EDMs:
particle physics for the poor

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"Beyond the Standard Model with neutrinos & nuclear physics"
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With Jordy de Vries, Emanuele Mereghetti, Cheng-Pang Liu, Bira van Kolck

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

A new world record

- ✓ J. Baron *et al.* (Harvard-Yale)
  - Science **343**, 269 (2014)
  - New J. Phys. **19**, 073029 (2017)

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

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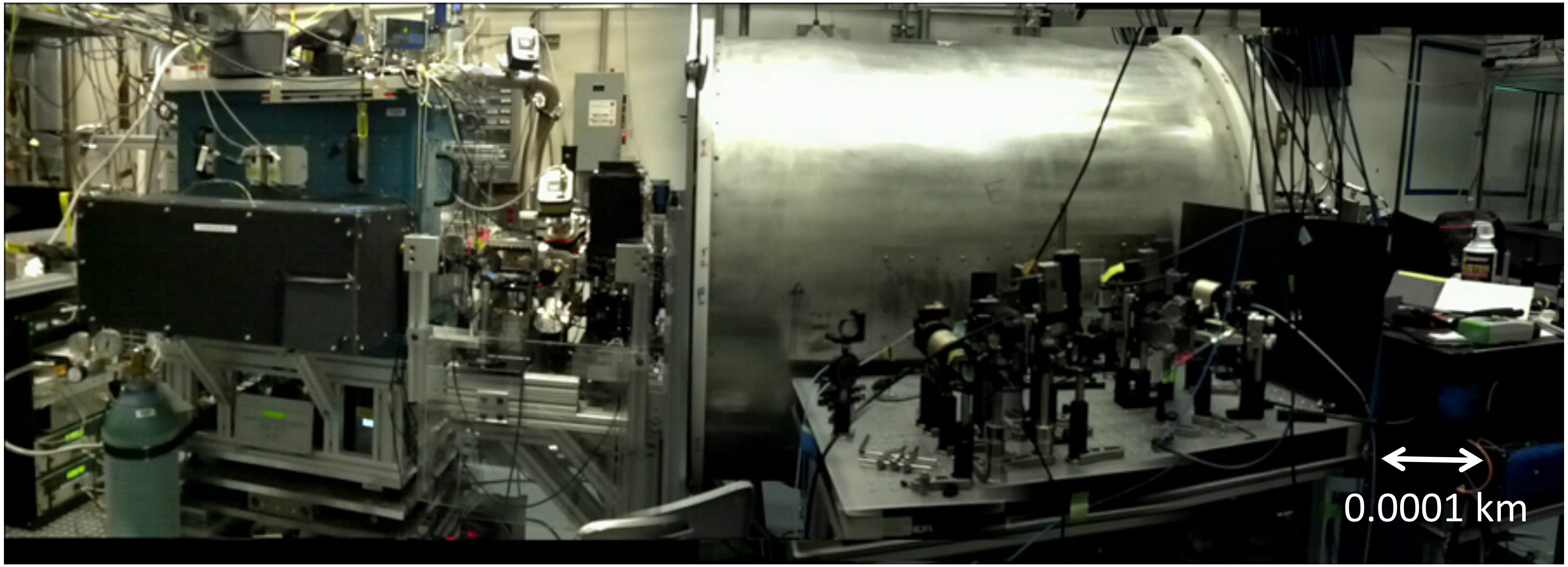
The Standard Model of particle physics is known to be incomplete. Extensions to the Standard Model, such as weak-scale supersymmetry, posit the existence of new particles and interactions that are asymmetric under time reversal (T) and nearly always predict a small yet potentially measurable electron 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 $d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ $e\cdot$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.



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

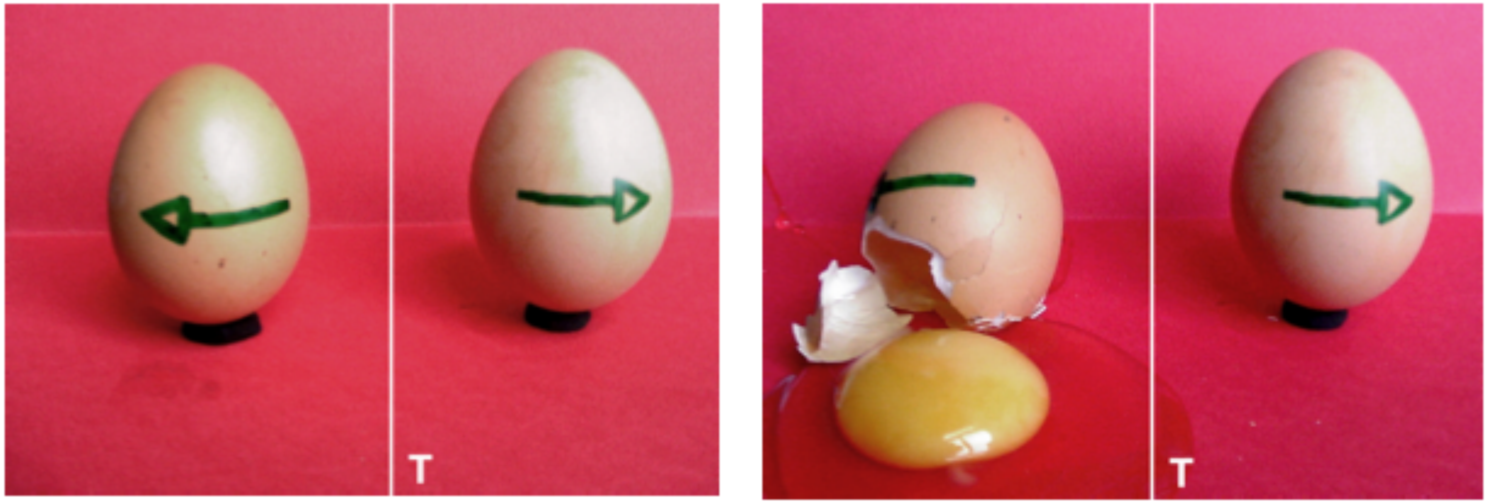
3. Hadronic EDMs
   - ✓ Nucleons, light nuclei & diamagnetic atoms

4. [… The electron EDM
   - ✓ Paramagnetic atoms & molecules…]

5. Take-home messages

What is an EDM?

- ✓ A permanent EDM violates P & T, hence [CPT theorem $\rightarrow$] 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

The hunt for discovery

electron

System	Group	Limit in *e* cm	C.L.	Value in *e* cm	Year
^{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/Boulder	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017
ThO	Harvard/Yale	9.4×10^{-29}	90	$-2.2(4.8) \times 10^{-29}$	2014
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	UMich	6.6×10^{-27}	95	$0.7(3.3)(0.1) \times 10^{-27}$	2001
^{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	$4.0(6.0)(0.2) \times 10^{-24}$	2016

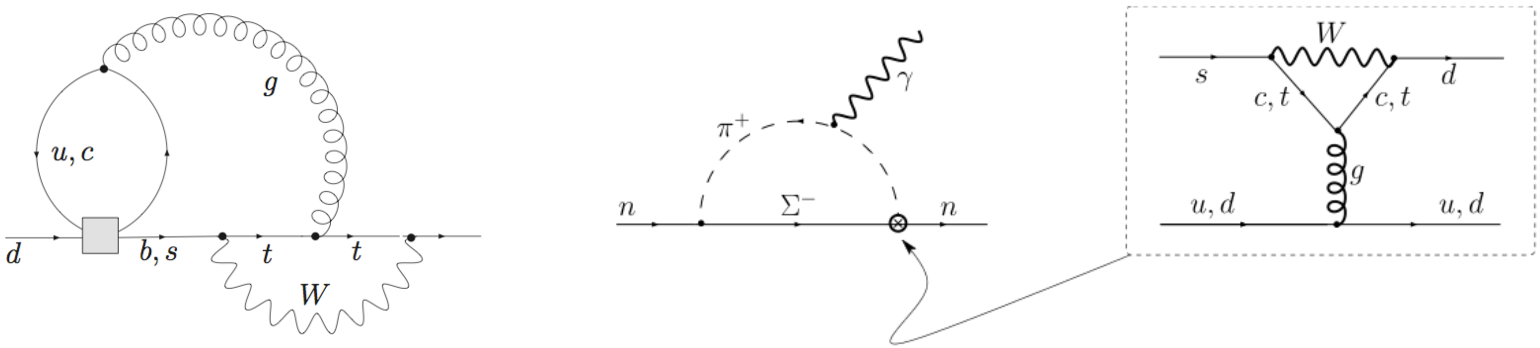
✓ 25-30 more-or-less small-scale expt's worldwide with ≈ 500 researchers

Electroweak CP violation

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

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

- ✓ "Long-distance" contributions to *n*EDM



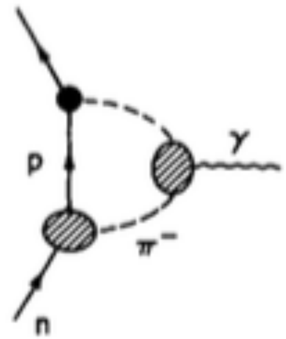
The QCD vacuum angle

- ✓ Observed symmetries *almost* perfectly match those of QCD

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

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

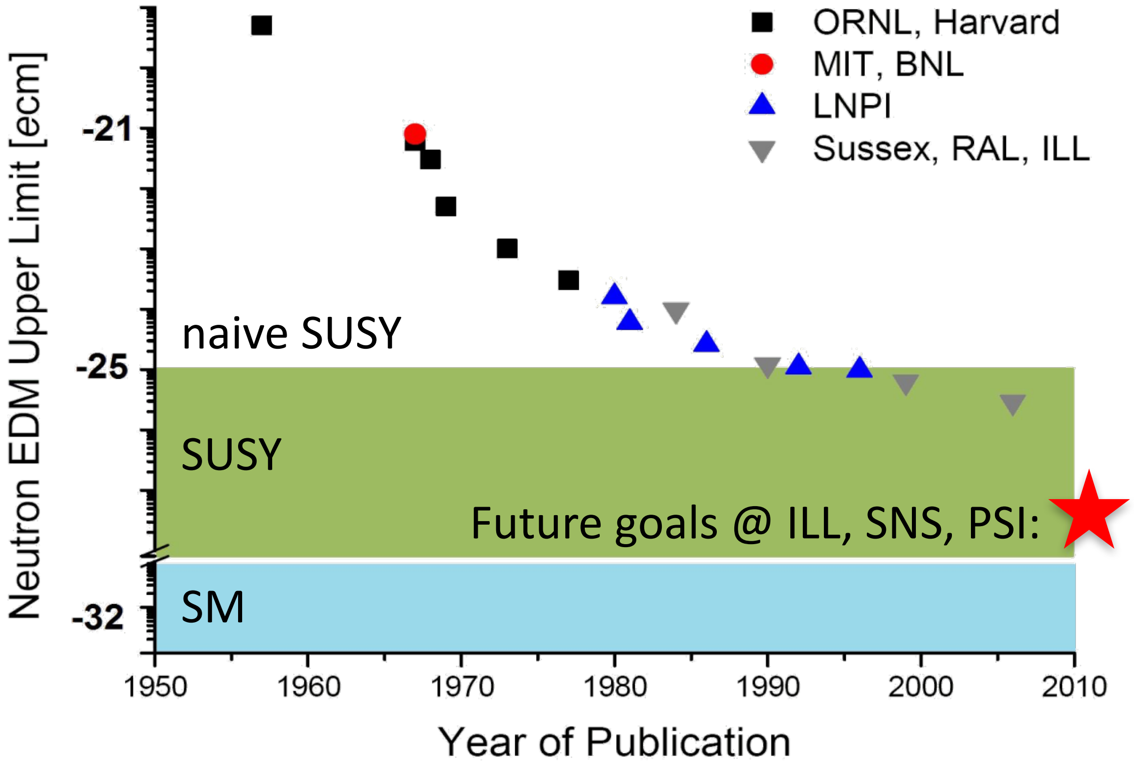
- ✓ Long-distance contributions to *n*EDM → non-perturbative QCD
  – "Soft-pion" theorem: Chiral log dominates $d_n \sim \theta \, \log m_\pi^2$
  – Nowadays: Chiral perturbation theory = EFT for QCD



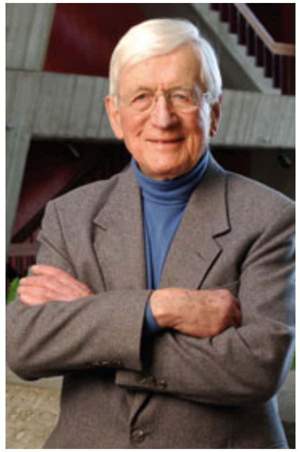
- ✓ A nonzero EDM implies new, super-weak physics
  – EDMs arise at 1-loop level from new δ_{CP}'s OR from θ_{QCD} (also new!)

Neutron EDM

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

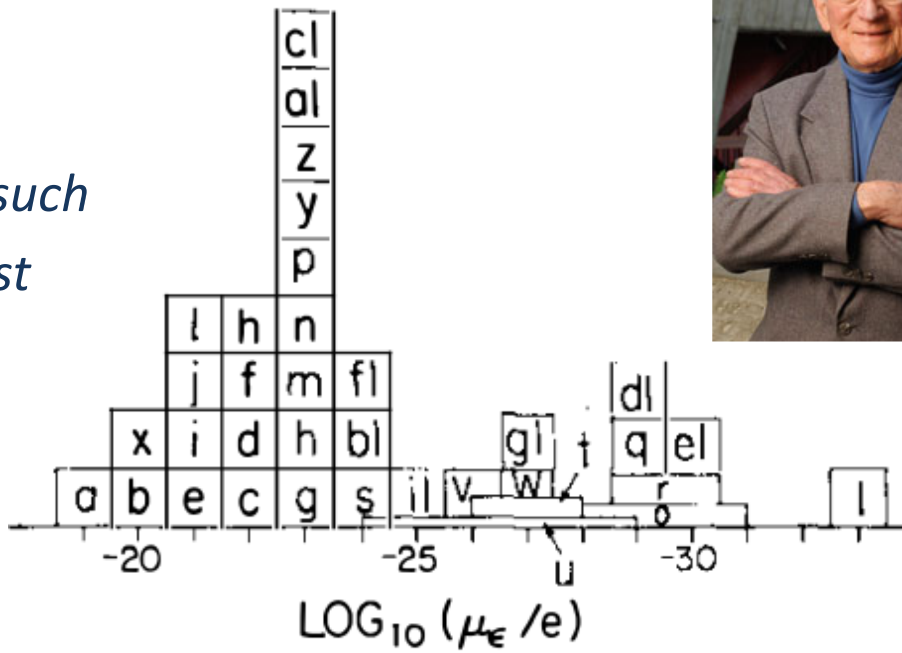


The killer *n*EDM



- ✓ 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)

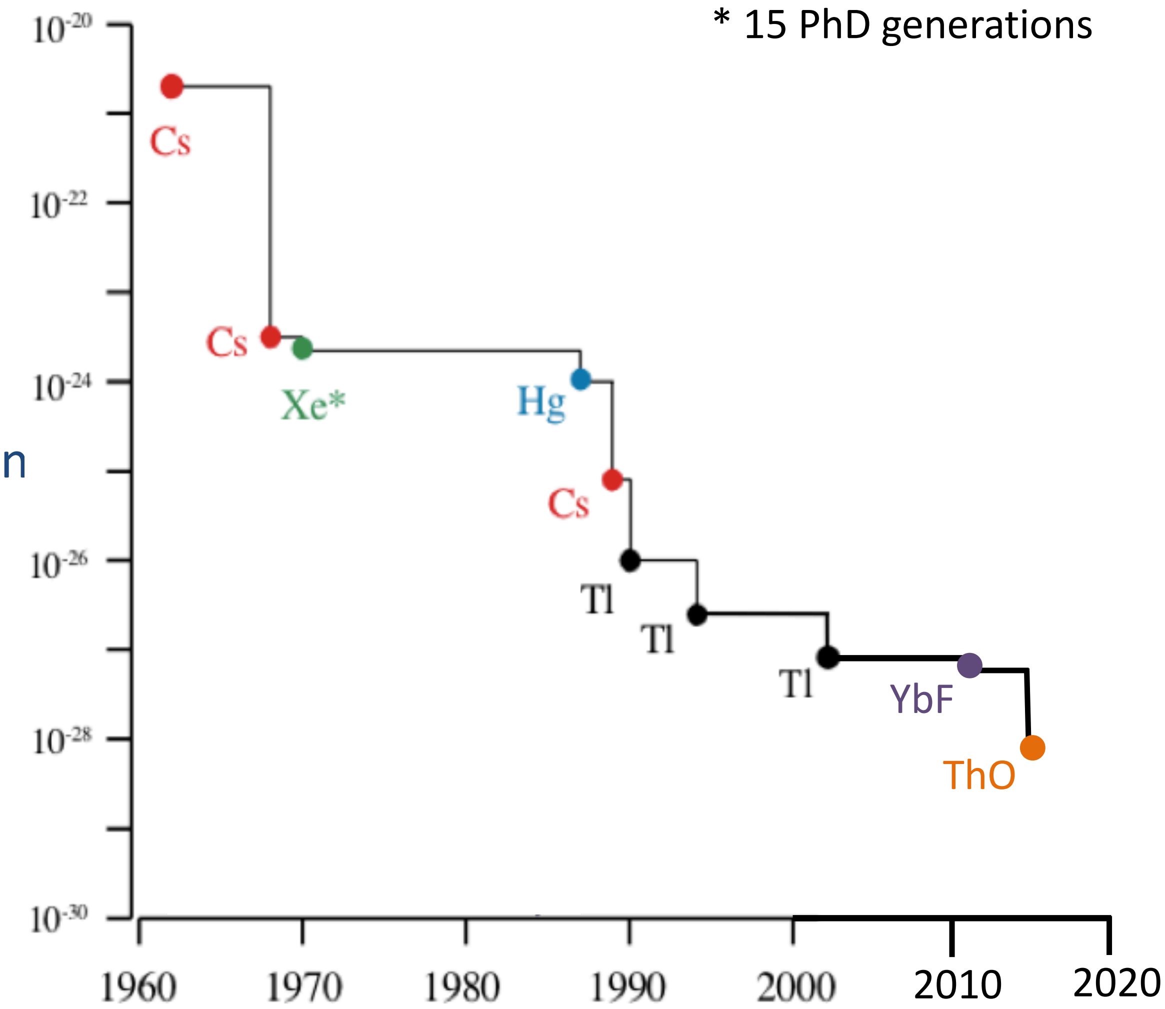
The killer *e*EDM

- ✓ 2014: 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 $|d_e| < 8.7 \times 10^{-29}$ *e* cm → scale of new physics Λ > few TeV

The need for interpretation

- ✓ Limit on ^{199}Hg EDM
  - Swallows *et al.*, 2013
  - Lots of crappy modeling

TABLE IV. Limits on *CP*-violating parameters (defined in the text) based on our new experimental limit for $d(^{199}\text{Hg})$ (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, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

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

- ✓ 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

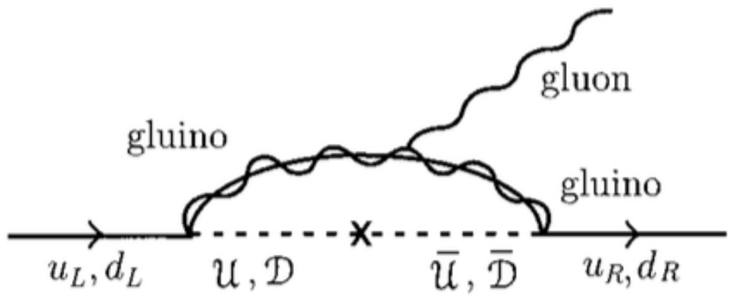
The SUSY CP problem

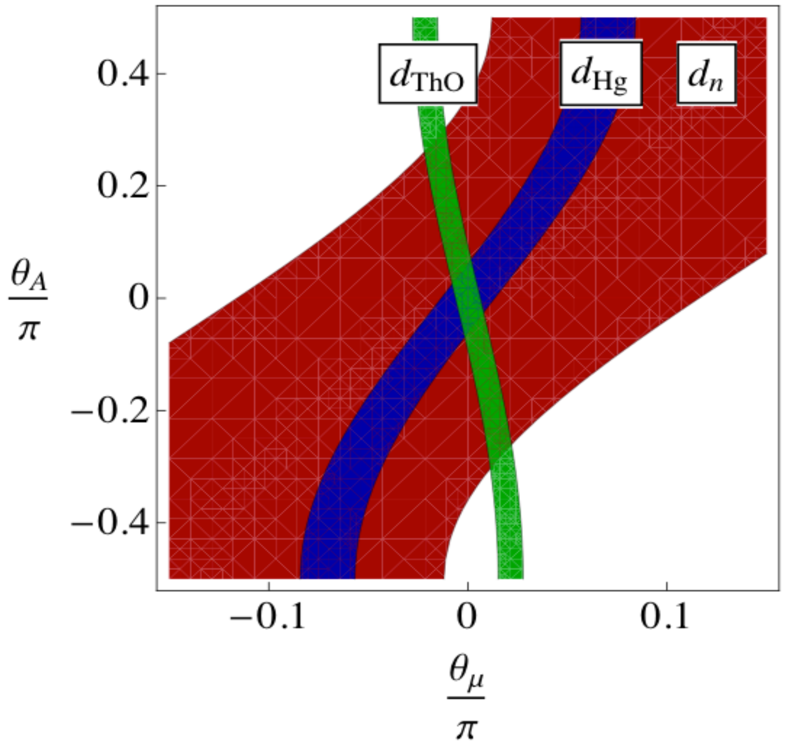
✓ MSSM has > 100 parameters, 10s δ_{CP}-like

✓ 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

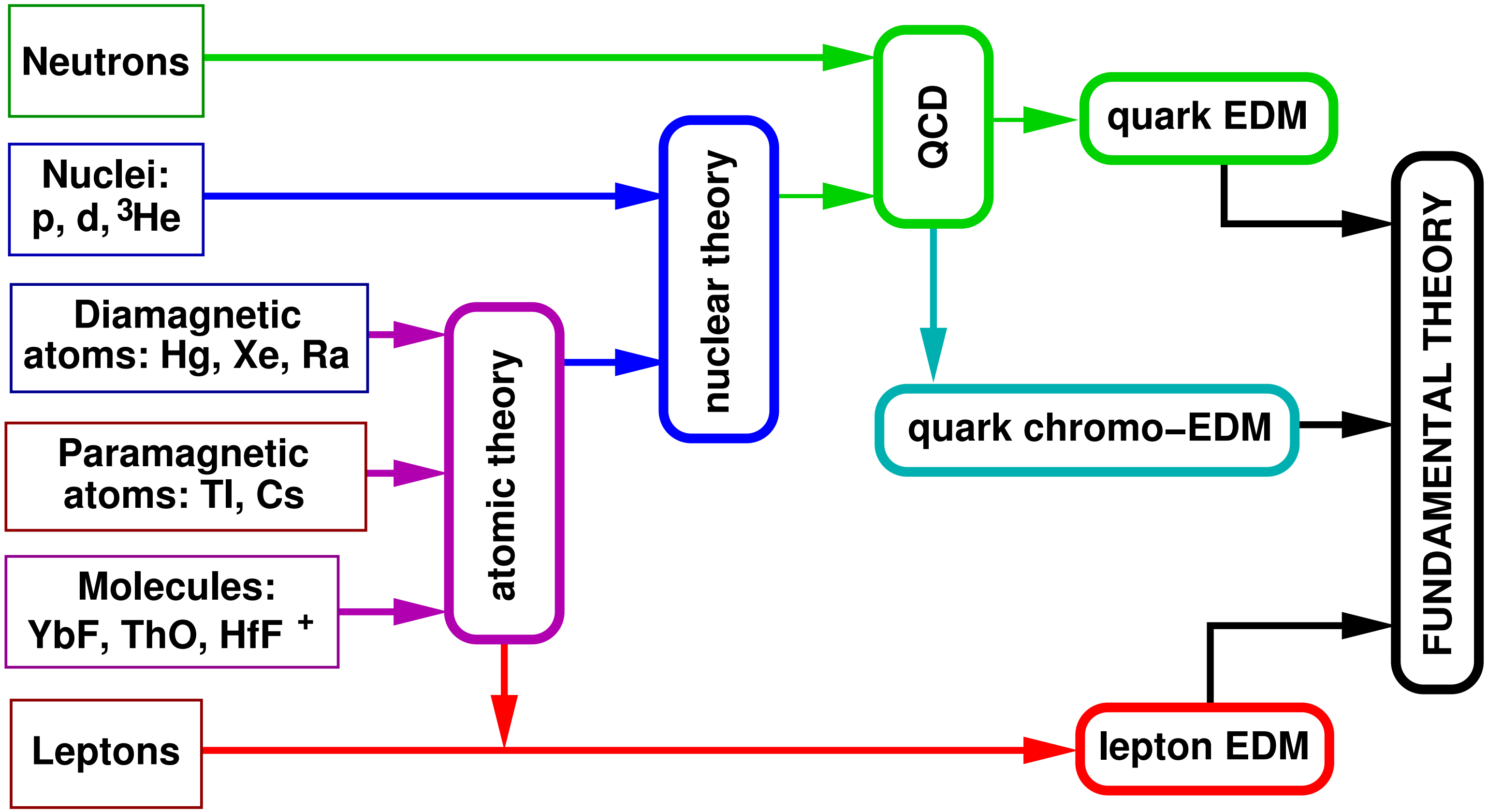
✓ Current EDM null results → probe 1-10 TeV scale or $\delta_{CP} \leq O(10^{-2})$

- Next generation → sensitive to 10-100 TeV scale or $\delta_{CP} \leq O(10^{-4})$

The EDM landscape

✓ Scales

– yeV keV MeV GeV TeV ??



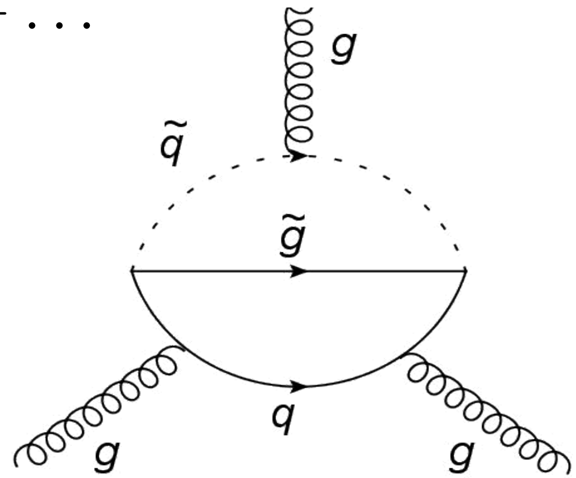
✓ Theory is essential for the interpretation of EDMs of complex systems

The Standard Model as an effective field theory

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

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

- ✓ Integrate out heavy (new) particles



- ✓ 1 TeV?

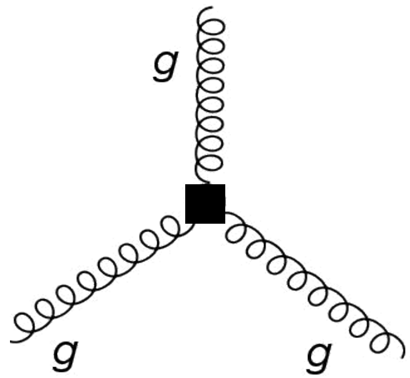
Q

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

- ✓ 100 GeV

gluon color-EDM

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

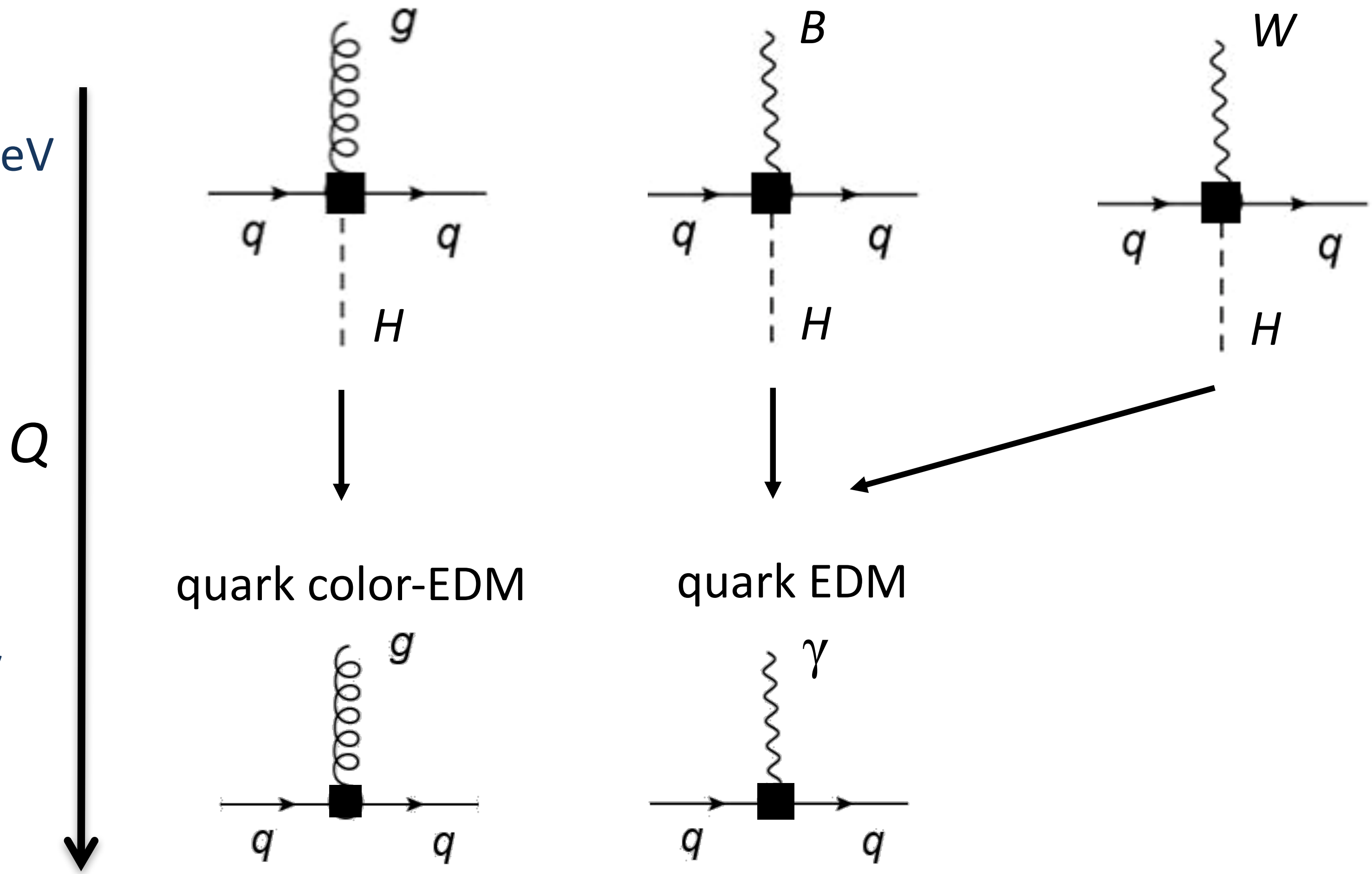


$$d_W \sim \frac{1}{\Lambda^2}$$

Dimension-6 sources

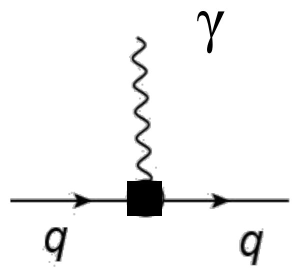
- ✓ Electroweak symmetry breaking, integrate out heavy particles
  - EDMs flip chirality → effectively dimension 6, prop. to $m = g_{\text{Yukawa}}\, v/\sqrt{2}$

- ✓ 100 GeV
- ✓ 1 GeV

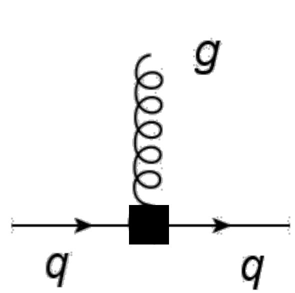


Summary: dimension-4 and -6 sources @ 1 GeV

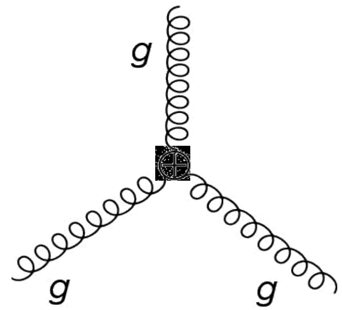
QCD θ-term



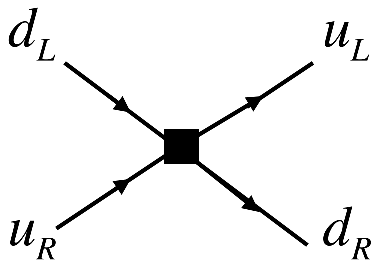
quark EDM



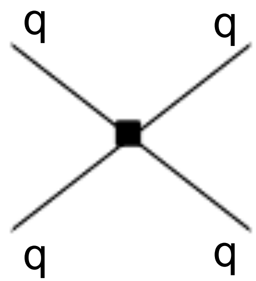
quark color-EDM



gluon color-EDM



left-right 4-quark term



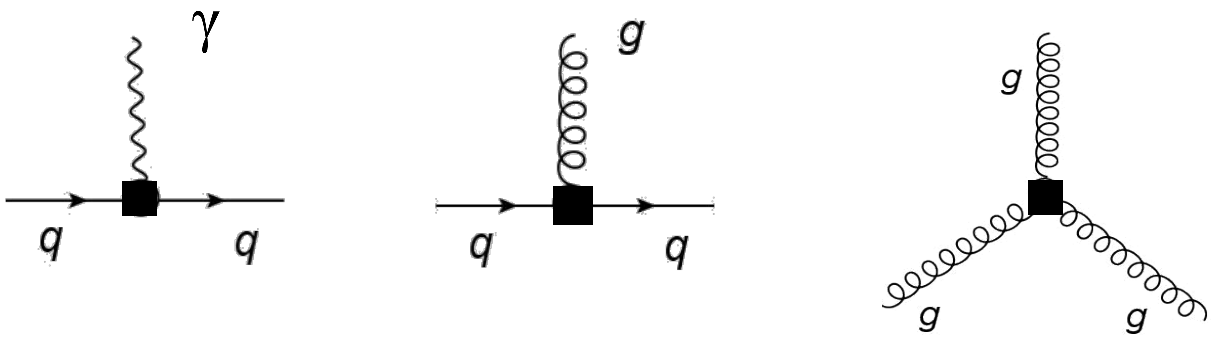
2 chiral-invariant 4-quark terms

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

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

Next: nonperturbative QCD

QCD θ-term

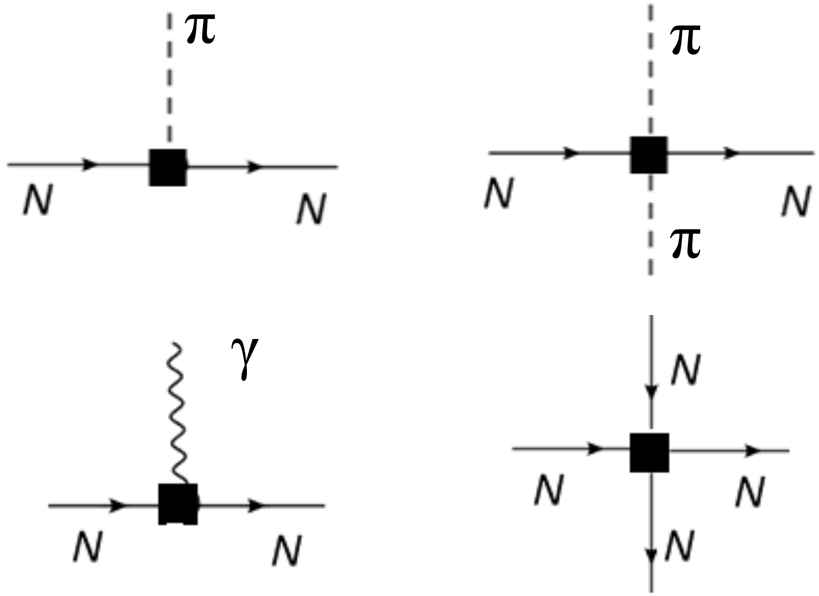


quark EDM | quark color-EDM | gluon color-EDM

✓ 1 GeV

Q

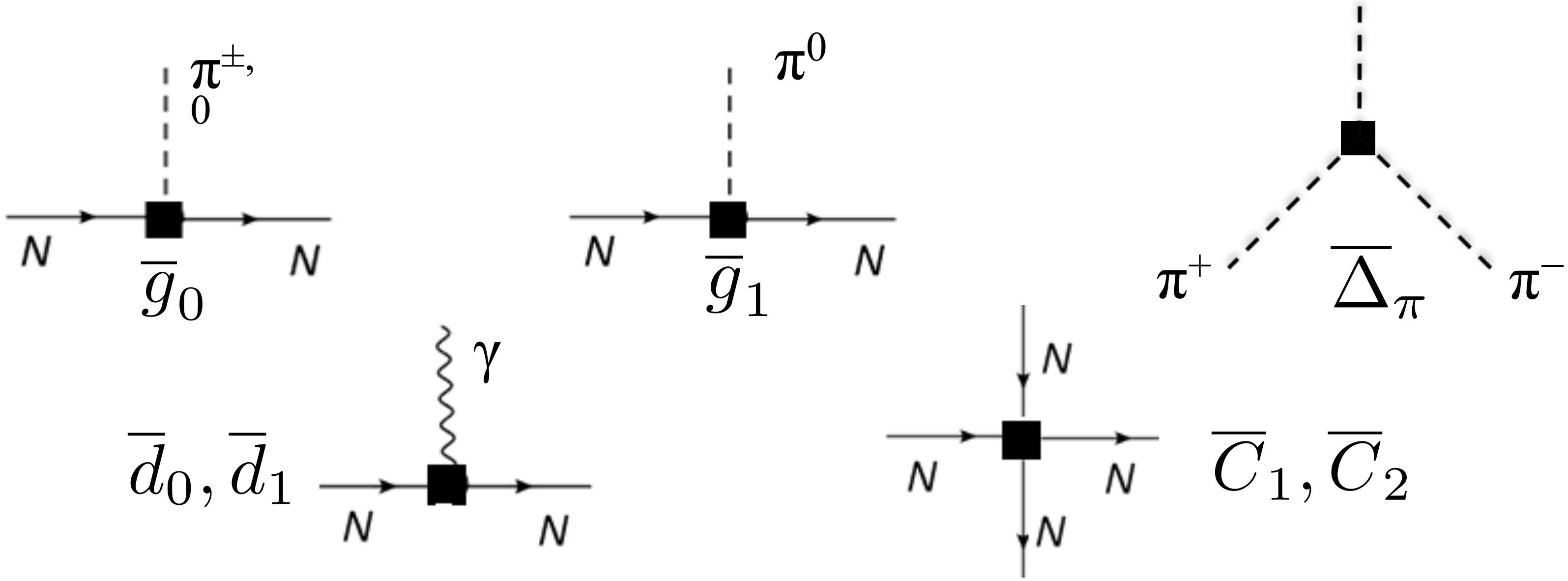
χPT = chiral perturbation theory



✓ 100 MeV

The magnificent seven

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



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

✓ 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
  - Link to isospin violation

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

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

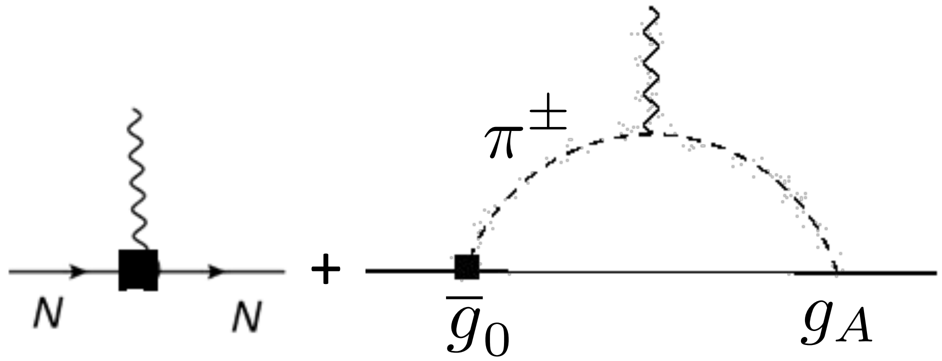
$$\bar{g}_0^\theta = \frac{(M_n - M_p)^{\mathrm{strong}}}{F_\pi}\frac{(1-\varepsilon^2)}{2\varepsilon}\bar{\theta} = -0.018(7)\,\bar{\theta}$$

$$\bar{g}_1^\theta = \frac{8c_1(\delta m_\pi^2)^{\mathrm{strong}}}{F_\pi}\frac{(1-\varepsilon^2)}{2\varepsilon}\bar{\theta} = 0.003(2)\,\bar{\theta}$$

  - Input from phenomenology (π*N* σ-term) & LQCD

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d} = -0.35(10)$$

Nucleon EDMs



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

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

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

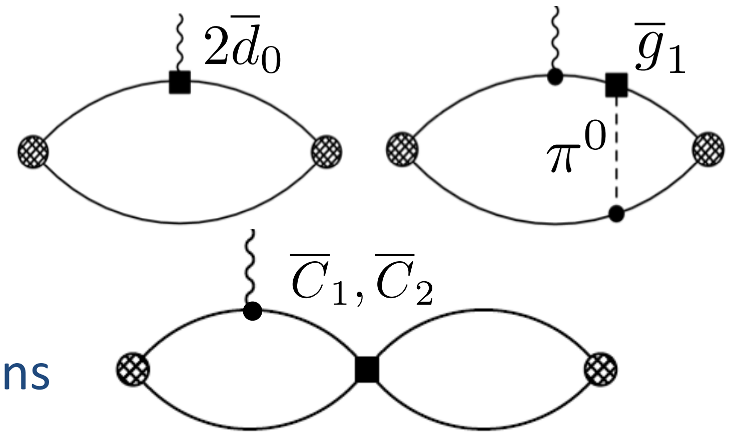
  - 3 unknowns… can be fitted by any source
  - For each source neutron & proton EDMs of same order
  - Absorb loop contributions in $\bar{d}_{0,1}$

- ✓ For theta term, with LQCD input:

$$d_n^\theta = -2.9(9) \times 10^{-16}\,\bar{\theta}\; e\,\mathrm{cm}$$

$$d_p^\theta = +1.1(1.1) \times 10^{-16}\,\bar{\theta}\; e\,\mathrm{cm}$$

Deuteron EDM



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

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

- ✓ Little model dependence

$$d_D = d_n + d_p + [0.180(23)\overline{g}_1 + 0.0028(3)\overline{g}_0]\, e\,\text{fm}$$

  - For quark color-EDM d_D is significantly larger than $d_n + d_p$

- ✓ Way to extract theta, or more generally $\overline{g}_1$, from data

$$d_D^{\overline{\theta}} = [-1.8(1.4) + 0.55(36)(5) - 0.05(2)(1)] \times 10^{-16}\,\overline{\theta}\, e\,\text{cm}$$

Helion & triton EDMs

- ✓ Calculated for all sources in consistent EFT framework
  - Hadronic uncertainties still dominate over nuclear ones
  - Unreliable but small contributions from interactions with $\overline{C}_1, \overline{C}_2$
- ✓ For *e.g.* QCD theta term

$$d^{\overline{\theta}}_{^3\mathrm{He}} = [-2.60(0.80) - 1.36(88)] \times 10^{-16}\,\overline{\theta}\,e\,\mathrm{cm}$$
$$d^{\overline{\theta}}_{^3\mathrm{H}} = [+1.10(0.96) + 2.16(85)] \times 10^{-16}\,\overline{\theta}\,e\,\mathrm{cm}$$

- ✓ Master table:

	d_0	d_1	g_0	g_1	C_1	C_2
n	1	−1	-	-	-	-
p	1	1	-	-	-	-
D	2	0	≈ 0	−0.19	-	-
^{3}He	0.83	−0.93	−0.15	−0.28	−0.01	0.02
^{3}H	0.85	0.95	0.15	−0.28	0.01	−0.02

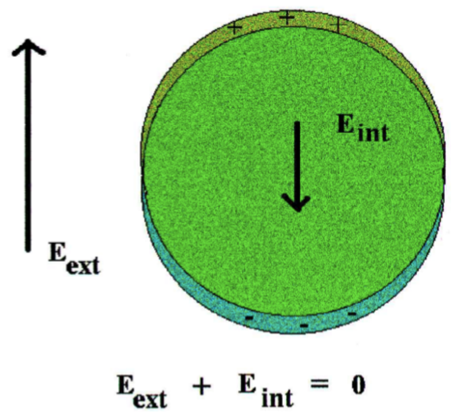
  - Clear strategy to disentangle the sources!

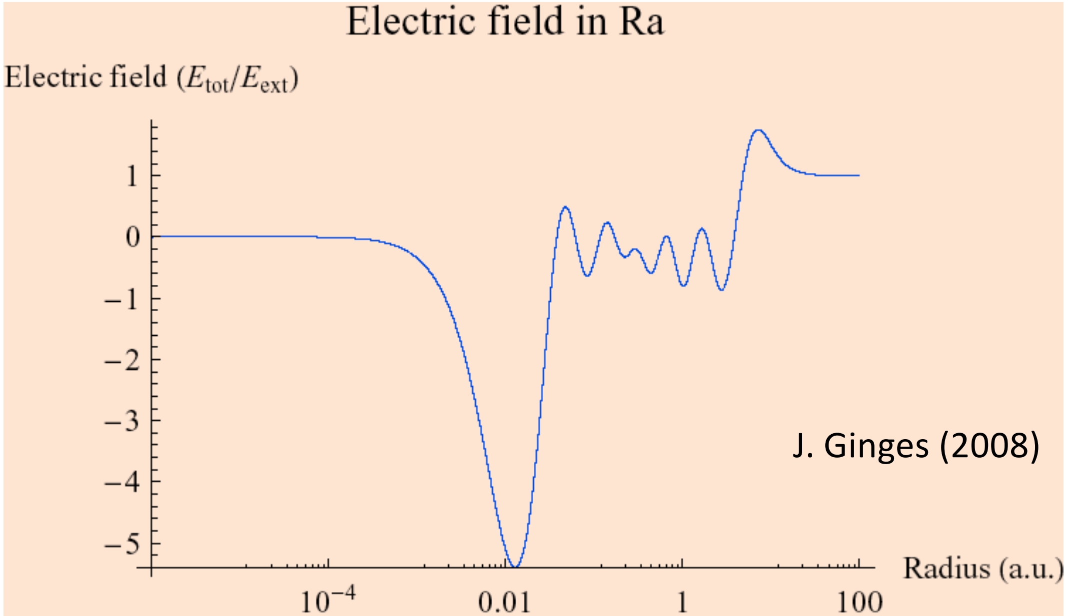
The Schiff shielding theorem

- ✓ 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:





EDMs of diamagnetic atoms

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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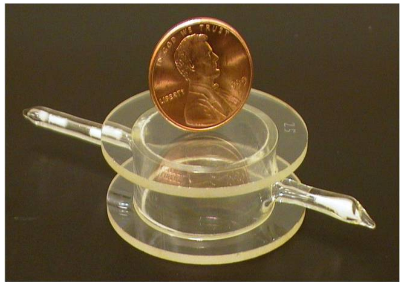
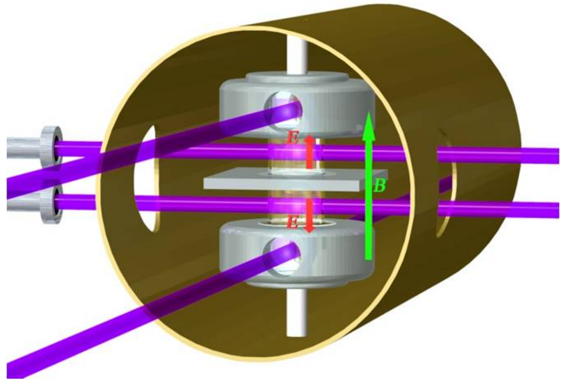
This Letter describes the results of the most recent measurement of the permanent electric dipole moment (EDM) of neutral ^{199}Hg atoms. Fused silica vapor cells containing enriched ^{199}Hg are arranged in a stack in a common magnetic field. Optical pumping is used to spin polarize the atoms orthogonal 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.





- ✓ Nuclear EDM shielded
  - Suppression factor $4Z^2 R_N/a_0 \approx 3\times10^{-4}$
  - Hypersensitive experiments possible
  - Difficult to interpret theoretically
- ✓ ^{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 $$d_{\rm Hg} = 2.8(6) \times 10^{-4}\, S_{\rm Hg}\ {\rm fm}^{-2}$$
- ✓ Nuclear part not… $$S_{\rm Hg} = [0.4(3)\bar{g}_0 + 0.4(8)\bar{g}_1]\ e\,{\rm fm}^3$$
  - 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

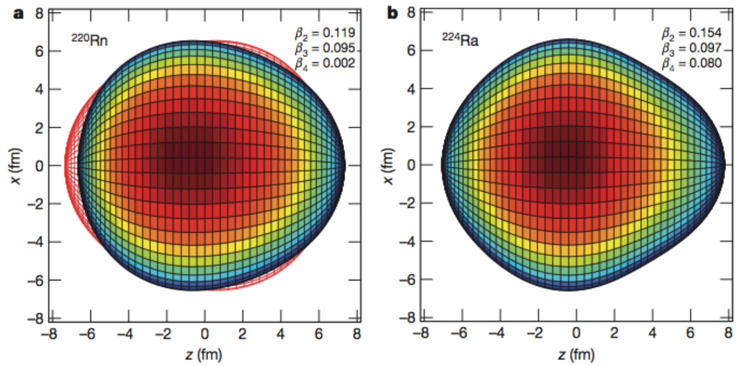
- ✓ At present could not be used to extract *e.g.* the value of θ_{QCD} …

EDM of the ^{225}Ra atom

- ✓ Big enhancement from atomic degeneracy
- ✓ Additional factor $O(5\times10^{1\text{-}2})$ 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) $K_{\text{atom}} = d_{\text{atom}}/d_e \simeq Z^3\alpha^2\chi$

– $Z^2\alpha^2$ is relativistic factor, *Z* from *E*-field of nucleus

– χ is polarizability, ≈ 10 for Cs

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

✓ Requires an atomic-structure calculation for $_{37}$Rb, $_{55}$Cs, $_{81}$Tl, $_{87}$Fr, $_{88}$Ra*

– d_{atom}/d_e ≈ 24, 114, −570, 1150, 40.000 for calculations

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

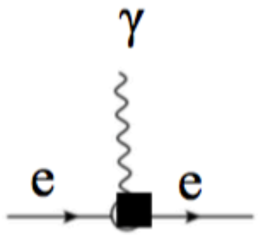
– *Caveat*: *T*-odd electron-nucleon forces!

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

(Semi-)leptonic CP violation

- ✓ Four operators @ 1 GeV

- ✓ 1 GeV



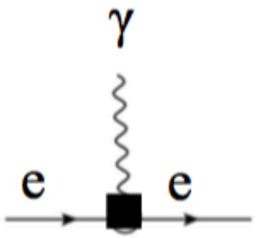
*e*EDM

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

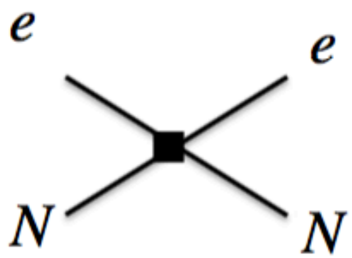
C_P C_T

Focus on these two

Usually left out



*e*EDM



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

Hadronic matrix elements relatively well-known

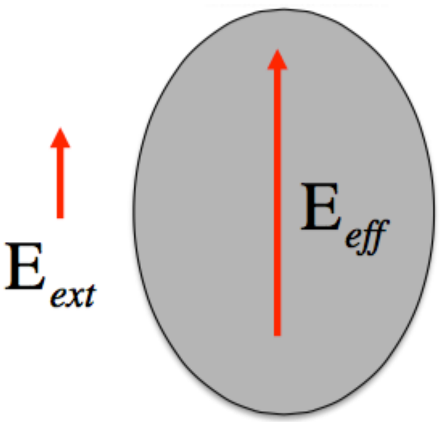
- ✓ 0.1 GeV

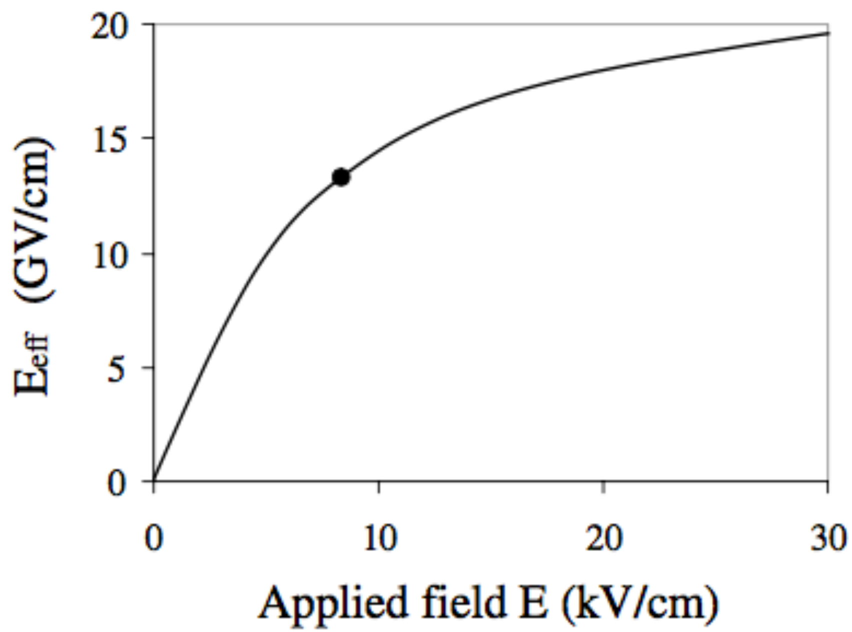
Polar molecules

✓ 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

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

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

Polar molecules

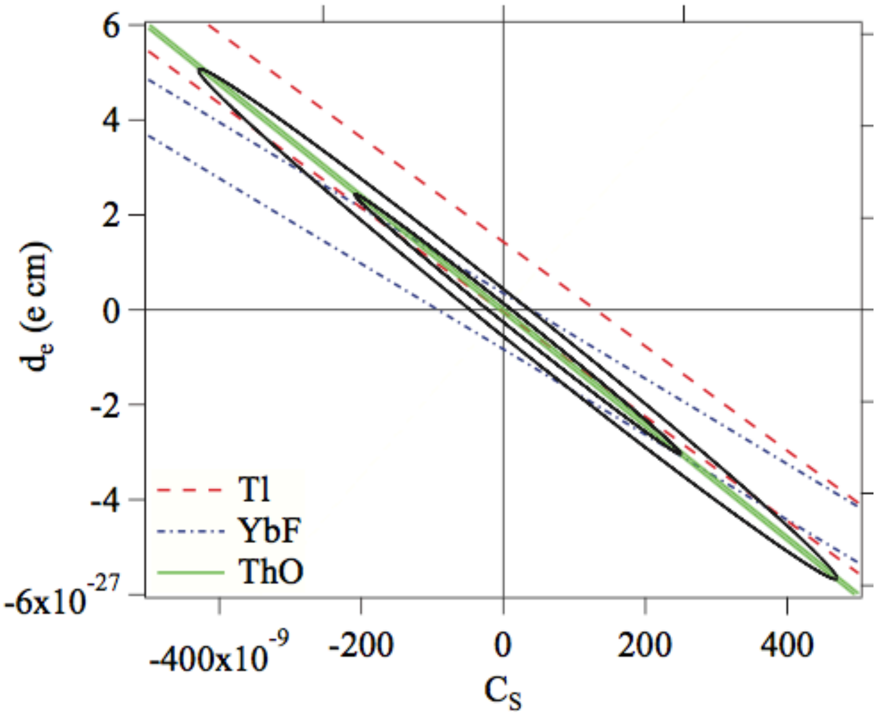
- ✓ Assume no cancellation with C_S
  - – OR no cancellation with eEDM

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

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

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

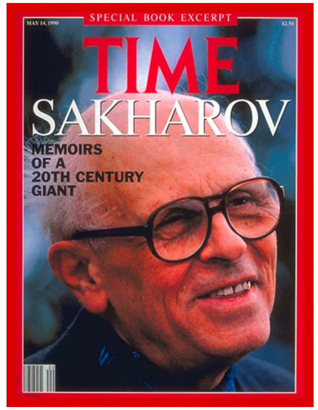
$$\Delta E = \alpha d_e + \beta C_S$$



- ✓ Pseudo-scalar & tensor interactions?
  - – Constraints from para- (Cs, Fr) or diamagnetic atoms (Xe, Hg, Ra)?

- ✓ Several models have one dominant source, *e.g.* *e*EDM in mLRSM

A historical curiosity @ Brussels



- ✓ Matter-antimatter asymmetry of the Universe requires (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) $\rightarrow$ measurable EDMs?
  - *Caveat*: Leptogenesis!

- ✓ *"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", Onzième conseil de physique, Bruxelles, 9-13 juin 1958

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

- ✓ *"Data! Data! Data! We cannot make bricks without clay!"*
  - *"It is quite a three-pipe problem…"*