Shining Light on Neutrinos: Exploring Electromagnetic Properties

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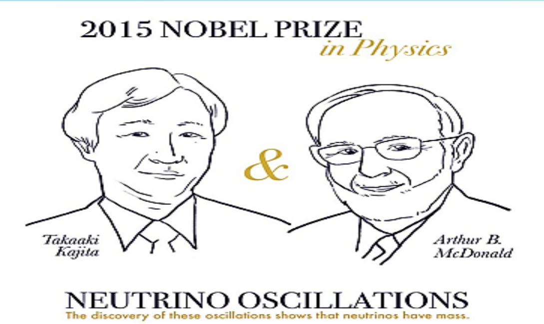
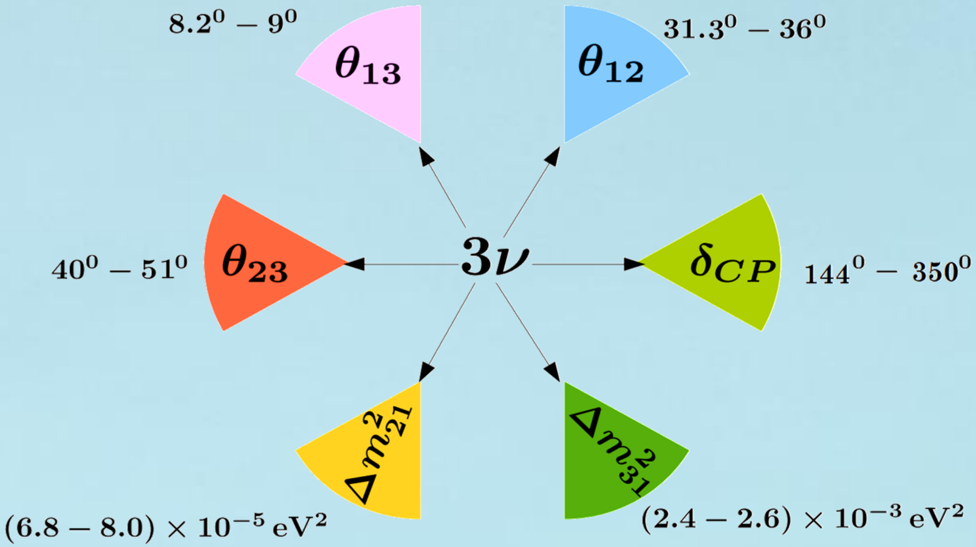
Current knowledge of neutrino oscillations

1. Neutrinos in the Standard Model are ***massless.*** $L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$ $\qquad m_\nu = 0$

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)

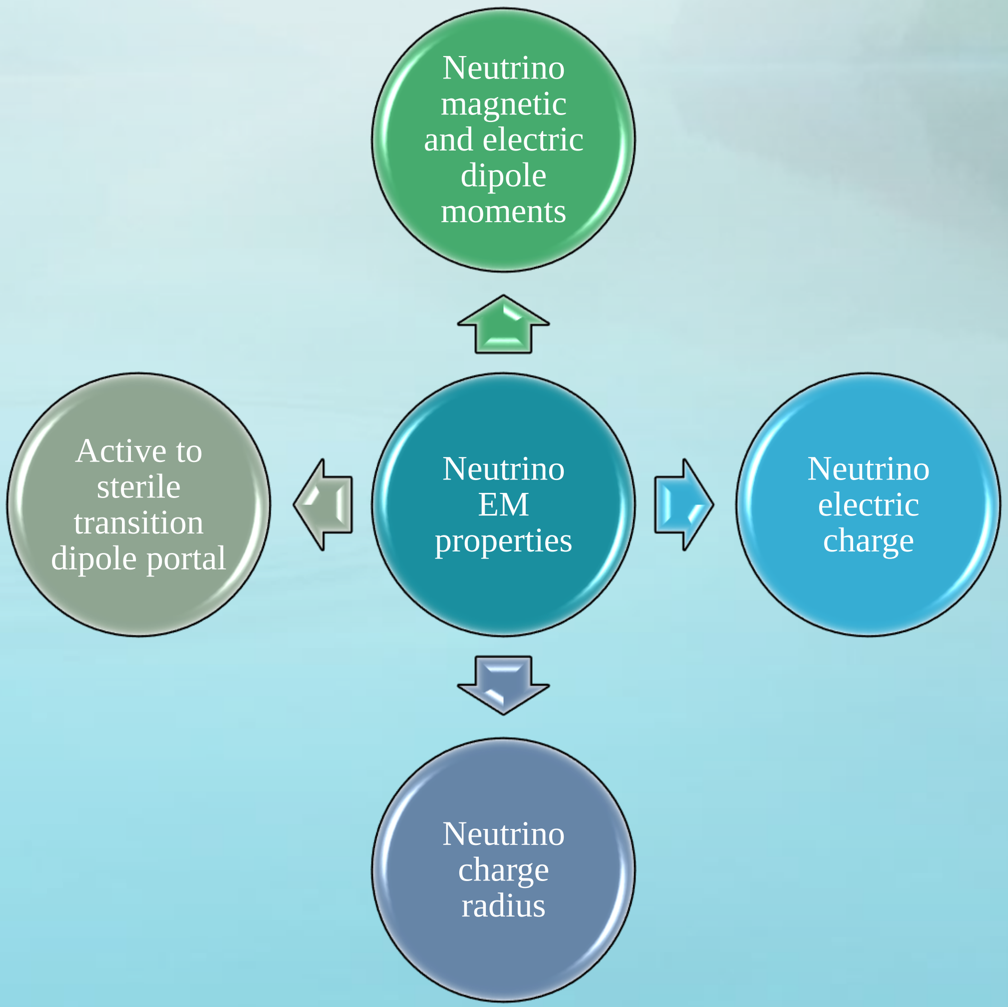
PMNS matrix

Flavor eigenstate — *Mass eigenstate*

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

Neutrino electromagnetic properties

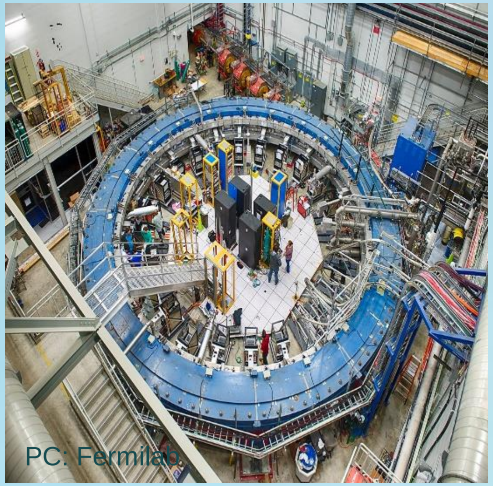
- *In the Standard Model, neutrinos do not have direct coupling to photons.*
- *Quantum loop corrections can induce electromagnetic properties of neutrino.*
- *Study of neutrino electromagnetic interactions may shed light on the underlying theory.*
- *Anomalous electromagnetic properties of charged leptons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



Talk is based on:

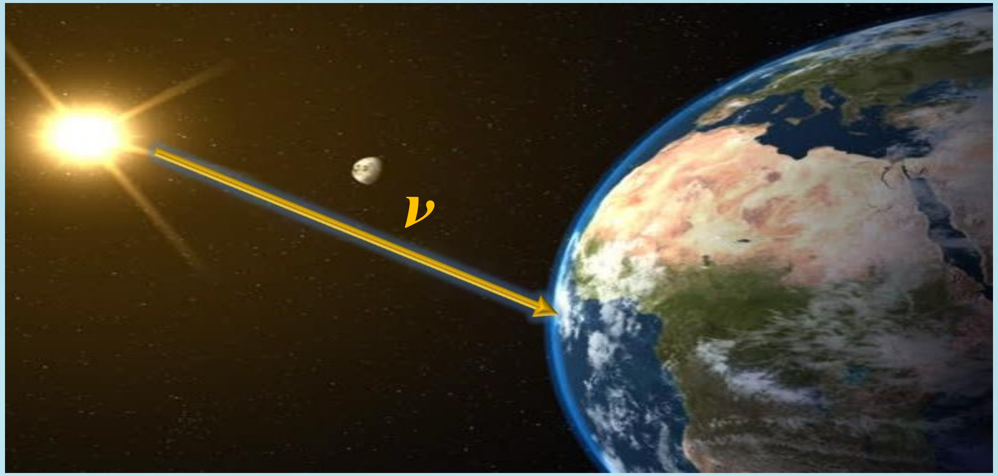
1. Babu, **SJ**, Lindner, (JHEP 2020)
2. Babu, **SJ**, Lindner, Vishnu, (JHEP 2021)
3. Ismail, **SJ**, Roshan, (PRD 2021)
4. **SJ**, Porto-Silva, Sen, (JCAP 2022)
5. Huang, **SJ**, Lindner, Rodejohann, (JCAP 2022)
6. **SJ**, Porto (2023)

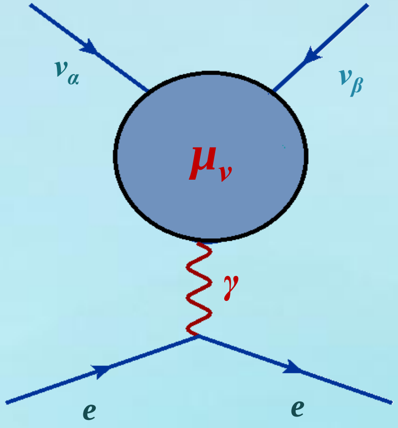
Charged lepton magnetic moments

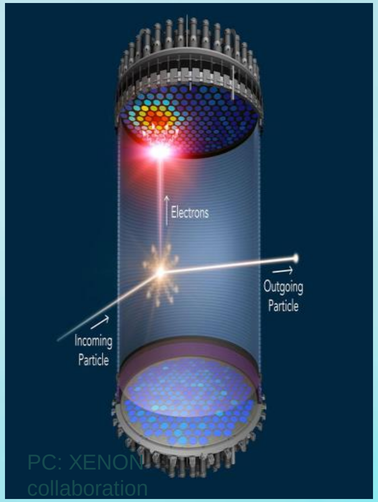


How much do they rotate
on their axes in a powerful magnetic field
as they race around the magnet?

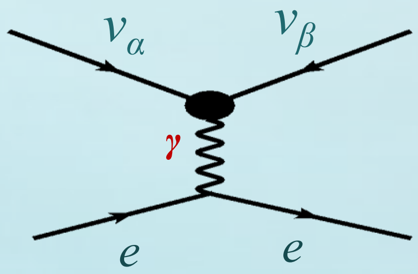
Neutrino magnetic moments





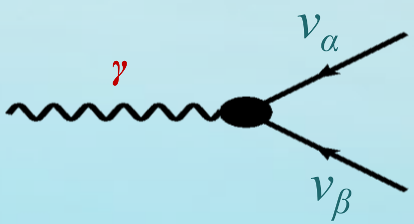


Consequences of neutrino magnetic moments



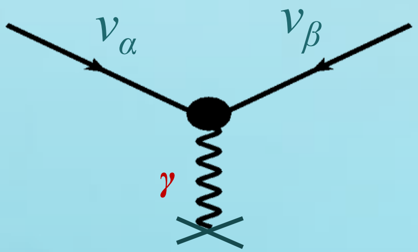
Scattering

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



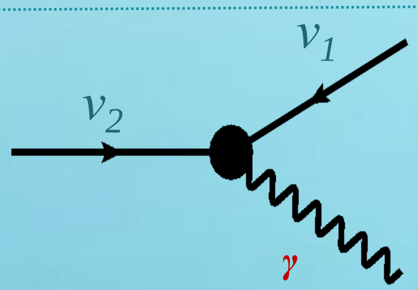
Plasmon decays in stars

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



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

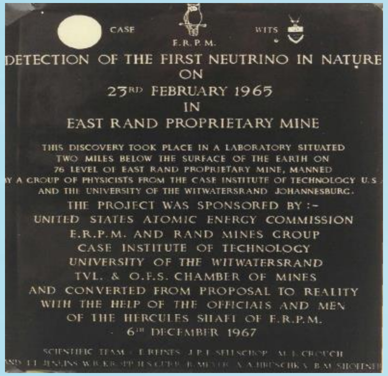
$$\Gamma = \frac{\mu_\nu^2}{8\pi}\left(\frac{m_2^2 - m_1^2}{m_2}\right)^3$$

Neutrino magnetic moments: experimental status

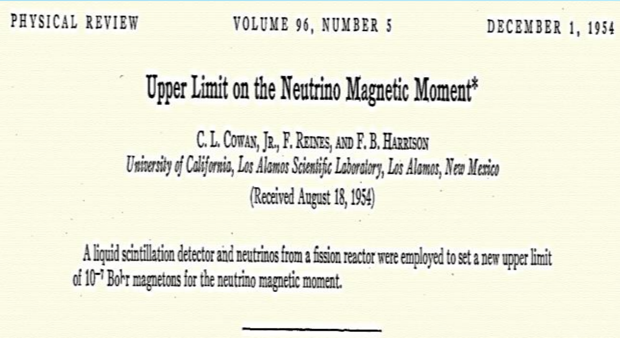
- The quest for measuring neutrino magnetic moments was begun <u>even before the discovery of the neutrino</u>.

Frederick Reines

1995 Nobel Prize in Physics
for his co-detection of the neutrino with Clyde Cowan in the neutrino experiment.



- Cowan, Reines and Harrison set an upper limit in the process of measuring background for a free neutrino search experiment with reactor antineutrinos.

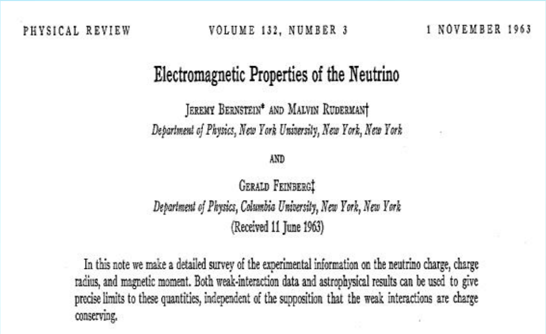


PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

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)

A liquid scintillation detector and neutrinos from a fission reactor were employed to set a new upper limit of 10^{-7} Bohr magnetons for the neutrino magnetic moment.



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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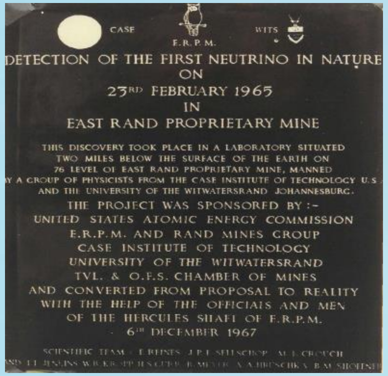

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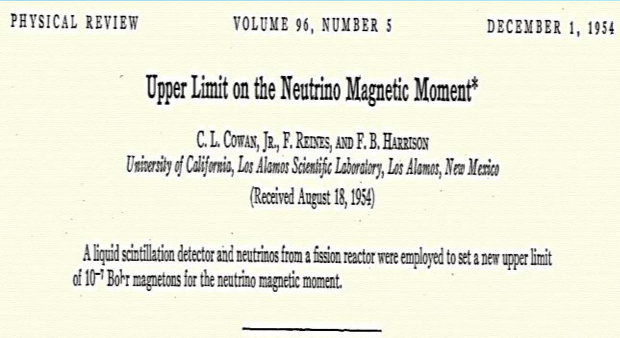

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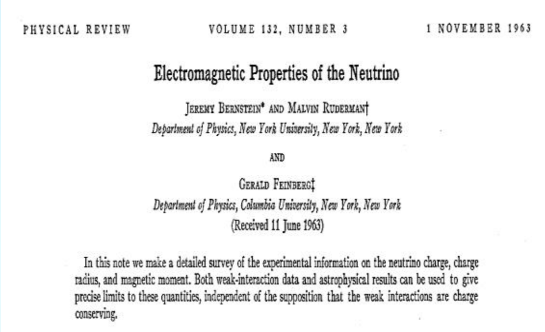

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Reactor

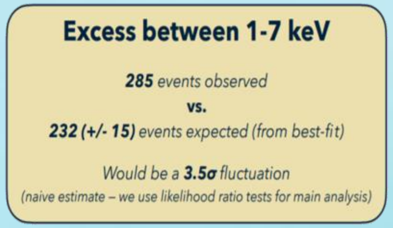
- KRASNOYARSK (1992): $\mu_\nu < 2.7 \times 10^{-10}\,\mu_B$
- ROVNO (1993): $\mu_\nu < 1.9 \times 10^{-10}\,\mu_B$
- MUNU (2005): $\mu_\nu < 1.2 \times 10^{-10}\,\mu_B$
- TEXONO (2010): $\mu_\nu < 2.0 \times 10^{-10}\,\mu_B$
- GEMMA (2012): $\mu_\nu < 2.9 \times 10^{-11}\,\mu_B$
- CONUS (2022): $\mu_\nu < 7.0 \times 10^{-11}\,\mu_B$

Accelerator

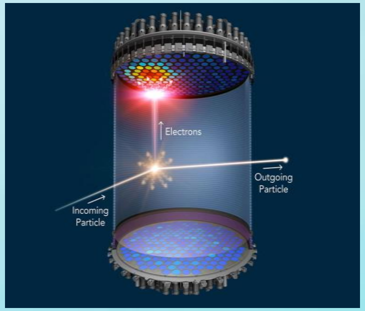
- LAPMF (1993): $\mu_\nu < 7.4 \times 10^{-10}\,\mu_B$
- LSND (2002): $\mu_\nu < 6.4 \times 10^{-10}\,\mu_B$

Solar

- Borexino (2017): $\mu_\nu < 2.8 \times 10^{-11}\,\mu_B$
- **XENONnT (2022):** $\boldsymbol{\mu_\nu < 6.4 \times 10^{-12}\,\mu_B}$

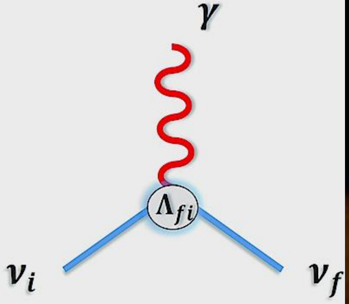


E. Aprile et al. (2020)



XENON Collaboration,

Neutrino Magnetic Moments: from astrophysics and cosmology

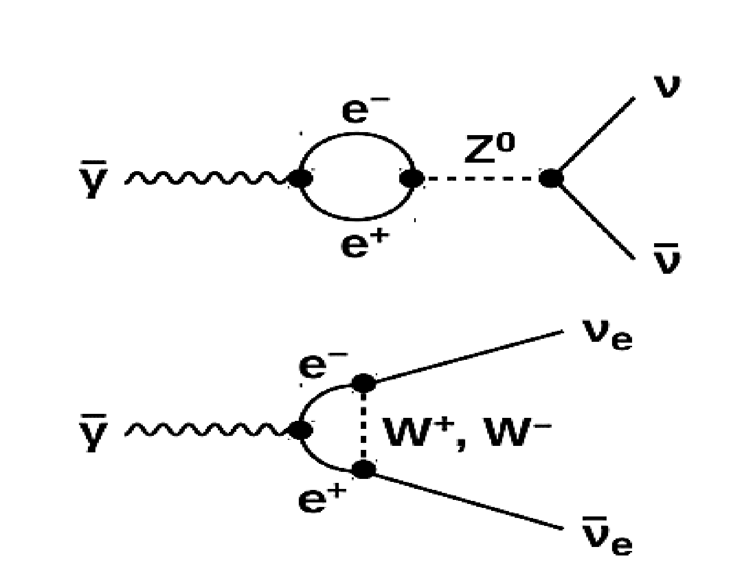


***Photons in the plasma** of stellar environments **can decay** either into $\nu\bar{\nu}$ for the case of Dirac neutrinos or into $\nu_\alpha \nu_\beta$ for the case of Majorana neutrinos.*

*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: $\boldsymbol{\mu_\nu < 1.5 \times 10^{-12}\, \mu_B}$ **Raffelt et al.(2013, 2021), Barbieri and Mohapatra (1988) from SN1987A signal***

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



esy: NASA

Neutrino Magnetic Moments: from astrophysics and cosmology

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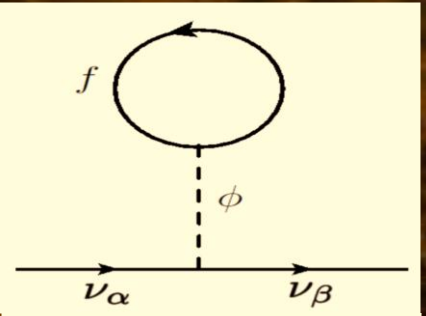
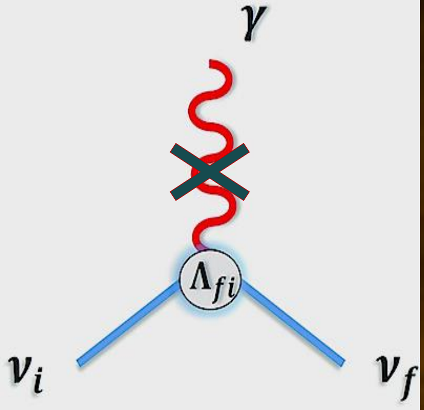
Neutrino Trapping Mechanism

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



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



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)

Courtesy: NASA

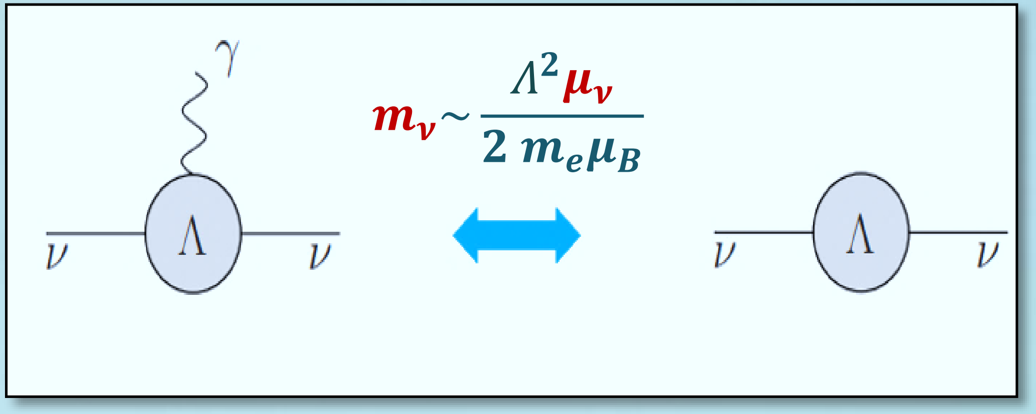
Neutrino magnetic moment – mass conundrum

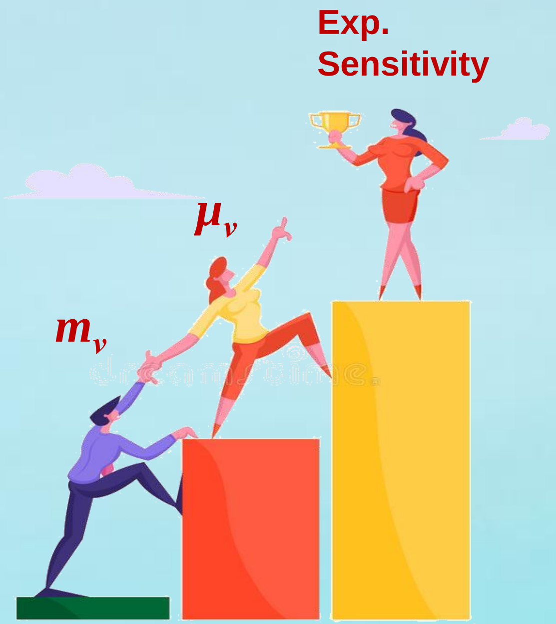
- The magnetic moment and the mass operators are both ***chirality flipping***.

- 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 $\boldsymbol{\mu_\nu \sim 10^{-11}\, \mu_B}$.

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





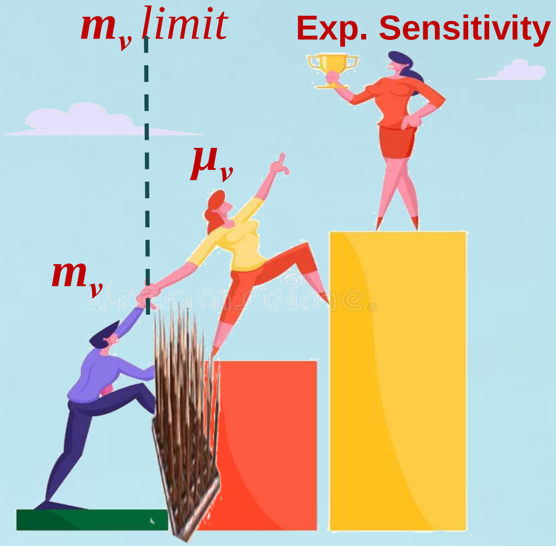
Neutrino magnetic moment – mass conundrum

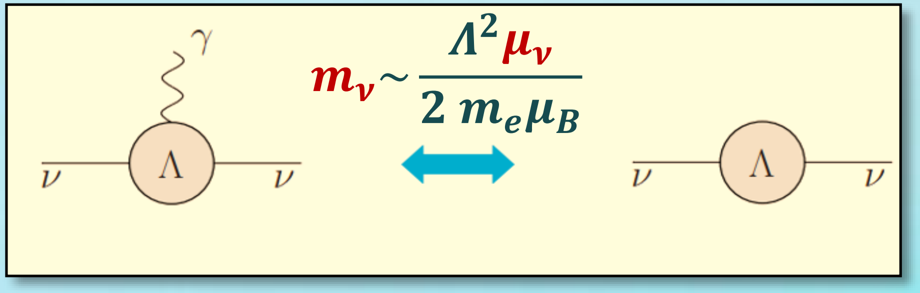
*This conundrum was well recognized **three decades ago** when there was great interest in explaining **the apparent time variation of solar neutrino flux detected by the Chlorine experiment in anti-correlation with the Sun-spot activity**.*

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.



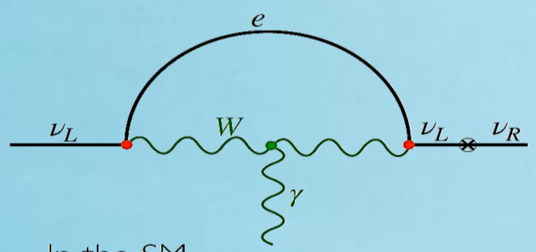


Neutrino magnetic moment – mass conundrum

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:

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



In the SM

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

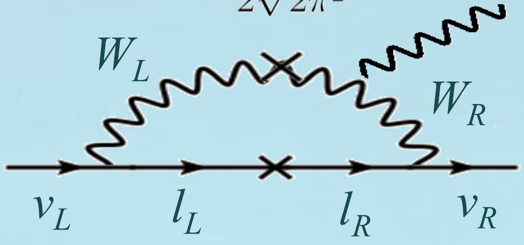
K. Fujikawa and R. Shrock (1980)

Bell et al. (2005)

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:

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



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

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 $\mu_\nu \sim 10^{-23} \mu_B$

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

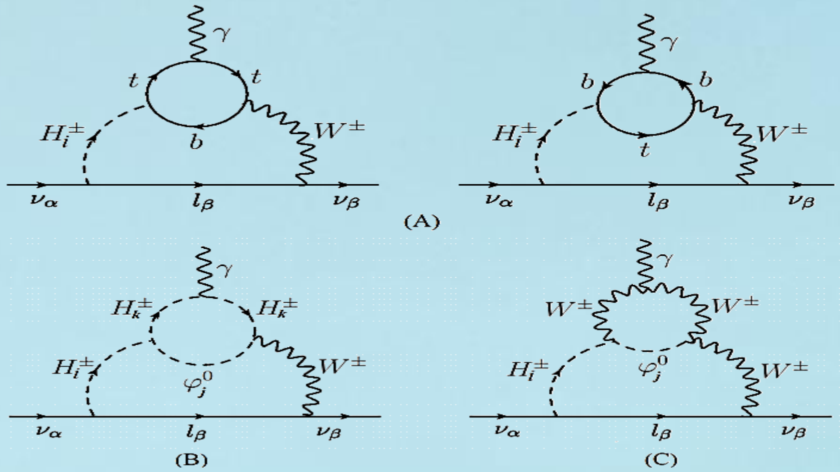
A. Spin Symmetry Mechanism

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

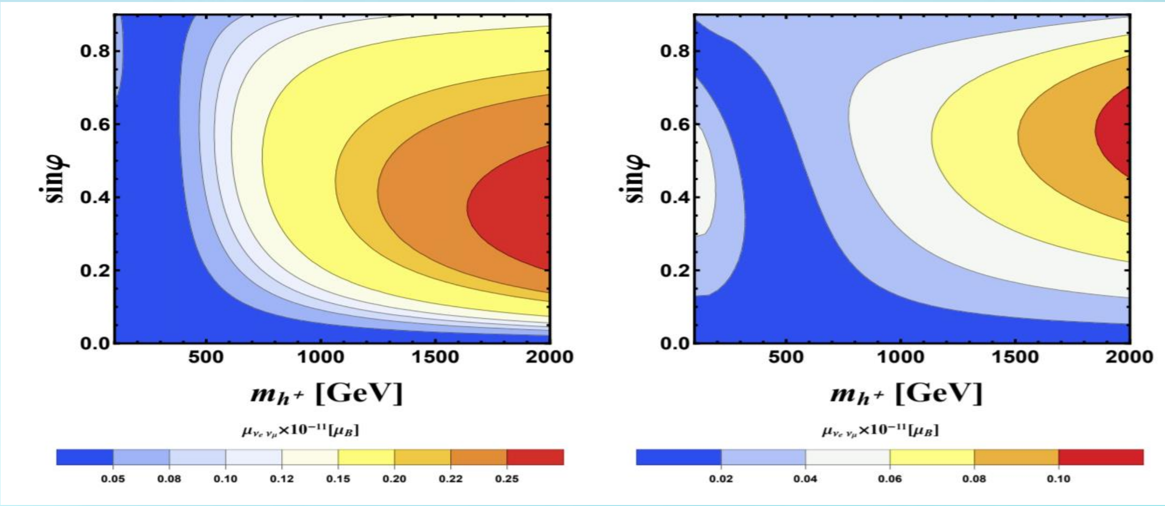
- *As for its contribution to m_ν, for transversely polarized vector bosons, the transition from **spin 1 to spin 0 cannot occur**. Only the longitudianl mode, the Goldstone mode, would contribute to such transitions.*

- *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 $SU(2)_L \times U(1)_Y \times SU(2)_H$ as follows:

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

Higgs sector:

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

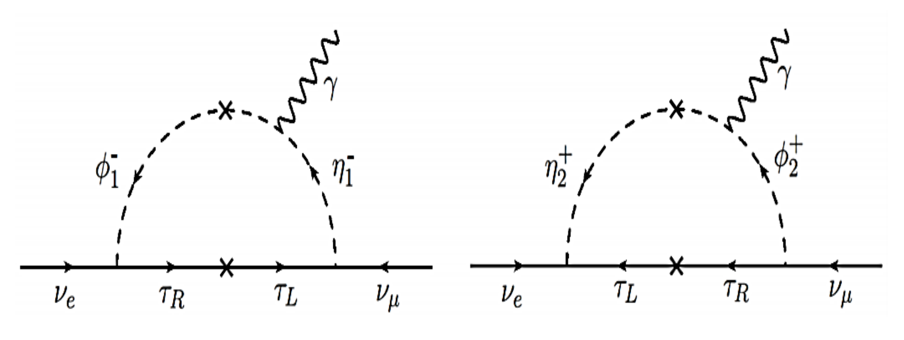
Babu, **SJ,** Lindner (2020)

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

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

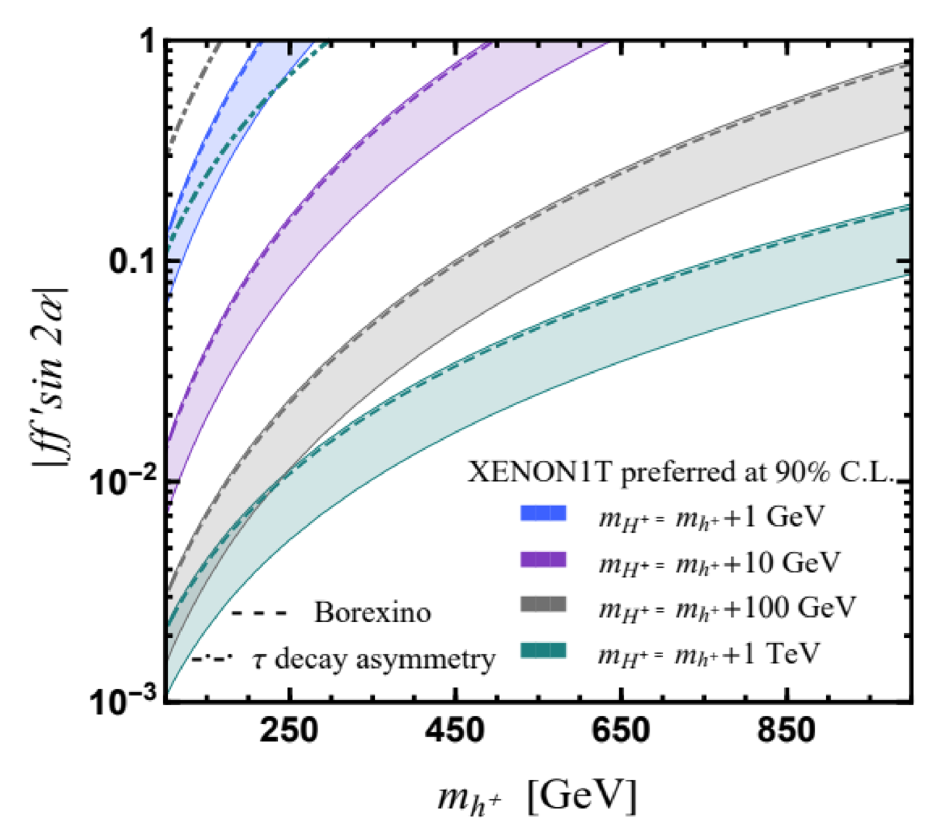
B. $SU(2)_H$ Symmetry for Enhanced Neutrino Magnetic Moment

- *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.*



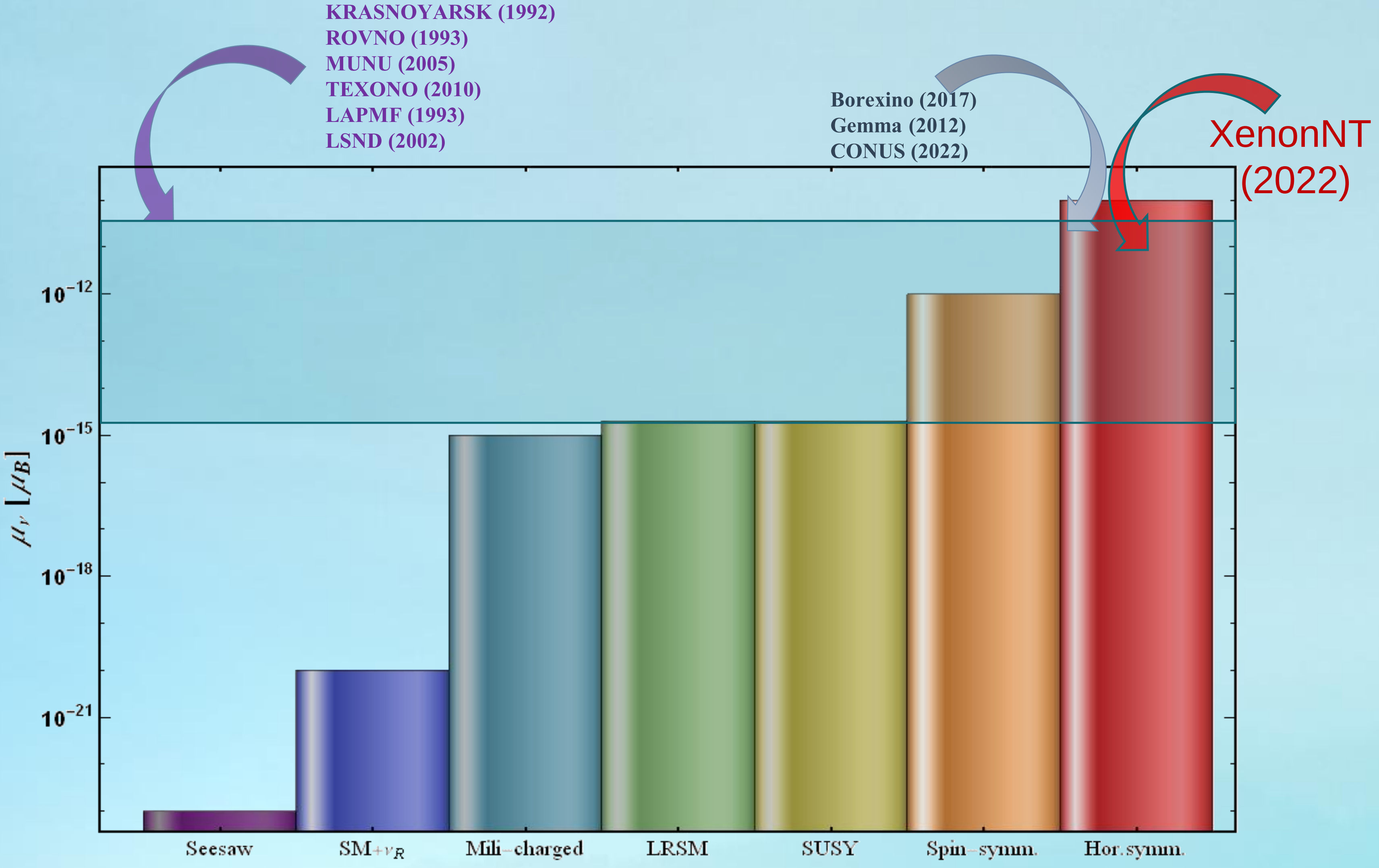
- *In the* ***$SU(2)_H$ symmetric limit, the two diagrams add for $\mu_{\nu e \nu \mu}$****, while they* ***cancel for m_ν****.*

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



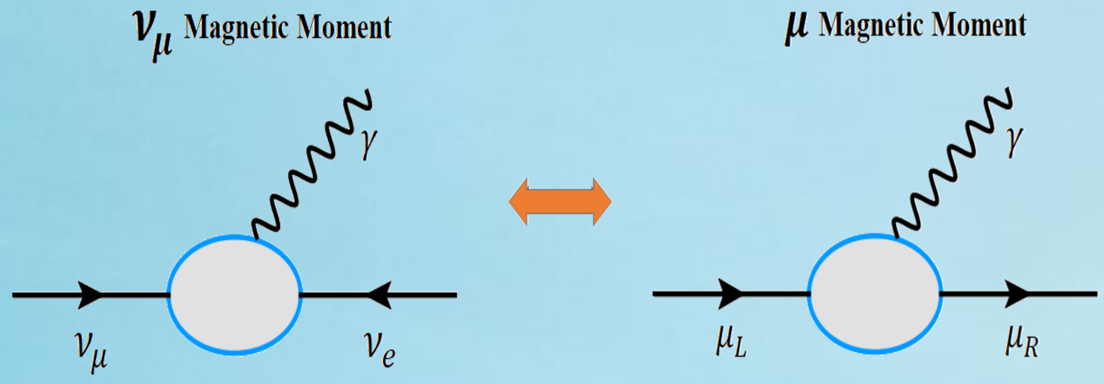
Babu, **SJ**, Lindner (2020)

Neutrino magnetic moments: a global picture

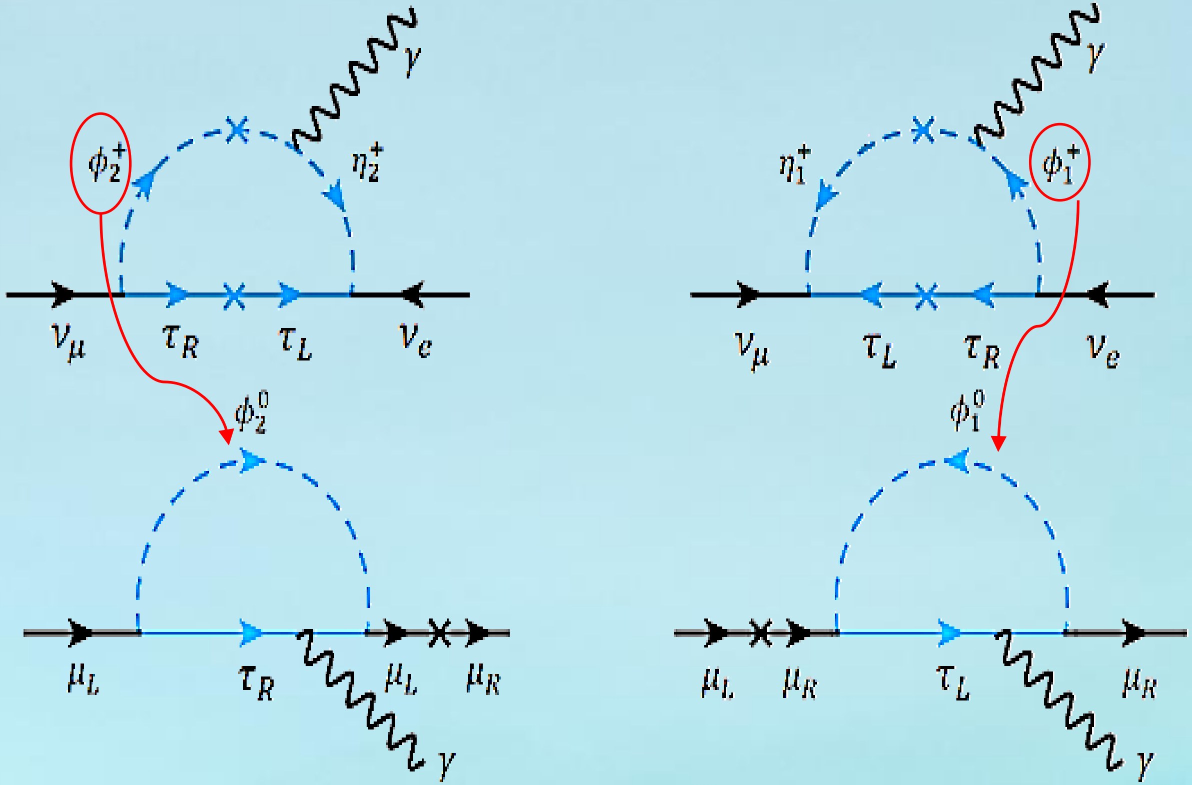


SJ, PoS(DISCRETE2020-2021)037

Neutrino magnetic moments – charged lepton g-2 correlation

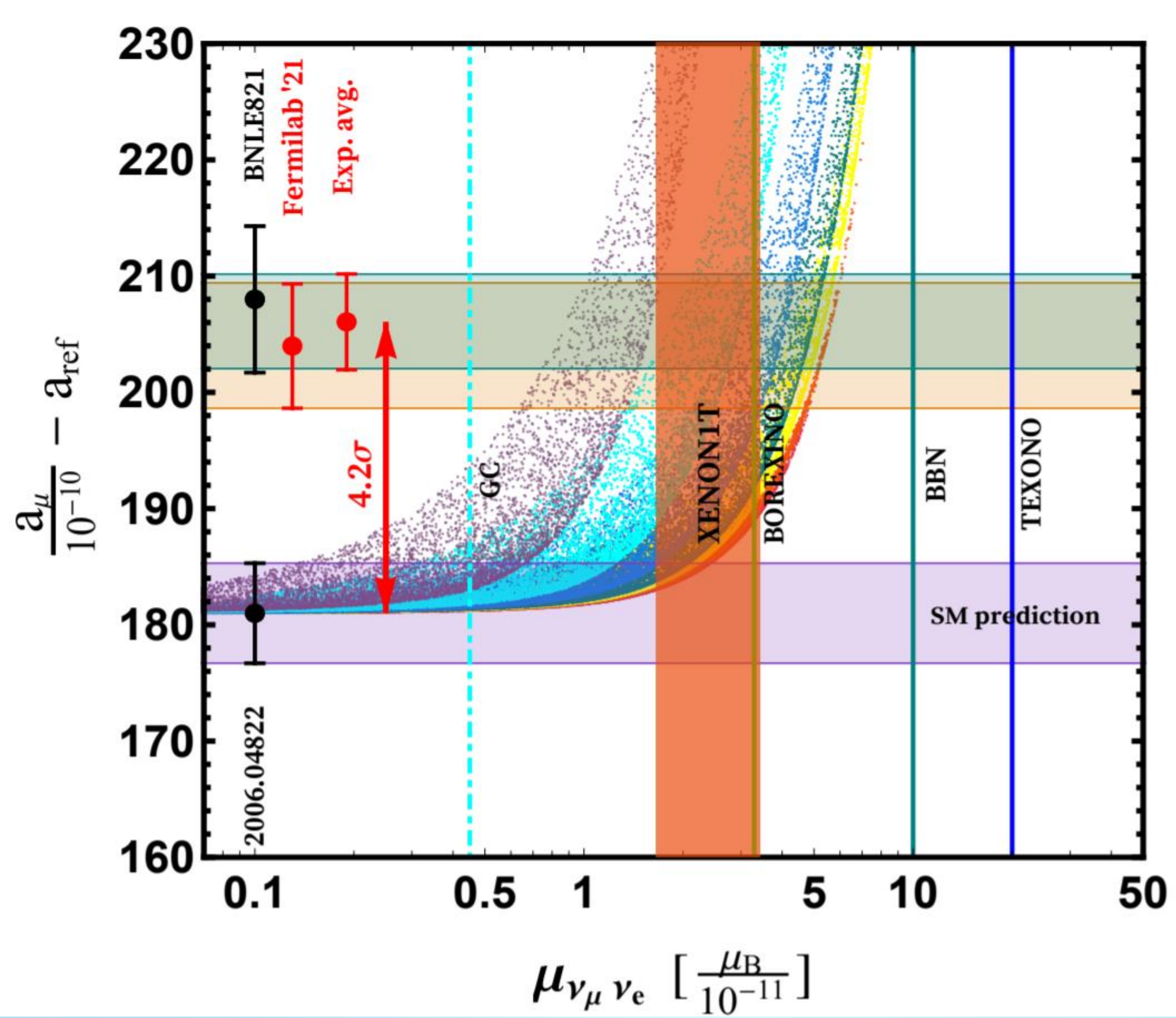


The models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the charged lepton anomalous magnetic moment.

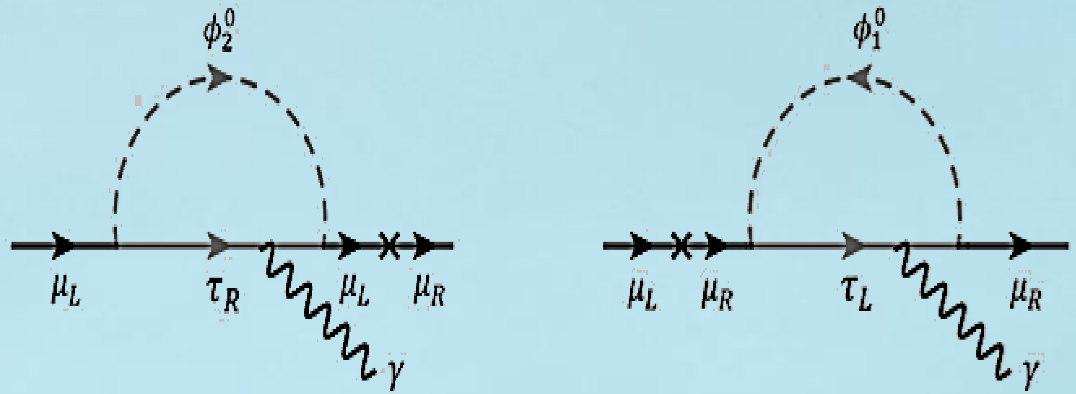


Babu, **SJ,** Lindner, Vishnu (2021)

Neutrino magnetic moments – Muon g-2 anomaly



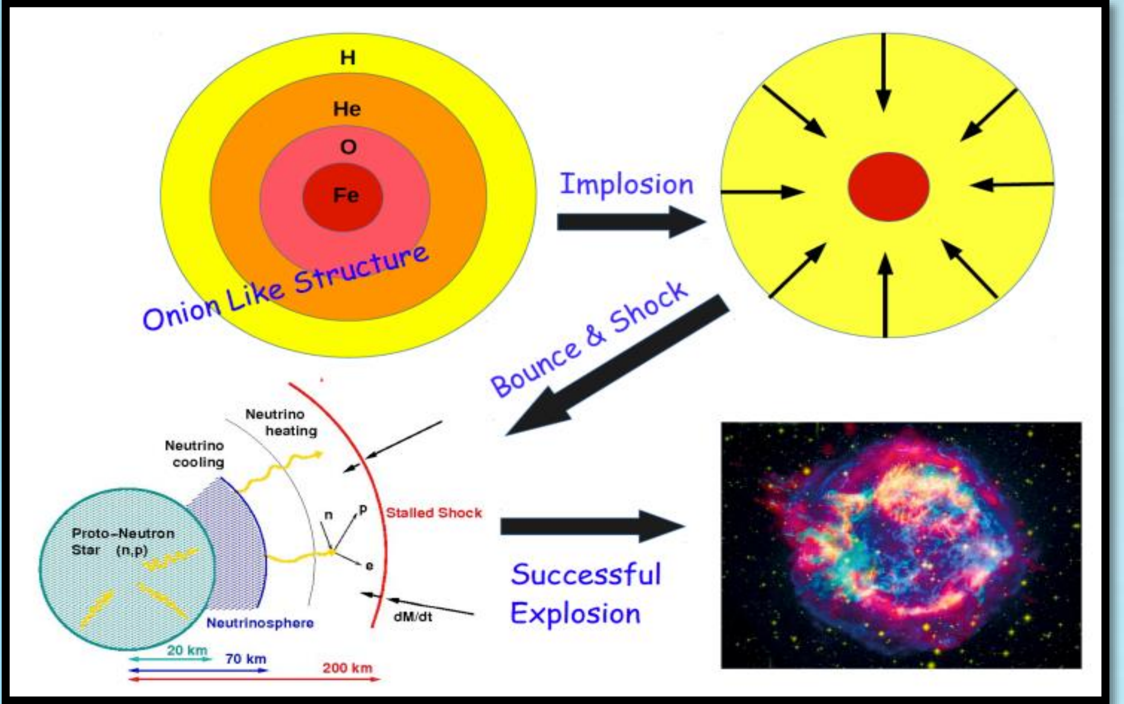
Babu, **SJ,** Lindner, Vishnu (2021)

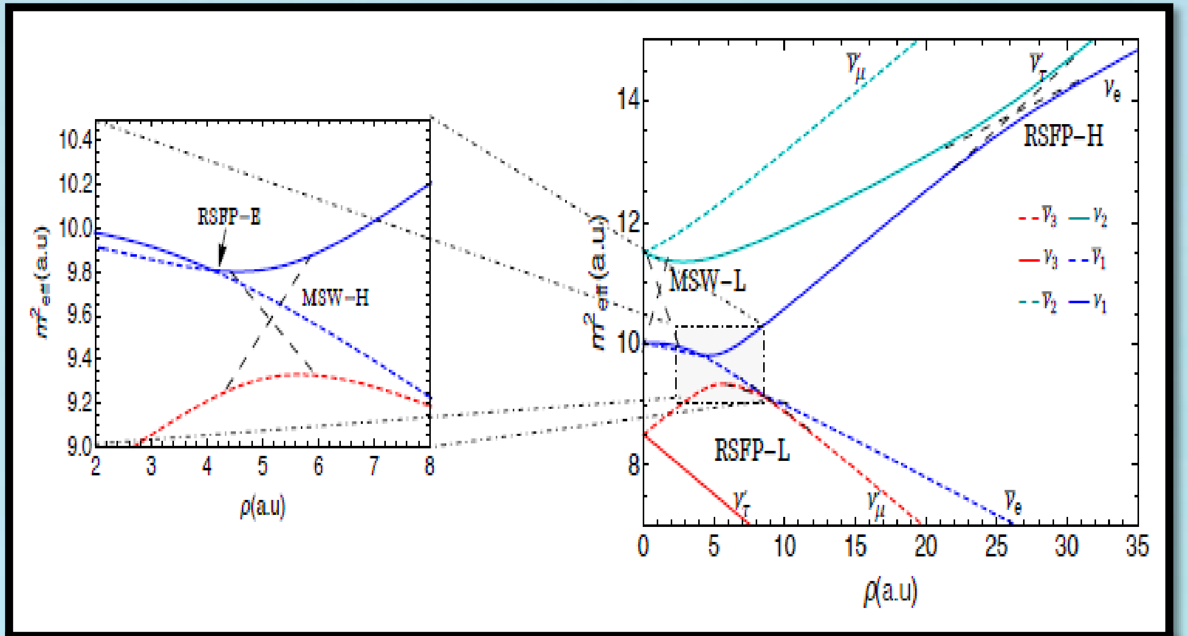


- *A direct correlation between the neutrino magnetic moment and muon g-2*
- Sign and strength are automatic here, no control over it.
- A minimal unified framework: μ_ν, m_ν, $(g\text{-}2)_\mu$.

Exploiting a future galactic supernova to probe neutrino magnetic moments

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



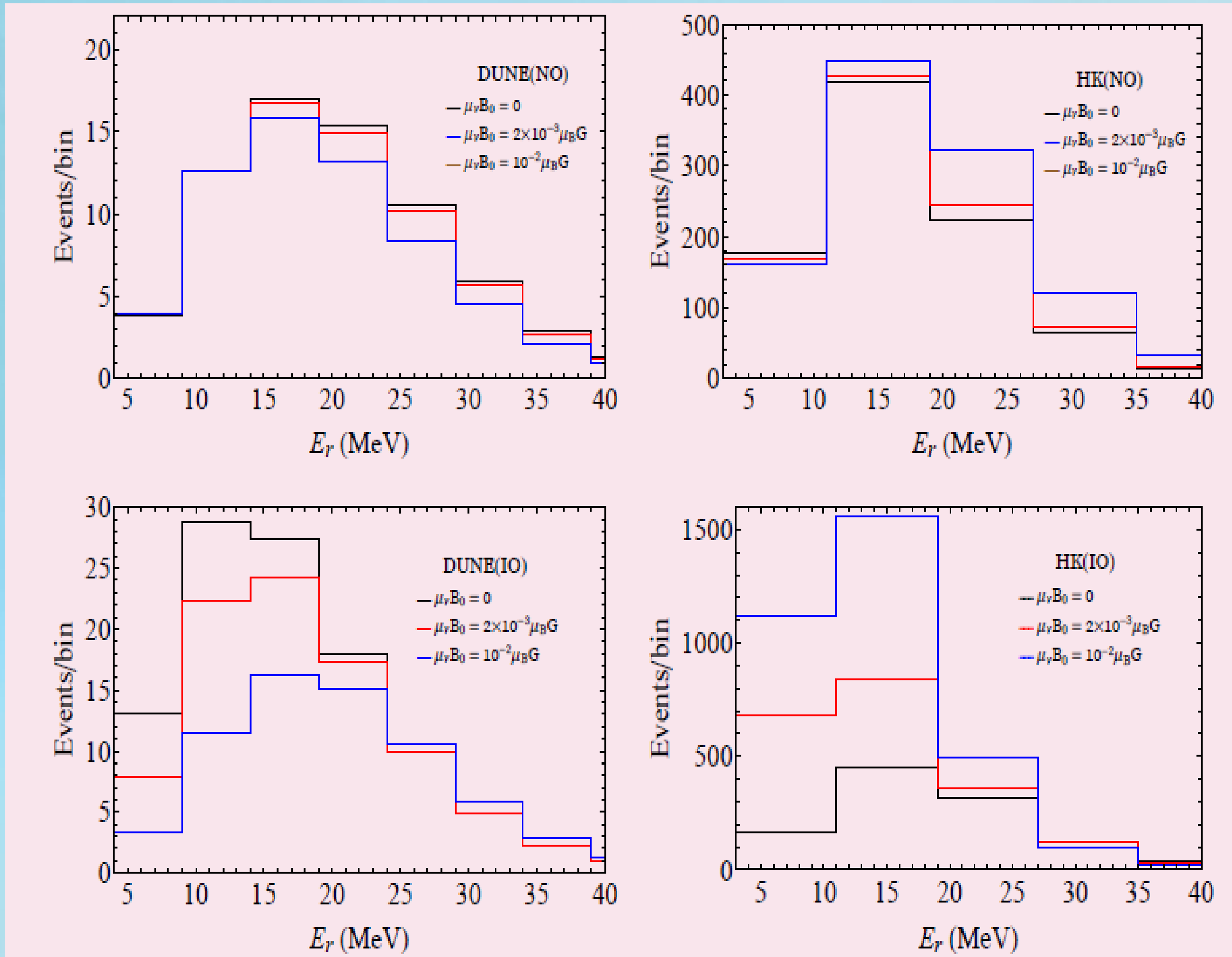


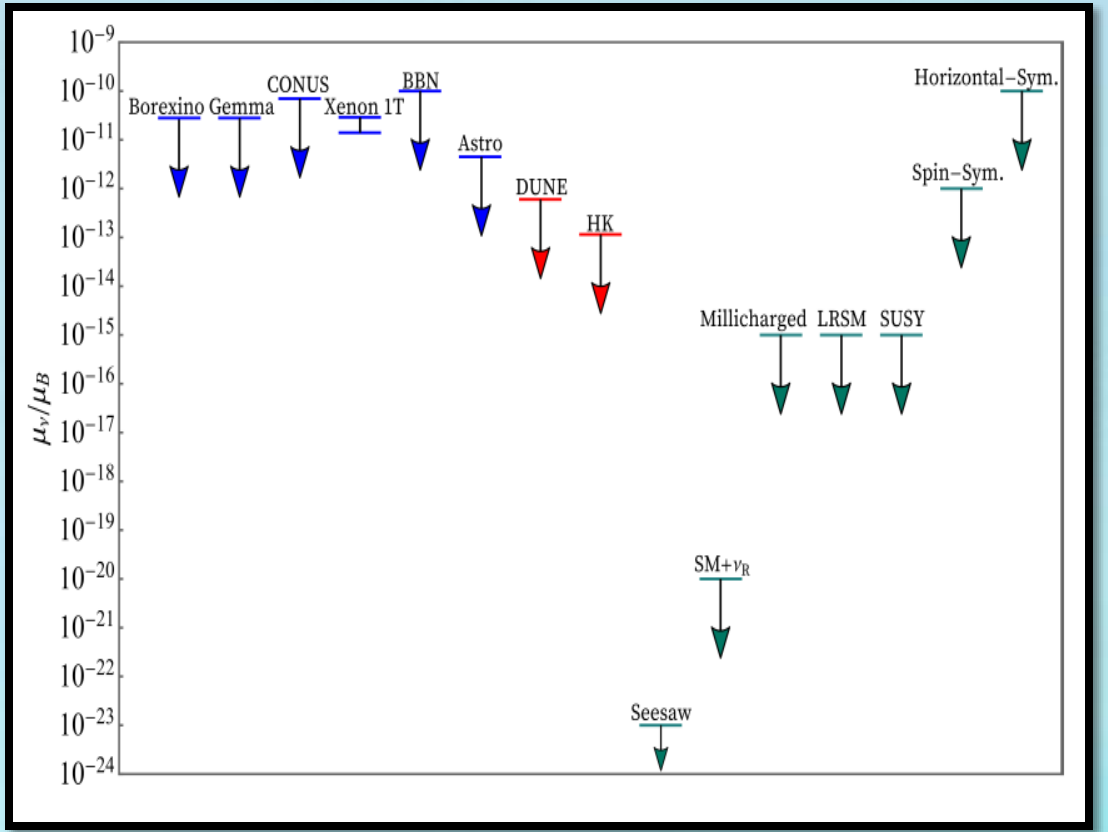
- Neutrino evolution equation: $$i\frac{d}{dr}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}=\begin{pmatrix}H_\nu & B_\perp M\\ -B_\perp M & H_{\bar{\nu}}\end{pmatrix}\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}$$
- Neutrino Hamiltonian in matter: $$H_\nu=\frac{1}{2E}U\begin{pmatrix}0&0&0\\0&\Delta m^2_{21}&0\\0&0&\Delta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

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 (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.

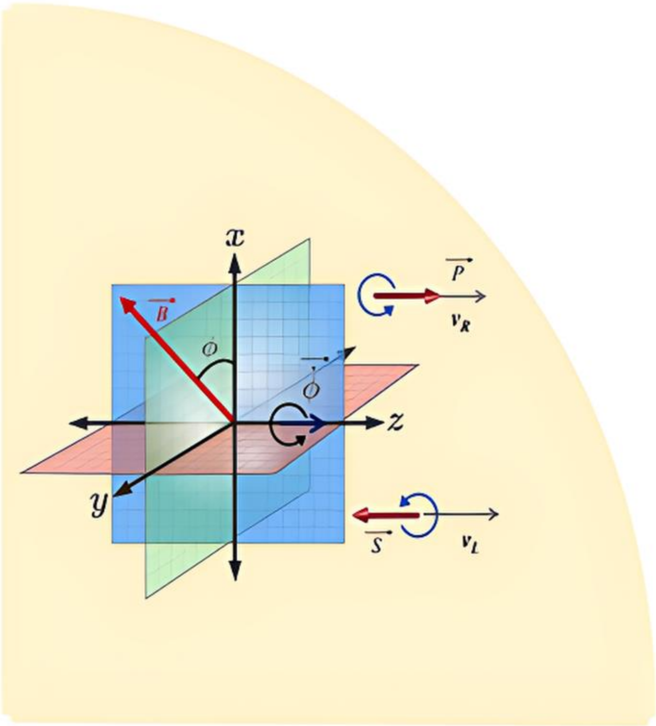
Dirac neutrino magnetic moments in Sne?

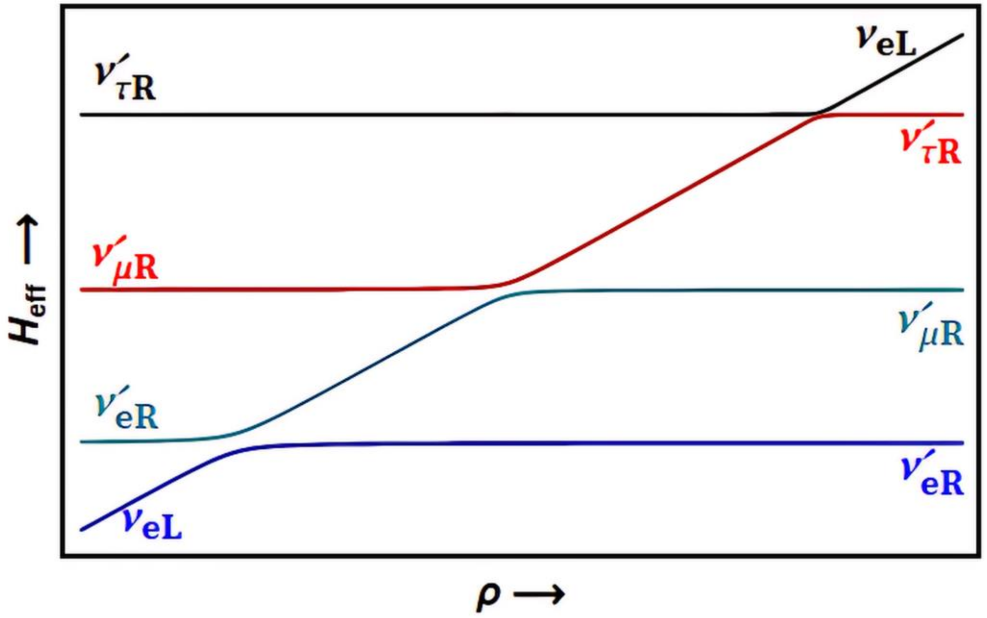
$$i\frac{d}{dr}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix} = \begin{bmatrix}V_e+\dot{\phi}/2 & \mu_\nu B(r)\\ \mu_\nu B(r) & -\dot{\phi}/2\end{bmatrix}\begin{bmatrix}\nu_{eL}\\ \nu_{eR}\end{bmatrix}$$

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

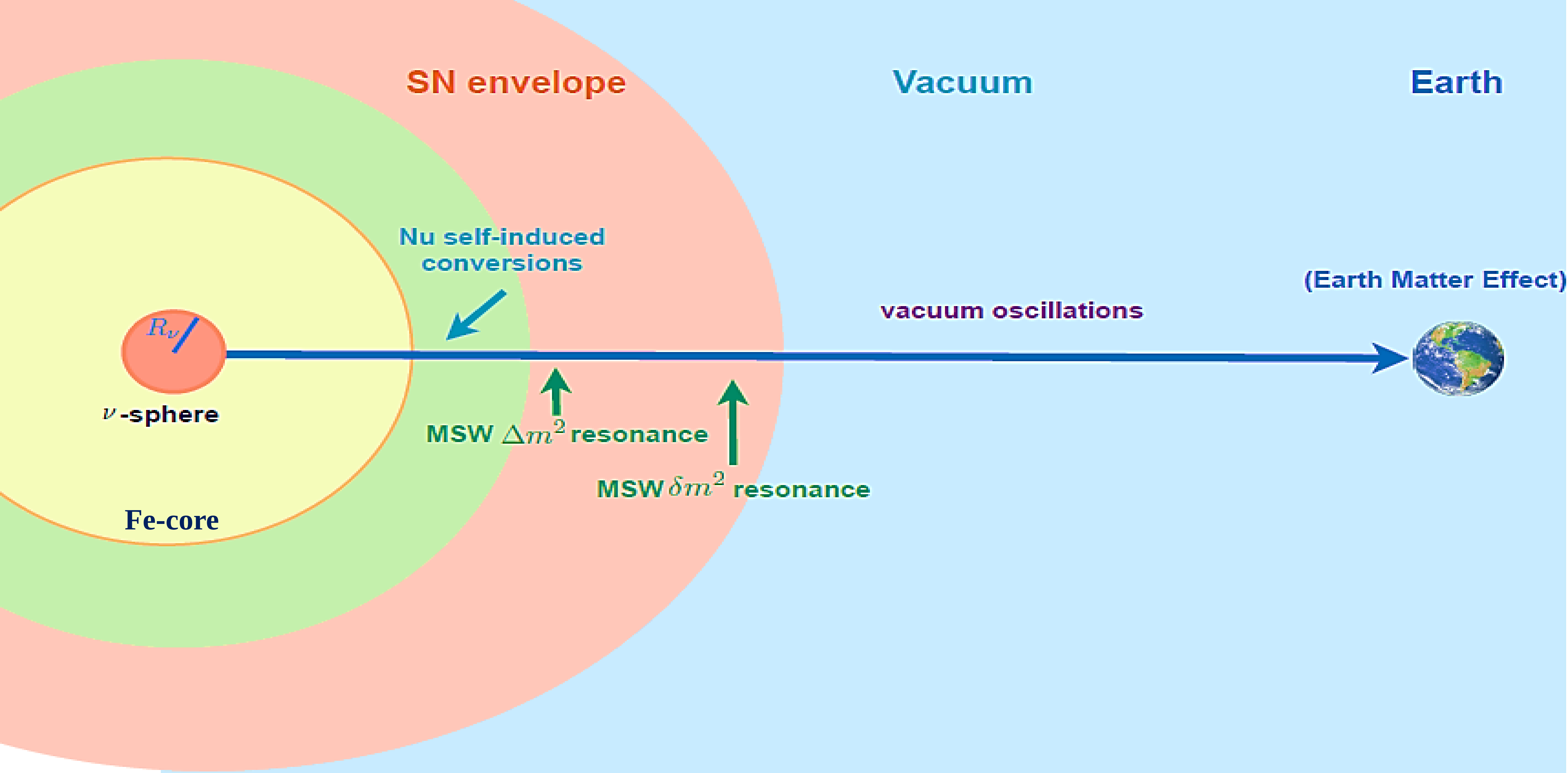
(Resonance Condition)

SJ, Porto (2023)

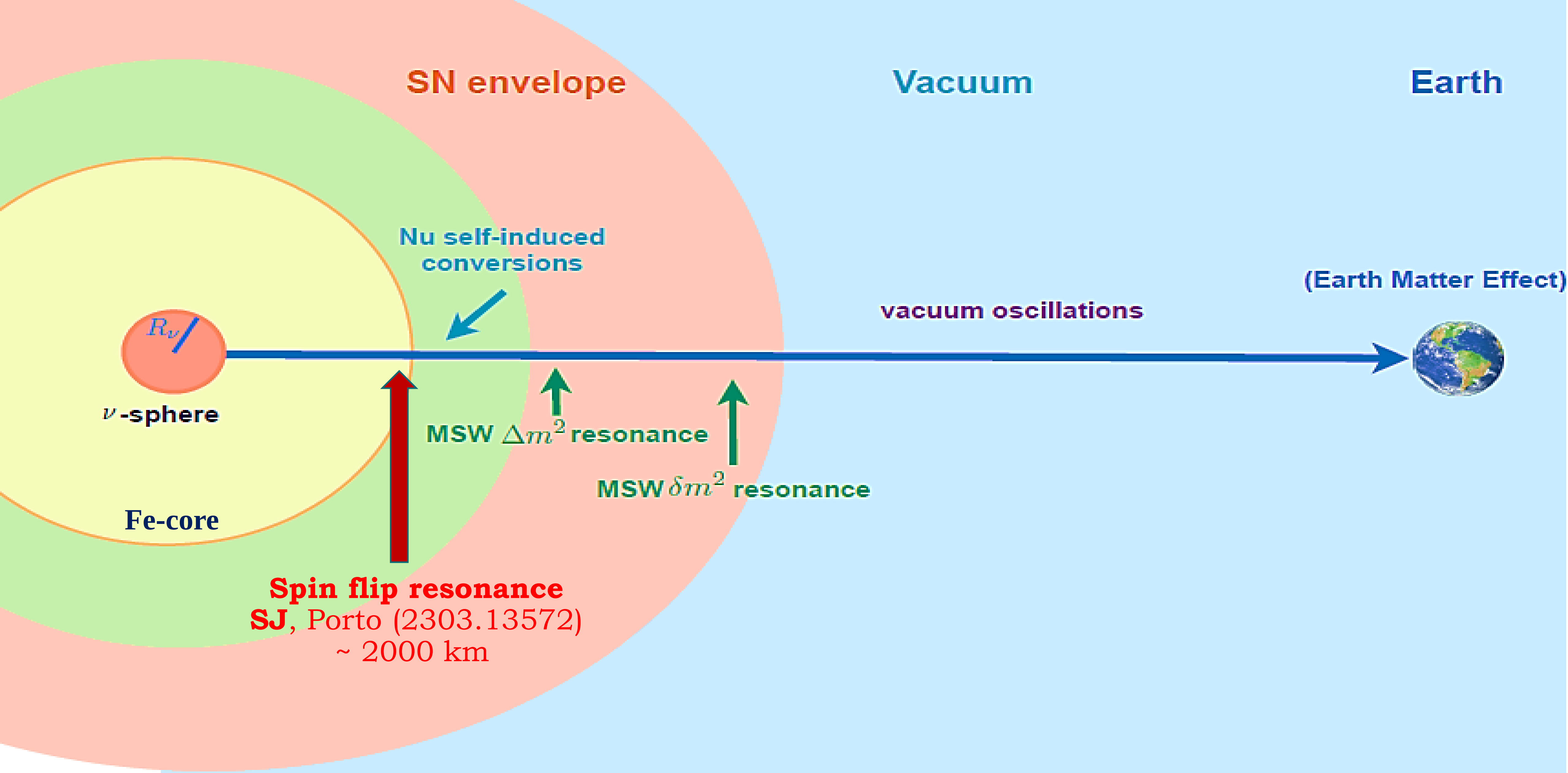




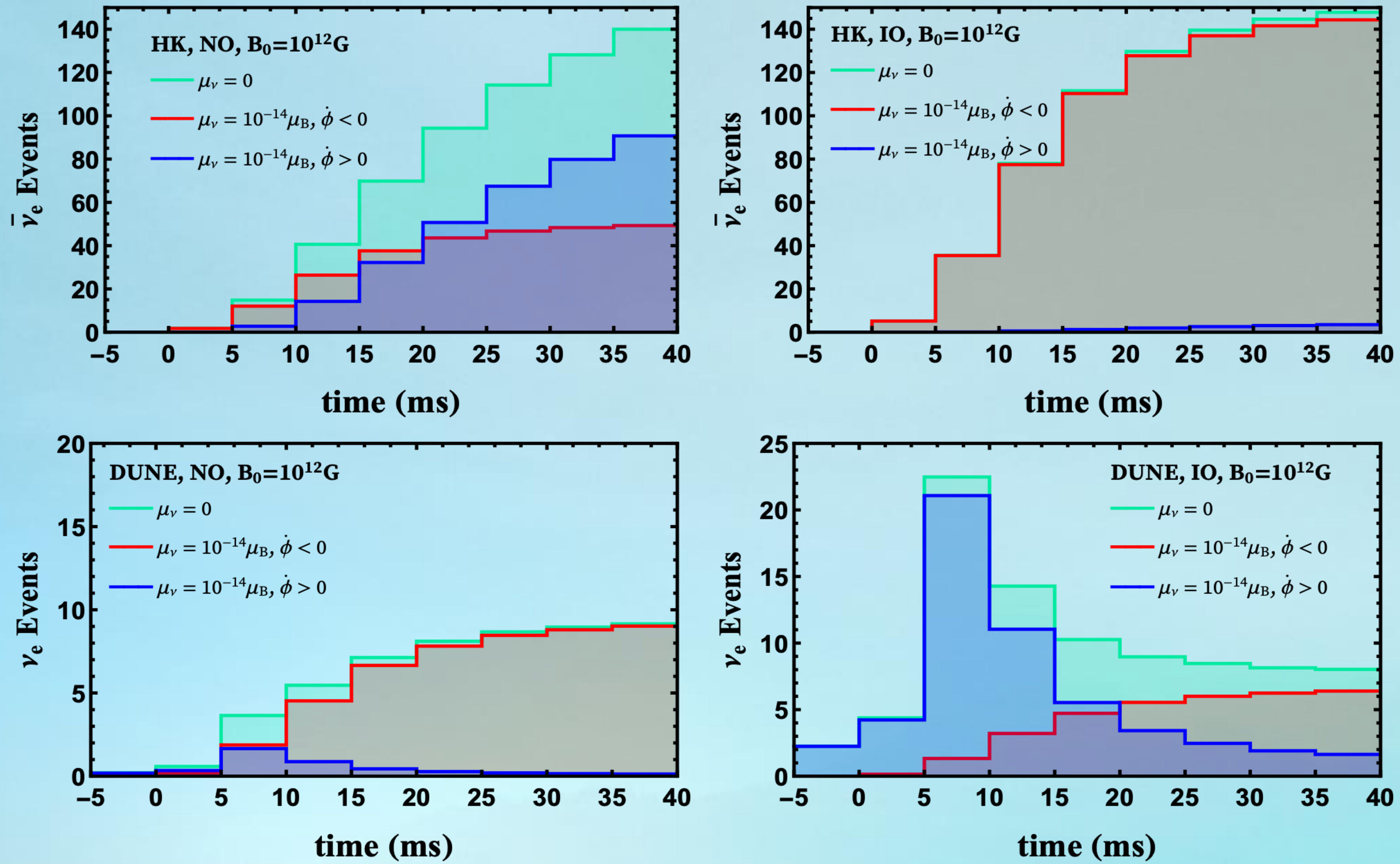
Simplified Picture of Flavor Conversions



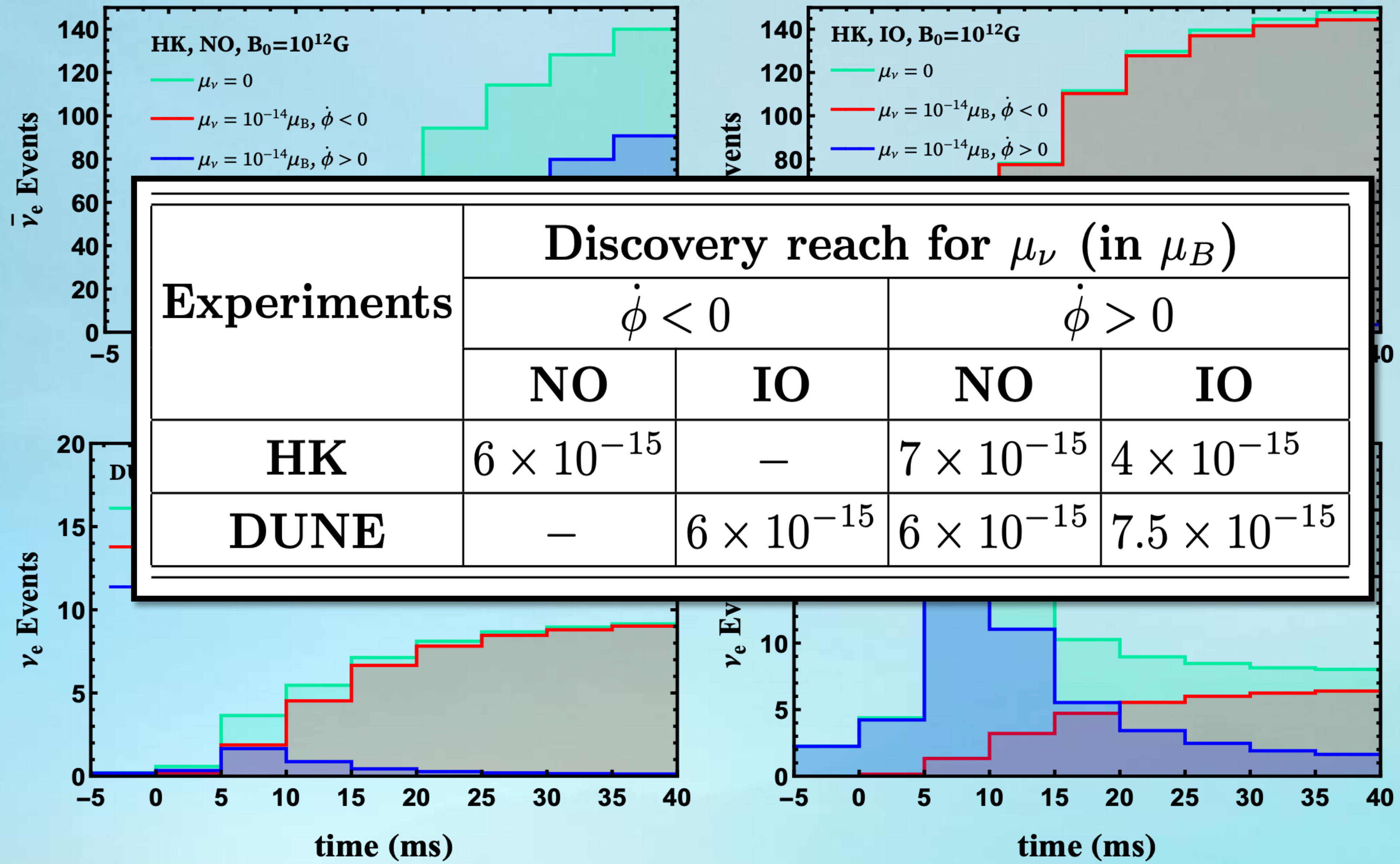
Simplified Picture of Flavor Conversions



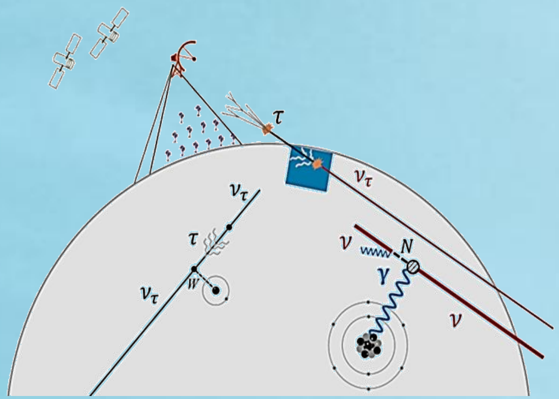
Neutrino spectra at DUNE and HK



Neutrino spectra at DUNE and HK

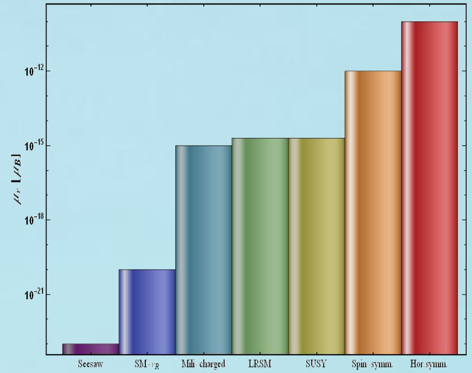


Experiments	Discovery reach for μ_ν (in μ_B)			
	$\dot{\phi} < 0$		$\dot{\phi} > 0$	
	NO	IO	NO	IO
HK	6×10^{-15}	–	7×10^{-15}	4×10^{-15}
DUNE	–	6×10^{-15}	6×10^{-15}	7.5×10^{-15}



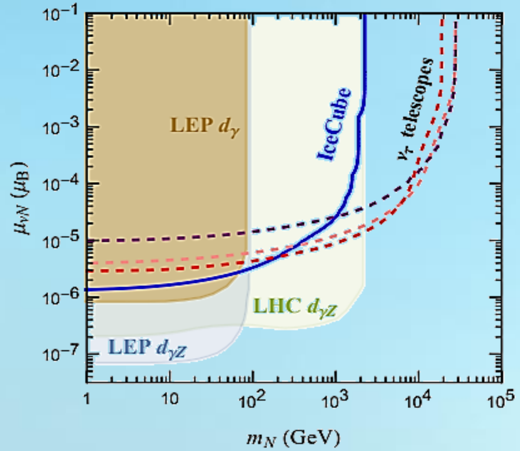
Summary

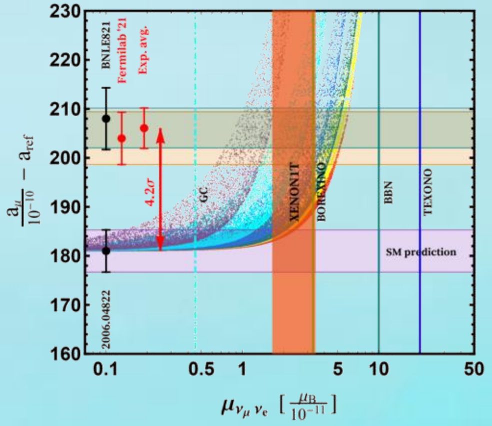
1. *The theoretical and experimental investigation of neutrino electromagnetic interactions can serve as a powerful tool in the search for the fundamental theory behind the neutrino mass generation mechanism.*



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.*





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Thank you!