$\hbar = c = 1$

WILHELM UND ELSE
HERAEUS-STIFTUNG

EDMs in EFT

Rob G. E. Timmermans

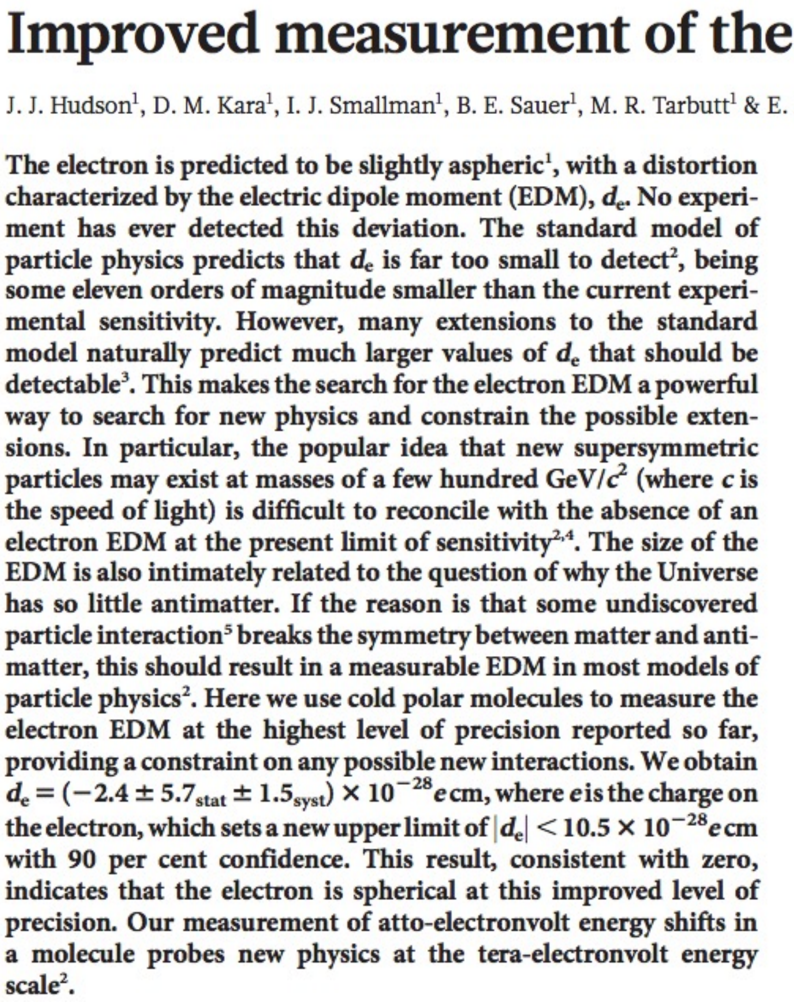
744. WE-Heraeus-Seminar “Towards Storage Ring EDM Measurements”

March 29, 2021

university of groningen / faculty of science and engineering / van swinderen institute for particle physics and gravity

NWO

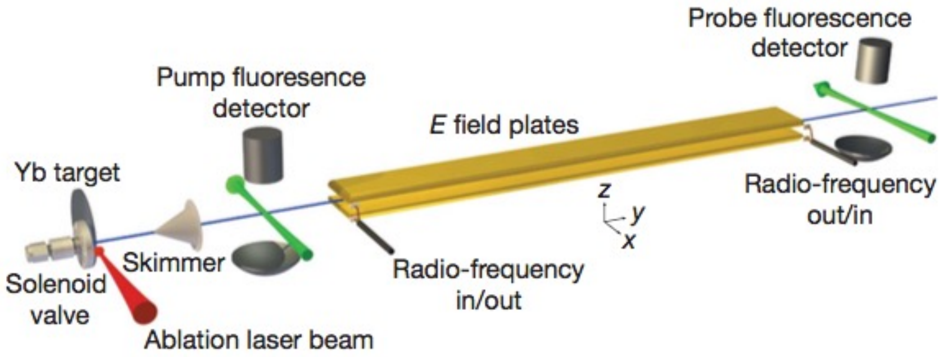
“Is the electron round?”



Improved measurement of the shape of the electron

J. J. Hudson[1], D. M. Kara[1], I. J. Smallman[1], B. E. Sauer[1], M. R. Tarbutt[1] & E. A. Hinds[1]

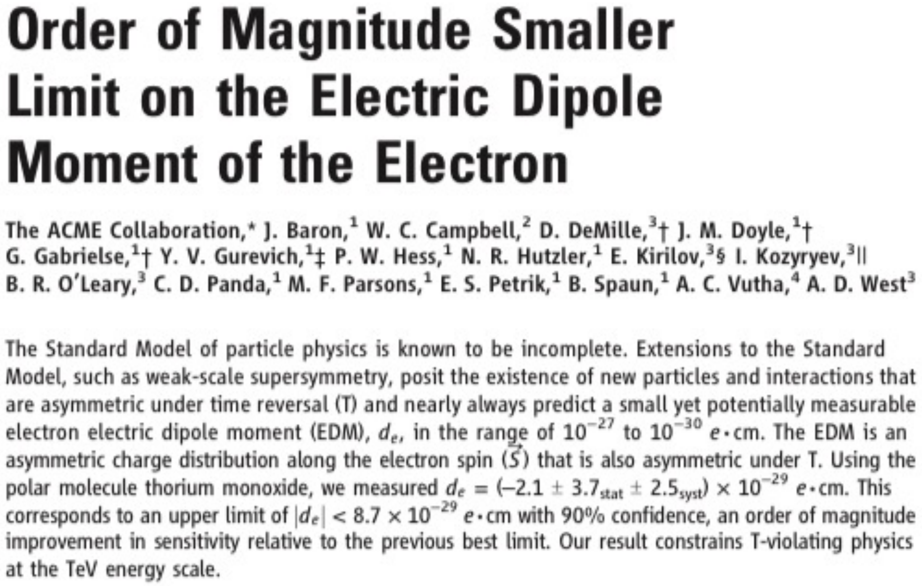
The electron is predicted to be slightly aspheric[1], with a distortion characterized by the electric dipole moment (EDM), d_e. No experiment has ever detected this deviation. The standard model of particle physics predicts that d_e is far too small to detect[2], being some eleven orders of magnitude smaller than the current experimental sensitivity. However, many extensions to the standard model naturally predict much larger values of d_e that should be detectable[3]. This makes the search for the electron EDM a powerful way to search for new physics and constrain the possible extensions. In particular, the popular idea that new supersymmetric particles may exist at masses of a few hundred GeV/c^2 (where c is the speed of light) is difficult to reconcile with the absence of an electron EDM at the present limit of sensitivity[2,4]. The size of the EDM is also intimately related to the question of why the Universe has so little antimatter. If the reason is that some undiscovered particle interaction[5] breaks the symmetry between matter and antimatter, this should result in a measurable EDM in most models of particle physics[2]. Here we use cold polar molecules to measure the electron EDM at the highest level of precision reported so far, providing a constraint on any possible new interactions. We obtain $d_e = (-2.4 \pm 5.7_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-28}\,e\,\mathrm{cm}$, where e is the charge on the electron, which sets a new upper limit of $|d_e| < 10.5 \times 10^{-28}\,e\,\mathrm{cm}$ with 90 per cent confidence. This result, consistent with zero, indicates that the electron is spherical at this improved level of precision. Our measurement of atto-electronvolt energy shifts in a molecule probes new physics at the tera-electronvolt energy scale[2].



- ✓ J. J. Hudson *et al*. (Imperial College London), Nature **473**, 493 (2011)

A new world record

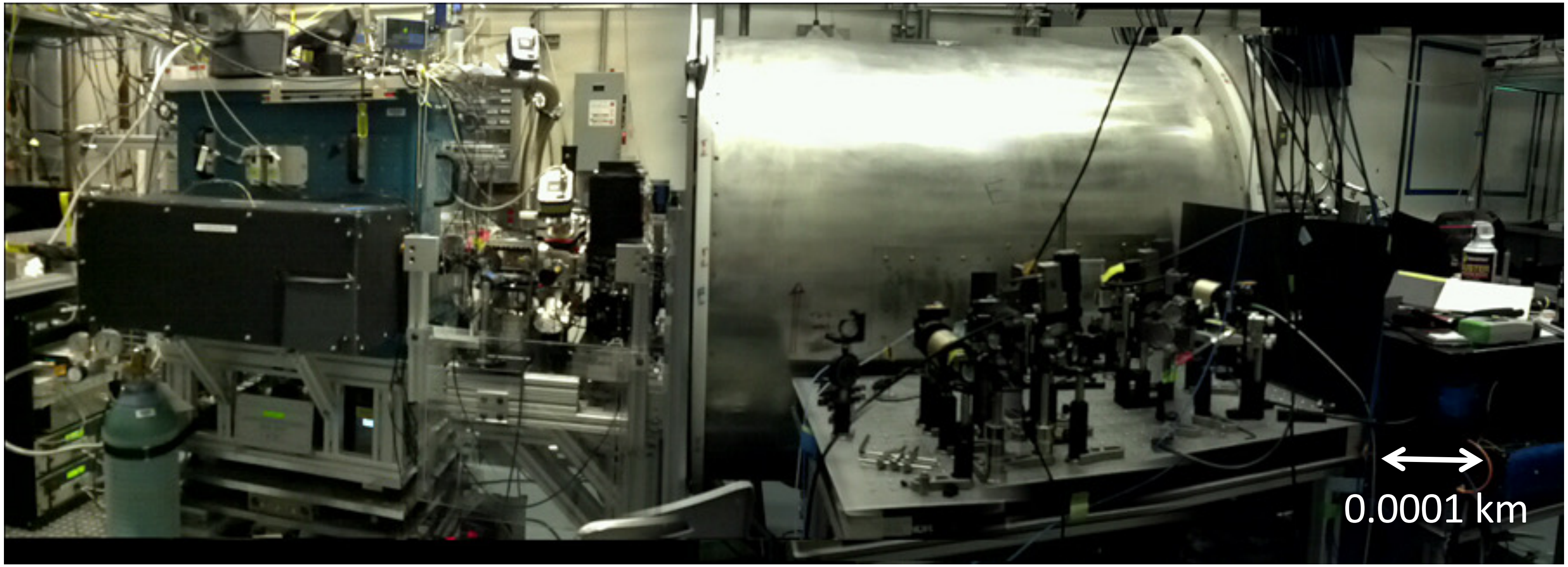
- ✓ ACME collaboration (Harvard-Yale)
  - Science **343**, 269 (2014)
  - Nature **562**, 355 (2018)



Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration,* J. Baron,[1] W. C. Campbell,[2] D. DeMille,[3]† J. M. Doyle,[1]†
G. Gabrielse,[1]† Y. V. Gurevich,[1]‡ P. W. Hess,[1] N. R. Hutzler,[1] E. Kirilov,[3]§ I. Kozyryev,[3]||
B. R. O'Leary,[3] C. D. Panda,[1] M. F. Parsons,[1] E. S. Petrik,[1] B. Spaun,[1] A. C. Vutha,[4] A. D. West[3]

The Standard Model of particle physics is known to be incomplete. Extensions to the Standard Model, such as weak-scale supersymmetry, posit the existence of new particles and interactions that are asymmetric under time reversal (T) and nearly always predict a small yet potentially measurable electron electric dipole moment (EDM), d_e, in the range of 10^{-27} to 10^{-30} $e \cdot$cm. The EDM is an asymmetric charge distribution along the electron spin ($\vec{S}$) that is also asymmetric under T. Using the polar molecule thorium monoxide, we measured $d_e = (-2.1 \pm 3.7_{\text{stat}} \pm 2.5_{\text{syst}}) \times 10^{-29}$ $e \cdot$cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ $e \cdot$cm with 90% confidence, an order of magnitude improvement in sensitivity relative to the previous best limit. Our result constrains T-violating physics at the TeV energy scale.

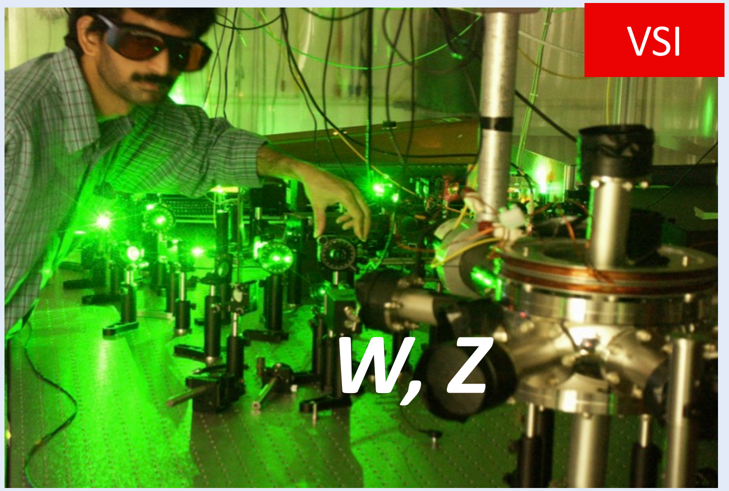


Low-energy tests of the Standard Model

The Standard Model (SM) of particle physics is incomplete →
searches for physics "beyond the SM" at two complementary fronts:

Collider experiments at high energy:
direct observation of new particles

Indirect searches at lower energies
but with high precision



$$E_{\mathrm{cm}} \sim \Lambda_{\mathrm{UV}}$$

$$\delta E \sim \frac{m^{n+1}}{\Lambda_{\mathrm{UV}}^{n}}$$

SM "background" absent

The EDM: A harbinger* of the new Standard Model?

" Ultimately, the validity of all such symmetry arguments must rest on experiment "

Norman Ramsey

" It may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron EDM. These EDMs seem to me to offer one of the most promising possibilities for progress in particle physics "

Steven Weinberg

✓ *One that initiates a major change;
one that foreshadows what is to come

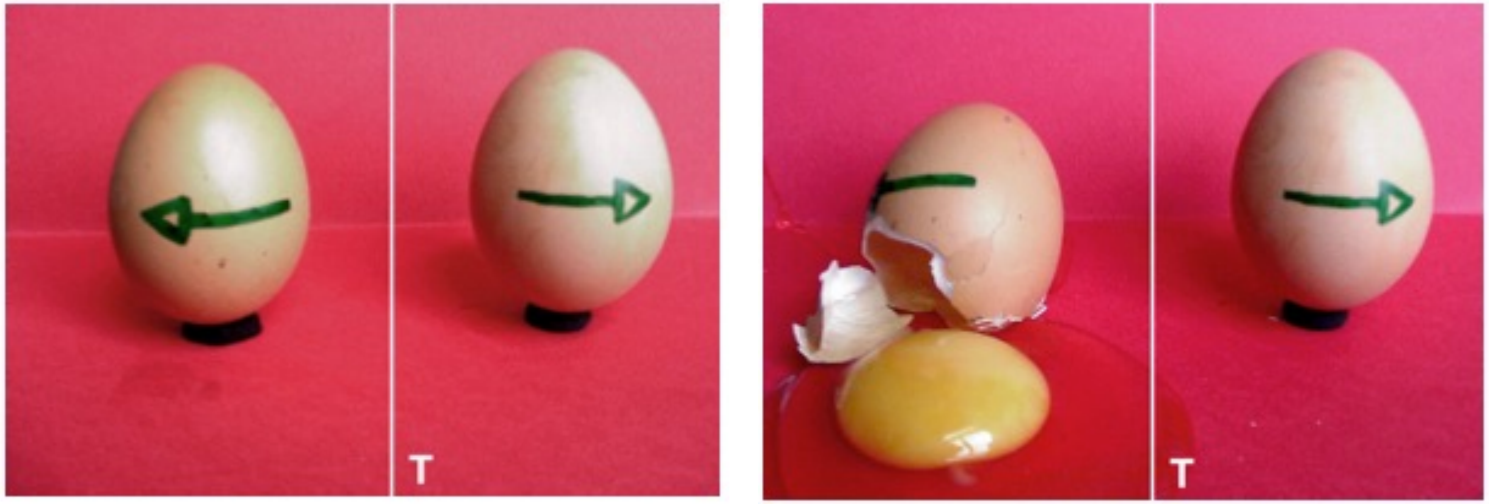
Game plan

1. Towards discovery
   - ✓ EDMs in the SM and beyond
   - ✓ The classic experiments
2. Towards interpretation, top-down versus bottom-up
   - ✓ Unraveling microscopic T violation: EFT for EDMs
3. Hadronic EDMs
   - ✓ Nucleons, light nuclei & diamagnetic atoms
4. The electron EDM
   - ✓ Paramagnetic atoms & molecules
5. Take-home messages

What is an EDM?

✓ A permanent EDM violates P & T, hence [CPT theorem →] also CP

- Permanent charge separation along the spin axis, unit = “*e* cm”



PhD thesis
J. J. Hudson

✓ An atomic physics quantity of interest to particle physics

$$\mathcal{L} = \frac{d}{2}\,\overline{\psi}\gamma_5\sigma_{\mu\nu}\psi F^{\mu\nu} \rightarrow H = -d\,\vec{\sigma}\cdot\vec{E}$$

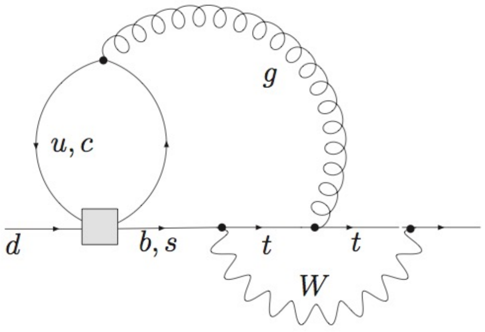
- EDM = “dimension-6 operator”
- SM EDMs are inaccessible, but expected just “beyond” SM

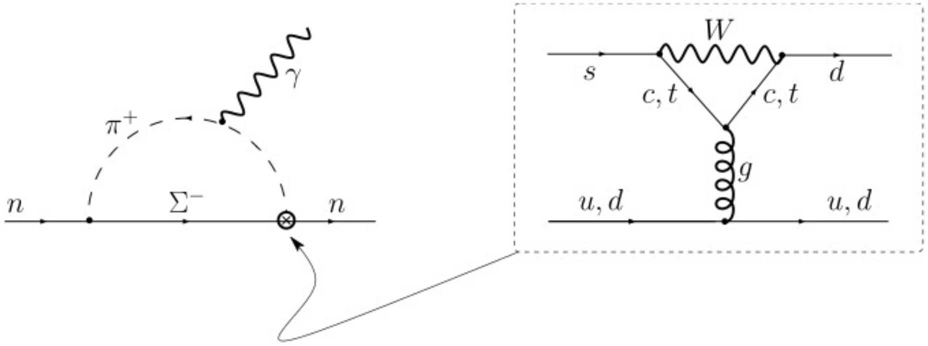
Electroweak CP violation

- ✓ CKM quark-mixing matrix
  - All CP-odd effects involve 3 quark families
  - Jarlskog invariant $J_{\mathrm{CP}} = \sin^2\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta_{\mathrm{CKM}} \approx 3 \times 10^{-5}$

- ✓ EDMs due to δ_{CKM} are unmeasurably small
  - EDM = 2nd-order T-violation at least *e.g.* $(d_n)_{\mathrm{CKM}} \approx (10^{-7})^2 J_{\mathrm{CP}}\, e/M$
  - Quark EDMs = 0 at 2-loop order $\rightarrow (d_n)_{\mathrm{CKM}} = O(10^{-32})\ e$ cm
  - Electron EDM = 0 at 3-loop order $\rightarrow (d_e)_{\mathrm{CKM}} = O(10^{-38})\ e$ cm

- ✓ “Long-distance” contributions to *n*EDM





The QCD vacuum angle

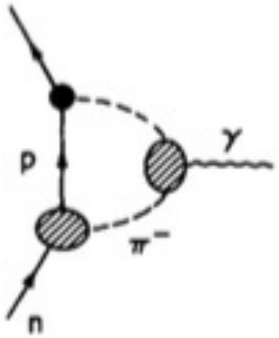
✓ Observed symmetries *almost* perfectly match those of QCD

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \bar{q}(i\not{D} - M)q - \bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

- Due to topological properties of QCD vacuum
- Total derivative, but modifies physics: P and T violation
- Strong CP problem: $d_n \to \overline{\theta} = \theta + \arg\det M_q \leq O(10^{-10})$, not $O(1)$…

✓ Long-distance contributions to *n*EDM → nonperturbative QCD

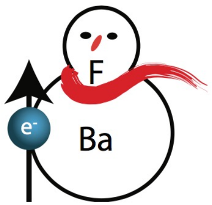
- "Soft-pion" theorem: Chiral log dominates $d_n \sim \theta \log m_\pi^2$
    - Crewther, Di Vecchia, Veneziano, Witten (1979)
- Nowadays: Chiral perturbation theory = EFT for QCD

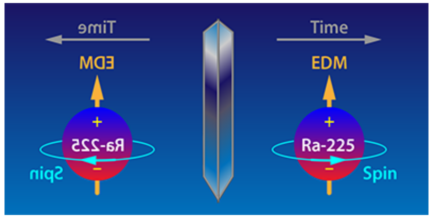


✓ A nonzero EDM implies new, super-weak physics

- EDMs arise at 1-loop level from new δ_{CP}'s OR from θ_{QCD} (also new!)

The hunt for discovery





	System	Group	Limit in *e* cm	C.L.	Value in *e* cm	Year
electron	^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
	YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
	$Eu_{0.5}Ba_{0.5}TiO_3$	Yale	6.05×10^{-25}	90	$-1.07(3.06)(1.74) \times 10^{-25}$	2012
	PbO	Yale	1.7×10^{-26}	90	$-4.4(9.5)(1.8) \times 10^{-27}$	2013
	HfF^+	JILA	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017
	ThO	Harvard & Yale	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
	muon	E821 BNL *g*−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009
	neutron	Sussex-RAL-ILL	3.0×10^{-26}	90	$-0.21(1.82) \times 10^{-26}$	2015
	^{129}Xe	MIXed	1.5×10^{-27}	95	$-4.7(6.4) \times 10^{-27}$	2019
	^{199}Hg	UWash	7.4×10^{-30}	95	$-2.20(2.75)(1.48) \times 10^{-30}$	2016
	^{225}Ra	ANL	1.4×10^{-23}	95	$4(6)(0.2) \times 10^{-24}$	2016

✓ CeNTREX: *p*EDM from ^{205}TlF ; NL-*e*EDM @ Groningen: *e*EDM from BaF

Neutron EDM

- ✓ Strong CP problem
  - If θ = $O(1) \rightarrow d_n = O(10^{-15})$ would have been discovered in 1950s

- ✓ Challenge of an EDM search

Energy shift

$$\Delta E = \hbar\omega = 2\,dE$$

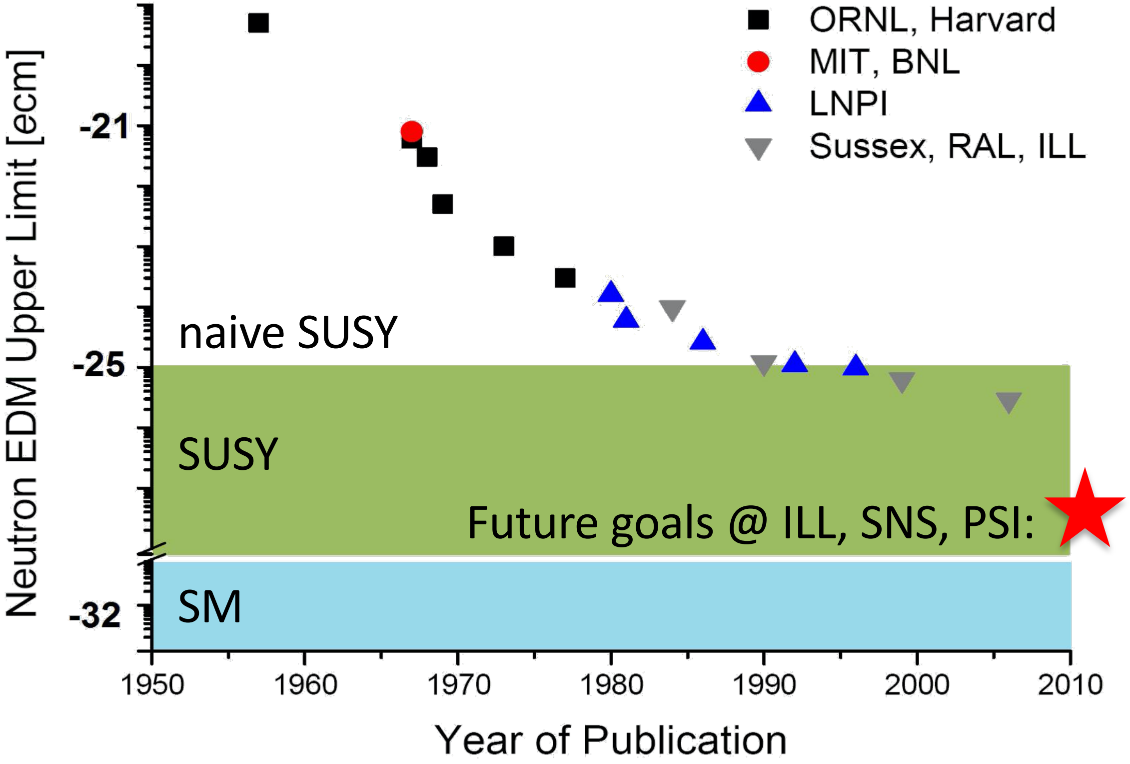
For $(d_n)_{\mathrm{CKM}} = 10^{-32}\ e$ cm

$E = 1$ MV/m

$\Delta E = O(10^{-25})$ eV = O(yeV)

i.e. $\omega = O$(nHz) ≈ 1/century

equivalent to B ≈ aT

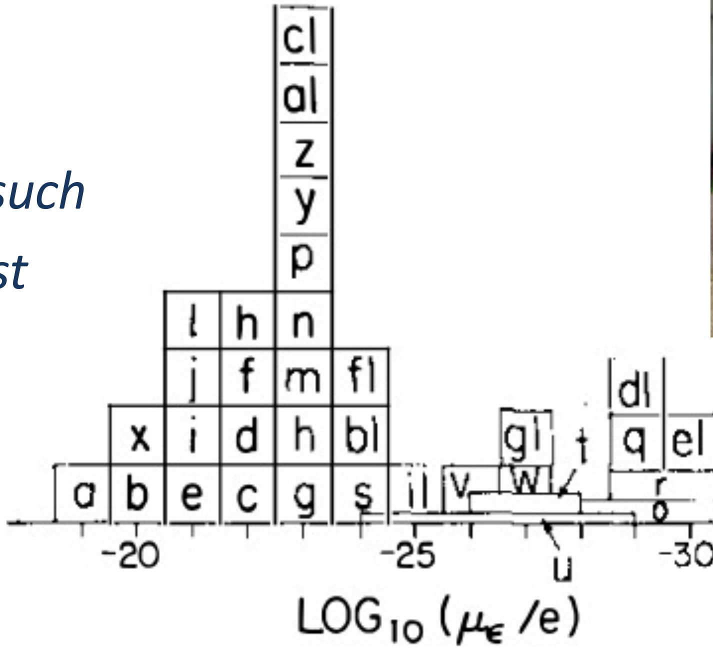


The killer *n*EDM

- ✓ Norman Ramsey (1915-2011)

  “Ultimately the validity of all such symmetry arguments must rest on experiment”

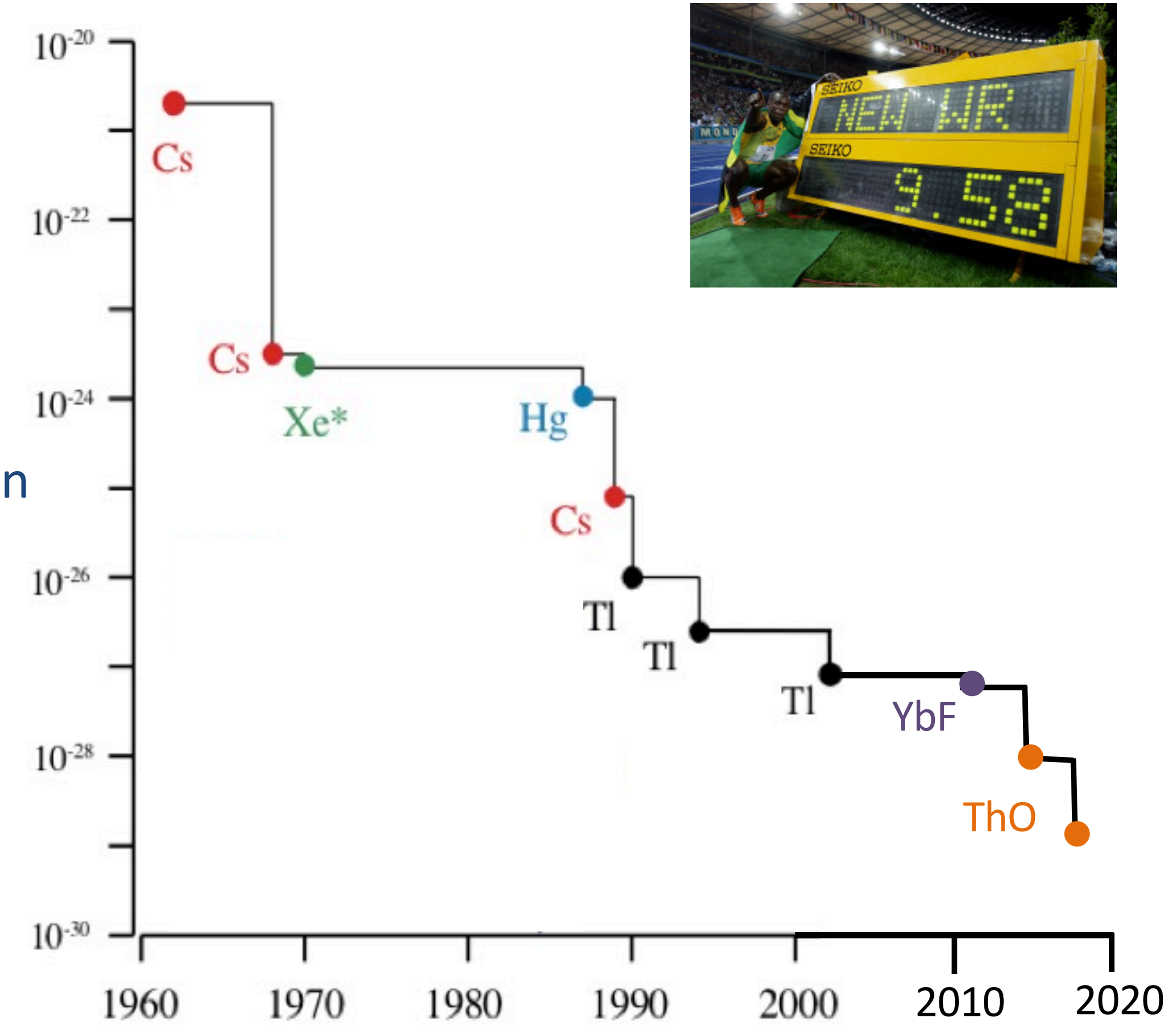
- ✓ Purcell & Ramsey (1950)
  - P violation
- ✓ Lee & Yang, Landau (1957)
  - T violation
  - CP = true mirror?
    - No! (1964)
- ✓ First direct limit (1951→ 1957)
  - $d_n = -0.1(2.4) \times 10^{-20}$ *e* cm



a. Feinberg (1965) (EM)
b. Salzman & Salzman (1965) (EM)
c. Barton & White (1969) (EM)
d. Broadhurst (1970) (EM)
e. Babu & Suzuki (1967) (MW, $\Delta S = 0$)
f. Meister & Rhada (1964) (MW, $\Delta S = 0$)
g. Gourishankar (1968) (MW, $\Delta S = 1$)
h. McNamee & Pati (1969) (MW, $\Delta S = 0, 1$)
i. Nishijima & Swank (1967) (MW, $\Delta S = 0$)
j. Nishijima (1969) (MW, $\Delta S = 0$)
k. Boulware (1965) (MW, $\Delta S = 0$)
l. Wolfenstein (1964a,b) (SW, $\Delta S = 2$)
m. Pais & Primack (1973a,b) (MW)
n. Lee (1973, 1974) (MW)
o. Okun (1969) (SW)
p. Mohapatra (1972) (MW)
q. Frenkel & Ebel (1974a) (MW)
r. Wolfenstein (1974) (SW)
s. Weinberg (1976) (MW)
t. Pakvasa & Tuan (1975) (MW)
u. Mohapatra & Pati (1975) (MW)
v. Clark & Randa (1975) (MS)
w. Chodos & Lane (1972) (MW)
x. Feinberg & Mani (1965) (W, $\Delta S = 1$)
y. Gourishankar (1968) (MW, $\Delta S = 1$)
z. Filipov et al (1968) (EM)
a1. McNamee & Pati (1969) (MW, $\Delta S = 0, 1$)
b1. Barton & White (1969) (EM, MW, $\Delta S = 0, 1$)
c1. McCliment & Teeters (1970) (MW)
d1. Frenkel & Ebel (1974a,b)
e1. Nanopoulos & Yildiz (1979) (Q)
f1. Eichten et al (1980) (MW, H)
g1. Ellis et al (1980, 1981) (this paper has the interesting characteristic that it establishes an order-of-magnitude lower limit to *D* of 3×10^{-28} cm)
h1. Crewther et al (1979)
i1. Shizuya & Tye (1980) (MW, H)
j1. Epstein (1980)

The killer *e*EDM

* 15 PhD generations



- ✓ 2018: new world record
- ✓ Paramagnetic atoms
  - – $d_{atom} = K_{relativistic} \times d_e$
- ✓ Polar molecules

  Ion-like charge separation

  $E_{int} \approx 75$ GV/cm

  $E_{ext} \approx 10\text{-}10^4$ V/cm
- ✓ SM value reached in
  - – 2075 for neutron*
  - – 2115 for electron…

- ✓ Upper limit $|d_e| < 1.1 \times 10^{-29}\, e$ cm → scale of new physics Λ > few TeV

The need for interpretation

- ✓ Limit on ^{199}Hg EDM
  - Griffith *et al*., PRL 2012
  - Swallows *et al*., PRA 2013
  - Graner *et al*., PRL 2016

  - Lots of crappy modeling…

- ✓ "Just one number?"
  - Gives *scale* of new physics

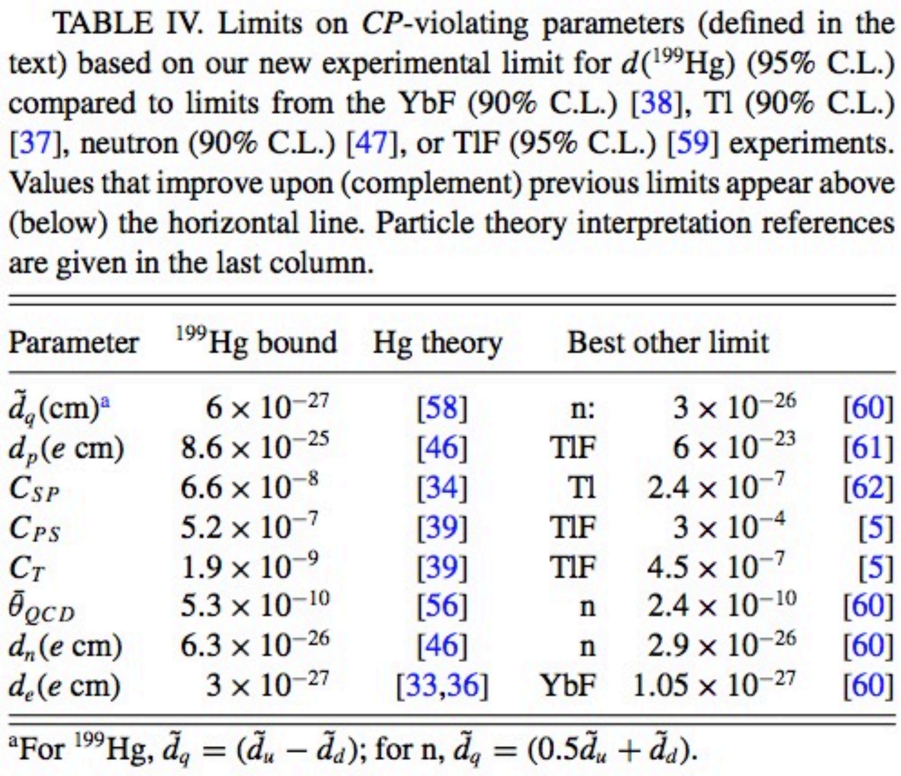


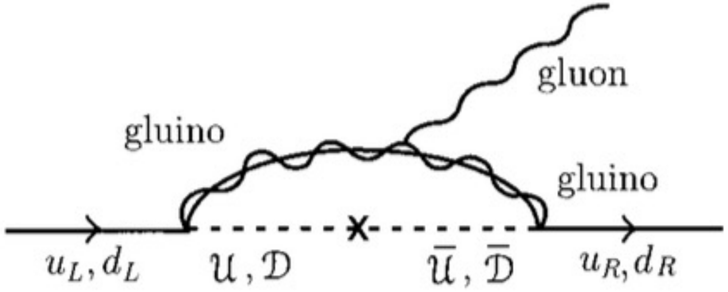
TABLE IV. Limits on *CP*-violating parameters (defined in the text) based on our new experimental limit for $d(^{199}\mathrm{Hg})$ (95% C.L.) compared to limits from the YbF (90% C.L.) [38], Tl (90% C.L.) [37], neutron (90% C.L.) [47], or TlF (95% C.L.) [59] experiments. Values that improve upon (complement) previous limits appear above (below) the horizontal line. Particle theory interpretation references are given in the last column.

Parameter	^{199}Hg bound	Hg theory	Best other limit		
$\tilde{d}_q$(cm)[a]	6×10^{-27}	[58]	n:	3×10^{-26}	[60]
d_p(e cm)	8.6×10^{-25}	[46]	TlF	6×10^{-23}	[61]
C_{SP}	6.6×10^{-8}	[34]	Tl	2.4×10^{-7}	[62]
C_{PS}	5.2×10^{-7}	[39]	TlF	3×10^{-4}	[5]
C_T	1.9×10^{-9}	[39]	TlF	4.5×10^{-7}	[5]
$\bar{\theta}_{QCD}$	5.3×10^{-10}	[56]	n	2.4×10^{-10}	[60]
d_n(e cm)	6.3×10^{-26}	[46]	n	2.9×10^{-26}	[60]
d_e(e cm)	3×10^{-27}	[33,36]	YbF	1.05×10^{-27}	[60]

[a] For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$; for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

- ✓ The EDM program:
  - How to disentangle the different sources of T violation?
  - How many & which observables are needed?
  - EFT from 1st principles: systematic + model independent + errors

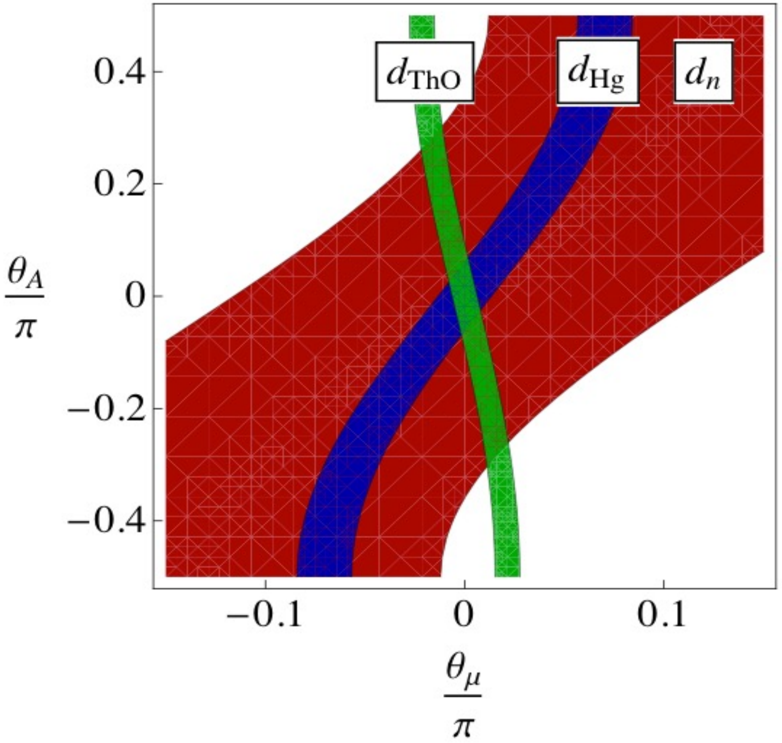
The SUSY CP problem



- ✓ MSSM has > 100 parameters, 10s δ_{CP}-like
- ✓ Typical SUSY prediction (NDA, m_d = 7 MeV)

$$d_n = 5 \cdot 10^{-24} \frac{\mathrm{Im} A'_d (100\,\mathrm{GeV})^2}{m^3_{\mathrm{gluino}}} \, e\,\mathrm{cm}$$

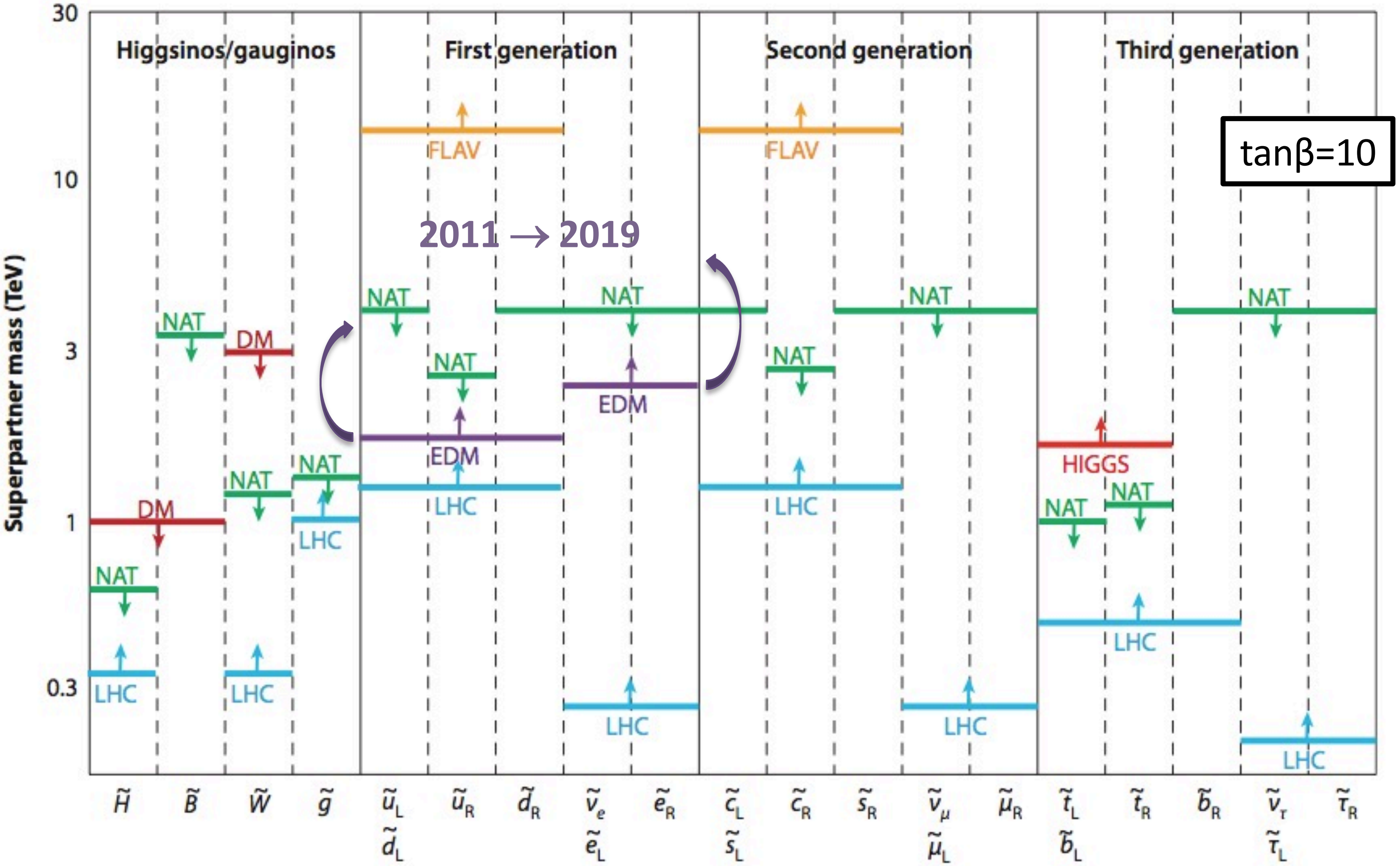
$$A'_d \sim \tan\beta = v_2/v_1$$



- ✓ *e*EDM & *d*EDM enhanced for large tanβ
  - Friction with Higgs mass?
- ✓ Unnatural SUSY scale?
  - M_{SUSY} from 500 GeV → 2 TeV
- ✓ Current EDM null results → probe 1-10 TeV scale or $\delta_{CP} \leq O(10^{-2})$
  - Next generation → sensitive to 10-100 TeV scale or $\delta_{CP} \leq O(10^{-4})$

Naturalness of SUSY?

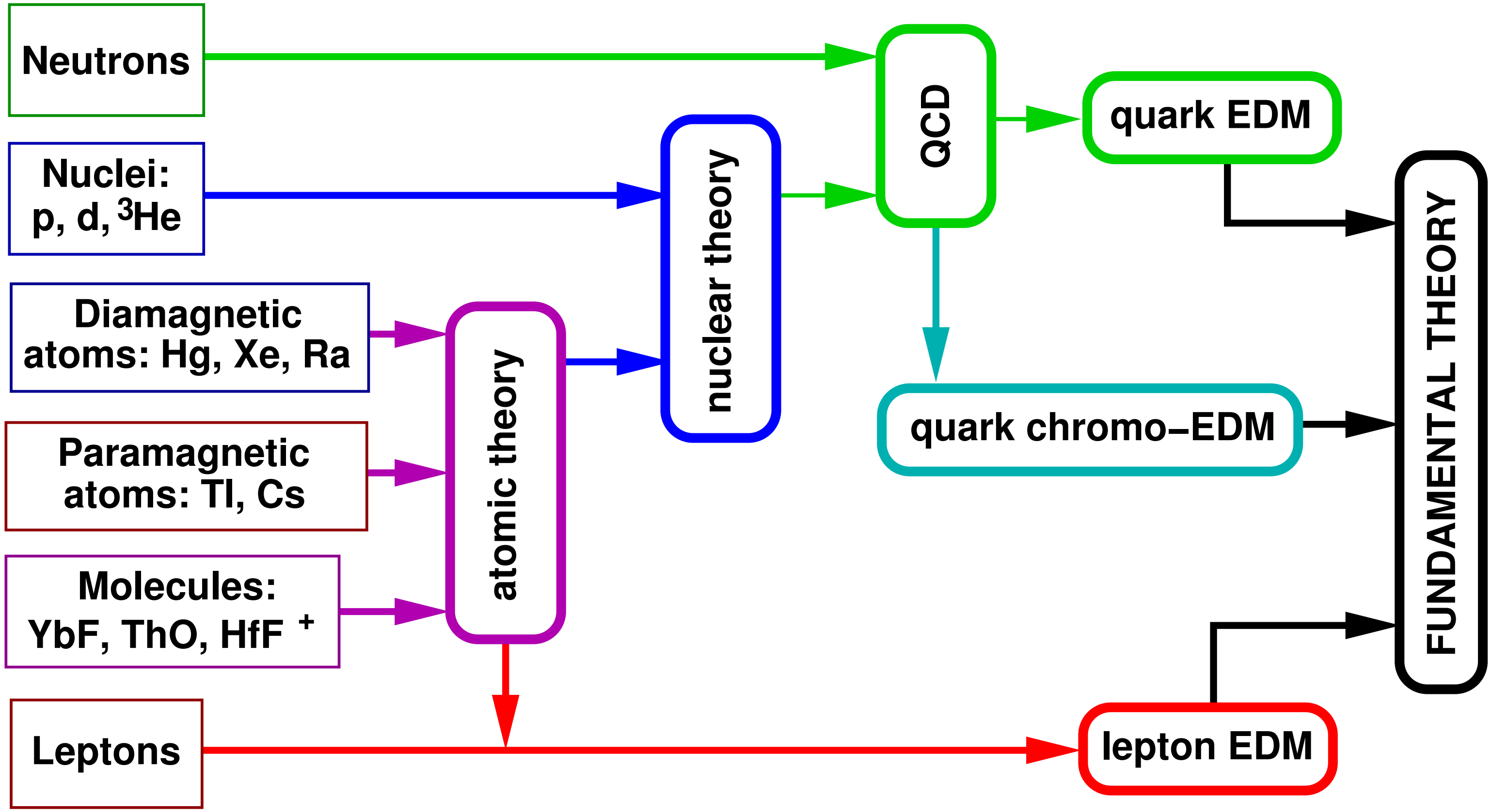
J. L. Feng, Ann. Rev. Nucl. Part. Sci. **63**, 351 (2013)



✓ “Extremely robust” → “multi-TeV 1st-generation superpartners required”

The EDM landscape

- ✓ Scales
  - yeV keV MeV GeV TeV ??



Neutrons

Nuclei: p, d, ^{3}He

Diamagnetic atoms: Hg, Xe, Ra

Paramagnetic atoms: Tl, Cs

Molecules: YbF, ThO, HfF $^{+}$

Leptons

atomic theory

nuclear theory

QCD

quark EDM

quark chromo–EDM

lepton EDM

FUNDAMENTAL THEORY

- ✓ Theory is essential for the interpretation of EDMs of complex systems

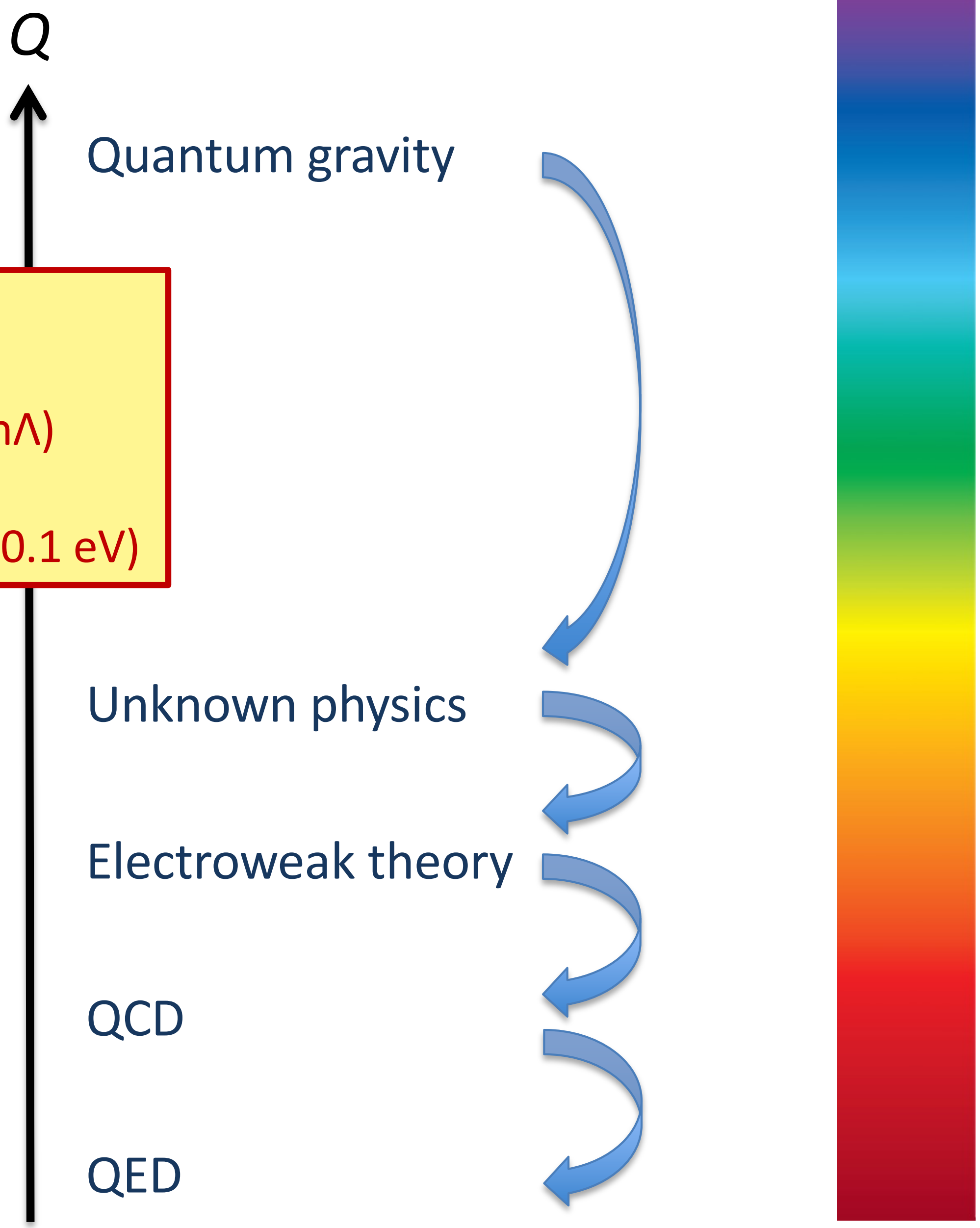
A new scale in physics?

- ✓ $\Lambda_{\text{Planck}} = 10^{19}$ GeV

Gauge hierarchy problem:
- in SM: M^2_{Higgs}(1-loop) = $O(\Lambda^2)$
- with SUSY: M^2_{Higgs}(1-loop) = $O(\ln\Lambda)$

Flavor hierarchy problem:
- M_{top} = 175 GeV vs $M_{\text{neutrino}} < O(0.1\text{ eV})$

- ✓ Λ_{new} = ??
- ✓ Λ_{Fermi} = 100 GeV
- ✓ Λ_{QCD} = 1 GeV
- ✓ Λ_{QED} = 1 eV



Quantum gravity

Unknown physics

Electroweak theory

QCD

QED

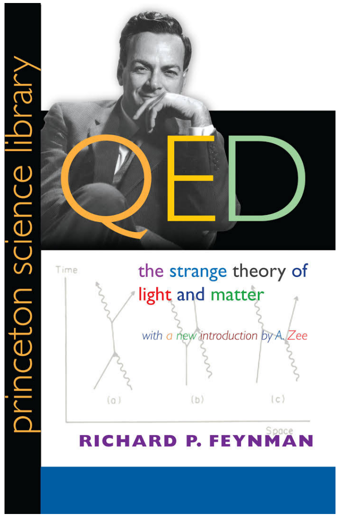
Effective field theory 101

- ✓ QED: $\mathcal{L}^{(4)}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \overline{\psi}(\gamma_\mu\partial^\mu + m)\psi + ie\overline{\psi}\gamma_\mu\psi A^\mu$

- ✓ What about "non-renormalizable" terms (mass dimension > 4)?

$$\mathcal{L}^{(5,6)}_{\rm QED} = -\mu\,\overline{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu} - g\,\overline{\psi}\psi\,\overline{\psi}\psi$$

  - Integrating out heavy particles → local interactions at low energy
  - Couplings suppressed by new scale $\mu = \mathcal{O}(1/\Lambda)\ ,\ g = \mathcal{O}(1/\Lambda^2)$
  - Electron magnetic moment → $\Lambda > O(1)$ TeV



- ✓ Standard Model = low-energy EFT

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{(4)}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots$$

$$\mathcal{L}^{(4)}_{\rm SM} \to \mathcal{L}^{(4)}_{\rm QCD} + \mathcal{L}^{(4)}_{\rm QED} + \frac{1}{M_W^2}\mathcal{L}^{(6)}_{\rm Fermi}$$

  - Dim 5: neutrino mass; dim 6: lots of stuff (*e.g.* T, B viol)

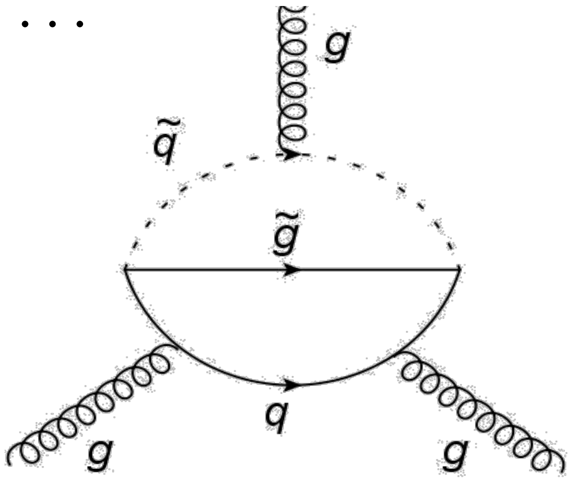
EDMs in the Standard Model EFT

- ✓ Add to the SM all possible P- and T-odd interactions

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \ldots$$

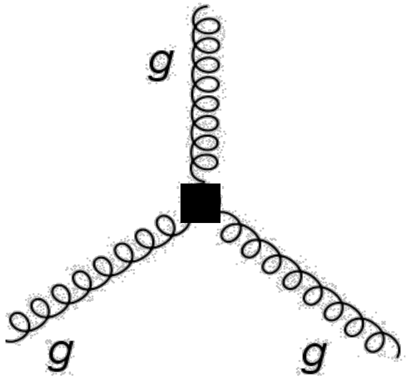
- ✓ Integrate out heavy (new) particles

- ✓ 1 TeV?



Q

Effectively becomes *O*($1/\Lambda^2$)



gluon color-EDM

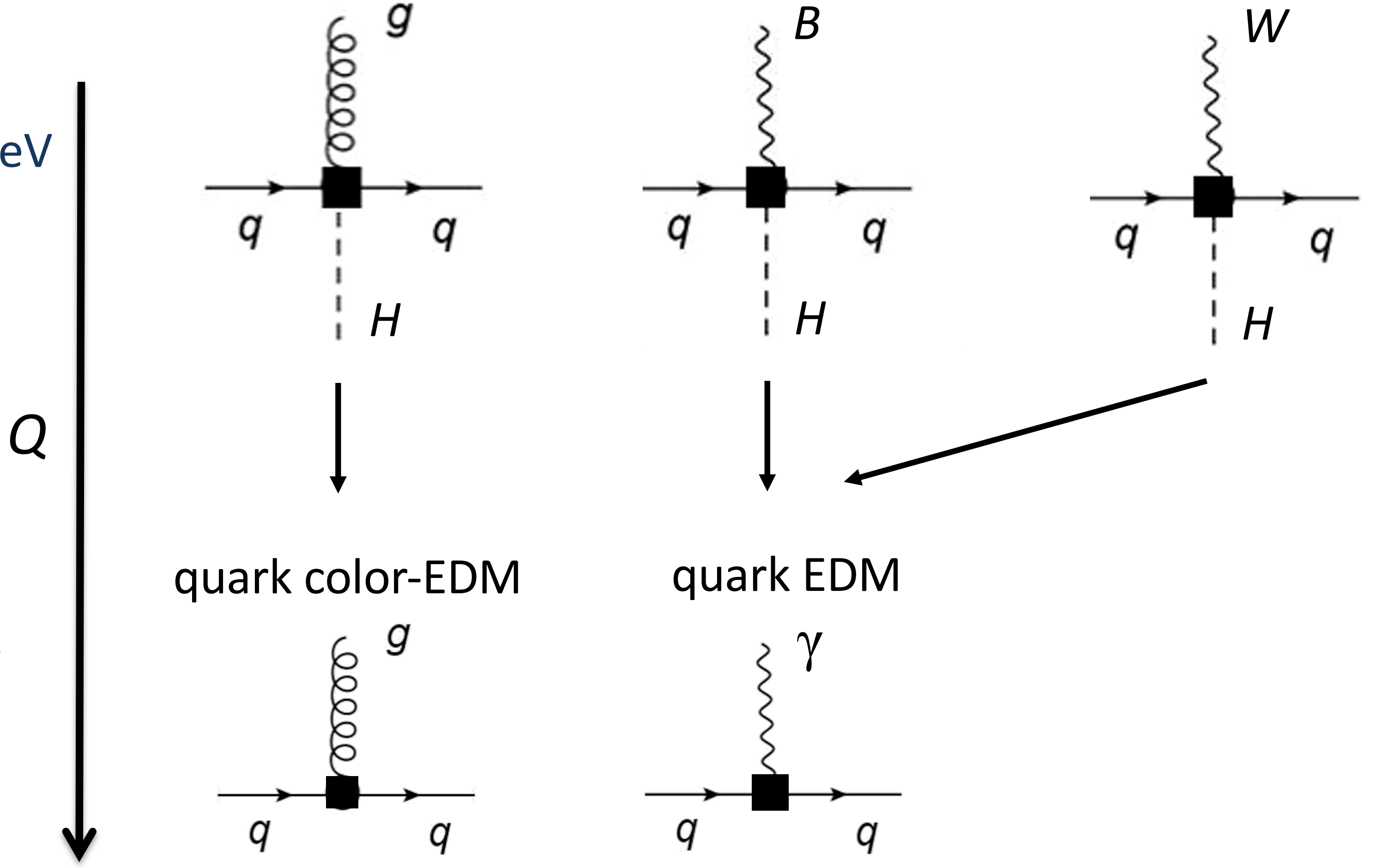
$$d_W f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\lambda} G^{c\lambda}_{\nu}$$

$$d_W \sim \frac{1}{\Lambda^2}$$

- ✓ 100 GeV

Dimension-6 sources

- Electroweak symmetry breaking, integrate out heavy particles
  - EDMs flip chirality → effectively dimension 6, prop. to $m = g_{\text{Yukawa}}\, v/\sqrt{2}$



- 100 GeV
- 1 GeV

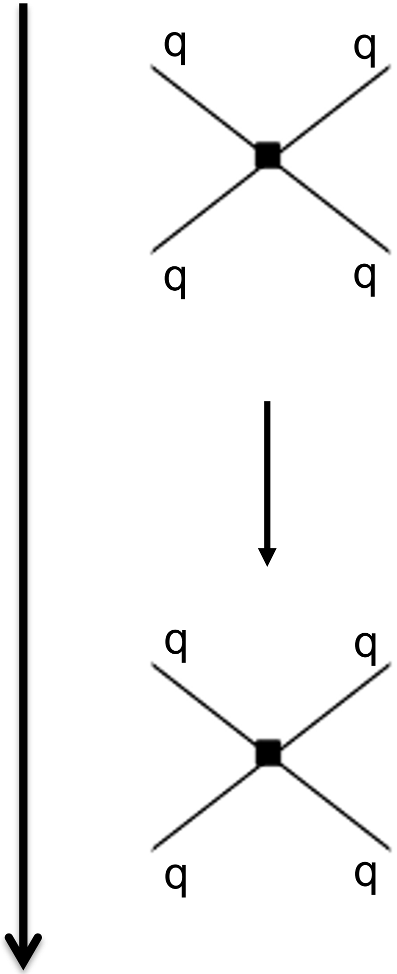
quark color-EDM

quark EDM

Four-quark operators

- ✓ Only 2 gauge-invariant four-quark (*u*,*d*) operators

- ✓ 1 TeV?
- ✓ 100 GeV
- ✓ 1 GeV



$$\Sigma_1 \left(\bar{u}_L u_R \bar{d}_R d_L - \bar{d}_L u_R \bar{u}_R d_L\right) + h.c.$$

Plus color analogue Σ_8

$$\Sigma_{1,8} \sim \frac{1}{\Lambda^2}$$

Significant QCD running

$$\Sigma_1(1\,\mathrm{GeV}) \simeq 7\,\Sigma_1(1\,\mathrm{TeV})$$

Four-quark operators

- ✓ Finally: 1 quark-Higgs-Higgs interaction

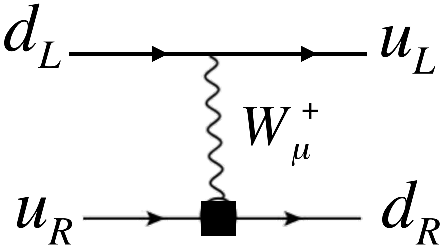
$$\Xi_1 \sim \frac{1}{\Lambda^2}$$

- ✓ 1 TeV?

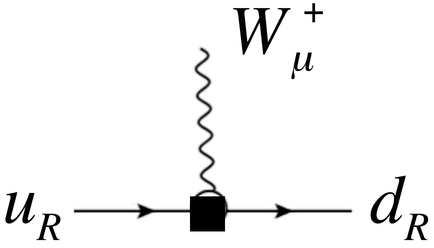
$$\Xi_1 \left(\overline{u}_R \gamma^\mu d_R\right) \tilde{\phi}^{*T} i D_\mu \phi + h.c.$$

- ✓ 100 GeV

$$\longrightarrow \Xi_1 v^2 \left(\overline{u}_R \gamma^\mu d_R\right) W_\mu^+ + h.c.$$

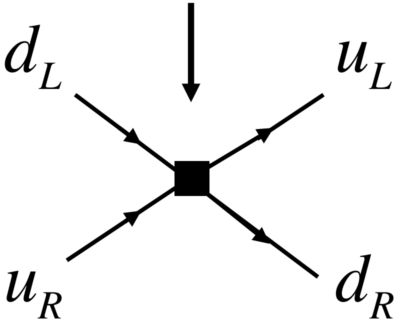


$\longleftarrow$



Q

$\downarrow$

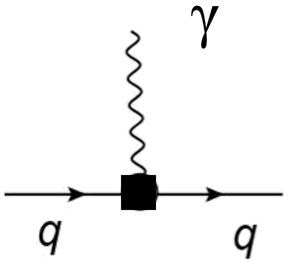


- ✓ 1 GeV

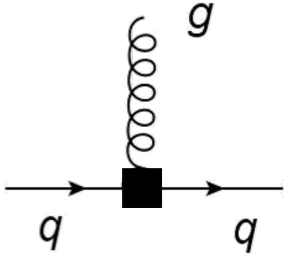
$\sim \frac{v^2}{M_W^2} \mathrm{Im}\Xi_1$ unsuppressed!

Summary: dimension-4 and -6 sources @ 1 GeV

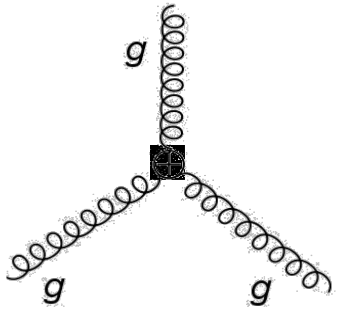
QCD θ-term



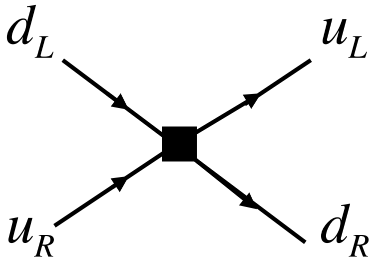
quark EDM



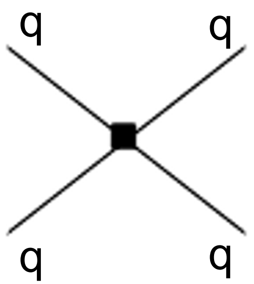
quark color-EDM



gluon color-EDM



left-right 4-quark term



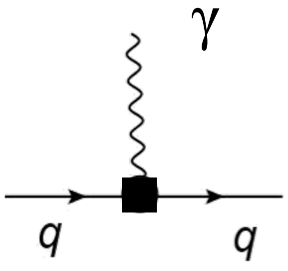
2 chiral-invariant 4-quark terms

$$\mathcal{L}_{\not P \not T} = -\bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} - \frac{1}{2}\sum_{q=u,d}\left(d_q\,\bar{q}i\sigma^{\mu\nu}\gamma_5 q\,F_{\mu\nu} + \tilde{d}_q\,\bar{q}i\sigma^{\mu\nu}\gamma_5 t_a q\,G^a_{\mu\nu}\right)$$

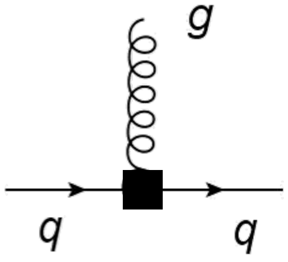
$$+\frac{d_W}{6}f_{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\,\rho}_{\nu} + \sum_{i,j,k,l=u,d} C_{ijkl}\,\bar{q}_i\Gamma q_j\,\bar{q}_k\Gamma' q_l$$

Next: nonperturbative QCD

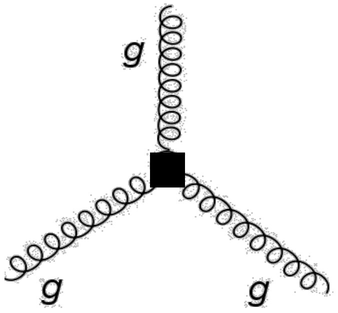
QCD θ-term



quark EDM



quark color-EDM

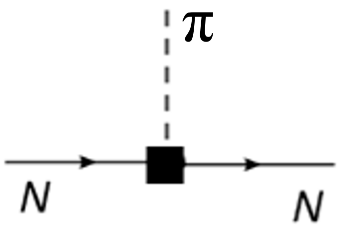


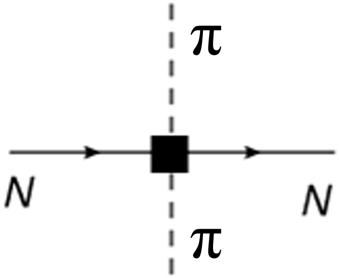
gluon color-EDM

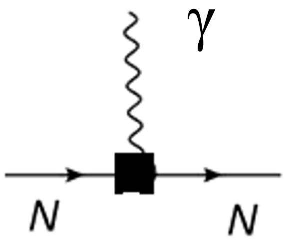
- ✓ 1 GeV

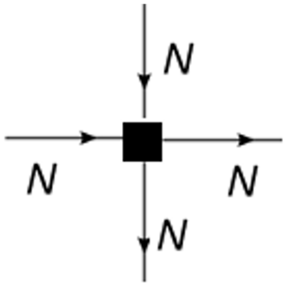
Q

χPT = chiral perturbation theory









- ✓ 100 MeV

Chiral perturbation theory

- ✓ EFT must mirror the (broken) symmetries of QCD

- ✓ Quark masses = 0 → QCD has $SU(2)_L \times SU(2)_R$ symmetry
  - Chiral-SU(2) *spontaneously* broken in QCD ground state
  - SU(2)-isospin remains
  - Goldstone bosons: pions with $m_\pi = 0$

- ✓ Small u, d masses: *explicit* breaking of chiral & isospin symmetry
  - Finite, but small pion mass: $m_\pi^2 = O(m_{\text{quark}}\Lambda_{\text{QCD}})$

- ✓ χPT = systematic expansion in Q/Λ_{QCD} and $m_\pi/\Lambda_{\text{QCD}}$
  - Operators order-by-order fixed by symmetry
  - Each operator multiplied by unknown *coupling constant*

    → Fit to data, or use “NDA” or from lattice QCD

Chiral properties of the sources

- ✓ Each operator breaks chiral symmetry in a particular way
  - And thus can induce different hadronic interactions
  - Key to disentangle the sources!

- ✓ Dimension-4 and -6 quark-gluon sources:
  - Theta term = chiral pseudo-vector
  - Quark color-EDM = chiral vector
  - Left-right 4-quark = rank-2 chiral tensor
  - Quark EDM = another rank-2 chiral tensor
  - Gluon color-EDM & 4-quark = chiral invariant → cannot be separated

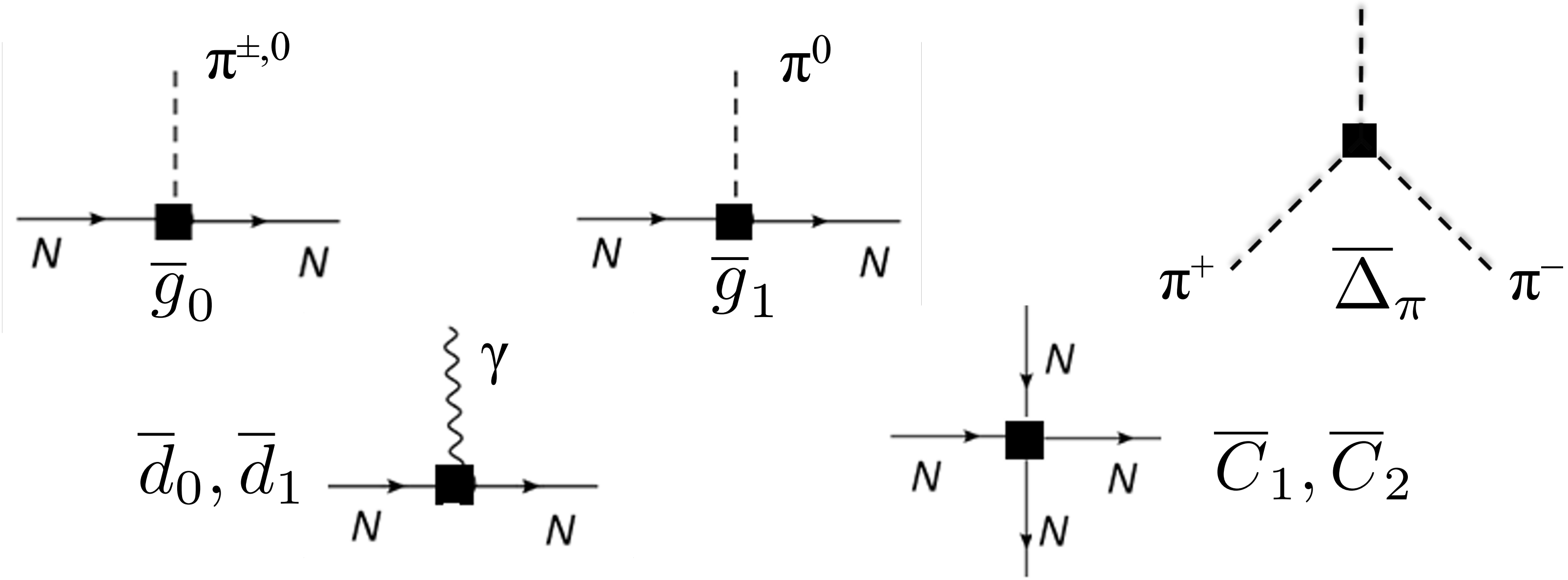
$$\mathcal{L} = -2\overline{N}(\bar{d}_0 + \bar{d}_1\tau_3)S^\mu N v^\nu F_{\mu\nu} + \bar{g}_0 \overline{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1\overline{N}\pi_3 N$$

$$+\overline{C}_1\overline{N}N\partial_\mu(\overline{N}S^\mu N) + \overline{C}_2\overline{N}\vec{\tau}N\cdot\partial_\mu(\overline{N}S^\mu\vec{\tau}N)$$

$$v^\mu = (1,\vec{0})$$
$$S^\mu = (0,\vec{\sigma}/2)$$

The magnificent seven

- ✓ T violation at nuclear scales (non-perturbative QCD) from



$$\mathcal{L} = -2\overline{N}(\bar{d}_0 + \bar{d}_1\tau_3)S^\mu N v^\nu F_{\mu\nu} + \bar{g}_0\overline{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_1\overline{N}\pi_3 N$$
$$+\bar{C}_1\overline{N}N\partial_\mu(\overline{N}S^\mu N) + \bar{C}_2\overline{N}\vec{\tau}N\cdot\partial_\mu(\overline{N}S^\mu\vec{\tau}N)$$

- ✓ Different models of CP violation predict a different hierarchy!
  - QCD theta term, left-right symmetric models, SUSY, multi-Higgs, …

Example: the QCD theta term

- ✓ Theta term = chiral pseudo-vector, same as quark-mass difference

$$-\bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} \longrightarrow \frac{m_u m_d}{m_u+m_d}\bar{\theta}\,\bar{q}i\gamma_5 q$$

- ✓ P- and T-odd pion-nucleon interactions
  - Traditionally expected to be dominant, since *e****r*** = long range

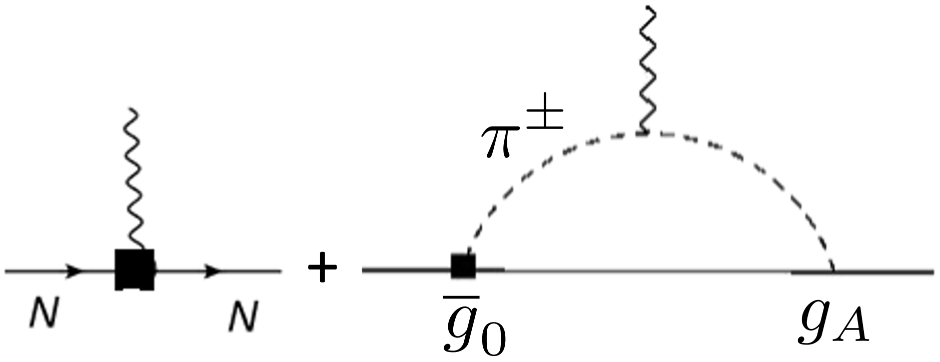
$$\bar{g}_0^\theta = \frac{\delta M_N}{F_\pi}\frac{(1-\varepsilon^2)}{2\varepsilon}\sin\bar{\theta} = -0.015(2)\sin\bar{\theta}$$

$$\bar{g}_1^\theta = \frac{8c_1\delta m_\pi^2}{F_\pi}\frac{(1-\varepsilon^2)}{2\varepsilon}\sin\bar{\theta} = 0.004(3)\sin\bar{\theta}$$

  - Input from phenomenology (π*N* σ-term) and/or LQCD, *e.g.*

$$\delta M_N = 2.39(21)\,\mathrm{MeV} \qquad \varepsilon = \frac{m_d-m_u}{m_u+m_d} = 0.37(3)$$

Nucleon EDMs



- ✓ 1-loop diagrams UV divergent
  - 2 counterterms needed

$$d_n = \bar{d}_0 - \bar{d}_1 - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{M_N^2} - \frac{\pi}{2}\frac{m_\pi}{M_N}\right)$$

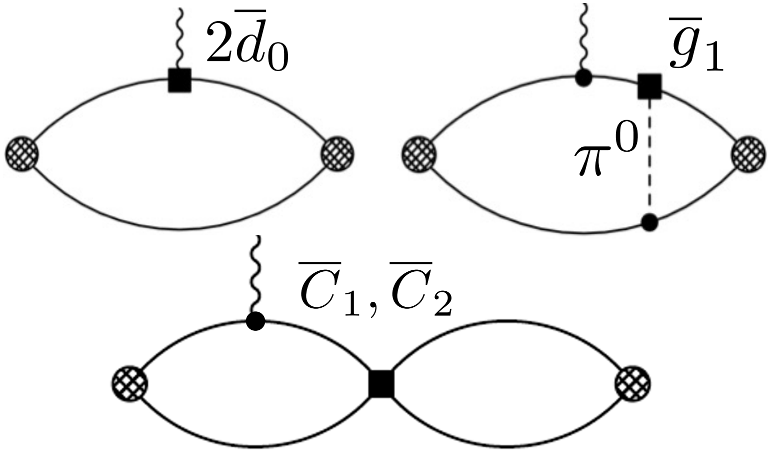
$$d_p = \bar{d}_0 + \bar{d}_1 + \frac{e g_A}{4\pi^2 F_\pi}\left[\bar{g}_0\left(\ln\frac{m_\pi^2}{M_N^2} - 2\pi\frac{m_\pi}{M_N}\right) - \bar{g}_1\frac{\pi}{2}\frac{m_\pi}{M_N}\right]$$

  - 3 unknowns… can be fitted by any source
  - For each source neutron & proton EDMs of same order
  - Absorb loop contributions in $\bar{d}_{0,1}$
- ✓ For theta term, with LQCD input:

$$d_n^\theta = -1.99(12)\cdot 10^{-16}\sin\bar{\theta}\; e\,\mathrm{cm}$$

$$d_p^\theta = 1.99(46)\cdot 10^{-16}\sin\bar{\theta}\; e\,\mathrm{cm}$$

Deuteron EDM



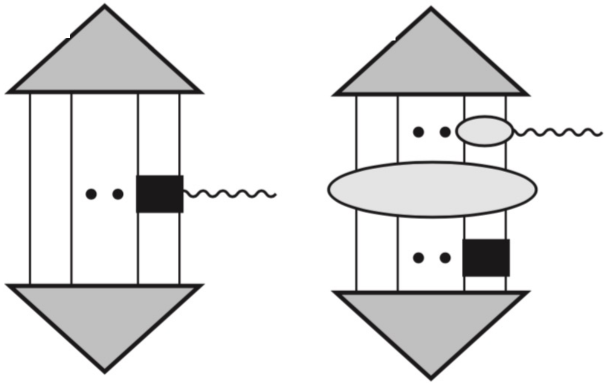
- ✓ 3 contributions:
  - Sum of nucleon EDMs = $d_n + d_p$
  - T-violating pion exchange
  - T-violating *NN* interactions

- ✓ "Chiral filter": deuteron is special case due to $N = Z$
  - $^3S_1 \rightarrow {}^3P_1$ with $\bar{g}_1$ coupling, back via E1 transition
  - $^3S_1 \rightarrow {}^1P_1$ with $\bar{g}_0$ coupling, no E1 back (same for $\bar{C}_1, \bar{C}_2$)

- ✓ Little model dependence, *e.g.* $d_D \simeq 0.94\,(d_n + d_p) + 0.18\,\bar{g}_1\ e\,\mathrm{fm}$
  - For quark color-EDM d_D is significantly larger than $d_n + d_p$
  - Way to extract theta, or more generally $\bar{g}_1$, from data

- ✓ The deuteron has also T-odd magnetic and toroidal quadrupole moments

EDMs of light nuclei



- ✓ Calculated for all sources in EFT framework
  - Hadronic uncertainties dominate over nuclear ones

- ✓ For helion and triton *e.g.*

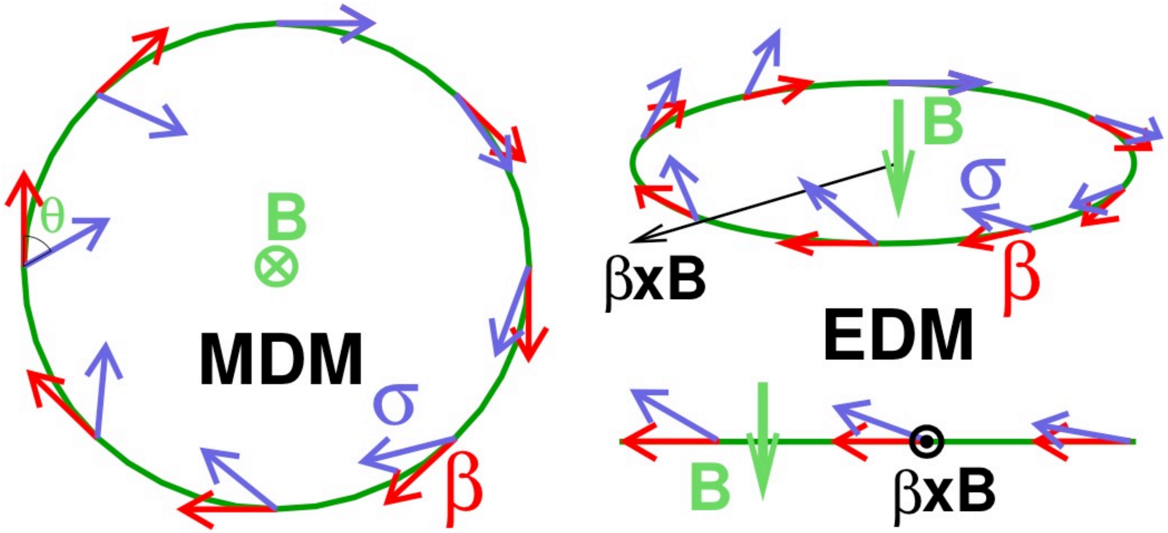
$$d_{^3\mathrm{He}} \simeq 0.90\, d_n - 0.03\, d_p + (0.11\, \bar{g}_0 + 0.14\, \bar{g}_1)\ e\,\mathrm{fm}$$

$$d_{^3\mathrm{H}} \simeq -0.03\, d_n + 0.92\, d_p - (0.11\, \bar{g}_0 + 0.14\, \bar{g}_1)\ e\,\mathrm{fm}$$

- ✓ Clear strategy to disentangle theta & the dimension-6 sources!

- ✓ *Caveats*:
  - Unreliable but small contributions from interactions with $\overline{C}_1, \overline{C}_2$
  - Three-pion contribution $\overline{\Delta}_\pi$ calculated by Bsaisou *et al*. (2015)
  - In general: Issues with nuclear chiral EFT…

EDM measurement for *charged* particles



- ✓ Spin precession in magnetic storage ring (muon "*g*−2")

$$d\mathbf{S}/d\tau = \mu \times \mathbf{B}^* + \mathbf{d} \times \mathbf{E}^*$$

  - Motional electric field large, *O*(GV/m)! $\mathbf{E}^* = \gamma c \beta \times \mathbf{B}$

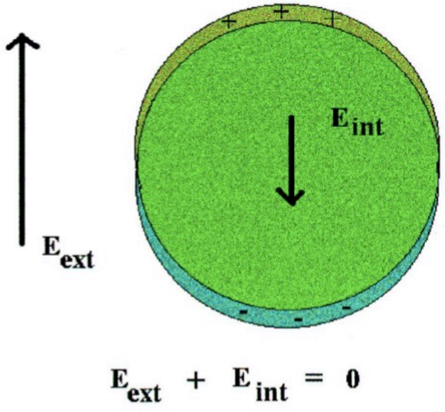
- ✓ Light nuclei: proton, deuteron, helion ^{3}He, triton ^{3}H
  - Ambitious (M€) plans $O(10^{-29})$ *e* cm @ BNL, KAIST (*p*), COSY (*D*)

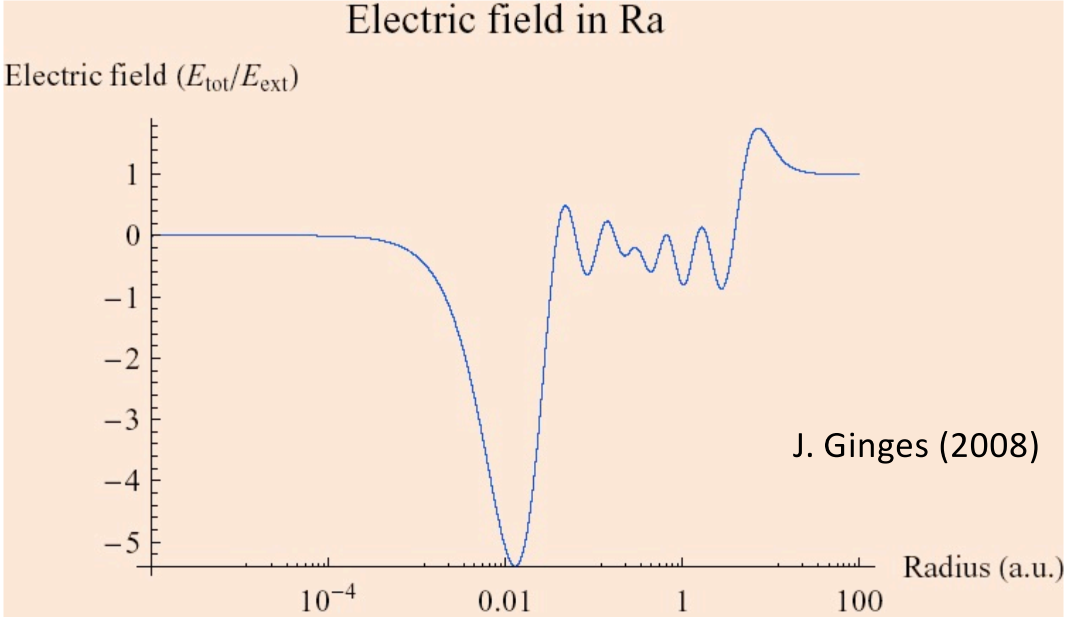
The Schiff shielding theorem

- ✓ EDM of a nonrelativistic atom = 0 *i.e.* point particles, Coulomb force
  - Electrostatic force balance, rearrangement of constituents

- ✓ Loopholes for measurability of EDMs (Schiff, 1963; Sandars, 1965)
  - Relativistic (*e*) + finite-size (*N*) + magnetic (*e*-*N*) effects
  - Residual interaction = P- and T-odd *Schiff moment*

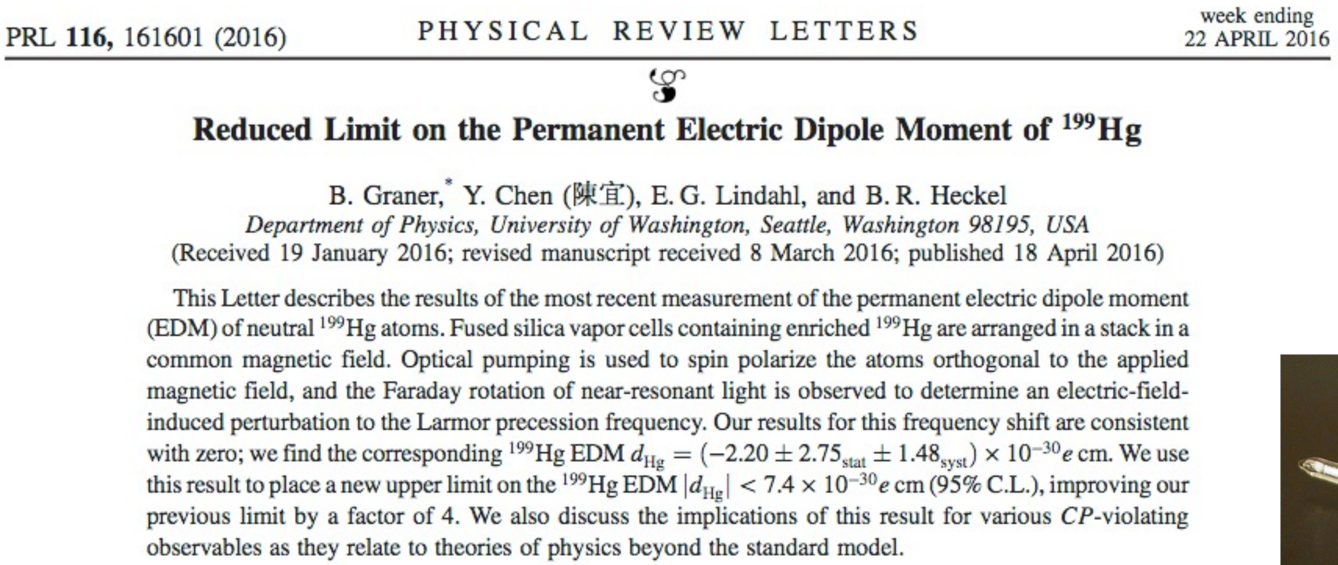
- ✓ The theorem at work:





J. Ginges (2008)

Mercury EDM



PRL **116,** 161601 (2016) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2016

Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

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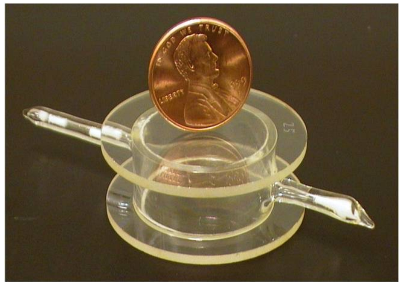
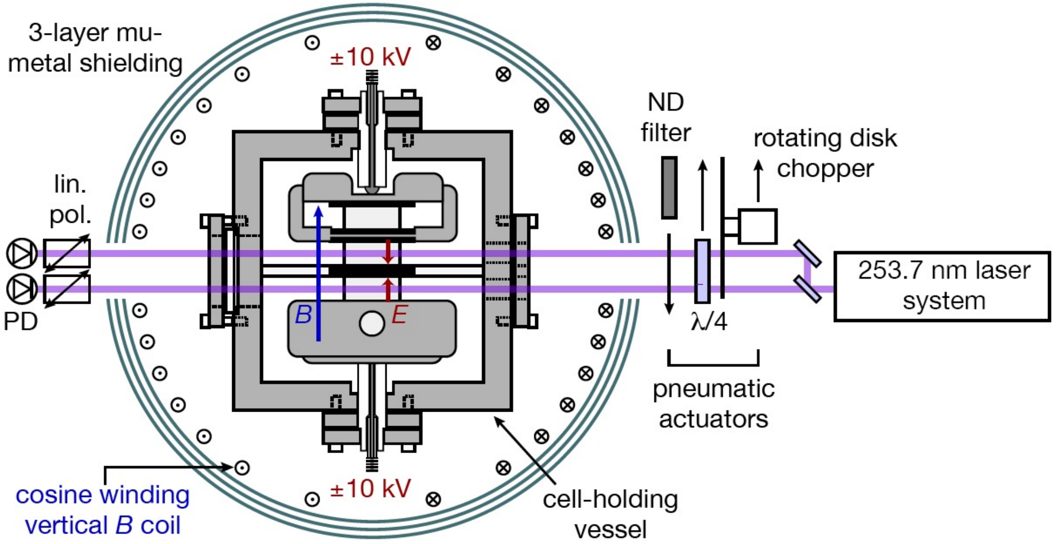
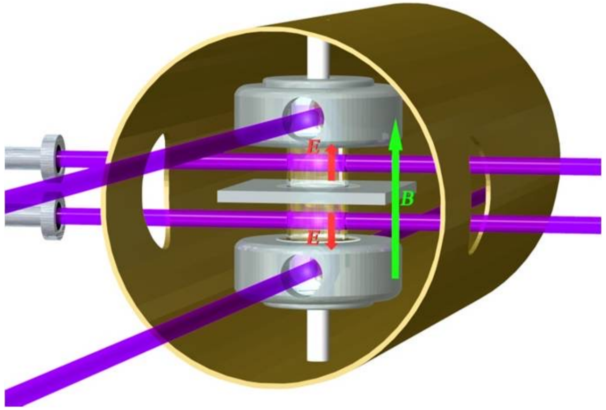
(Received 19 January 2016; revised manuscript received 8 March 2016; published 18 April 2016)

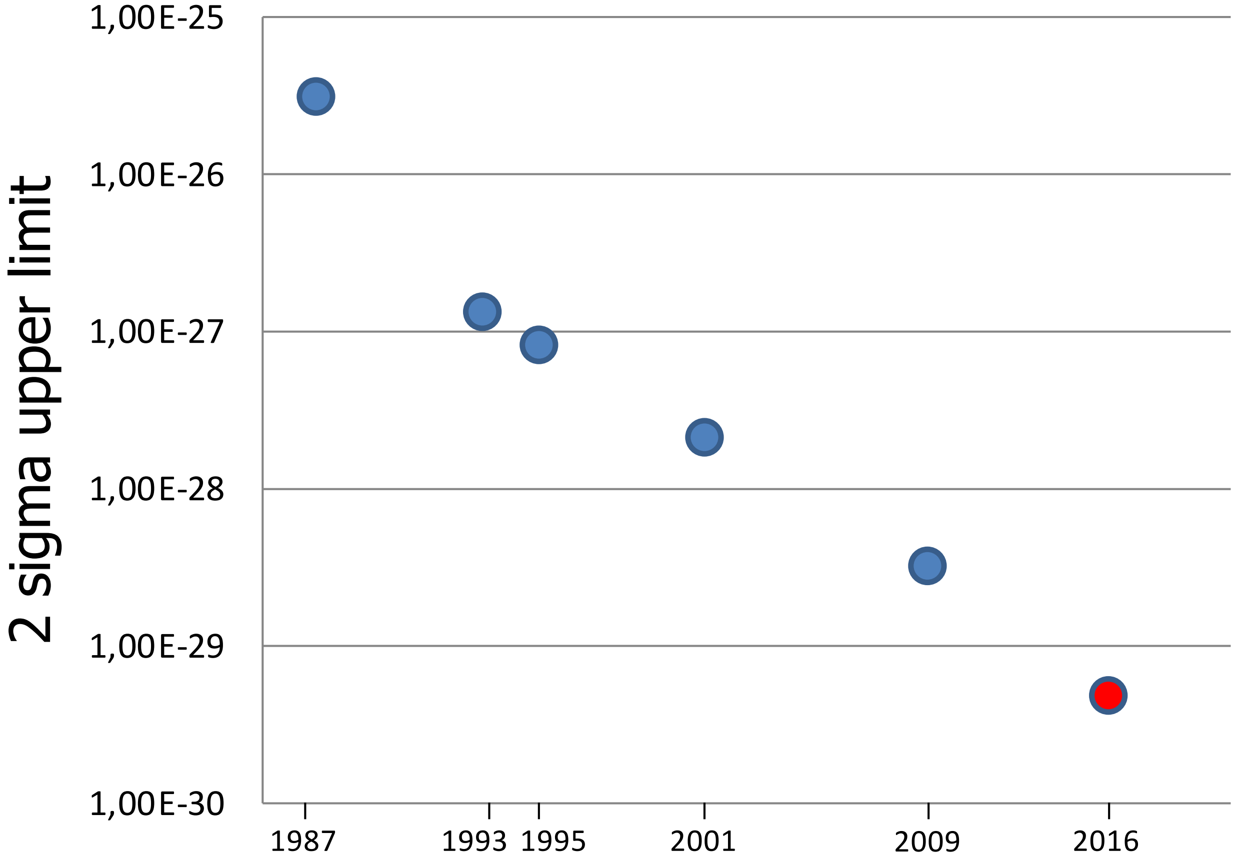
This Letter describes the results of the most recent measurement of the permanent electric dipole moment (EDM) of neutral ^{199}Hg atoms. Fused silica vapor cells containing enriched ^{199}Hg are arranged in a stack in a common magnetic field. Optical pumping is used to spin polarize the atoms orthogonal to the applied magnetic field, and the Faraday rotation of near-resonant light is observed to determine an electric-field-induced perturbation to the Larmor precession frequency. Our results for this frequency shift are consistent with zero; we find the corresponding ^{199}Hg EDM $d_{\mathrm{Hg}} = (-2.20 \pm 2.75_{\mathrm{stat}} \pm 1.48_{\mathrm{syst}}) \times 10^{-30} e$ cm. We use this result to place a new upper limit on the ^{199}Hg EDM $|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30} e$ cm (95% C.L.), improving our previous limit by a factor of 4. We also discuss the implications of this result for various *CP*-violating observables as they relate to theories of physics beyond the standard model.







History of ^{199}Hg



- ✓ Nuclear EDM shielded
  - Suppression factor $= 4Z^2 R_N/a_0 \approx 3\times10^{-4}$

- ✓ ^{225}Ra: octupole deformation → factor 10-100 enhancement
- ✓ ^{129}Xe: co-located with ^{3}He + SQUIDs → superlong spin coherence time

EDM of the ^{199}Hg atom

- ✓ Atomic part reasonably under control $d_{\mathrm{Hg}} = 2.8(6) \times 10^{-4}\, S_{\mathrm{Hg}}\ \mathrm{fm}^{-2}$
- ✓ Nuclear part not… $S_{\mathrm{Hg}} = [0.4(3)\bar{g}_0 + 0.4(8)\bar{g}_1]\ e\,\mathrm{fm}^3$
  - Complicated many-body calculation with a nuclear model

Group	**Method**	***a*$_0$**	***a*$_1$**	***a*$_2$**
Flambaum *et al.*	Schematic	0.087	0.087	0.174
Dmitriev, Sen’kov	Phen. RPA	0.00004	0.055	0.009
de Jesus, Engel	Skyrme QRPA	0.002-0.010	0.057-0.090	0.011-0.025
Engel *et al.*	Odd-*A* Skyrme MF	0.009-0.041	−0.027-+0.005	0.009-0.024

  - Core polarization is important, quenches single-particle result
  - Contribution from nucleon EDMs?
  - Reasons for discrepancies not clear… ^{199}Hg = difficult, “soft” nucleus

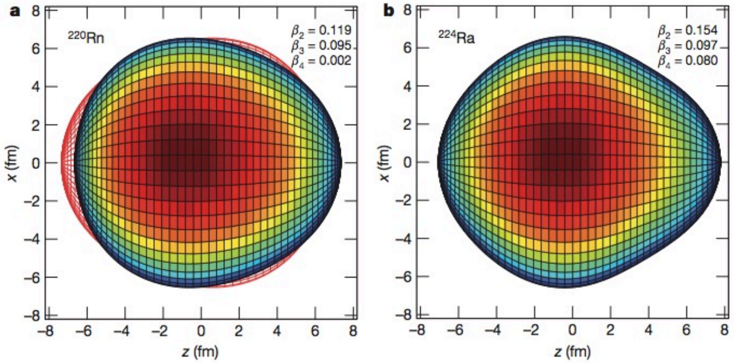
- ✓ At present could not be used to extract *e.g.* the value of θ_{QCD} …

EDM of the ^{225}Ra atom

- ✓ Big enhancement from atomic degeneracy
- ✓ Additional factor $O(5\times10^{1-2})$ from octupole ("pear-shaped") deformation
  - Shape asymmetry leads to parity doubling
  - ^{225}Ra: low-lying excited $1/2^-$ state 55 keV above $1/2^+$ ground state
  - Calculations claimed to be more reliable than for ^{199}Hg

Group	**Method**	a_0	a_1	a_2
Spevak *et al.*	Octupole-def. WS	−18.6	18.6	−37.2
Dobaczewski, Engel	Odd-*A* Skyrme MF	−1.0-(−4.7)	6.0-21.5	−3.9-(−11.0)

Gaffney *et al*. (2013)



- ✓ Schiff moment correlated with E3 transitions
  - Measured @ ISOLDE in ^{220}Rn, ^{224}Ra

- ✓ 2016: First limit on ^{225}Ra EDM

Comparison

Nucleus	Method	a_0	a_1	a_2
^{129}Xe	Phen. RPA	−0.0008	−0.0006	−0.0009
^{199}Hg	Several	0.01	±0.02	0.02
^{225}Ra	Odd-*A* Skyrme MF	−1.5	6.0	−4.0

- ✓ ^{129}Xe factor 10 less sensitive as ^{199}Hg, also “difficult” nucleus
- ✓ Enhancements in ^{225}Ra overcome the Schiff screening
  - Similar sensitivity as light nuclei

- ✓ Job of nuclear-structure calculations: $S = S(d_n, d_p, \bar{g}_0, \bar{g}_1, \overline{C}_1, \overline{C}_2, \overline{\Delta}_\pi)$
  - Requires a chiral EFT for heavy nuclei
  - Microscopic nuclear calculations using few-nucleon input
  - Careful implementation of the Schiff theorem

Amplification of *e*EDMs in paramagnetic atoms

- ✓ Shielding factor (Sandars, 1965) $K_{\rm atom} = d_{\rm atom}/d_e \simeq Z^3\alpha^2\chi$
  - $Z^2\alpha^2$ is relativistic factor, Z from E-field of nucleus
  - χ is polarizability, ≈ 10 for Cs

$$\mathbf{d}_{\rm atom} = \sum_{n'} \frac{\langle ns| - d_e(\beta-1)\sigma\cdot\mathbf{E}|n'p\rangle\langle n'p| - e\mathbf{r}|ns\rangle}{E_{ns} - E_{n'p}} + c.c.$$

- ✓ Requires an atomic-structure calculation for $_{37}$Rb, $_{55}$Cs, $_{81}$Tl, $_{87}$Fr, $_{88}$Ra*
  - $d_{\rm atom}/d_e \approx 24, 114, -570, 1150, 40.000$ for calculations

$$K_{\rm Tl} = -(570 \pm 20) \rightarrow d_e < 1.6 \times 10^{-27}\ e{\rm cm}$$

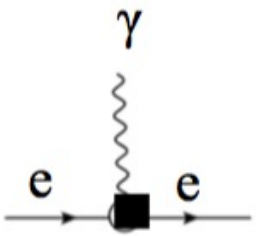
  - *Caveat*: *T*-odd electron-nucleon forces!

$$d_{\rm Tl} = -(570 \pm 20)d_e - (7.0 \pm 2.0) \times 10^{-18} C_S\ e{\rm cm}$$

(Semi-)leptonic CP violation

- ✓ Four operators @ 1 GeV

- ✓ 1 GeV



*e*EDM

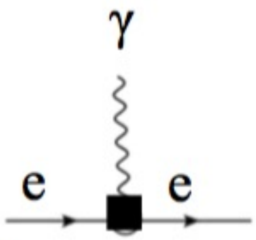
$C_S(\bar{e}\, i\gamma^5 e\, \bar{q}q)$

$C_P \quad C_T$

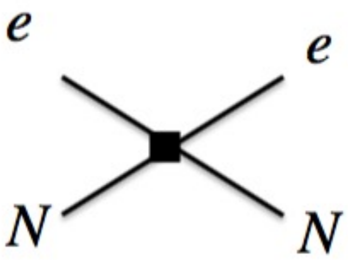
Focus on these two

Usually left out

- ✓ 0.1 GeV



*e*EDM



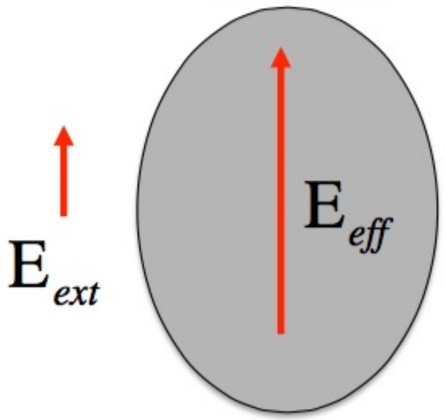
$C_S(\bar{e}\, i\gamma^5 e\, \bar{N}N)$

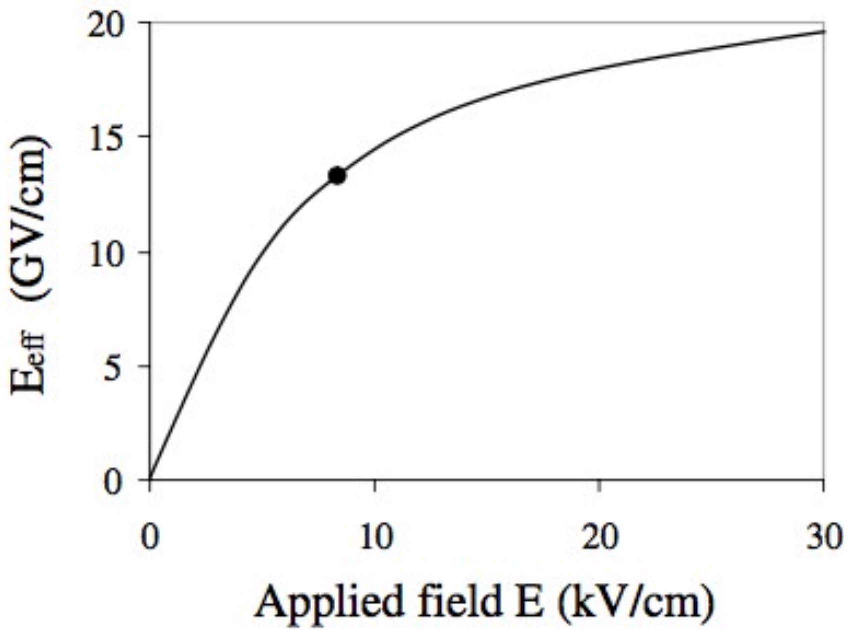
Hadronic matrix elements relatively well-known

Polar molecules

- ✓ Convert strong external electric field to HUGE internal field
  - Effective field = nonlinear function of external field

$$\Delta E \simeq E_{eff}(E_{ext})\, d_e$$





- From J. Hudson *et al.*, PRL 2002

$$\Delta E_{\mathrm{YbF}} = (15 \pm 2)\,\mathrm{GeV}\left[\frac{d_e}{e\mathrm{cm}}\right] + \mathcal{O}(C_S)$$

$$\Delta E_{\mathrm{ThO}} = (80 \pm 10)\,\mathrm{GeV}\left[\frac{d_e}{e\mathrm{cm}}\right] + \mathcal{O}(C_S)$$

Disentangling the sources

- ✓ Limits on CP violation
  - ASSUME no cancellation with C_S
  - OR no cancellation with *e*EDM

$$d_e < 8.7 \times 10^{-29}\ ecm$$
$$C_S < 5.9 \times 10^{-9}$$

  - Allow for cancellations

$$d_e < 5.4 \times 10^{-27}\ ecm$$
$$C_S < 4.5 \times 10^{-7}$$

- ✓ Find a signal, what is responsible?
  - Need two measurements

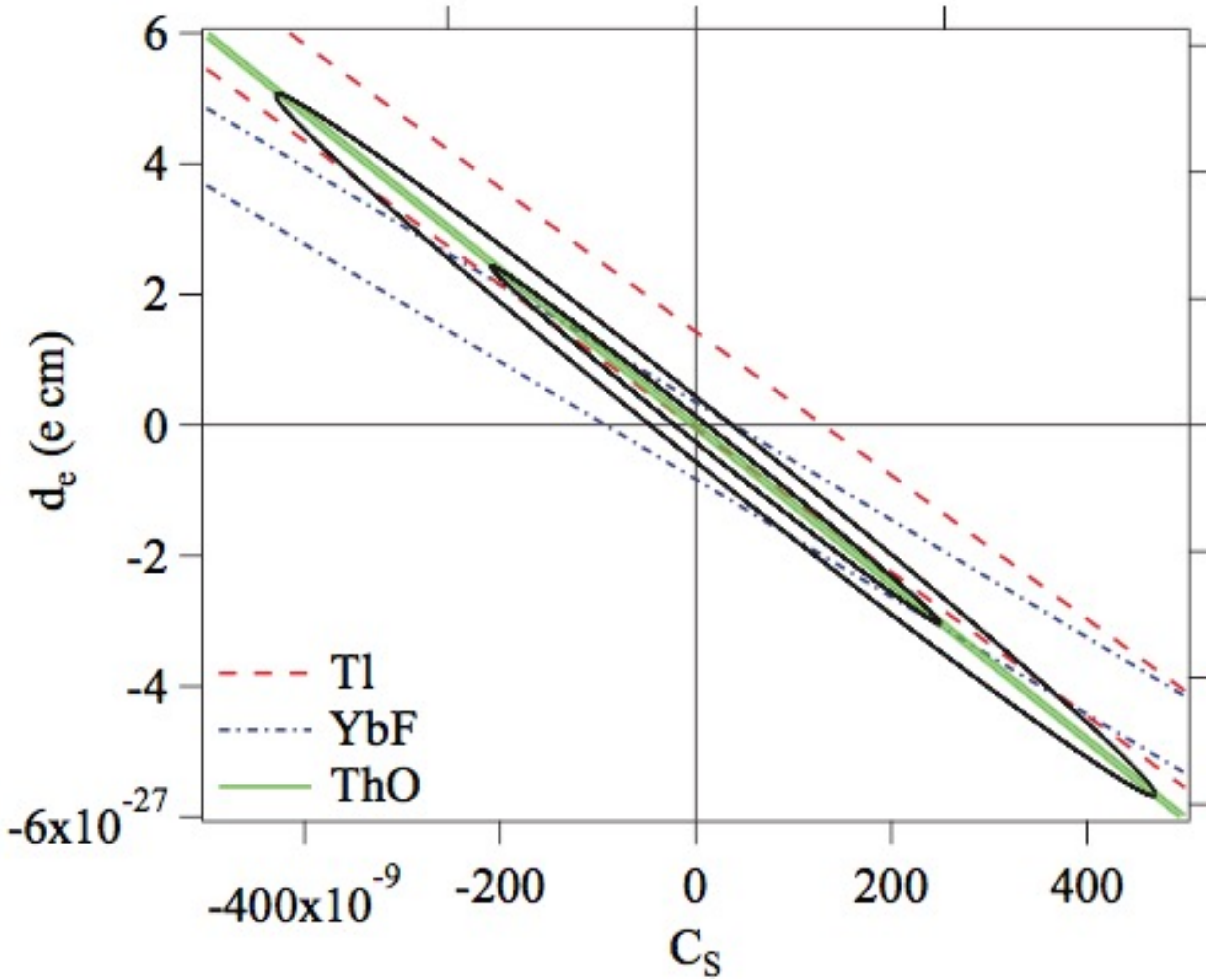
$$\Delta E = \alpha d_e + \beta C_S$$

	Tl	YbF	ThO
β/α in 10^{-20} *e*cm	1.15	0.85	1.25

  - Combine with para- (Cs, Fr) or diamagnetic atoms (Xe, Hg, Ra)

- ✓ Pseudo-scalar & tensor semi-leptonic interactions?
  - Constraints from diamagnetic atoms?

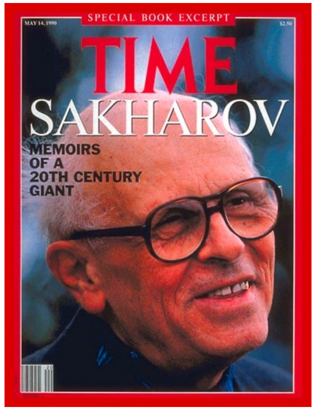
Correlations



- ✓ Depends on specific particle physics model
  - Several models have one dominant source, *e.g.* *e*EDM in mLRSM

Matter over antimatter

- ✓ Matter-antimatter asymmetry of the Universe requires (A. Sakharov, 1967)
  - Violation of baryon number
  - Violation of C and CP
  - Departure of thermal equilibrium
  - (Or: CPT violation!)



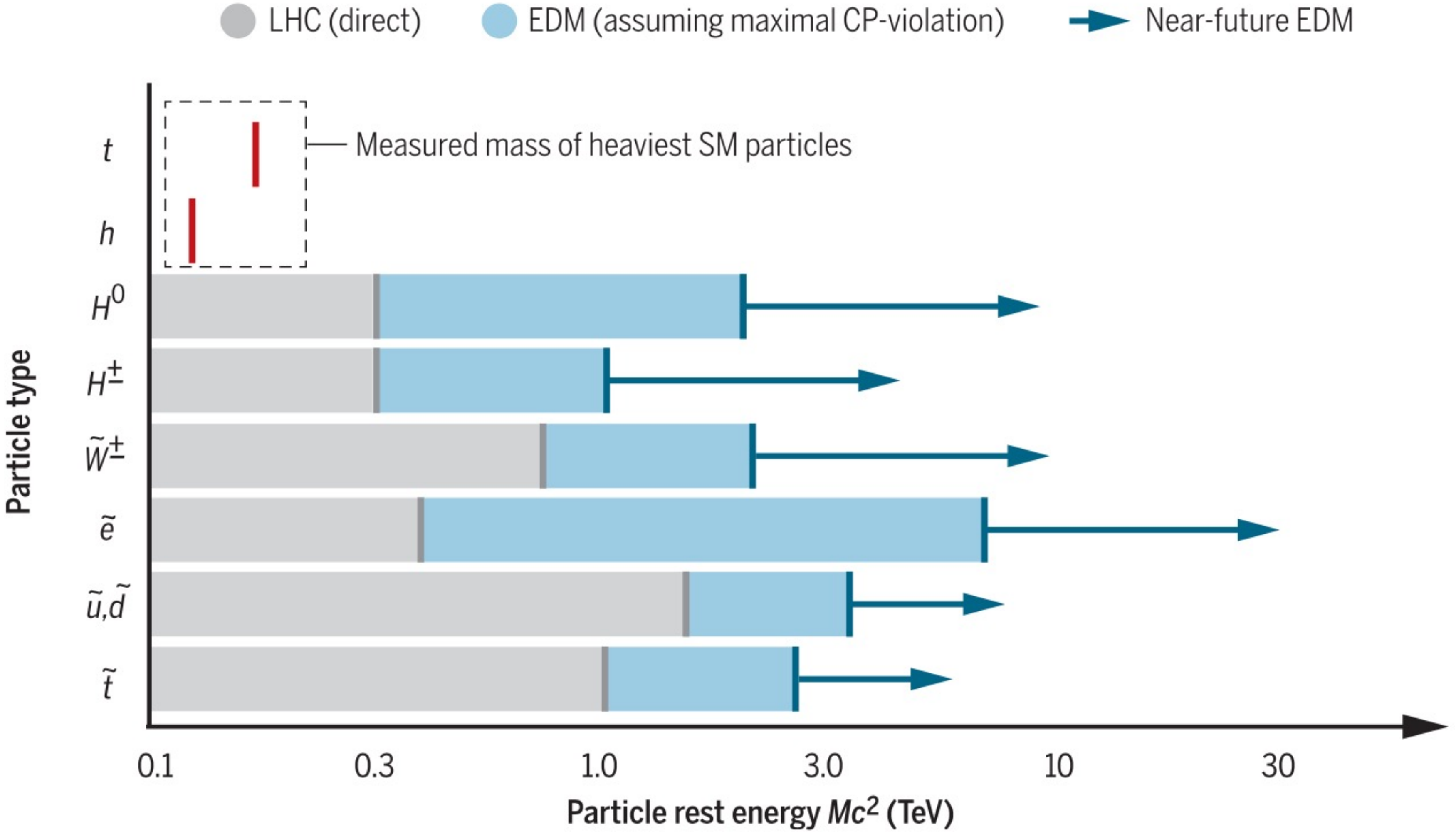
- ✓ Not enough CP violation within the SM, off by factor $O(10^9)$
  - Physics at a new scale of O(TeV) → measurable EDMs?

- ✓ *“If the weak interactions of atomic physics would – contrary to expectation – not be invariant for time inversion, would this have any consequences for cosmological or cosmogonic questions?”*

  - J. R. Oppenheimer after talk “The arrow of time” by T. Gold
  - “La structure et l’évolution de l‘Univers”, Bruxelles, 9-13 juin 1958

DeMille *et al.*, Science **357**, 990 (2017)

Summary: The killer EDM



✓ **EDM searches set the roadmap for particle (collider) physics (energy frontier)!**

Take-home messages

- ✓ Message 1: EDM experiments are HYPER-sensitive
  - Next generation probes energy scales up to 10 - 100 TeV

- ✓ Message 2: EDMs are ULTRA-relevant to SUPER-symmetry *et al*.
  - Upon discovery, we can disentangle the sources of CP violation

- ✓ To make progress we need:
  - Lattice QCD
  - *"Data! Data! Data! We cannot make bricks without clay!"*

That’s all, folks!

It is easier to measure things that stand still…