Neutrino Electromagnetic Properties: Current Status and Future Prospect

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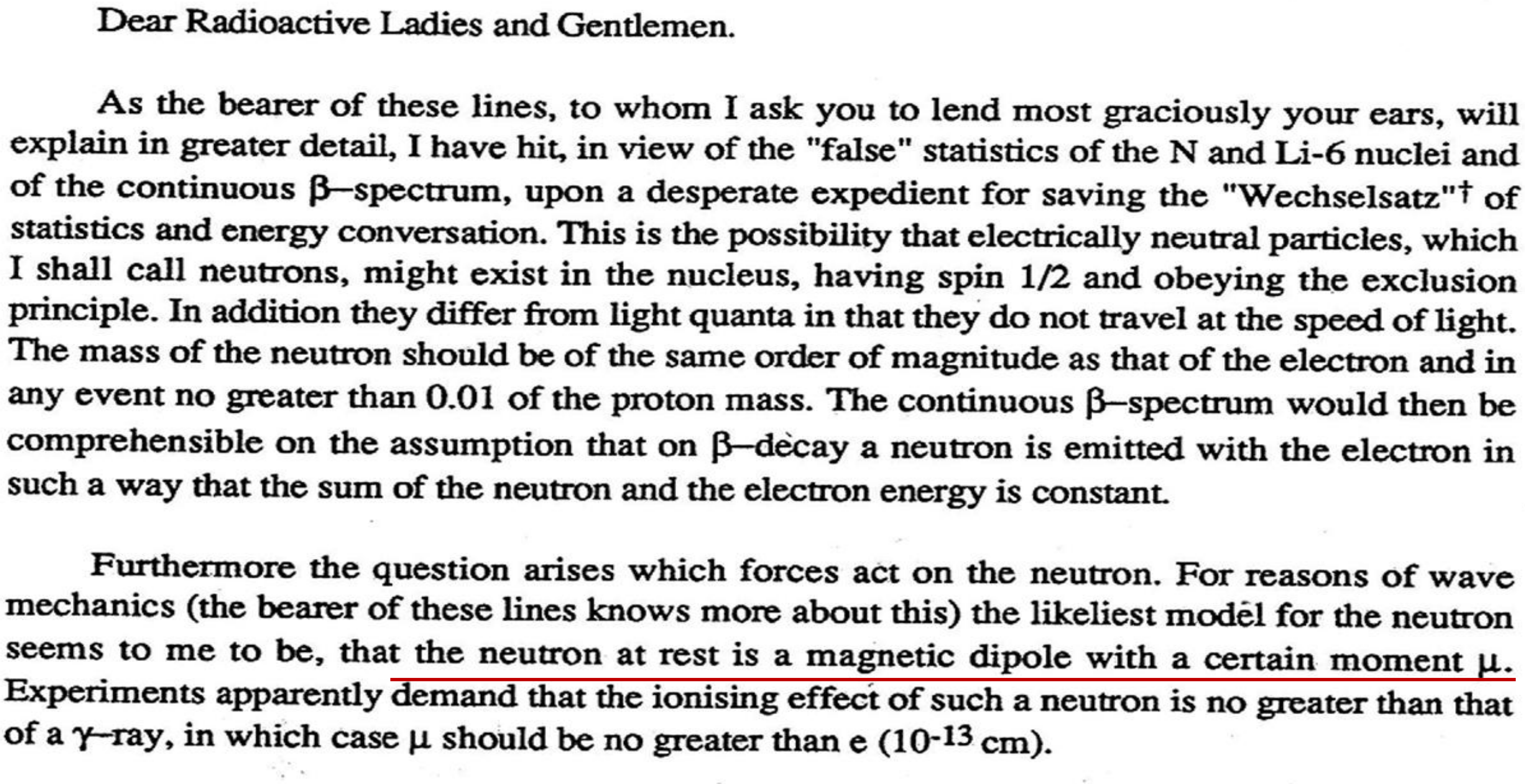
Neutrino magnetic moment

- **The neutrino magnetic moment** (MM) was introduced by Pauli in his famous letter (1930)



Dear Radioactive Ladies and Gentlemen.

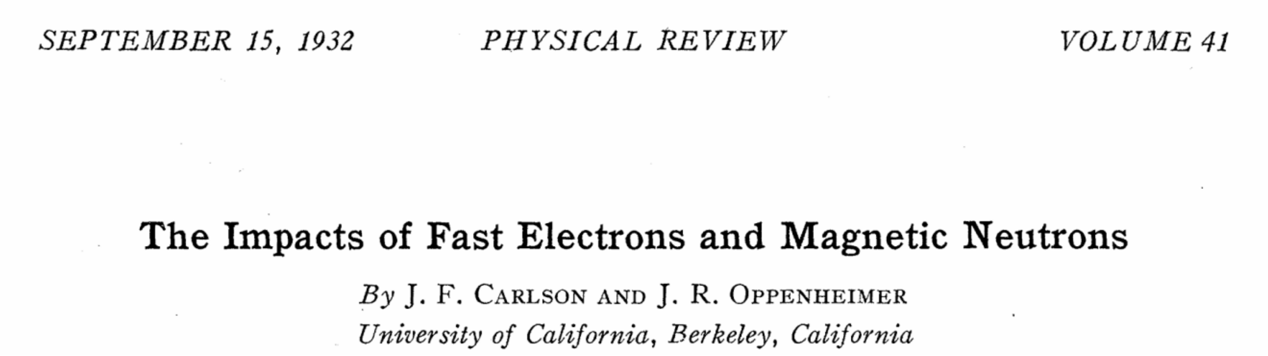
As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e (10^{-13} cm).

Neutrino magnetic moment

- **The neutrino magnetic moment (MM) was introduced by Pauli in his famous letter (1930)**

- **Carlson and Oppenheimer (1932):**
  Neutrino propagation in matter with nonzero magnetic moment



SEPTEMBER 15, 1932 *PHYSICAL REVIEW* *VOLUME 41*

The Impacts of Fast Electrons and Magnetic Neutrons

By J. F. Carlson and J. R. Oppenheimer
University of California, Berkeley, California

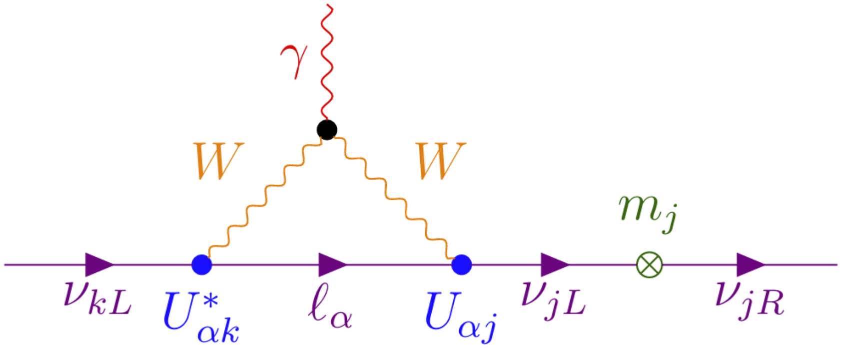
- **Bethe (1935): The neutrino-electron cross section with MM could be larger than that of IBD (Bethe & Peierls Nature 1934)**

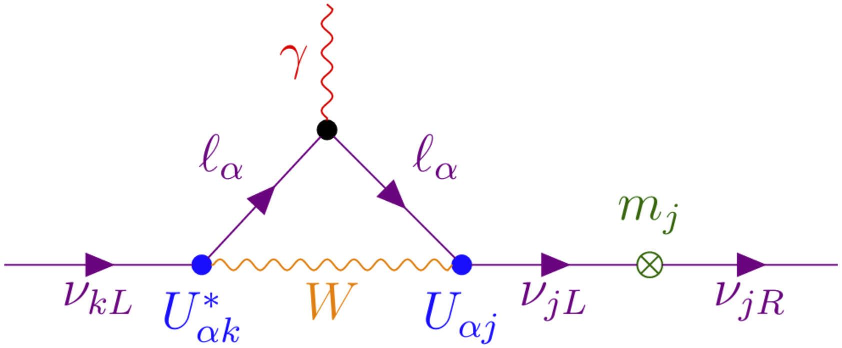
- **First limit by Nahmias (1935):** $\mu_\nu < 2 \times 10^{-4}\,\mu_B$

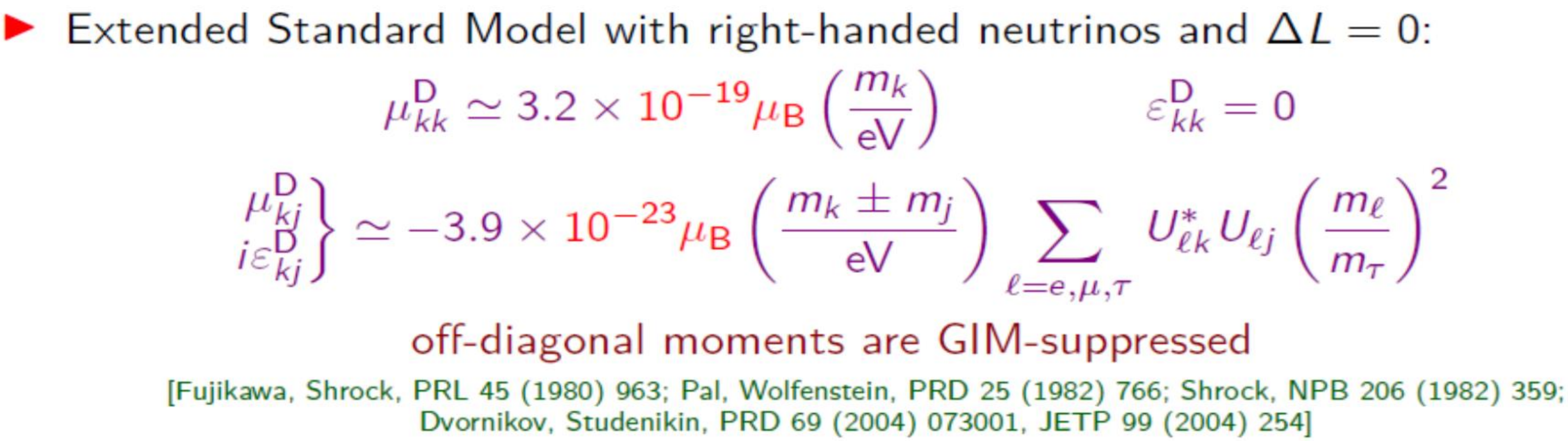
- **Limits by Cowan and Reines (neutrino detection with IBD in 1956)**
  $\mu_\nu < 10^{-7}\mu_B$ **(1954);** $\mu_\nu < 10^{-9}\mu_B$ **(1957)**

Neutrino magnetic and electric moment

- **After the discovery of neutrino oscillation (and thus neutrino mass), neutrino can have nonzero magnetic moment !**







- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu^{\rm D}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\rm B} \left(\frac{m_k}{\rm eV} \right) \qquad \varepsilon^{\rm D}_{kk} = 0$$

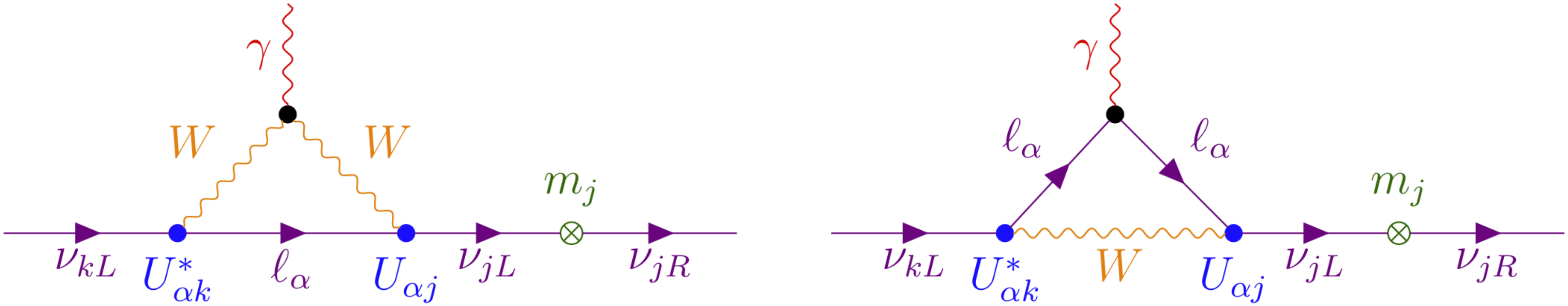
$$\left. \begin{matrix} \mu^{\rm D}_{kj} \\ i\varepsilon^{\rm D}_{kj} \end{matrix} \right\} \simeq -3.9 \times 10^{-23} \mu_{\rm B} \left(\frac{m_k \pm m_j}{\rm eV} \right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

Neutrino magnetic and electric moment

- **After the discovery of neutrino oscillation (and thus neutrino mass), neutrino can have nonzero magnetic moment !**



- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu^{\mathrm{M}}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Im}\left[U^*_{\ell k} U_{\ell j}\right] \frac{m_\ell^2}{m_W^2}$$

$$\varepsilon^{\mathrm{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Re}\left[U^*_{\ell k} U_{\ell j}\right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

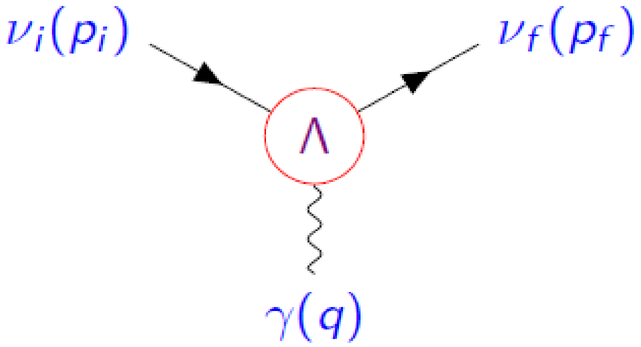
GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \implies$ q, a, μ, ε

helicity-conserving

helicity-flipping

Neutrino Electromagnetic Interactions

$$\Lambda_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\,[F_Q(q^2) + F_A(q^2)q^2\gamma_5] - i\sigma_{\mu\nu}q^\nu\,[F_M(q^2) + iF_E(q^2)\gamma_5]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \implies$ q, a, μ, ε

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$

- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis

- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.

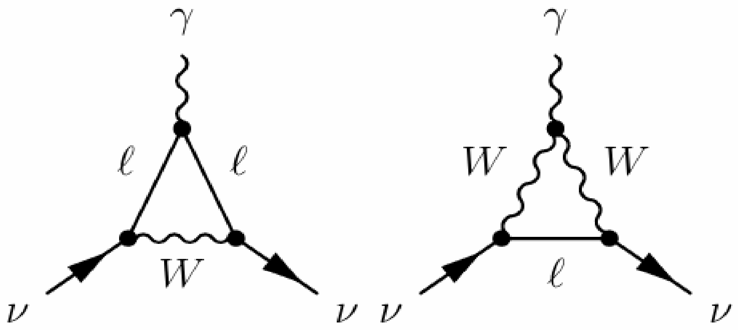
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

Neutrino charge radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \xcancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model:

[Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Constraints on magnetic moments

Laboratory tests

- **Short baseline test: intensive beam + low threshold sensitive detectors by the electron or nucleus scattering process**

$$\nu_\ell + e^- \to \nu_{\ell'} + e^- \qquad \nu_\ell + {}^A_Z\mathcal{N} \to \nu_{\ell'} + {}^A_Z\mathcal{N}$$

$$\frac{d\sigma(\mu_\nu)}{dT} = C\,\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\frac{\mu_\nu^2}{\mu_\mathrm{B}^2} \qquad \boxed{\mu_{\ell'\ell} = \sum_{j,k} U_{\ell' j}\mu_{jk}U^*_{\ell k}}$$

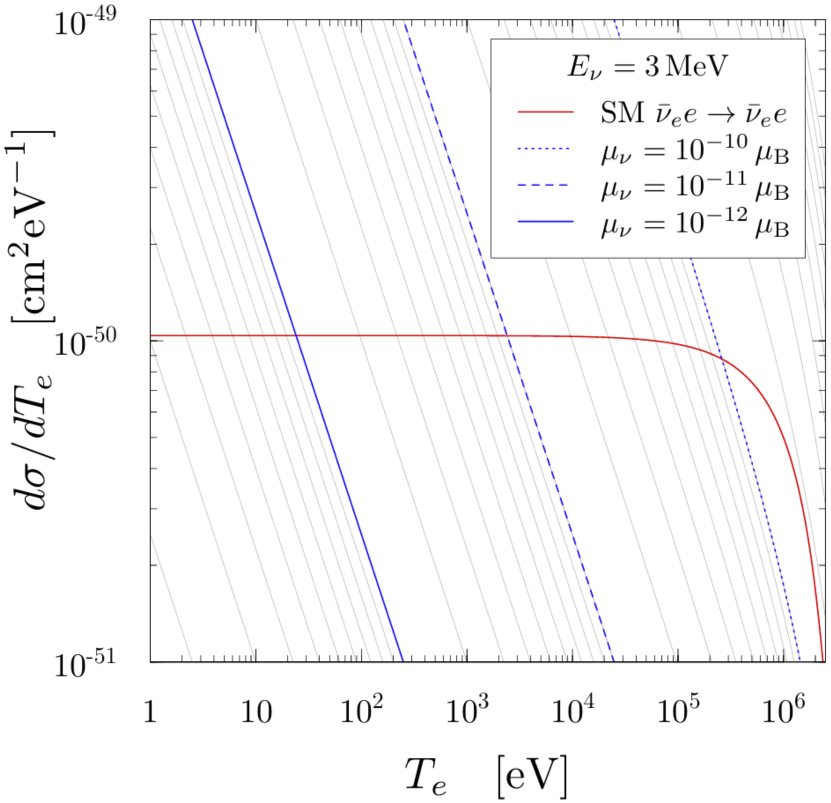
$C = Z_\mathrm{eff}^{\mathcal{A}}(T_e)$ and $T = T_e$ for elastic scattering with an electron bound in an atom $\mathcal{A}$; $C = Z^2[F_Z^{\mathcal{N}}(|\vec{q}|)]^2$ and $T = T_{\mathcal{N}}$ in CEνNS with a nucleus with atomic number Z.

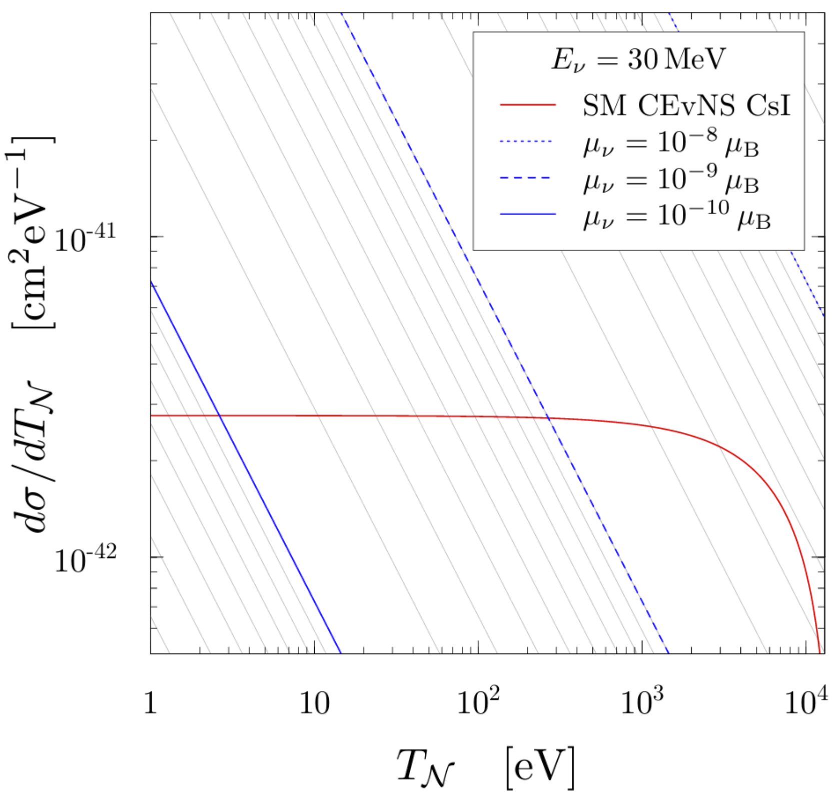
- **Long baseline test: solar neutrino beam + large sensitive detectors**

$$\boxed{\mu_\nu^2 = \sum_{\ell'}\left|\sum_{\ell''}\mu_{\ell'\ell''}A_{\ell''}(E_\nu, L)\right|^2} \qquad \mu_\mathrm{S}^2 \simeq \sum_\ell P^\mathrm{S}_{e\ell}(E_\nu)\sum_{\ell'}|\mu_{\ell'\ell}|^2$$

- **Short and long baseline tests are probing different combinations**

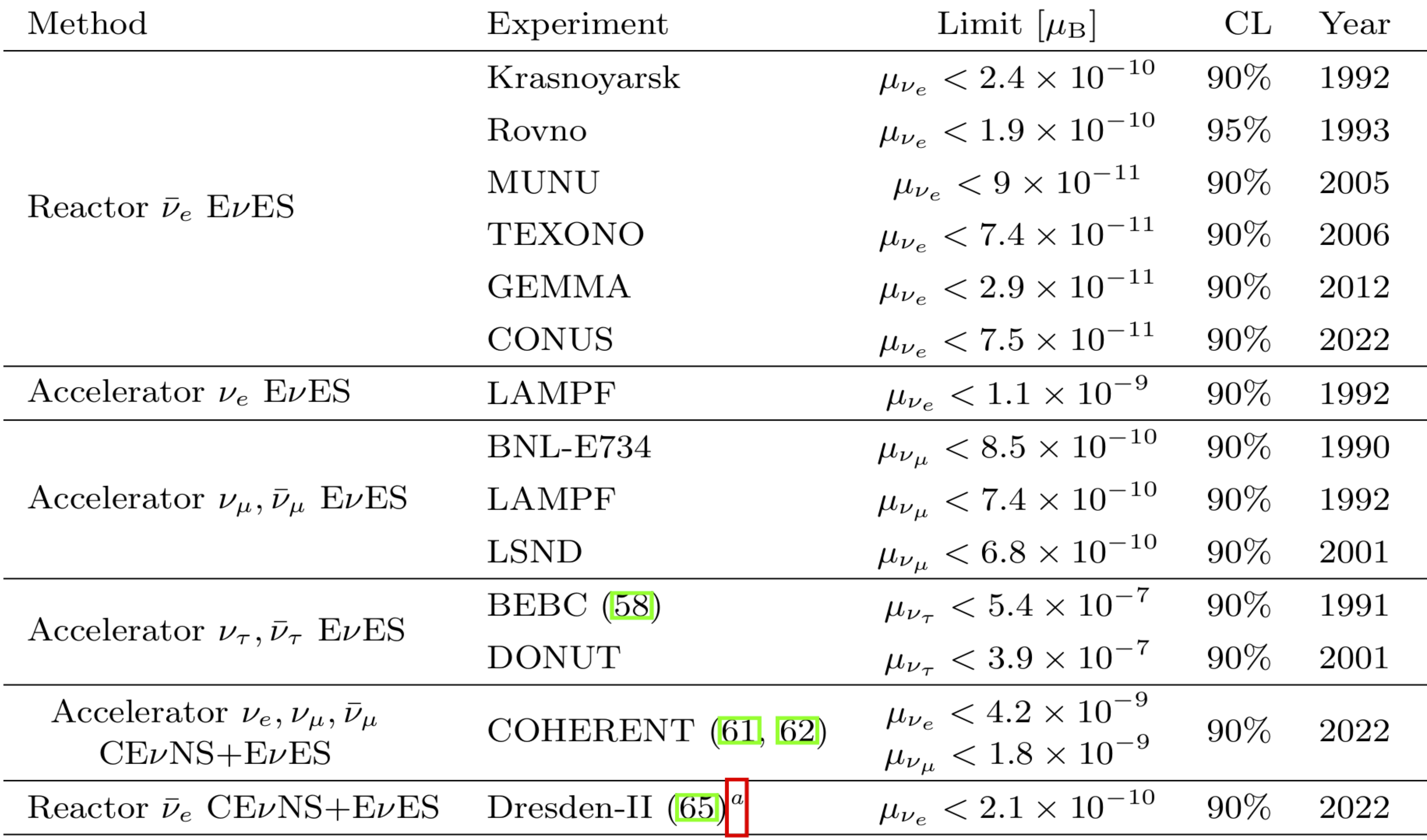
Laboratory tests





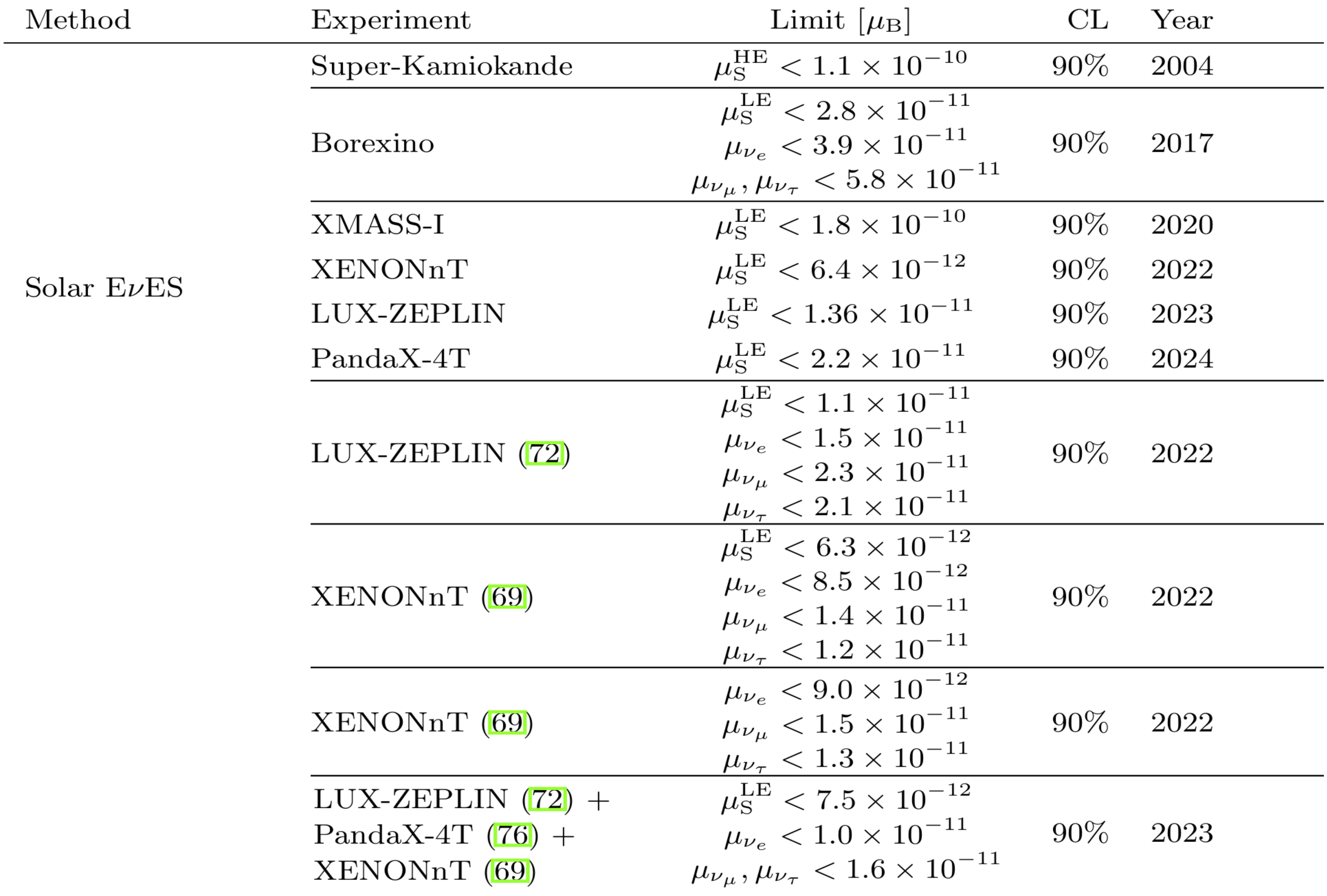
- **Magnetic moment contribute could be much enhanced at lower recoils.**
- **Going to smaller!**

Laboratory tests (Short baseline)



Method	Experiment	Limit $[\mu_{\mathrm{B}}]$	CL	Year
Reactor $\bar{\nu}_e$ EνES	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
	CONUS	$\mu_{\nu_e} < 7.5 \times 10^{-11}$	90%	2022
Accelerator ν_e EνES	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $\nu_\mu, \bar{\nu}_\mu$ EνES	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $\nu_\tau, \bar{\nu}_\tau$ EνES	BEBC (58)	$\mu_{\nu_\tau} < 5.4 \times 10^{-7}$	90%	1991
	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ CEνNS+EνES	COHERENT (61, 62)	$\mu_{\nu_e} < 4.2 \times 10^{-9}$ $\mu_{\nu_\mu} < 1.8 \times 10^{-9}$	90%	2022
Reactor $\bar{\nu}_e$ CEνNS+EνES	Dresden-II (65)[a]	$\mu_{\nu_e} < 2.1 \times 10^{-10}$	90%	2022

Laboratory tests (Long baseline)



Method	Experiment	Limit $[\mu_B]$	CL	Year
Solar EνES	Super-Kamiokande	$\mu_S^{HE} < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S^{LE} < 2.8 \times 10^{-11}$ $\mu_{\nu_e} < 3.9 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 5.8 \times 10^{-11}$	90%	2017
	XMASS-I	$\mu_S^{LE} < 1.8 \times 10^{-10}$	90%	2020
	XENONnT	$\mu_S^{LE} < 6.4 \times 10^{-12}$	90%	2022
	LUX-ZEPLIN	$\mu_S^{LE} < 1.36 \times 10^{-11}$	90%	2023
	PandaX-4T	$\mu_S^{LE} < 2.2 \times 10^{-11}$	90%	2024
	LUX-ZEPLIN (72)	$\mu_S^{LE} < 1.1 \times 10^{-11}$ $\mu_{\nu_e} < 1.5 \times 10^{-11}$ $\mu_{\nu_\mu} < 2.3 \times 10^{-11}$ $\mu_{\nu_\tau} < 2.1 \times 10^{-11}$	90%	2022
	XENONnT (69)	$\mu_S^{LE} < 6.3 \times 10^{-12}$ $\mu_{\nu_e} < 8.5 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.4 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.2 \times 10^{-11}$	90%	2022
	XENONnT (69)	$\mu_{\nu_e} < 9.0 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.5 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.3 \times 10^{-11}$	90%	2022
	LUX-ZEPLIN (72) + PandaX-4T (76) + XENONnT (69)	$\mu_S^{LE} < 7.5 \times 10^{-12}$ $\mu_{\nu_e} < 1.0 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 1.6 \times 10^{-11}$	90%	2023

Astrophysical & Cosmological bounds

- **Astrophysical bound:**
  large uncertainty, model dependence, & flavor universal

(1) Supernova bound: energy loss from MM-induced scattering from left-handed to right handed (sterile) neutrinos (escape from environment)

(2) Bounds from TRGB, Solar Cooling, Cepheid Stars, and White Dwarfs: energy loss from plasmon decay into a neutrino-antineutrino pair

$$\Gamma_{\gamma^* \to \nu\bar{\nu}}(\mu_\nu) = \frac{\mu_\nu^2}{24\pi} Z \frac{\omega_{\mathrm{P}}^2}{\omega_\gamma}$$

(3) Cosmological bounds: constraints on the production of right-handed neutrinos by in the primordial plasma (from the scattering of neutrinos and charged particles)

Depending on the evolution history and production time

Astrophysical & Cosmological bounds

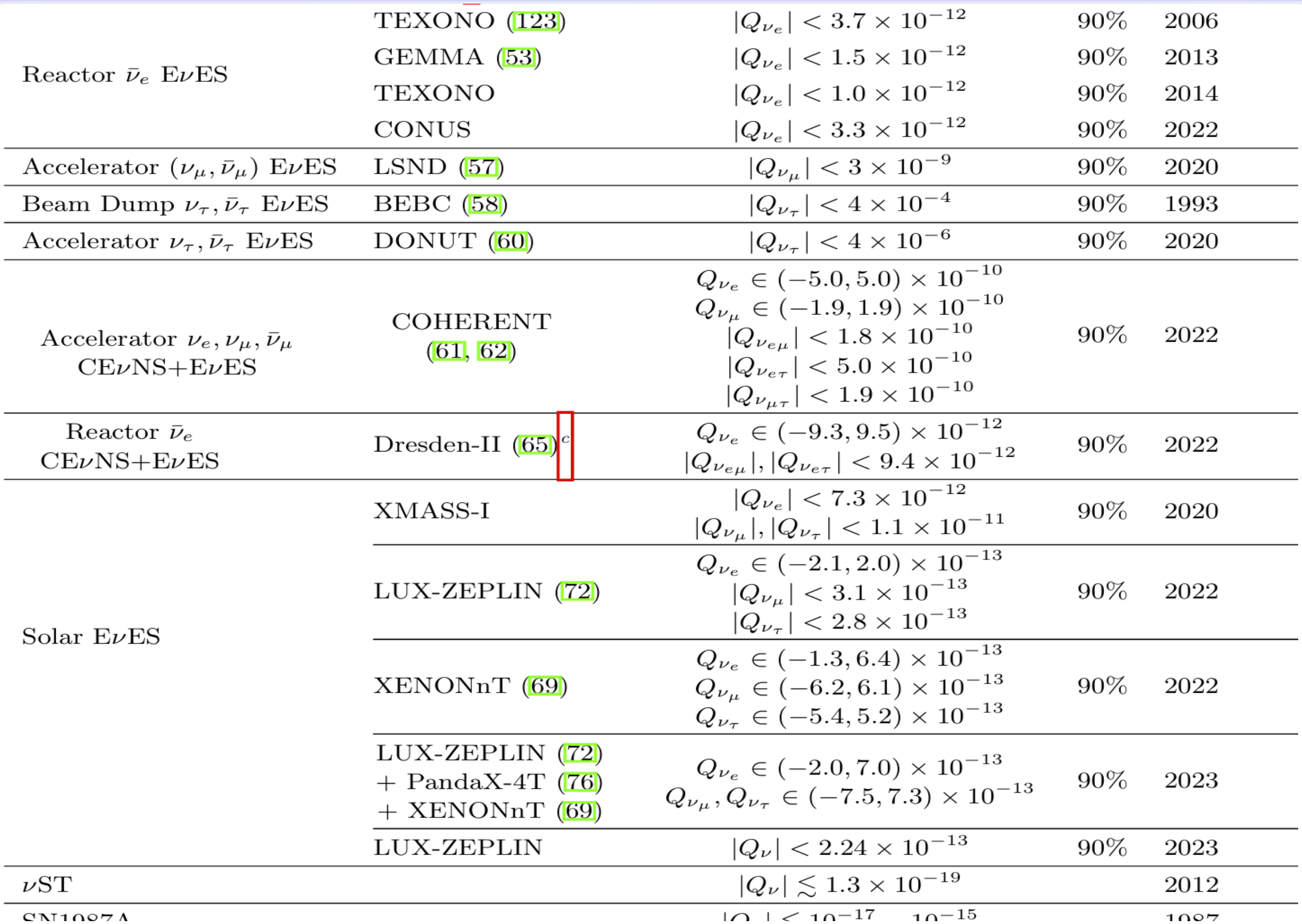
Core-Collapse Supernovae	$\mu_\nu \lesssim (2-8) \times 10^{-12}$		1988
	$\mu_\nu \lesssim (1-4) \times 10^{-12}$		1998
	$\mu_\nu \lesssim (1.1-2.7) \times 10^{-12}$		2009
Tip of the Red Giant Branch (TRGB)	$\mu_\nu \lesssim 3 \times 10^{-12}$		1989
	$\mu_\nu \lesssim 1 \times 10^{-12}$		1993
	$\mu_\nu < 4.5 \times 10^{-12}$	95%	2013
	$\mu_\nu \lesssim 2.6 \times 10^{-12}$		2015
	$\mu_\nu < 1.2 \times 10^{-12}$	95%	2020
	$\mu_\nu \lesssim (1-5) \times 10^{-12}$		2020
	$\mu_\nu \lesssim 6 \times 10^{-12}$		2023
Solar Cooling	$\mu_\nu \lesssim 4 \times 10^{-10}$		1999
Cepheid Stars	$\mu_\nu \lesssim 2 \times 10^{-10}$		2020
White Dwarfs	$\mu_\nu \lesssim (7-9) \times 10^{-12}$		2014
	$\mu_\nu < 5 \times 10^{-12}$	95%	2014
Big-Bang Nucleosynthesis (BBN)	$\mu_\nu \lesssim (1-2) \times 10^{-11}$		1981
	$\mu_\nu \lesssim 6.2 \times 10^{-11}$		1997
	$\mu_\nu \lesssim 4 \times 10^{-12}$		2023
Cosmological N_{eff}	$\mu_\nu < 2.7 \times 10^{-12}$	95%	2022
	$\mu_\nu < 2.6 \times 10^{-12}$	95%	2022
	$\mu_\nu < 5 \times 10^{-12}$	68%	2023

Constraints on other electromagnetic properties

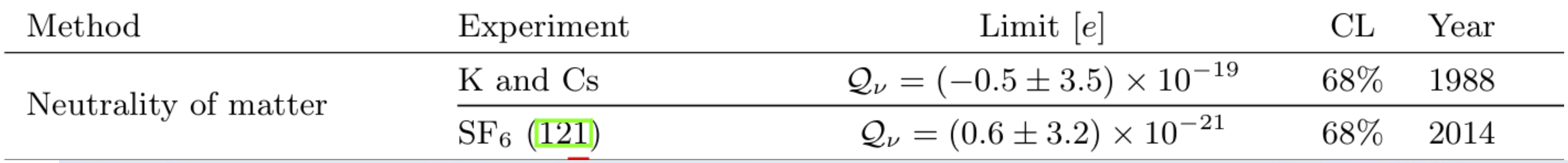
Constraints on the neutrino charge radius

Method	Experiment	Limit $[10^{-32}\ \mathrm{cm}^2]$	CL	Year
Reactor $\bar{\nu}_e$ EνES	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$\langle r^2_{\nu_e}\rangle \in (-4.2, 6.6)$	90%	2009
Accelerator ν_e EνES	LAMPF	$\langle r^2_{\nu_e}\rangle \in (-7.12, 10.88)$	90%	1992
	LSND	$\langle r^2_{\nu_e}\rangle \in (-5.94, 8.28)$	90%	2001
Accelerator ν_μ EνES	BNL-E734	$\langle r^2_{\nu_\mu}\rangle \in (-5.7, 1.1)$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2$	90%	1995
	CHARM-II (114) + CCFR (115)	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert \in (-0.52, 0.68)$	90%	2003
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ + Reactor $\bar{\nu}_e$ CEνNS	COHERENT (61, 62) + Dresden-II (65)[c]	$\langle r^2_{\nu_e}\rangle \in (-7.1, 5)$ $\langle r^2_{\nu_\mu}\rangle \in (-5.9, 4.3)$	90%	2022
Solar EνES	XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-85, 2.0)$ $\langle r^2_{\nu_\mu}\rangle \in (-45, 52)$ $\langle r^2_{\nu_\tau}\rangle \in (-40, 45)$	90%	2022
	XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-93.4, 9.5)$ $\langle r^2_{\nu_\mu}\rangle \in (-50.2, 54)$ $\langle r^2_{\nu_\tau}\rangle \in (-43, 46.8)$	90%	2022
	LUX-ZEPLIN (72) + PandaX-4T (76) + XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-99.5, 12.8)$ $\langle r^2_{\nu_\mu}\rangle, \langle r^2_{\nu_\tau}\rangle \in (-82.2, 88.7)$	90%	2023

Constraints on neutrino electric charges



Reactor $\bar{\nu}_e$ EνES	TEXONO (123)	$\lvert Q_{\nu_e}\rvert < 3.7 \times 10^{-12}$	90%	2006
	GEMMA (53)	$\lvert Q_{\nu_e}\rvert < 1.5 \times 10^{-12}$	90%	2013
	TEXONO	$\lvert Q_{\nu_e}\rvert < 1.0 \times 10^{-12}$	90%	2014
	CONUS	$\lvert Q_{\nu_e}\rvert < 3.3 \times 10^{-12}$	90%	2022
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$ EνES	LSND (57)	$\lvert Q_{\nu_\mu}\rvert < 3 \times 10^{-9}$	90%	2020
Beam Dump $\nu_\tau, \bar{\nu}_\tau$ EνES	BEBC (58)	$\lvert Q_{\nu_\tau}\rvert < 4 \times 10^{-4}$	90%	1993
Accelerator $\nu_\tau, \bar{\nu}_\tau$ EνES	DONUT (60)	$\lvert Q_{\nu_\tau}\rvert < 4 \times 10^{-6}$	90%	2020
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ CEνNS+EνES	COHERENT (61, 62)	$Q_{\nu_e} \in (-5.0, 5.0) \times 10^{-10}$ $Q_{\nu_\mu} \in (-1.9, 1.9) \times 10^{-10}$ $\lvert Q_{\nu_{e\mu}}\rvert < 1.8 \times 10^{-10}$ $\lvert Q_{\nu_{e\tau}}\rvert < 5.0 \times 10^{-10}$ $\lvert Q_{\nu_{\mu\tau}}\rvert < 1.9 \times 10^{-10}$	90%	2022
Reactor $\bar{\nu}_e$ CEνNS+EνES	Dresden-II (65)^c	$Q_{\nu_e} \in (-9.3, 9.5) \times 10^{-12}$ $\lvert Q_{\nu_{e\mu}}\rvert, \lvert Q_{\nu_{e\tau}}\rvert < 9.4 \times 10^{-12}$	90%	2022
Solar EνES	XMASS-I	$\lvert Q_{\nu_e}\rvert < 7.3 \times 10^{-12}$ $\lvert Q_{\nu_\mu}\rvert, \lvert Q_{\nu_\tau}\rvert < 1.1 \times 10^{-11}$	90%	2020
	LUX-ZEPLIN (72)	$Q_{\nu_e} \in (-2.1, 2.0) \times 10^{-13}$ $\lvert Q_{\nu_\mu}\rvert < 3.1 \times 10^{-13}$ $\lvert Q_{\nu_\tau}\rvert < 2.8 \times 10^{-13}$	90%	2022
	XENONnT (69)	$Q_{\nu_e} \in (-1.3, 6.4) \times 10^{-13}$ $Q_{\nu_\mu} \in (-6.2, 6.1) \times 10^{-13}$ $Q_{\nu_\tau} \in (-5.4, 5.2) \times 10^{-13}$	90%	2022
	LUX-ZEPLIN (72) + PandaX-4T (76) + XENONnT (69)	$Q_{\nu_e} \in (-2.0, 7.0) \times 10^{-13}$ $Q_{\nu_\mu}, Q_{\nu_\tau} \in (-7.5, 7.3) \times 10^{-13}$	90%	2023
	LUX-ZEPLIN	$\lvert Q_\nu\rvert < 2.24 \times 10^{-13}$	90%	2023
νST		$\lvert Q_\nu\rvert \lesssim 1.3 \times 10^{-19}$		2012
SN1987A		$\lvert Q_\nu\rvert < 10^{-17}$ … 10^{-15}		1987



Method	Experiment	Limit $[e]$	CL	Year
Neutrality of matter	K and Cs	$Q_\nu = (-0.5 \pm 3.5) \times 10^{-19}$	68%	1988
	SF$_6$ (121)	$Q_\nu = (0.6 \pm 3.2) \times 10^{-21}$	68%	2014

Future prospects

- Low threshold + giant detectors for scattering processes:
  solar neutrinos at dark matter direct detection & JUNO

- Dedicated detection with controlled beam
  (1) semiconductor detectors (reactors) → enhancement of screening effect
  YFL & Xia, JHEP 10:021 (2023)

  (2) Coherent elastic neutrino-atom scattering (SATURNE project)
  Cadeddu et al. Phys. Rev. D 100:073014 (2019)

- Atomic & molecular probes (e.g., neutrino pair production in atom)
  Ge & Pasquini, JHEP 12:083 (2023)

- Astrophysical & Cosmological bounds with better control

Conclusion

- **Neutrino electromagnetic (EM) properties and interactions are fundamental for massive neutrinos and physics beyond the Standard Model.**

- **An effective neutrino charge radius could be generated in SM.**

- **There could be three effective EM properties: magnetic moment, charge radius, & electric charges in BSM.**

- **Promising Laboratory tests & Astrophysical & Cosmological bounds**

More details see Annu. Rev. Nucl. Part. Sci. (submitted)

Thank you !