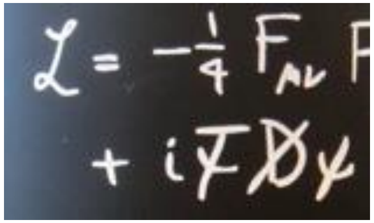
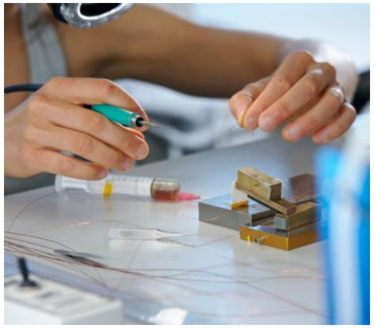


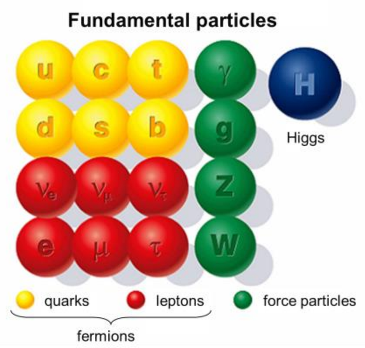


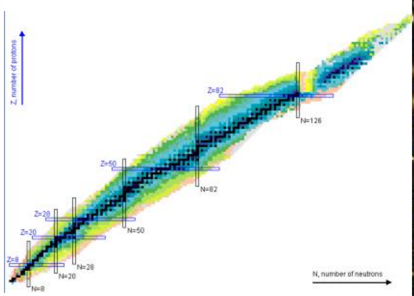
Electric dipole moments

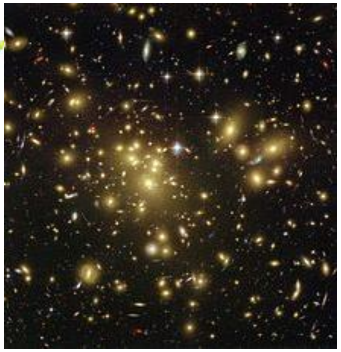
Summer school, Chiemsee

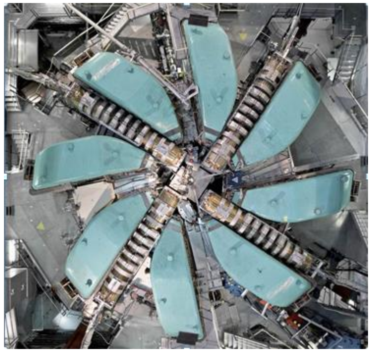
"Symmetry Breaking in Fundamental Interactions"

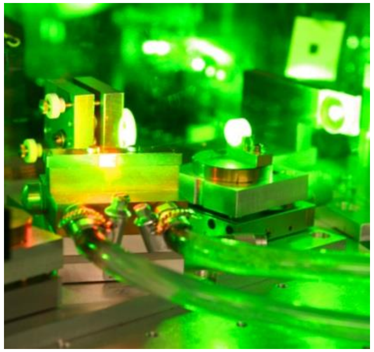
K.Kirch, ETH Zurich – PSI Villigen, Switzerland



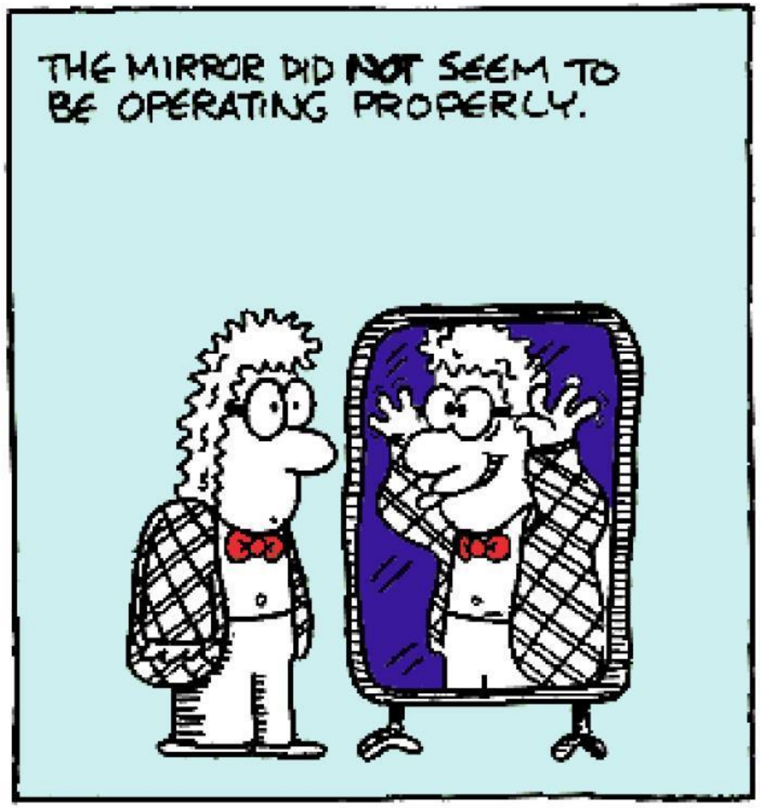






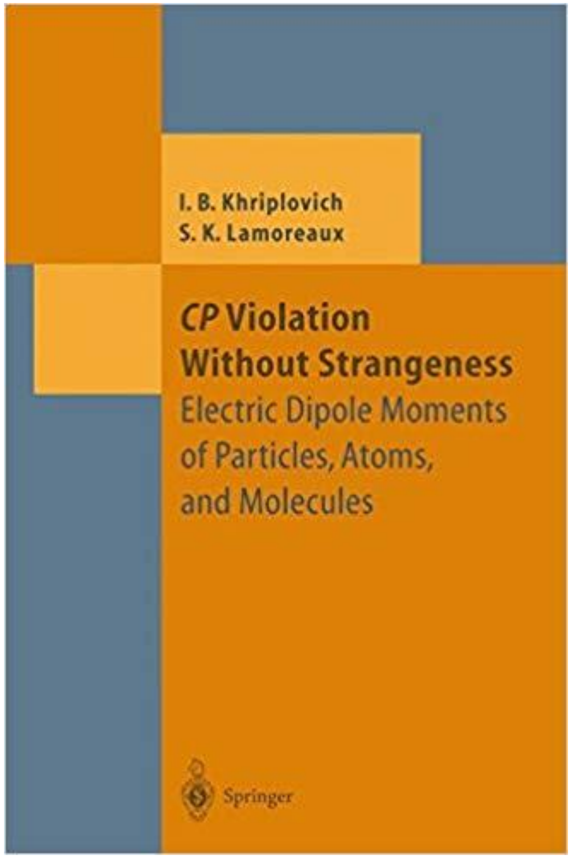


Follow up on Javier's parity violation …



EDMs - recommendable starting points

1997



2005

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Available online at www.sciencedirect.com

SCIENCE DIRECT®

Annals of Physics 318 (2005) 119–169

ANNALS of PHYSICS

www.elsevier.com/locate/aop

Electric dipole moments as probes of new physics

Maxim Pospelov [a,b,c,*], Adam Ritz [d]

2013

Progress in Particle and Nuclear Physics 71 (2013) 21–74

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Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Electric dipole moments of nucleons, nuclei, and atoms: The Standard Model and beyond

CrossMark

Jonathan Engel [a], Michael J. Ramsey-Musolf [b,c,*], U. van Kolck [d,e]

PROCEEDINGS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Quantum Theory of the Electron

P. A. M. Dirac

Proc. R. Soc. Lond. A 1928 **117**, doi: 10.1098/rspa.1928.0023,
published 1 February 1928

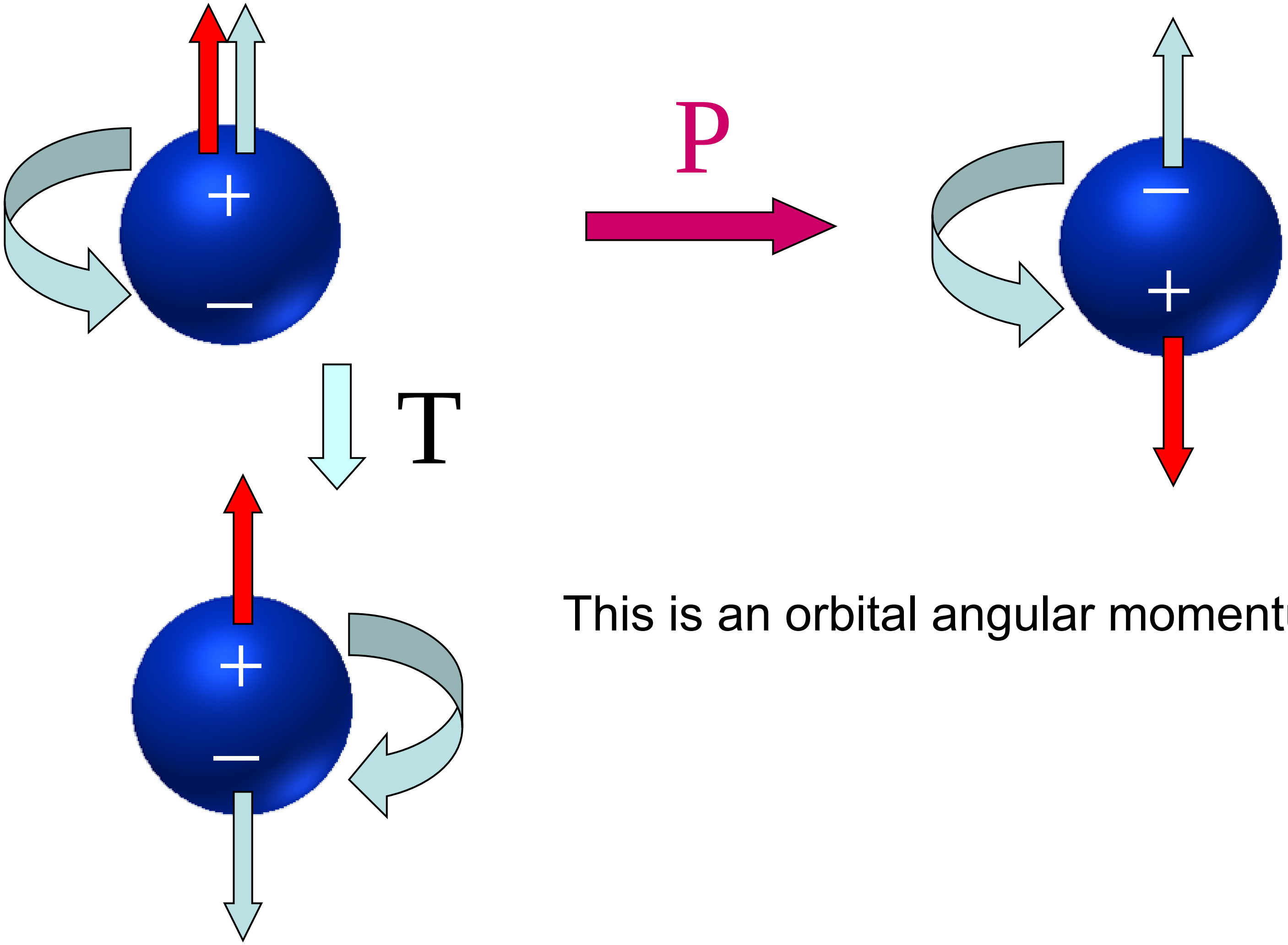
where **E** and **H** are the electric and magnetic vectors of the field.

This differs from (1) by the two extra terms

$$\frac{eh}{c}(\boldsymbol{\sigma}, \mathbf{H}) + \frac{ieh}{c}\rho_1(\boldsymbol{\sigma}, \mathbf{E})$$

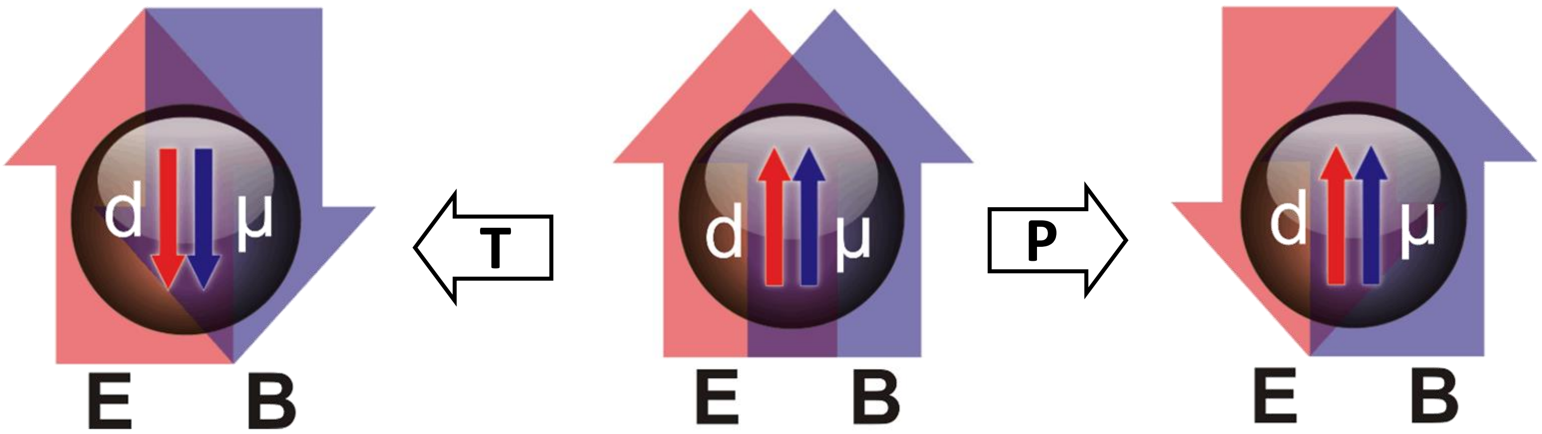
in F. These two terms, when divided by the factor $2m$, can be regarded as the additional potential energy of the electron due to its new degree of freedom. The electron will therefore behave as though it has a magnetic moment $eh/2mc \,.\, \boldsymbol{\sigma}$ and an electric moment $ieh/2mc \,.\, \rho_1 \boldsymbol{\sigma}$. This magnetic moment is just that assumed in the spinning electron model. The electric moment, being a pure imaginary, we should not expect to appear in the model. It is doubtful whether the electric moment has any physical meaning, since the Hamiltonian in (14) that we started from is real, and the imaginary part only appeared when we multiplied it up in an artificial way in order to make it resemble the Hamiltonian of previous theories.

EDM and symmetries



This is an orbital angular momentum picture …

EDM and symmetries



A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

Purcell and Ramsey, PR78(1950)807; Lee and Yang; Landau

Courtesy: H.W. Wilschut

PCT-Theorem a la Escher

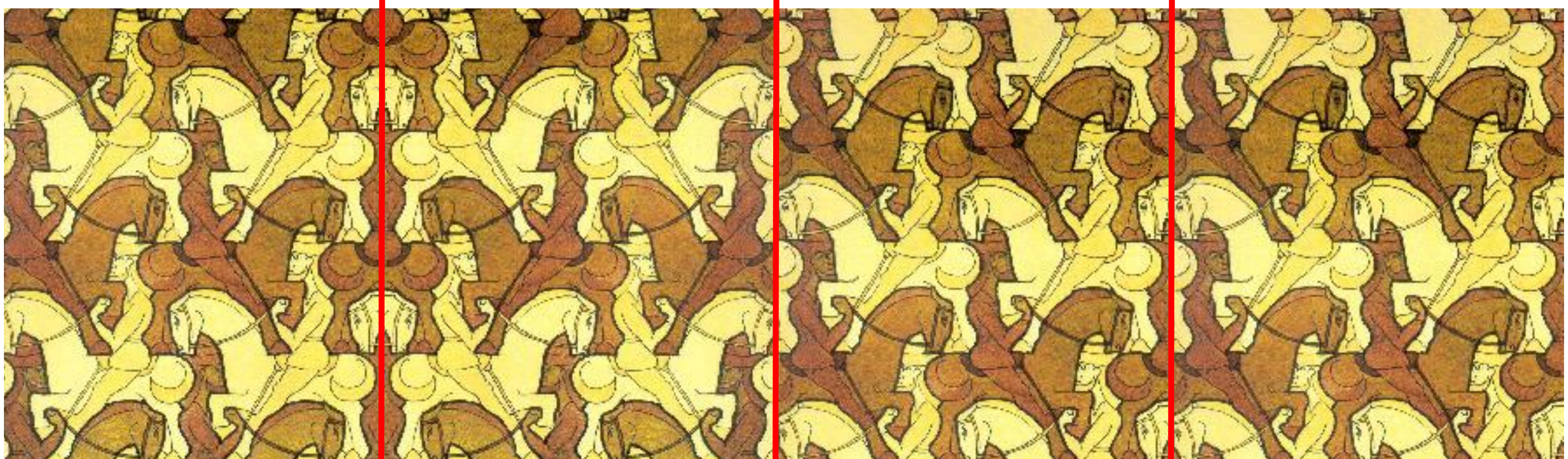
P **C** **T**

Start

Matter

Antimatter

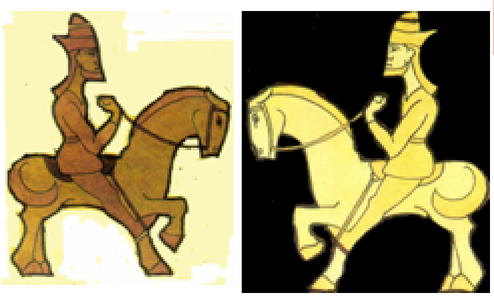
identical to Start



Mirror image

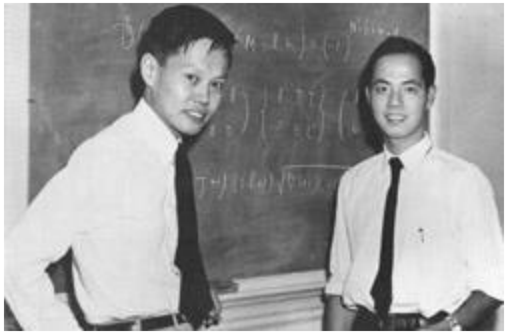
Time →

← Time



Antiparticle **Particle**

Parity violation



Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

and

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

and

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles."

Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+-\mu^+-e^+$*†

Jerome I. Friedman and V. L. Telegdi

Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 17, 1957)

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

What are Experiments?

It is a well known [scientific] technique to try to answer questions by inverting a problem …

So:

"What is a theoretical physicist?"

(by Alvaro de Rújula)

What is a "theoretical physicist"?
by Alvaro de Rújula

Previously at: http://public.web.cern.ch/Public/en/People/Theorists-en.html ... but no longer available

What is similar and what is different between the following two sets?:

The first set consists of a farmer,
his pig and the truffles:

What is a "theoretical physicist"?
by Alvaro de Rújula
http://public.web.cern.ch/Public/en/People/Theorists-en.html

What is similar and what is different between the following two sets?:

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The second set consists of the theorist, the experimentalist and the big discoveries:

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What is similar and what is different between the following two sets?:

The first set consists of a farmer, his pig and the truffles:



The second set consists of the theorist, the experimentalist and the big discoveries:



The answer to the riddle is:
The farmer takes his pig to the woods.
The pig snifs around looking for a truffle.
When the pig gets it and is about to eat it,
the farmer kicks the pig on the head
with his club and steals the truffle.

What is a "theoretical physicist"?
by Alvaro de Rújula
http://public.web.cern.ch/Public/en/People/Theorists-en.html

What is similar and what is different between the following two sets?:

The first set consists of a farmer, his pig and the truffles:

The second set consists of the theorist, the experimentalist and the big discoveries:

Those are the similarities:
a theorist would also claim recognition for an experimenter's discovery (if it has anything to do with her/his theories) even if [s]he did not make it!

The difference is
that the farmer always takes the pig to woods where there are truffles, while more often than not, the suggestions by the theorists take the experimentalists to "woods" where there are no "truffles" (by suggesting experiments that do not lead to interesting discoveries).

What is a "theoretical physicist"?
by Alvaro de Rújula
http://public.web.cern.ch/Public/en/People/Theorists-en.html

What is similar and what is different between the following two sets?:

The first set consists of a farmer, his pig and the truffles:



The second set consists of the theorist, the experimentalist and the big discoveries:



Not to be unfair to theorists, one must add that
there are notable exceptions to these rules,
progress is made by trial and error, and the theorists' guidance
is occasionally in the right direction!
Even more often, while looking for the theorists' "truffles"
the experimentalists find "gold": something unexpected
but even more interesting!
(Nature tends to be more creative than we are).

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 3 JULY, 1949

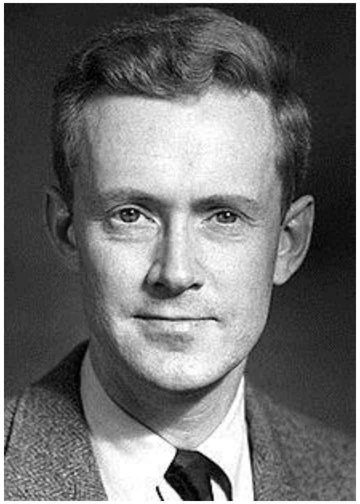
Forms of Relativistic Dynamics

P. A. M. DIRAC
St. John's College, Cambridge, England

1949

A transformation of the type (1) may involve a reflection of the coordinate system in the three spacial dimensions and it may involve a time reflection, the direction du_0 in space-time changing from the future to the past. I do not believe there is any need for physical laws to be invariant under these reflections, although all the exact laws of nature so far known do have this invariance. The restricted principle of rela-

Experimental evidence for absence of nuclear EDM?



On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. PURCELL AND N. F. RAMSEY
Department of Physics, Harvard University, Cambridge, Massachusetts

April 27, 1950

1950

We are now undertaking, in collaboration with Mr. James H. Smith, an experiment which should directly measure the electric dipole moment of the neutron if it has a value of *D* of approximately the above magnitude. The experiment will utilize a neutron beam magnetic resonance[5] apparatus of high resolution[6] to detect a possible shift of the neutron precession frequency upon the application of a strong electric field.

The Nobel Prize in Physics 1952 was awarded jointly to Felix Bloch and Edward Mills Purcell "for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith."

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey "for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks", the other half jointly to Hans G. Dehmelt and Wolfgang Paul "for the development of the ion trap technique."

Experimental evidence for absence of nuclear EDM?

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,* E. M. PURCELL, AND N. F. RAMSEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

1957

Time Reversal, Charge Conjugation, Magnetic Pole Conjugation, and Parity

N. F. RAMSEY
Lyman Physics Laboratory, Harvard University, Cambridge, Massachusetts

(Received November 14, 1957)

The discovery of CP-violation

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

1964

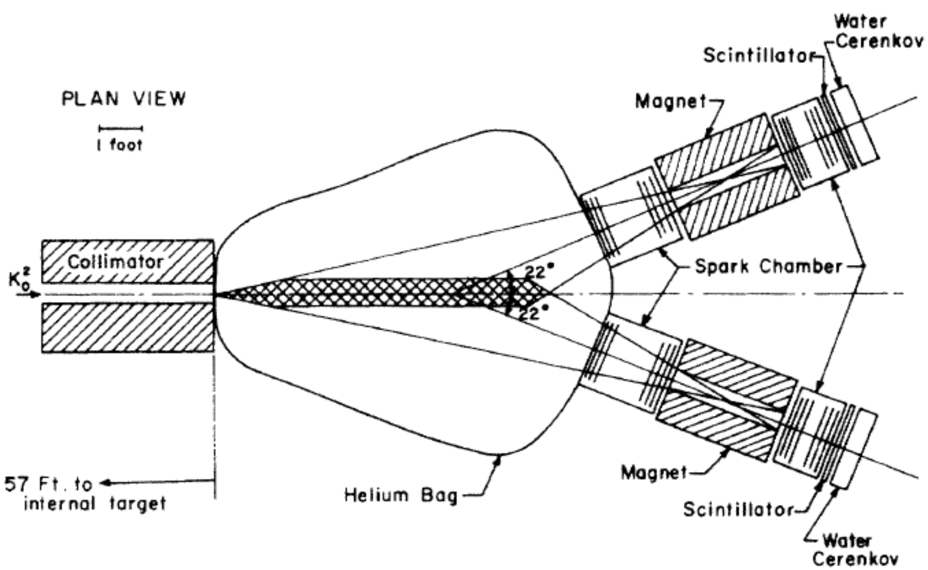


FIG. 1. Plan view of the detector arrangement.

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons."

CP-Violation in semileptonic K^0-decays

$$A_L = \frac{\Gamma(K_L^0 \to \pi^- \ell^+ \nu) - \Gamma(K_L^0 \to \pi^+ \ell^- \nu)}{\Gamma(K_L^0 \to \pi^- \ell^+ \nu) + \Gamma(K_L^0 \to \pi^+ \ell^- \nu)}$$

$$A_L = (3.32 \pm 0.06) \times 10^{-3}$$

Maybe you have been told to ask your alien friends about it if you get to talk to them before meeting ….

Nature has probably violated CP when generating the Baryon asymmetry !?

Observed*:

$$(n_B - n_{\bar{B}}) / n_\gamma = 6 \times 10^{-10}$$

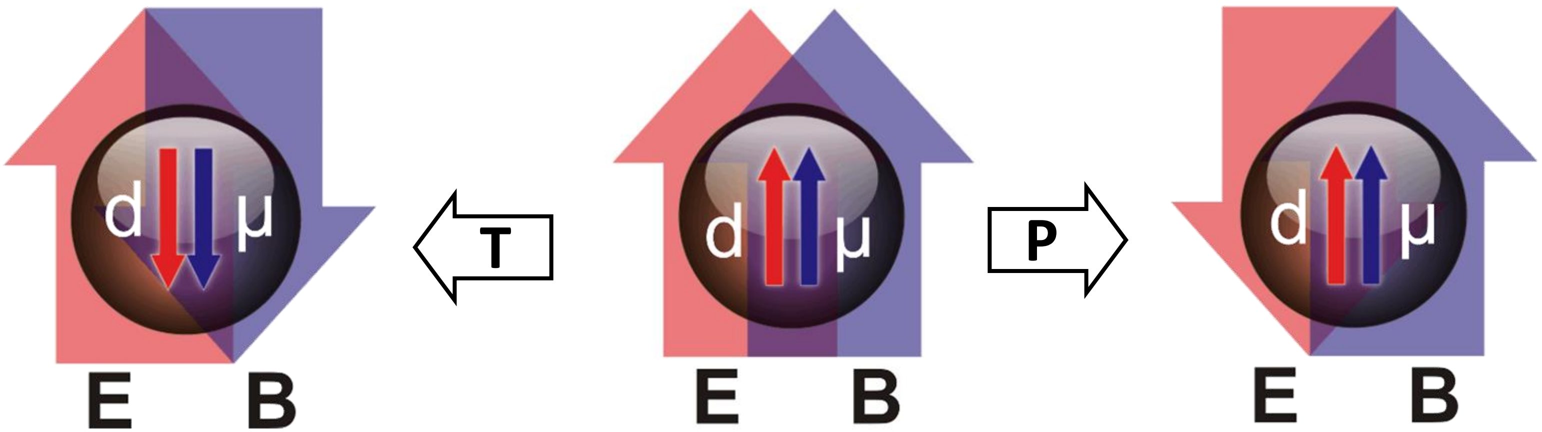
SM expectation:

$$(n_B - n_{\bar{B}}) / n_\gamma \sim 10^{-18}$$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
[JETP Lett. 5 (1967) 24]

* WMAP + COBE, 2003
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$

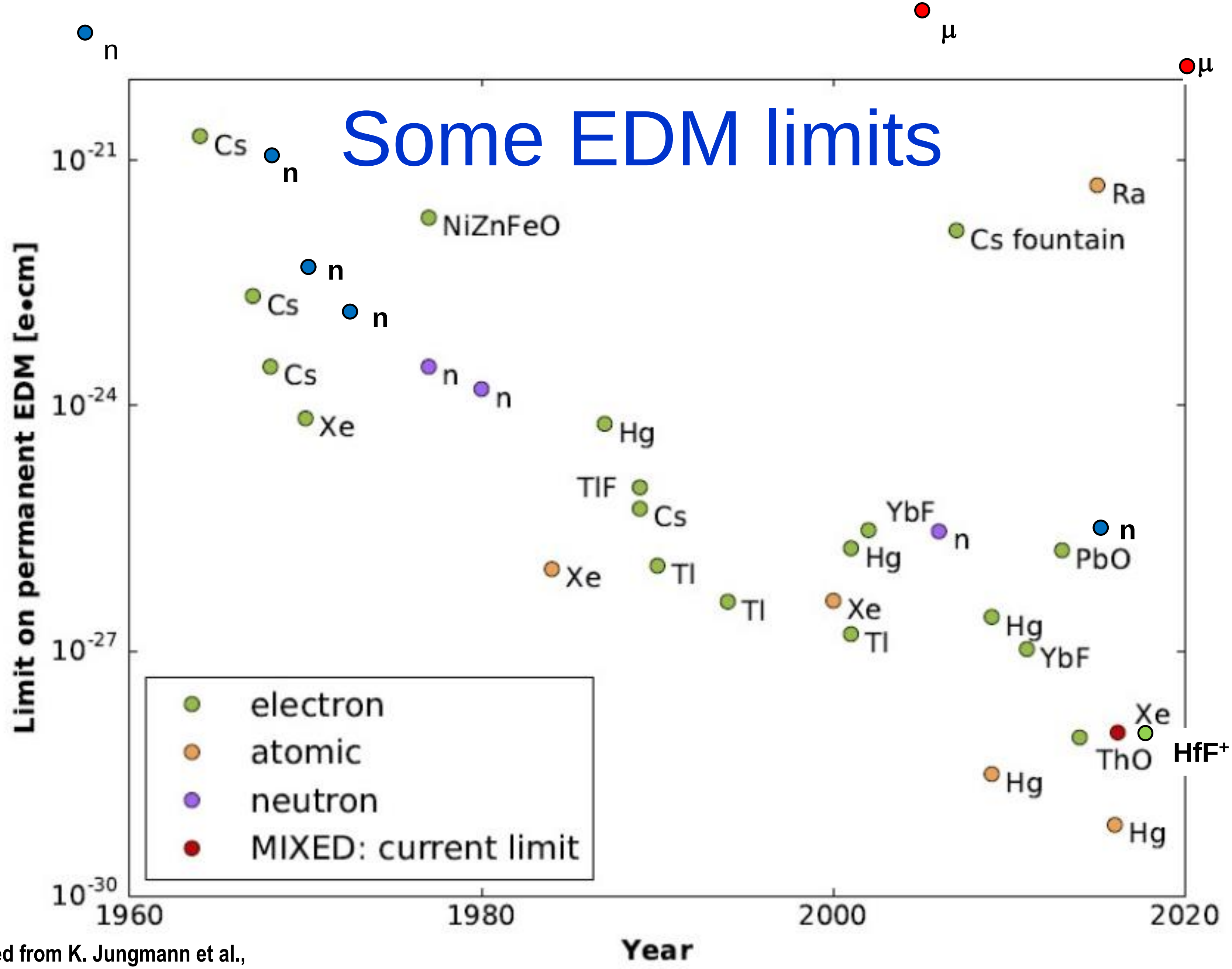
EDM and symmetries



A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

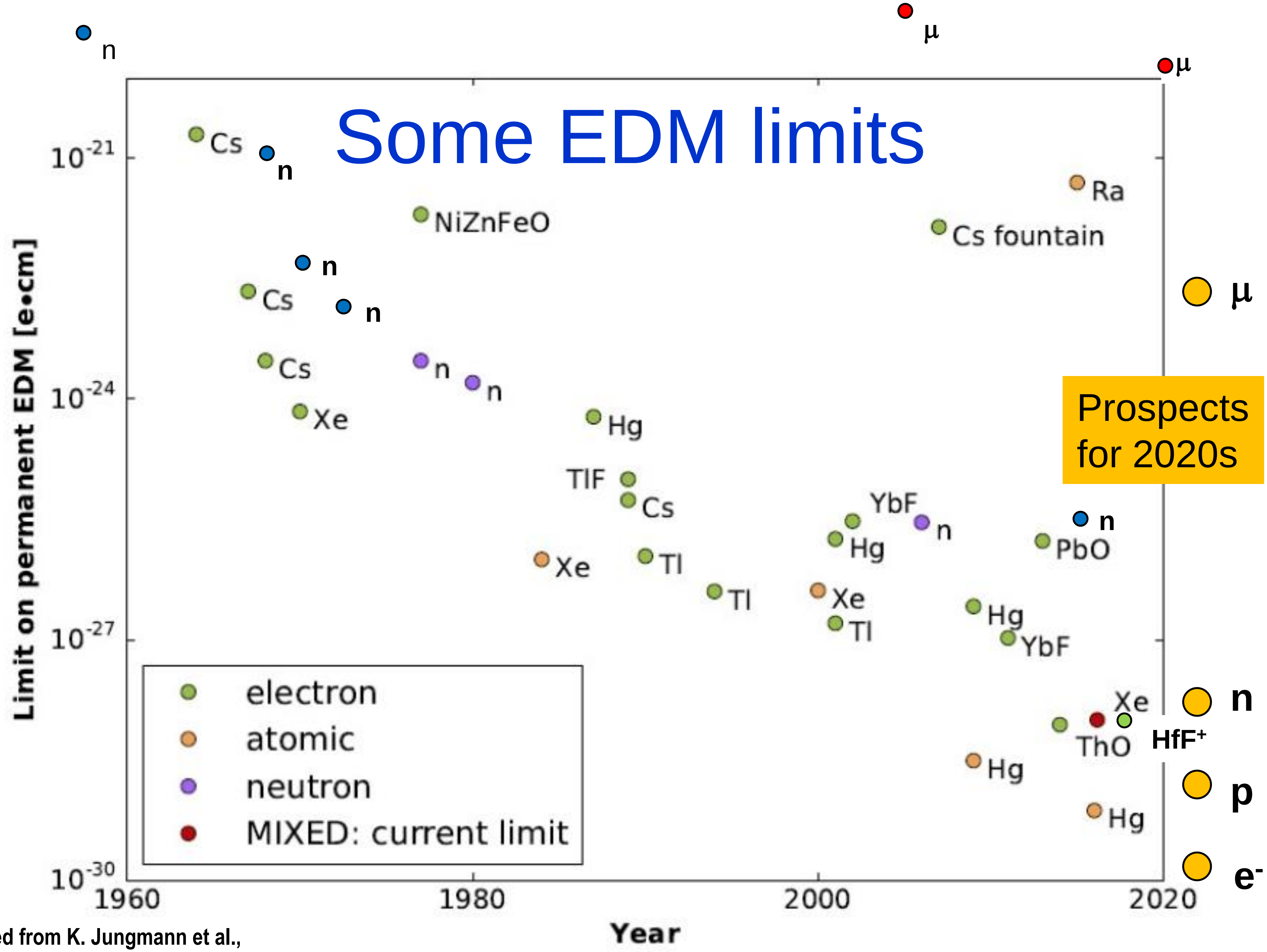
Purcell and Ramsey, PR78(1950)807; Lee and Yang; Landau

Some EDM limits



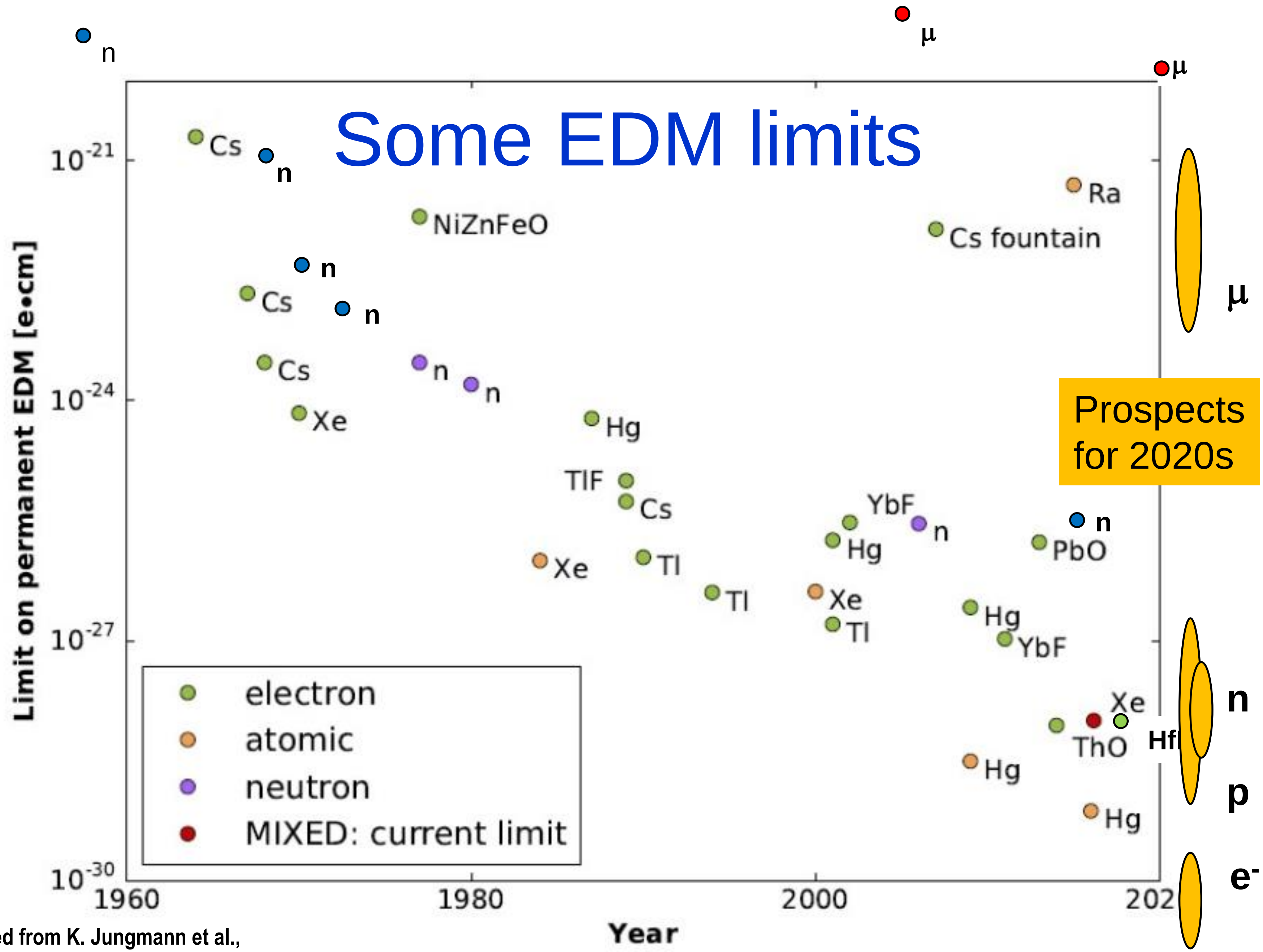
Adapted from K. Jungmann et al.,
JPS Conf. Proc. 18(2017)011017

Some EDM limits



Adapted from K. Jungmann et al.,
JPS Conf. Proc. 18(2017)011017

Some EDM limits



Adapted from K. Jungmann et al.,
JPS Conf. Proc. 18(2017)011017

Complex composite systems have constituents and interactions

Paramagnetic atoms

$$d_{\text{para}}(d_e) \sim 10\alpha^2 Z^3 d_e \Longrightarrow d_{\text{Tl}} = -585 d_e - 43\ \text{GeV} \times e\, C_S^{\text{singlet}}$$ enhancement

Paramagnetic molecules

additional enhancement from large internal electric fields of order 10 GV/cm or more, influenced by molecular level structure

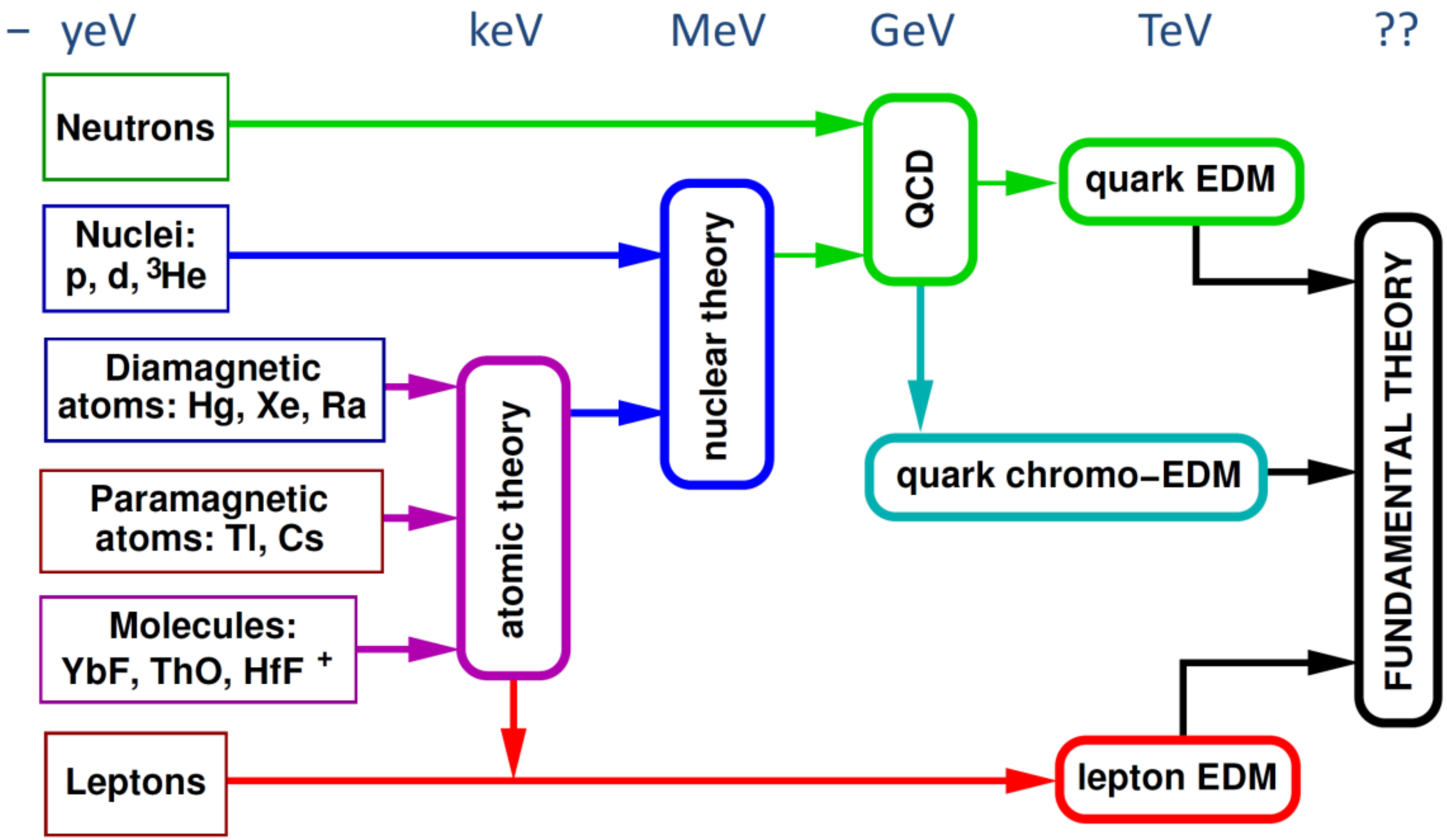
Diamagnetic atoms

$d_{\text{dia}} \sim 10 Z^2 (R_N/R_A)^2 \tilde{d}_q$ suppression of order 10^3

$$\Longrightarrow d_{\text{Hg}} = 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d) + 10^{-2}\, d_e + \mathcal{O}(C_S, C_{qq})$$

enhancement factors possible due to atomic state mixing and nuclear deformation.

Connecting experiments and theory



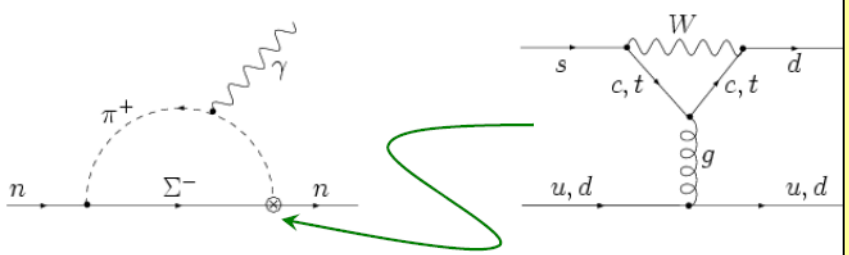
Scheme: courtesy Rob G. E. Timmermans

See also: Pospelov, Ritz, Ann. Phys. 318(2005)119

See for a 'global analysis': Chupp, Ramsey-Musolf PRC91(2015)035502

Electric Dipole Moments tiny in SM

- Neutron, Proton, ..

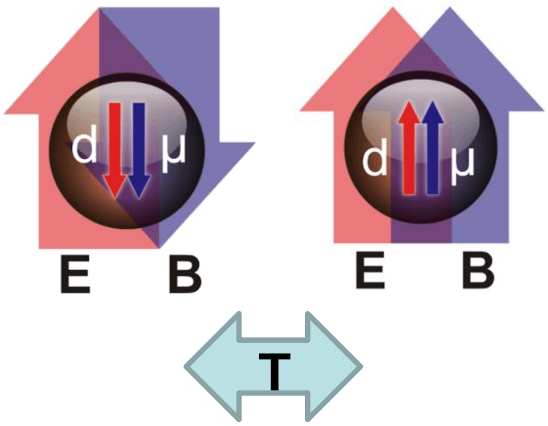


$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky '86]

Expect from SM:
$d_n < 10^{-30}$ e•cm

Experimentally:
$< 3.0 \times 10^{-26}$ e•cm
Pendlebury et al., PRD92(2015)092003



Most sensitive probe of BSM CP violation

- Leptons: 4^{th} order EW

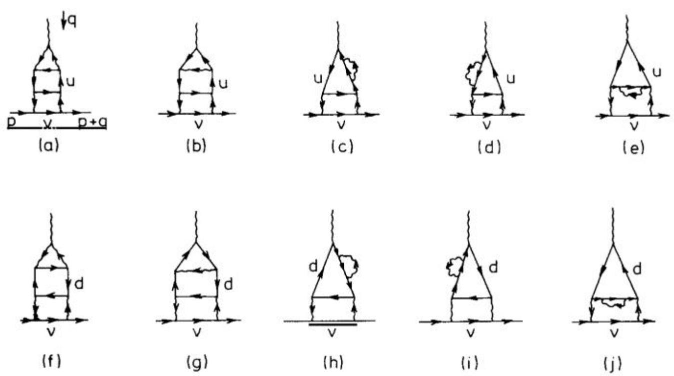


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[Hoogeveen '90, Pospelov, Ritz 2014]

Expect from SM:
$d_e \leq 10^{-44}$ e•cm — new to me, recently
$d_\mu \leq 10^{-42}$ e•cm
$d_\tau \leq 10^{-41}$ e•cm

Experimentally:
$d_e < 9 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

ThO molecule
Baron et al., Science 343(2014)269

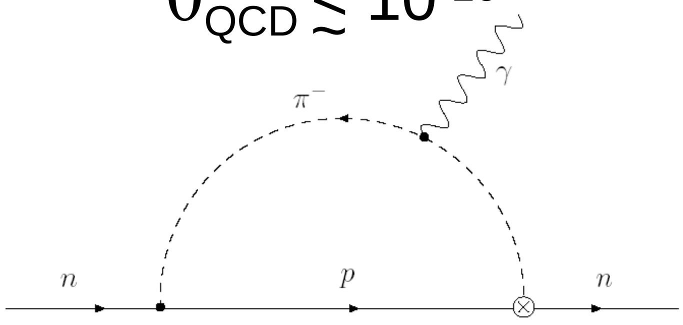
muon g-2 storage ring
Bennett et al., PRD80(2009)052008

The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$$

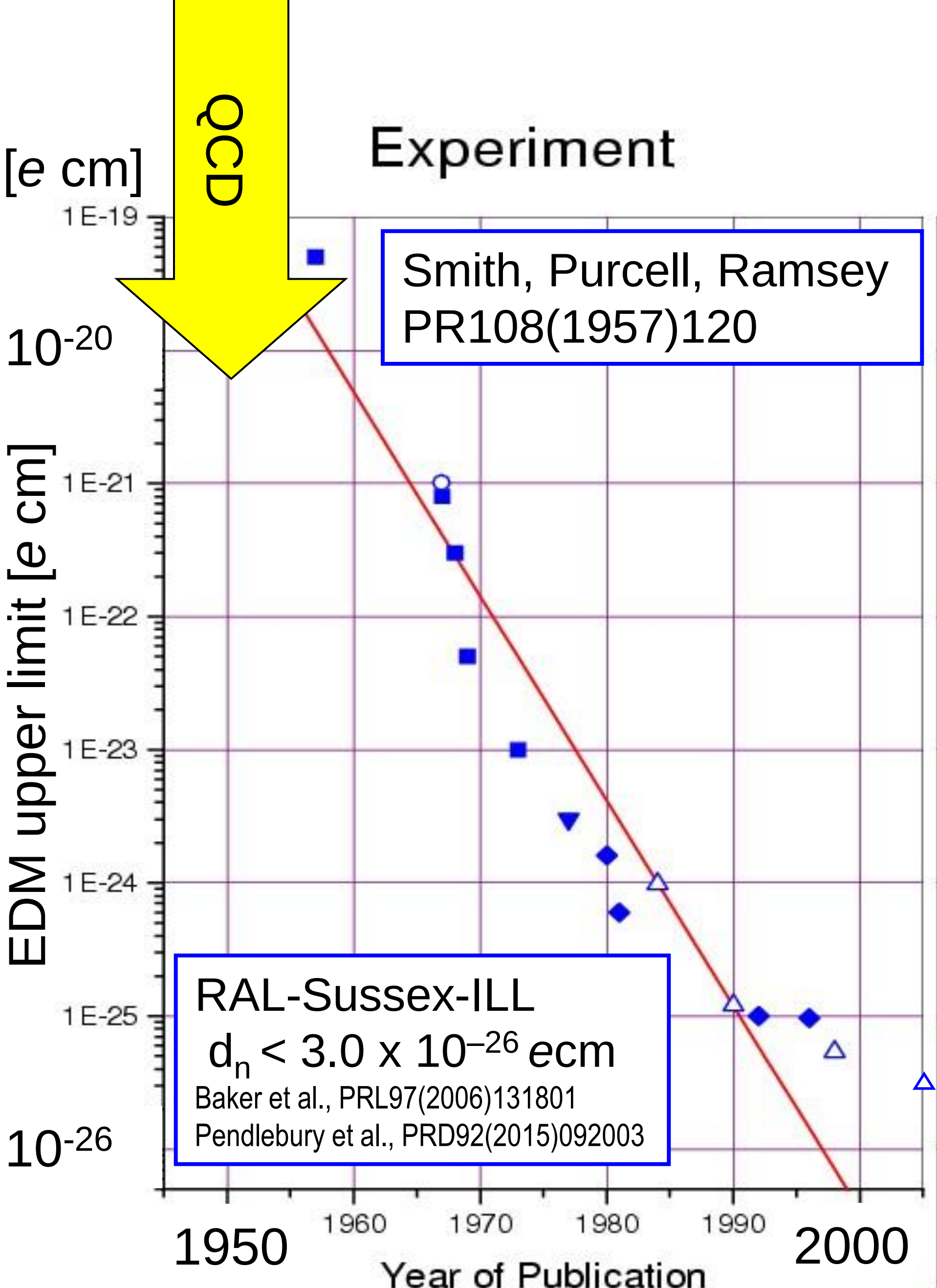
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

→ accidentally small !?



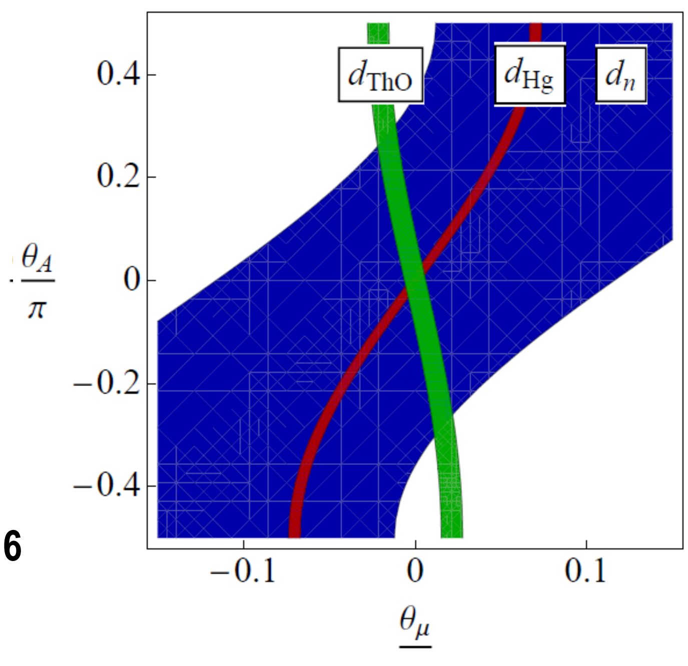
The SUSY CP problem

(for neutron and electron!)

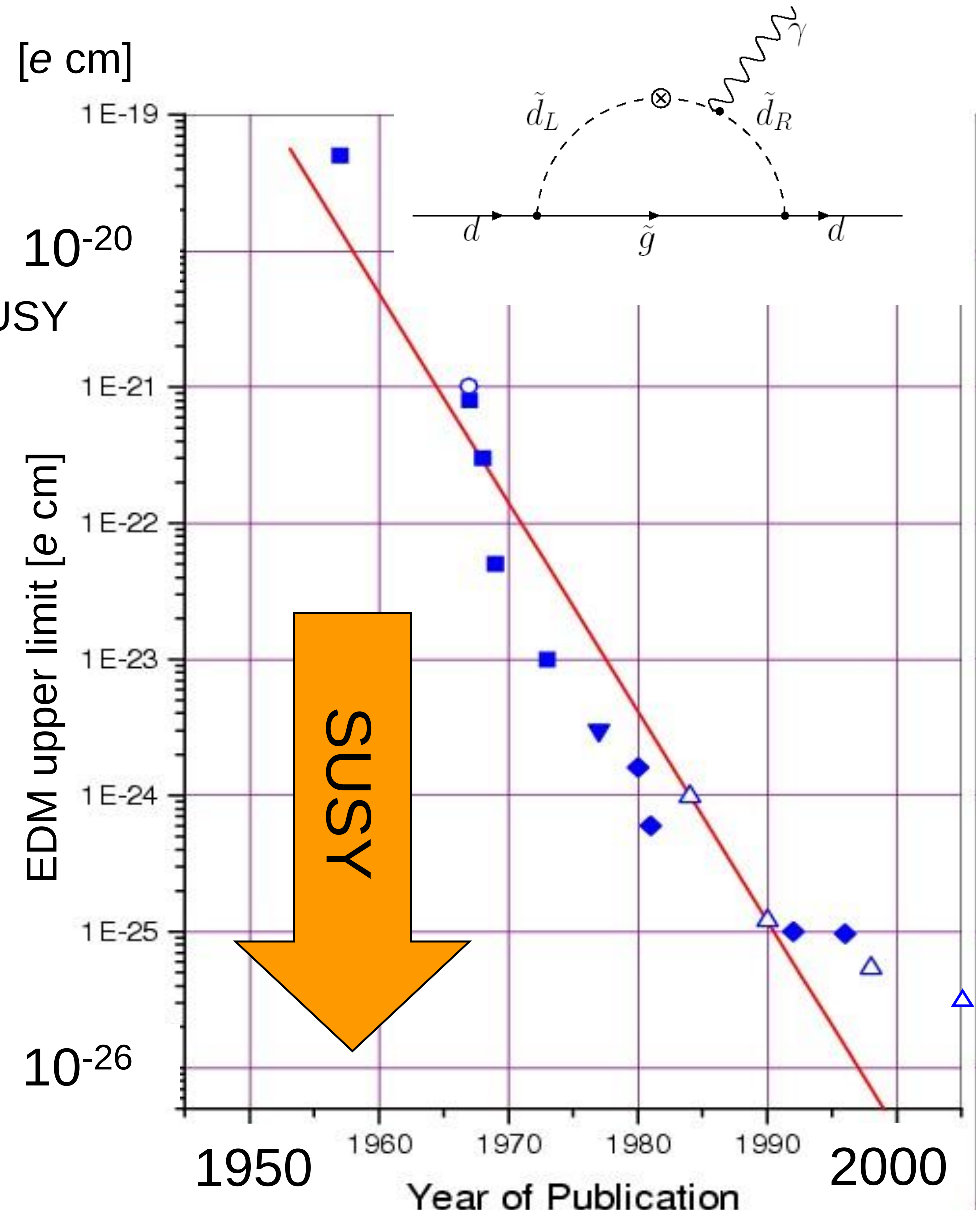
$$d_n \approx 10^{-23}\, e\ \mathrm{cm} \left(\frac{300\ \mathrm{GeV/c^2}}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)

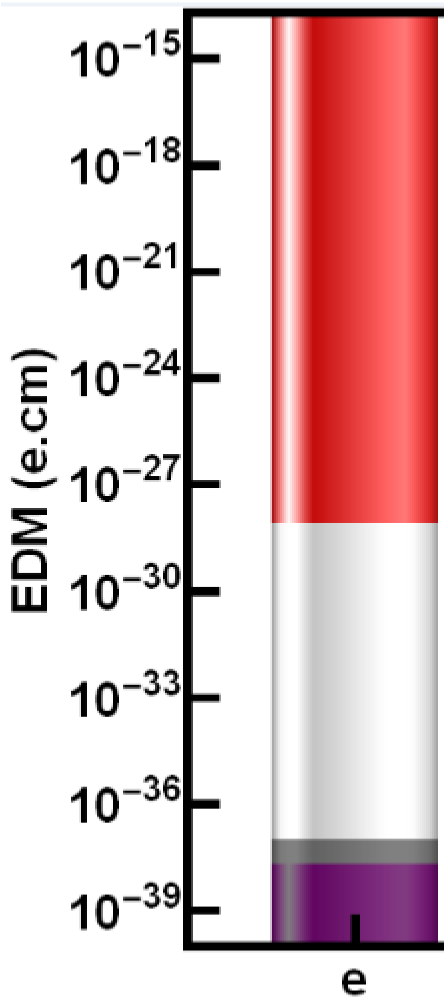


A. Ritz, update 2016



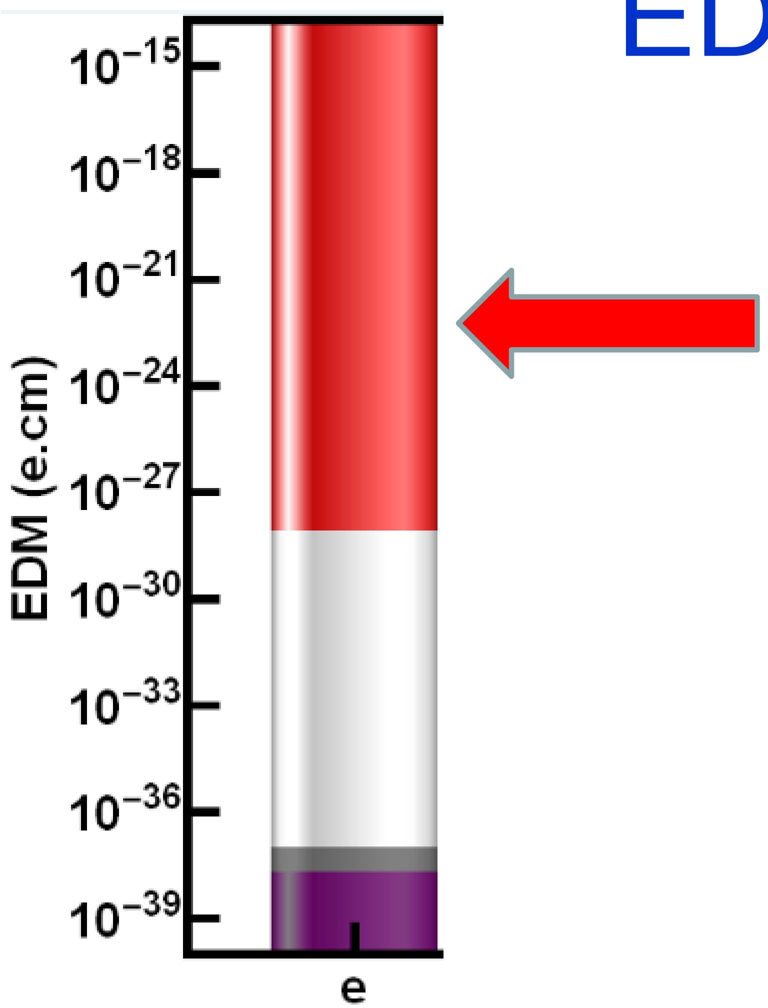
ETH

EDM display



Displays by Prajwal Mohan Murthy
PhD thesis in preparation, ETHZ 2018

EDM display

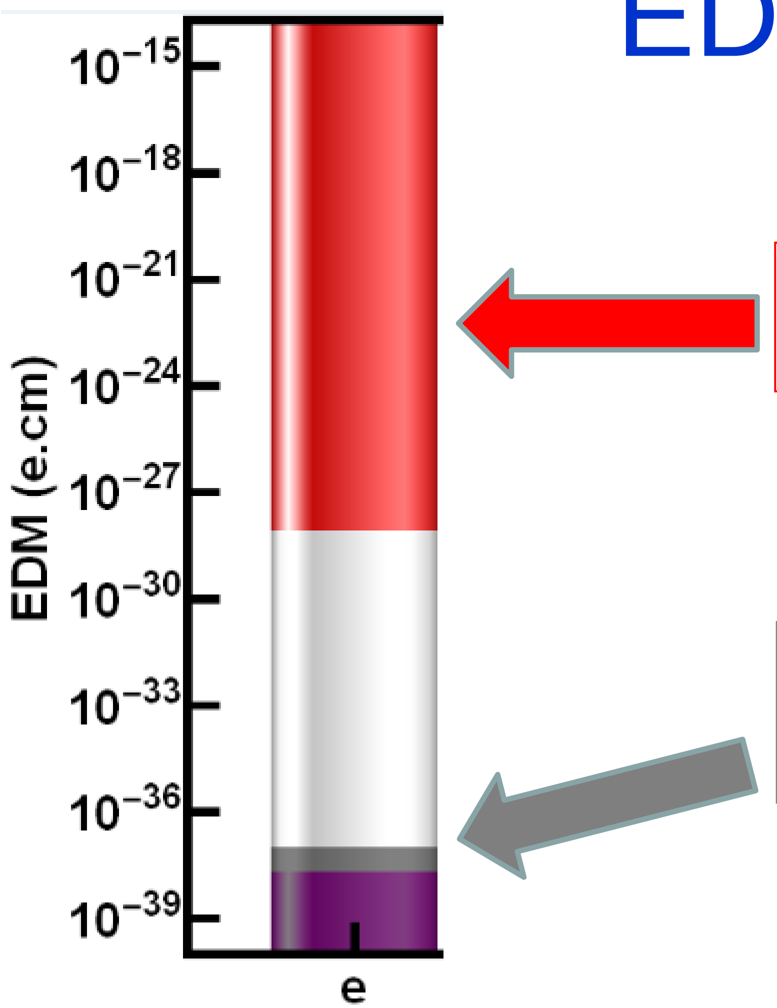


The experimental constraint, can be direct or indirect and under certain assumptions*

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg; here eEDM from measurement on ThO by ACME, NJP19(2017)073029

see talk by Jordy de Vries for better approach than 'single source'

EDM display

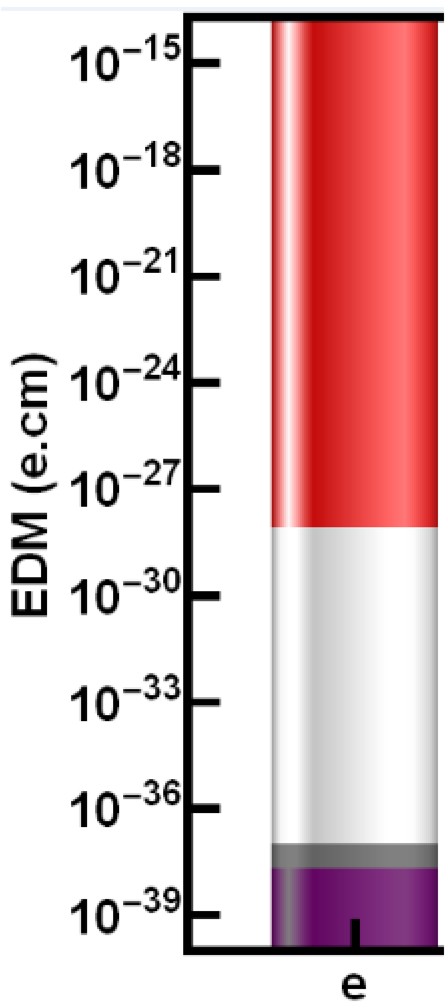


The experimental constraint, can be direct or indirect and under certain assumptions*

Estimated θ_{QCD} contribution**, we have assumed θ_{QCD} < 1E-10 * everywhere

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg;
** see Ghosh&Sato, PLB777(2018)335 for leptons

EDM display



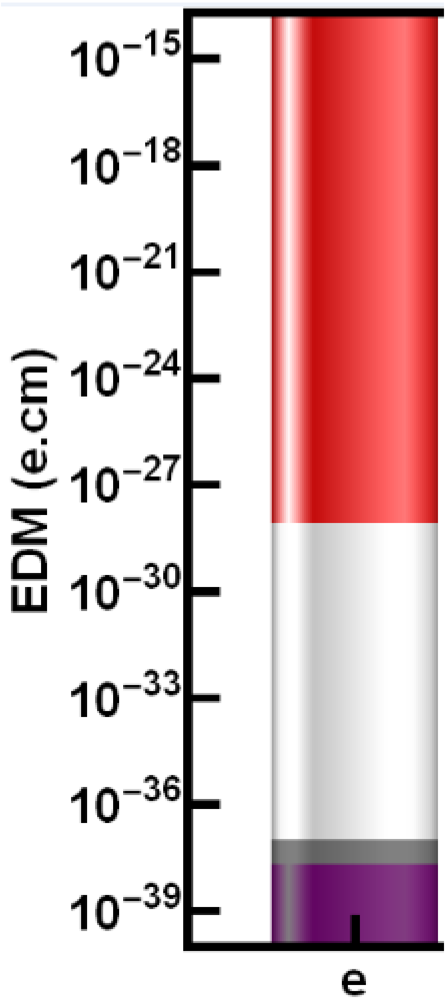
The experimental constraint, can be direct or indirect and under certain assumptions*

Estimated θ_{QCD} contribution**, we have assumed θ_{QCD} < 1E-10 * everywhere

Estimated CKM contribution***

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg;
** see Ghosh&Sato, PLB777(2018)335 for leptons
*** see Pospelov&Ritz, PRD89(2014)056006; eEDM 1E-38 → 1E-44 ecm

EDM display



The experimental constraint, can be direct or indirect and under certain assumptions*

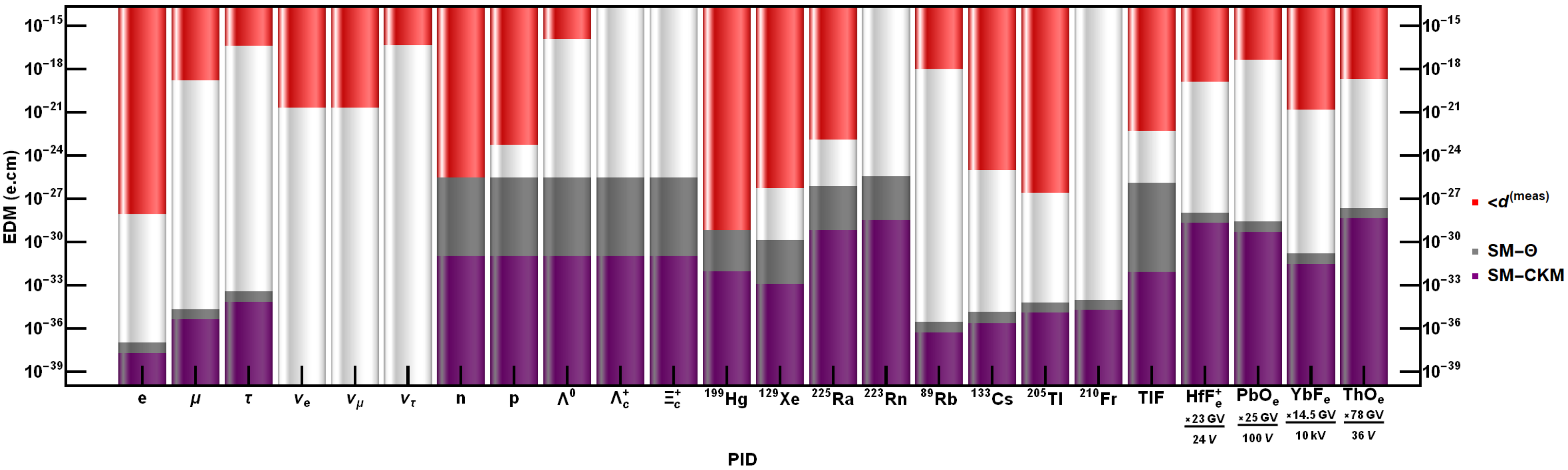
'safe' BSM discovery territory

Estimated θ_{QCD} contribution**, we have assumed θ_{QCD} < 1E-10 * everywhere

Estimated CKM contribution***

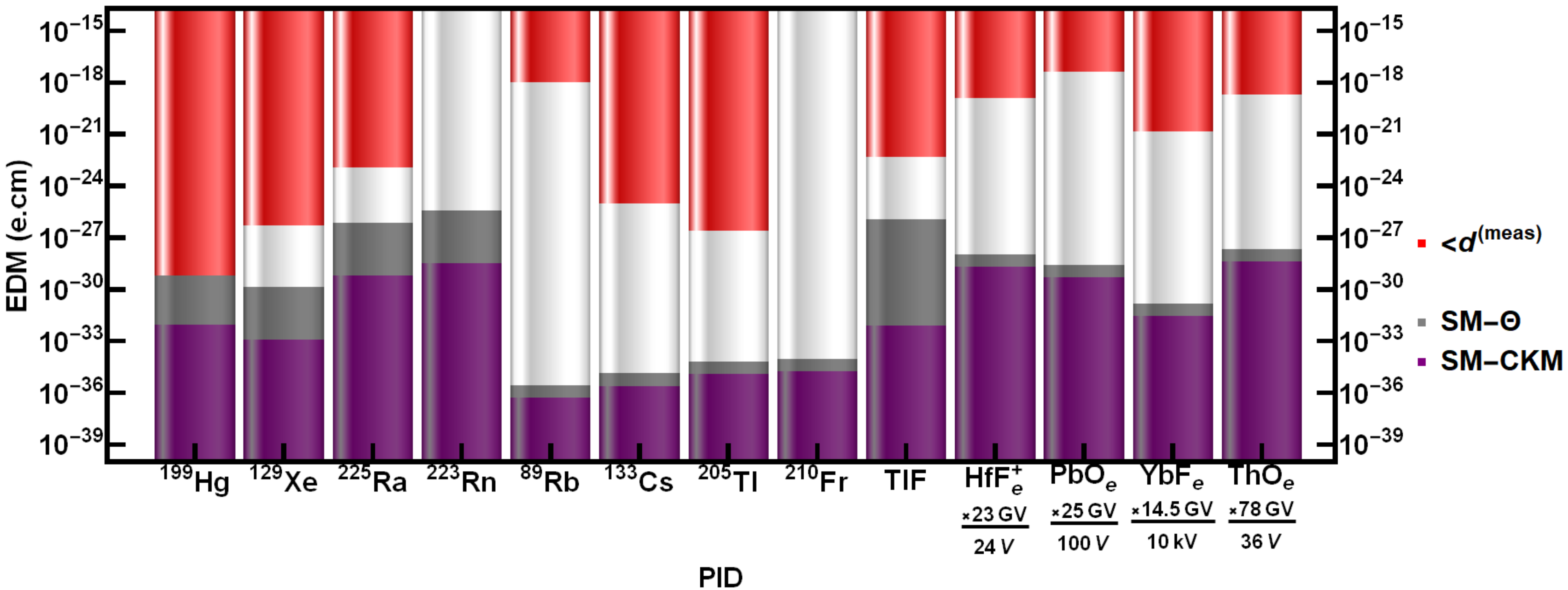
* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg;
** see Ghosh&Sato, PLB777(2018)335 for leptons
*** see Pospelov&Ritz, PRD89(2014)056006; eEDM 1E-38 → 1E-44 ecm

An overview



Disclaimer: CKM and strong CP contributions are sometimes rough guesses → needs more theory consultation

Atoms and molecules



Extract the best limits for eEDM, CPV eN interactions and nuclear moments.
Need to disentangle various sources. Need atomic and nuclear theory.
Uncertainties in the theoretical calculations can be unknown and large.

The strongest experimental limit: ^{199}Hg

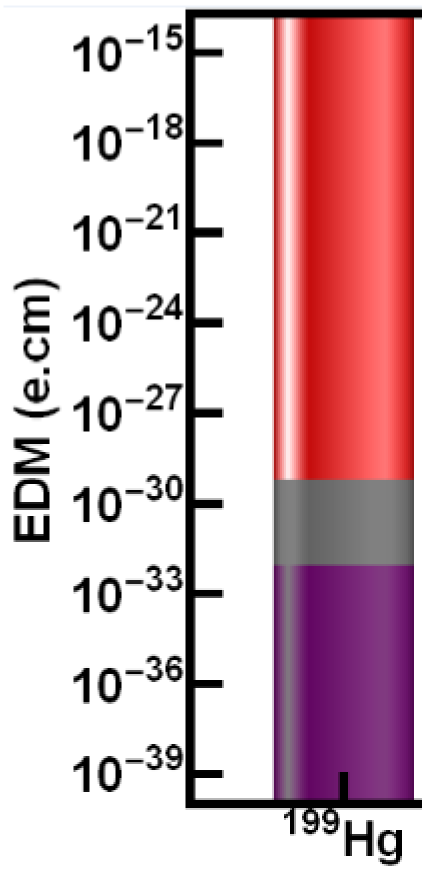


TABLE III. Limits on *CP*-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole*contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{\rm Hg}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e\,\mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{\rm Hg}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e\,\mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{\rm Hg}/(0.135\ e\,\mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{\rm Hg}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{\rm Hg}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22,23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\ \mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[25]
C_S	$\mathbf{d}_{\rm Hg}/(5.9 \times 10^{-22}\ e\,\mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{\rm Hg}/(6.0 \times 10^{-23}\ e\,\mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{\rm Hg}/(4.89 \times 10^{-20}\ e\,\mathrm{cm})$	1.5×10^{-10}	see text

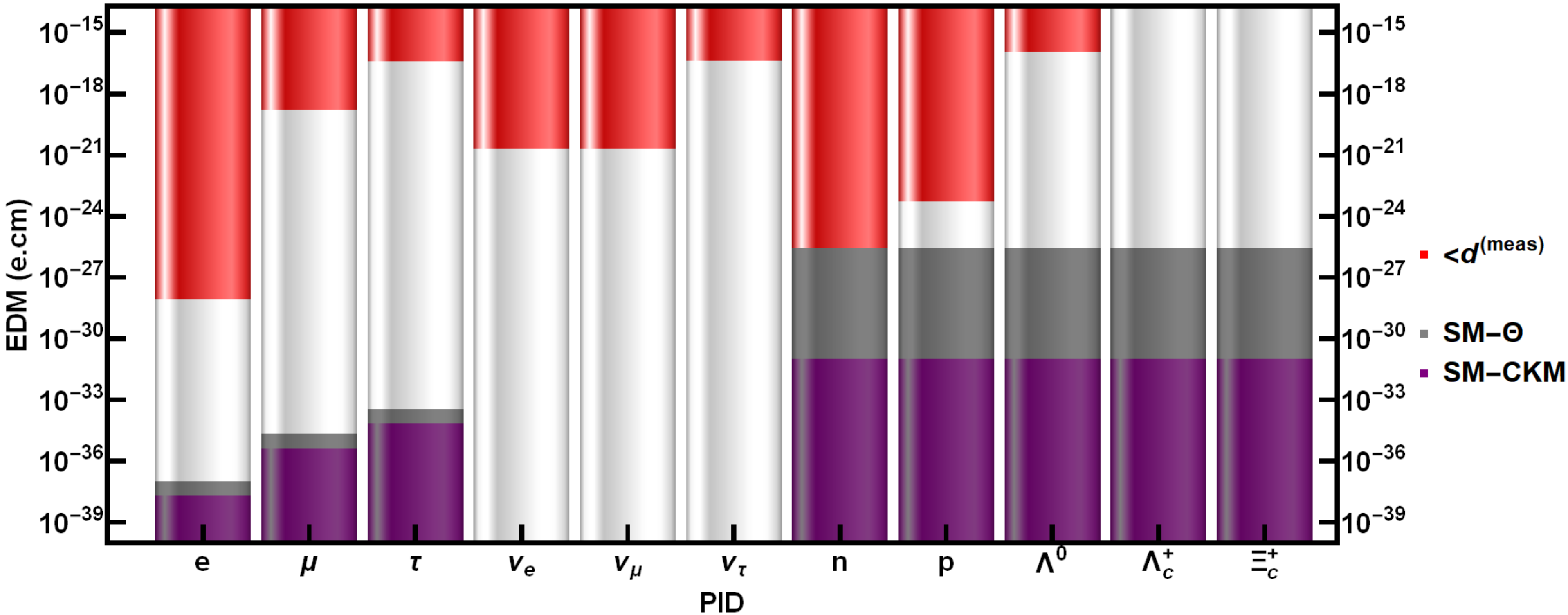
$$|d_{\rm Hg}| < 7.4 \times 10^{-30} e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

Graner et al., PRL116(2016)161601

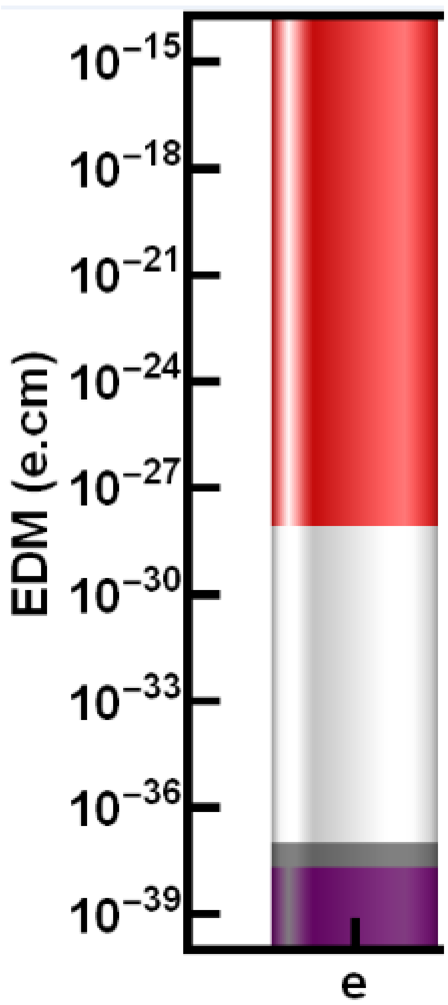
* e.g. otherwise θ_{QCD} ~< 1E-6

Chupp, Ramsey-Musolf, PRC91(2015)035502

Particles



A mix of indirect and direct bounds

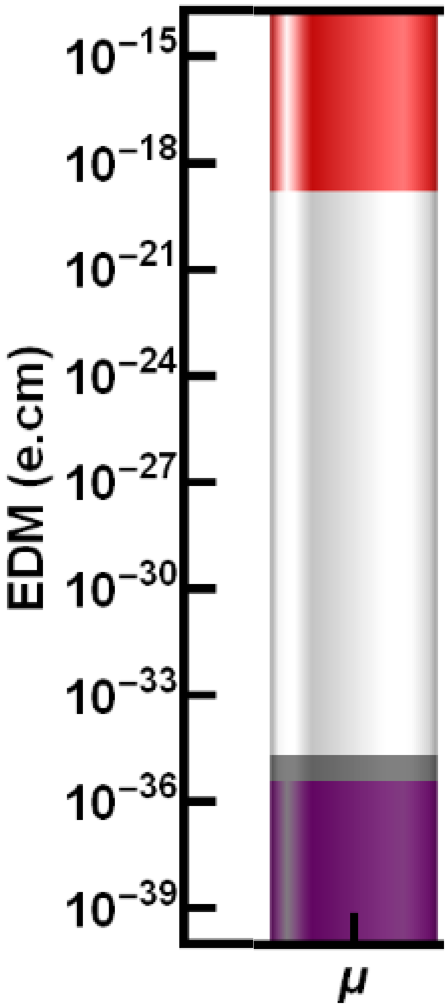


Electron:

The tightest EDM limit on a fundamental fermion

System	Electron EDM limit	Latest reference	Improving
$^{232}Th^{16}O$	9.4E-29 ecm	**NJP19(2017)073029**	y
$^{180}Hf^{19}F+$	13E-29 ecm	**PRL119(2017)153001**	y
$^{174}Yb^{19}F$	105E-29 ecm	**NJP14(2012)103051**	y

Remarkably: ^{199}Hg and ‘sole source’ → eEDM < 104E-29 ecm



Muon:

The best direct EDM limit on a fundamental fermion

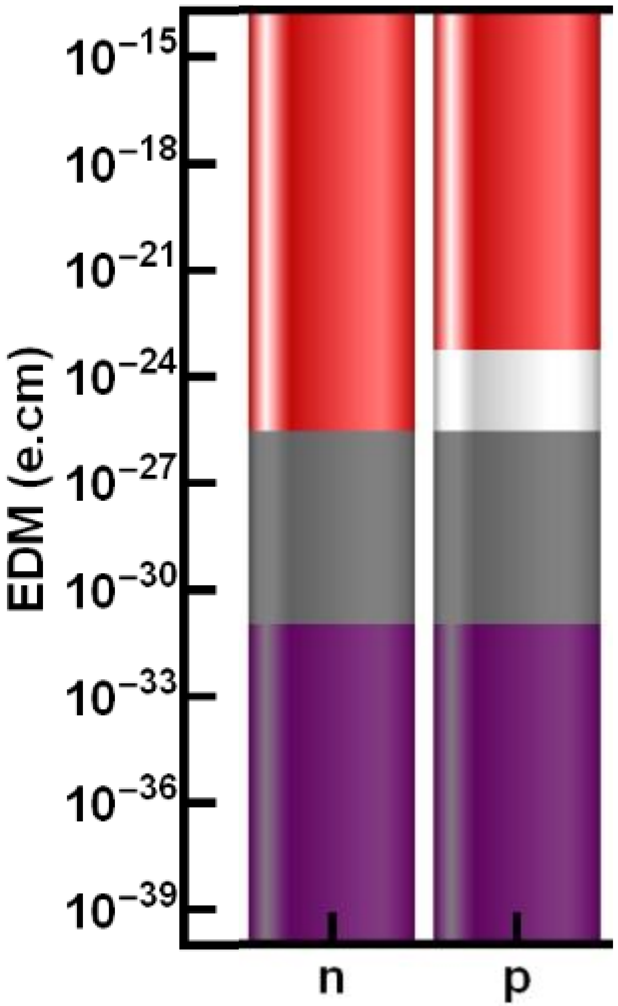
- Side analysis of muon g-2 experiment

$$|d_\mu| \leq 1.8 \times 10^{-19}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}),$$

Bennett et al., RD80(2009)052008

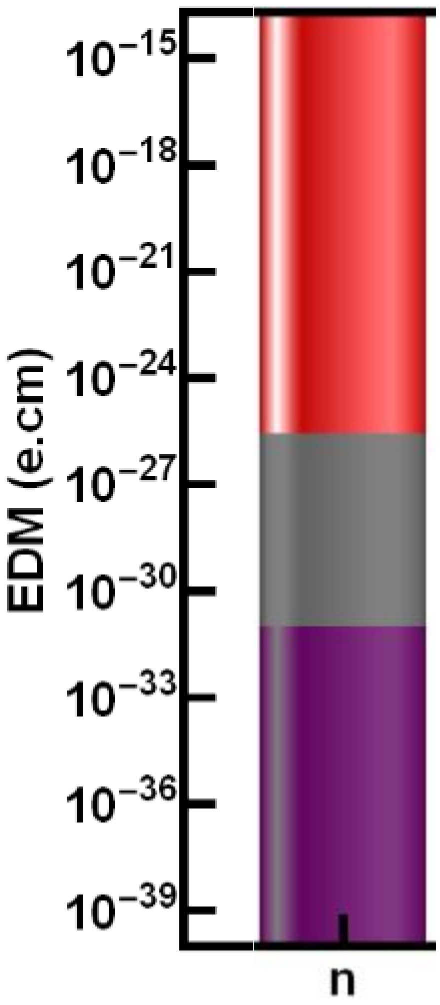
- Improvement to ~1E-21 ecm possible as byproduct of new g-2
- Improvement to few E-23 ecm with dedicated (small) storage ring
  - demonstrator for frozen spin ring EDM
  - BSM theory motivation!?

Neutron and Proton



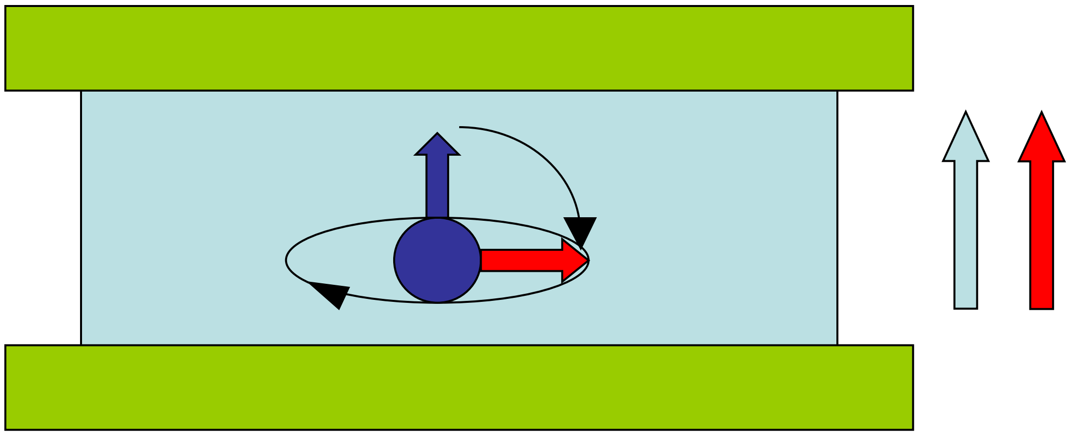
- Present best proton (and neutron) EDM limit derived from ^{199}Hg under the 'sole source assumption'.
- Present best direct nEDM limit 3.0E-26 ecm (**Pendlebury et al., PRD92(2015)092003**)
- neutron EDM constrains θ_{QCD} < 1E-10 under single source assumption (as does ^{199}Hg)
- finite neutron and proton EDM could eventually support or rule out θ_{QCD} as source of EDM signals together with advanced lattice QCD (very active but not conclusive yet)

Neutron



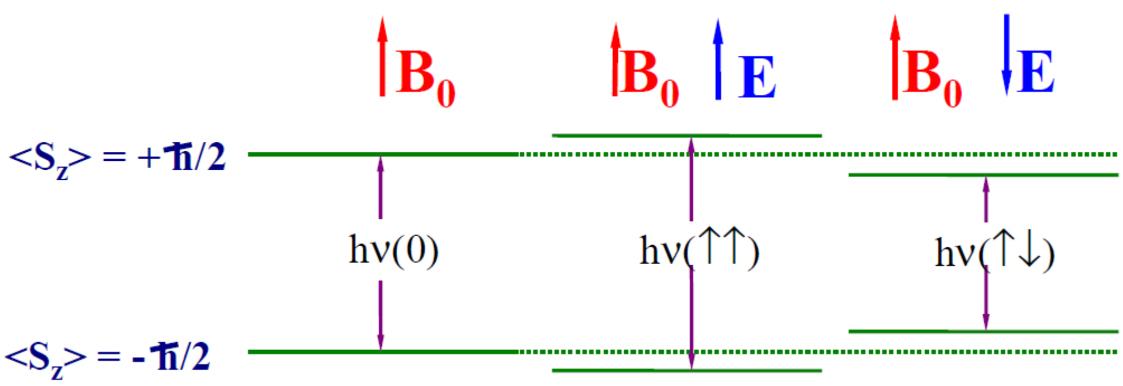
- Several nEDM efforts world-wide: presently leading effort at PSI
  (more at SNS, ILL, LANL, TRIUMF, PNPI, ESS)
- nEDM: the prototype of experimental EDM search for symmetry violations, since 1950
- nEDM poses the strong CP problem
- together with EDM limits of the e^- and ^{199}Hg giving some of the tightest BSM constraints
- Discovery potential at the current limit; could be SM

How to measure the neutron (or other) electric dipole moment ?



$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

$$h\Delta\nu = 4\, d_n E$$



$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

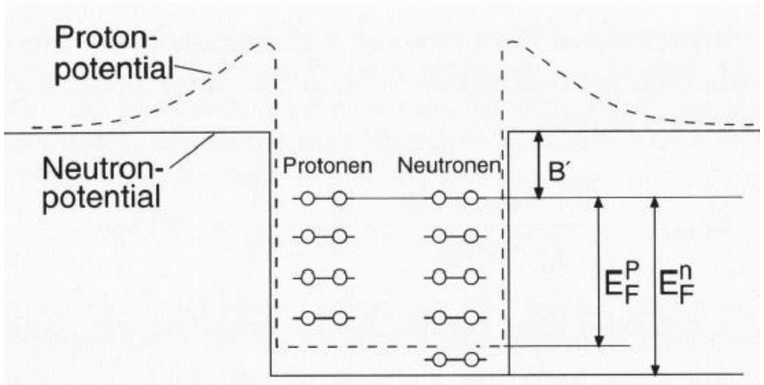
Time over

Next: Will try to ….

- Explain neutron EDM related experimental things
- Give some insight into storage ring EDM

Bottle of wine question:

- To a slow neutron, all nuclei are attractive potential wells from 10 to 60 MeV deep and a few fm in diameter. Nevertheless, most elements, when made into mirrors, reflect (i.e., repel) slow neutrons. Why??



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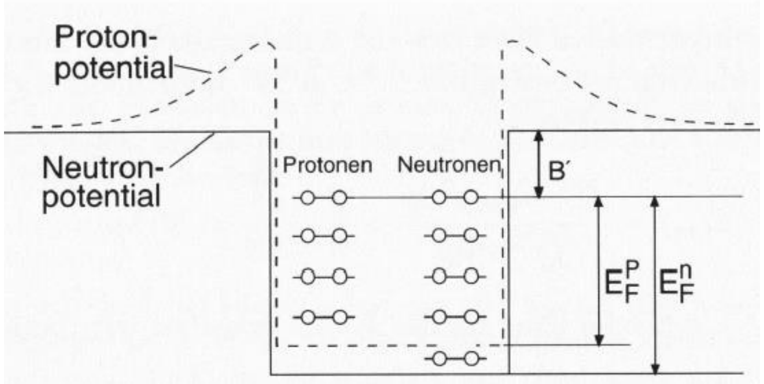

  - Answers that reach me by 8pm today in form of 1 page handwritten short explanations take part in the competition.
  - The winner will get the bottle of sparkling wine which I brought (‘Engelhof’ 2012 Rivaner Brut)