Neutrino magnetic moments

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Solvay Workshop

'Beyond the Standard Model with Neutrinos and Nuclear Physics'

30.11.2017

Why?

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich

...

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

...

gez. W. Pauli

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Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than e • (10^{-13}cm).

~0.01 μ_B.

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Why?

- Neutrino masses & mixing = solid evidence for BSM.
- Implies other observables, such as (for Dirac ν)
  - Lepton flavor violation:

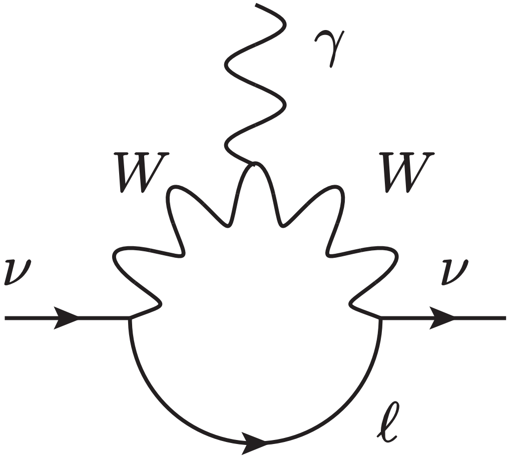
$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\mathrm{EM}}}{32\pi} \left| \sum_{j=2,3} U_{\alpha j} \frac{\Delta m_{j1}^2}{M_W^2} U_{j\beta}^\dagger \right|^2 < 5 \times 10^{-53}\,.$$

[Petcov, '77; Cheng & Li, '77]

  - Neutrino magnetic moment:

$$\mu_{ii}^{D} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \simeq 3 \times 10^{-19} \mu_B \left(\frac{m_i}{\mathrm{eV}}\right).$$

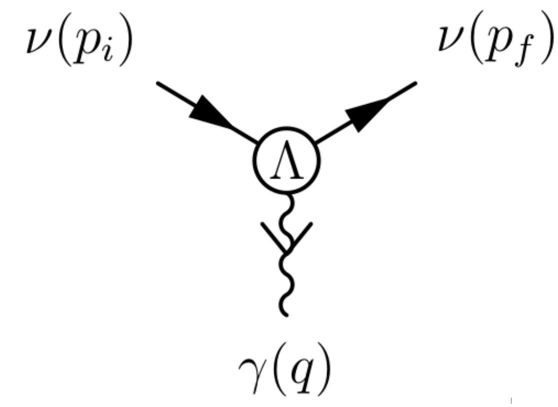
[Fujikawa, Shrock, '80]



Observation = physics beyond m_ν!

[Giunti, Studenikin, 1403.6344]

Framework



- General interaction of ν mass eigenstates with photon A: $\mathcal{H} = \sum_{i,j=1}^{3} \overline{\nu}_f \Lambda_\mu^{fi} \nu_i \, A^\mu .$

$$(\gamma_\mu - q_\mu \not{q}/q^2)[f_Q(q^2) + f_A(q^2) q^2 \gamma_5] - i\sigma_{\mu\nu} q^\nu [f_M(q^2) + i f_E(q^2) \gamma_5]$$

charge | anapole | magnetic | electric

- Hermitian form factor matrices f_X give moments $f_X(0)$:

$$\mu = f_M(0)\, , \epsilon = f_E(0)\, , \ \ldots$$

- For Majorana ν = ν^c: $f_A = +f_A^T\, , \ f_{Q,M,E} = -f_{Q,M,E}^T\, .$

[Giunti, Studenikin, 1403.6344]

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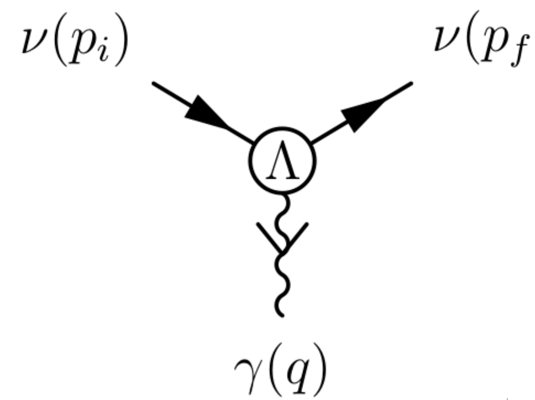

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$$\mu_{\text{Maj.}} = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix} .$$

- Hermitian form factor ma

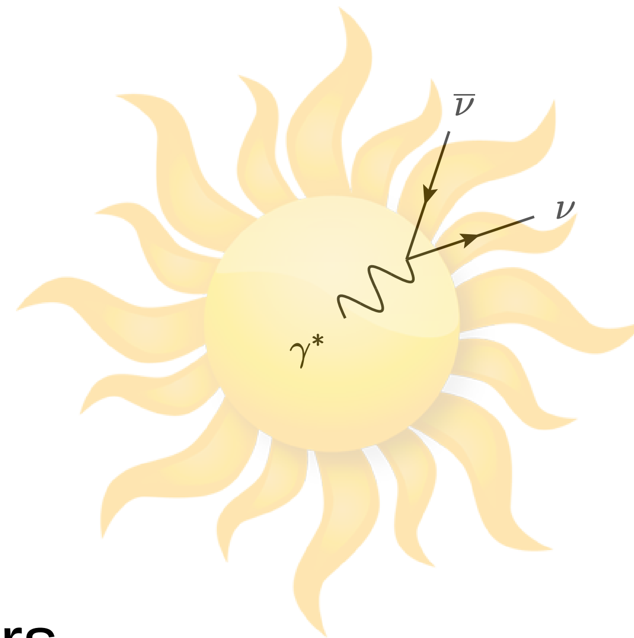
$$\mu = f_M(0)$$

- For Majorana ν = ν^c: $f_A = +f_A^T$, $f_{Q,M,E} = -f_{Q,M,E}^T$.

μ_ν in cosmology and astrophysics

- γ has plasma mass $\propto \sqrt{n_e/m_e}$.

  ⇒ Plasmon decay: $\gamma^* \to \nu\nu$.



- New cooling channel for stars!

  [Bernstein+, '63; Raffelt, '90s; Viaux+, '13]

$$\sqrt{\sum_{i,j} |\mu_{ij}|^2} < 4.5 \times 10^{-12} \mu_B.$$

  from red-giant branch in globular clusters.

- Big Bang Nucleosynthesis: $|\mu_{ij}| < 6 \times 10^{-10} \mu_B$.

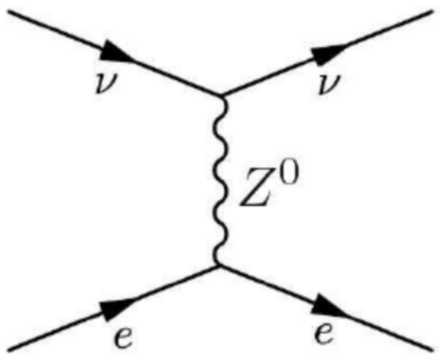
  [Vassh+ '15]

- For Dirac: $e\, \nu_L \to e\, \nu_R$ (in SN1987): $|\mu_{ij}| \lesssim 5 \times 10^{-13} \mu_B$.

  [Morgan, '81; Fukugita, Yazaki, '87; Barbieri, Mohapatra, '88; Ayala+, '99; Kuznetsov, Mikheev, '07]

Magnetic moment in lab

- Clean probe: elastic $\nu_\alpha + e \to \nu_\beta + e$.
- Observable recoil energy T_e.
- Incoherent: $\frac{d\sigma}{dT_e} = \left(\frac{d\sigma}{dT_e}\right)_{SM} + \left(\frac{d\sigma}{dT_e}\right)_{\mu_\nu}$.



$$r_1 + r_2 T_e + r_3 T_e^2$$

$$\frac{\pi\alpha^2}{m_e^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

[Engel, Vogel, ‘89]

- μ_ν wins for

$$T_e \lesssim \frac{\pi^2\alpha^2}{G_F^2 m_e^3}\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

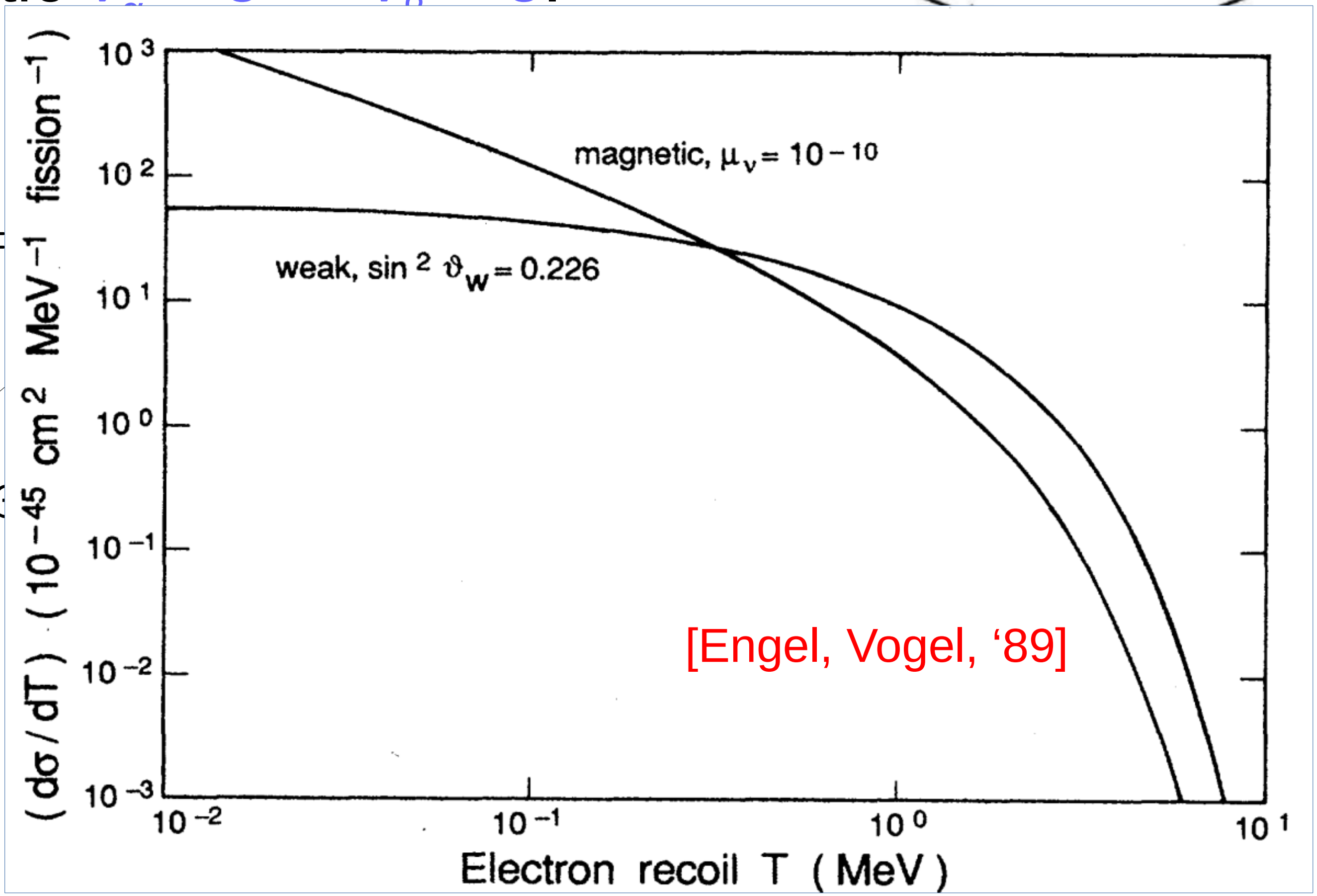
$$\simeq \text{few keV}\left(\frac{\mu_\nu}{10^{-11}\mu_B}\right)^2 .$$

Need low thresholds!

Magnetic moment in lab

- Clean probe: elastic $\nu_e + e \to \nu_e + e$.
- Observable recoil
- Incoherent: $\frac{d\sigma}{dT_e} =$

$r_1 + r_2 T_e + r_3$



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Need low thresholds!

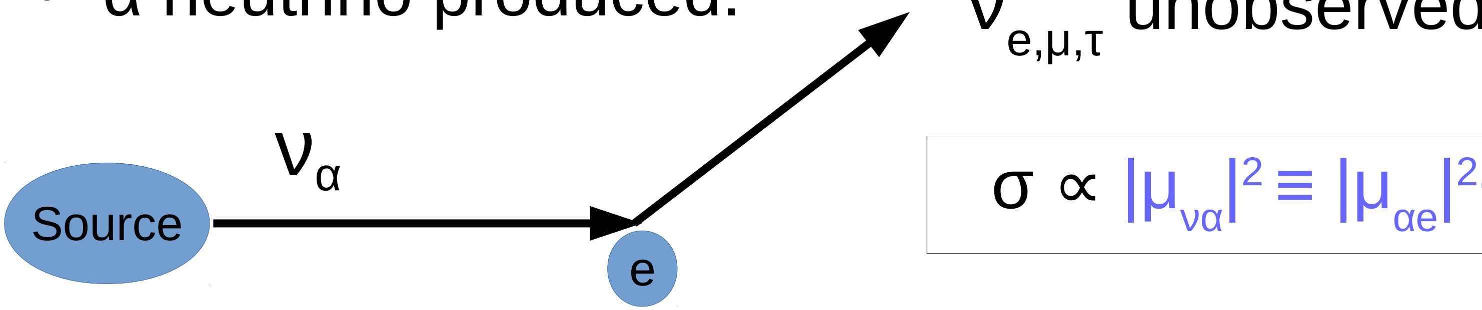
Current limits

- GEMMA, $\bar{\nu}_e$ from reactor: $|\mu_{\nu e}| < 3\times10^{-11}\,\mu_B$.
- LSND, $\bar{\nu}_\mu,\nu_\mu$ from accelerator: $|\mu_{\nu\mu}| < 7\times10^{-10}\,\mu_B$.
- DONUT, $\bar{\nu}_\tau,\nu_\tau$ from accelerator: $|\mu_{\nu\tau}| < 4\times10^{-7}\,\mu_B$.
- GEMMA-II will improve by factor 3, SHiP could test nu-tau.
- Far from neutrino-induced $10^{-19}\,\mu_B$.
- (Borexino, solar ν, $3\times10^{-11}\,\mu_B$, see talk by Oleg Smirnov.)

But what are we measuring here?

Effective magnetic moment $\mu_{\nu\alpha}$

- α neutrino produced:



$$\sigma \propto |\mu_{\nu\alpha}|^2 \equiv |\mu_{\alpha e}|^2+|\mu_{\alpha\mu}|^2+|\mu_{\alpha\tau}|^2$$

Effective magnetic moment $\mu_{\nu\alpha}$

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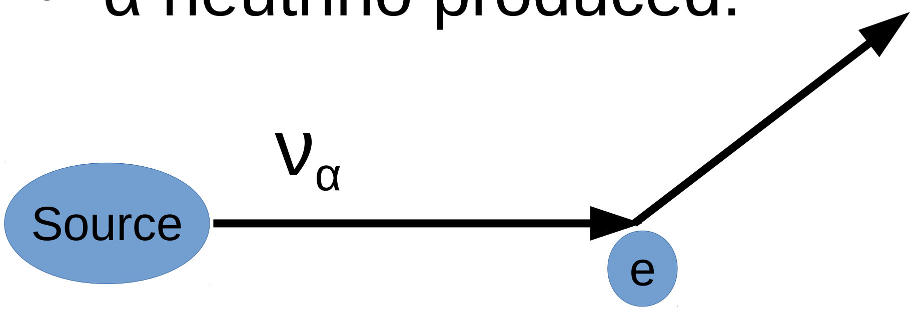
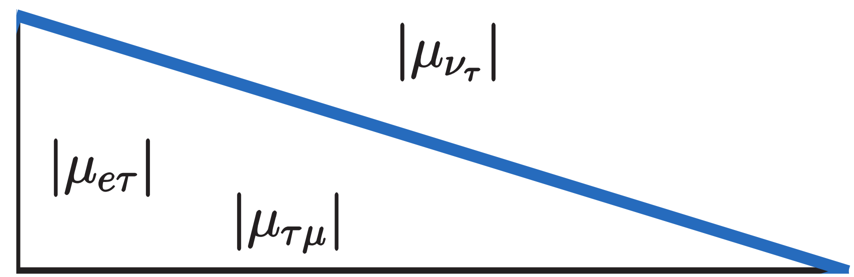


$\nu_{e,\mu,\tau}$ unobserved

$$\sigma \propto |\mu_{\nu\alpha}|^2 \equiv |\mu_{\alpha e}|^2+|\mu_{\alpha\mu}|^2+|\mu_{\alpha\tau}|^2$$

- For Majorana: $|\mu_{\alpha\alpha}| = 0$.



$$\mu_{\text{Maj.}} = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix} .$$

Effective magnetic moment $\mu_{\nu\alpha}$

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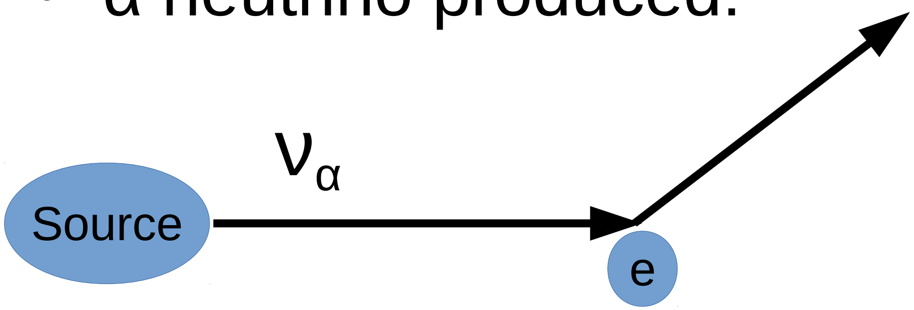
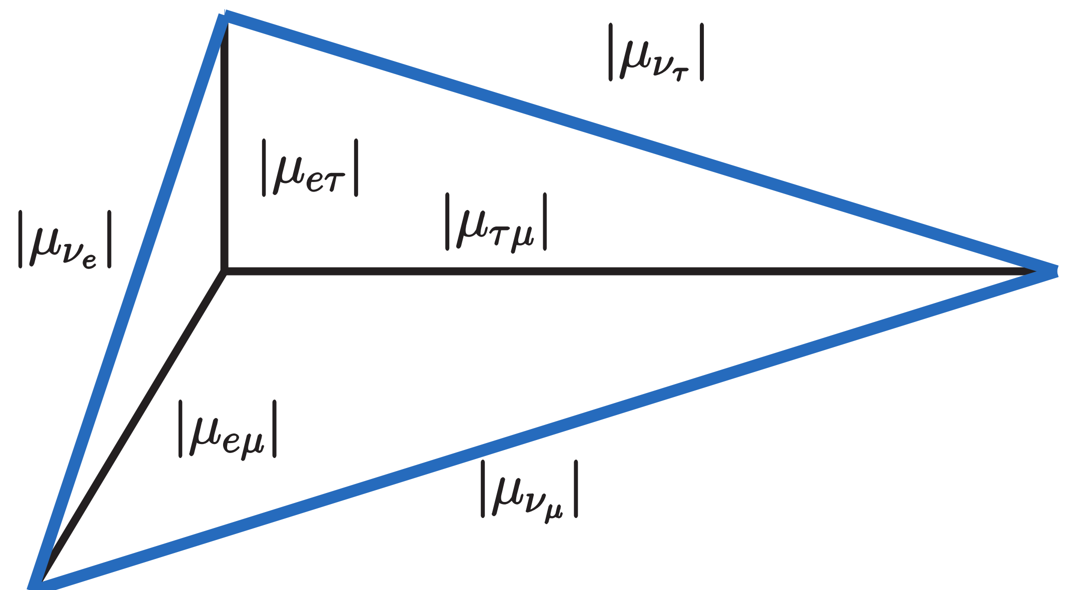


$$\sigma \propto |\mu_{\nu\alpha}|^2 \equiv |\mu_{\alpha e}|^2 + |\mu_{\alpha\mu}|^2 + |\mu_{\alpha\tau}|^2$$

- For Majorana: $|\mu_{\alpha\alpha}| = 0$.
- Majorana triangle:

$$|\mu_{\nu_I}| \geq \left||\mu_{\nu_J}| - |\mu_{\nu_K}|\right| ,$$
$$|\mu_{\nu_I}| \leq |\mu_{\nu_J}| + |\mu_{\nu_K}| .$$



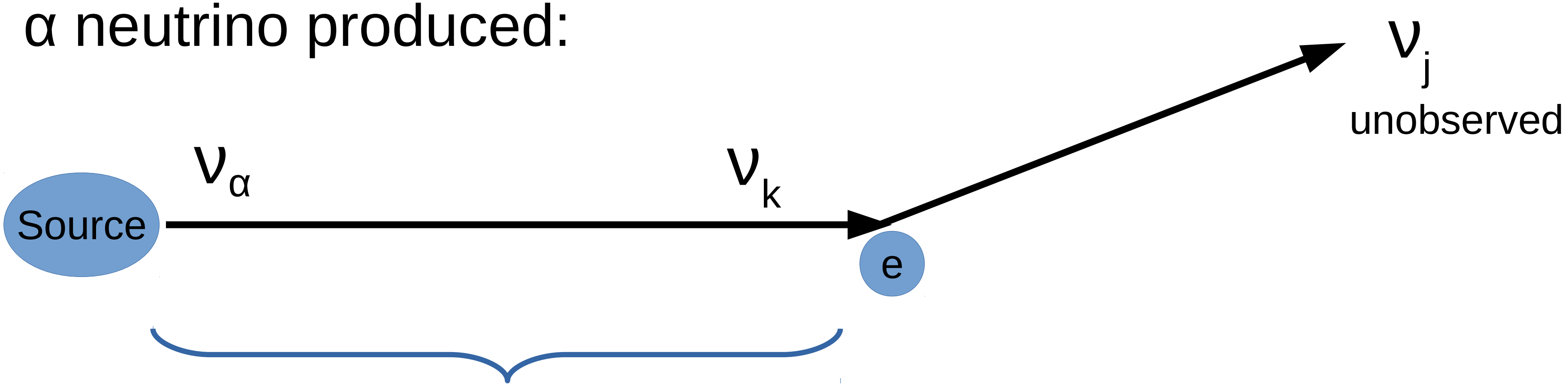
[Frère, Heeck, Mollet, 1506.02964]

- Special triangle:

$$|\mu_{\nu_\tau}|^2 \leq |\mu_{\nu_\mu}|^2 + |\mu_{\nu_e}|^2 \text{ plus cyclic permutations.}$$

Including neutrino mixing

- α neutrino produced:



- Oscillation length L between source and detector.
- Oscillation, then scattering into all mass eigenstates j:

$$|\mu_{\nu_\alpha}|^2 = \sum_j \left| \sum_k U^*_{\alpha k}\, e^{-i\Delta m^2_{kj} L/2E_\nu}\, \mu_{jk} \right|^2 .$$

- In above experiments: L/E → 0.

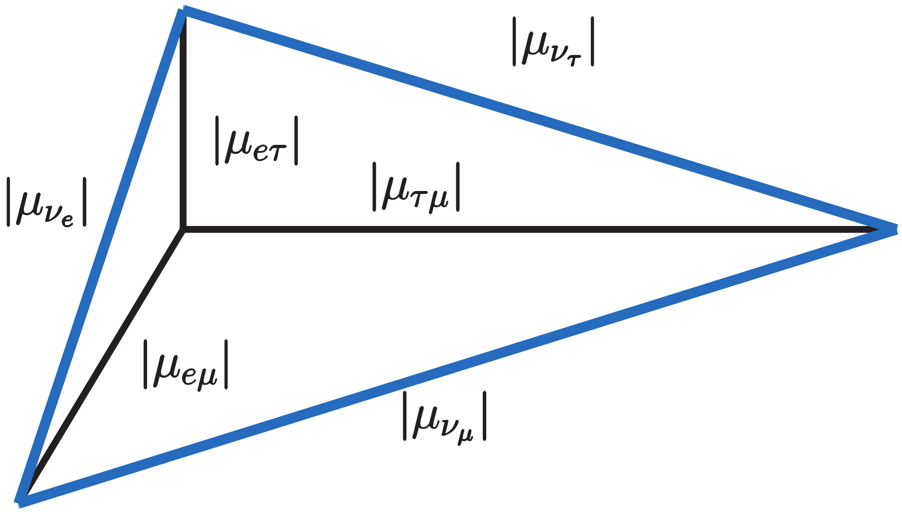
[Grimus, Stockinger, ‘98]

Triangle inequalities

- Short distance L/E → 0: $|\mu_{\nu_\alpha}|^2 = \sum_j |\sum_k U^*_{\alpha k}\mu_{jk}|^2$.
- For Majorana ν: μ antisymmetric!
- For unitary U, same inequalities as before,

$$|\mu_{\nu_\tau}|^2 \leq |\mu_{\nu_\mu}|^2 + |\mu_{\nu_e}|^2 \text{ plus cyclic permutations.}$$

- If violated ⇒ Not 3 Majorana ν!
- E.g. by SHiP measuring $\mu_{\nu\tau}$.
- Implies Dirac or light sterile ν.



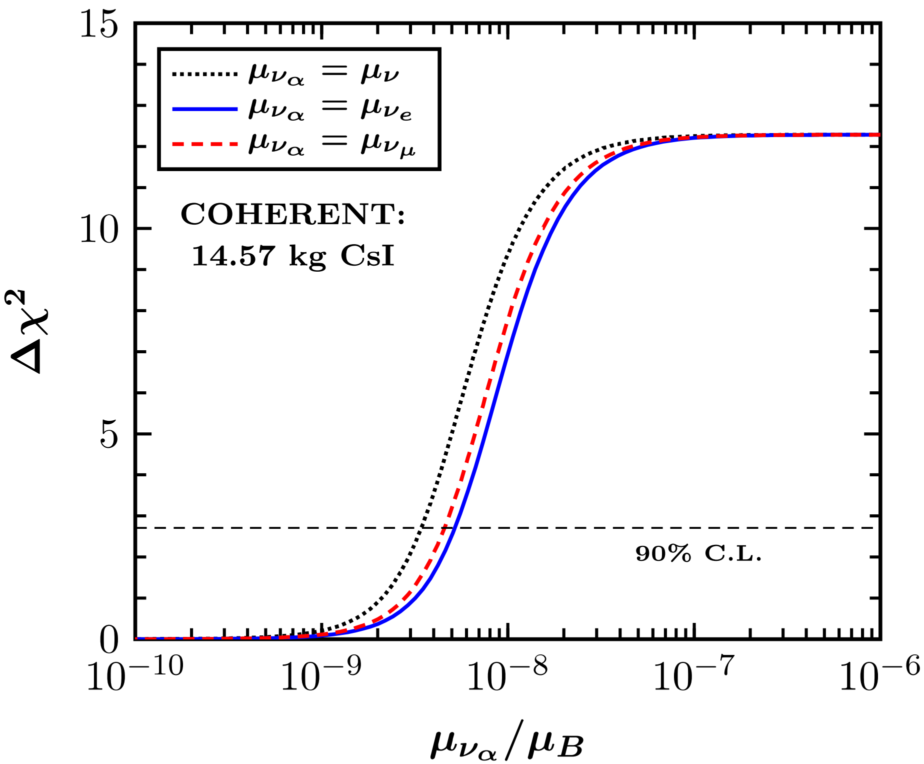
[Frère, Heeck, Mollet, 1506.02964]

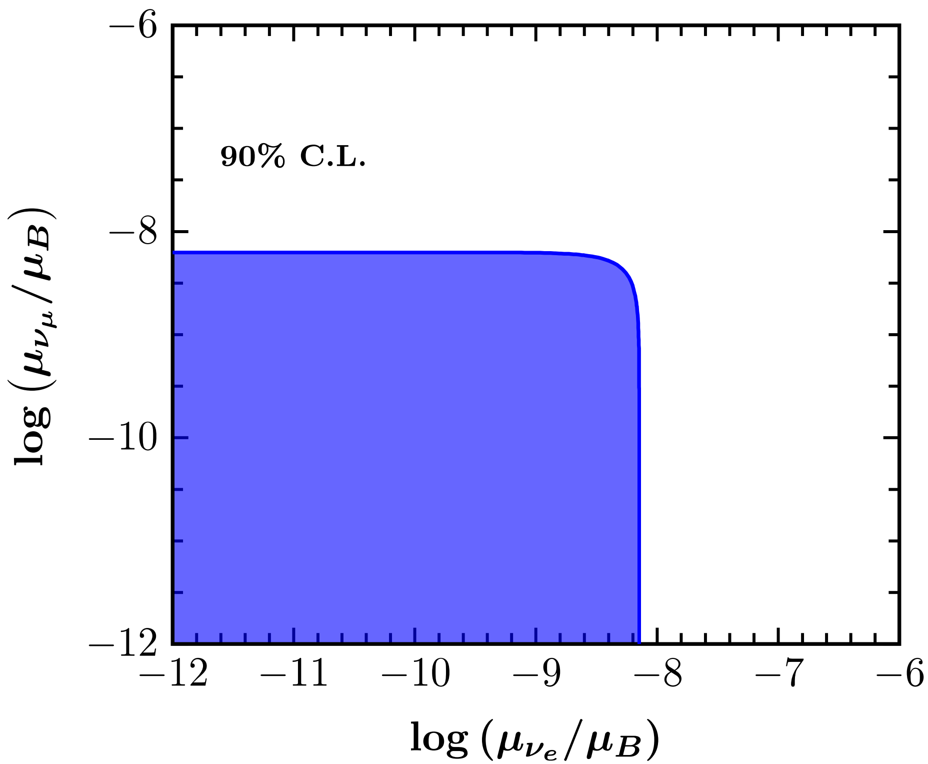
COHERENT

- Coherent elastic ν-nucleus scattering:
  [Dodd, Papageorgiu, Ranfone, '91; Kosmas+, '15]

$$\frac{d\sigma}{dT_N} \propto \mu^2 \frac{Z^2}{T_N}$$

- Pion at rest: mixture of ν_e and ν_μ.
- Improvement possible!





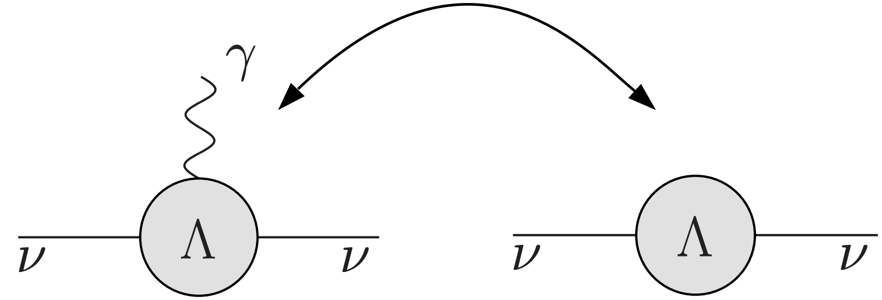
[Kosmas, Papoulias, 1711.09773]

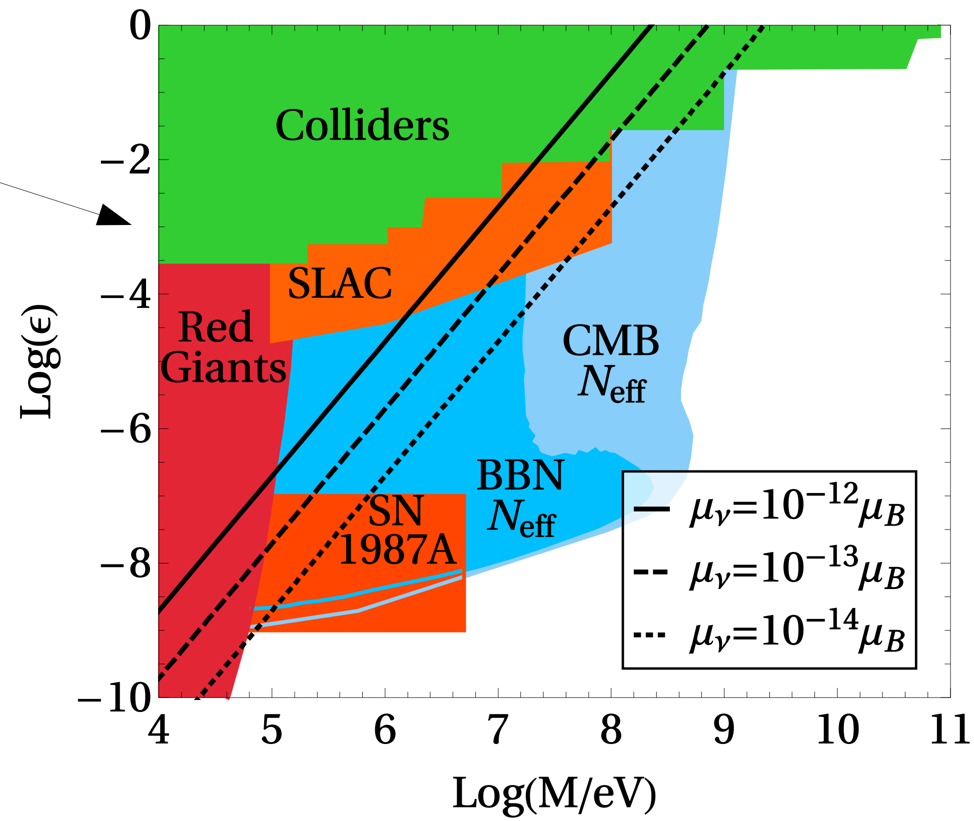
How to get large μ_ν?

- Main problem: $\mu_\nu \propto \delta m_\nu/\Lambda^2$.
  [Voloshin, ‘88; Davidson+, ‘05; Bell+, ‘06]
- Light new physics?

  → $\mu_\nu/\delta m_\nu = \varepsilon e/4M^2$.
- Majorana ν can have

  $\mu_\nu \sim$ 10^-12 μ_B:
  - Horizontal $SU(2)_H$.
    [Babu, Mohapatra, ‘89]
  - Barr-Freire-Zee model.
    [Barr, Freire, Zee, ‘90]
- Dirac ν: need finetuning!





[Lindner, Radovčić, Welter, 1706.02555]

Barr-Freire-Zee model

- Spin-suppression:

$$\delta m_{ab} \propto \frac{m_b^2 - m_a^2}{M_W^2} \mu_{ab} M^2_{\mathrm{scalar}}.$$

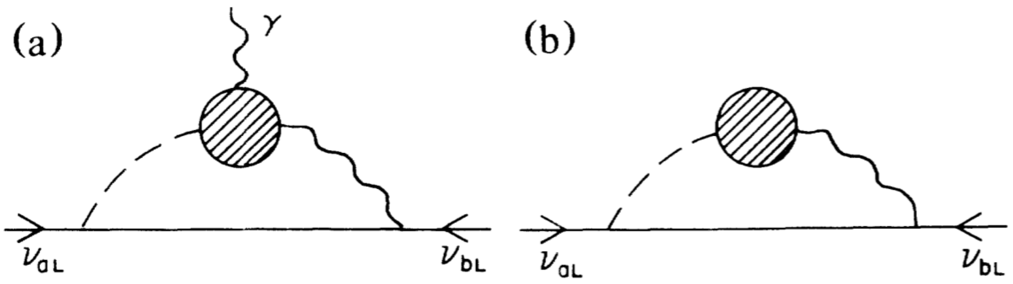


FIG. 1. (a) A graph that gives a contribution to the neutrino magnetic dipole moment. (b) The same graph with the photon removed contributes to the neutrino mass. However, this effect is suppressed by two powers of lepton mass because the virtual vector must be longitudinally polarized.

- Zee model:
  3 doublets φ_a,
  1 singlet h^+:

[Barr, Freire, Zee, '90]

$$f_{ab} h^+ L_a L_b + M_{ab} h^+ \varphi_a \varphi_b + \lambda_{ab} \varphi_1^\dagger \varphi_a \varphi_1^\dagger \varphi_b.$$

- Majorana ν mass at loop level.
- Scalars @ TeV ⇒ still easily $\mu_\nu \sim 10^{-12}\, \mu_B$.

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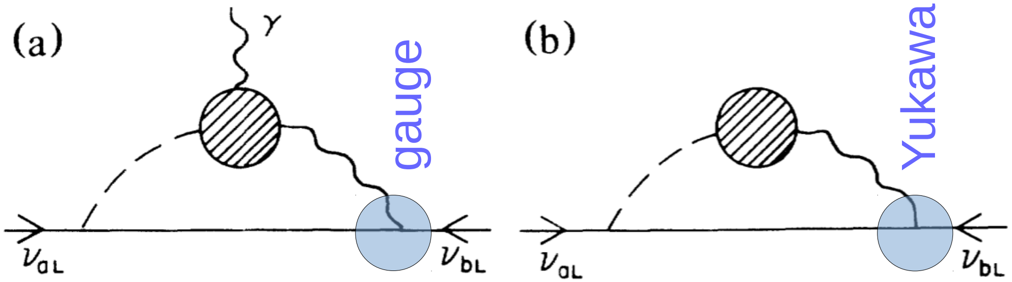

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[Lindner, Radovčić, Welter, 1706.02555]

Summary

- m_ν induced magnetic moment: $\mu_\nu < 10^{-19}\,\mu_B$.
- Astrophysics reaches $10^{-12}\,\mu_B$, lab $10^{-11}\,\mu_B$.
- Improvement with GEMMA, COHERENT, SHiP,...
- Difficult to distinguish Majorana vs. Dirac.
- Model-building required for testable μ_ν.

Neutrinos always good for a surprise!