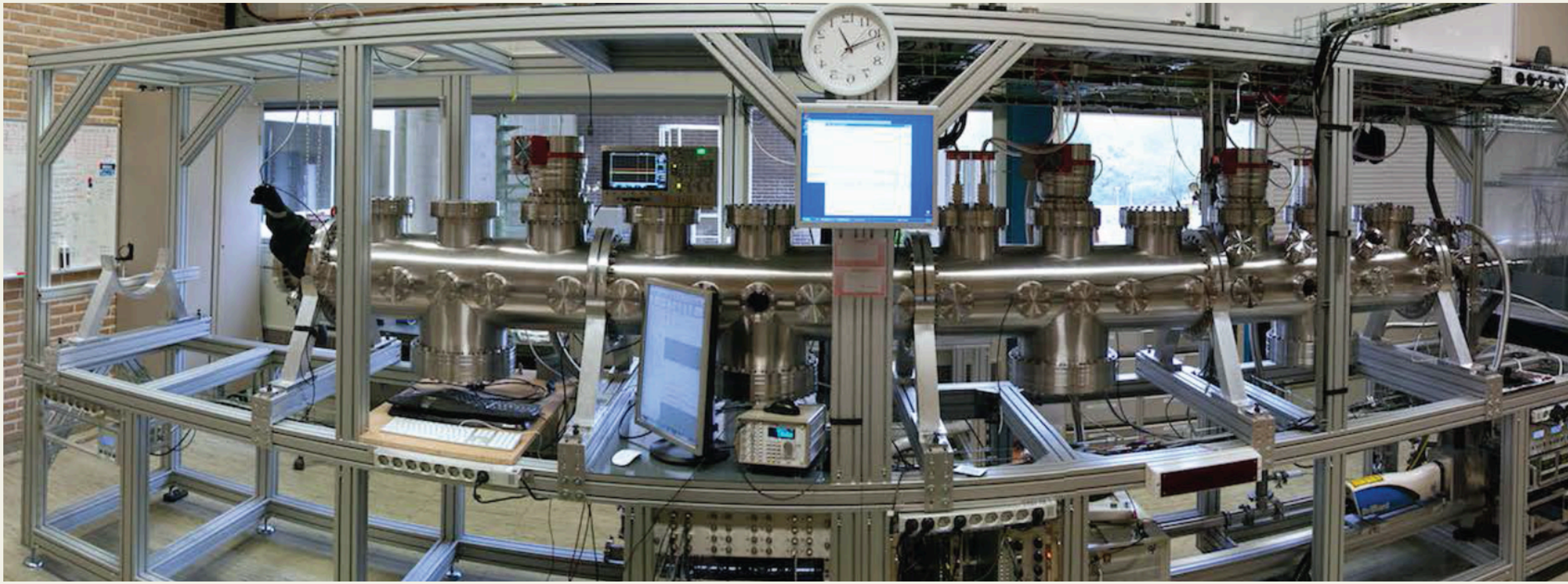
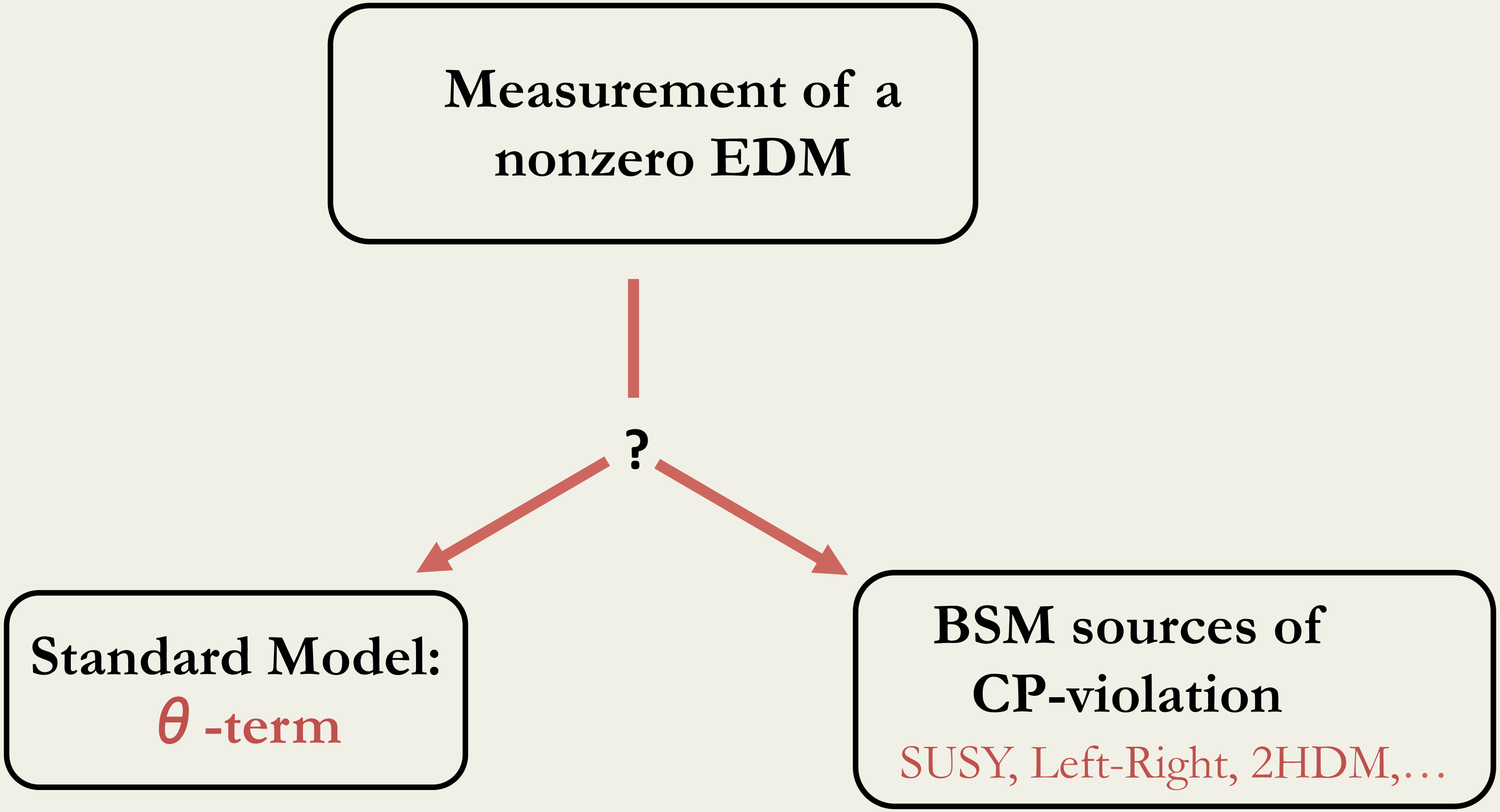
Classes of EDM experiments

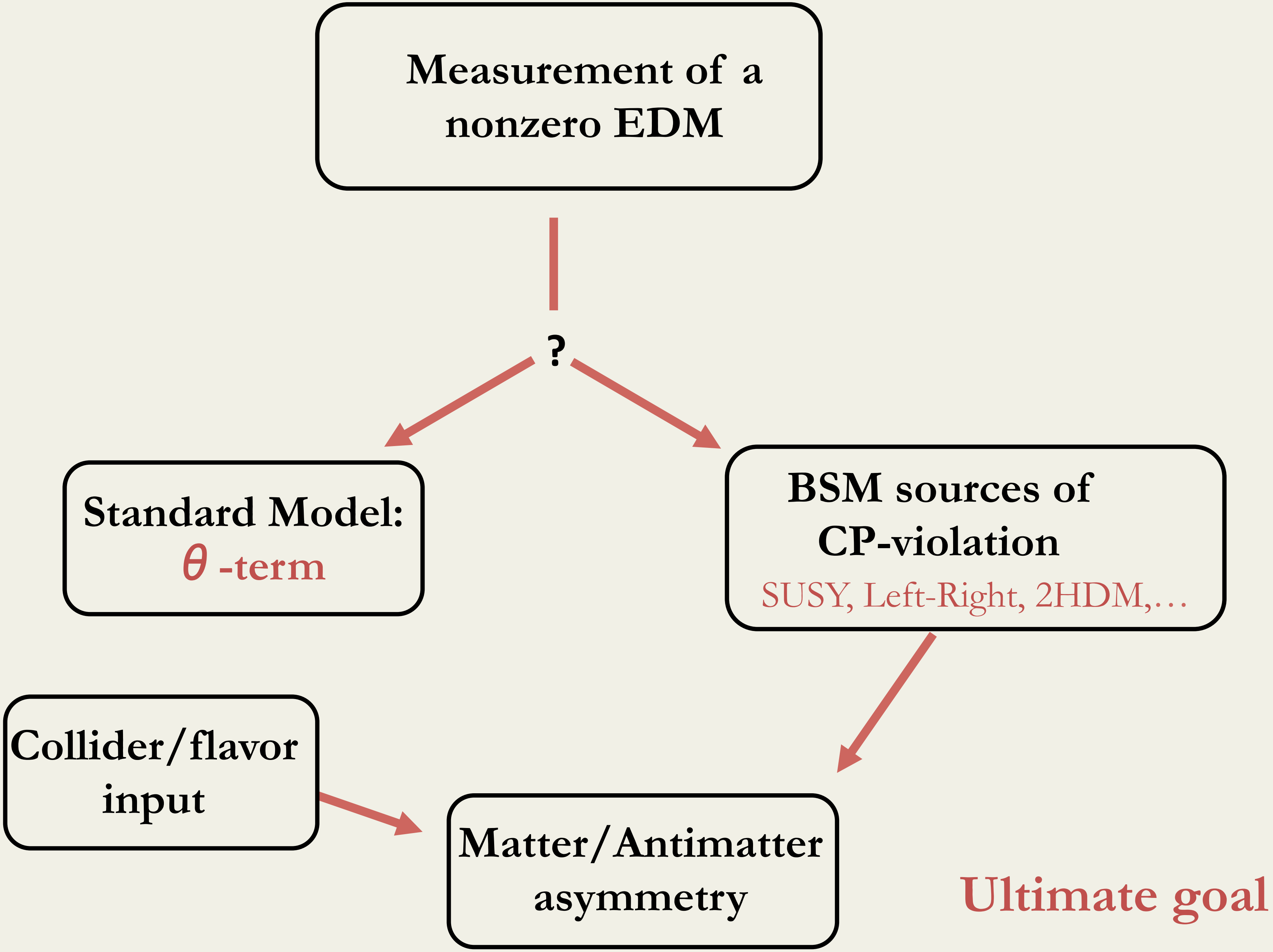


Jordy de Vries, Nikhef, Amsterdam

Topical Lectures on electric dipole moments, Dec. 14-16



For the forseeable future: EDMs are **‘background-free’** searches for new physics


Measurement of a nonzero EDM
?
Standard Model:
θ -term
BSM sources of CP-violation
SUSY, Left-Right, 2HDM,…
Collider/flavor input
Matter/Antimatter asymmetry
Ultimate goal

Very active experimental field

	System	Group	Limit	C.L.	Value	Year
	^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
e	YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
	ThO	ACME	8.7×10^{-29}	90	$-2.1(3.7)(2.5) \times 10^{-29}$	2014
	n	Sussex-RAL-ILL	3.0×10^{-26}	90	$0.2(1.5)(0.7) \times 10^{-26}$	2006
	^{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	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
	^{225}Ra	Argonne	1.4×10^{-23}	95	$-0.5(1.5)(0.01) \times 10^{-23}$	2016
	muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

- **Why do experiments on all these systems? Why not pick one !**
- How do the experiments compare? What does dn/dHg $\sim 10^{-3,-4}$ imply?
- Are there new systems that would be interesting to study ?

Classes of EDM experiments

- Class 1: **neutron EDM experiments**
  (traditional, but running out of steam ?)

- Class 2: **Paramagnetic atoms and molecules**
  (powerful, but 'limited scope'. My EDM bet! Dutch experiment !)

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  (powerful but hard to understand, nuclear physics uugh)

- Class 4: **Storage ring experiments (the future?)**
  (my favorite experiment but expensive and perhaps science fiction)

Neutron EDM experiments

- First EDM experiment (Ramsey, Smith, Purcell '1951) used a neutron beam
- Experiment in 1951, published in 1957….
- Not realized that EDMs implied CPV, but knew that PV was required
- They measured zero, and since strong interactions were assumed to be P invariant, they did not care to publish....

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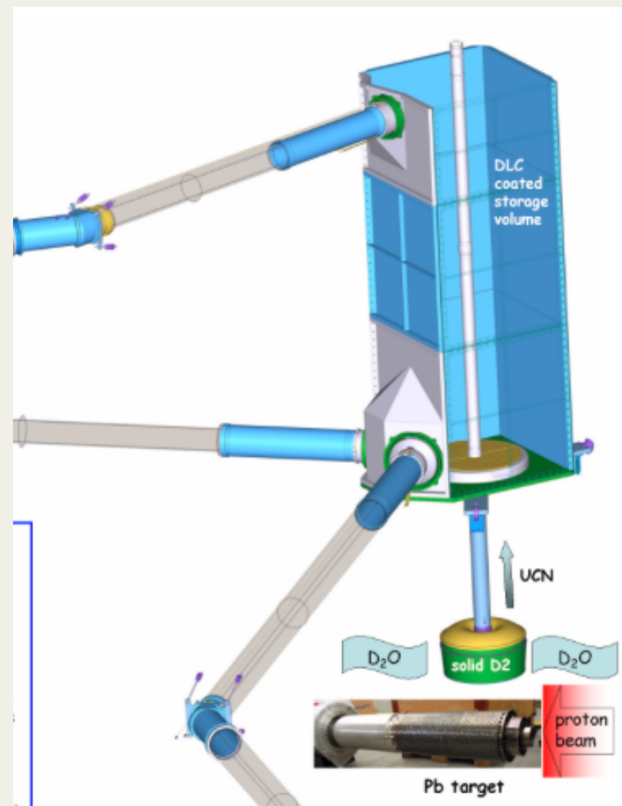
- Not realized that EDMs implied CPV, but knew that PV was required
- They measured zero, and since strong interactions were assumed to be P invariant, they did not care to publish....
- In 1956/57 Lee/Yang propose P violation, and Wu measures it
- They then decide to publish the paper

- They got $d_n < 5*10^{-20}$ e cm
- So theta < 10^{-4}, **but they did not know**
- After discovery of CPV in ’64, the field restarted

- Current limit : $d_n < 3*10^{-26}$ e cm (2006)

Modern Experiments

- Originally neutron beams were used but systematics too hard to control
- Since 80's-90's use ultracold neutrons (speeds ~ 7 m/s)
- 6 ongoing/planned experiments (PSI, TRIUMF, LANL, SNS, Munich, ILL)
- At these energies (100 nano-eV) neutrons become reflective
- At PSI: guided from the production via a beamline to a trap



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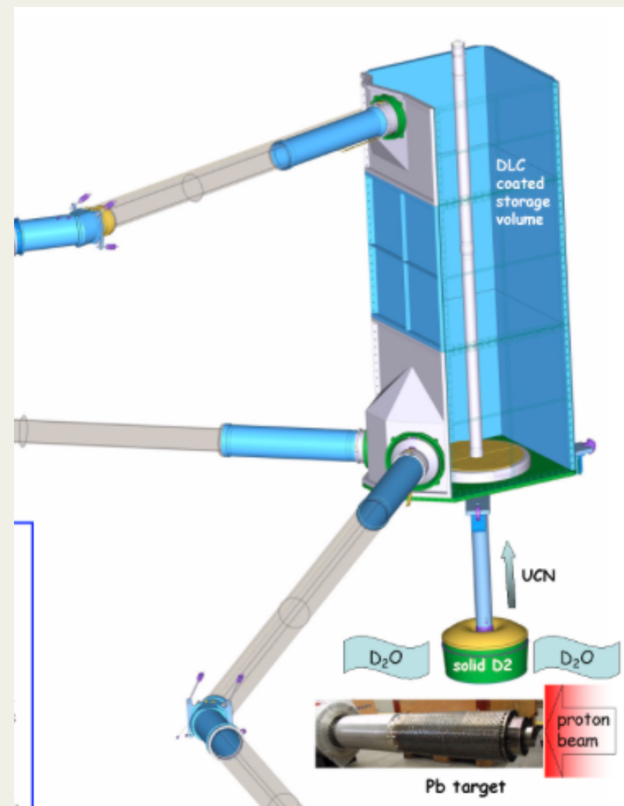
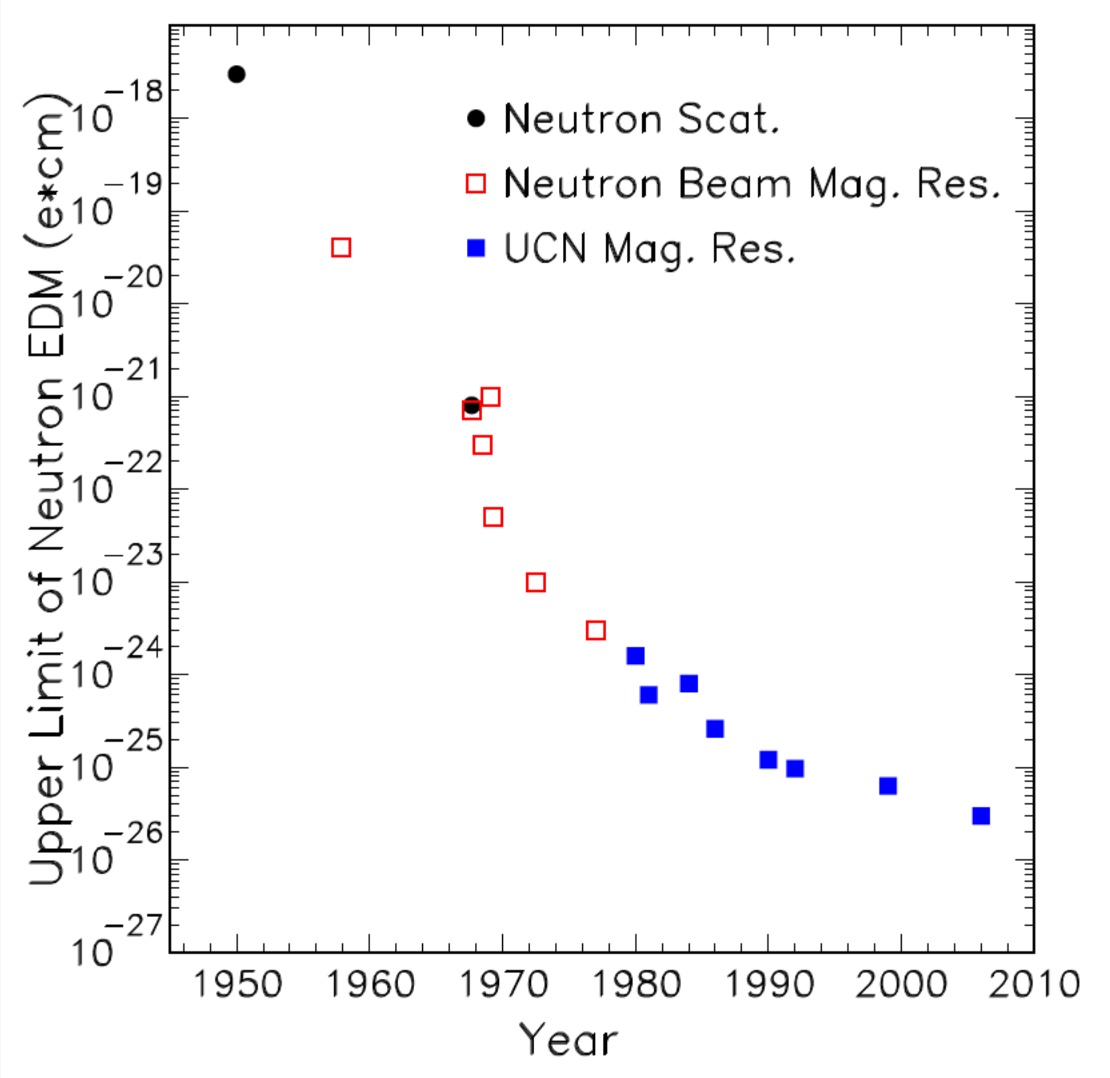
- At these energies (100 nano-eV) neutrons become reflective
- At PSI: guided from the production via a beamline to a trap
- Gravitional selection
- Main source of uncertainty: stable B field
- Use Hg as comagnometer





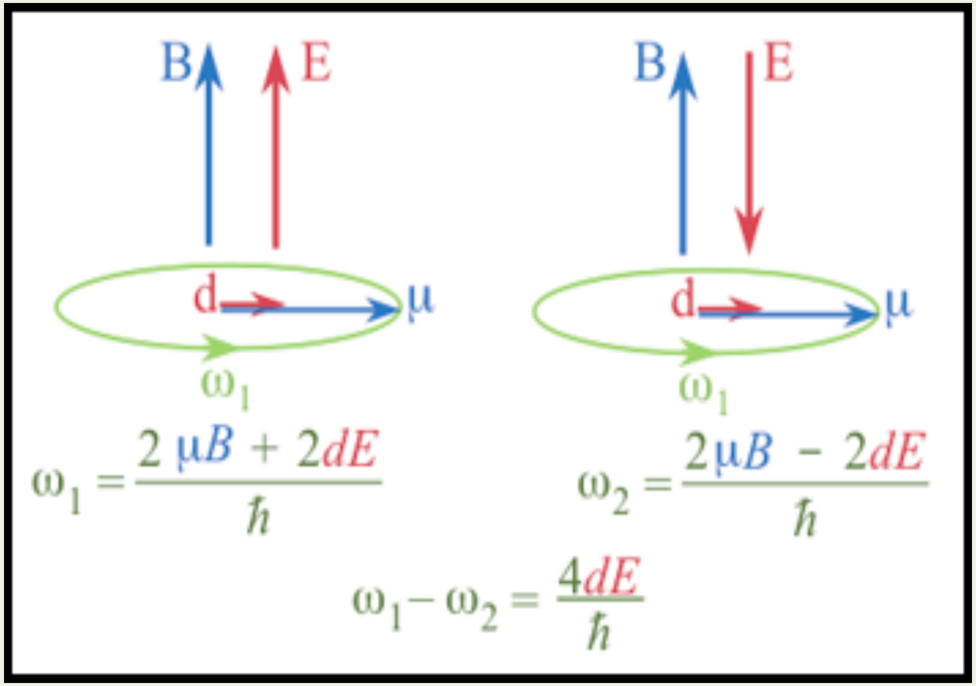
Running out of steam?

All experiments suffer from lack of neutrons

Statistics limited, difficult to improve by a large factor

Why neutrons ?

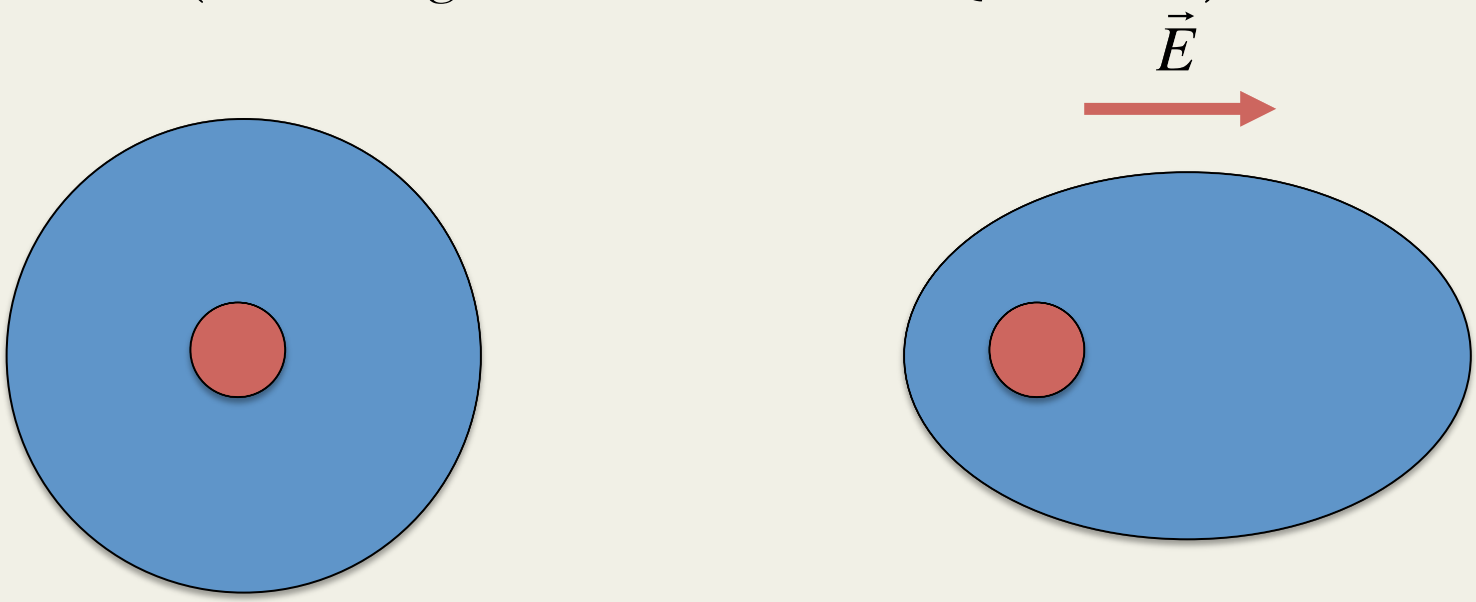
- Why not protons? Much easier to produce
- **Remember the measurement idea !**



Why not atoms?

- Why not protons? Much easier to produce
- **Remember the measurement idea !**
- So we need neutral systems ! Why not pick hydrogen atoms !?

- **Schiffs theorem:** the electron cloud will rearrange so that the nucleus does not 'feel' an external E-field. The EDMs of the nucleus and electron are screened (clasical argument but works in QM as well)



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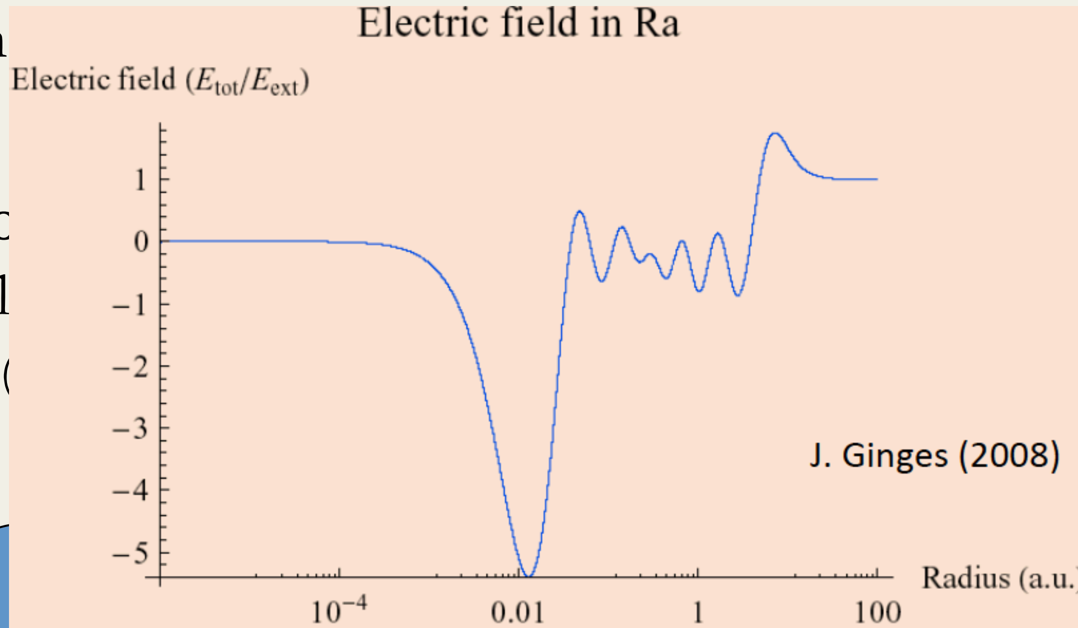
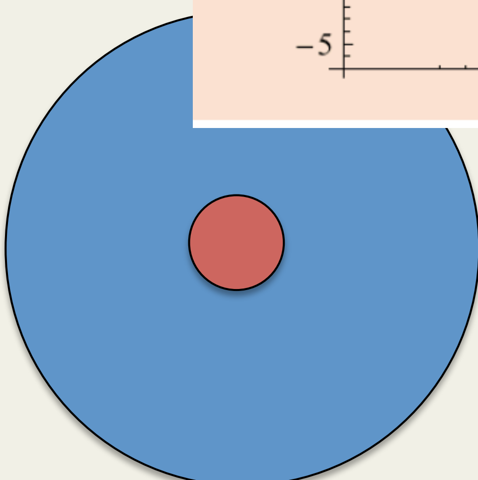
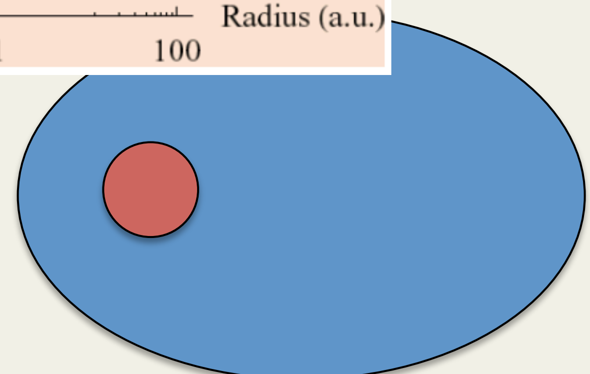
- **Schiffs theo…** …at the nucleus does not 'feel… …us and electron are screened (…







Why heavy atoms ?

- **Schiffs theorem is exact for point particles and non-relativistic dynamics**

- **So 2 loopholes:** 1) The nucleus is not pointlike

  2) Electrons in heavy atoms are relativistic

1) paramagnetic, no nuclear spin, but unclosed electron shell.

Sensitive to electron EDM but **need heavy atoms** !

2) Diamagnetic, closed electron shell and nonzero nuclear spin. **Need heavy atoms** !

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Probing the electron EDM

e

System	Group	Limit	C.L.	Value	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
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- Schiff's theorem overcome by relativity (electric and magnetic fields mix)

$$d_A(d_e) = K_A d_e \qquad K_A \propto Z^3 \alpha_{em}^2$$

- So for light systems large suppression
- But for heavy systems we can even enhance the EDM !

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- So for light systems large suppression
- But for heavy systems we can even enhance the EDM !

Bound on atomic Tl EDM : $d_{^{205}Tl} < 9 \cdot 10^{-25}\ e\ cm$

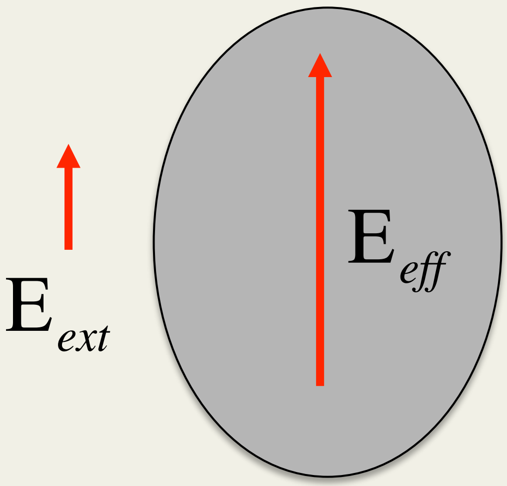
$$d_A(d_e) = K_A d_e \qquad K_{Tl} = -(570 \pm 20)$$

Strong enhancement!

$$\longrightarrow \quad d_e < 1.6 \cdot 10^{-27}\ e\ cm$$

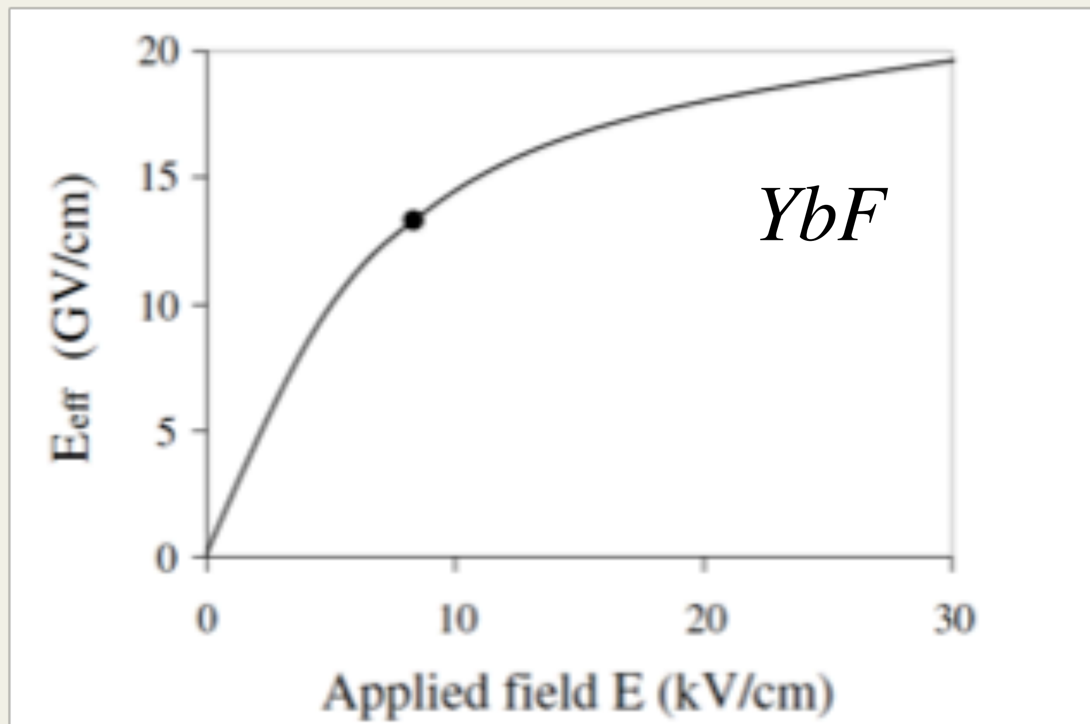
State-of-the-art: polar molecules

Polar molecules: Convert small external to huge internal field



$$\Delta E \sim \mathrm{E}_{eff}(E_{ext})d_e$$

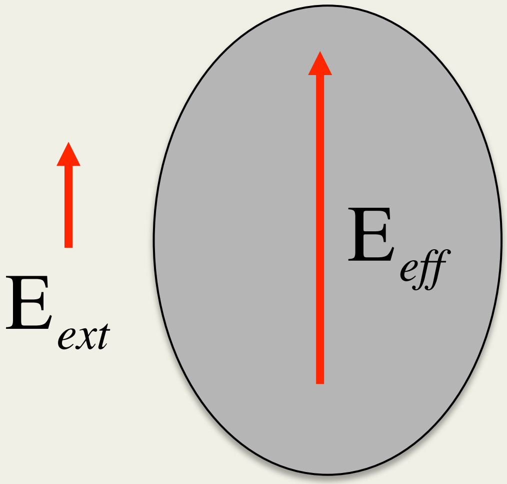
Nonlinear function of external field



Plot from Hudson et al PRL '02

State-of-the-art: polar molecules

Polar molecules: Convert small external to huge internal field



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

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

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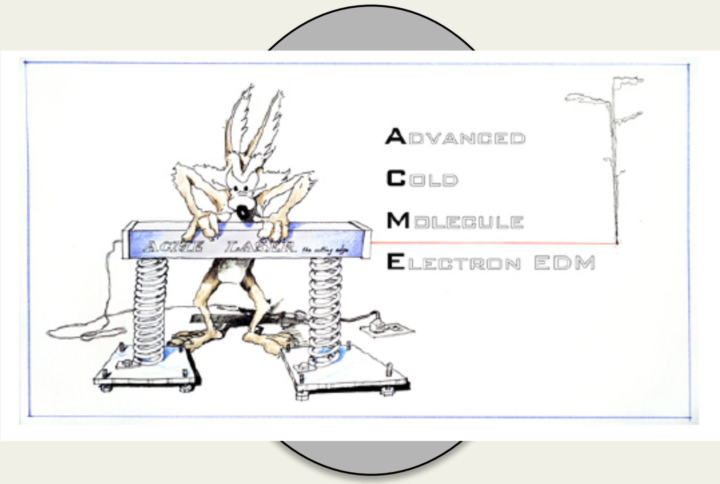

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$$E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\ cm} \right) + O(C_S)$$

$$d_e < 8.7 \cdot 10^{-29}\ e\ cm$$

Current world record

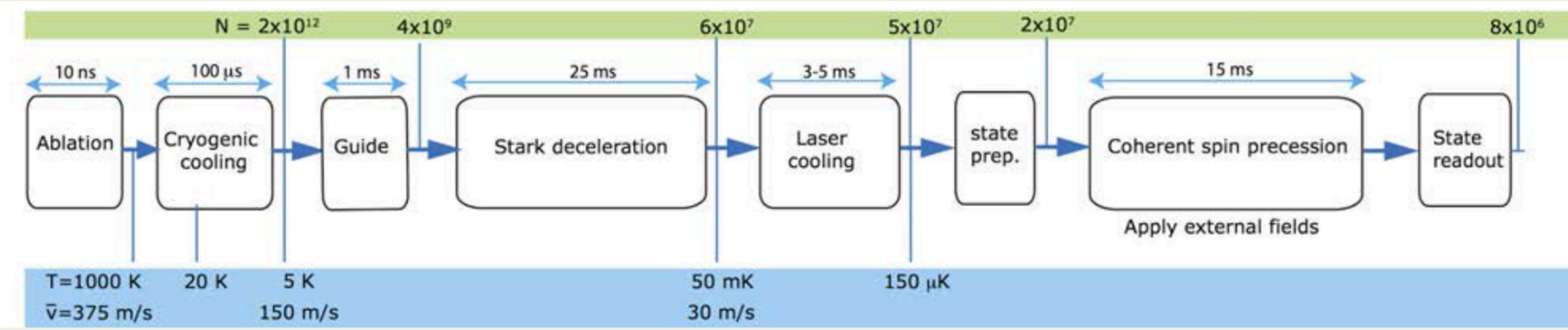
From ACME (Harvard/Yale) collaboration (2014)

Can be improved a lot!

Table-top experiment ! O(5-10) people, few million euro

EDMs @ Nikhef/RUG

Use new methods to decelerate and laser-cool BaF molecules



$$\sigma_d = \frac{\hbar}{e} \frac{1}{2\mathcal{E}_{\text{eff}} \tau \sqrt{\dot{N} T}}$$

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Probing nuclear CP violation

Graner et al, '16

- Diamagnetic, closed electron shell and nonzero nuclear spin.
- Best EDM limit in the world !

$$d_{^{199}Hg} < 8.7 \cdot 10^{-30}\ e\ cm$$

- What about Schiff screening, nucleus is not relativistic….

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- Diamagnetic, closed electron shell and nonzero nuclear spin.
- Best EDM limit in the world ! $d_{^{199}Hg} < 8.7 \cdot 10^{-30}\ e\ cm$

- What about Schiff screening, nucleus is not relativistic….
- But it has a finite size !

Typical suppression: $$\frac{d_{Atom}}{d_{nucleus}} \propto 10 Z^2 \left(\frac{R_N}{R_A}\right)^2 \approx 10^{-3}$$

- **Atomic** part well under control

$$d_{^{199}Hg} = (2.8 \pm 0.6) \cdot 10^{-4}\ S_{Hg}\ e\ fm^2$$

- So the atomic limit gets screened by a factor 1000 roughly
- Xe screening is a bit worse, but less for Ra.

Huge collaboration…..

The Team

Graduate Students
Jennie Chen
Brent Graner*

Scientific Glassblower
Eric Lindahl

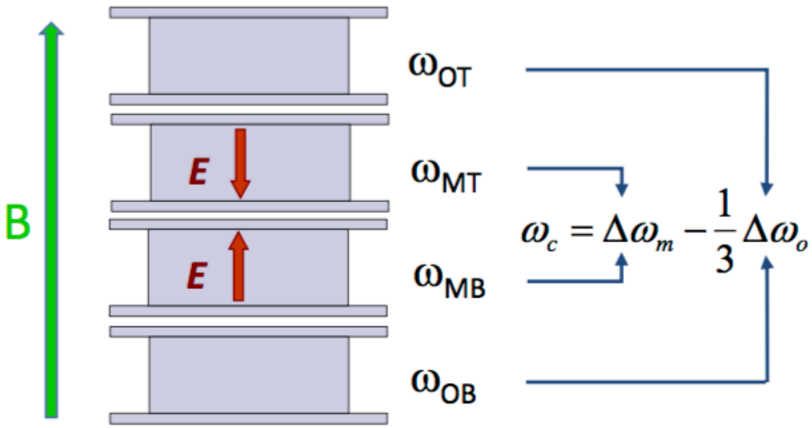
Faculty
B. R. Heckel

Primary support from NSF
* Supported by DOE Office of Nuclear Science

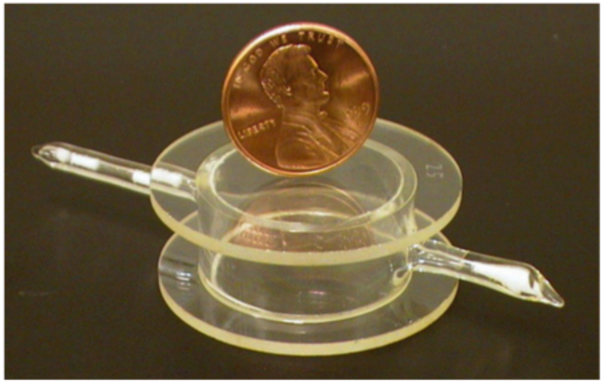
Slide from B. Heckel, KITP ‘16

Current EDM Experiment

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



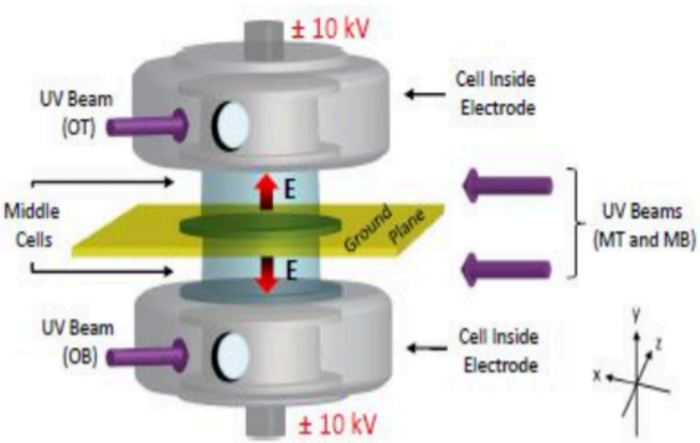
$$\omega_c = \Delta\omega_m - \frac{1}{3}\Delta\omega_o$$



T_2 Spin Relaxation: 300 - 600 sec

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

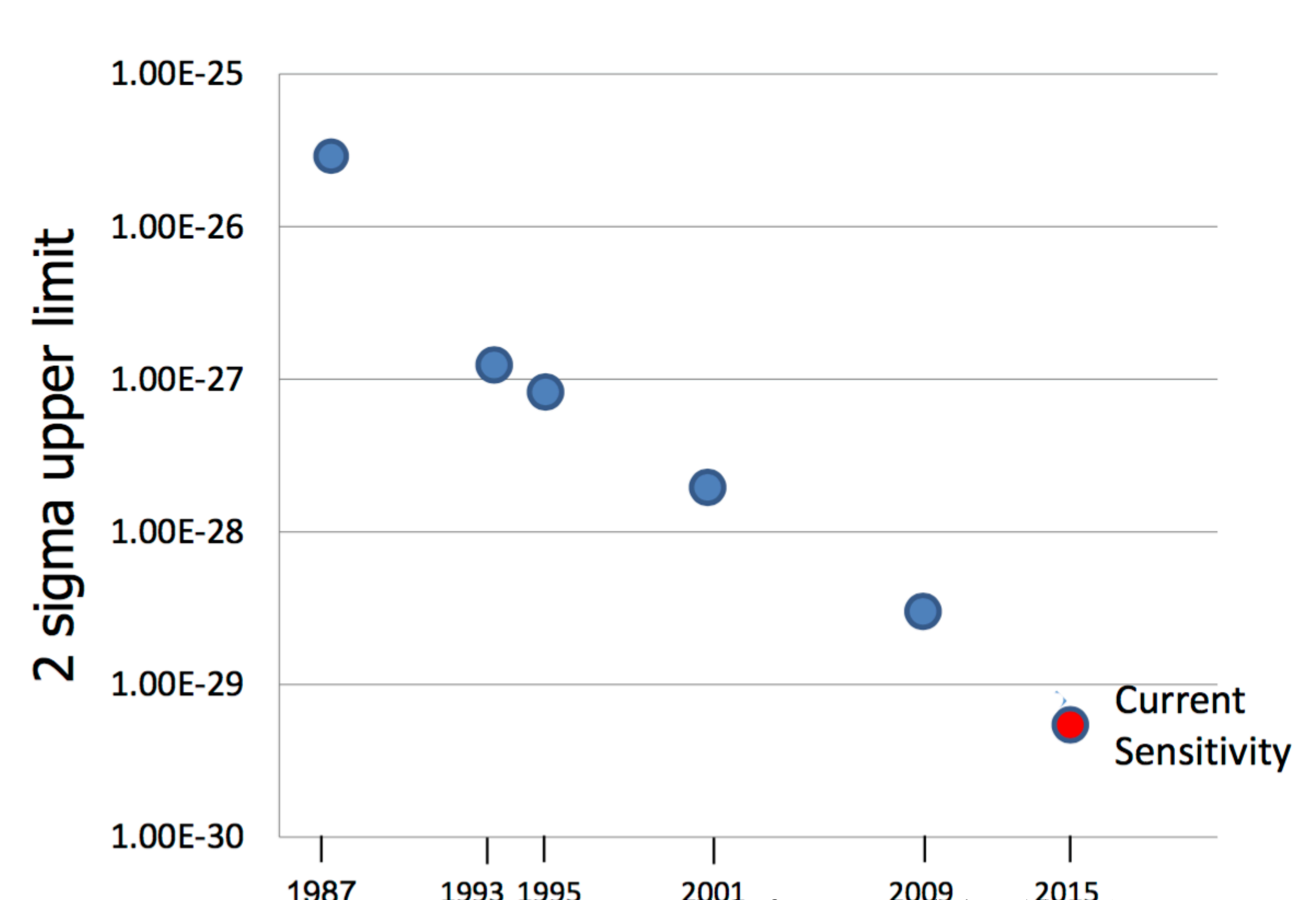
Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



CENPA
Center for Experimental Nuclear Physics and Astrophysics

Slide from B. Heckel, KITP '16

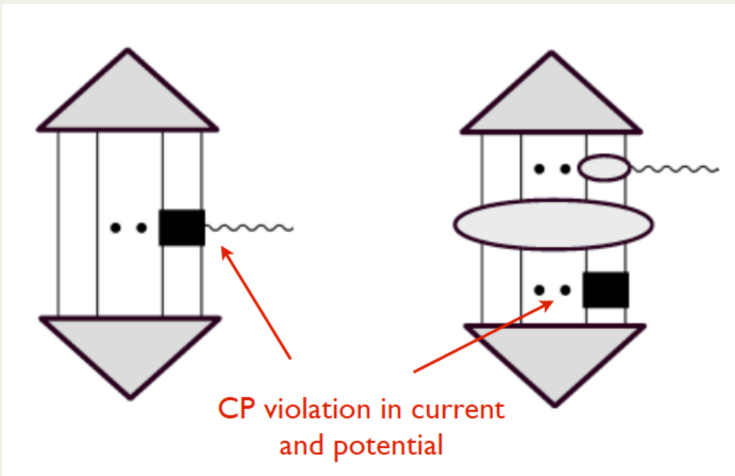
Probing nuclear CP violation



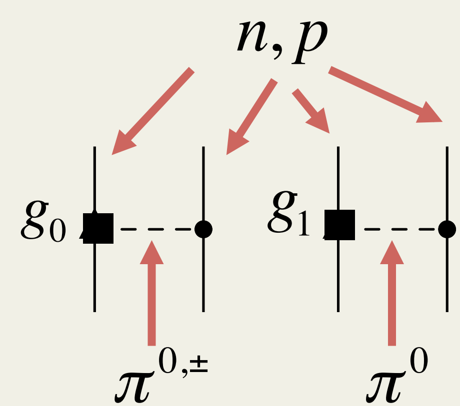
Slide from B. Heckel, KITP '16

Calculating Schiff Moments

Flambaum, de Jesus,
Engel, Dobaczewski,
Dmitriev, Sen'kov,…..



CP-odd potential



- **Nuclear Schiff moment dominated by CP-violating pion exchange**
- Same couplings that contribute to nEDM at loop level !

- **Very complicated** many-body calculation
- Use some nuclear model and mean-field theory

Nuclear theory… Uuugh....

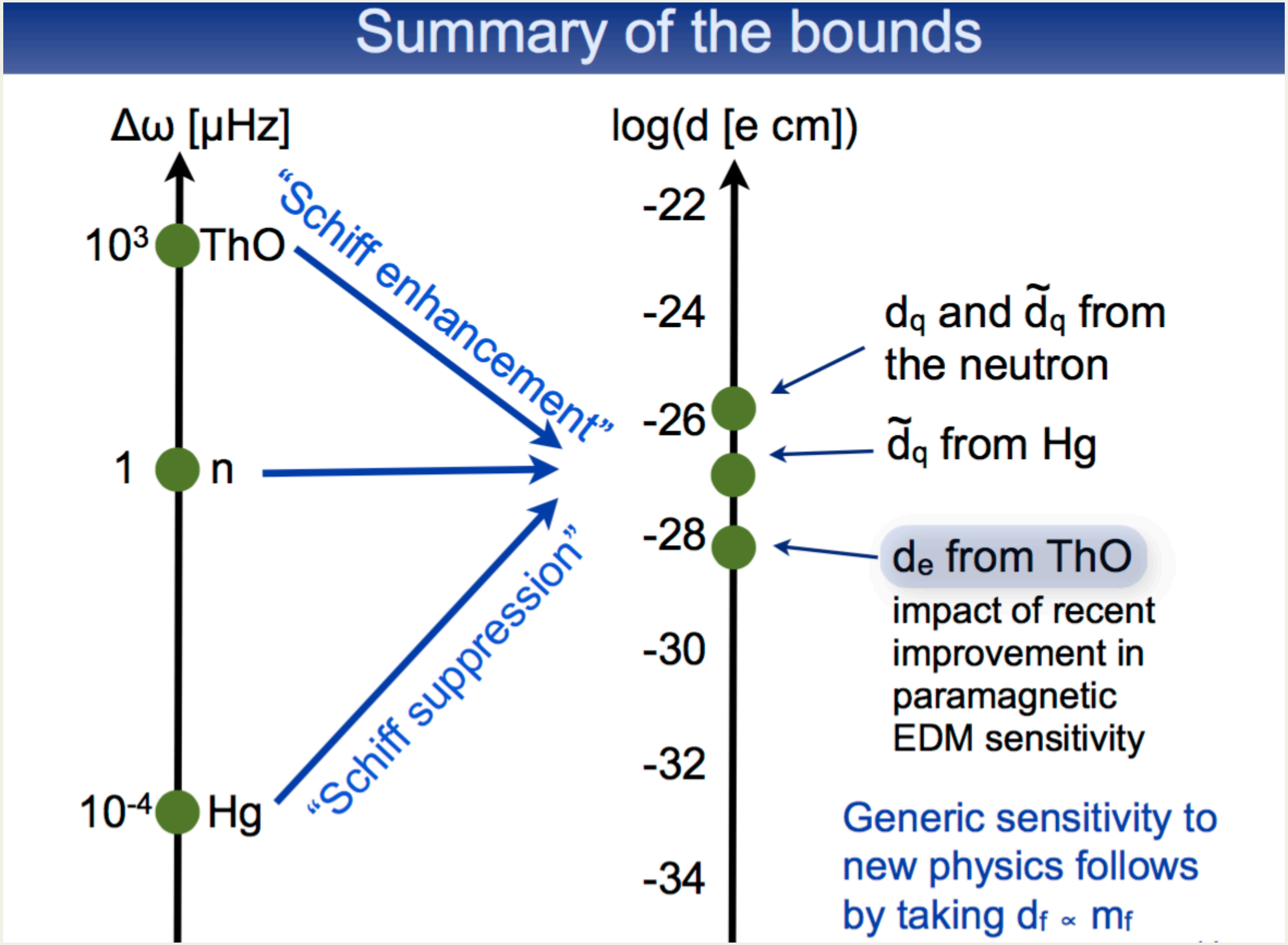
$$S_A \sim g(a_0\bar{g}_0 + a_1\bar{g}_1)\, e\ fm^3 \qquad g = 13.5$$

Flambaum, de Jesus, Engel, Dobaczewski, Dmitriev, Sen'kov,…..

	a_0 range (best)	**a_1 range (best)**
^{199}Hg	0.03 ± 0.025 (0.01)	0.030 ± 0.060 (±0.02)
^{225}Ra	-3.5 ± 2.5 (-1.5)	14 ± 10 (6)

table from review: Engel et al, '13

- Based on calculations from various groups
- Hg : spread >100% Ra: ~ 80%, not clear how to interpret this
- Worse: not clear how to improve this….
- Makes interpretation of experiments difficult....



Slide from Adam Ritz, Trento, '16

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EDMs of light nuclei

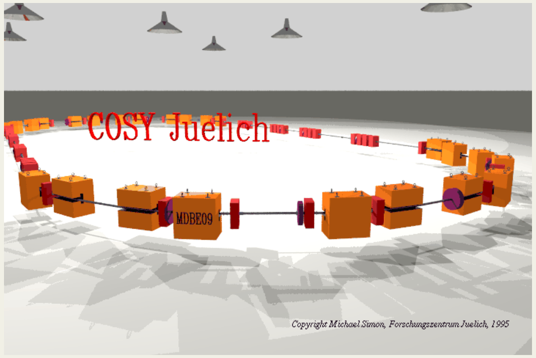
Anomalous magnetic moment

Electric dipole moment

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega} \qquad \vec{\Omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{v^2} - a\right)\vec{v} \times \vec{E}\right] + 2d\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

All-purpose ring (^{1}H, ^{2}H, ^{3}He, …) $\sim 10^{-28,29}\ e\,cm$

100-1000 x current neutron EDM sensitivity! (takes a while tough….)



Already used for muon EDM

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

Bennett *et al* (BNL g-2) PRL '09

Major progress in:

JEDI collaboration, *PRL* '15, '16

Why EDMs of light nuclei

- Several advantages of using light instead of heavy systems

- **No Schiff screening !** No suppression associated to Hg/Ra/Xe
- This means a measurement at 10^{-26} level would be world-leading

- Theory is well under control. Few-body equations are 'easy'

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

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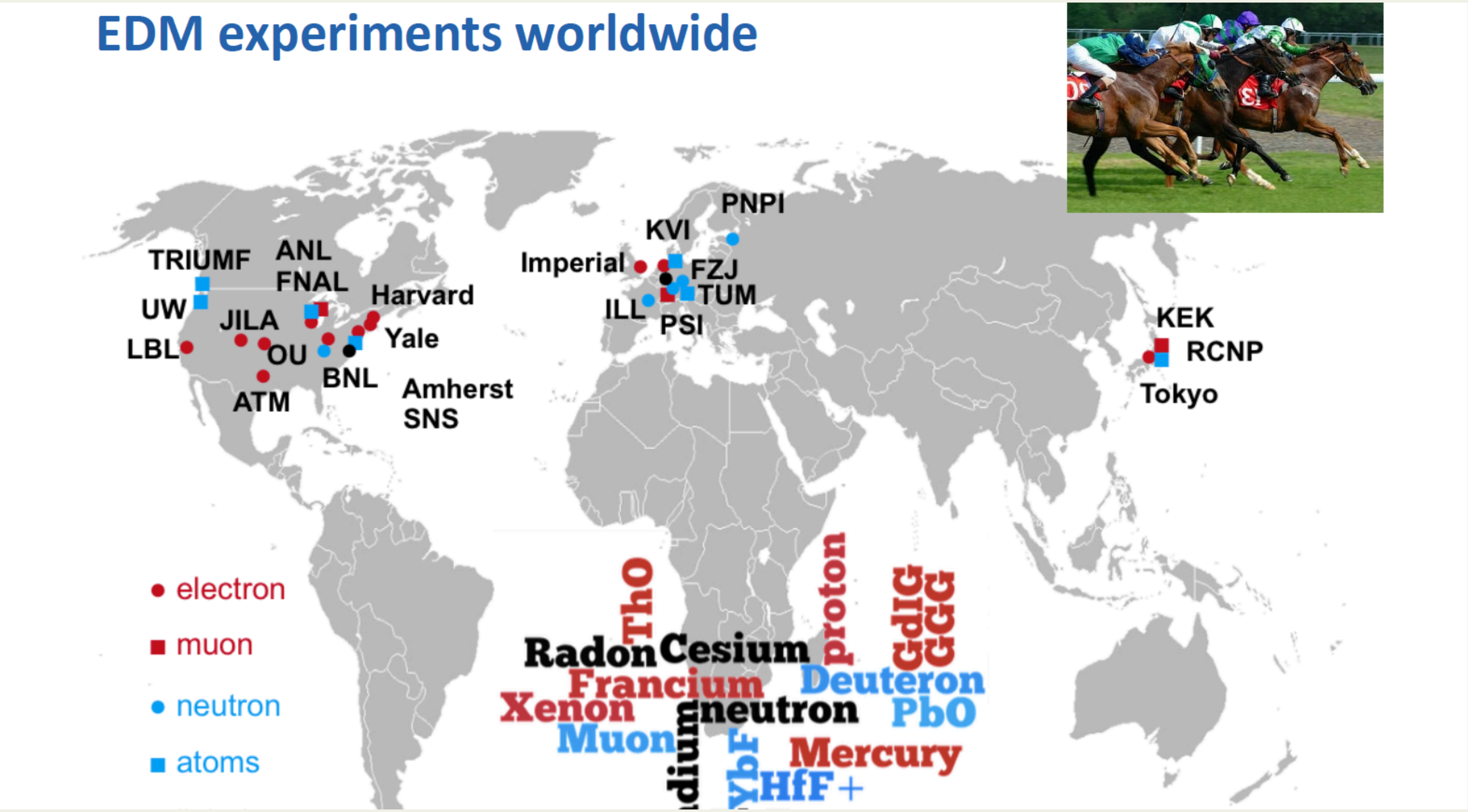
- **Ratio of EDMs indicate source of CP violation**
- Theta term: dD < dn, for BSM generally; dD >> dn **(next lecture)**

- **Disadvantage: Expensive, requires a big storage ring (50 million..)**
- Under development in Germany and Korea but funding not guaranteed

Complementary measurements

- Class 1: **neutron EDM experiments**
  - Theta + BSM CP violation involving quarks and gluons
  - Difficult to improve
- Class 2: **Paramagnetic atoms and molecules**
  - Very sensitive to electron EDM, but not much more
  - No SM background, not even theta.
  - Atomic theory is under control
- Class 3: **Diagmagnetic atoms**
  - Sensitive to nuclear CPV and thus complements nEDM
  - Very good measurements but Schiff screening and theory…
- Class 4: **Light nuclei**
  - New idea, no Schiff screening and good theory
  - Expensive and requires new technology

Race for an EDM



- And new experiment at Groningen/Nikhef using BaF molecule

Will we reach the CKM

System	Current limit	CKM contribution
Neutron	$< 10^{-26}$ e cm	$10^{-31,-32}$ e cm
^{199}Hg	$< 10^{-29}$ e cm	$10^{-33,-35}$ e cm
Electron	$< 10^{-28}$ e cm	$10^{-38,-39}$ e cm

- Not in the near future….
- If we would, the EDMs will become ‘ordinary’ observables and then the limiting theory will probably make them a check of the CKM paradigm but not much more.

My take

- The molecular experiments can still go far
- That makes them, in my mind, the **discovery system**
- But note: they probe mostly the electron EDM

- The Ra-EDM is extremely interesting as well. Experiments are now at : dRa < 10^{-23} e cm (100x improvement in 1 year) and expected to reach 10^{-27} in a couple of years

- Storage rings, if promises are achieved, could have a bigger reach then other experiments. But still far away….

- **If a nonzero EDM would be measured anywhere: to figure out the source we need several systems.**