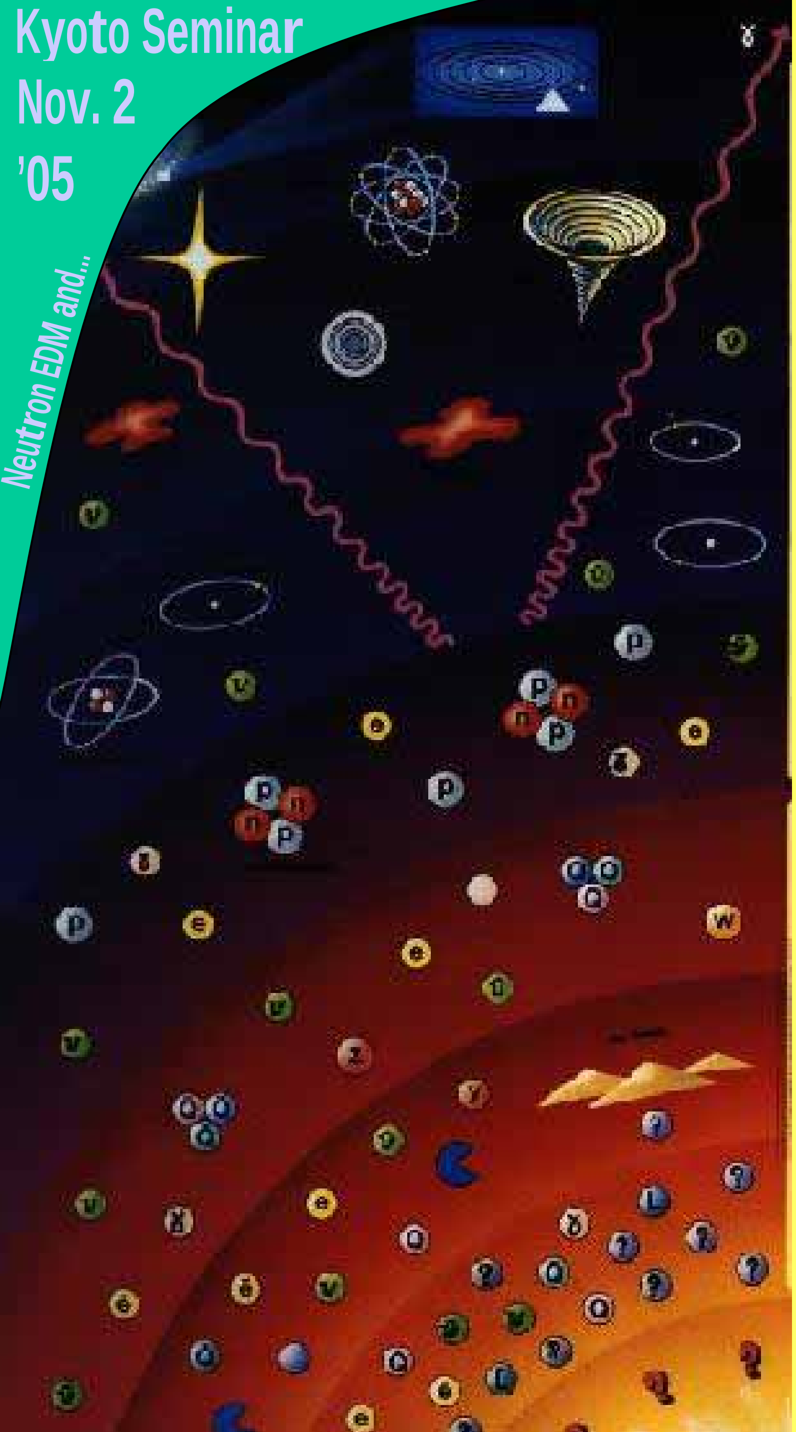
Measuring the Neutron Electric Dipole Moment - A Tiny Number with Big Implications

Dave Wark
Imperial/RAL

Kyoto University
Nov. 2nd, 2005

Imperial College London

CCLRC
Rutherford Appleton Laboratory



The Universe passed through a period of the very high energy density early in the Big Bang

Matter was produced via reactions like $\gamma+\gamma\rightarrow p+\overline{p}$

This should have produced equal quantities of matter and anti-matter.

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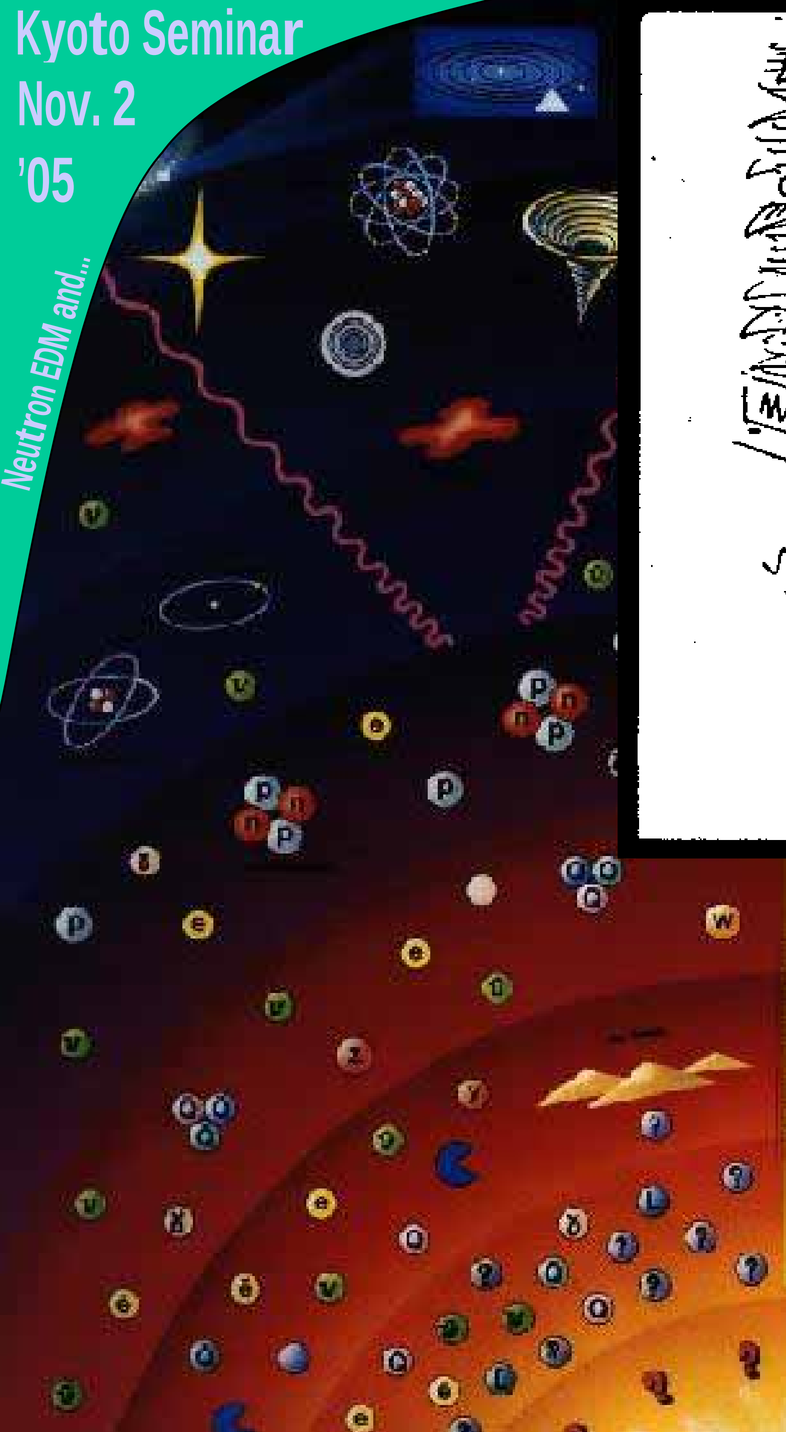

It didn't....

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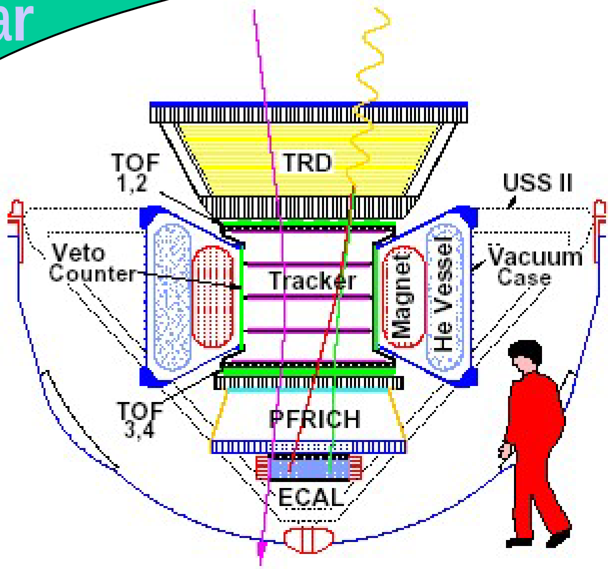
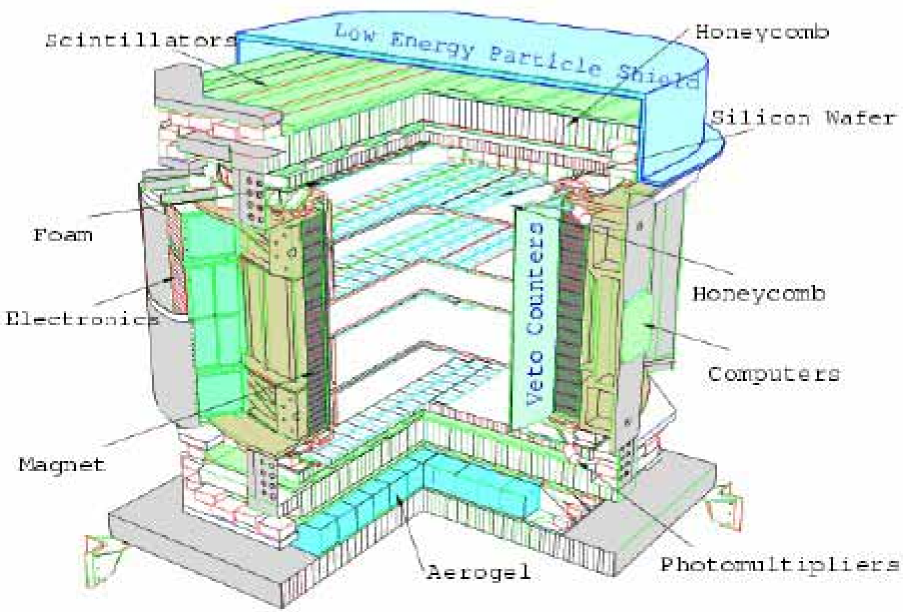
Imperial College/RAL

Kyoto Seminar
Nov. 2
'05

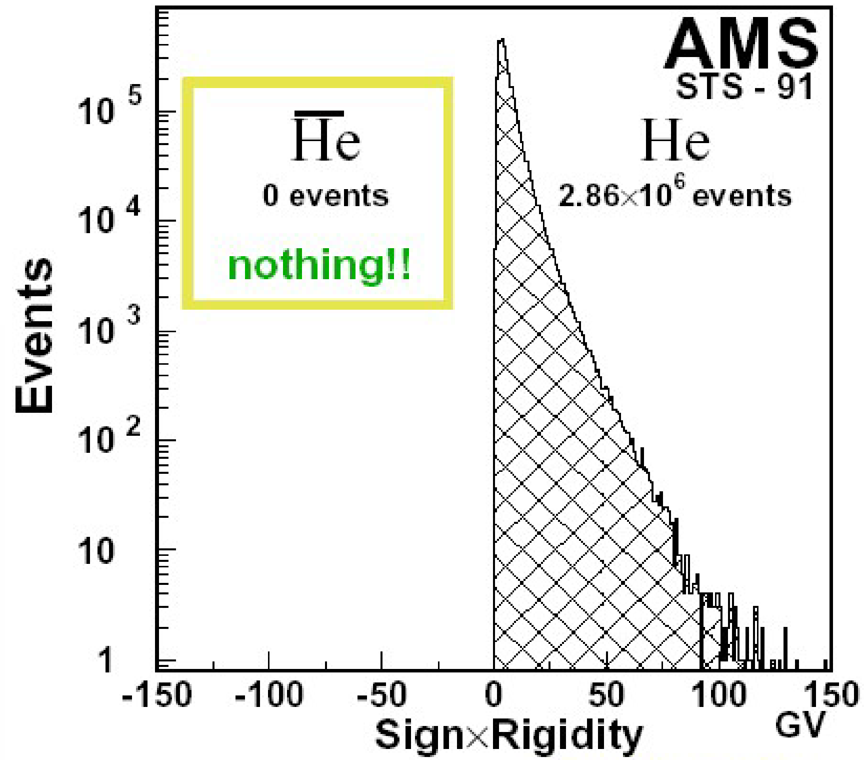
Neutron EDM and...



The AMS-01 Detector



Results of AMS-01
$\overline{He}$ search |Z| =2



(Rigidity = p/Z)

Also, no antinuclei found with |Z|>2

"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.

...CP violation

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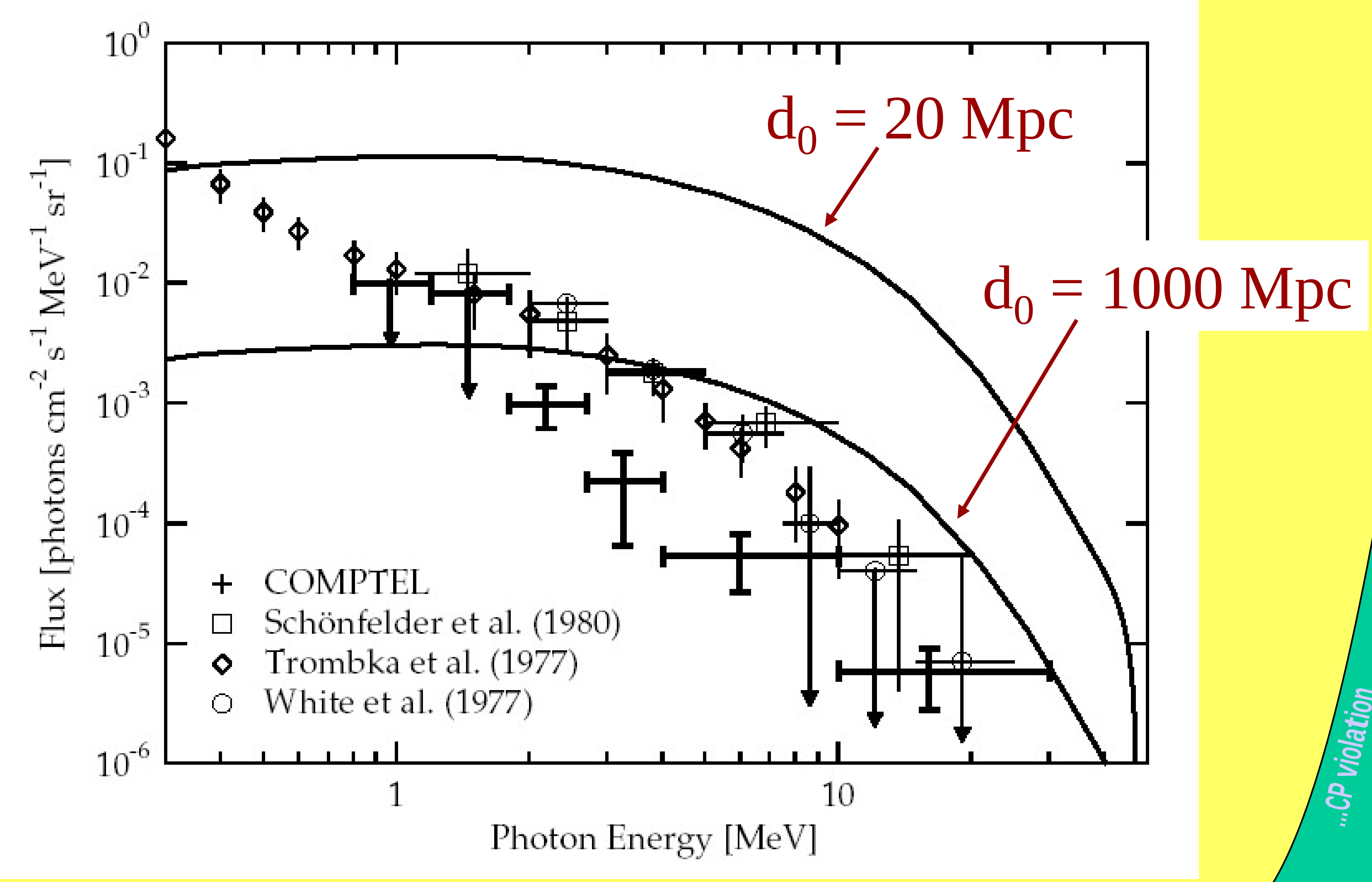
Diffuse γ-ray flux expected from annihilation



See Cohen, De Rujula, Glashow; astro-ph/9707087

Sakharov Conditions:

(A.D. Sakharov, JETP Lett. 5, 24-27, 1967)

- To produce a matter ↔ anti-matter asymmetry requires:
  - Baryon number violation
    - ☒ Conserved at tree level in the Standard Model
    - ☑ More complex SM processes lead to B violation
  - C violation

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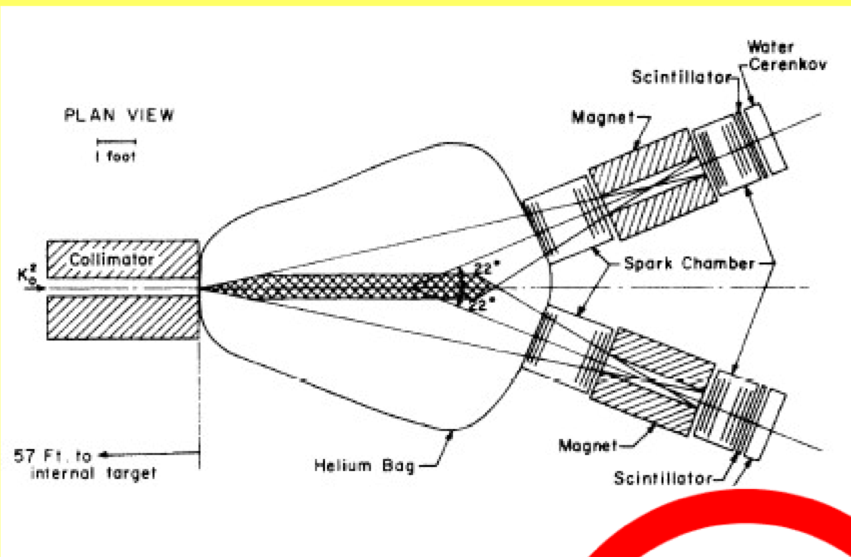
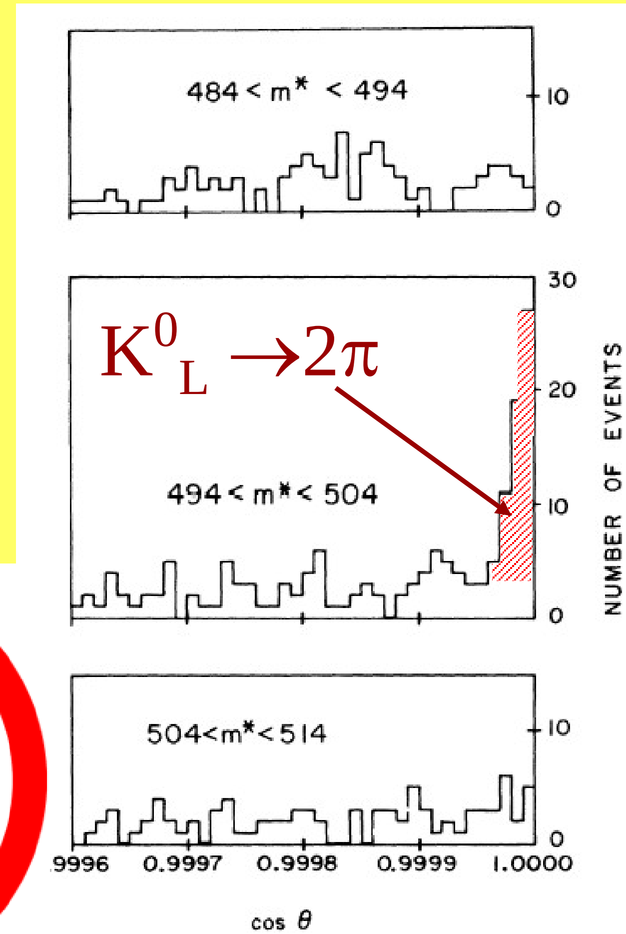
  - ➢ C and CP violation

UME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

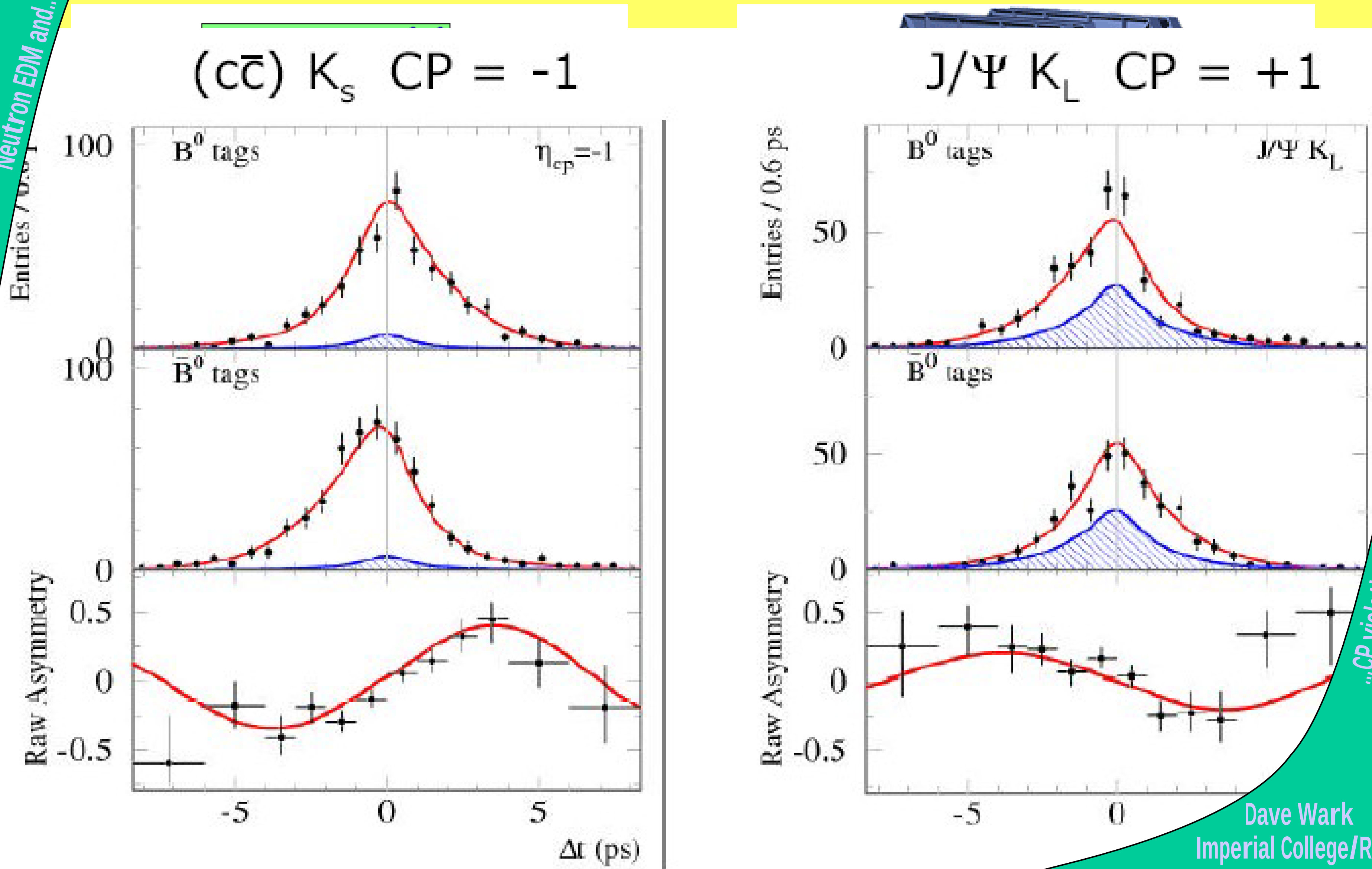
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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





CP violation in weak decays



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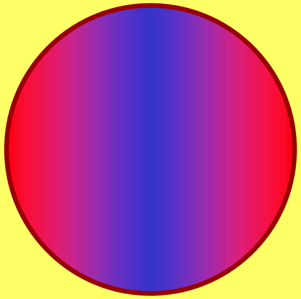
  - C and CP violation ☑
  - Departure from thermal equilibrium
    - ☑ Phase transitions
    - ☑ Expansion of the Universe

So are we done now?

- No (you don't get out of this talk that easy)
- The CP violation in the Standard Model is too small by many orders of magnitude to explain the observed matter-anti-matter asymmetry (also called the baryon asymmetry) of the Universe (hep-ph/0303065)
- There must be CPV in laws of physics we don't know yet!
- We have to keep looking…

Neutron Electric Dipole Moment



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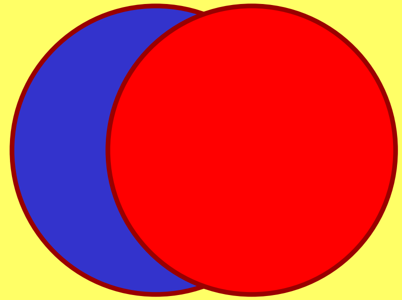

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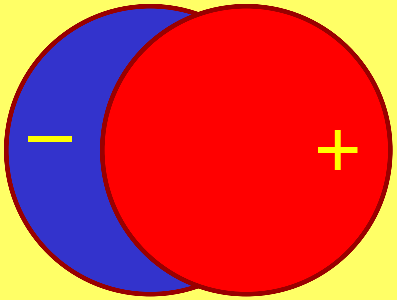

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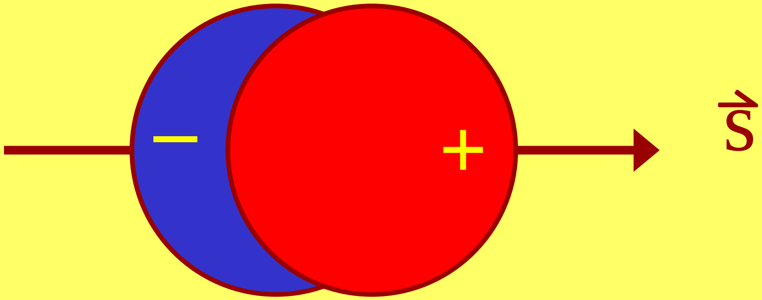
Neutron Electric Dipole Moment



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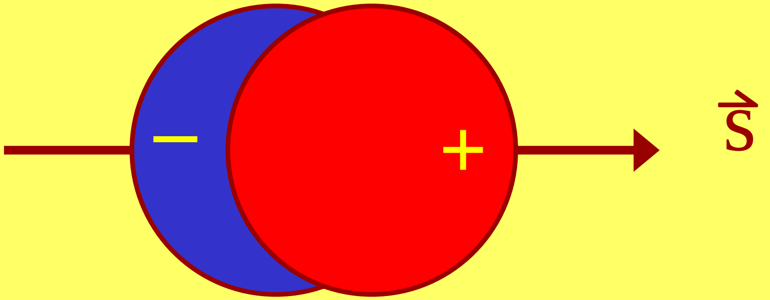

Would lead to a non-zero value for $\vec{d}_n$, either parallel or anti-parallel to $\vec{s}$

$\vec{d}_n$ would be:

P odd

T odd

CP odd!

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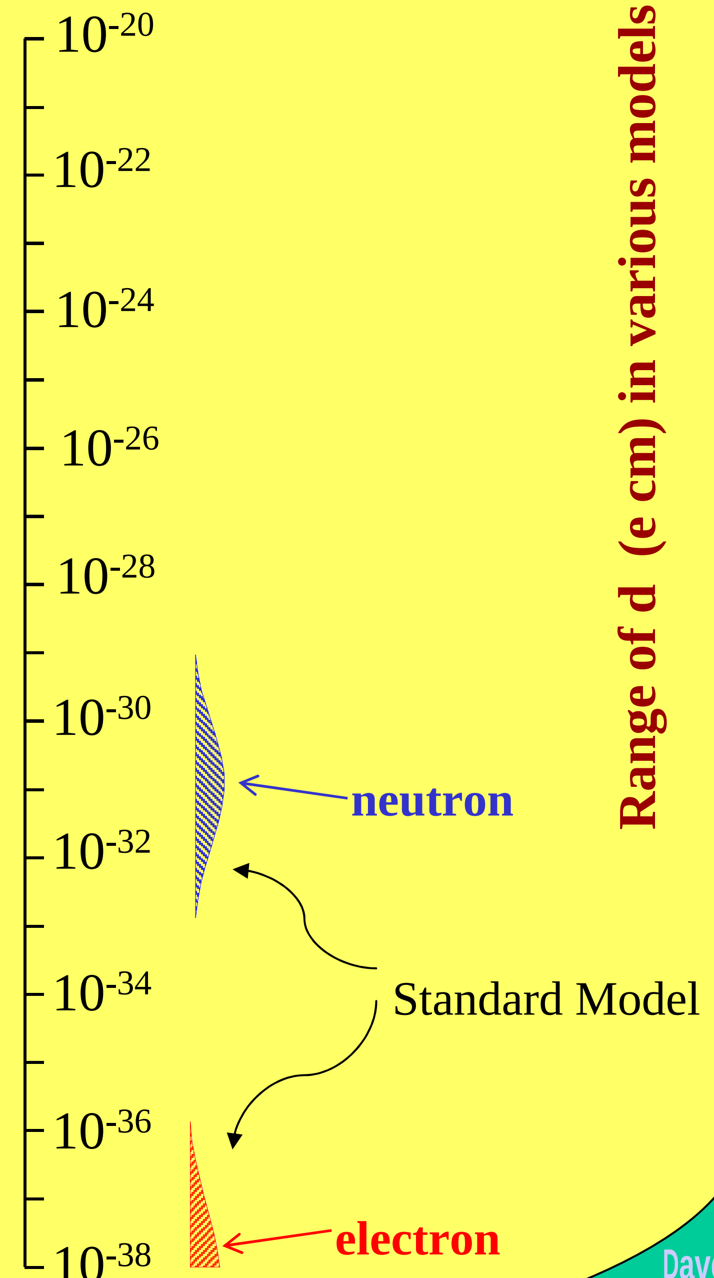
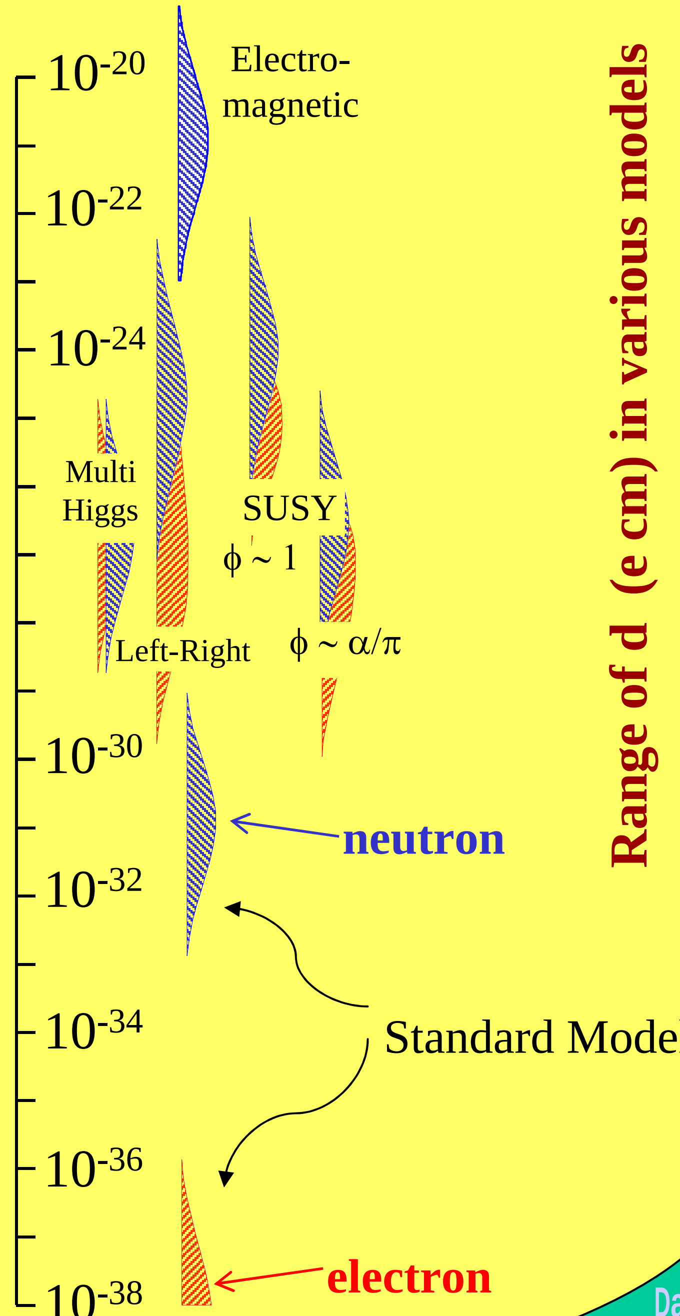
- Particle EDMs are a particularly promising laboratory for CP violation
  - The Standard Model contribution is very small
  - Contributions from new physics tend not to be


10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
neutron
Standard Model
electron
Range of d (e cm) in various models



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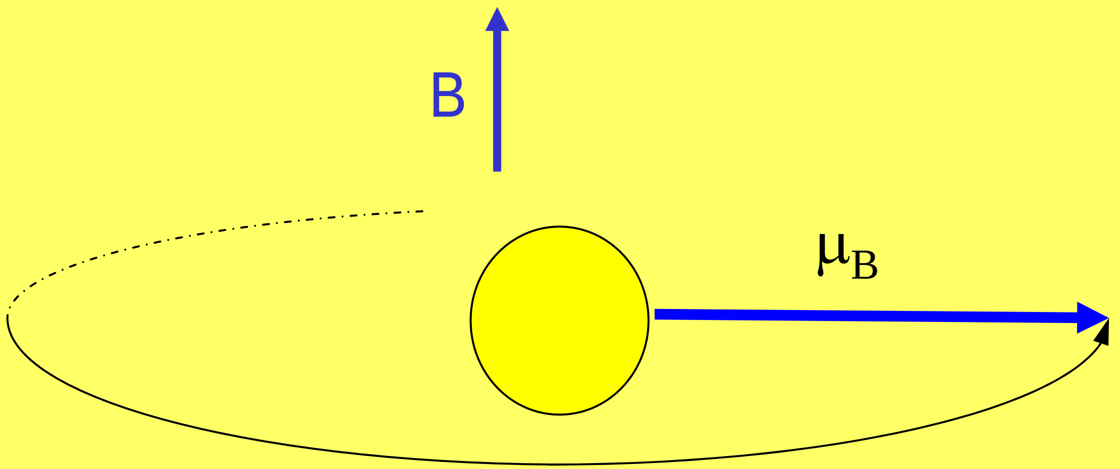
Basic Idea of the Measurement



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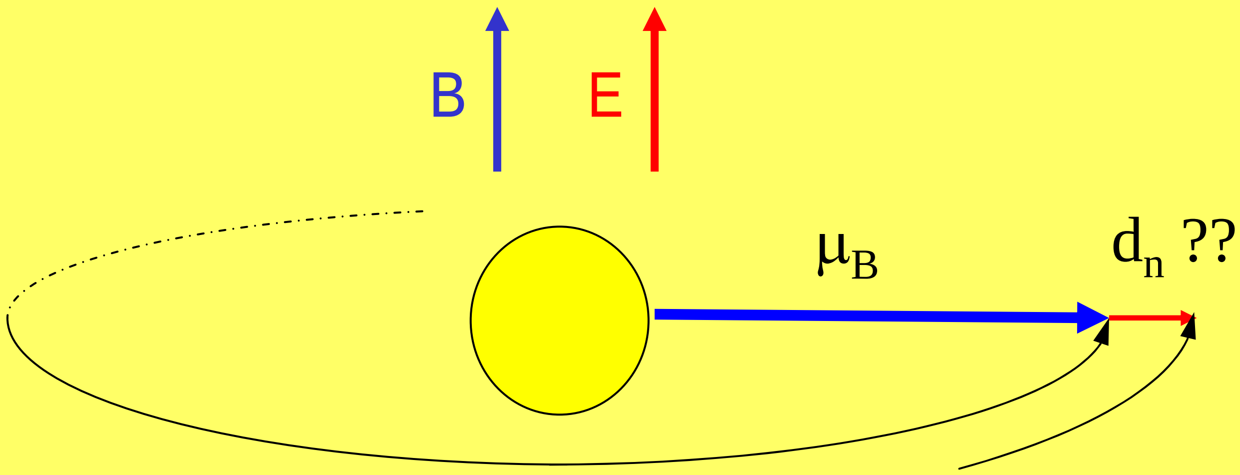

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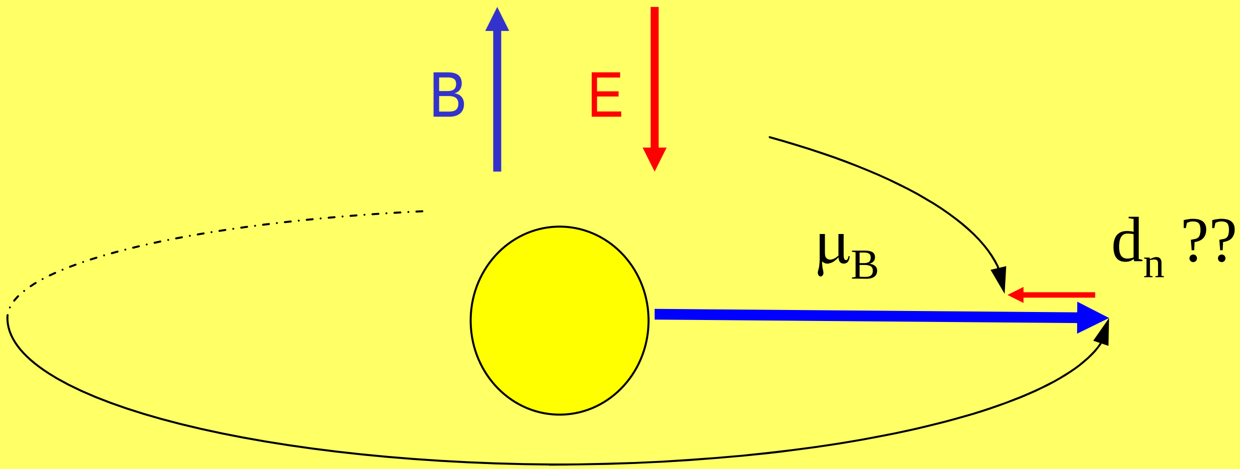
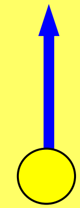


Look for a shift in the Larmor frequency of $2 \cdot E \cdot d_n$ as E is flipped relative to B

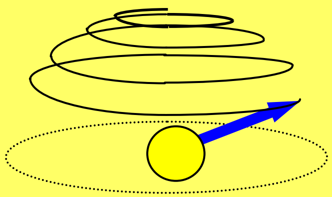
The Ramsey Separated Oscillator Method

1.



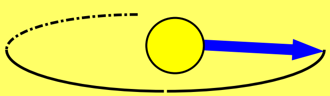
"Spin up" neutron...

2.



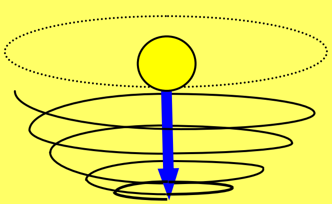
Apply π/2 spin flip pulse...

3.

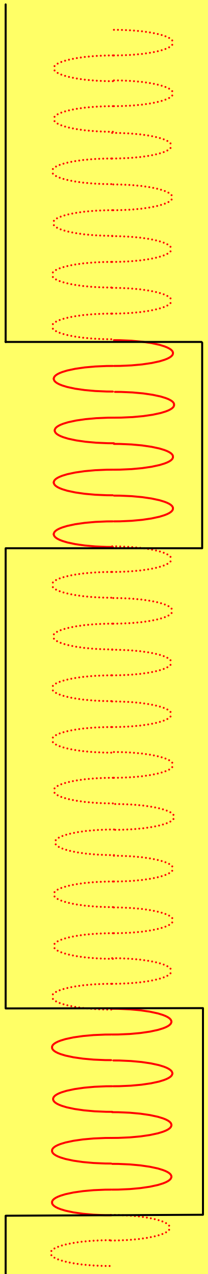


Free precession ...

4.

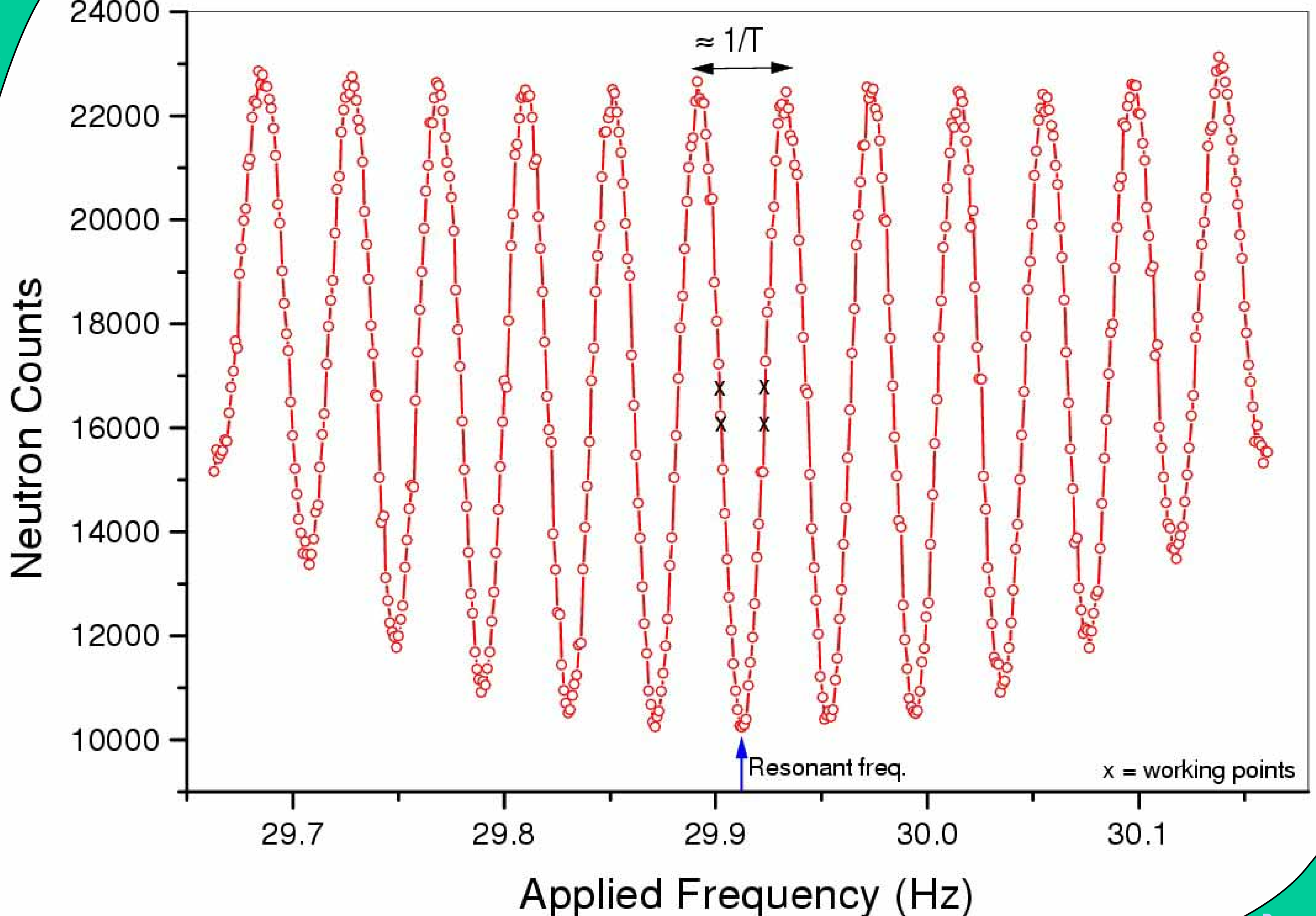


Second π/2 spin flip pulse.



N.F. Ramsey, Phys.Rev.**76** 996 (1949)

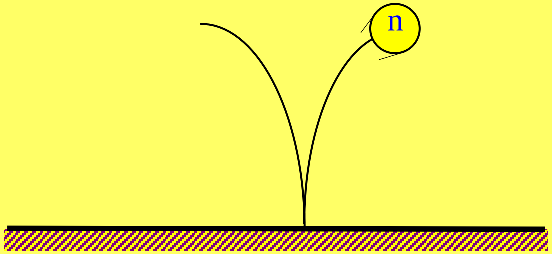
Ramsey Resonance Curve



- 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.



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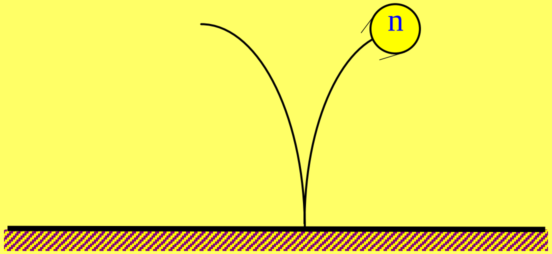


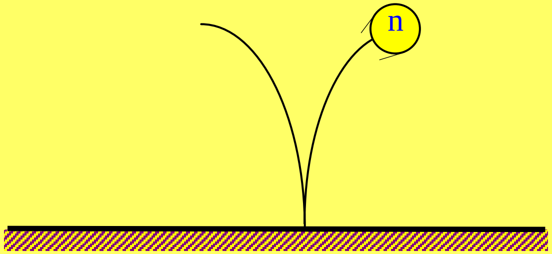
v_c depends on orientation of neutron spin, so can polarise by transmission.

λ>> interatomic spacing; neutrons see Fermi potential V_F

Critical velocity for reflection:

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

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



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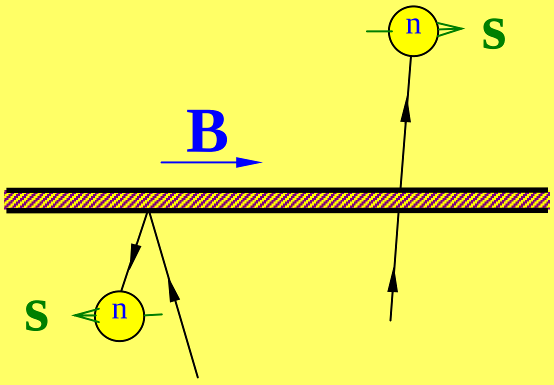

Prepare neutrons in polarisation state 1, execute Ramsey cycle and measure the number left in states 1 and 2, repeat with B and E fields parallel (↑↑) and anti-parallel (↑↓), then:

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

Where α = the product of the neutron polarisation and the analyzing power, E is the applied field strength, T is the storage time, and N is the number of neutrons detected

The resulting "statistical" sensitivity is:

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

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

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The Institute Laue-Langevin

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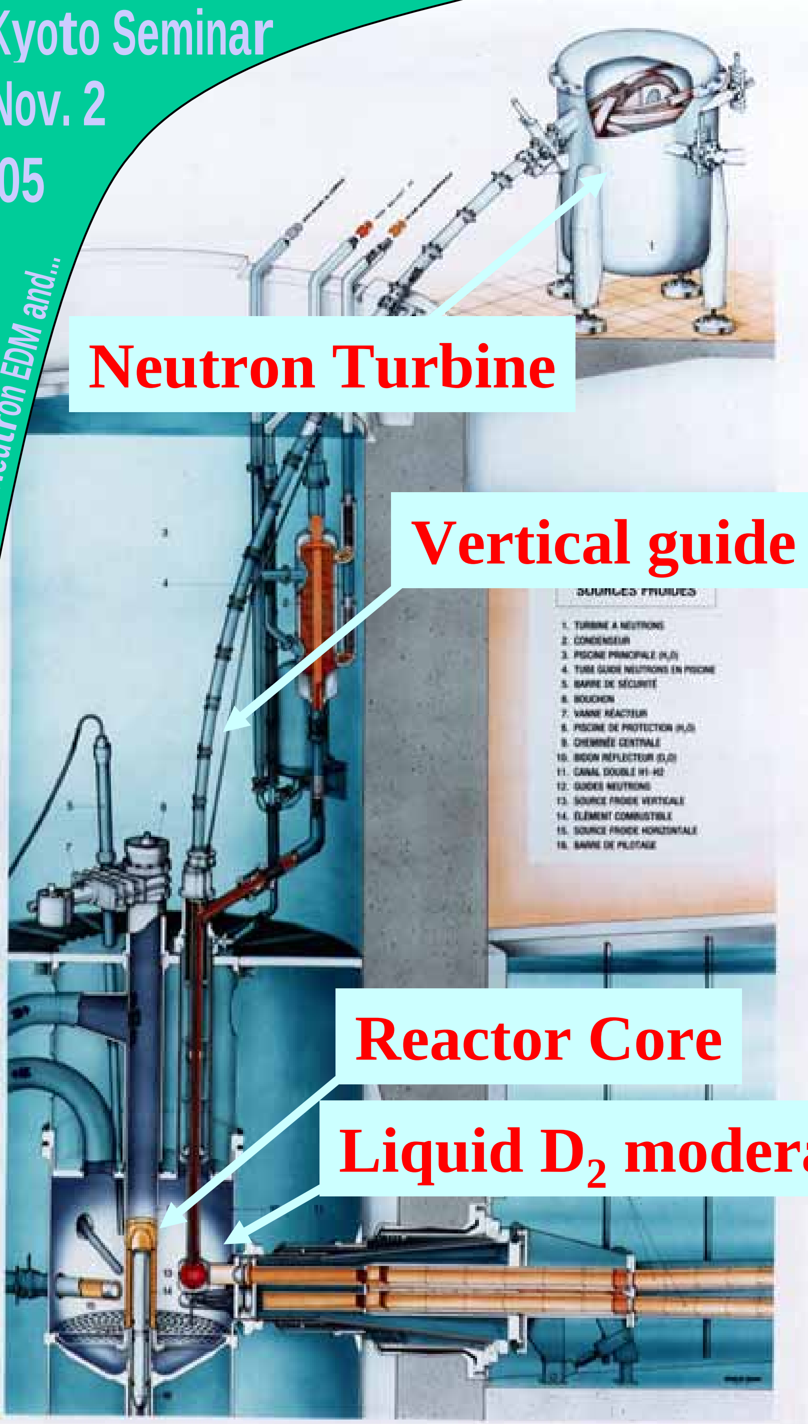

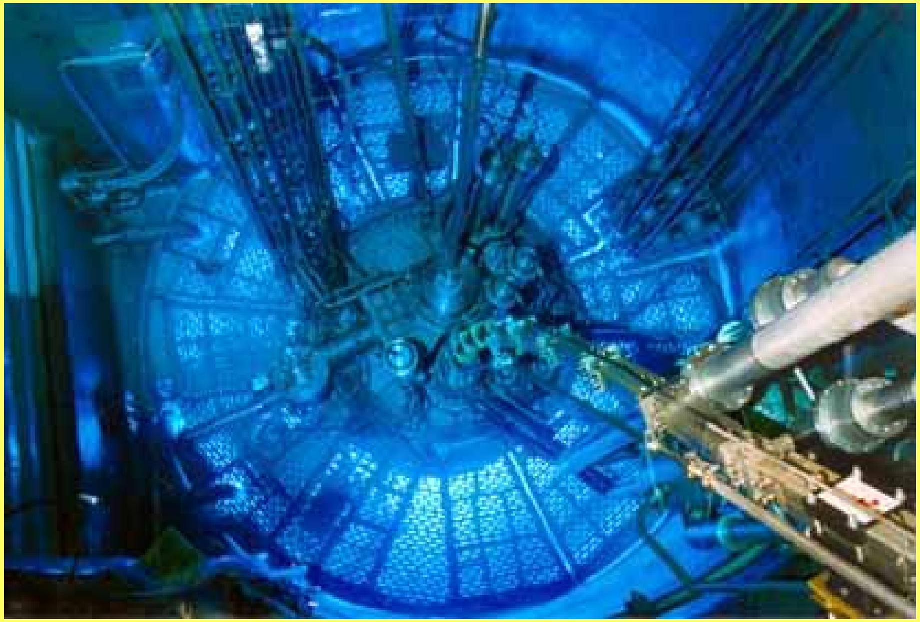

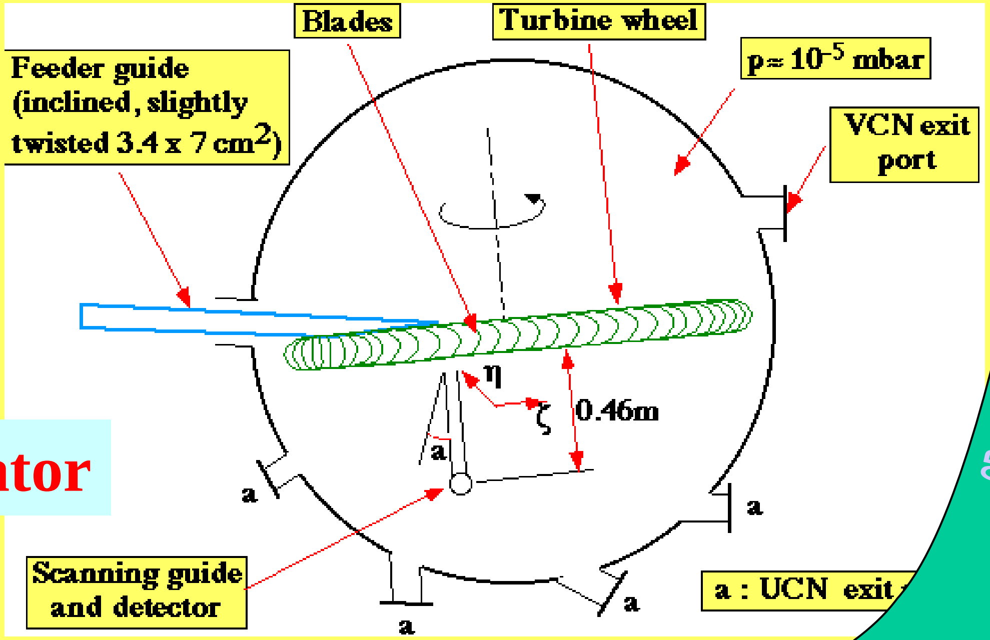

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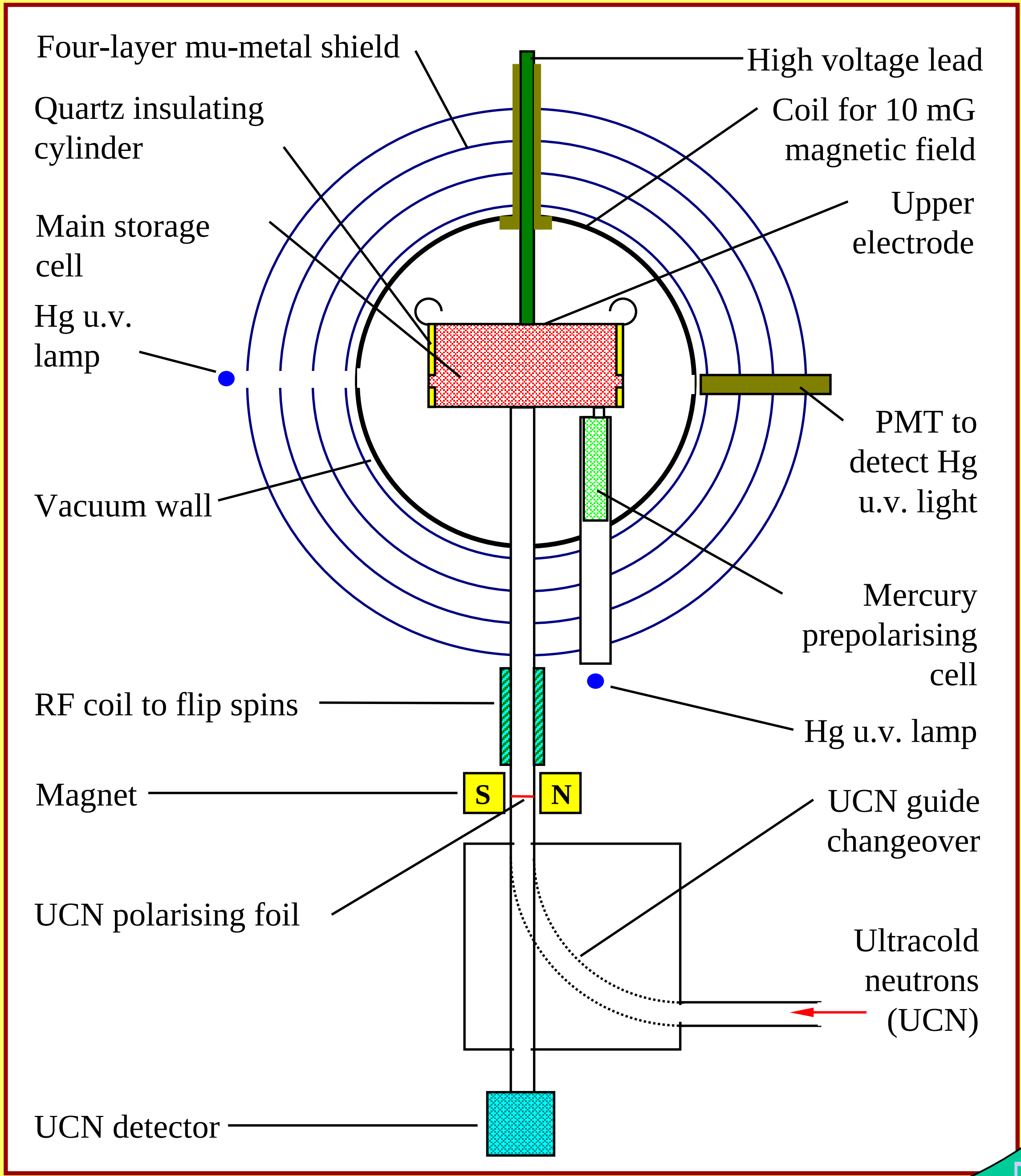
Neutron Energy Annoyances

- "Cold" neutrons have:
  - E ≈ 0.1 – 1 meV
  - v ≈ 100 m/s
  - λ ≈ 1-10 Å
  - T ≈ 10 K
- "Ultra-cold" neutrons have:
  - E ≈ 1 – 10 neV
  - v ≈ 0-15 m/s
  - λ ≈ 1000 Å
  - T ≈ real small (normally not thermal)

Current Room-Temperature nEDM Experiment



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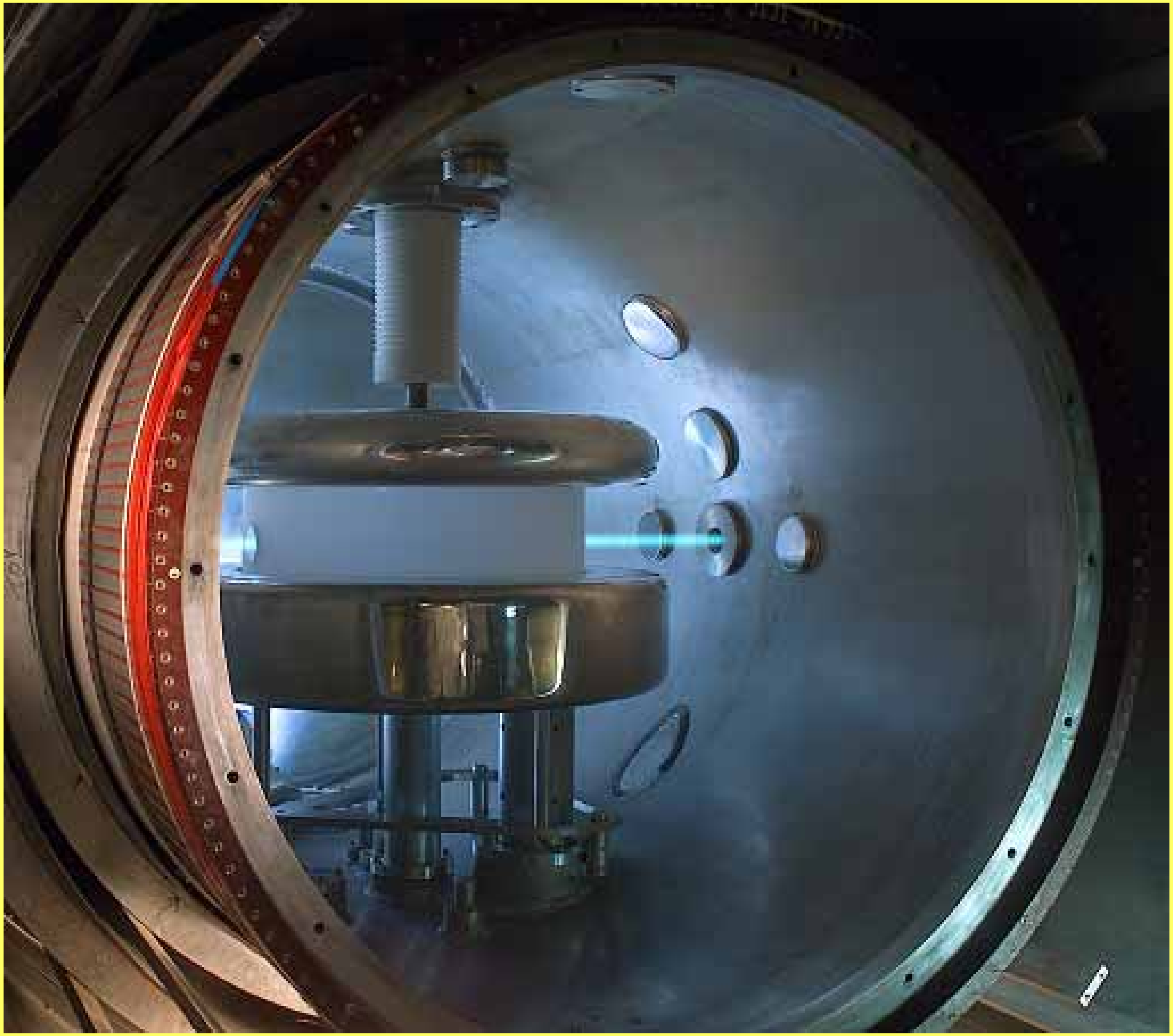

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NEUTRONS FOR SCIENCE

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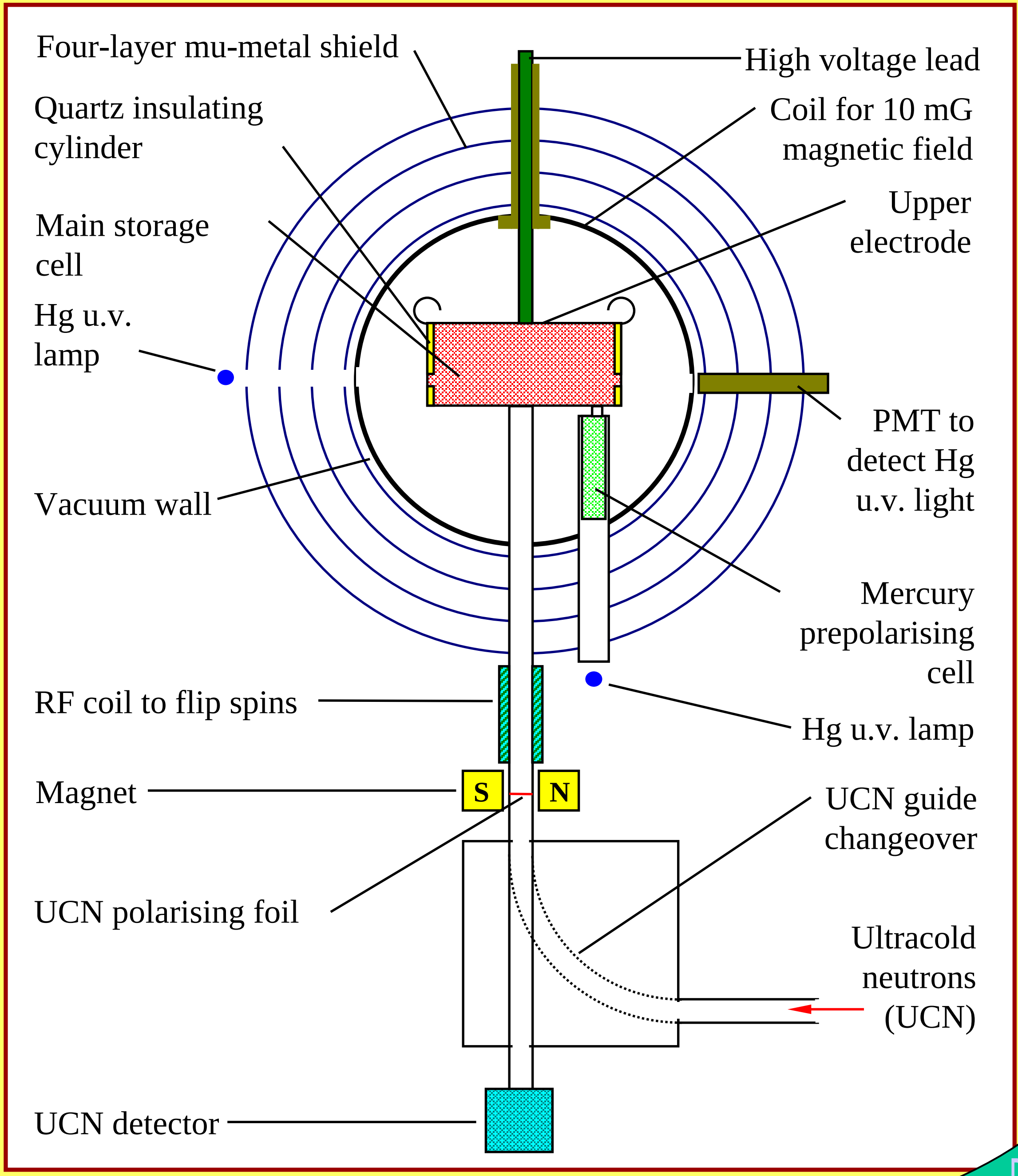

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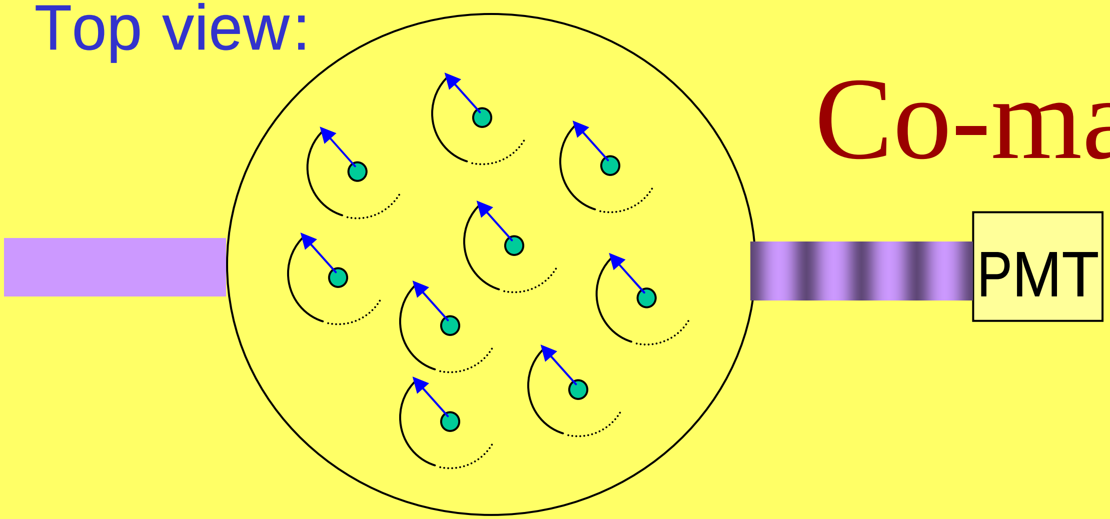
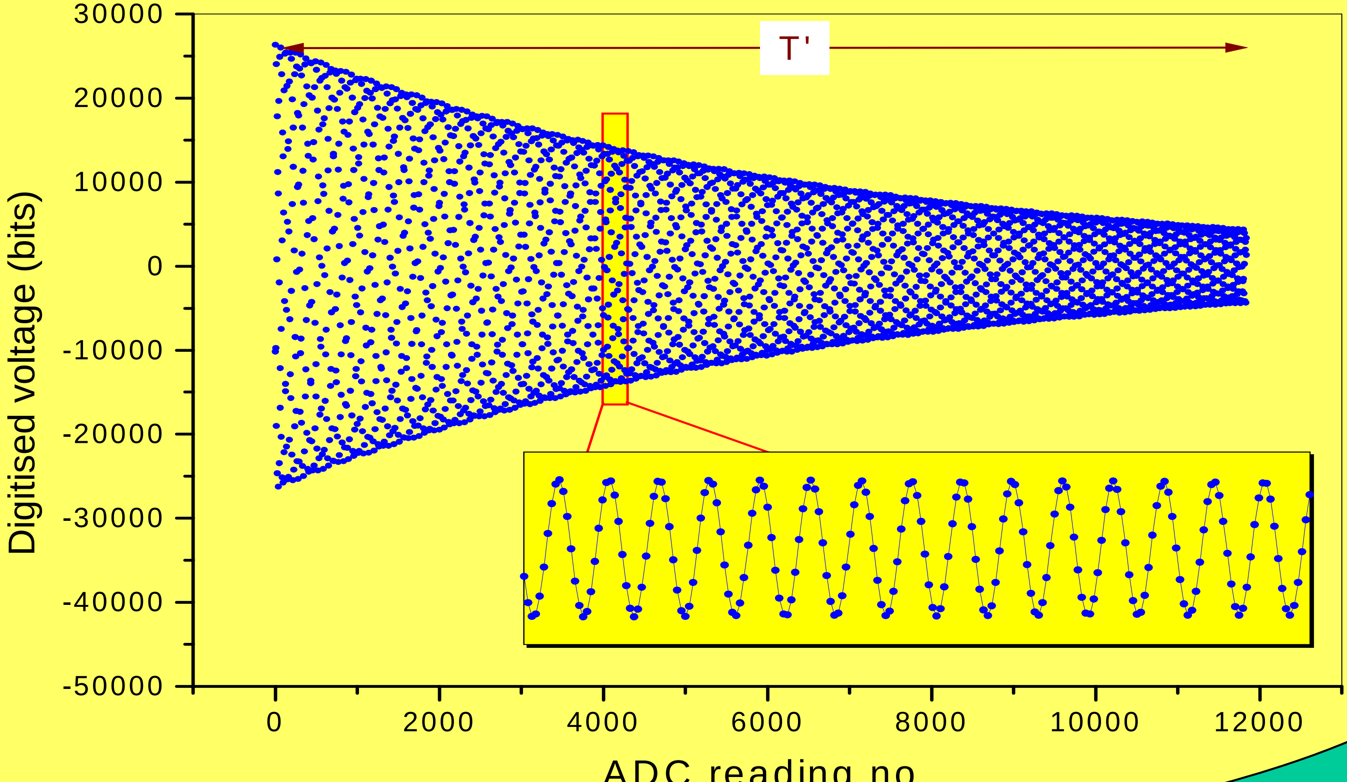
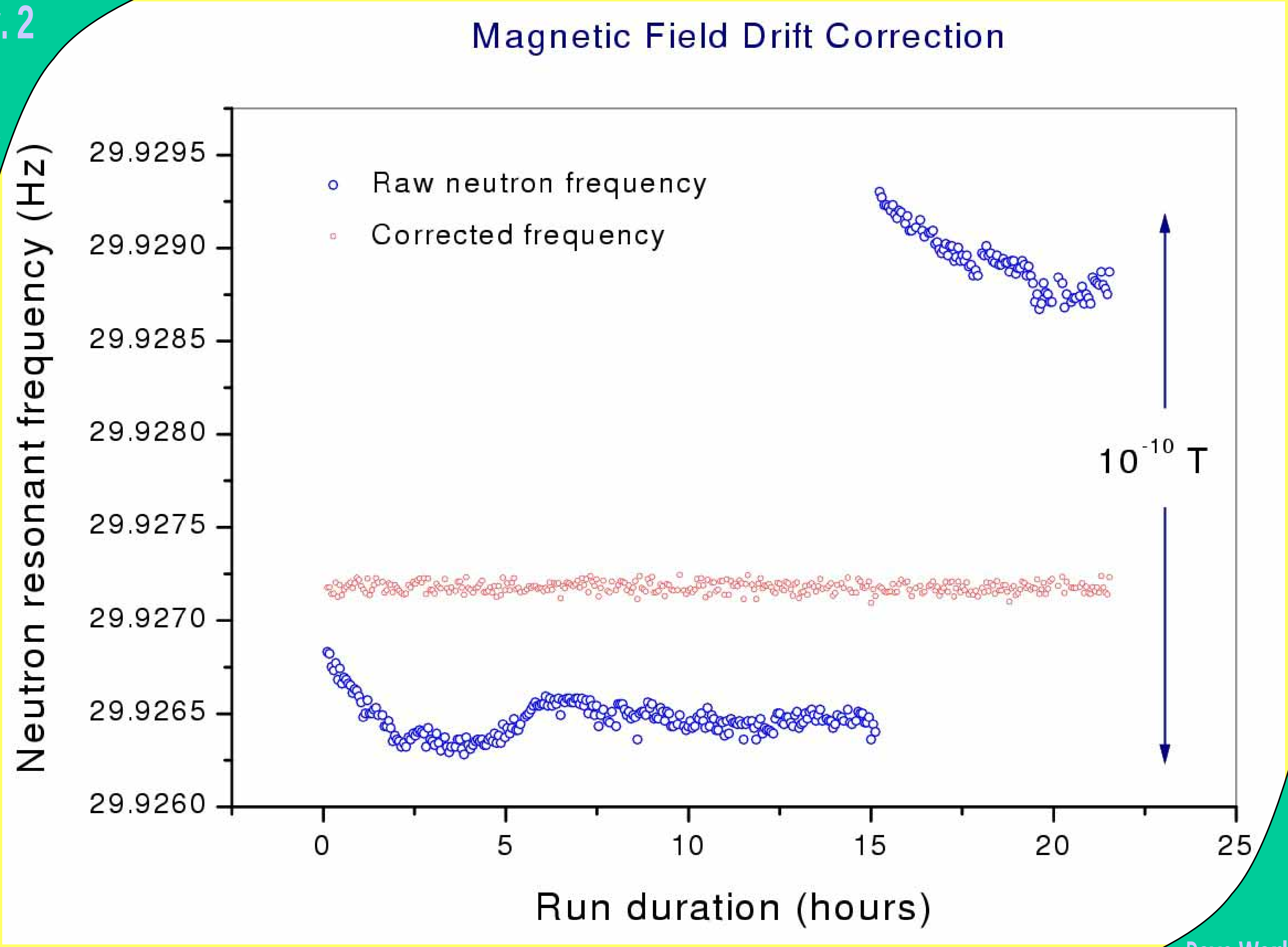
Hg Co-magnetometer

Top view:







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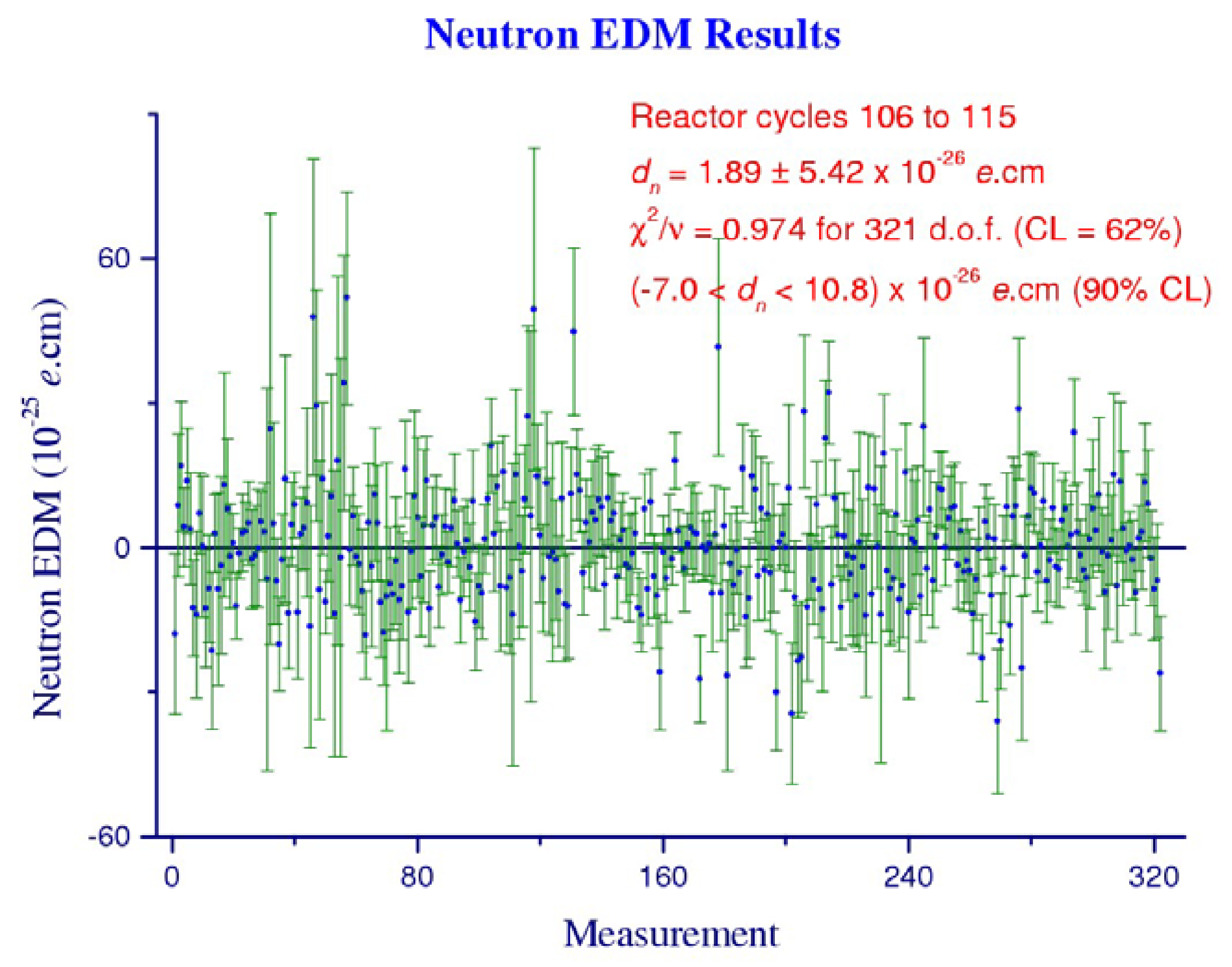
1999 Results

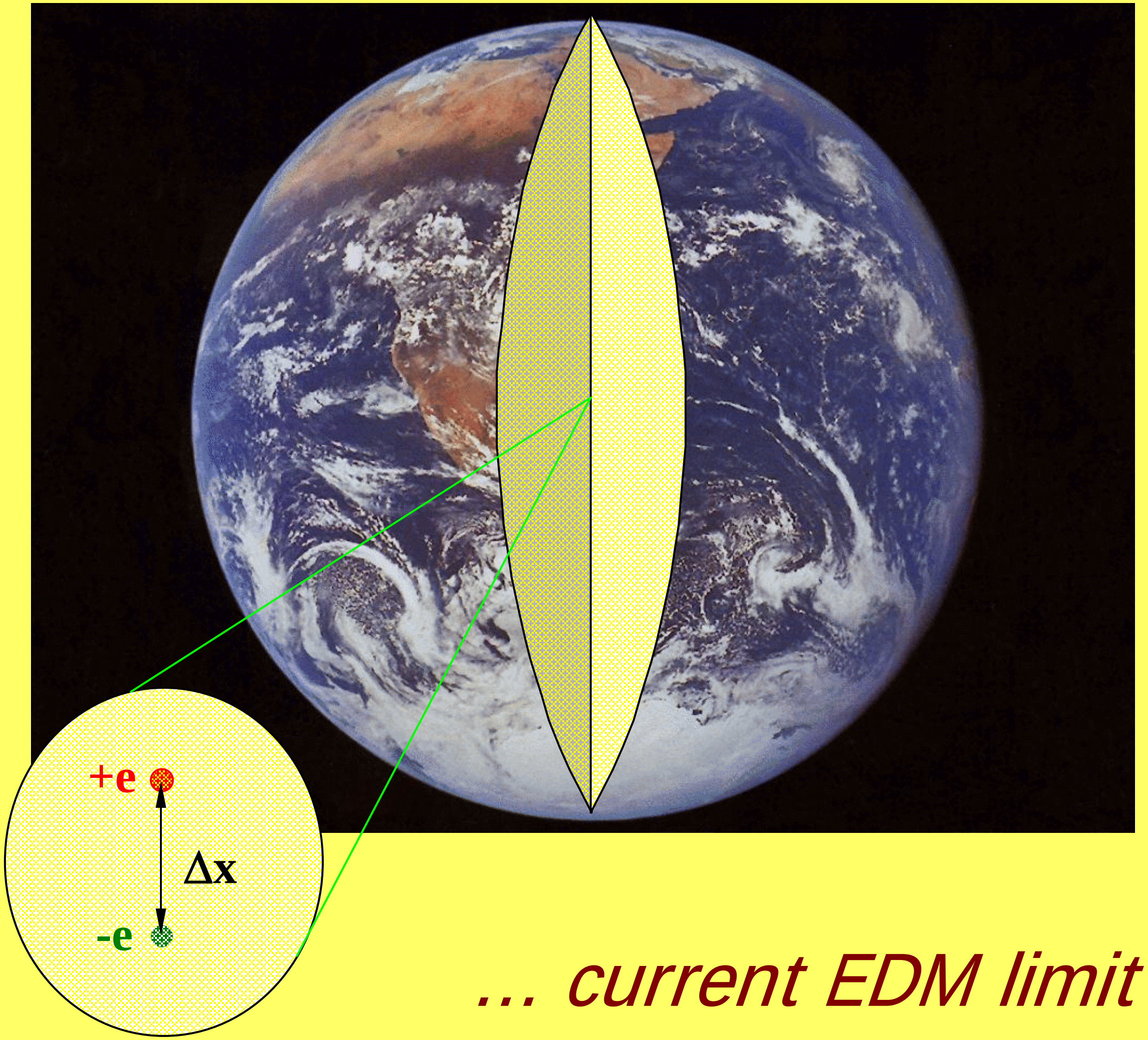
(PG Harris *et al*, PRL **82**, 904 (1999))



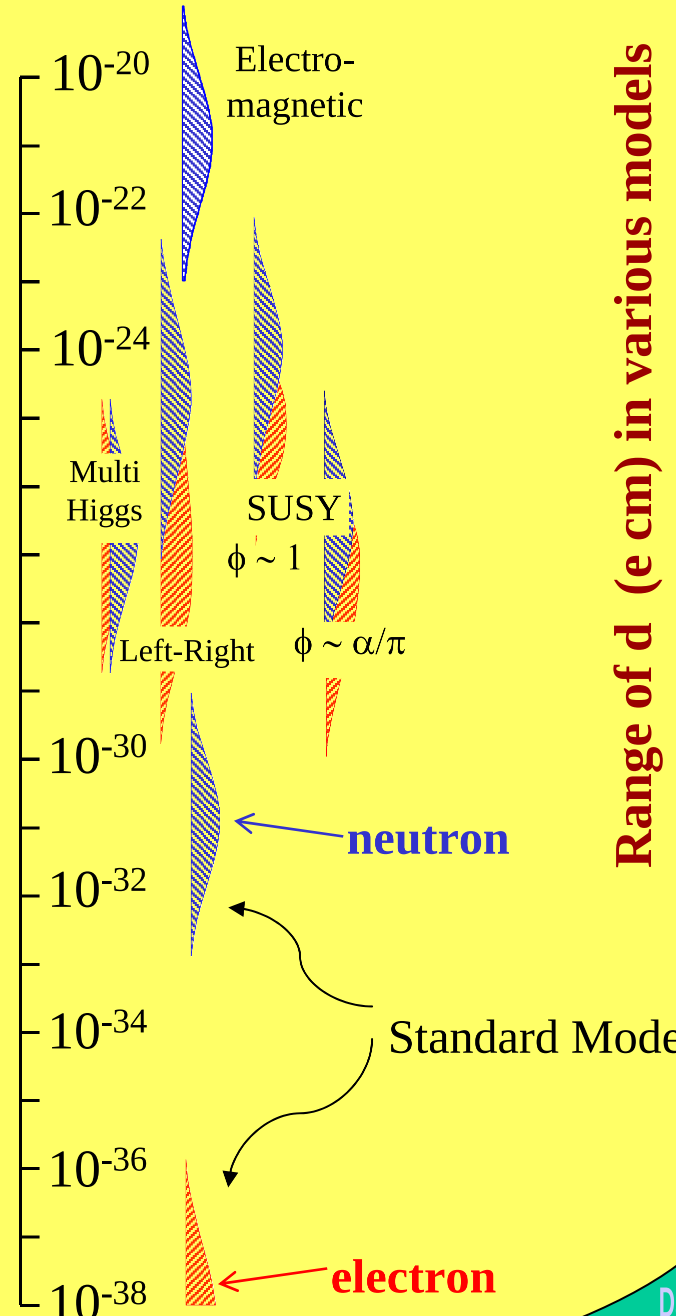
$$d_n = (1.9 \pm 5.4)\times 10^{-26}\ \mathrm{e\ cm} \Rightarrow$$

$$d_n \leq 6.3 \times 10^{-26}\ \mathrm{e\ cm}\ (90\%\ \mathrm{c.l.})$$

If neutron were the size of the earth...



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



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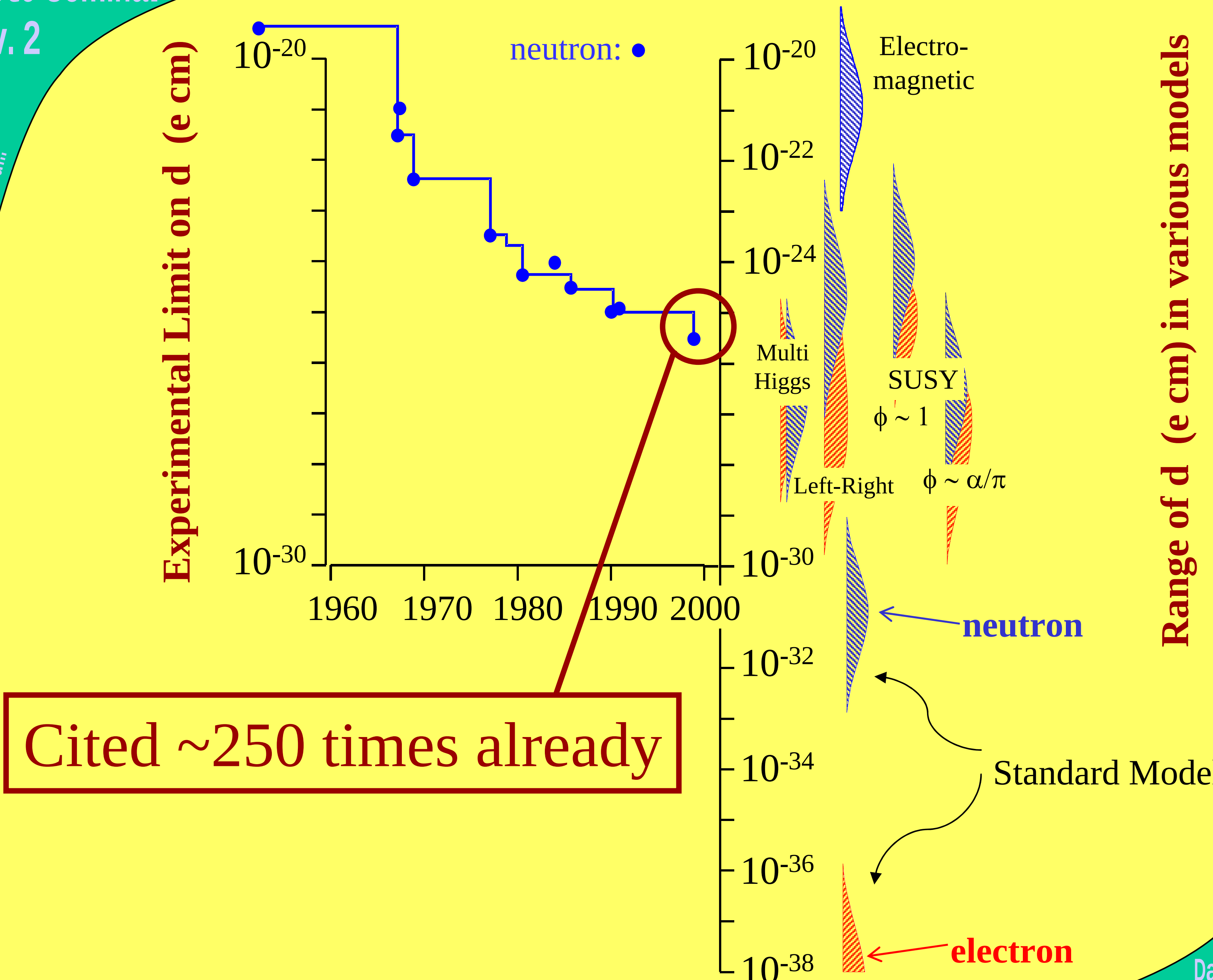

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Recall: $$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

	Published Data	Current Room-Temp	Cryogenic Experiment
α			
E			
T			
N			

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

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

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

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

New polarisers on Si wafers

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**	
	s		
	)		

Shorter, wider bottle
^{4}He buffer gas
Better cleaning methods

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		

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

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

Larger volume bottle
Better neutron guides
Loss of 50% from source

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

	Published Data	Current Room-Temp	Cryogenic Experiment
α	0.5	0.7	
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T	130 s	130 s	
N	13000	14000	

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Overall factor of ~3 improvement

	Published Data	Current Room-Temp	Cryogenic Experiment
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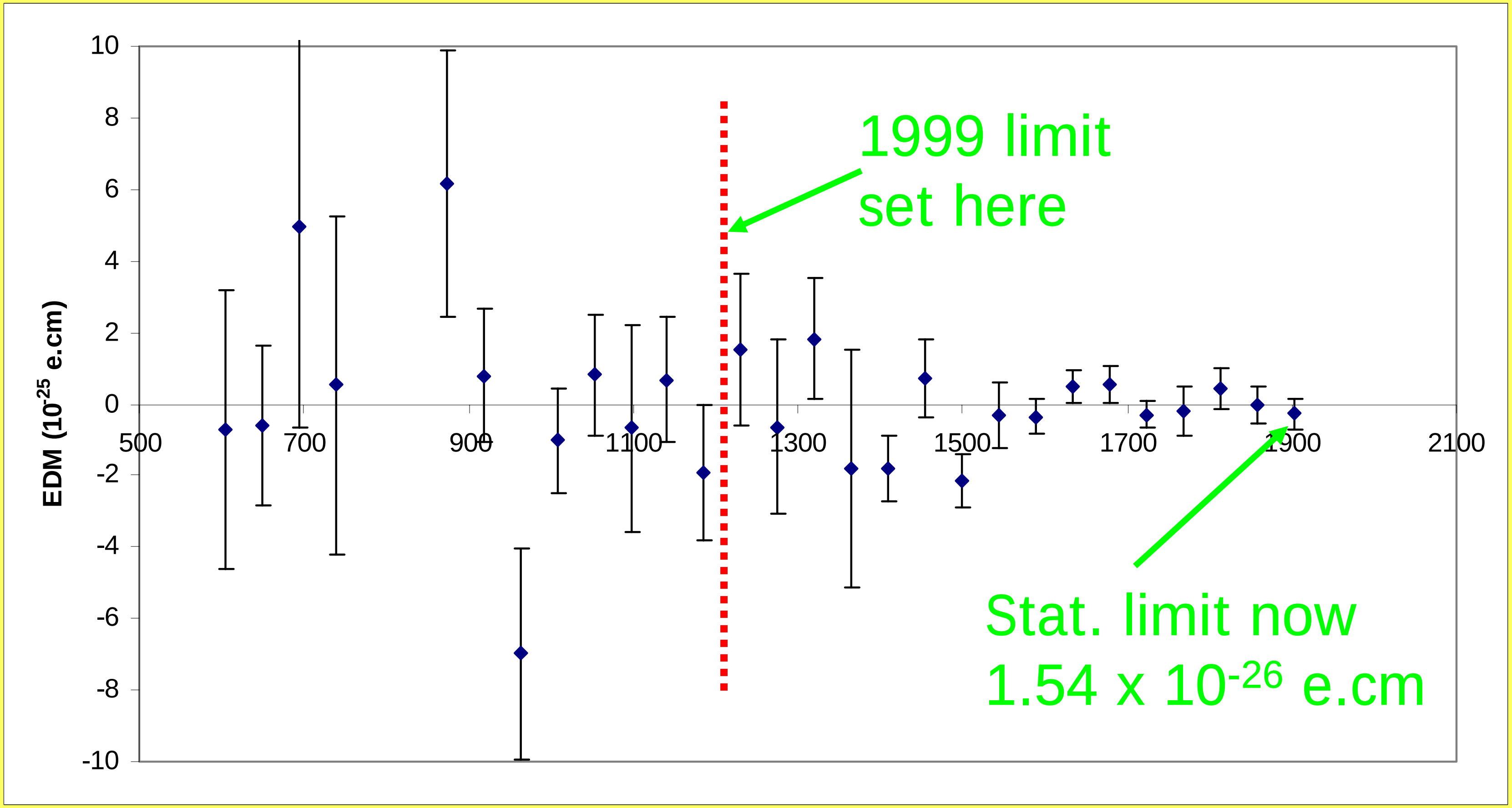

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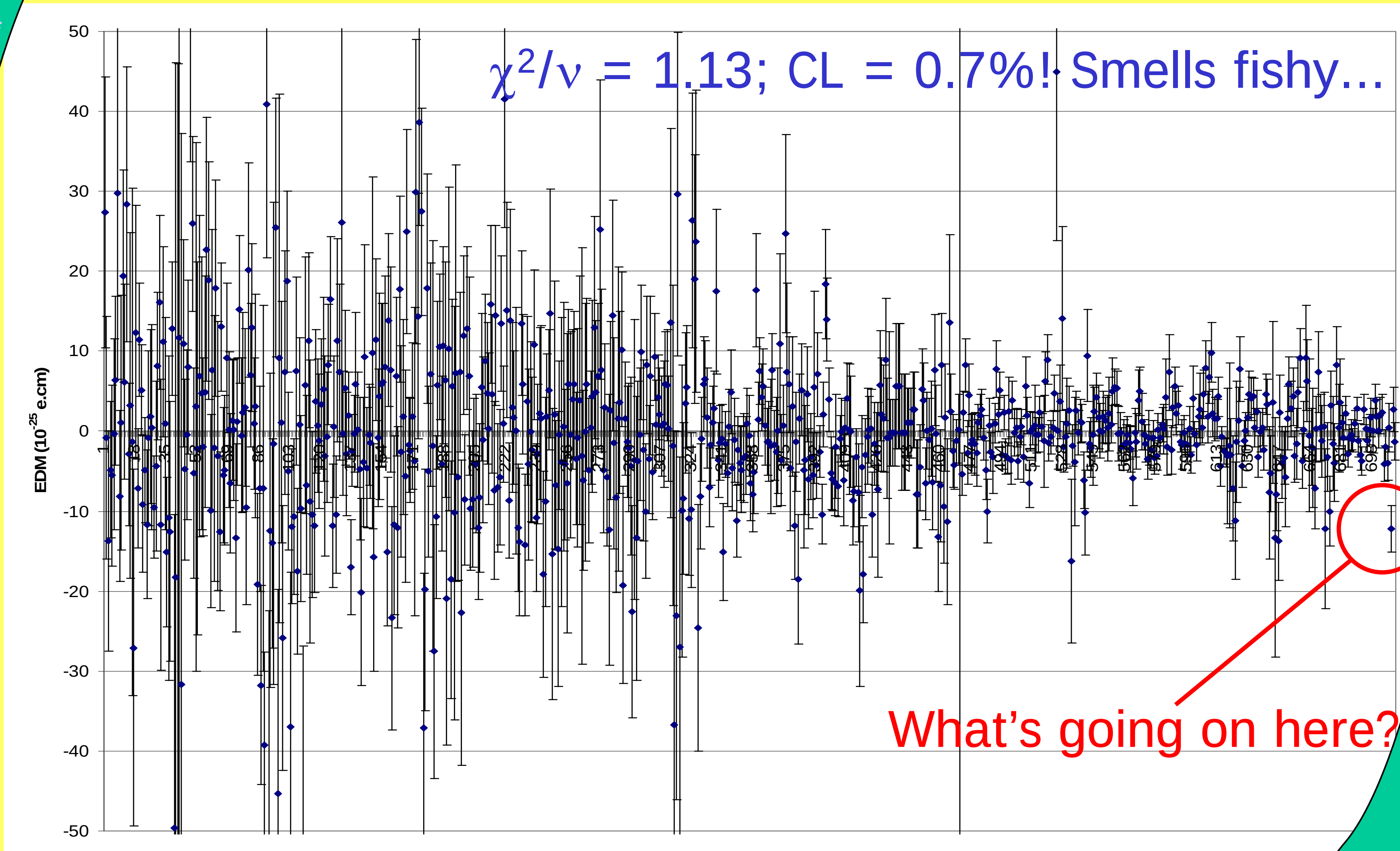
New nEDM data



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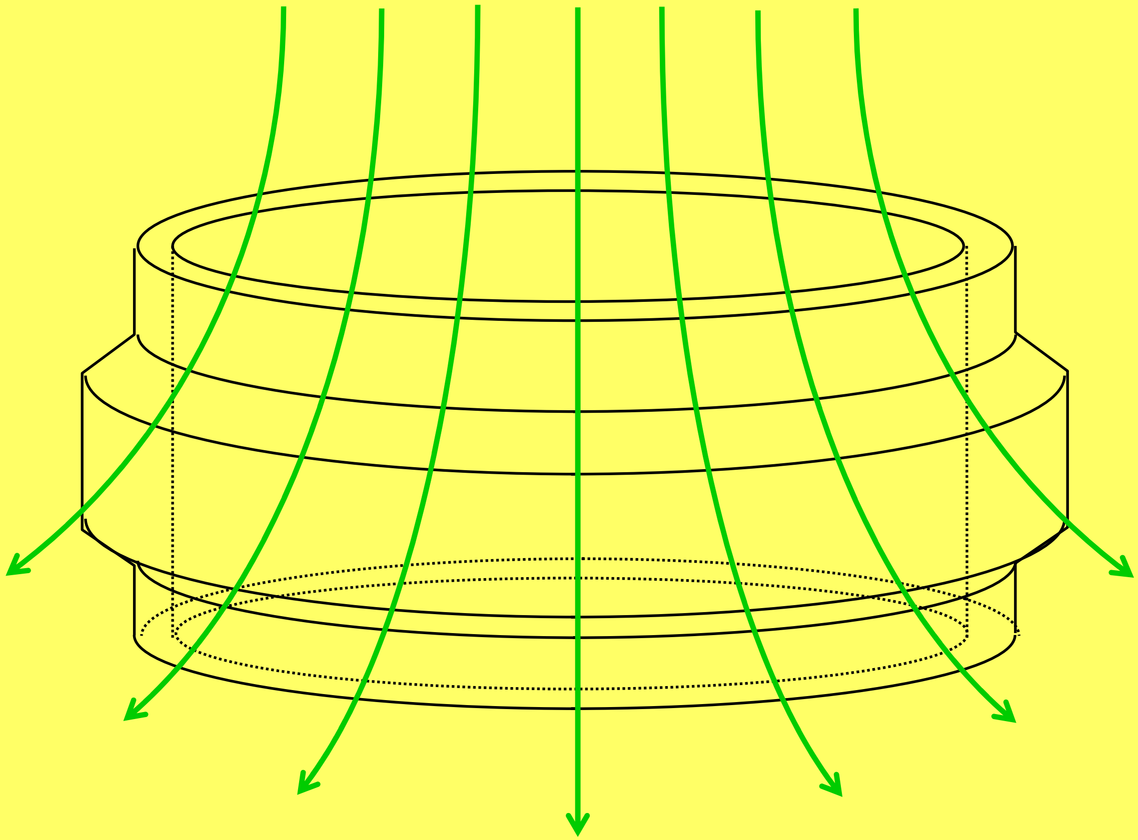
Conspiracy Theory

Two effects:

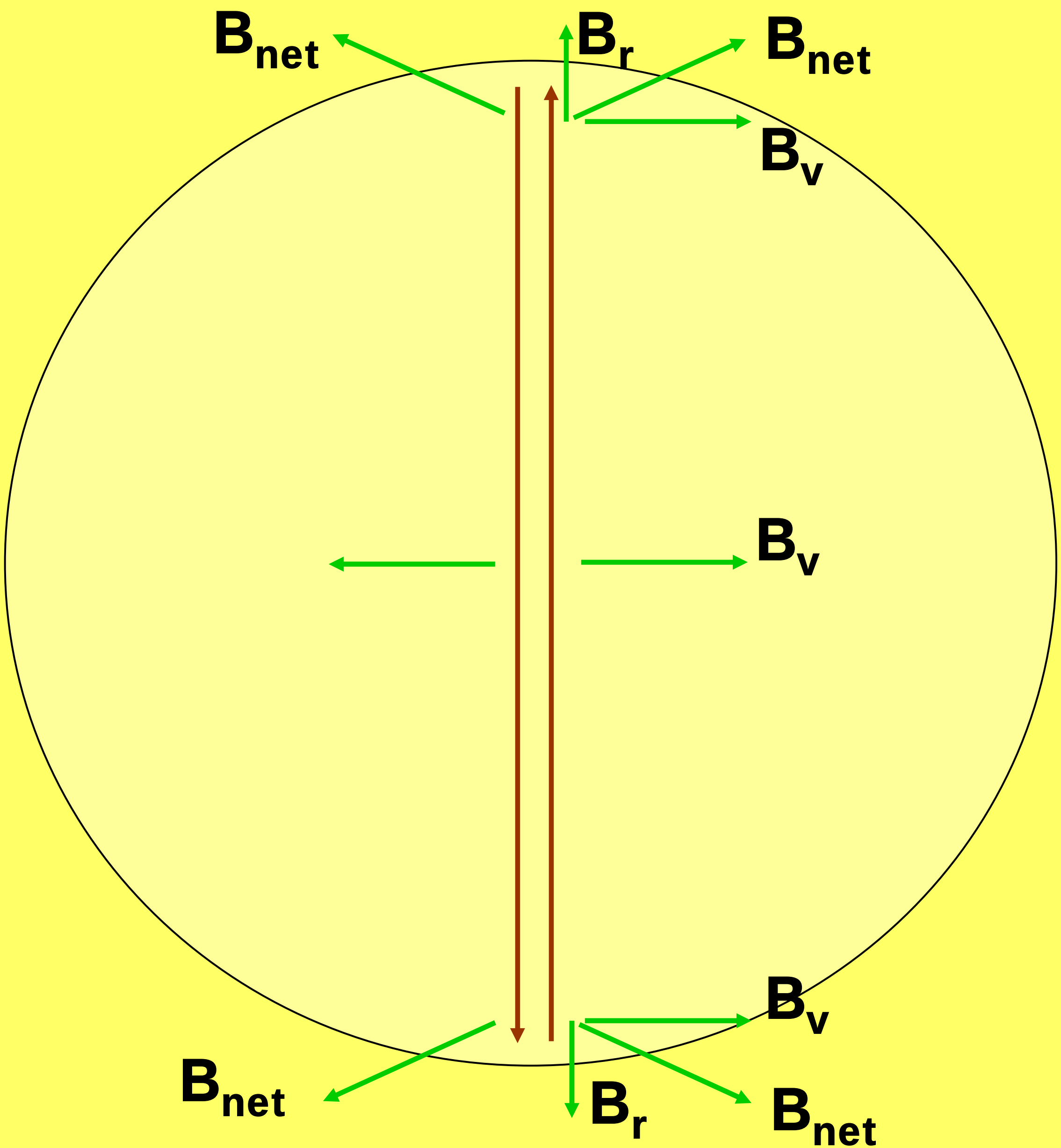
$$\frac{\partial B}{\partial z} \Rightarrow B_r \propto r$$



and, from Special Relativity, extra motion-induced field

$$B' = \frac{1}{\gamma} \frac{\vec{v} \times \vec{E}}{c^2}$$

Geometric Phase



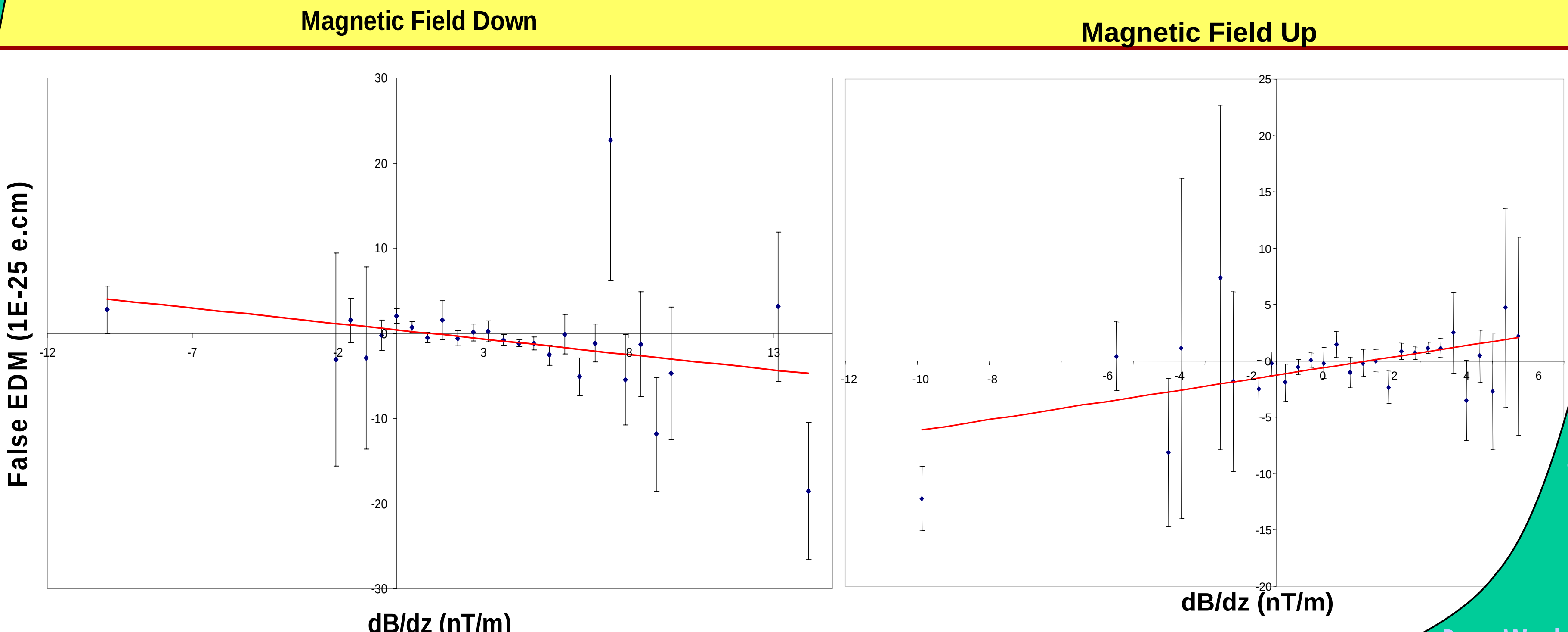
... so particle sees additional rotating field

Frequency shift $\propto$ E

Looks like an EDM

Field Gradient Effect

- Verified in data: Measured EDM depends upon applied magnetic field gradient, with exactly predicted dependence
- Mercury magnetometer now provides our largest systematic!
- More precise field measurements will allow us to compensate this effect to ~4x10^{-27} e.cm



Error Budget for Total Data Set

Statistical	1.54E-26 e.cm
Dipole & quadrupole shifts	6E-27 e.cm
Enhanced GP dipole shifts	4E-27 e.cm
(**E** x **v**)/c^2 from translation	1E-27 e.cm
(**E** x **v**)/c^2 from rotation	1E-27 e.cm
Light shift: direct	8E-28 e.cm
B fluctuations	7E-28 e.cm
E forces – distortion of bottle	4E-28 e.cm
Tangential leakage currents	1E-28 e.cm
AC B fields from HV ripple	<1E-28 e.cm
Light shift: GP effects	included

My colleagues announced new results at SUSY05 (preliminary)

$d_n = (-0.31 \pm 1.54 \pm 1.00) \times 10^{-26}$ e.cm

New (preliminary) limit:
$|d_n| < 3.1 \times 10^{-26}$ e.cm (90% CL)

Preprint expected soon

How will we do better?

Dave Wark
Imperial College/RAL

Do we want to do better?

- Existing limits are already a challenge for theorists – for instance, the strong interaction CP phase θ_s must be $\leq 10^{-10}$
- Many other models are also challenged, for instance the "natural" scale for nEDM caused by CP violation in SUSY models is 10^{-23} to 10^{-24} e cm.
- We have therefore already learned something significant about SUSY – if SUSY exists, there is some structure to the theory to suppress CP violation.

Do we want to do better?

- If we can push our sensitivity to ~ 10^{-28} e cm, then either:
  - We will observe an nEDM
  - SUSY is not a property of nature (see below)
  - CP violation is an approximate symmetry of nature
  - CP violation has an off-diagonal structure, or there are large cancellations, or some as-of-yet unknown other mechanism strongly suppresses EDMs
- If SUSY does not exist, we still must explain the baryon asymmetry so investigations sensitive to new sources of CP violation are critical.

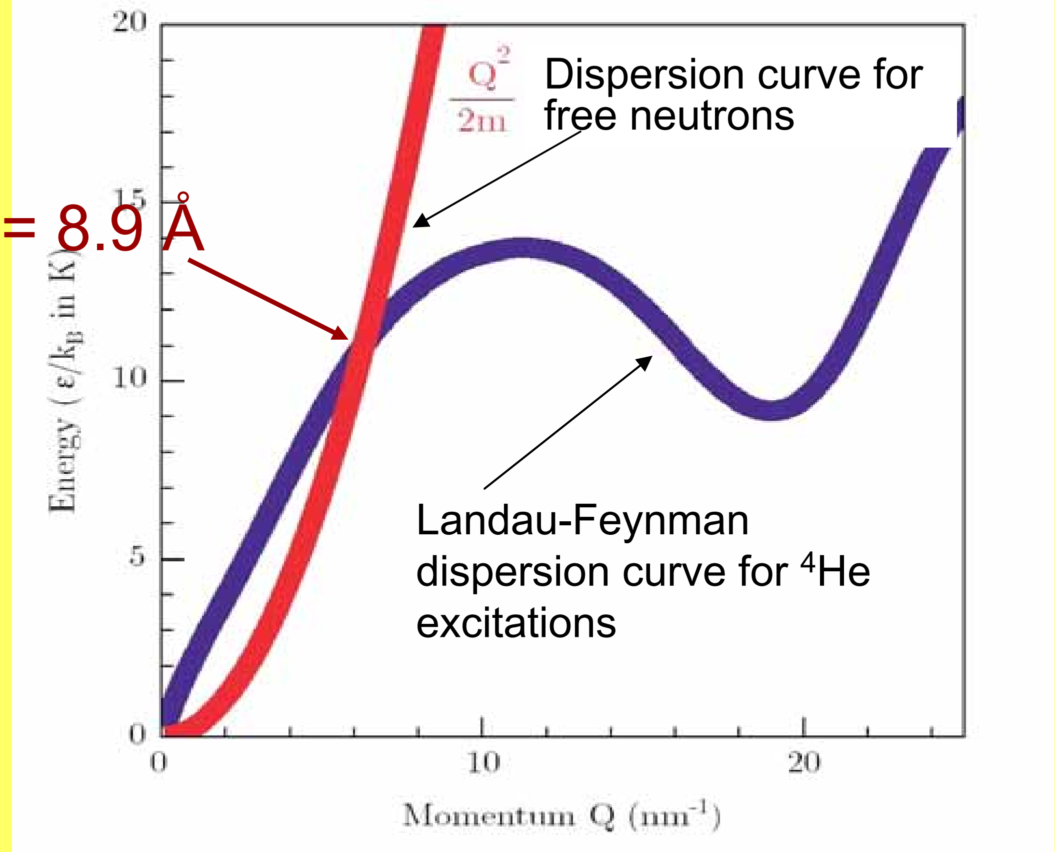
Cryogenic nEDM Collaboration

- University of Sussex - K. Green, M.G.D. van der Grinten, P.G.Harris, J.M.Pendlebury, D.B.Shiers, K.Zuber
- RAL - S.N.Balashov, M.A.H.Tucker, D.L.Wark
- University of Oxford - H.Kraus, S. Henry
- Kure University – H. Yoshiki
- Visiting Scientists – P. Iaydjiev and S. Ivanov.

How will we do better?

- Need a new source of UCN….

11 K; $2\pi/k$ = 8.9 Å

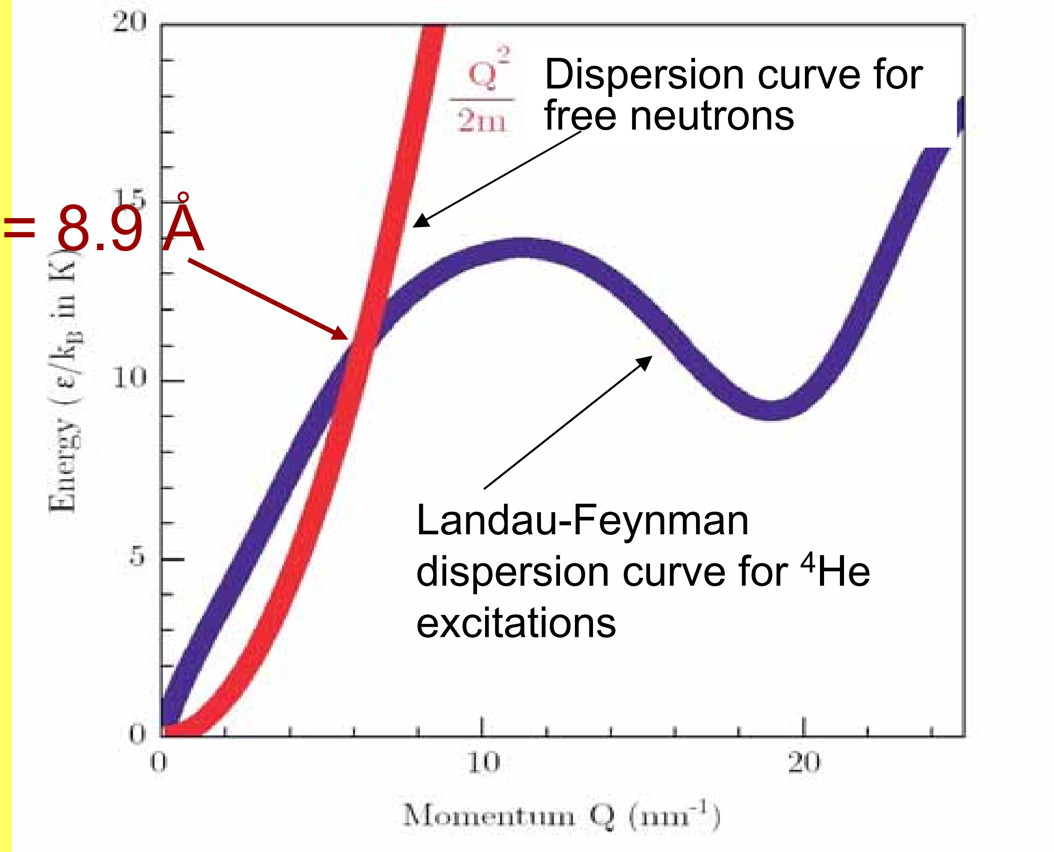


Golub and Pendlebury, Phys. Lett. **A53** 133(1975)

How will we do better?

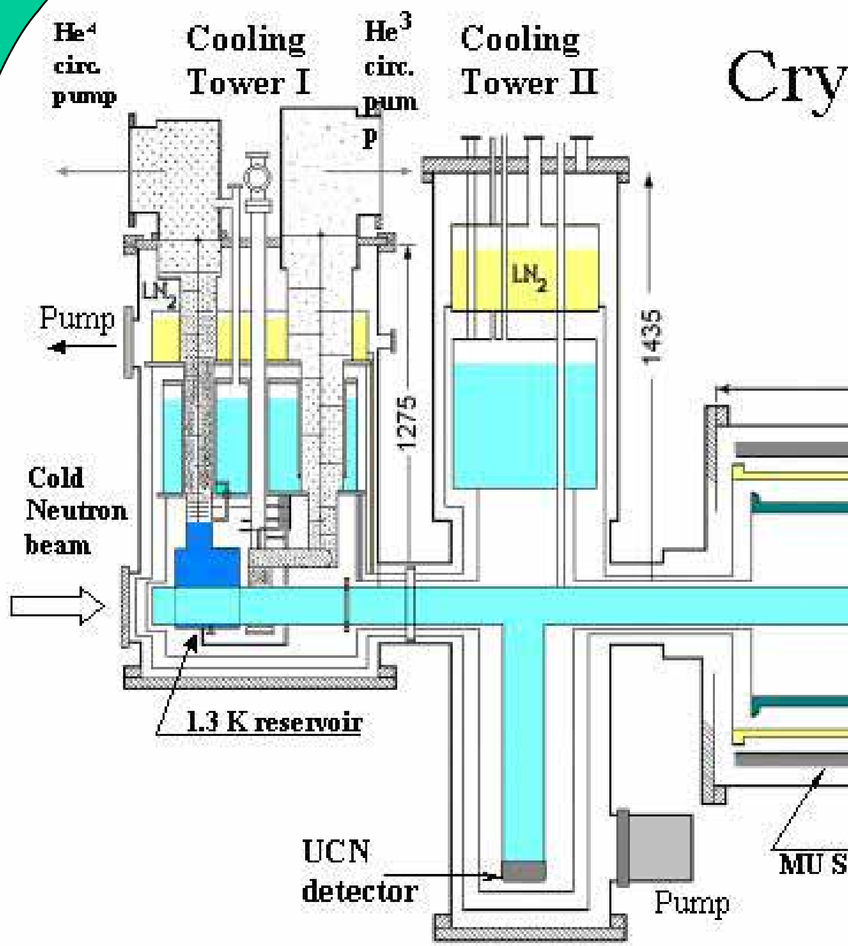
- Need a new source of UCN….

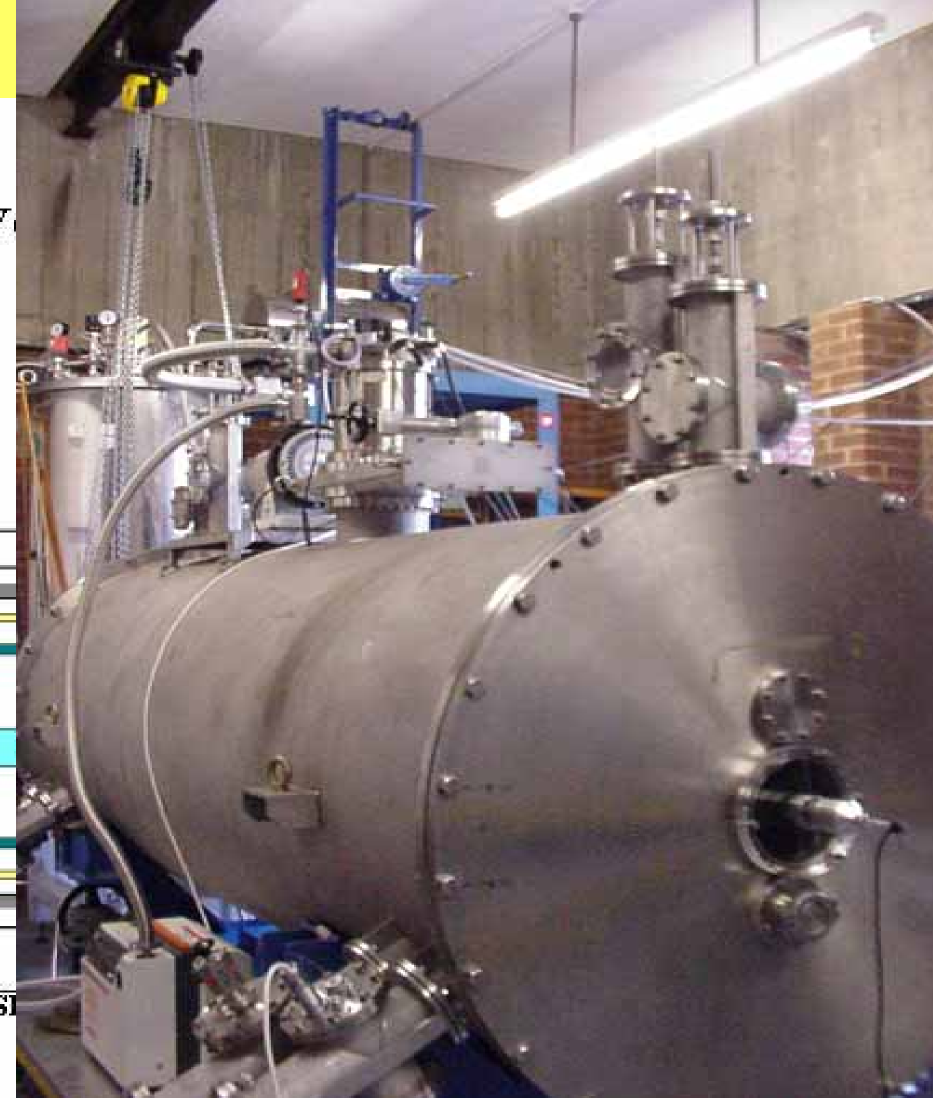
11 K; 2π/k = 8.9 Å



Golub and Pendlebury, Phys. Lett. **A53** 133(1975)

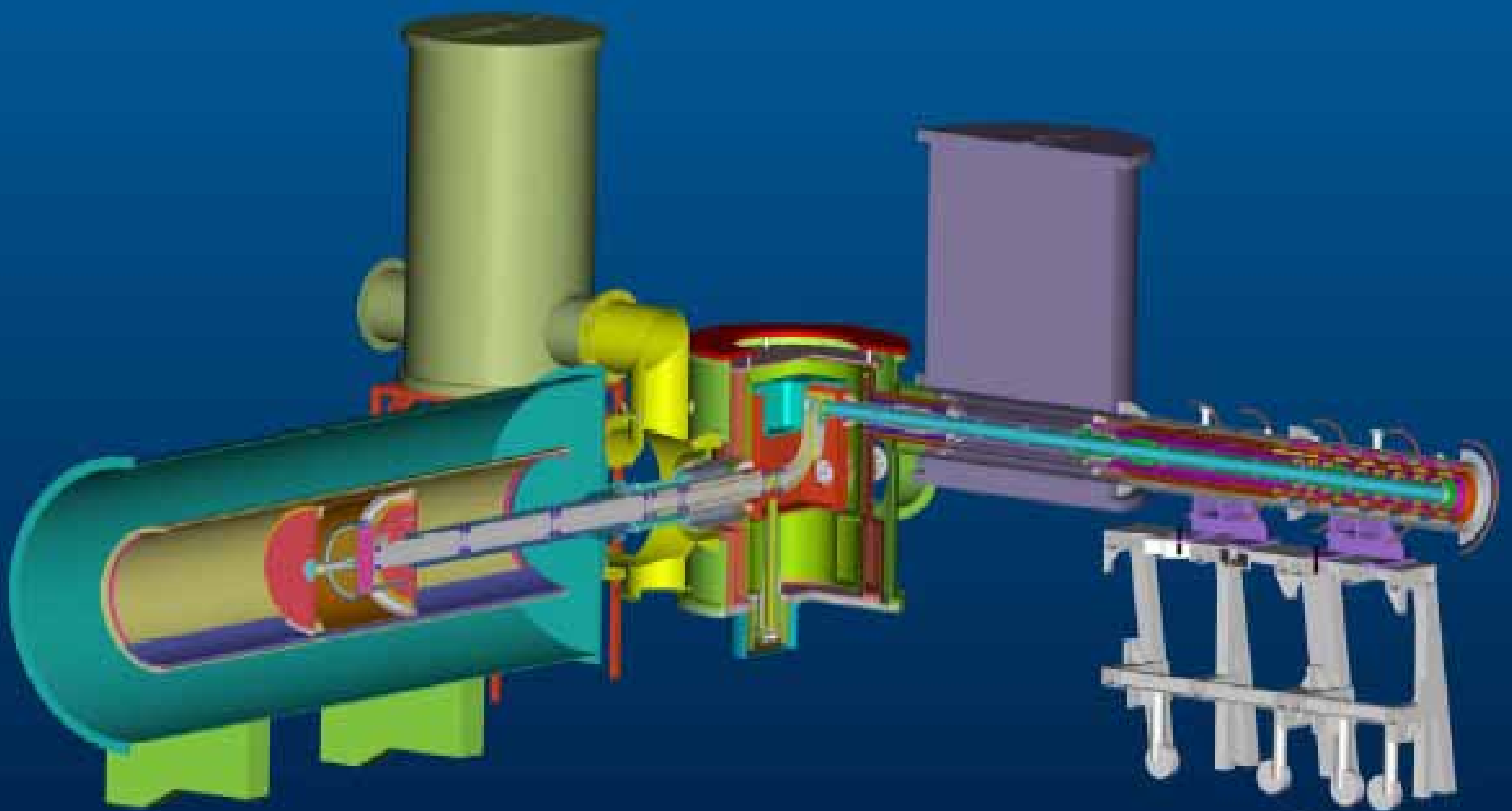
- To use this we need….





Entire Cryostat and pumps provided
by Hajime Yoshiki from Kure

Next Generation Experiment



University of Sussex

CCLRC

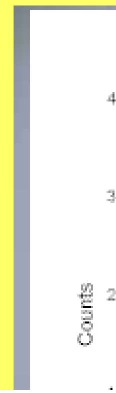
NEUTRONS FOR SCIENCE

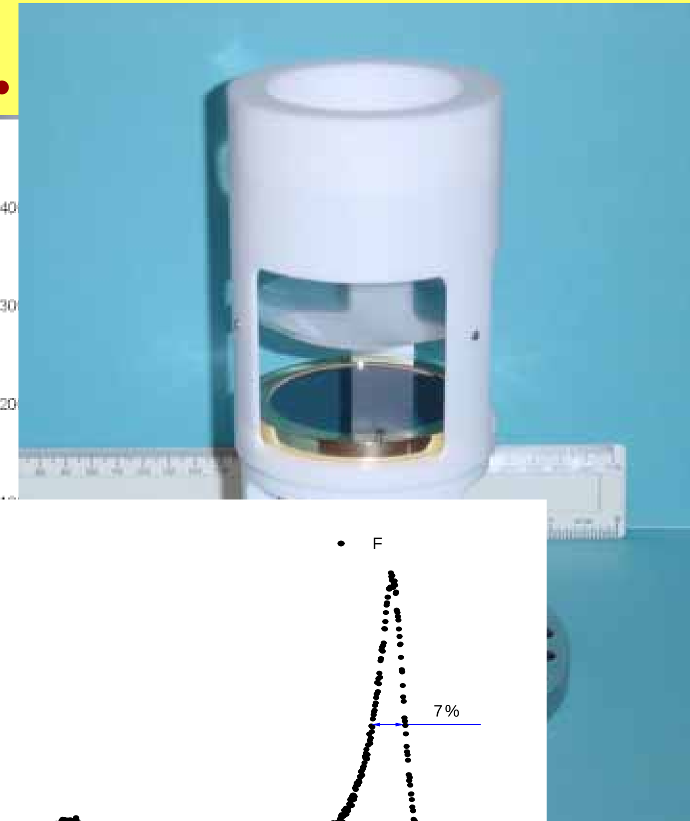
呉大学
KURE UNIVERSITY

UNIVERSITY OF OXFORD

Dave Wark
Imperial College/RAL

Detectors that will work in 0.5K LHe…



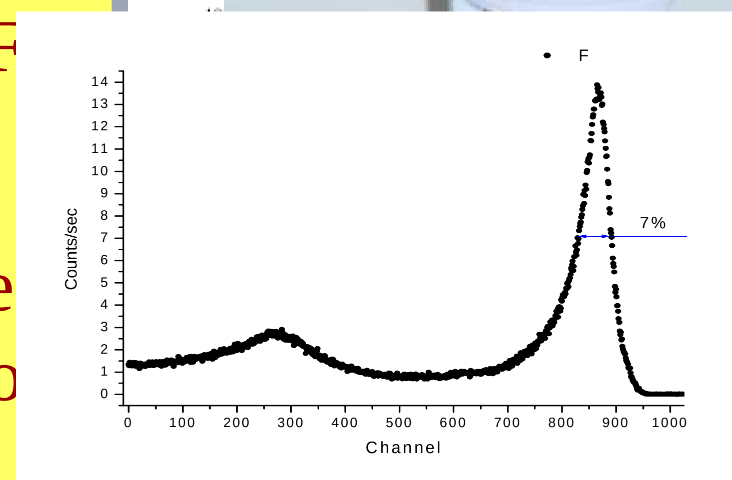


Development funded by PPARC Blue Skies Detector Fund

ORTEC ULTRA silicon detectors
Coated with a thin layer of ^{6}LiF

Observe $n + {}^6Li \rightarrow \alpha + t$

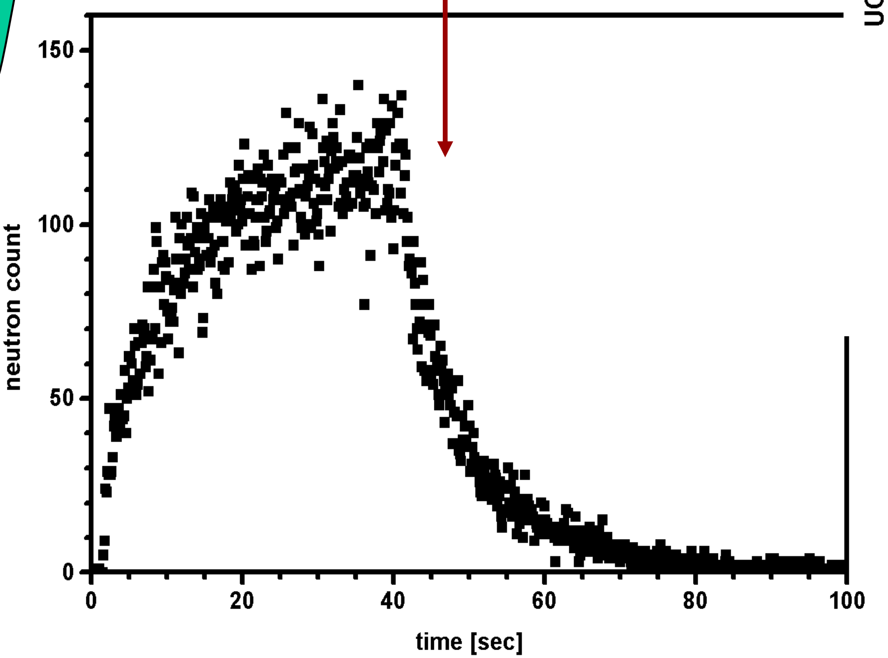
They work, although the efficie
could be further improved by lo

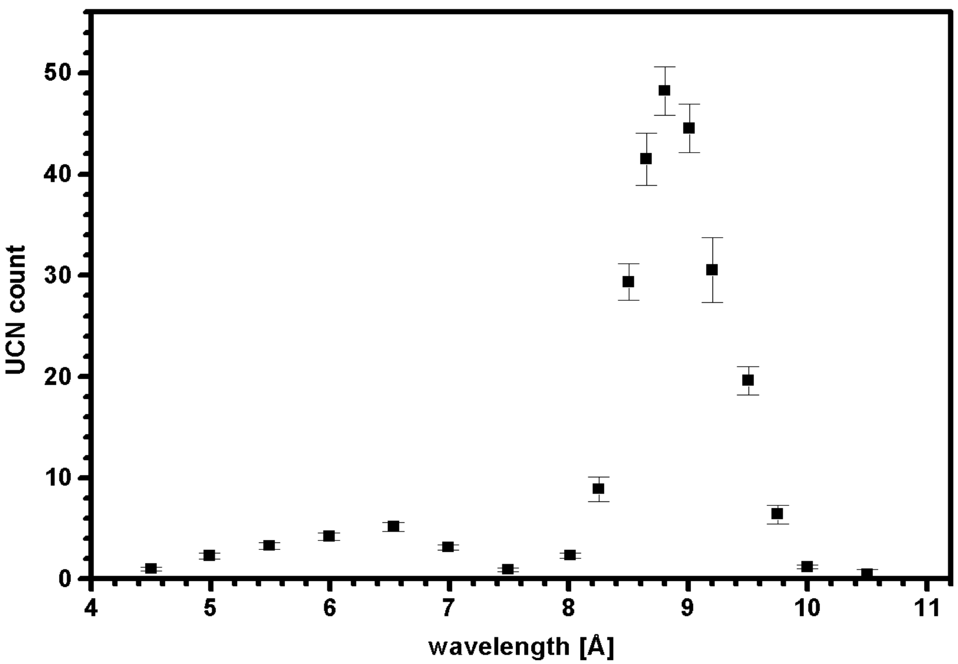


See C.A.Baker *et al.*, NIM **A487** 511-520 (2002)

Must demonstrate that the production mechanism really works…

A velocity-selected beam of cold neutrons passes through LHe, the UCN are bottled and detected



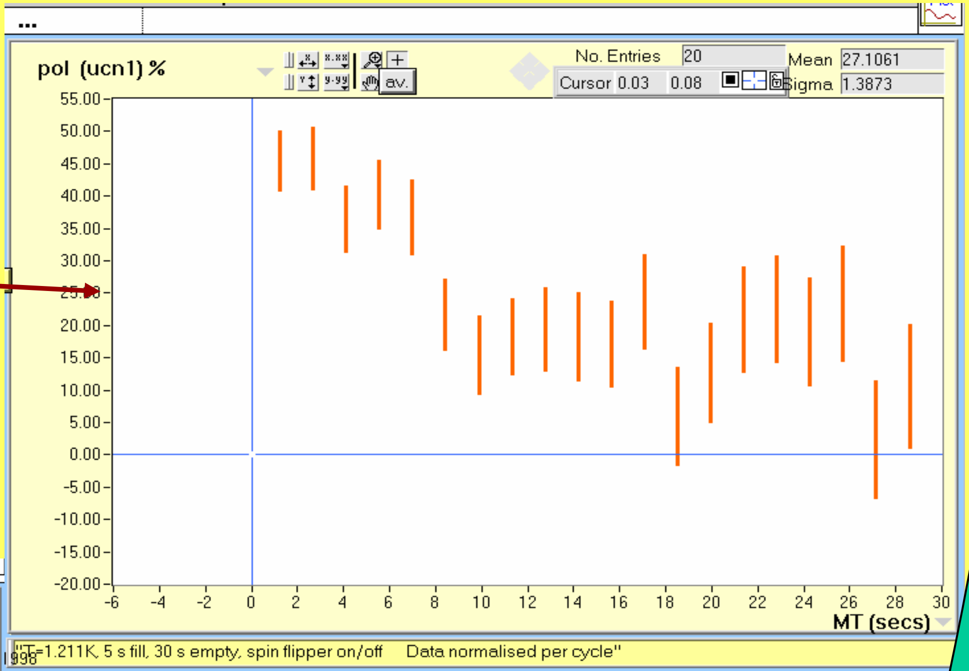


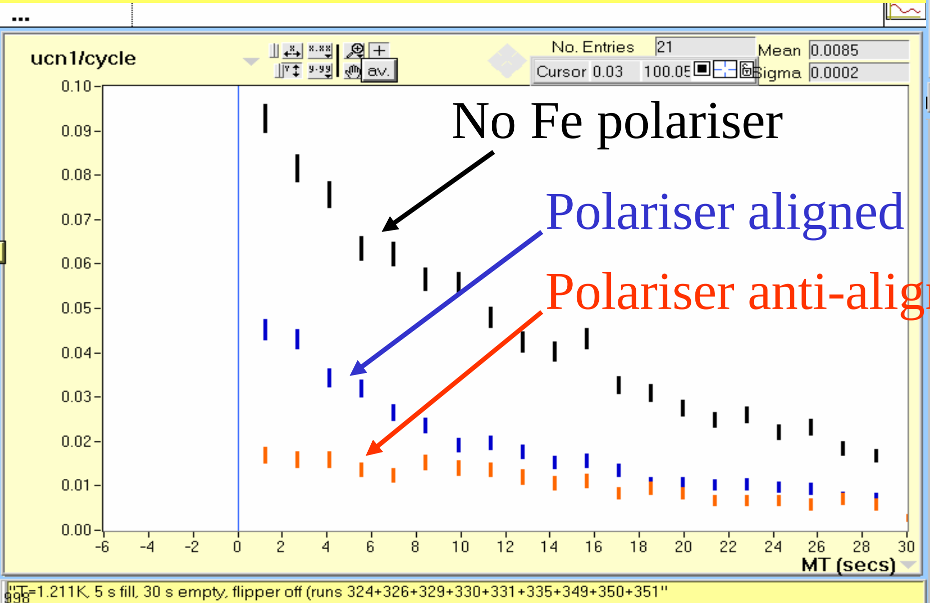
1.19±0.18 UCN cm^{-3} s^{-1} expected, 0.91± 0.13 observed

See C.A.Baker *et al.*, Phys.Lett. **A308** 67-74 (2002)

Show that polarisation is retained during downscattering…

Inferred polarisation





UCN polarisation is **(0.93 ± 0.10)** of the polarisation of the incoming beam

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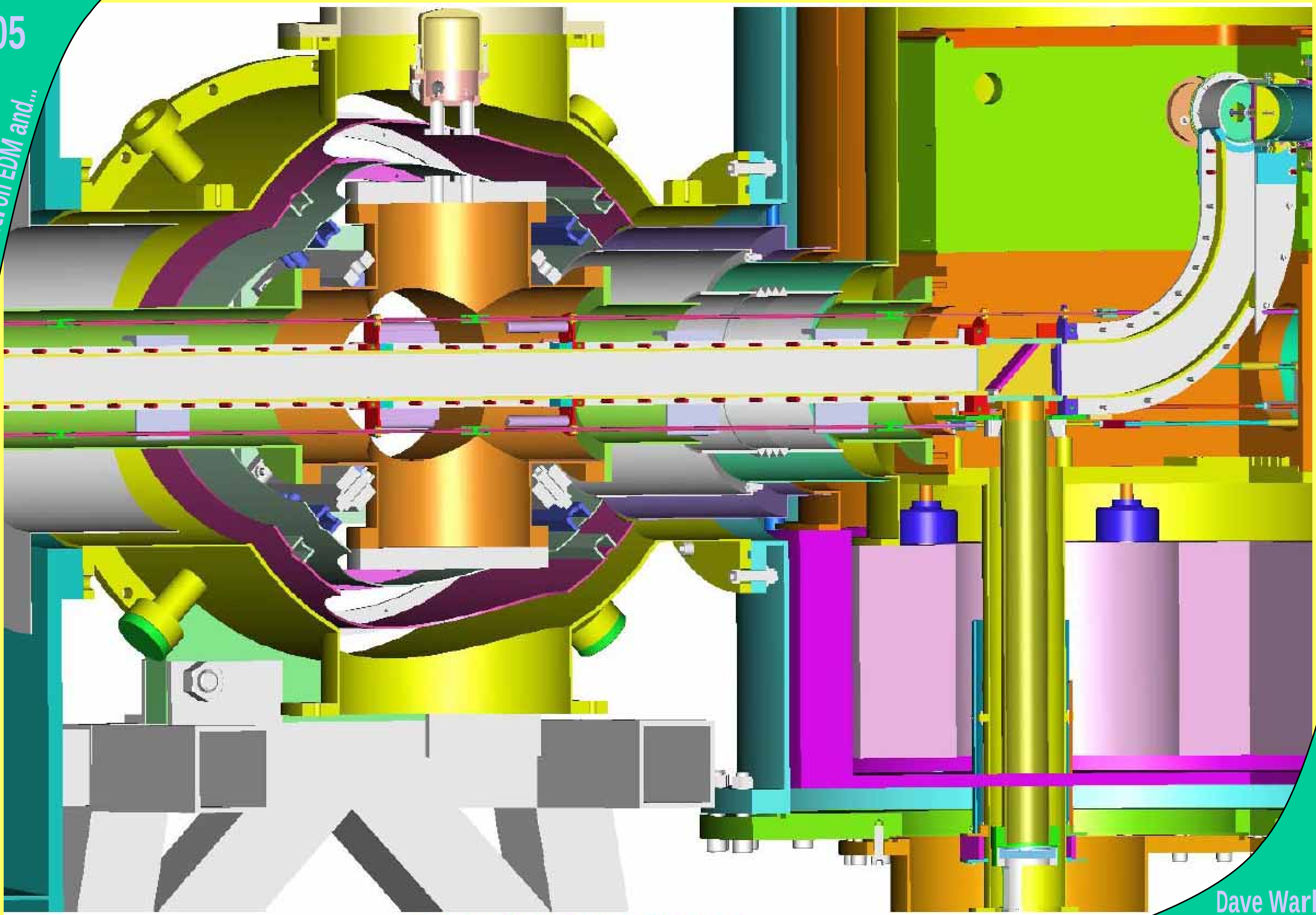
Imperial College/RAL



6 WAY SECTION

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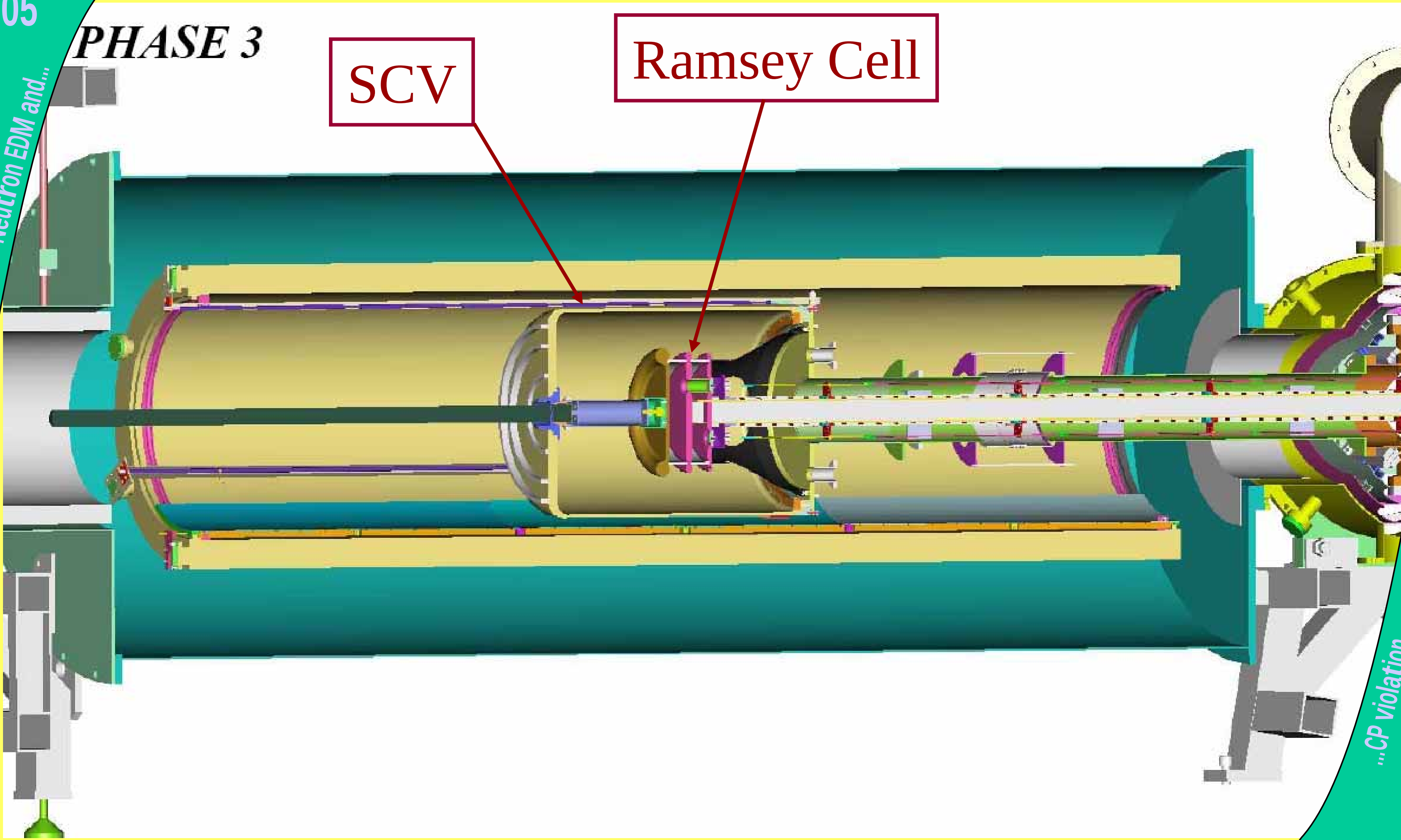
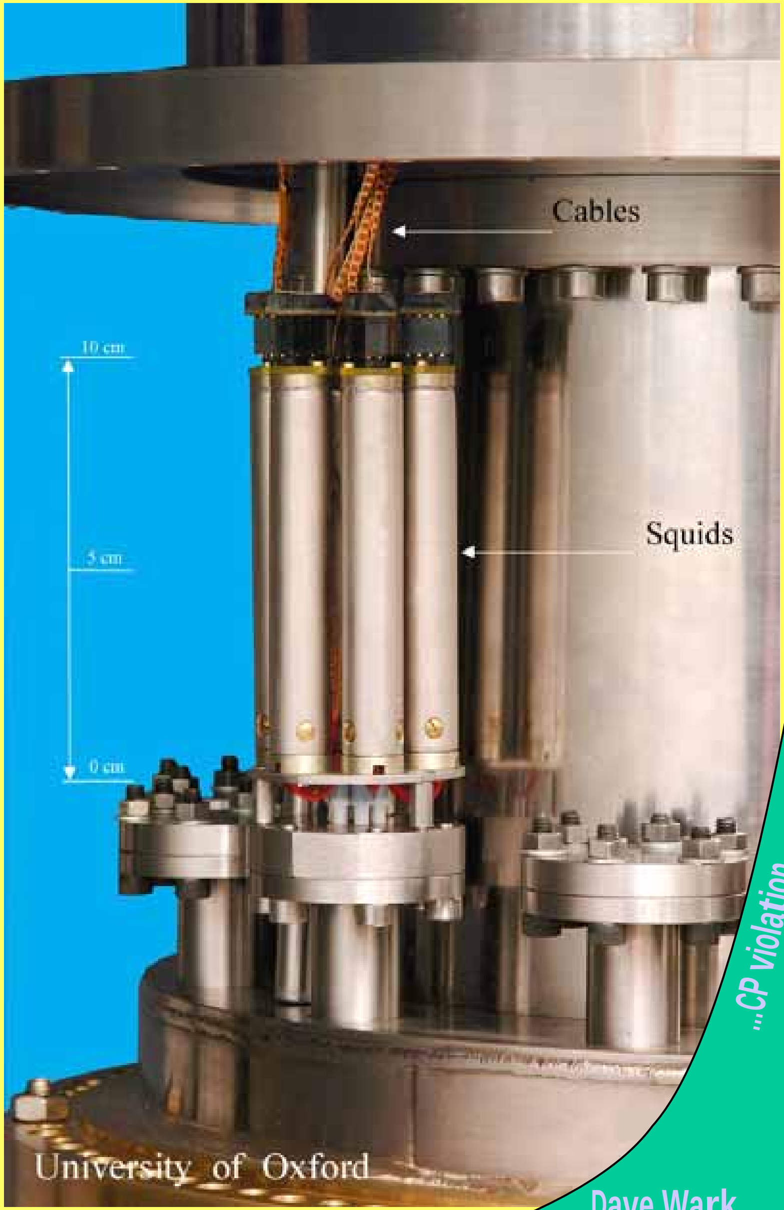

PHASE 3
SCV
Ramsey Cell

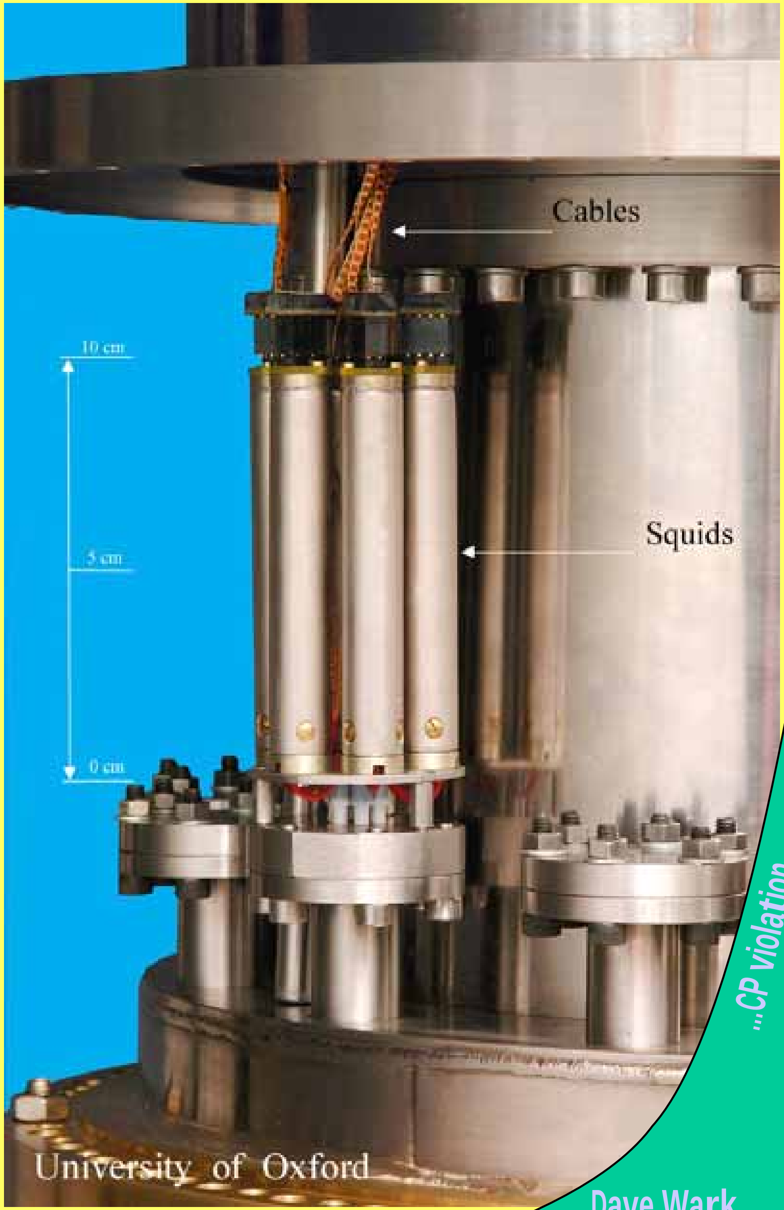
All New Magnetometry System

- SQUID Magnetometers
  - Developed at Oxford for CRESST
  - Sensitivity sufficient to monitor field
  - Measure field coupling a loop rather than volume average, therefore need quite a few



All New Magnetometry System

- SQUID Magnetometers
  - Developed at Oxford for CRESST
  - Sensitivity sufficient to monitor field
  - Measure field coupling a loop rather than volume average, therefore need quite a few
- Neutron Magnetometers



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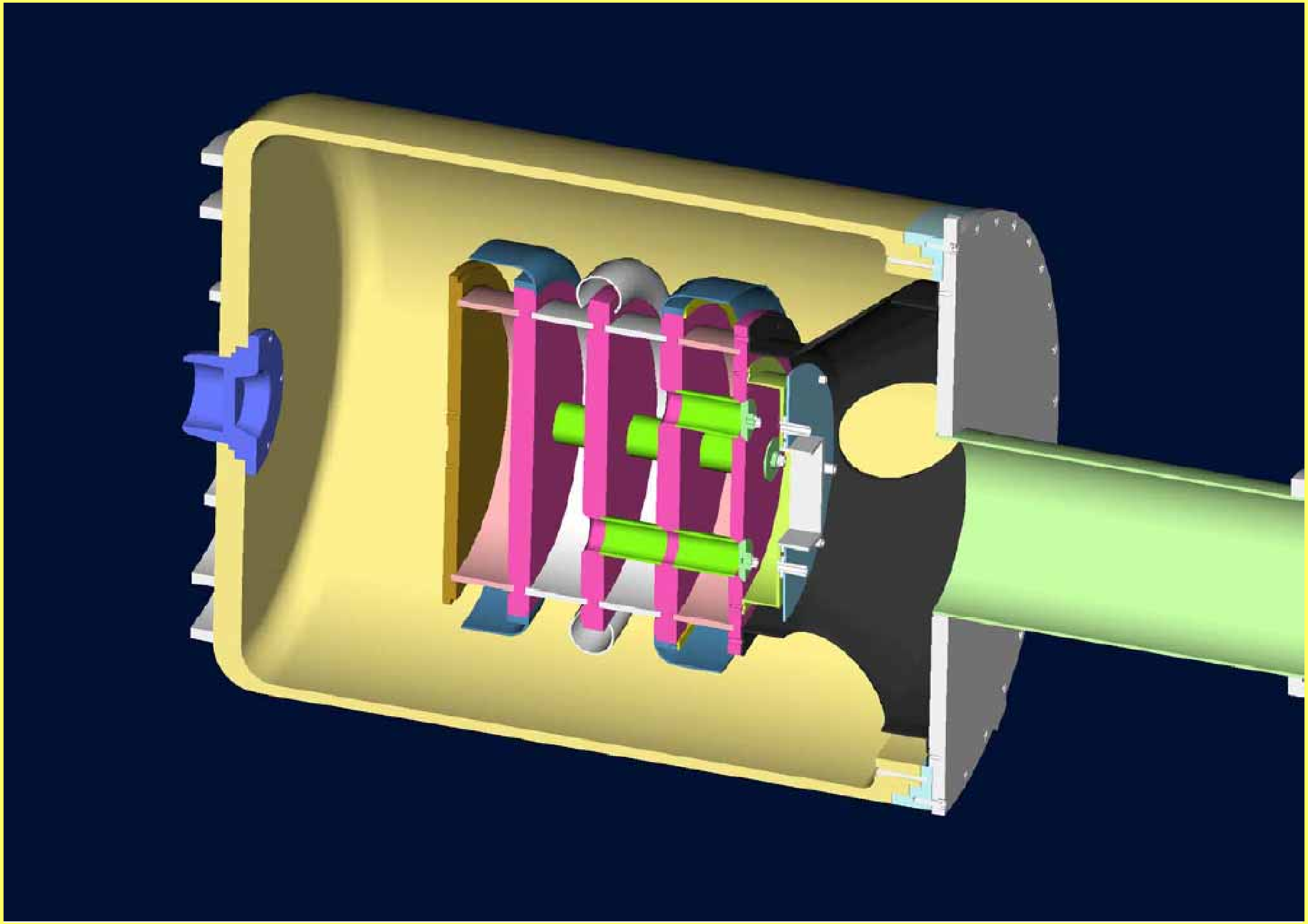
Ramsey Cell and SF Vessel



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

	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

	Current value	Reasonably expect		Gain in Sensitivity	edm/day x 10^{-26} e.cm	Reactor days to reach 1×10^{-27} e.cm	Calendar years to reach 1×10^{-28} e.cm
EDM cell							
Electric field (E)	20 kV.cm^{-1}	40 kV.cm^{-1}	a	2.0x	10.5x10^{-26}	11,025	7,350
Polarization product (α)	0.6	0.9	b	1.5x	7.0	4,900	3,267
Storage time (T)	130 s	300 s	a	1.8x	3.9	1,521	1,014
Neutron factors							
UCN detection efficiency	41%	90%	c	1.5x	2.6	676	451
H53 beam flux at 9A	Φ=2.6 x 10^7 n.cm^{-2}.s^{-1}.A^{-1}	Φ=1.0 x 10^8 n.cm^{-2}.s^{-1}.A^{-1}	d	2.0x	1.3	169	113
transmission polariser	20%	50%	e	1.5x	0.9	81	54
Beam/He^4 areas	24%	100%	f	2.0x	0.45	20	13
UCN density dilution source to edm cell	20%	50%	g	1.5x	0.3	9	6
narrow/broad band beam	75%	100%	h	1.1x	0.26	7	4.7
New Beamline							
H53/H112 neutron beam	15%	100%	i	2.6x	0.10	1	0.7

N.B. 150 reactor days = 1 calendar year

Enabling factors :

a). Inherent in the properties of liquid He^4
b). Rebuild spin analyzer with higher B field + R&D on spin retaining materials
c). Lower noise to detect both α and tritons from n+ Li^6 => α +t
d). Put neutron guide between H53 exit and experiment
e). Build new polariser using sapphire substrate optimized for 9A neutrons
f). Match beam area to area of UCN containment source
g). Either increase UCN source volume or R&D on low volume (small tubes) UCN transfer system
h). Remove velocity selector but this will increase the activation of the apparatus
i). New guide at ILL can be built.

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Imperial College/RAL

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 $\Delta E_r = E/10$ 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 $(E\uparrow - E\downarrow)/\langle E\rangle = 0.05$ $\langle E\rangle = 60$ 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	$dB_0/dz = 1\ \mu$G/m after trimming. $B_0 = 25$ mG Rms v (UCN) = 5 m/s

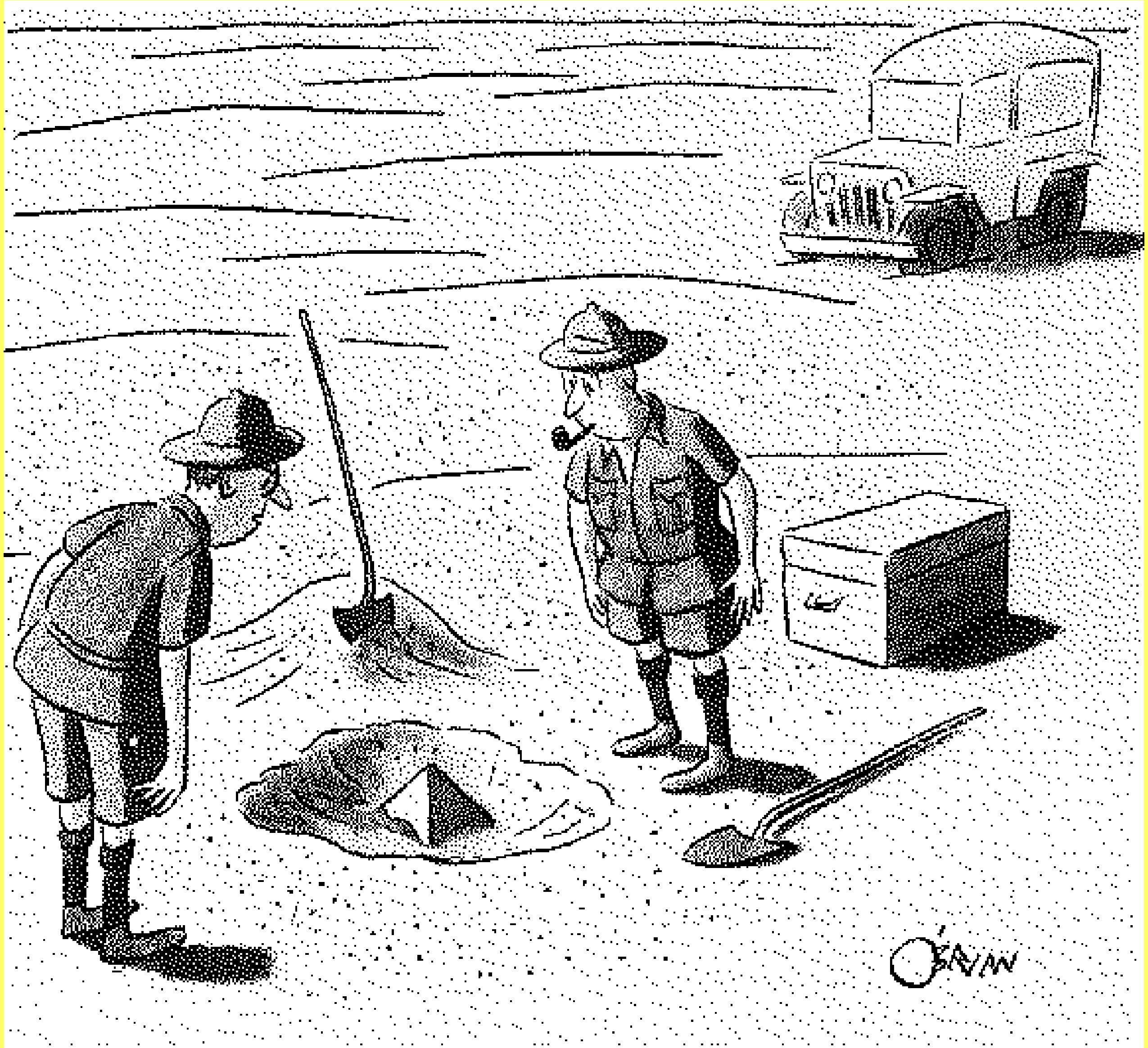
Overall systematic error	1.7×10^{-28} e cm	All the above errors are uncorrelated

The Competition…

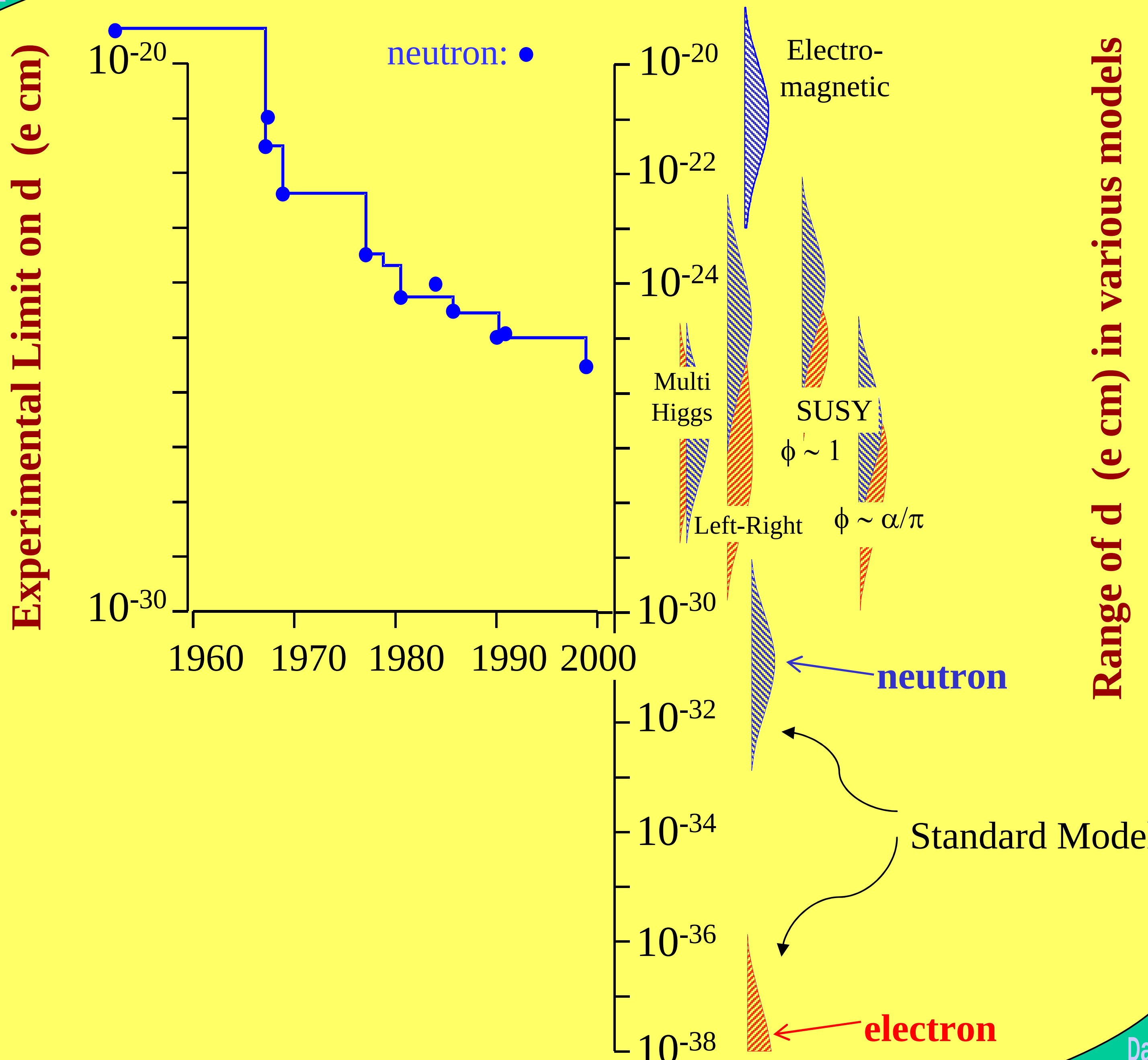
- A group at KEK/Osaka is building an experiment to be used at JPARC
- A group at PSI based around the group from PNPI are proceeding with an experiment.
- A very large American collaboration is proposing an experiment at the SNS – their proposal lists 36 names, requests $11M, with a target date for first data of 2007.
- There is a German group at the new reactor in Munich.
- There are also experiments to measure the eEDM, atomic EDMs, and even the muon EDM.
- Competition is good, but uncomfortable when you are the target of it!
- However any observation would need to be confirmed extended, so many experiments are needed.

Conclusions…

- Strong evidence exists from astrophysical measurements that CP violation exists in some as-of-yet undiscovered properties of fundamental interactions.
- Particle EDMs offer a sensitive probe of such new physics (at very modest cost) – the final nEDM limit from the existing experiment extends the sensitivity by another factor of 2.
- We have not yet reached any fundamental limits to increased sensitivity.
- The Japanese have made a very significant contribution to our new cryogenic experiment, and are welcome to help exploit it.
- Other EDM experiments are just as important.



"This could be the discovery of the century. Depending, of course, on how far down it goes."



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Kyoto Seminar
Nov. 2
'05

Neutron EDM and...

New Limit on the Electron Electric Dipole Moment

B. C. Regan,* Eugene D. Commins,† Christian J. Schmidt,‡ and David DeMille§
Physics Department, University of California, Berkeley, California 94720
and Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 August 2001; published 1 February 2002)

We present the result of our most recent search for T violation in ^{205}Tl, which is interpreted in terms of an electric dipole moment of the electron d_e. We find $d_e = (6.9 \pm 7.4) \times 10^{-28} e$ cm, which yields an upper limit $|d_e| \leq 1.6 \times 10^{-27} e$ cm with 90% confidence. The present apparatus is a major upgrade of the atomic beam magnetic-resonance device used to set the previous limit on d_e.

DOI: 10.1103/PhysRevLett.88.071805 PACS numbers: 13.40.Em, 11.30.Er, 14.60.Cd, 32.10.Dk

An intrinsic electric dipole moment (EDM) can exist only if parity (P) and time reversal (T) invariance are violated [1]. The weak interaction violates P, while CP violation (equivalent to T violation from CPT invariance) is observed in neutral kaon and B-meson decay [2]. Hence, the weak interaction and CP violation could induce EDMs by means of radiative corrections to the electromagnetic interaction. In the standard model intrinsic EDMs are much too small to be detected [3], but various extensions to the standard model predict observable values [4,5]. Sensitive searches [6,7] for EDMs constrain these models. In heavy paramagnetic atoms an electron EDM results in an atomic EDM enhanced by a factor $R \equiv d_{\text{atom}}/d_e$ [8]. We study atomic thallium in its $6^2P_{1/2} F = 1$ ground state, where $R \simeq -585$ [9].

Like its predecessor [10,11], the new experiment [12] uses magnetic resonance with two oscillating rf fields [13] separated by a space containing an intense electric field $\mathbf{E}$, and employs laser optical pumping for state selection and analysis. To control systematic effects from motional magnetic fields $\mathbf{E} \times \mathbf{v}/c$, the previous experiment employed a single pair of counterpropagating vertical atomic beams. The present experiment has two pairs separated by 2.54 cm, each consisting of Tl and Na (see Fig. 1). The spatially separated beams are nominally exposed to identical magnetic but opposite electric fields; this provides common-mode noise rejection and control of some systematic effects. Sodium serves as a comagnetometer: it is susceptible to the same systematic effects but insensitive to d_e, since R is roughly proportional to the cube of the nuclear charge. Also, Na's two $3^2S_{1/2}$ ground-state hyperfine levels $F = 2, 1$ have $g_F = \pm 1/2$, which permits the separation of two different types of $\mathbf{E} \times \mathbf{v}$ effects.

Figure 1 shows the apparatus with the up beams active. Atoms leave the trichamber oven thermally distributed among the ground state hyperfine levels. After some collimation they enter the quantizing magnetic field $\mathbf{B}$, nominally in the $\hat{\mathbf{z}}$ direction and typically 0.38 G. Laser beams then depopulate the states with nonzero magnetic quantum numbers m_F. Thus, in the first optical region 378 nm $\hat{\mathbf{z}}$ polarized light selects the $m_F = 0$ Zeeman sublevel of the Tl $F = 1$ ground state. In the second optical region 590 nm $\hat{\mathbf{z}}$ light selects the $m_F = 0$ sublevel of either the $F = 2$ or the $F = 1$ Na ground state. The first rf region contains an oscillating magnetic field $\mathbf{B}_{\text{rf}} = (B_{\text{Tl}} \cos\omega_{\text{Tl}} t + B_{\text{Na}} \cos\omega_{\text{Na}} t)\hat{\mathbf{x}}$, where $2B_{\text{Tl}} = B_{\text{Na}}$ and $1.506\omega_{\text{Tl}} \simeq \omega_{\text{Na}}$. These resonant fields apply "$\pi/2$" pulses, creating coherent superpositions of the $m_F \neq 0$ states of each species.

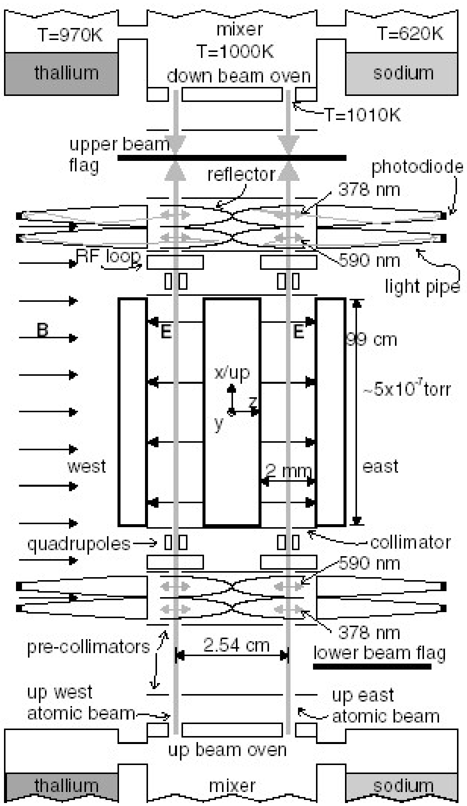

FIG. 1. Schematic diagram of the experiment; not to scale.

...CP violation

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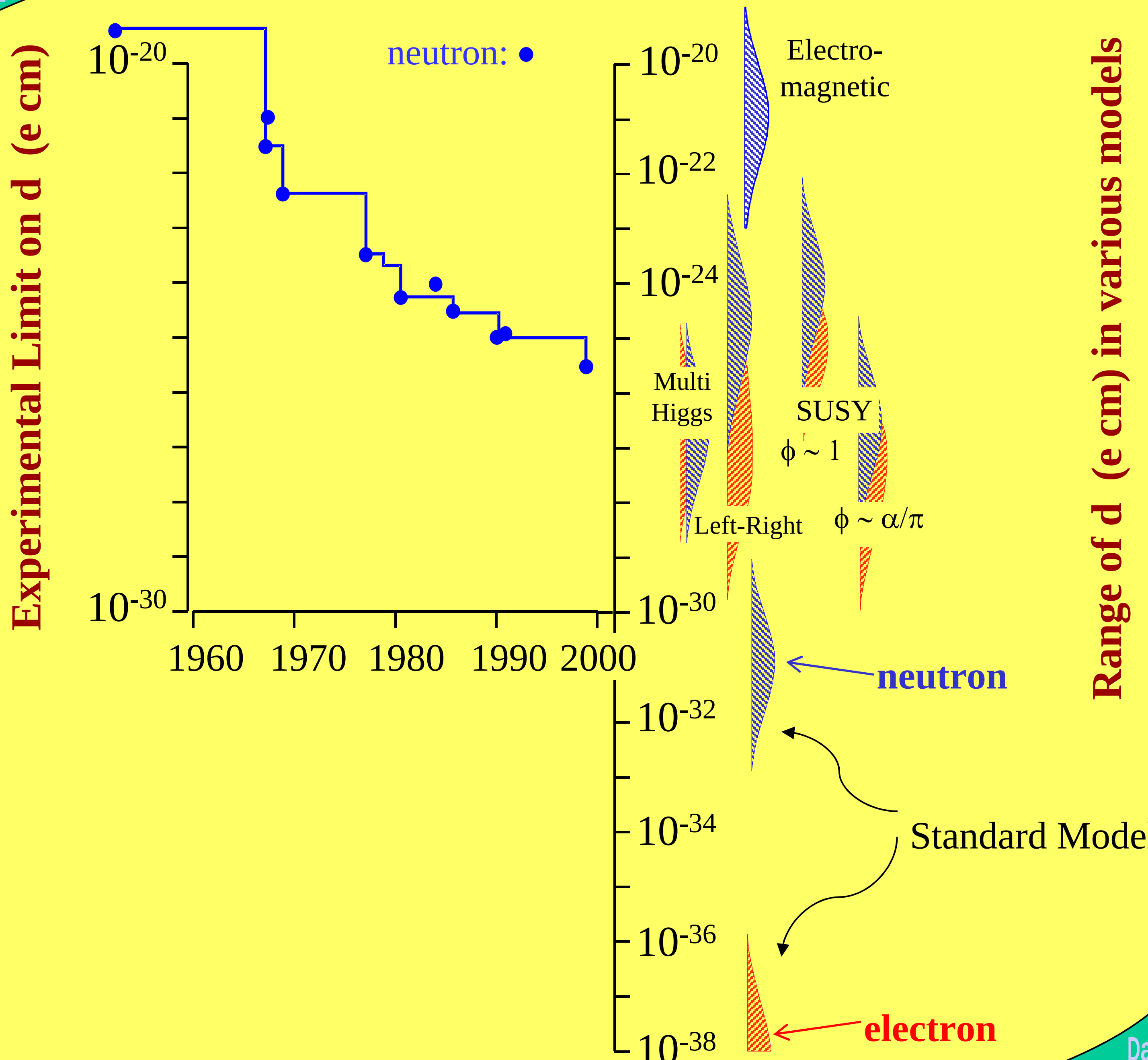
Imperial College/RAL



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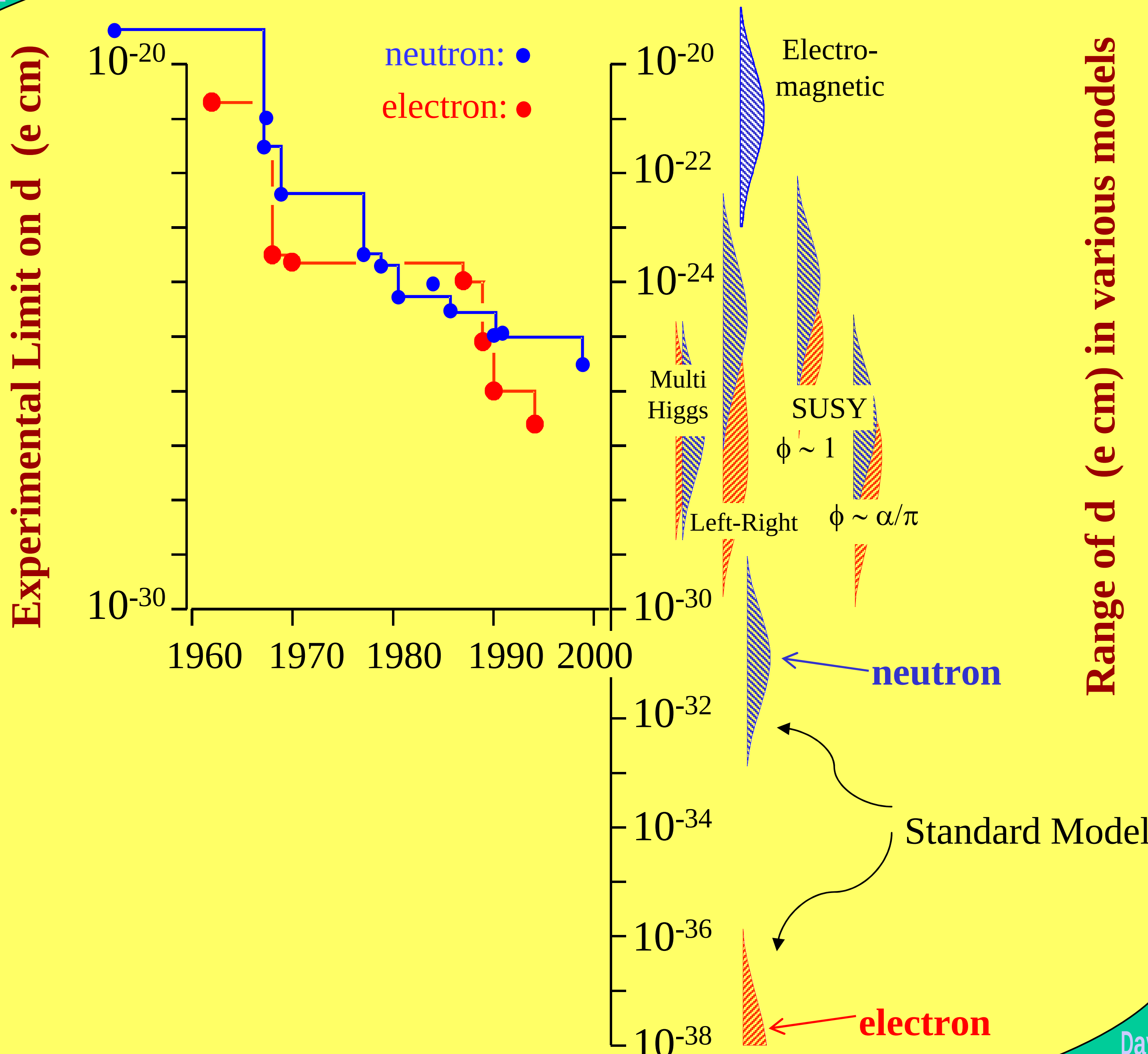

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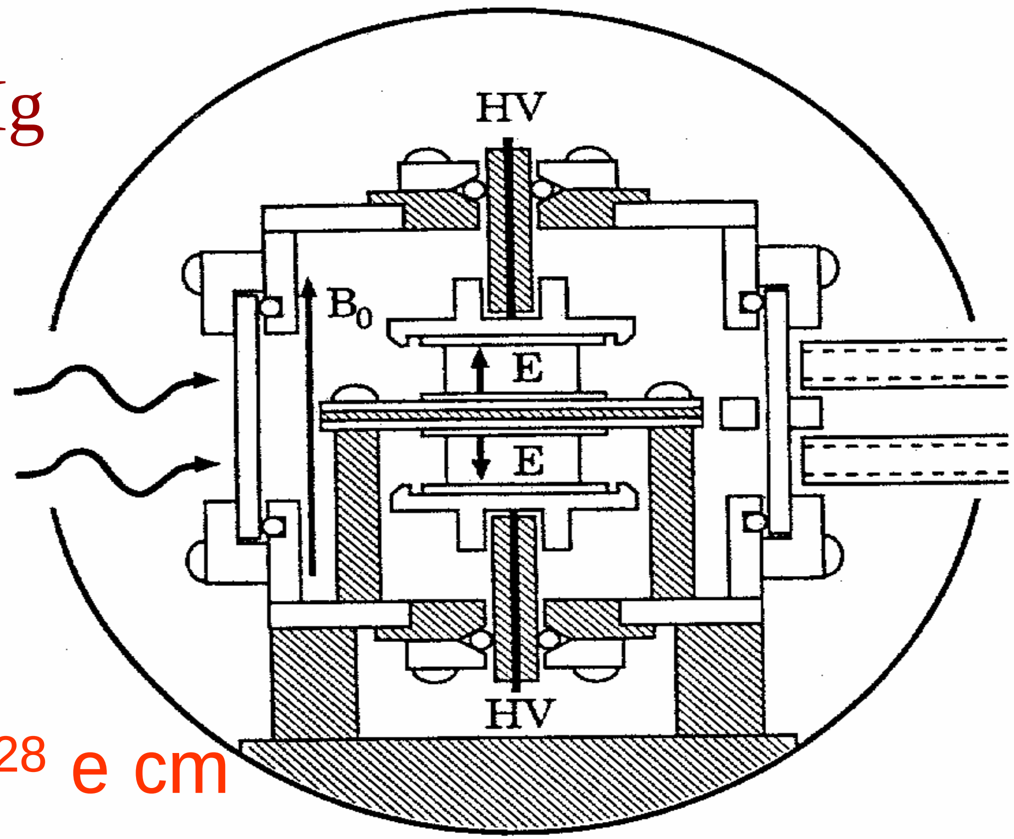
^{199}Hg Electric Dipole Moment

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.

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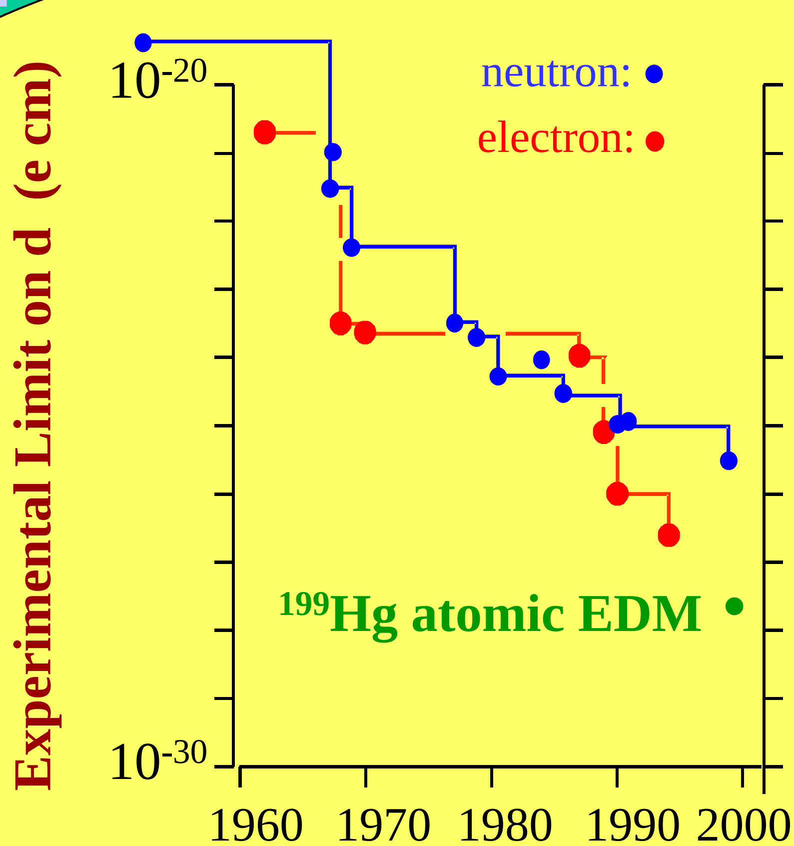

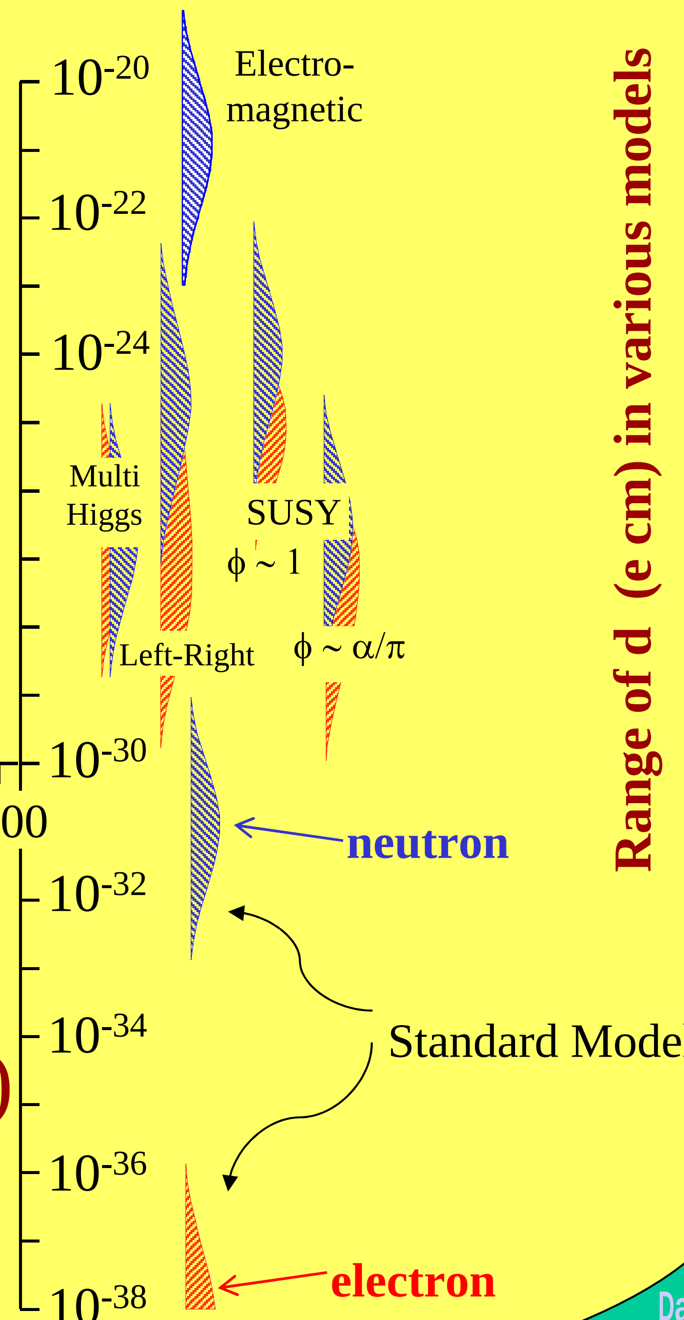

Relative value of neutron, electron, atomic (and μ and τ) EDM is model-dependent, must pursue all

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