

# CP violation ordinary matter: $\beta$ -decay and EDMs

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w/ John Ng (PRD – arXiv:1111.0649)

# CP violation in ordinary matter

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- ▶ **Standard Model: CP violation connected with flavor**
  - ▶ 3 generations required (Kobayashi & Maskawa)
  - ▶ Evidence for CP violation in K, B, D meson systems
  - ▶ Consistent (mostly) with Standard Model predictions
- ▶ **CP violation beyond the Standard Model?**
  - ▶ New CP violation generic in theories beyond SM
  - ▶ Required (likely) to explain cosmological baryon asymmetry

**New CP violation may not be connected with flavor**  
**Search for CP violation in systems of first generation quarks and leptons**



# CP violation in ordinary matter

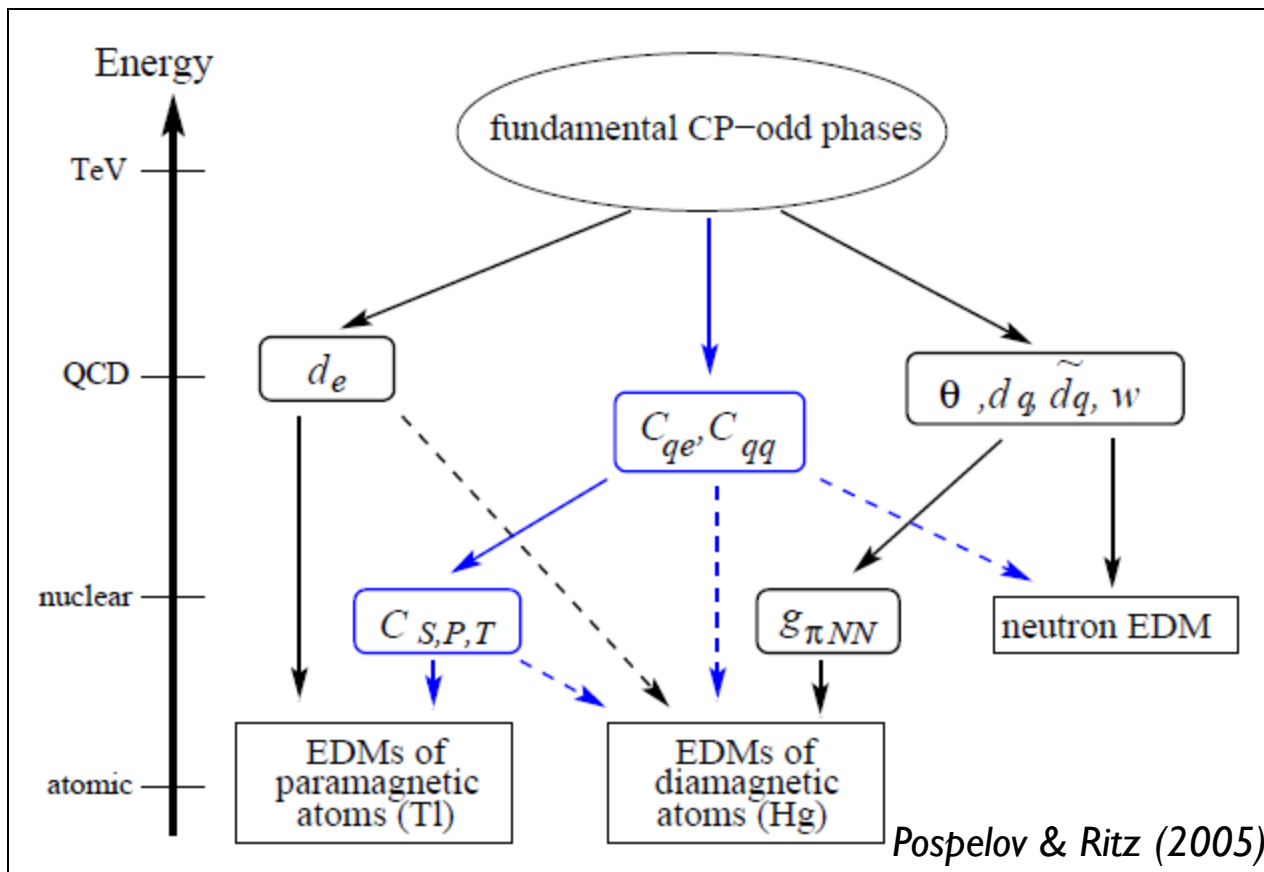
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- ▶ EDMs of nucleons, nuclei, and atoms
- ▶ CP violation in nuclear beta decay
  - ▶ T-odd triple product correlations *Jackson, Treiman, Wyld (1957)*



# EDMs as probes of CP violation

1. Sensitive to many operators
2. Theoretical challenge to relate to underlying CP-phases



$\theta_{QCD}$  term

$$\frac{g_s^2}{32\pi^2} \bar{\theta} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a}$$

Fermion EDMs

$$\frac{i}{2} d_f \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$$

Quark Chromo-EDMs

$$\frac{i}{2} \tilde{d}_q \bar{q} \sigma^{\mu\nu} \gamma_5 \lambda^a q G_{\mu\nu}^a$$

Weinberg (3-gluon)

$$\frac{1}{3} w f^{abc} G_{\mu\nu}^a \tilde{G}^{\nu\beta,b} G_{\beta}^{\mu,c}$$

Four-fermion ints.

$$C_{ij} (\bar{\psi}_i \psi_i) (\bar{\psi}_j i \gamma_5 \psi_j)$$

# Currently most stringent EDM bounds

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$$|d_n| < 2.9 \times 10^{-26} \text{ e cm} \quad (90\% \text{ CL}) \quad \text{Baker et al (2006)}$$

$$|d_{\text{Hg}}| < 3.1 \times 10^{-29} \text{ e cm} \quad (95\% \text{ CL}) \quad \text{Griffith et al (2009)}$$

$$|d_{\text{Tl}}| < 9 \times 10^{-25} \text{ e cm} \quad (90\% \text{ C.L.}) \quad \text{Regan et al (2002)}$$

$$|d_e| < \begin{cases} 10.5 \times 10^{-28} \text{ e cm} & (90\% \text{ CL}) & \text{YbF molecule} \\ 16 \times 10^{-28} \text{ e cm} & (90\% \text{ CL}) & d_{\text{Tl}} \end{cases}$$

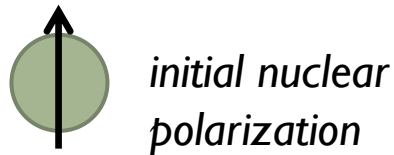
*Hudson et al. (2011)*



# CP violation in beta decay

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- ▶ CP violation in nuclear beta decay
  - ▶ Time-reversal-odd triple product correlations

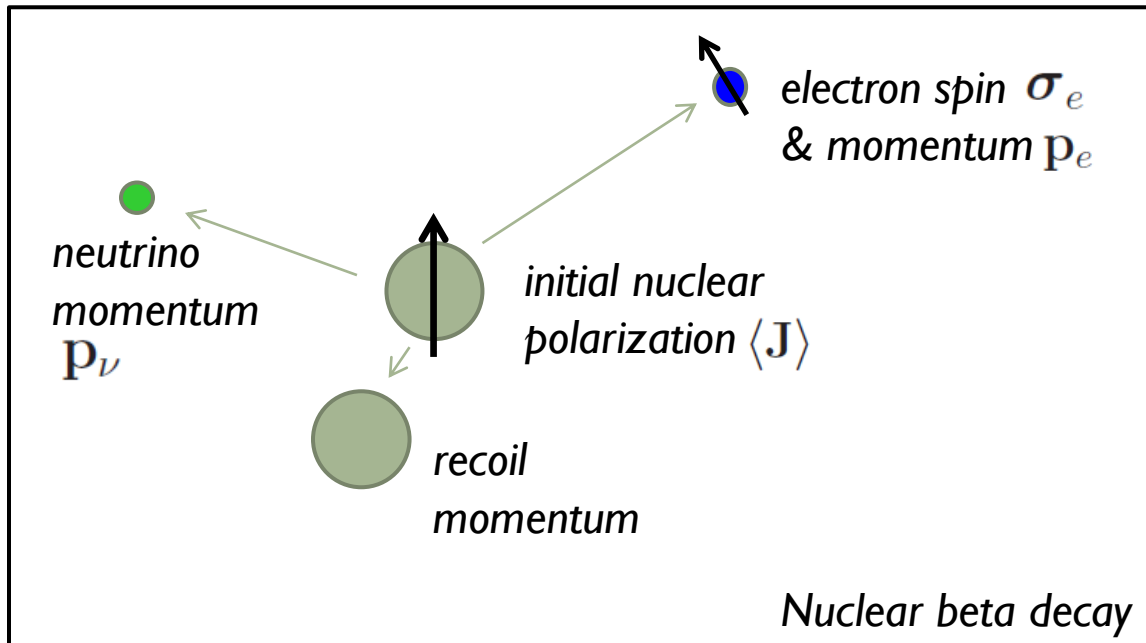


*Nuclear beta decay*



# CP violation in beta decay

- ▶ CP violation in nuclear beta decay
  - ▶ Time-reversal-odd triple product correlations



Correlations:

## **D-correlation**

$$\langle \mathbf{J} \rangle \cdot \mathbf{p}_e \times \mathbf{p}_\nu$$

(P-even, T-odd):

## **R-correlation**

$$\langle \mathbf{J} \rangle \cdot \sigma_e \times \mathbf{p}_e$$

(P-odd, T-odd):

# CP violation in beta decay

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Differential decay rate (polarized nuclei, unpolarized electron):

$$\begin{aligned}
 & \omega(\langle J \rangle | E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu \\
 &= \frac{1}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \xi \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} \right. \\
 & \quad \left. + c \left[ \frac{1}{3} \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} - \frac{(\mathbf{p}_e \cdot \mathbf{j})(\mathbf{p}_\nu \cdot \mathbf{j})}{E_e E_\nu} \right] \left[ \frac{J(J+1) - 3\langle (\mathbf{J} \cdot \mathbf{j})^2 \rangle}{J(2J-1)} \right] \right. \\
 & \quad \left. + \frac{\langle \mathbf{J} \rangle}{J} \cdot \left[ A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right] \right\}.
 \end{aligned}$$

Jackson, Treiman, Wyld (1957)





# CP violation in beta decay

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Differential decay rate

(polarized nuclei, polarized electron,  $\nu$  momentum integrated over):

$$\begin{aligned} & \omega(\langle \mathbf{J} \rangle, \boldsymbol{\sigma} | E_e, \Omega_e) dE_e d\Omega_e \\ &= \frac{1}{(2\pi)^4} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e \\ & \times \xi \left\{ 1 + b \frac{m}{E_e} + \left( A \frac{\langle \mathbf{J} \rangle}{J} + G \boldsymbol{\sigma} \right) \cdot \frac{\mathbf{p}_e}{E_e} + \boldsymbol{\sigma} \cdot \left[ N \frac{\langle \mathbf{J} \rangle}{J} \right. \right. \\ & \quad \left. \left. + Q \frac{\mathbf{p}_e}{E_e + m} \left( \frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}_e}{E_e} \right) + R \frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e} \right] \right\}. \end{aligned}$$

*Jackson, Treiman, Wyld (1957)*



# Current experimental status

## R correlation $\langle \mathbf{J} \rangle \cdot \boldsymbol{\sigma}_e \times \mathbf{p}_e$

### ▶ neutron

$$R_n = (8 \pm 16) \times 10^{-3}$$

*Kozela et al. (2009)*

### ▶ ${}^8\text{Li} \rightarrow {}^8\text{Be}$ :

$$R_{\text{Li}} = (9 \pm 22) \times 10^{-4}$$

*Huber et al. (2003)*

## D correlation $\langle \mathbf{J} \rangle \cdot \mathbf{p}_e \times \mathbf{p}_\nu$

### ▶ neutron

$$D_n = (-1.0 \pm 2.1) \times 10^{-4}$$

*Mumm et al. (2011+2012) [emiT experiment]*

### ▶ ${}^{19}\text{Ne} \rightarrow {}^{19}\text{F}$ :

$$D_{\text{Ne}} = (1 \pm 6) \times 10^{-4}$$

*Baltrusaitis & Calaprice (1977),  
Hallin et al. (1984)*

# Questions

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- ▶ How do D and R probe CP violating beyond the SM?
  - ▶ What operators?
  - ▶ What new physics models?
- ▶ How are D and R related to EDM constraints?
  - ▶ Given current EDM constraints, how large can D or R be?
- ▶ Caveat:
  - ▶ Assume no cancellations between CP-violating contributions
  - ▶ EDMs and  $\beta$  decay are complementary, probe different linear combinations of phases



# Standard lore

R correlation  $\langle \mathbf{J} \rangle \cdot \boldsymbol{\sigma}_e \times \mathbf{p}_e$

P-odd, T-odd

Correlated with EDMs

EDM constraints constrain R  
to be much smaller than  
direct measurements

D correlation  $\langle \mathbf{J} \rangle \cdot \mathbf{p}_e \times \mathbf{p}_\nu$

P-even, T-odd

Less correlated with EDMs

In some models, D can be as  
large as direct measurements  
allow

Mainly focus on D



# CP violation in beta decay

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- ▶ A top-down perspective: e.g. Deutch & Quinn (1995), Herczeg (2001)

$$H = \frac{4G_F}{\sqrt{2}} V_{ud} \left( \begin{aligned} & a_{LL}^V \bar{e}_L \gamma^\mu \nu_L \bar{u}_L \gamma_\mu d_L + a_{LR}^V \bar{e}_L \gamma^\mu \nu_L \bar{u}_R \gamma_\mu d_R \\ & + a_{RL}^V \bar{e}_R \gamma^\mu \nu_R \bar{u}_L \gamma_\mu d_L + a_{RR}^V \bar{e}_R \gamma^\mu \nu_R \bar{u}_R \gamma_\mu d_R \\ & + a_{LL}^S \bar{e}_L \nu_R \bar{u}_L d_R + a_{LR}^S \bar{e}_L \nu_R \bar{u}_R d_L \\ & + a_{RL}^S \bar{e}_R \nu_L \bar{u}_R d_L + a_{RR}^S \bar{e}_R \nu_L \bar{u}_L d_R \\ & + a_{LR}^T \bar{e}_L \frac{\sigma^{\mu\nu}}{\sqrt{2}} \nu_R \bar{u}_R \frac{\sigma_{\mu\nu}}{\sqrt{2}} d_L + a_{RL}^T \bar{e}_R \frac{\sigma^{\mu\nu}}{\sqrt{2}} \nu_L \bar{u}_R \frac{\sigma_{\mu\nu}}{\sqrt{2}} d_L \end{aligned} \right)$$

Most general beta-decay effective Hamiltonian

Long history to understand and probe structure of SM



# CP violation in beta decay

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- A top-down perspective: e.g. Deutch & Quinn (1995), Herczeg (2001)

$$H = \frac{4G_F}{\sqrt{2}} V_{ud} \left( \begin{aligned} & \boxed{a_{LL}^V} \bar{e}_L \gamma^\mu \nu_L \bar{u}_L \gamma_\mu d_L + \boxed{a_{LR}^V} \bar{e}_L \gamma^\mu \nu_L \bar{u}_R \gamma_\mu d_R \\ & + \boxed{a_{RL}^V} \bar{e}_R \gamma^\mu \nu_R \bar{u}_L \gamma_\mu d_L + \boxed{a_{RR}^V} \bar{e}_R \gamma^\mu \nu_R \bar{u}_R \gamma_\mu d_R \\ & + \boxed{a_{LL}^S} \bar{e}_L \nu_R \bar{u}_L d_R + \boxed{a_{LR}^S} \bar{e}_L \nu_R \bar{u}_R d_L \\ & + \boxed{a_{RL}^S} \bar{e}_R \nu_L \bar{u}_R d_L + \boxed{a_{RR}^S} \bar{e}_R \nu_L \bar{u}_L d_R \\ & + \boxed{a_{LR}^T} \bar{e}_L \frac{\sigma^{\mu\nu}}{\sqrt{2}} \nu_R \bar{u}_R \frac{\sigma_{\mu\nu}}{\sqrt{2}} d_L + \boxed{a_{RL}^T} \bar{e}_R \frac{\sigma^{\mu\nu}}{\sqrt{2}} \nu_L \bar{u}_R \frac{\sigma_{\mu\nu}}{\sqrt{2}} d_L \end{aligned} \right)$$

Coefficients parameterize beta decay interaction:

$$a_{LL}^S, a_{LR}^S, a_{RL}^S, a_{RR}^S, a_{LL}^V, a_{LR}^V, a_{RL}^V, a_{RR}^V, a_{LR}^T, a_{RL}^T$$

Standard Model (leading order):  $a_{LL}^V = 1$

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# D correlation coefficient

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Two contributions to D:  $D \equiv D_t + D_f$



# D correlation coefficient

Two contributions to D:  $D \equiv D_t + D_f$

I. Fundamental T-violation (or CP violation)

$$D_t = \kappa \operatorname{Im} (a_{LR}^V a_{LL}^{V*} + a_{RL}^V a_{RR}^{V*}) + \kappa \frac{g_S g_T}{g_V g_A} \operatorname{Im} (a_{L+}^S a_{LR}^{T*} + a_{R+}^S a_{RL}^{T*})$$

where  $a_{L+}^S \equiv (a_{LL}^S + a_{LR}^S)$   $a_{R+}^S \equiv (a_{RL}^S + a_{RR}^S)$

$$\kappa \equiv \frac{4g_V g_A M_F M_{GT}}{g_V^2 M_F^2 + g_A^2 M_{GT}^2} \sqrt{\frac{J}{J+1}} \delta_{JJ'} \simeq \begin{cases} 0.87 & \text{for } n \\ -1.03 & \text{for } {}^{19}\text{Ne} \end{cases}$$

$D_t < 10^{-12}$  in Standard Model  $\rightarrow$  probes CP violation beyond SM

*Herczeg & Khriplovich (1997)*





# D correlation coefficient

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## 2. Electromagnetic final state effects (Callan & Treiman, 1967)

neutron  $D_f = \mathcal{O}(10^{-5})$     Known to better than 1%. Ando et al (2009)

${}^{19}\text{Ne}$   $D_f \sim 10^{-4}$



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Interference of new physics scalar and tensor amplitudes

R coefficient more sensitive to scalar and tensor amplitudes, unless amplitudes are large ( $a^{S,T} \sim 0.1$ )



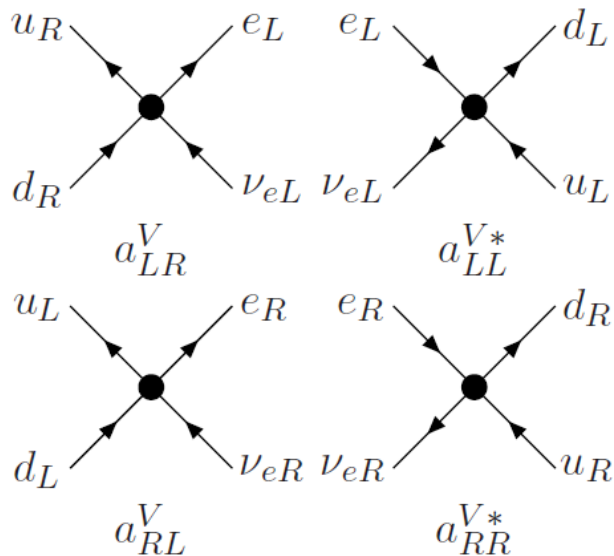
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Focus on vector terms  $a^V$

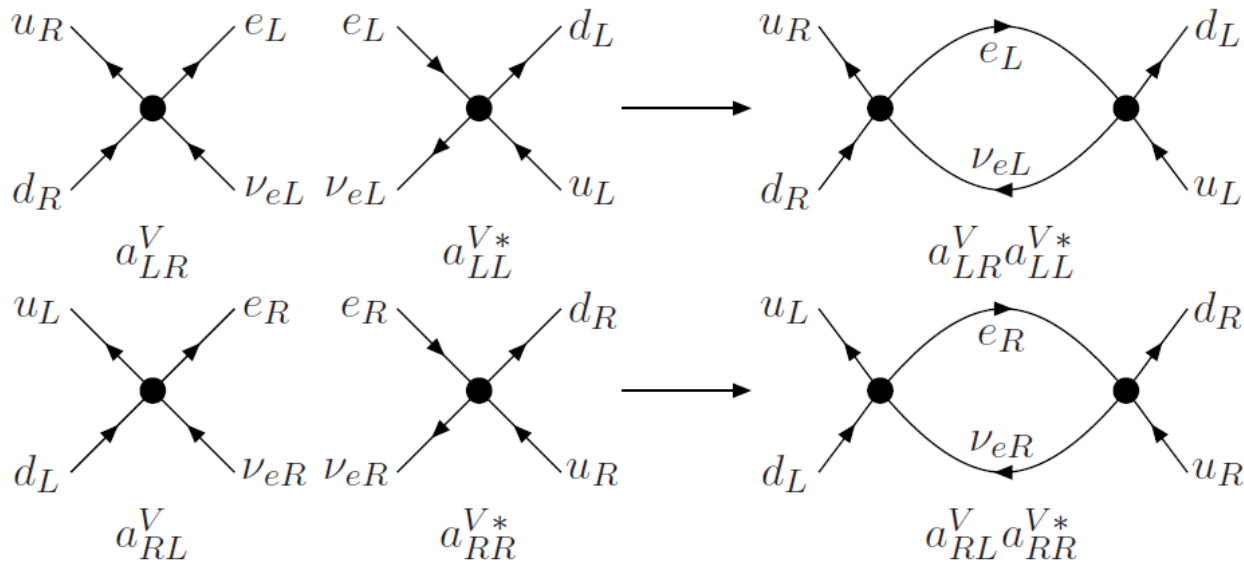


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D from interference terms

Four-quark operators  $\rightarrow$  EDMs

# D correlation coefficient

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- ▶ Any vector-type new physics contribution to D generates:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} k_{LR} \mathcal{O}_{LR}, \quad \mathcal{O}_{LR} \equiv i(\bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R)$$

*CP-odd four-quark operator*

- ▶ How sensitive are EDMs to this operator?

*Contributes to neutron, deuteron, and mercury EDMs*



# D correlation coefficient

---

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*CP-odd four-quark operator*

- ▶ How sensitive are EDMs to this operator?

**neutron:** Recent comprehensive analysis by An, Ji, Xu (2009) computing neutron EDM from four-quark operators

$$d_n = -1 \times 10^{-19} k_{LR} \text{ e cm}$$

Naïve order-of-magnitude estimate

$$d_n \sim e M_{QCD} / \Lambda^2 \sim 2 |k_{LR}| \times 10^{-19} \text{ e cm}$$

$$M_{QCD} \sim 1 \text{ GeV} \quad \Lambda^{-2} \sim G_F k_{LR}$$

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# D correlation coefficient

- How sensitive are EDMs to this operator?

## mercury:

*Contributes to EDM via nuclear Schiff moment*

$$d_{\text{Hg}} = -2.6 \times 10^{-17} \text{ e cm} \times \left( \frac{S_{\text{Hg}}}{\text{e fm}^3} \right) \quad \text{Dzuba et al. (2009)}$$

*Schiff moment sourced by CP-odd isovector pion-nucleon coupling*

$$\bar{g}_1 = 2 \times 10^{-6} k_{LR} \quad \text{Khatsimovsky et al. (1988)}$$

*Constant of proportionality has large theoretical uncertainty:*

*Ban, Dobaczewski, Engel, Shukla (2010)*

	$E_{\text{gs}}$	$\beta$	$E_{\text{exc.}}$	$a_0$	$a_1$	$a_2$	$b$
SLy4	-1561.42	-0.13	0.97	0.013	-0.006	0.022	0.003
SIH	-1562.63	-0.11	0	0.012	0.005	0.016	0.004
SV	-1556.43	-0.11	0.68	0.009	-0.0001	0.016	0.002
SLy4	-1560.21	-0.10	0.83	0.013	-0.006	0.024	0.007
SkM*	-1564.03	0	0.82	0.041	-0.027	0.069	0.013
Ref. [6]	—	—	—	0.0004	0.055	0.009	—
Ref. [8]	—	—	—	0.007	0.071	0.018	—

# D correlation coefficient

- How sensitive are EDMs to this operator?

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SkM*	-1564.03	0	0.82	0.041	-0.027	0.069	0.013
$ d_{\text{Hg}}  = 7 \times 10^{-24}  k_{LR}  \text{ e cm}$				—	0.0004	0.055	0.009
				—	0.007	0.071	0.018



# D correlation coefficient

- Any vector-type new physics contribution to D generates:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} k_{LR} \mathcal{O}_{LR}, \quad \mathcal{O}_{LR} \equiv i(\bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R)$$

*CP-odd four-quark operator*

## Summary:

$$|d_{\text{Hg}}| = 7 \times 10^{-24} |k_{LR}| \text{ e cm} \quad |d_{\text{Hg}}| < 3.1 \times 10^{-29} \text{ e cm} \quad (95\% \text{ CL})$$

*(Order-of-magnitude uncertainty)*

$$d_n = -1 \times 10^{-19} k_{LR} \text{ e cm} \quad |d_n| < 2.9 \times 10^{-26} \text{ e cm} \quad (90\% \text{ CL})$$

*O(1) uncertainty*

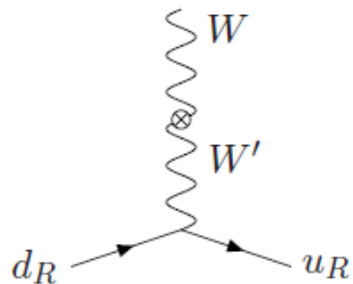
$$|d_D| \approx 1.9 \times 10^{-14} |\bar{g}_1| \text{ e cm} \approx 4.5 \times 10^{-20} |k_{LR}| \text{ e cm}$$

*de Vries et al. (2011)*

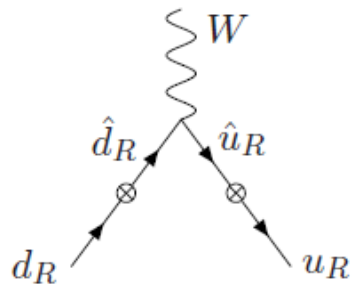
Future deuteron EDM measurement at BNL may reach  $10^{-27} \text{ e cm}$  or better

# New physics models for D

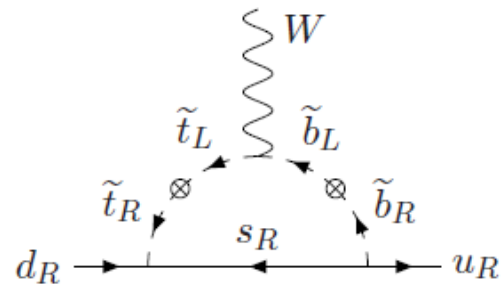
## I. Anomalous coupling of W to RH quark charge current



*W-W' mixing*



*Exotic heavy fermions*

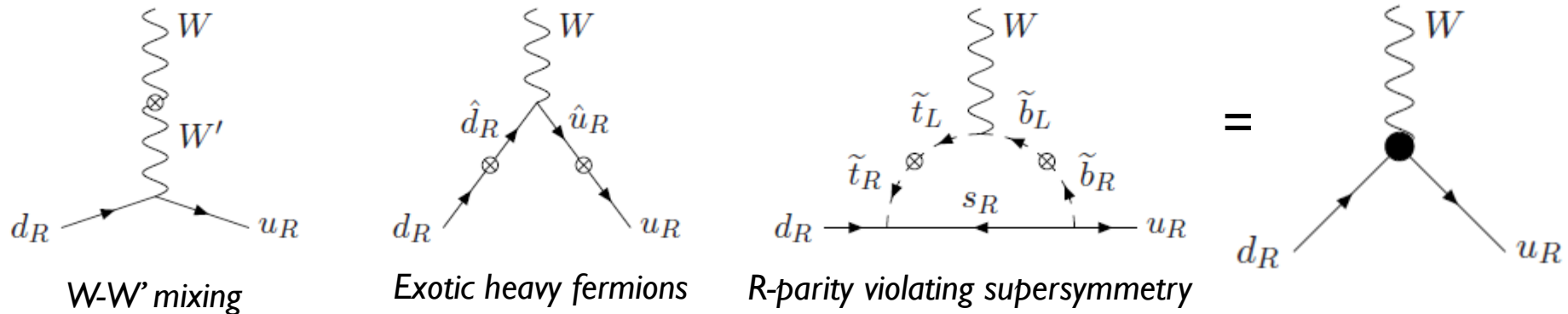


*R-parity violating supersymmetry*



# New physics models for D

## I. Anomalous coupling of W to RH quark charge current



New physics operator:  $\mathcal{L}_{\text{dim } 6} = \frac{c}{\Lambda^2} \bar{u}_R \gamma^\mu d_R i H^T \epsilon D_\mu H + \text{h.c.}$

Integrate out the  $W$  (setting  $V_{ud} = 1$ ):

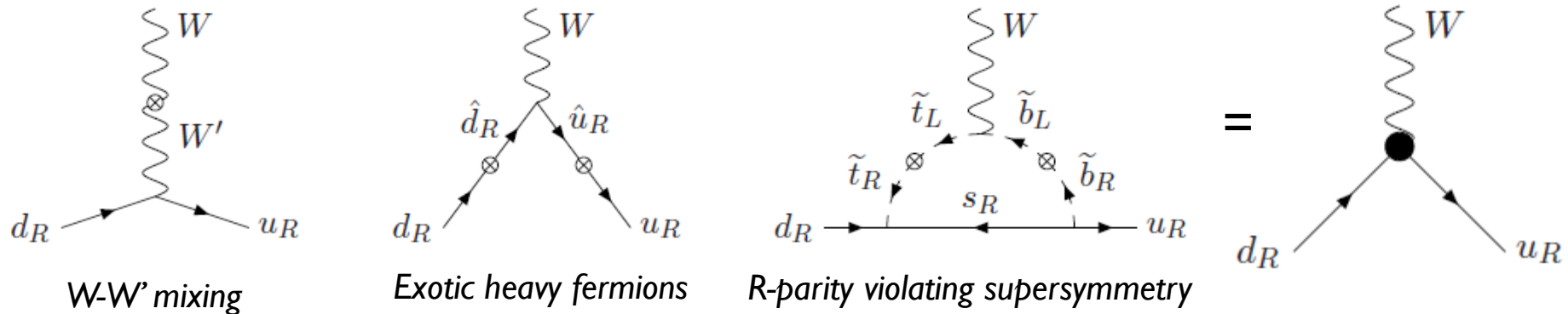
$$\mathcal{L}_{\text{dim } 6} = -\frac{c}{\Lambda^2} \left( \bar{u}_R \gamma^\mu d_R \bar{e}_L \gamma_\mu \nu_{eL} + \bar{u}_R \gamma^\mu d_R \bar{d}_L \gamma_\mu u_L \right) + \text{h.c.}$$

$$\text{Im}(a_{LR}^V) = k_{LR} = \frac{\text{Im}(c)}{2\sqrt{2} G_F \Lambda^2}$$



# New physics models for D

## I. Anomalous coupling of W to RH quark charge current



*EDMs directly related to D coefficient:*

$$|d_n| = 1 \times 10^{-19} \text{ e cm} \times |D_t/\kappa|$$

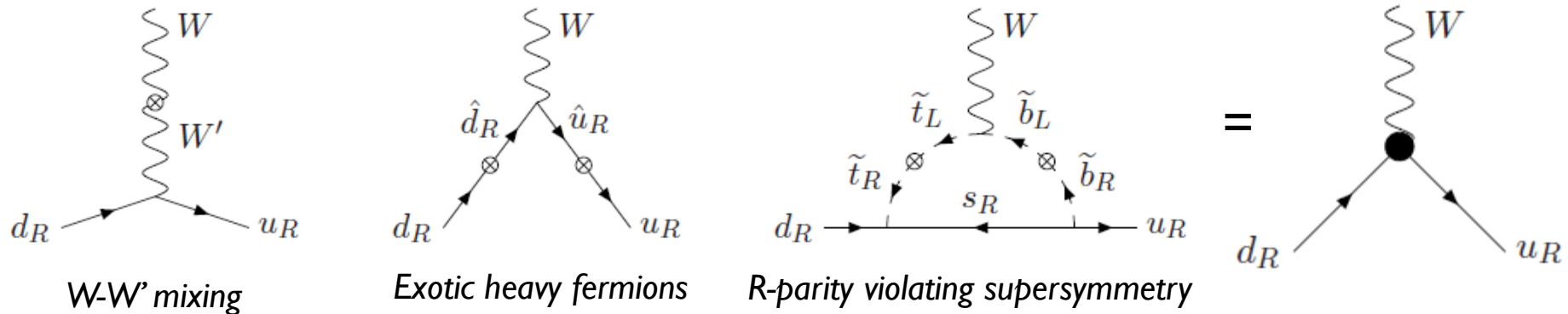
$$|d_{\text{Hg}}| = 7 \times 10^{-24} \text{ e cm} \times |D_t/\kappa|$$

$$|d_D| = 4.5 \times 10^{-20} \text{ e cm} \times |D_t/\kappa|$$



# New physics models for D

## I. Anomalous coupling of W to RH quark charge current



EDMs directly related to D coefficient:

$$\begin{aligned}
 |d_n| &= 1 \times 10^{-19} \text{ e cm} \times |D_t/\kappa| \longrightarrow |D_t/\kappa| < 3 \times 10^{-7} \\
 |d_{\text{Hg}}| &= 7 \times 10^{-24} \text{ e cm} \times |D_t/\kappa| \\
 |d_D| &= 4.5 \times 10^{-20} \text{ e cm} \times |D_t/\kappa|
 \end{aligned}$$

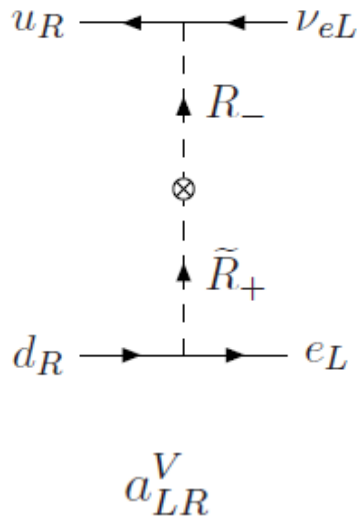
$10^3$  stronger than direct bound.

# New physics models for D

## 2. New four-fermion interactions: leptoquarks

Scalar leptoquarks:  $R = \begin{pmatrix} R_+ \\ R_- \end{pmatrix} \sim (3, 2, 7/6)$        $\tilde{R} = \begin{pmatrix} \tilde{R}_+ \\ \tilde{R}_- \end{pmatrix} \sim (3, 2, 1/6)$

$$\mathcal{L}_{\text{int}} = h_L \bar{u}_R L_L^T \epsilon R + \tilde{h}_L \bar{d}_R L_L^T \epsilon \tilde{R} + \text{h.c.}$$



Contribution to D

Standard lore:

Leptoquark contributions to D are “EDM-safe”

D can be as large as present sensitivities allow without conflicting with EDMs

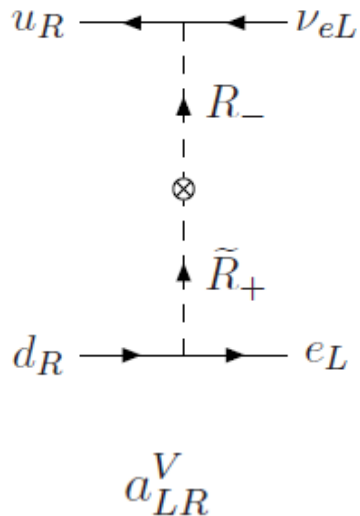


# New physics models for D

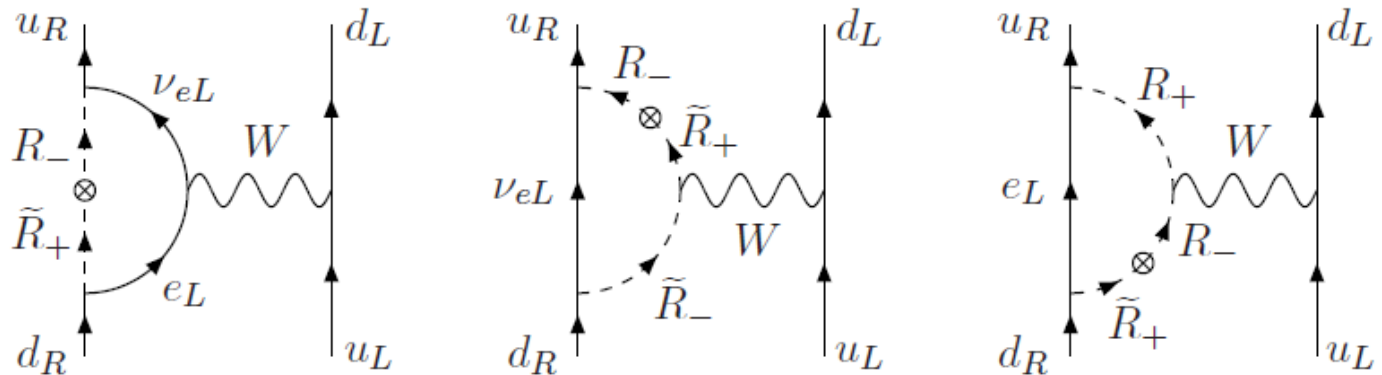
## 2. New four-fermion interactions: leptoquarks

Scalar leptoquarks:  $R = \begin{pmatrix} R_+ \\ R_- \end{pmatrix} \sim (3, 2, 7/6)$   $\tilde{R} = \begin{pmatrix} \tilde{R}_+ \\ \tilde{R}_- \end{pmatrix} \sim (3, 2, 1/6)$

$$\mathcal{L}_{\text{int}} = h_L \bar{u}_R L_L^T \epsilon R + \tilde{h}_L \bar{d}_R L_L^T \epsilon \tilde{R} + \text{h.c.}$$



Contribution to D



Contributions to EDMs



# New physics models for D

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## ► Leptoquark models

“EDM-safe” leptoquark models are in fact not EDM-safe!

$$\begin{aligned} |d_n| &> 9 \times 10^{-22} \text{ e cm} \times |D_t/\kappa| \left( \frac{m_{LQ}}{300 \text{ GeV}} \right)^2 \\ |d_{Hg}| &> 7 \times 10^{-26} \text{ e cm} \times |D_t/\kappa| \left( \frac{m_{LQ}}{300 \text{ GeV}} \right)^2 \\ |d_D| &> 4 \times 10^{-22} \text{ e cm} \times |D_t/\kappa| \left( \frac{m_{LQ}}{300 \text{ GeV}} \right)^2 \end{aligned}$$

Current LHC constraints  $m_{LQ} > 600 \text{ GeV}$  (CMS 2012) implies  $D_t < 10^{-6}$

Constraints on LQ models with RH neutrinos weaker by factor 4.





# Summary of D coefficient

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- ▶ Dimension-6: only one operator can contribute to D

$$\mathcal{L}_{\text{dim } 6} = \frac{c}{\Lambda^2} \bar{u}_R \gamma^\mu d_R i H^T \epsilon D_\mu H + \text{h.c.}$$

- ▶ Models: W', Fourth generation, RPV SUSY (B violation)
- ▶ nEDM constraint stronger by factor 1000

- ▶ Dimension-8: leptoquark models

$$\frac{1}{\Lambda^4} (\bar{L}_L H) \gamma^\mu (L \epsilon H) \bar{u}_R \gamma_\mu d_R \rightarrow \frac{v^2}{\Lambda^4} \bar{e}_L \gamma^\mu \nu_L \bar{u}_R \gamma_\mu d_R$$

- ▶ Generates EDM at one-loop (but lower dim)
- ▶ nEDM constraint stronger by factor 100



# R coefficient

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## ► CP violating scalar and tensor interactions

$$R_t = (\kappa_1 \mp \kappa_2) \left( \frac{g_T}{g_A} \right) \text{Im}(a_{RL}^T) - \kappa_1 \left( \frac{g_S}{2g_A} \right) \text{Im}(a_{RL}^S + a_{RR}^S)$$

Keeping only terms interfering linearly with SM amplitude

Three dim-6 operators contributing to R

$$\begin{aligned} \frac{c_1}{\Lambda^2} \bar{Q}_L d_R \bar{e}_R L_L &= \frac{c_1}{\Lambda^2} (\bar{u}_L d_R \bar{e}_R \nu_L + \bar{d}_L d_R \bar{e}_R e_L) \\ \frac{c_2}{\Lambda^2} \bar{u}_R Q_L \bar{e}_R L_L &= \frac{c_2}{\Lambda^2} (\bar{u}_R d_L \bar{e}_R \nu_L - \bar{u}_R u_L \bar{e}_R e_L) \\ \frac{c_3}{\Lambda^2} \bar{u}_R \sigma^{\mu\nu} Q_L \bar{e}_R \sigma_{\mu\nu} L_L &= \frac{c_3}{\Lambda^2} (\bar{u}_R \sigma^{\mu\nu} d_L \bar{e}_R \sigma_{\mu\nu} \nu_L - \bar{u}_R \sigma^{\mu\nu} u_L \bar{e}_R \sigma_{\mu\nu} e_L) \end{aligned}$$



# R coefficient

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Keeping only terms interfering linearly with SM amplitude

Three dim-6 operators contributing to R

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Generate  $\beta$  decay coefficients

$$a_{RR}^S, a_{RL}^S, a_{RL}^T$$

Generate CP-odd  
e-N interaction



# R coefficient

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- ▶ Same CP-violating operator  $\rightarrow$  relate R to EDMs
- ▶ Scalar coefficients constrained by Thallium EDM

$$|d_{\text{Tl}}| \approx 10^{-16} \text{ e cm} \times |R_t| \quad \begin{array}{l} \text{Using } g_s = 0.8 \\ \text{Bhattacharya et al. (2011)} \end{array}$$

$$|d_{\text{Tl}}| < 9 \times 10^{-25} \text{ e cm (90\% C.L.)}$$

- ▶ Scalar and tensor coefficients constrained by Hg EDM
- ▶ Indirect limit is  $R < 10^{-8}$  compared to direct limit  $\sim 10^{-3}$
- ▶ Can have dimension-8 operators  $\rightarrow$  EDMs at 1-loop
  - ▶ Loop suppression, but EDM is lower dimensional
  - ▶ Still very strongly constrained



# Conclusions

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- ▶ CP violation for D or R provides an **irreducible** EDM.
  - ▶  $D \rightarrow$  CP-odd nucleon interaction (n, D, Hg)
  - ▶  $R \rightarrow$  CP-odd electron-nucleon interaction (Tl, Hg)
- ▶ Best indirect limit on D from nEDM,  $100\text{--}10^3$  times better than direct limit on  $D_n$
- ▶ Deuteron EDM bound at  $10^{-28}$  e cm will increase limits on D by 100
- ▶ Caveats
  - ▶ EDMs suppressed by fine-tuned cancellations
  - ▶ Hadronic uncertainties larger than previously thought
- ▶  $\beta$  decay less competitive for BSM CP violation discovery, but can play role in interpreting a positive EDM signal

