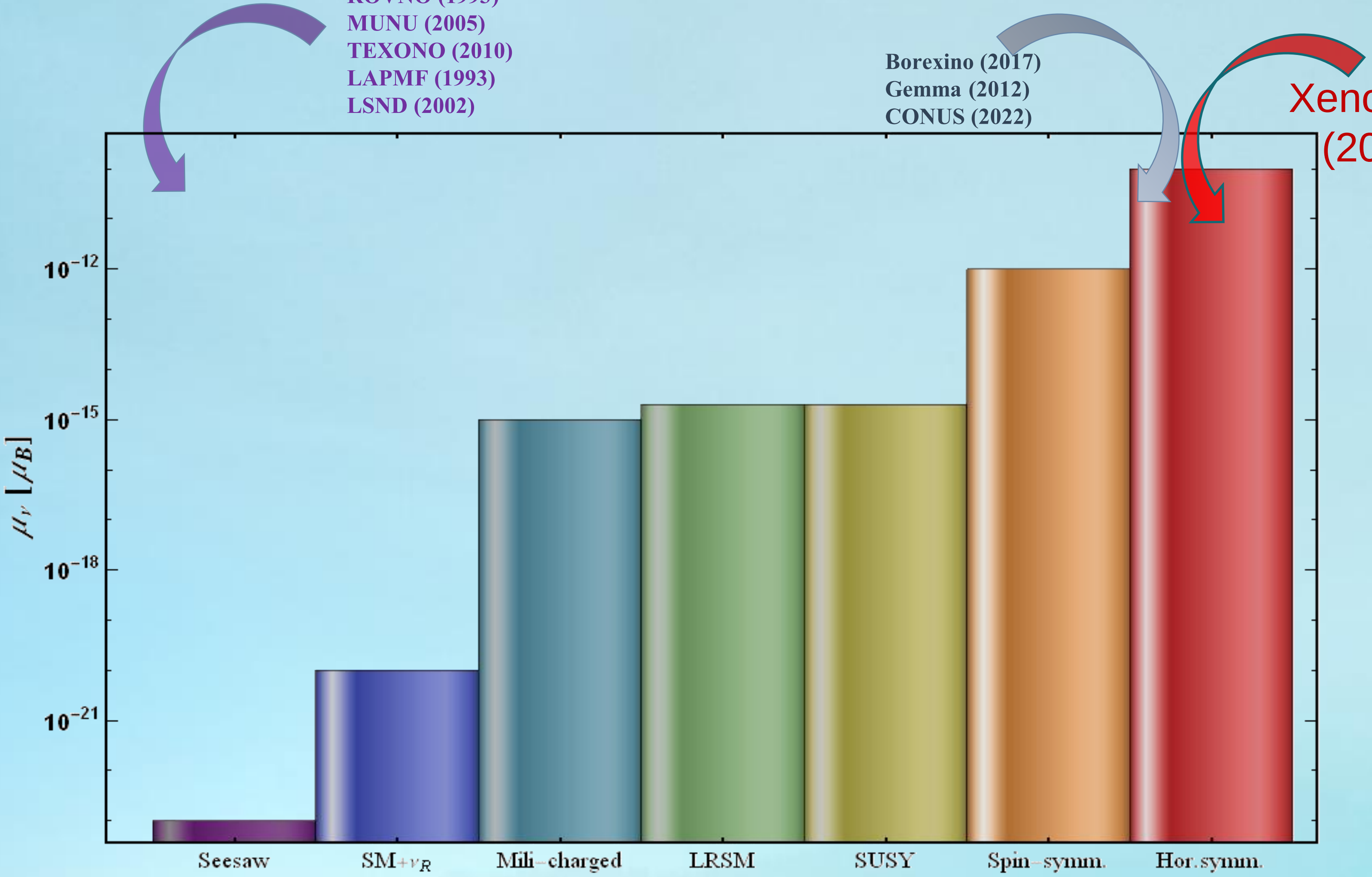
- *In the* ***$SU(2)_H$ symmetric limit, the two diagrams add for $\mu_{\nu e \nu \mu}$****, while they* ***cancel for m_ν****.*

$$\boxed{\mu_{\nu_e\nu_\mu} = \frac{ff'}{8\pi^2} m_\tau \sin 2\alpha \left[\frac{1}{m_{h^+}^2}\left\{\ln\frac{m_{h^+}^2}{m_\tau^2}-1\right\} - \frac{1}{m_{H^+}^2}\left\{\ln\frac{m_{H^+}^2}{m_\tau^2}-1\right\}\right]}$$



Babu, **SJ**, Lindner (2020)

Neutrino magnetic moments: a global picture



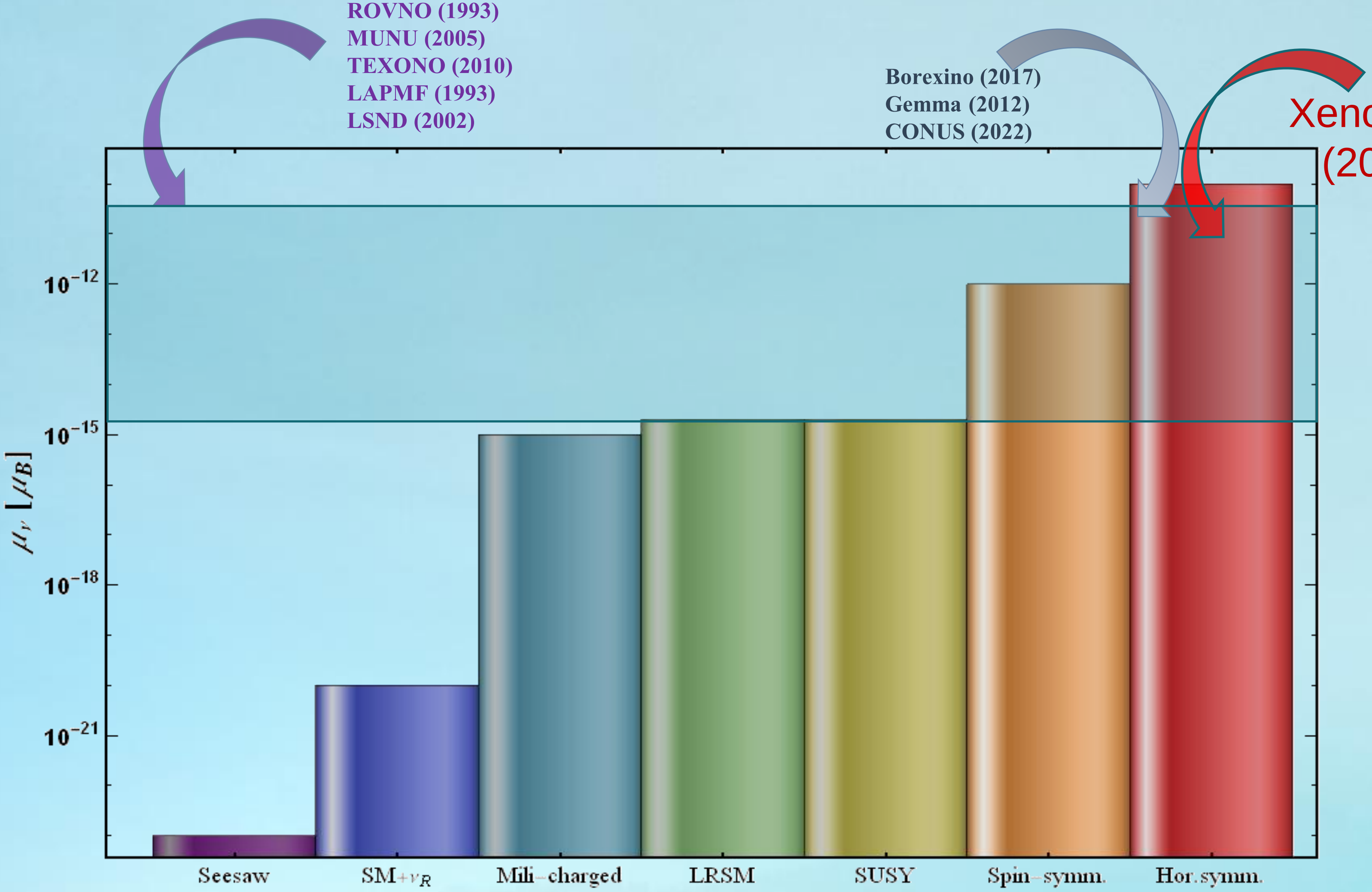
KRASNOYARSK (1992)
ROVNO (1993)
MUNU (2005)
TEXONO (2010)
LAPMF (1993)
LSND (2002)

Borexino (2017)
Gemma (2012)
CONUS (2022)

XenonNT
(2022)

SJ, PoS(DISCRETE2020-2021)037

Neutrino magnetic moments: a global picture



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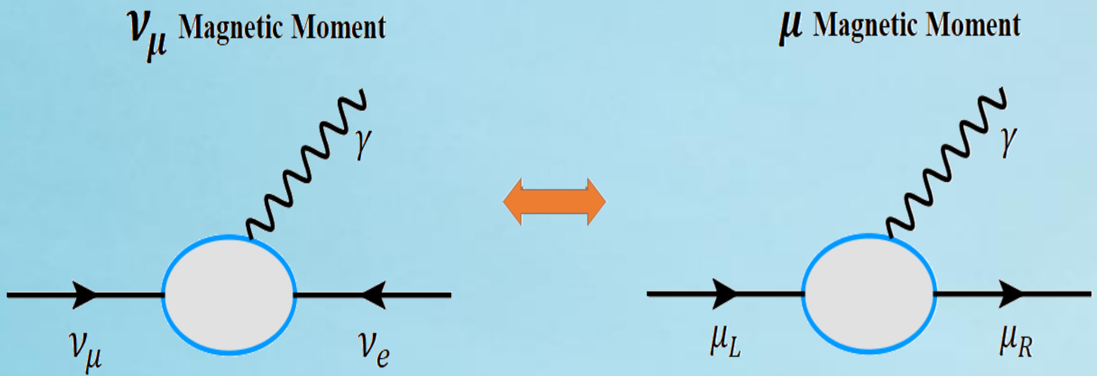
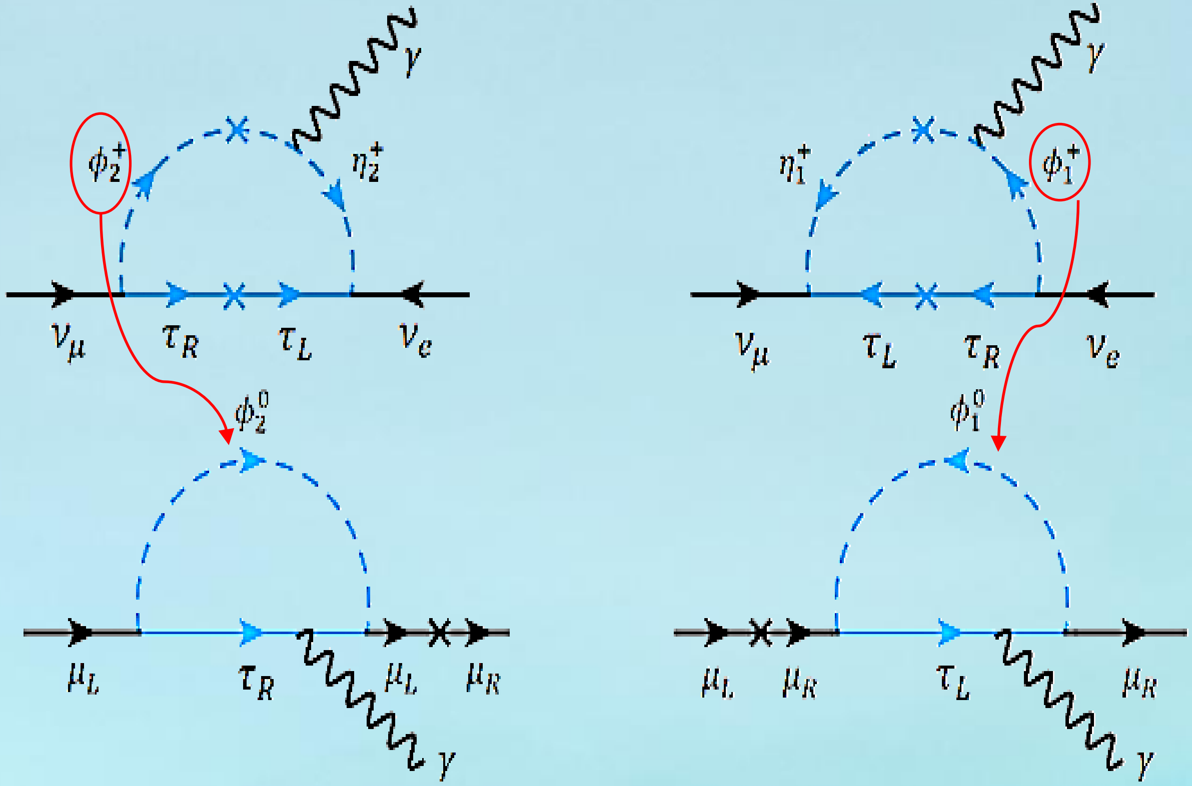
SJ, PoS(DISCRETE2020-2021)037

Neutrino magnetic moments – charged lepton g-2 correlation

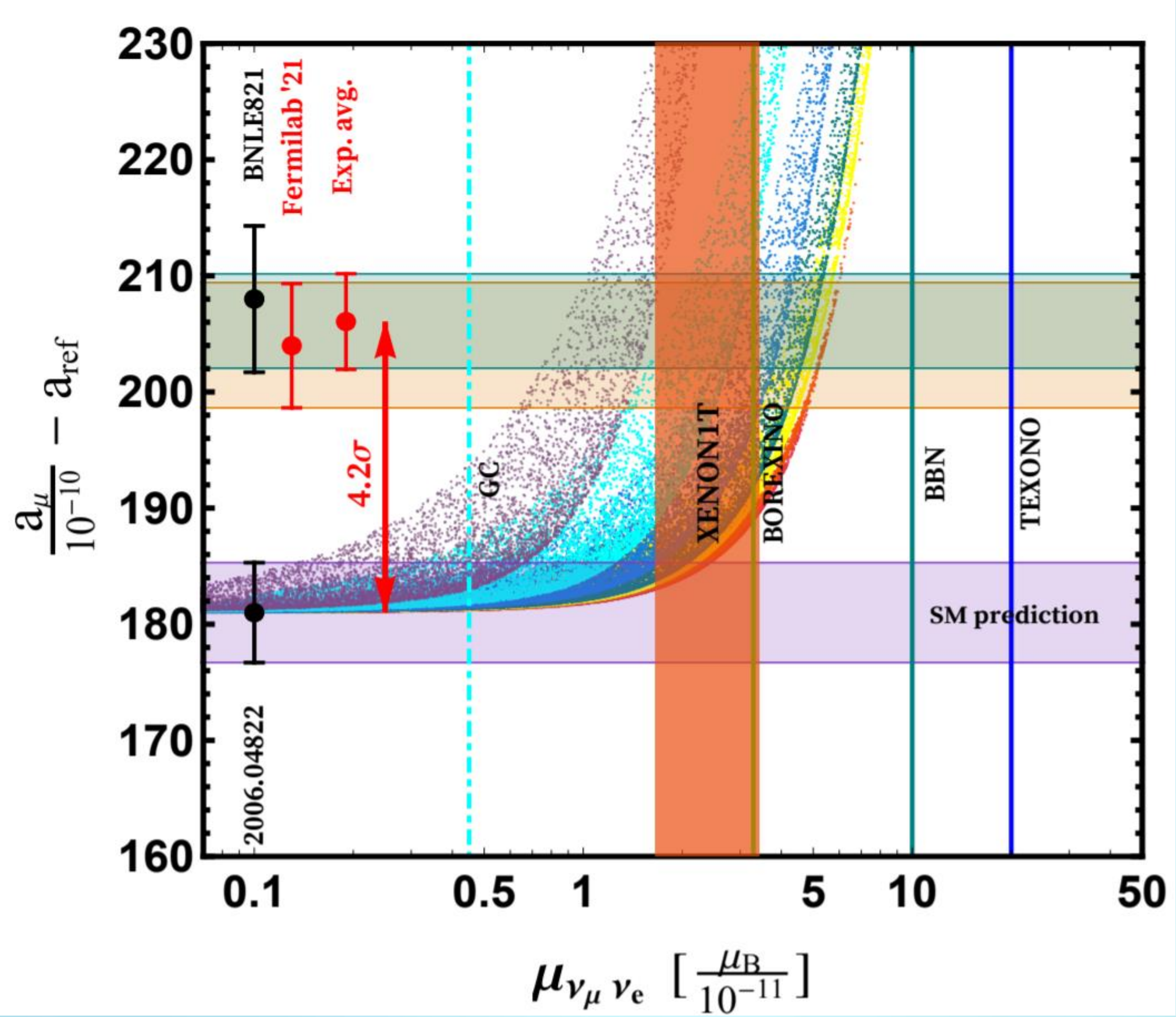




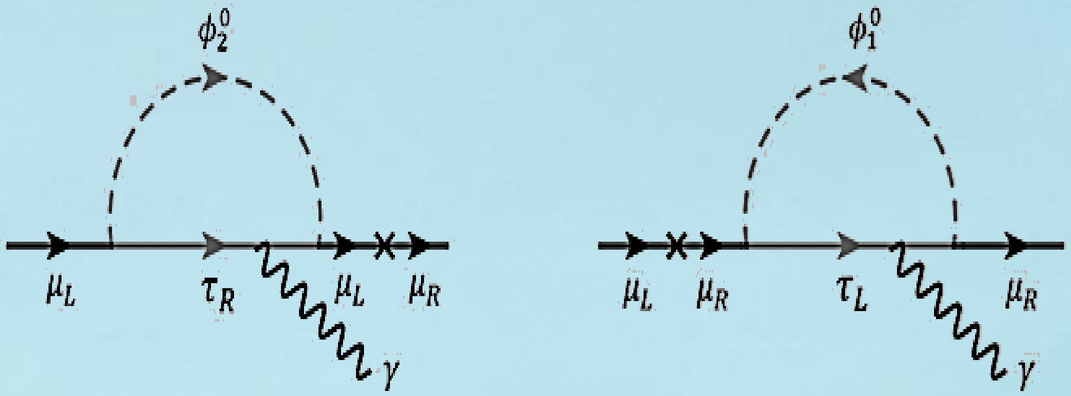
The models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the charged lepton anomalous magnetic moment.

Babu, **SJ,** Lindner, Vishnu (2021)

Neutrino magnetic moments – Muon g-2 anomaly



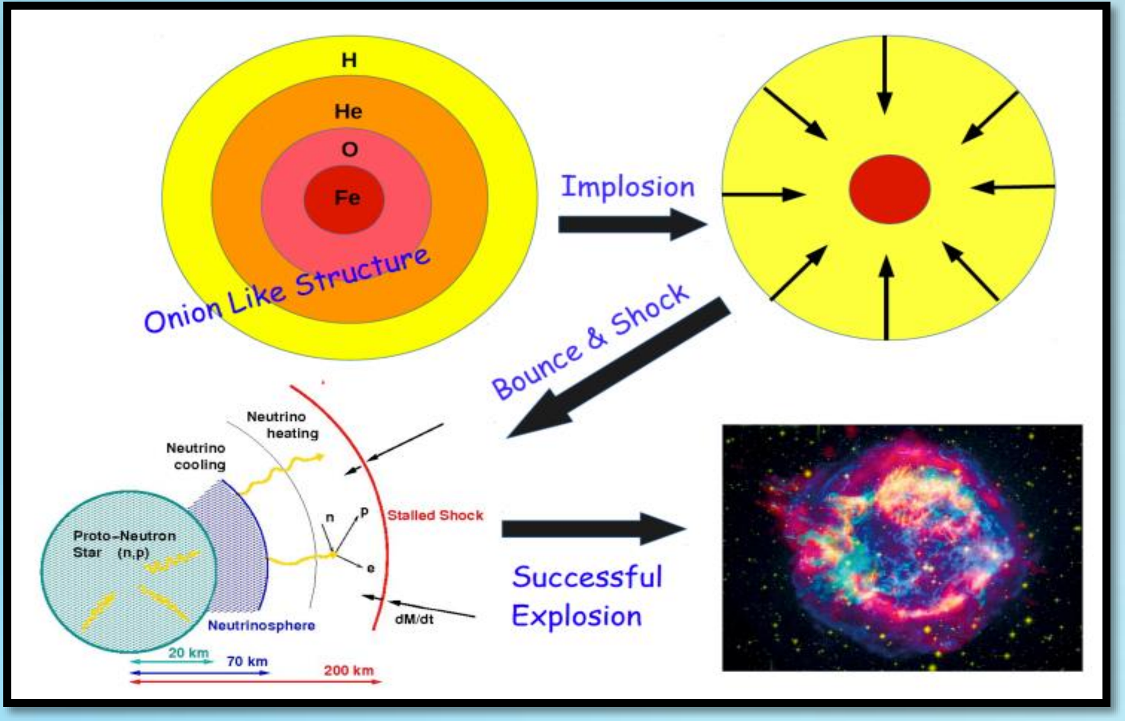
Babu, **SJ,** Lindner, Vishnu (2021)

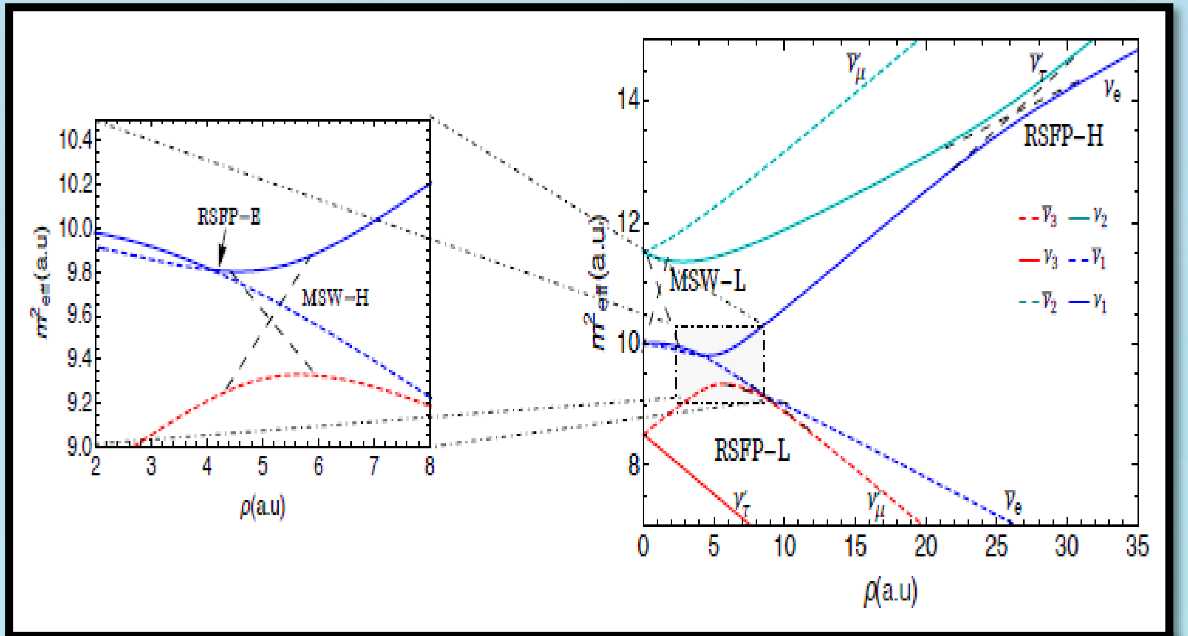


- *A direct correlation between the neutrino magnetic moment and muon g-2*
- Sign and strength are automatic here, no control over it.
- A minimal unified framework: μ_ν, m_ν, $(g\text{-}2)_\mu$.

Exploiting a future galactic supernova to probe neutrino magnetic moments

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





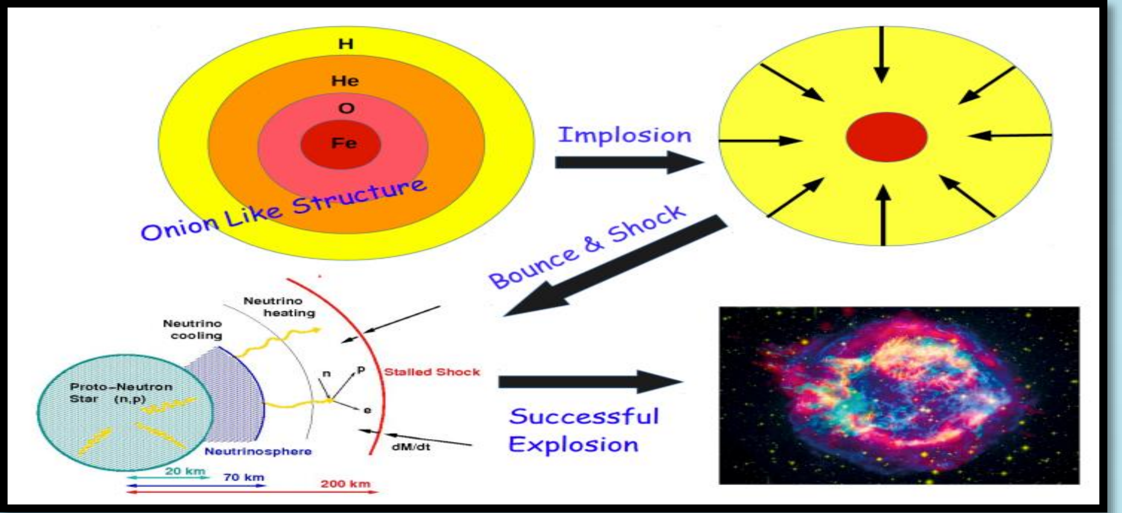
- Neutrino evolution equation: $i\frac{d}{dr}\begin{pmatrix}\nu\\ \bar\nu\end{pmatrix} = \begin{pmatrix} H_\nu & B_\perp M \\ -B_\perp M & H_{\bar\nu}\end{pmatrix}\begin{pmatrix}\nu\\ \bar\nu\end{pmatrix}$
- Neutrino Hamiltonian in matter: $H_\nu = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21}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

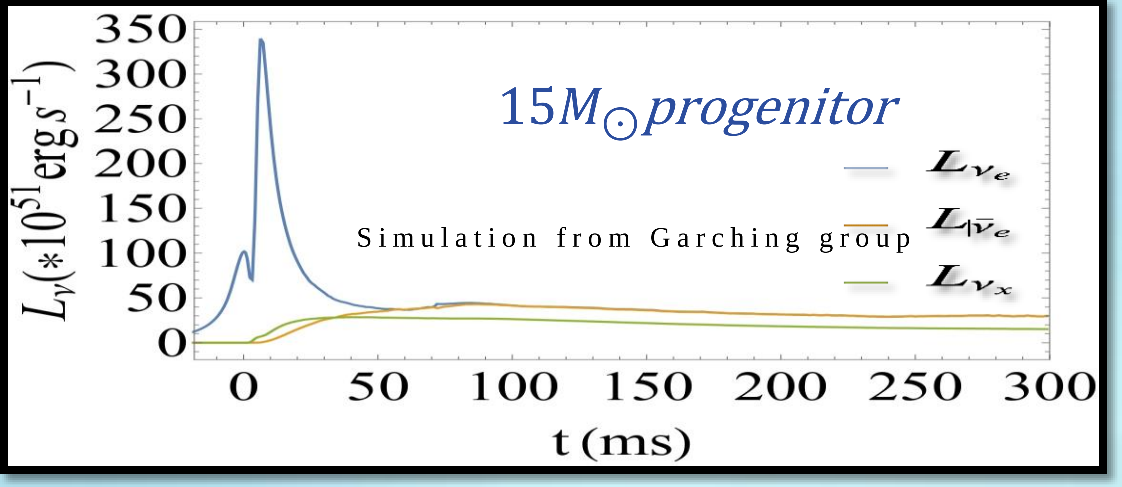
Akhmedov and T. Fukuyama (2003),
Ando and Sato (2003)

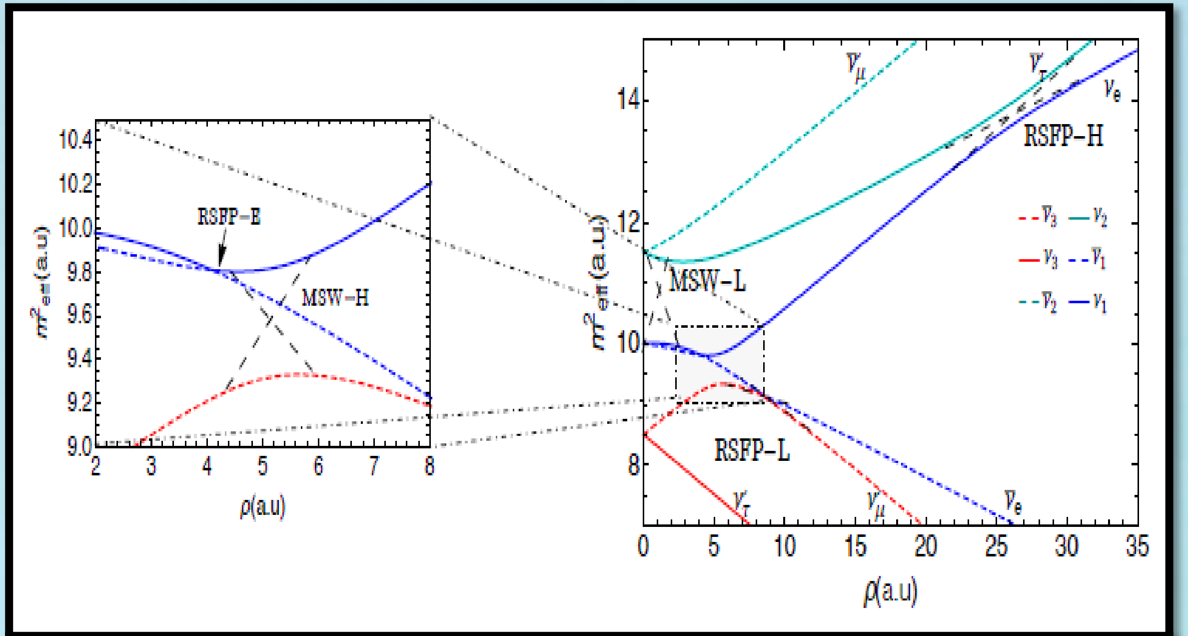
Resonance Condition: $\frac{\Delta m^2_{21}}{2E_\nu}\cos 2\theta_{12} + \bar V_\mu - V_e = 0$

Exploiting a future galactic supernova to probe neutrino magnetic moments

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







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Akhmedov and T. Fukuyama (2003),
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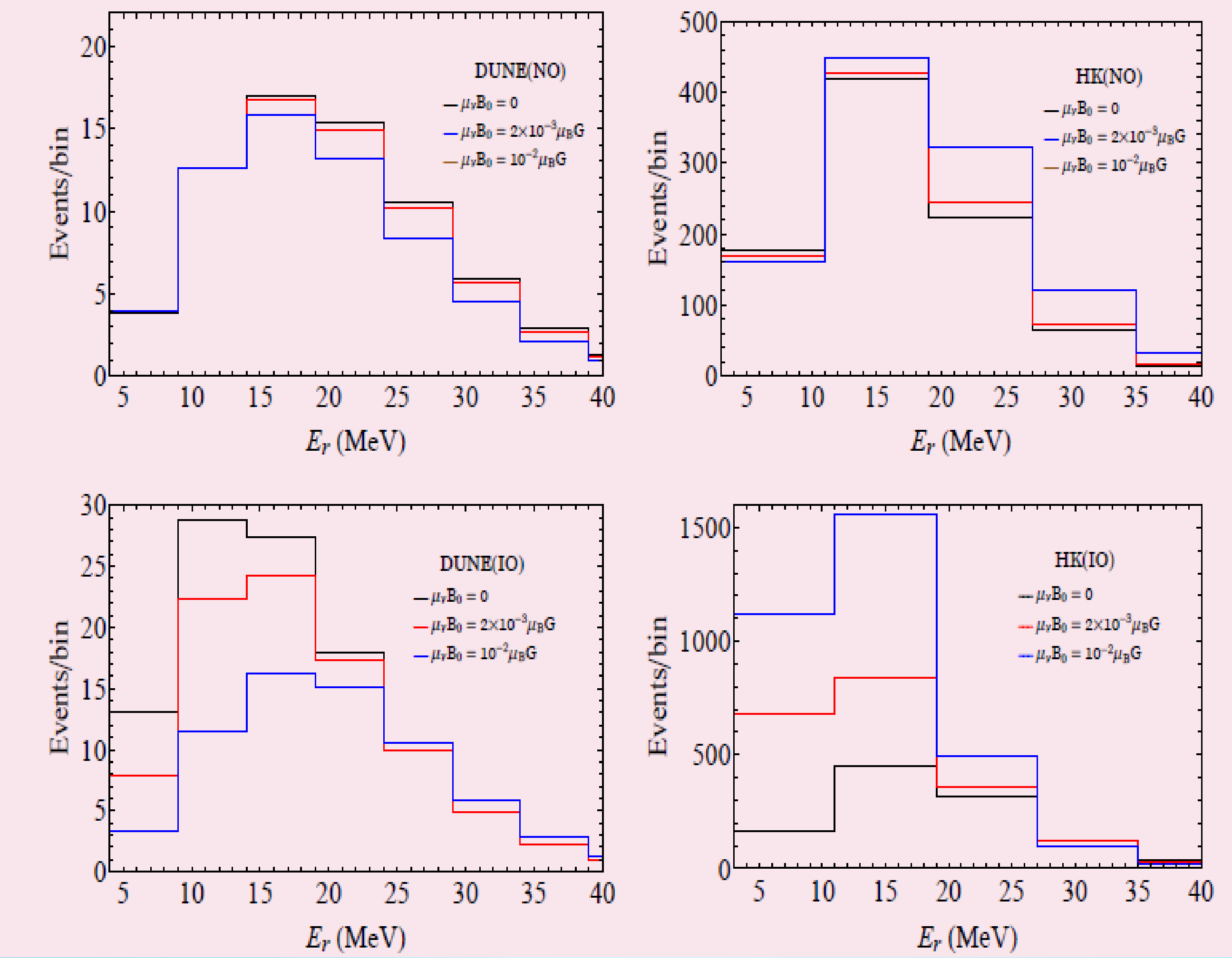
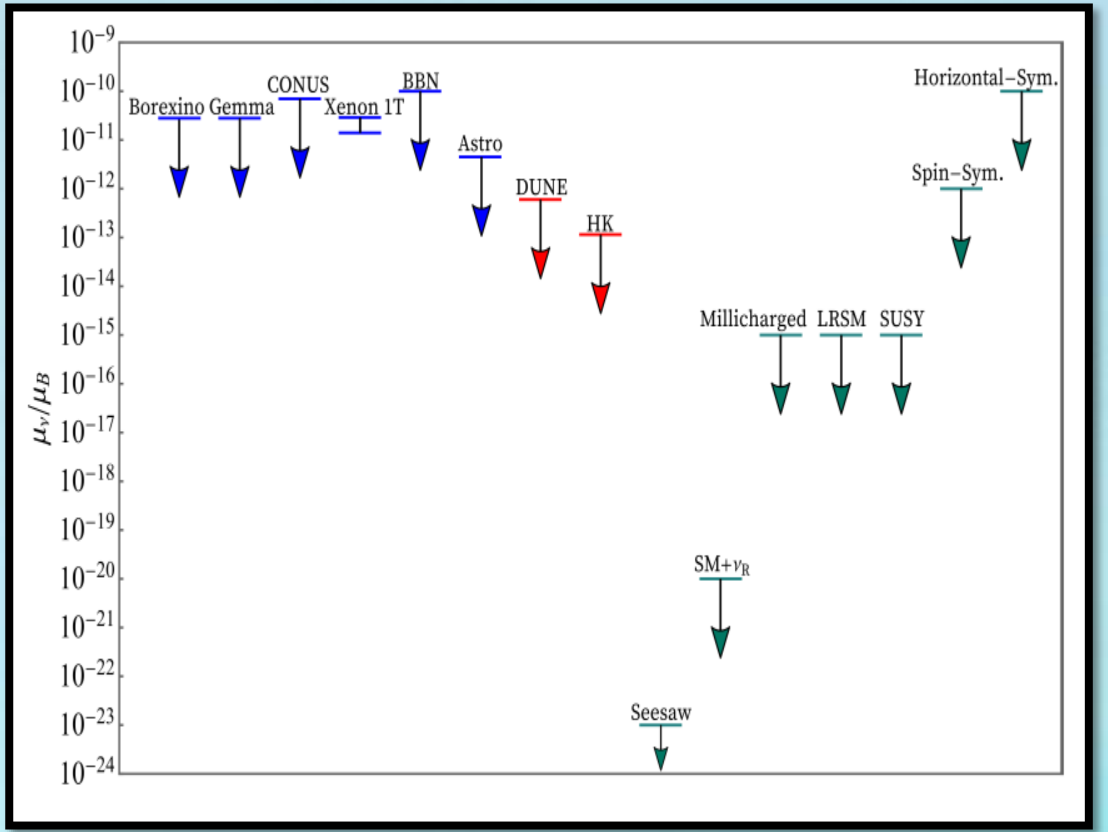
Exploiting a future galactic supernova to probe neutrino magnetic moments





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

Dirac neutrino magnetic moments in Sne?

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

But $V_e \neq 0$ “Always”

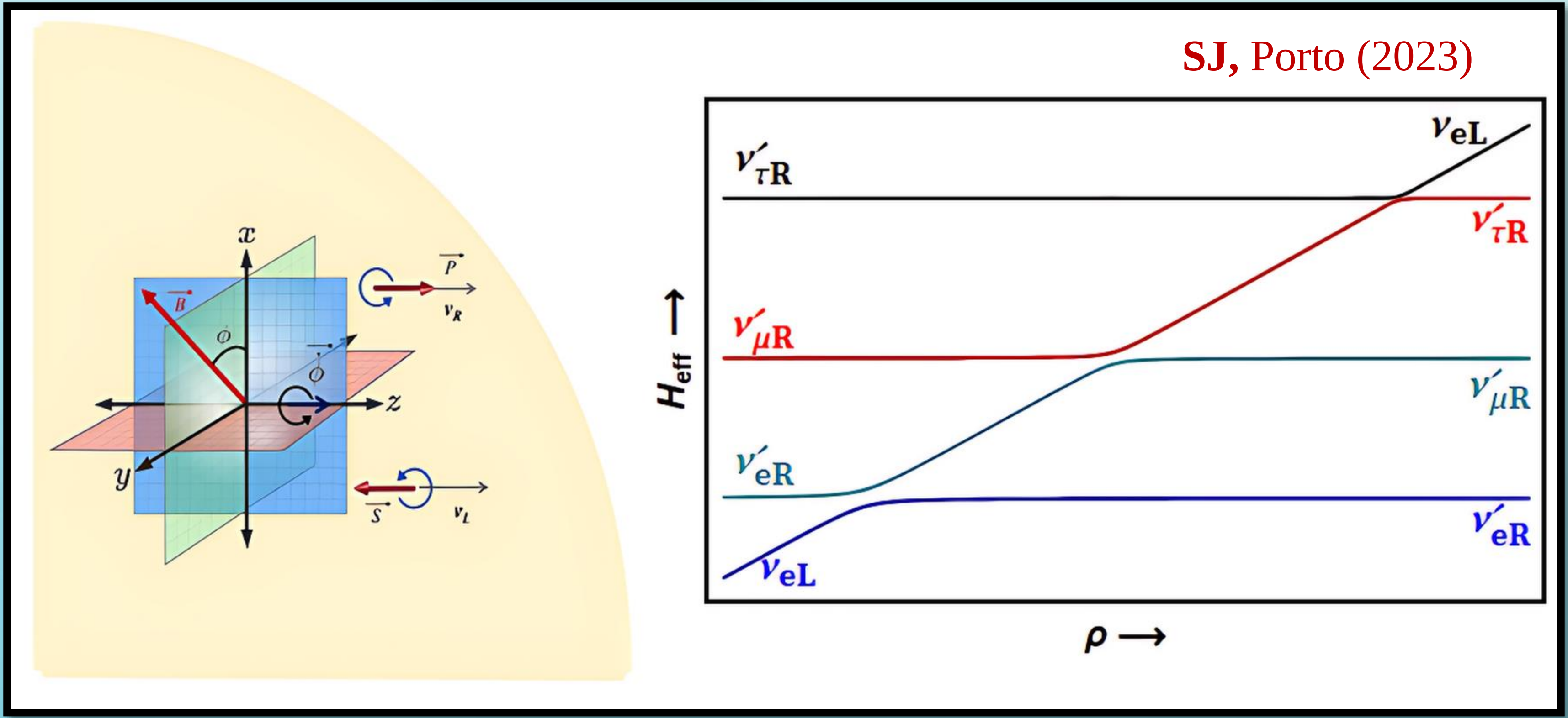
SN neutrino flavor conversion was thought to be insensitive to Dirac Magnetic Moments.

Dirac neutrino magnetic moments in Sne?

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

$$V_e+\dot{\phi}=0$$

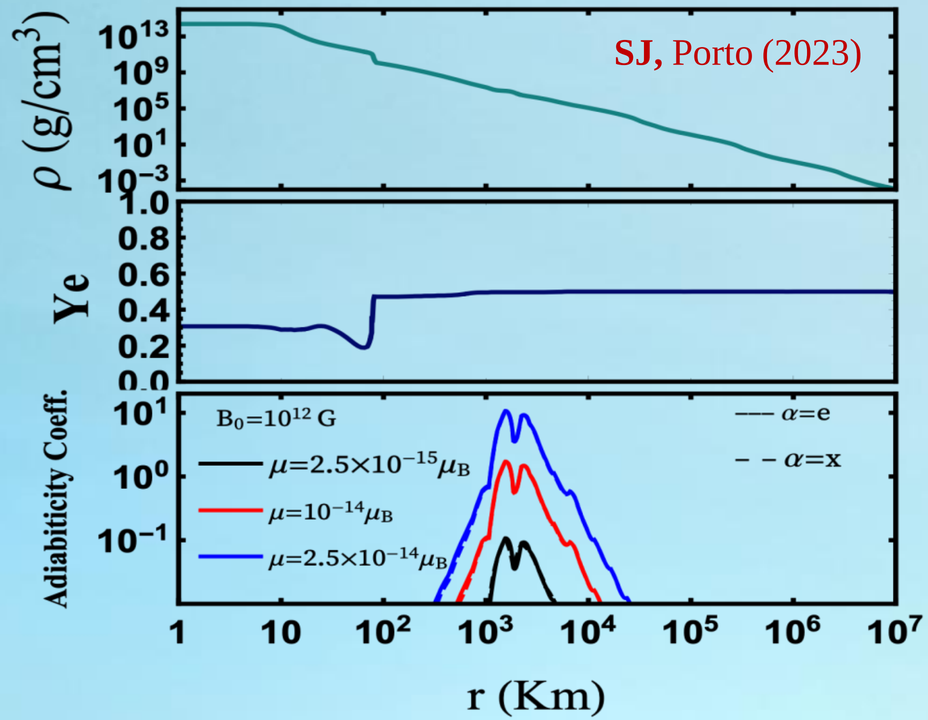
(Resonance Condition)

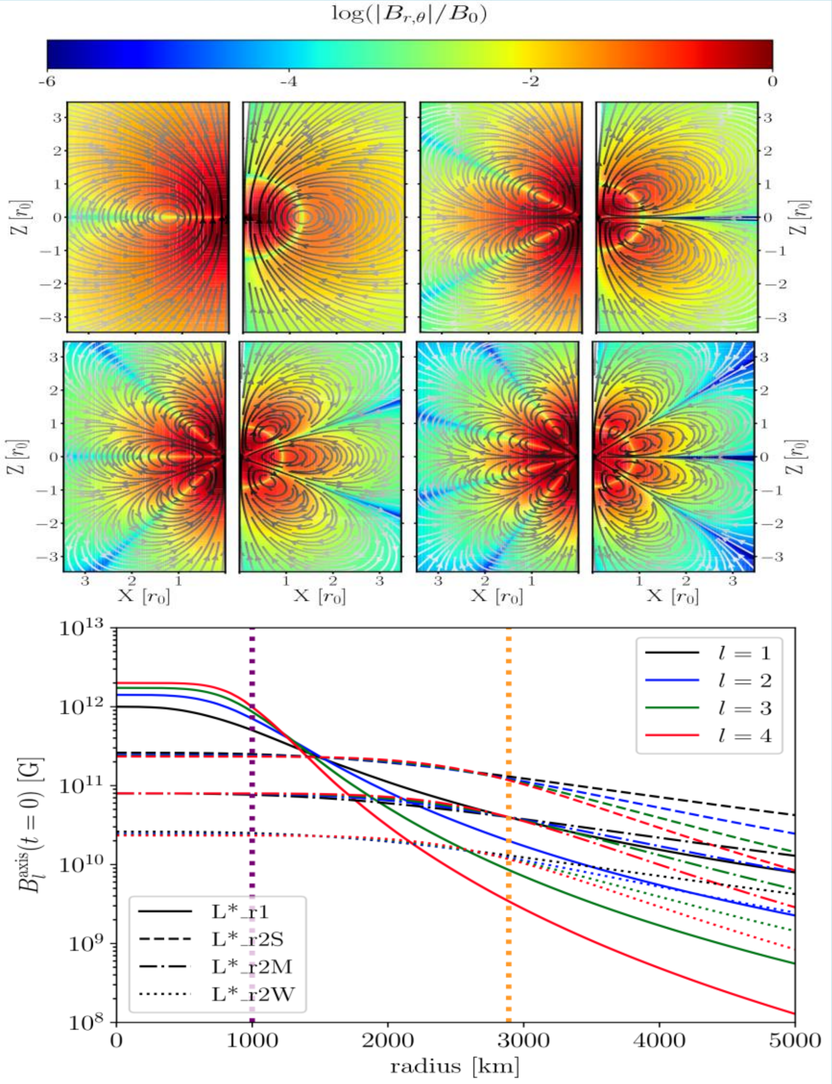


SJ, Porto (2023)

Neutrino evolution in Twisting Magnetic Fields

$$i\frac{d}{dr}\begin{bmatrix}\nu_L\\ \nu_R\end{bmatrix} = \begin{bmatrix} H_L + (\dot{\phi}/2)I & \mu B(r) \\ \mu^\dagger B(r) & H_R - (\dot{\phi}/2)I\end{bmatrix}\begin{bmatrix}\nu_L\\ \nu_R\end{bmatrix}$$



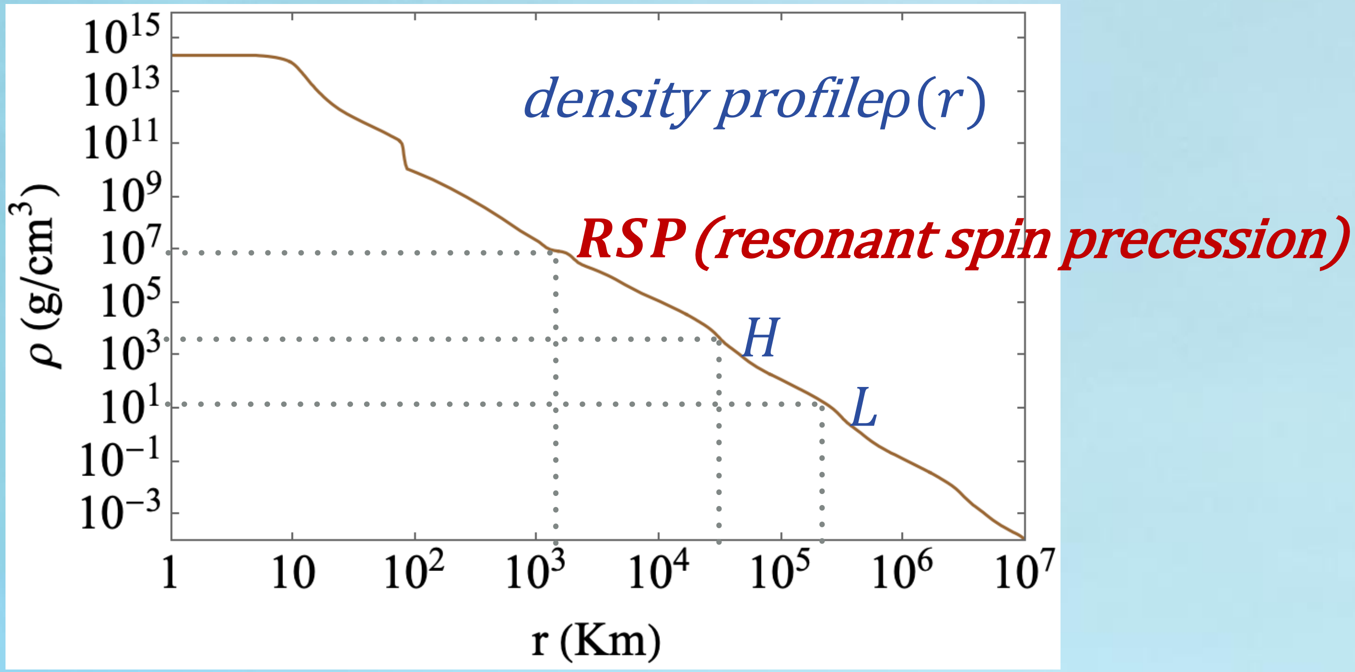


Efficient conversion in the edge of the Fe-core

$$\gamma_\alpha = \frac{2(2\mu_\nu B)^2}{|\dot{V}_\alpha + \ddot{\phi}|}$$ >> 1

Bugli *et al. "The impact of non-dipolar magnetic fields in core-collapse supernovae,"* Mon. Not. Roy. Astron. Soc. 492 (2020) no. 1, 58–71,

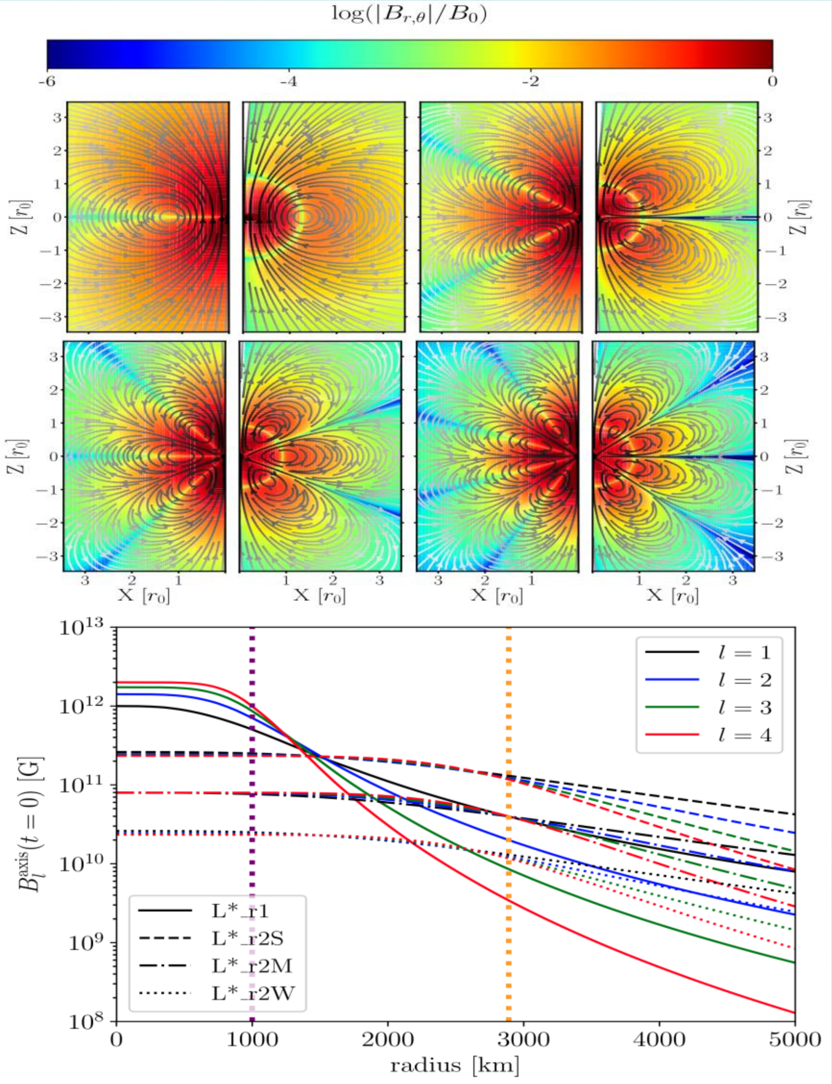
Neutrino evolution in Twisting Magnetic Fields



RSP converts left-handed neutrinos (ν_L) to their right-handed counterparts (ν_R) via interaction μ_ν and magnetic fields.

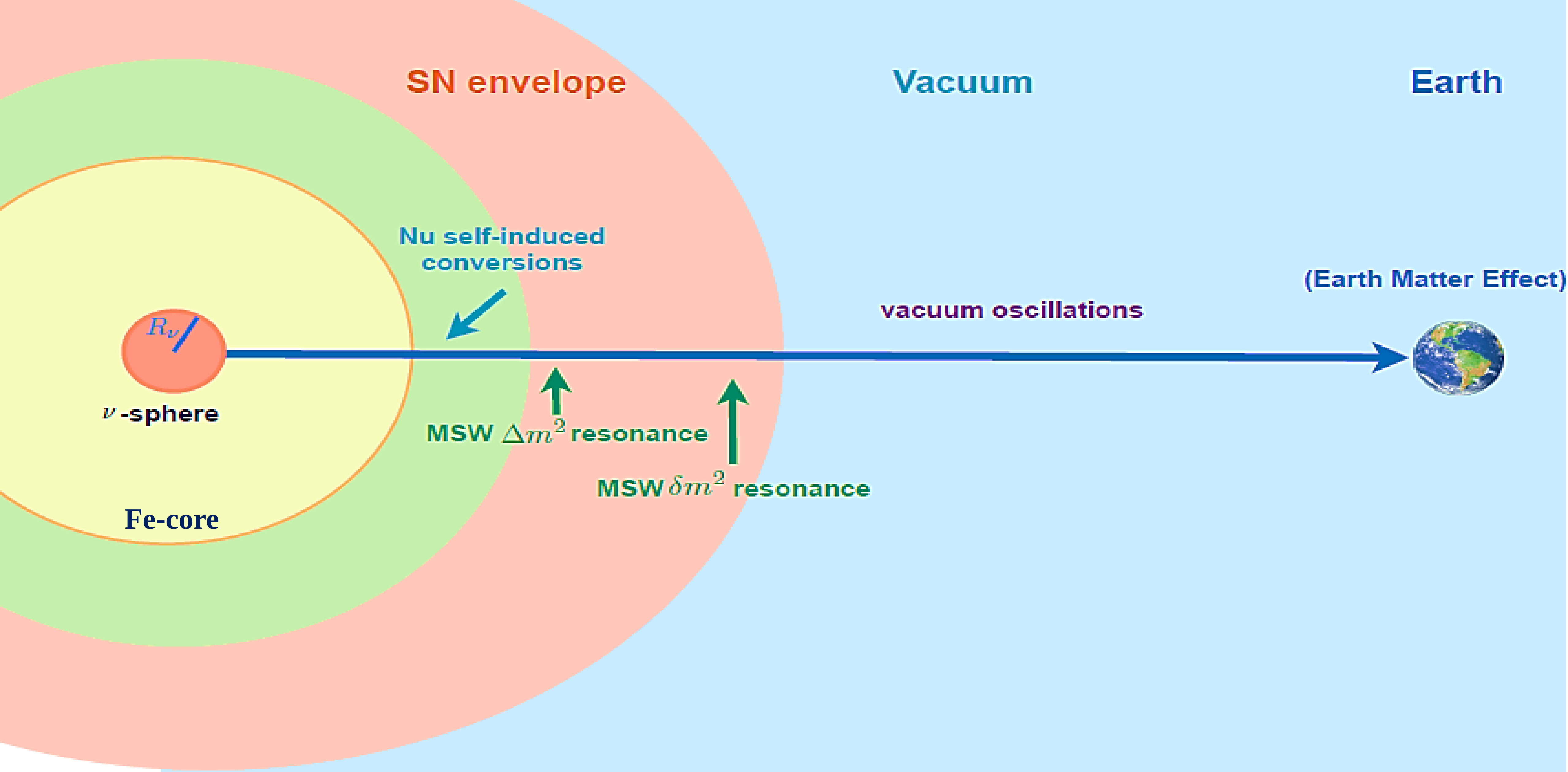
RSP happens at the edge of the Fe-core at $r_0 \sim [1,3] \times 10^3\,Km$.

SJ, Porto (2023)

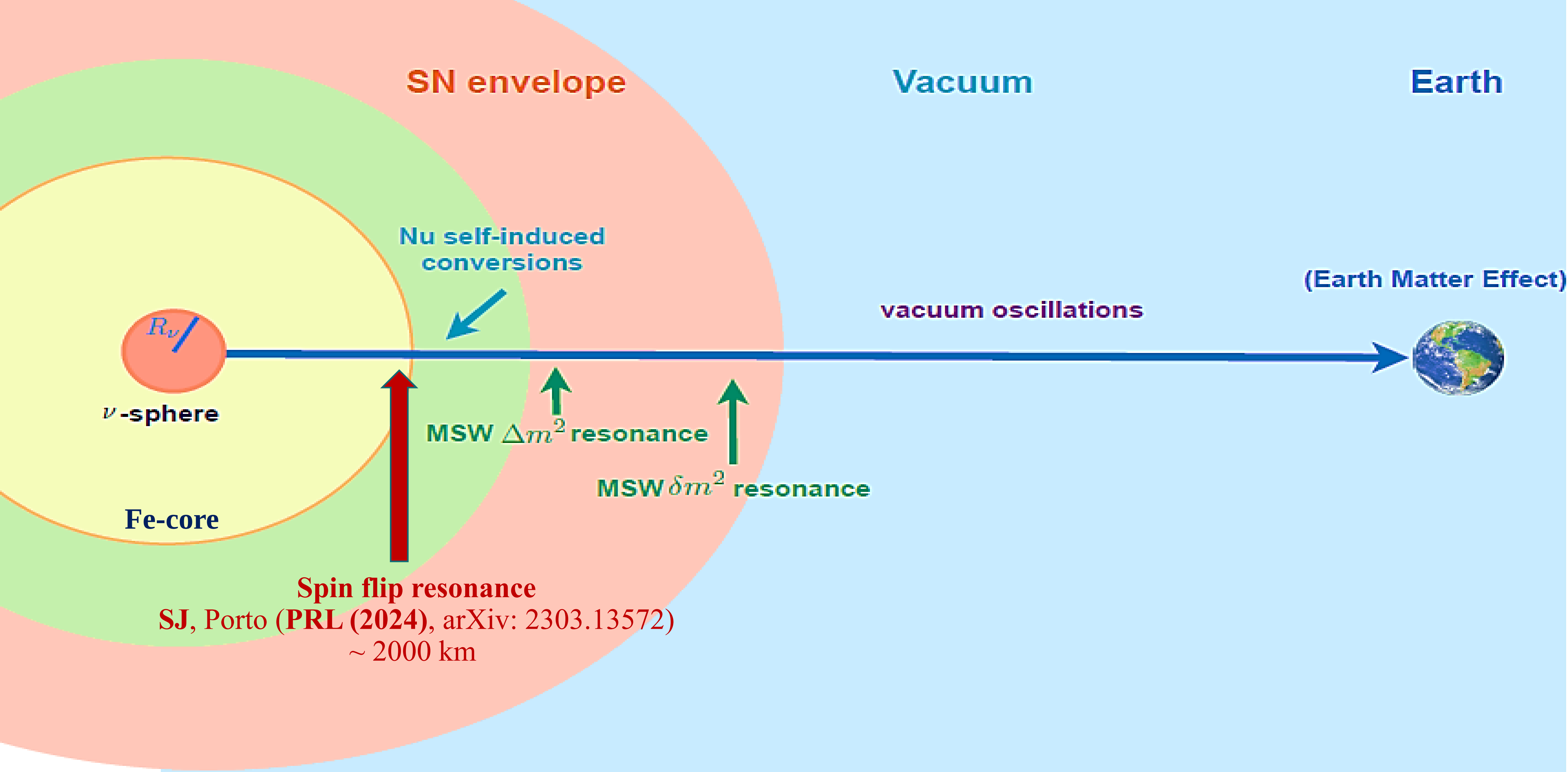


Bugli *et al.* *"The impact of non-dipolar magnetic fields in core-collapse supernovae,"* Mon. Not. Roy. Astron. Soc. 492 (2020) no. 1, 58–71,

Simplified Picture of Flavor Conversions

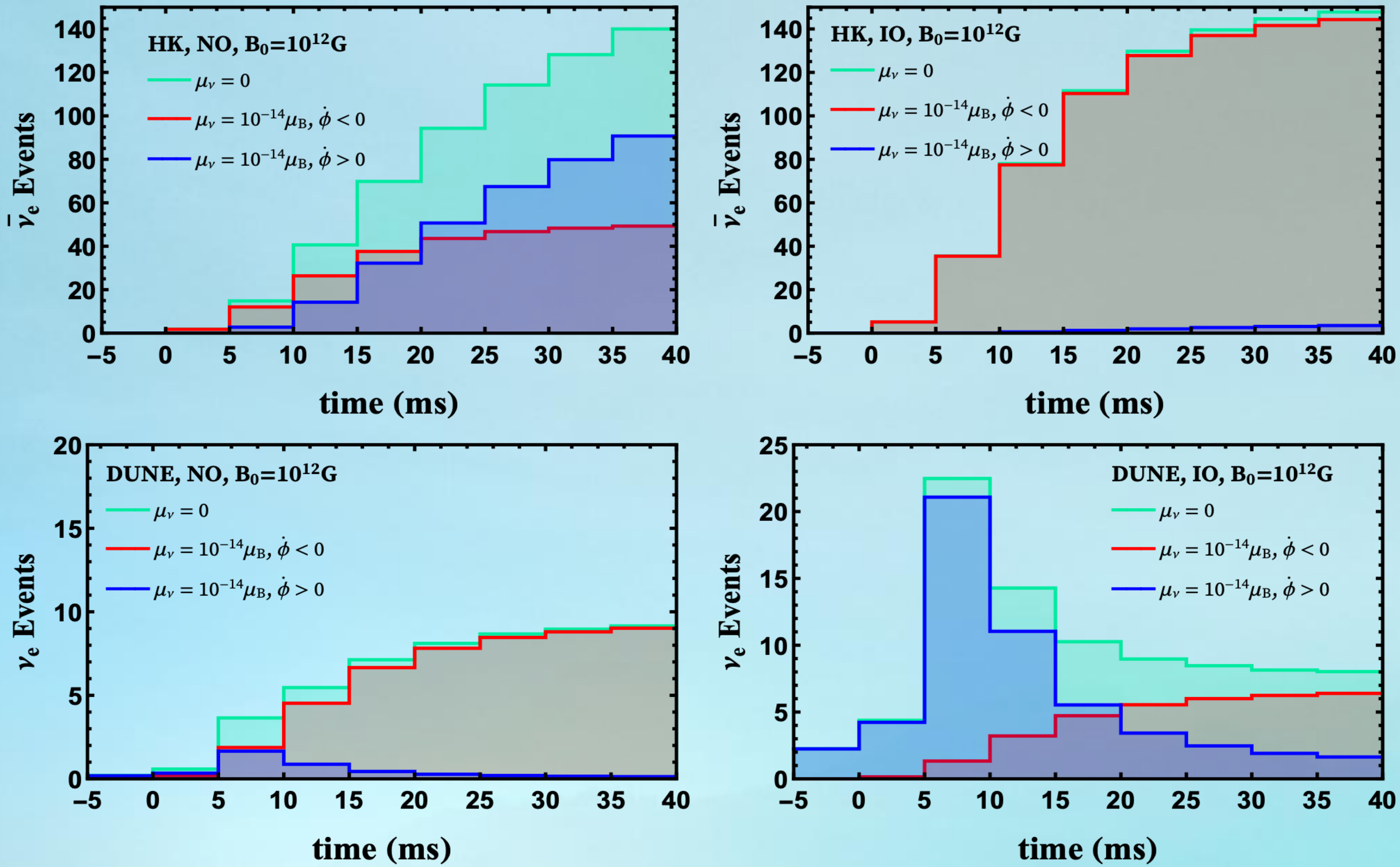


Simplified Picture of Flavor Conversions

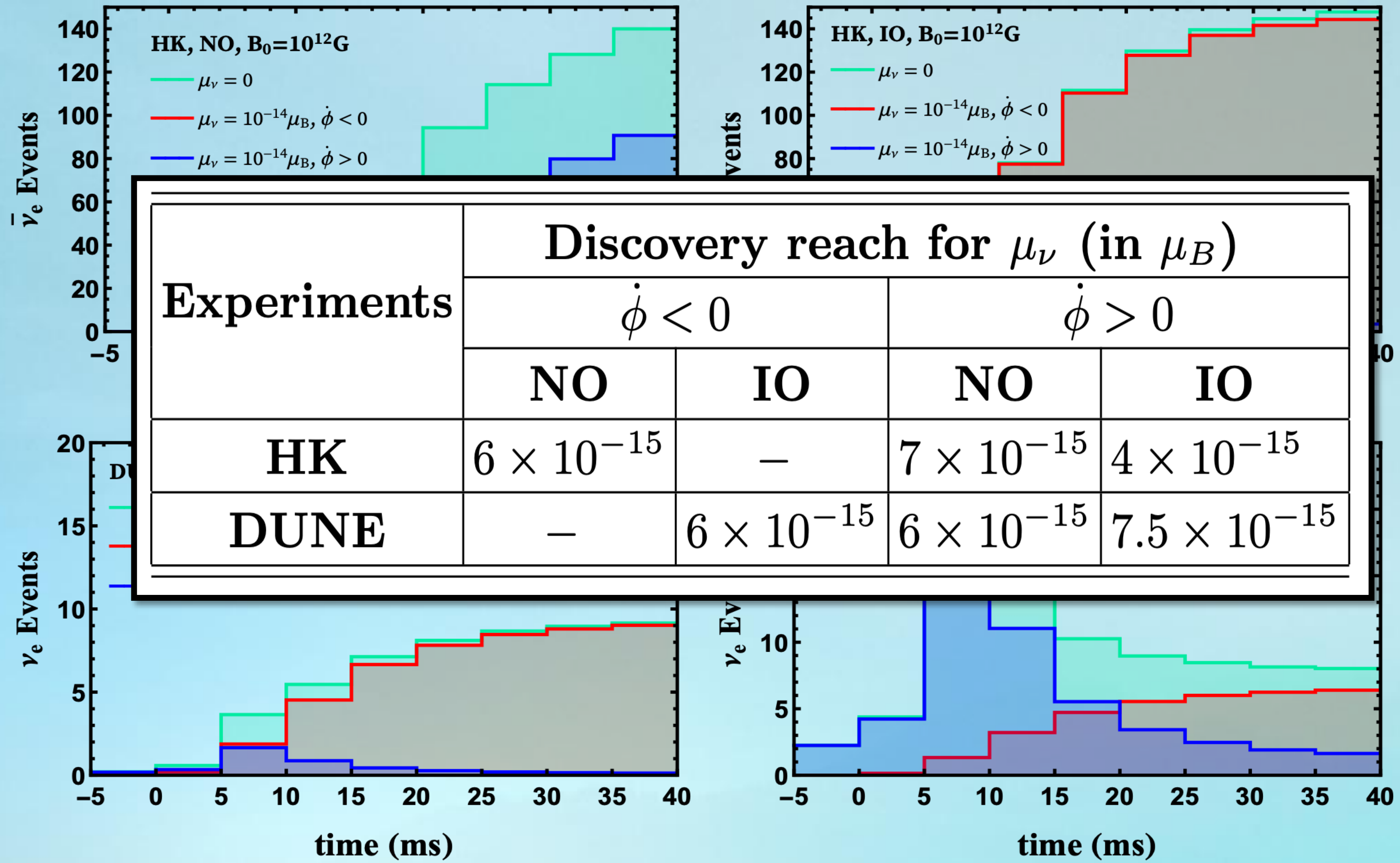


Spin flip resonance
SJ, Porto (**PRL (2024)**, arXiv: 2303.13572)
~ 2000 km

Neutrino spectra at DUNE and HK



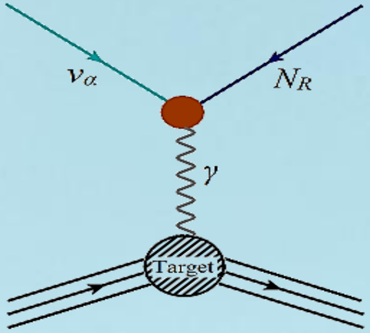
Neutrino spectra at DUNE and HK



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}

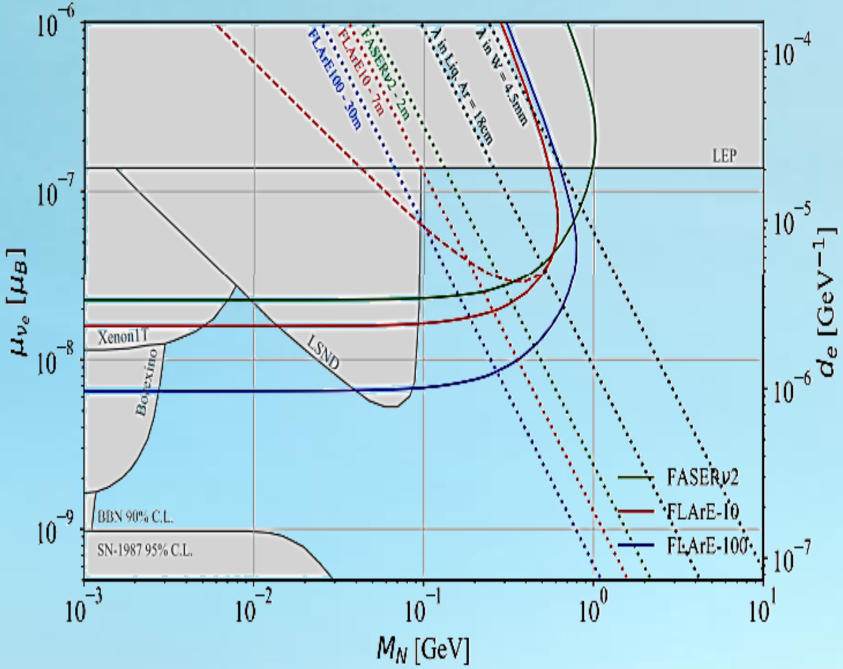
Active to sterile transition magnetic moments

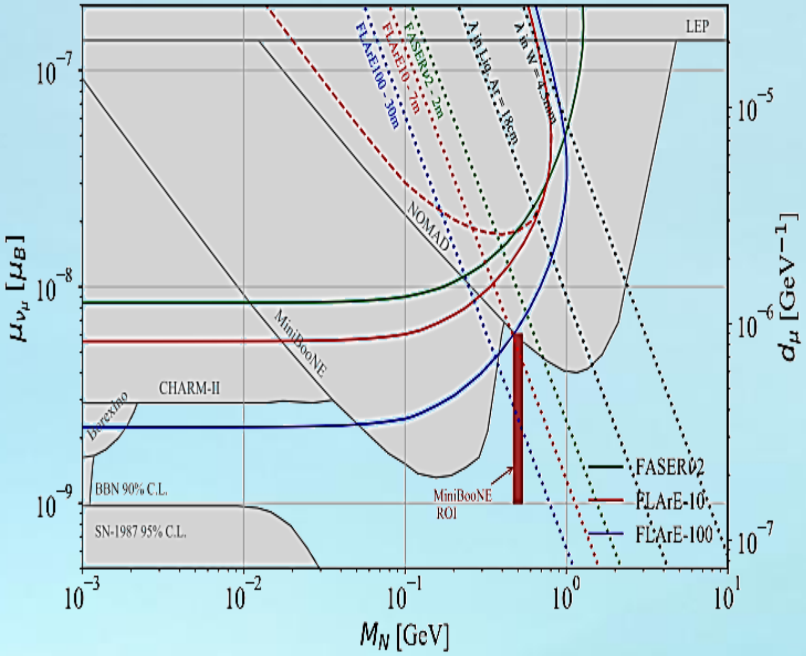
*Triggered by the several anomalies such as **XENON1T** and the long-standing **MiniBooNE** anomalies, the **magnetic dipole portal** linking the active and sterile neutrinos has been recently received attention and studied at various facilities.*

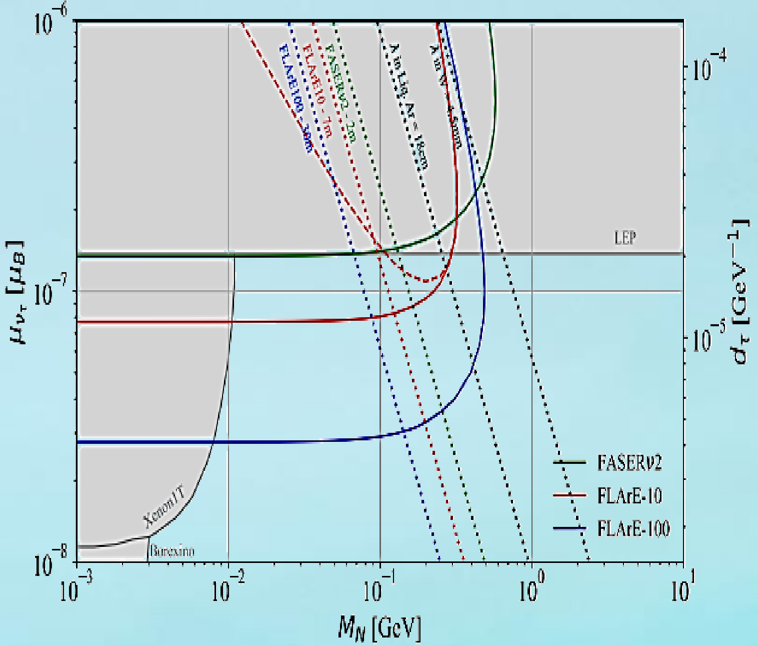


$$\mathcal{L}_{dipole} \supset \frac{1}{2}\mu_\nu^\alpha \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$

Ismail, **SJ**, Mammen Abraham (2021)





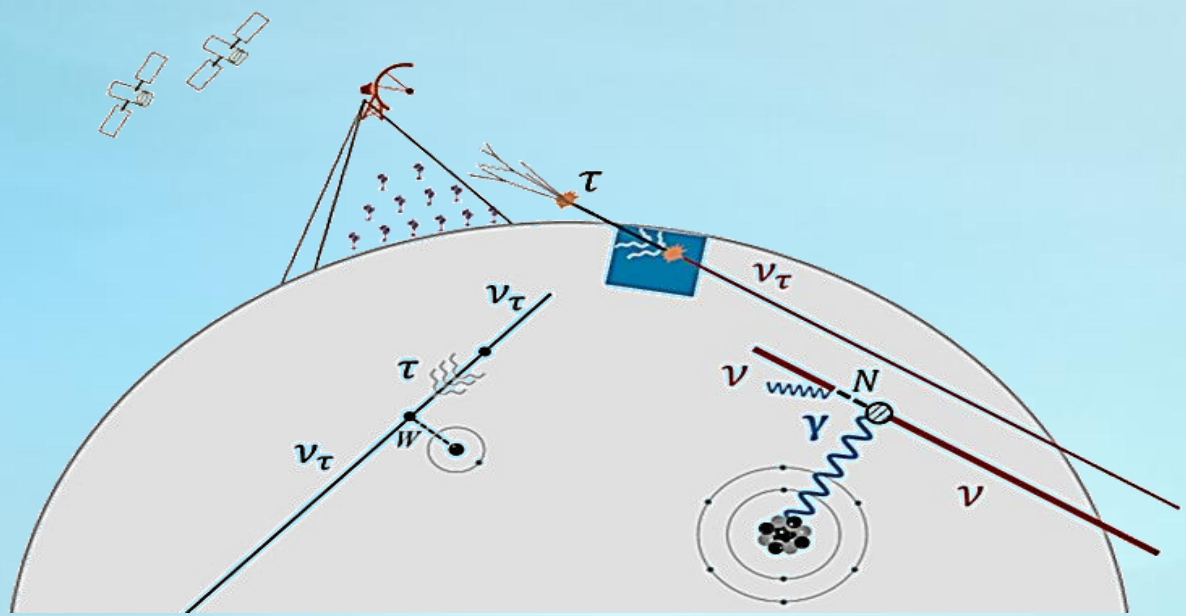


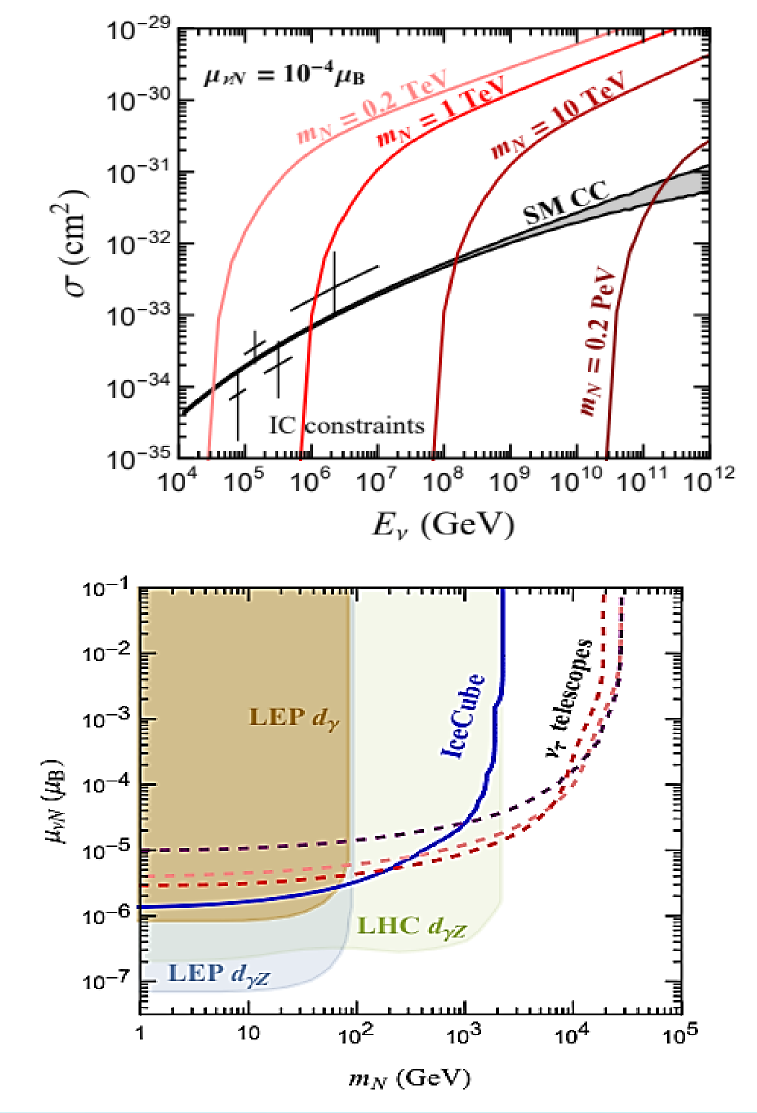
For other works on dipole portal in different contexts, see S. Gninenko (2009, 2012), Magill et al. (2018), Schwetz et al. (2020), Brdar et al. (2021), Shoemaker et al. (2021), Bolton et al. (2021), Miranda et al. (2021), Zhange et al. (2022), Jodłowski et al. (2020), Machado et al. (2023) …

Active to sterile transition magnetic moments

The EeV cosmogenic neutrino flux, though uncontrollable, represents a new energy frontier with collision energies much higher than what has been achieved by colliders. With this energy frontier, UHE neutrino telescopes have many advantages in probing certain new physics processes.

Primakoff production of heavy sterile neutrino via nu transition magnetic moment





Huang, **SJ**, Lindner, Rodejohann (2022)

How Charged is the Neutrino?

Electric (milli-) charge of neutrinos

Neutrinos can have nonzero neutrino electric millicharges. The introduction of a right-handed neutrino ν_R into the standard model brings a new hypercharge parameter, into the anomaly equations which destroys the charge quantization.

$$\mathcal{L} \supset q_{\nu_\alpha} \overline{\nu_\alpha} \gamma_\mu \nu_\alpha A^\mu$$

$$Q_{st} + \epsilon(L_i - L_j)$$

Consequences:

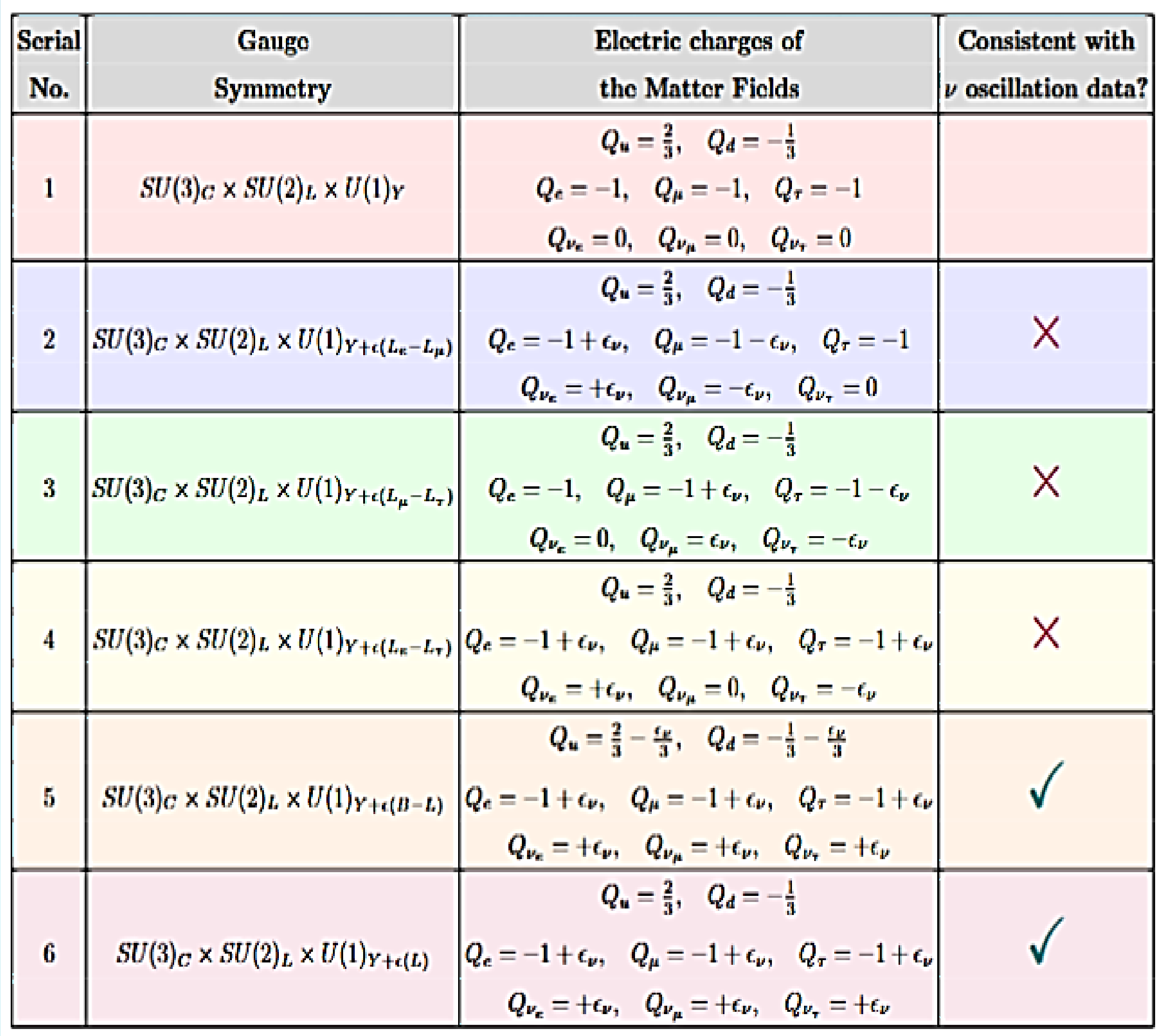
1. Charge conservation in β-decay
2. Physical consequences of charged atoms
3. Anomalous magnetic moments of charged leptons
4. Neutrino-electron/nucleon scattering
5. Energy loss in red giant and white dwarf stars
6. Limits on a cosmologically induced thermal photon mass

Constraints:

- $q_\nu \sim 10^{-21}$ **e** from neutrality of the hydrogen atom
- $q_\nu \leq 10^{-19}$ **e** from astrophysical limit (from the impact of the neutrino star turning mechanism)
- $q_\nu \leq 1.5 \times 10^{-11}$ **e** from reactor neutrino constraint

Studenikin (2019), Babu et al (1989), Foot et al. (1989), Sarkar et al. (2020), …

SJ, Vishnu, Klassen (to appear)



Serial No.	Gauge Symmetry	Electric charges of the Matter Fields	Consistent with ν oscillation data?
1	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$Q_u = \frac{2}{3},\ Q_d = -\frac{1}{3}$ $Q_e = -1,\ Q_\mu = -1,\ Q_\tau = -1$ $Q_{\nu_e} = 0,\ Q_{\nu_\mu} = 0,\ Q_{\nu_\tau} = 0$	
2	$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L_e - L_\mu)}$	$Q_u = \frac{2}{3},\ Q_d = -\frac{1}{3}$ $Q_e = -1+\epsilon_\nu,\ Q_\mu = -1-\epsilon_\nu,\ Q_\tau = -1$ $Q_{\nu_e} = +\epsilon_\nu,\ Q_{\nu_\mu} = -\epsilon_\nu,\ Q_{\nu_\tau} = 0$	✗
3	$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L_\mu - L_\tau)}$	$Q_u = \frac{2}{3},\ Q_d = -\frac{1}{3}$ $Q_e = -1,\ Q_\mu = -1+\epsilon_\nu,\ Q_\tau = -1-\epsilon_\nu$ $Q_{\nu_e} = 0,\ Q_{\nu_\mu} = \epsilon_\nu,\ Q_{\nu_\tau} = -\epsilon_\nu$	✗
4	$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L_e - L_\tau)}$	$Q_u = \frac{2}{3},\ Q_d = -\frac{1}{3}$ $Q_e = -1+\epsilon_\nu,\ Q_\mu = -1+\epsilon_\nu,\ Q_\tau = -1+\epsilon_\nu$ $Q_{\nu_e} = +\epsilon_\nu,\ Q_{\nu_\mu} = 0,\ Q_{\nu_\tau} = -\epsilon_\nu$	✗
5	$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(B-L)}$	$Q_u = \frac{2}{3} - \frac{\epsilon_\nu}{3},\ Q_d = -\frac{1}{3} - \frac{\epsilon_\nu}{3}$ $Q_e = -1+\epsilon_\nu,\ Q_\mu = -1+\epsilon_\nu,\ Q_\tau = -1+\epsilon_\nu$ $Q_{\nu_e} = +\epsilon_\nu,\ Q_{\nu_\mu} = +\epsilon_\nu,\ Q_{\nu_\tau} = +\epsilon_\nu$	✓
6	$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L)}$	$Q_u = \frac{2}{3},\ Q_d = -\frac{1}{3}$ $Q_e = -1+\epsilon_\nu,\ Q_\mu = -1+\epsilon_\nu,\ Q_\tau = -1+\epsilon_\nu$ $Q_{\nu_e} = +\epsilon_\nu,\ Q_{\nu_\mu} = +\epsilon_\nu,\ Q_{\nu_\tau} = +\epsilon_\nu$	✓

Other electromagnetic properties of neutrino

Electric (milli-) charge of neutrinos

Neutrinos can have nonzero neutrino electric millicharges. The introduction of a right-handed neutrino ν_R into the standard model brings a new hypercharge parameter, into the anomaly equations which destroys the charge quantization.

$$\mathcal{L} \supset q_{\nu_\alpha} \overline{\nu_\alpha} \gamma_\mu \nu_\alpha A^\mu$$

$$Q_{st} + \epsilon(L_i - L_j)$$

Consequences:

1. Charge conservation in β-decay
2. Physical consequences of charged atoms
3. Anomalous magnetic moments of charged leptons
4. Neutrino-electron/nucleon scattering
5. Energy loss in red giant and white dwarf stars
6. Limits on a cosmologically induced thermal photon mass

Constraints:

- **$q_\nu \sim 10^{-21}$ e** from neutrality of the hydrogen atom
- **$q_\nu \leq 10^{-14}$ e** from astrophysical limit (from the impact of the neutrino star turning mechanism)
- **$q_\nu \leq 2 \times 10^{-14}$ e** from reactor neutrino constraint

Studenikin (2019), Babu et al (1989), Foot et al. (1989), Sarkar et al. (2020), …

Neutrino charge-radius

- Even if a neutrino millicharge is vanishing, the electric form factor can still contain nontrivial information about neutrino electromagnetic properties.

$$\langle r_{ij}^2 \rangle = -6 \frac{d f_Q^{ij}(q^2)}{dq^2} \Big|_{q^2=0}$$

- For a massless neutrino the neutrino charge radius is the only electromagnetic characteristic that can have nonzero value.

$$\langle r^2_{\nu_\alpha} \rangle_{\mathrm{SM}} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_\ell^2}{m_W^2}\right]$$

$$\langle r^2_{\nu_e} \rangle_{\mathrm{SM}} \simeq 4.1 \times 10^{-33}\ \mathrm{cm}^2$$

$$\langle r^2_{\nu_\mu} \rangle_{\mathrm{SM}} \simeq 2.4 \times 10^{-33}\ \mathrm{cm}^2$$

$$\langle r^2_{\nu_\tau} \rangle_{\mathrm{SM}} \simeq 1.5 \times 10^{-33}\ \mathrm{cm}^2$$

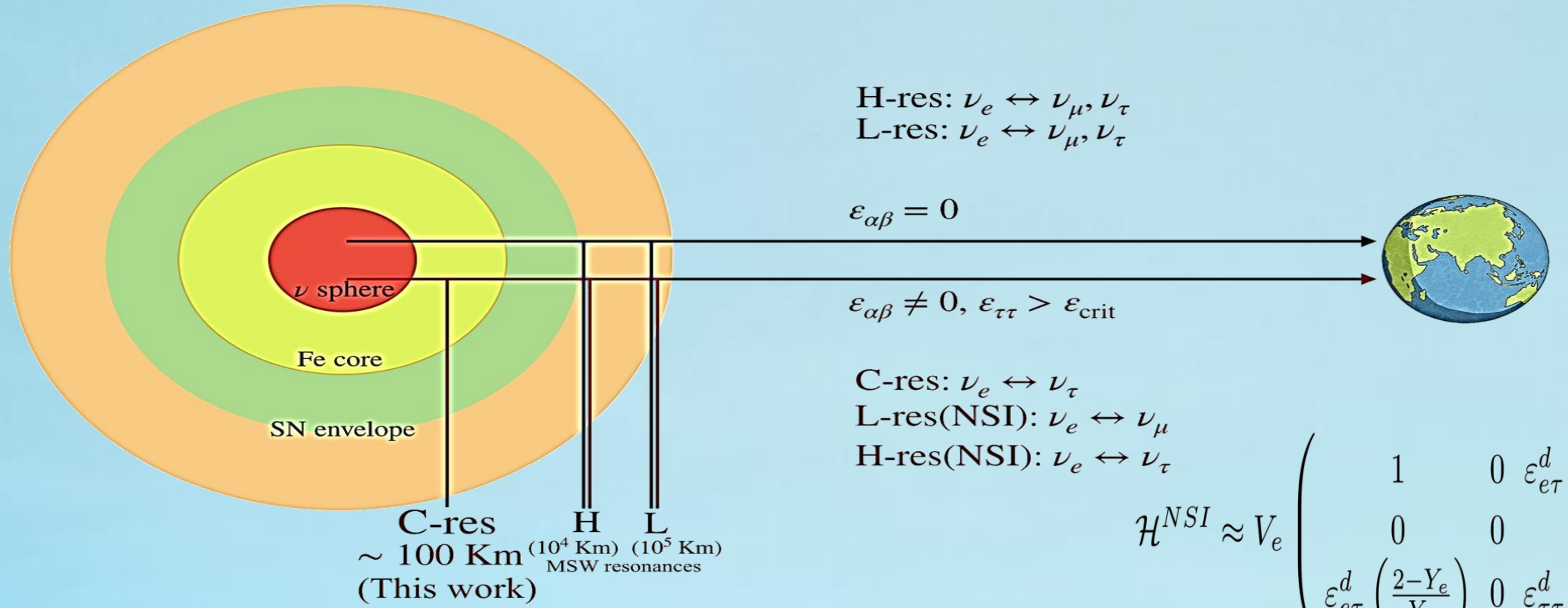
- The best constraints (in cm^2)come from CCFR and CHARM-II:

$$-2.6 \times 10^{-33} < \langle r^2_{\nu_e} \rangle < 6.6 \times 10^{-32}$$

$$-5.2 \times 10^{-33} < \langle r^2_{\nu_\mu} \rangle < 6.8 \times 10^{-33}$$

Bernabeu et al. (2000), Hirsch et al. (2003)…

Simplified Picture of Flavor Conversions due to NSI



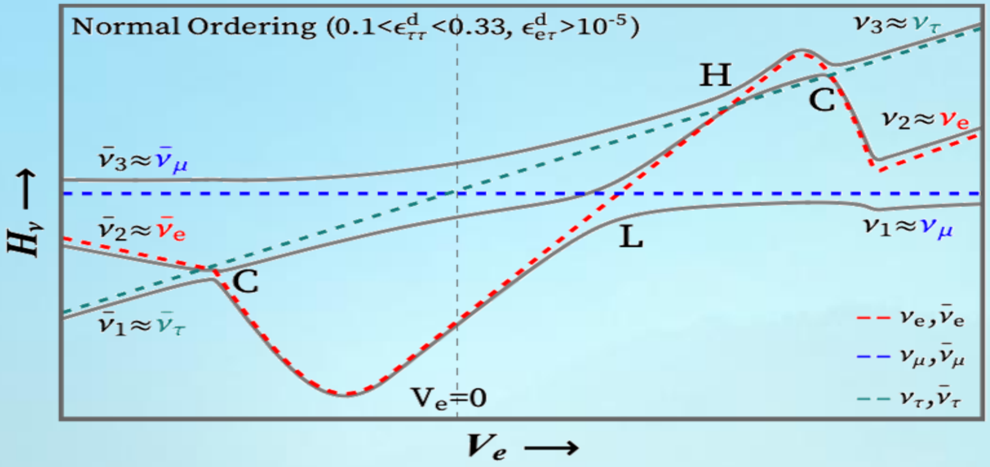
H-res: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$
L-res: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

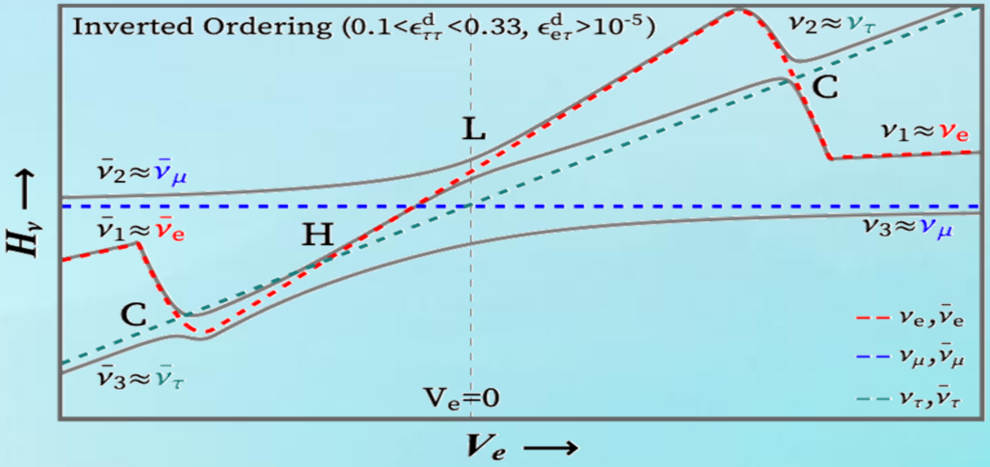
$\varepsilon_{\alpha\beta} = 0$

$\varepsilon_{\alpha\beta} \neq 0,\ \varepsilon_{\tau\tau} > \varepsilon_{\text{crit}}$

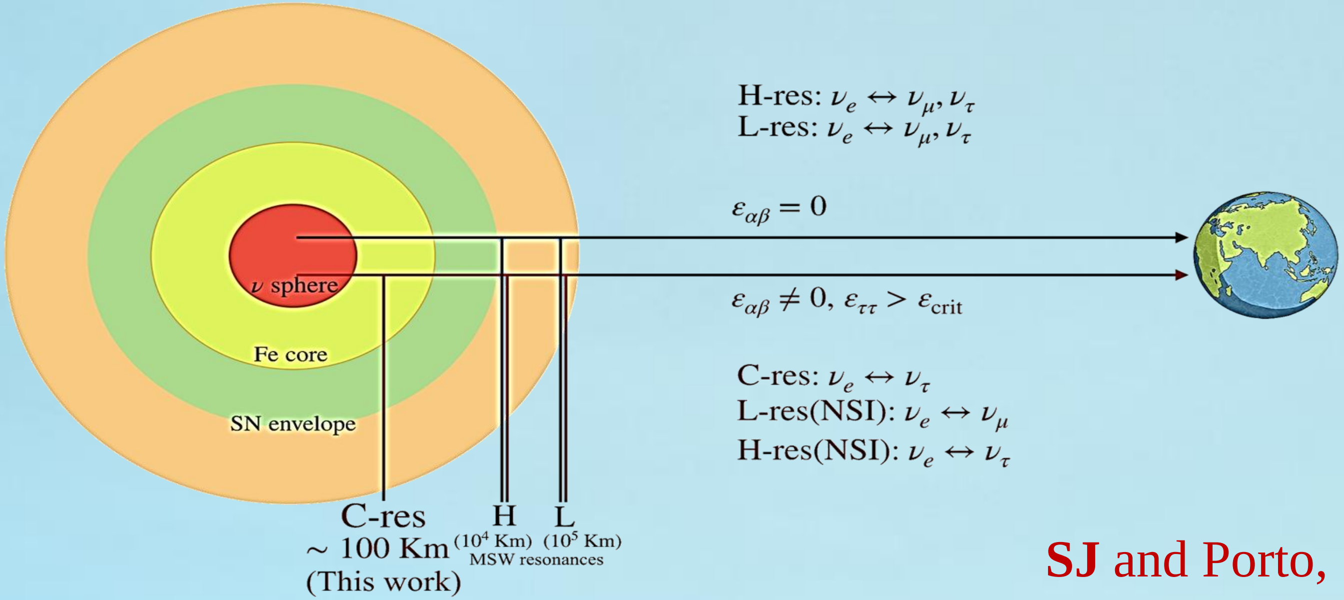
C-res: $\nu_e \leftrightarrow \nu_\tau$
L-res(NSI): $\nu_e \leftrightarrow \nu_\mu$
H-res(NSI): $\nu_e \leftrightarrow \nu_\tau$

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





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



H-res: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$
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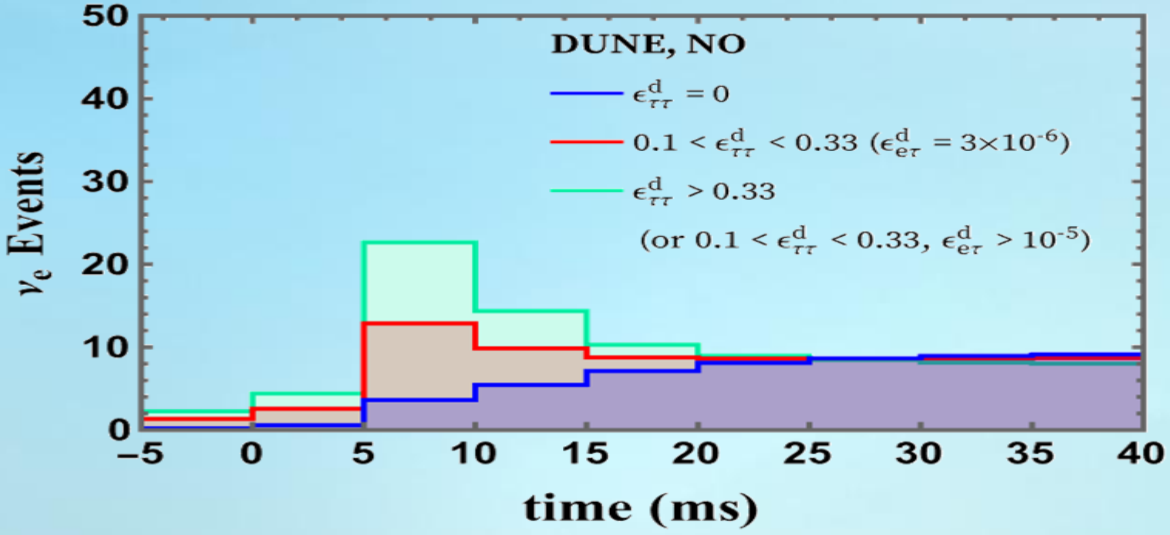
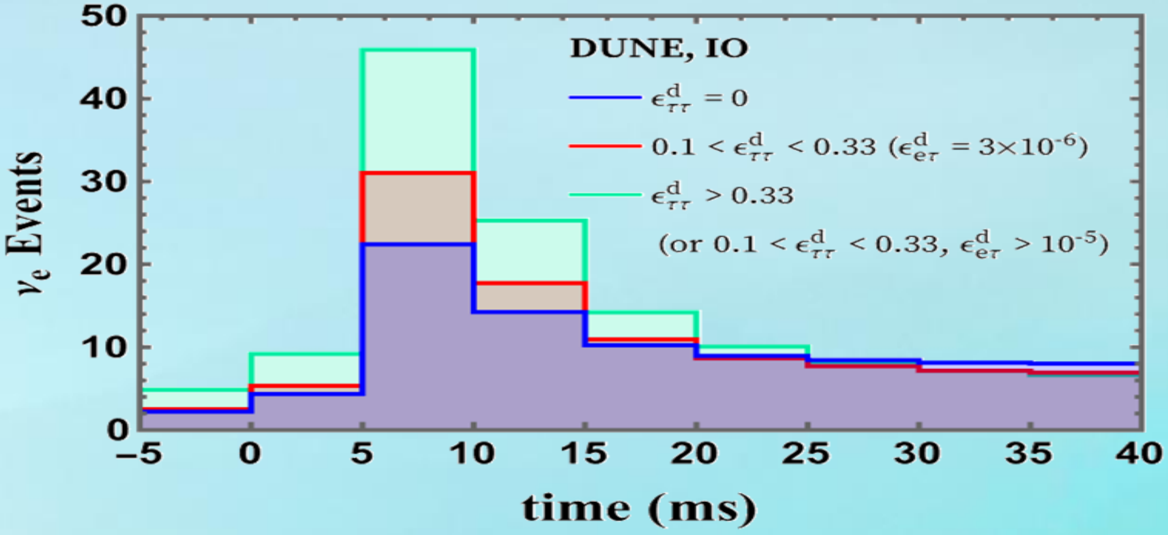
SJ and Porto, arXiv:2403:14762





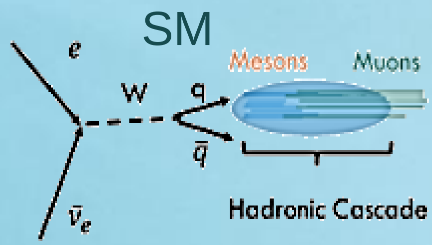
Many TeV–EeV ν telescopes in planning for 2020–2040

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediterranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational	☐	Date full operations began
Prototype	▨	Date protoype operations began or begin
Planning	▩	Projected full operations

Abraham *et al.* (inc. **MB**),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]

Probing neutrino mass models at neutrino telescopes



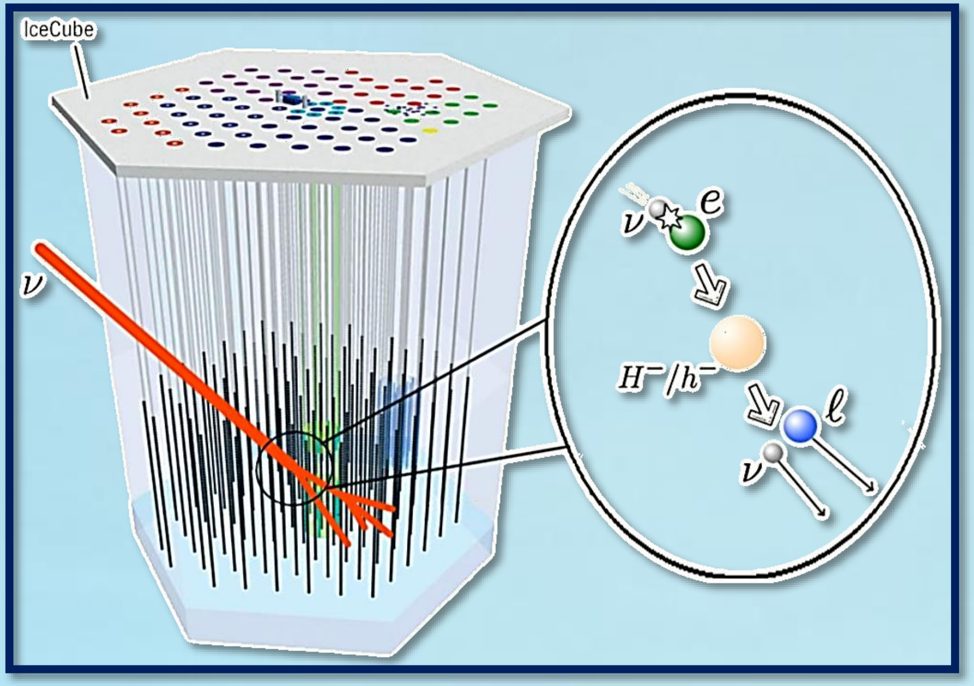
[Glashow (Phys. Rev. '60)]

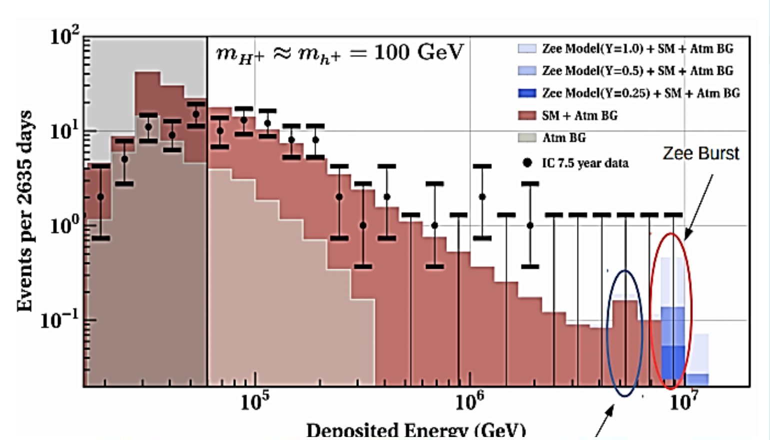
Glashow resonance

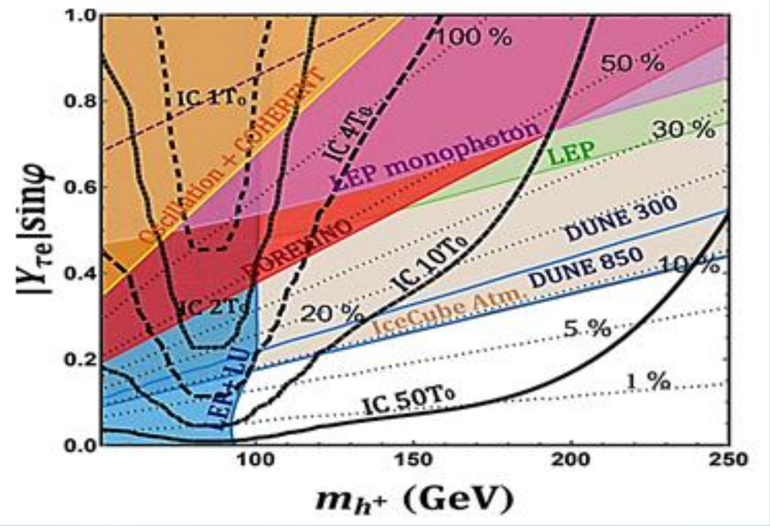
$$E_\nu = \frac{m_W^2}{2m_e} = 6.3\ \mathrm{PeV}$$

Recently observed by IceCube

[Nature **591**, 220 (2021)]







- Ultra High Energy neutrinos at IceCube can probe NSI in the Zee model
- $\overline{\nu_e} + e^- \to W^- \to$ anything has a resonant enhancement at

  $$E_\nu = \frac{m_W^2}{2m_e} = 6.3\,\mathrm{PeV} \quad \text{Glashow resonance}$$

- Since $h^\pm$ and $H^\pm$ in Zee model are allowed to be as light as 100 GeV, $\overline{\nu}_\alpha + e^- \to h^- \to$ anything is resonantly enhanced

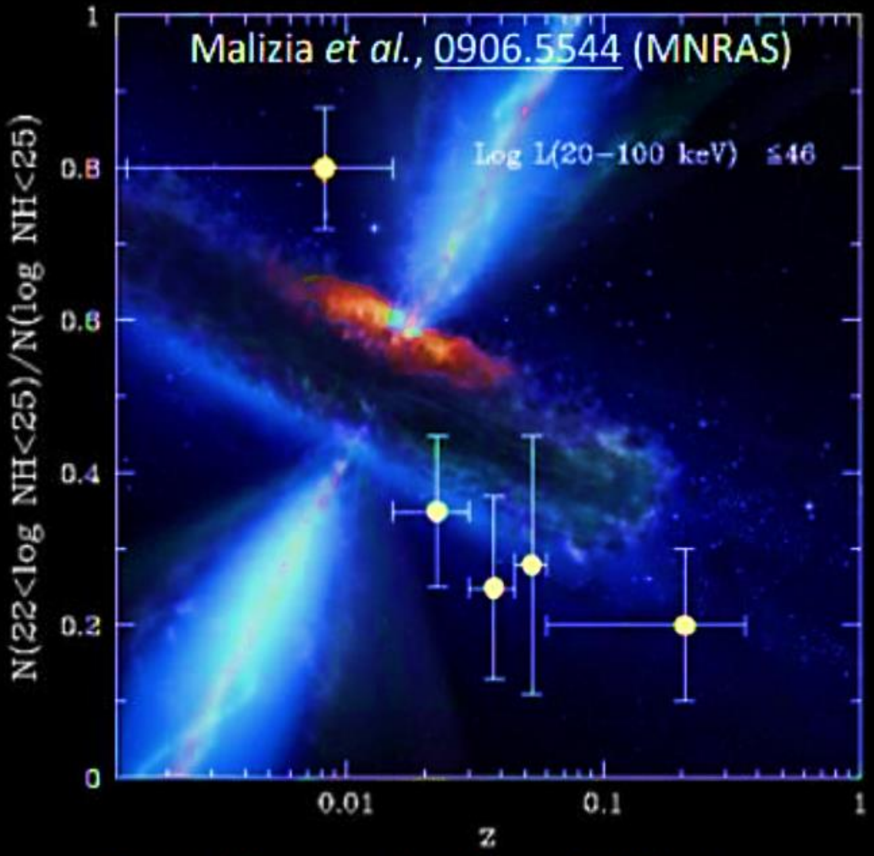
  $$E_\nu = \frac{m_h^2}{2m_e} \simeq 9.3\,\mathrm{PeV} \quad \text{“Zee burst”}$$

- We have analyzed this possibility of “Zee burst”

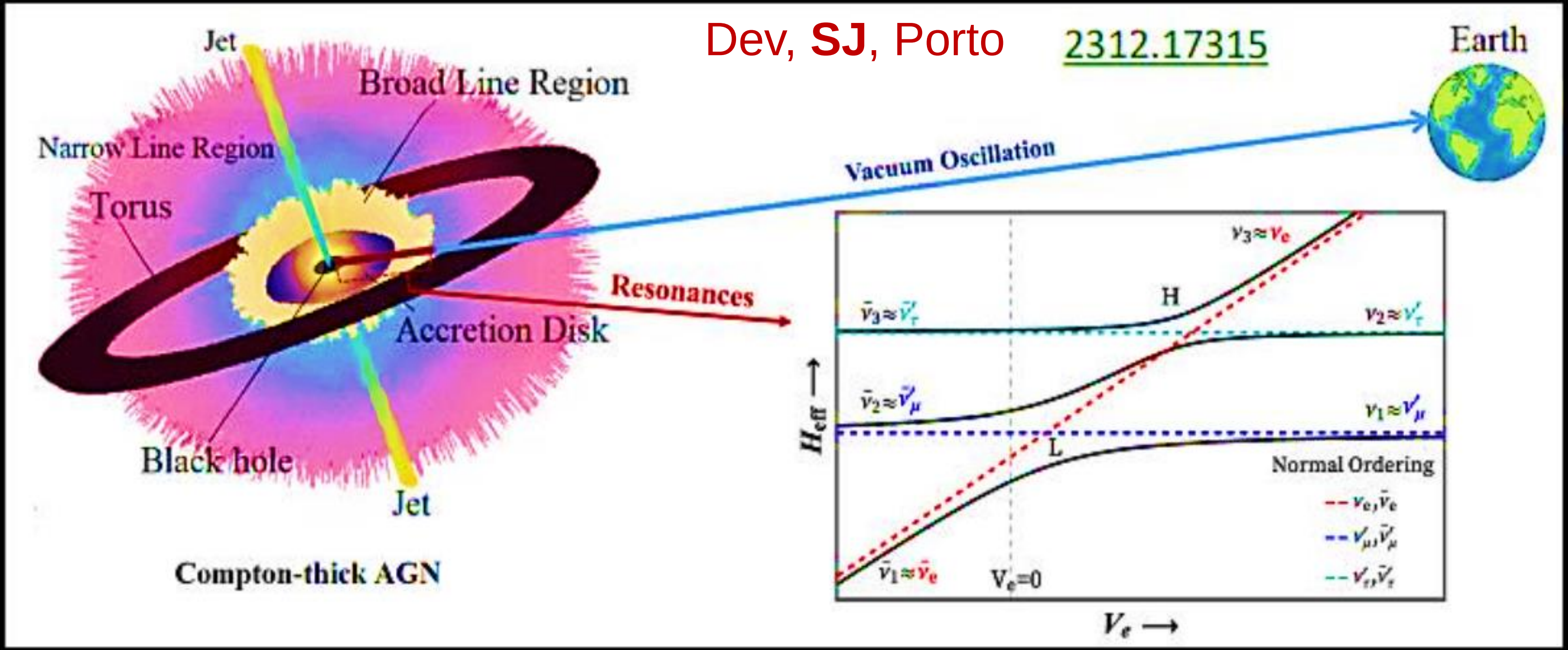
Babu, Dev, **SJ** , Sui (PRL 2019)
Babu, Dev, **SJ** (IJMPA 2020)
Huang, **SJ**, Lindner, Rodejohann (JCAP 2022)
Huang, **SJ**, Lindner, Rodejohann (PLB 2022)

MSW Resonance in Hidden Neutrino Sources

Column density $N_{\rm H} = \int n_e dr \geq \sigma_T^{-1} \simeq 1.5 \times 10^{24}\ \rm cm^{-2}$ corresponds to unity optical depth.


Malizia *et al.*, 0906.5544 (MNRAS)

- Roughly one in four AGNs is Compton thick.
- Maybe the reason why most of the HEN sources are unknown.

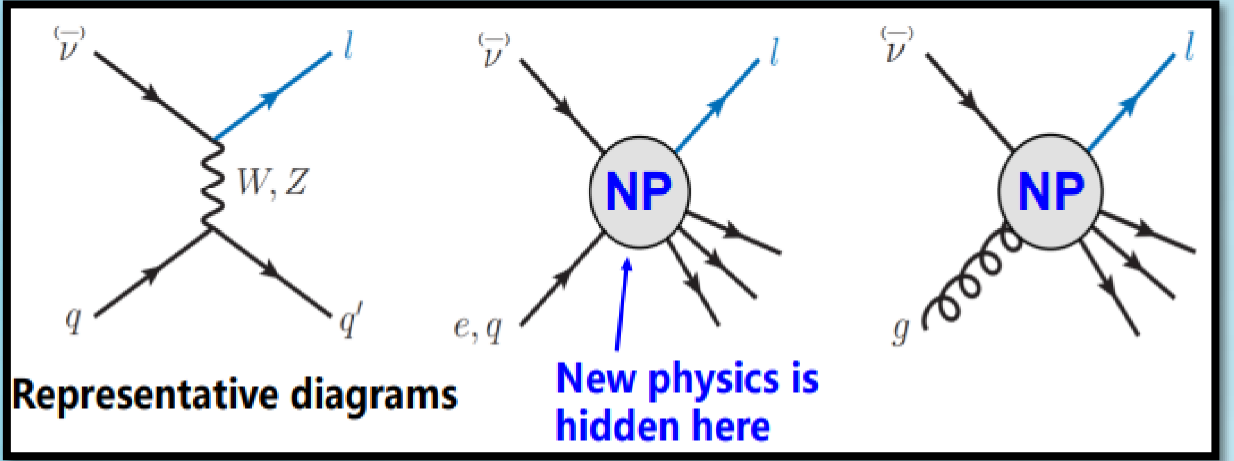

Dev, **SJ**, Porto 2312.17315

- Neutrinos from Compton-thick AGNs *must* undergo source matter effect.
- Resonant flavor conversion, analogous to the supernova case.

$$\boxed{\sqrt{2} G_F n_e^{\rm res} = \frac{\Delta m_{i1}^2}{2E_\nu} \cos 2\theta_{1i}.}$$

Can drastically change the flavor composition of HENs.

BSM physics with neutrino telescopes

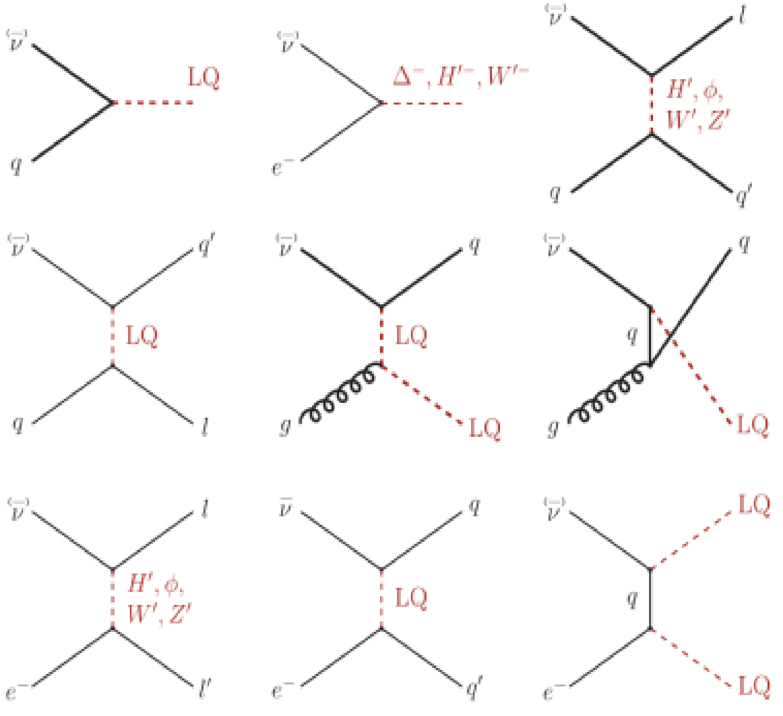


Representative diagrams

New physics is hidden here

*The **EeV cosmogenic neutrino flux**, represents **a new energy frontier** with collision energies much higher than what has been achieved by colliders. With this energy frontier, UHE neutrino telescopes have many advantages in probing certain new physics processes.*

Our beams: neutrino + electron, quark, gluon



Leptoquark

$y^{\mathrm{QL}}_{i\alpha}\overline{Q^{c}}^{i}\left(\epsilon\sigma^{a}\right)L^{\alpha}S_{3}^{a}$

Charged/neutral Higgs

$y^{l}_{\alpha\beta}h^{-}\bar{l}_{\alpha}\nu^{c}_{\beta}+y^{q}_{\alpha\beta}h^{-}\bar{D}_{\alpha}U_{\beta}$

W'

$\frac{g'}{2\sqrt{2}}W'_{\mu}\bar{f}^{i}\gamma^{\mu}(1\pm\gamma_{5})f^{j}$

Z'

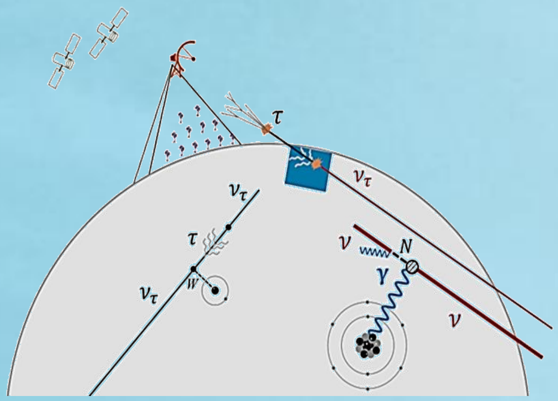
$\frac{g'}{2\sqrt{2}}Z'_{\mu}\bar{f}^{i}\gamma^{\mu}(1\pm\gamma_{5})f^{i}$

Leptophilic forces

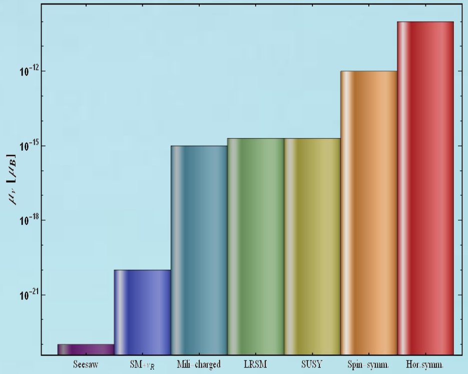
$y^{l}\phi\bar{l}l+y^{\nu}\phi\bar{\nu}\nu$

Huang, **SJ**, Lindner, Rodejohann (JCAP 2022)
Huang, **SJ**, Lindner, Rodejohann (PLB 2022)

1. *Lorentz invariance, quantum gravity*
2. *Test of equivalence principle*
3. *Fifth Force*
4. *Unitarity*
5. *Microscopic black hole*
6. *Transition magnetic moment*



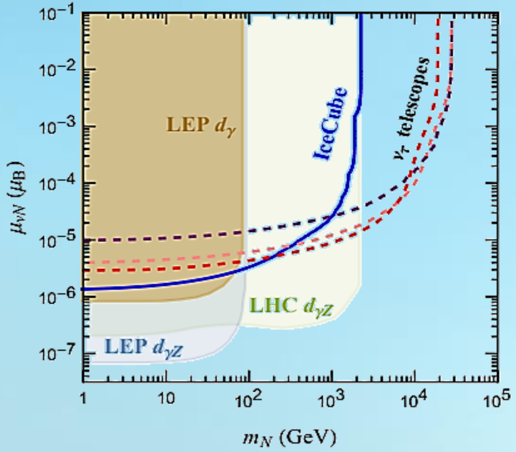
Summary

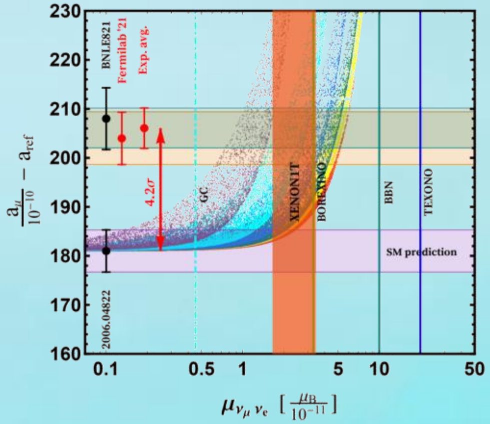


1. ***The theoretical and experimental investigation of neutrino electromagnetic interactions can serve as a powerful tool in the search for the fundamental theory behind the neutrino mass generation mechanism.***

2. ***Anomalous electromagnetic properties of charged leptons and neutrinos can be correlated.***

3. ***If neutrinos are Dirac particles possessing large magnetic moments, the new resonance effect will present the most optimal avenue towards unravelling the scenario at hand.***





……

Thank you!