Neutrino Magnetic Moment–Mass Conundrum in the Light of Recent Experiments

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Based on: **arXiv: 2007.04291 [hep-ph]**

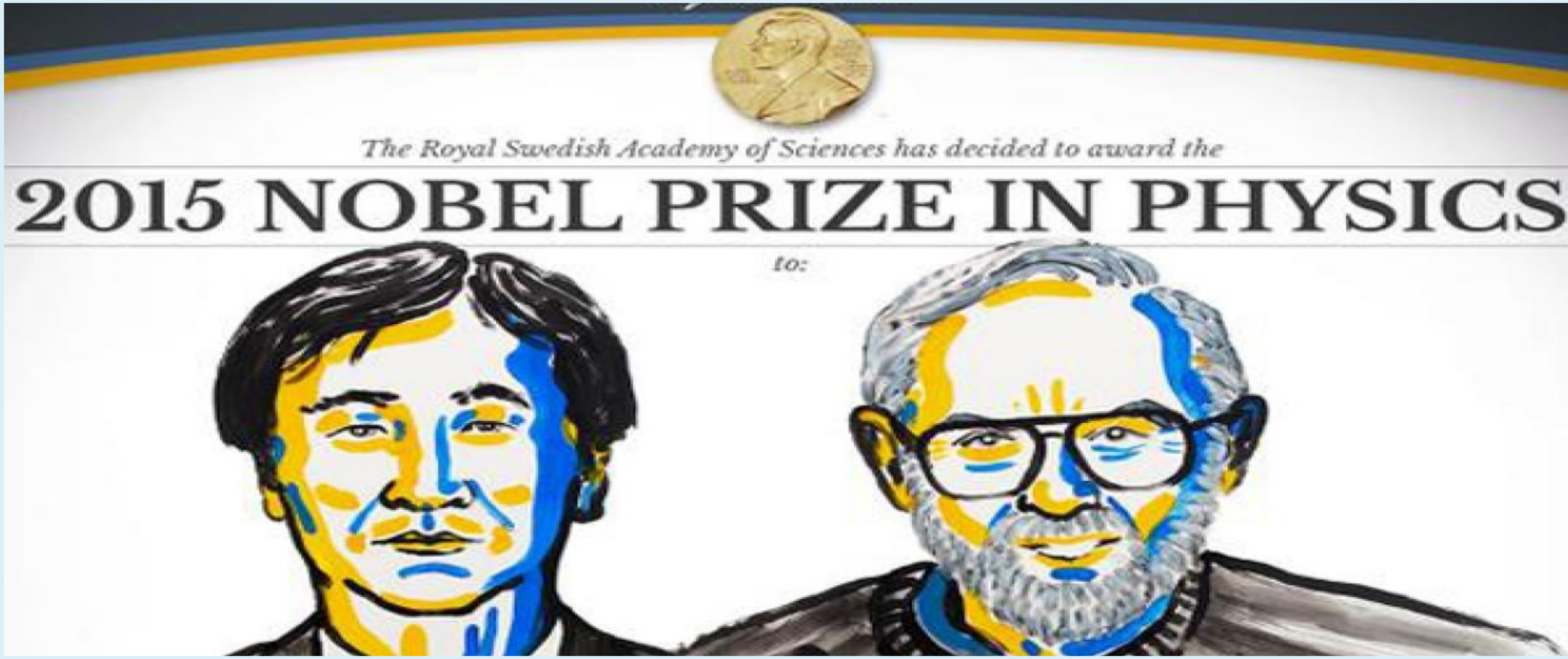
K.S. Babu

SJ

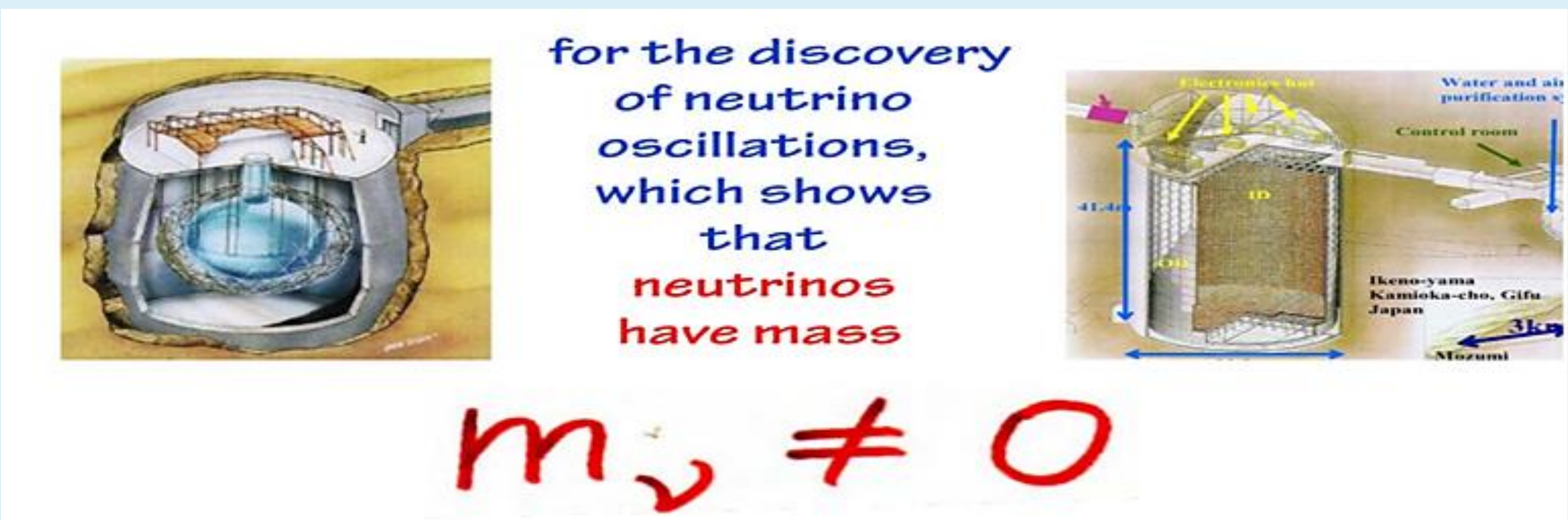
Manfred Lindner

Outline

- Neutrino Magnetic Moment Overview
- The experimental situation
  - XENON1T
  - Other experimental searches
  - Limits from astrophysics and cosmology
- Neutrino magnetic moment in the Standard Model and beyond
- Large magnetic moment from spin symmetry
- Horizontal symmetry for enhanced neutrino magnetic moment
- Dirac vs Majorana neutrino magnetic moments
- Phenomenological implications
- Mechanism to evade astrophysical limits on neutrino magnetic moments
- Conclusion



Takaaki Kajita **Arthur B. McDonald**

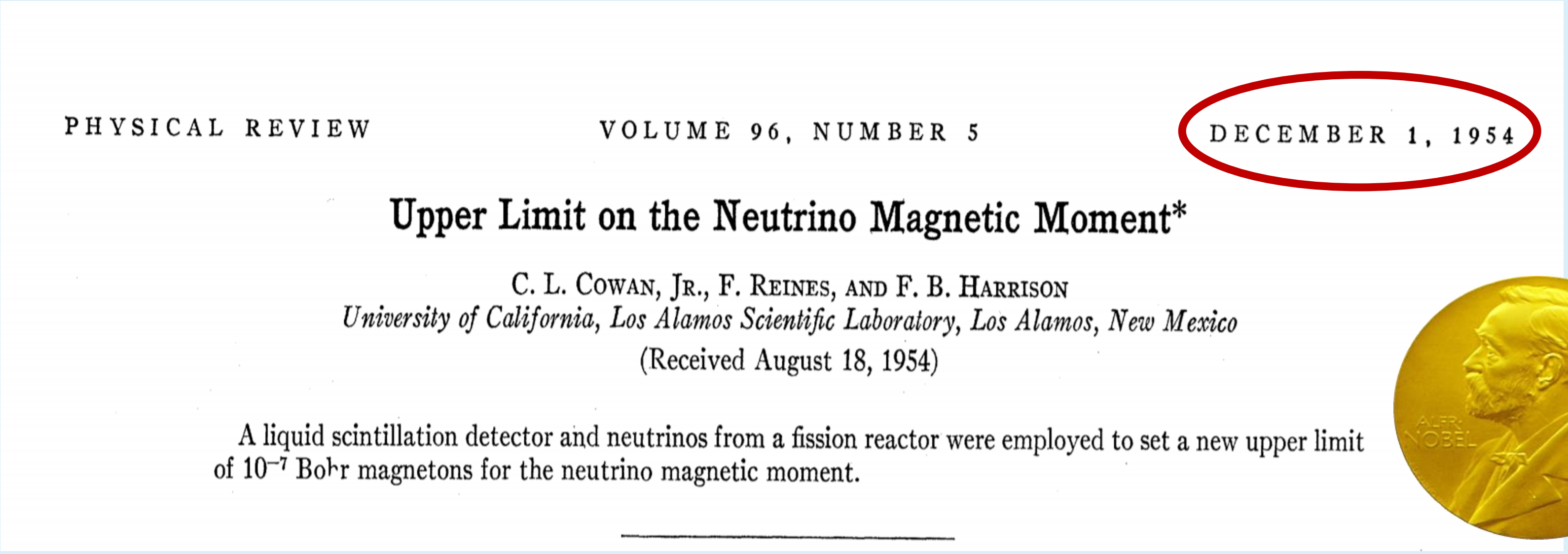


Neutrino Magnetic Moment

- *The quest for measuring a possible magnetic moment of the neutrino was begun **even before the discovery of the neutrino**. Cowan, Reines and Harrison set an upper limit on in the process of measuring background for a free neutrino search experiment with reactor antineutrinos.*

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

Frederick Reines



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.

Neutrino Magnetic Moment: Experimental Searches

Reactor based experiments

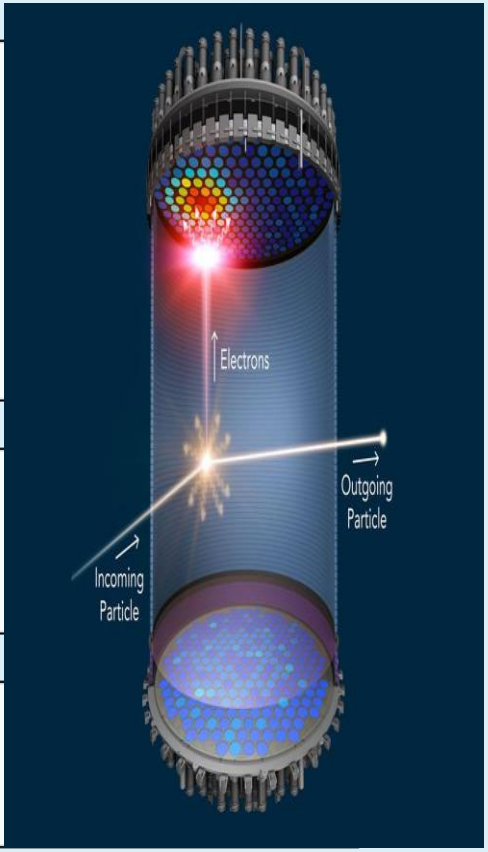
- **KRASNOYARSK (1992):** $\mu_\nu < 2.7 \times 10^{-10}\, \mu_B$
- **ROVNO (1993):** $\mu_\nu < 1.9 \times 10^{-10}\, \mu_B$
- **MUNU (2005):** $\mu_\nu < 1.2 \times 10^{-10}\, \mu_B$
- **TEXONO (2010):** $\mu_\nu < 2.0 \times 10^{-10}\, \mu_B$
- **GEMMA (2012):** $\mu_\nu < 2.9 \times 10^{-11}\, \mu_B$

Accelerator based experiment

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

Solar neutrino experiment

- **Borexino (2017):** $\mu_\nu < 2.8 \times 10^{-11}\, \mu_B$
- **XENON1T (2020)**



Neutrino Magnetic Moment: From Astrophysics and Cosmology

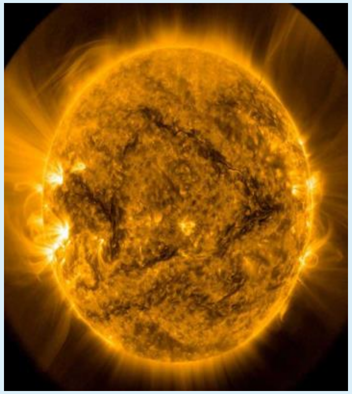
Evolution of stars can provide indirect constraints on the magnetic moments of either Dirac or Majorana neutrinos.

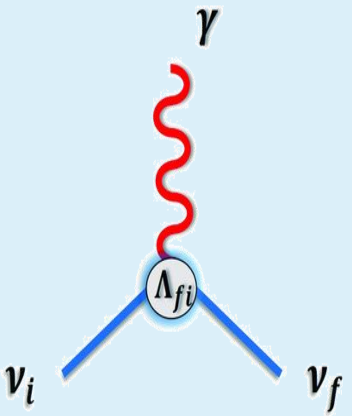
Photons in the plasma of stellar environments can decay either into $\nu\bar{\nu}$ for the case of Dirac neutrinos or into $\nu_\alpha\nu_\beta$ for the case of Majorana neutrinos.

Such decays are kinematically allowed in a plasma since the photon acquires a mass.

If such decays occur too rapidly, that would drain energy of the star, in conflict with standard stellar evolution models which appear to be on strong footing.

Limits on μ_ν have been derived by requiring the energy loss in such decays to be not more than via standard processes.





Neutrino Magnetic Moment: From Astrophysics and Cosmology

The best limit on μ_ν from this argument arises from red giant branch of globular clusters, resulting in a limit of

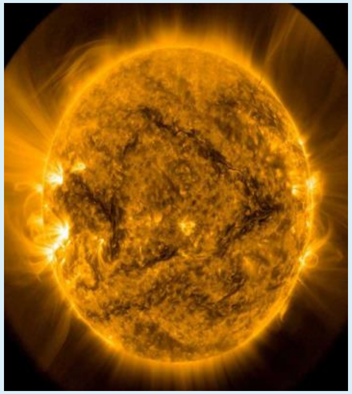
$\mu_\nu < 4.5 \times 10^{-12}\, \mu_B$.

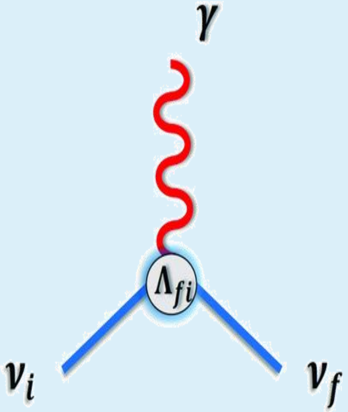
Validity of this limit would make the neutrino magnetic moment interpretation of the XENON1T excess *questionable*.

We note that these indirect constraints from astrophysics may be evaded if the plasmon decay to neutrinos is kinematically forbidden.

There are also cosmological limits arising from big bang nucleosynthesis.

However, these limits are less severe, of order $10^{-10}\, \mu_B$.





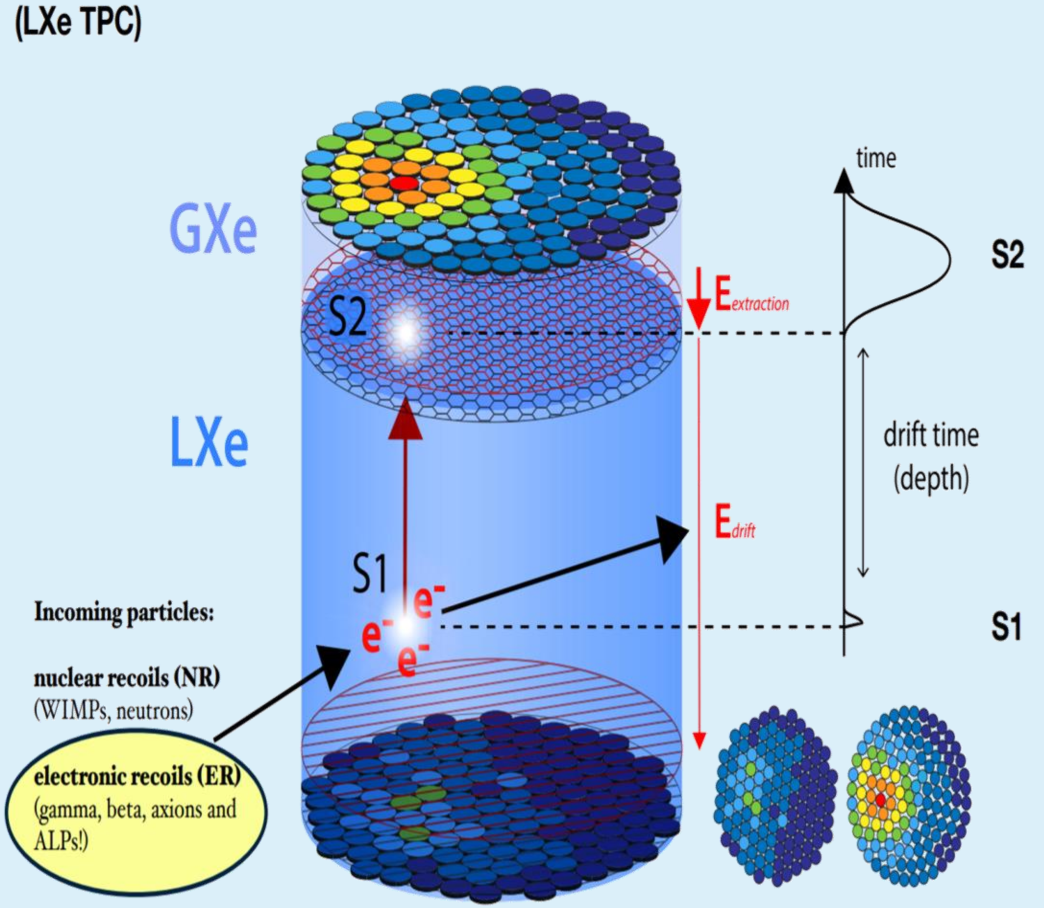
Neutrino Magnetic Moment and Xenon1T electron recoil excess

Particle detector with

- *low background,*
- *low threshold,*
- *large exposure*

Particle ID

- *Electronic Recoil (ER)*
- *Nuclear Recoil (NR)*



Neutrino Magnetic Moment and Xenon1T electron recoil excess

Excess between 1-7 keV

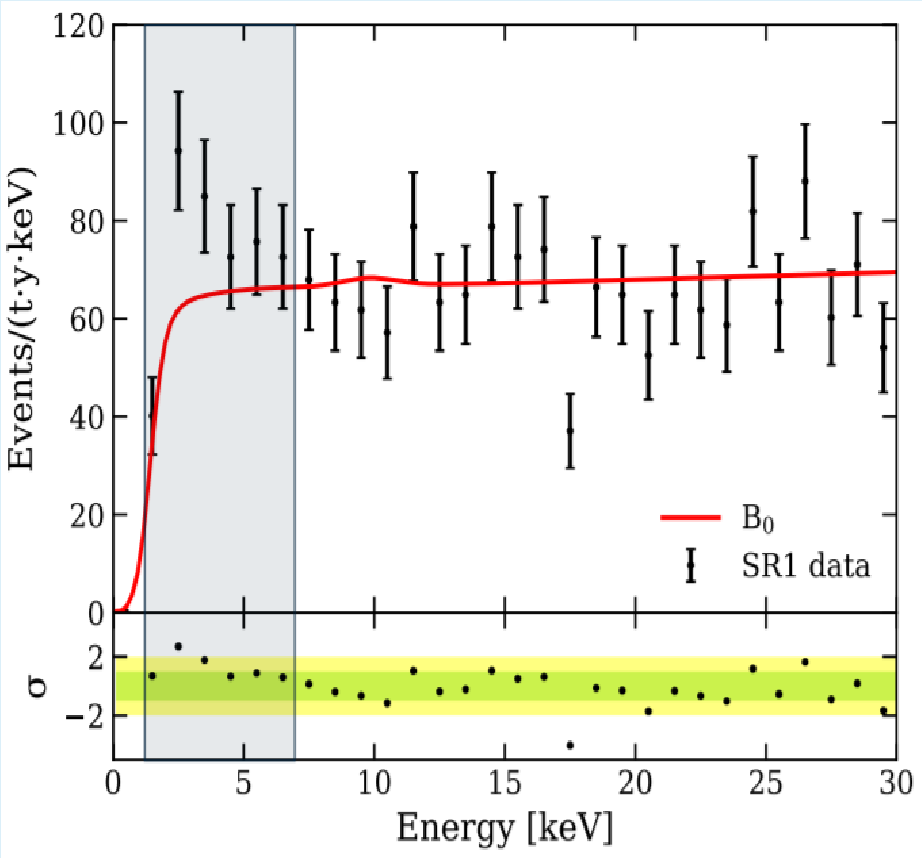
285 *events observed*

vs.

232 (+/- 15) *events expected (from best-fit)*

Would be a ***3.5σ*** *fluctuation*

(naive estimate – we use likelihood ratio tests for main analysis)



XENON Collaboration, E. Aprile et al. (2020)

Neutrino Magnetic Moment and Xenon1T electron recoil excess

Background model (10 components)

Internal Backgrounds

- ^{214}Pb
- ^{85}Kr

Intrinsic Backgrounds

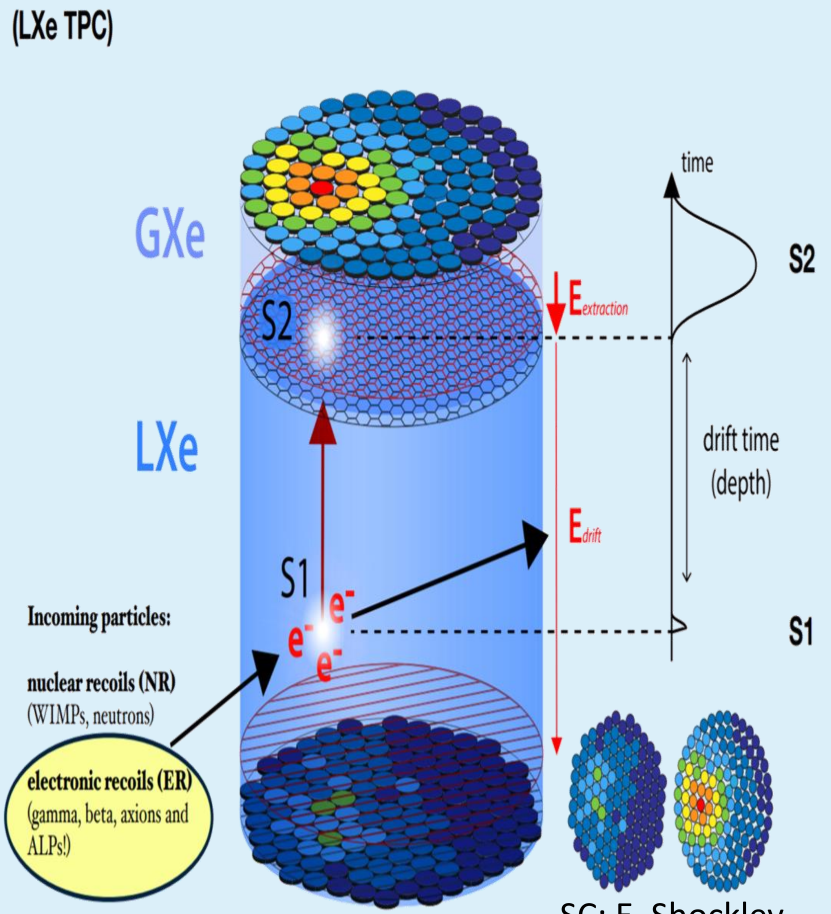
- ^{124}Xe
- ^{136}Xe
- *Solar neutrino*

Activated Backgrounds

- ^{131m}Xe
- ^{133}Xe
- *125I*

Contaminant Backgrounds

- ^{83m}Kr
- *Materials*

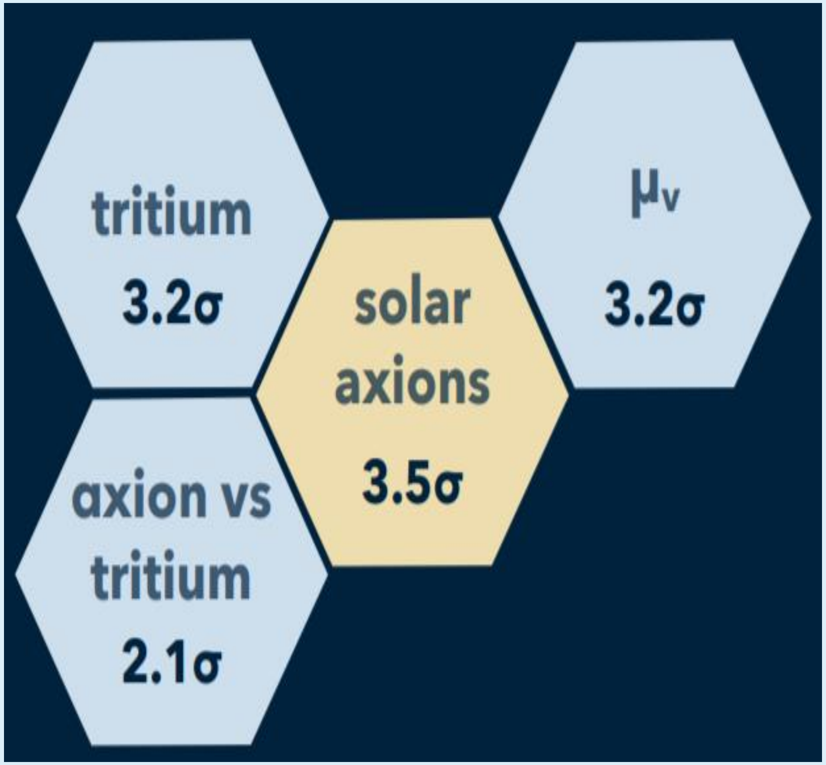


SC: E. Shockley

Neutrino Magnetic Moment and Xenon1T electron recoil excess

1. *Solar axion*
2. *Neutrino magnetic moment*
3. *Tritium*
4. *Dark mater*
5. *Light mediator*
6. *Statistical fluctuation*
7. *Other Backgrounds*

*****Without any bias, for the full list of references , I will recommend to follow the last paper (2009.02315 until now) appeared on arXiv.**



XENON Collaboration, E. Aprile *et al.* (2020)

Neutrino Magnetic Moment and Xenon1T electron recoil excess

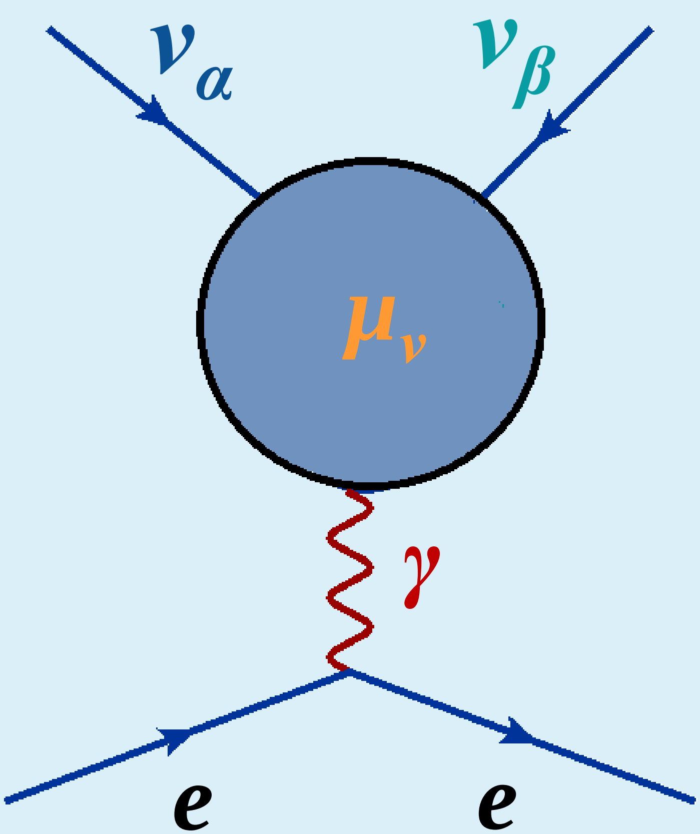
1. *Solar axion*
2. *Neutrino magnetic moment*
3. *Tritium*
4. *Dark mater*
5. *Light mediator*
6. *Statistical fluctuation*
7. *Other Backgrounds*

The origin of such excess is unclear – it could be the presence of new physics, or a large background mismodeling.

However, the Xenon1T result, if due to new physics, would revolutionize the field of particle physics.

*****Without any bias, for the full list of references , I will recommend to follow the last paper (2009.02315 until now) appeared on arXiv.**

Neutrino Magnetic Moment and Xenon1T electron recoil excess



The excess in electron recoil events observed by XENON1T collaboration may be explained by solar neutrinos which have nonzero magnetic moments. The preferred range of an effective neutrino magnetic moment is

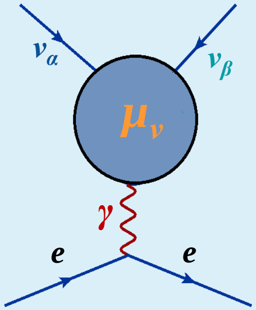
$$\mu_\nu \in (1.4 - 2.9) \times 10^{-11}\,\mu_B$$

With its low threshold, XENON1T detector is very sensitive to magnetic moments of Dirac neutrinos or to transition moments of Majorana neutrinos, since in either case the neutrino-electron scattering cross-section at low energies will increase

We show the consistency of this scenario when a single component transition magnetic moment takes values

$$\mu_{\nu_e \nu_\mu} \in (1.65 - 3.42) \times 10^{-11}\,\mu_B$$

Neutrino Magnetic Moment and Xenon1T electron recoil excess



In order to compute XENON1T signal prediction and analyze the recoiled electron spectrum for a single component transition magnetic moment, one can define the differential event rate in terms of the reconstructed recoiled energy (*T*) as

$$\frac{dN}{dT_r} = n_e \times \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \int_{T^{th}}^{T^{max}} dT \left(\frac{d\sigma_{\nu_e e}}{dT} P_{ee} + \frac{d\sigma_{\nu_\mu e}}{dT} P_{e\mu} \right) \times \frac{d\phi}{dE_\nu} \times \epsilon(T) \times \mathcal{G}(T, T_r)$$

number of target electrons in fiducial volume of one ton Xenon

solar neutrino flux spectrum

$\phi_{pp} = 5.94 \times 10^{10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$,

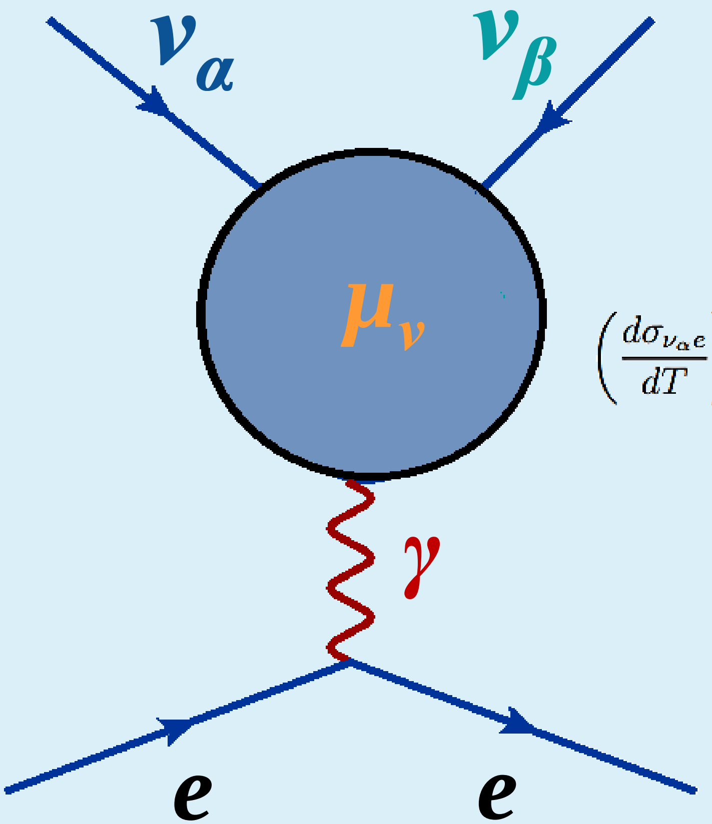
$\phi_{^7Be} = 4.86 \times 10^{9}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

detector efficiency

a normalized Gaussian smearing function in order to account for the detector finite energy resolution

It is clear that the *pp* flux is dominant with the ^{7}Be flux an order of magnitude smaller. Flux from ^{8}B and other sources are even smaller at low energies. It is sufficient then to keep only the *pp* flux in the calculation of electron recoil excess.

Neutrino Magnetic Moment and Xenon1T electron recoil excess



The differential cross section for the neutrino-electron scattering in the presence of a magnetic moment

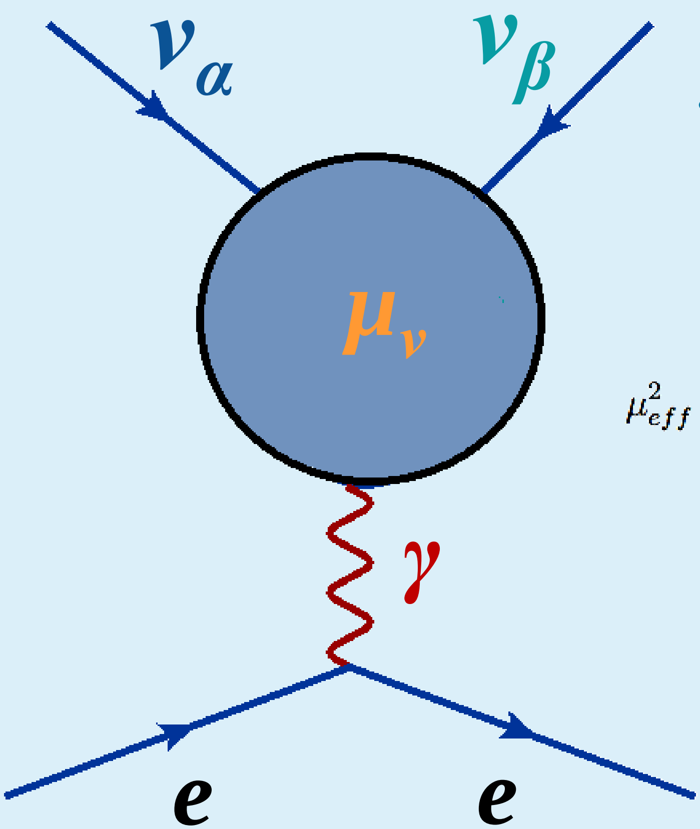
$$\left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{tot} = \left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{SM} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{eff}}{\mu_B}\right)^2$$

$$\left(\frac{d\sigma_{\nu_\alpha e}}{dT}\right)_{SM} = \frac{G_F^2 m_e}{2\pi}\left[(g_V^\alpha + g_A^\alpha)^2 + (g_V^\alpha - g_A^\alpha)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left(g_A^{\alpha^2} - g_V^{\alpha^2}\right)\frac{m_e T}{E_\nu^2}\right]$$

The flavor dependent vector and axial vector coupling is given by:

$$g_V^e = 2\sin^2\theta_W + \frac{1}{2}; \quad g_A^e = +\frac{1}{2}$$
$$g_V^{\mu,\tau} = 2\sin^2\theta_W - \frac{1}{2}; \quad g_A^{\mu,\tau} = -\frac{1}{2}$$

Neutrino Magnetic Moment and Xenon1T electron recoil excess



- **ν_e s produced in the solar core oscillate into ν_α with $\alpha = \mu, \tau$, with the flavor transition being adiabatic inside the Sun.**

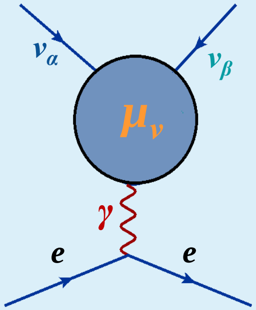
- **Since solar neutrinos arriving at earth are a mixture of incoherent states, the effective magnetic moment relevant for the neutrino-electron scattering can be defined as**

$$\mu_{eff}^2 = \cos^2\theta_{13}\,|\lambda_{12}|^2 + \left[1-\cos^2\theta_{13}(1-P_{e1}^{2\nu})\right]|\lambda_{13}|^2 + \left(1-\cos^2\theta_{13}P_{e1}^{2\nu}\right)|\lambda_{23}|^2$$

$$\lambda_{ij} = \mu_{ij} - i d_{ij}$$

$$\boxed{\mu_{eff}^2 = 0.72\,\mu_{\nu_e\nu_\mu}^2}$$

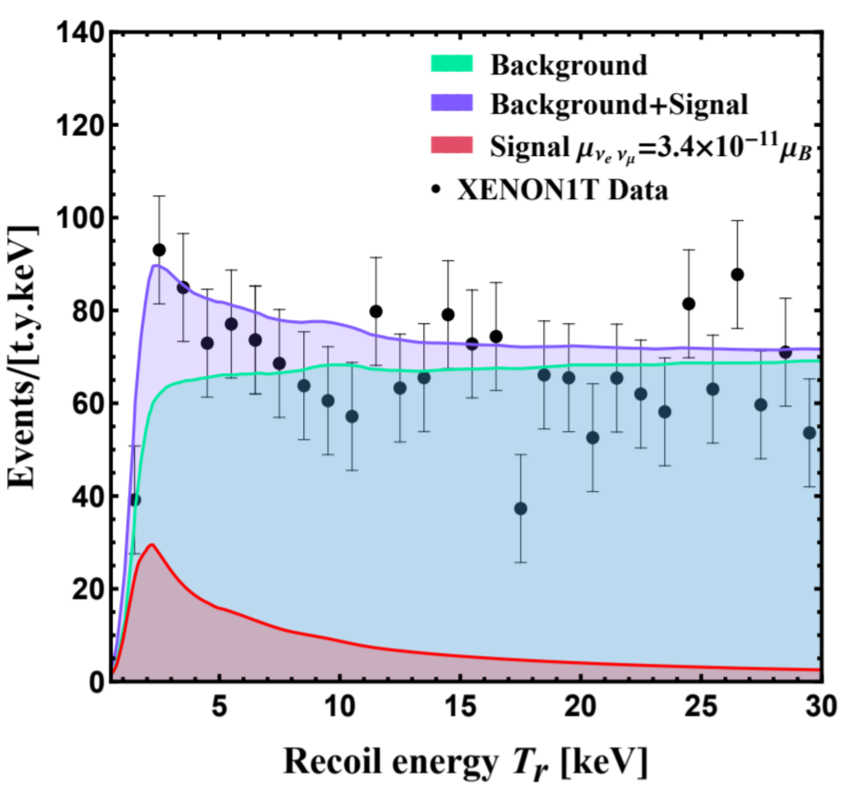
Neutrino Magnetic Moment and Xenon1T electron recoil excess



One sees that owing to the presence of sizable neutrino magnetic moment, and the resulting 1/T enhancement in the cross section, the signal spectrum gives a good fit to the observed data in the electron recoil energy range between (1 − 7) keV peaking around 2.5 keV.

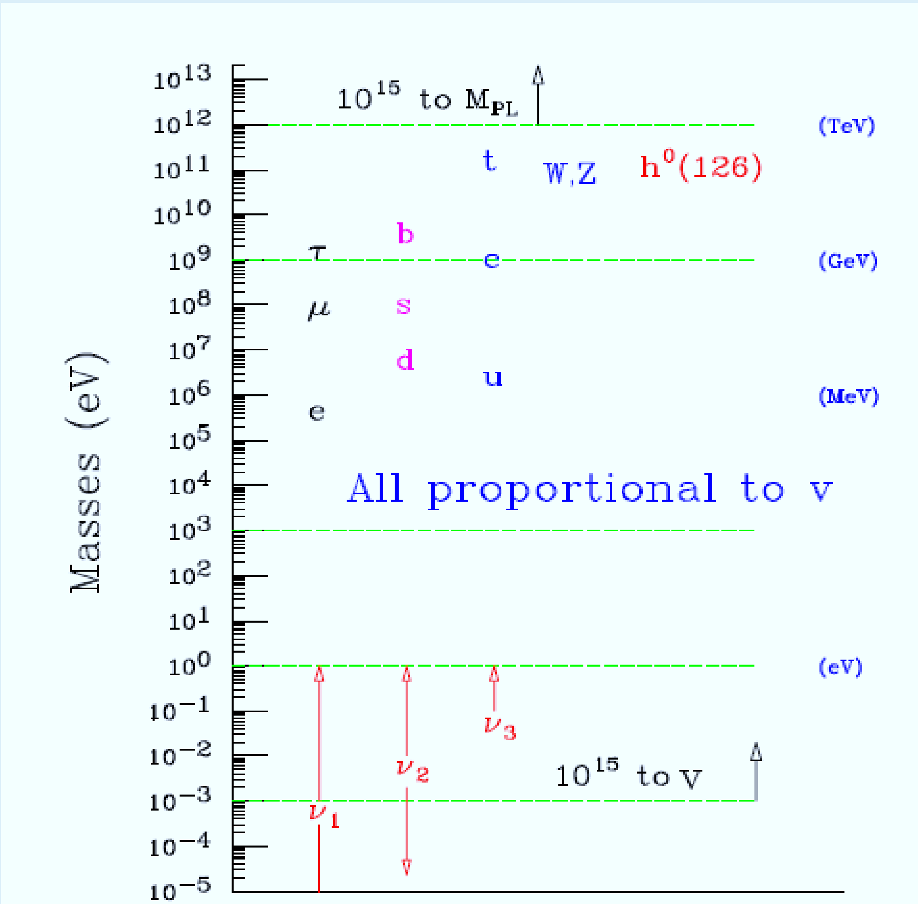
We show the consistency of this scenario when a single component transition magnetic moment takes values

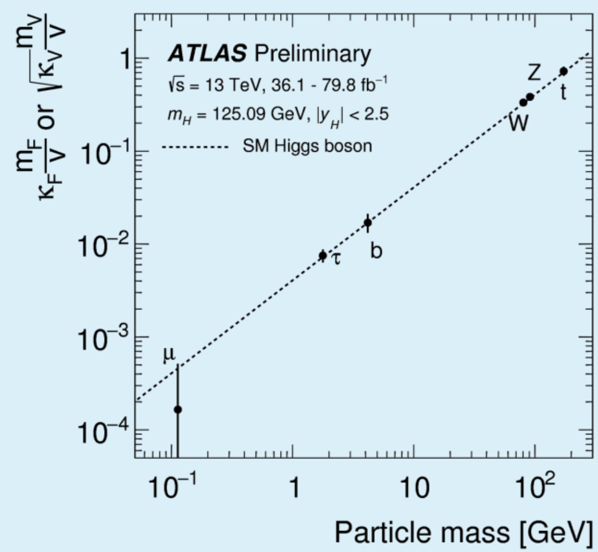
$\mu_{\nu_e \nu_\mu} \in (1.65 - 3.42) \times 10^{-11}\, \mu_B$



Babu, SJ, Lindner (2020)

Neutrino masses and mixings: New physics beyond the SM





$$m_\nu \sim y_\nu^{eff}\ v$$

$$y_\nu^{eff} < 10^{-12}$$

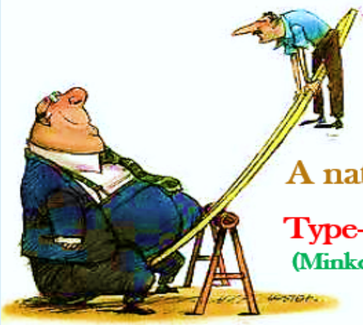
Neutrino Mass Generation

- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (79) 1566

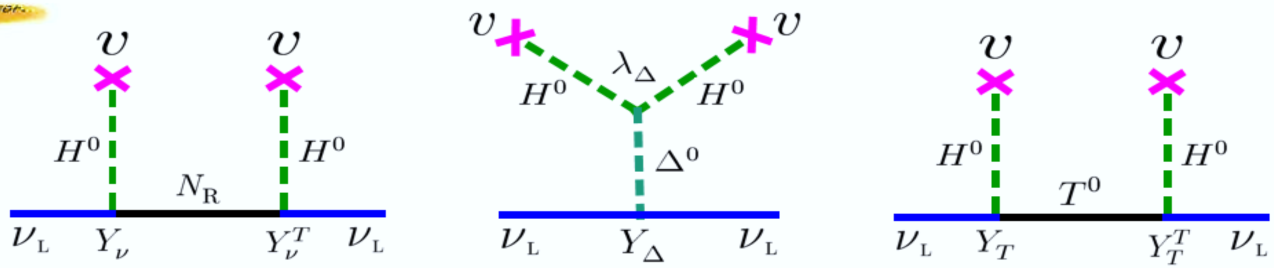
- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ★ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ★ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ★ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ★ Linear, Inverse, etc ...
  - Loop-induced:
    - ★ 1-loop Zee (80), Ma (99)
    - ★ 2-loop Babu (88)

Seesaw Model



A natural theoretical way to understand why 3 ν-masses are very small.

Type-I: SM + 3 right-handed Majorana ν's
(Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)



$$\boxed{M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T}$$

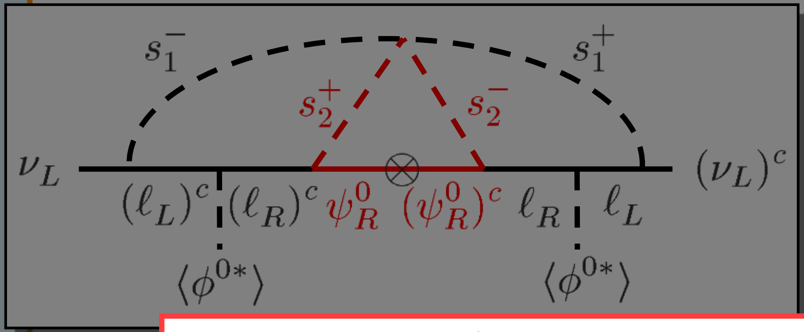
$$\boxed{M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}}$$

$$\boxed{M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T}$$

Type-II: SM + 1 Higgs triplet
(Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

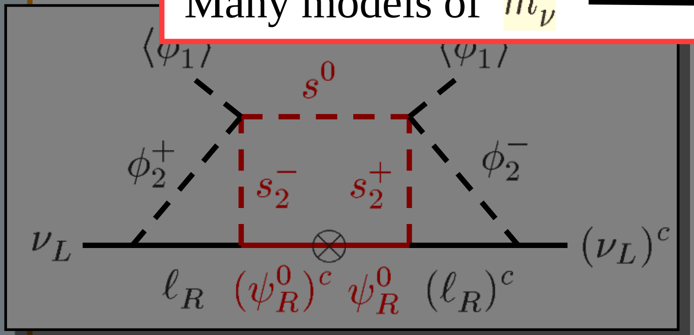
Type-III: SM + 3 triplet fermions
(Foot, Lew, He, Joshi 89)

Higher-loop models with DM

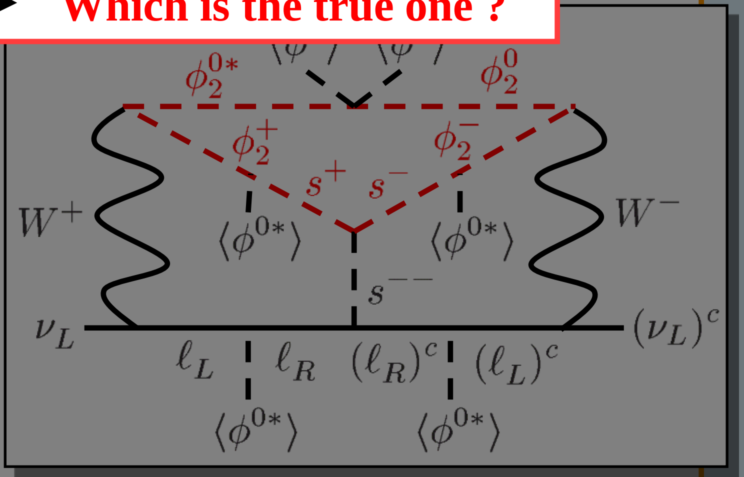


Krauss-Nasri
M.L. Krauss, S. I

Many models of m_ν $\longrightarrow$ **Which is the true one ?**

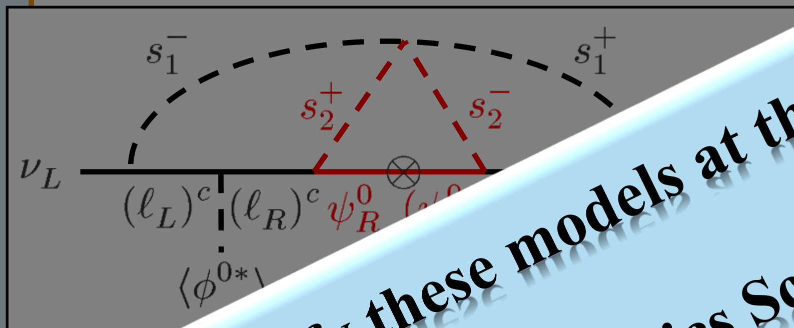


Aoki-Kanemura-Seto model
M. Aoki, S. Kanemura and O. Seto,
PRL**102**, 051805 (2009)



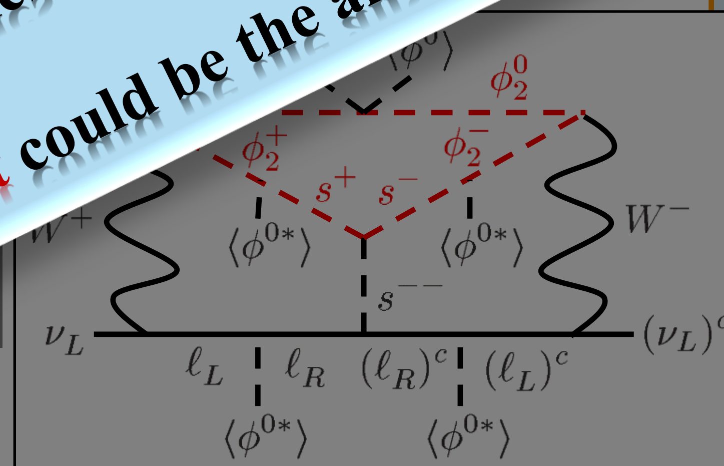
Gustafsson-No-Rivera model
M. Gustafsson, J.M. No, and M.A. Rivera,
PRL**110**, 21802 (2013)

Higher-loop models with DM



...o model

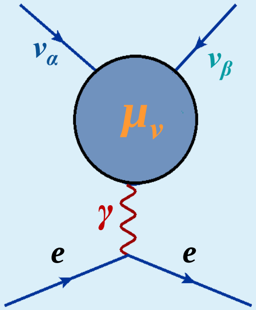
...ura and O. Seto,
PRL**102**, 051805 (2009)



Gustafsson-No-Rivera model
M. Gustafsson, J.M. No, and M.A. Rivera,
PRL**110**, 21802 (2013)

1. Can we test / falsify these models at the experiments ?
2. Can we explore the new Physics Scale M ?
3. Neutrino magnetic moment could be the answer……

Neutrino Magnetic Moment–Mass Conundrum

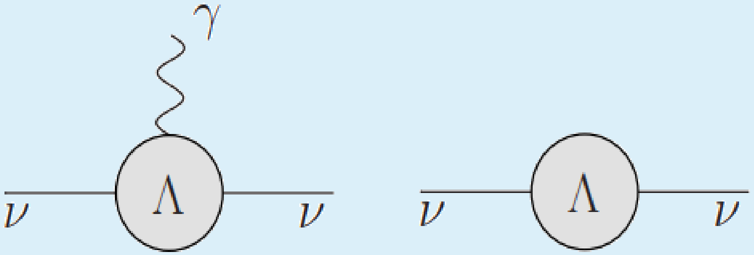


In the absence of additional symmetries (and without severe fine-tuning) one would expect neutrino masses several orders of magnitude larger than their measured values., if $\mu_\nu \sim 10^{-11}\,\mu_B$

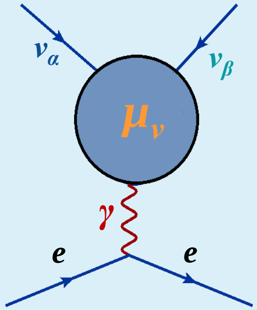
The main reason for this expectation is that the magnetic moment and the mass operators are both chirality flipping, which implies that by removing the photon line from the loop diagram that induces μ_ν one would generate a neutrino mass term.

This would lead to the naive estimate of m_ν originating from such diagrams given by $m_\nu \sim \frac{M^2 \mu_\nu}{2\, m_e \mu_B}$

M represents the mass of a heavy particle circling inside the loop diagram.



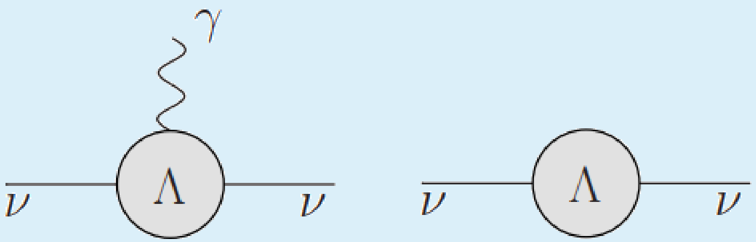
Neutrino Magnetic Moment–Mass Conundrum

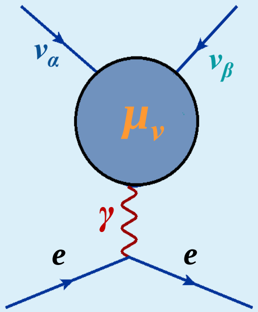


Since the photon is emitted from an internal line to induce a magnetic moment operator, at least some of the particles inside the loop must be electrically charged.

Experimental limits show that any such charged particle should be heavier than about 100 GeV and it would lead to $m_\nu \sim 0.1$ MeV, some six orders of magnitude larger than the observed masses.

If the internal particles are milli-charged, direct experimental limits won't exclude them from being light. Even in this case, owing to other experimental constraints on milli-charged particles, the maximum induced $\mu_\nu \sim 10^{-15} \mu_B$





Neutrino Magnetic Moment–Mass Conundrum

This magnetic moment–mass 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.

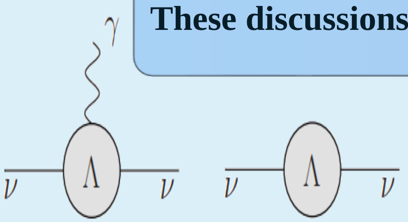
Such a time variation could be explained if the neutrino has a $\mu_\nu \sim 10^{-10}\,\mu_B$ which would lead to spin-flip transition inside the solar magnetic field. Such transitions could even undergo a matter enhanced resonance.

This explanation of the solar neutrino data has faded with the advent of other experiments,

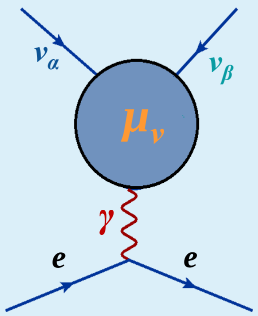
In the late 1980's and early 1990's there were significant theoretical activities that addressed the compatibility of a large neutrino magnetic moment with a small mass.

After that, in the theory side, no interesting developments have been made.

These discussions become very relevant today.



Neutrino Magnetic Moment–Mass Conundrum in the SM and beyond



- **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:**

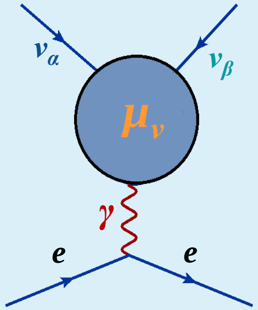
$$\mathcal{L} \supset \mu_\nu \overline{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} + m_\nu \overline{\nu}_L \nu_R + \mathrm{H.c.}$$

- **In the Standard Model (SM), when right-handed neutrinos are introduced so that the neutrino has a small Dirac mass, its magnetic moment is given by**

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

K. Fujikawa and R. Shrock (1980)

Neutrino Magnetic Moment–Mass Conundrum in the SM and beyond



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

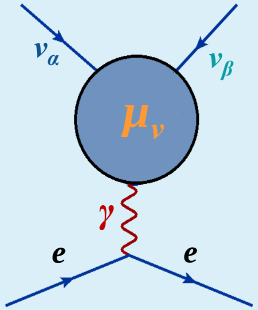
$$\mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j)\sum_{\ell=e,\mu,\tau} U^*_{\ell i}U_{\ell j}\frac{m_\ell^2}{m_W^2}$$

- The resulting transition magnetic moment is even smaller than the previous estimate: at most of order $\mu_\nu \sim 10^{-23}\,\mu_B$.

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

P. B. Pal and L. Wolfenstein **(1982)**

Neutrino Magnetic Moment–Mass Conundrum in the SM and beyond



- **LRSM:** **Nonstandard interactions of the neutrinos can lead to enhanced magnetic moments, esepcially when the new physics lies near the TeV scale. For example, in left-right symmetric models, the right-handed neutrino couples to a W_R gauge boson, which also has mixing with the W boson:**

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

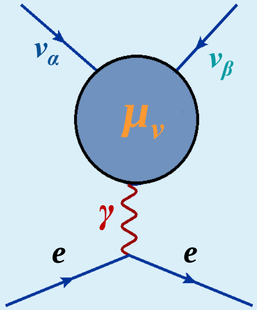
C. Giunti and A. Studenikin (2014)

- **This mixing angle is constrained by muon decay asymmetry parameters, as well as by $b \to s\gamma$ decay rate, leading to a limit $\mu_\nu <$ $10^{-14}\,\mu_B$**

- **In supersymmetric extensions of the SM, lepton number may be violated by *R*-parity breaking interactions. In such contexts, without relying on additional symmetries, the neutrino transition magnetic moment will be (imposing experimental constraints on the SUSY parameters) of the order at most about $10^{-14}\,\mu_B$.**

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

A. Spin Symmetry Mechanism and Large Neutrino Magnetic Moment



In *1990, Barr, Freire, and Zee (BFZ)* proposed a spin symmetry mechanism which provides for a large neutrino transitional magnetic moment with a relatively small neutrino mass.

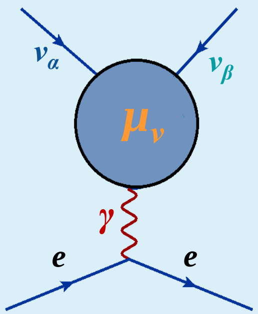
To illustrate the mechanism, they extended the scalar sector of the popular Zee model of neutrino mass with an additional Higgs doublet.

Subsequently it was shown in *1992 by Babu et al.* that this mechanism can be realized within the Zee model without the addition of a third scalar doublet, providing large neutrino magnetic moment.

However, the contribution of two-loop graphs for the neutrino transition magnetic moments have not been quantitatively analyzed thus far.

We perform such an analysis and derive admissible values of the neutrino transition magnetic moment in the Zee model as well as in its BFZ extension.

A. Spin Symmetry Mechanism and Large Neutrino Magnetic Moment



In renormalizable gauge theories there are no direct couplings of the type $\gamma W^+ S^-$ where S^- is a charged scalar field.

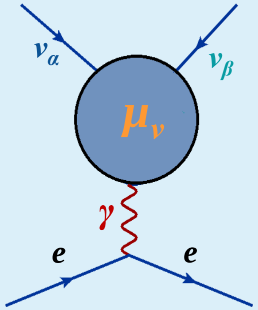
However, such a coupling could be generated via loops. Barr, Friere and Zee used this induced vertex to construct models of large μ_ν. At the two loop level, this vertex will contribute to μ_ν.

As for its contribution to m_ν, it is well known that for transversely polarized vector bosons, the transition from spin 1 to spin 0 cannot occur.

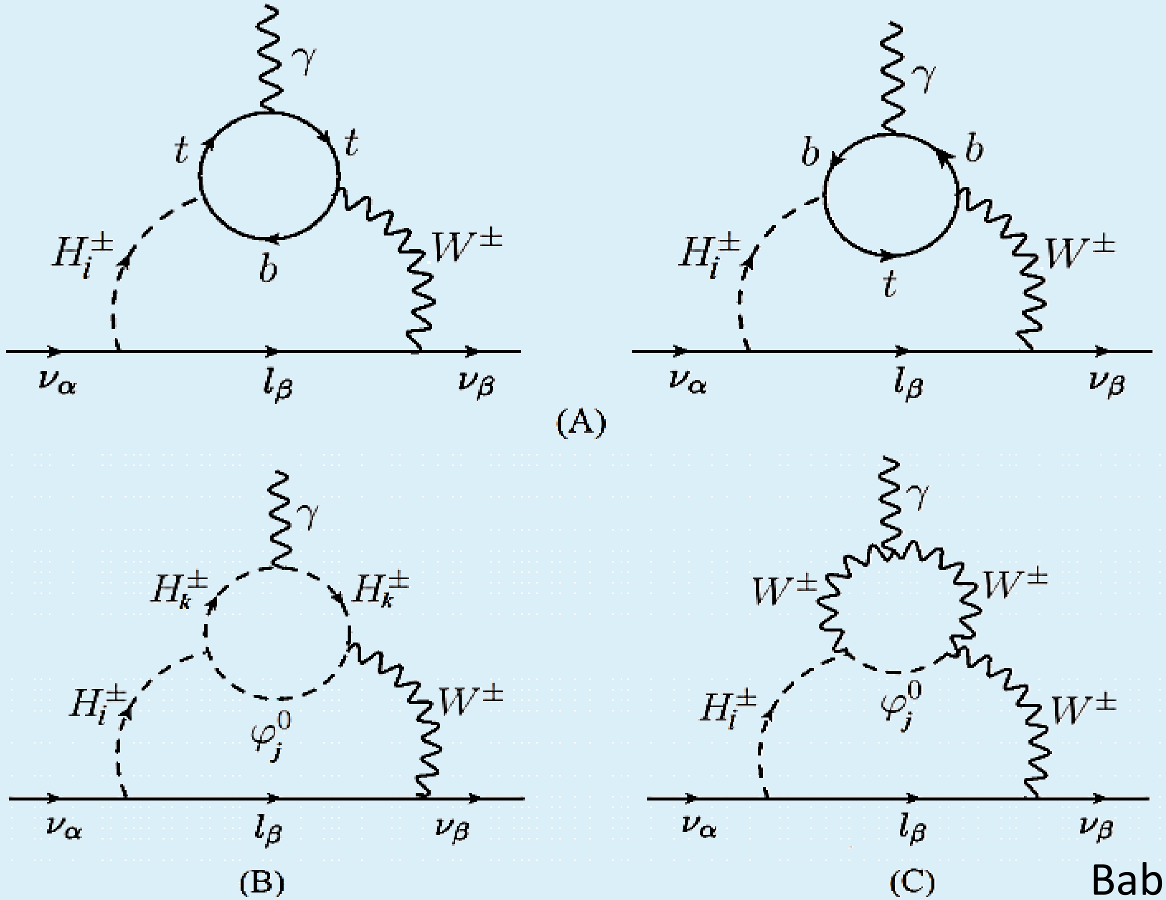
Only the longitudianl mode, the Goldstone mode, would contribute to such transitions.

This implies that in the two loop diagram utilizing the $\gamma W^+ S-$ for generating $\mu\nu$, 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.

We perform a thorough analysis and derive admissible values of the neutrino transition magnetic moment in the Zee model as well as in its BFZ extension.

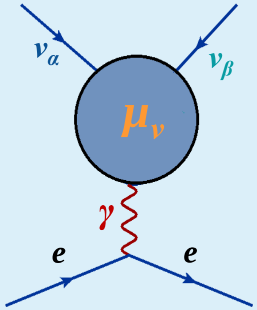


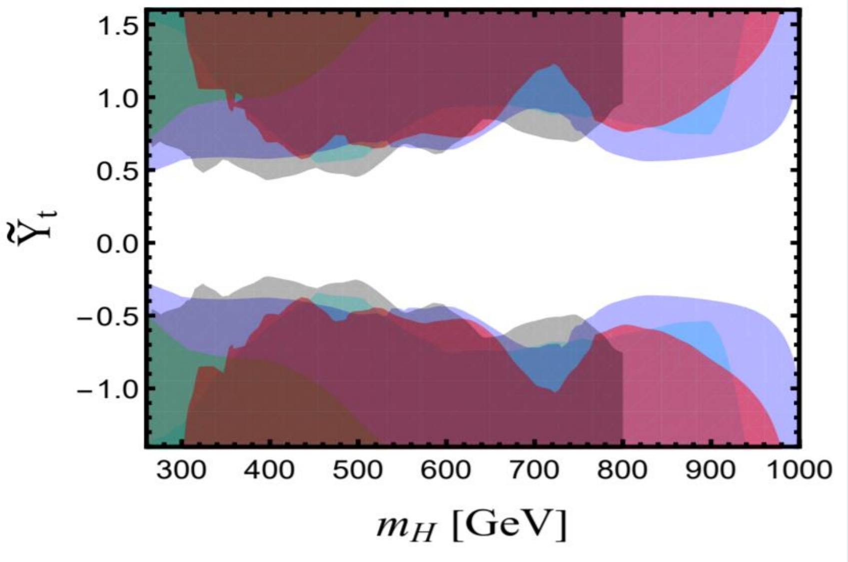
A. Spin Symmetry Mechanism and Large Neutrino Magnetic Moment



Babu, SJ, Lindner (2020)

A. Spin Symmetry Mechanism and Large Neutrino Magnetic Moment





Current limits in top quark Yukawa coupling in Zee model in from SM Higgs observables as well as Heavy Higgs searches. Gray, red and cyan shaded regions are excluded from current di-Higgs limit looking at different final states *2b2γ, 4b*, and *2b2τ* respectively; Blue and green shaded zones are excluded from the resonant *ZZ* and *WW* searches

$$\mathcal{L}_y = Y_d \bar{Q}_L d_R H_1 + \widetilde{Y}_d \bar{Q}_L d_R H_2 + Y_u \bar{Q}_L u_R \widetilde{H}_1 + \widetilde{Y}_u \bar{Q}_L u_R \widetilde{H}_2$$
$$+ Y_\ell \bar{\psi}_L H_1 \psi_R + \widetilde{Y}_\ell \bar{\psi}_L H_2 \psi_R + f \bar{\psi}_L \psi_L \eta^+ + \mathrm{H.}c.$$

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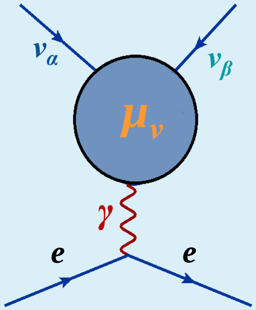
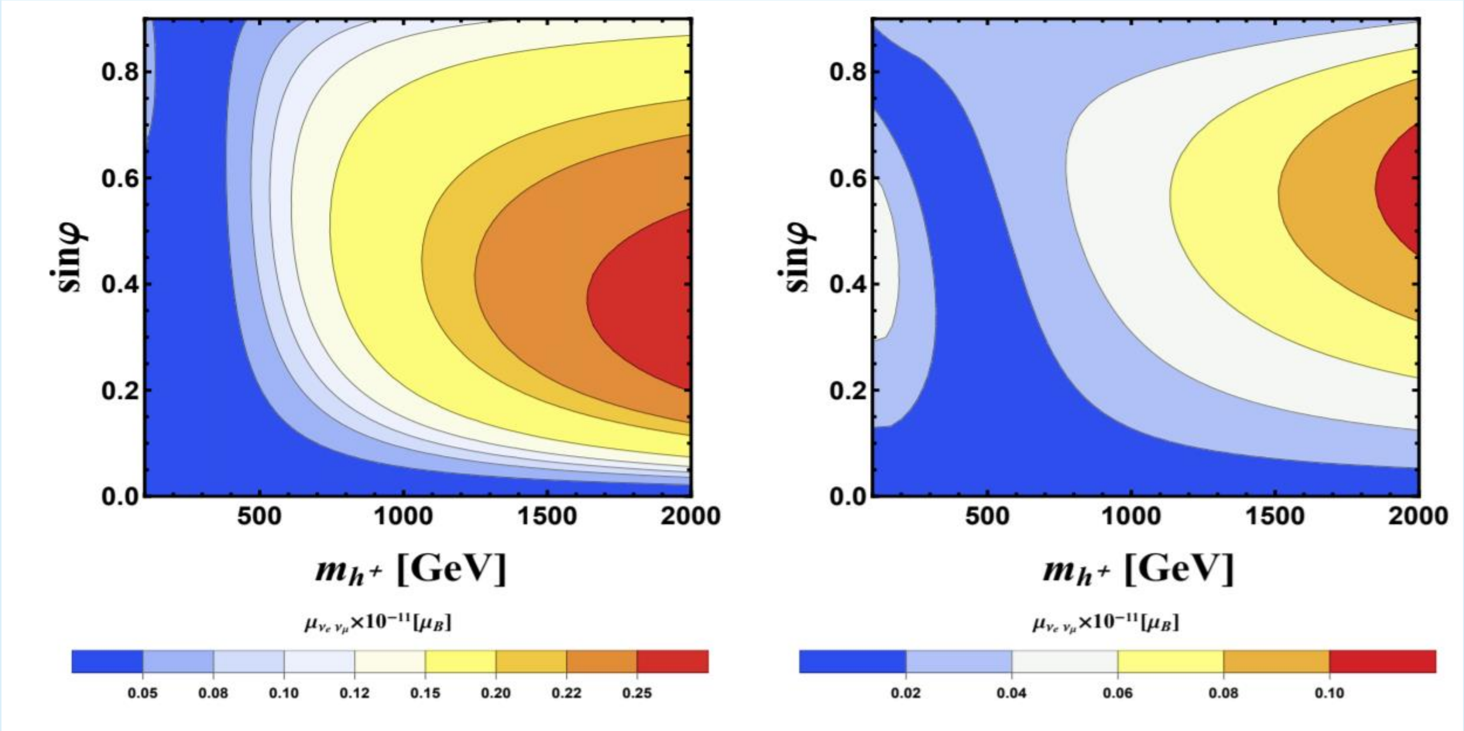


A. Spin Symmetry Mechanism and Large Neutrino Magnetic Moment



In this optimized setup, one can achieve neutrino transition magnetic moment as big as $3 \times 10^{-12}\,\mu_B$, which is insufficient to explain the observed XENON1T electron recoil excess

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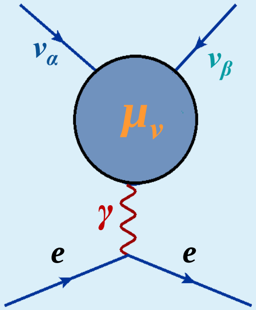
B. $SU(2)_H$ Symmetry for Enhanced Neutrino Magnetic Moment



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

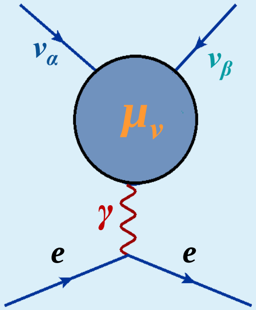
The mass operator, being a Lorentz scalar, is symmetric, while the magnetic moment, being a Lorentz tensor operator is antisymmetric in the two fermion fields.

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.

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



We showed that a horizontal symmetry acting on the electron and the muon families can serve the same purpose, which is easier to implement as such a symmetry commutes with the weak interactions. This would lead to a transition magnetic moments for Majorana neutrinos.

Our simplification is that the symmetry is only approximate, broken explicitly by electron and muon masses. Fewer new particles would then suffice to complete the model.

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.

Such breaking will have to be included in the neutrino sector as well. $SU(2)_H$ cannot be exact, as it would imply $m_e = m_\mu$. We propose to include explicit but small breaking of $SU(2)_H$, so that realistic electron and muon masses can be generated.

We have computed the one-loop corrections to the neutrino mass from these explicit breaking terms and found them to small enough so as to not upset the large magnetic moment solution.

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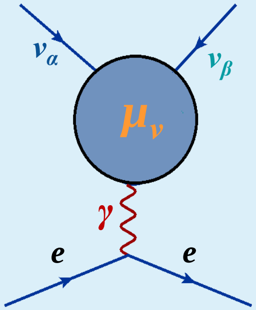
B. *SU(2)$_H$* Symmetric model for Enhanced Neutrino Magnetic Moment



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

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

The Higgs sector of the model:

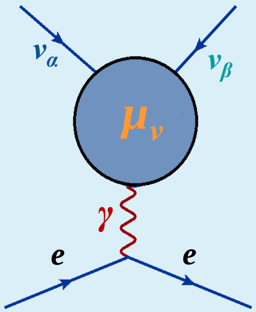
$$\phi_S = \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} \qquad (2, \tfrac{1}{2}, 1)$$

$$\Phi = \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} \qquad (2, \tfrac{1}{2}, 2)$$

$$\eta = (\eta_1^+ \quad \eta_2^+) \qquad (1, 1, 2) \ .$$

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

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



Yukawa Lagrangian of the model:

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm Yuk} &= \delta h_1 \left[(\bar\nu_e e_R \phi_S^+ + \bar e_L e_R \phi_S^0) - (\bar\nu_\mu \mu_R \phi_S^+ + \bar\mu_L \mu_R \phi_S^0)\right] \\
&+ \delta h_3 \left[-(\bar\nu_\tau e_R \phi_2^+ + \bar\tau_L e_R \phi_2^0) - (\bar\nu_\tau \mu_R \phi_1^+ + \bar\tau_L \mu_R \phi_1^0)\right] \\
&+ \delta f \left[\left(\nu_e^T C \tau_L - e_L^T C \nu_\tau\right) \eta_2^+ + \left(\nu_\mu^T C \tau_L - \mu_L^T C \nu_\tau\right) \eta_1^+\right] \\
&+ \delta f' \left[(\bar\nu_e \tau_R \phi_1^+ + \bar e_L \tau_R \phi_1^0) - (\bar\nu_\mu \tau_R \phi_2^+ + \bar\mu_L \tau_R \phi_2^0)\right] + H.c.
\end{aligned}
$$

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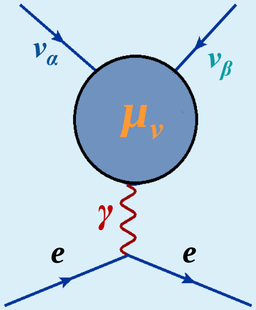
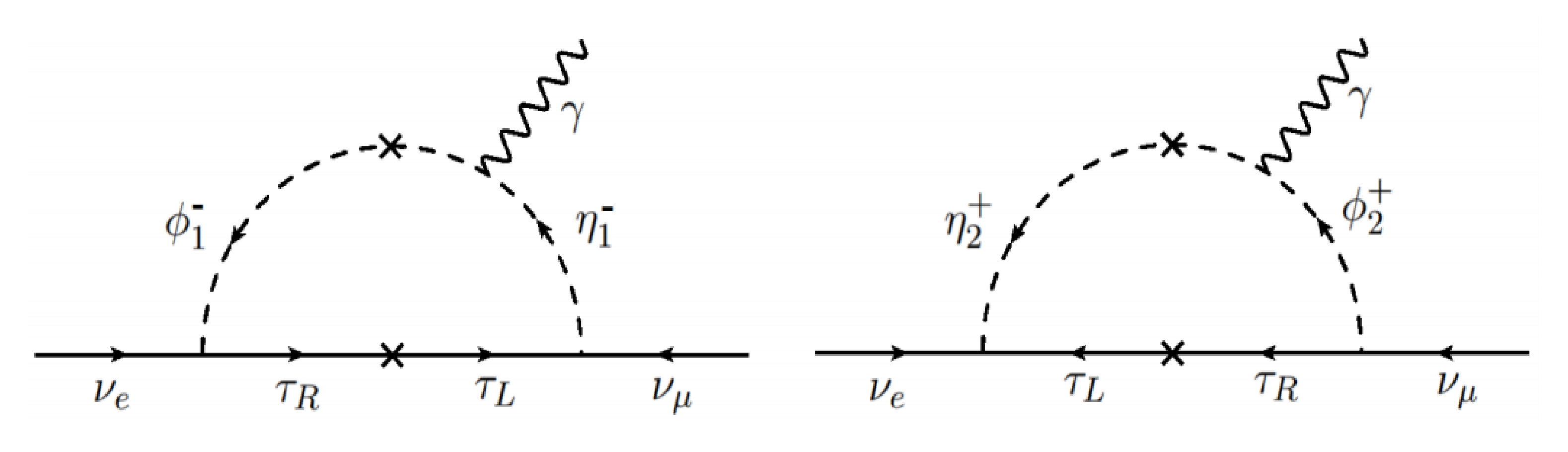
B. $SU(2)_H$ Symmetric model for Enhanced Neutrino Magnetic Moment





- **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.**

- **Feynman diagrams generating neutrino transition magnetic moment in the *$SU(2)_H$* model. There are additional diagrams where the photon is emitted from the τ lepton line. The same diagrams with the photon line removed would contribute to Majorana mass of the neutrino.**

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

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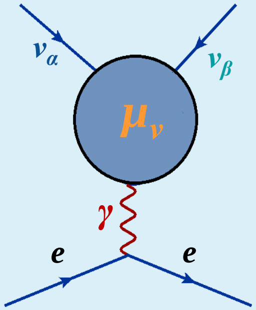
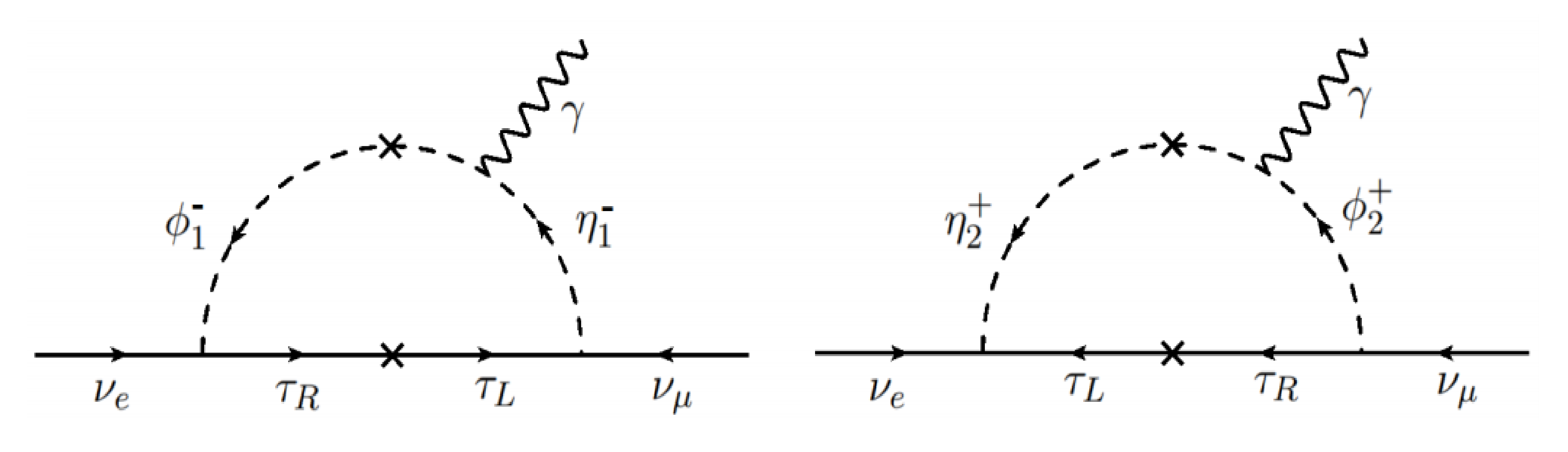
B. $SU(2)_H$ Symmetric model for Enhanced Neutrino Magnetic Moment





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

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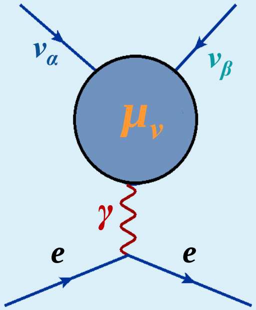
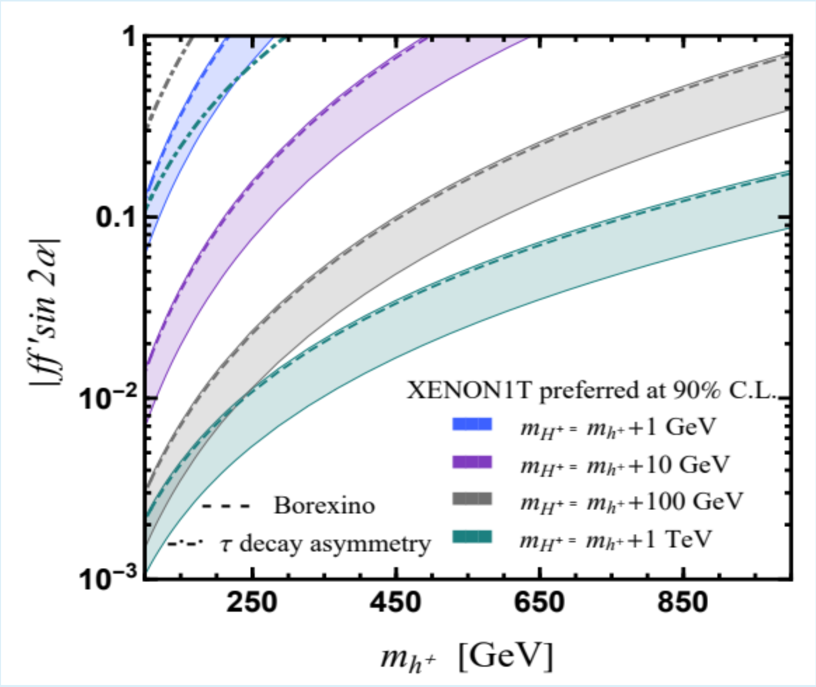
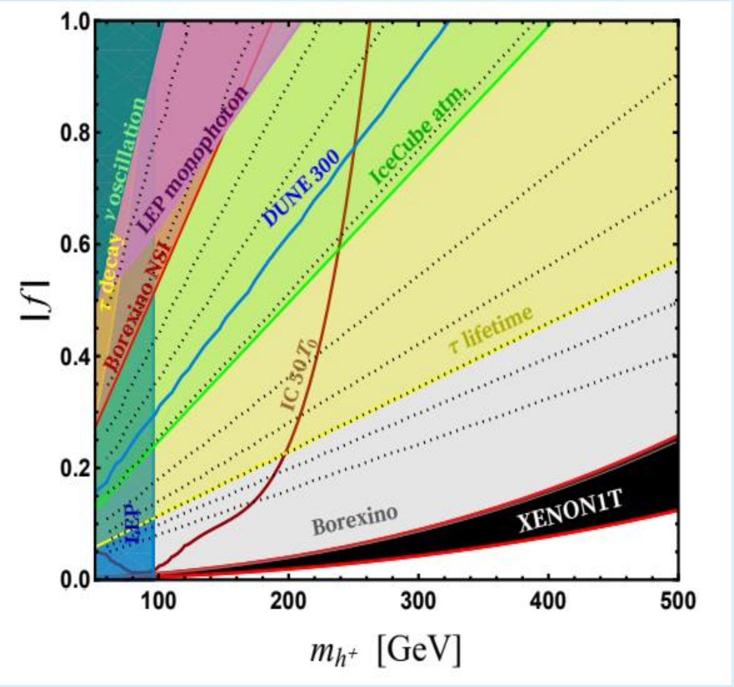


B. $SU(2)_H$ Symmetric model for Enhanced Neutrino Magnetic Moment





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

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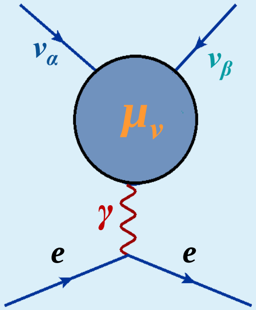

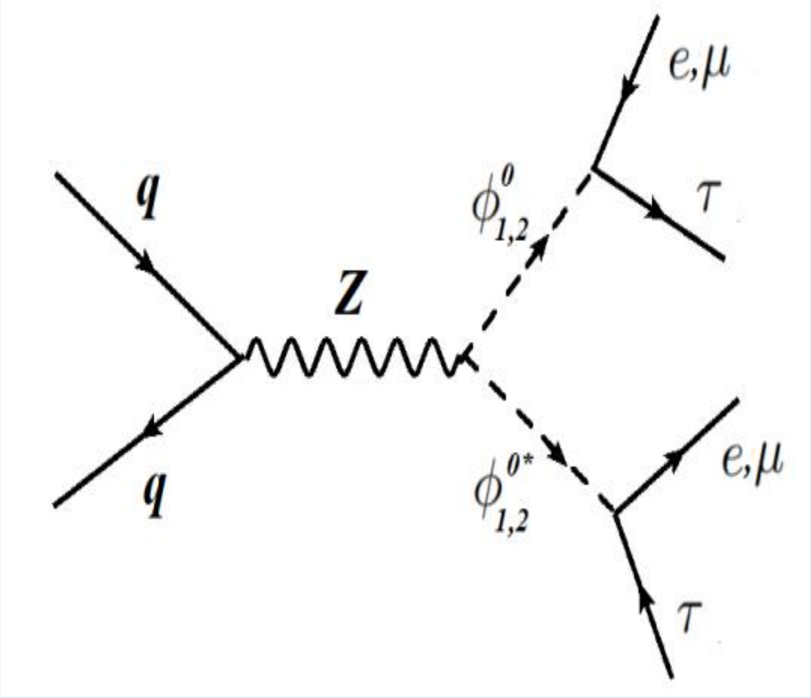

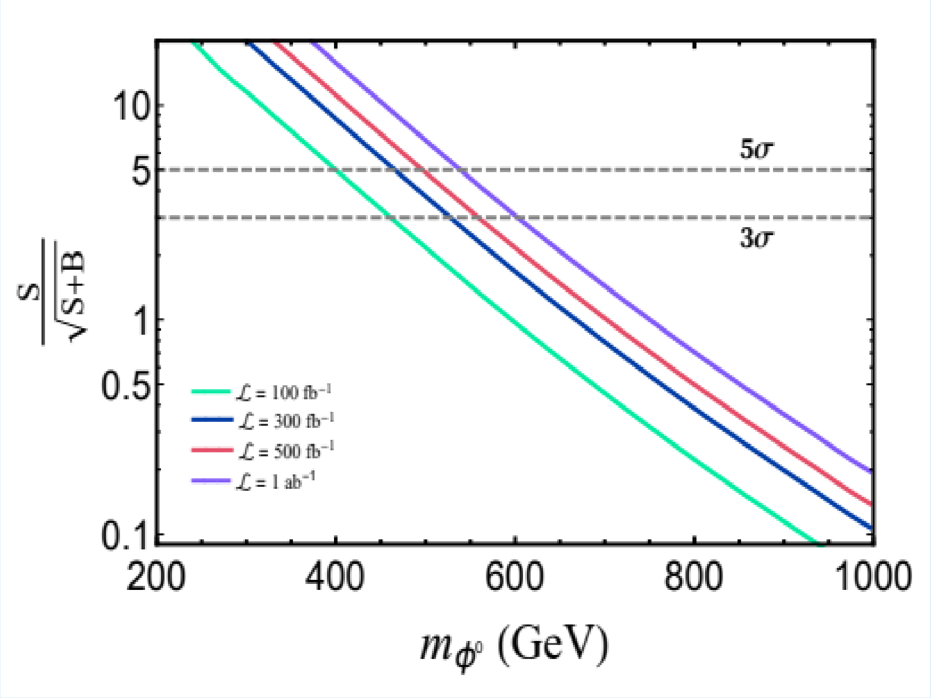

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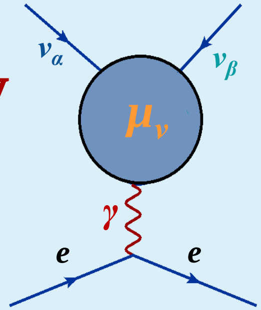
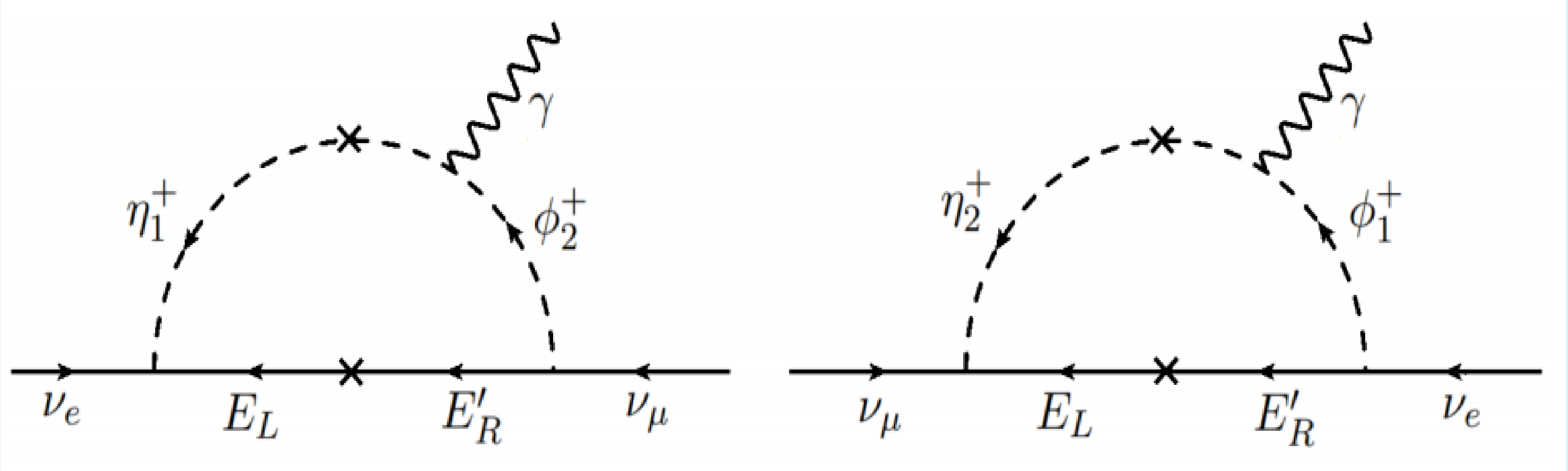
C. Generalization to $SU(3)_H$ Symmetry for Enhanced Neutrino Magnetic Moment



The main idea is that if the three lepton families transform as a 3 of an $SU(3)_H$ symmetry, the neutrino magnetic moment term, which is part of the antisymmetric 3^{*a} in the decomposition $3\times3 = 3^{*a} + 6^s$ of $SU(3)_H$ may be allowed, while the neutrino mass term belonging to the 6^{*s} could be suppressed. This could happen if the symmetry breaking sector does not include a 6 of $SU(3)_H$, but contains a 3.



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Neutrino Magnetic Moment: From Astrophysics and Cosmology

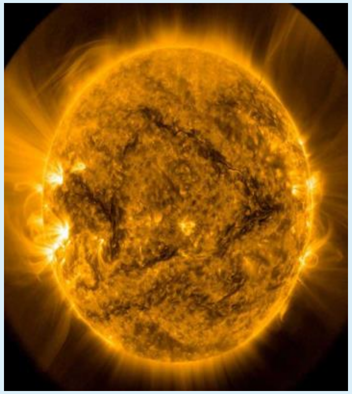
Evolution of stars can provide indirect constraints on the magnetic moments of either Dirac or Majorana neutrinos.

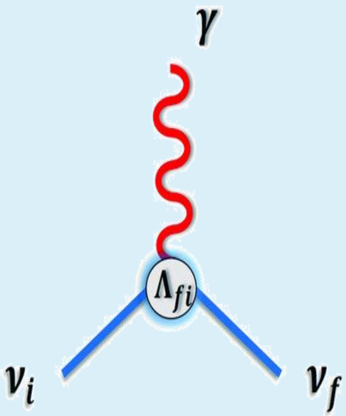
Photons in the plasma of stellar environments can decay either into $\nu\bar{\nu}$ for the case of Dirac neutrinos or into $\nu_\alpha\nu_\beta$ for the case of Majorana neutrinos.

Such decays are kinematically allowed in a plasma since the photon acquires a mass.

If such decays occur too rapidly, that would drain energy of the star, in conflict with standard stellar evolution models which appear to be on strong footing.

Limits on μ_ν have been derived by requiring the energy loss in such decays to be not more than via standard processes.





Neutrino Magnetic Moment: From Astrophysics and Cosmology

The best limit on μ_ν from this argument arises from red giant branch of globular clusters, resulting in a limit of

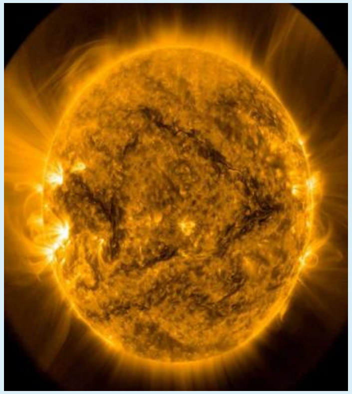
$\mu_\nu < 4.5 \times 10^{-12}\,\mu_B$.

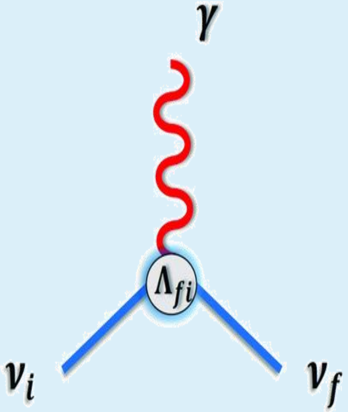
Validity of this limit would make the neutrino magnetic moment interpretation of the XENON1T excess *questionable*.

We note that these indirect constraints from astrophysics may be evaded if the plasmon decay to neutrinos is kinematically forbidden.

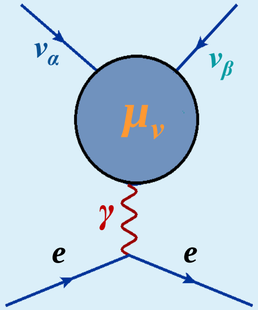
There are also cosmological limits arising from big bang nucleosynthesis.

However, these limits are less severe, of order $10^{-10}\,\mu_B$.





Mechanism to evade astrophysical limits on neutrino magnetic moments

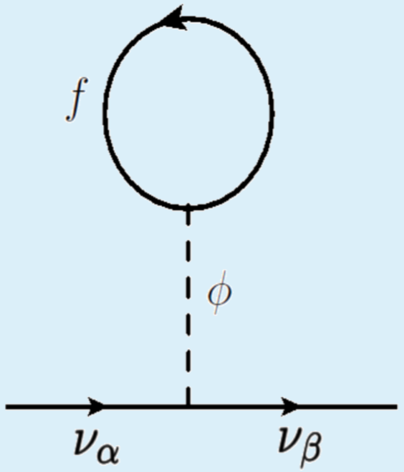


$$\mathcal{L} \supset -\frac{y_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\phi\nu_\beta - y_f\bar{f}\phi f - \frac{m_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\nu_\beta - \frac{m_\phi^2}{2}\phi^2$$

We closely follow the recent field theoretic evaluation of the medium-dependent mass of the neutrino in the presence of a light scalar that also couples to ordinary matter in illustrating our mechanism. Such interactions would provide the neutrino with a matter-dependent mass.

Phenomenological implications of this scenario, including long-range force effects, were studied and phenomenological constraints from laboratory experiments, fifth force experiments, astrophysics and cosmology are analyzed. [Parke et al. (2018), Smirnov et al.(2019), Babu et al. (2019)]

We make use of these constraints here in providing a neutrino trapping mechanism.



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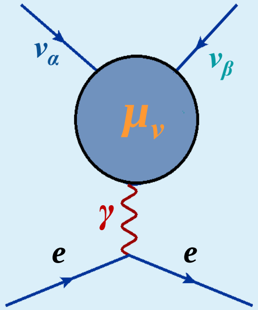
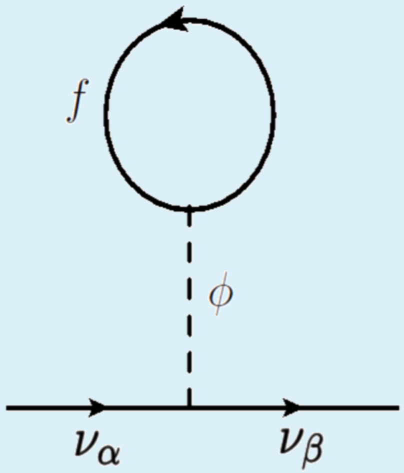


Mechanism to evade astrophysical limits on neutrino magnetic moments

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

We recall that horizontal branch stars have core temperature of order 10 keV, radius of 5×10^4 km and density of 10^4 g/cc. Red giants have core temperature of order 10 keV, radius of 10^4 km and density of 10^6 g/cc. Thus, $R^{-1} = 2\times10^{-14}$ eV for the case of red giants. Using $m_\varphi = 2 \times 10^{-14}$ eV, $y_e = 5 \times 10^{-30}$, $y_\nu = 2 \times 10^{-7}$, we obtain from the effective mass of the neutrino inside red giants to be 12 MeV, which is essentially the largest value of the induced neutrino mass can have, consistent with other constraints.

Since the induced mass of the neutrino inside red giants can be as large as 12 MeV, plasmon decays would be highly suppressed. We could also consider interactions of φ with the nucleon instead of the electron.



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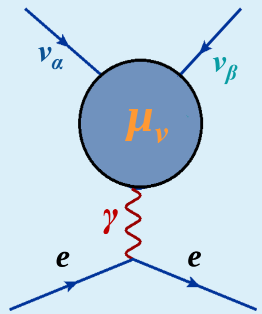

Conclusions

We have revived and proposed a simplified model based on $SU(2)_H$ horizontal symmetry that can generate large neutrino transition magnetic moment without inducing unacceptably large neutrino masses. The simplification we suggest is based on the symmetry being approximate.

We investigated a spin symmetry mechanism that can generate large μ_ν while keeping m_ν small.

We have proposed a mechanism to evade this constraint based on interactions of neutrinos with a light scalar. Such interactions can induce a medium dependent mass for the neutrino in the interior of stars, which could prevent kinematically energy loss by plasmon decay into neutrinos.


Thank you!