SEARCH FOR CP-VIOLATION AS A GUIDING STAR TOWARDS

NEW PHYSICS

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In memory of dear Durmus

Charge conjugation

- Quantum Field Theory:
- Each charged particle has an antiparticle.

Electron $\Leftrightarrow$ Anti-electron (positron)

Muon $\Leftrightarrow$ Anti-muon

Proton. $\Leftrightarrow$ Anti-proton

Hydrogen $\Leftrightarrow$ Anti-Hydrogen

Charge conjugation

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Hydrogen ⟺ Anti-Hydrogen

Neuron ⟺ Anti-Neutron

Photon=Anti-Photon

Neutrino ⟺ Anti-Neutrino

Parity

- Spatial inversion

- x $\Leftrightarrow$ -x
- y $\Leftrightarrow$ -y
- z $\Leftrightarrow$ -z

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \in O(3), \quad \cancel{\in} \, SO(3)$$

$$\mathrm{Det}[\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}] \neq -1$$

Time inversion

- $t \Leftrightarrow -t$

Time inversion

- t $\Leftrightarrow$ -t

Time inversion

- t ⟺ -t

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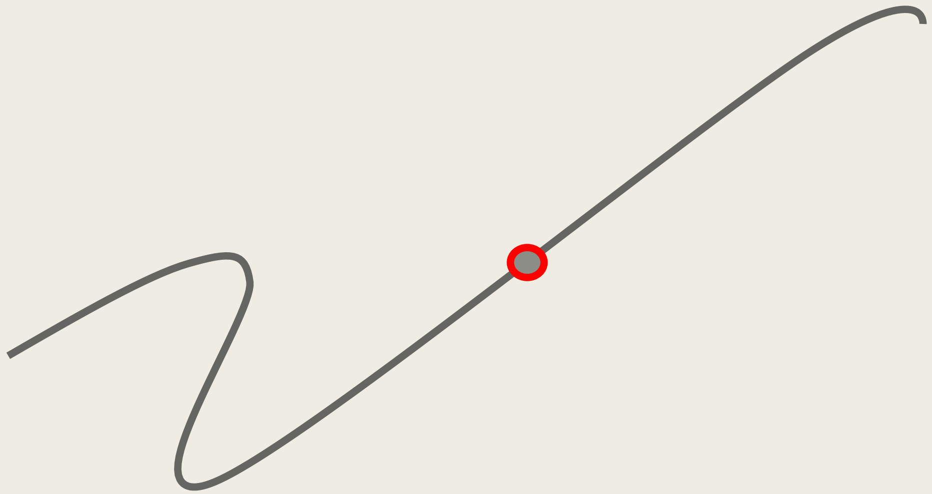

Time inversion

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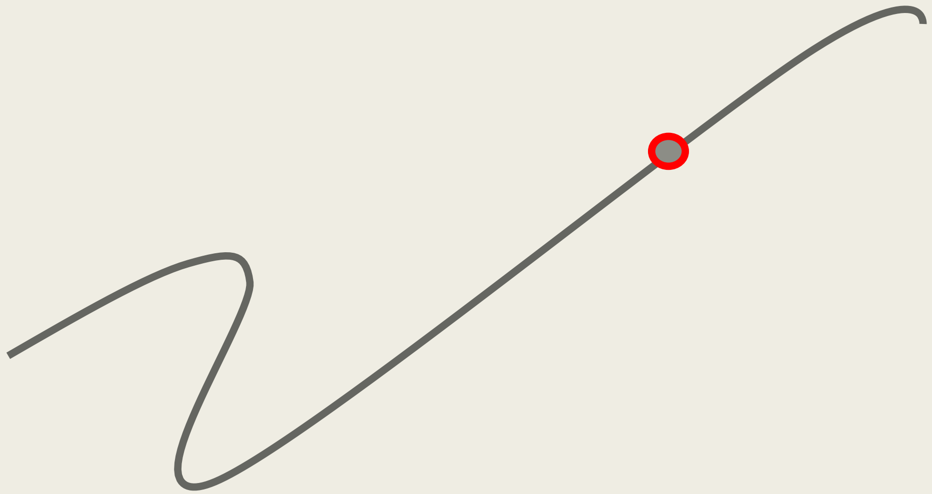

Time inversion

- t ⟺ -t

Time inversion

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Time inversion

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	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
$\vec{r}$	-	+	+
$\vec{v}$	-	-	+
$\vec{p}$	-	-	+
$\vec{r} \times \vec{p}$	+	-	+
$\vec{s}$	+	-	+
E	+	+	+

	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
$\vec{r}$	-	+	+
$\vec{v}$	-	-	+
$\vec{p}$	-	-	+
$\vec{r} \times \vec{p}$	+	-	+
$\vec{s}$	+	-	+
E	+	+	+

	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
$\mathbf{E} = \frac{q}{4\pi\varepsilon_0} \frac{\hat{\mathbf{r}}'}{\lvert\mathbf{r}'\rvert^2}$	-	+	-
$\mathbf{B} = \frac{\mu_0}{4\pi} q \frac{\mathbf{v} \times \hat{\mathbf{r}}'}{\lvert\mathbf{r}'\rvert^2}$	+	-	-

Fundamental interactions

- Gravity
- Electromagnetism
- Strong interaction
- Weak interaction
- Yukawa interaction (Higgs interaction with elementary fermions)

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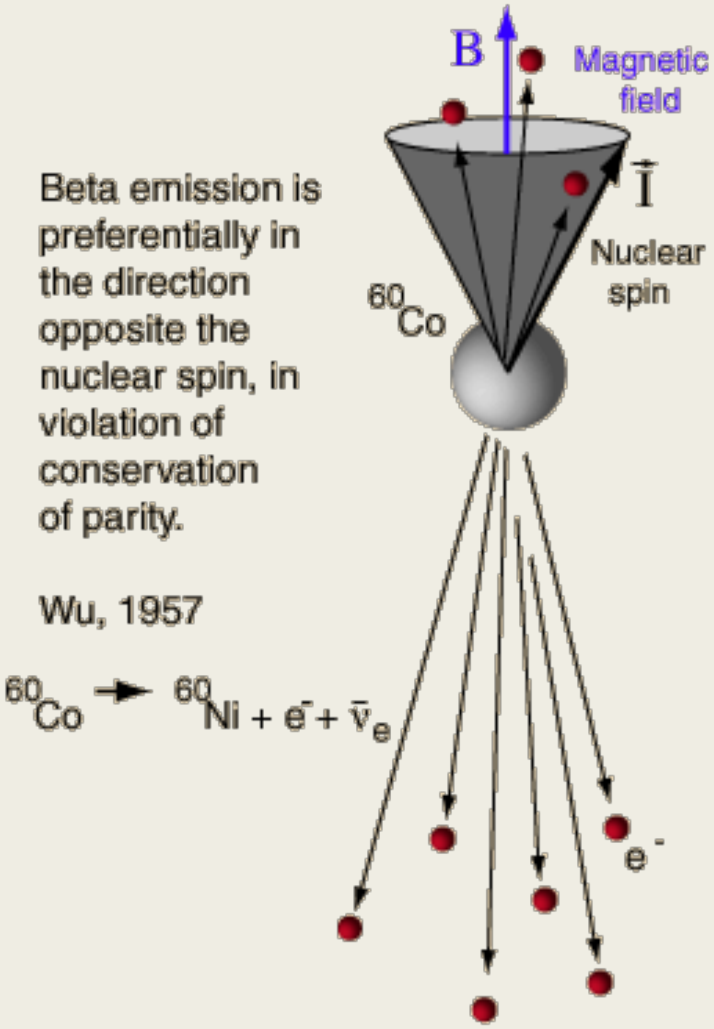
- Gravity
- Electromagnetism
- Strong interaction
- Weak interaction
- Yukawa interaction (Pion-nucleon Yukawa interaction is not a fundamental interaction but a form of strong interaction at low energies.)

Fundamental interactions

	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
Gravity	✅	✅	✅
Electromagnetism	✅	✅	✅
Strong interaction	✅	✅	✅
Weak interaction	❌	⭕	❌
Yukawa interaction	⭕	⭕	⭕

Discovery of parity violation



December 1956

In weak interaction

- P is violated.
- C is violated.
- T is violated.

- CP?
- -+T?

- CPT is anyway conserved!

Weak interaction and CP

$$\boxed{W_\mu(J^\mu_{hadron} + J^\mu_{lepon})}$$

$$J^\mu_{lepon} = \bar{e}\gamma^\mu(1-\gamma_5)\nu_e + \bar{\mu}\gamma^\mu(1-\gamma_5)\nu_\mu + \bar{\tau}\gamma^\mu(1-\gamma_5)\nu_\tau$$

$$J^\mu_{hadron} = (V_{CKM})_{ij}\bar{d}_i\gamma^\mu(1-\gamma_5)u_j$$

$$u_i = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \quad d_i = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstates $\neq$ Flavor (weak) eigenstates

$$\boxed{(V_{CKM})^\dagger \neq V_{CKM}} \Rightarrow$$ CP is violated

Establishing CP violation

$$K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d}$$

$$CP|K^0\rangle = |\bar{K}^0\rangle \quad CP|\bar{K}^0\rangle = |K^0\rangle$$

CP eigenstates

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle + |K^0\rangle)$$

$$CP|K_1\rangle = |K_1\rangle \quad CP|K_2\rangle = -|K_2\rangle$$

Mass eigenstates

$$|K_S\rangle \quad |K_L\rangle$$

$$K_S \to 2\pi^0, \pi^+\pi^- \qquad K_L \to 3\pi^0, \pi^+\pi^-\pi^0$$

$$|K_L\rangle = \frac{1}{\sqrt{2(1+|\bar{\epsilon}|^2)}}[|K_2\rangle + \bar{\epsilon}|K_1\rangle]$$

$$|K_S\rangle = \frac{1}{\sqrt{2(1+|\bar{\epsilon}|^2)}}[|K_1\rangle + \bar{\epsilon}|K_2\rangle]$$

$$Br(K_L \to \pi^+\pi^-) = 1.97 \times 10^{-3}$$

$$Br(K_L \to \pi^0\pi^0) = 8.64 \times 10^{-4}$$

Matter anti-matter asymmetry

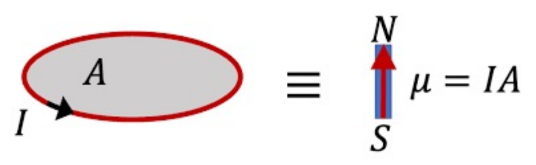
- Sakharov's conditions:

- Out of equilibrium
- Baryon number violation
- C and CP violation

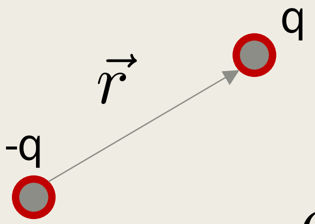
Dipole moment

$$\boxed{-\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}}$$

Magnitude dipole moment



Electric dipole moment



$$\vec{d} = q\vec{r}$$

	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
$\vec{r}$	-	+	+
$\vec{v}$	-	-	+
$\vec{p}$	-	-	+
$\vec{r} \times \vec{p}$	+	-	+
$\vec{s}$	+	-	+
E	+	+	+

	$\mathcal{P}$	$\mathcal{T}$	$\mathcal{C}$
$\mathbf{E} = \frac{q}{4\pi\varepsilon_0} \frac{\hat{\mathbf{r}}'}{\left\|\mathbf{r}'\right\|^2}$	-	+	-
$\mathbf{B} = \frac{\mu_0}{4\pi} q \frac{\mathbf{v} \times \hat{\mathbf{r}}'}{\left\|\mathbf{r}'\right\|^2}$	+	-	-
$\vec{d}$	-	+	-
$\vec{\mu}$	+	-	-

$$\boxed{-\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}}$$

Elementary fermions

$\mathcal{CP}$ $\mathcal{T}$

$\vec{\mu} \propto q\vec{S}$

$\vec{d} \propto q\vec{S}$ - -

$$-\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}$$

CP and T odd

CPT is of course conserved

EDM and MDM

$$\underbrace{\mu F_{\mu\nu}\bar{\psi}[\gamma^\mu,\gamma^\nu]\psi}^{\text{MDM}} + \underbrace{dF_{\mu\nu}\bar{\psi}[\gamma^\mu,\gamma^\nu]\gamma^5\psi}^{\text{EDM}}$$

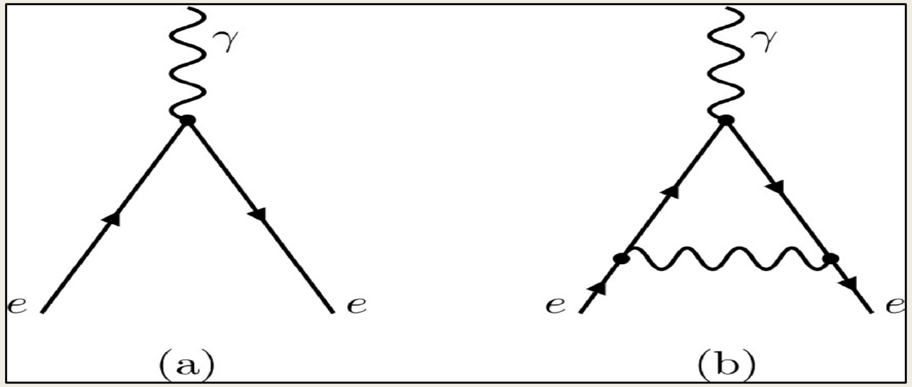
$\mathcal{CP}$ Even $\mathcal{CP}$ odd

$\mathcal{T}$ $\mathcal{T}$

$$\boxed{\begin{gathered}\mu = \frac{gq}{2m}\\ g = 2 \text{ tree level}\end{gathered}}$$

$$\boxed{d = 0 \text{ tree level}}$$

Radiative correction



Schwinger in 1948:

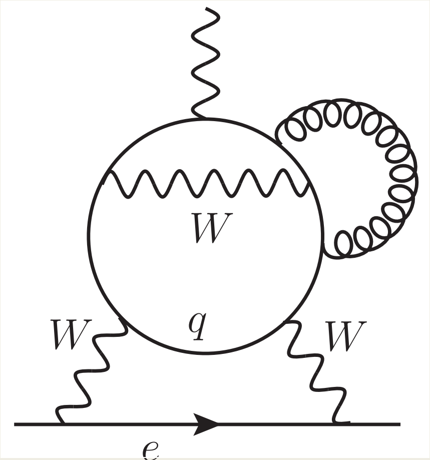
$$\mu = \frac{gq}{2m}$$

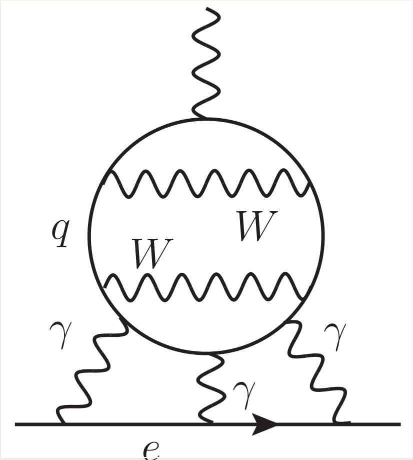
$$g = 2 \text{ tree level}$$

$$a_e = \frac{g-2}{2} = \frac{\alpha}{2\pi} = 0.0011614$$

No EDM at any loop level from QED
Because of CP symmetry

Loop level electron EDM from CKM matrix





$$\mathcal{J} = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta \simeq 2.9 \times 10^{-5},$$

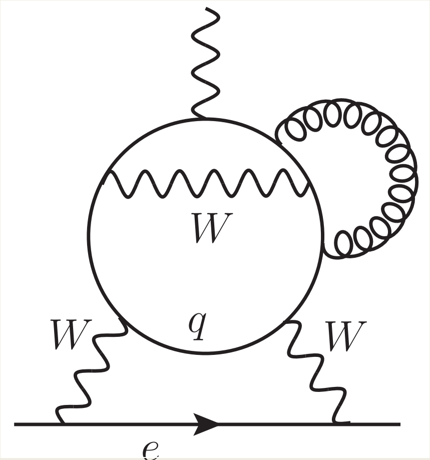
Pospelov and Ritz, *Phys.Rev.D* 89 (2014) 5, 056006

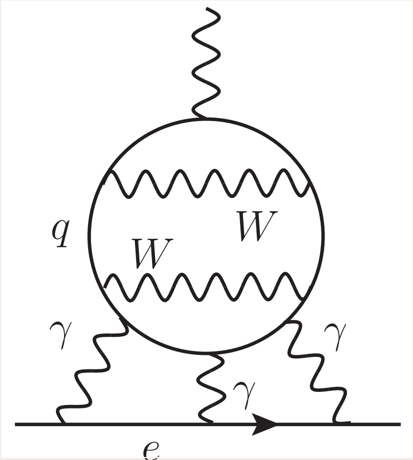
$$d_e^{\mathrm{Fig.1a}} \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3\alpha_s}{(4\pi)^4},$$

$$d_e^{\mathrm{Fig.1b}} \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^4 m_{\mathrm{had}}^2}\frac{\alpha_W^2\alpha^3}{(4\pi)^5},$$

$$d_e(\mathcal{J}) \sim O(10^{-44})\ e\mathrm{cm}.$$

Loop level electron EDM from CKM matrix





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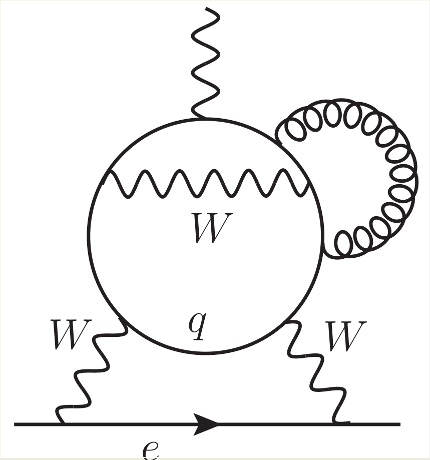
$$d_e^{\mathrm{Fig.1a}} \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3 \alpha_s}{(4\pi)^4},$$

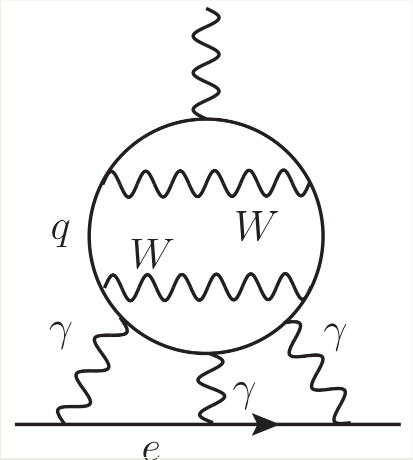
$$d_e(\mathcal{J}) \sim O(10^{-44})\ e\mathrm{cm}.$$

$$d_e^{\mathrm{Fig.1b}} \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^4 m_{\mathrm{had}}^2}\frac{\alpha_W^2 \alpha^3}{(4\pi)^5},$$

$$m_e^{-1} \sim 4 \times 10^{-11}\mathrm{cm}$$

Loop level electron EDM from CKM matrix





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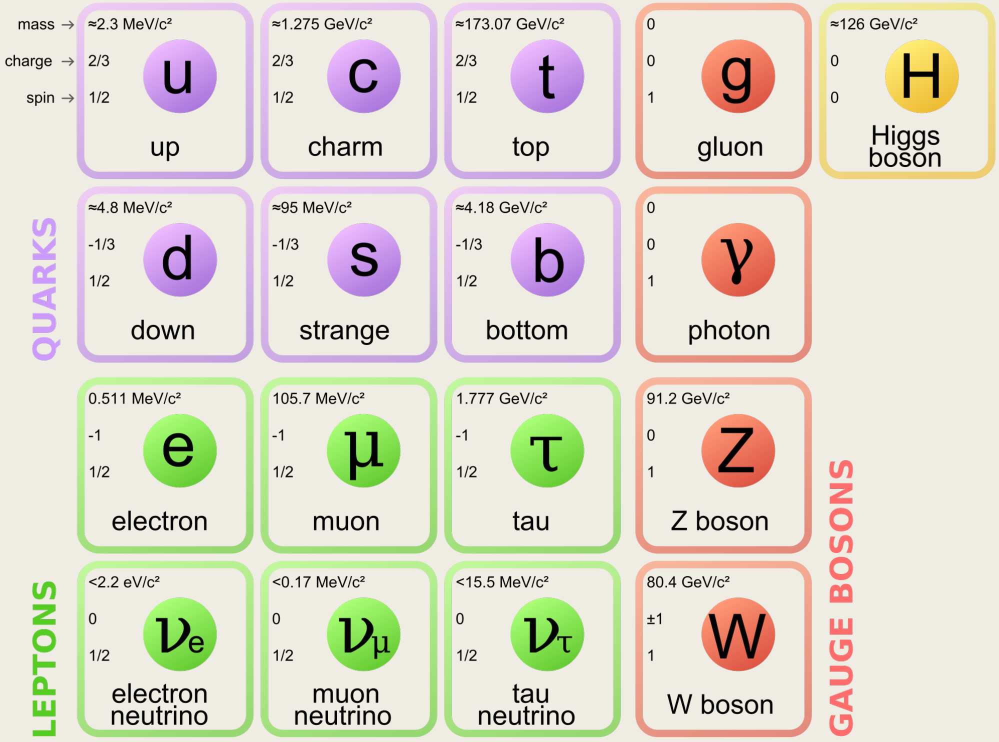
D. A. Demir and Y. F.,
“Can measurements of electric dipole moments determine the seesaw parameters?,”
JHEP 10 (2005), 068
D.A. Demir and Y.F., “Correlating mu parameter and right-handed neutrino masses in N=1 supergravity," JHEP **03** (2006), 010
D. A .Demir and Y.F.,
“On the Sources of CP-violation Contributing to the Electric Dipole Moments,’’
eConf C0605151 (2006), 0005

ELEMENTARY PARTICLES

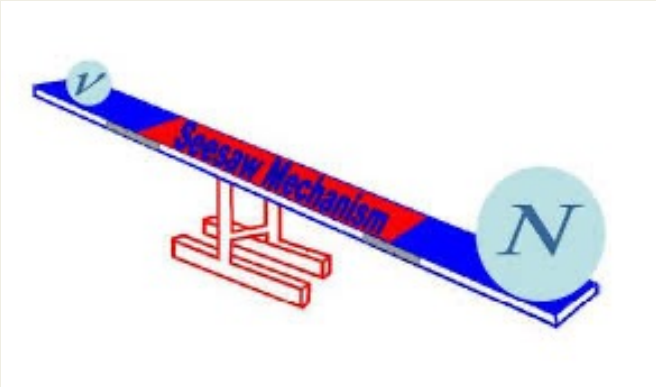


$$m_\nu \ll m_e$$

$$m_\nu < 10^{-12} m_t, m_H$$

Seesaw mechanism

$$(\nu^T \ N^T) c \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \qquad c = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$



$$m_D \ll m_N \Longrightarrow m_\nu = -\frac{m_D^2}{m_N} \ll m_D$$

Yukawa couplings

$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ \ell_\alpha \end{pmatrix}$$

$$Y_{i\alpha} H^T \bar{N}_i c L_\alpha + M_i N_i^T c N_i$$

$$(m_D)_{i\alpha} = Y_{i\alpha} \langle H \rangle$$

$$\boxed{m_\nu = -\frac{m_D^2}{m_N} \ll m_D}$$

$$\left.\begin{aligned} Y_{i\alpha} &\sim 1 \\ \langle H \rangle &\sim 100 \text{ GeV} \\ M &\sim 10^{15} \text{ GeV} \end{aligned}\right\} \Rightarrow \boxed{m_\nu \sim 0.01 \text{ eV}}$$

Complex Yukawa couplings

$$Y_{i\alpha} H^0 \bar{N}_i \nu_\alpha + \underbrace{Y^*_{i\alpha} H^0 \bar{\nu}_\alpha N_i}_{\text{Hermitian conjugate}}$$

Some phases can be absorbed by rephasing the left-handed neutrinos

$$\boxed{\begin{aligned} Y_{i\alpha} H^T \bar{N}_i c L_\alpha + M_i N_i^T c N_i \\ (m_D)_{i\alpha} = Y_{i\alpha} \langle H \rangle \end{aligned}}$$

Remaining phases are physical and source of CP violation

Leptogenesis

$$Y_{i\alpha} H^T \bar{N}_i c L_\alpha + M_i N_i^T c N_i$$

$$(m_D)_{i\alpha} = Y_{i\alpha} \langle H \rangle$$

Lepton number violation

Baryon number violation

New sources of CP violation

Super-symmetry

- Each particle has a super-partner

- Electron ⟺ Selectron
- Muon ⟺ Smuon
- Higgs ⟺ Higgsino

New sources of CP violation

$$W = Y_\ell^{ik}\epsilon_{\alpha\beta}H_{1\alpha}E_iL_{j\beta} - Y_\nu^{ij}\epsilon_{\alpha\beta}H_{2\alpha}N_iL_{j\beta} - \mu\epsilon_{\alpha\beta}H_{1\alpha}H_{2\beta} + \frac{1}{2}M_{ij}N_iN_j \ .$$

Y.F. and M. Peskin, Phys Rev D 70 (2004) 095001

- Bound back then (2005)

$$\boxed{d_e < 1.7 \times 10^{-27} \quad e \text{ cm}}$$

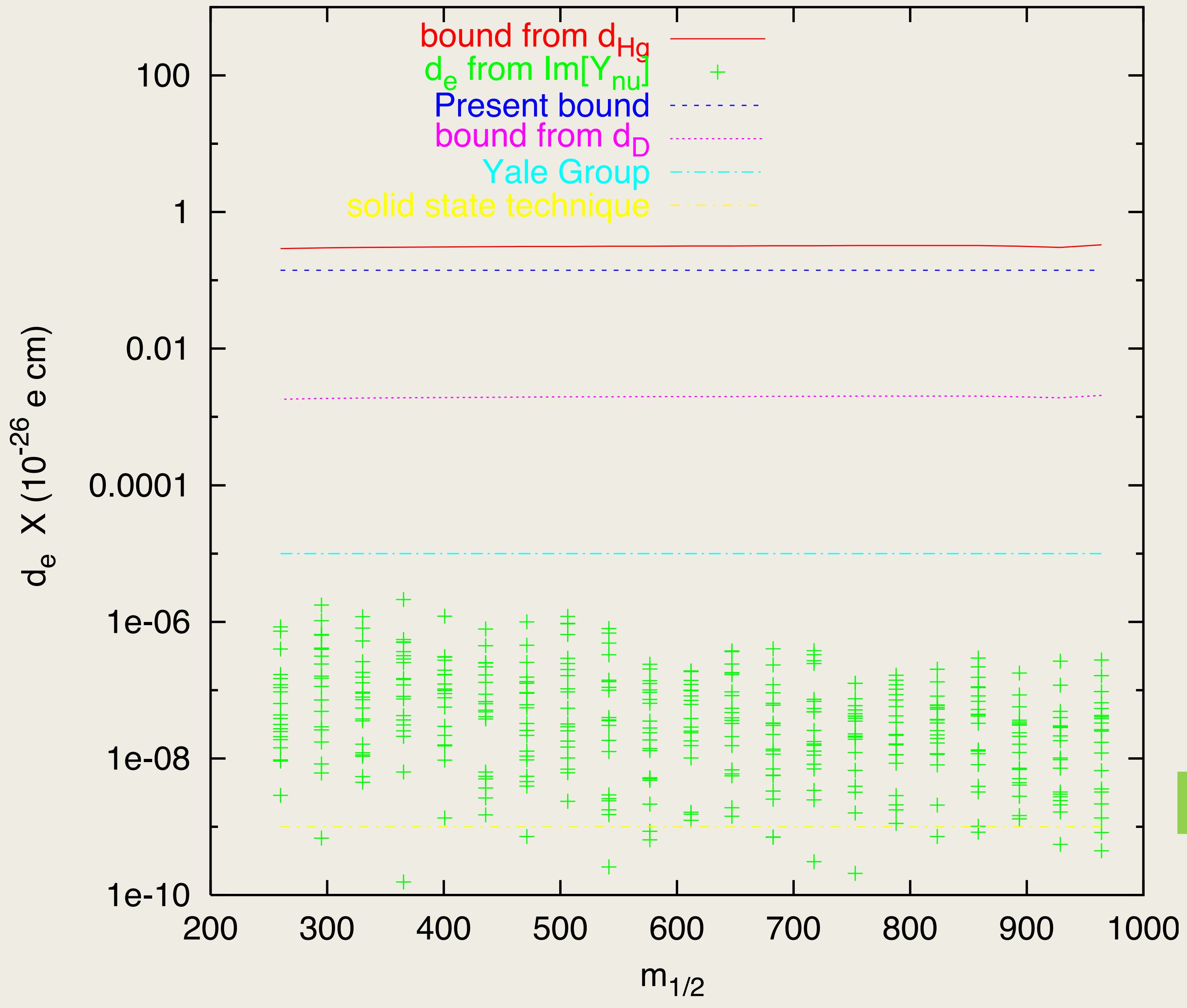
- Now

$$\boxed{d_e < 4.1 \times 10^{-30} e \cdot \text{cm}}$$

$$\boxed{d_e \sim 4.1 \times 10^{-35} e \cdot \text{cm}}$$

- Future ??

S. K. Lamoreaux, arXiv:nucl-ex/0109014



Mu term as source of CP violation

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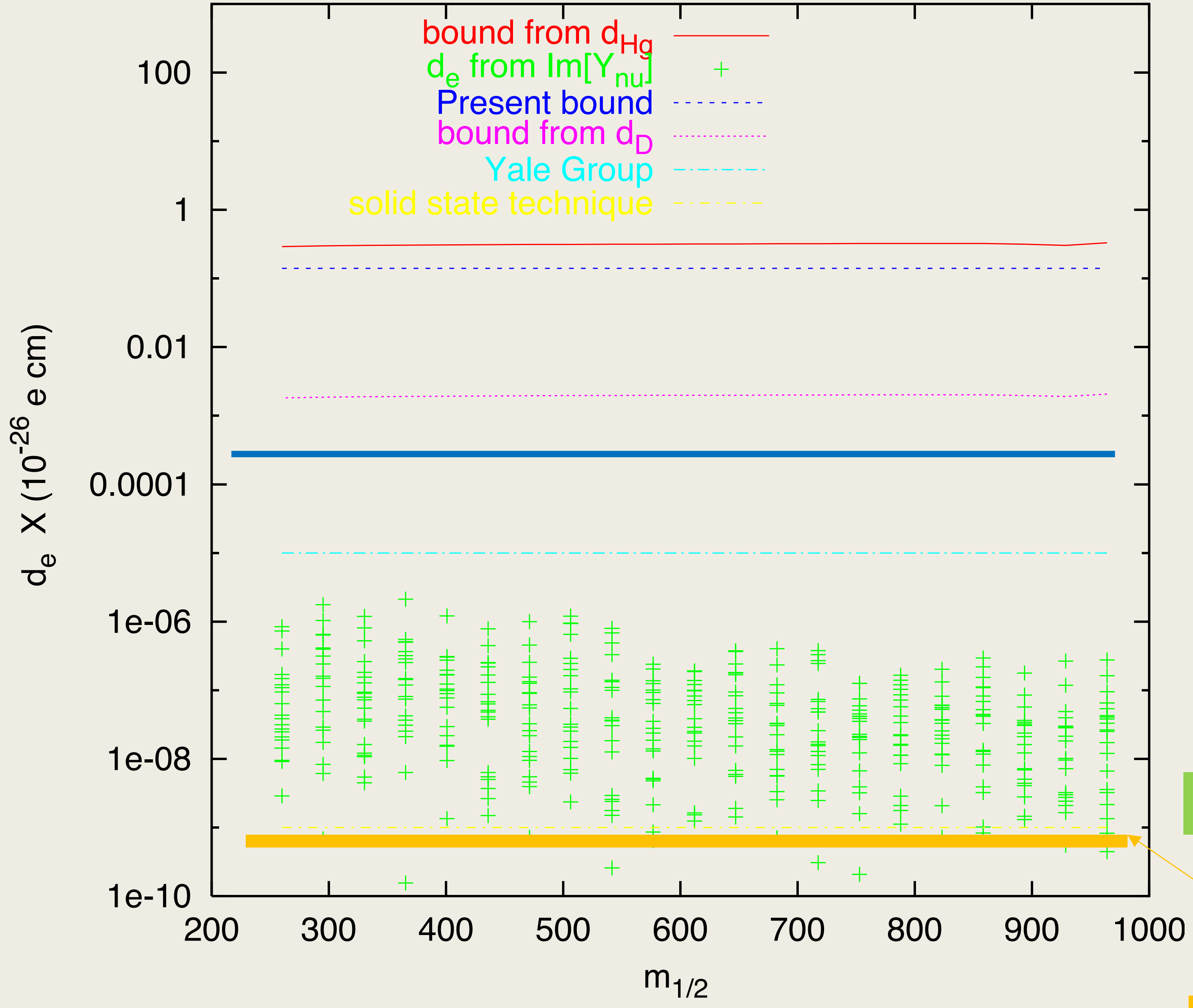
Yukawa coulings as source of CP violation



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Testing supersymmetric leptogenesis

Take-home message

- Relatively low budget experiments looking for electron EDM can give us great insight:

1) symmetries of nature
2) Matter asymmetry of universe

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- Relatively low budget experiments looking for electron EDM can give us great insight:

1) symmetries of nature
2) Matter asymmetry of universe

Durmus was a great friend and a dedicated physicists whose memory and enthusiam for science will be remembered and will be a guiding star in the stormy days of research.

Low energy scheme

- Hadrons are all color singlets:

$$N = \begin{pmatrix} p \\ n \end{pmatrix} \quad \Pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

- Yukawa interaction: $\bar{N}\Pi \cdot \tau\gamma_5 N$

Short range: Range given by inverse of mass pion.