QED & Quantum Vaccum, Low Energy Frontier, 05003 (2012)
DOI: 10.1051/iesc/2012qed05003

Neutron and electron electric dipole moments (EDMs)

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Article published online by EDP Sciences and available at http://www.iesc-proceedings.org or http://dx.doi.org/10.1051/iesc/2012qed05003

Imperial College London

Neutron and electron electric dipole moments (EDMs)

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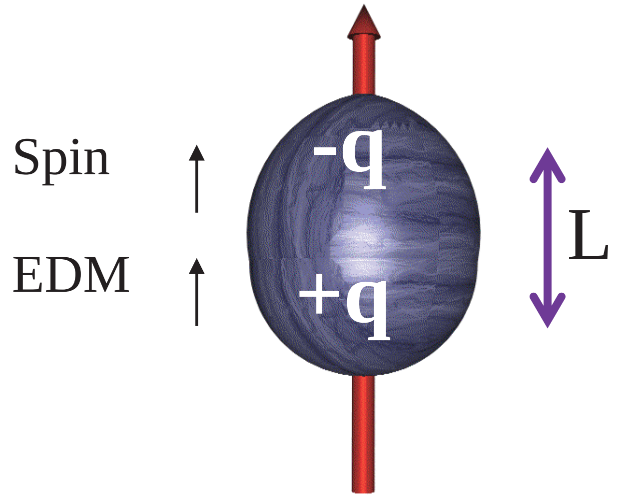
Lectures given at QED2012, Cargèse, Corsica, April 18th - 19th 2012

What is an EDM?



EDM, $d = q\,L$

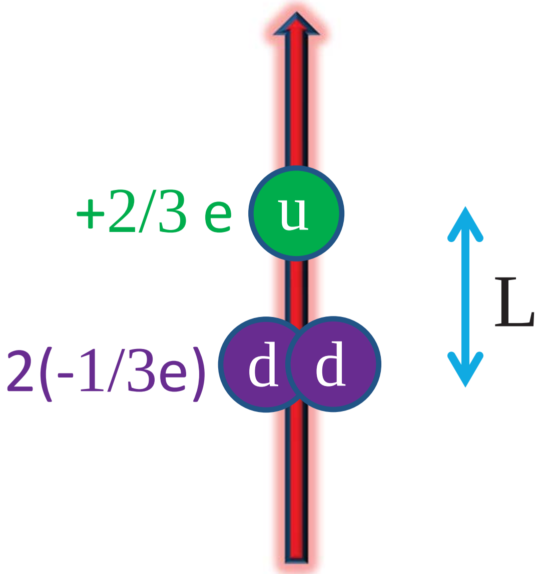
A *magnetic dipole moment* **μ** in a *magnetic field* **B** has energy **−μ.B**

An *electric dipole moment* **d** in an *electric field* **E** has energy **−d.E**

N.B. Both **μ** and **d** are parallel (or antiparallel) to the spin

What is an EDM?

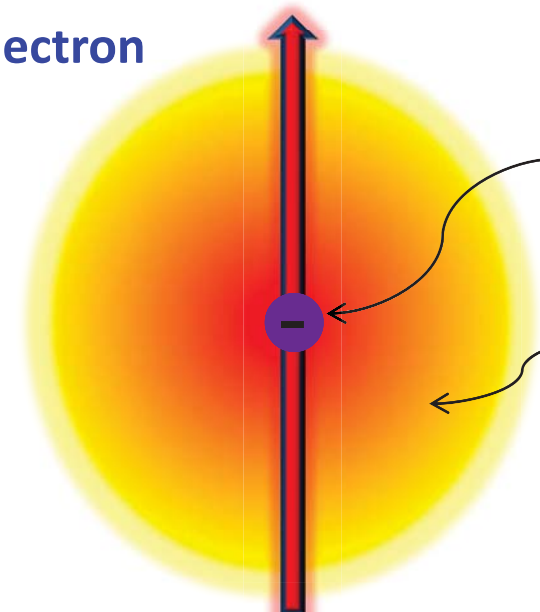
Neutron



Example: If L ~ 0.1 times neutron radius: d_n ~ 10^{-15} e.cm

Experimental upper limit: $|d_n| < 2.9 \times 10^{-26}$ e.cm

Electron



point electron

polarizable vacuum with increasingly rich structure at short distances:

[(anti)leptons, (anti)quarks, non-standard-model particles]

Setting the scale

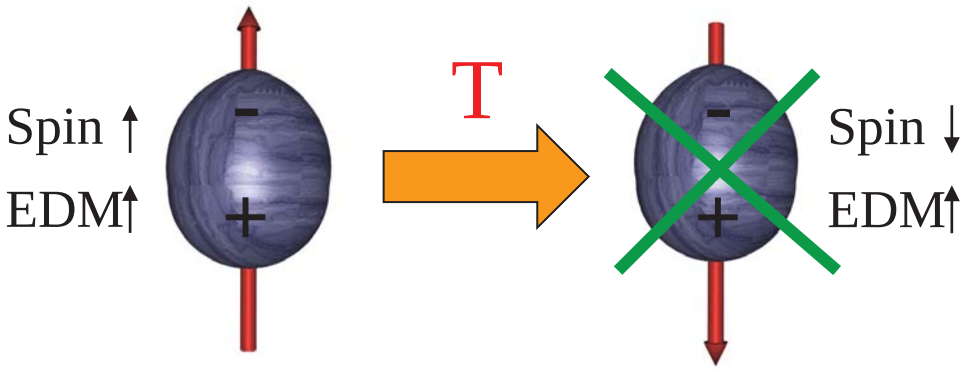
Suppose the neutron EDM is $d_n = 2.0 \times 10^{-26}$ e.cm
(just below current upper limit)

In an electric field of 10kV/cm the interaction energy is:

0.0002 atto-eV or 0.05 μHz or 0.002 f cm^{-1} or 0.002 fK.

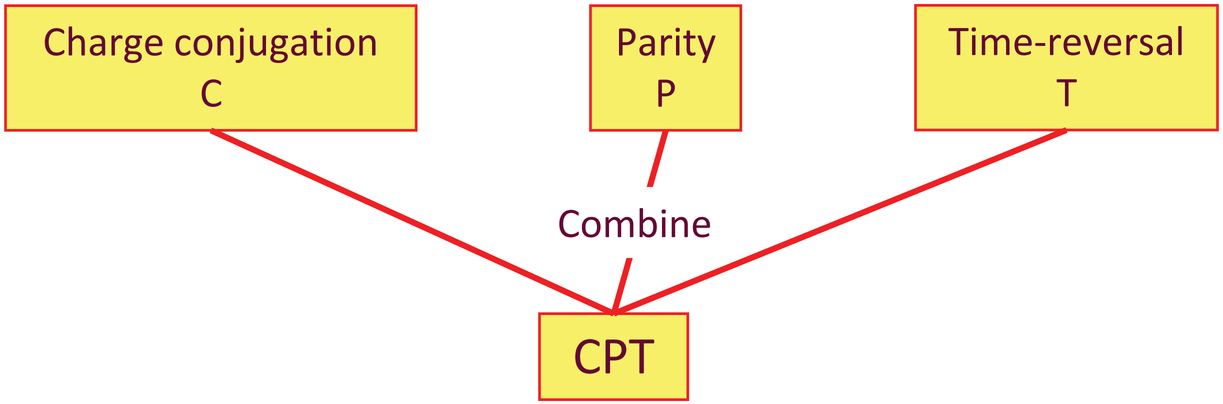
The neutron has a magnetic dipole moment.
The magnetic field that produces the same interaction energy is only **2 fT**.

A non-zero EDM violates time-reversal symmetry



Either $d_e = 0$, or ~~T~~

Discrete symmetries



All local, Lorentz-invariant quantum field theories are invariant under CPT

A non-zero EDM violates CP symmetry

We need CP violation!

The entire observable universe appears to be made of matter

CP violation is necessary to explain how the universe came to be this way

CP violation in the Standard Model is insufficient to explain the observed matter-antimatter asymmetry

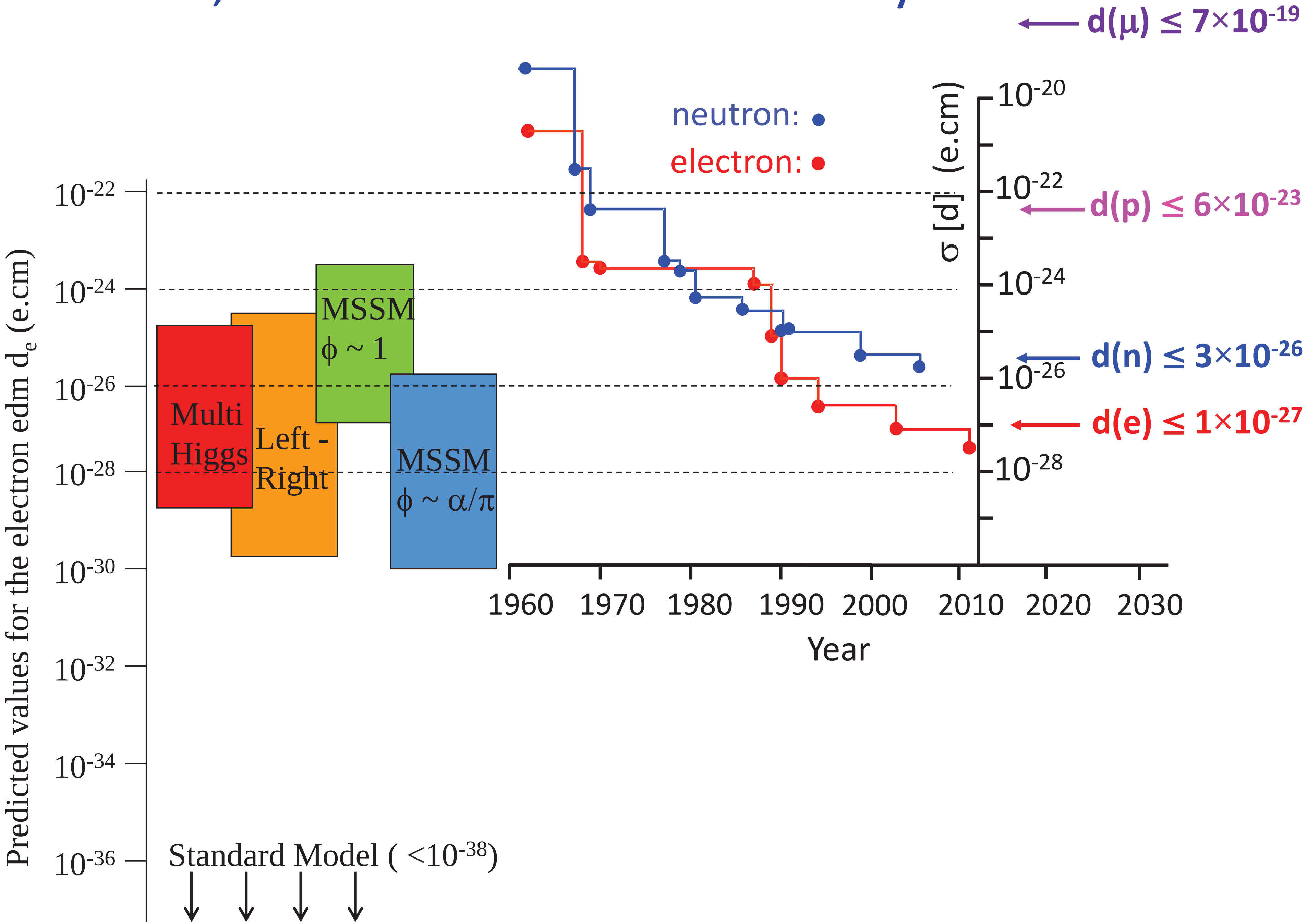
Theories beyond the Standard Model introduce new CP-violating interactions

Our solar system – 2 billion billion billion tonnes of matter

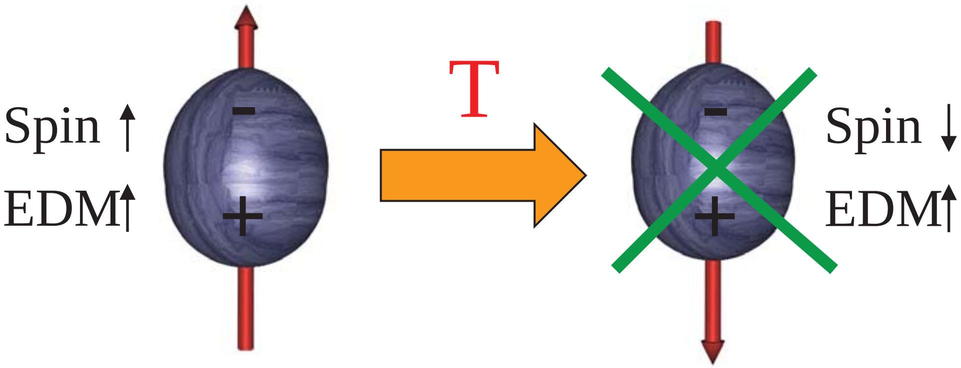
Our galaxy – 200 billion stars

Observable universe – 80 billion galaxies

EDMs, the Standard Model and beyond

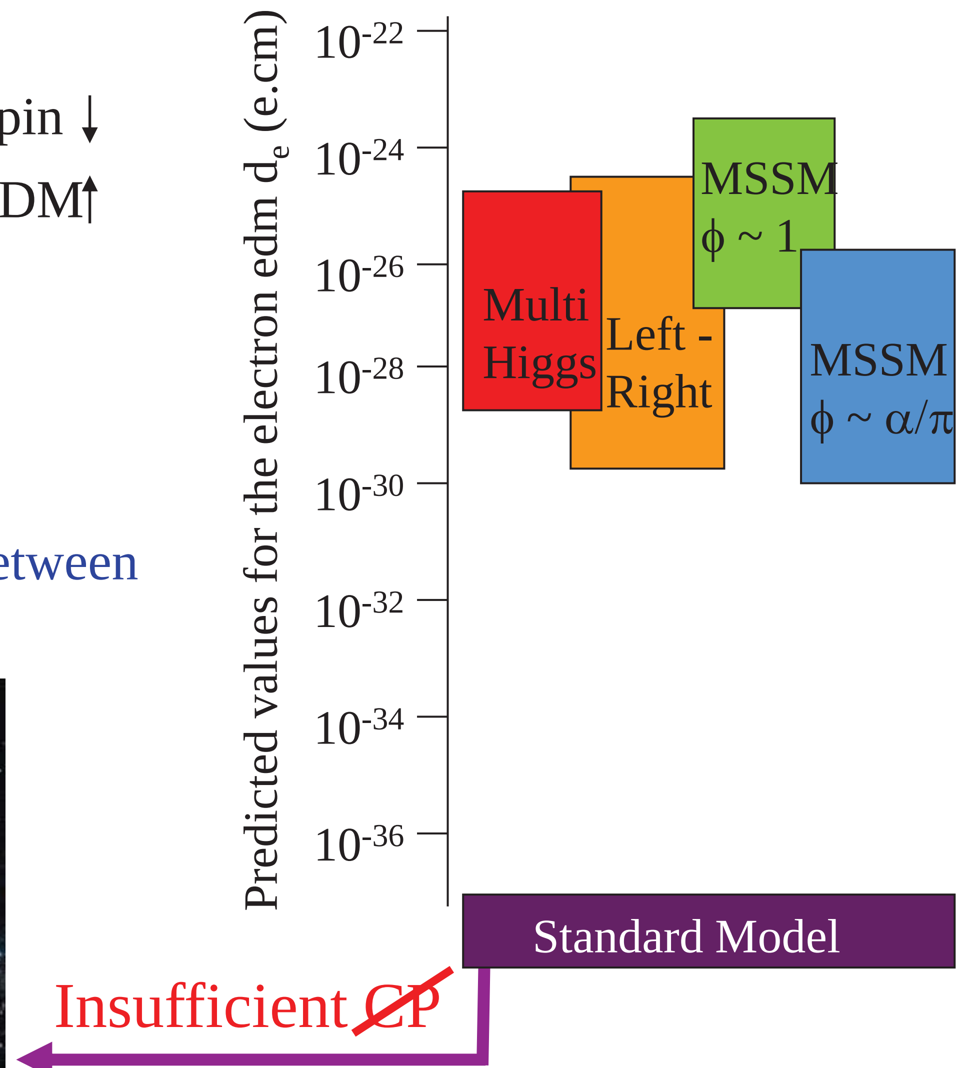


Summary of motivations for measuring EDMs

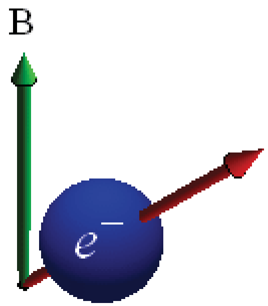


Either $d_e = 0$, or ~~T~~

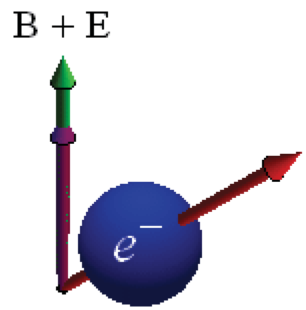
A non-zero EDM breaks the symmetry between matter and antimatter (CP symmetry)



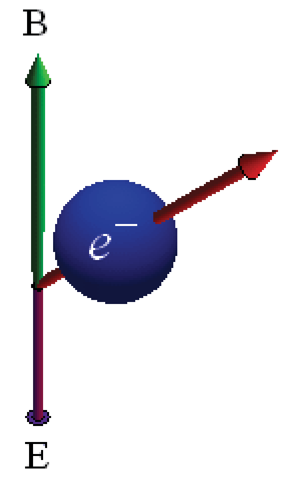
How to measure EDMs – spin precession



Particle precessing in a magnetic field



Particle precessing in parallel magnetic and electric fields – precession rate increases due to additional EDM interaction

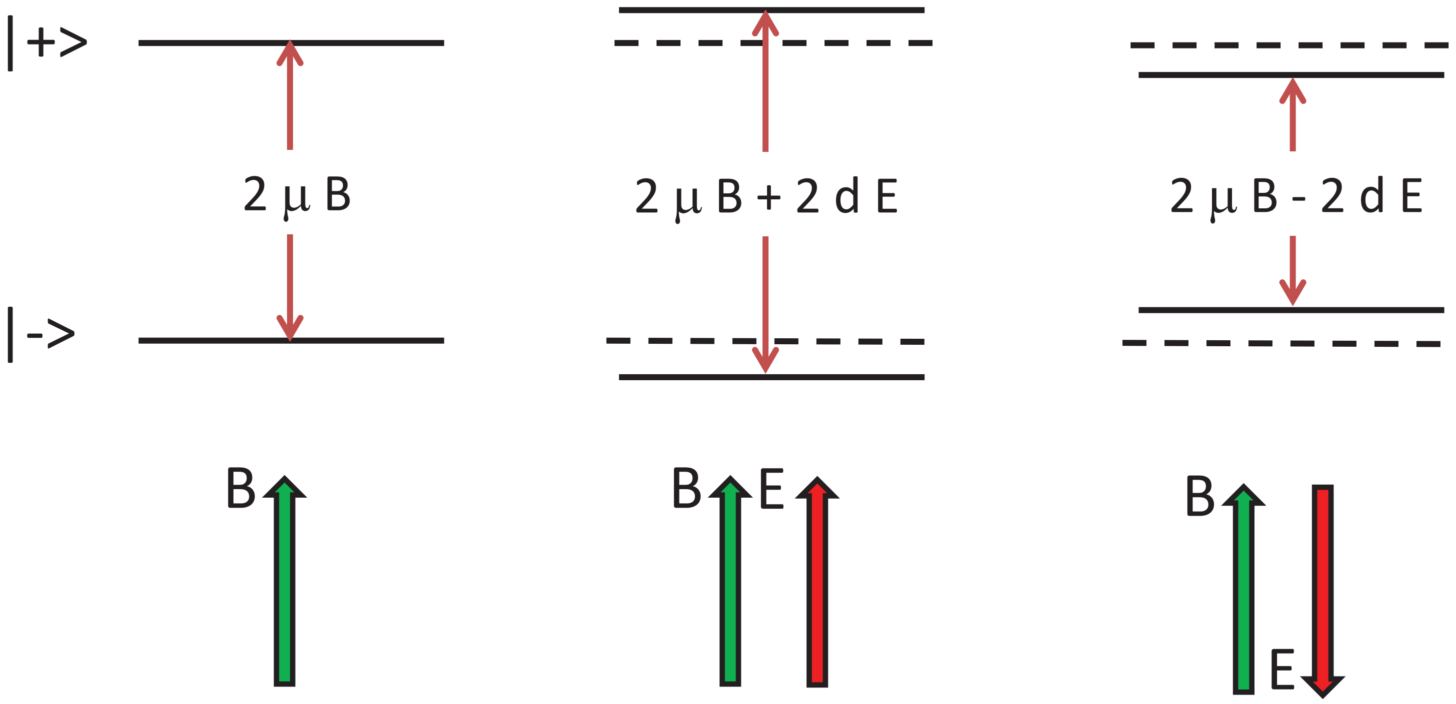


Particle precessing in anti-parallel magnetic and electric fields - precession rate decreases due to additional EDM interaction

Measure change in frequency when electric field direction is reversed – this determines the EDM

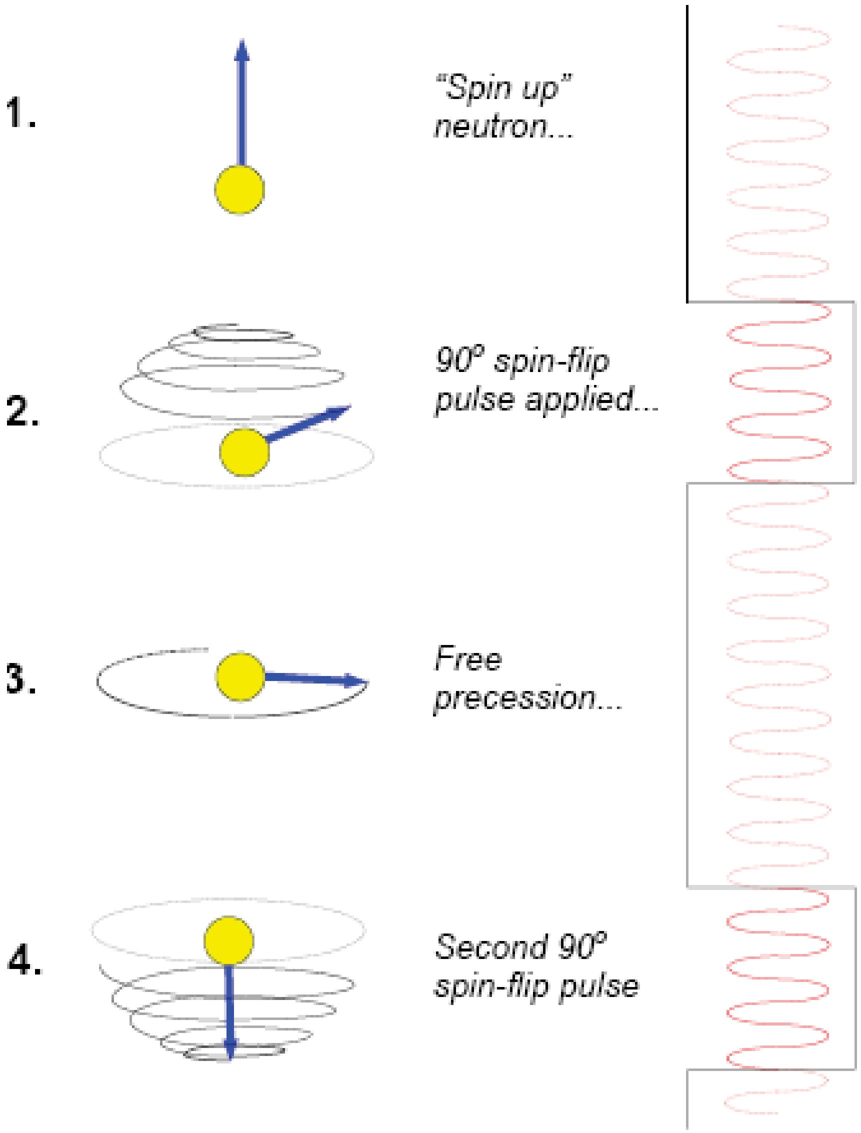
How to measure EDMs

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



Measure change in frequency when electric field direction is reversed – this is 4 d E – determines the EDM, d

Measuring precession frequency – the Ramsey method

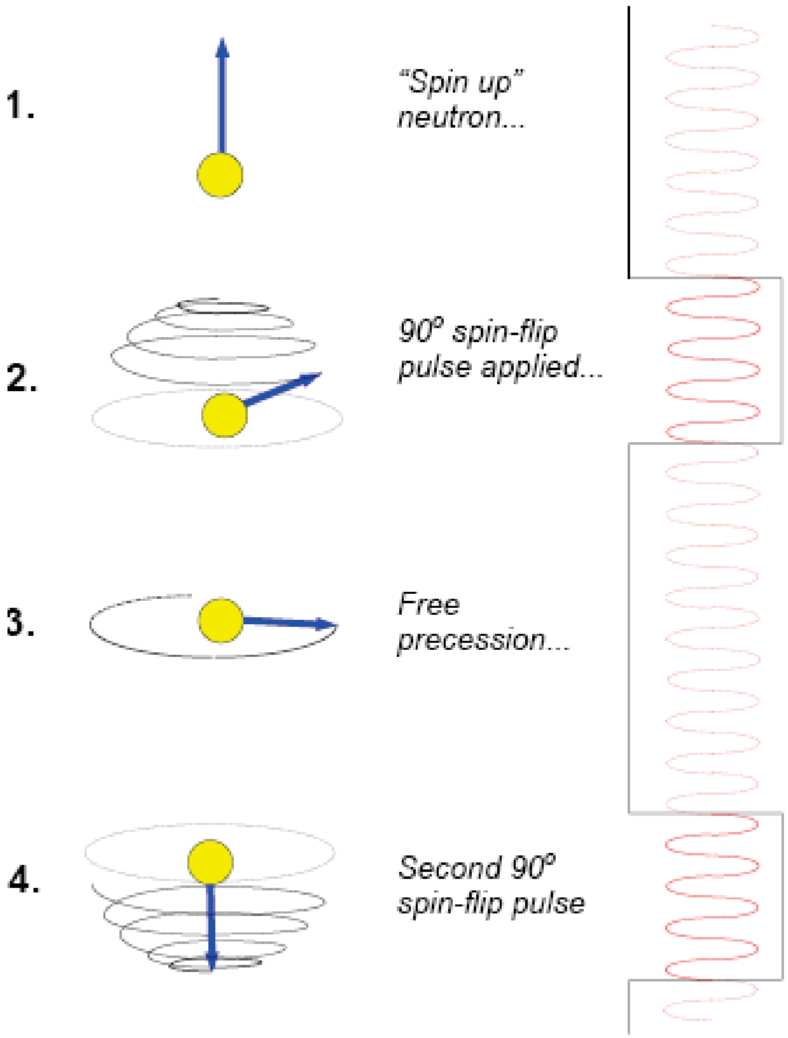


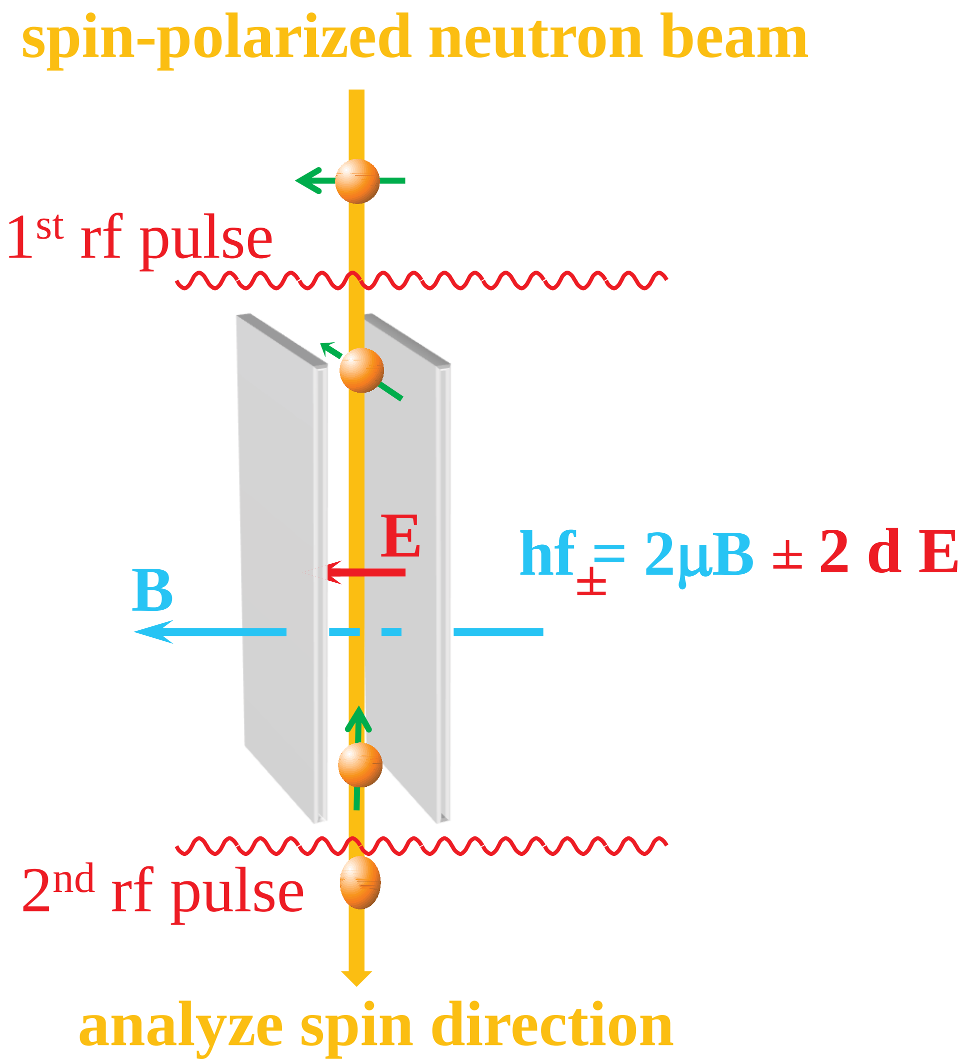
$$P_{-} = \cos^2\left[\frac{1}{2}\left(\omega_{rf} - \omega_0\right) T\right]$$

$$\omega_0 = 2\left(\mu B \pm d E\right) / \hbar$$

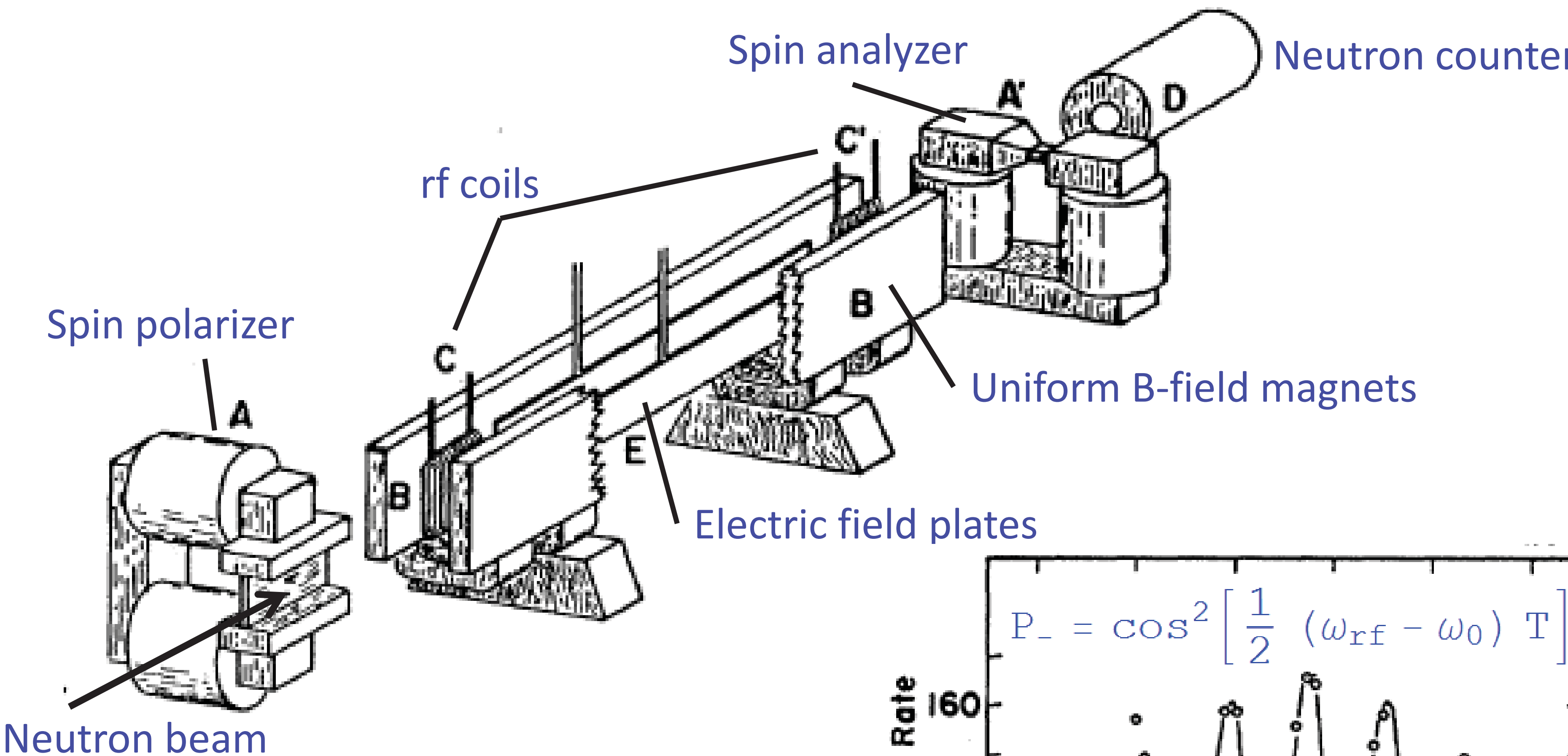
P. Harris, arXiv:0709.3100v3

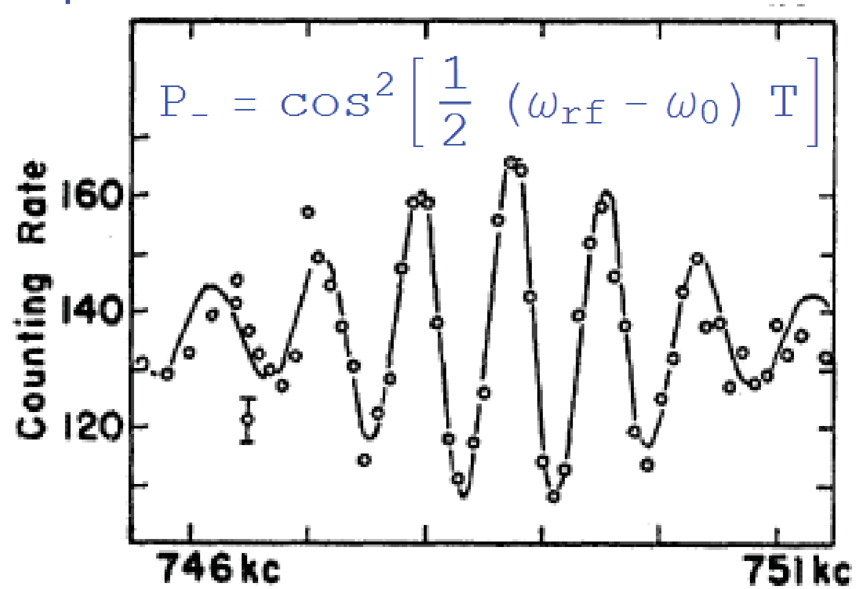
Measuring the neutron EDM using a neutron beam





First EDM measurement





$|d_n| < 5 \times 10^{-20}$ e.cm

J.H. Smith, E.M. Purcell and N.F. Ramsey, Phys. Rev. **108**, 120 (1957)

How to make better measurements

Measure the period of a pendulum by three different methods:

(1) Measure time for 1 swing

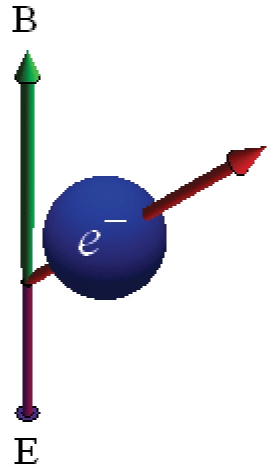
(2) Measure time for 1 swing; repeat 100 times

(3) Measure time for 100 swings

Method (2) is 10 times more precise than method (1)

Method (3) is 100 times more precise than method (1)

Let it precess for longer!



How to make a sensitive EDM measurement

The statistical uncertainty scales as: $$\frac{1}{\sqrt{N}} \times \frac{1}{T} \times \frac{1}{E}$$

Total number of participating particles

Spin-precession time

Electric field

(1) Make N as big as possible (but note square-root scaling)

(2) Make T as big as possible

(3) Make E as big as possible (but there are limits!)

But note well – you will only reach the statistical noise limit if you also:

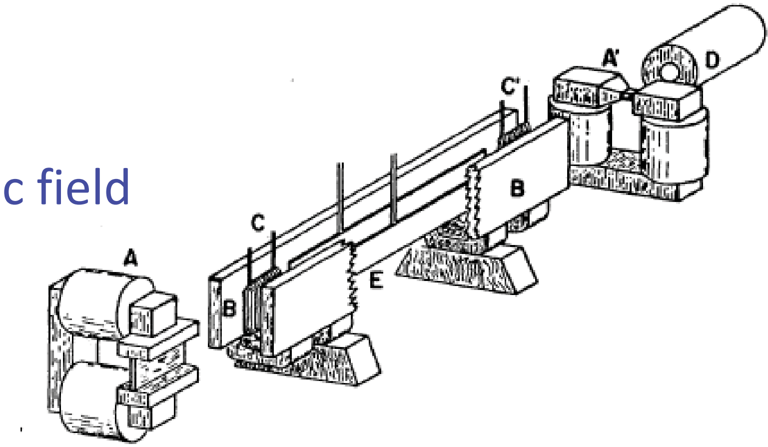
(4) Eliminate excess noise (particularly magnetic noise) – more on this later

(5) Eliminate systematic effects that mimic the EDM – more on this later

Problems with beam experiments

(1) T is limited by the length and speed to a few ms

(2) Huge systematic effect due to motional magnetic field



Motional magnetic field: $\boldsymbol{B}_{\mathrm{mot}} = -\frac{1}{c^2}(\boldsymbol{v} \times \boldsymbol{E})$

$-\boldsymbol{\mu}.\boldsymbol{B}_{\mathrm{mot}}$ is an energy shift that changes sign when E is reversed

If the applied E and B fields are not perfectly parallel (and they never are), this appears as a false EDM.

From beams to bottles

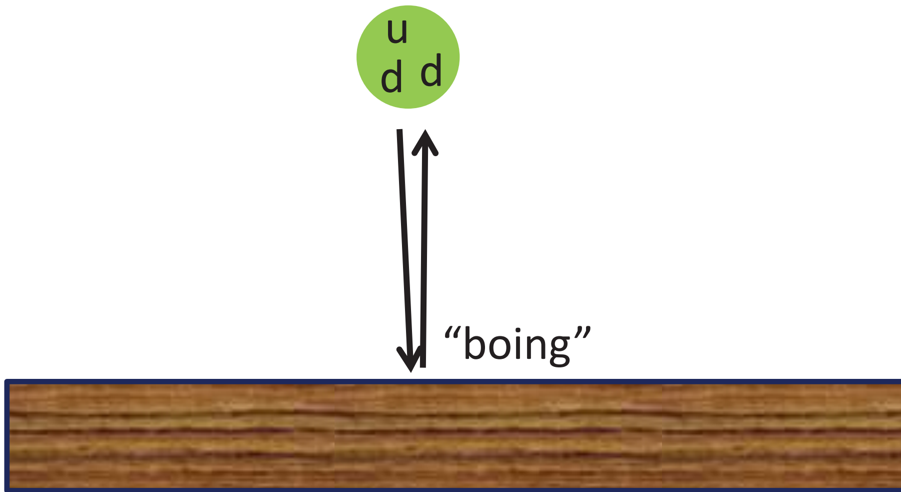
Slow neutrons bounce off walls!

There's a material-specific critical velocity, v_c (e.g. ~7m/s for Ni, Be, BeO)

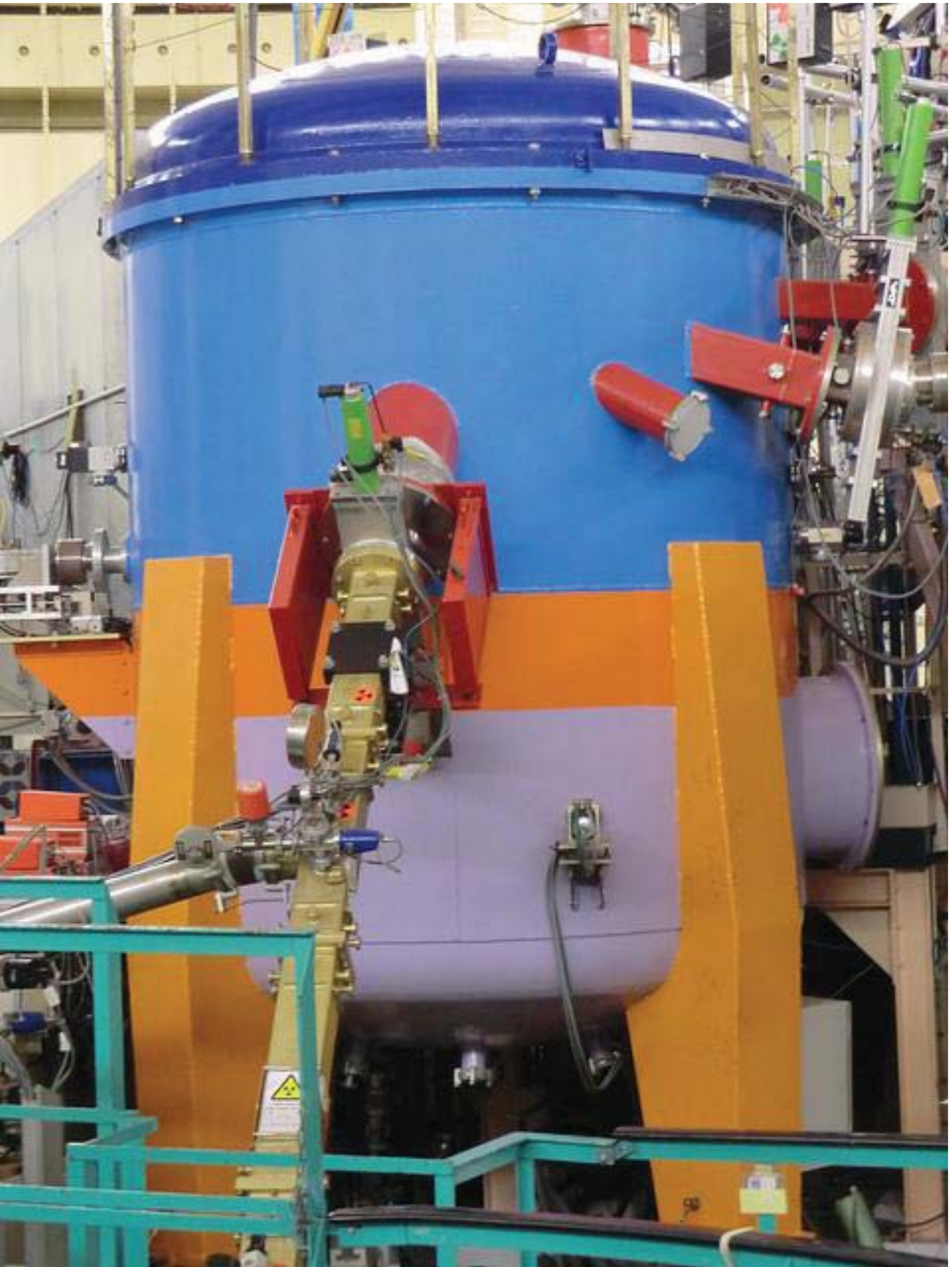
Neutrons with $v < v_c$ are called ultracold neutrons (UCN) – they reflect elastically under any angle of incidence

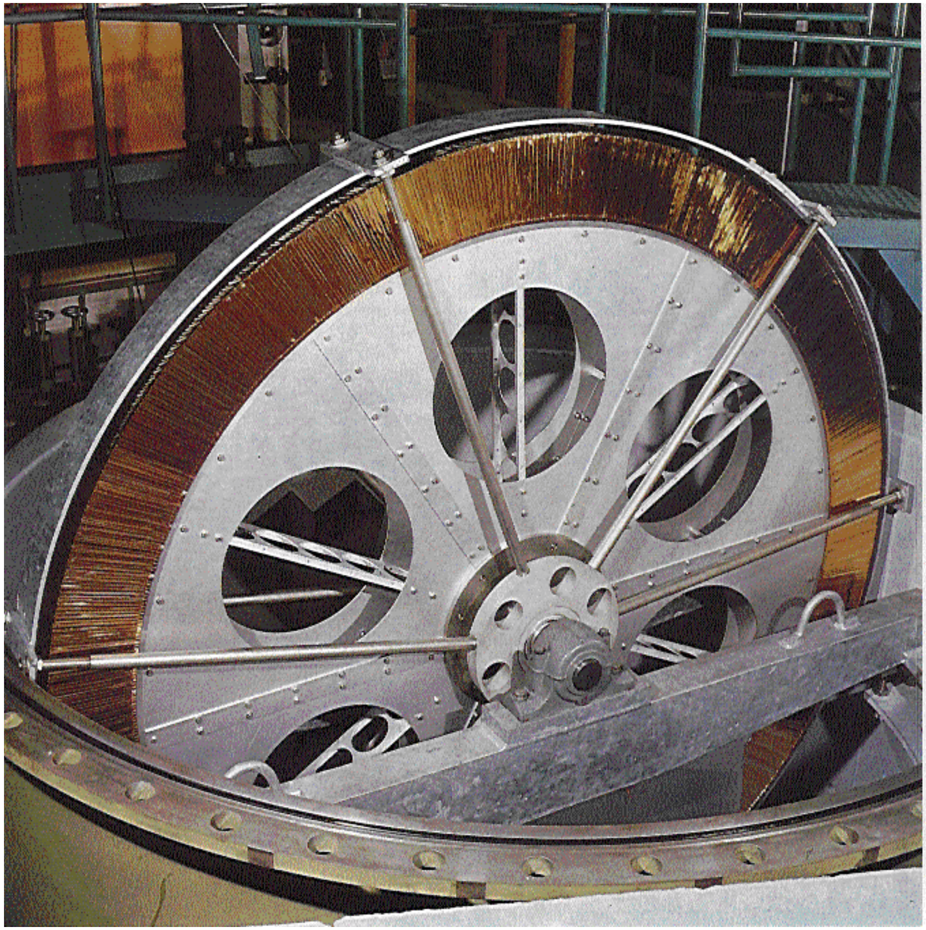
Temperature < 2 mK

Using bottled neutrons the spin precession time T can be very long, ultimately limited by the neutron lifetime (about 15 minutes).



Generating ultracold neutrons – neutron turbine





A. Steyerl et al., Phys. Lett. A 116 (1986) 347

Measuring the neutron EDM with bottled neutrons

Procedure used in latest Sussex \ RAL \ ILL experiment:

(1) Fill bottle with spin-polarized ultra-cold neutrons (20s)

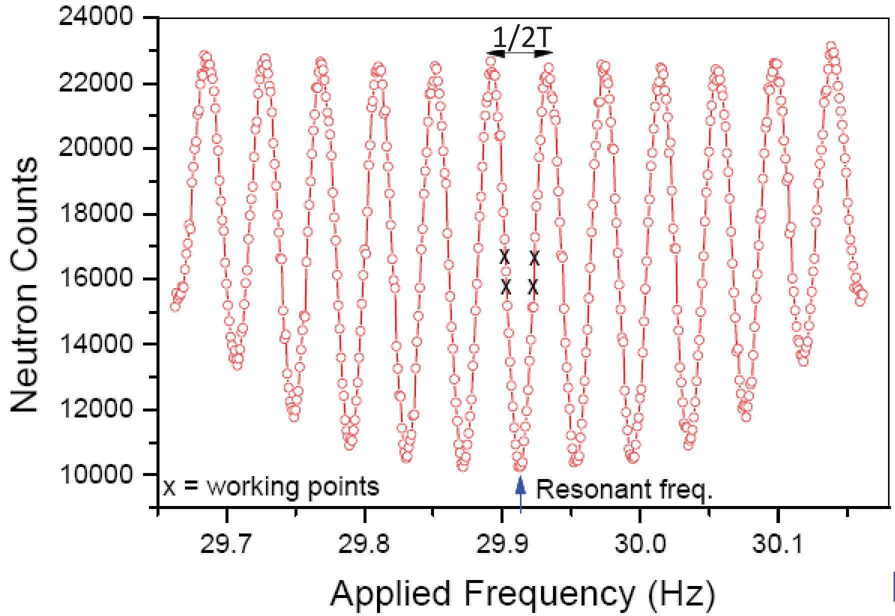
(2) Use rf field at Larmor frequency to rotate spins perpendicular to E and B (2s)

(3) Free precession in parallel \ antiparallel E (10kV/cm) and B (1 μT) for 130s

(4) Second pulse of rf coherent with the first (2s)

(5) Open trap door and measure how many neutrons have spin-up and spin-down

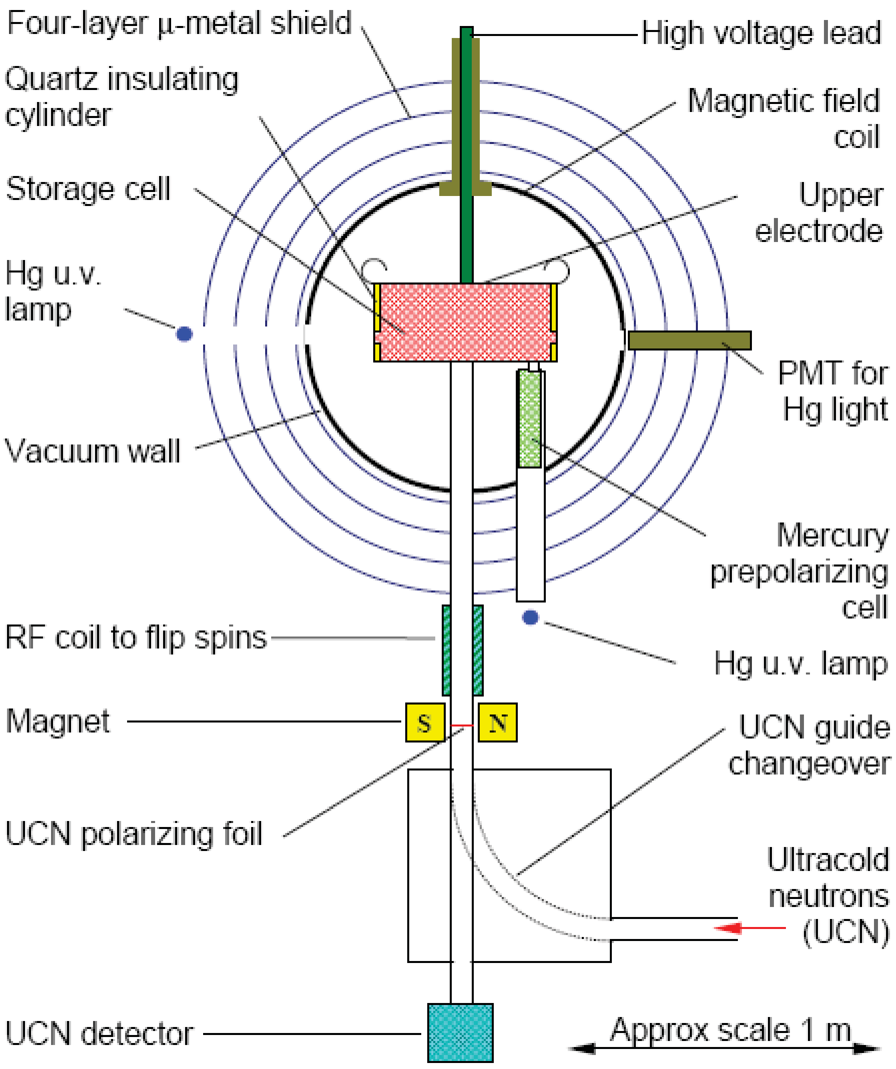
(6) Reverse E and do it again....and again, and again, and again, and again, and again...

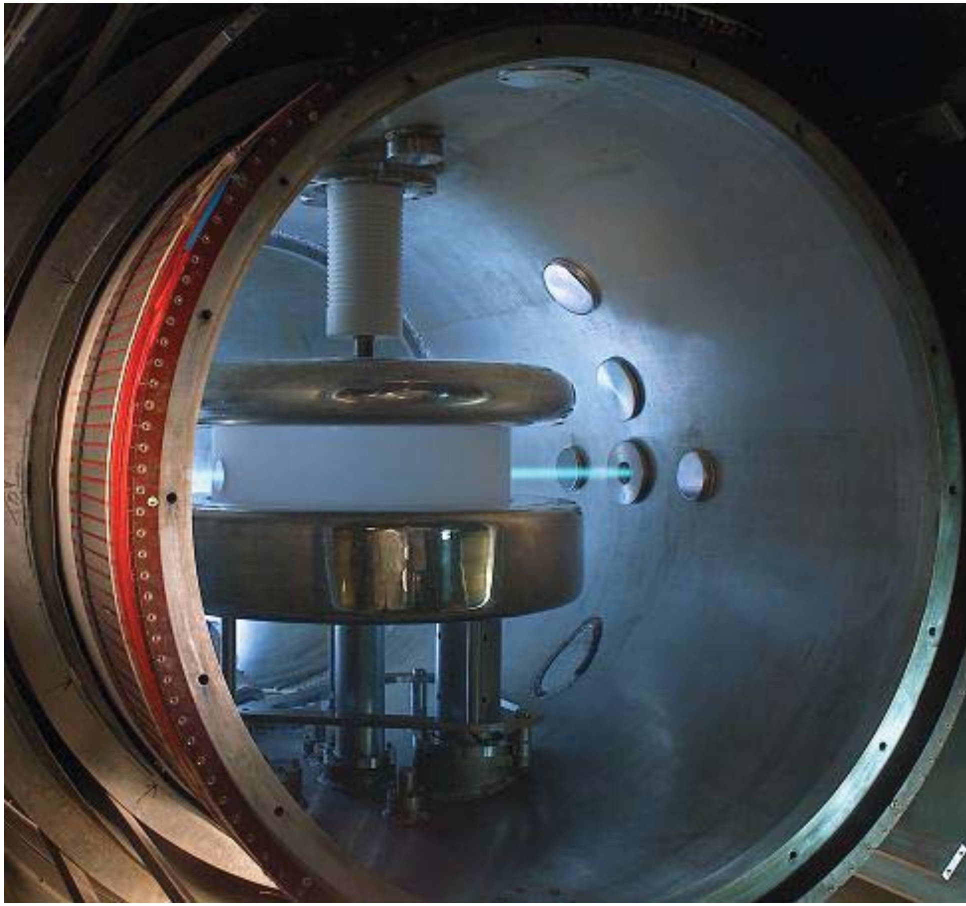


B = 1 μT
T = 10 s

Nucl. Instr. Meth. A 404, 381 (1998)

Measuring the neutron EDM with bottled neutrons

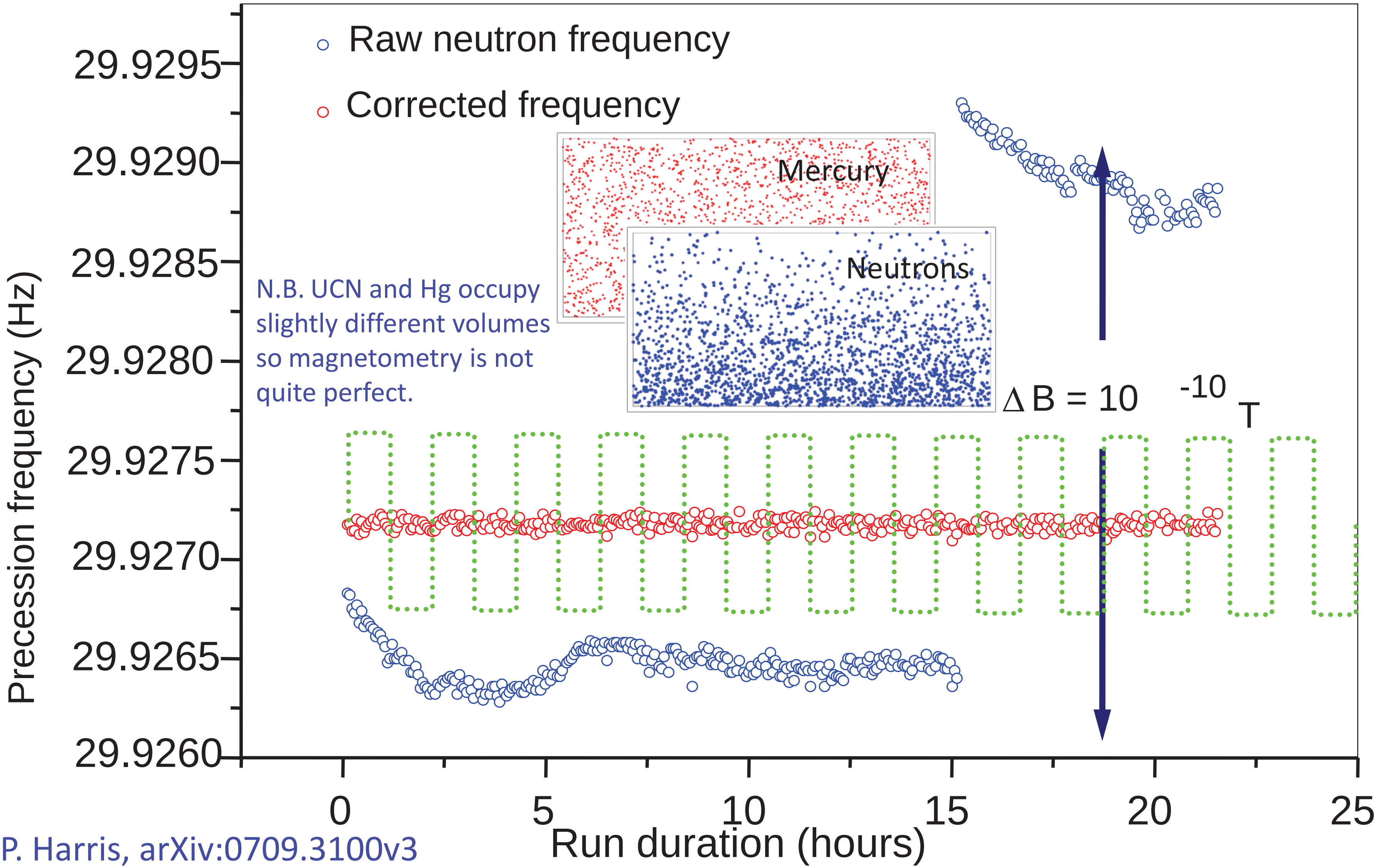




P. Harris, arXiv:0709.3100v3

Good magnetometry is essential

Use spin precession of mercury atoms co-habiting in the bottle to determine the magnetic field and correct the neutron precession frequency



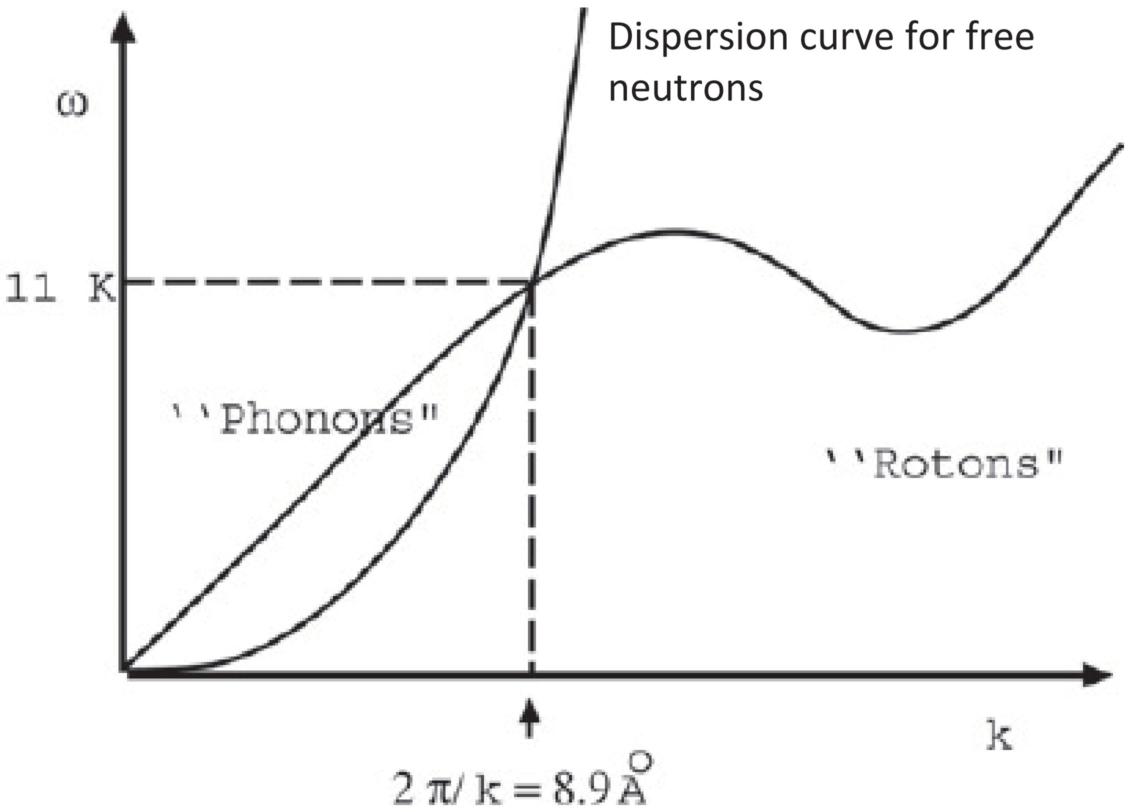
P. Harris, arXiv:0709.3100v3

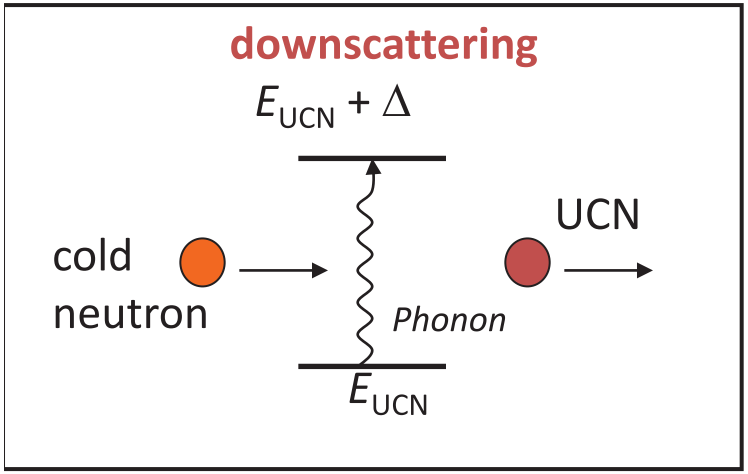
Some systematic effects

- Magnetic fields correlated with E-reversal
- Motional magnetic field, **v x E**
- Geometric phase

Future directions for neutron EDM experiments

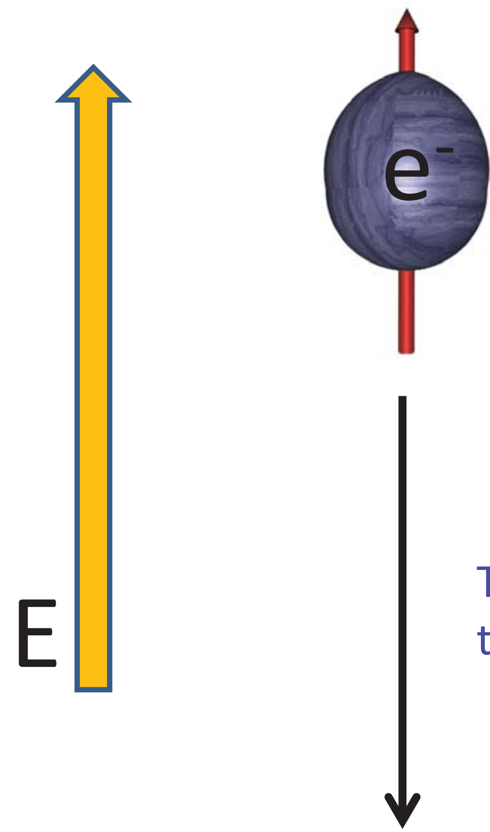
- More neutrons (superfluid helium)
- Longer precession time
- Larger electric field





R. Golub and J.M. Pendlebury, Phys. Lett. **53A** (1975), Phys. Lett. **62A** (1977)

Measuring the electron EDM – an obvious problem!

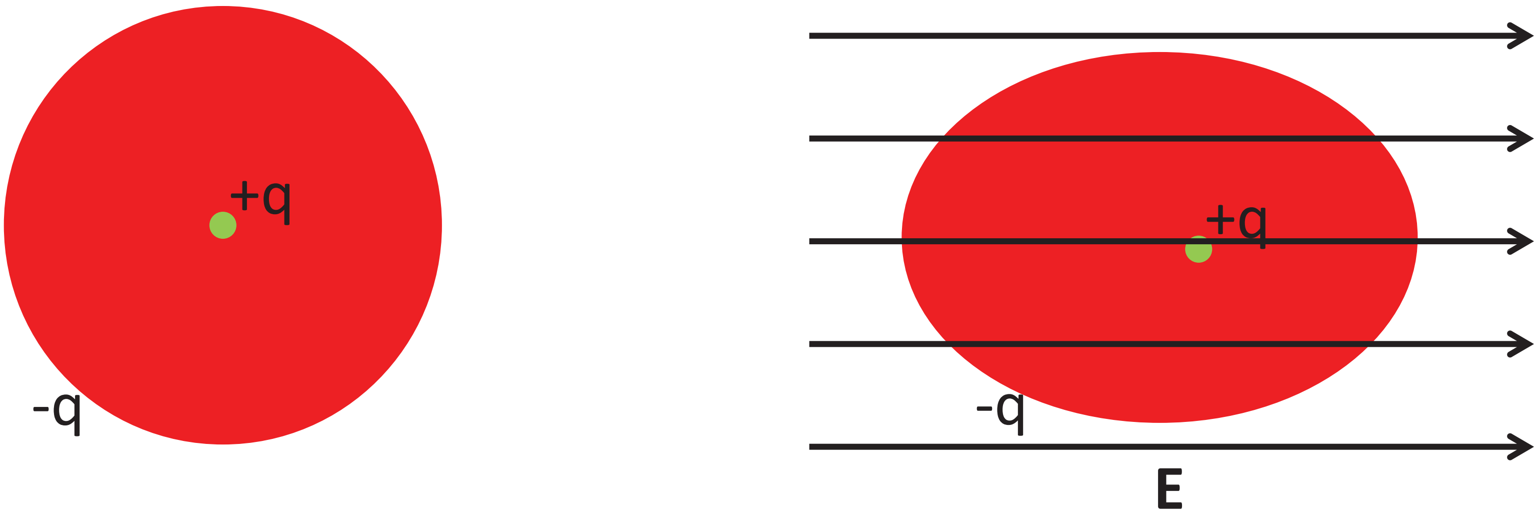


The electron accelerates away as soon as the electric field is applied

Solution: use a neutral system – an atom or a molecule

Schiff theorem

When an electric field is applied to a system of non-relativistic point charges held together by electrostatic forces, the charges re-arrange so that the net electric field at every charge is zero



The EDM interaction energy will be zero even if the EDM of the constituents is non-zero!

Screening of the EDM

Evasion of the Schiff theorem

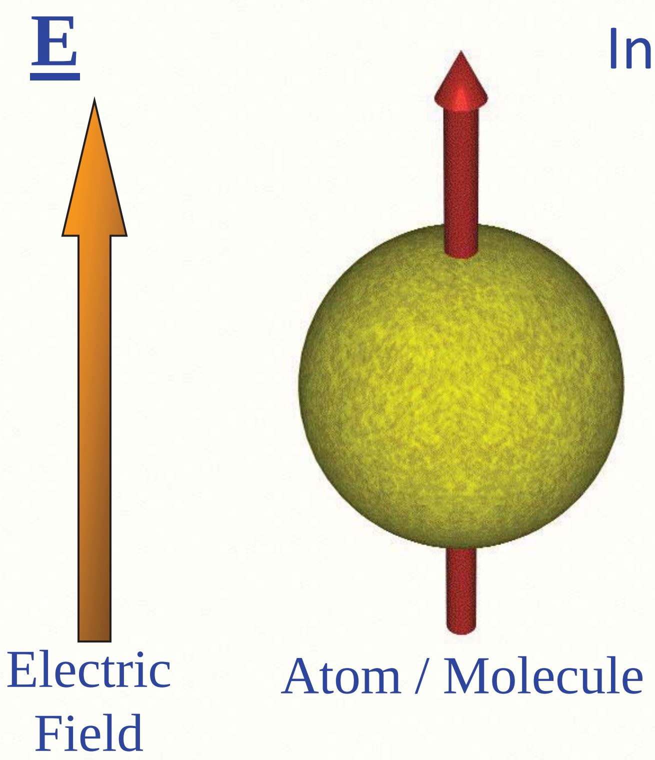
The theorem applies to non-relativistic point particles held together only by electrostatic forces.

The electrons are relativistic, particularly for heavy atoms and molecules, so the screening is incomplete – in fact the electron EDM is not 'screened' but enhanced!

The nucleons are not point particles and are not held together only by electrostatic forces. So the screening is incomplete for the nucleons too.

Using atoms & molecules to measure d_e

For a free electron in an applied field $\underline{\mathbf{E}}$, expect an interaction energy $-\underline{\mathbf{d}}_e.\underline{\mathbf{E}}$



Enhancement factor

Interaction energy = $- \underline{\mathbf{d}}_e \cdot \underline{\mathbf{E}}_{eff} = - \underline{\mathbf{d}}_e \cdot (\eta \underline{\mathbf{E}})$

$E_{eff} = F\ P$

Structure dependent, $\sim 10\ (Z/80)^3$ GV/cm

Polarization factor

For more details, see E. A. Hinds, Physica Scripta T70, 34 (1997)

Enhancement factors for some atoms

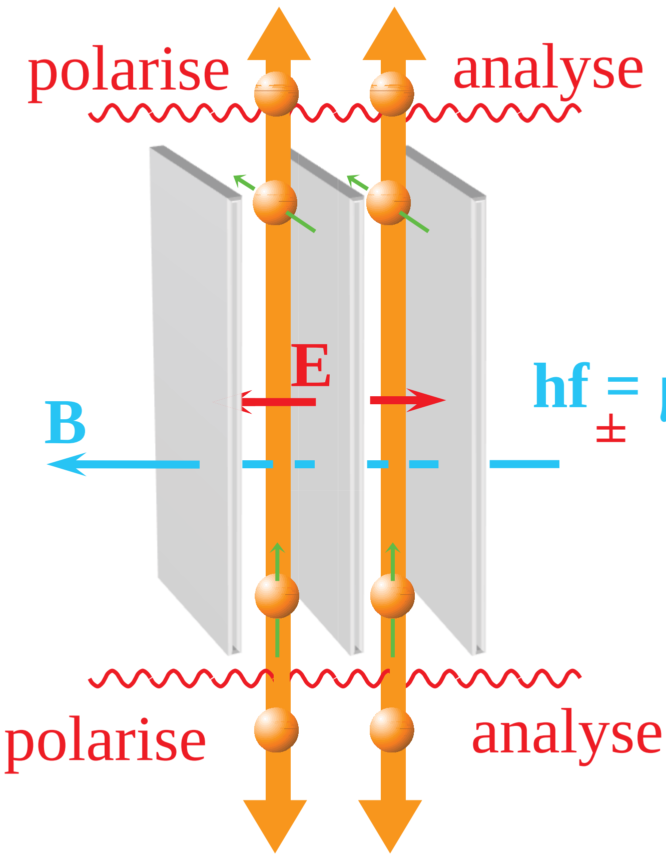
Enhancement factor, $\eta = d_{atom} / d_{electron}$

Atom	Z	State	Enhancement factor	Experiments
Li	3	$2\ ^2S_{1/2}$	0.0043	
Na	11	$3\ ^2S_{1/2}$	0.32	
K	19	$4\ ^2S_{1/2}$	2.4	
Rb	37	$5\ ^2S_{1/2}$	25	
Cs	55	$6\ ^2S_{1/2}$	115	Early experiments. New experiments being developed with ultracold Cs (Texas & Penn State)
Fr	87	$7\ ^2S_{1/2}$	1150	Radioactive. Experiment with ultracold ^{210}Fr being developed at RCNP, Osaka and TRIUMF, Vancouver
Tl	81	$6\ ^2P_{1/2}$	-585	Long-running experiment – world-leading results for two decades. Now completed.

The Tl EDM experiment

B.C. Regan, E.D. Commins, C.J. Schmidt and D. DeMille, PRL **88**, 071805 (2002)

Tl – enhancement factor η = -585



$hf = \mu B \pm d\eta E$
±

4 Tl atomic beams
+ 4 Na atomic beams

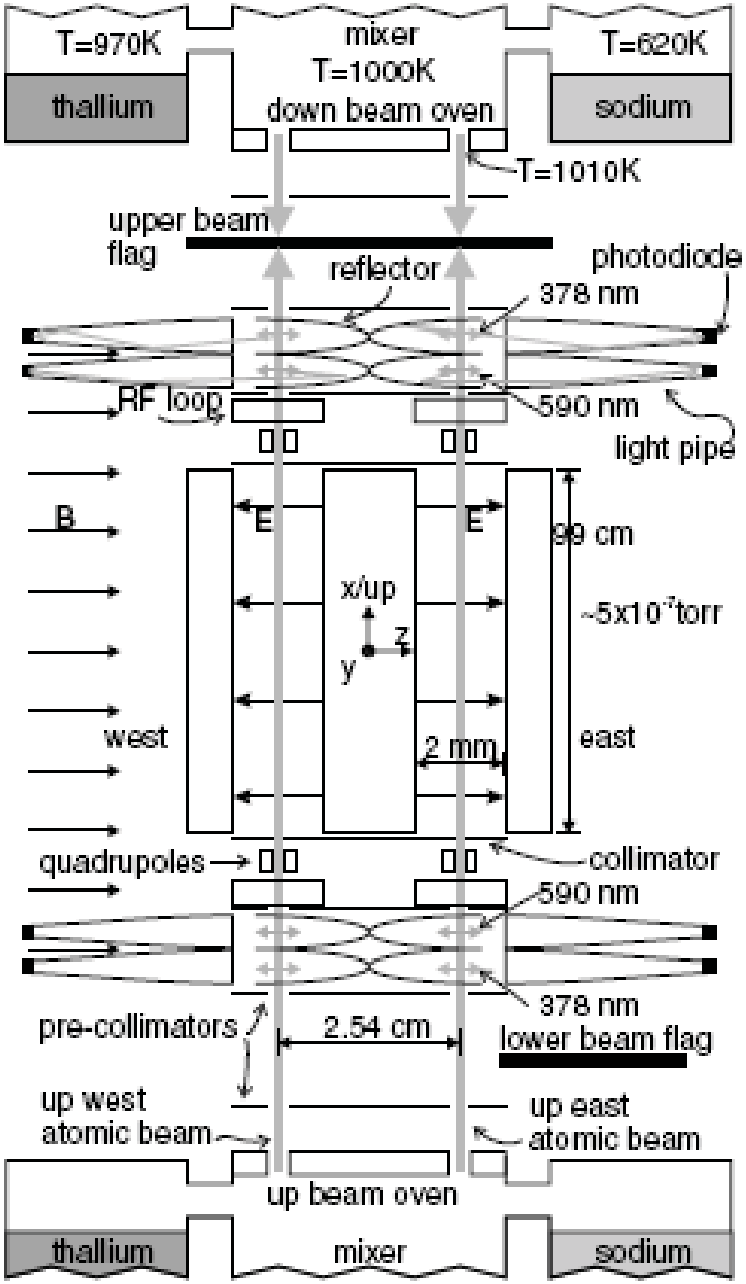
1st problem:
motional interaction $\mu \cdot \mathbf{v} \times \mathbf{E} / c^2$

The solution:
add 2 more Tl beams going down

2nd problem:
stray static magnetic fields

The solution:
Add 4 Na beams for magnetometry

The Tl EDM experiment



$E = 123$ kV/cm

$E_{eff} = 72$ MV/cm

$T_{coherence} = 2.3$ms

Final result (2002)

$|d_e| < 1.6 \times 10^{-27}$ e.cm (90% CL)

B.C. Regan, E.D. Commins, C.J. Schmidt & D. DeMille, Phys. Rev. Lett. **88** , 071805(2002)

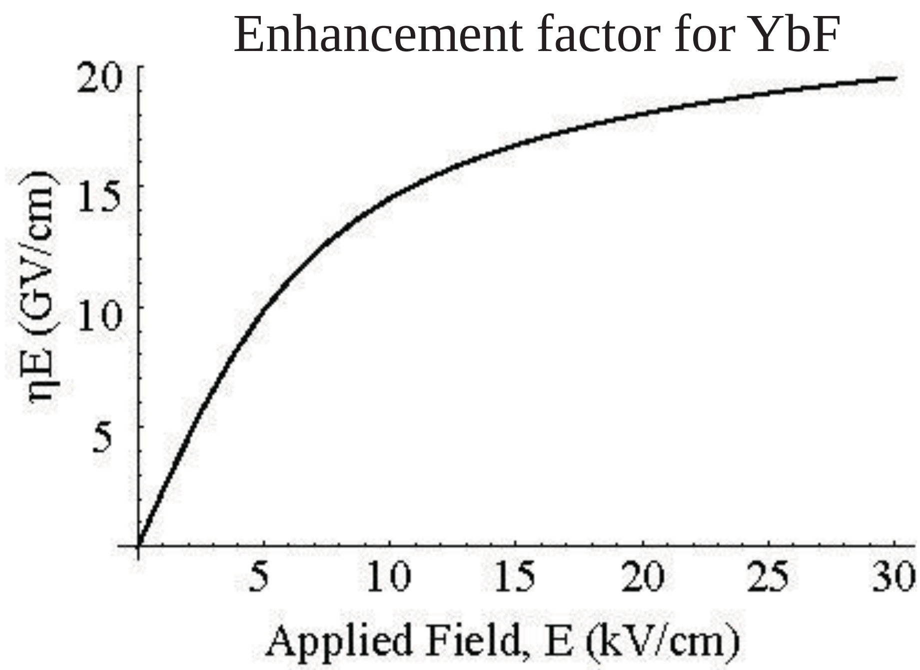
From atoms to molecules

$E_{eff} = F\, P$

Structure dependent, ~ 10 (Z/80)^3 GV/cm

Polarization factor

For atoms, P ~ 10^{-3}
For molecules, P ~ 1



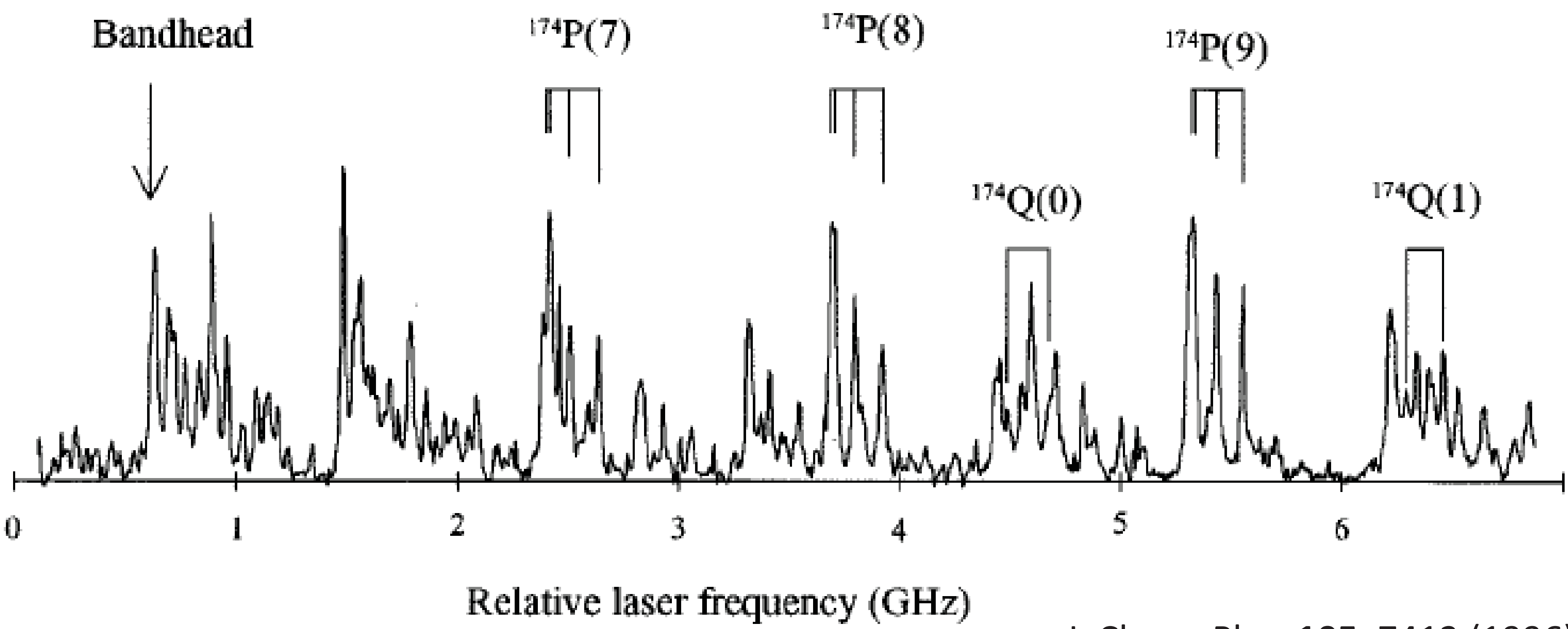
- "Huge" edm interaction energy (10aeV, 2mHz, 80f cm^{-1}, 100 fK)
- Less demanding magnetic field control (d_{false}= 3x10^{-27} e.cm/pT)
- Insensitive to B perpendicular to E (suppressed by 10^{10})
- Thus, insensitive to motional-B ($B_{mot} = -\mathbf{v} \times \mathbf{E} / c^2 = 10^4$ pT)

For more details, see PRL 89, 023003 (2003)

With molecules, there’s a price to pay

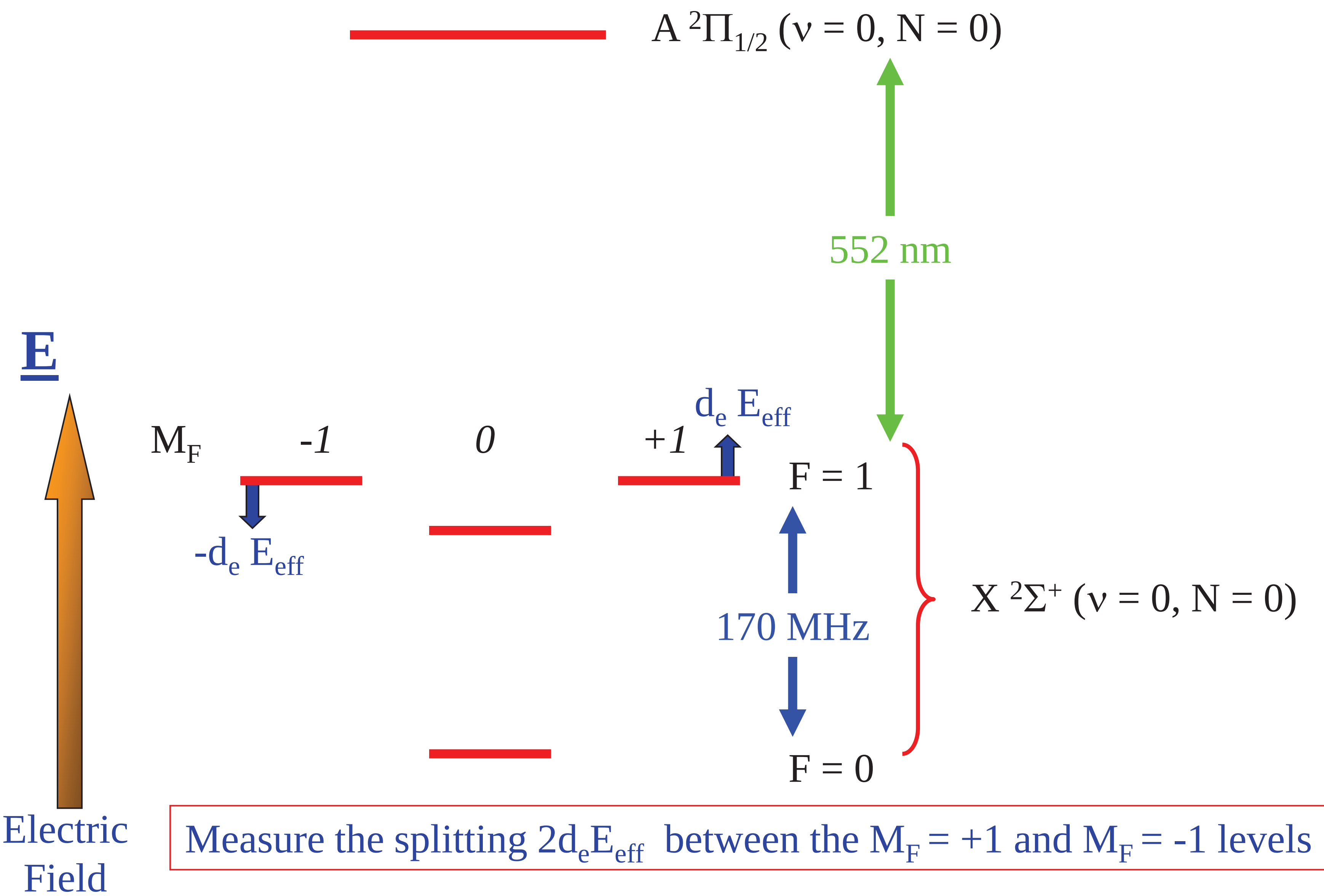
- Molecules are far more difficult to produce and detect than atoms
- They have a much more complicated structure \ spectrum
- Often not much is known – so you have to do a lot of preliminary spectroscopy

Sauer, Wang, and Hinds: Spectroscopy of ^{174}YbF



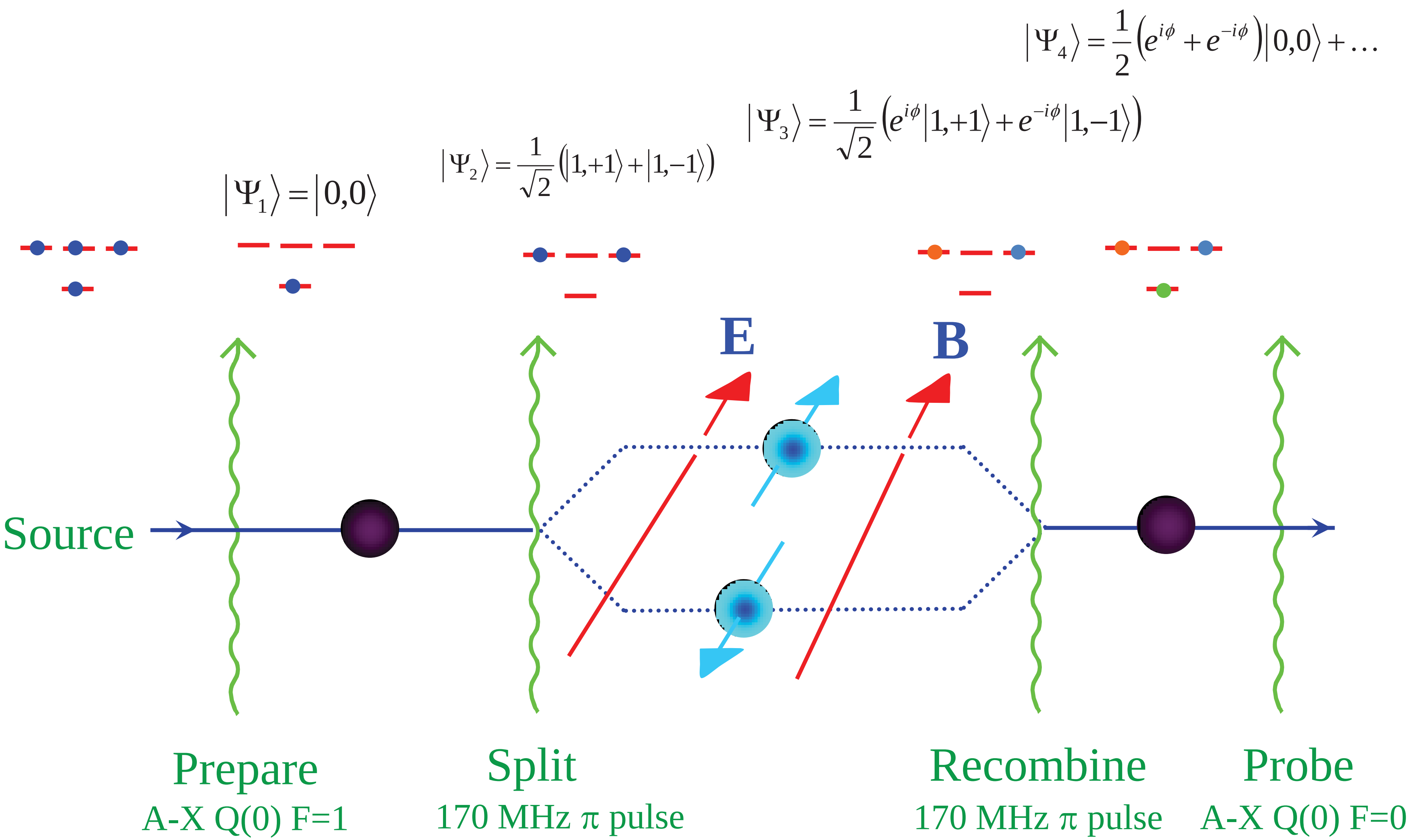
J. Chem. Phys **105**, 7412 (1996)

Relevant energy levels in the YbF molecule



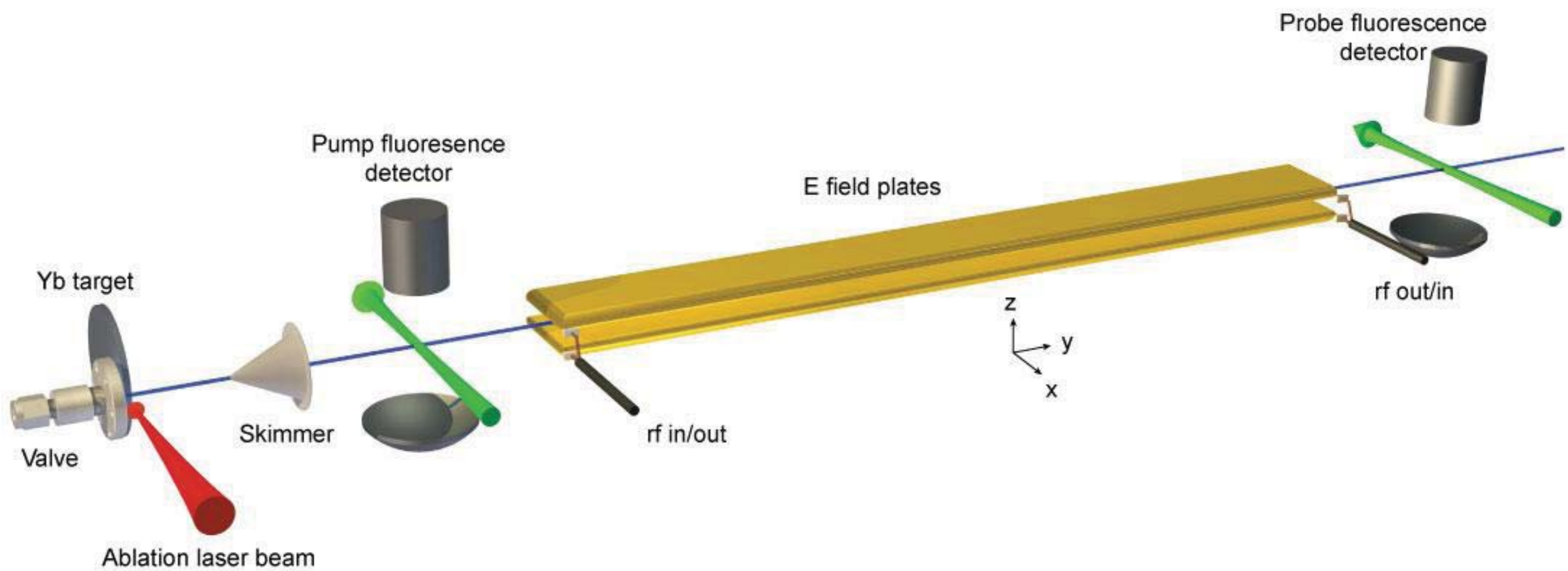
Measure the splitting $2d_eE_{eff}$ between the $M_F = +1$ and $M_F = -1$ levels

The YbF EDM experiment – measurement scheme



Phase difference, $\phi = 2\,(\mu_B B - d_e E_{eff})\,T / \hbar$

The YbF EDM experiment – schematic



J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt & E. A. Hinds, Nature **473**, 493 (2011)

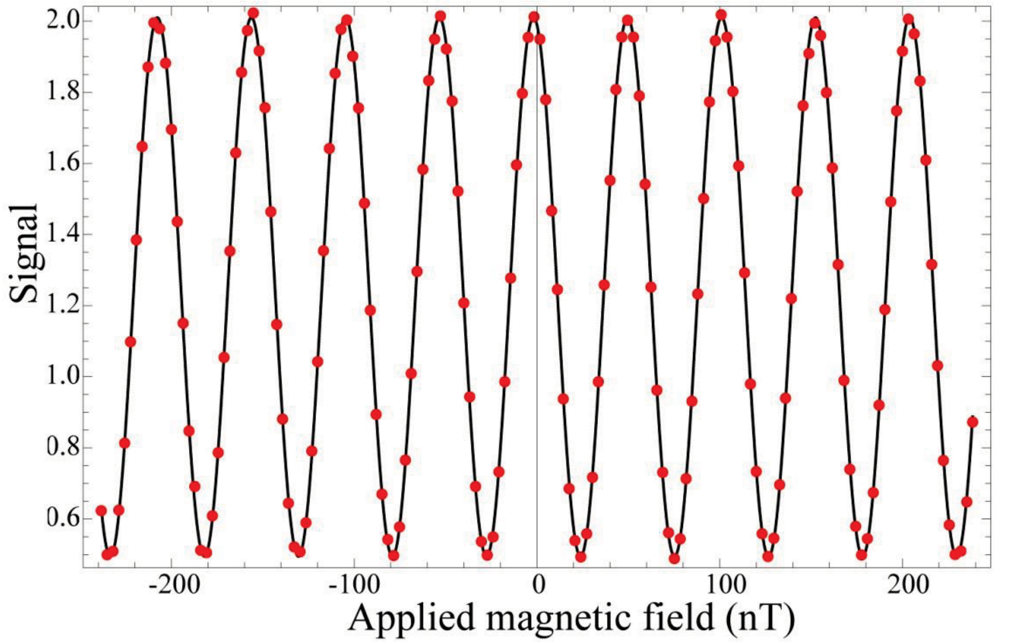
Measurement scheme continued

$$\left|\Psi_4\right\rangle = \frac{1}{2}\left(e^{i\phi} + e^{-i\phi}\right)\left|0,0\right\rangle + \ldots$$

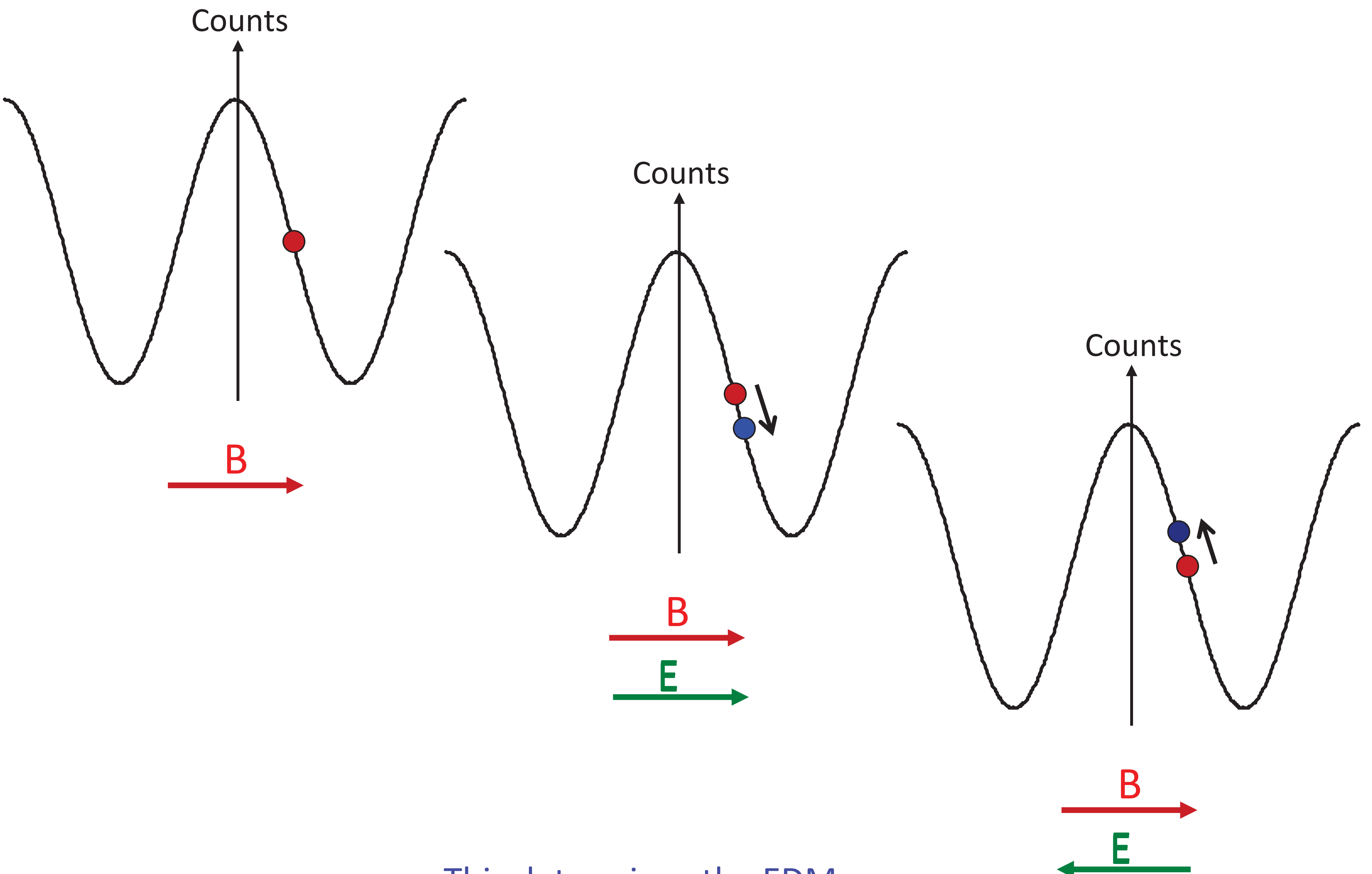
The signal is proportional to $\left|\left\langle 0,0 \middle| \Psi_4 \right\rangle\right|^2$

$$\text{Signal} \; \alpha \; \text{Cos}^2[\phi/2] = \text{Cos}^2\left[\frac{\mu_B B - \eta \, d_e E}{\hbar} T\right]$$

Measured F=0 population versus applied magnetic field

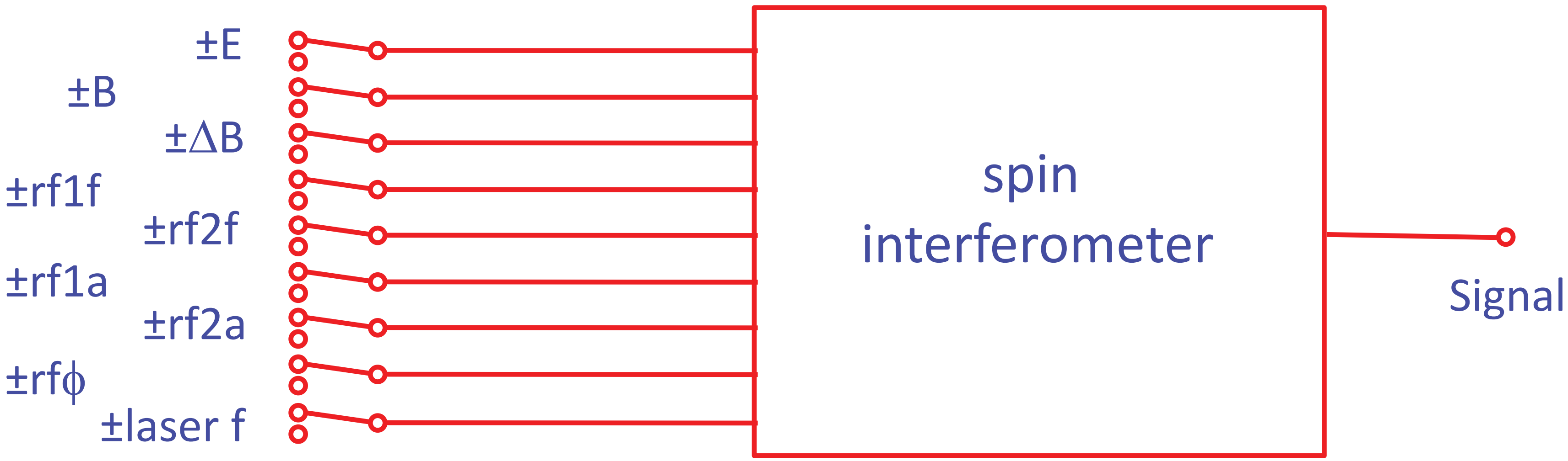


Measure the change in signal when E is reversed



This determines the EDM

Modulate everything



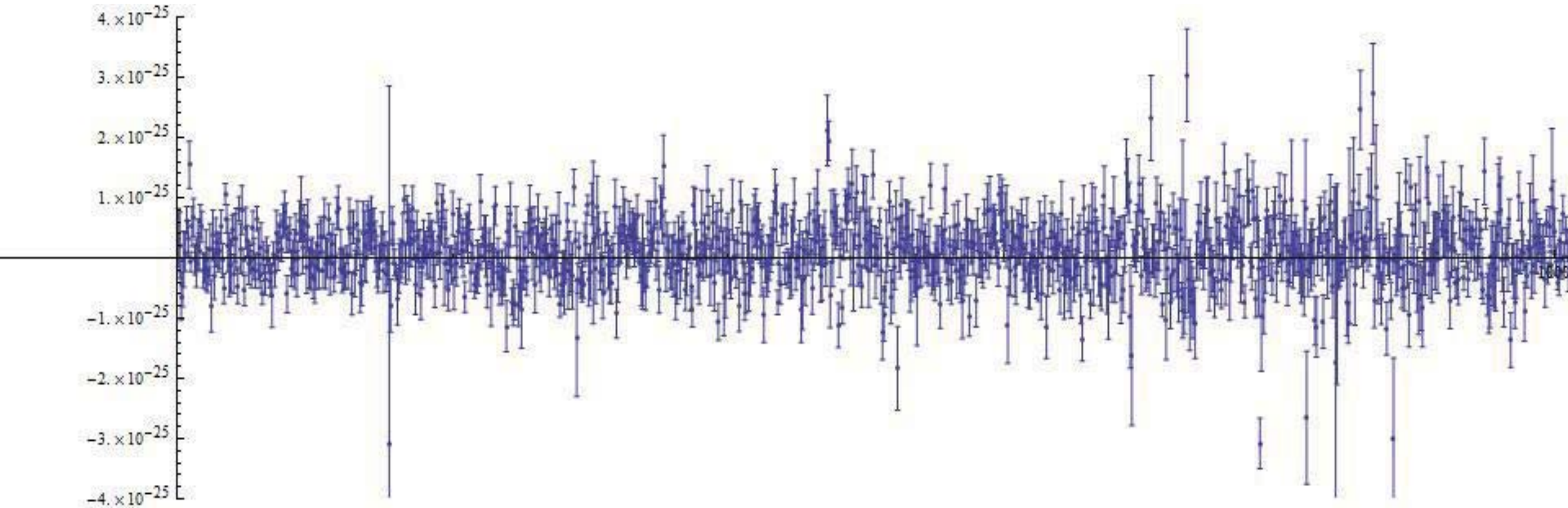
9 switches:

512 possible correlations

- The EDM is the signal correlated with the sign of E.B (N.B. Blind in the analysis)
- Study all the other 511 correlations in detail

Result (2011)

- 6194 measurements of the EDM, each derived from 4096 beam pulses
- Each measurement takes 6 minutes



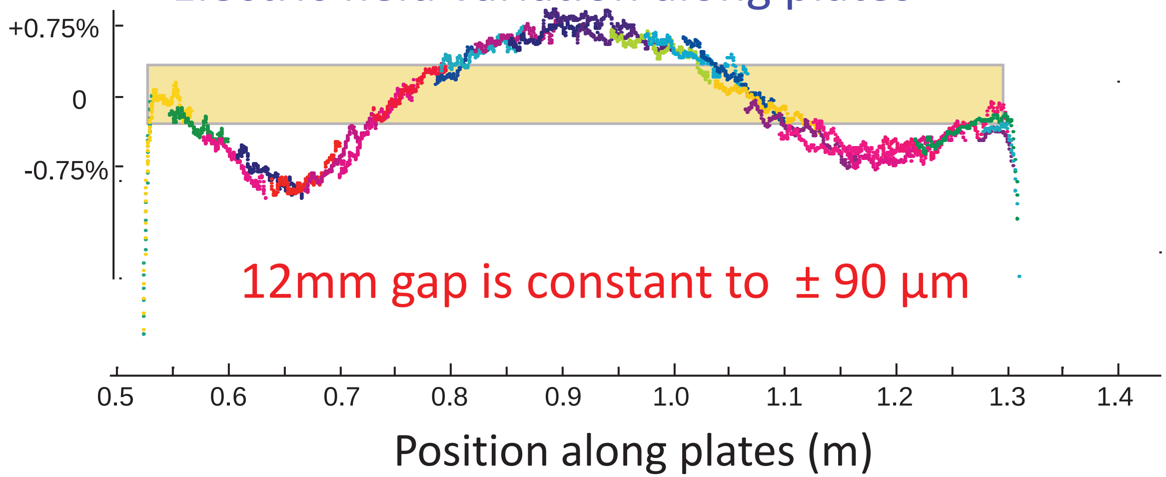
- $d_e = (-2.4 \pm 5.7_{stat} \pm 1.5_{syst}) \times 10^{-28}\ e.\text{cm}$
- $|d_e| < 10.5 \times 10^{-28}$ e.cm (90% confidence level)

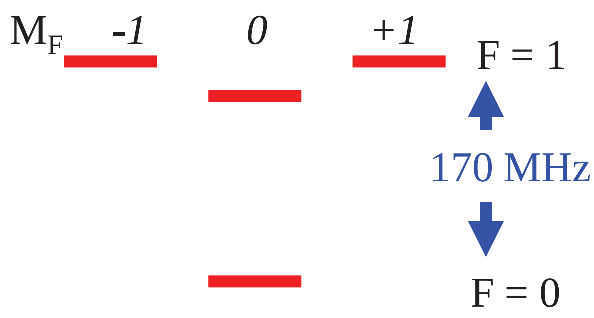
J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt & E. A. Hinds, Nature **473**, 493 (2011)

Controlling systematics...

➢ Use the molecules to make maps of the electric, magnetic and rf fields

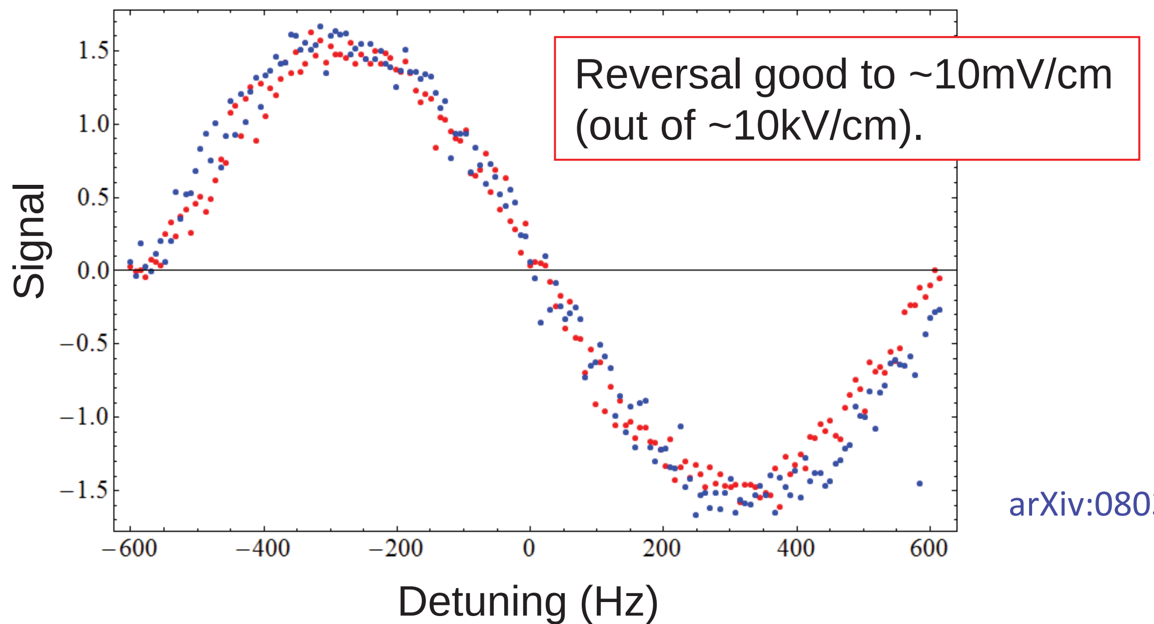
Electric field variation along plates





Phys. Rev. A **76**, 033410 (2007)

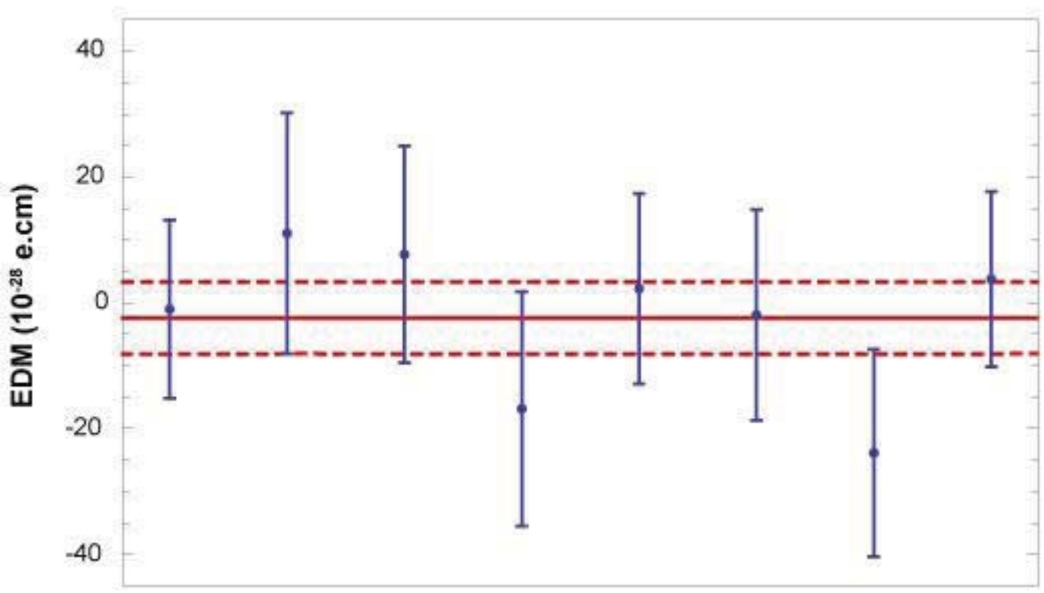
➢ Use the molecules to determine how well the electric field reverses



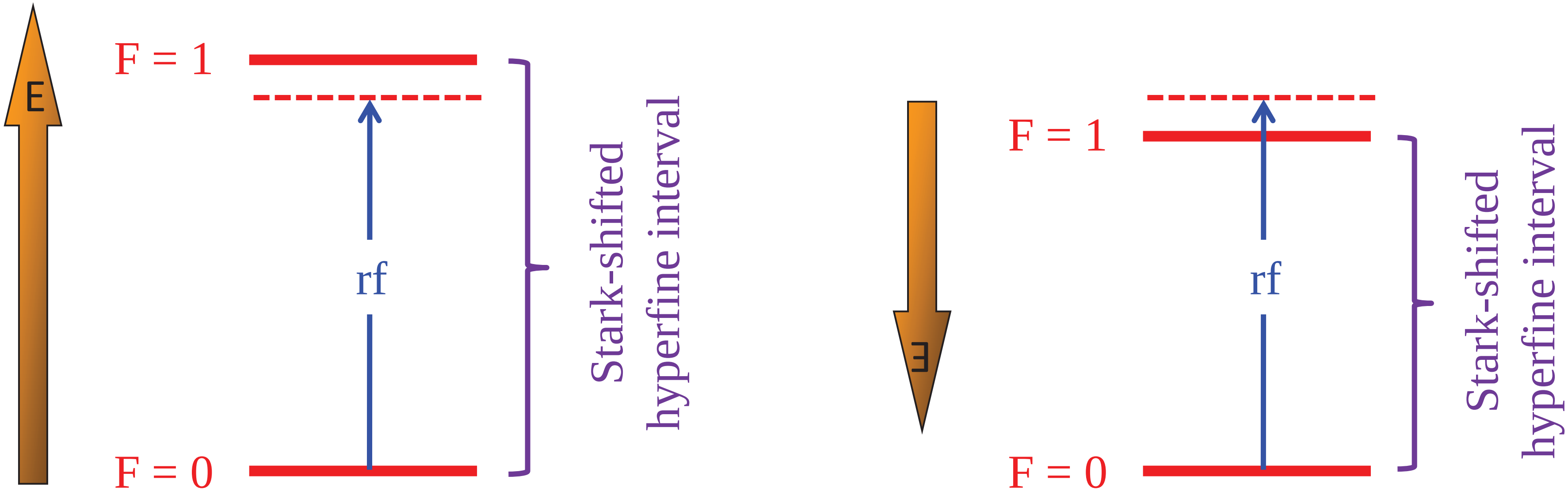
arXiv:0803.0967v2

Controlling systematics...

- Look for suspicious channels – ones that should be zero but are not
- Take data with imperfections deliberately emphasized (e.g. E asymmetry)
- Simultaneous data from pump PMT, 4 separate magnetometers, 2 leakage current monitors, a battery and a short-circuit.
- Divide molecular pulses into early-half and late-half. Check for consistency.
- Manual reversals of E-direction, B-direction and rf propagation direction



Correcting a systematic error



rf detuning → phase shift: ~100 nrad/Hz

Imperfect E-reversal → Changes detuning via Stark shift

→ Phase correlated with E-direction

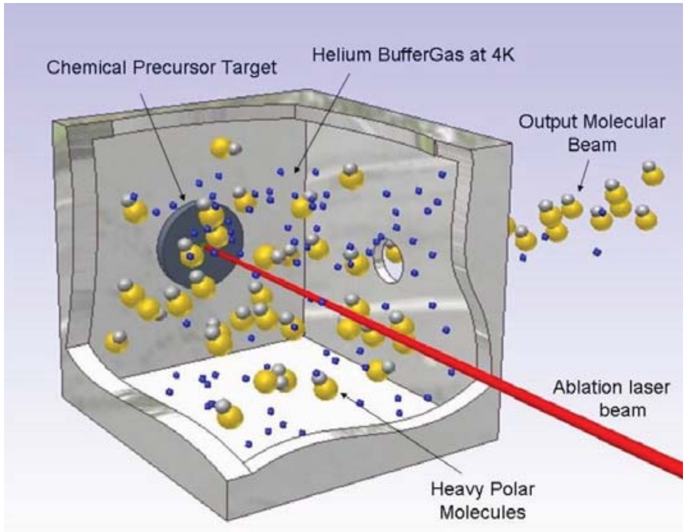
Correction to EDM: $(5.5 \pm 1.5) \times 10^{-28}\ e.\mathrm{cm}$

Systematic uncertainties

Effect	Systematic uncertainty (10^{-28} *e*.cm)
Electric field asymmetry	1.1
Electric potential asymmetry	0.1
Residual RF1 correlation	1.0
Geometric phase	0.03
Leakage currents	0.2
Shield magnetization	0.25
Motional magnetic field	0.0005

Some new methods for future experiments

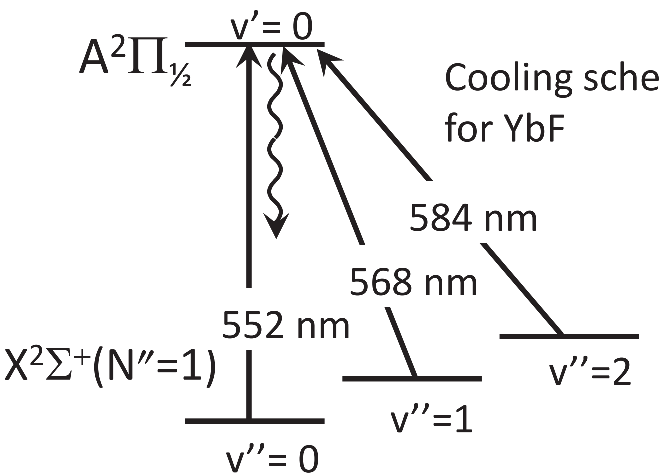
Cryogenic sources of molecules



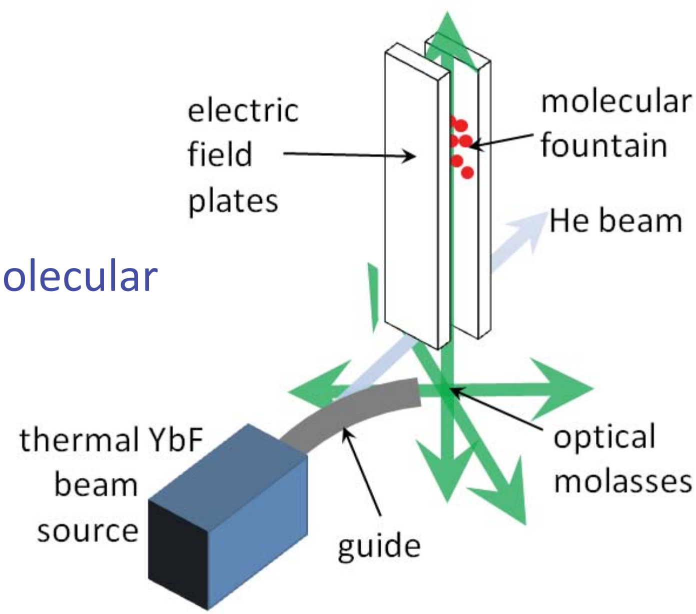
e.g. H.-I. Lu, J. Rasmussen, M. J. Wright, D. Patterson and J. M. Doyle, Phys. Chem. Chem. Phys. **13,** 18986 (2011)

Laser cooling of molecules

See E. S. Shuman, J. F. Barry and D. DeMille, Nature **467**, 820 (2010)



Laser-cooled molecular fountain:

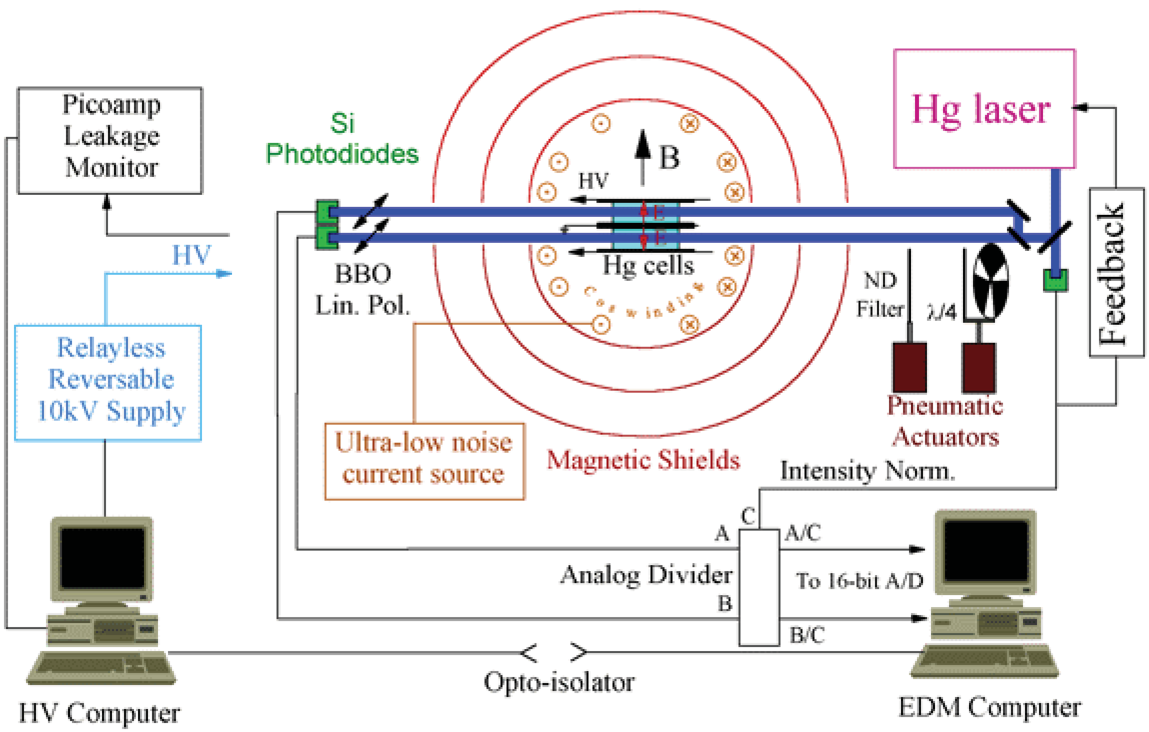


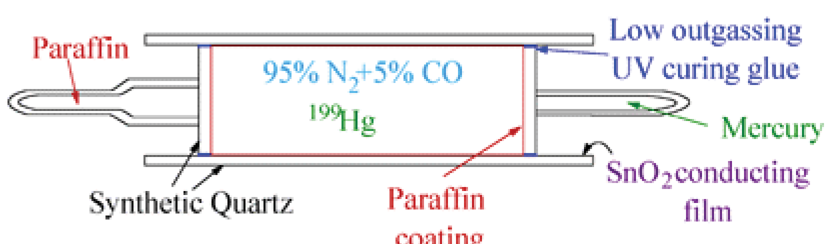
Some ongoing and future electron EDM experiments

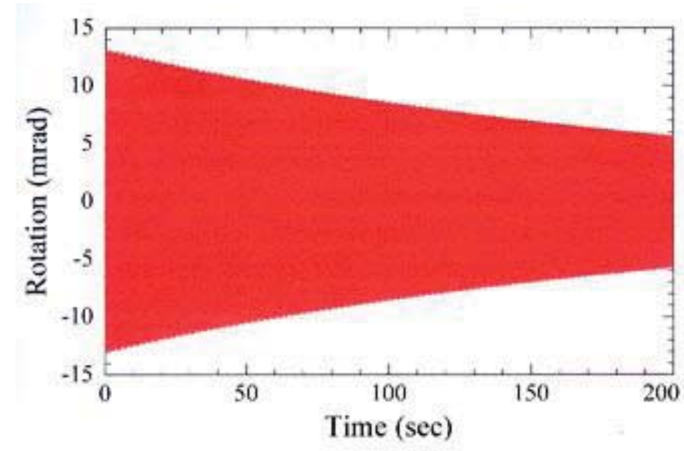
System	References	E_{eff} (GV/cm)	Features
YbF	Nature 473, 493 (2011).	26	Current best limit. New measurements and upgrades in progress.
PbO	Phys. Rev. Lett. 92 133007 (2004).	26	Cell expt. Fully polarized at low field. Internal co-magnetometer. Metastable state (82 μs).
ThO	J. Phys. B 43 074007 (2010).	104	Cryogenic beam expt. Fully polarized at low field. Internal co-magnetometer. Small g-factor. Metastable state (2ms).
WC	J. Mod. Optics 56, 2005 (2009).	54	Ground-state. Fully polarized at low field. Internal co-magnetometer. Small g-factor.
PbF	Phys. Rev. A 73, 034102 (2006).	-29	Zero g-factor.
Cs	Phys. Rev. A 63, 033401 (2001); Bull. Am. Phys. Soc. APR03, J1.008 (2003).	0.01	New experiments with optically trapped ultracold Cs (Penn State and U. Texas)
Fr	http://www.rcnp.osaka-u.ac.jp/~sakemi/EDM/edmRiken.pdf; http://eedm.info/index.html.	0.1	Radioactive. Experiment with ultracold ^{210}Fr being developed (RCNP, Osaka and TRIUMF, Vancouver)
HfF^+	J. Mol. Spectrosc. 270,1 (2011).	18	Ion trap experiment with rotating electric and magnetic fields.
Solids	Phys. Rev. A 66, 022109 (2002); Phys. Rev. Lett. 95, 253004 (2005); Mod. Phys. Lett. A 19, 1235 (2004)	0.00003	Lots of electrons. Difficult to control systematic effects.

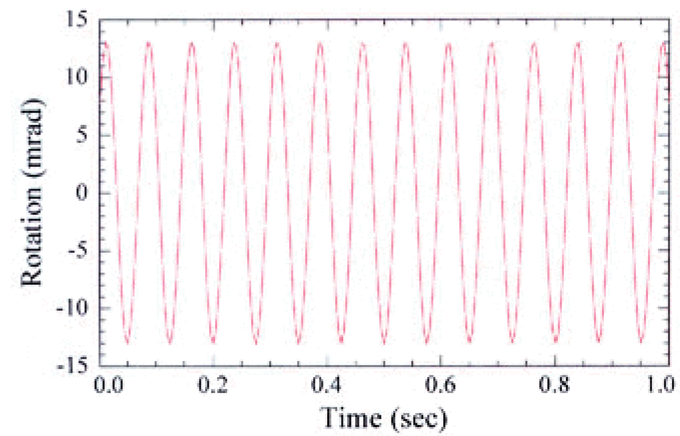
Mercury EDM experiment

^{199}Hg EDM Experimental Setup









University of Washington

Phys. Rev. Lett. **102**, 101601 (2009)

Mercury EDM experiment

Result: $|d\,(^{199}Hg)| < 3.1 \times 10^{-29}$ e.cm (95% CL)

Phys. Rev. Lett. **102**, 101601 (2009)

The most precise measurement of the EDM of *anything*

Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{QCD}$	3×10^{-10}	[20]	n: 1×10^{-10} [3]
d_n (e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26} [3]
d_e (e cm)	3×10^{-27}	[21,22]	Tl: 1.6×10^{-27} [18]

[a] For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

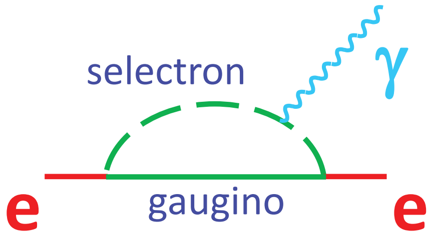
$|d(p)| < 7.9 \times 10^{-25}$ e.cm

$|d(n)| < 5.8 \times 10^{-26}$ e.cm

Consequences of electron EDM measurements

Electron EDM from a one-loop diagram in supersymmetry is

$$d_e \sim \left(\frac{\alpha}{\pi}\right)\frac{m_e}{\Lambda^2}\sin\phi_{CP}$$



CP-violating phase (naturally order 1)

Scale of SUSY breaking ~ 200GeV

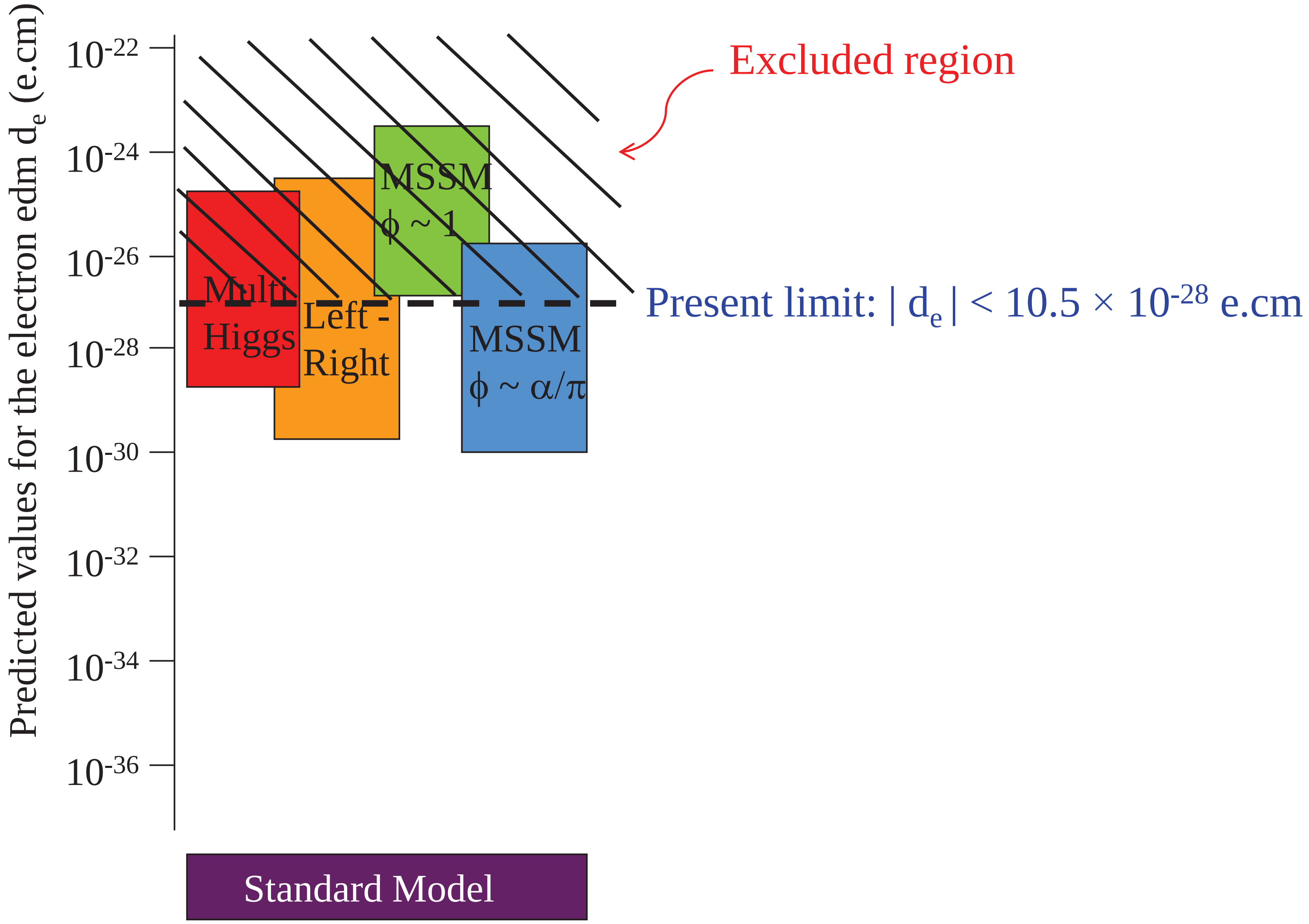
$d_e \sim 5 \times 10^{-25}$ e.cm naturally

"Natural" SUSY EDM is 500 times too big

$\Lambda > 4$ TeV ??

$\phi_{CP} < 10^{-3}$??

Consequences of electron EDM measurements



Consequences of neutron EDM measurements

For the neutron there is a CP-violating term in the QCD Lagrangian, parametrized by θ.

This gives a neutron EDM: $d_n \sim \theta\,(6 \times 10^{-17})$ e.cm

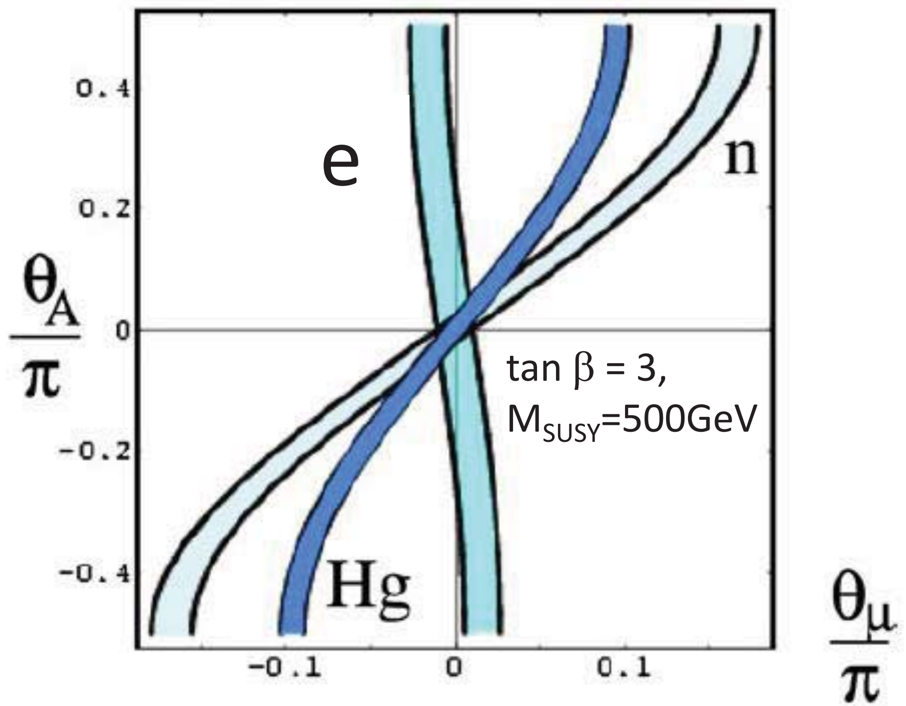
So the experimental upper limit for the neutron EDM gives $|\theta| < 5 \times 10^{-10}$

This fine tuning of the θ parameter is the *strong CP problem*

This problem can be resolved by introducing the *axion*

If we assume that (for whatever reason) the θ contribution is suppressed to zero, then d_n in the Standard Model is smaller than 10^{-32} e.cm

Constraints from EDM measurements



M. Pospelov, A. Ritz, Annals of Physics 318, 119 (2005)

Acknowledgements

Thanks to Jony Hudson, Ben Sauer and Ed Hinds for their help and advice.