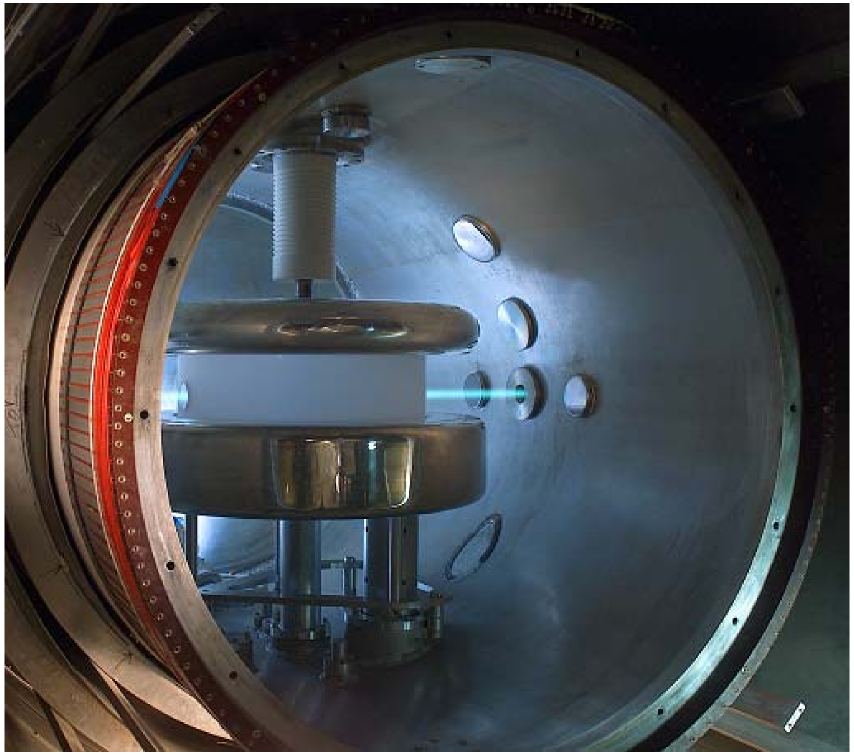
The Neutron EDM Experiment: Progress, plans, systematics

Philip Harris

University of Sussex

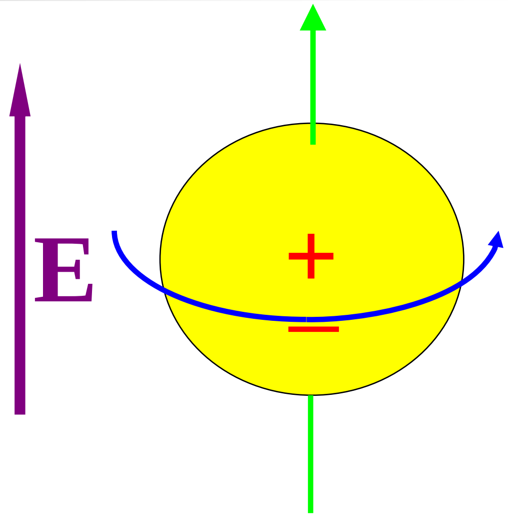


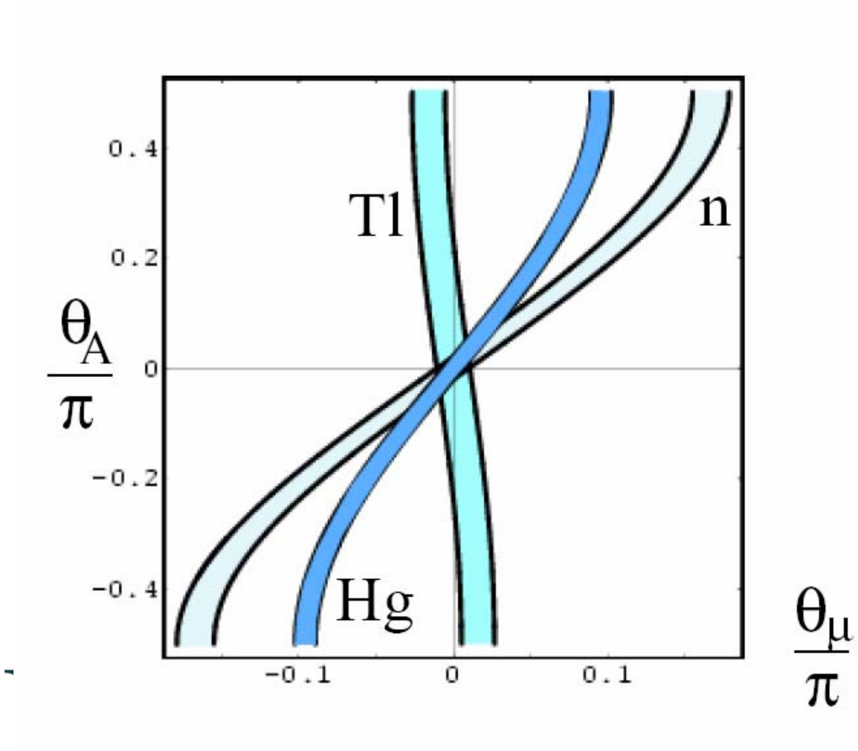
Overview

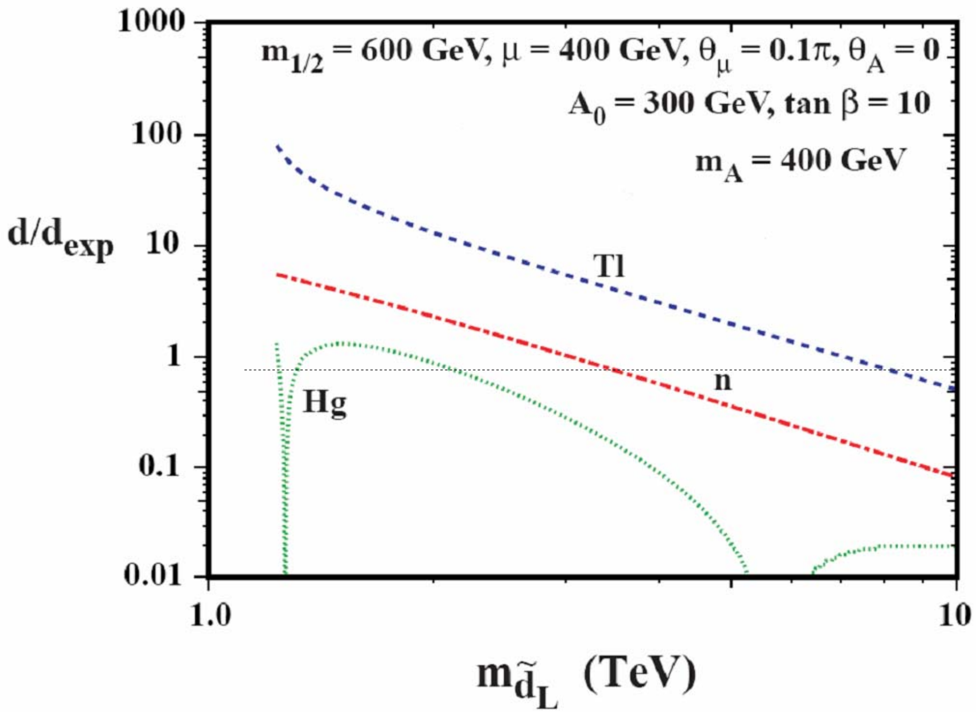
1. nEDM "Classic"
   - New limit:
     $|d_n| < 3.0 \times 10^{-26}$ e.cm
   - Discovery of new systematic effect
2. CryoEDM
   Under development:
   100x improved sensitivity
3. Details of Systematics
   by request

Electric Dipole Moments

- EDMs are P, T odd
- Complementary study of CPv
- Constrains models of new physics

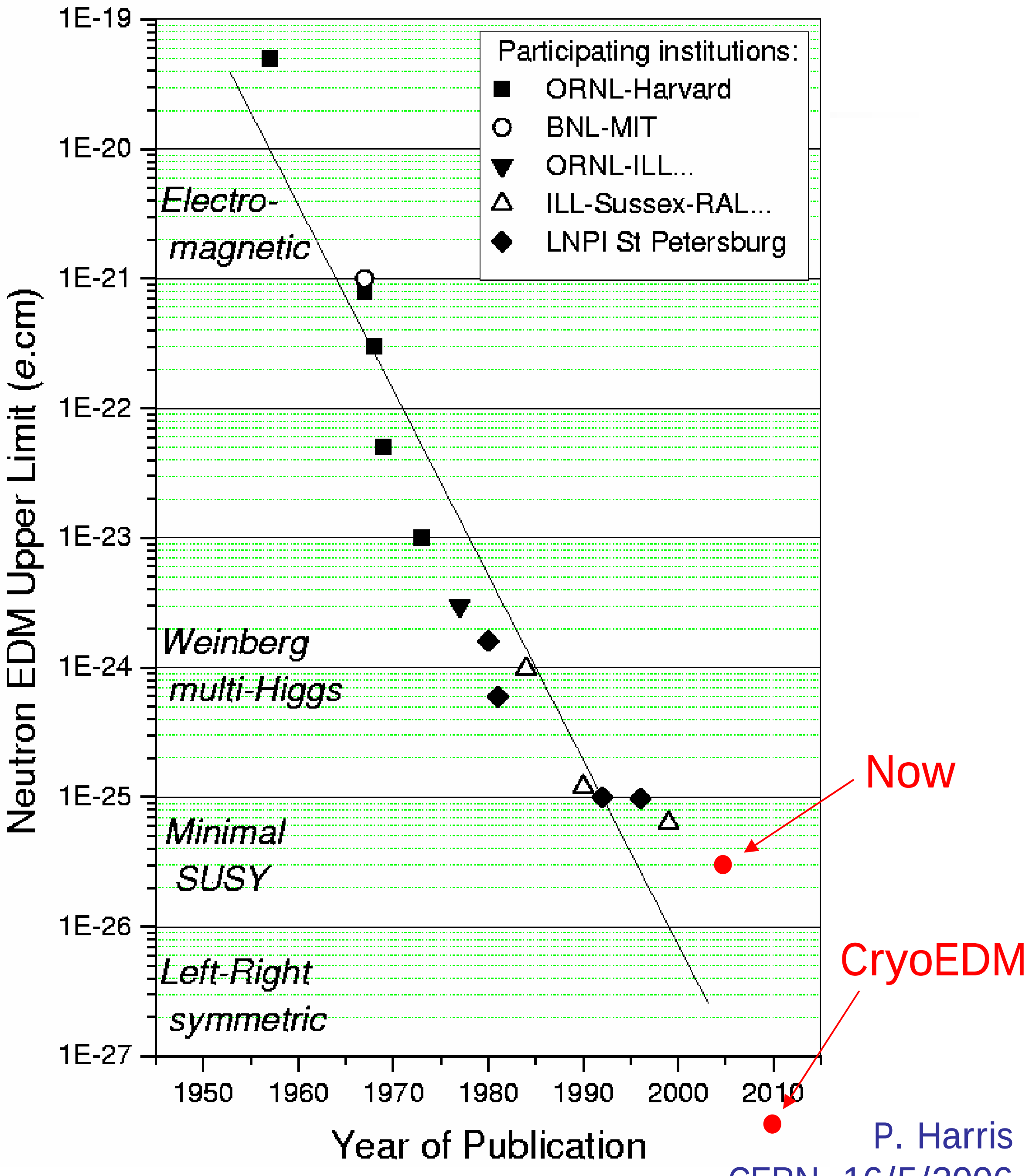






History

Factor 10
every 8 years
on average



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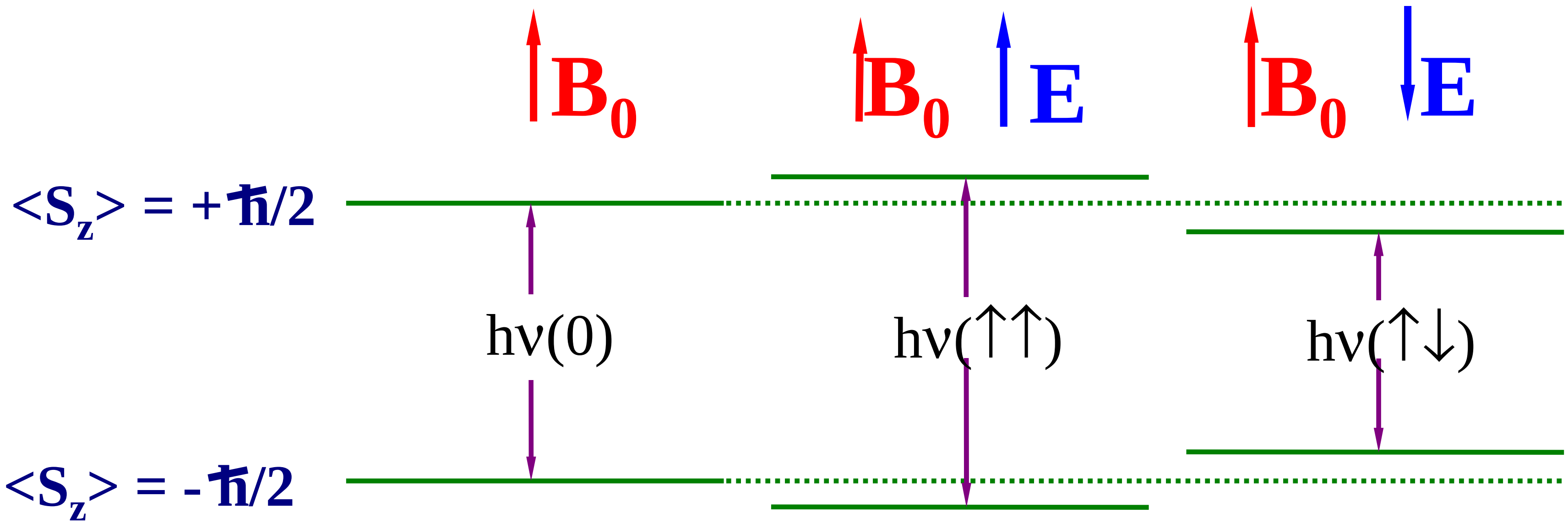
Measurement principle

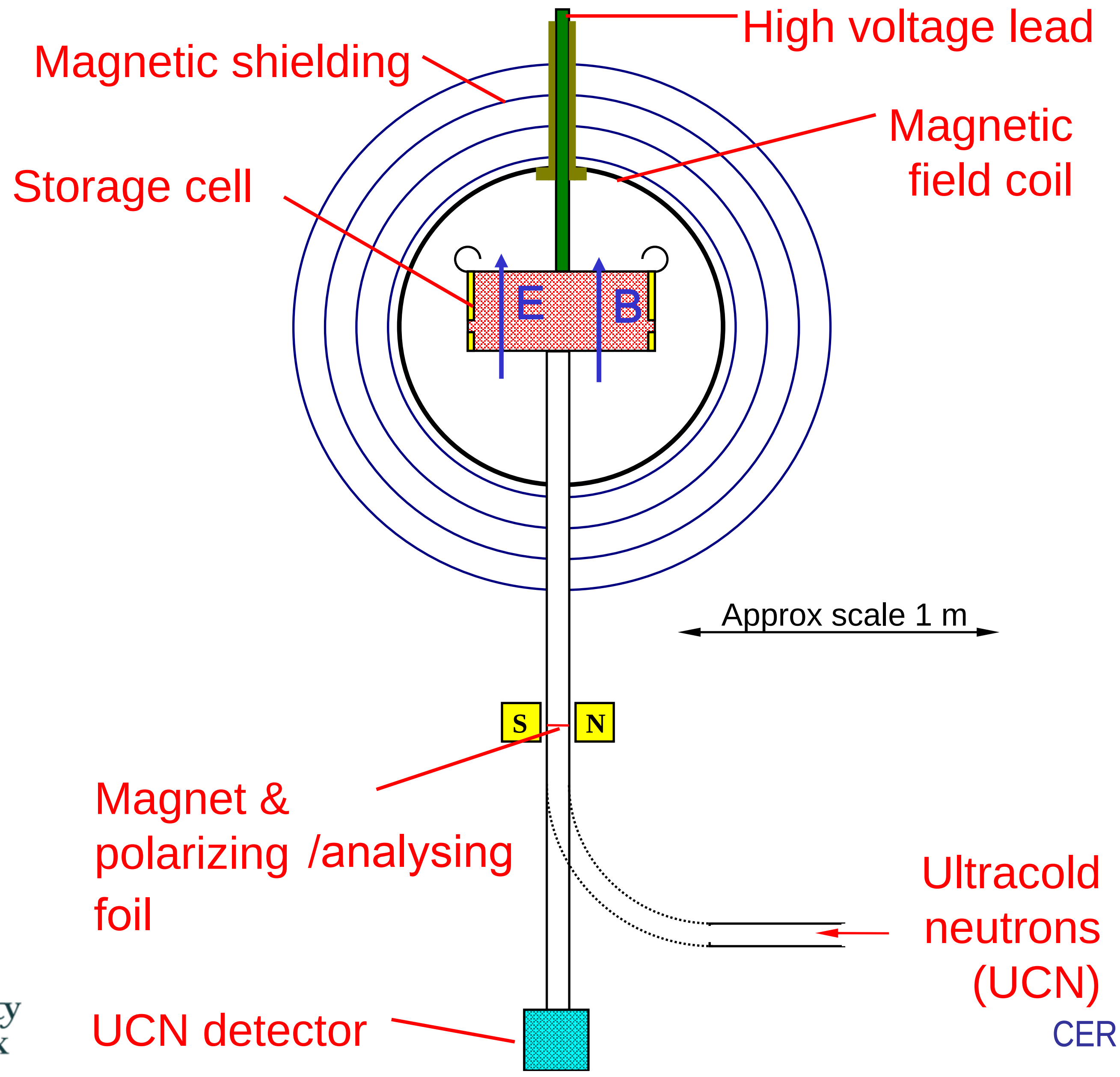
Use NMR on ultracold neutrons in **B, E** fields.



$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/h$$

assuming **B** unchanged when **E** is reversed.

Apparatus



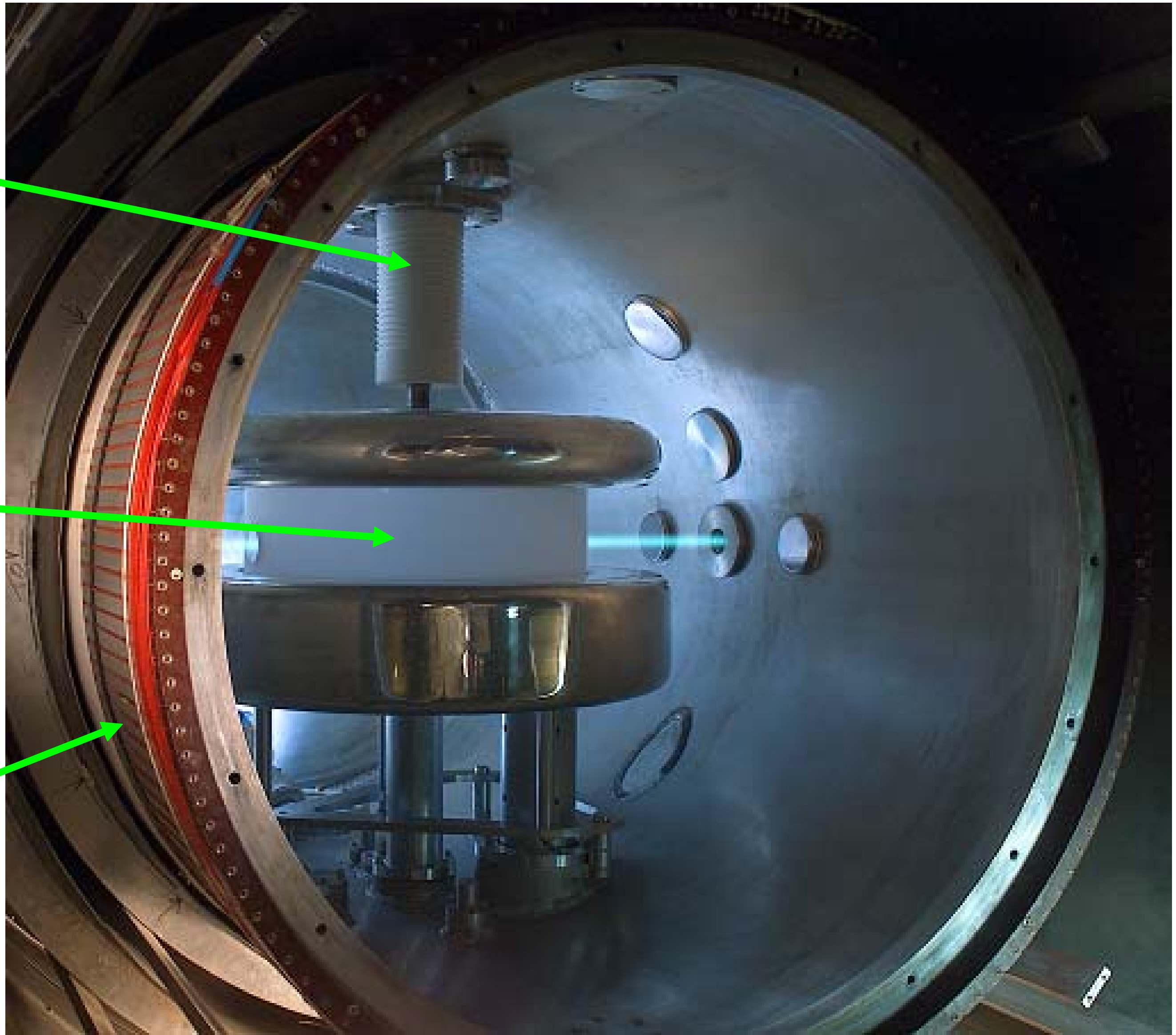
High voltage lead
Magnetic shielding
Magnetic field coil
Storage cell
E
B
Approx scale 1 m
S
N
Magnet & polarizing /analysing foil
Ultracold neutrons (UCN)
UCN detector

Apparatus

HV
feedthru

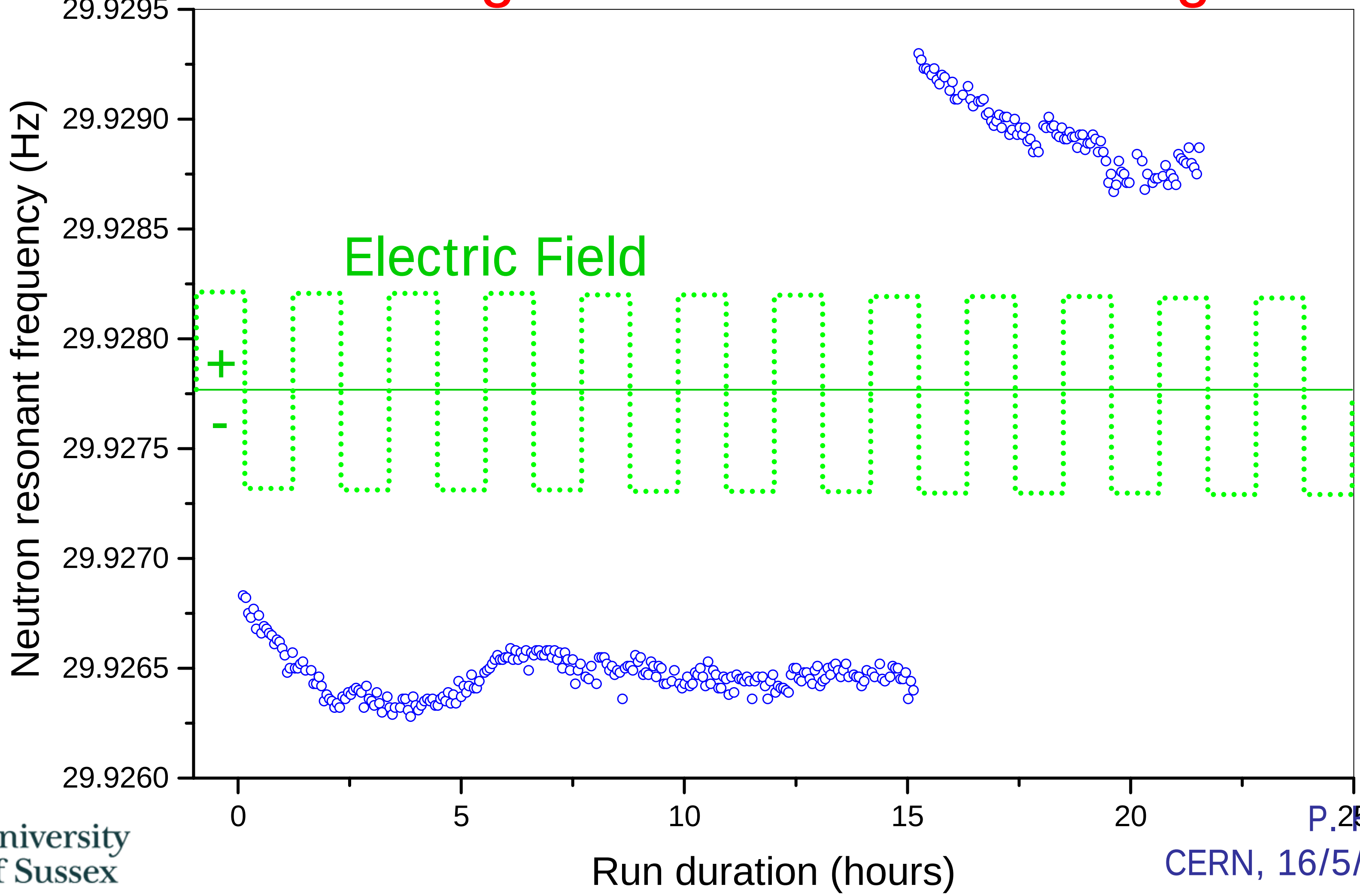
Neutron
storage
chamber

B-field
coils



nEDM measurement

- Keep track of neutron resonant frequency
- Look for changes correlated with changes in E



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Mercury magnetometer

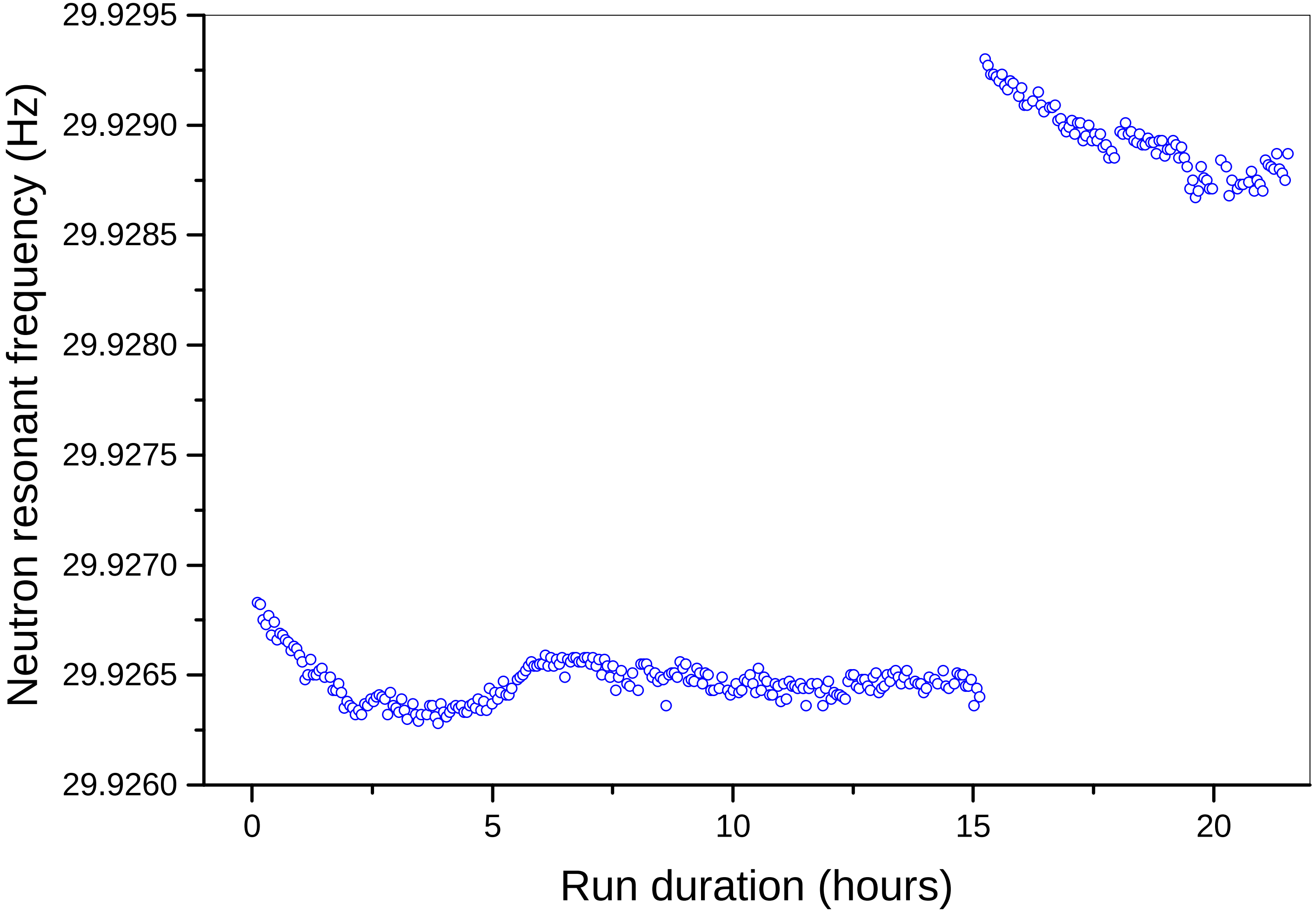
- Need to track changes in B in neutron storage volume
- Better than 0.1 ppm sensitivity needed
- Must not be sensitive to E fields

Use polarised atomic Hg:

$$|d_{Hg}| < 2.1 \times 10^{-28}\ e\ \mathrm{cm}$$

[Romalis et al., PRL 86 (2001) 8505]

Neutron frequency (from before; 1 day)



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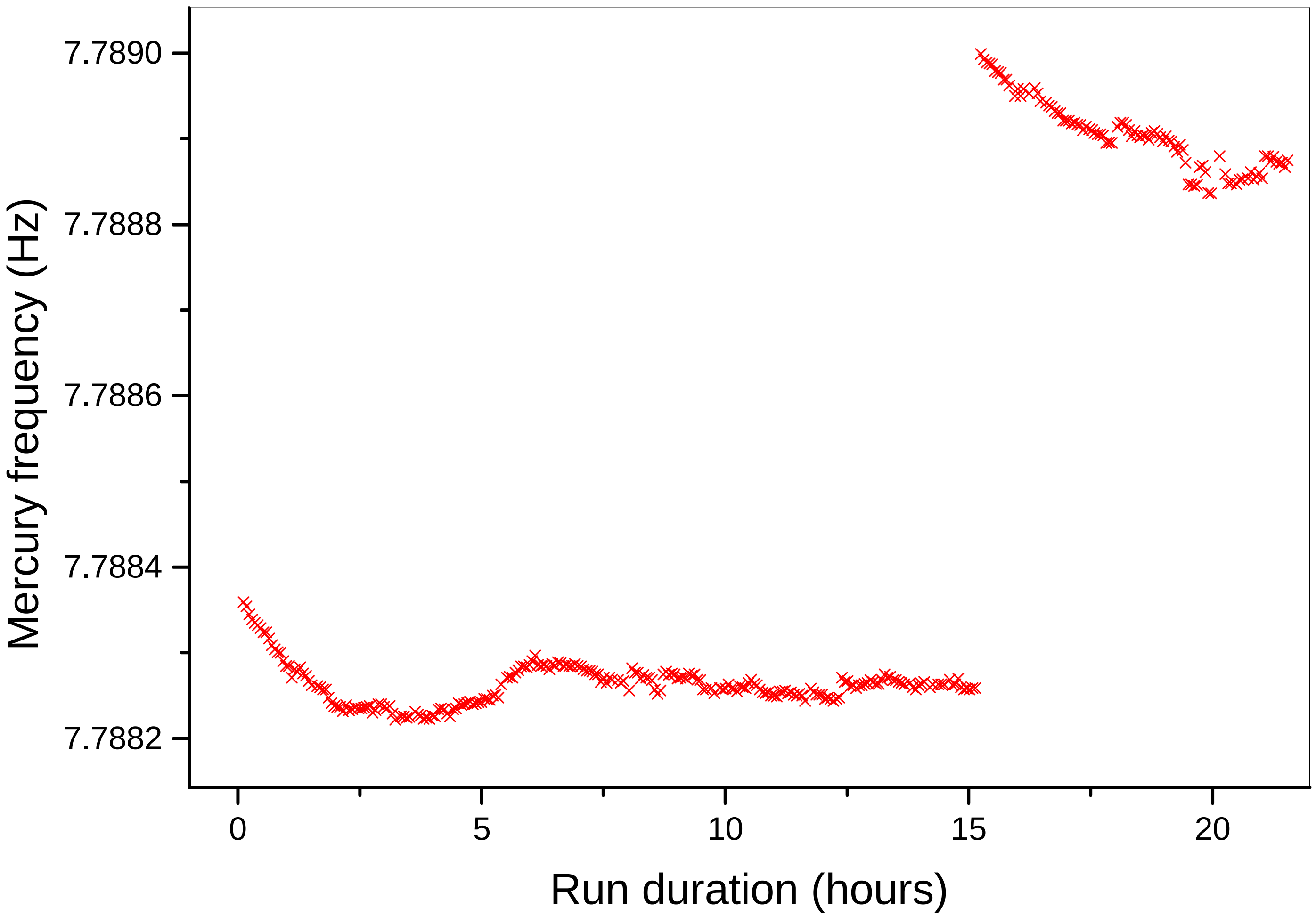
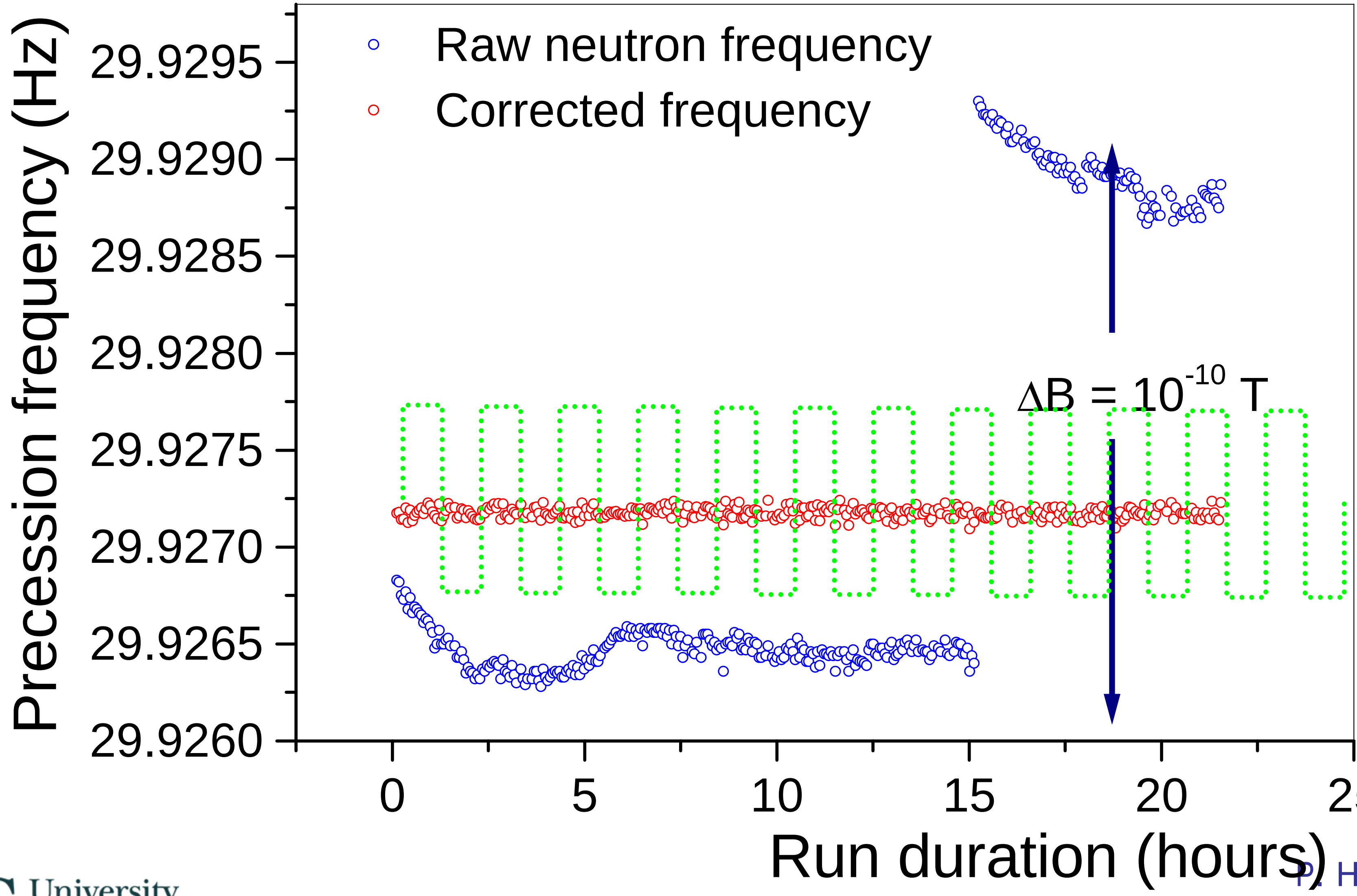
Mercury frequency



nEDM measurement



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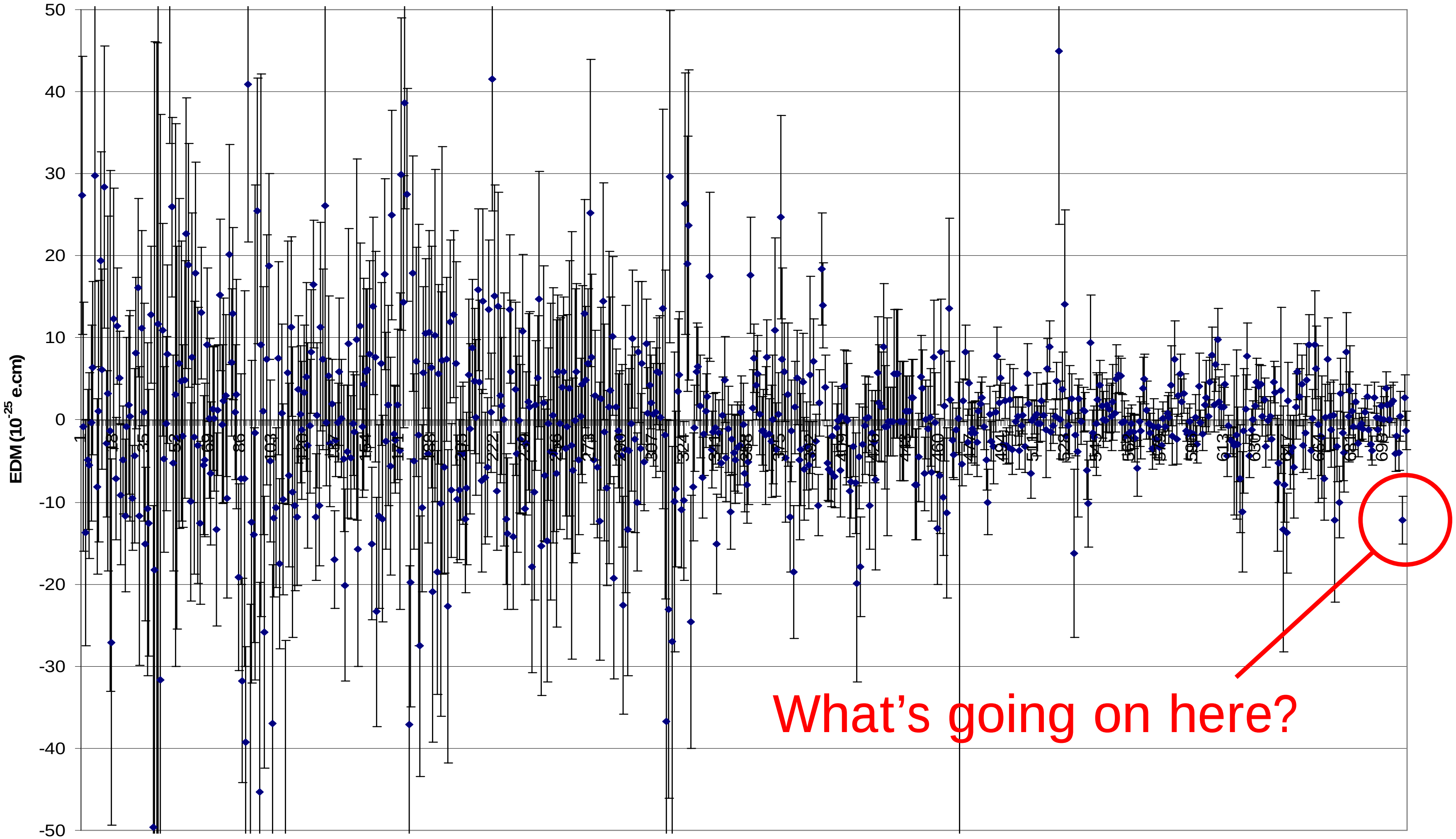
Neutron EDM results (individual runs)



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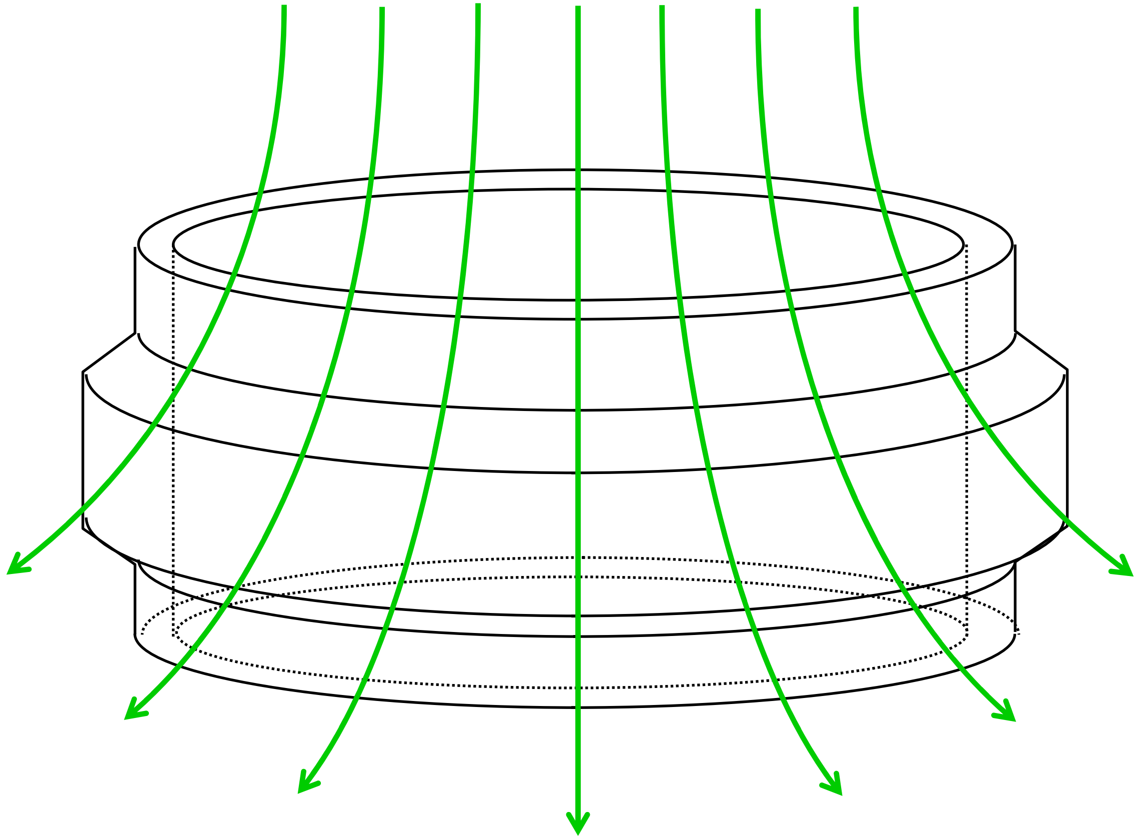
Conspiracy theory

Two effects:

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



and, from Special Relativity, extra motion-induced field

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

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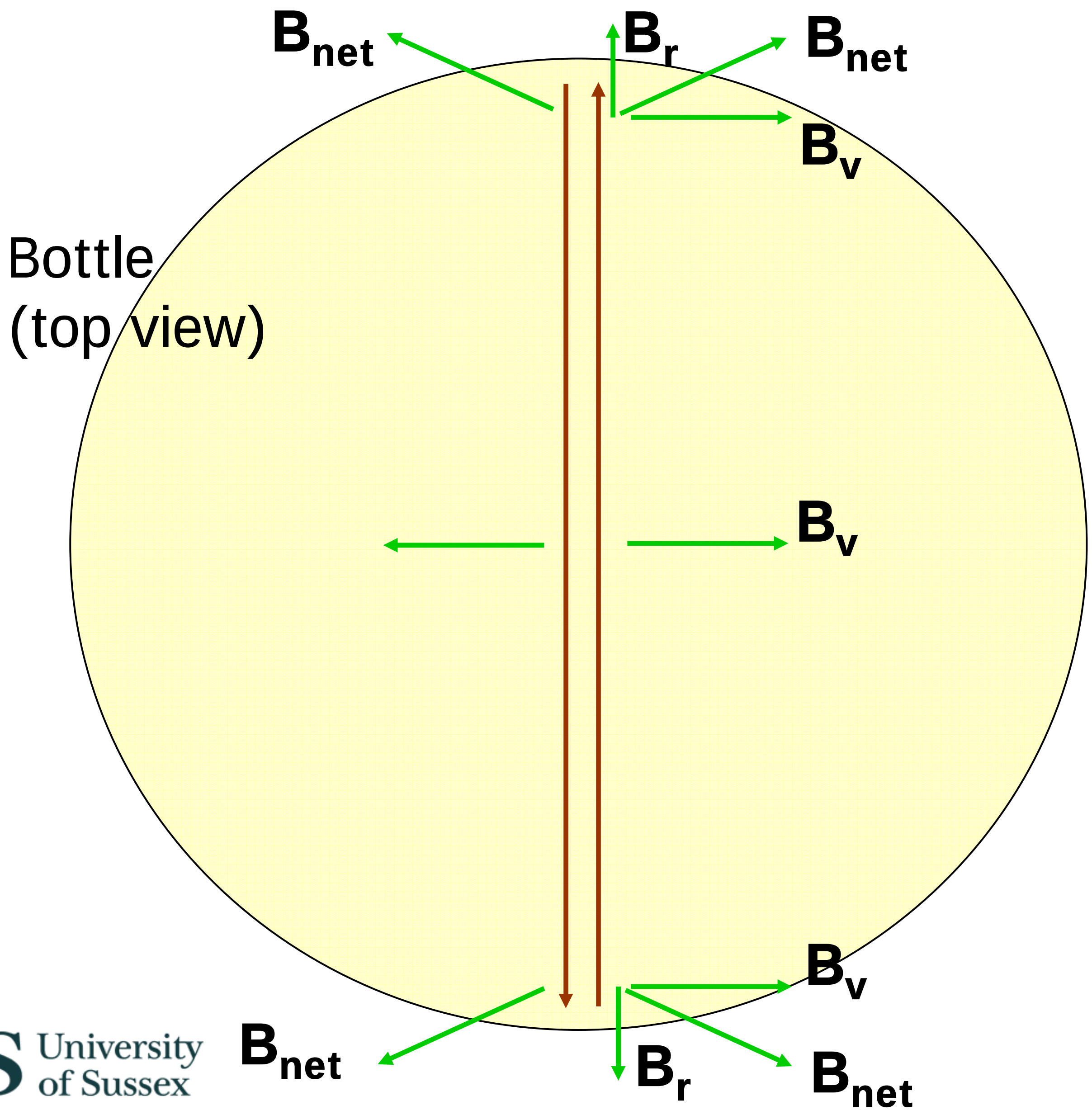
Geometric Phase

J. Pendlebury et al., PRA 70 032102 (2004)
P. Harris, J. Pendlebury, PRA 73 014101 (2006)



… so particle sees additional rotating field

Frequency shift $\propto$ E

Looks like an EDM, but scales with dB/dz

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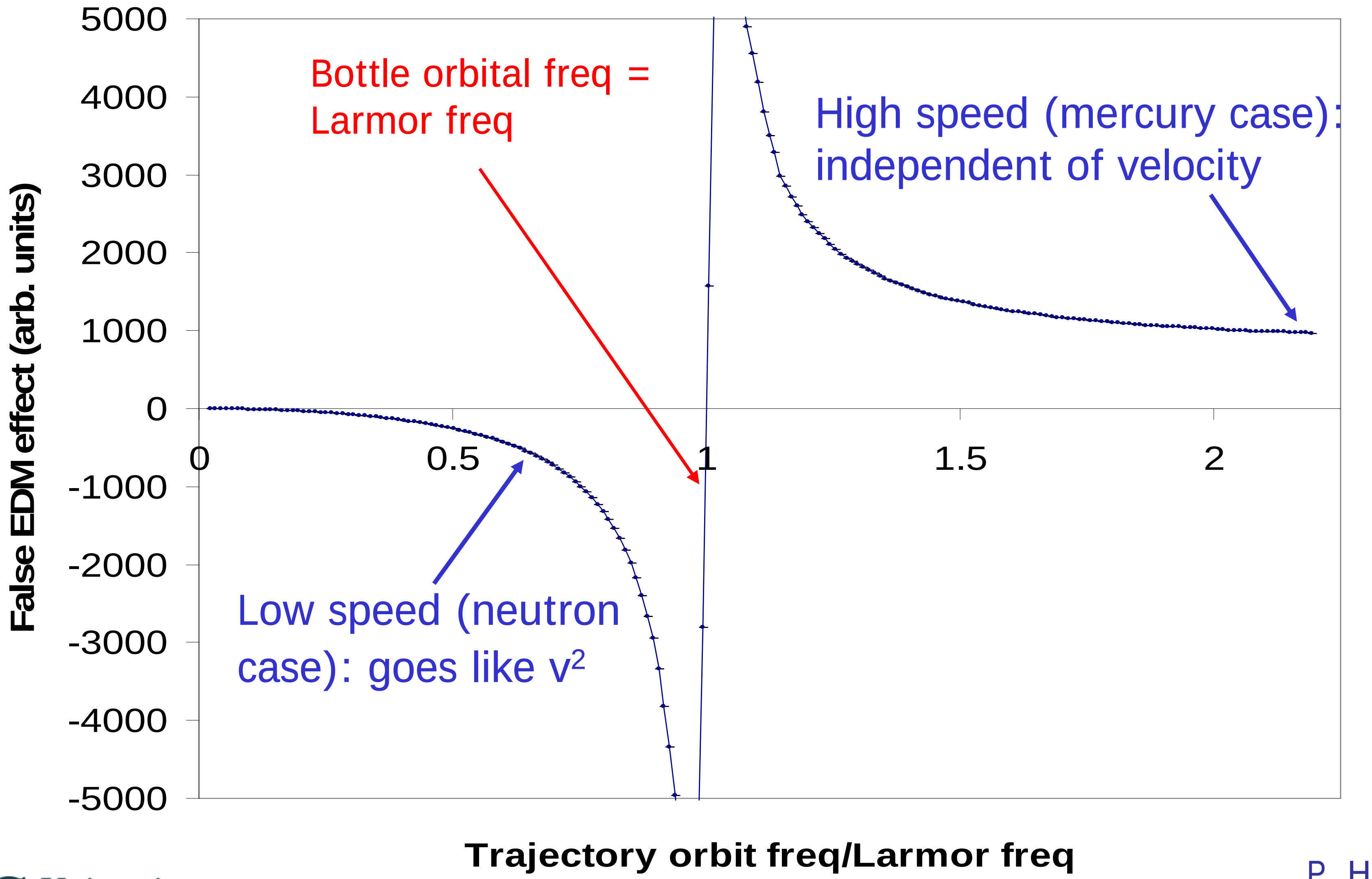
Geometric Phase Velocity dependence



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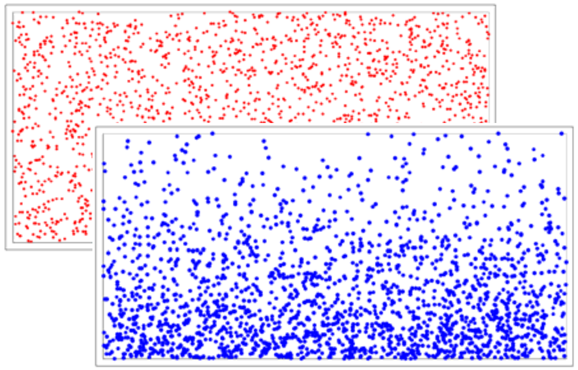
Geometric Phase How to measure it

- Consider

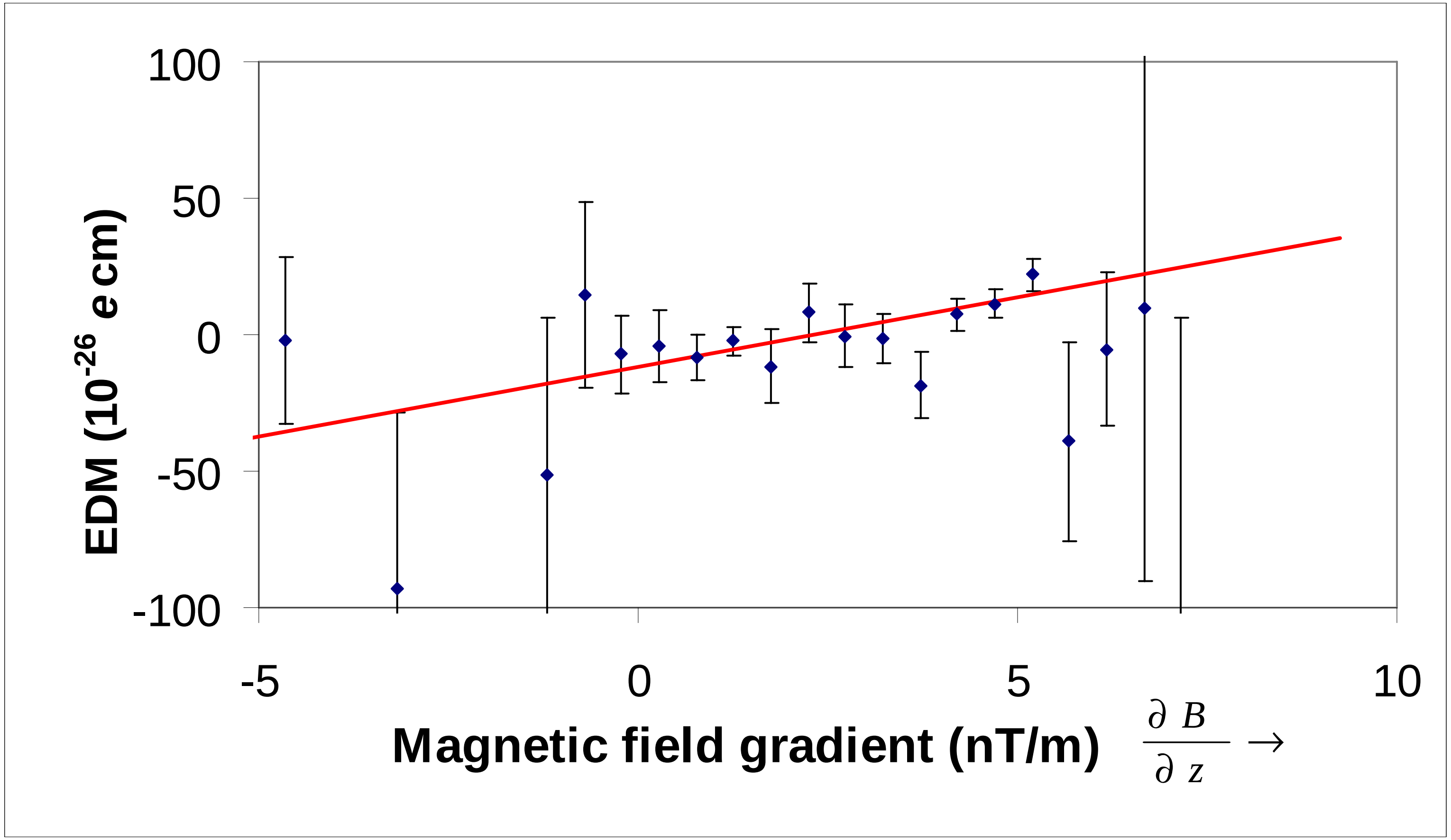
$$R = \frac{\nu_n}{\nu_{Hg}} \cdot \frac{\gamma_{Hg}}{\gamma_n}$$



- Should have value 1
- R is shifted by magnetic field gradients
- Plot EDM vs measured R-1:

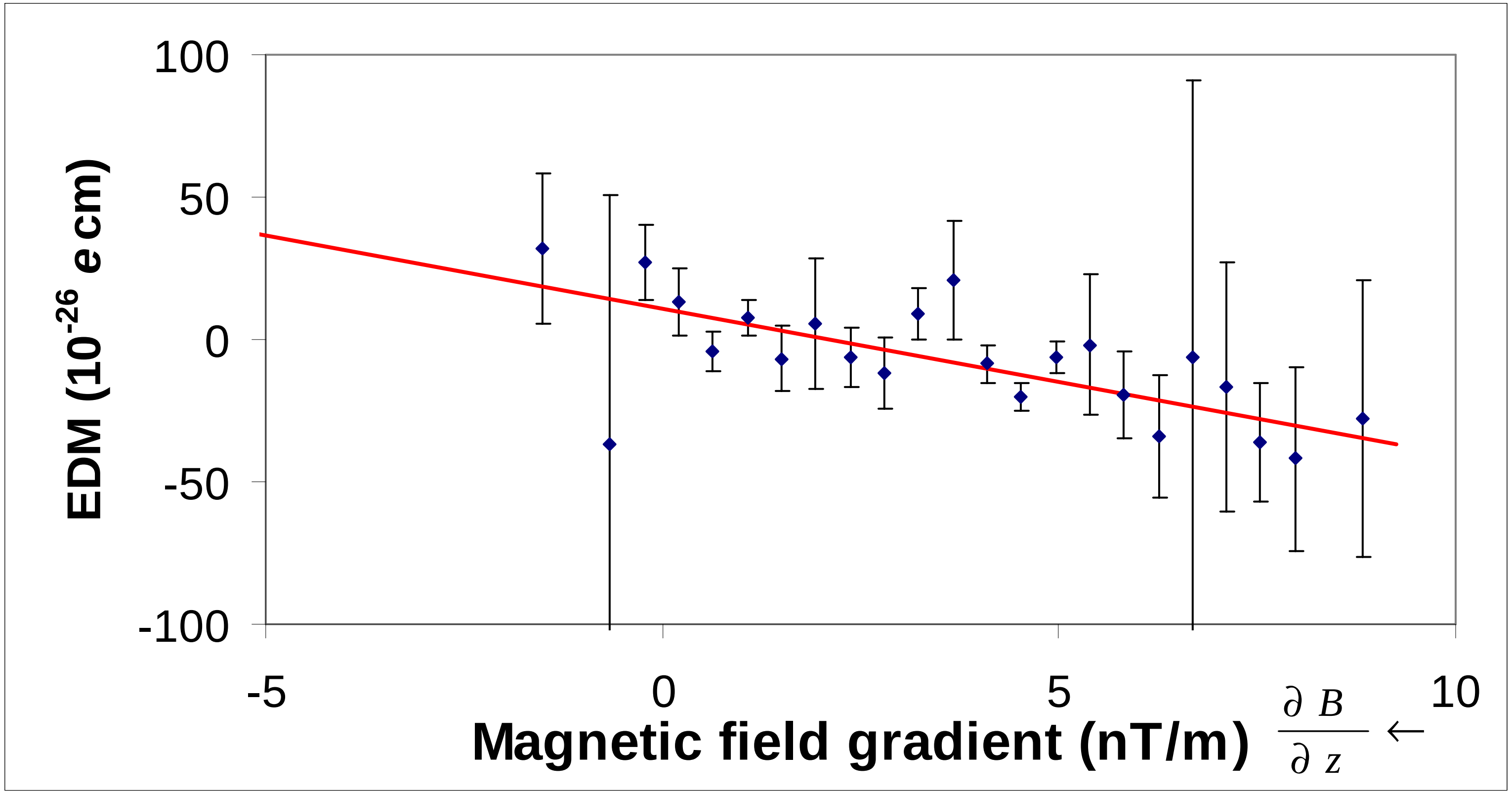
Geometric Phase

Magnetic field down

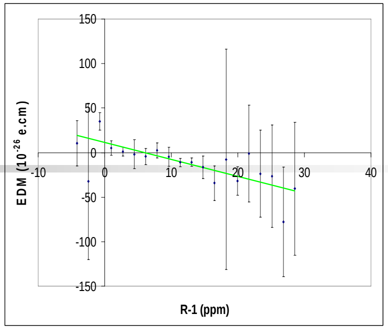


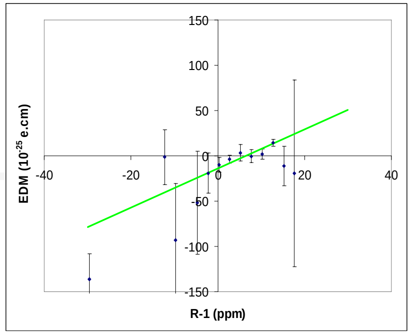
Geometric Phase

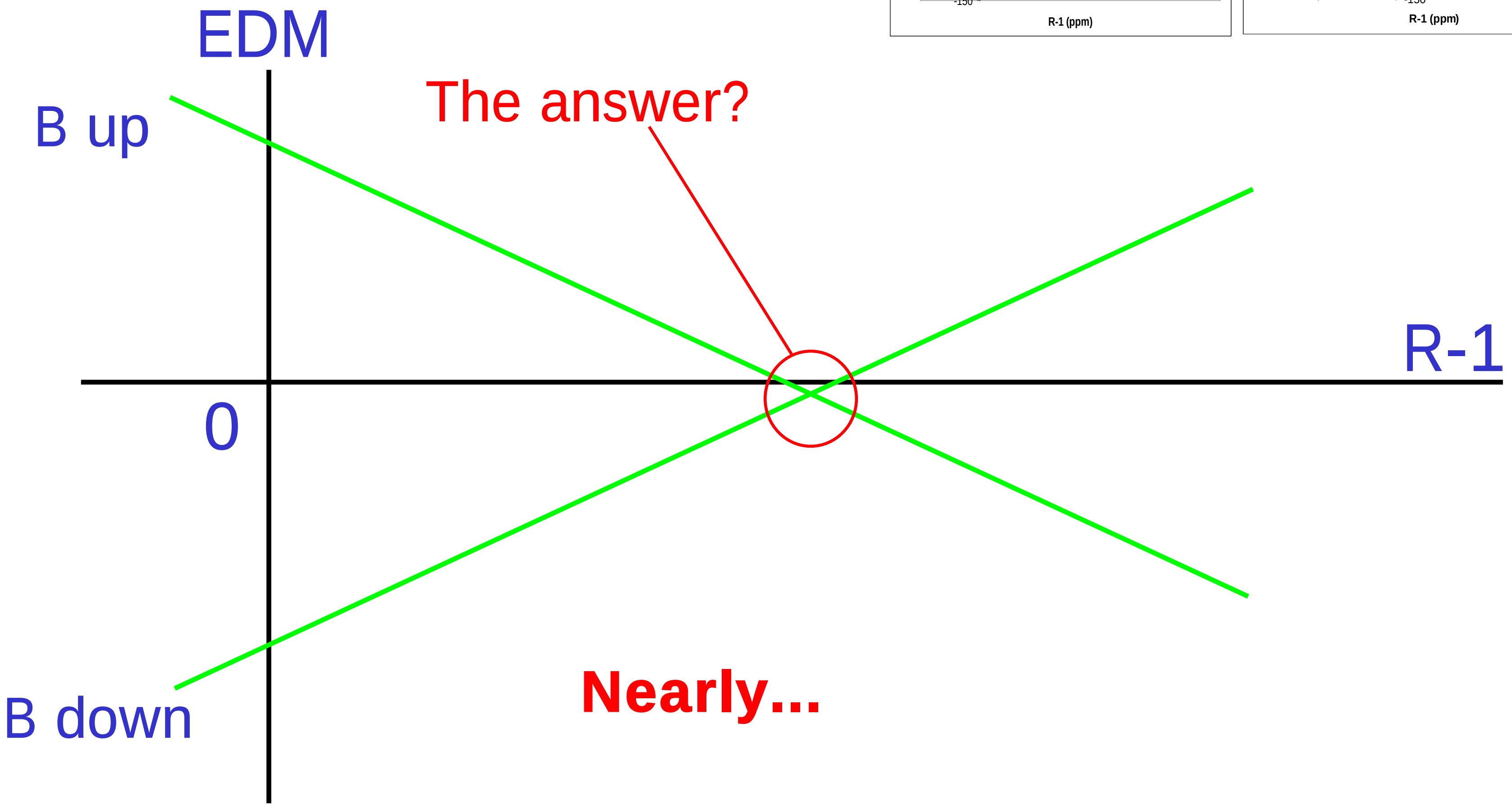
Magnetic field up



Results







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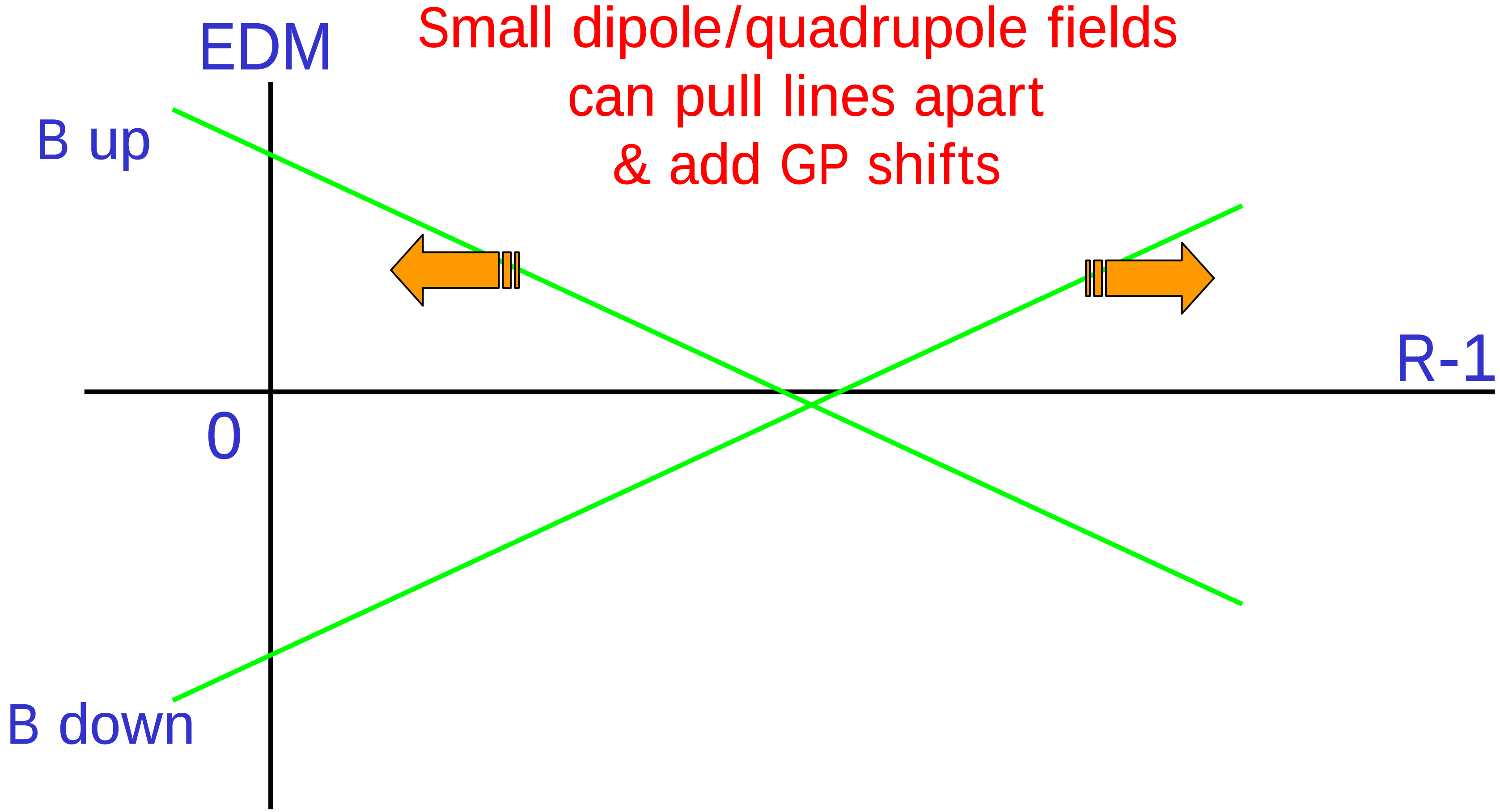
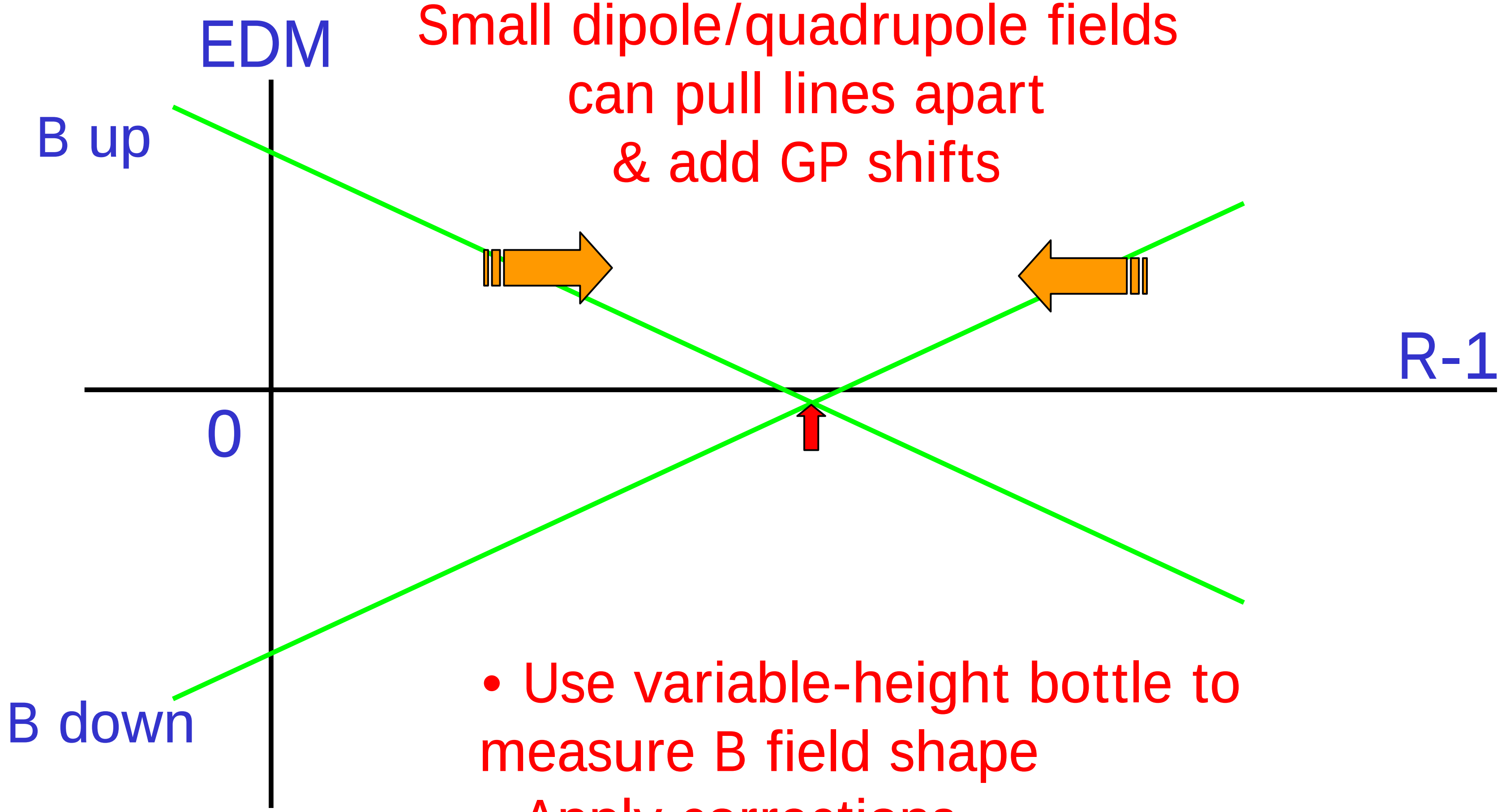
Results


EDM
Small dipole/quadrupole fields
can pull lines apart
& add GP shifts
B up
R-1
0
B down

Results



Small dipole/quadrupole fields can pull lines apart & add GP shifts

- Use variable-height bottle to measure B field shape
- Apply corrections

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Error budget (10^{-26} *e*.cm)

Effect	Shift	Uncertainty
Statistical	0	1.51
Door cavity dipole; quadrupole fields	-1.10	0.45
Other GP dipole shifts	0	0.60
(**E** x **v**)/c^2 from translation	0	0.05
(**E** x **v**)/c^2 from rotation	0	0.10
Light shift: direct & GP	0.35	0.08
B fluctuations	0	0.24
E forces – distortion of bottle	0	0.04
Tangential leakage currents	0	0.01
AC B fields from HV ripple	0	0.001
Hg atom EDM	0	0.05
2^{nd} order **E**x**v**	0	0.002
Total	–0.75	1.51 stat, 0.80 sys

Final Result

New limit:

$|d_n| < 3.0 \times 10^{-26}$ e.cm (90% CL)

Preprint hep-ex/0602020

("probable acceptance" from PRL)

www.neutronedm.org

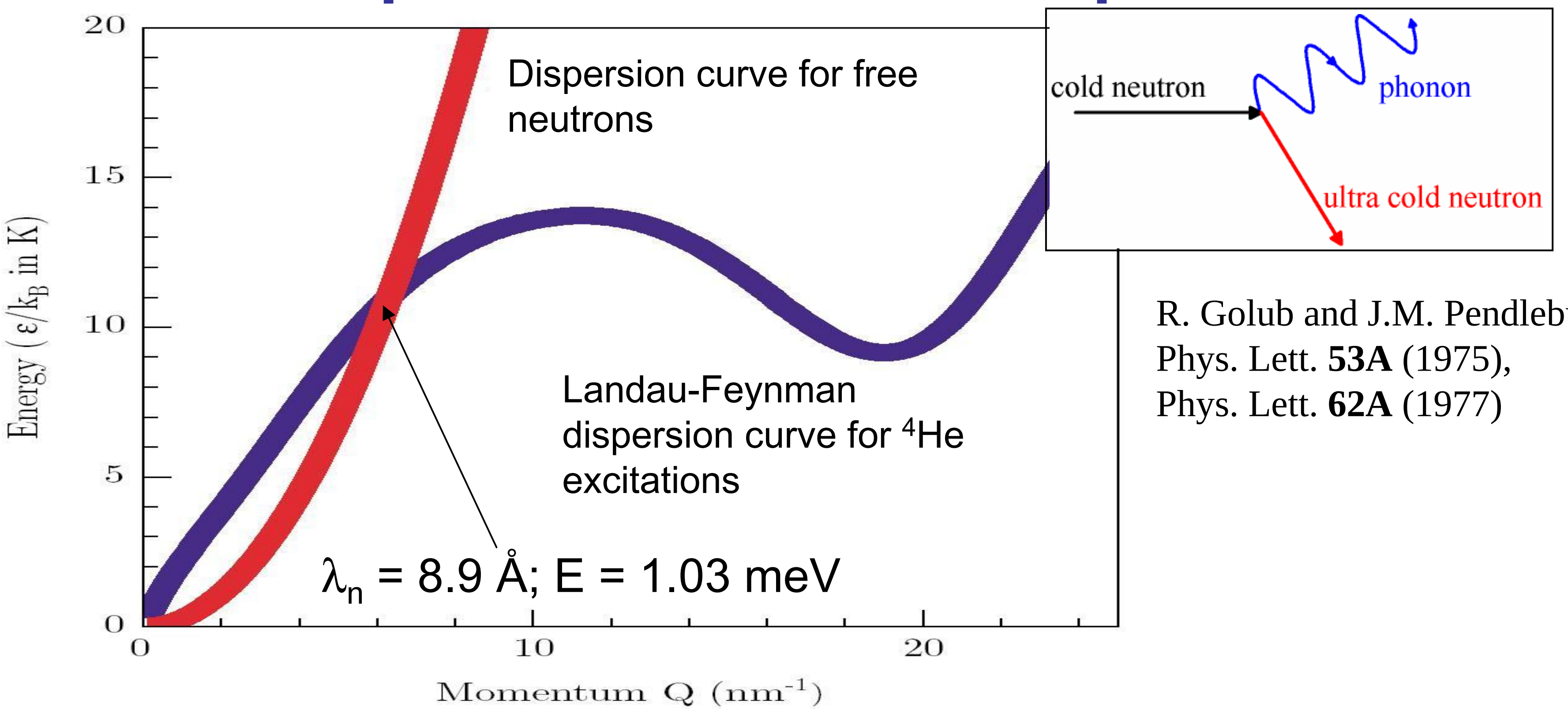
CryoEDM: The Next Generation

New technology:

- More neutrons
- Higher E field
- Better polarisation
- Longer NMR coherence time

100-fold improvement in sensitivity

UCN production in liquid helium



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

- 1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K
- Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ means not many 11 K phonons present
- **Observed:** C.A.Baker *et al.*, Phys.Lett. **A308** 67-74 (2002)

Statistical limits

$$\sigma_d = \frac{\hbar / 2}{\alpha\, E\, T \sqrt{N}}$$

Parameter	Room-tmpr. expt	Sensitivity
▪ Polarisation+detection	$\alpha = 0.75$	x 1.2
▪ Electric field:	$E = 10^6$ V/m	x 4
▪ Precession period:	$T = 130$ s	x 2
▪ Neutrons counted:	$N = 6 \times 10^6$ /day	x 4.5
(with new beamline)		x 2.6

Total increase approx factor 100

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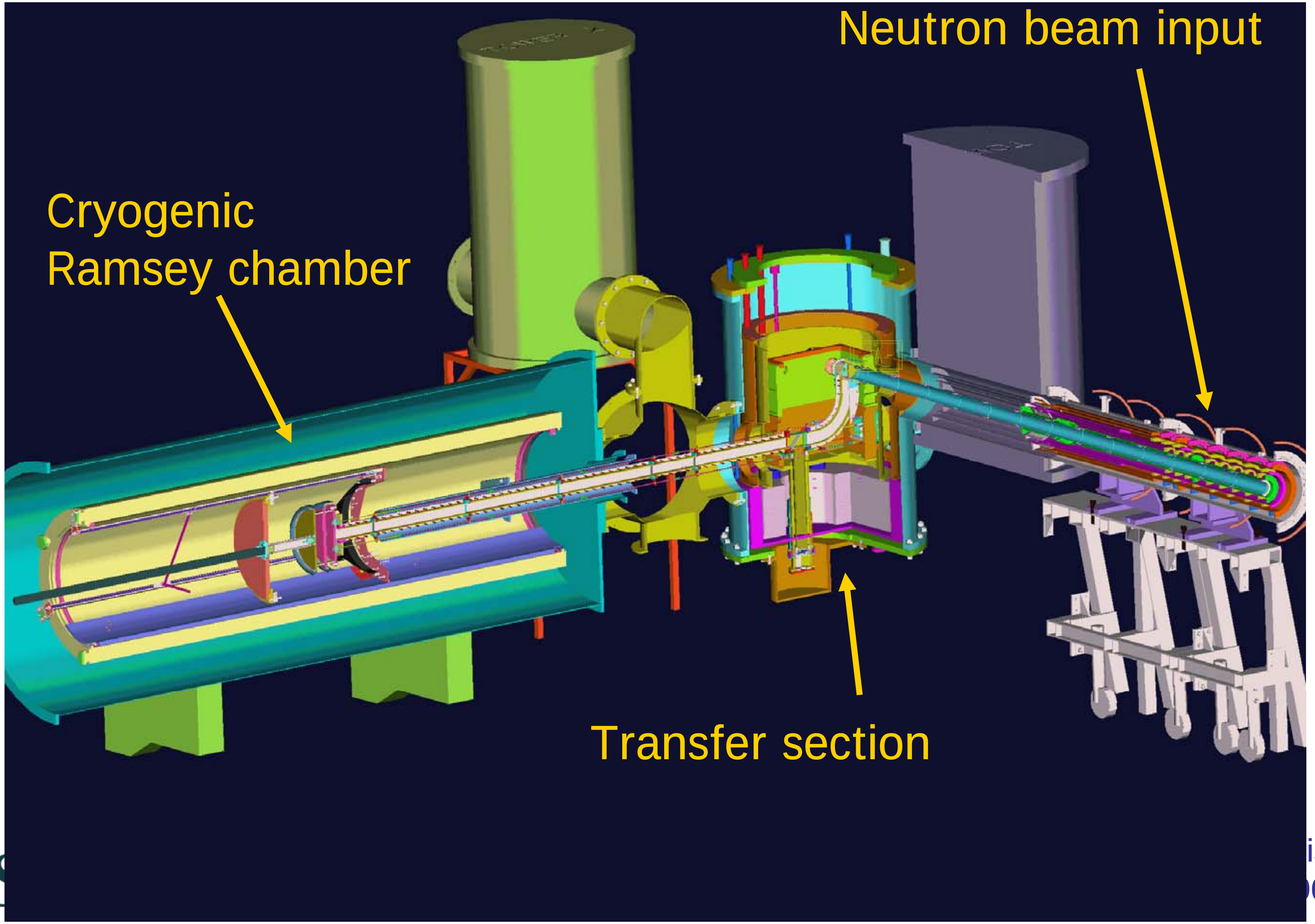
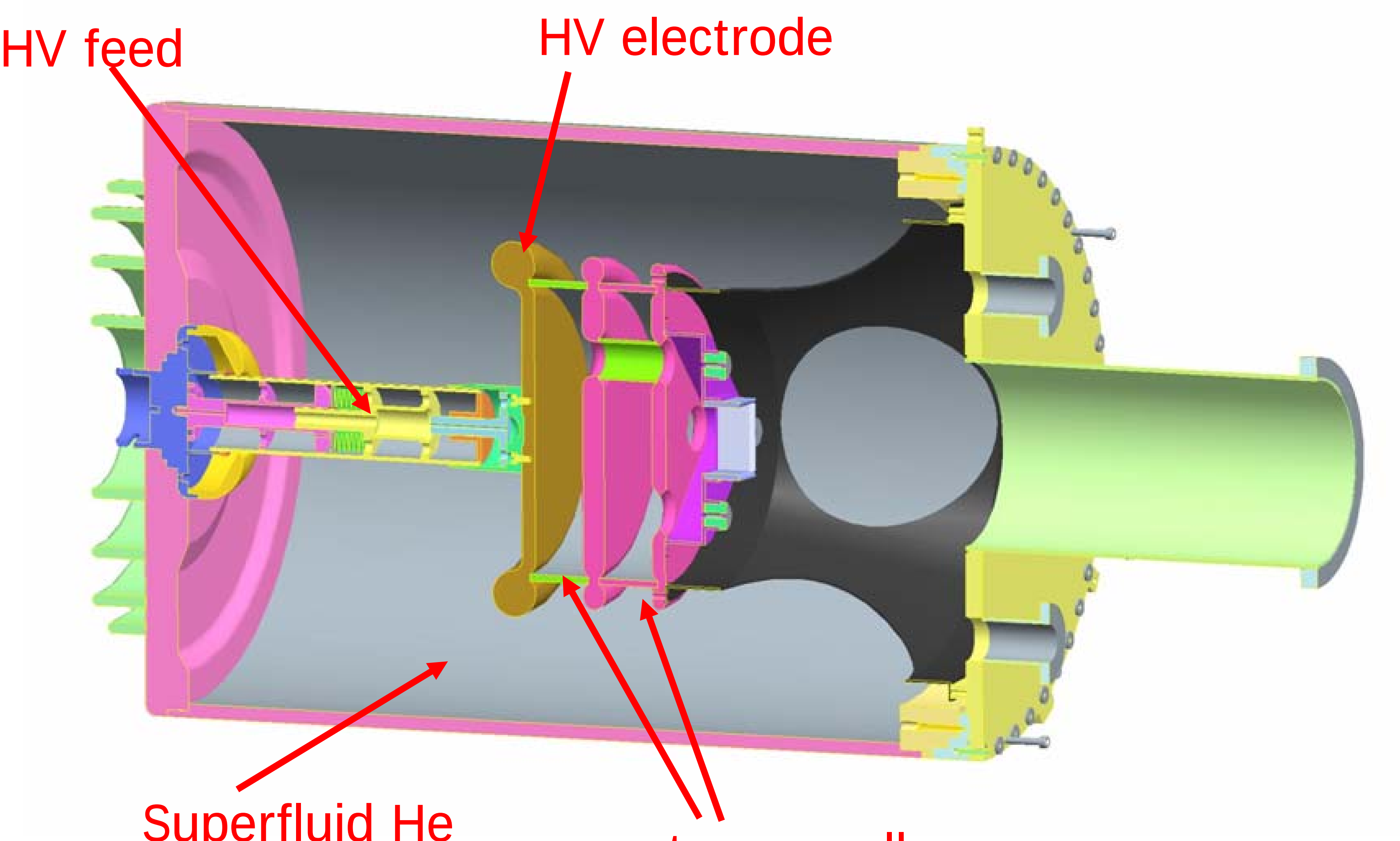
CryoEDM overview



Cryogenic Ramsey chamber

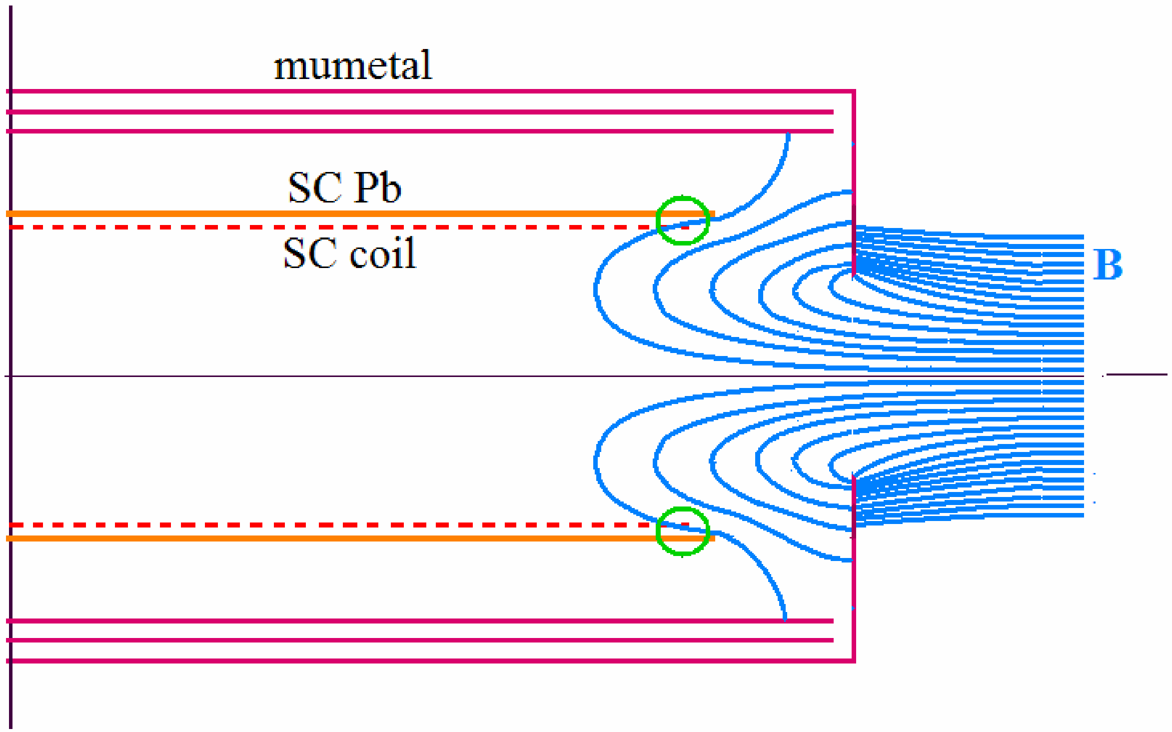


Systematics: General

- Systematics minimised by highly symmetric data taking:
  - **B** and **E** field reversals
  - Alternating either side and above/below middle of central Ramsey fringe
  - Eventually: opposite **E** in adjacent cells
  - neutron magnetometers in adjacent (outer) cells

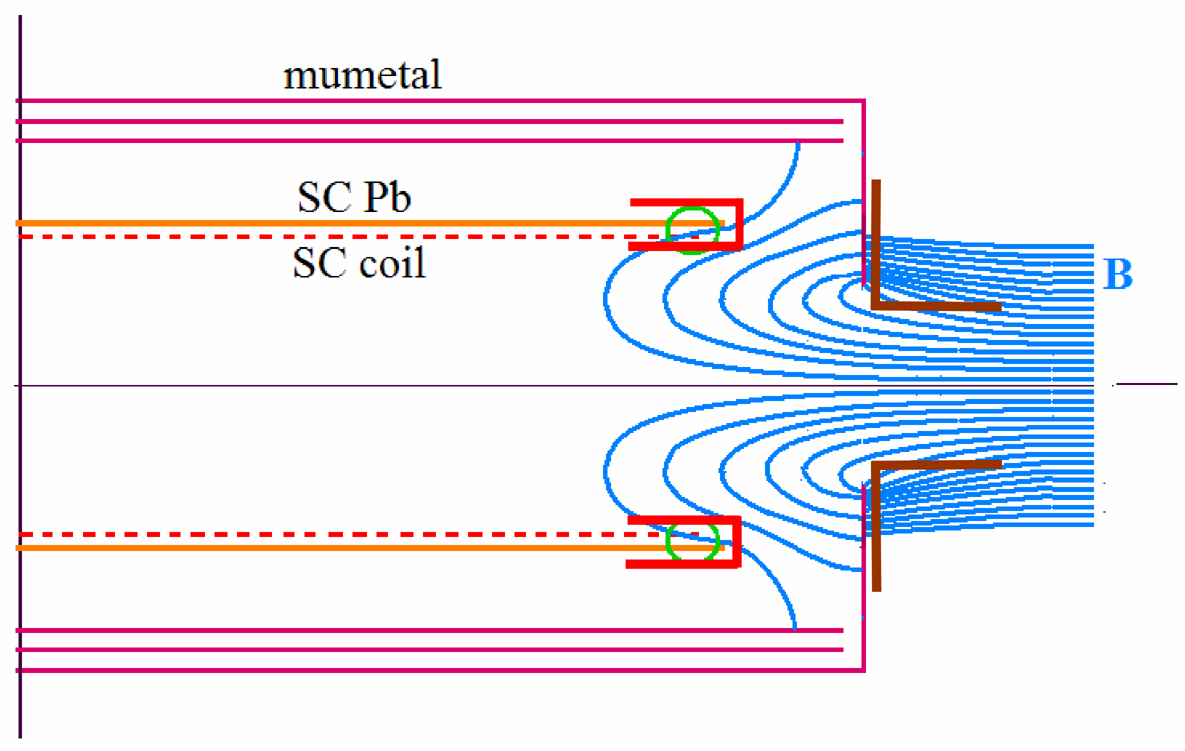
Systematics: B field fluctuations

- At present, Pb shield too short: flux lines clip coil end, inducing current in whole coil
- Introduces common-mode noise, limiting sensitivity to 1E-27 e.cm



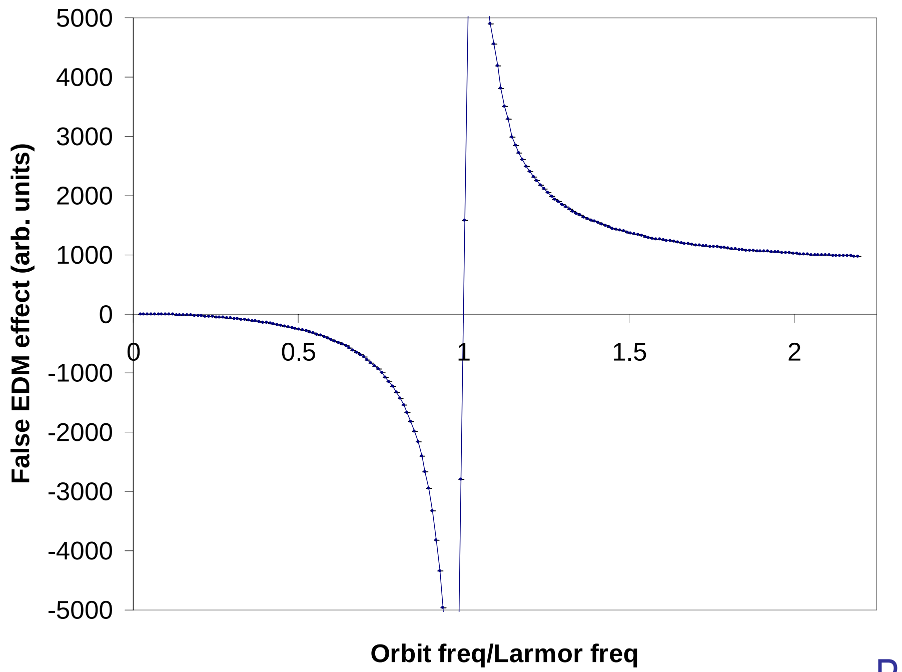
Systematics: B field fluctuations

- Additional μ metal (factor 4) and Pb end caps (250) to increase shielding by factor 1000



Systematics: Geometric phase

- Room-temperature: 1 nT/m $\rightarrow$ 4E-26 ecm
- Neutrons 50x less sensitive than Hg
- For neutrons, scales as $1/B^2$; increase B 5x to obtain factor 25 protection
- Net protection factor 50x25 = 1250, so 1 nT/m
  $\rightarrow$ 3E-29 e.cm



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Systematics: **E** x **v**

- Translational:
  - Vibrations may warm UCN, cause CM to rise ~1 mm in 300 s $\rightarrow$ 3E-6 m/s
  - If **E**, **B** misaligned 0.05 rad., gives 2E-29 e.cm
- Rotational:
  - Net rotation damped quickly: matt walls
  - Delay before NMR pulses allows rotation to die away
  - Neutrons enter E-field cells centred horizontally; no preferred rotation
  - Below 1E-29 e.cm

Systematics: 2^{nd} order **E** x **v**

- Perpendicular component, adds in quadrature to **B**.
- Prop. to $\mathbf{E}^2$; gives signal if **E** reversal is asymmetric
- Cancellations (double cell; **B** reversals) reduce effect to < 3E-29 e.cm

Systematics: μ metal hysterisis

- Room-temp expt: Pickup in B coil from E field reversals; return flux causes hysterisis in μ metal
- Coil here is SC, not power-supply driven
- Inner shield is SC also
- Small effect from trim coils, enhanced by any misalignments
- Net estimate < 1E-30 e.cm

Systematics: **E** induced cell movement

- Electrostatic forces of order 20 N; $\propto E^2$
- Radial gradients of order 3 nT/m
- Must keep displacement on E reversal to ~ 0.01 μm
- Cancellation with double cell
- Symmetric voltages to ~2%
- Net effect < 1E-28 e.cm

Systematics: Leakage currents

- Azimuthal current components generate axial contributions to B
- Cancellation in adjacent cells
- Conservative estimate: 1 nA $\rightarrow$ 5E-29 e.cm
- In reality LHe should keep currents much below this
- New source of current: ionisation from UCN decay electrons

Systematics: HV supply contamination

- HV circuit isolated as far as possible to minimise earth contamination. Separate computer control.
- 10 kHz ripple on HV line can “pull” resonant freq. Estimate 1E-30 e.cm
- Likewise 50 Hz ripple: estimate ~1E-29 e.cm
- Directly generated AC **B** fields negligible

Systematics: Summary

Effect	Size (e.cm)
B fluctuations	1×10^{-30}
Geometric phase	3×10^{-29}
Ex**v** translational	2×10^{-29}
Ex**v** rotational	1×10^{-29}
Ex**v** 2^{nd} order	3×10^{-29}
μ metal hysterisis	1×10^{-30}
E-induced cell movement	1×10^{-28}
Leakage currents	5×10^{-29}
HV line contamination	1×10^{-29}

CryoEDM

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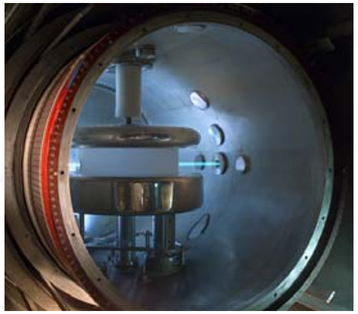
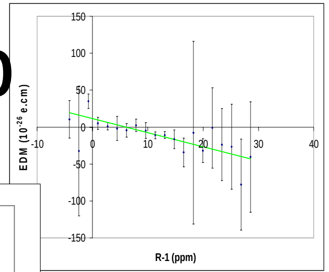
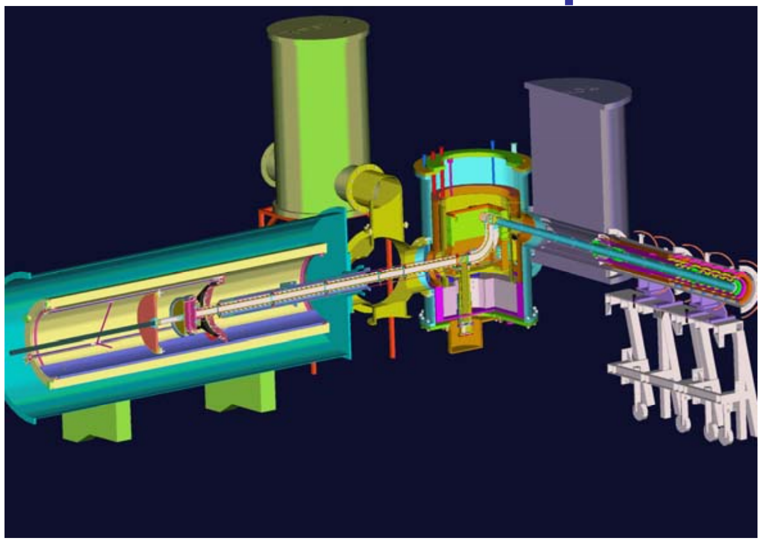
Conclusions

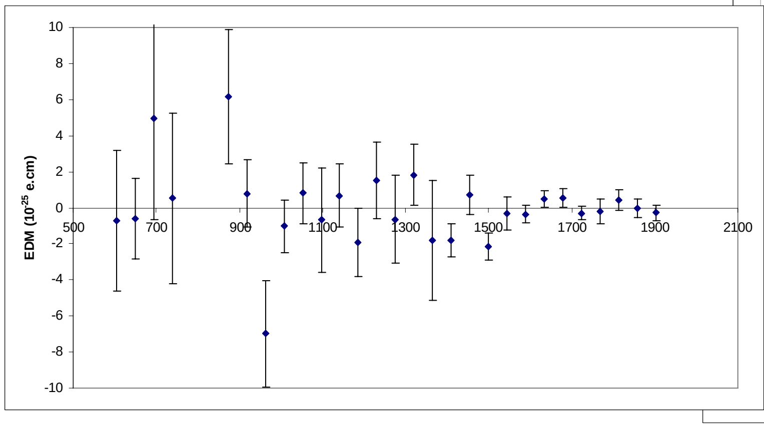


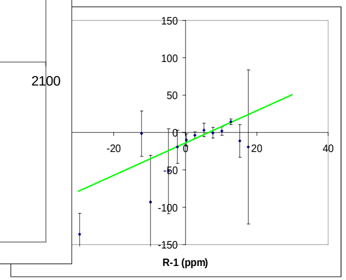
- New nEDM limit, 3.0 x 10^{-26} e.cm
  - Tightens the constraints on beyond-SM CPv
- Systematics understood as never before
- CryoEDM coming soon – 100x more sensitive
- Several new measurements starting up



- Watch this space!







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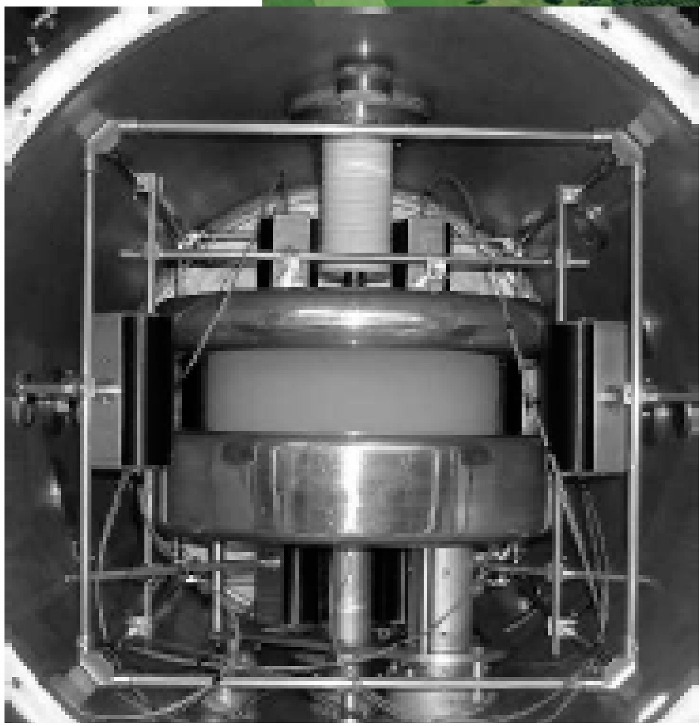
spare slides

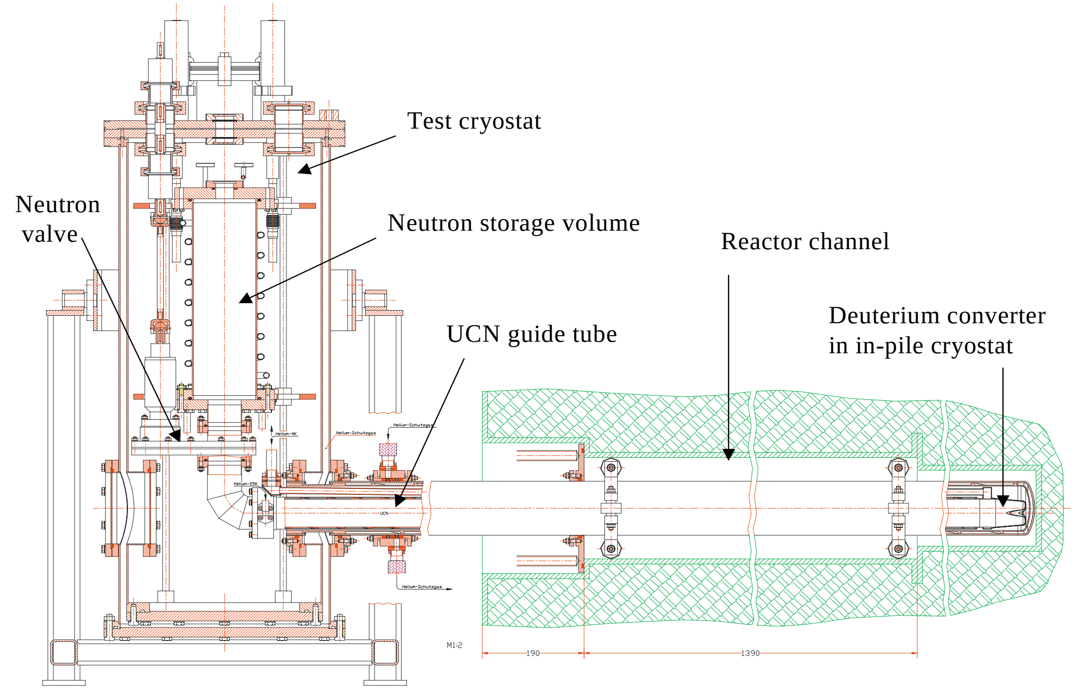
Other EDM experiments: PSI

- spallation target
- D_2O moderator
- currently testing apparatus from ILL



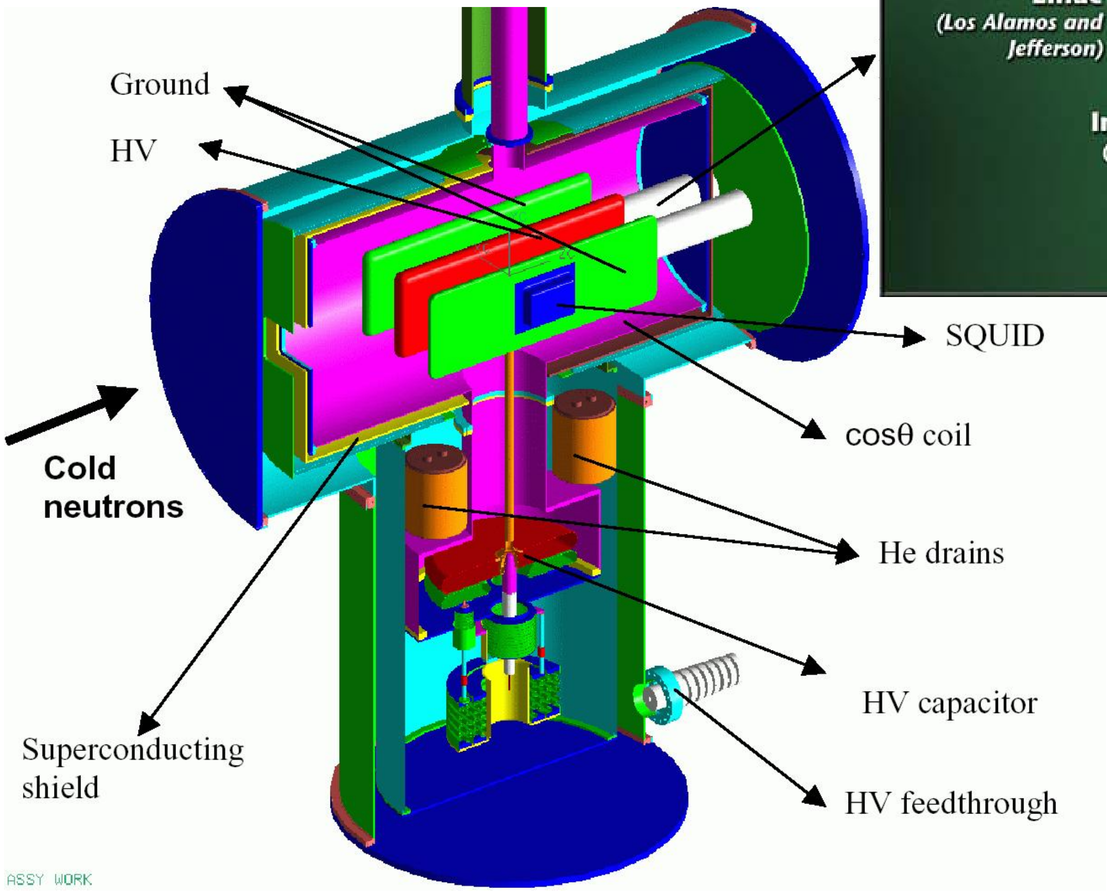
Other nEDM experiments: Mainz

- Testing UCN source at TRIGA, Mainz for later installation at FRM, Munich



Other nEDM experiments: USA

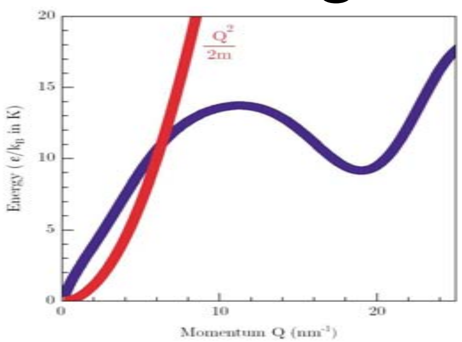
- SNS at ORNL



- LANL-led
- testing underway
- not yet funded

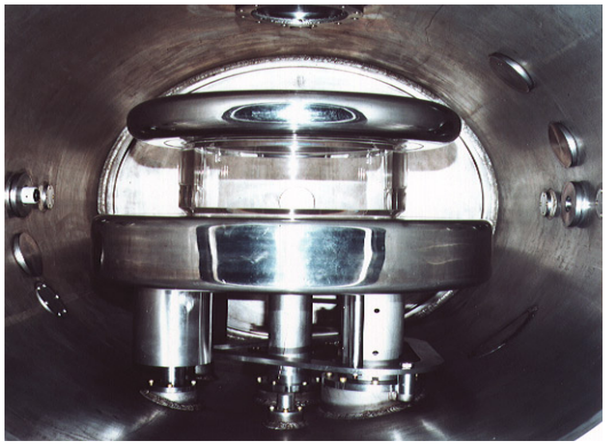
And finally...

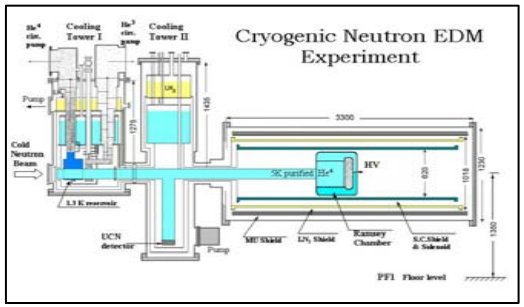
"It may be that the next exciting thing to come along will be the

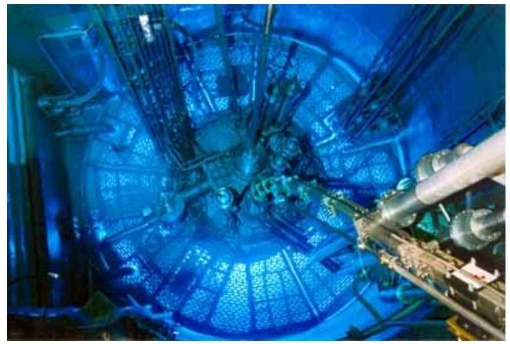


discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments... seem to me to offer one of the most exciting possibilities for progress in particle physics."

- S. Weinberg



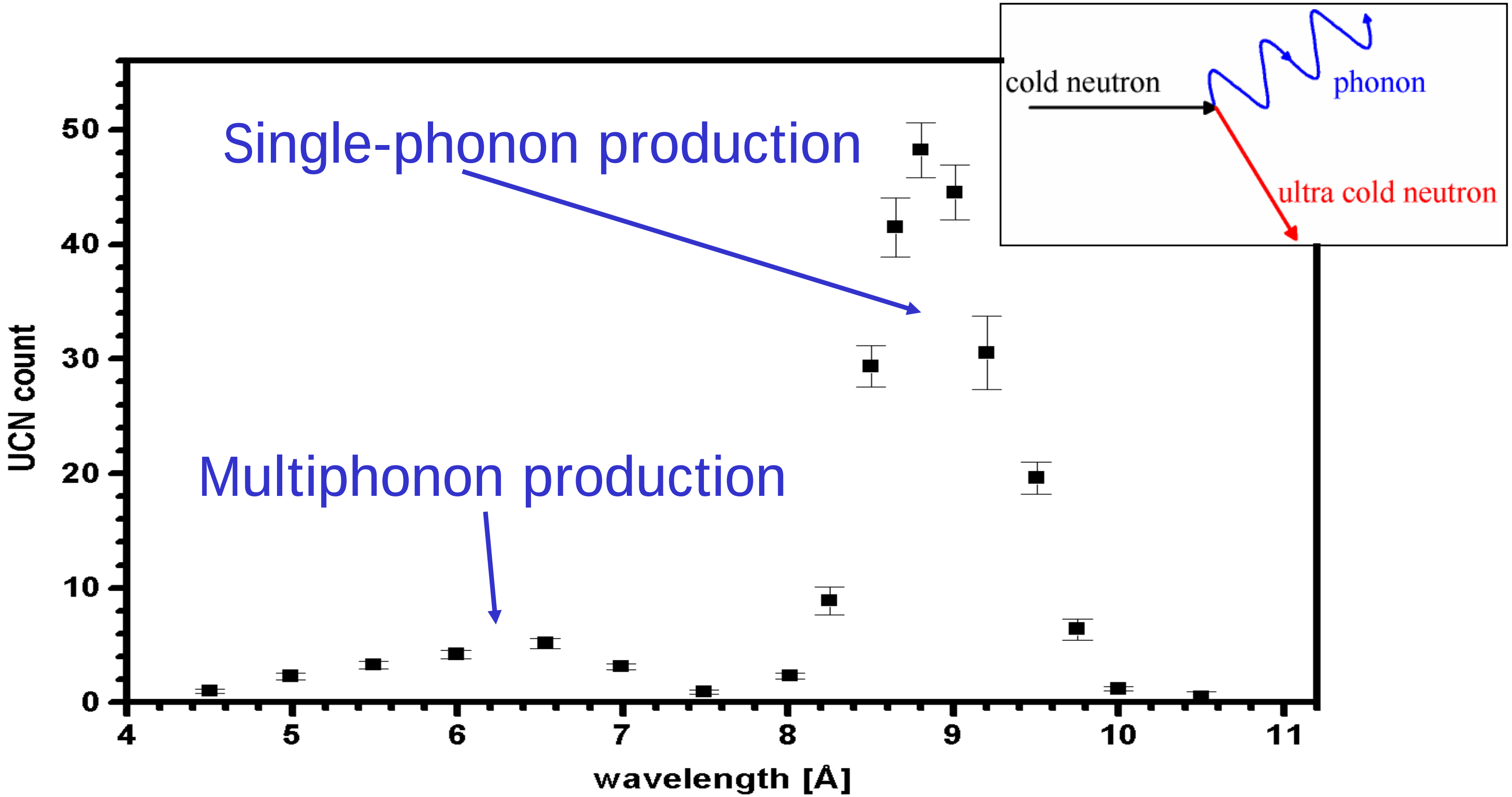




Further reading

- Web site www.neutronedm.org
- Room-temperature result: hep-ex/0602020
- Theory: see, e.g., refs in hep-ex/0602020
- Geometric phase: J. Pendlebury et al., PRA 70 032102 (2004); and P. Harris, J. Pendlebury, PRA 73 014101 (2006)
- n production in helium: C.A.Baker *et al.*, Phys.Lett. A308 67-74 (2002)
- Detectors: C.A.Baker *et al.*, NIM A487 511-520 (2002)

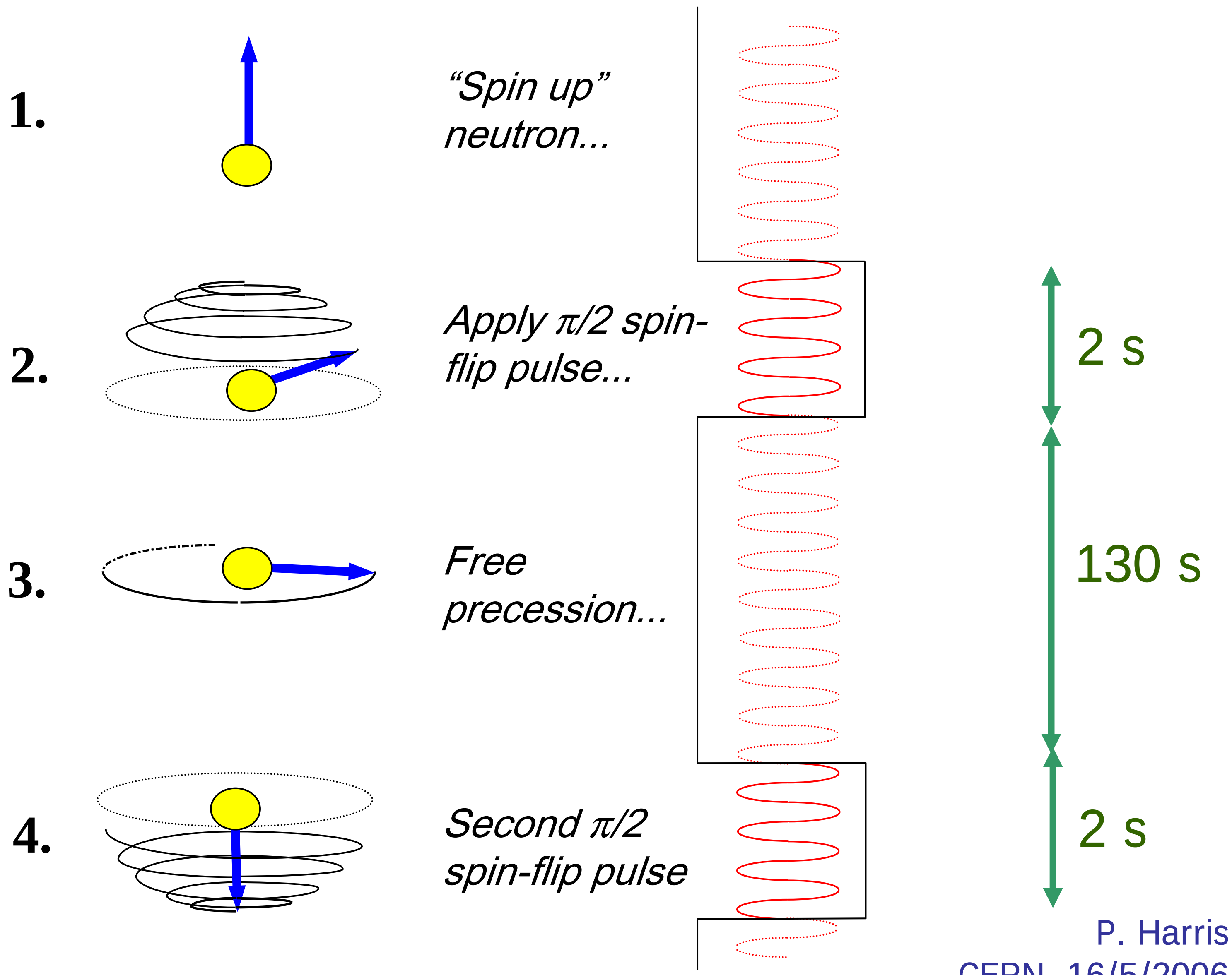
UCN production rate vs λ_n



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

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

Ramsey method of Separated Oscillating Fields



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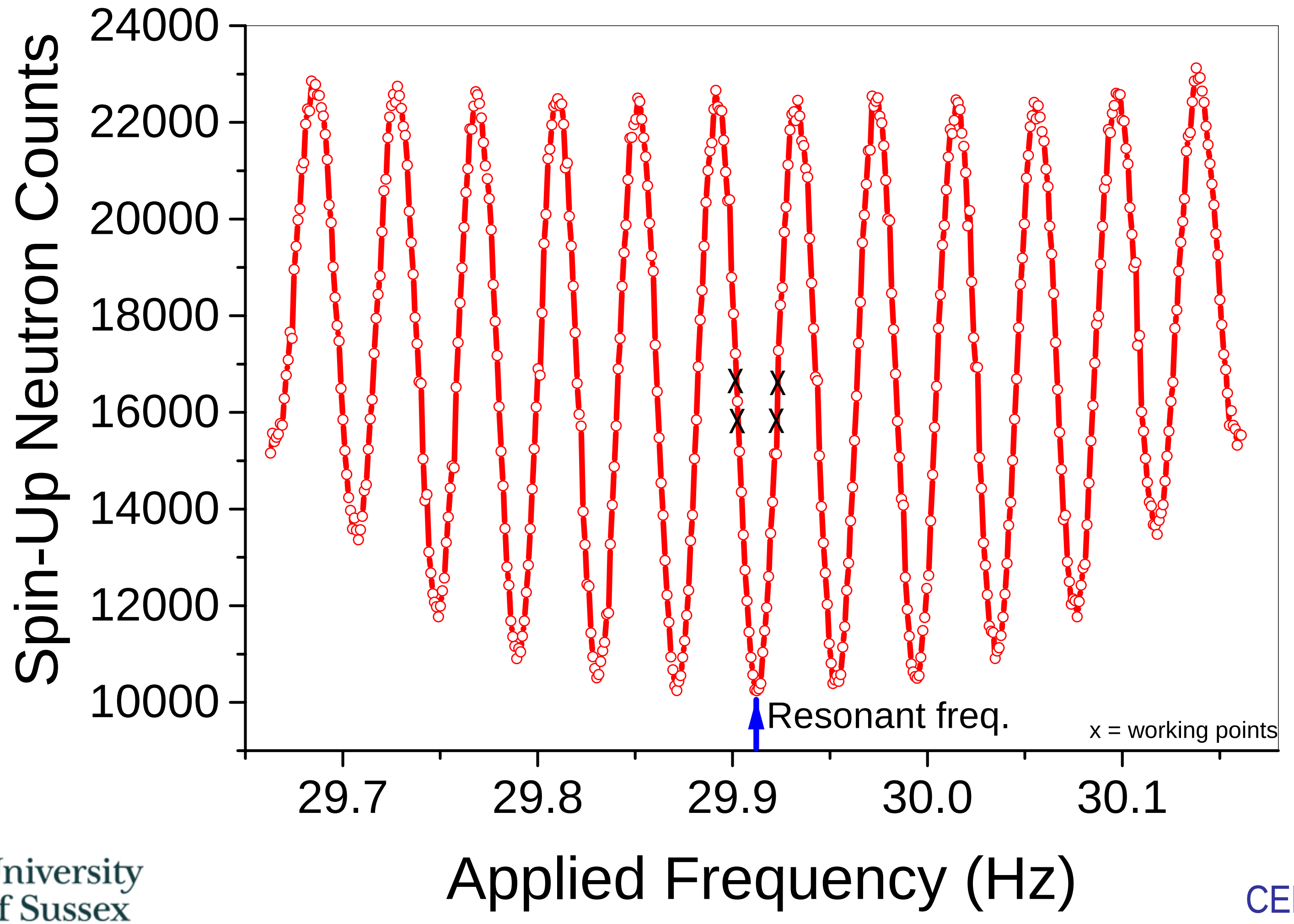
Ramsey resonance

- "2-slit" interference pattern
- Phase gives freq offset from resonance



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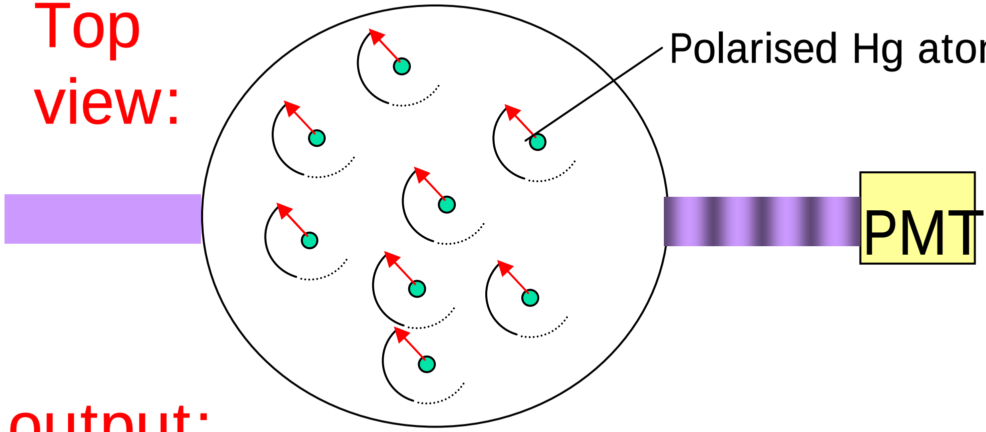
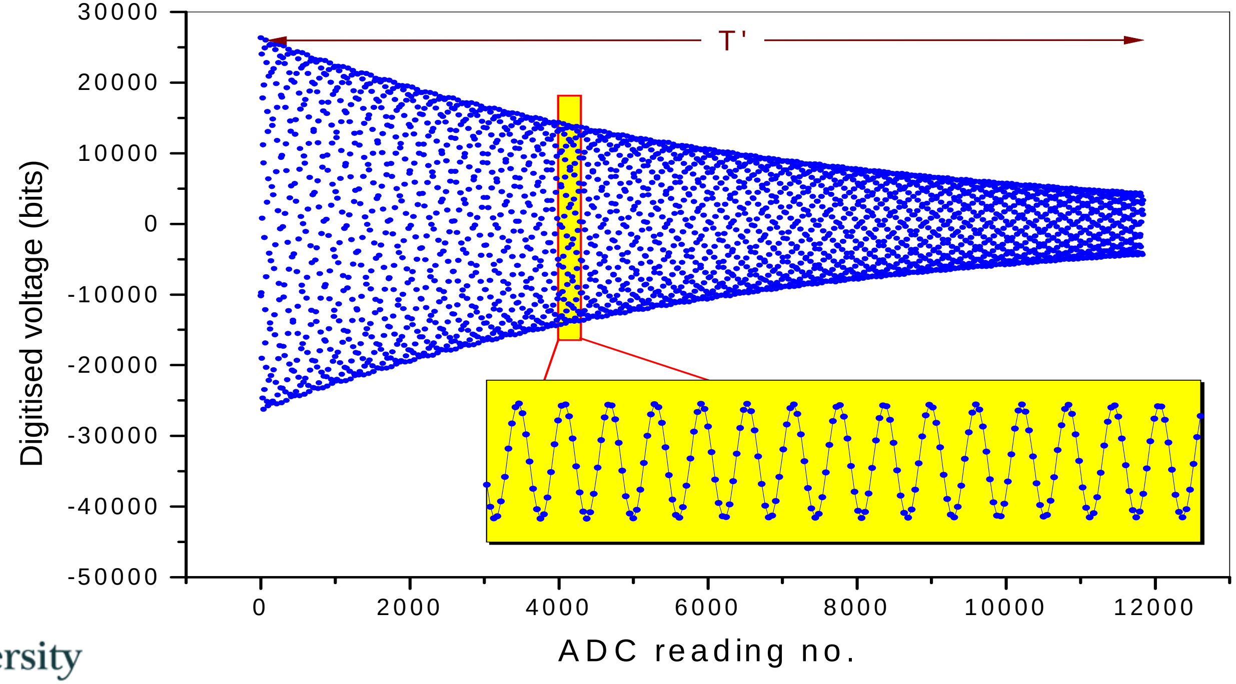
Hg co-magnetometer

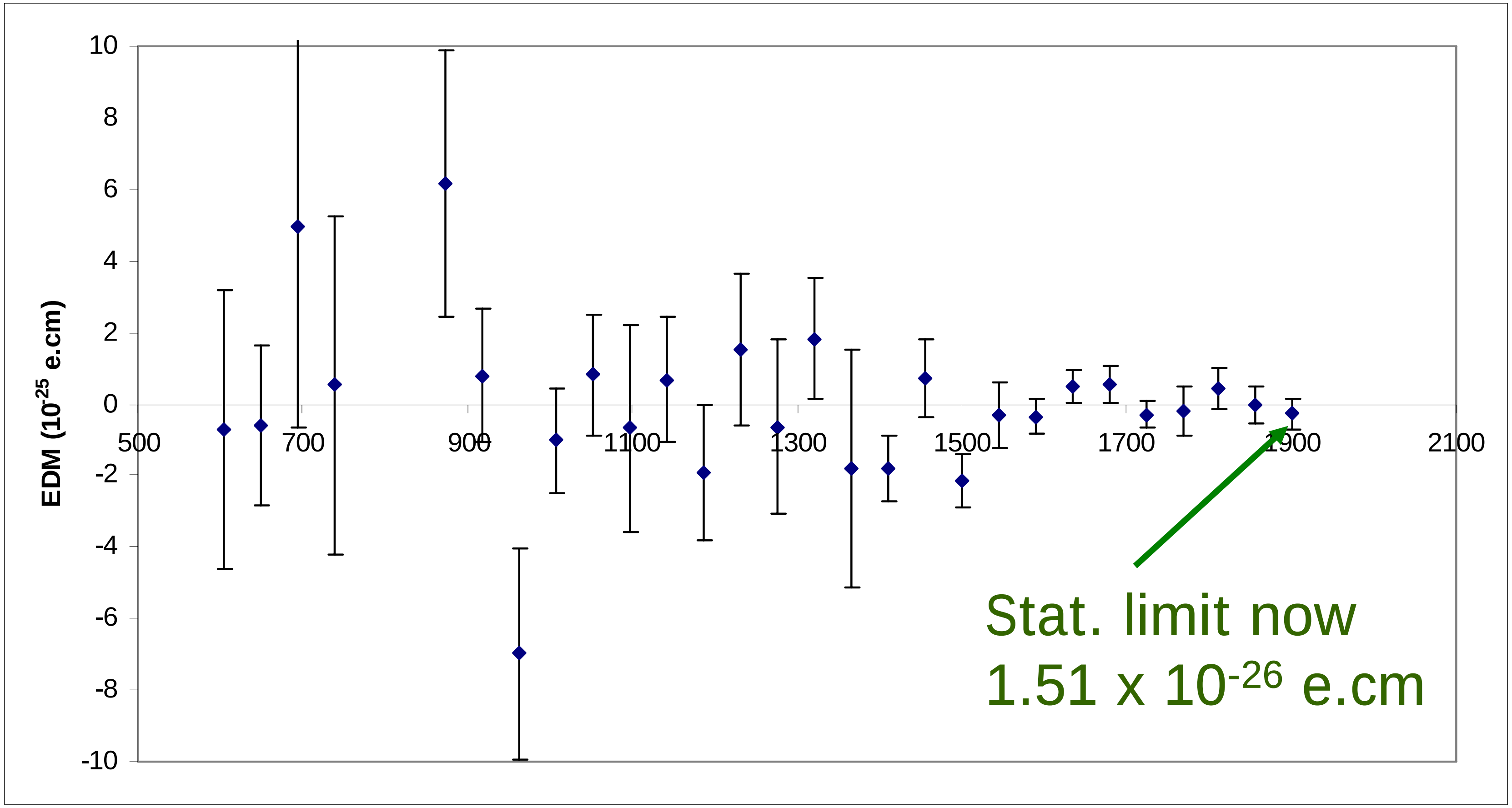
Top view:



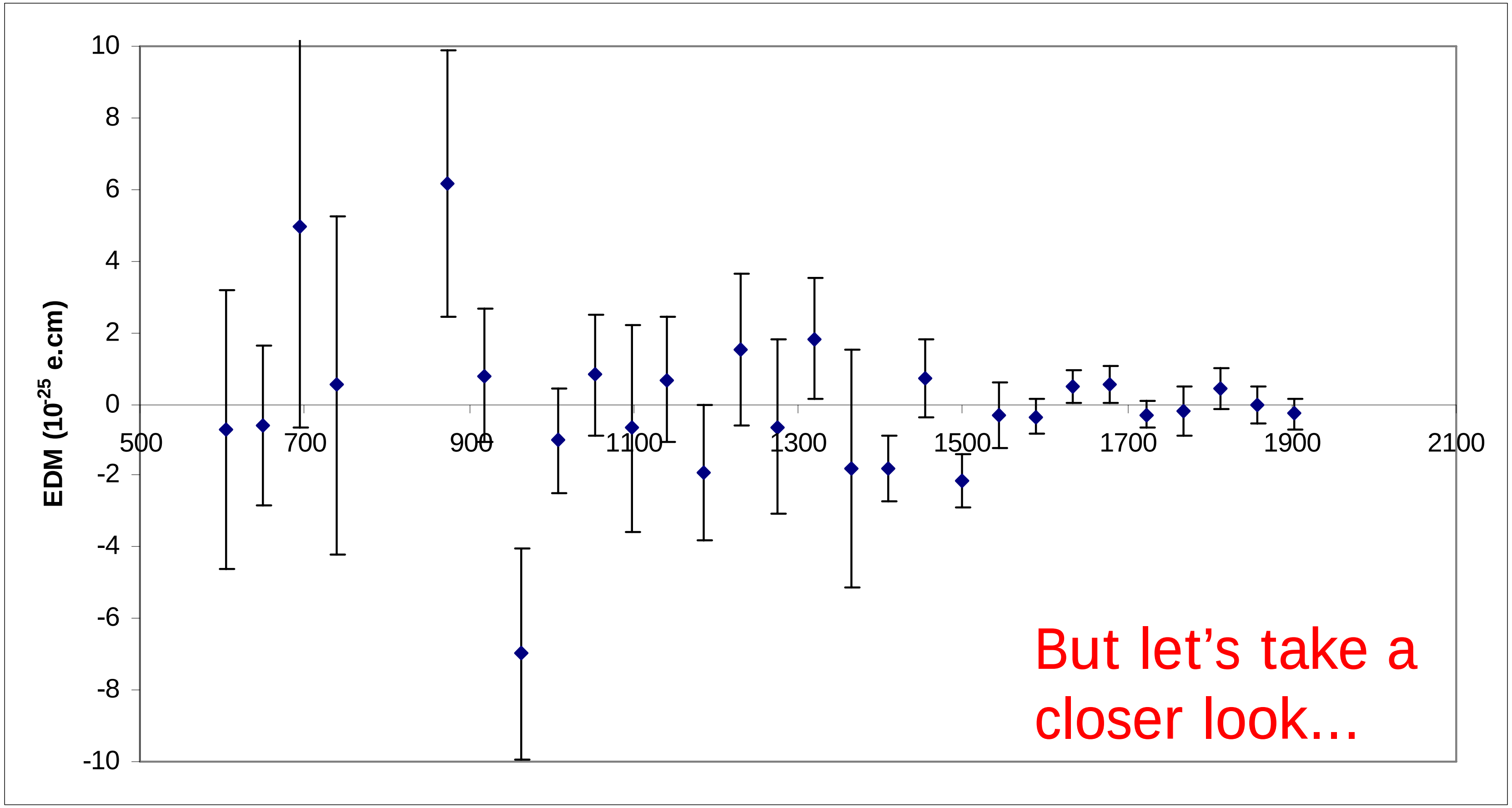
PMT output:



Neutron EDM results (binned)



Neutron EDM results (binned)



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CERN, 16/5/2006