# EDMs and CP Violation

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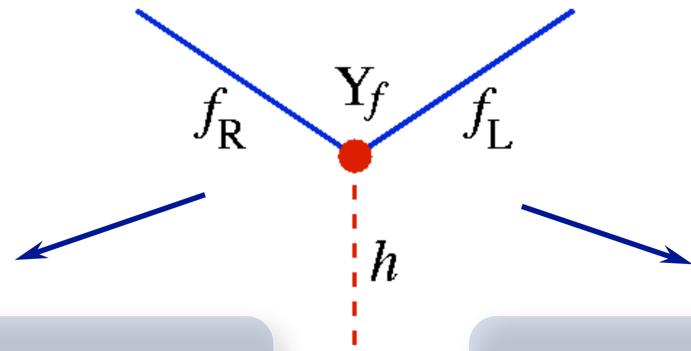
work with M. Pospelov

(also D. Demir, S. Huber, O. Lebedev, K. Olive, Y. Santoso)

[For reviews, see hep-ph/0504231, and *Lepton Dipole Moments*, ed. B.L. Roberts & W.J. Marciano]

# CP Violation in the Standard Model




$$\sin(\delta_{KM}) \propto \mathrm{Arg\,Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$\delta_{KM} \sim O(1)$

Explains CP-violation in K and B meson mixing and decays

$$\bar{\theta}_{QCD} \sim \mathrm{Arg\,Det}[Y_u Y_d]$$

(in a convenient basis)

$\theta < 10^{-10}$ !

Constrained experimentally (strong CP problem)

Do we anticipate other CP-odd sources ?

- Required by baryogenesis
- Generic with more fields (eg MSSM)

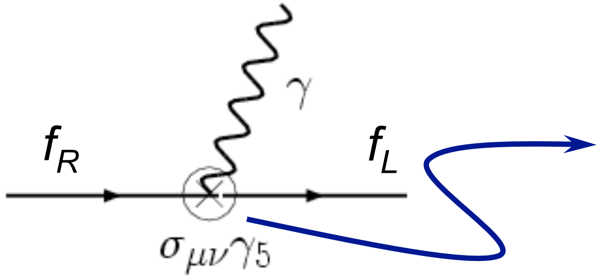
# CP-violation and EDMs

Within the SM, CP-violation is hidden behind the flavour structure $J_{CP} \sim 10^{-5} \sin(\delta_{KM})$

[Jarlskog '85]

$\Longrightarrow$

Look for new sources of CP-violation in flavour diagonal channels, with small SM bkgd



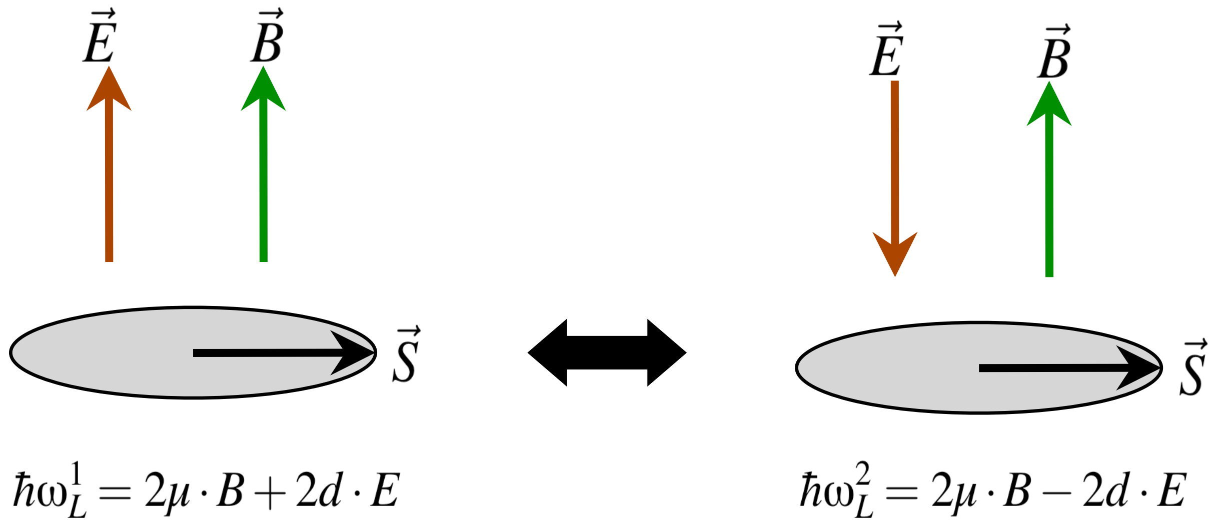

$$H = -d\vec{S}\cdot\vec{E}$$

Current sensitivity through EDMs of neutrons, para- and dia-magnetic atoms and molecules (violate T,P)

Currently, all experimental data $\Rightarrow$ EDMs vanish to very high precision leading to very strong constraints on new physics.

# Sensitivity

- Measure Larmor precession frequency in (anti-)aligned E and B fields



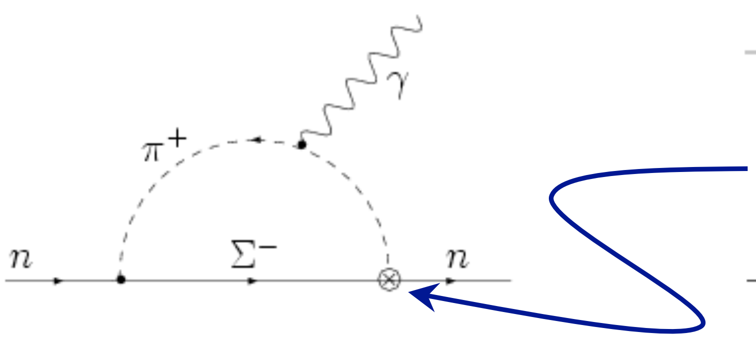

$$d = \frac{\hbar}{4E}(\omega_L^1 - \omega_L^2) \sim (\text{loop})\frac{m_f}{\Lambda_{\text{CP}}^2}$$

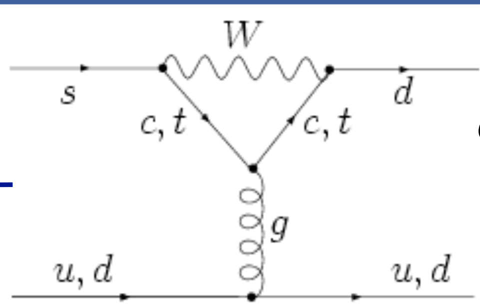
$$\text{Given } E \sim 10\, kV/cm,\ \delta\omega \sim 10^{-6}\,\text{Hz} \implies \Lambda_{\text{CP}} \sim 1\,\text{TeV}$$

# Experimental Status

| | | |
|---|---|---|
| Neutron EDM | $\lvert d_n \rvert < 3 \times 10^{-26} e\, cm$ | [Baker et al. '06] |
| Thallium EDM (paramagnetic) | $\lvert d_{Tl} \rvert < 9 \times 10^{-25} e\, cm$ | [Regan et al. '02] |
| YbF "EDM" (paramagnetic) | $\lvert \text{“}d_{YbF}\text{”} \rvert < 1.3 \times 10^{-22} e\, cm$ | [Hudson et al. '11] |
| Mercury EDM (diamagnetic) | $\lvert d_{Hg} \rvert < 3 \times 10^{-29} e\, cm$ | [Griffith et al. '09] |

*Small* SM background (via CKM phase)



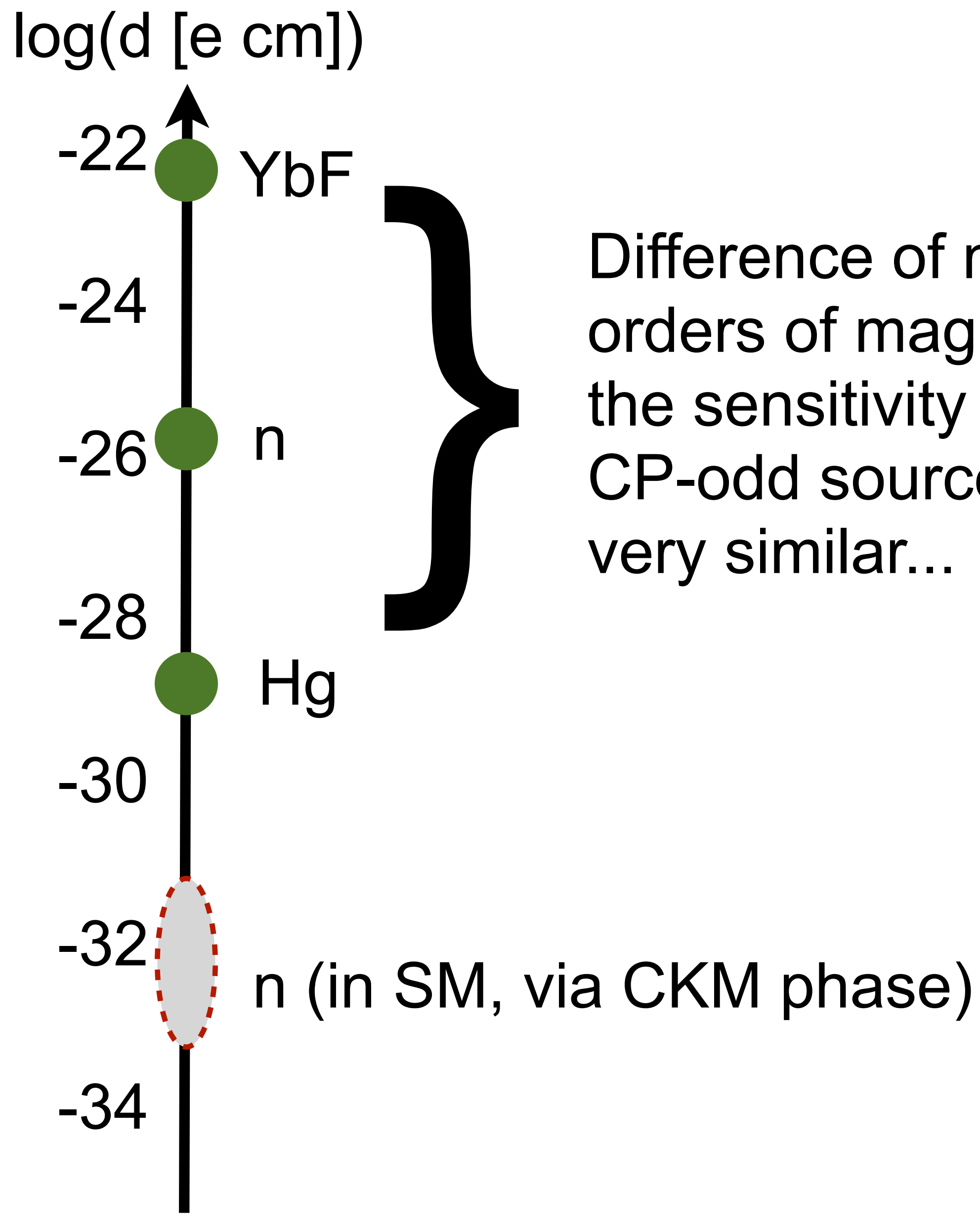




$$d_n \sim 10^{-32} - 10^{-31} e\, \text{cm}$$

[Khriplovich & Zhitnitsky '82; McKellar et al '87]

[Mannel & Uraltsev '12 (related dim-9 contribution)]

# Schematic view of the bounds




Difference of more than 6 orders of magnitude, but the sensitivity to underlying CP-odd sources is actually very similar...

# Classification of CP-odd operators at 1GeV

Effective field theory provides a model-independent parametrization of (flavor-diagonal) CP-violating operators at 1GeV

$$\mathcal{L} = \sum_i \frac{c_i}{M^{d-4}} O_d^{(i)}$$

Dimension 4: $\bar{\theta}\alpha_s G\tilde{G}$

$$\bar{\theta} = \theta_0 + ArgDet(M_q)$$

Dimension “6”: $\sum_{q=u,d,s} d_q \bar{q} F\sigma\gamma_5 q + \sum_{q=u,d,s} \tilde{d}_q \bar{q} G\sigma\gamma_5 q + d_e \bar{e} F\sigma\gamma_5 e + w g_s^3 G G\tilde{G}$

Dimension “8”: $\sum_{q=u,d,s} C_{qq} \bar{q} q \bar{q} i\gamma_5 q + C_{qe} \bar{q} q \bar{e} i\gamma_5 e + \cdots$

$$C_S \bar{N} N \bar{e} i\gamma_5 e$$

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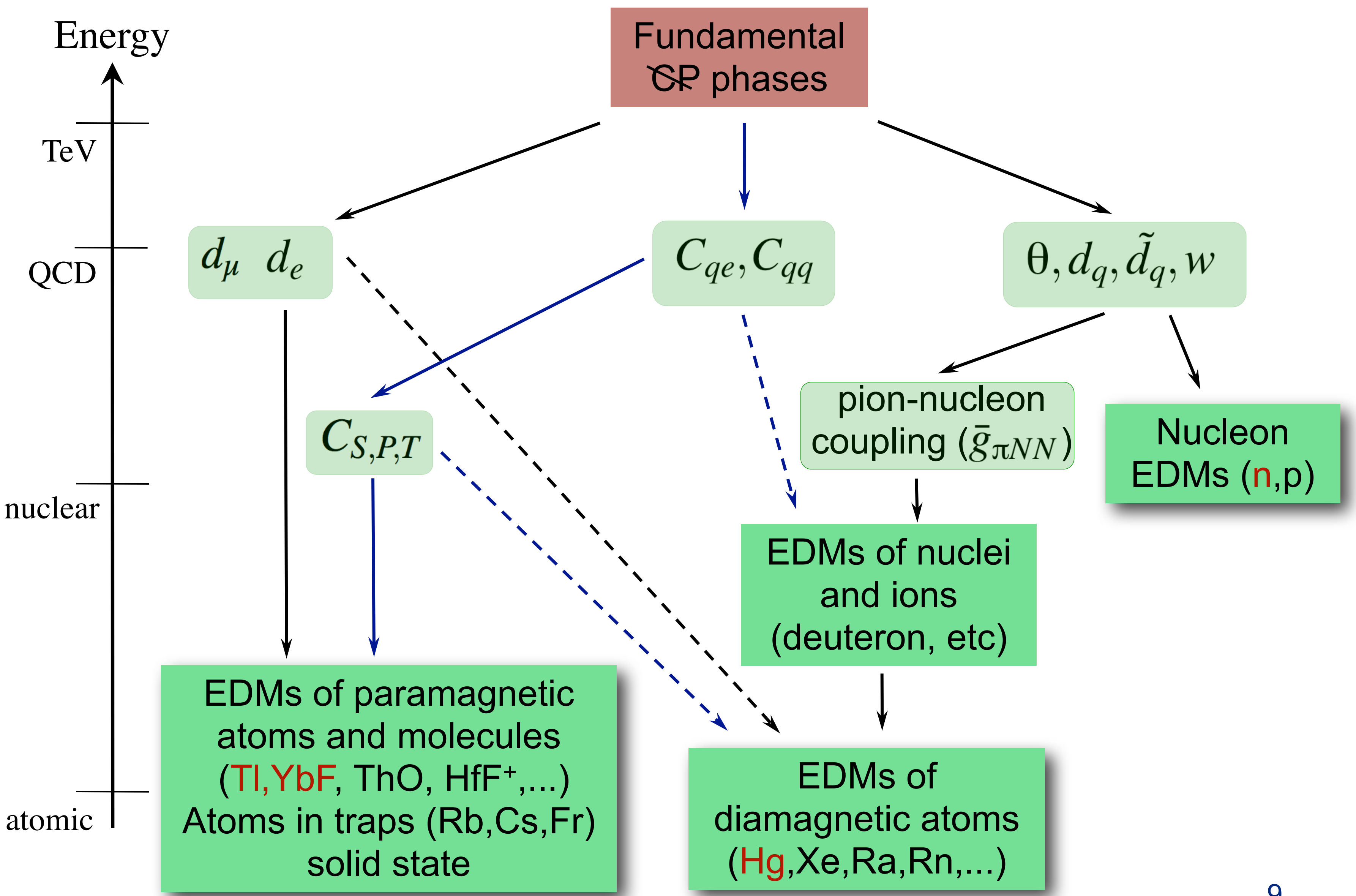
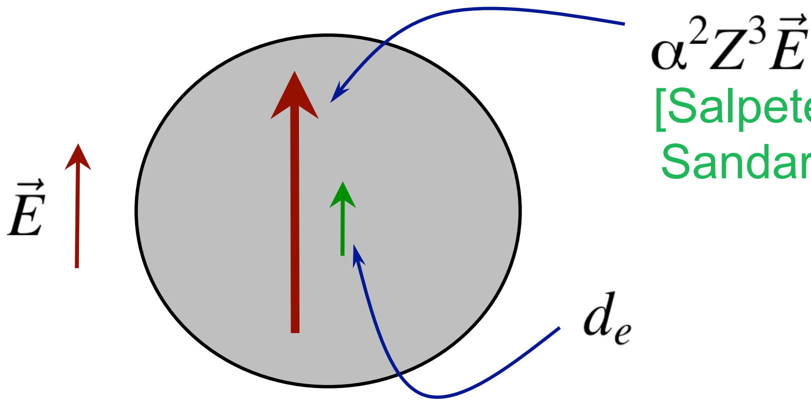
# Origin of the EDMs



# Paramagnetic EDMs - Schiff screening

## Atoms (e.g. Tl)

(relativistic violation of Schiff screening)



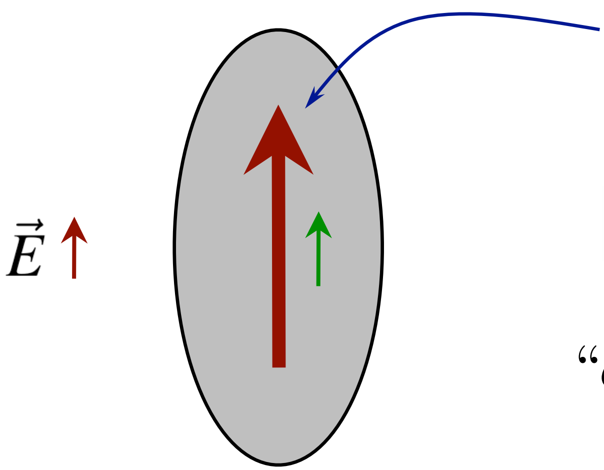

[Salpeter '58; Sandars '65]

$$d_{Tl} \sim -20\alpha^2 Z^3 d_e$$

$$20\alpha^2 Z^3 \sim \mathcal{O}(600)$$

[Liu & Kelly '92]

## Polar molecules (e.g. YbF, ThO)




$$\mathcal{E}_{eff}(E_{\text{ext}}) \sim \mathcal{O}(10^5 - 10^6) E_{\text{ext}}$$

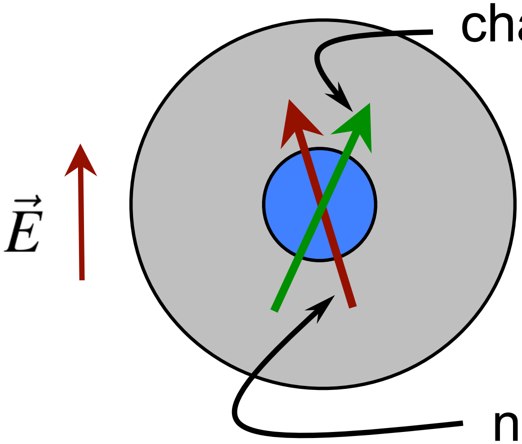
$$\Delta\omega \sim \mathcal{E}_{eff} d_e + \mathcal{O}(C_S)$$

$$\text{“}d_{YbF}\text{”} \sim 1.3 \times 10^5 d_e + \mathcal{O}(C_S)$$

[Kozlov et al. 94-98]

# Diamagnetic EDMs - Schiff screening

Atoms (e.g. Hg) (finite size violation of Schiff screening)




$$d_{Hg} \sim 10 Z^2 (R_N/R_A)^2 d_{\rm nuc}$$

$O(10^{-3})$

$$d_{Hg} \sim -3 \times 10^{-17} S\ fm^{-3} + O(d_e, C_{qq})$$ [Dzuba et al '02]

Schiff moment [Schiff '63]

- Octopole enhancements (e.g. Ra, Rn) [Holt et al, Chupp et al]
  - Schiff moment O(100-1000) larger than Hg [Flambaum et al.]

# Nuclear EDMs - avoiding Schiff screening

- Nuclear EDMs (e.g. p,D,$^3$He,...) in storage rings

[Brookhaven, Julich]

$$d_{Hg} \sim 10 Z^2 (R_N/R_A)^2 d_{\rm nuc}$$

O($10^{-3}$) suppression could be avoided with a direct measurement of the EDM. (May also be the only practical means of measuring the EDM of light atoms/nuclei.)

E.g. $$d_D = (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi NN}(\bar{\theta}, \tilde{d}_q)$$

[Lebedev, Olive, Pospelov, AR ‘04]

$$\approx -2 \times 10^{-14} \bar{g}^{(1)}_{\pi NN}\, e\text{cm} + \mathcal{O}(\bar{g}^{(0)}_{\pi NN})$$

[Khriplovich & Korkin ‘00; Liu & Timmermans ’04; de Vries et al ’11]

Extended to other light nuclei (e.g. $^3$H, $^3$He) in recent work

[Stetcu et al ’08, de Vries et al ’11]

# Computations

## 1. Tl EDM & YbF "EDM" (paramagnetic) (atomic/molecular)

$$d_{Tl} \sim -585 d_e - 2e \sum_{q=d,s,b} C_{qe}/m_q$$

$\alpha^2 Z^3$ [Liu & Kelly '92; Khatsymovsky et al. '86]

$$\Delta E_{Y_bF} = -1.5 \times 10^{10} eV \left( \frac{d_e}{e\,cm} \right) + \mathcal{O}(C_{qe})$$

Nonlinear function of $E_{ext}$ [Kozlov et al. 94-98]

## 2. neutron EDM (chiralPT, NDA, QCD sum rules, …) $\Rightarrow |\theta| < 10^{-10}$

$$d_n \sim (0.4 \pm 0.2)[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) + \cdots] + O(d_s, w, C_{qq})$$

[Pospelov & AR '99,'00]

[Recently verified by Hisano et al '12. NB: they proposed using a much larger nucleon coupling, which appears inconsistent with other sum rules, implying e.g. $\Sigma_N \sim O(10\ \mathrm{MeV})$, 4 times too small.]

## 3. Hg EDM (diamagnetic) (atomic+nuclear+QCD)

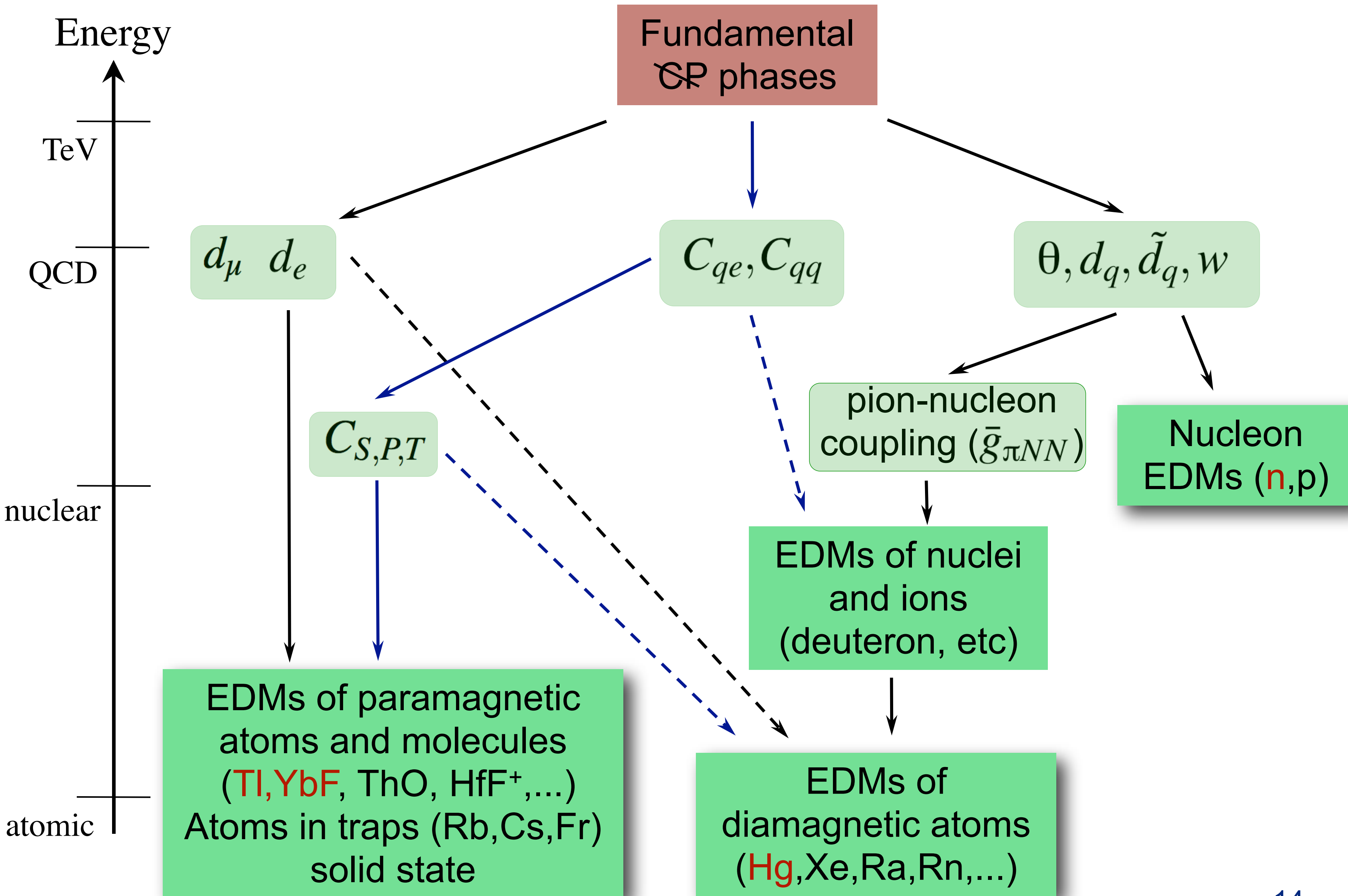
$$d_{Hg} \sim 10^{-3} d_{\rm nuc} \sim -3 \times 10^{-17} S(\bar{g}_{\pi NN}^{(0,1,2)}, d_n, d_p)\,[e\,{\rm fm}^3] + \mathcal{O}(d_e, C_{qq})$$

[Dzuba et al. '02; Flambaum et al. '86; Dmitriev & Senkov '03; de Jesus & Engel '05; Ban et al '10]

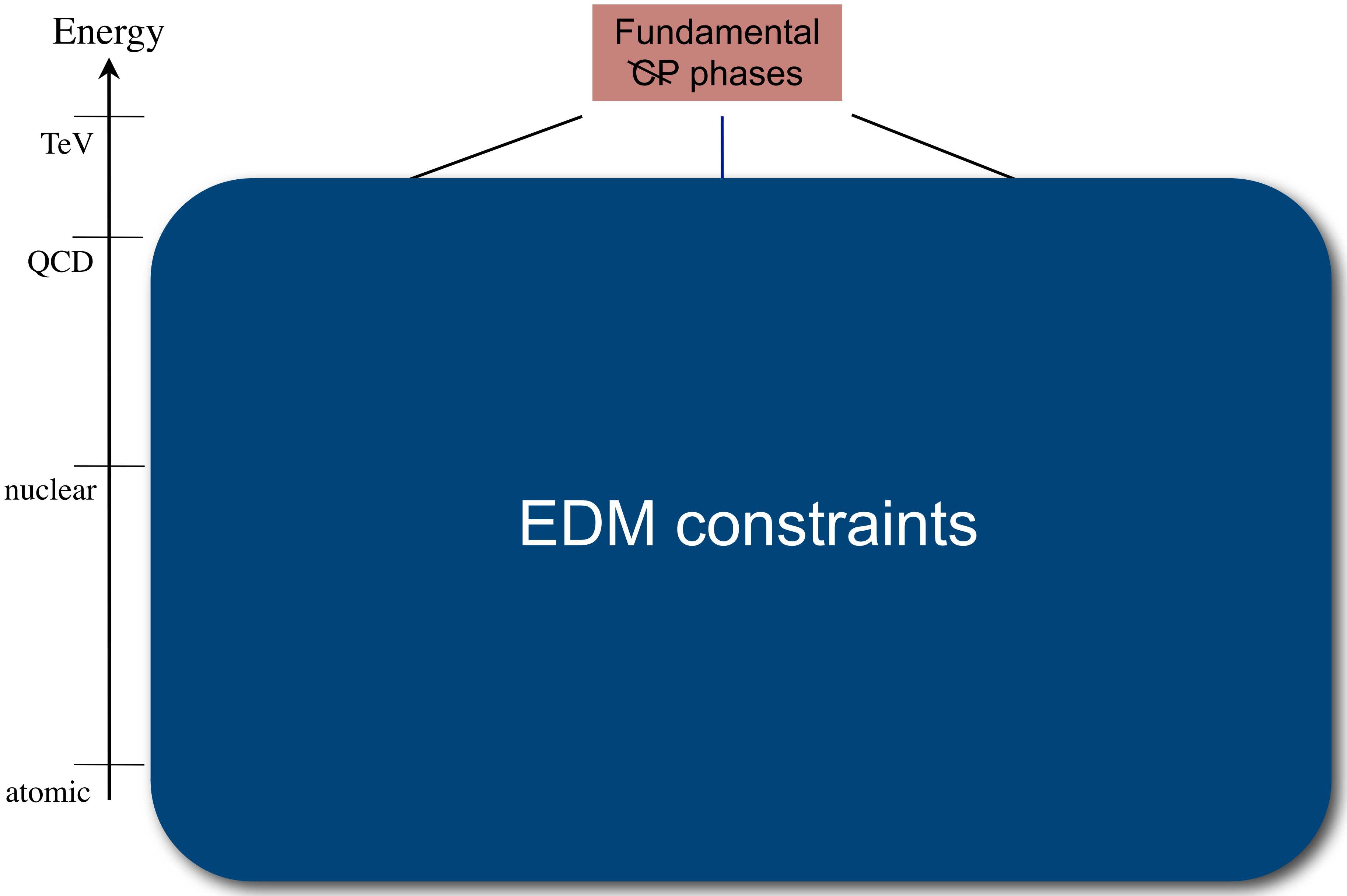
$$\bar{g}_{\pi NN}^{(1)}(\tilde{d}_q) \sim (1-6)(\tilde{d}_u - \tilde{d}_d) + O(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w)$$ [Pospelov '01]

NB: concern about precision of $S(\bar{g}_{\pi NN}^{(0)}, \bar{g}_{\pi NN}^{(1)}, \bar{g}_{\pi NN}^{(2)})$ [Ban et al '10]

# Origin of the EDMs



# Origin of the EDMs



# Resulting Bounds on fermion EDMs & CEDMs

| | |
|---|---|
| YbF EDM (±20%) | $\lvert d_e + \mathcal{O}(C_{eq}) \rvert < 1.1 \times 10^{-27} e\, cm$ |
| Tl EDM (±20%) | $\left\lvert d_e + e(26\,\mathrm{MeV})^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b}\right)\right\rvert < 1.6 \times 10^{-27} e\, cm$ |
| Neutron EDM (±50%) | $\left\lvert e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25 d_u) + O(\tilde{d}_s, w, C_{qq})\right\rvert < 2 \times 10^{-26} e\ cm$ |
| Hg EDM (±100%) | $e\lvert \tilde{d}_d - \tilde{d}_u + O(d_e, \tilde{d}_s, C_{qq}, C_{qe})\rvert < 3 \times 10^{-27} e\ cm$ |

Generic sensitivity: $d_f \sim (couplings) \times \frac{m_f}{\Lambda_{CP}^2}$

# Resulting Bounds on fermion EDMs & CEDMs

| | |
|---|---|
| TL + YbF EDM (±20%) | $|d_e| < 1.6 \times 10^{-27} e\, cm$ (even with cancelations) |
| Neutron EDM (±50%) | $\left|e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25 d_u) + O(\tilde{d}_s, w, C_{qq})\right| < 2 \times 10^{-26} e\ cm$ |
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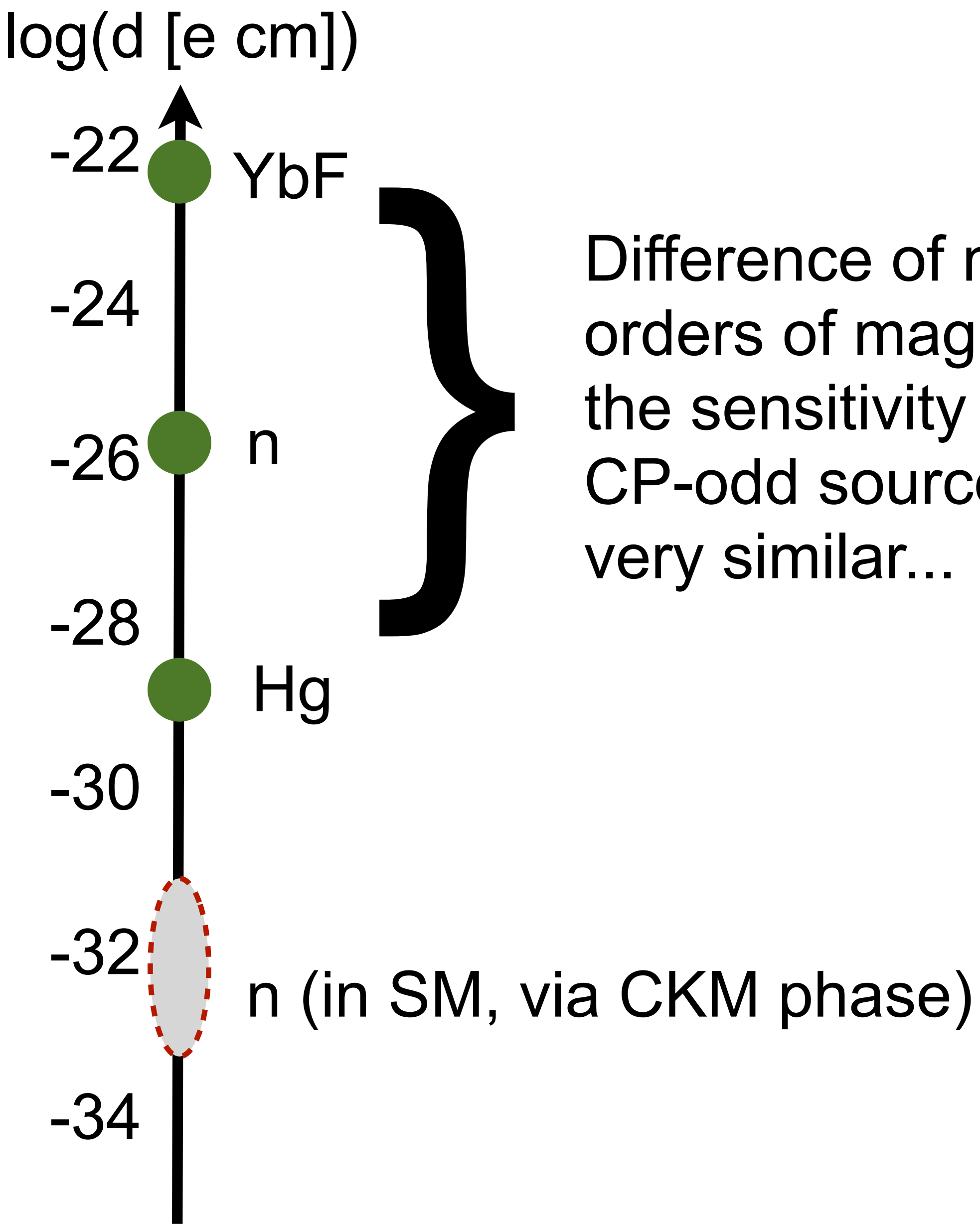
# Summary of the bounds

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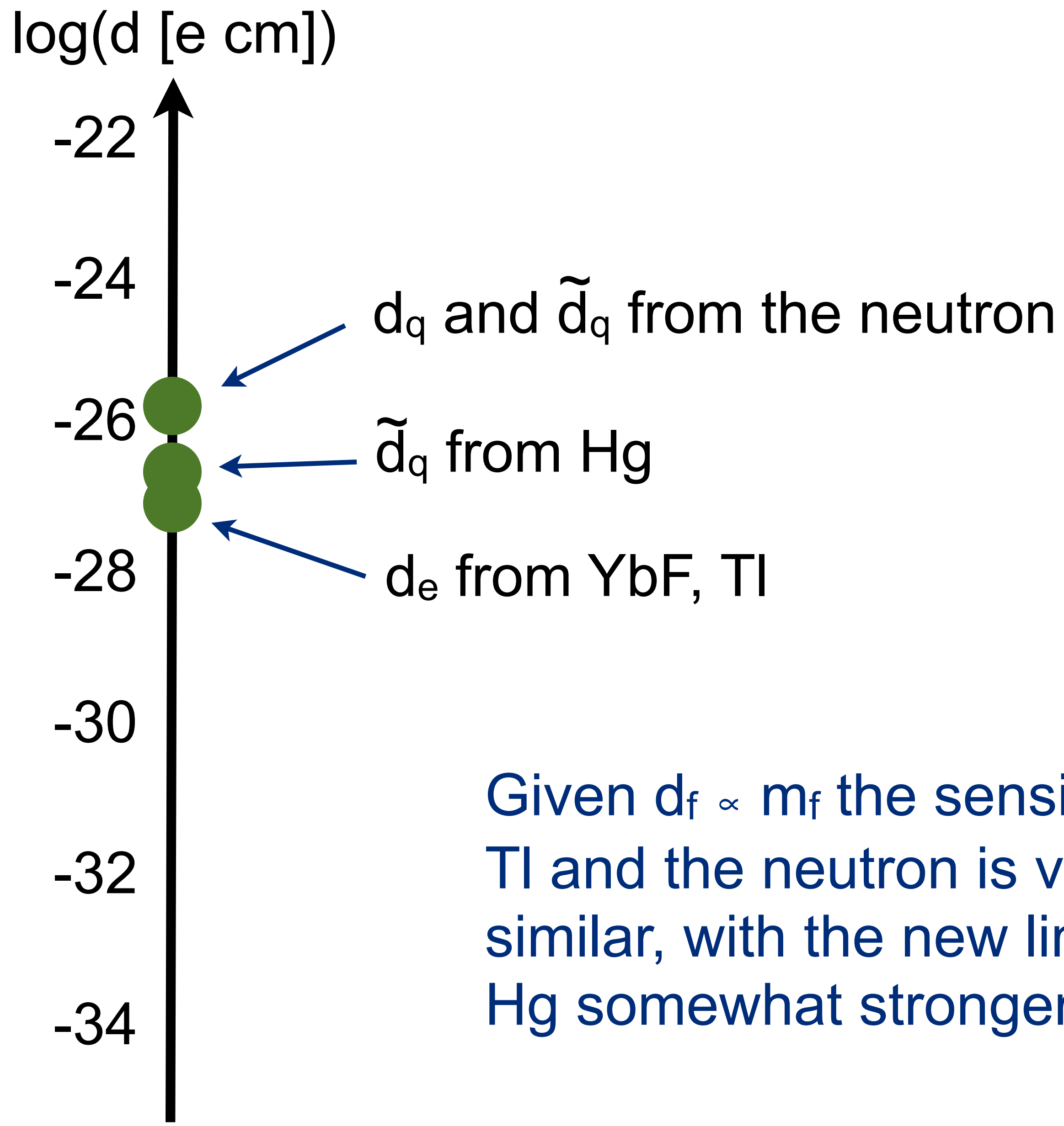
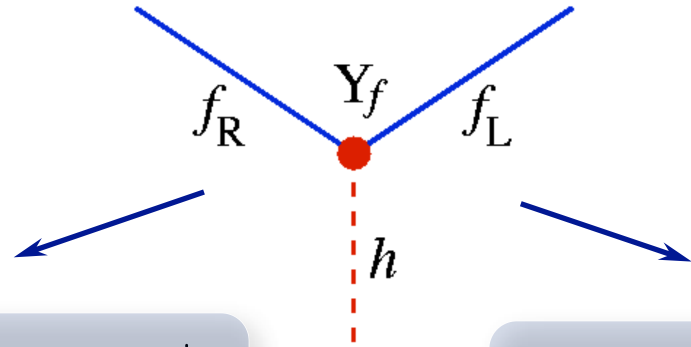



Given $d_f \propto m_f$ the sensitivity of Tl and the neutron is very similar, with the new limit from Hg somewhat stronger

# CP-violating New Physics

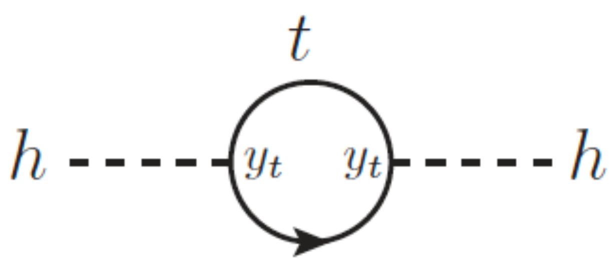
In the SM, CP-violation is associated with Yukawas...




$$\sin(\delta_{\rm KM}) \propto \text{Arg}\,\text{Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$\bar{\theta}_{\rm QCD} \sim \text{Arg}\,\text{Det}[Y_u Y_d]$$

Expectation of new EW-scale physics is primarily associated with stabilising the Higgs sector...



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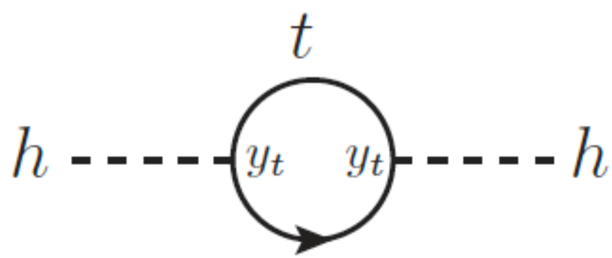



- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...

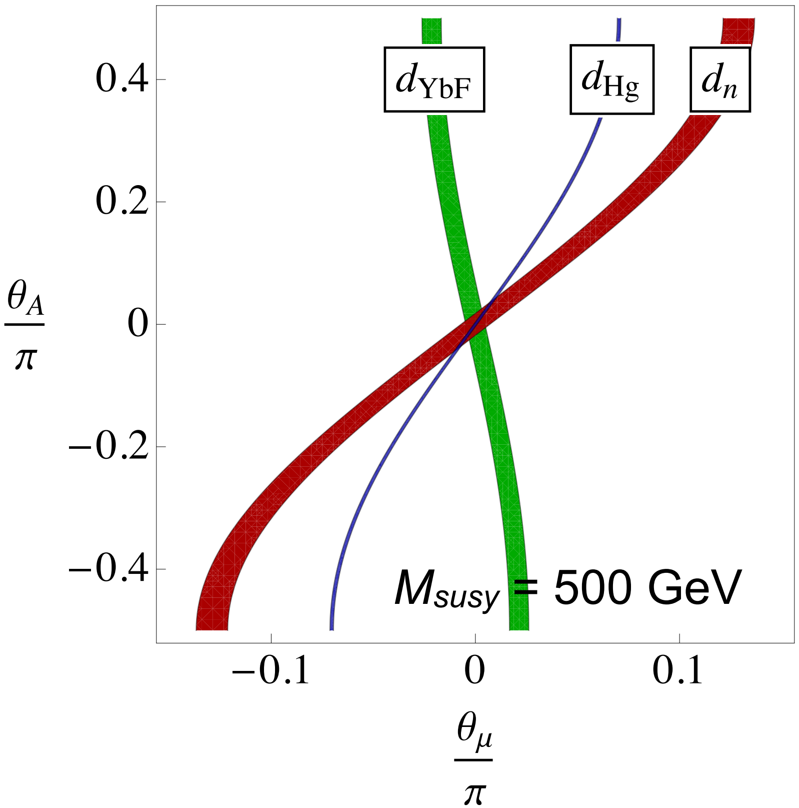
  ⇒ EDMs at 2-loops

- SUSY provides new physics with strong coupling to 1st generation

  ⇒ EDMs at 1-loop!

→ SUSY CP problem!

# SUSY CP Problem (prior to LHC)

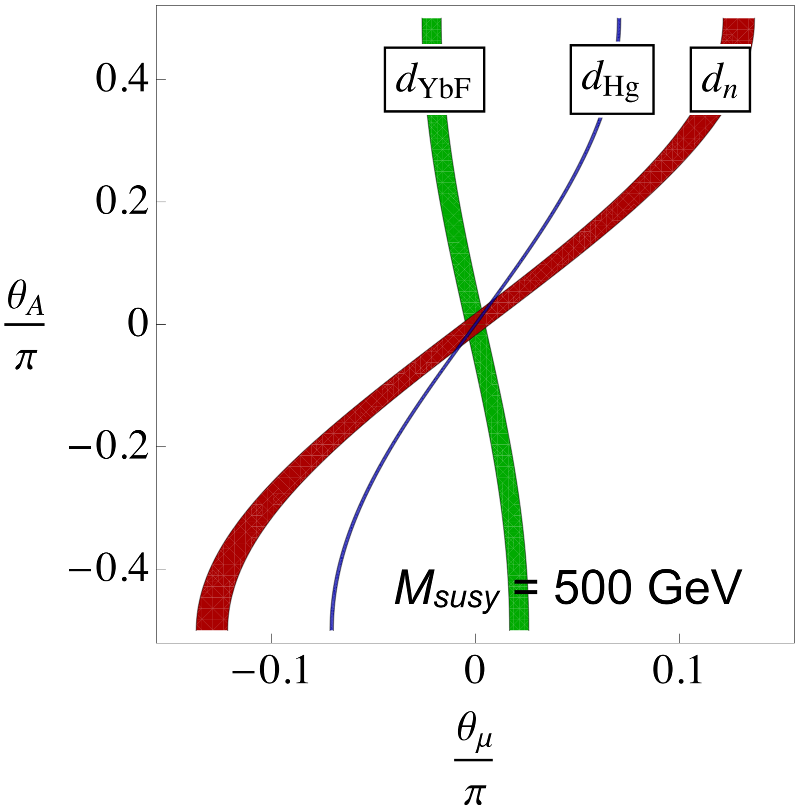



EDM bounds provide complementary constraints on SUSY CP phases

Generic Implications $\Rightarrow$ Soft CP-odd phases $O(10^{-2} - 10^{-3})$

[Some more analyses: Barger et al ’01; Abel et al ’01; Pilaftsis ’02; Olive, Pospelov, AR, Santoso ’05; Argyrou et al ’08; Ellis et al ’08; Li et al. ’10]

# SUSY CP Problem (prior to LHC)

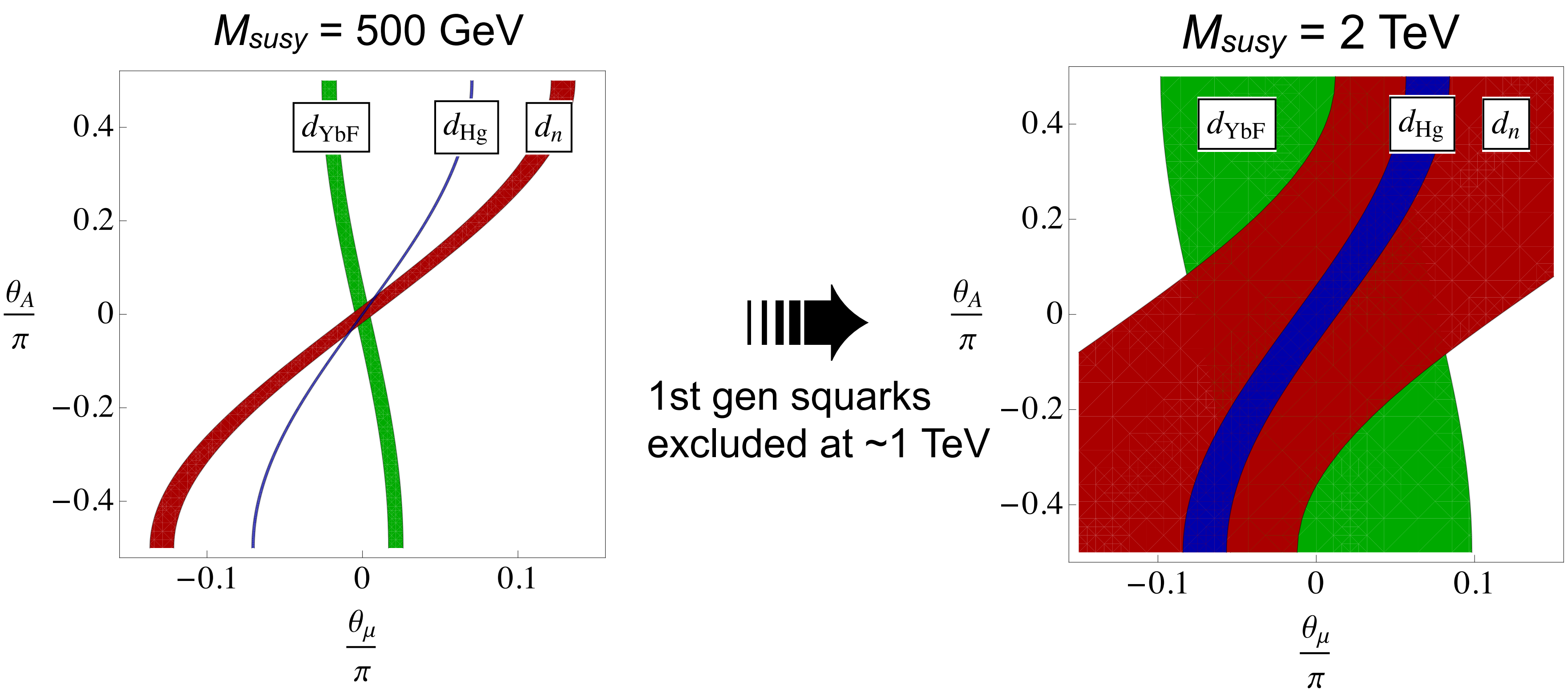



EDM bounds provide complementary constraints on SUSY CP phases

Generic Implications ⇒

- All phases small (tuned and boring)
  - problem for (EW) baryogenesis!
- Cancelations (tuned, but interesting!)
  [Ibrahim & Nath '98,...]
- Heavy 1st, 2nd generations...

# SUSY CP Problem (now...)




Generic Implications ⇒

- All phases small (tuned and boring)
  - problem for (EW) baryogenesis!
- Cancelations (tuned, but interesting!)
  [Ibrahim & Nath '98,...]

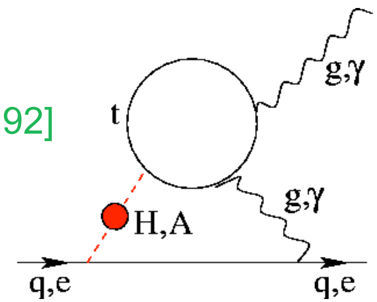
Now need

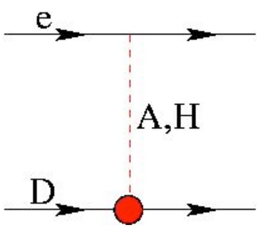
- Heavy 1st, 2nd generations...

# Generic 2-loop Sensitivity to O(1) phases

Extended
Higgs sector

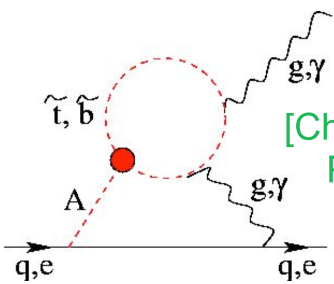
[Barr, Zee ‘92]



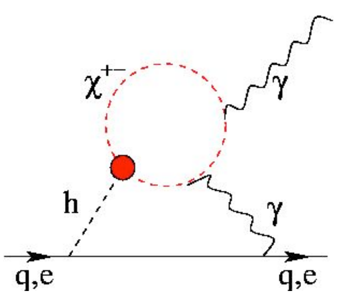




[Barr ‘92; Lebedev & Pospelov ‘02]

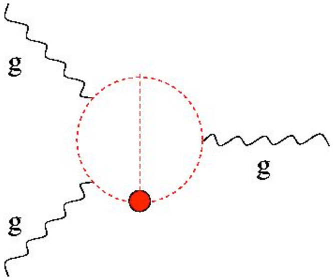
EW-scale new
physics
(e.g. MSSM)




[Chang, Keung & Pilaftsis ‘98]

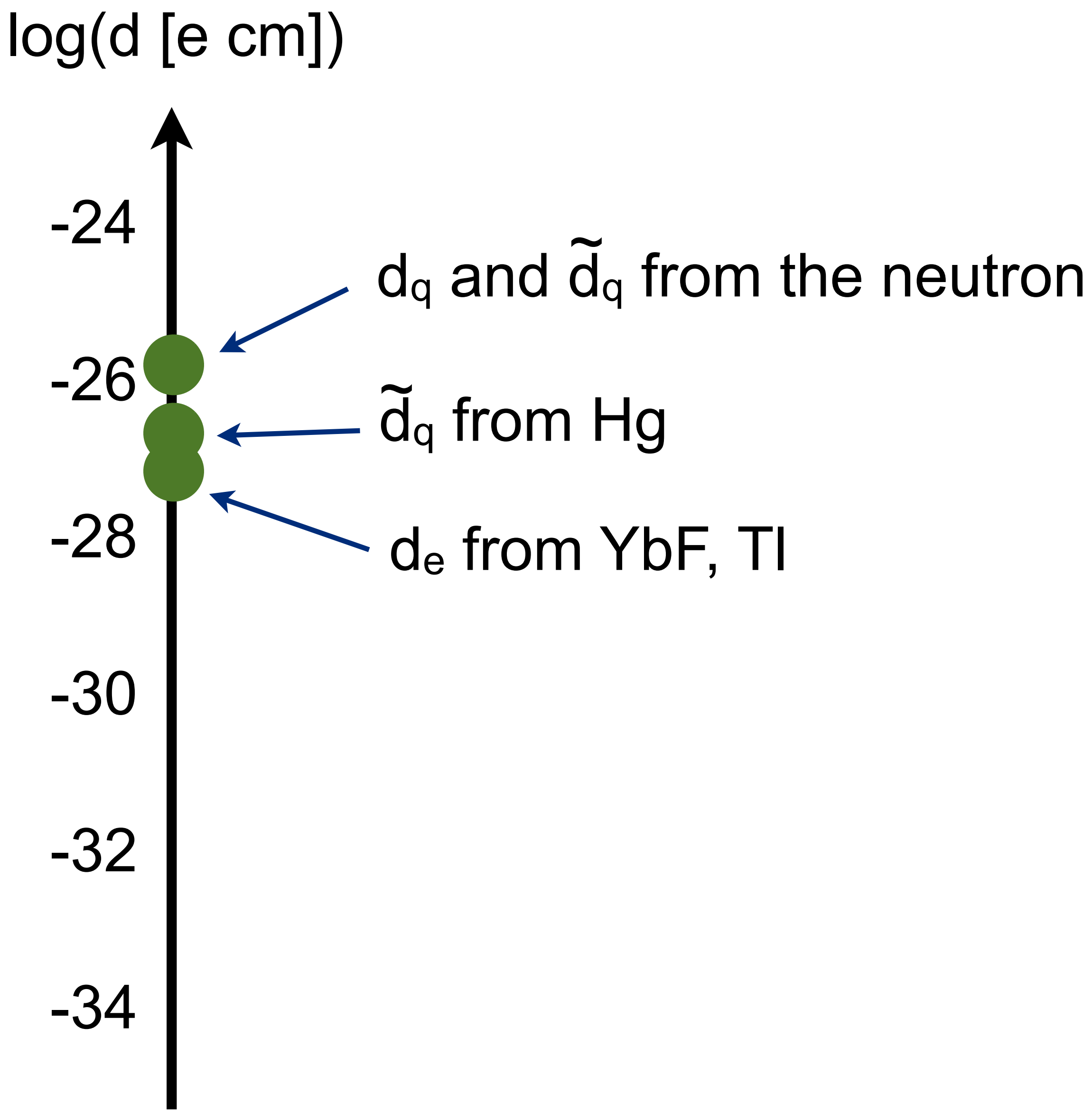



“Natural” new physics
coupled to Higgs and
3rd generation




[Weinberg ‘89; Dai et al. 90]

# Generic Sensitivity at 2-loops



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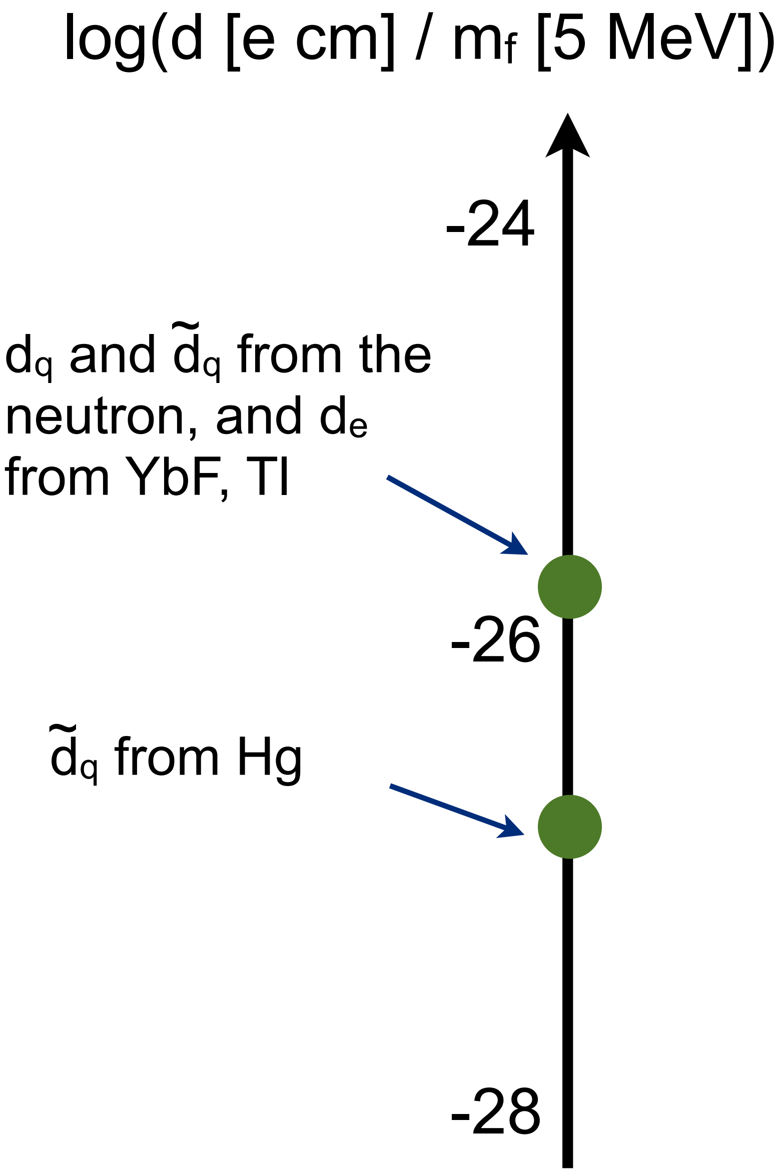

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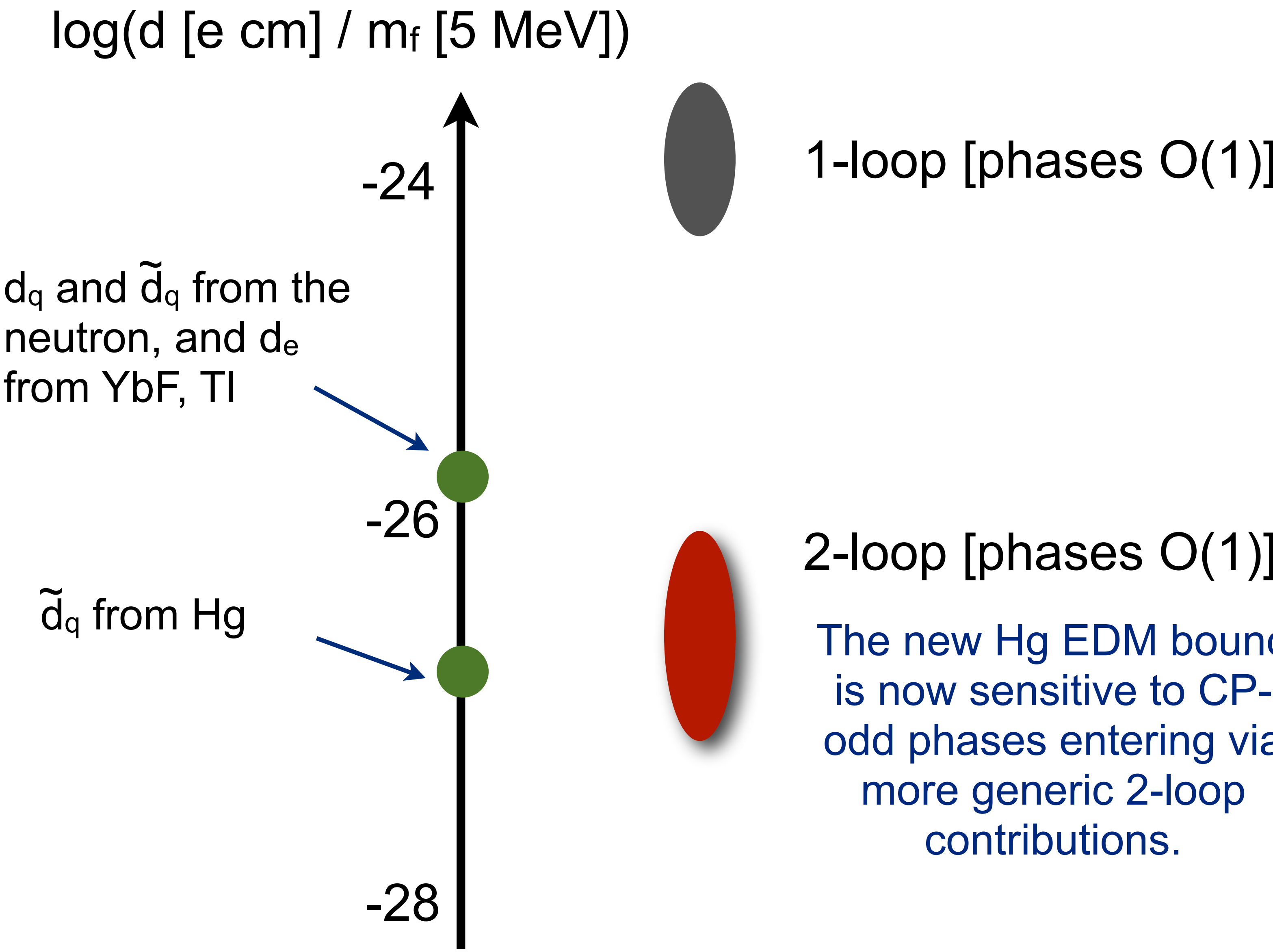
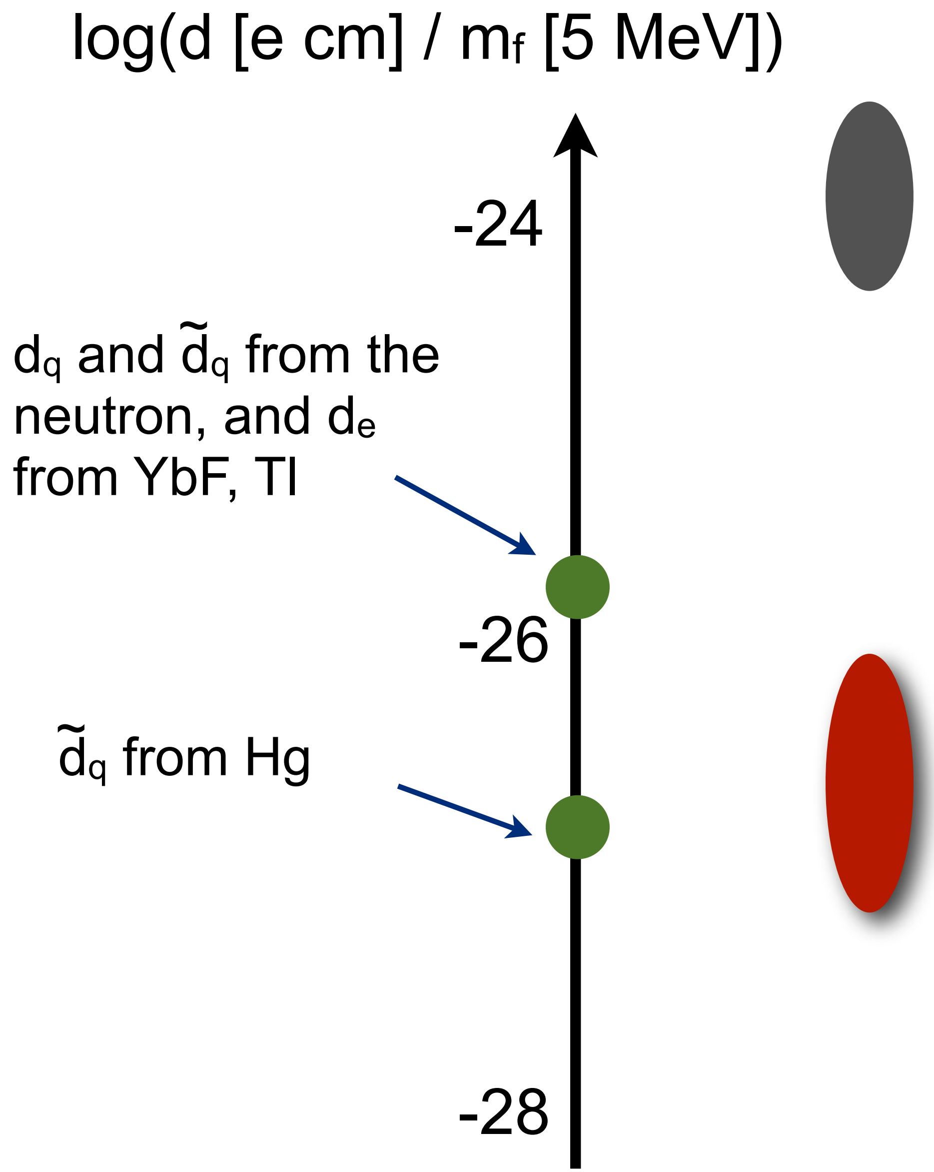
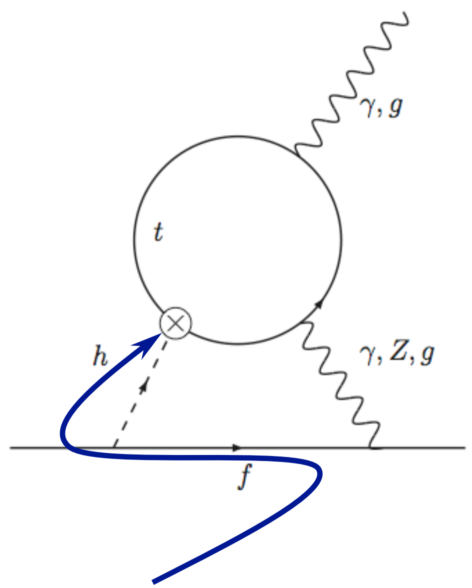



The new Hg EDM bound is now sensitive to CP-odd phases entering via more generic 2-loop contributions.

# Generic Sensitivity at 2-loops




E.g. CP-odd top-Higgs coupling

[Huber, Pospelov, AR '06 ]

# Concluding Remarks

Ongoing progress in EDM searches continues to provide important guidance and constraints on new physics

- The SUSY CP problem hinted at by (1-loop) EDMs for more than 20 years has been confirmed by the LHC.
- Naturalness suggests that generic EW-scale new physics should couple to the Higgs/3rd generation. This is now being probed by (2-loop) EDMs via the current Hg EDM limit.

⬇

- Full suite of next-generation EDM experiments will probe generic 2-loop Higgs-mediated (EW scale) contributions
- Interplay with LHC explorations of the EWSB and the Higgs sector.