Another Route to CP Violation Beyond the SM – Particle Dipole Moments

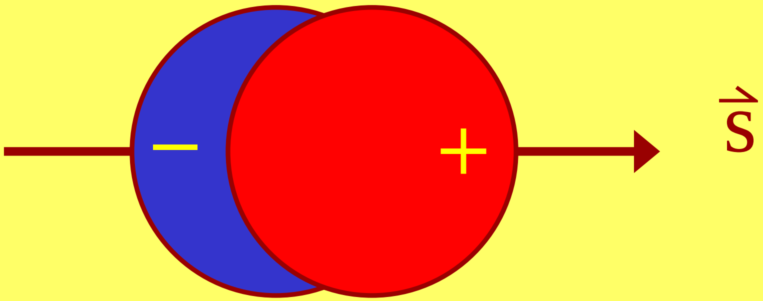
Dave Wark
Imperial/RAL

WIN05
Delphi
June 10, 2005

rial College
lon

CCLRC
Rutherford Appleton Laboratory

Particle Electric Dipole Moment



Would lead to a non-zero value for $\vec{d}_n$, either parallel or anti-parallel to $\vec{s}$

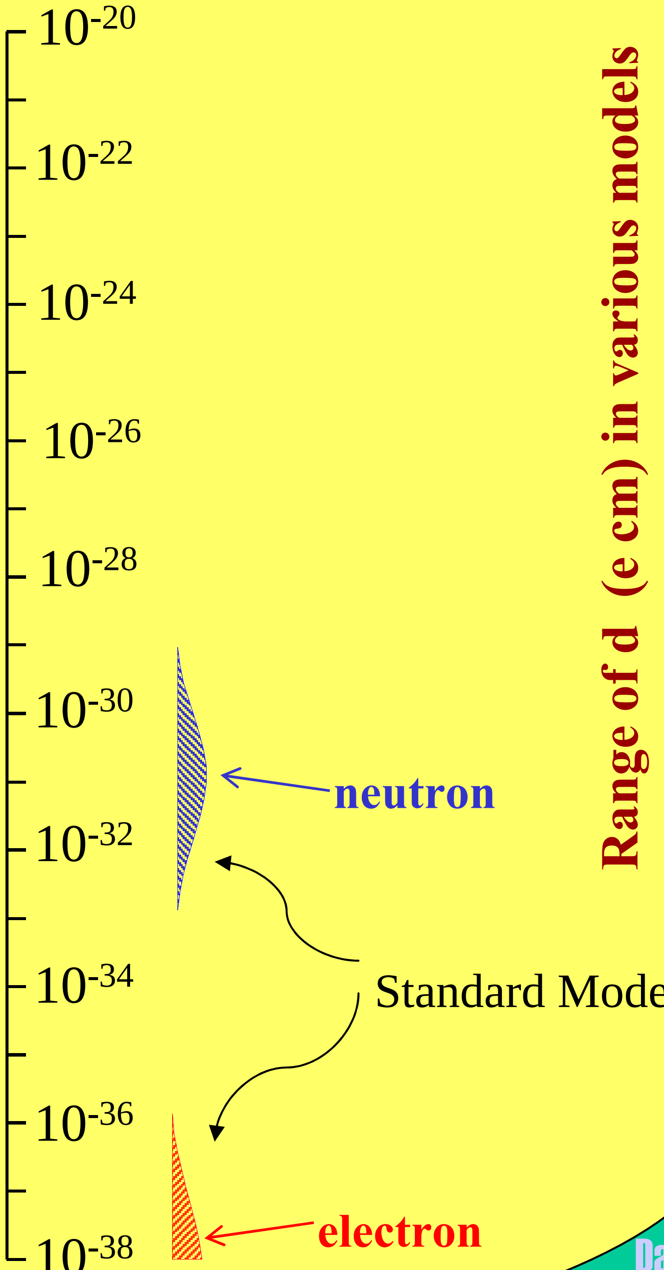
$\vec{d}_n$ would be:

P odd

T odd

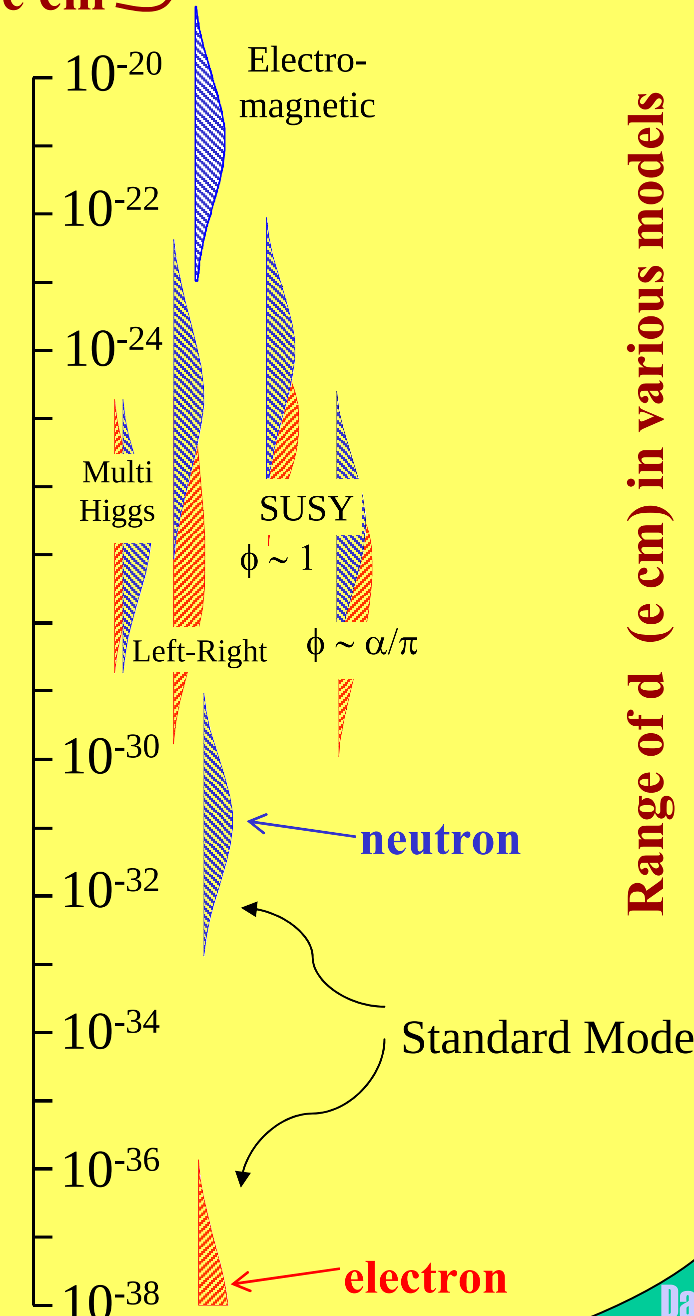
CP odd!

Dave Wark
Imperial College/RAL

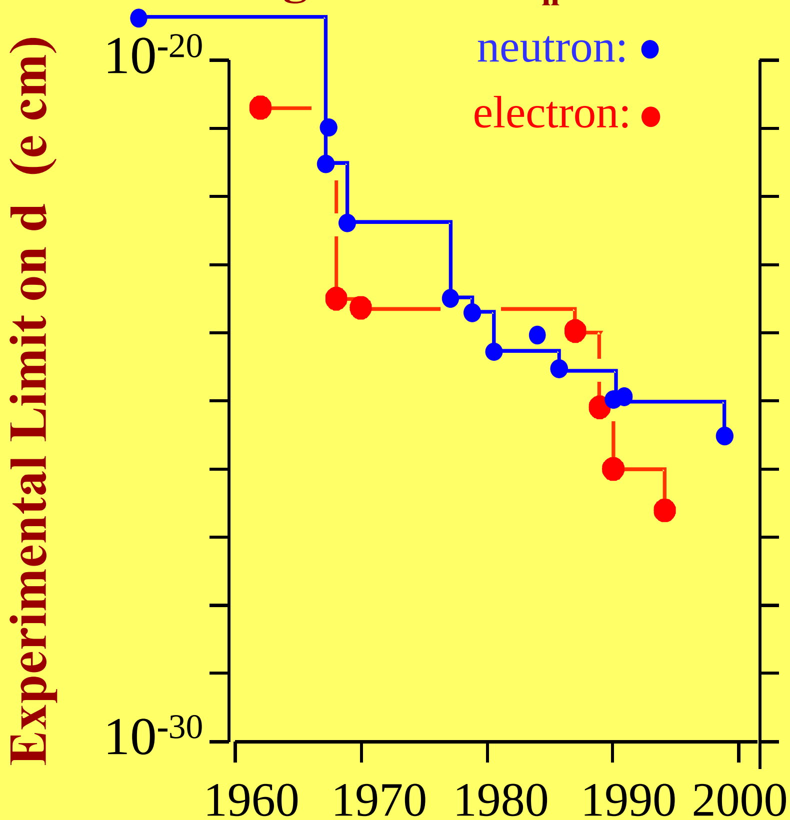


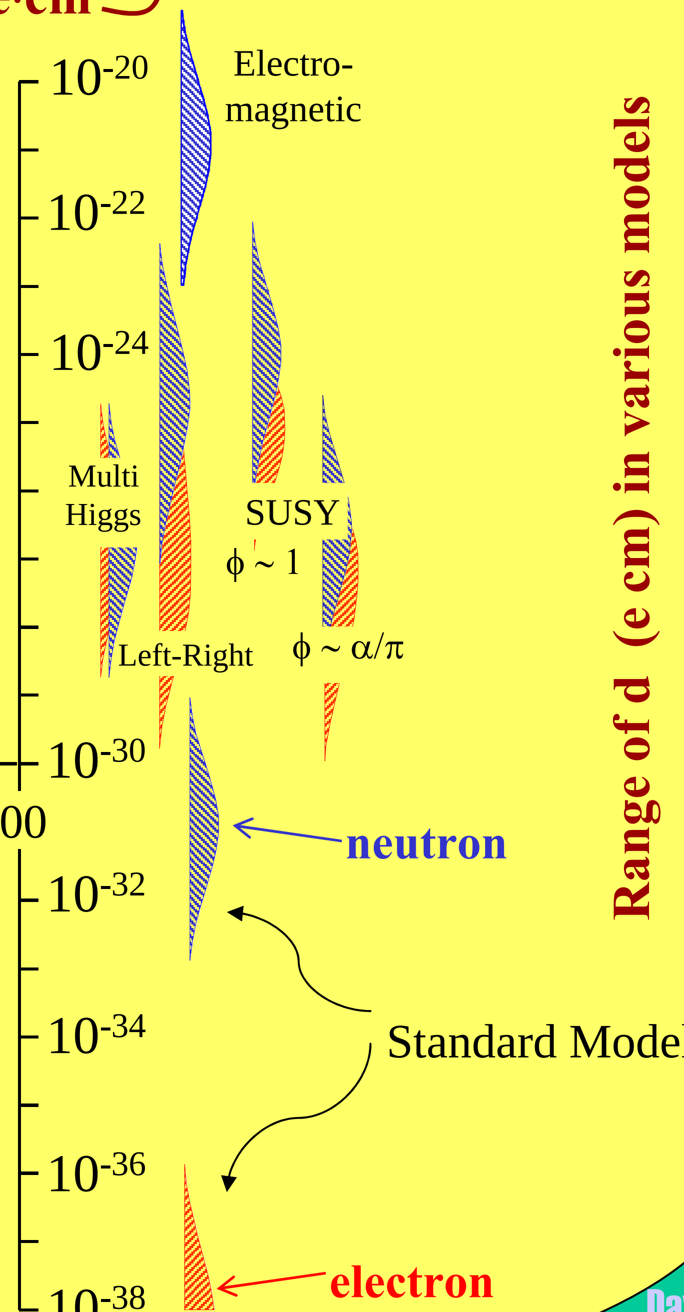
Dave Wark
Imperial College/RAL

Strong CPV → $d_n \sim 10^{-16}$ e·cm



Strong CPV → $d_n \sim 10^{-16}$ e·cm





Relative value of neutron and electron EDM is model-dependent, must pursue both

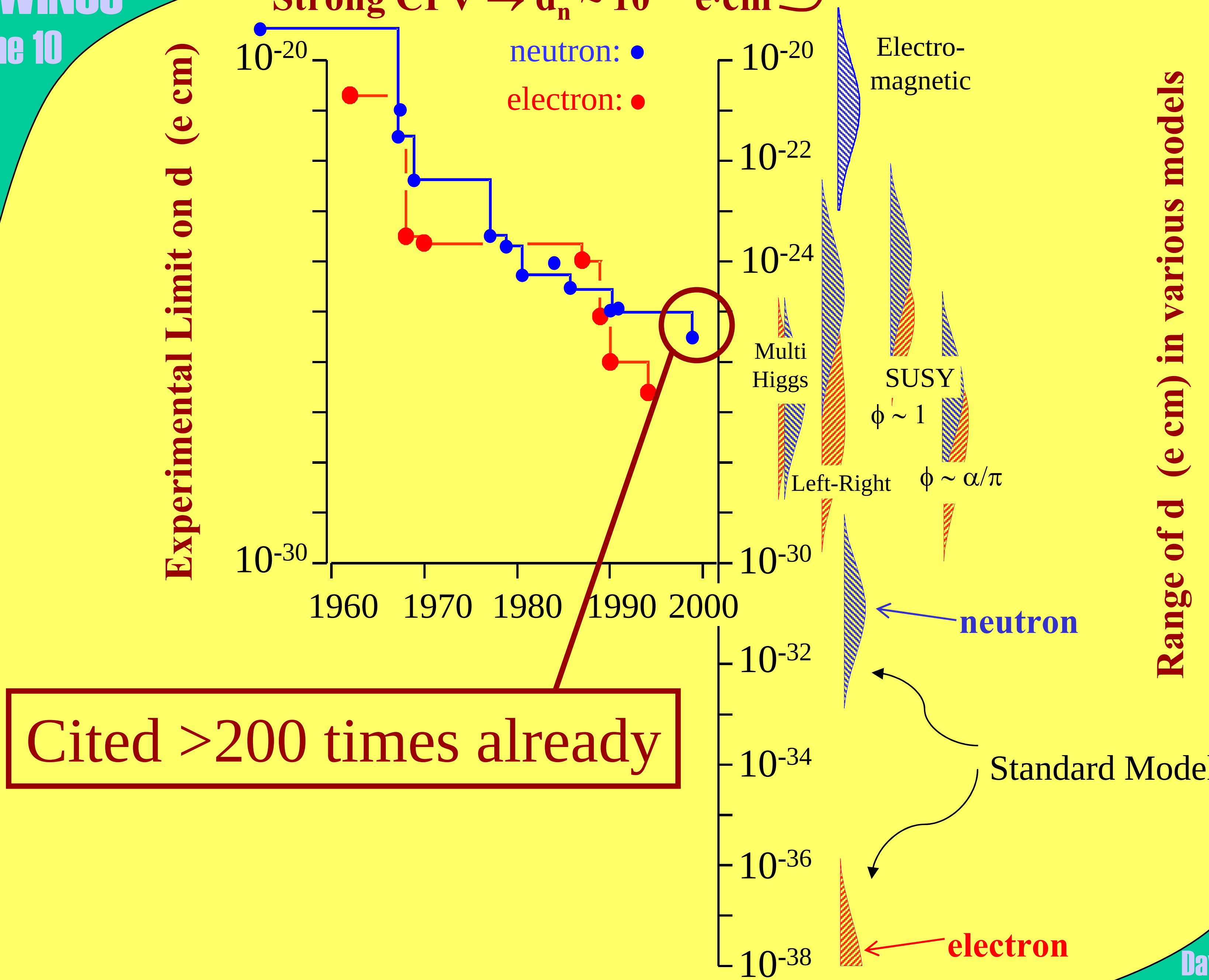
Dave Wark
Imperial College/RAL

WIN05

June 10 '05

nEDM...

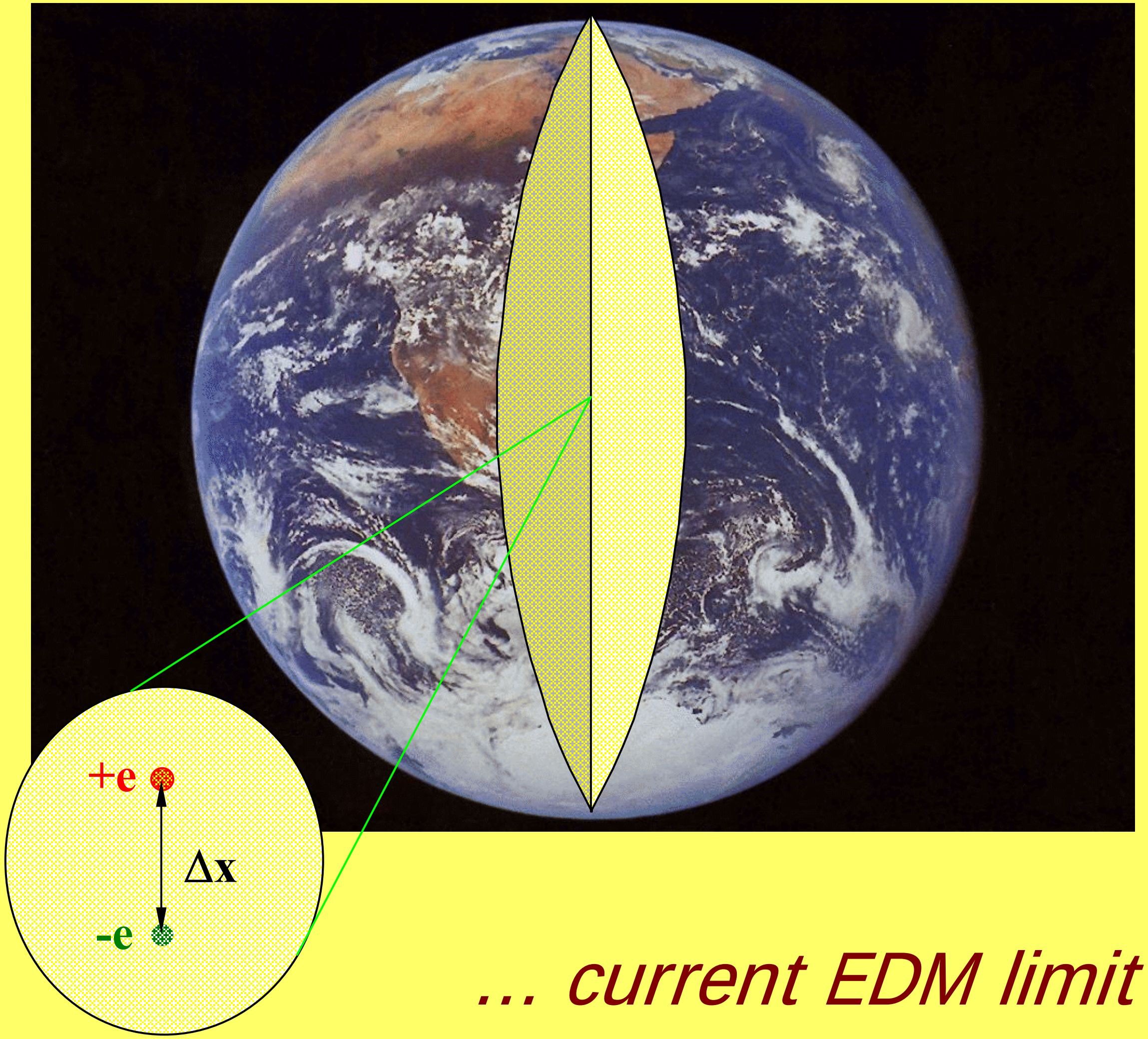
Strong CPV → $d_n \sim 10^{-16}$ e·cm



...and CP

Dave Wark
Imperial College/RAL

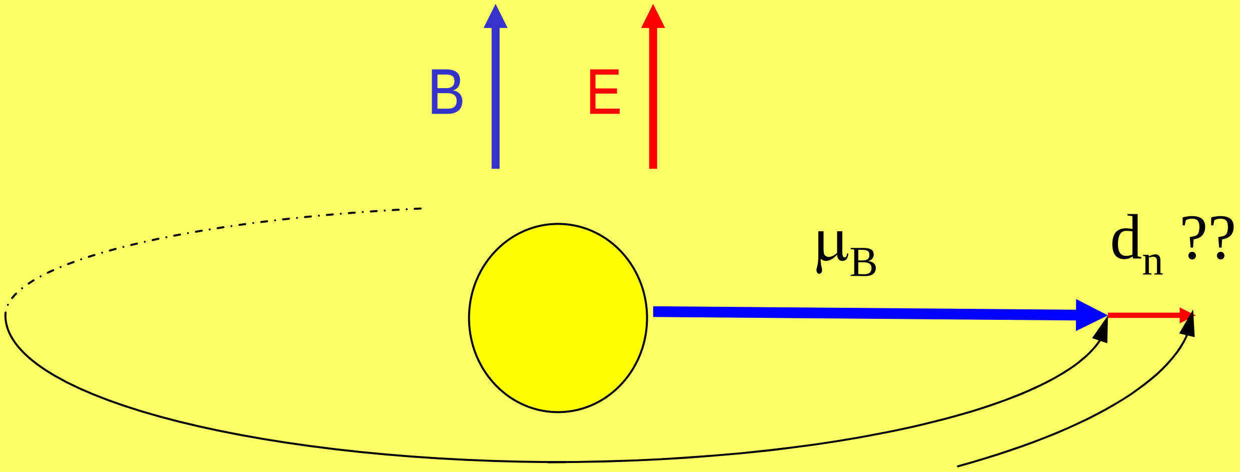
If neutron were the size of the earth...



... current EDM limit would correspond to charge separation of $\Delta x \approx 10\,\mu$.

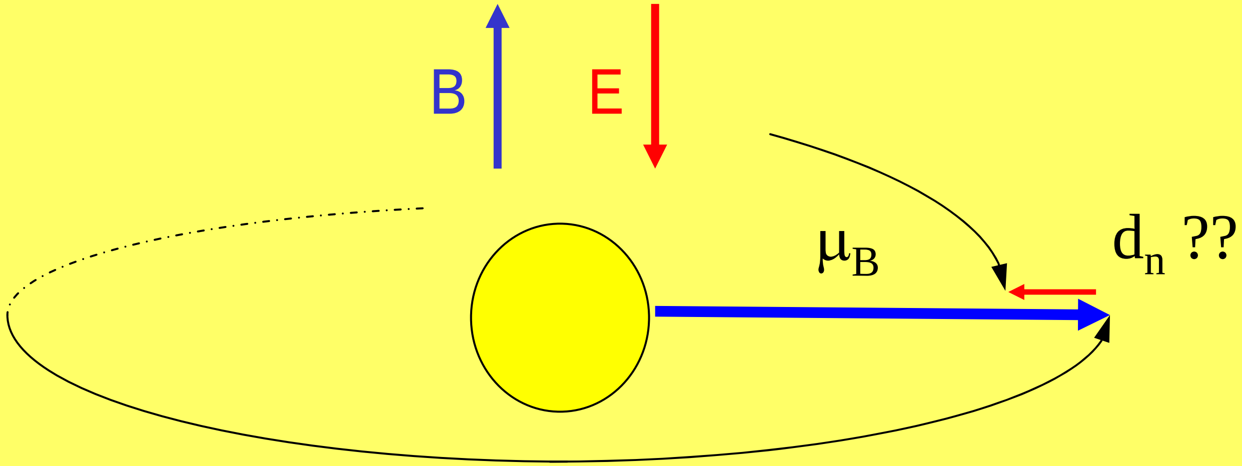
Dave Wark
Imperial College/RAL

Basic Idea of the Measurement



Dave Wark
Imperial College/RAL

Basic Idea of the Measurement

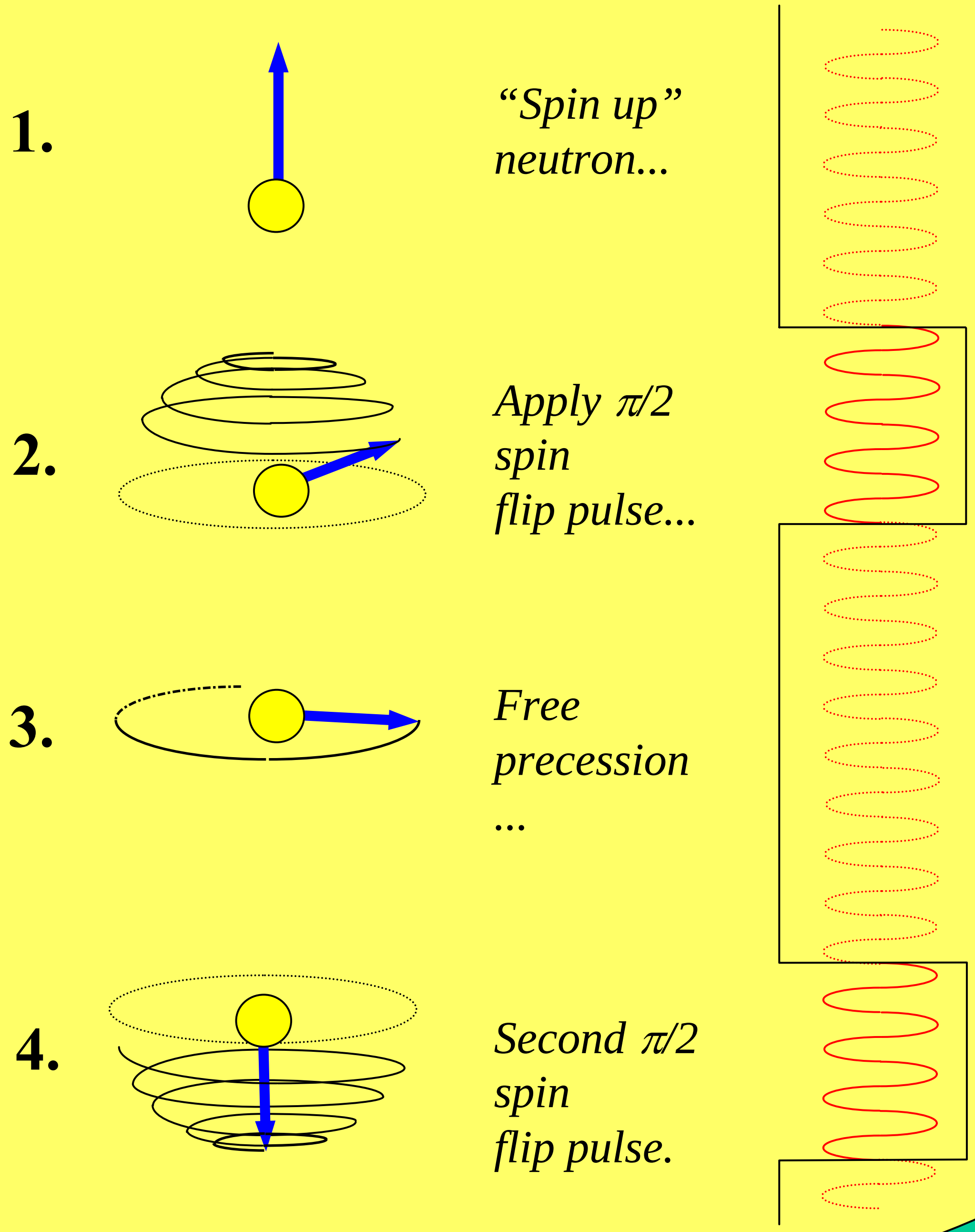


Look for a shift in the Larmor frequency of $2 \cdot E \cdot d_n$ as E is flipped relative to B

Dave Wark
Imperial College/RAL

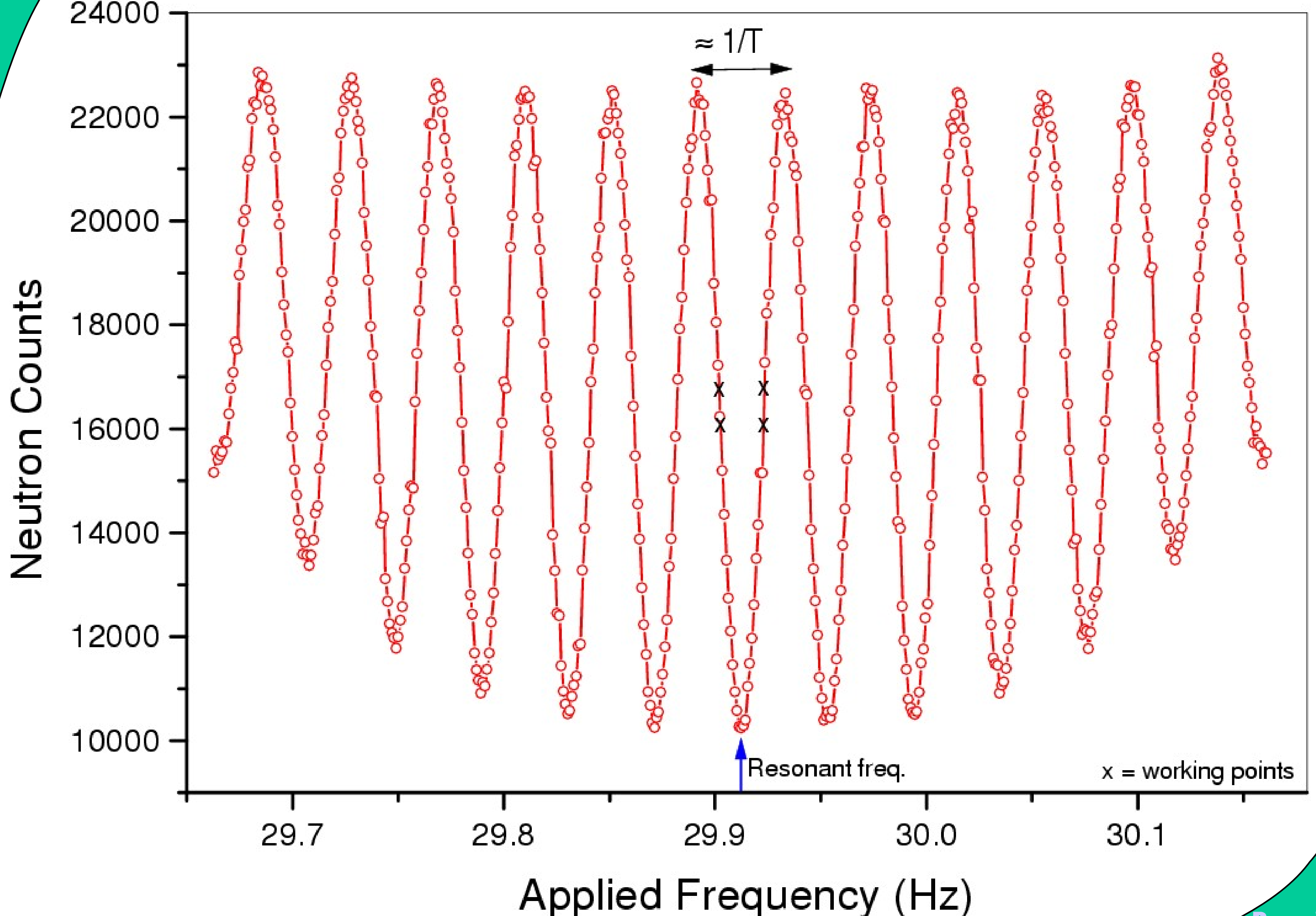
nEDM...

The Ramsey Separated Oscillator Method



...and CP

Ramsey Resonance Curve



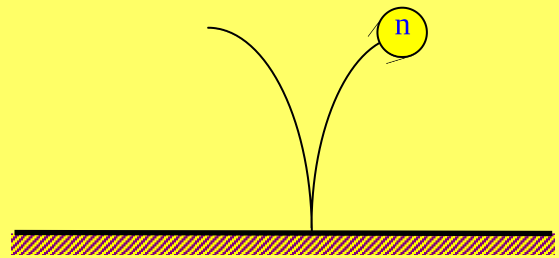
Dave Wark
Imperial College/RAL

λ>> interatomic spacing; neutrons see Fermi potential V_F

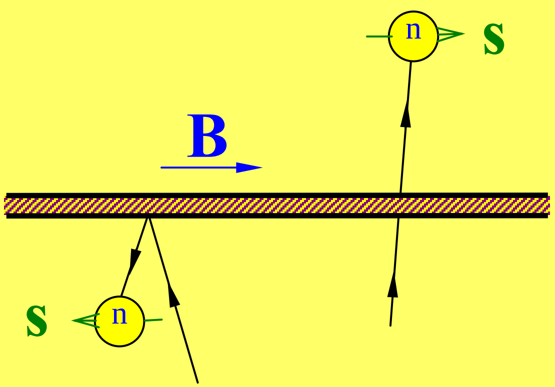
Critical velocity for reflection:

$$\tfrac{1}{2}mv_c^2 = V_F$$

Ultracold neutrons (UCN): v ~ 6 m/s: total internal reflection possible.



v_c depends on orientation of neutron spin, so can polarise by transmission.



Prepare neutrons in polarisation state 1, execute Ramsey cycle and measure the number left in states 1 and 2, repeat with B and E fields parallel (↑↑) and anti-parallel (↑↓), then:

$$d_n = \frac{(N_{1\uparrow\uparrow} - N_{2\uparrow\uparrow} - N_{1\uparrow\downarrow} + N_{2\uparrow\downarrow})\hbar}{2\alpha ETN}$$

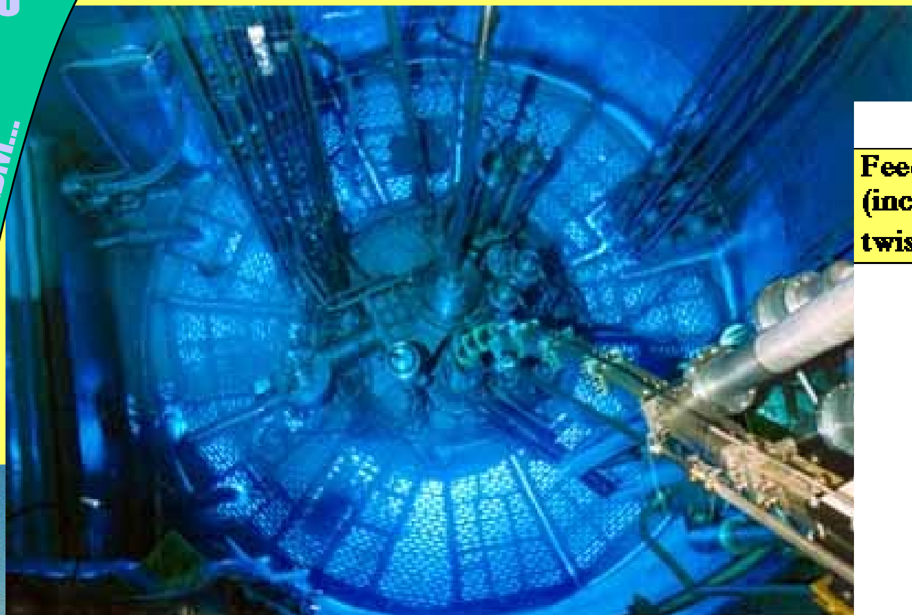
With the resulting "statistical" sensitivity:

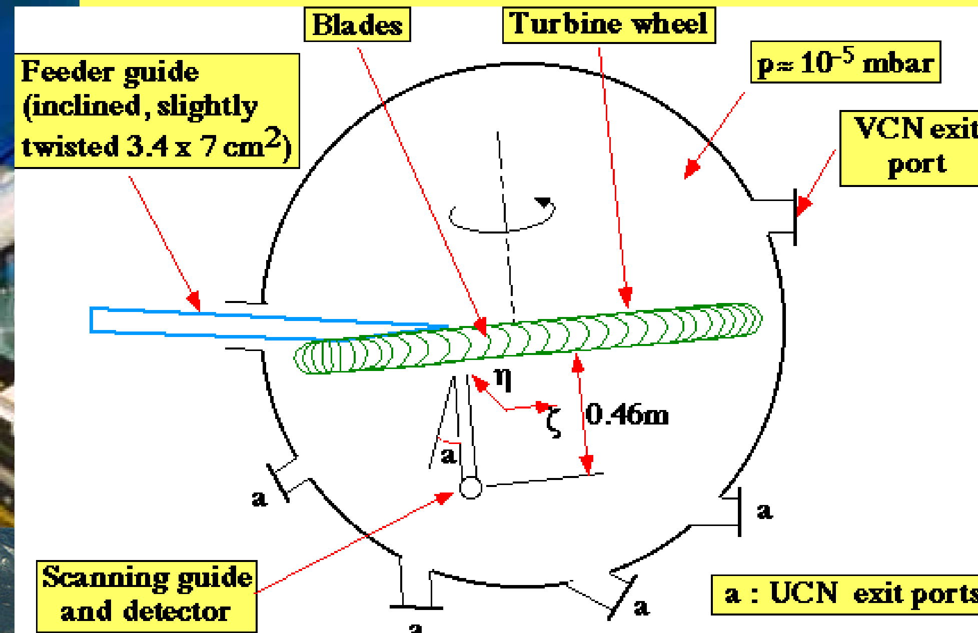
$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

Must add any systematics to this to determine the sensitivity of the experiment.

Dave Wark
Imperial College/RAL

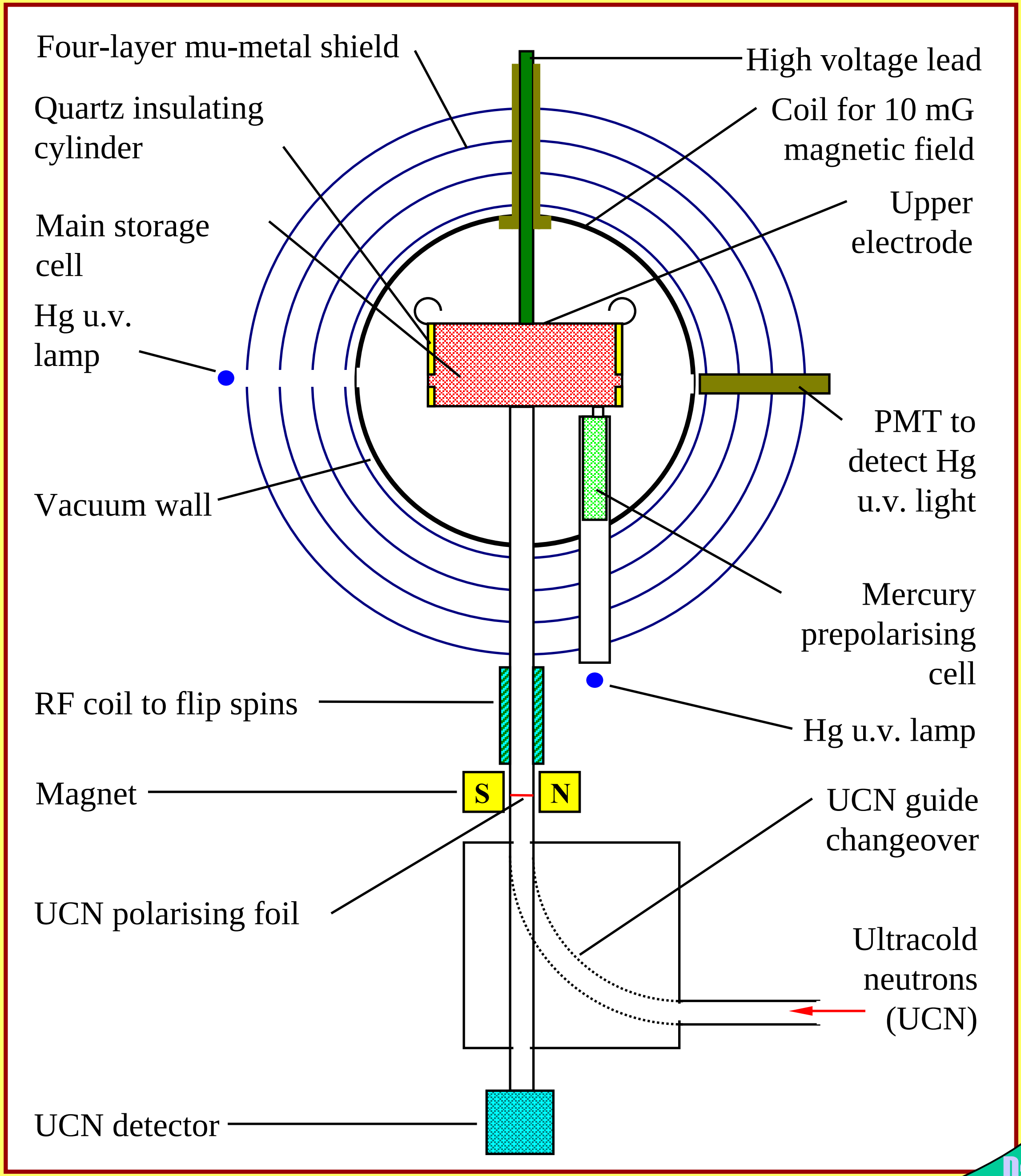
The Institute Laue-Langevin





nEDM...

Current Room-Temperature nEDM Experiment



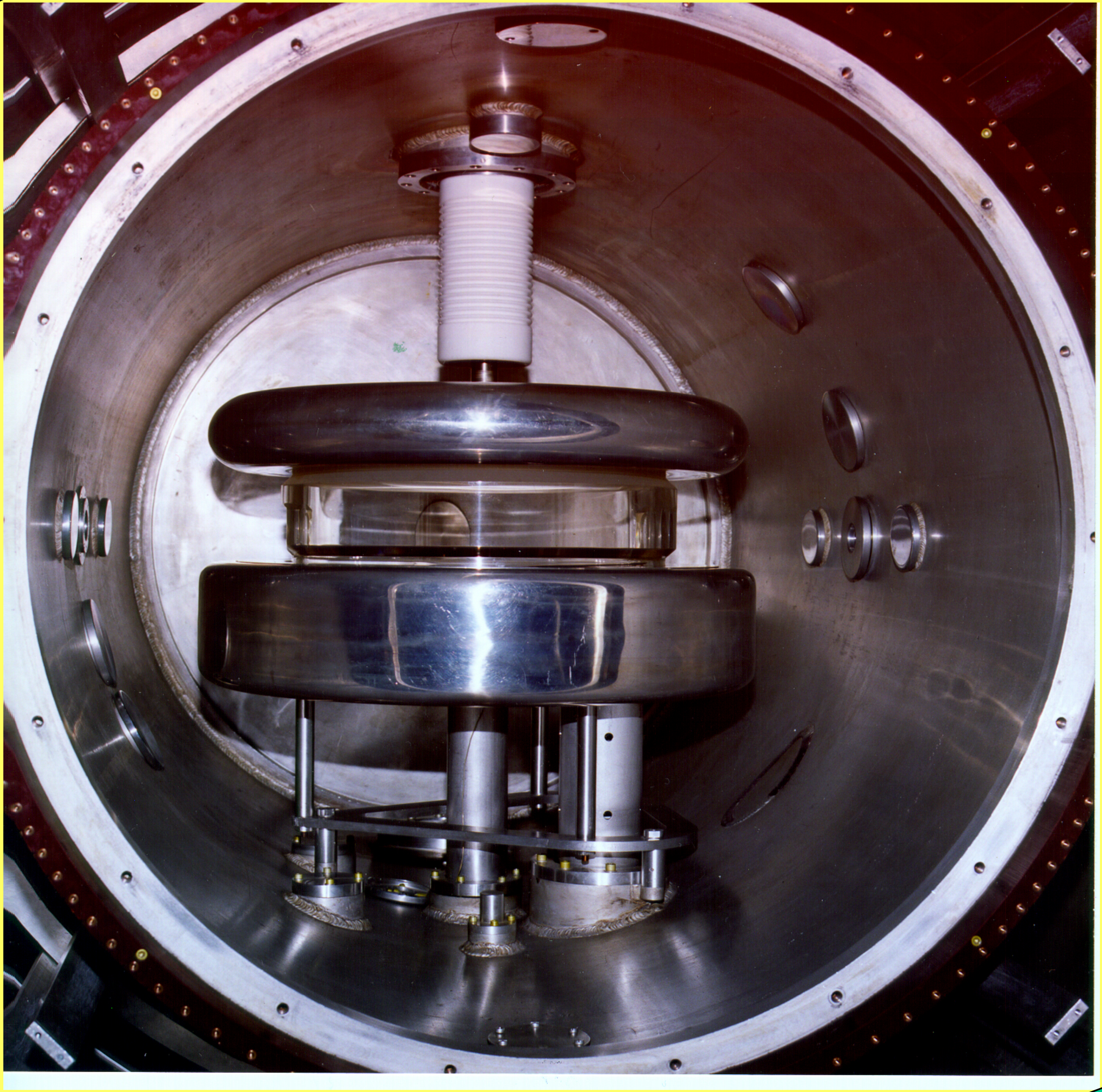
...and CP

Dave Wark
Imperial College/RAL

WIN05

June 10 '05

nEDM...

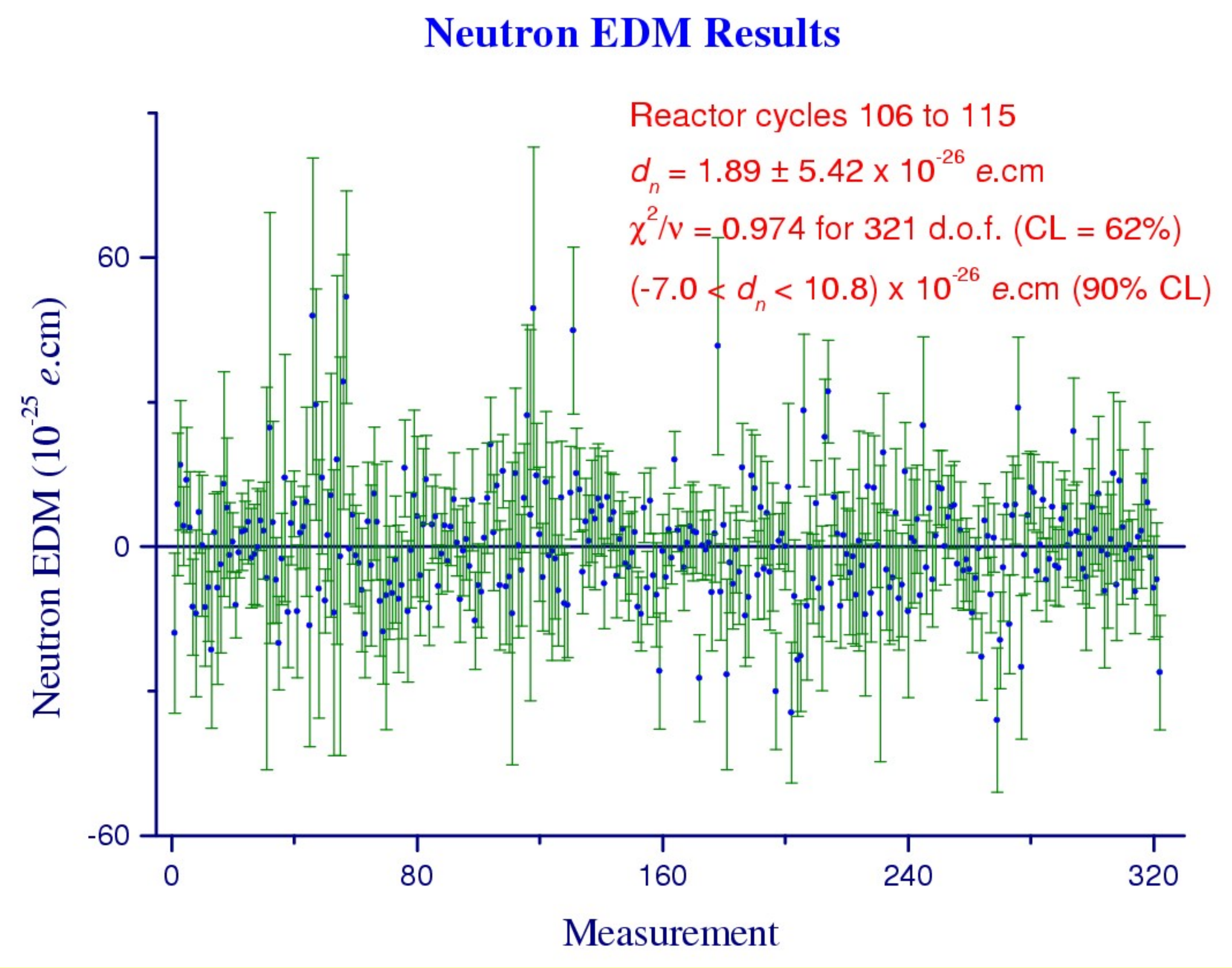


...and CP

Dave Wark
Imperial College/RAL

1999 Results

(PG Harris *et al*, PRL **82**, 904 (1999))



$d_n = (1.9 \pm 5.4)\times10^{-26}$ e cm $\Rightarrow$

$d_n \leq 6.3 \times10^{-26}$ e cm (90% c.l.)

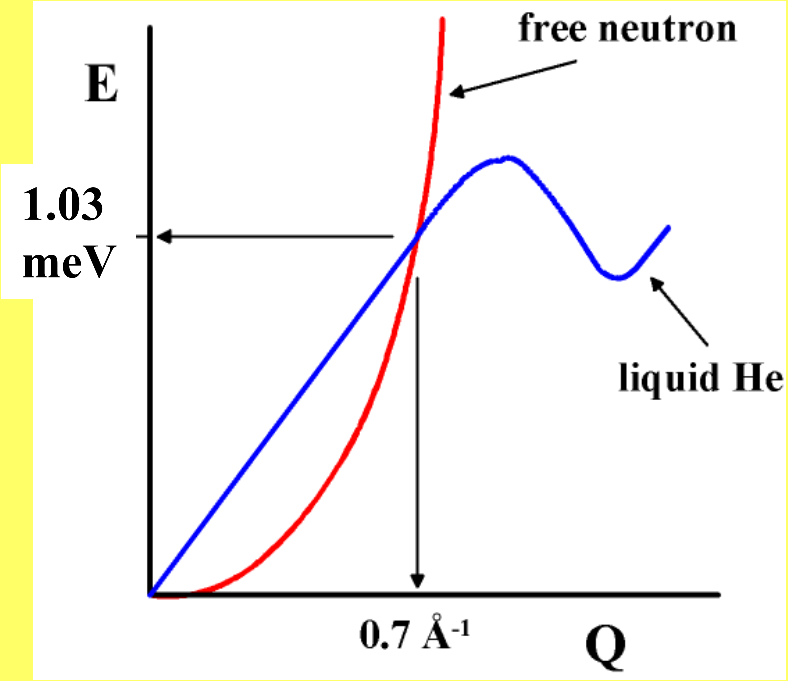
Dave Wark
Imperial College/RAL

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

	Published Data	Current Room-Temp	Cryogenic Experiment
α	0.5	0.7	
E	4.5 kV/cm	12 kV/cm	
T	130 s	130 s	
N	13000	14000	

How will we do better?

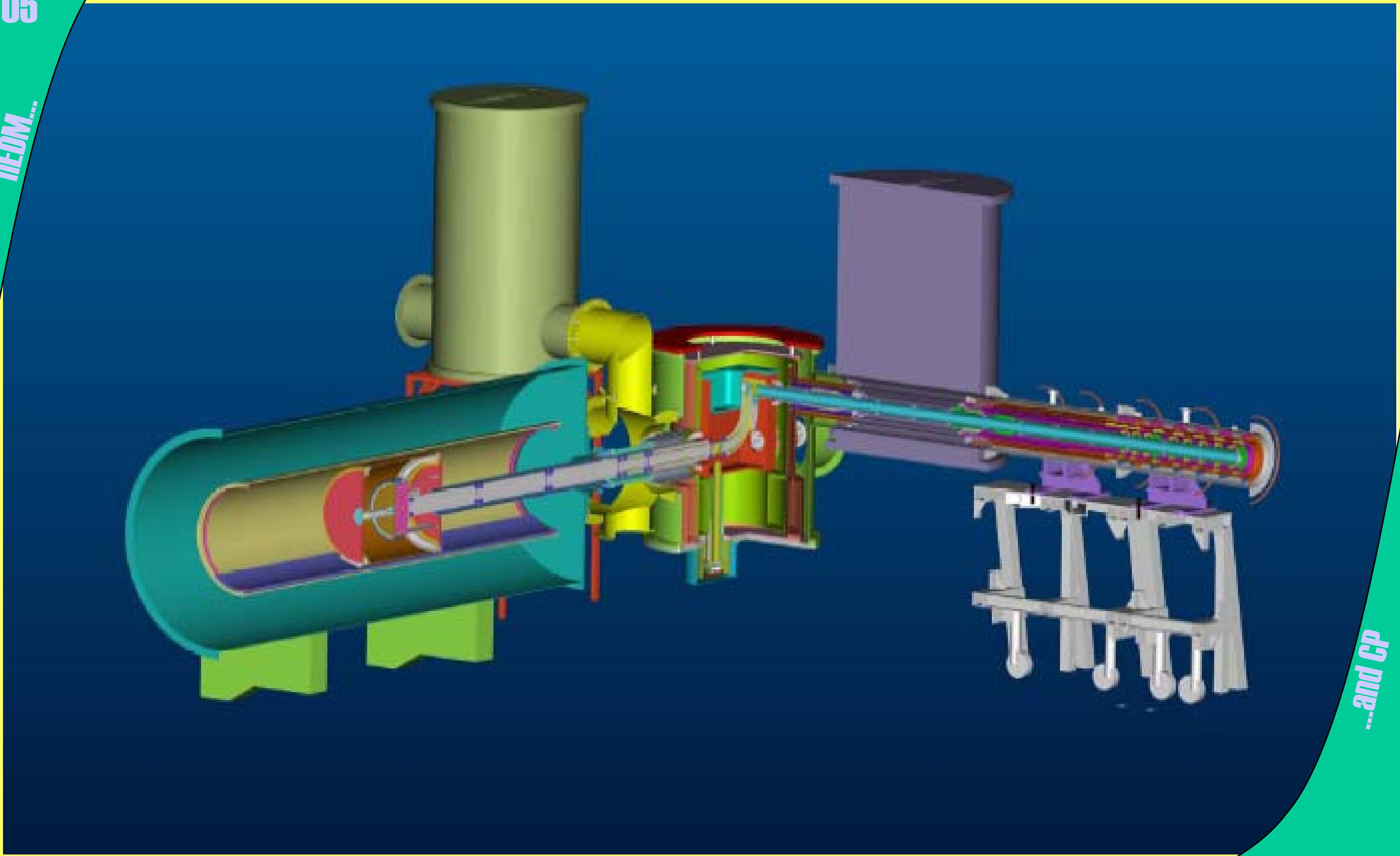
- Need a new source of UCN….



- To use this we need….

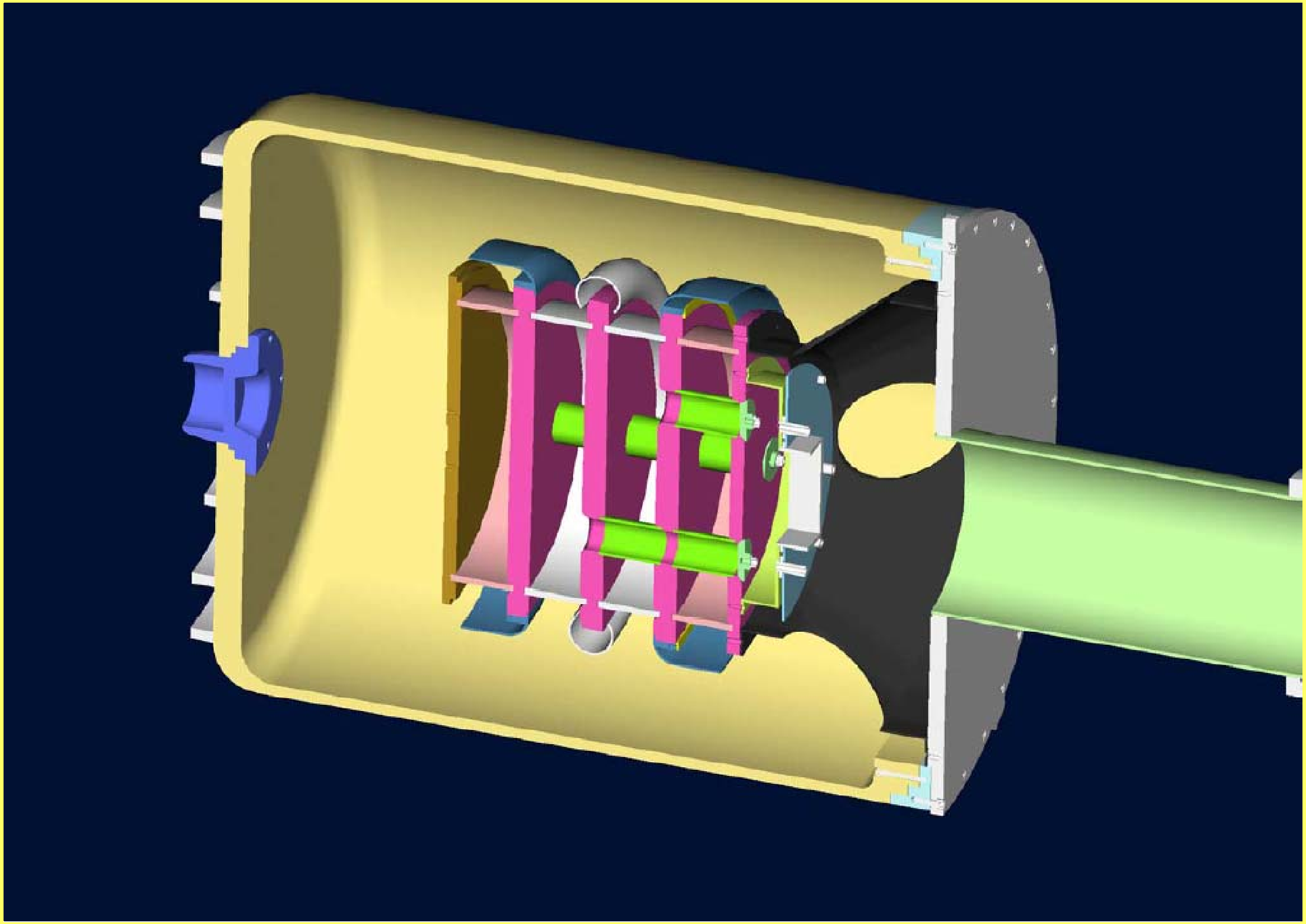
Dave Wark
Imperial College/RAL

Next Generation Experiment



Dave Wark
Imperial College/RAL

Ramsey Cell and SF Vessel



Dave Wark
Imperial College/RAL

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

	Published Data	Current Room-Temp	Cryogenic Experiment
α	0.5	0.7	0.9
E	4.5 kV/cm	12 kV/cm	40 kV/cm
T	130 s	130 s	300 s
N	13000	14000	700000

nEDM...

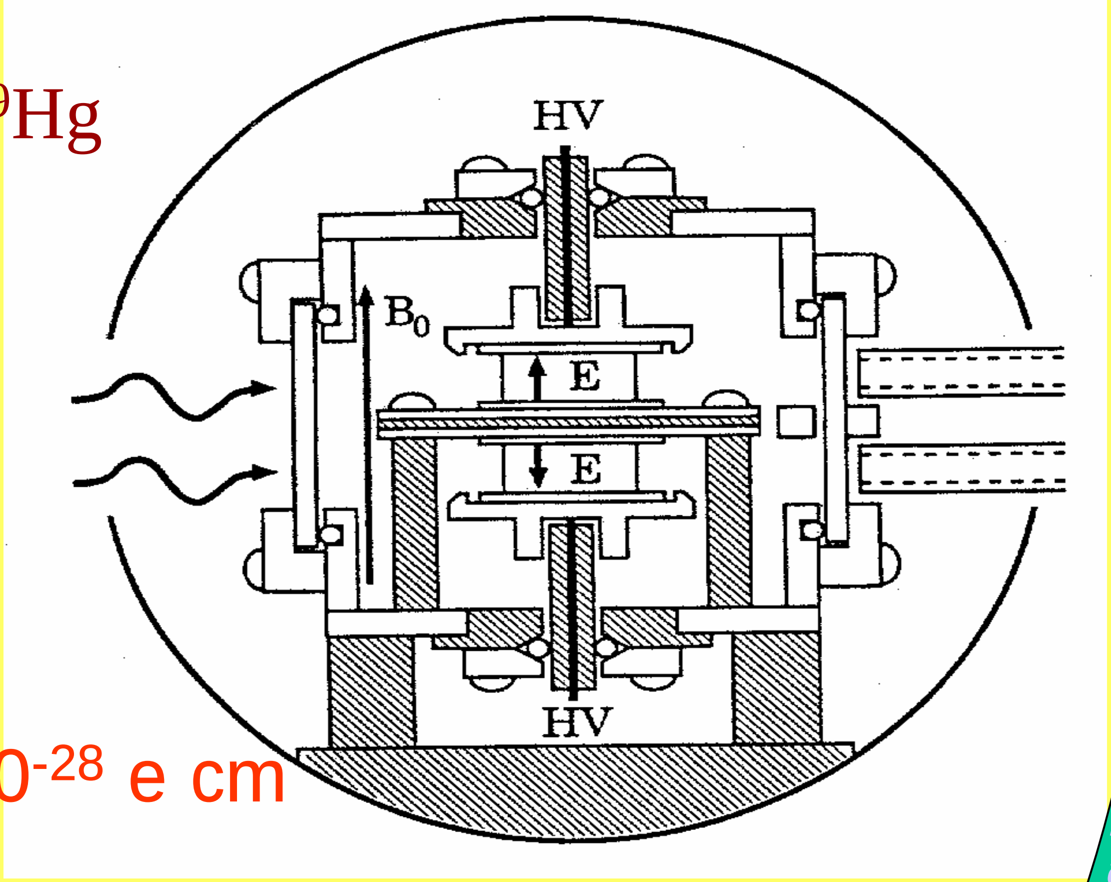
Mechanism	False EDM Uncertainty	Assumptions
Non-zero ($B_0\uparrow\uparrow - B_0\uparrow\downarrow$) from mu-metal hysteresis	$10^{-2} \times 10^{-28}$ e cm	($B_0\uparrow\uparrow - B_0\uparrow\downarrow$) outside the super-conducting shield is that previously experienced in our nEDM experiments
Electric forces - cell displacement - dB_0/dr	1.0×10^{-28} e cm	$dB_0/dr = 3\times10^{-8}$ G/mm Rigidity of radial displacement of cells = 100 kg/mm
Electrical leakage currents caused by **E**	1.0×10^{-28} e cm	Current of 1 nA at 40 kV/cm An asymmetric tangential flow of 50 mm
DC B- and E-fields directly from the high voltage supply	$10^{-5} \times 10^{-28}$ e cm	DC current 1 mA in 40 cm diameter circuit 1.6 m from the shield end – current reverses with sign of HV
AC B-fields from the high voltage and dE/dt	0.05×10^{-28} e cm	Ripple on the high voltage 0.04 % - manufacturers figure. 10 kHz and 50 Hz considered
$(\mathbf{E} \times \mathbf{v})/c^2$ 1st order UCN ensemble translation of CM	0.2×10^{-28} e cm	Upwards displacement of the UCN due to warming in storage = 1 mm. Volume ave. angle **E** to $\mathbf{B_0}$ = 0.1 radian
$(\mathbf{E} \times \mathbf{v})/c^2$ 1st order UCN ensemble net circulation about CM	0.3×10^{-28} e cm	Circulation decay τ = 1s $\Delta E_T = E/10$ in outer 30 mm UCN enter at $R/4$ 2s wait before 1st $\pi/2$ flip
$((\mathbf{E} \times \mathbf{v})/c^2)^2$ 2nd order affects all individual trajectories	0.3×10^{-28} e cm	Gives E^2 shift ($E\uparrow - E\downarrow$)/<E> = 0.05 <E> = 60 kV/cm used Two cells cancel effect to 10%
$(\mathbf{E} \times \mathbf{v})/c^2$ & dB_0/dz geometric phase affects all individl. trajectories	0.8×10^{-28} e cm	dB_0/dz = 1 µG/m after trimming. B_0 = 25 mG Rms v(UCN) = 5 m/s
Overall systematic error	1.7×10^{-28} e cm	All the above errors are uncorrelated

...and CP

Dave Wark
Imperial College/RAL

^{199}Hg Electric Dipole Moment

hep-ex/0012001



Optically pumped ^{199}Hg atoms precess in B, E fields, modulating absorption signal

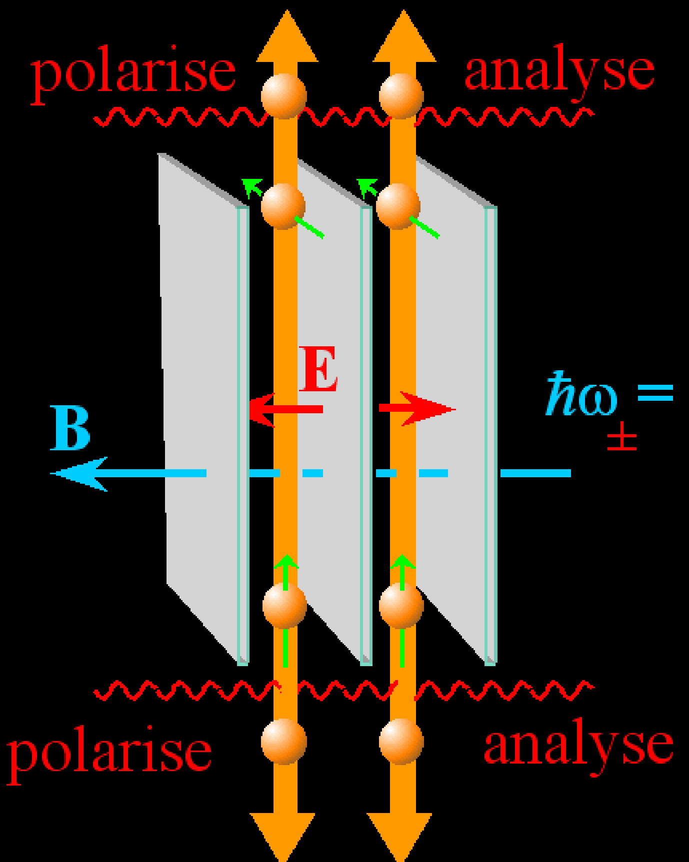
- Dual cells remove effect of drifts in B
- Result: $d(^{199}Hg) < 2.1 \times 10^{-28}$ e cm

- Provides good limit on CPv effects in nuclear forces, inc. θ_{QCD}
- If from valence neutron, corresponds to $d_n < 2 \times 10^{-25}$ ecm, because of electrostatic shielding.

The Thallium EDM experiment

Slide from Ed Hinds

Berkeley B.C. Regan, E.D. Commins, C.J. Schmidt and D. DeMille



$$\hbar\omega_{\pm} = \mu B \pm dE$$

4 Tl atomic beams

1st huge problem:

motional interaction $\mu \cdot \mathbf{v} \times \mathbf{E}$

The solution:

add 2 more Tl beams going down

2nd huge problem:

stray static magnetic fields

The solution:

Add 4 Na beams for magnetometry

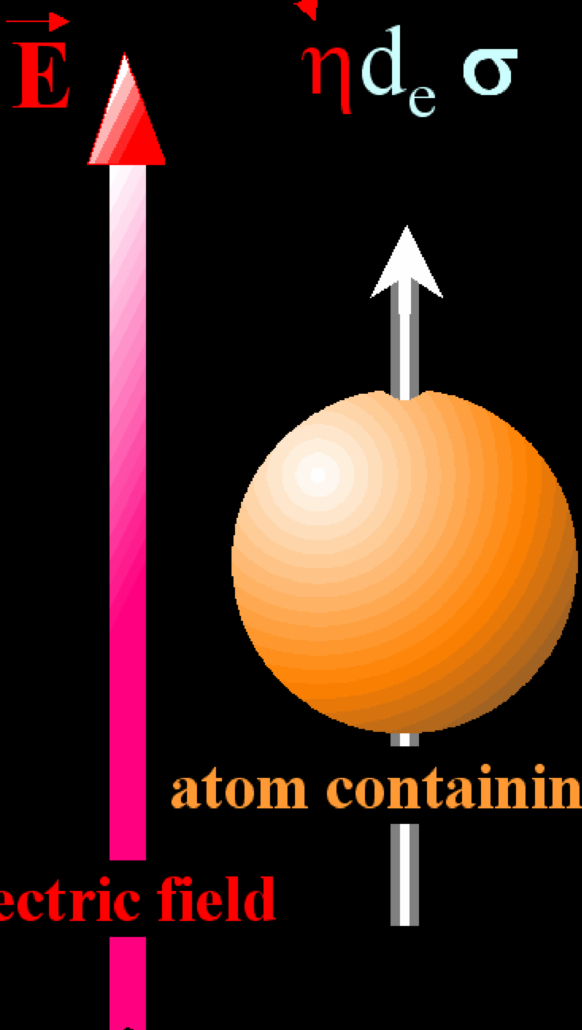
Slide from Ed Hinds

A beautiful feature of the method

(Sandars)

amplification

$\eta d_e \boldsymbol{\sigma}$



Interaction energy

$-d_e\, \eta\, \vec{\mathbf{E}} \cdot \boldsymbol{\sigma}$

-585 for Tl

Slide from Ed Hinds

Final Tl result: PRL 88, 071805 (2002)

E = 123 kV/cm $\xrightarrow{\times 585}$ Effective field = 72 MV/cm

B = 38 μT

$T_{coherence} = 2.4$ ms

Na co-magnetometer

$|d_{Tl}| < 9.4 \times 10^{-25}$ e.cm $\xrightarrow{\div 585}$

electron edm result:

$|d_e| < 1.6 \times 10^{-27}$ e.cm

The future for electron EDM experiments

Slide from Ed Hinds

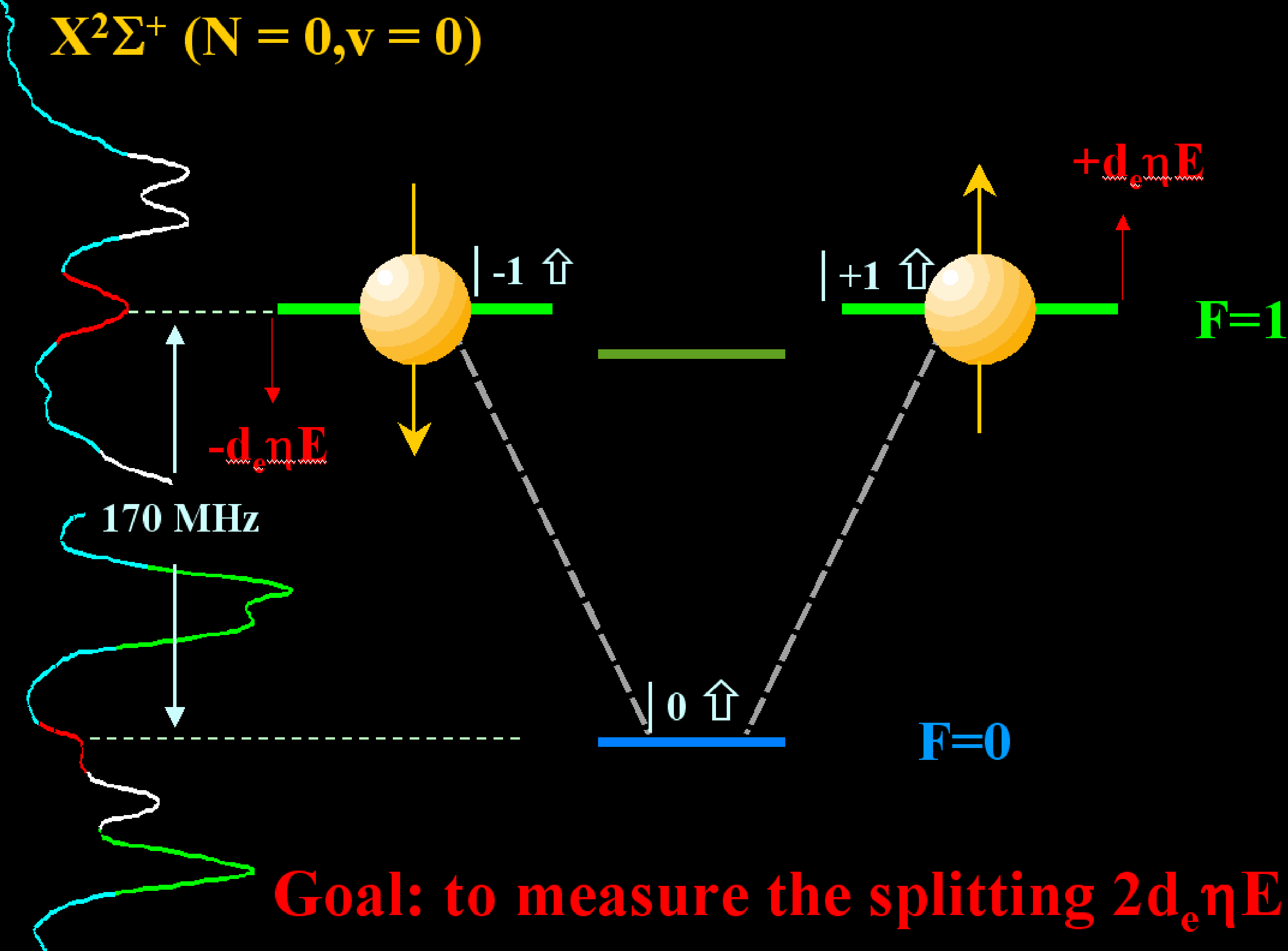
polar molecules

potentially 1000 × more sensitive

The **Imperial** experiment uses **ytterbium fluoride molecules**

E.A. Hinds, B.E. Sauer, J.J. Hudson, P Condylis,
M.R. Tarbutt, R. Darnley

The lowest two levels of YbF in an electric field E



Goal: to measure the splitting $2d_e\eta E$

Slide from Ed Hinds

Slide from Ed Hinds

Projections for the future

	2002 result	cold YbF beam	trapped molecules
background	150kHz	640kHz	40kHz
fringe height	1.5 kHz	160 kHz	10 kHz
coherence time	1.5 ms	1 ms	1 s
d_e in 1 day	$3\ 10^{-26}$ e cm	$6\ 10^{-28}$ e cm	$3\ 10^{-30}$ e cm

long time = narrow fringes

Conclusions

- Particle EDMs are sensitive probes of CP violation both within ($\theta_s < 2\text{-}6 \times 10^{-10}$) and in models beyond the SM (The natural scale for the nEDM is SUSY is 10^{-23}, already stressed).
- Experiments are in progress to improve sensitivities by factors 100-1000.
- There are other competing experiments for both neutrons (PSI, US) and electrons that I have no time to discuss.
- There are also plans to push limits on the muon EDM at future facilities (JPARC).
- The two CP violation communities seem completely separate, which is a pity….