EDMs and Nucleon Matrix Elements

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Based on the reviews

M. Pospelov & AR, Ann. Phys. 318, 119 (2005) [hep-ph/0504231]

M. Pospelov & AR, in *Lepton Dipole Moments*, ed. Roberts & Marciano

Experimental EDM Limits

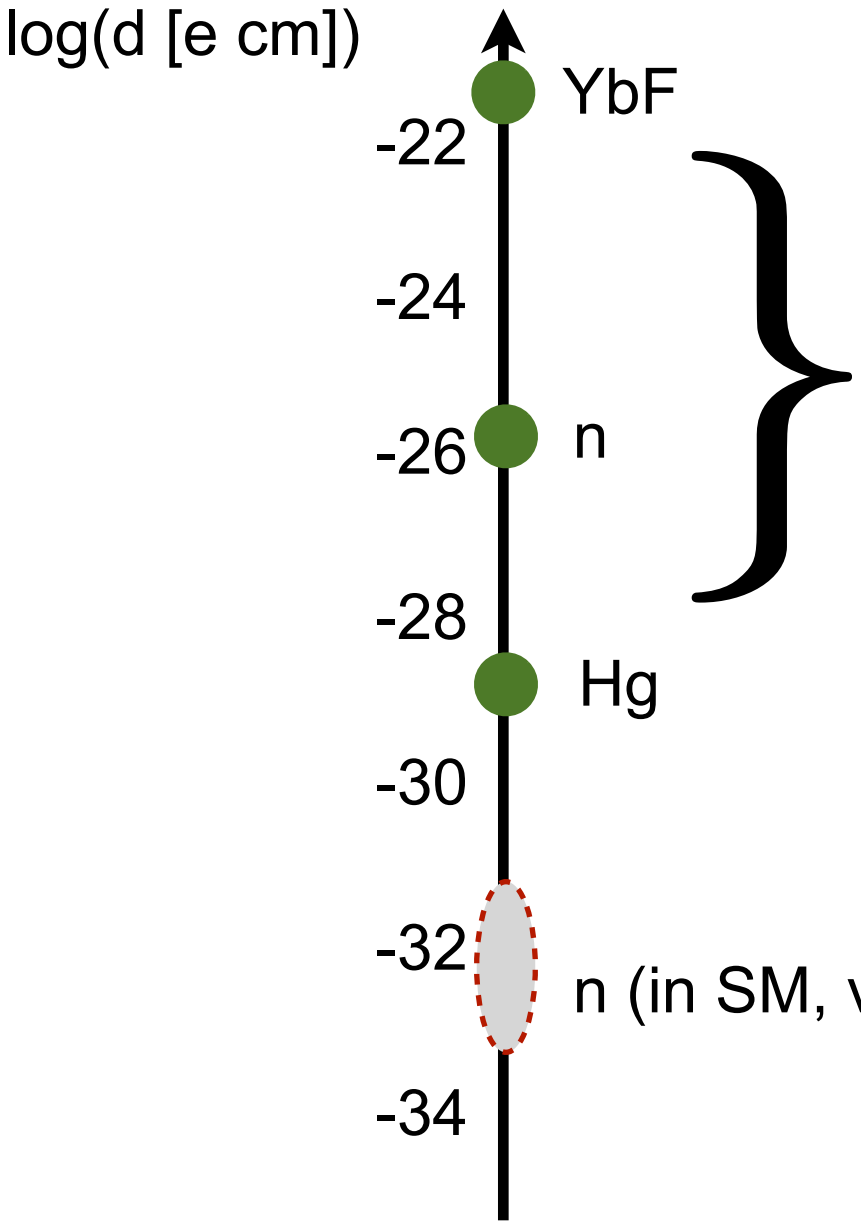
$$H = -d\vec{E} \cdot \frac{\vec{S}}{S}$$

- EDMs are powerful (amplitude-level) probes for new (T,P) violating sources, motivated e.g. by baryogenesis.
- Best current limits from neutrons, para- and dia-magnetic atoms and molecules

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)	$\lvert \text{"}d_{YbF}\text{"} \rvert < 1.4 \times 10^{-21} e\ \text{cm}$	[Hudson et al. '11]
Mercury EDM (diamagnetic)	$\lvert d_{Hg} \rvert < 3 \times 10^{-29} e\ cm$	[Griffith et al. '09]

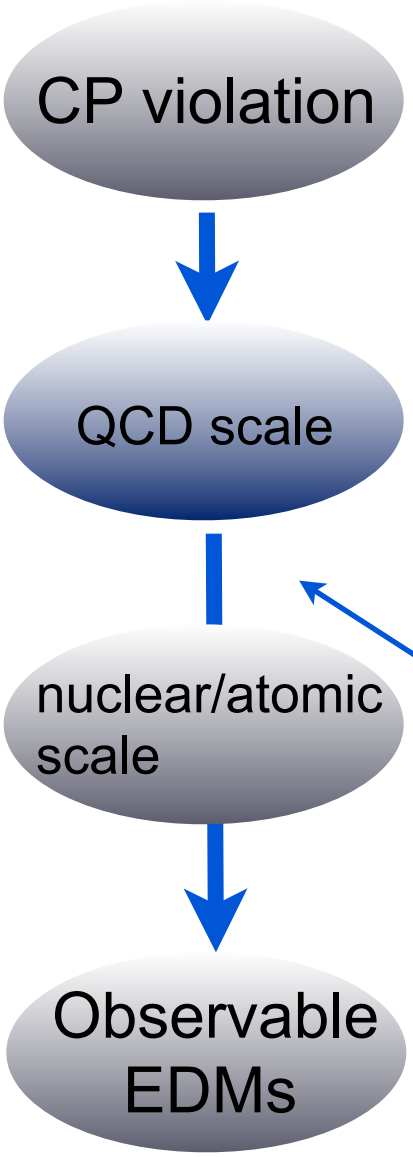
SM background from CKM phase is down by O(10^5-10^8) in each case, due to mixing angles and Yukawa couplings (Jarlskog invariant)

Schematic view of the bounds



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

Plan



- Review of CP-odd operator expansion at 1GeV [induced by UV sources of CP violation]
- Overview of the dependence of observable EDMs on nuclear parameters
- Focus on the computation of nucleon matrix elements

CP-odd operator expansion (at ~1GeV)

(Flavor-diagonal) CP-violating operators at ~1GeV

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$\mathcal{L}_{\dim 4} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\bar{\theta} = \theta_0 - \text{ArgDet}(M_u M_d) \equiv \theta_0 - \theta_q$$

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$$\mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s G\tilde{G}$$

$$d_i \sim c Y_i \frac{v}{\Lambda^2}$$

$$\mathcal{L}_{\text{“dim 6”}} \supset \sum_{q=u,d,s} \left(d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$$

$$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G} + \sum_{q,\Gamma} C_{qq} (\bar{q}\Gamma q)_{LL} (\bar{q}\Gamma q)_{RR}$$

$$C \sim \frac{c}{\Lambda^2}$$

but requires “RH currents”

[➠ talk by S. Tulin]

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$$C_{ij} \sim c Y_i Y_j \frac{v^2}{\Lambda^4}$$

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(Flavor-diagonal) CP-violating operators at ~1GeV

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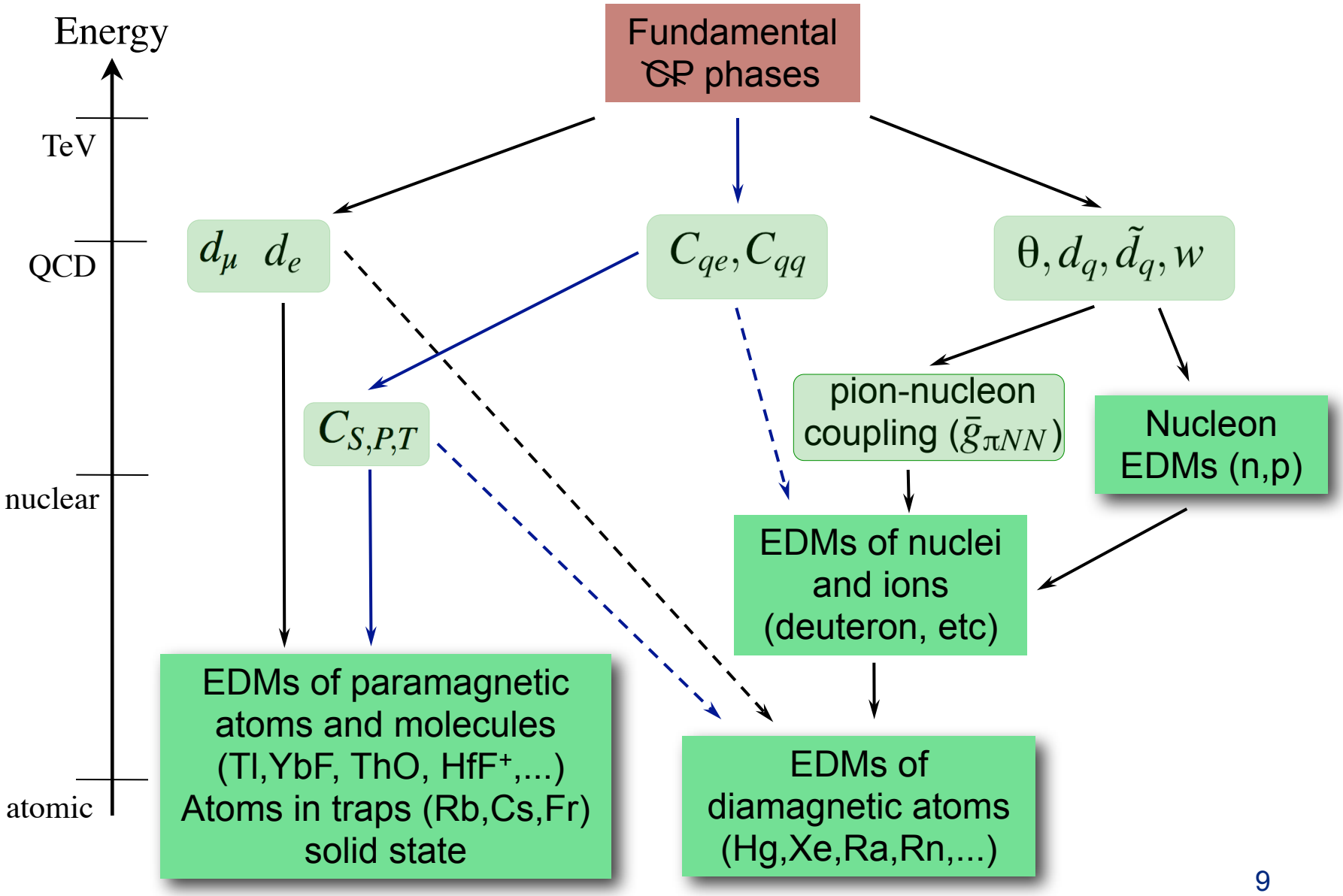
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$$C_S \bar{N} N \bar{e} i\gamma_5 e + \cdots$$

EFT hierarchy

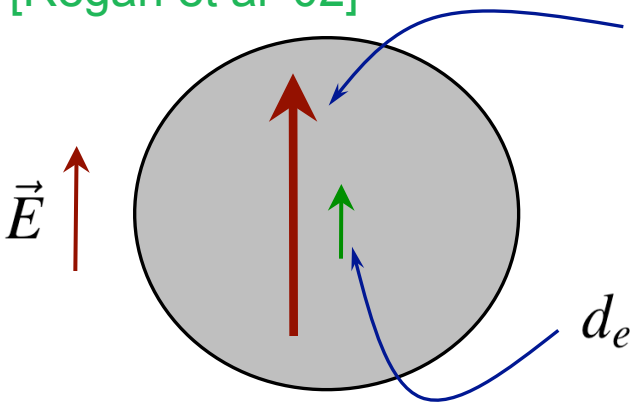


Paramagnetic EDMs - “Schiff enhancement”

Atoms (e.g. Tl [Berkeley])

[Regan et al ’02]

(relativistic violation of Schiff screening)



$\alpha^2 Z^3 \vec{E}$

[Salpeter ‘58; Sandars ‘65]

≈ 585 [Liu & Kelly ’92]

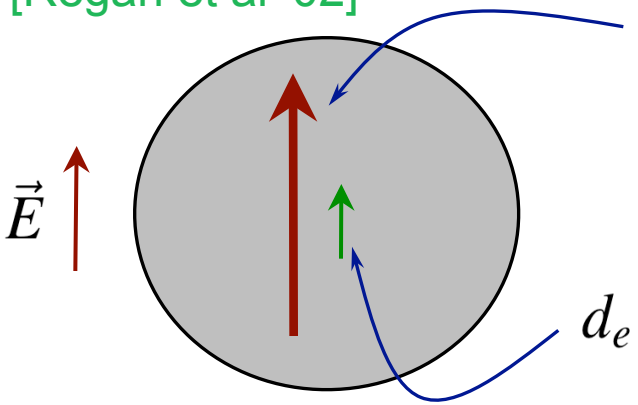
$$d_{Tl} \sim -20\alpha^2 Z^3 d_e + \mathcal{O}(C_S)$$

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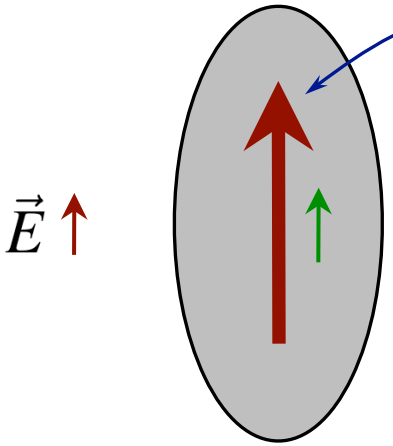
$\alpha^2 Z^3 \vec{E}$ [Salpeter ‘58; Sandars ‘65]

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$$d_{Tl} \sim -20\alpha^2 Z^3 d_e + \mathcal{O}(C_S)$$

Polar molecules (e.g. YbF [Imperial]) [also ThO [Harvard/Yale]]

[Hudson et al ’11]



Nonlinear function of E_{ext}

$$\Delta E_{\mathrm{YbF}} \sim \mathcal{E}_{\mathrm{eff}}(E_{\mathrm{ext}}) d_e + \mathcal{O}(C_S)$$

$$\text{“}d_{\mathrm{YbF}}\text{”} \sim 10\alpha^2 Z^3 \frac{M_{\mathrm{mol}}}{m_e} d_e + \mathcal{O}(C_S)$$

[Sushkov & Flambaum, ’78]

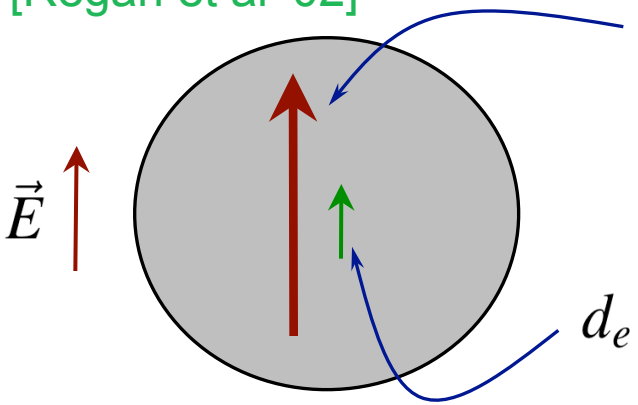
[➠ talk by J. Sapirstein]

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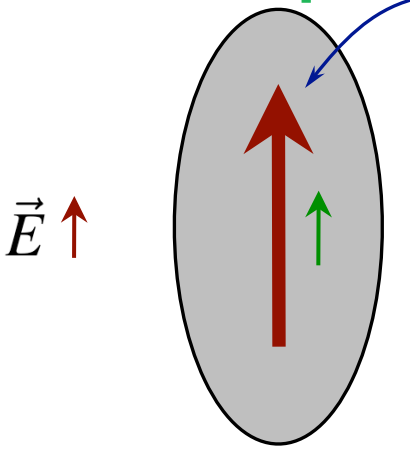
$$d_{\mathrm{Tl}} \sim -585 d_e - e\,(43\,\mathrm{GeV}) C_S^{(0)}(C_{qe}) + \cdots$$

[Liu & Kelly ’92]

[Bouchiat ‘75; Khatsymovsky et al. ‘86]

Polar molecules (e.g. YbF [Imperial]) [also ThO [Harvard/Yale]]

[Hudson et al ’11]



$\mathcal{E}_{\mathrm{eff}}(E_{\mathrm{ext}})$

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

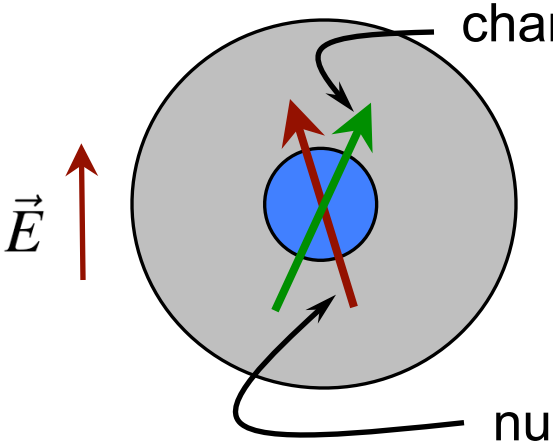
$$\text{“}d_{YbF}\text{”} \sim 1.4 \times 10^6 d_e + \mathcal{O}(C_S)$$

[Kozlov et al. 94-98]

Diamagnetic EDMs - “Schiff suppression”

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

[Griffith et al ’09]



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

$O(10^{-3})$

$$d_{\rm Hg} \sim -3 \times 10^{-17} S[e\,{\rm fm}^2] + \mathcal{O}(d_e, C_{qe}, C_{qq})$$

Schiff moment

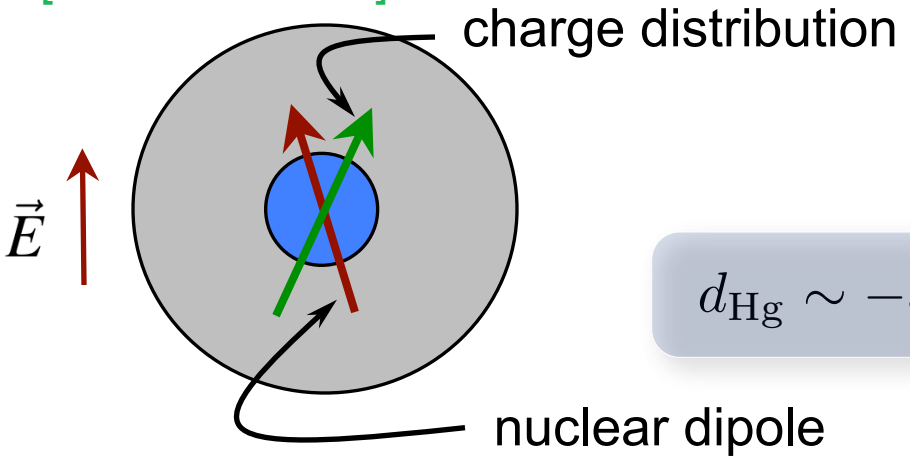
[Schiff ‘63]

[Flambaum et al ’86; Dzuba et al. ’02]

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Schiff moment [Schiff ‘63]

$$S = S(\bar{g}^{(i)}_{\pi NN}, d_N, ...)$$

$$\sim -0.06 g_{\pi NN} \bar{g}^{(1)}_{\pi NN}\ {\rm fm}^3 + \cdots$$

[Flambaum et al. ‘86; Dmitriev & Senkov ‘03; de Jesus & Engel ’05; Ban et al ‘10]

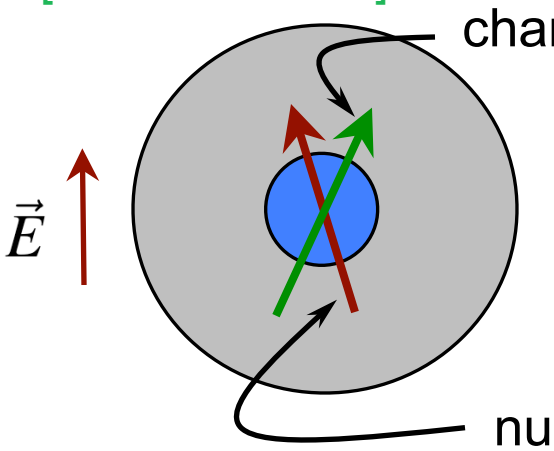
NB: concern about precision [Ban et al ’10]

[➠ talk by J. Engel]

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NB: concern about precision [Ban et al '10]

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

Nuclear EDMs - avoiding Schiff screening

- Neutron EDM [...., Sussex/ILL, PSI, ORNL, Osaka/TRIUMF]
- 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 nuclear EDM.

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

via η-π mixing

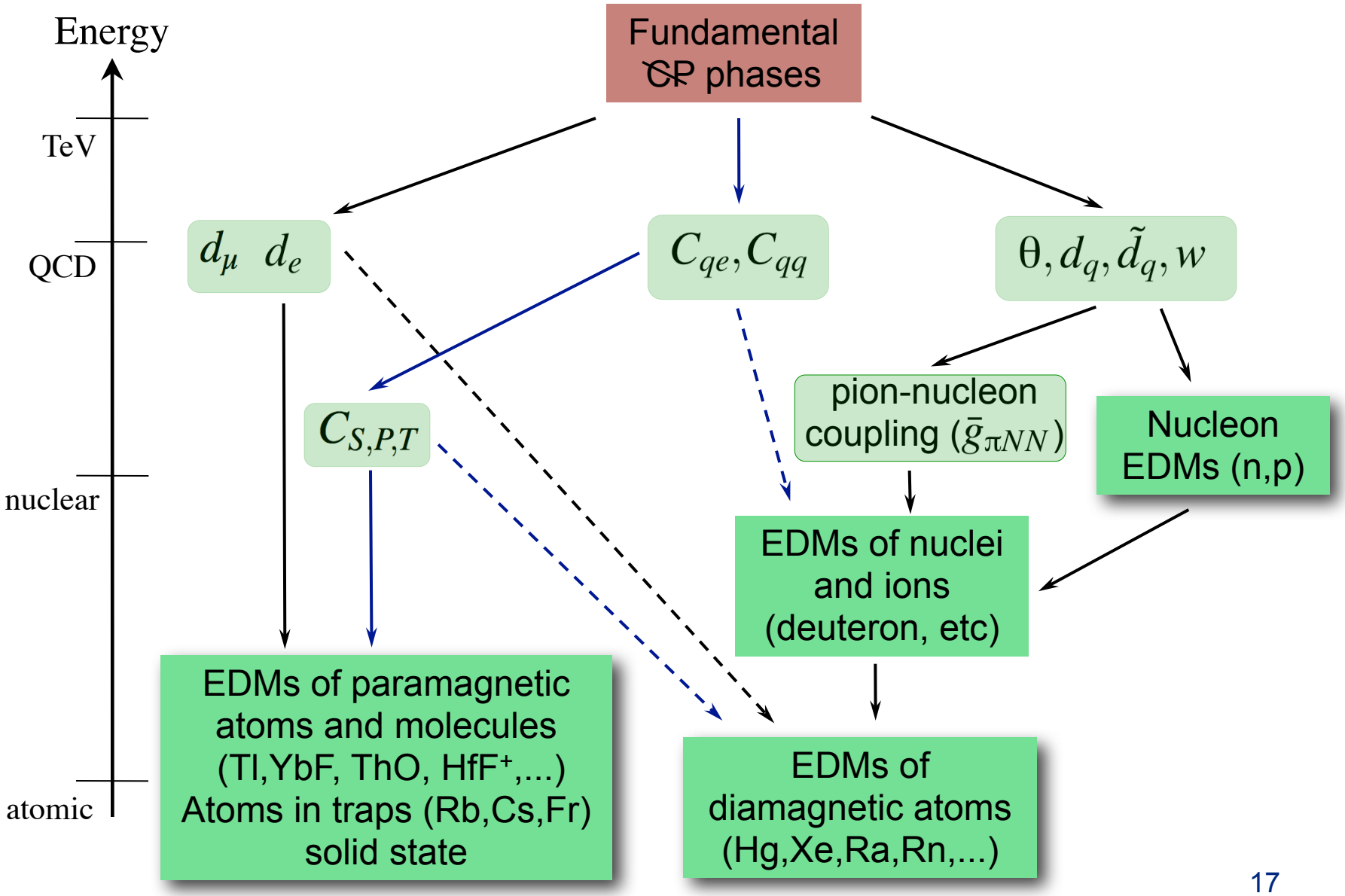
$$\approx -2 \times 10^{-14} \bar{g}^{(1)}_{\pi NN}(\bar{\theta}, \tilde{d}_q) e\,{\rm cm} + \mathcal{O}(\bar{g}^{(0)}_{\pi NN})$$

[Lebedev, Olive, Pospelov, AR '04]
[Khriplovich & Korkin '00; Liu & Timmermans '04; de Vries et al '11]

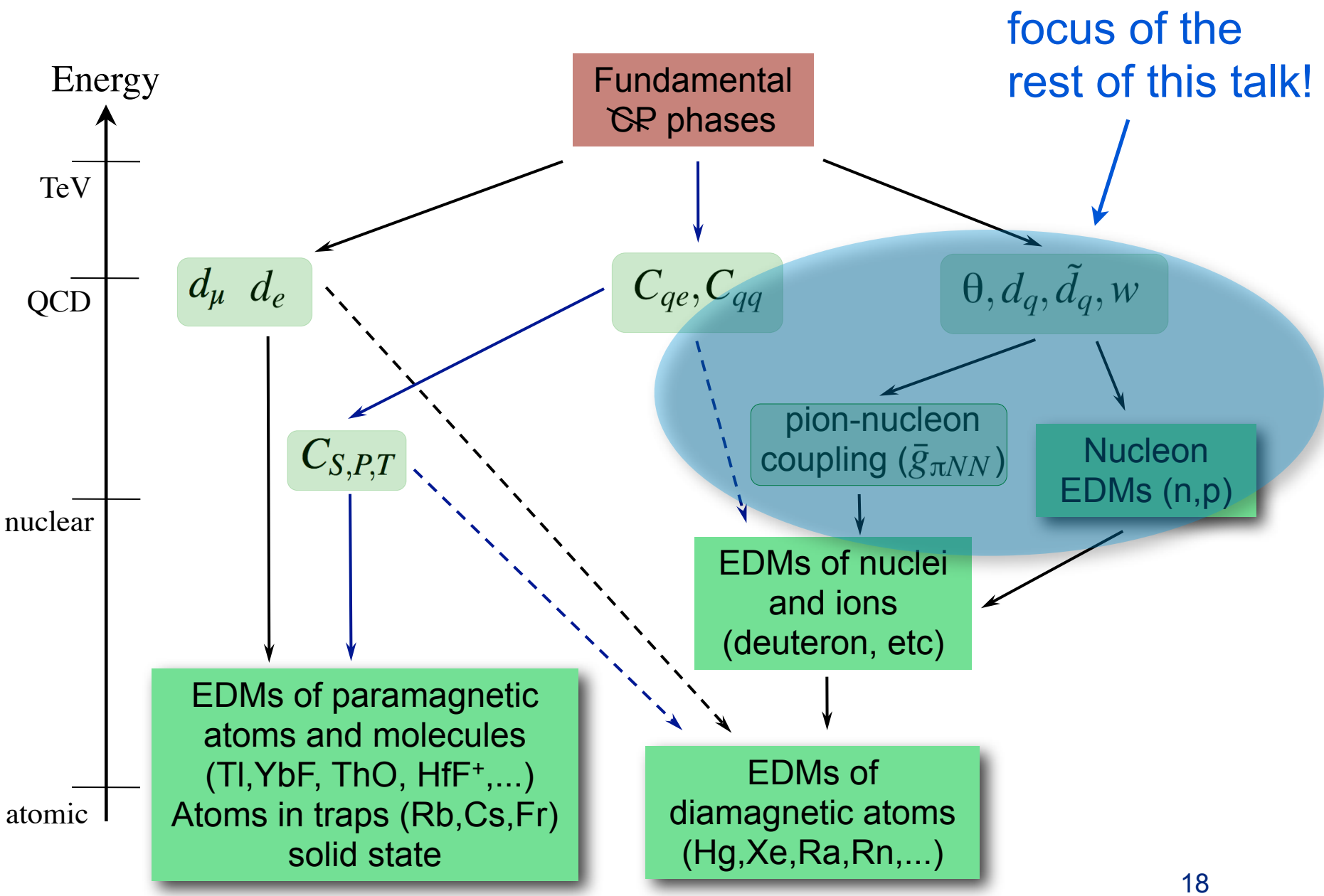
Also extended to other light nuclei (e.g. ^{3}H, ^{3}He) in recent work
[Stetcu et al '08, de Vries et al '11]

[➠ talk by E. Mereghetti]

EFT hierarchy



EFT hierarchy



The QCD scale

- Chiral EFT

$$\mathcal{L} = \mathcal{L}(\pi, (K), N, \cdots)$$

$$= -\frac{i}{2}\bar{N}(d_n\tau^- + d_p\tau^+)F\sigma\gamma_5 N - \bar{N}(\bar{g}^{(0)}_{\pi NN}\tau^a\pi^a + \bar{g}^{(1)}_{\pi NN}\pi^0)N + \cdots$$

low energy constants

$$\begin{cases} d_N(\bar{\theta}, d_q, \tilde{d}_q, w, C_{ij}, \ldots) \\ \bar{g}^{(0,1)}_{\pi NN}(\bar{\theta}, \tilde{d}_q, C_{ij}, \ldots) \end{cases}$$

- continuing development of CP-odd structure

[Crewther, Di Vecchia, Veneziano & Witten ‘79]

[Hisano & Shimizu ’04]

[Stetcu et al ’08, de Vries et al ‘11,12]

[An, Ji and Xu ’12]

[Guo & Meissner ’12]

[➠ talks by M. Ramsey-Musolf, E. Mereghetti]

The QCD scale

- Chiral EFT

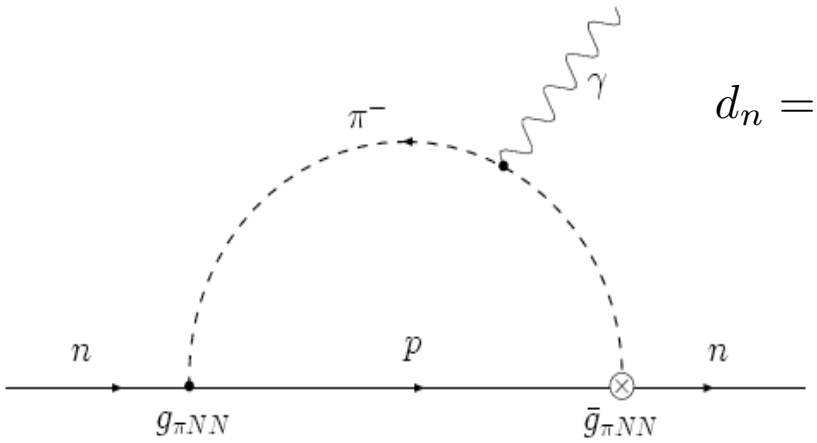
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low energy constants

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- LEC's related by loop corrections
  - e.g. chiral logarithm [Crewther, Di Vecchia, Veneziano & Witten '79]



unknown threshold corrections

$$d_n = \frac{e}{4\pi^2 m_n} g_{\pi NN}\bar{g}^{(0)}_{\pi NN} \ln\frac{\Lambda}{m_\pi} + C_{\rm ct}$$

$$\bar{g}^{(0)}_{\pi NN}(\theta_q) \sim \frac{\theta_q m_*}{f_\pi}\langle p|\bar{q}\tau^3 q|p\rangle$$

$$|\theta| < 10^{-9}$$ (in 1979)

[also Baluni '79]

The QCD scale

- Chiral EFT

$$\mathcal{L} = \mathcal{L}(\pi, (K), N, \cdots)$$

$$= -\frac{i}{2}\bar{N}(d_n\tau^- + d_p\tau^+)F\sigma\gamma_5 N - \bar{N}(\bar{g}^{(0)}_{\pi NN}\tau^a\pi^a + \bar{g}^{(1)}_{\pi NN}\pi^0)N + \cdots$$

low energy constants

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- LEC's related by loop corrections
  - e.g. chiral logarithm [Crewther, Di Vecchia, Veneziano & Witten '79]
- Difficult to compute the dependence on many CP-odd sources (other than θ)
  - need extra input to fix LECs, including counterterms

[
- NDA
- QCD sum rules
- Lattice QCD (➠ talk by T. Izubuchi)
]

Nucleon Matrix Elements

Focussing on the parameters that are (usually) the most important for hadronic EDMs:

$$d_{n,p}(\bar{\theta}, d_q, \tilde{d}_q, w, C_{ij}, \ldots),\ \bar{g}^{(0,1)}_{\pi NN}(\bar{\theta}, \tilde{d}_q, w, C_{ij}, \ldots),\ \cdots$$

NDA estimates (with $\Lambda_{\rm had}/f_\pi \sim g_s(\mu) \sim 4\pi$, $m_{q,\,\rm av} \sim m_\pi^2/\Lambda_{\rm had}$):

	θ_q	d_q	$\tilde{d}_q$
d_n	$\dfrac{e m_q}{\Lambda_{\rm had}^2}$	$\mathcal{O}(1)$	$\dfrac{e g_s}{4\pi}$
$\bar{g}^{(0)}_{\pi NN}$	$\dfrac{m_q}{f_\pi}$	$\sim \mathcal{O}(\alpha)$	$\dfrac{\Lambda_{\rm had}^2}{f_\pi}$

cf. naive SU(6) Quark Model: $d_n(d_q) = \dfrac{4}{3} d_d - \dfrac{1}{3} d_u$

(CP-odd) QCD sum rules

- Consider the two-point function of the nucleon interpolating current in the presence of CP-odd sources

$$\int d^4x e^{ip\cdot x}\langle \bar{j}_n(x), j_n(0)\rangle_{\not{C}P,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p)F_{\mu\nu} + \cdots$$

- Notes:
  - multiple interpolating currents with lowest dimension

$$j_n = 2\epsilon_{abc}(d_a^T C\gamma_5 u_b)d_c + \beta \times 2\epsilon_{abc}(d_a^T C u_b)\gamma_5 d_c$$

unphysical parameter

  - CP mixing (and chiral WI)

$$\langle 0|j_n|n\rangle = (\lambda_1 + \beta\lambda_2)e^{i\alpha\gamma_5/2}v$$

CP-odd sources render the current chirally variant, and able to mix with CP-conjugate currents

$$\tilde{j}_n = CPj_nCP$$

(CP-odd) QCD sum rules

- Approach:
  - work in a general basis of CP sources, as a cross-check
  - isolate EDM from a chirally-invariant structure

$$\Pi_1(p)\cdot F \sim \{F\sigma\gamma_5, \not{p}\}\left(\frac{d_n\lambda^2 m_n}{(p^2-m_n^2)^2}+\frac{A}{p^2-m_n^2}+\cdots\right)+\cdots$$

independent of α (avoids mixing of d and μ structures)

  - account for current mixing explicitly, to linear order in the CP sources

$$j_n \to j_n + i\epsilon_{\rm CP}\tilde{j}_n$$

  - fit for the EDM, using other CP-even sum rules to determine $\{m_n,\lambda,A\}$

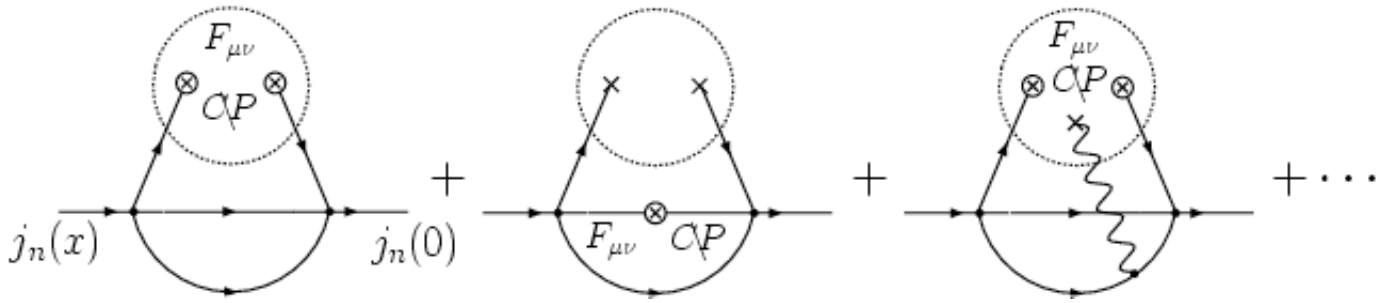
$\lambda_1+\beta\lambda_2$ choose β to "optimize convergence" of the OPE

Neutron EDM

- schematic structure of the OPE [Pospelov & AR '99-'00]

$$\int d^4x e^{ip\cdot x}\langle \bar{j}_n(x), j_n(0)\rangle_{\not{C}P,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p)F_{\mu\nu} + \cdots$$

$$\Pi_1(p)\cdot F \sim \{F\sigma\gamma_5, \not{p}\}\left(\frac{d_n\lambda^2 m_n}{(p^2-m_n^2)^2} + \frac{A}{p^2-m_n^2} + \cdots\right) + \cdots$$



- depends on vacuum condensates, e.g. $\langle\bar{q}\sigma_{\mu\nu}q\rangle_F = \chi e_q F_{\mu\nu}\langle\bar{q}q\rangle$
  $\langle\bar{q}G\sigma q\rangle = -m_0^2\langle\bar{q}q\rangle$
- implicit dependence of condensates on the CP-odd sources determined via χPT, and saturation with π and η exchange.
  (vacuum "realignment")

Neutron EDM

- Results:

$$d_n(\bar{\theta}) = (1 \pm 0.5)\frac{|\langle \bar{q}q \rangle|}{(225\,\mathrm{MeV})^3}\,\bar{\theta} \times 2.5 \times 10^{-16} e\,\mathrm{cm}$$

- If the axion relaxes θ, the CEDM sources shift the minimum of the axion potential V(θ) away from zero

$$\theta_{ind} = \frac{1}{2} m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}$$

$$d_n = (0.4 \pm 0.2)\frac{|\langle \bar{q}q \rangle|}{(225\ MeV)^3}\left[4d_d - d_u + \frac{1}{2}\chi m_0^2 (4e_d\tilde{d}_d - e_u\tilde{d}_u) + \cdots\right] + O(d_s, w, C_{qq})$$

$$2.7e(\tilde{d}_d + 0.5\tilde{d}_u)$$ [Pospelov & AR '99,'00]

Sensitive only to ratios of light quark masses
(via GMOR relation, given $d_q \sim m_q$ etc.)

- at this order, s-quark CEDM contribution cancels under axion relaxation

Neutron EDM

- Precision?
  - numerical coefficients are consistent with NDA, NQM (for d_q), and the chiral log (for θ)
  - another test for $d_n(d_q)$ via (LQCD) nucleon tensor charge

[e.g. Falk et al '99]

$$\langle N|\frac{1}{2}d_q\bar{q}\tilde{F}\sigma q|N\rangle = \frac{1}{2}d_q\tilde{F}^{\mu\nu}\langle N|\sigma_{\mu\nu}|N\rangle = \frac{1}{2}g_T^q d_q \bar{N}\tilde{F}\sigma N$$

$$\Longrightarrow d_n(d_q) = g_T^d(1\,\mathrm{GeV})d_d + g_T^u(1\,\mathrm{GeV})d_u \sim 1.1d_d - 0.25d_u$$

inserting LQCD results
(15% larger than at 2 GeV)

[Hagler '09; Bhattacharya et al '11]

Neutron EDM

- Precision?
  - numerical coefficients are consistent with NDA, NQM (for d_q), and the chiral log (for θ)
  - another test for $d_n(d_q)$ via (LQCD) nucleon tensor charge

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  - sum-rules fixes ($d_n \sim \langle qq\rangle/\lambda^2$), so the normalization of the coupling matters

$$\lambda \sim 0.025\,\mathrm{GeV}^3$$

from analysis of CP-even sum rules for m_n, sigma term, etc (or lattice result for tensor charge above)

[Pospelov & AR '99,'00]

$$\lambda \sim 0.044 \pm 0.01\,\mathrm{GeV}^3$$

from LQCD [Aoki et al '08] run down from 2 GeV, *BUT* $\langle qq\rangle$ is also larger with LQCD values for m_q

[Hisano et al '12, Fuyuto et al '12]

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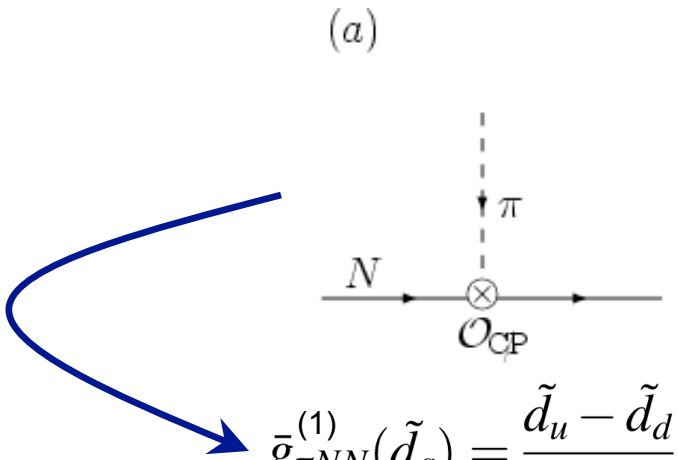
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  - higher order dependence on s-quark EDM?

Pion-nucleon couplings

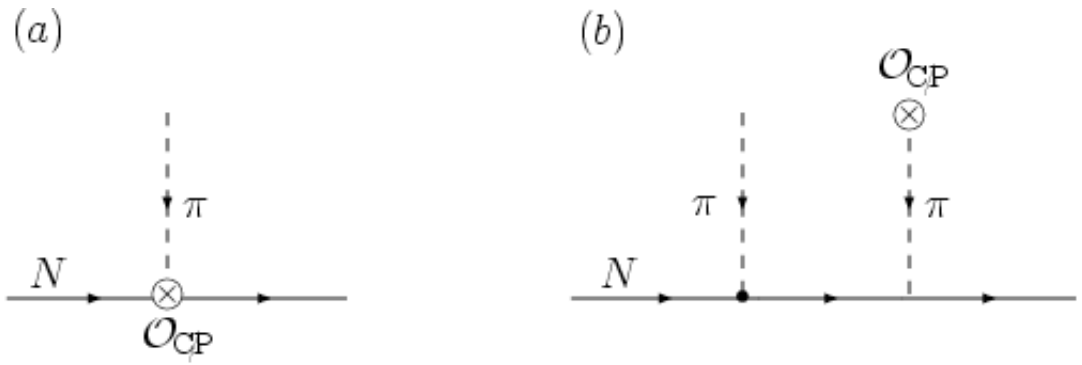
- Can follow a similar approach for the pion-nucleon couplings
  - focus on the isovector coupling [Pospelov '01]



$$\bar{g}^{(1)}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2 f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q} g_s G \sigma q \right| N \right\rangle + \cdots$$

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Pion-nucleon couplings

- Using QCD sum rules

$$\int d^4x e^{ip\cdot x}\langle \bar{j}_n(x), j_n(0)\rangle_{\tilde{d}_q H_q} \sim \not{p}\left(\frac{2\lambda^2 \bar{g}_{\pi NN} m_N}{(p^2-m_N^2)^2} + \frac{A}{p^2-m_N^2} + \cdots\right) + \cdots$$

chirally invariant

$$\bar{g}^{(1)}_{\pi NN}(\tilde{d}_q) \sim (2 \leftrightarrow 12)\text{GeV}\frac{|\langle\bar{q}q\rangle|}{(225\,\text{MeV})^3}(\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_s, w)$$

$$\bar{g}^{(0)}_{\pi NN}(\tilde{d}_q) \sim (-1 \leftrightarrow 3)\text{GeV}\frac{|\langle\bar{q}q\rangle|}{(225\,\text{MeV})^3}(\tilde{d}_u + \tilde{d}_d) + \mathcal{O}(\tilde{d}_s, w)$$

[Pospelov '01]

NB: larger errors due to cancelations between the direct and rescattering terms

Pion-nucleon couplings

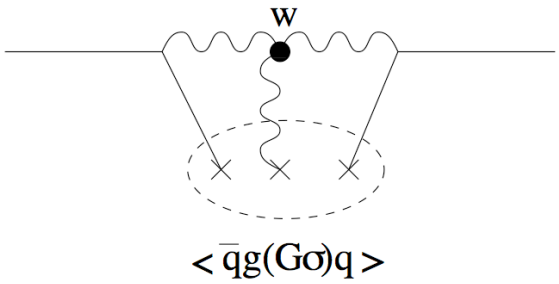
- Precision?
  - normalization again consistent with NDA, but the errors are larger due to cancelations

    [result slightly smaller than estimates using LETs: Falk et al ‘99; Hisano & Shimizu ‘04]

  - smaller result for the isoscalar coupling, covers a range including 0!
  - dependence on quark EDMs suppressed by α_{em}

Further operators

- Weinberg operator:



[Demir, Pospelov, AR '02]

$\bar{g}^{(1)}_{\pi NN} = \bar{g}^{(1)}_{\pi NN}(w)$ suppressed by light quark masses

- 4-quark (factorizable) operators:

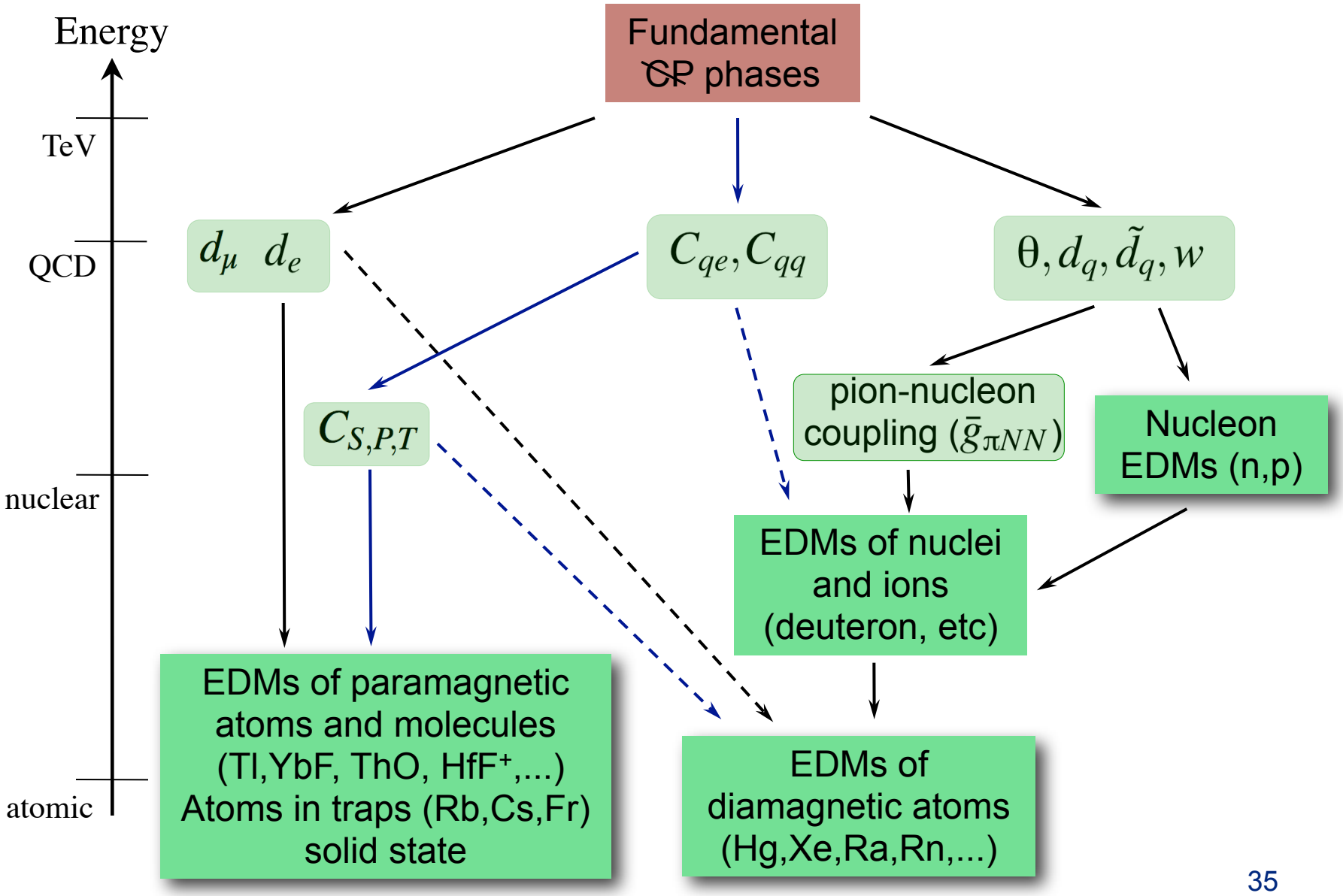
$d_n(C_{qq}) \sim ({\rm few}) \times 10^{-2}\,{\rm GeV}\, C_{qq}$

[Khatsimovsky et al '88; Hamzaoui & Pospelov '99; An, Ji & Xu '09]

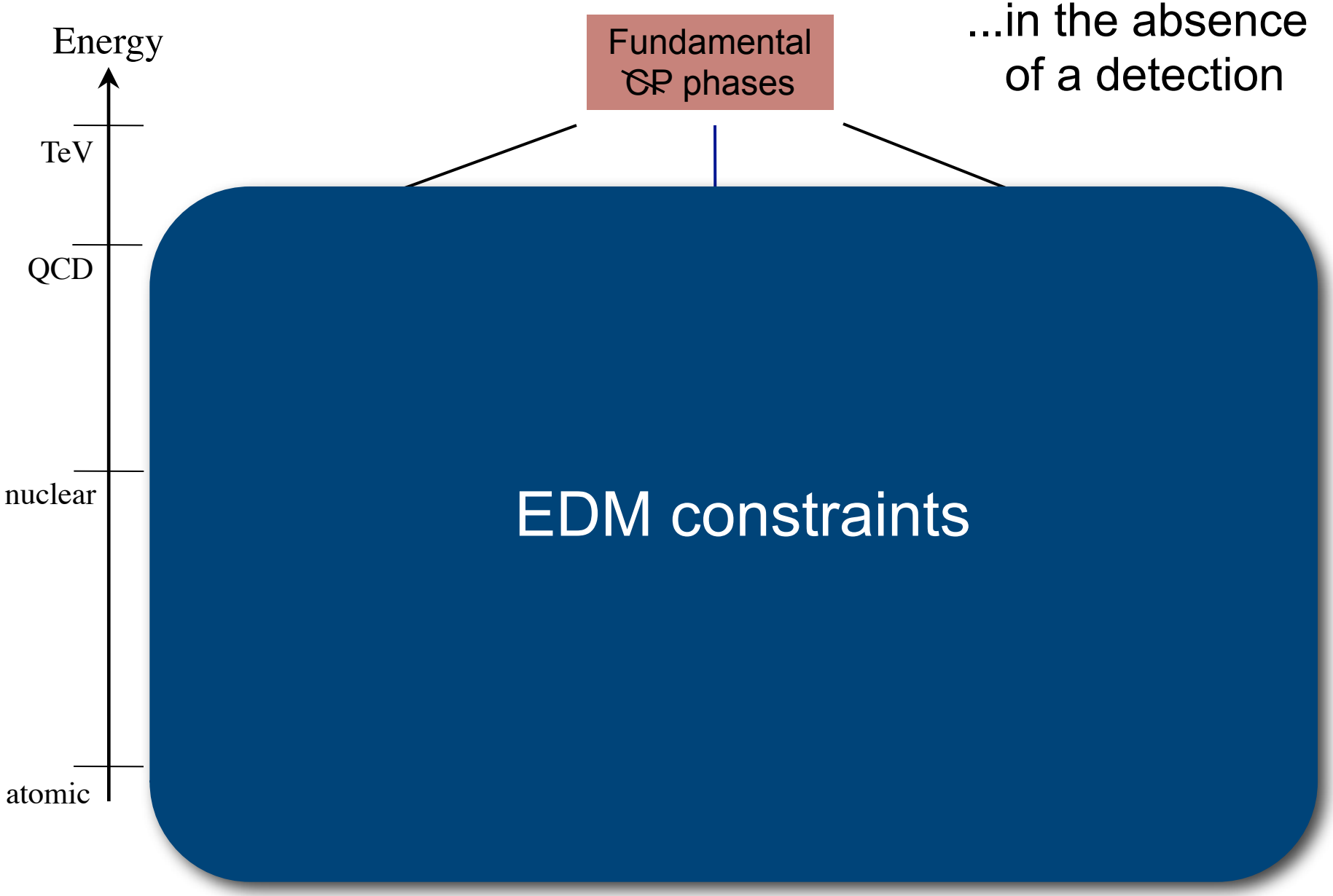
$\bar{g}^{(1)}_{\pi NN}(C_{ij}) = C_{ij} \frac{\langle q_i \bar{q}_i\rangle}{2 f_\pi} \langle N|q_j \bar{q}_j|N\rangle$

via PCAC, vacuum saturation

EFT hierarchy



EFT hierarchy



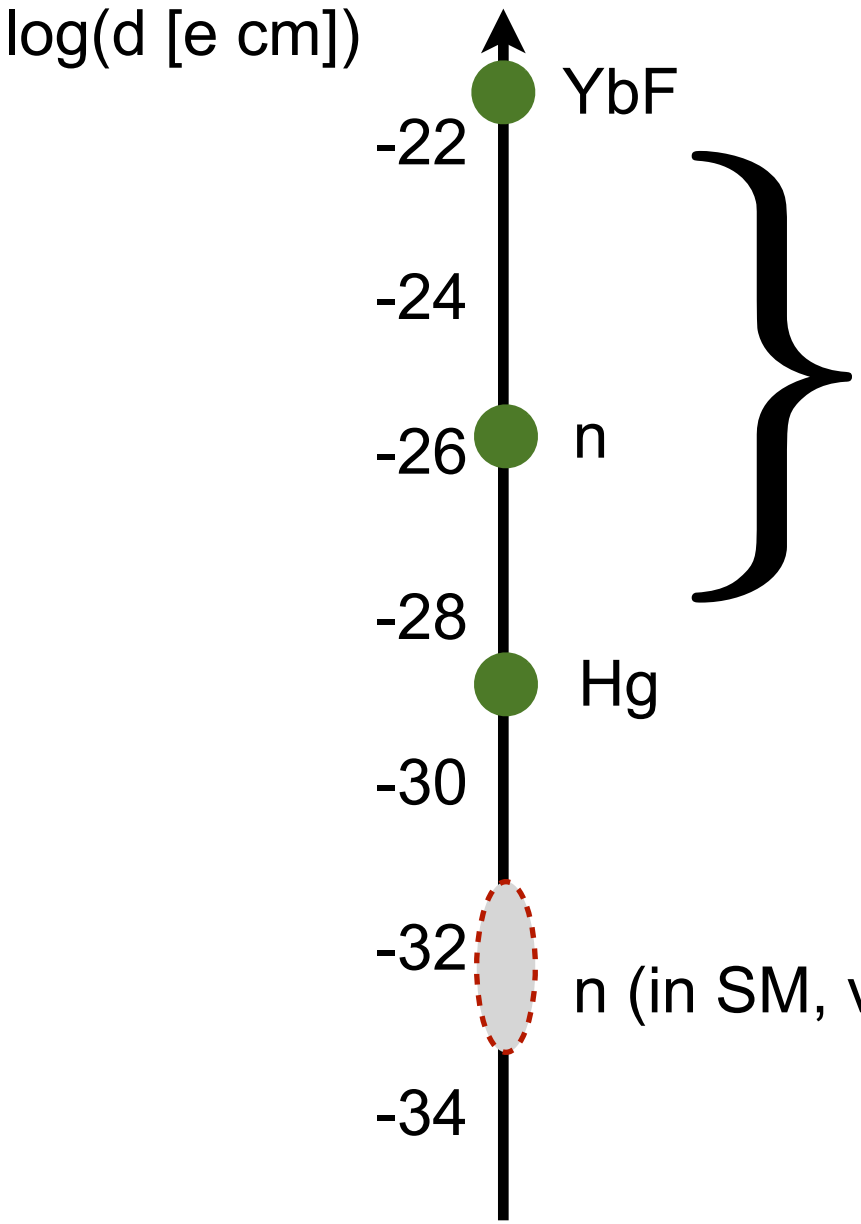
Resulting Bounds on fermion EDMs & CEDMs

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%?)	$\lvert e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25 d_u) + O(\tilde{d}_s, w, C_{qq})\rvert < 2 \times 10^{-26} e\,cm$
Hg EDM (±100%?)	$e\lvert\tilde{d}_d - \tilde{d}_u + \mathcal{O}(d_e, \tilde{d}_s, C_{qq}, C_{qe})\rvert < 6 \times 10^{-27} e\,\mathrm{cm}$

Generic scaling: $d_d\langle q\bar{q}\rangle \Rightarrow m_d\langle q\bar{q}\rangle \sim -m_\pi^2 f_\pi^2 \left(1 + \frac{m_u}{m_d}\right)^{-1}$

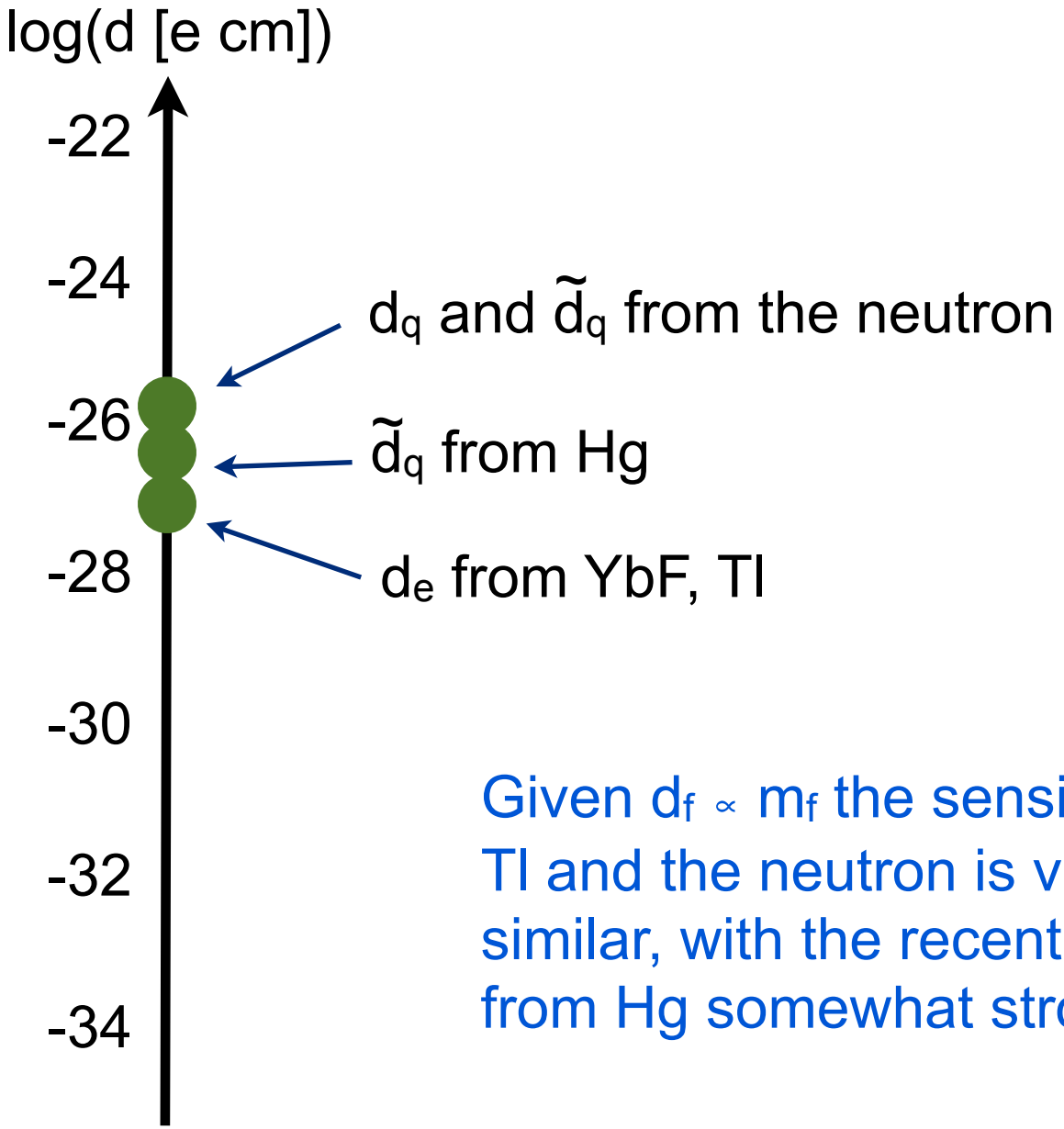
reduces uncertainty due to overall light quark mass scale

Summary of the bounds



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

Summary of the bounds



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

Concluding Remarks

- EDMS are a powerful (amplitude-level) probe of new physics, with impressive recent (and ongoing) experimental progress
- Computations require a multi-scale approach, and various matrix elements enter at atomic/molecular, nuclear and QCD scales
- Reviewed some of the techniques used at the QCD scale to compute/estimate nucleon matrix elements of CP-odd quark/gluon operators
  - lattice QCD approaches discussed later [➠ talk by T. Izubuchi]
- Uncertainties from QCD matrix elements are still large, but...

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$$d_{\rm exp}(C_{\rm atomic}(C_{\rm nuclear}(C_{\rm QCD}(C_{\rm new\ physics}))))$$

largest uncertainty is still here!