When you measure it, measure it like you mean it

Do I mean “don’t do an experiment unless
you think there is a chance it will discover new physics.”   ?

No. A fully realized precision measurement with capability of reaching record precision of a quantity that has a chance of revealing new physics is a MAJOR undertaking. Meanwhile…

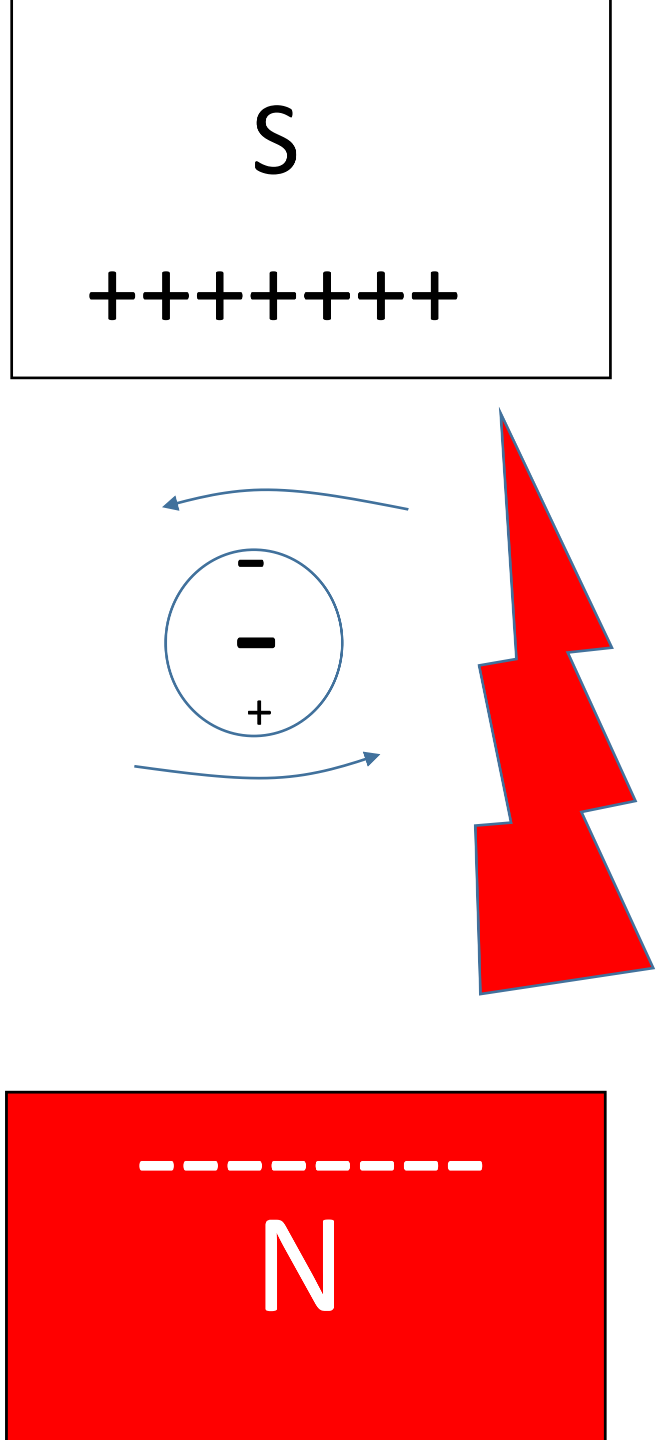
…developing new techniques, new capabilities, learing how to do things, even without an immediate new-physics search planned, those things are worthwhile.

But, especially as you start to “emerge from the time-machine”, keep the bigger picture in mind.

Combined
Figure-of-merit:

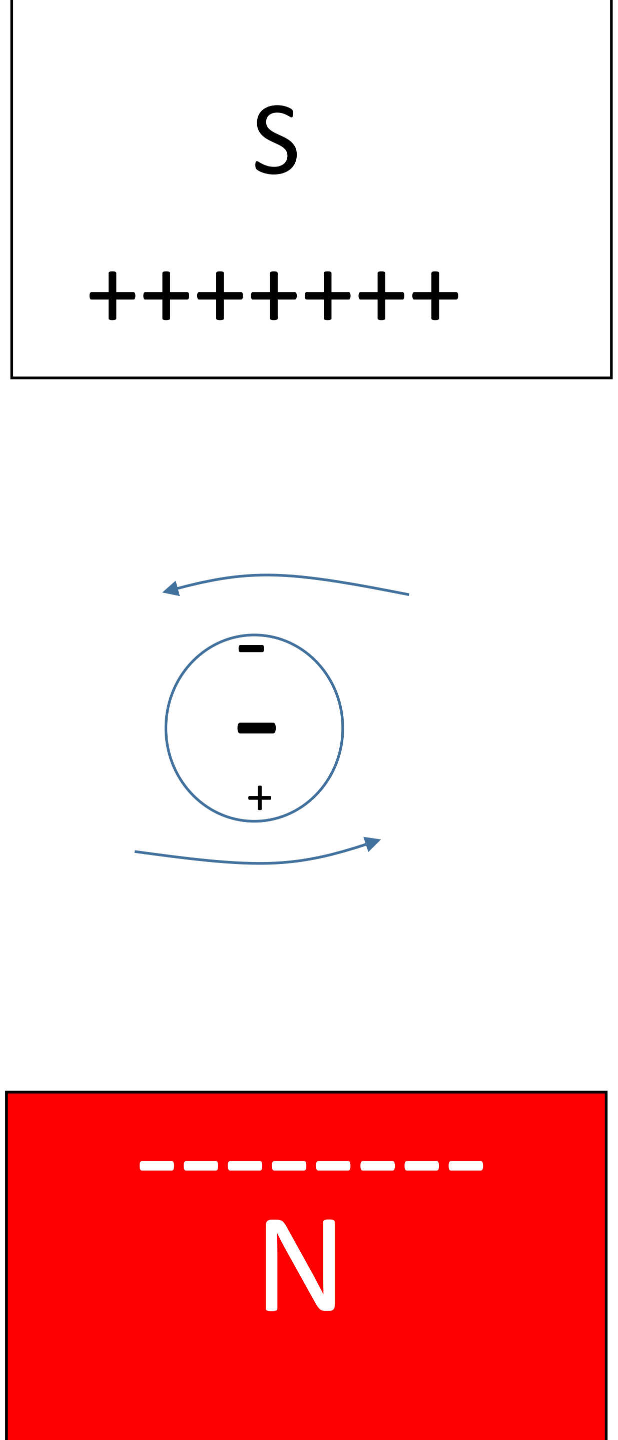
$$(\text{Field})\ \tau\ \sqrt{N_{eff}}$$

If electron EDM exists
at all, it is very small.
We must apply a
VERY large
electric field.
Two problems!

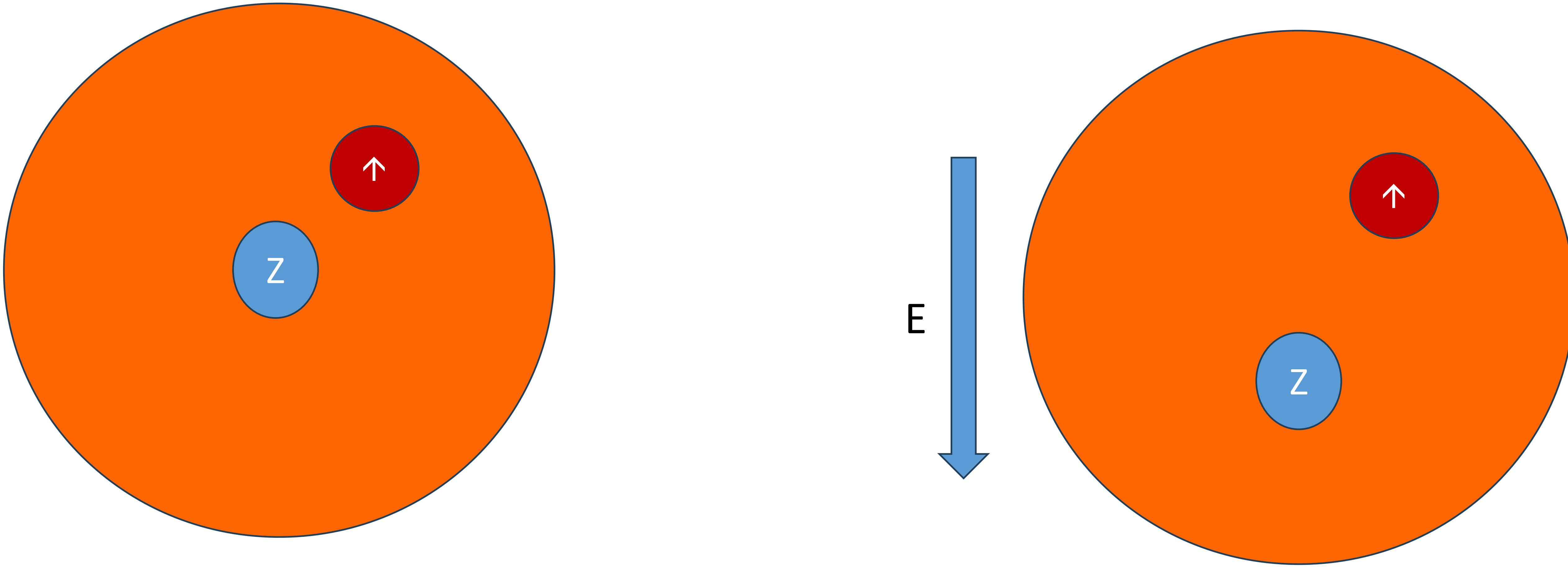


Problem 1:
Lightning!
Spark!
(If electric field
is too big.)

If electron EDM exists
at all, it is very small.
We must apply a
VERY large
electric field.
Two problems!

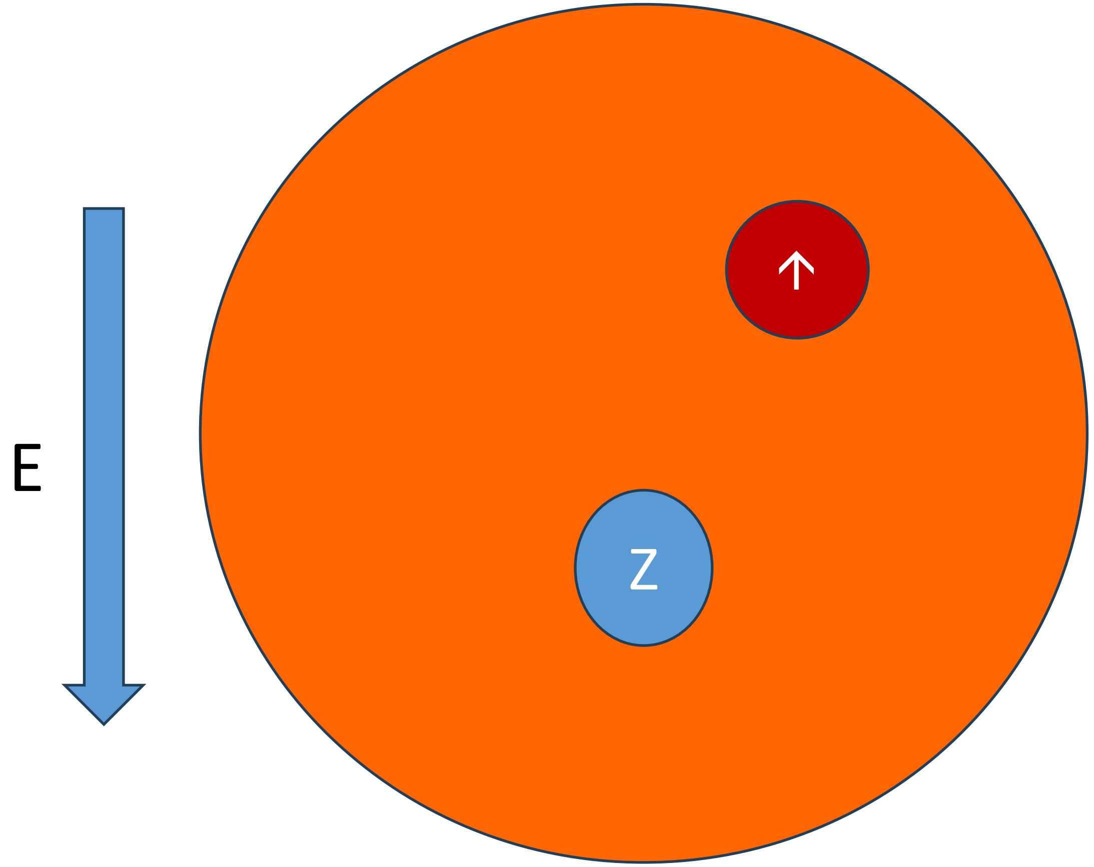


Problem 2:
Electron gets
pulled away by
electric field.



$$\langle \psi | \; \mathbf{E} \text{ dot } \mathbf{d_e} \; | \boldsymbol{\psi} \rangle$$
$$= \langle \psi | \; \mathbf{E} \text{ dot } d_e \, \mathbf{s} \, | \boldsymbol{\psi} \rangle$$
$$= \langle \psi | \; \mathbf{E} \; | \boldsymbol{\psi} \rangle \text{ dot } d_e \, \mathbf{s}$$
$$= \mathbf{0} \quad \text{dot } d_e \, \mathbf{s}$$
$$= \mathbf{0}$$

Schiff’s theorem



$$\langle \psi | \ \mathbf{E} \text{ dot } \mathbf{d_e} \ | \psi \rangle$$
$$= \langle \psi | \ \mathbf{E} \text{ dot } d_e \, \mathbf{s} \, | \psi \rangle$$
$$= \langle \psi | \ \mathbf{E} \ | \psi \rangle \ \text{ dot } d_e \, \mathbf{s}$$
$$= \mathbf{0} \quad \text{dot } d_e \, \mathbf{s}$$
$$= \mathbf{0}$$

Pat Sandars showed that the idea
“electron
feels no net electric field, thus no d_e
energy” is true only in the nonrelativistic
limit.
I can’t do justice to this argument, but…

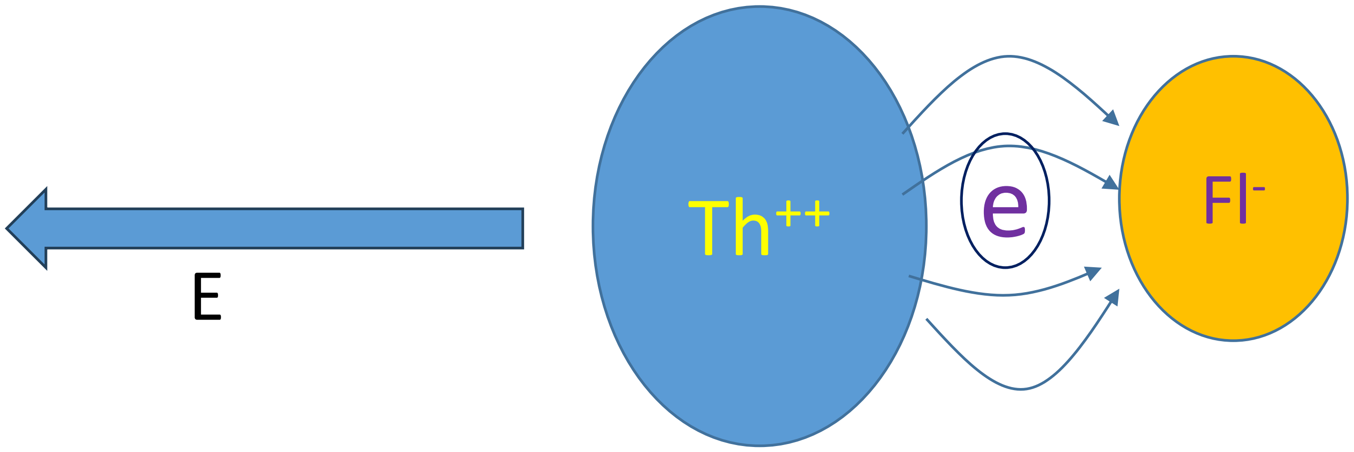
Sandars shows that in an atom with
unpaired electron spin, with a highly
charged (= large Z) nucleus, the
effective electric field

$E_{eff} \sim$ (numerical factor) Z^3 E_{lab}

for example, in Thalium,
$E_{eff} = -573 \ E_{lab}$

Two kinds of thank yous!

10^5 V/cm in lab become 6×10^7 V/cm on
electron



Again Pat Sandars points out that polar molecules are readily alignable in the lab. Dave Demille points out that molecules with closely spaced states of opposite parity are particularly good choices.

The one atom can apply a big electric field to the other. And you still get the Z^3 effect if one if the two atoms is really heavy.

For instance 20 V/cm in the lab polarized ThF+, and the effective electric field on the electron is 40 GeV/cm, an enhancement of a factor of 10^9.

With one exception, electron EDM experiments current and proposed all use molecules

E-field continued:

For molecules and atoms without uppaired electron spin but with nuclear spin, there is the possibility to look for CP-violating effects in the nucleus. “Schiff moments”.

Sensitive to very different combinations of hypothetical new physics!

Octupole nuclei. Much as molecules can have closely spaced states of opposite parity, so can nuclei.   These are radioactive. Put the molecular enhancement ot gether with the ocupole sensitivity enhancement and one gets very large enhancement in sensitivity. Thus “radioactive molecules”.

Difficult to compare directly to E_{eff} in electron EDM. Different models.

Coherence time, τ

Vapor Cells

Simplest. Does not work for molecules or open-shell atoms, but τ ~ seconds to minutes! Mercury!

Beams.

Simpler, but τ ~ few ms. Hard to vary T_{ramsey} widely.

Traps

Much harder, but τ ~ few seconds.

Neutral molecules require a lot of cooling (not easy) to be trappable.

Superfluid Liquid Helium. Could work for neutrons, maybe atoms?

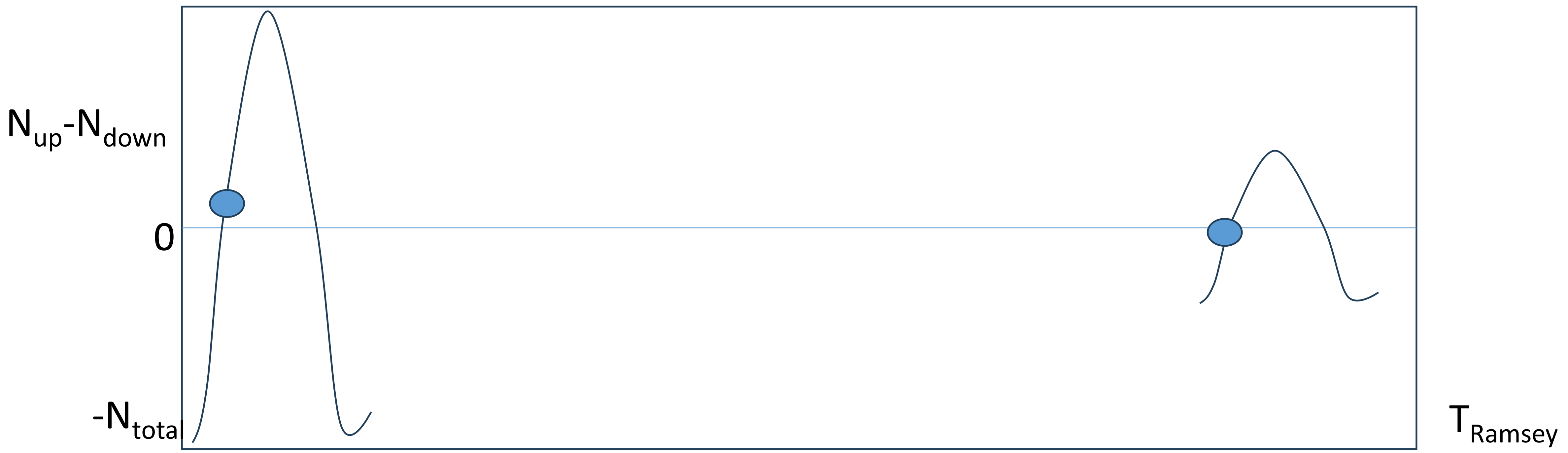
Combined Figure-of-merit:

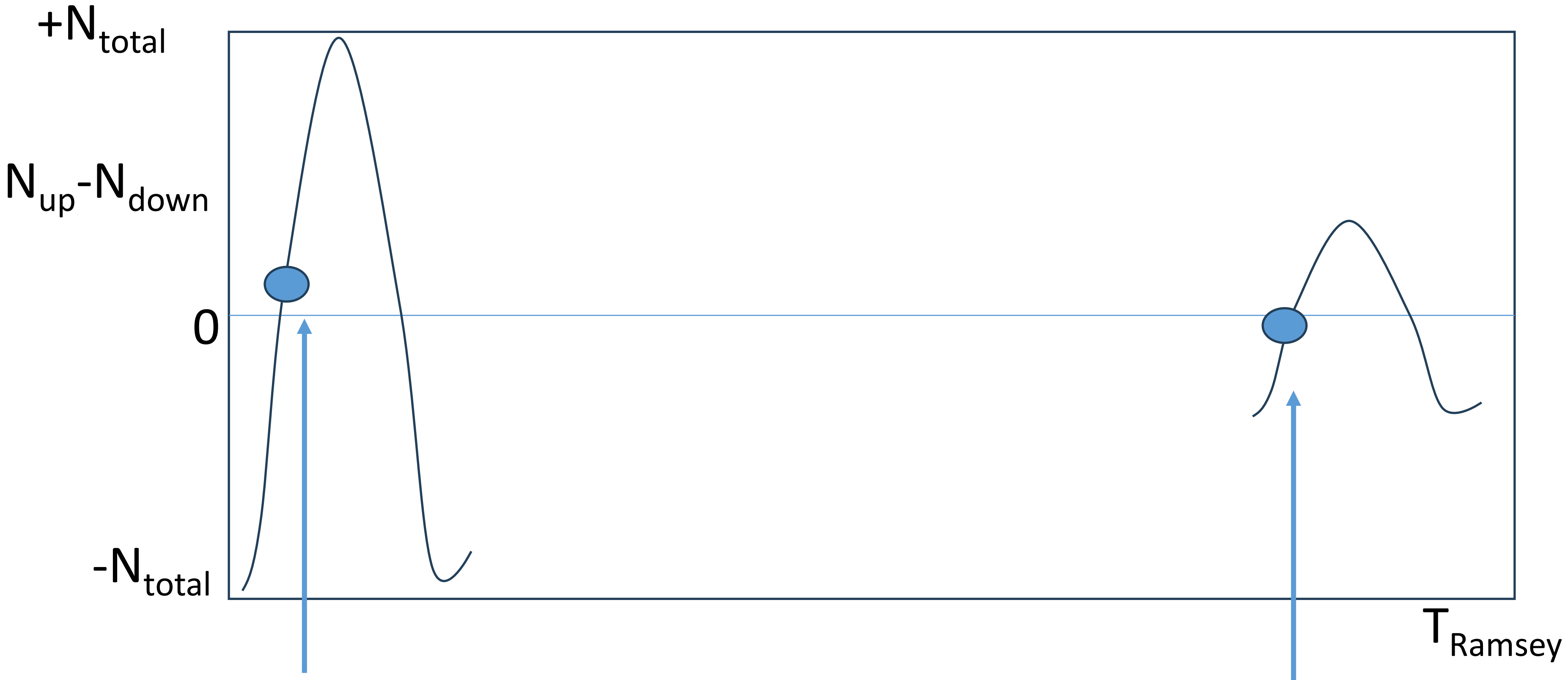
$$(\text{Field})\,\tau\sqrt{N_{eff}}$$

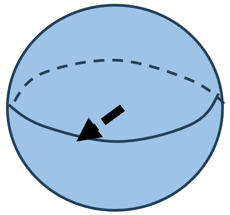
The number of spin-flips counted sets the maximum realizeable signal-noise

Combined Figure-of-merit:

$$(\text{Field})\ \tau \sqrt{N_{eff}}$$





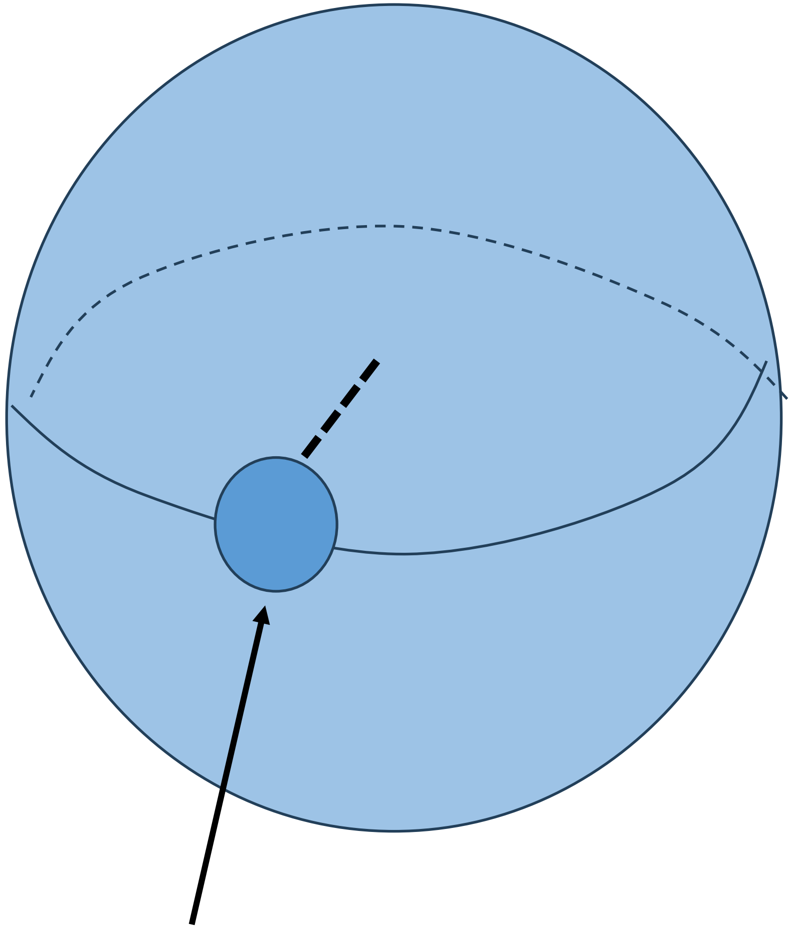


$\phi \sim \; (N_{up} - N_{down}) \,/\, N \qquad d\phi_{initial} \sim \; 1/\,N^{1/2}$

$d\phi_{final} \sim \; 1/\,N^{1/2}\,(1/\mathrm{fringecontrast})$

Optimal $\quad T_{ramsey} \sim \; \tau/2$

$$\mathrm{hbar}\,\omega \;=\; e\,d_e \;=\; (\mathrm{twopi} * n_{fringes} + \phi_{final} - \phi_{initial})/\;T_{Ramsey}$$



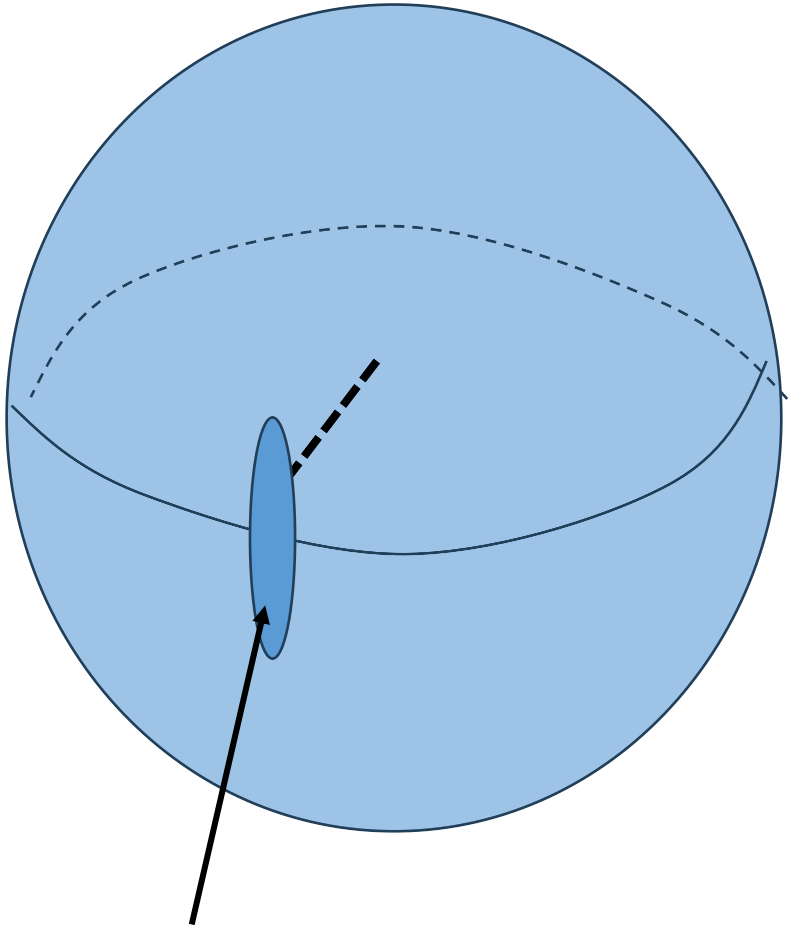
$\delta\ \phi \sim 1/N^{1/2} \quad \delta N \sim N^{1/2}$

$\delta\phi\ \delta N \sim 1$

But wait! This summer school is "Frontiers of ***Quantum*** Metrology" !!!!

$\delta\phi_{\text{initial}} \sim 1/N^{1/2}$????

Feels like an old-school, "Quantum 1.0" result



$\delta\ \phi \ \sim\ a/N^{1/2}$ $\delta N \ \sim\ (1/a)\, N^{1/2}$

$\delta\phi\ \ \delta N\ \ \sim 1$

But wait! This summer school is “Frontiers of ***Quantum*** Metrology” !!!!

$\delta\phi_{initial} \ \sim\ 1/N^{1/2}$????

Feels like an old-school, “Quantum 1.0” result

Spin squeezing!! In principle, can have signal-noise in the desired quadrature ~N, instead of only $N^{1/2}$!!!

But…. anything that causes coherence to decay causes squeezing to decay, too. So, no big win. But, special cases, where for some reason optimal $T_{ramsey} << \tau$ and spins are “expensive”.

Combined
Figure-of-merit:

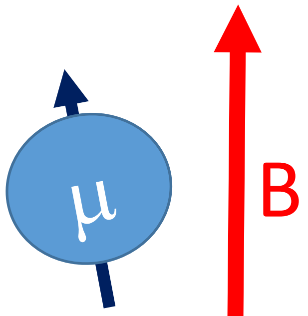
$$(\text{Field})\,\tau\sqrt{N_{eff}}$$

More on $N^{1/2}$

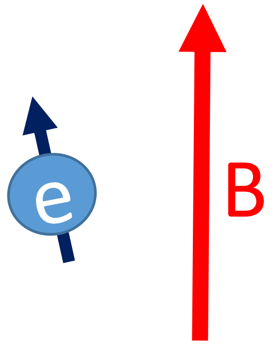
1) usually lower for molecules than atoms
2) usually lower for ions – space charge
3) Surprising effect of experimental complexity. See Hg experiment

In last three years there have been three new record-setting measurements of lepton dipole moments:

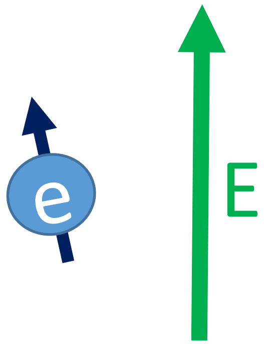
muon magnetic dipole (fermi lab)



electron magnetic dipole (northwestern/harvard)



electron electric dipole (JILA)



How do they compare?

Combined Figure-of-merit: (Field) $\tau \sqrt{N_{eff}}$

Experiment	
eMDM "g_e – 2"	trapped "ion"
μMDM "g_μ-2"	"ions" in beam
JILA eEDM	ion trapped **Molecules**
ACME eEDM	neutral **Molecules** in beam

Combined Figure-of-merit: (Field) $\tau \sqrt{N_{eff}}$

recall 1T
= $3x10^6$ V/cm

Experiment	Field Strength [10^7 V/cm]	
eMDM "$g_e - 2$"	~2	trapped "ion"
μMDM "g_μ-2"	~2	"ions" in beam
JILA eEDM	2000	ion trapped **Molecules**
ACME eEDM	7000	neutral **Molecules** in beam

Combined Figure-of-merit: (Field) $\tau \sqrt{N_{eff}}$

recall 1T
= 3×10^6 V/cm

Experiment	Field Strength [10^7 V/cm]	coherence time τ [ms]	
eMDM "g_e – 2"	~2	5000	trapped "ion"
μMDM "g_μ-2"	~2	0.2	"ions" in beam
JILA eEDM	2000	3000	ion trapped **Molecules**
ACME eEDM	7000	3	neutral **Molecules** in beam

Combined Figure-of-merit: (Field) $\tau \sqrt{N_{eff}}$

recall 1T
= 3×10^6 V/cm

Experiment	Field Strength [10^7 V/cm]	coherence time τ [ms]	count rate [s^{-1}]	
eMDM "$g_e - 2$"	~2	5000	$1/\tau$ * duty cycle = 0.02	trapped "ion"
μMDM "g_μ-2"	~2	0.2	1000 ?	"ions" in beam
JILA eEDM	2000	3000	200 / τ = 60	ion trapped **Molecules**
ACME eEDM	7000	3	many * 10^6	neutral **Molecules** in beam

Combined Figure-of-merit: (Field) $\tau \sqrt{N_{eff}}$

recall 1T
= $3\text{x}10^{6}$ V/cm

Experiment	Field Strength [10^{7} V/cm]	coherence time τ [ms]	count rate [s^{-1}]
eMDM "$g_e - 2$"	~2	5000	1/τ * duty cycle = 0.02
μMDM "g_μ-2"	~2	0.2	1000 ?
JILA eEDM	2000	3000	200 / τ = 60
ACME eEDM	7000	3	many * 10^{6}

Combined Figure-of-merit: (Field) $\tau\sqrt{N_{eff}}$

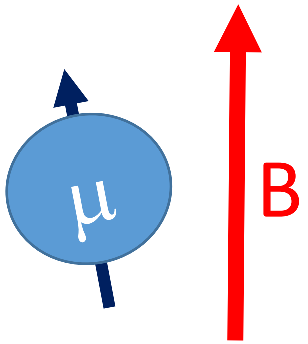
recall 1T = 3×10^{6} V/cm

recall 1 $\mu_B = 2\times10^{11}$ e-cm

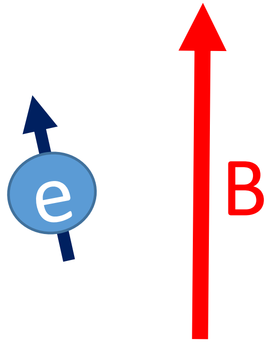
Experiment	Field Strength [10^{7} V/cm]	coherence time τ [ms]	count rate [s^{-1}]	one-sigma accuracy on dipole moment, [e-cm]
eMDM "$g_e - 2$"	~2	5000	$1/\tau$ * duty cycle = 0.02	2×10^{-24}
μMDM "g_μ-2"	~2	0.2	1000 ?	5×10^{-23}
JILA eEDM	2000	3000	$200 / \tau = 60$	2×10^{-30}
ACME eEDM	7000	3	many * 10^{6}	4×10^{-30}

In last two years there have been three new record-setting measurements of lepton dipole moments:

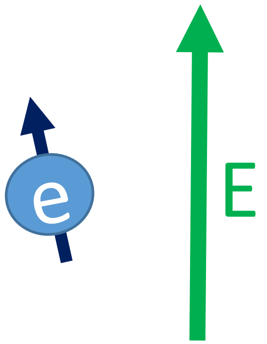
muon magnetic dipole (fermi lab)



electron magnetic dipole (northwestern/harvard)

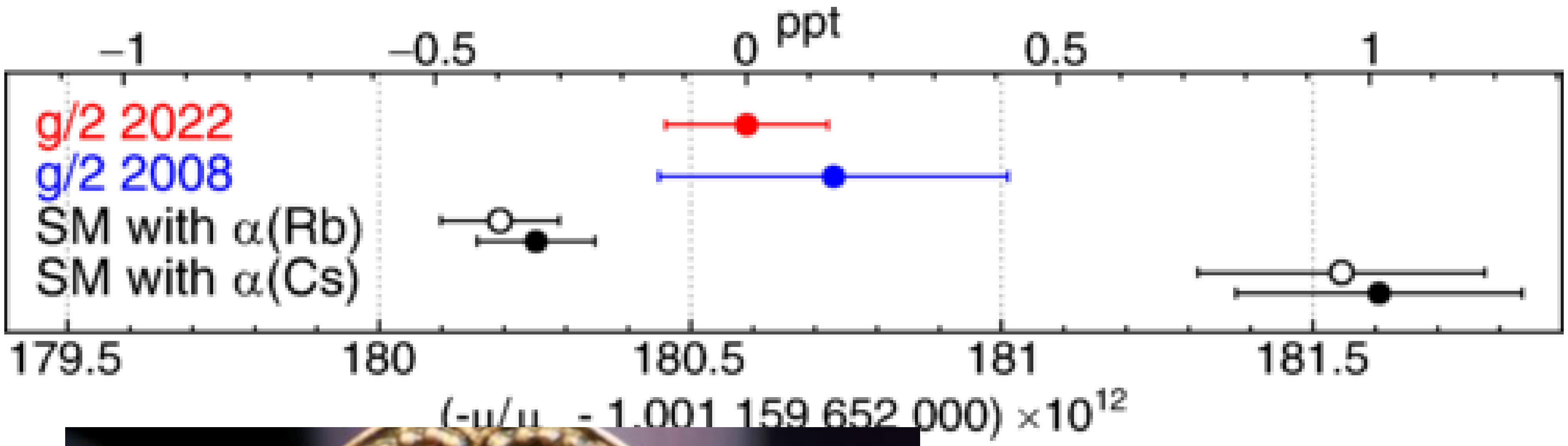


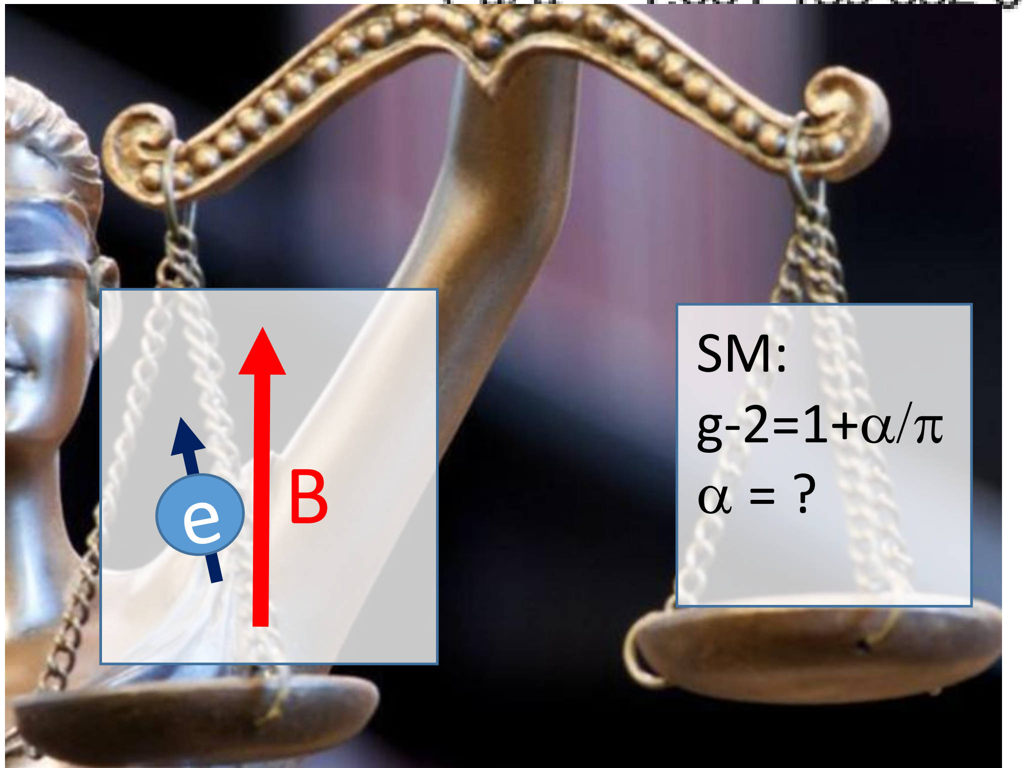
electron electric dipole (JILA)

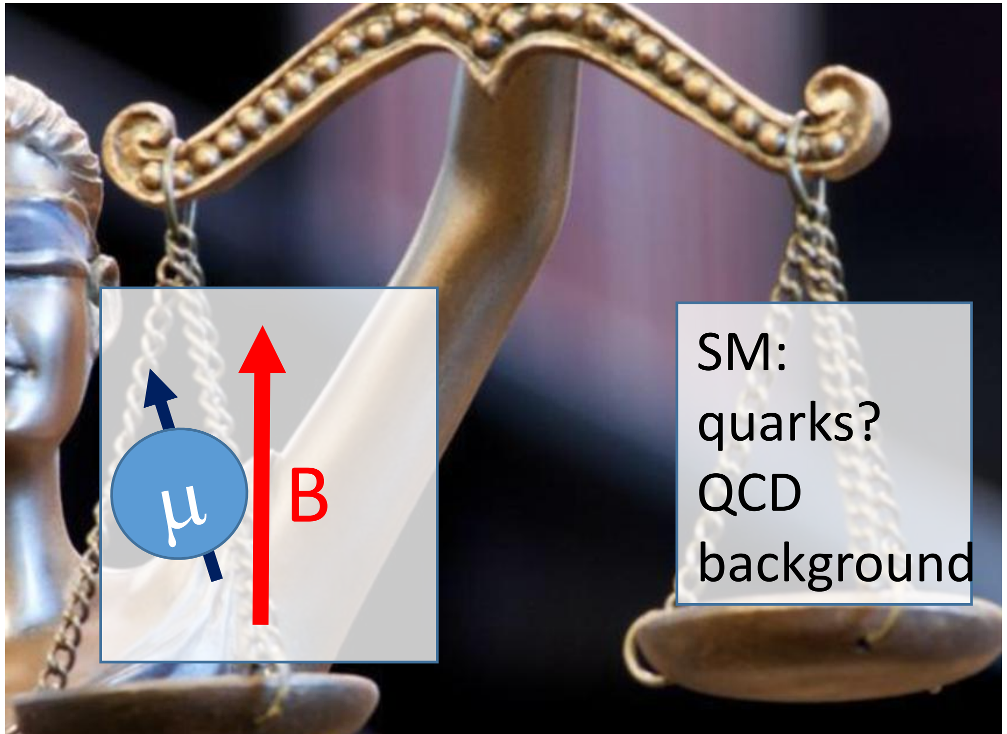


How do they compare?

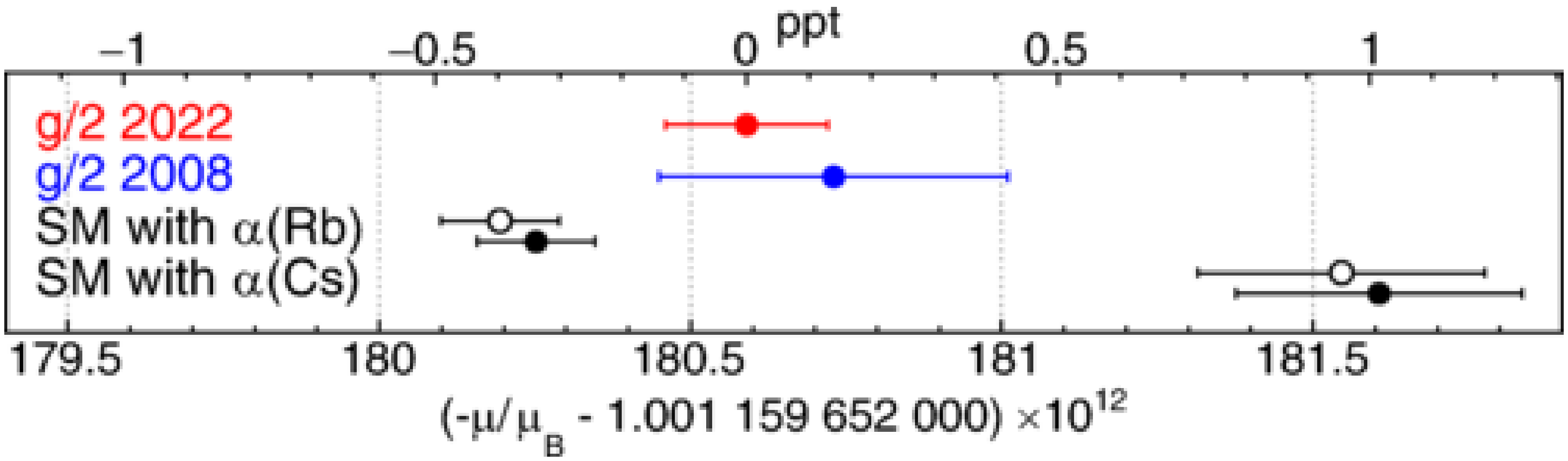
Best electron magnetic moment measurement -- Northwestern







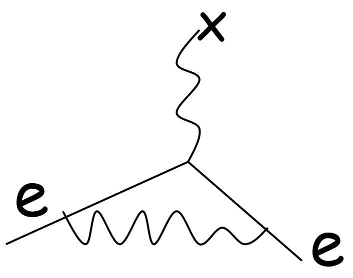
Best electron magnetic moment measurement -- Northwestern



Discovery potential of electron and muon MDM currently limited by SM background, not g-2 precision.

BUT, for the next few slides let's assume SM background problems are fixed!

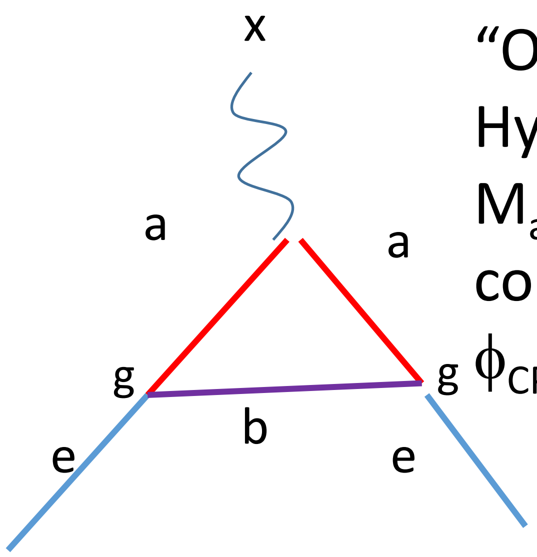
$\mu_e = 2 + \text{alpha/pi}$



this diagram adds

$\delta\mu_e = \text{alpha/pi}$

$\delta d_e = 0$



"One-loop" model for discovery.
Hypothetical undiscovered new particles
$M_a \sim M_b \sim M$ [Ramsey-Musolf; Reece]
coupling strength g at the e-a-b vertex
ϕ_{CP} is CP-violating angle
ADDS:

$$\delta(d_e/e) \sim (a_0\, \alpha\, g^2)/(4\pi)\ \sin\phi_{CP}\ (m^2/M^2)$$

$$\delta(\mu_e/e) \sim (a_0\, \alpha\, g^2)/(4\pi)\ \cos\phi_{CP}\ (m^2/M^2)$$

So, make a good measurement of μ_e or d_e and have sensitivity to possible new particles with mass up to M:

$$M \sim (\text{various constants}) * [\,(m/\delta d_e)\, g^2 \sin\phi_{CP}\,]^{1/2}$$

$$M \sim (\text{various constants}) * [\,(m/\delta\mu_e)\, g^2 \cos\phi_{CP}\,]^{1/2}$$

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit
eMDM Northwester	10^{-13}
μMDM fermilab	10^{-9}
eEDM JILA/ACME	$\sim 10^{0}$

LHC

Summary of Recent Measurements of Lepton Dipole Moments; Implications

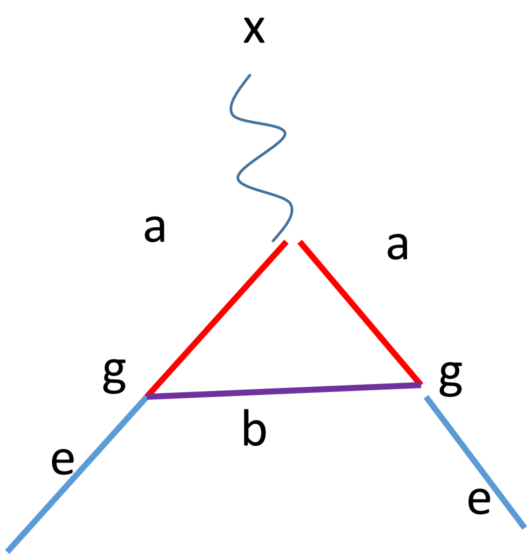
	relative precision on lab limit	absolute precision [10^{-30} e-cm]
eMDM Northwester	10^{-13}	2×10^6
μMDM fermilab	10^{-9}	5×10^7
eEDM JILA/ACME	$\sim 10^0$	2

LHC

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit	absolute precision [10^{-30} e-cm]	Detectable $M \sim (m_l/\delta d)^{1/2}$ (arb units)
eMDM Northwester	10^{-13}	2×10^{6}	1
μMDM fermilab	10^{-9}	5×10^{7}	3
eEDM JILA/ACME	$\sim 10^{0}$	2	1000

LHC

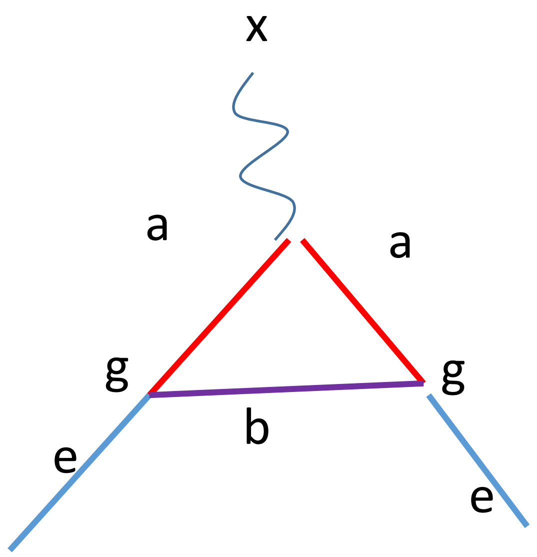


$$M \quad \sim \text{(various constants)} * \; [\, (m/\delta\mu_e)\, g^2 \cos\phi_{CP} \,]^{1/2}$$

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit	absolute precision [10^{-30} e-cm]	Detectable $M \sim (m_l/\delta d)^{1/2}$ (arb units)	"Typical" detectable phat BSM, one-loop*
eMDM Northwester	10^{-13}	2×10^6	1	0.04 TeV
μMDM fermilab	10^{-9}	5×10^7	3	0.12
eEDM JILA/ACME	$\sim 10^0$	2	1000	40 TeV

LHC



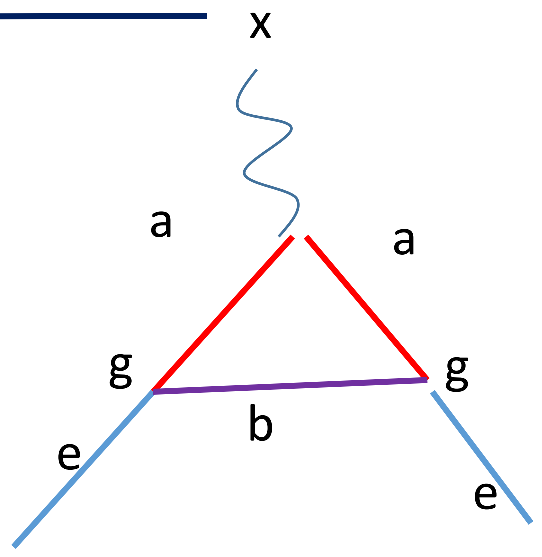
$$M \sim (\text{various constants}) * [(m/\delta\mu_e)\, g^2 \cos \phi_{CP}]^{1/2}$$

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit	absolute precision [10^{-30} e-cm]	Detectable $M \sim (m_l/\delta d)^{1/2}$ (arb units)	"Typical" detectable phat BSM, one-loop*	Detectable for "weakest*" to strongest interactions
eMDM Northwester	10^{-13}	2×10^{6}	1	0.04 TeV	0.0004~0.4 TeV
μMDM fermilab	10^{-9}	5×10^{7}	3	0.12	0.001~1 TeV
eEDM JILA/ACME	$\sim 10^{0}$	2	1000	40 TeV	0.4~400 TeV

$10^{-6} < g < 1$

LHC



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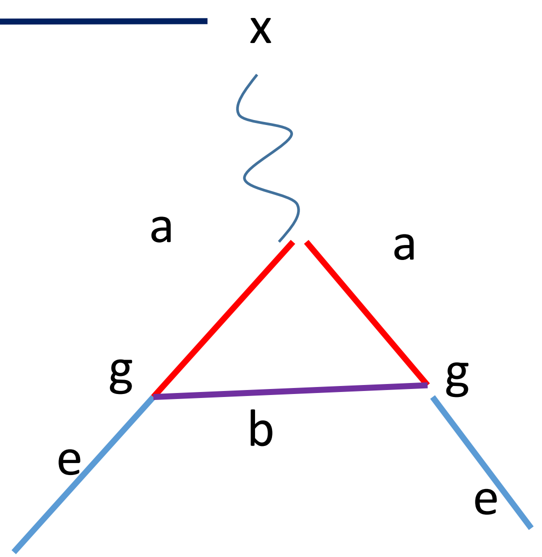
eEDM JILA/ACME	$\sim 10^0$	2	1000	40 TeV	0.4~400 TeV

$10^{-6} < g < 1$

LHC

LHC ??? <2 TeV ???



$$M \sim (\text{various constants}) * [(m/\delta\mu_e)\, g^2 \cos \phi_{CP}]^{1/2}$$

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit	absolute precision [10^{-30} e-cm]	Detectable $M \sim (m_l/\delta d)^{1/2}$ (arb units)	"Typical" detectable phat BSM, one-loop*	Detectable for "weakest*" to strongest interactions	CP violation! reduce mass sensitivity by
eMDM Northwester	10^{-13}	2×10^{6}	1	0.04 TeV	0.0004~0.4 TeV	$(\cos \alpha_{cpv})^{1/2}$
μMDM fermilab	10^{-9}	5×10^{7}	3	0.12	0.001~1 TeV	$(\cos \alpha_{cpv})^{1/2}$
eEDM JILA/ACME	$\sim 10^{0}$	2	1000	40 TeV	0.4~400 TeV	$(\sin \alpha_{cpv})^{1/2}$
LHC			LHC	??? <2 TeV ???		For LHC, α_{cpv} not a factor

Summary of Recent Measurements of Lepton Dipole Moments; Implications

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eMDM Northwester	10^{-13}	2×10^6	1	0.04 TeV	0.0004~0.4 TeV	$(\cos \alpha_{cpv})^{1/2}$	α = ?
μMDM fermilab	10^{-9}	5×10^7	3	0.12	0.001~1 TeV	$(\cos \alpha_{cpv})^{1/2}$	QCD terms
eEDM JILA/ACME	$\sim 10^0$	2	1000	40 TeV	0.4~400 TeV	$(\sin \alpha_{cpv})^{1/2}$	none
LHC				LHC	??? <2 TeV ???	For LHC, α_{cpv} not a factor	

Summary of Recent Measurements of Lepton Dipole Moments; Implications

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LHC				LHC	??? <2 TeV ???	For LHC, α_{cpv} not a factor	***Q:Does LHC have SM issues?***

Summary of Recent Measurements of Lepton Dipole Moments; Implications

	relative precision on lab limit	absolute precision [10^{-30} e-cm]	Detectable $M\sim(m_l/\delta d)^{1/2}$ (arb units)	"Typical" detectable phat BSM, one-loop*	Detectable for "weakest*" to strongest interactions	CP violation! reduce mass sensitivity by	SM Background issues
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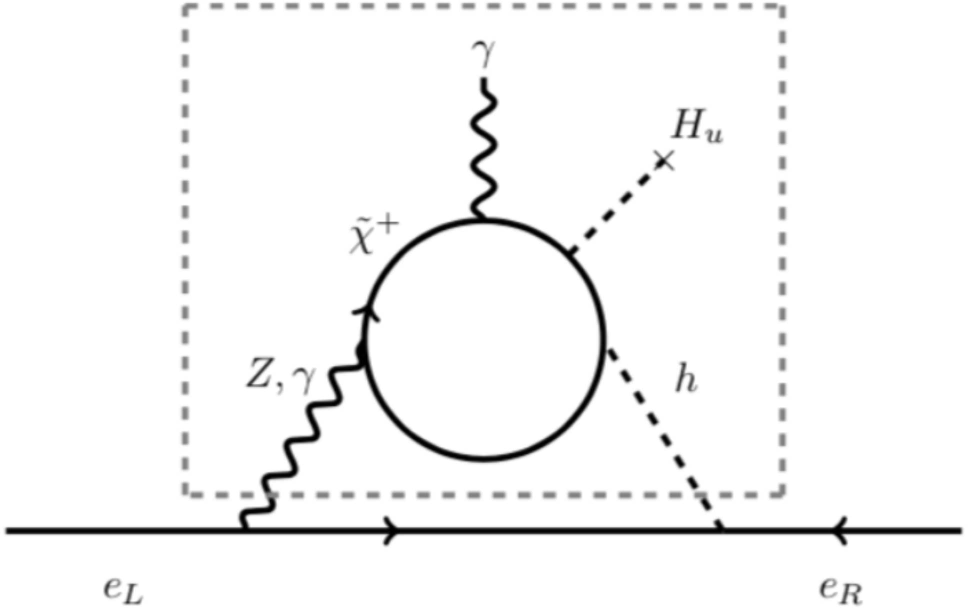
eEDM JILA/ACME	$\sim 10^0$	2	1000	40 TeV	0.4~400 TeV	$(\sin \alpha_{cpv})^{1/2}$	none
LHC				LHC	??? <2 TeV ???	For LHC, α_{cpv} not a factor	***A: SO MANY ISSUES!***

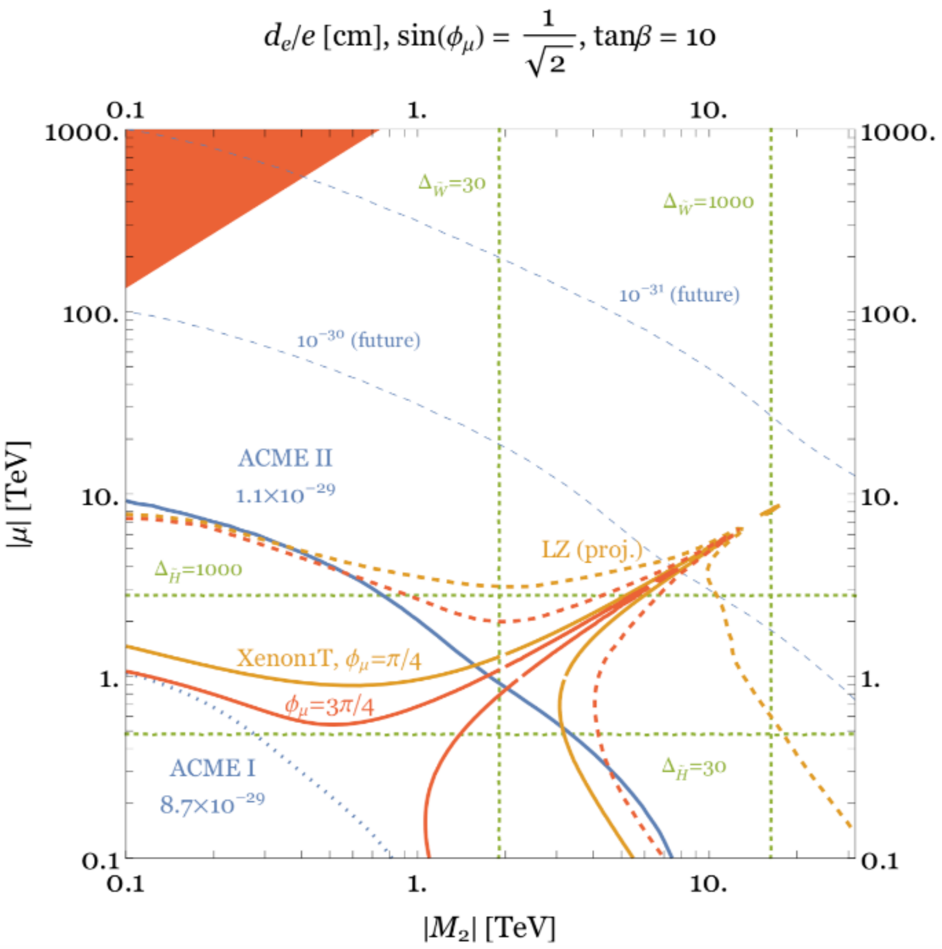
Slide borrowed from Matt Reece

Quite generally, electroweak new physics coupling to the Higgs boson gives rise to an electron EDM (Barr-Zee).



[Cesarotti, Lu, Nakai, Parikh, MR, '18]

Powerful split SUSY electroweakino constraints from ACME 2!



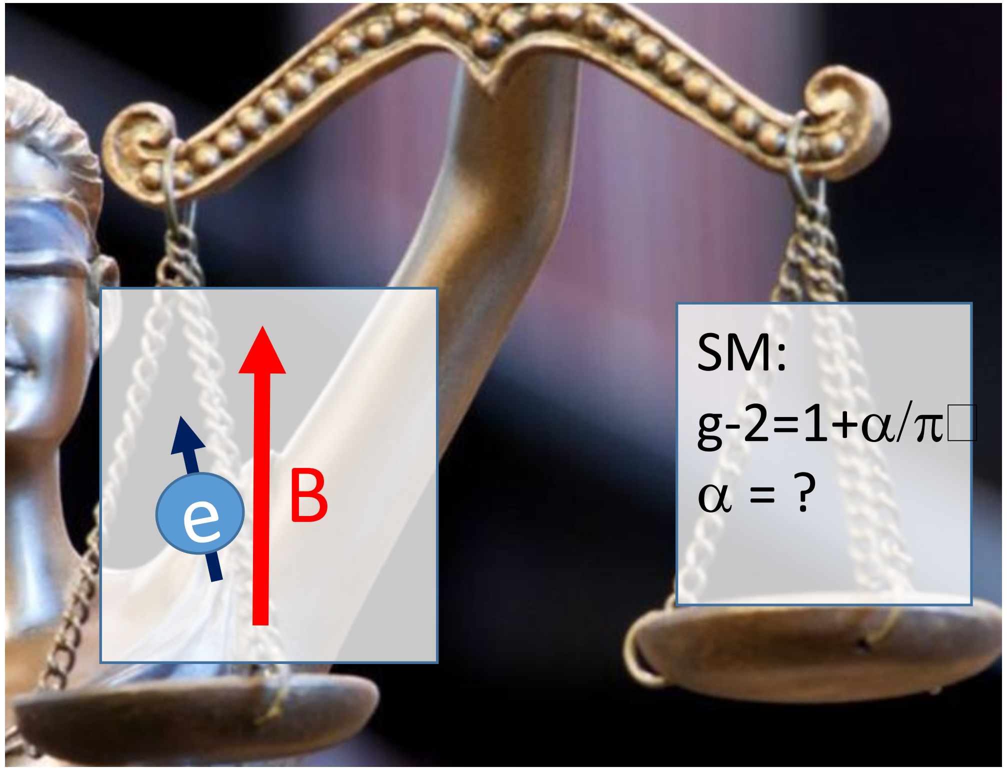
Let’s Play:

“Bug?..... or Feature! Feature? …… or Bug!”

And now, your contrarian host,
heeeeere’s Eric!

Bug?..... or Feature! Feature? …… or Bug!

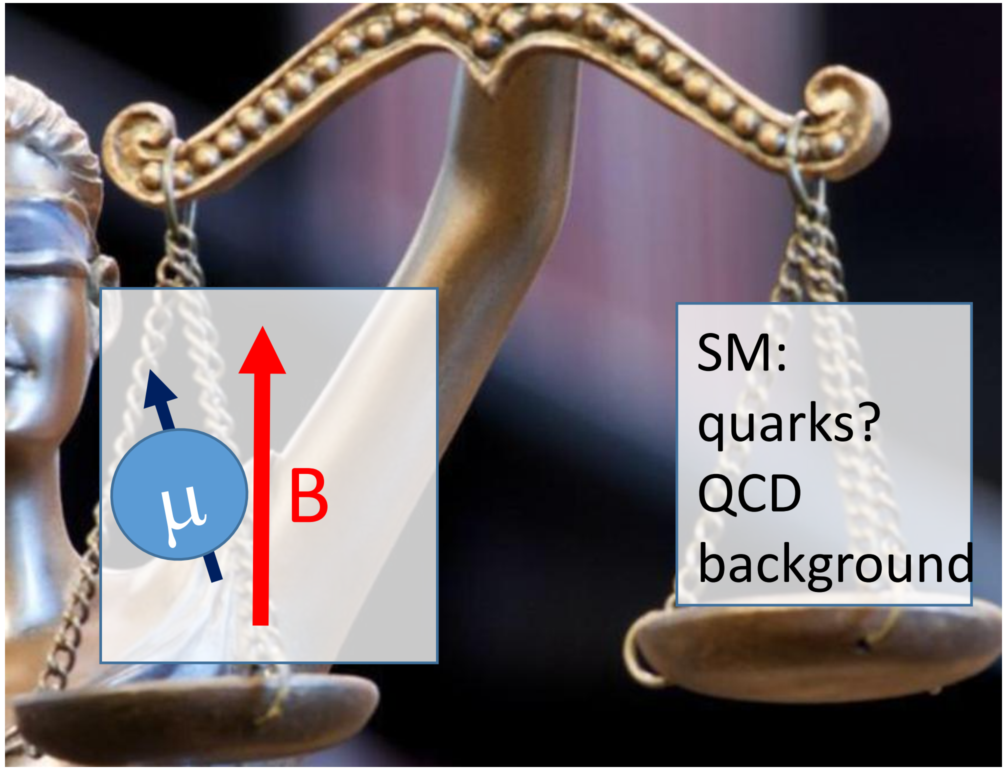
electron MDM has SM sensitivity to uncertainties in experimental value of alpha. **This is a bug**.



Maybe. The electron MDM has *the best fractional sensitivity of any SM calculable fundamental quantity ever.* This means e.g. it can be used to measure alpha better than other methods. **This is a feature!**
More generally, eMDM is the most stringent limit to anything that looks more like a multiplicative correction to SM (ie, not additive) or a limitation to many-loop perturbation theory.
Moreover MDM is sensitive to contributions on weakly interaction low-mass bosons

Bug?..... or Feature! Feature? …… or Bug!

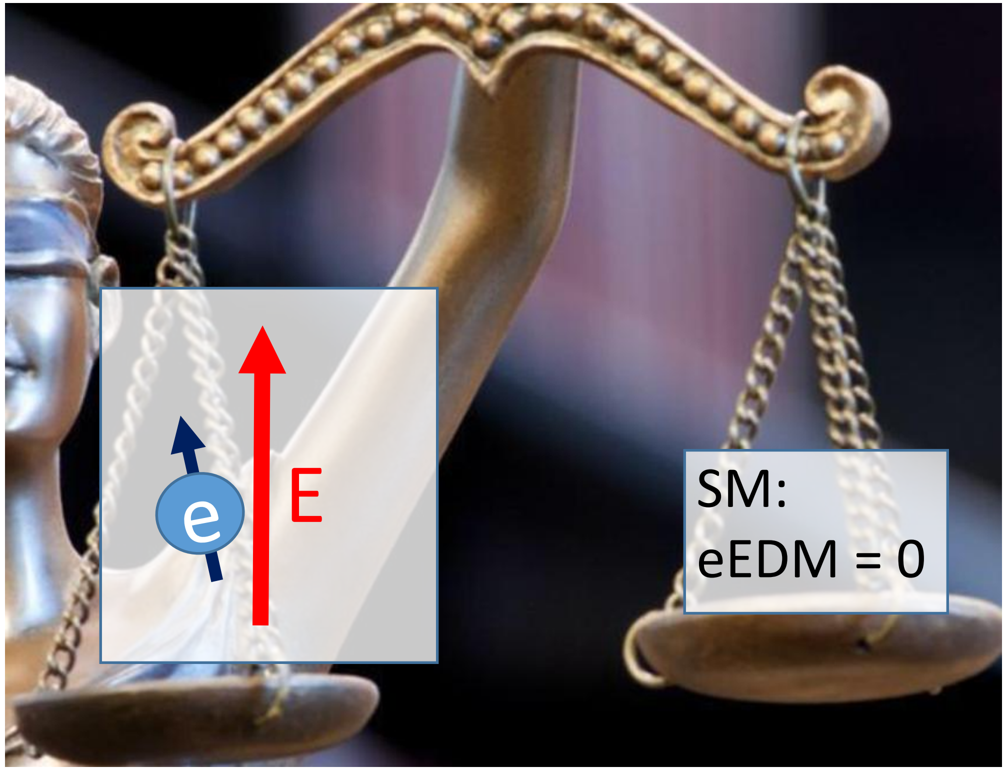
muon MDM has sensitivity to uncertainties in SM QCD predictions. This is a **bug** vis-à-vis electron MDM.



Well, maybe. The μMDM is more troubled by QCD corrections than eMDM, precisely because the muon measurement is more sensitive to corrections from heavy particles -- which after all is something we are looking for!

Feature! When eMDM absolute precision improves to where it is competitive with muon MDM, e MDM too will have to worry about QCD corrections.

Bug?..... or Feature! Feature? …… or Bug!



electron eEDM has basically no sensitivity at all to SM background. This is a **feature!**

Well, sort of. The reason that eEDM doesn't see any SM background is that eEDM can see only CP violating physics (which SM has very little of.) EDMs in general are blind to CP-preserving new physics. This is a **bug!**

Bug?..... or Feature! Feature? …… or Bug!

electron eEDM can look deeper into "Extra-Phat Exotic Particle Parameter Space" than can the LHC, and much deeper than can the MDM experiments. This is a **feature!**

Well, ok, actually, yeah. That *is* pretty rad.

Current EDM-based limits on new particle physics all come from

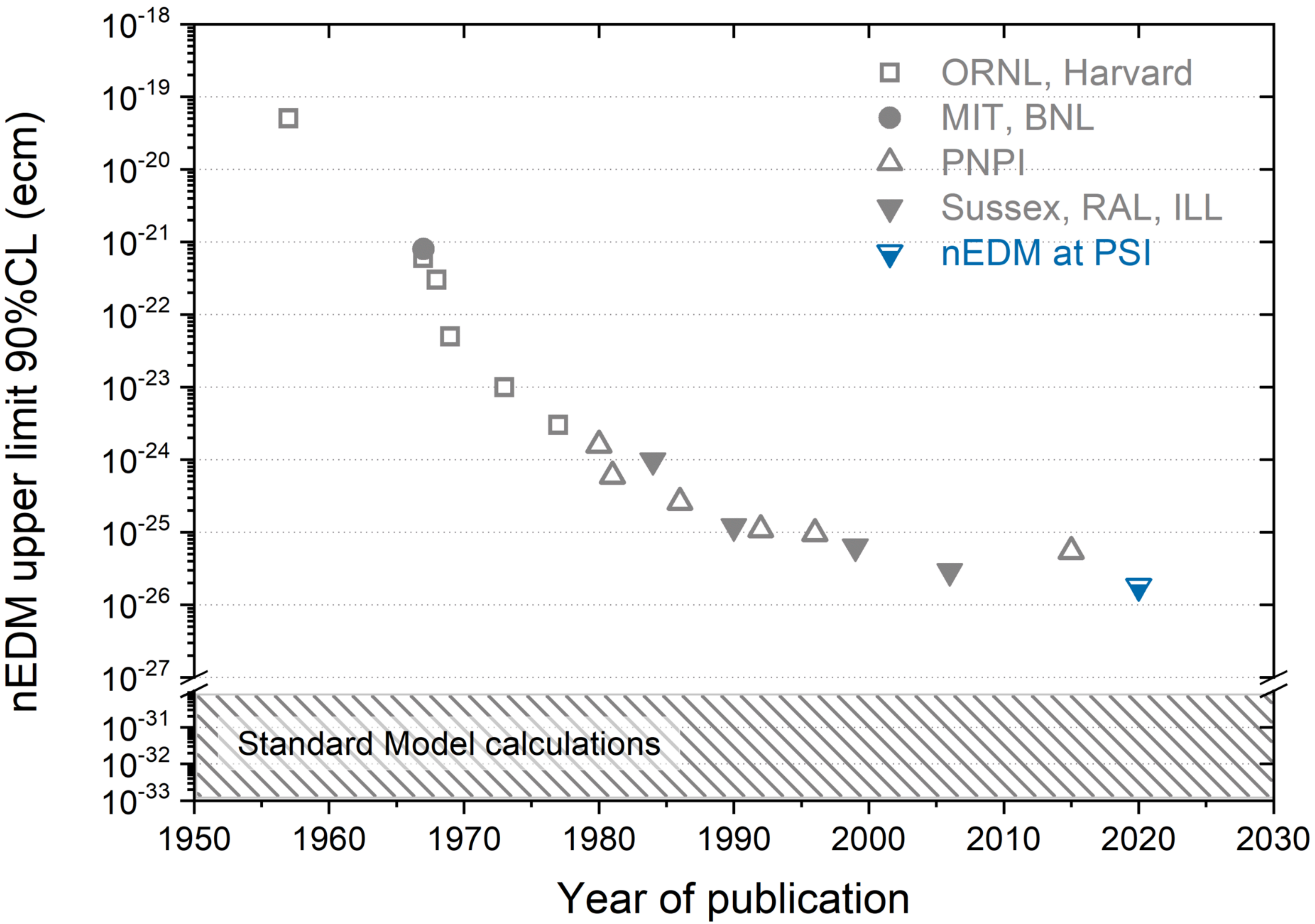
electrons

neutrons

mercury.

neutron EDM . First experiment done in 1951
by Ramsey and Purcell.
nEDM < 10^{-20} e-cm
Not published until 1957. Why not?
I don't know, but parity nonconservation was first observed
in 1956! Hmmm.

This was the start of the EDM push.

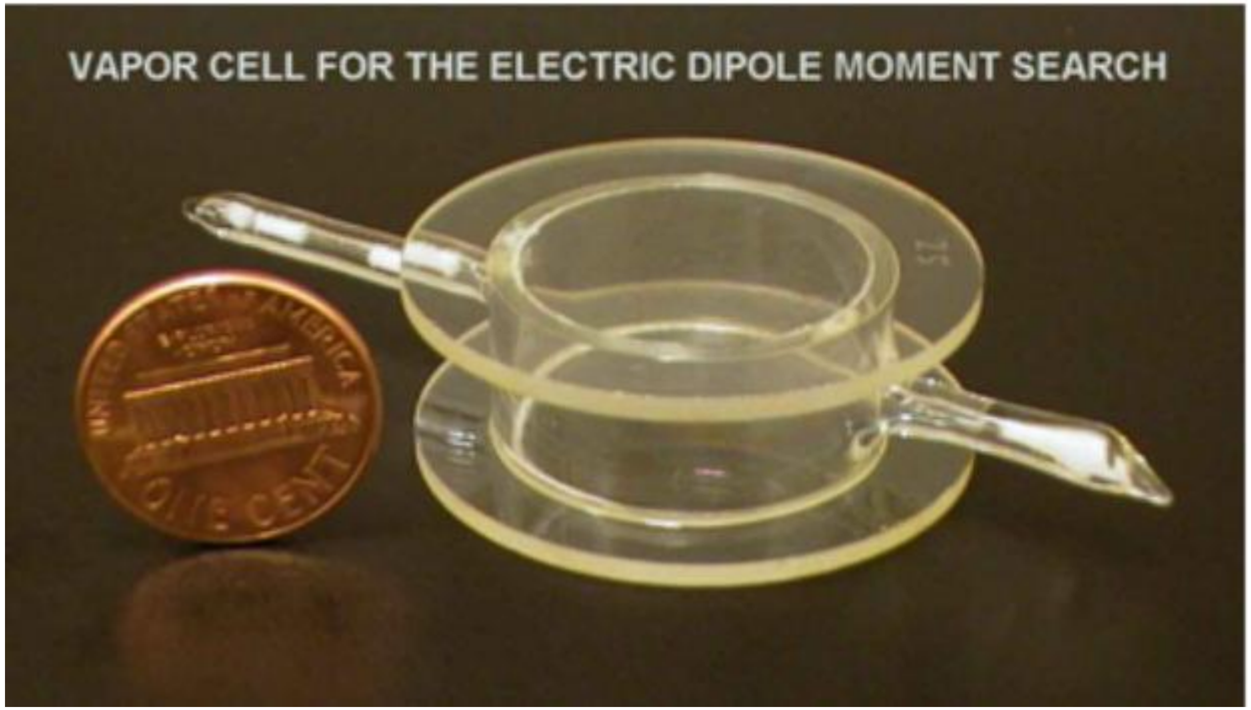


Just factor of 2 improvement has been since 2007, 18 years ago.

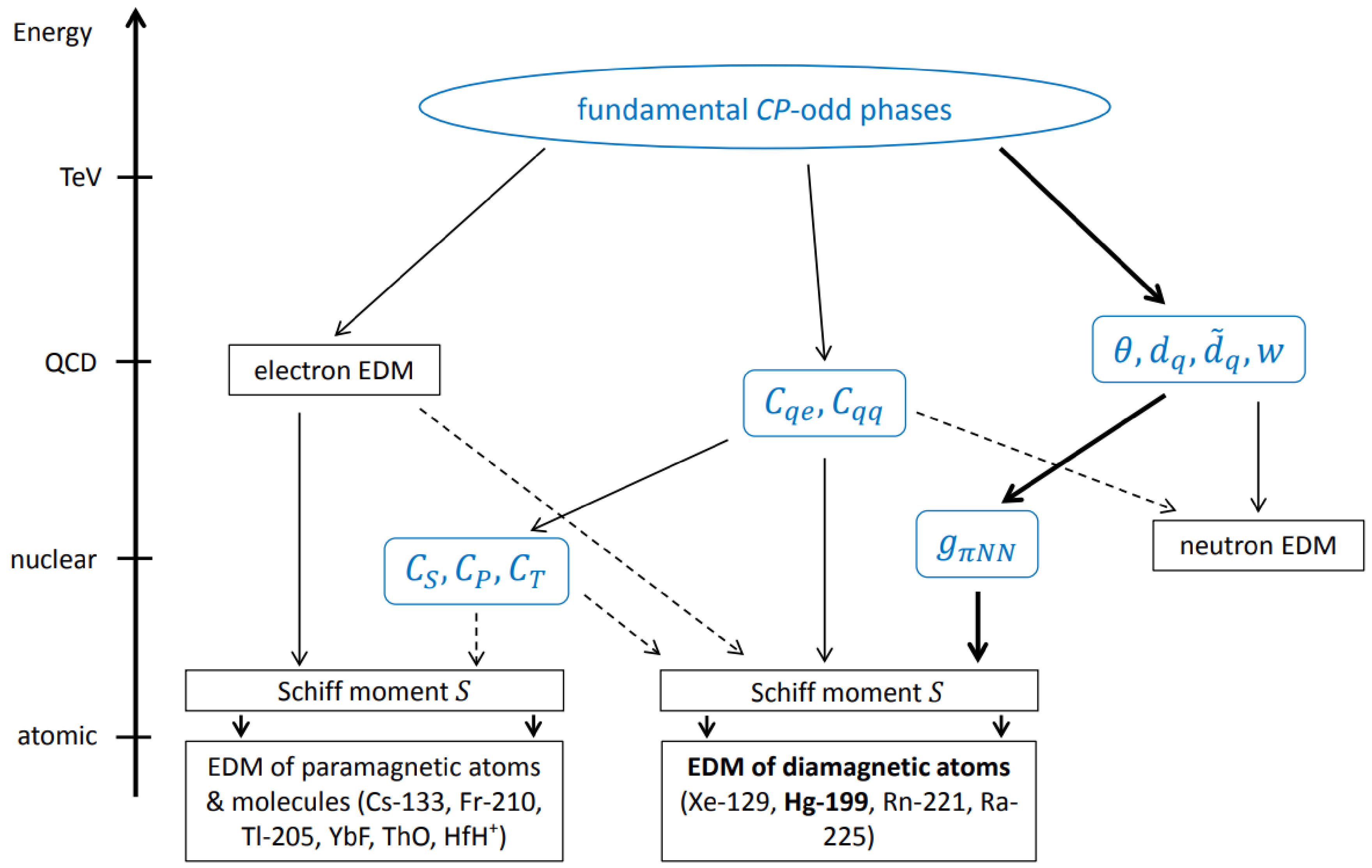
Suggests that future progress also may be slow, but multiple projects exist.

Mercury

This has set some of the best limits on various new physics models.
Blayne Heckel and predecessors including Norval Fortson,
at University of Washington. I think the experiment has wrapped up.



Mechanisms to generate EDMs



adapted from M. Pospelov & A. Ritz

Most but not quite all new EDM experiments are in molecules.

Most of these will be in traps.

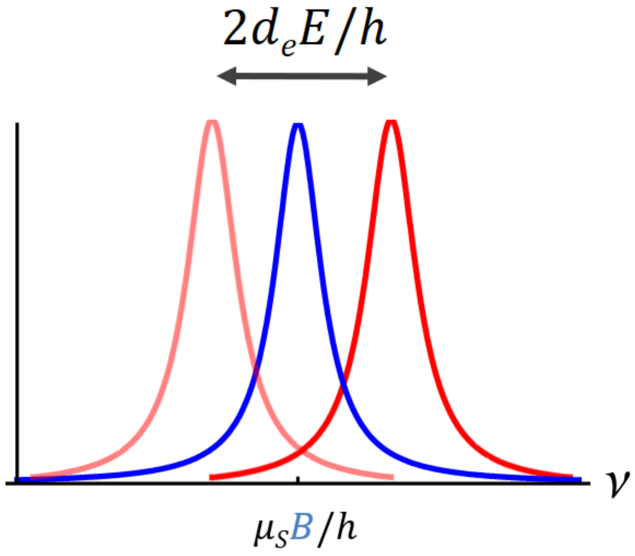
Some, not all will be on octupole-deformed nuclei

Traps for neutral molecules are very shallow and so molecules must be very cold

- Laser cool component atoms, and assemble? (FrAg proposal.)
- Laser cool the molecules? diatomic and polyatomic (!!) projects ongoing.
  - Franck-Condon factors and electronic branching ratios mean MANY lasers.

Traps for ionic molecules are much deeper. Cooling can by buffer gas, or
by supersonic expansion.
Tricky part is to apply a electric bias field

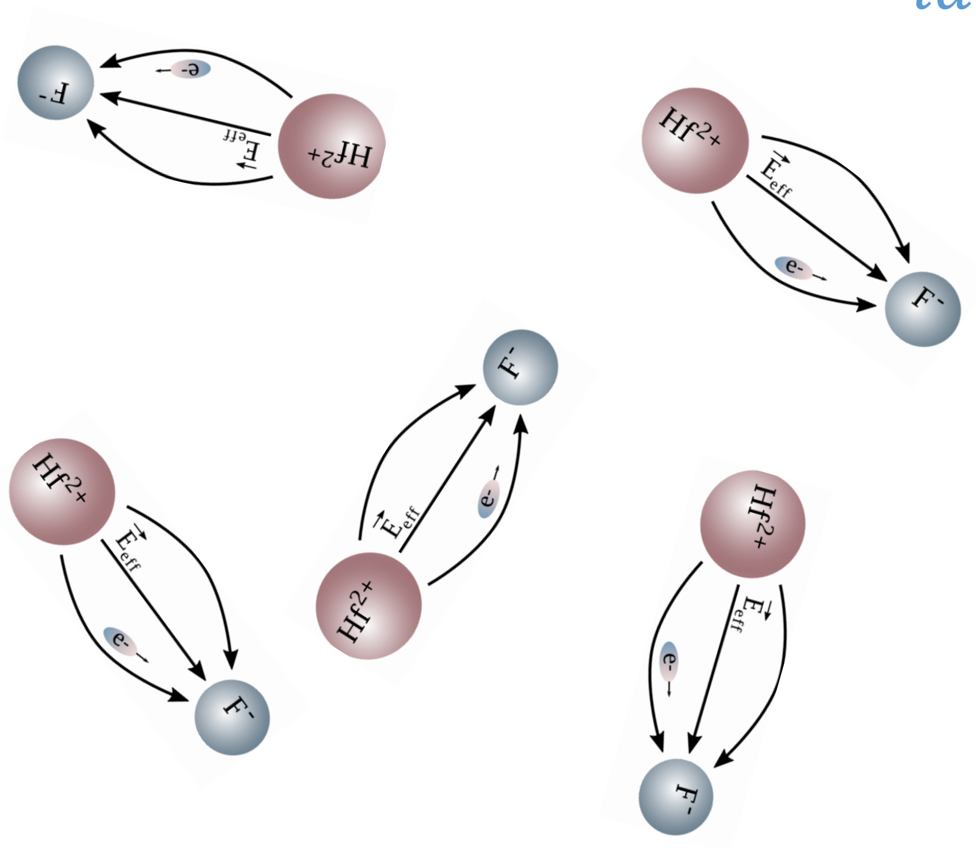
Molecular Alignment



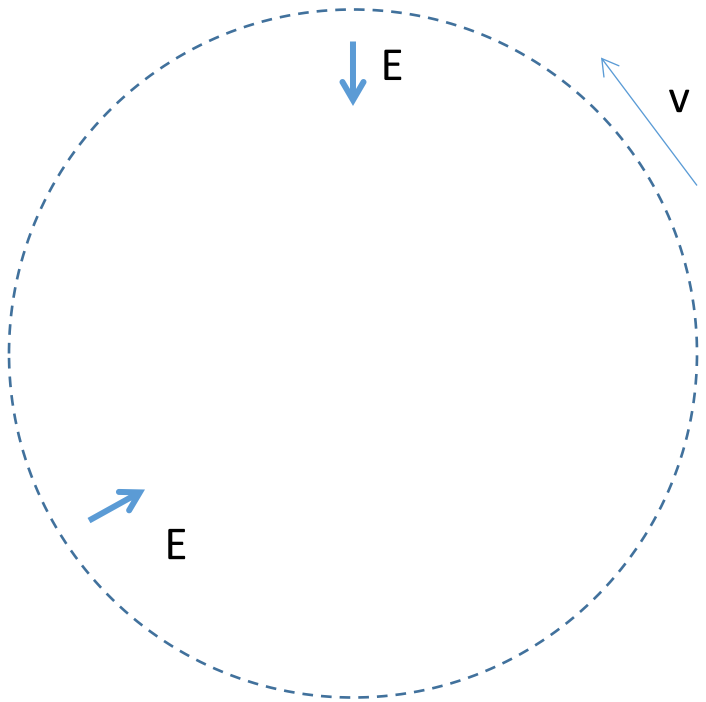
$\vec{E} = \vec{E}_{eff}$

$\vec{B} = \vec{B}_{lab}$

$\vec{E} = \vec{E}_{lab}$

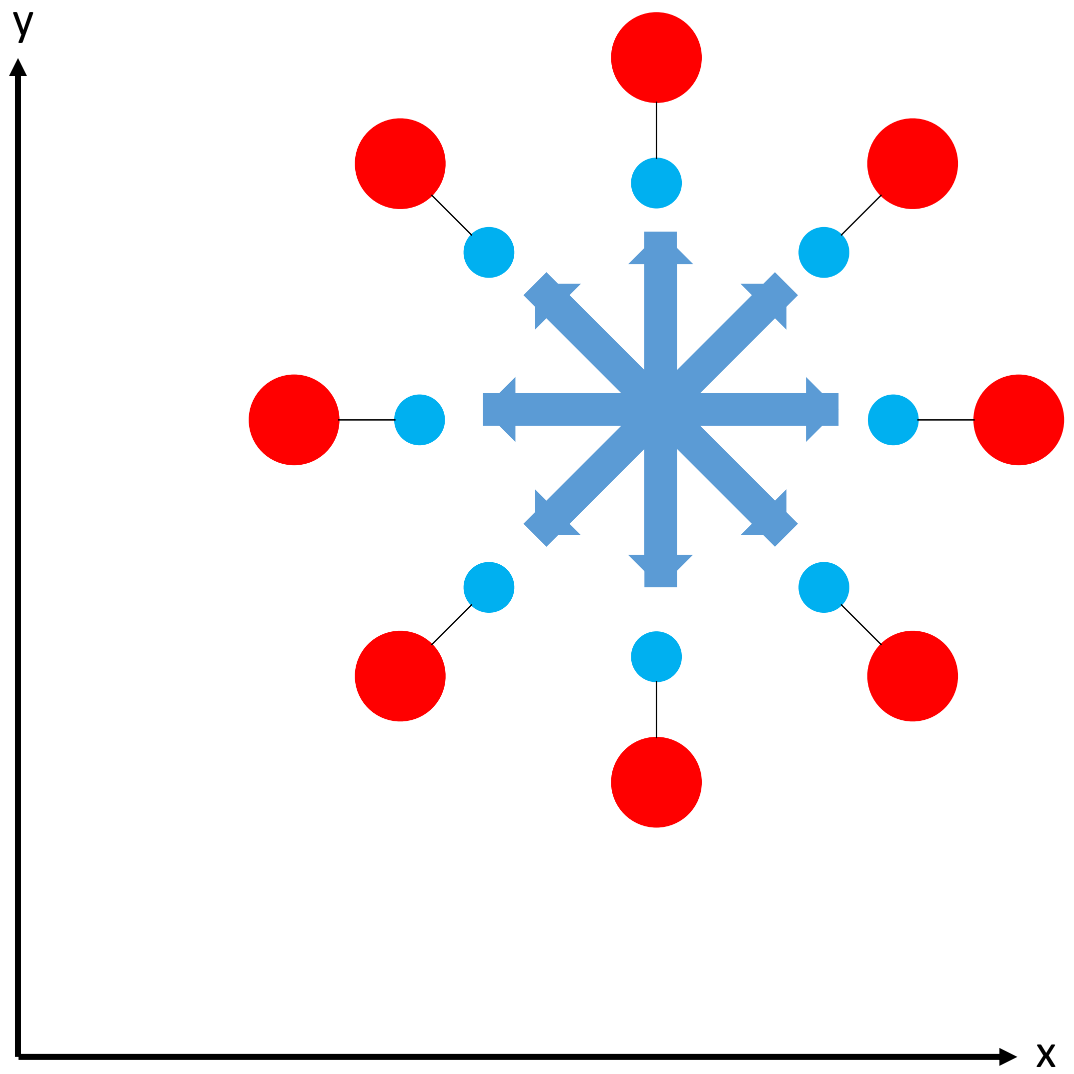


Q: How do you apply
an electric bias field to an ion?
A: In a heavy-ion storage ring!




57371
1PK

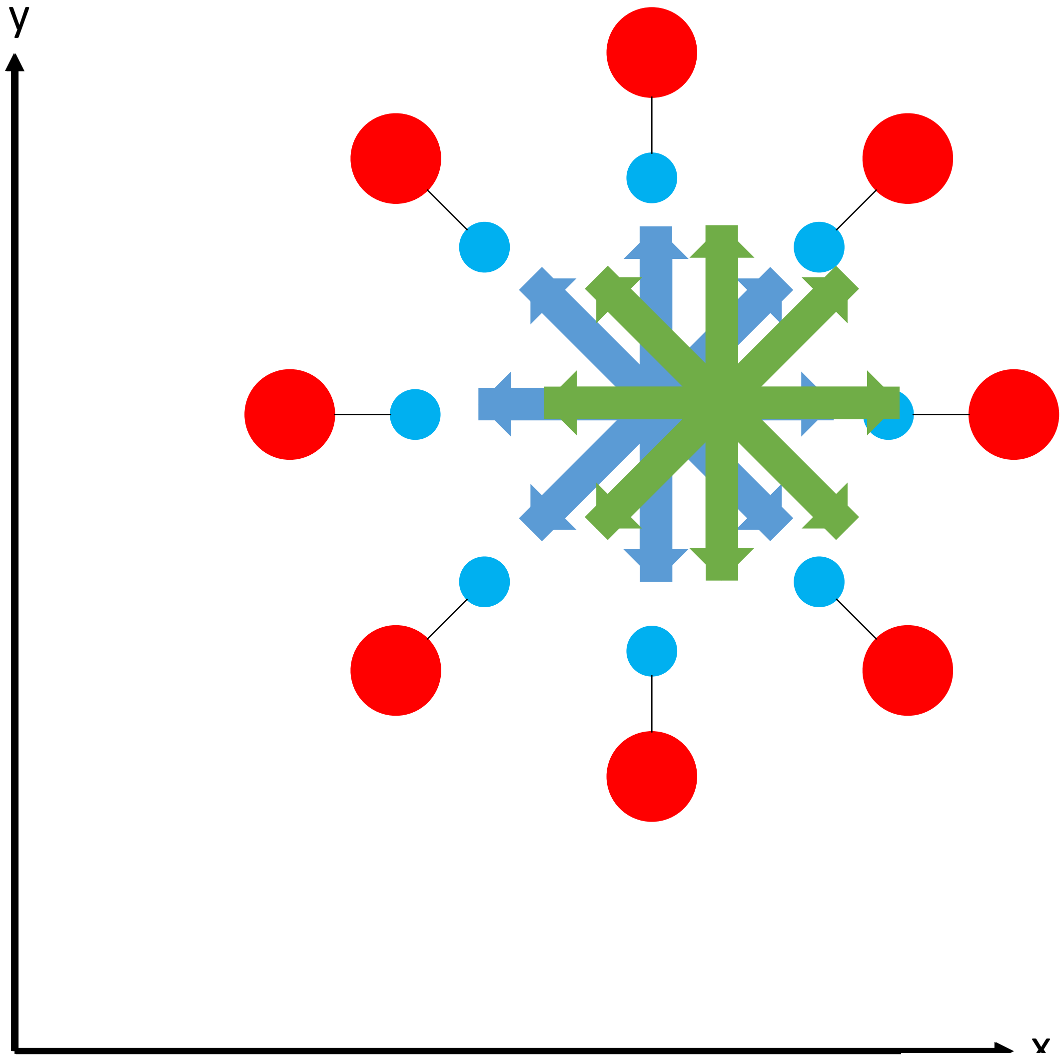
Rotating Fields



$\vec{E}_{rot}$

- Rotating E-Field:
  - $E_{rot} = 60\,\frac{\mathrm{V}}{\mathrm{cm}}$
  - $f_{rot} = 375\ \mathrm{kHz}$
  - Can switch between CW and CCW
  - Molecules rotate with $r_{rot} = 0.5\ \mathrm{mm}$

Rotating Fields



- Rotating E-Field:
  - $E_{rot} = 60\,\frac{\mathrm{V}}{\mathrm{cm}}$
  - $f_{rot} = 375\ \mathrm{kHz}$
  - Can switch between CW and CCW
  - Molecules rotate with $r_{rot} = 0.5\ \mathrm{mm}$

$\vec{E}_{rot}$

- "Rotating" B-Field
  - Static B-field gradient
  - $B_{ax} = 200\,\frac{\mathrm{mG}}{\mathrm{cm}}$
  - $B_{rot} = 10\ \mathrm{mG}$

$\vec{B}_{rot}$

Ions travel in 1 mm circle, VVN-RHI~~C~~SR

EDMs: What about some really out-there ideas?

Embed molecules in a solid matrix!

“trapping” is automatic.

N can be extraordinarily high.

Systematic issues so far are a big challenge.

When you measure it, measure it like you mean it

A measurement with 14 digits of precision has a lot less meaning when the last three digits are precise, but wrong.

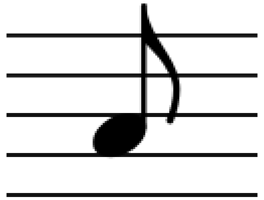
These lectures have been focused on raw statistical precision.

Systematic error are a separate challenge, and a lecture ot themselves.

“Make things better by making then worse.”

a LOT worse.

~~“When you kiss me, kiss me like you mean it”~~



Turns out here is not a song with exactly these lyrics, but several kind of like it.

In any case, today’s sermon is, instead:

When you measure it, measure it like you mean it

(that is, not as a routine polite thing to do but instead
with ***intention***,
with ***passion***, and with
the hope that it means something)