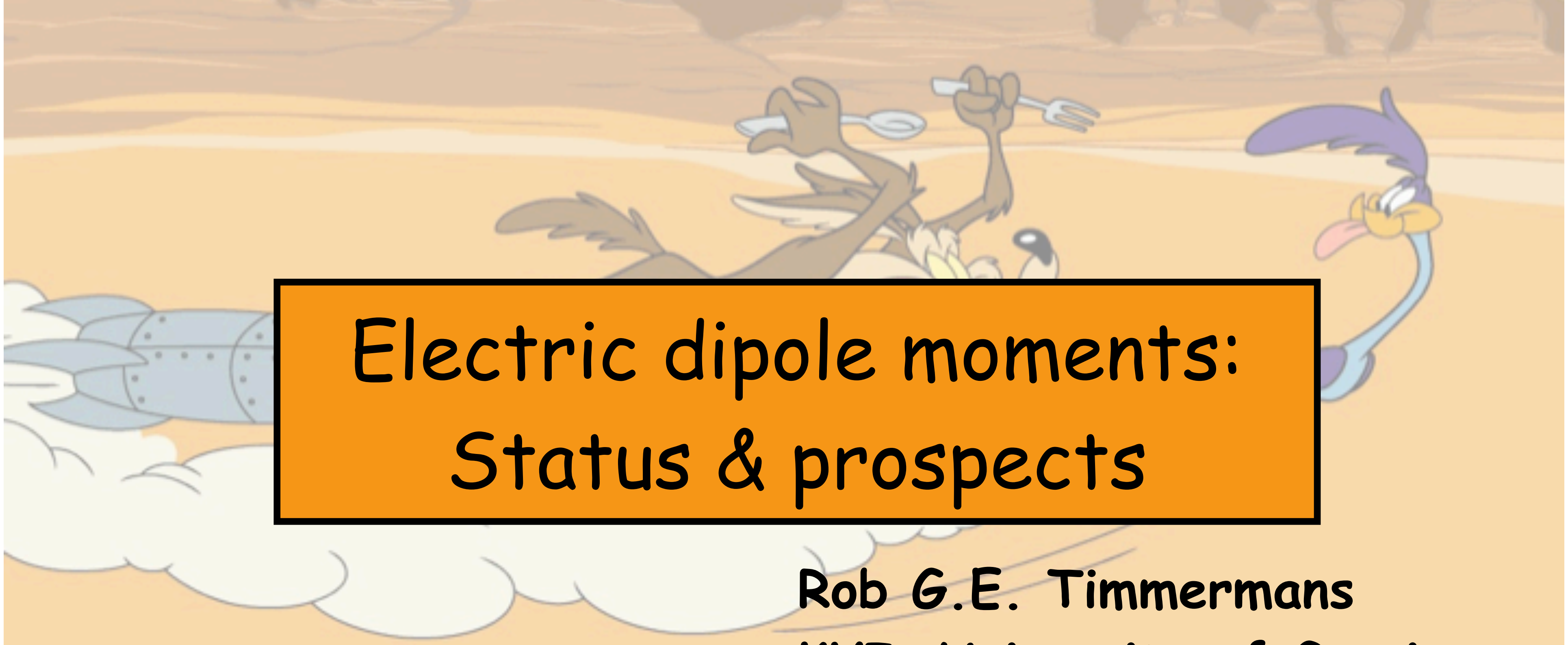
Flavor in the era of the LHC
CERN, March 26-28, 2007



Electric dipole moments: Status & prospects

Rob G.E. Timmermans
KVI, University of Groningen

With Cheng-Pang Liu (LANL) & TRIμP group @ KVI

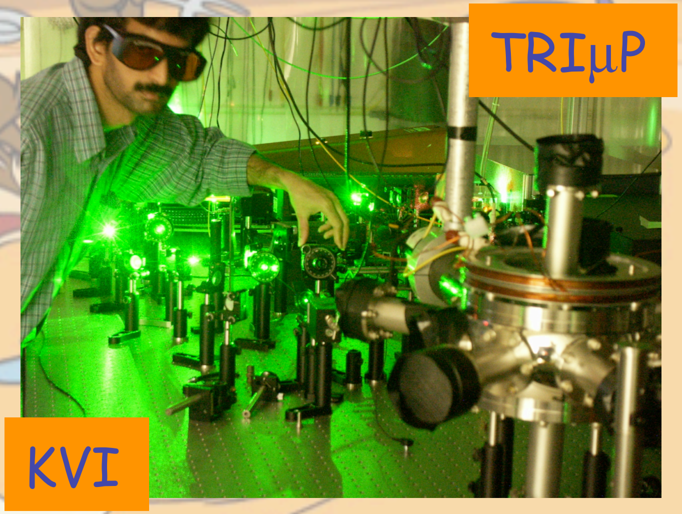
In search of a New Standard Model

Two frontiers

Collider expt's at high energy:
direct observation of new particles

Indirect searches at lower
energies, but with high precision

⇔

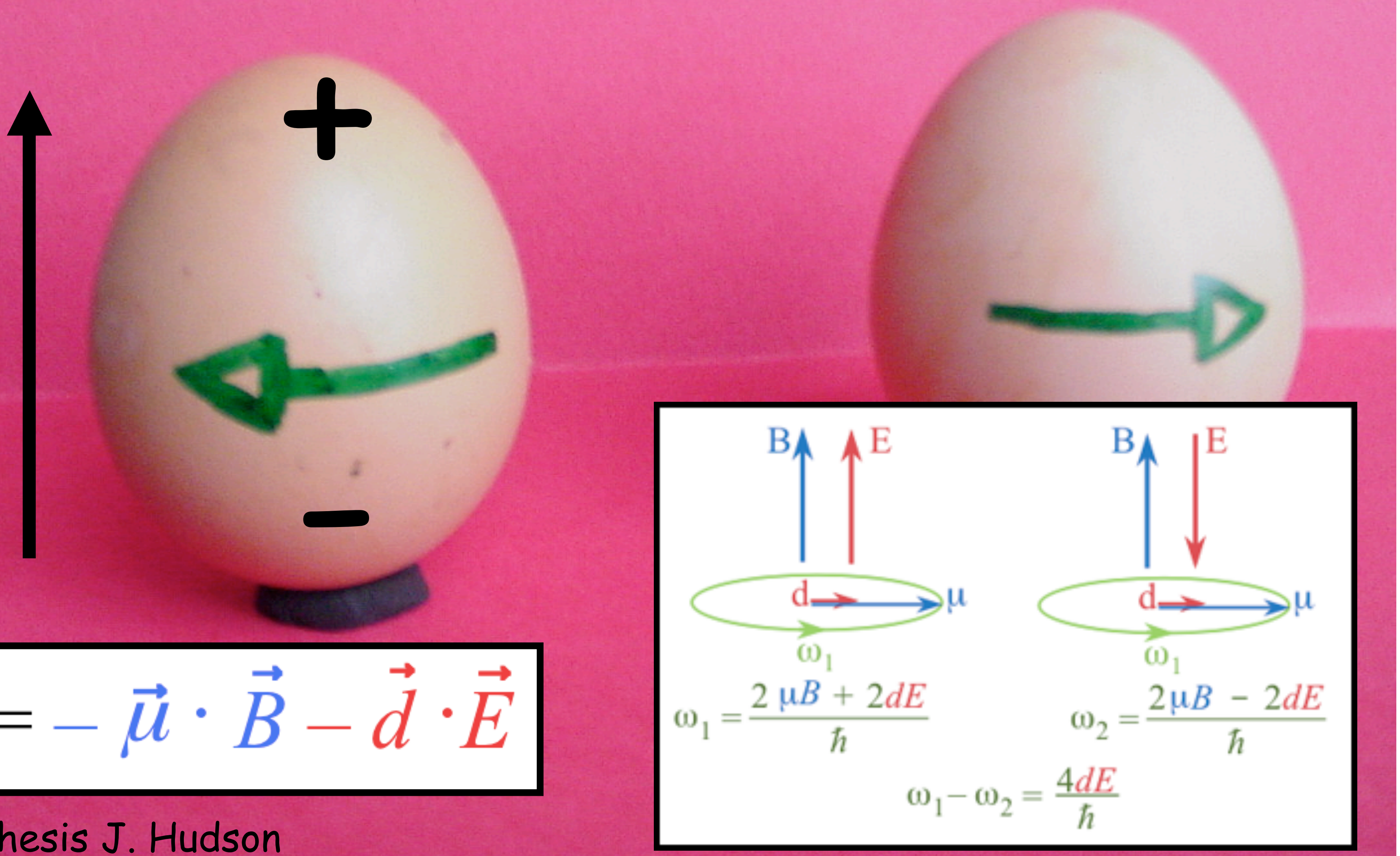


High-energy physics

Particle, nuclear & atomic physics

EDM = "the poor man's high-energy physics" (S. Lamoreaux)

A permanent *electric dipole moment* violates P and T.
The experimental signature is a *linear* Stark effect,
or a *spin precession* in an external electric field.



$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

Ph.D. thesis J. Hudson

Static EM moments:

Spin-1/2:
- Electric dipole moment
- Magnetic dipole moment
- "Anapole" moment

J	CJ	EJ	MJ
0	PT		
1	$\not{P}\not{T}$	$\not{P}T$	PT
2	PT	$P\not{T}$	$\not{P}\not{T}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

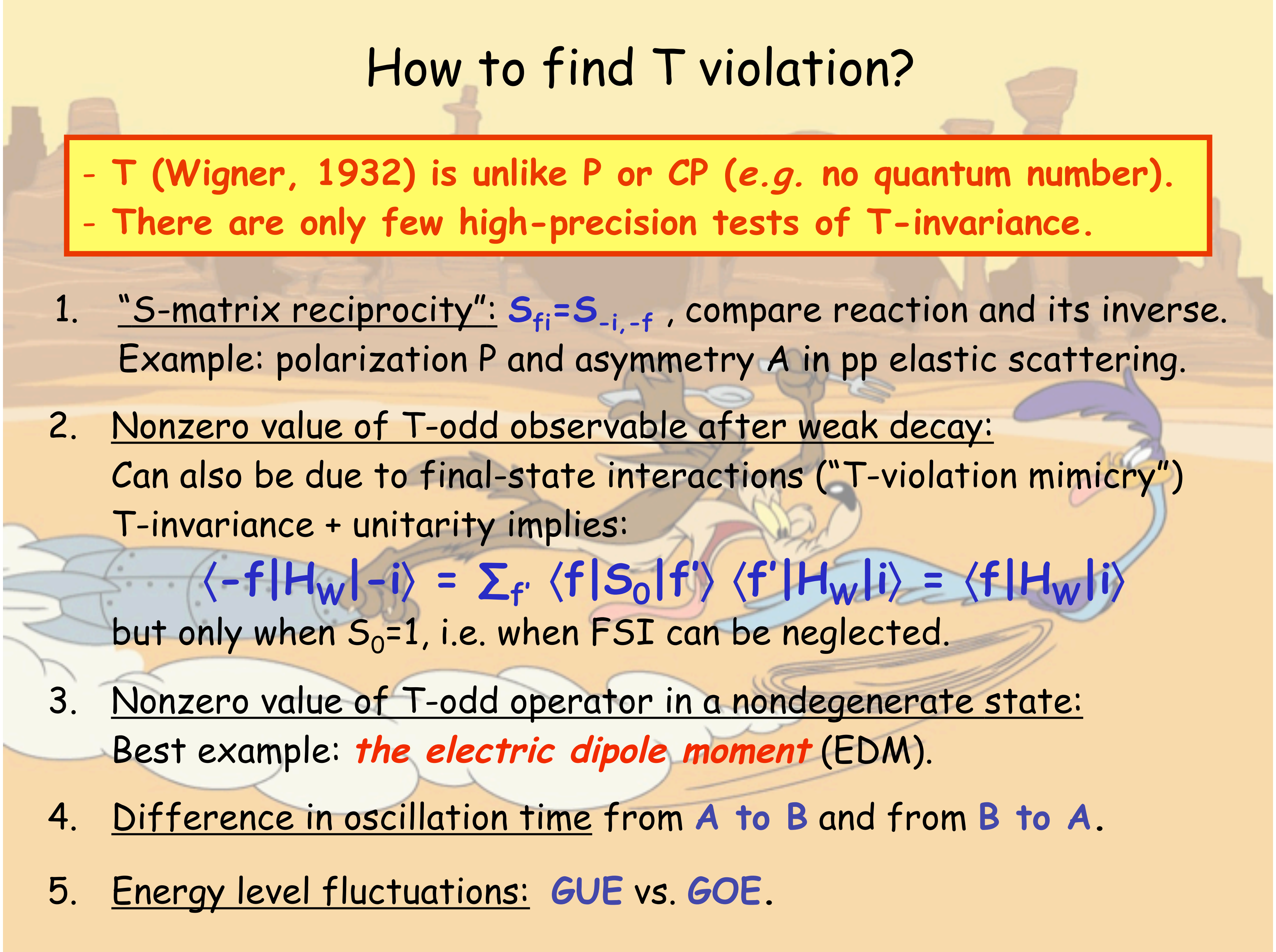
* $C1$: EDM, $M2$: MQM
* $E1$: Anapole

Spin-1:
Also electric & magnetic quadrupole moments

Nucleon EM current:

$$\langle n|(J_{EM})_\mu|n\rangle = \overline{u}_n(p')[f_1\gamma_\mu+\ldots+d_n\sigma_{\mu\nu}\gamma_5 q^\nu]u_n(p)$$

An atomic-physics quantity of interest to particle physics



How to find T violation?

- T (Wigner, 1932) is unlike P or CP (*e.g.* no quantum number).
- There are only few high-precision tests of T-invariance.

1. "S-matrix reciprocity": $S_{fi}=S_{-i,-f}$, compare reaction and its inverse. Example: polarization P and asymmetry A in pp elastic scattering.

2. Nonzero value of T-odd observable after weak decay: Can also be due to final-state interactions ("T-violation mimicry") T-invariance + unitarity implies:

$$\langle -f|H_W|-i\rangle = \Sigma_{f'} \langle f|S_0|f'\rangle \langle f'|H_W|i\rangle = \langle f|H_W|i\rangle$$

but only when $S_0=1$, i.e. when FSI can be neglected.

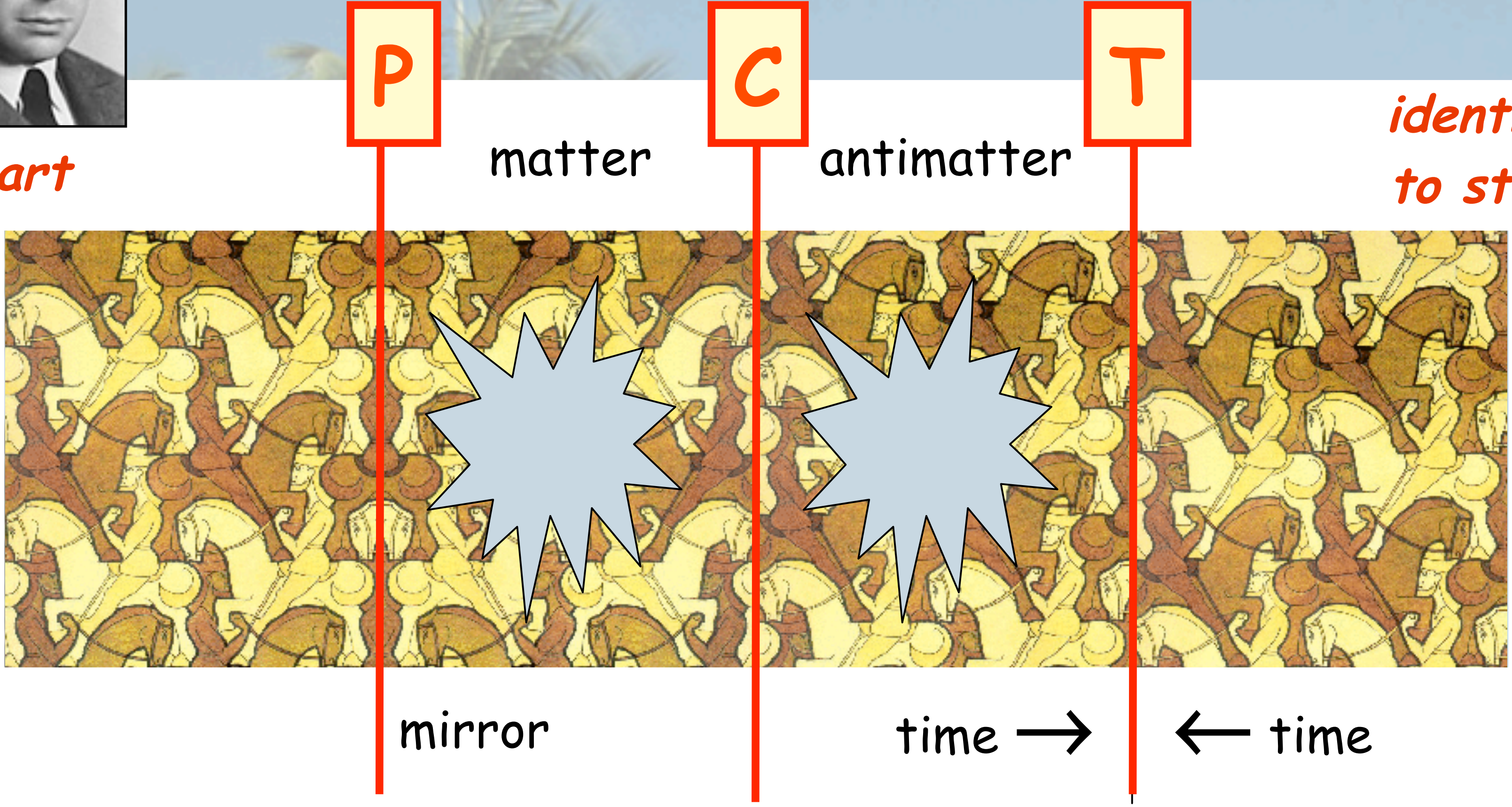
3. Nonzero value of T-odd operator in a nondegenerate state: Best example: ***the electric dipole moment*** (EDM).

4. Difference in oscillation time from **A to B** and from **B to A**.

5. Energy level fluctuations: **GUE** vs. **GOE**.

The CPT theorem (Pauli *et al.*, 1955)

start



P

C

T

matter

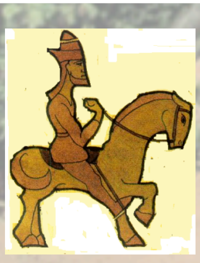
antimatter

mirror

time →

← time

identical to start



antiparticle

particle

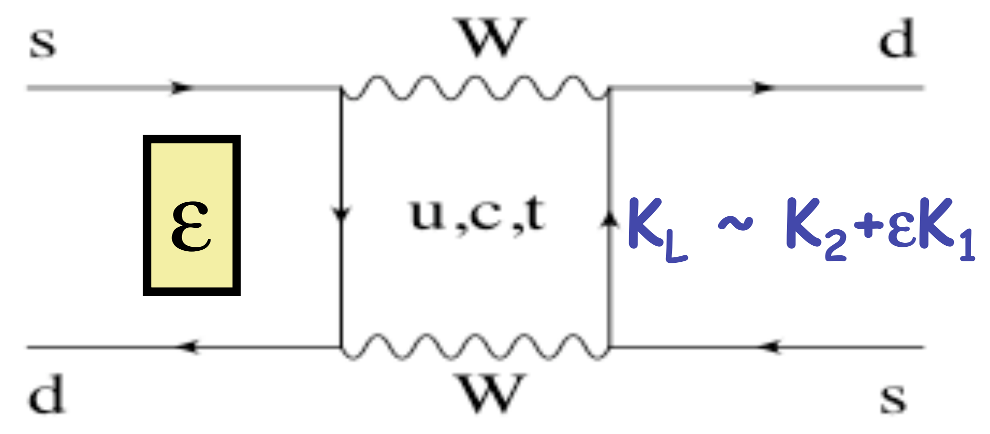
Holds on very general grounds:

Nature is local, causal & Lorentz invariant.

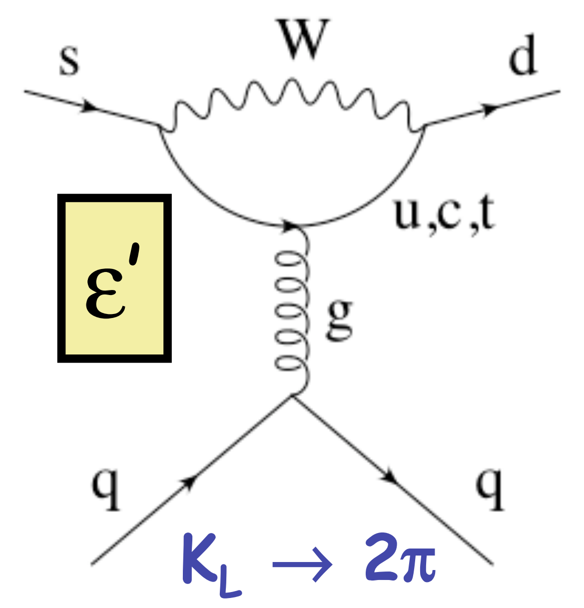
True for all gauge theories!

After H. Wilschut

CP & T violation in the SM



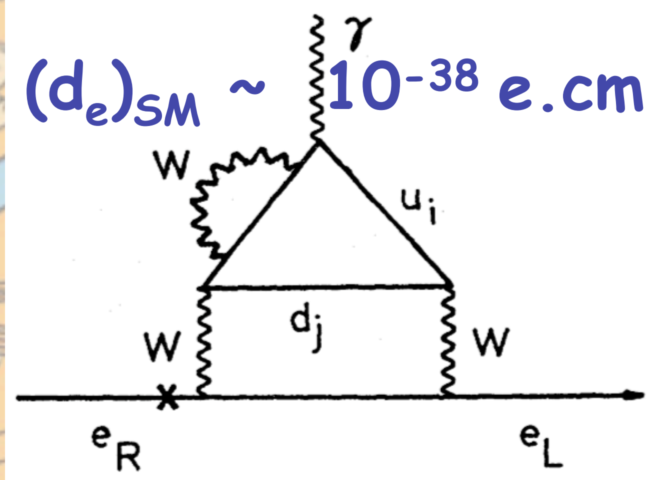
$K_L \sim K_2+\varepsilon K_1$



$K_L \to 2\pi$

All $\cancel{CP}$ effects involve $J \sim s_1^2 s_2 s_3 s_\delta$

In flavor-conserving nonleptonic interactions: *no 1st-order T-violation*

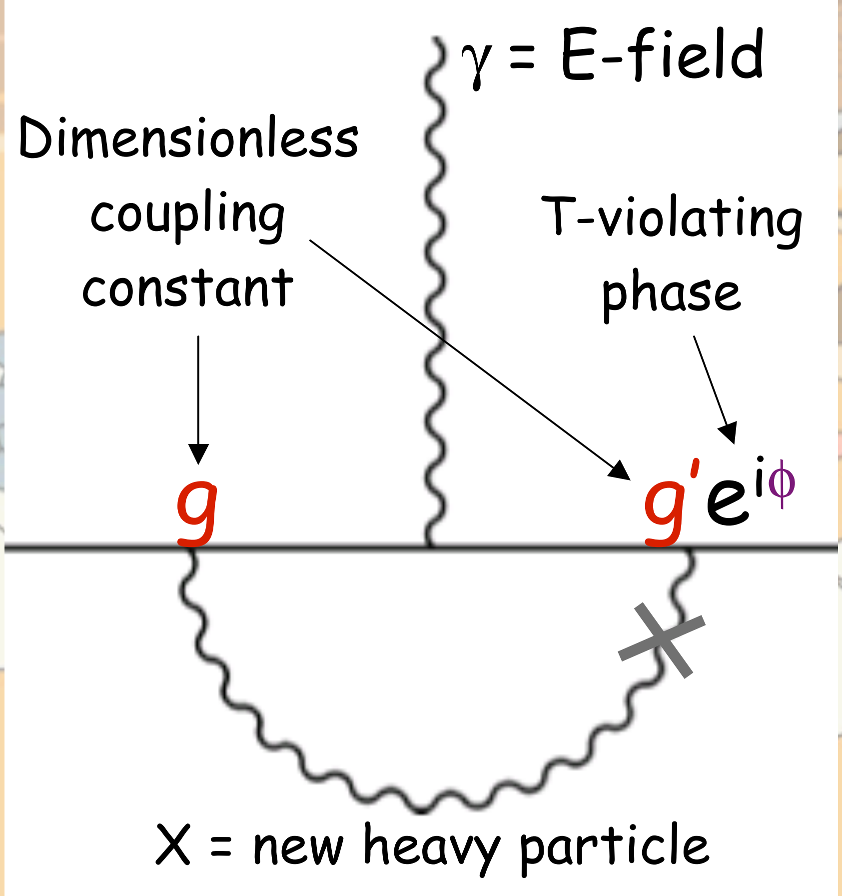


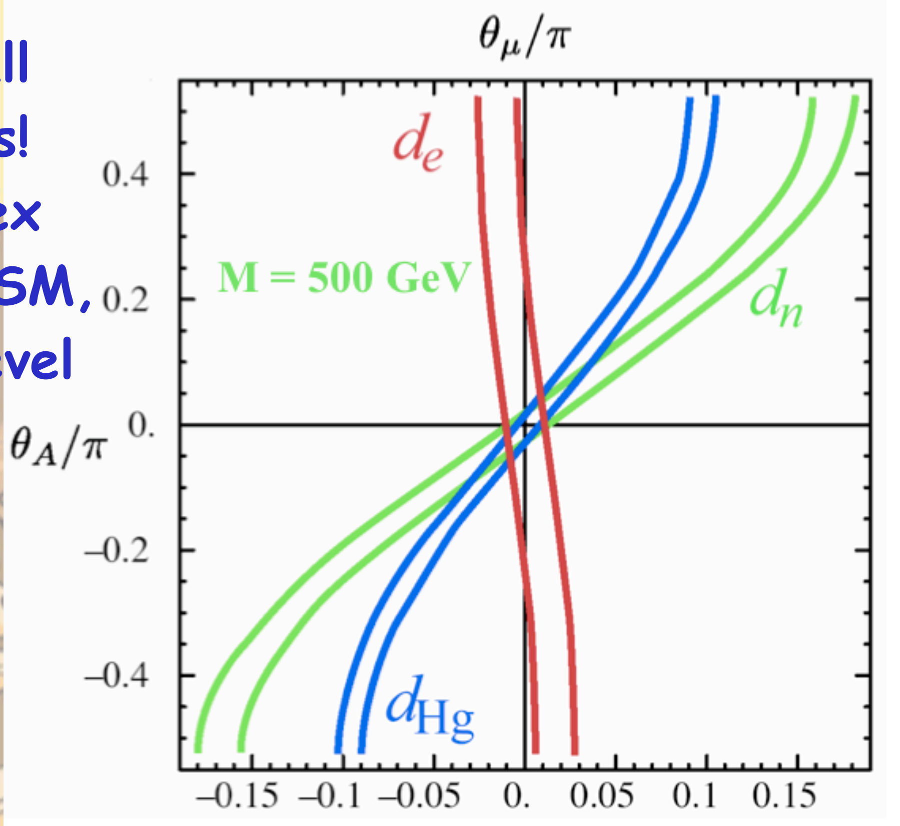
$(d_e)_{SM} \sim 10^{-38}$ e.cm

A nonzero EDM implies new physics!

$(d_n)_{SM} \sim 10^{-7}.10^{-7}.s_1^2 s_2 s_3 s_\delta \times e/M \sim 10^{-32}$ e.cm

- SM EDMs are unmeasurably small
- A finite EDM implies new physics!
- In SUSY models, several complex phases occur. In contrast to the SM, EDMs arise already at one-loop level





Neutron EDM (10^{-23} e.cm):

$d_n = K.\sin\varphi.(100\text{GeV})^2/M^2$

The limits for SUSY are becoming uncomfortably tight ("SUSY CP problem")...

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

it may be that the next exciting thing to come along will be the discovery of a neutron or electron *electric dipole moment*… these seem to me to offer one of the most promising possibilities for progress in particle physics

Steven Weinberg, 1992

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

- E.M. Purcell & N.F. Ramsey, 1950
- L.D. Landau, 1957
- N.F. Ramsey, 1958

---

* One that initiates a major change; one that foreshadows what is to come [M-W].

EDM limits: How close are we?

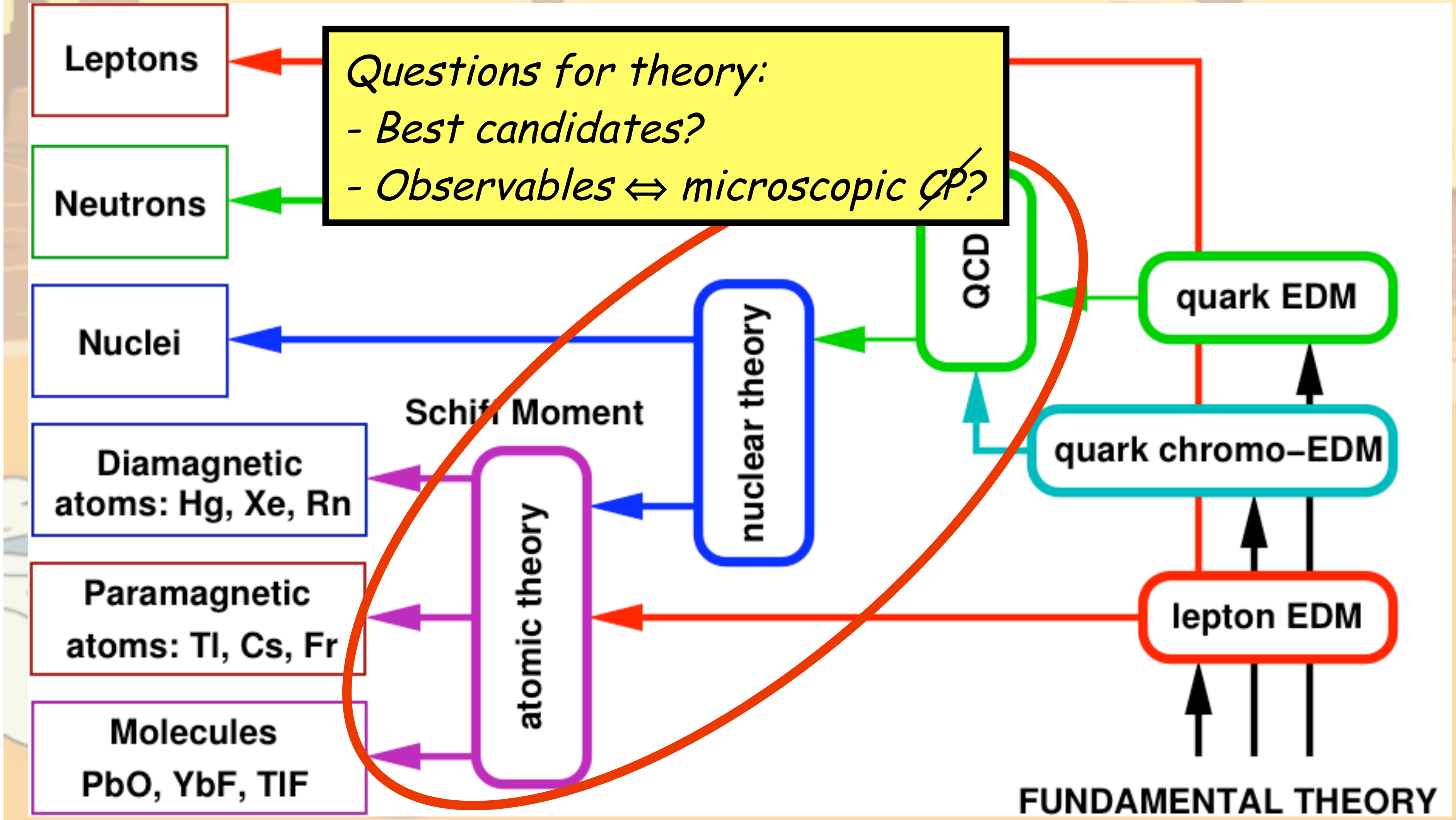
Particle	EDM limit (95% C.L.)	System	Prediction SM [e.cm]	New Physics limit [e.cm]
electron	1.9×10^{-27}	^{205}Tl atom	10^{-38}	10^{-27}
muon	1.05×10^{-19}	rest frame E	10^{-35}	10^{-22}
tau	3.1×10^{-16}	$e^+e^-\rightarrow\tau^+\tau^-\gamma$	10^{-34}	10^{-20}
proton	6.5×10^{-23}	^{205}Tl-F mol.	10^{-31}	5×10^{-26}
neutron	7.5×10^{-26}	UCN	10^{-31}	5×10^{-26}
Λ hyperon	1.5×10^{-16}	rest frame E	10^{-30}	5×10^{-25}
^{199}Hg	2.1×10^{-28}	^{199}Hg atom	10^{-33}	10^{-28}

- The most precise experiments are done with *neutral systems.*
- The results for charged particles (except μ) are *indirectly inferred.*

The EDM landscape

Scale ~ 1 yeV

Scale ~ 1 TeV



Questions for theory:

- *Best candidates?*
- *Observables ⇔ microscopic* $\cancel{CP}$*?*

The first nonzero EDM will be a major discovery. Ultimately, we need the <u>whole</u> picture to address the origin of CP violation.

Hadronic T-odd Lagrangian at the few GeV

Dimension

$\bar{\theta}\,\frac{\alpha_s}{4\pi}\mathrm{Tr}\left[G^{\mu\nu}\tilde{G}_{\mu\nu}\right]$	θ-term (dim=4)
$+\bar{q}(d_q^{(0)}+d_q^{(1)}\tau_3)\sigma_{\mu\nu}q\tilde{F}^{\mu\nu}$	q-EDM (dim=5,6)
$+\bar{q}(c_q^{(0)}+c_q^{(1)}\tau_3)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q$	q-color-EDM (dim=5,6)
$+\frac{w}{3}f^{abc}G^{a}_{\mu\nu}\tilde{G}^{b\nu\rho}G^{c\mu}_{\rho}$	3-gluon operator (dim=6)
$+\ldots$	4-quark operators (dim=6-8)

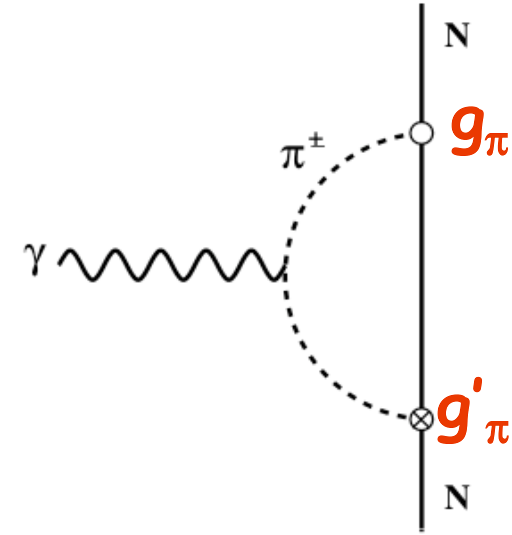
These generate nucleon EDMs and T-odd e-N & NN interactions at atomic and nuclear scales.

Can we learn about the various mechanisms from the several EDM experiments ("bottom-up")?

EDM of the neutron in the SM

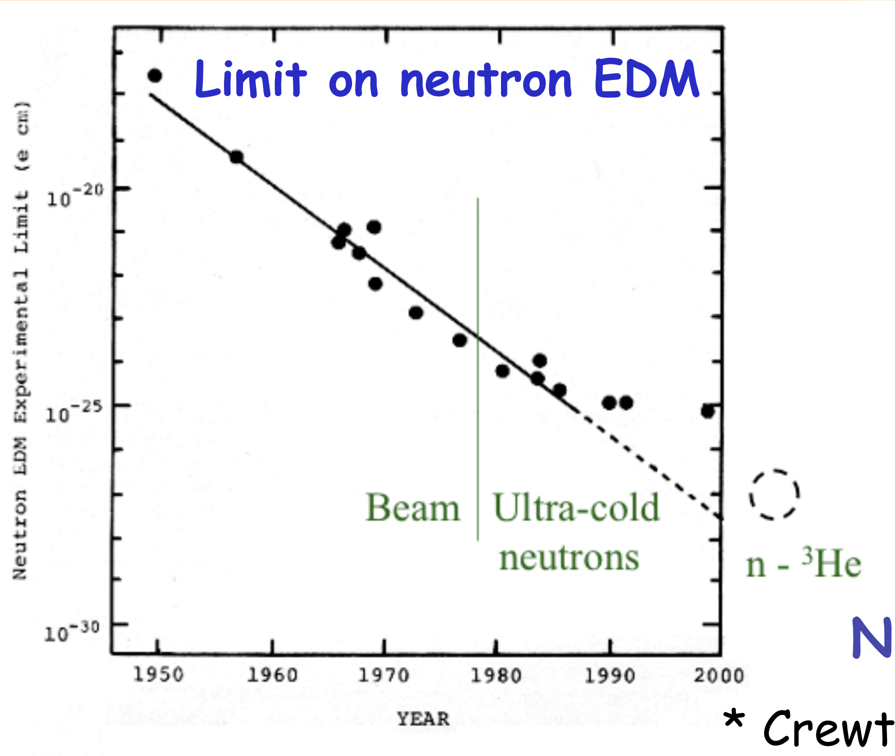
Weak $\cancel{CP}$ (CKM): $d_n \sim 10^{-31}$ e.cm

Strong $\cancel{CP}$ (QCD): θ vacuum angle

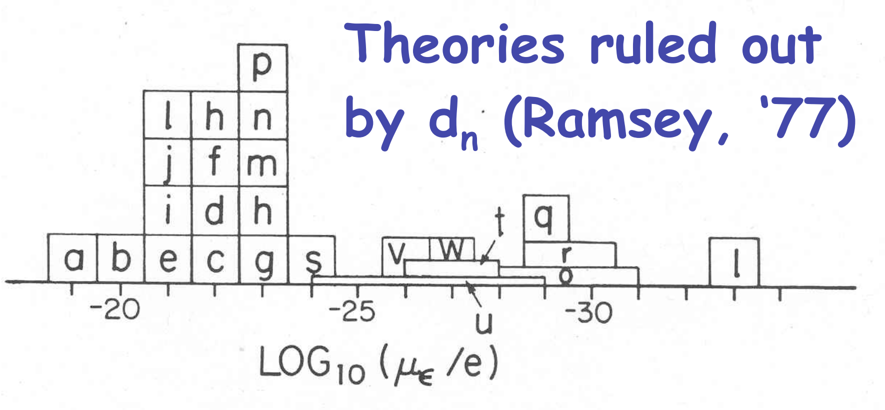


Soft-pion theorem* ($m_\pi \to 0$):

$$d_n \sim g_\pi g'_\pi \ln(M/m_\pi)\, e/M$$



Exp. limit ⇒ $\theta < 3 \times 10^{-10}$



New expt's: ILL, PSI, LANL, Munich

* Crewther, Di Vecchia, Veneziano, Witten (1979).

Atomic & molecular EDMs

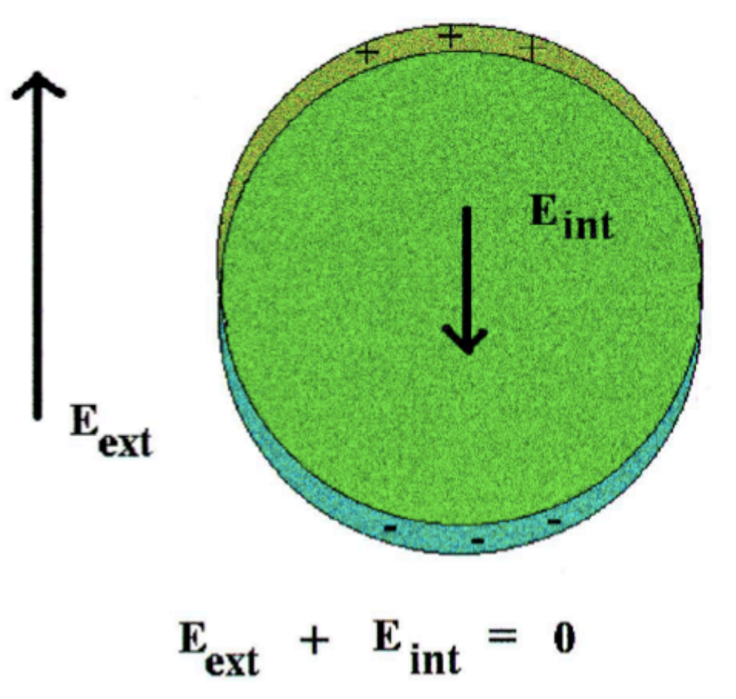
Shielding theorem (Schiff, 1963):

EDM of a nonrelativistic atom ≡ 0

Electrostatic force balance:

- Electron cloud screens nucleus.
- Zero E-field on nucleus.

"Loopholes": relativistic, finite-size, magnetic effects, …



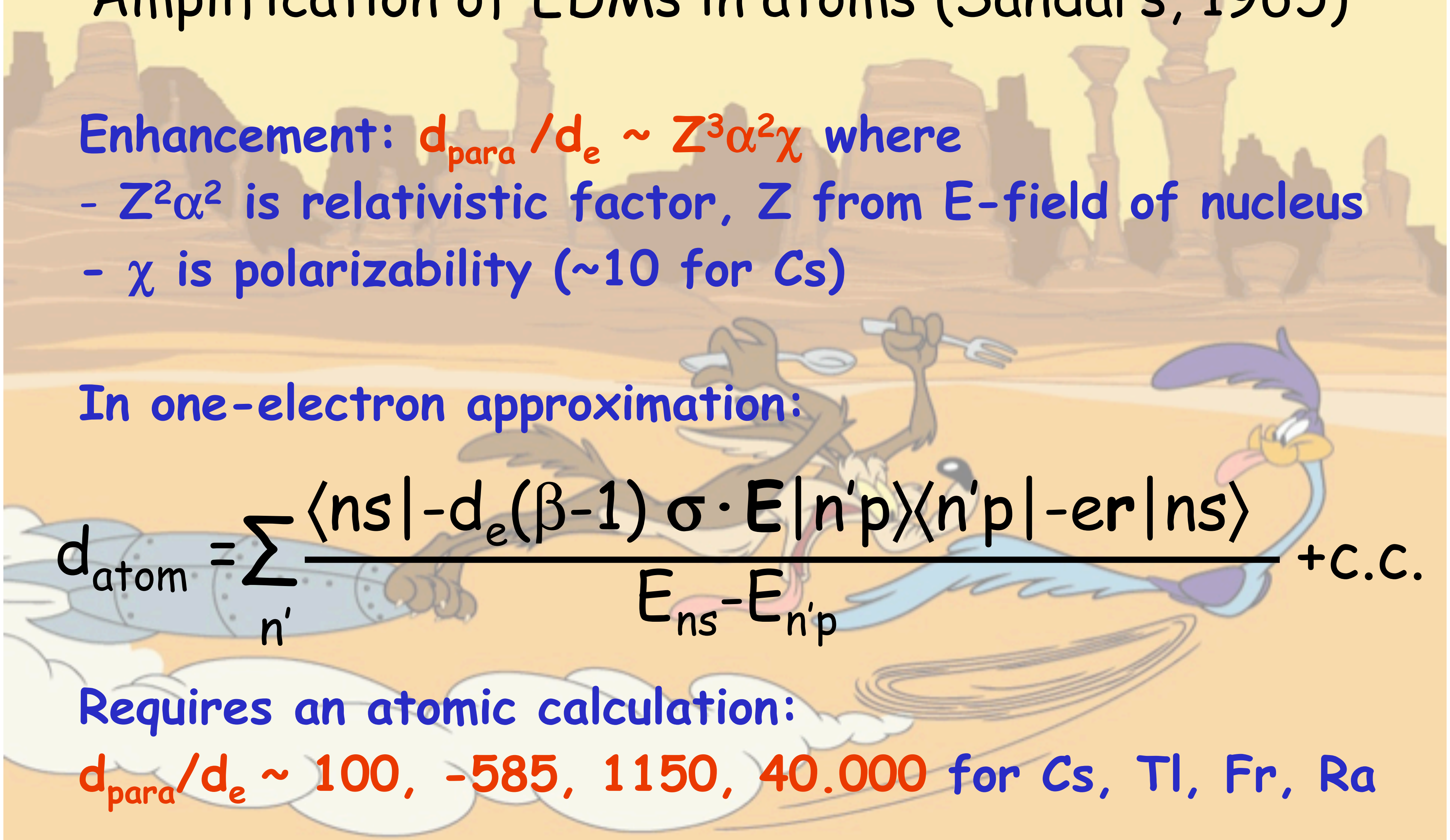
Residual interaction: $H_{EDM} = -e\mathbf{S}\cdot[\nabla,\delta(r_e)]$

S = P- & T-odd EM moment, "*Schiff moment*"

S ~ offset of charge & dipole distributions in nucleus.

C.-P. Liu, W.C. Haxton, M.J. Ramsey-Musolf, RT, A.E.L. Dieperink, nucl-th/0703xxx.

Amplification of EDMs in atoms (Sandars, 1965)



Enhancement: $d_{para}/d_e \sim Z^3\alpha^2\chi$ where

- $Z^2\alpha^2$ is relativistic factor, Z from E-field of nucleus
- χ is polarizability (~10 for Cs)

In one-electron approximation:

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

Requires an atomic calculation:

$d_{para}/d_e \sim$ 100, -585, 1150, 40.000 for Cs, Tl, Fr, Ra

Caveats:

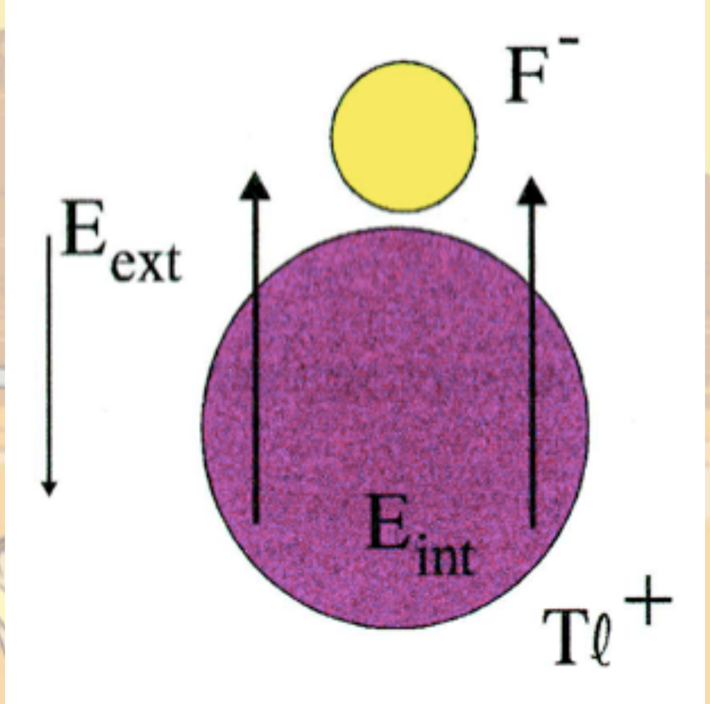
C.-P. Liu, W.C. Haxton, M.J. Ramsey-Musolf, RT, A.E.L. Dieperink, nucl-th/0703xxx.

Amplification of **E** with a polar molecule

A polar molecule has a large charge separation, almost fully “ion-like”:

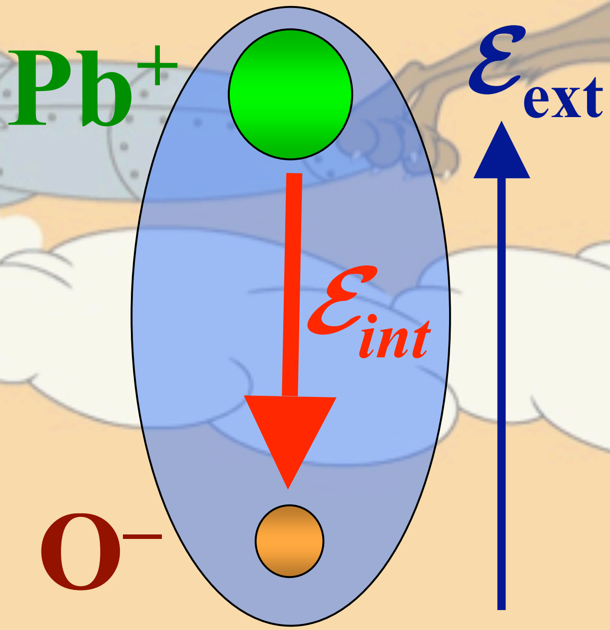
$\Rightarrow$ Schiff effect ~ cancelled

Shielding/Enhancement = 0.67



Limit on proton EDM:

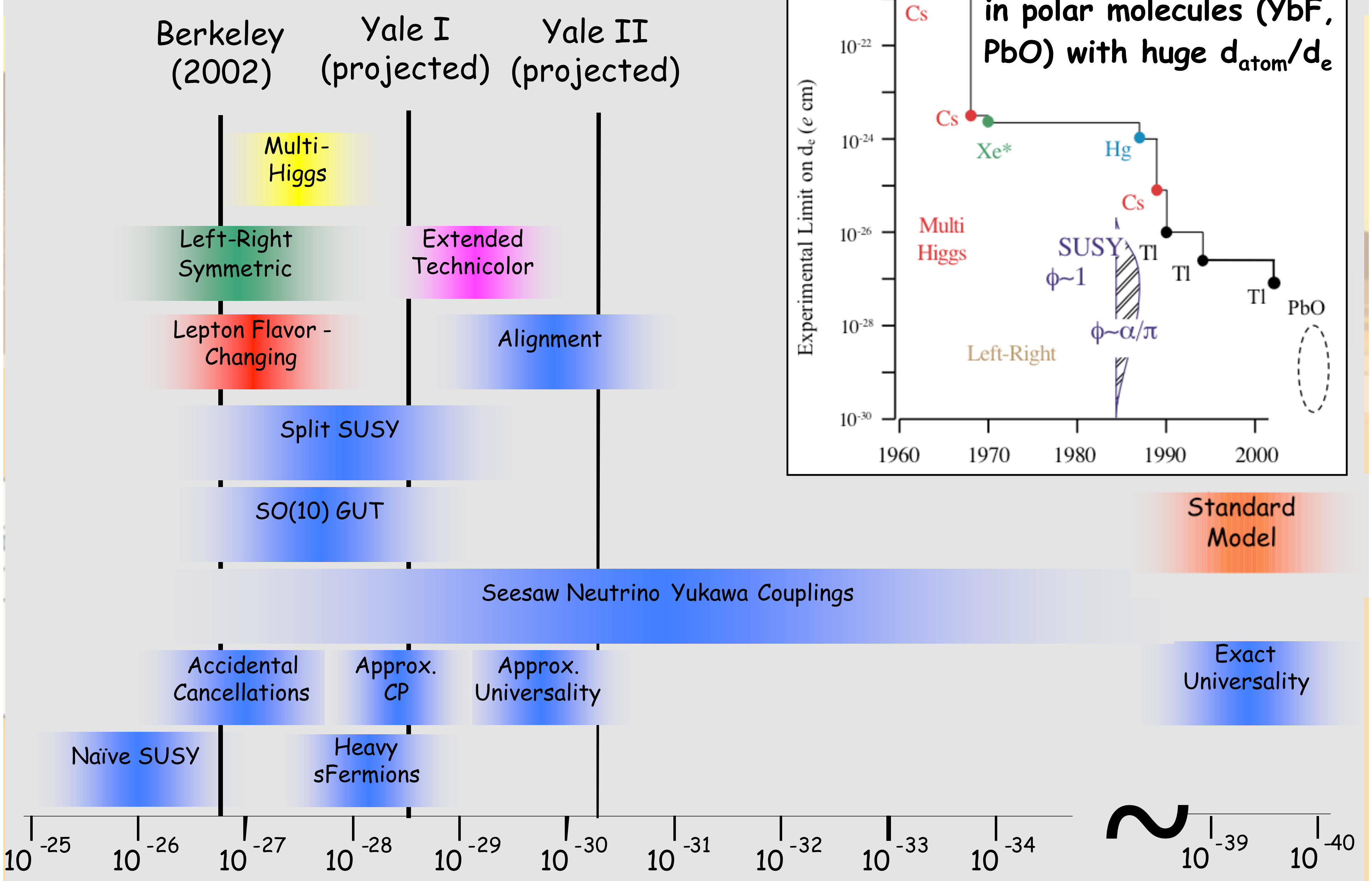
$d_p \sim d(^{205}\mathrm{Tl}) = -1.5(2.5)\mathrm{X}10^{-23}$ e.cm



For $E_{ext} \sim 10\text{-}10^4$ V/cm, the valence electron in PbO* feels $E_{int} \sim Z^3\alpha^2 e/a_0^2 \sim 2.1\text{-}4.0\times10^{10}$ V/cm

A.N. Petrov *et al.*, PRA **72**, 022505 (2005).

The electron EDM



The future for d_e lies in polar molecules (YbF, PbO) with huge d_{atom}/d_e

d_e (e.cm)

Adapted from D. DeMille

A new generation of lepton EDM searches

Group	System	Advantages	Proj. gain
D. Weiss (Penn St.)	Cs opt. latt.	Long coherence	400
D. Heinzen (Texas)	Trapped Cs	Long coherence	100?
H. Gould (LBL)	Cs fountain	Long coherence	100?
L. Hunter (Amherst)	GdIG solid	Huge S/N	100?
S. Lamoreaux (LANL) C.-Y. Liu (Indiana)	GGG solid	Huge S/N	100-10^5?
E. Hinds (Imperial)	YbF beam/trap	Int. E, long T	10-100
D. DeMille (Yale)	PbO* cell	Int. E, good S/N	2-100?
E. Cornell (JILA)	Trapped HfF^+	Int. E, huge T	100?
N. Shafer-Ray (Okla.)	PbF beam/trap	Int. E, long T	100?
L. Willmann (KVI)	^{213}Ra	At. enhanc.	10^4?
J. Miller, Y. Semertzidis, Y. Kuno (J-PARC)	Muon	Dedicated magn. storage ring	10^5-10^6

Cf. 3rd Int. Symp. On Lepton Moments, Cape Code, June 2006

The EDM of the mercury atom

Result:

$[-10.6 \pm 4.9_{\mathrm{stat.}} \pm 4.0_{\mathrm{syst.}}] \times 10^{-29}\ e\ \mathrm{cm}$

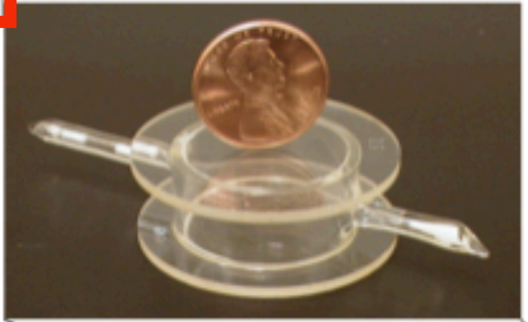
d(^{199}Hg) < 2.1 x 10^{-28} *e* cm

Romalis, Griffith, Jacobs, Fortson

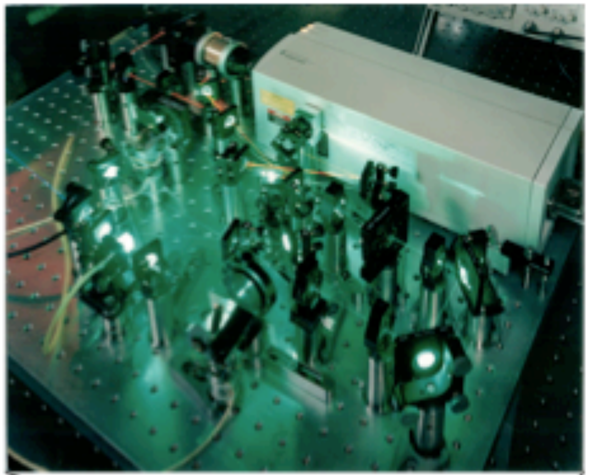
Frequency uncertainty = 1 nHz

~ 80 days data

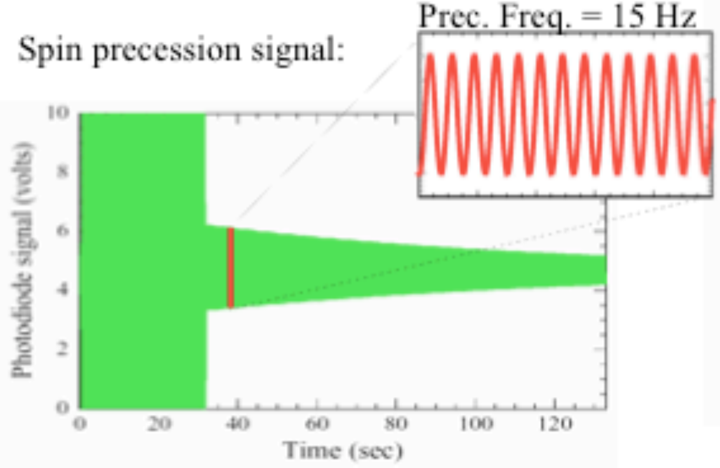
Vapor cells:
10^{14} Hg atoms
Coherence time 200 sec
Wall resistance > 10^{16} Ω

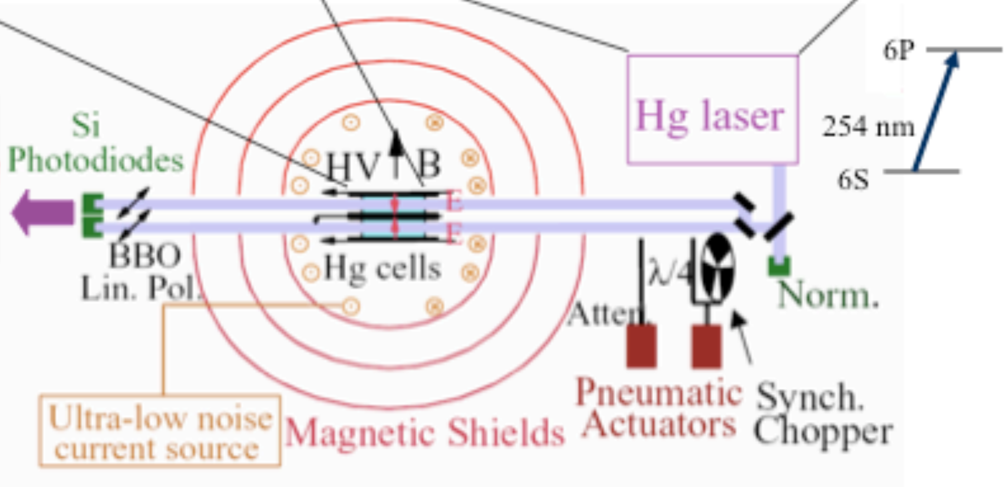


6mW, 254 nm laser from
quadrupled 1016 diode:



Spin precession signal:

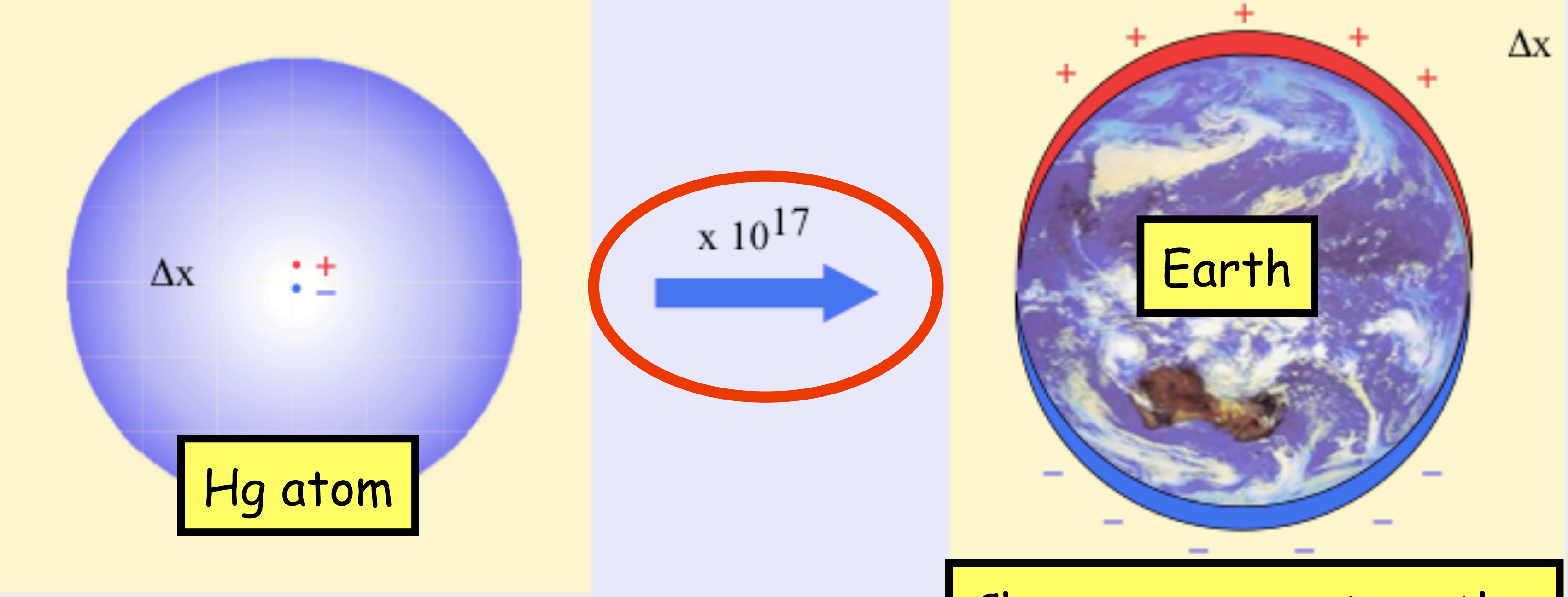

Prec. Freq. = 15 Hz



Fortson Group, Seattle, Washington

The EDM of the mercury atom

Expt: d(^{199}Hg) = $-1.0(2.4)(3.6)\times10^{-28}$ e.cm



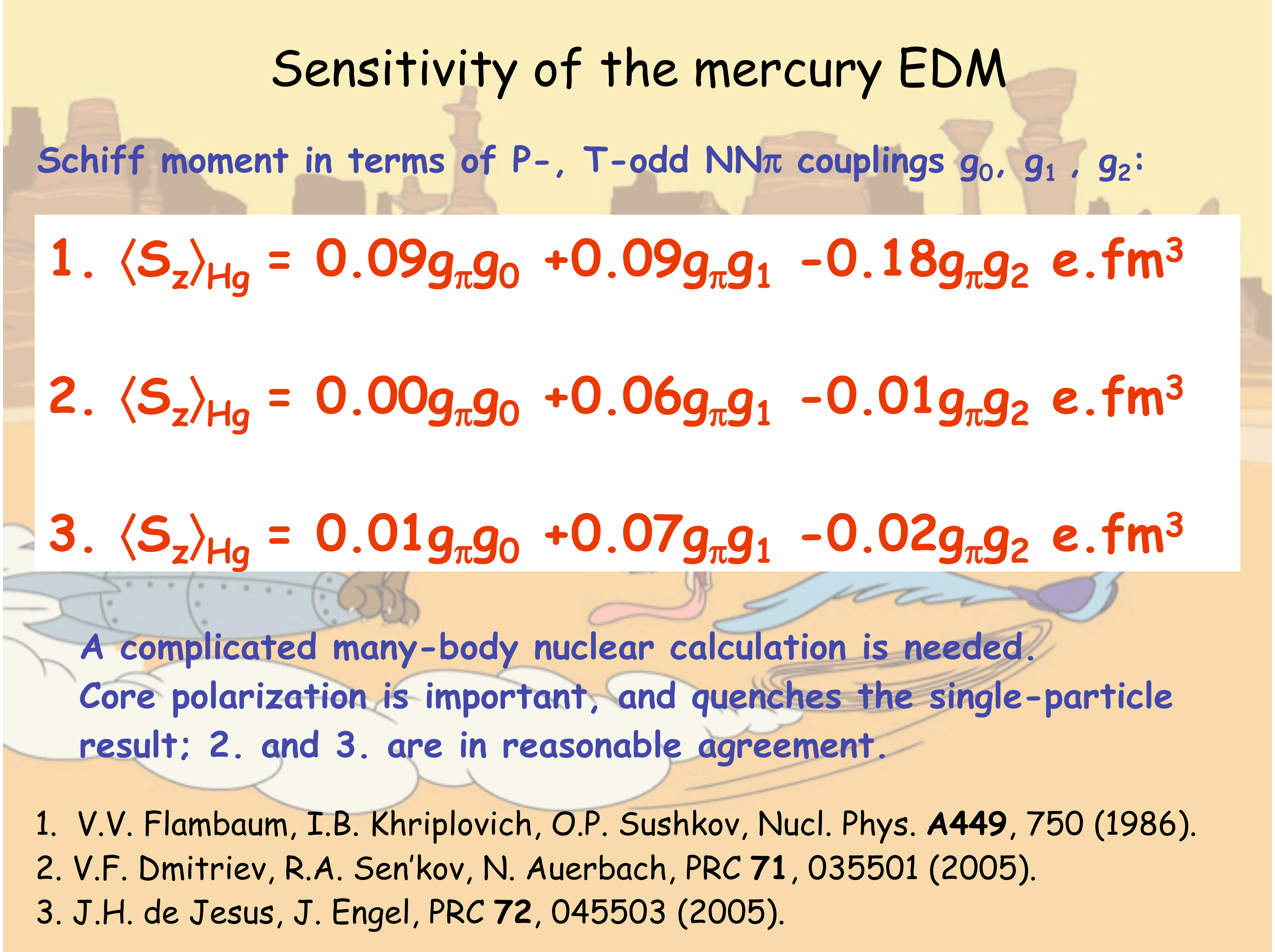
d=eΔx~10^{-28} e-cm

Charge excess at north pole of depth ~ 200 fm.

For E ~ 10 kV/cm, shift in ground-state energy of ~10^{-24} eV…

Nett shielding: $\mathbf{S}\cdot\nabla\rho_e/\mathbf{D}_N\cdot\mathbf{E}_{ext} \sim [R_N/R_A]^2 Z^2 A^{2/3} \sim 10^{-3}\text{-}10^{-4}$

M.V. Romalis, W.C. Griffith, J.P. Jacobs, E.N. Fortson, PRL **86**, 2505 (2001).



Sensitivity of the mercury EDM

Schiff moment in terms of P-, T-odd NNπ couplings g_0, g_1, g_2:

1. $\langle S_z \rangle_{Hg} = 0.09 g_\pi g_0 + 0.09 g_\pi g_1 - 0.18 g_\pi g_2 \ e.fm^3$

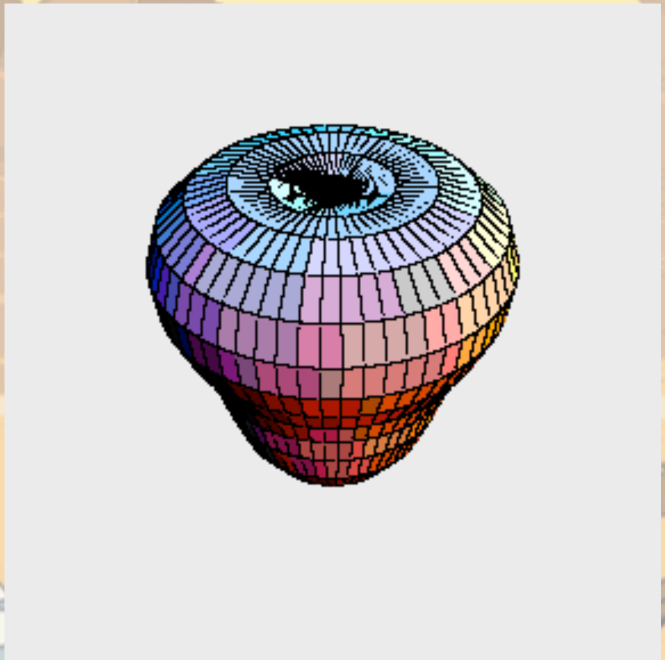
2. $\langle S_z \rangle_{Hg} = 0.00 g_\pi g_0 + 0.06 g_\pi g_1 - 0.01 g_\pi g_2 \ e.fm^3$

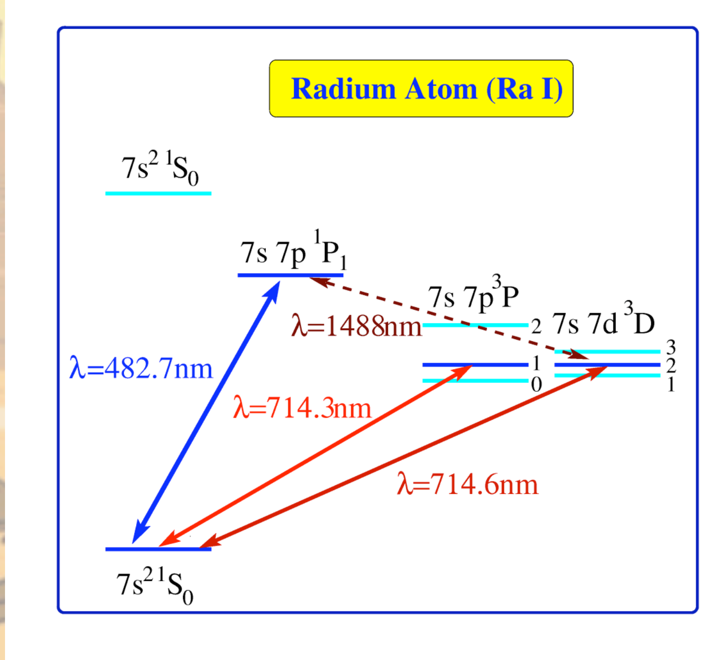
3. $\langle S_z \rangle_{Hg} = 0.01 g_\pi g_0 + 0.07 g_\pi g_1 - 0.02 g_\pi g_2 \ e.fm^3$

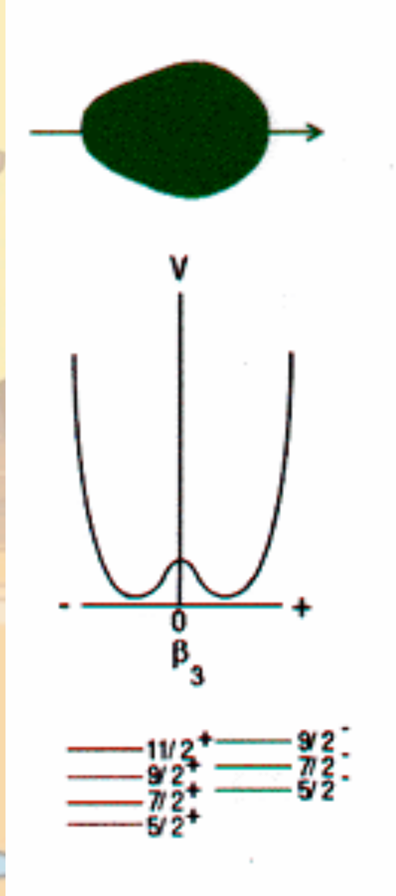
A complicated many-body nuclear calculation is needed. Core polarization is important, and quenches the single-particle result; 2. and 3. are in reasonable agreement.

1. V.V. Flambaum, I.B. Khriplovich, O.P. Sushkov, Nucl. Phys. **A449**, 750 (1986).
2. V.F. Dmitriev, R.A. Sen'kov, N. Auerbach, PRC **71**, 035501 (2005).
3. J.H. de Jesus, J. Engel, PRC **72**, 045503 (2005).

Amplification in radium atoms





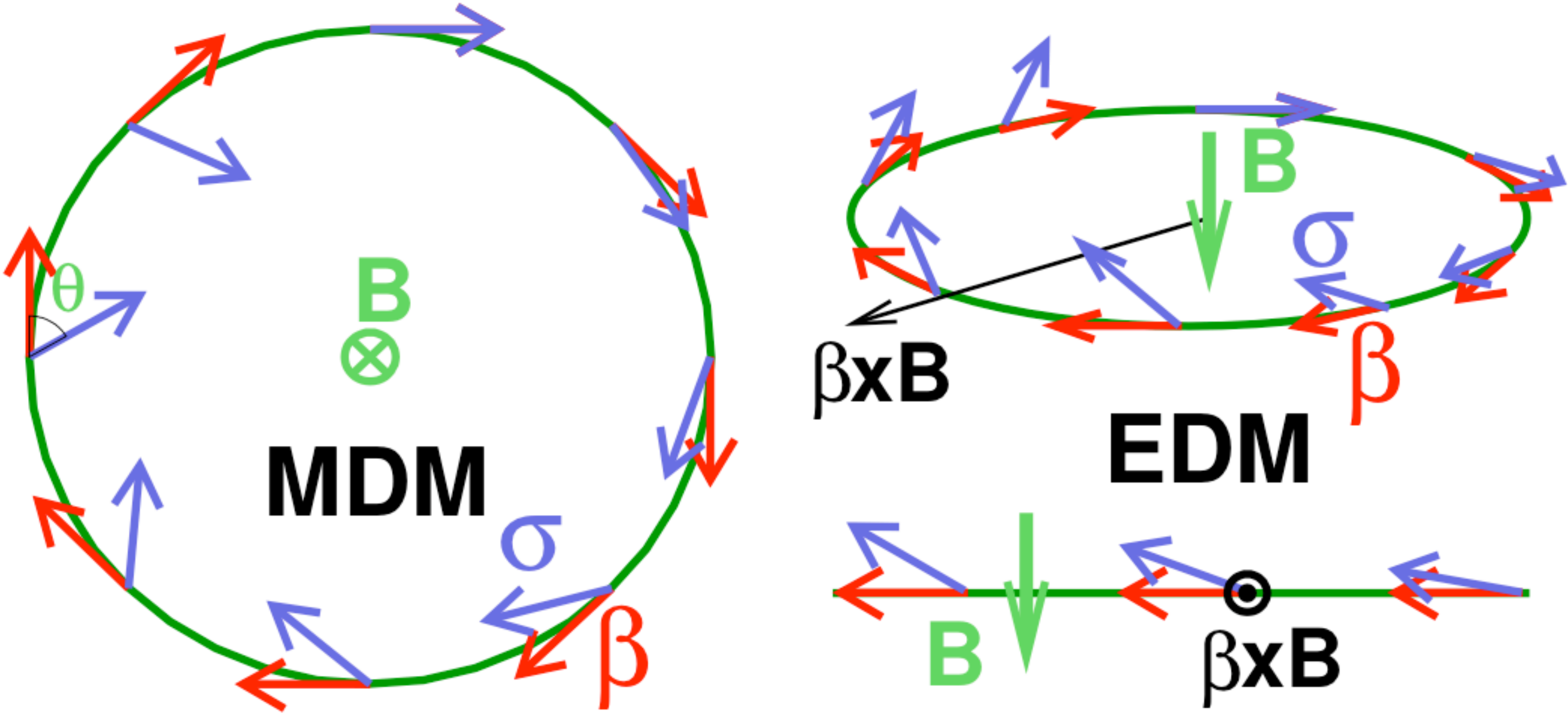


- Big enhancement ~10^4 from atomic degeneracy.
- Additional factor from octupole deformation in ^{225}Ra?

1. $\langle S_z \rangle_{Hg} = 0.01 g_\pi g_0 + 0.07 g_\pi g_1 - 0.02 g_\pi g_2$ e.fm^3
2. $\langle S_z \rangle_{Ra} = -1.5\ g_\pi g_0 + 6.0\ g_\pi g_1 + 4.0\ g_\pi g_2$ e.fm^3

J. Dobaczewski, J. Engel, PRL **94**, 232502 (2005).

EDM measurement for *charged* particles

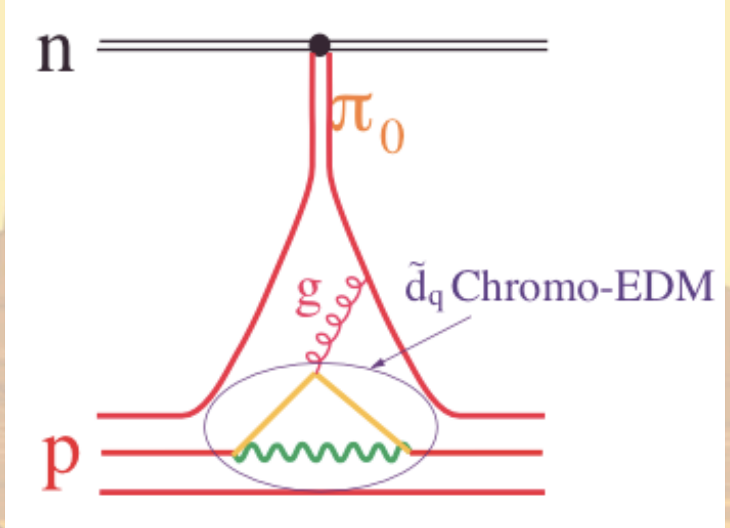


Precession: $dS/d\tau = \mu \times B^* + d \times E^*$

- Motional E-field, $E^* = \gamma c \beta \times B$, large (GV/m)!
- Suitable for muon & for deuteron (proton, ^{3}He, …)

F.J.M. Farley *et al.*, PRL **93**, 052001 (2004);
Yu.F. Orlov, W.M. Morse, Y.K. Semertzidis, PRL **96**, 214802 (2006).

The EDM of the deuteron



The simplest case with a P-, T-odd NN interaction:

$$d_D = d_n + d_p + d(\text{“two-body”})$$

$$d_D^{pol} = \langle {}^3S_1 || \tau^z_- \, er || {}^3P_1 \rangle / \sqrt{6}$$

In terms of P-, T-odd pion-nucleon couplings:

$$d_D = 0.23 g_1 + 0.09 g_0 + \ldots$$

$$d_n = 0.14 \, [g_0 - g_2] + \ldots$$

With QCD sum rules, express the g's in quark (color-)EDMs:

$$\boxed{\begin{aligned} d_D &= -4.67 \, d^c_d + 5.22 \, d^c_u \\ d_n &= -0.01 \, d^c_d + 0.49 \, d^c_u \end{aligned}}$$

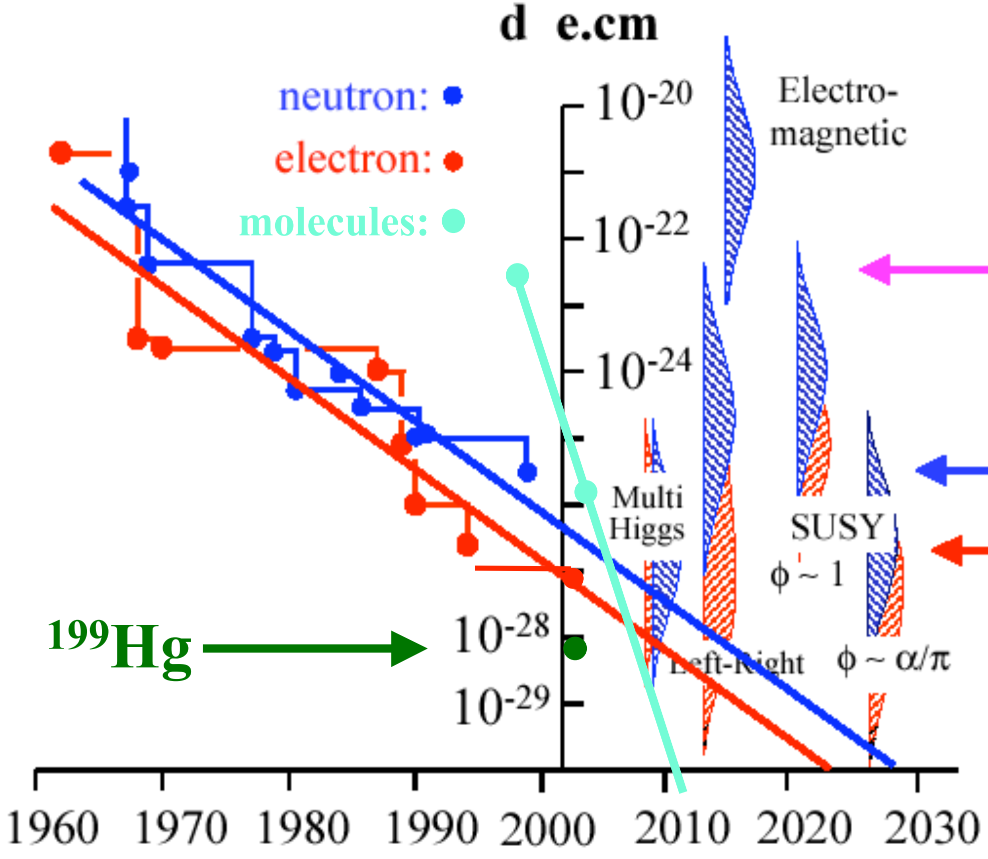
The (nuclear) theory is very well under control. D and n are always complementary; D could be more sensitive!

C.-P. Liu & RGET, PRC **70**, 055501 (2004).

A new generation of hadronic EDM searches

Group	System	Advantages	Proj. gain
D. Wark, M. v.d. Grinten (Sussex/RAL, ILL)	UCN	Cryogenic	10-100?
S. Paul (Munich)	UCN		?
O. Naviliat-Cuncic, K. Kirch (PSI)	UCN	Neutron intensity	10-100?
S. Lamoreaux, M. Cooper, J.C. Peng (LANSCE, SNS)	UCN in superfluid ^{4}He	^{3}He comagnetometer	100-10^3?
N. Fortson (Washington)	^{199}Hg vapor cell		3?
M. Romalis (Princeton)	Liquid ^{129}Xe	Density, long T	100-10^5
T.E. Chupp, C.E. Svensson	^{223}Rn cell	Nucl. enhanc.	10-100?
Z.-T. Lu, R. Holt (ANL)	Trapped ^{225}Ra	At.+nucl. enhanc.	?
L. Willmann (KVI)	^{213}Ra, ^{225}Ra	At.+nucl. enhanc.	?
J. Miller, Y. Semertzidis, E. Stephenson (BNL,CERN?)	Deuteron	Dedicated magn. storage ring	10-10^3

The race for a nonzero EDM…



^{199}Hg →

← **$d(\text{proton}) < 6\times10^{-23}$**

← **$d(\text{neutron}) < 6\times10^{-26}$**

← **$d(\text{electron}) < 1.6\times10^{-27}$**

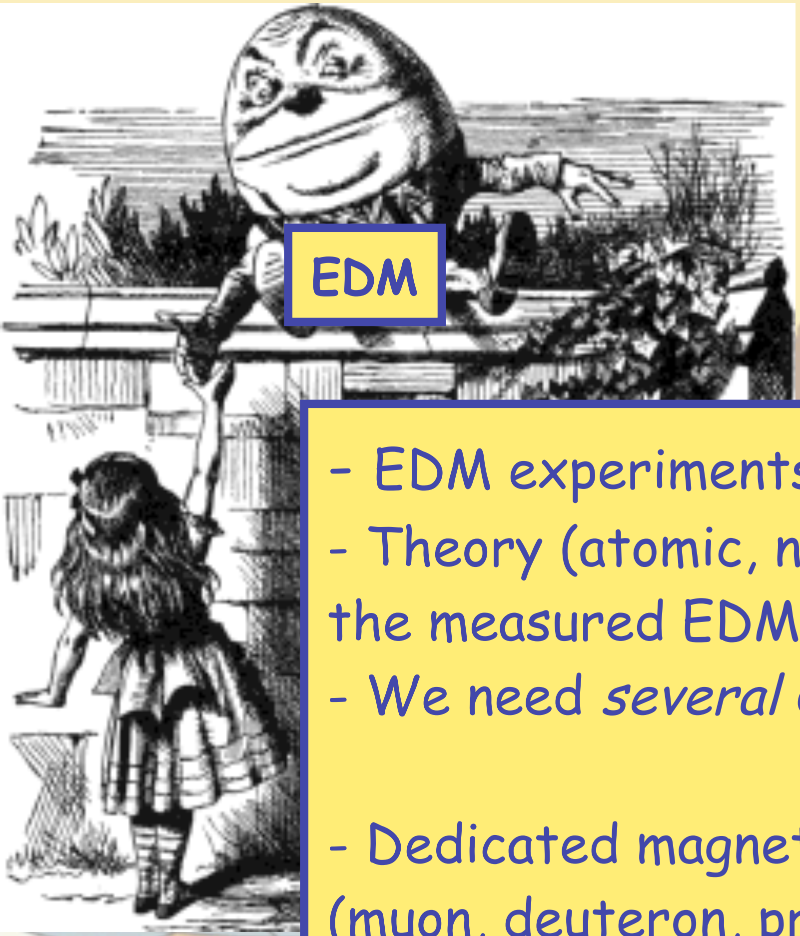
← ***n*/D potential**

← **^{129}Xe, ^{225}Ra potential**

The bottom-line: Sensitivity to CP violation

	Short-term goal [e.cm]	Final goal [e.cm]	g_0	g_1	g_2	Limit on θ
n	$5\text{x}10^{-27}$	$5\text{x}10^{-28}$	0.14		-0.14	$2\text{x}10^{-12}$
D	10^{-27}	10^{-29}	0.10	0.23	0.00	10^{-13}
^{129}Xe	10^{-30}-10^{-31}	10^{-33}	$6\text{x}10^{-5}$	$6\text{x}10^{-5}$	$12\text{x}10^{-5}$	10^{-13}
^{199}Hg	$5\text{x}10^{-29}$	-	$2\text{x}10^{-6}$	$2\text{x}10^{-4}$	$-3\text{x}10^{-5}$	$5\text{x}10^{-10}$
^{225}Ra	?	?	-0.06	-0.12	0.11	?

- The neutron & the deuteron are complementary;
- ^{129}Xe is intrinsically ~10 less sensitive than ^{199}Hg;
- D & ^{129}Xe *at their final goals* are comparable;
- Enhancements in ^{225}Ra overcome the Schiff screening.



Conclusions

- EDM experiments search for a “new Standard Model.”
- Theory (atomic, nuclear/hadronic) is needed to relate the measured EDMs to microscopic CP violation.
- We need *several* experiments to unravel its origin.

- Dedicated magnetic storage rings for charged particles (muon, deuteron, proton, …): a new horse in the race!
- D & ^{129}Xe are complementary to the neutron, and, at their final goals (10^{-29} vs. 10^{-33}), comparable in sensitivity.
- For ^{225}Ra the atomic & nuclear enhancements overcome more-or-less completely the Schiff screening.