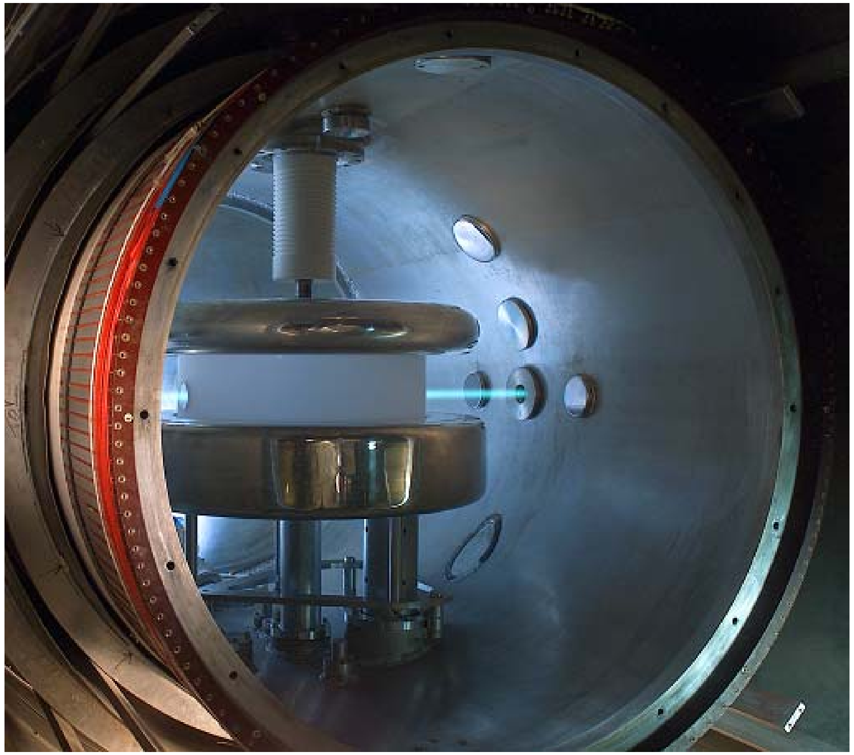
Neutron EDM Experiments at ILL and SNS

Philip Harris

University of Sussex

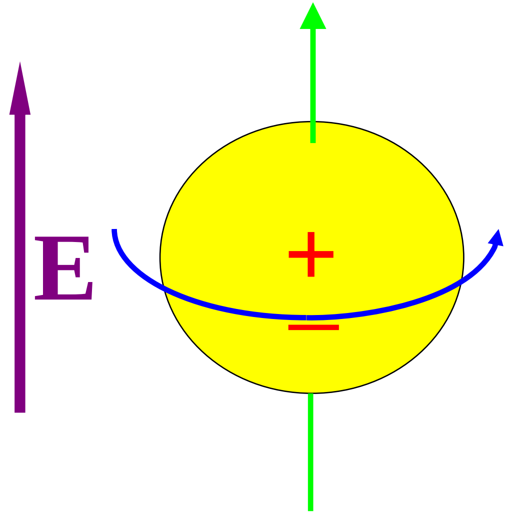


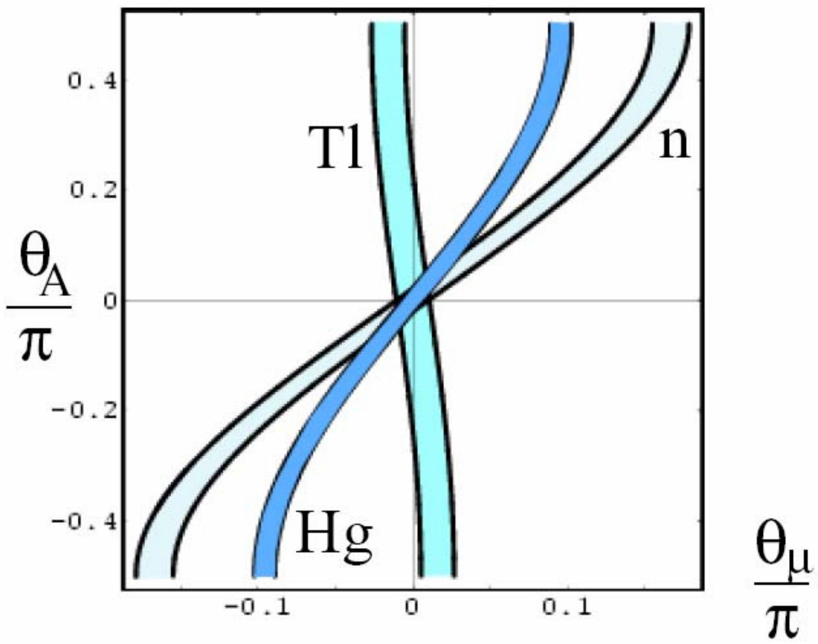
Overview

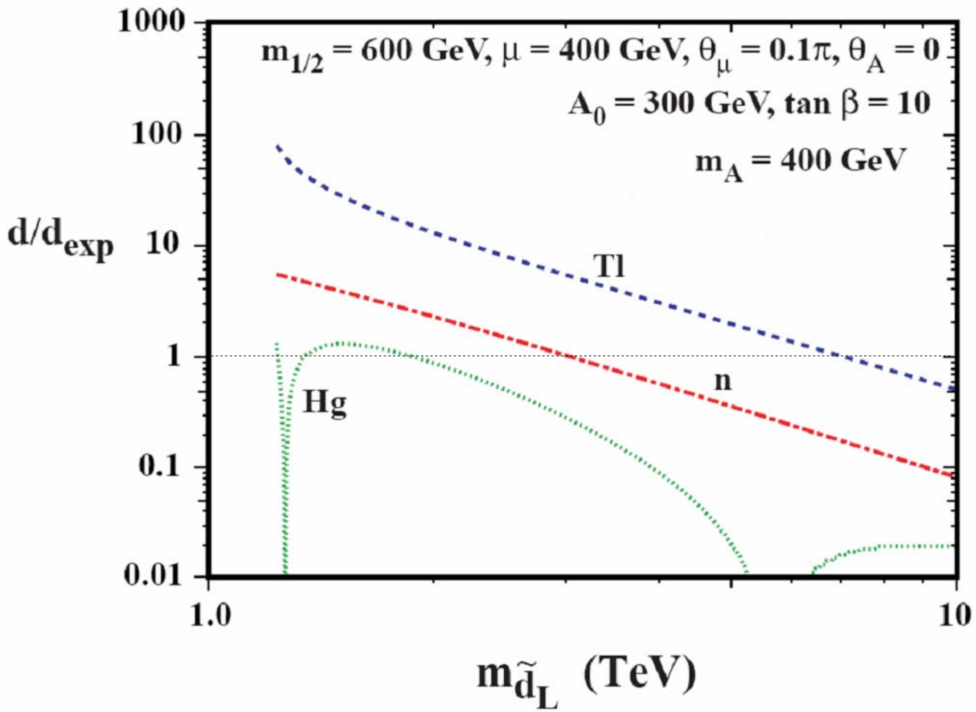
1. nEDM "Classic"
   - New limit:
     $|d_n| < 2.9 \times 10^{-26}$ e.cm
   - Discovery of new systematic effect
2. CryoEDM at ILL
   - Starting shortly:
     100x improved sensitivity
3. SNS nEDM Proposal

Electric Dipole Moments

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

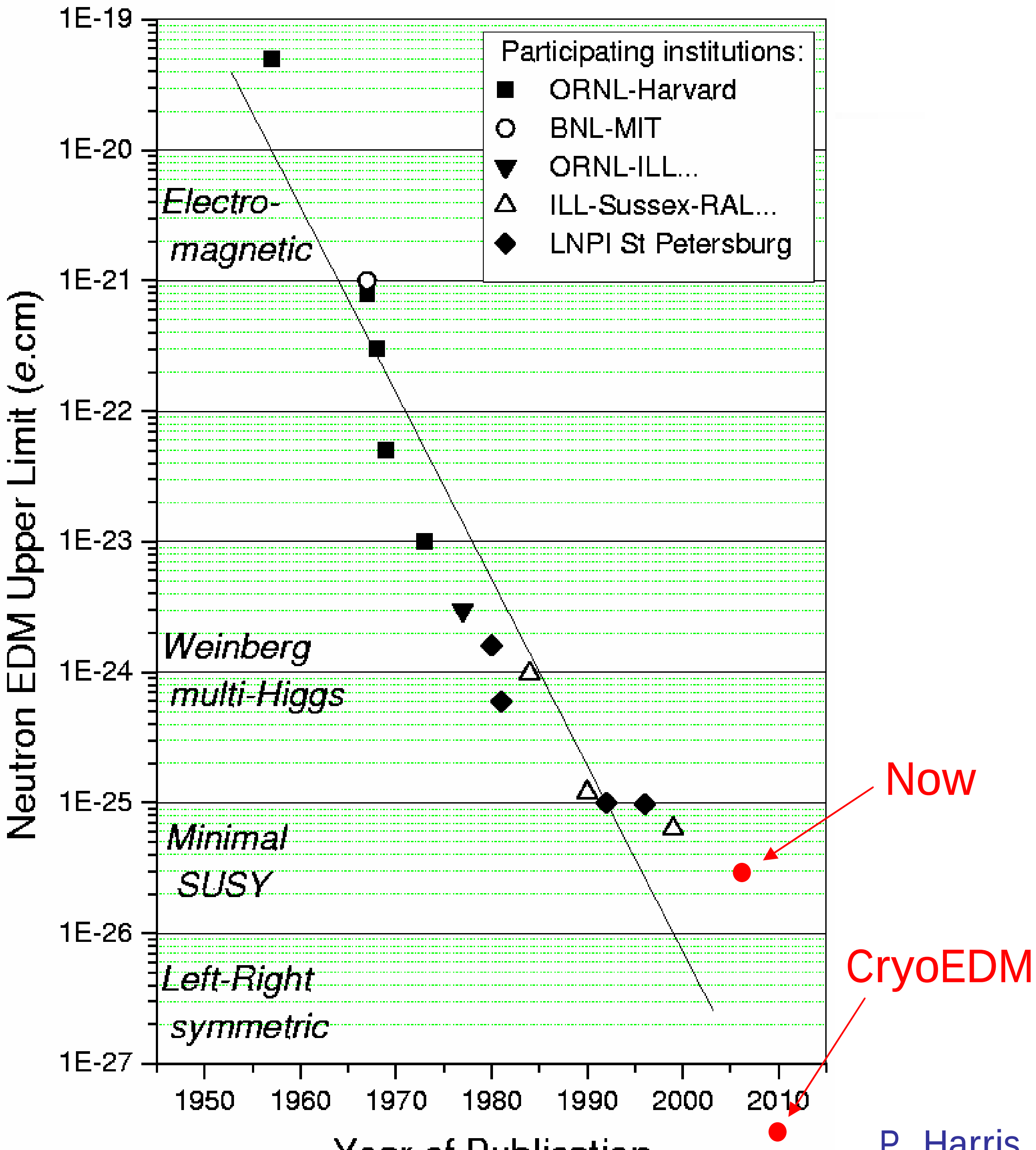






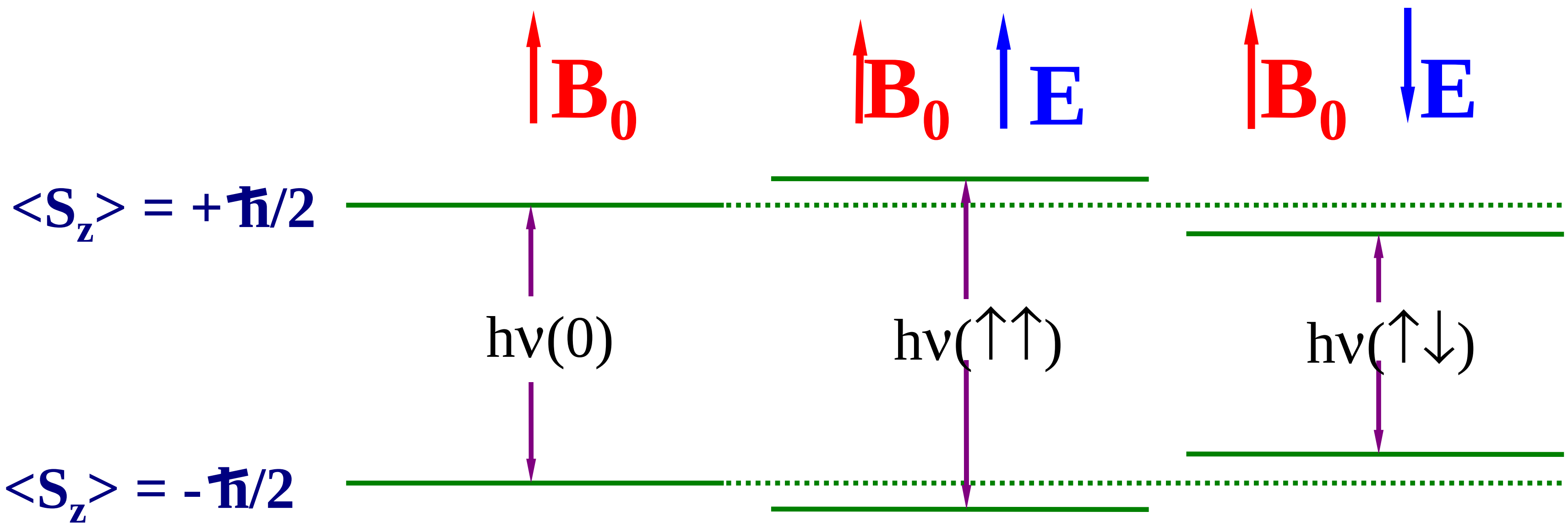
History

Factor 10
every 8 years
on average



Measurement principle

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



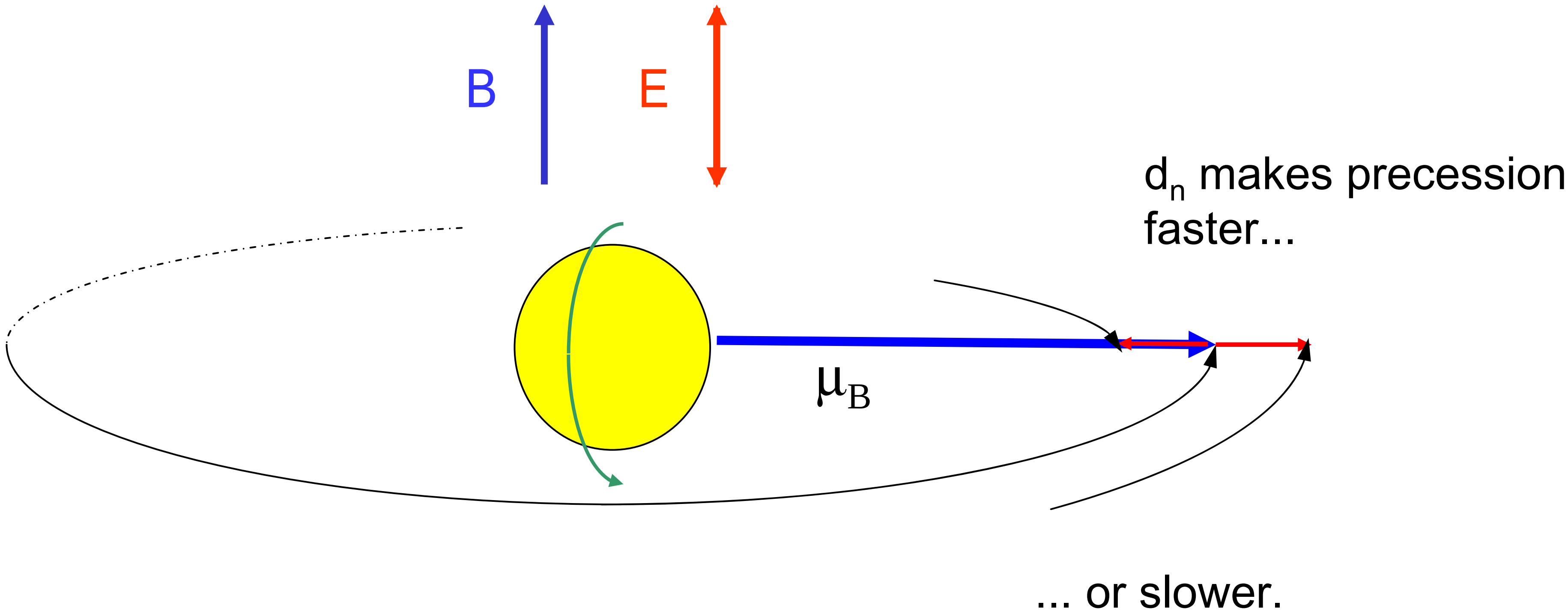
$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/h$$

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

Energy resolution of our detector: $<10^{-21}$ eV

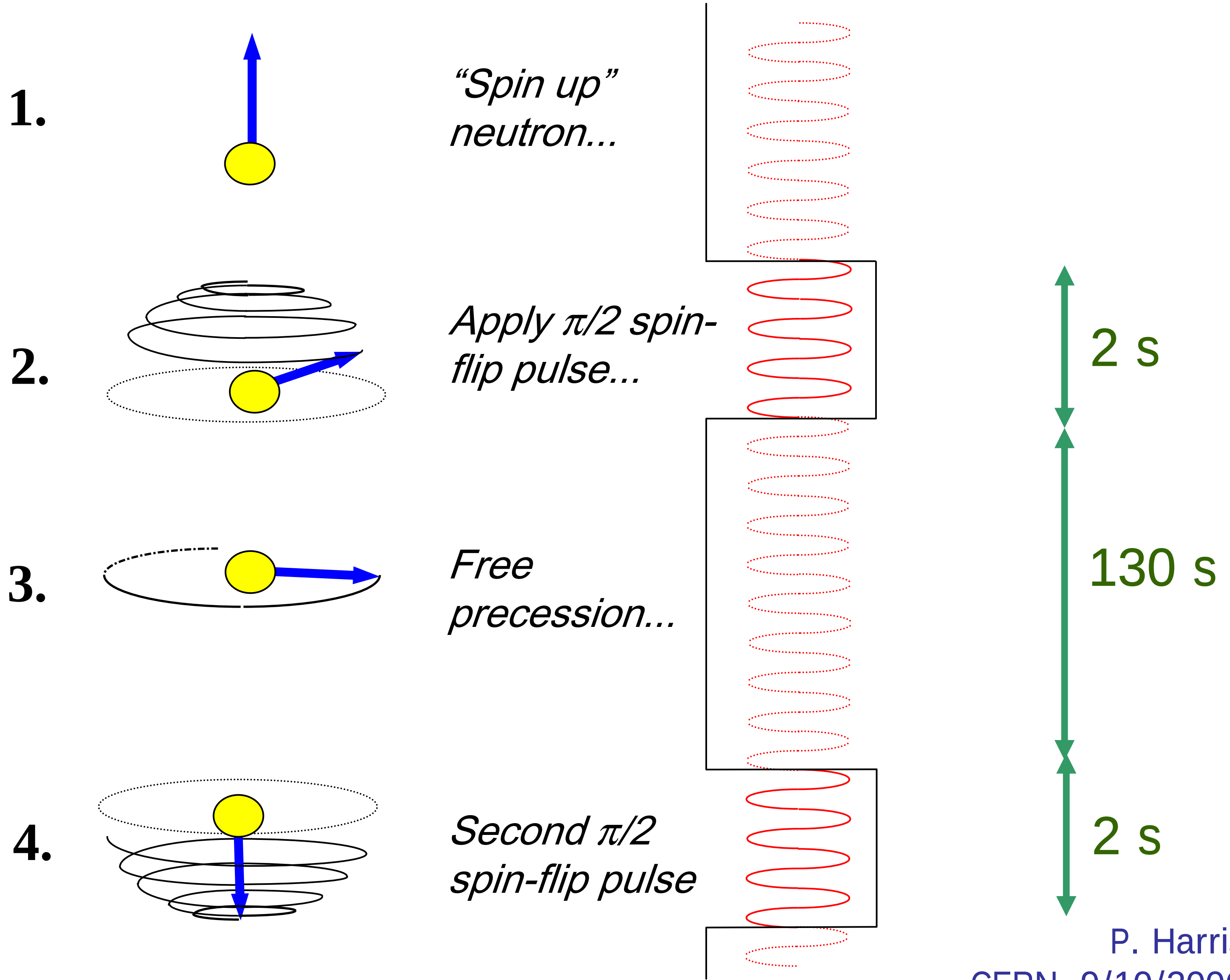
Measurement principle

Measure Larmor spin precession freq in parallel & antiparallel **B** and **E** fields



Reverse E relative to B, look for freq shift.

Ramsey method of Separated Oscillating Fields



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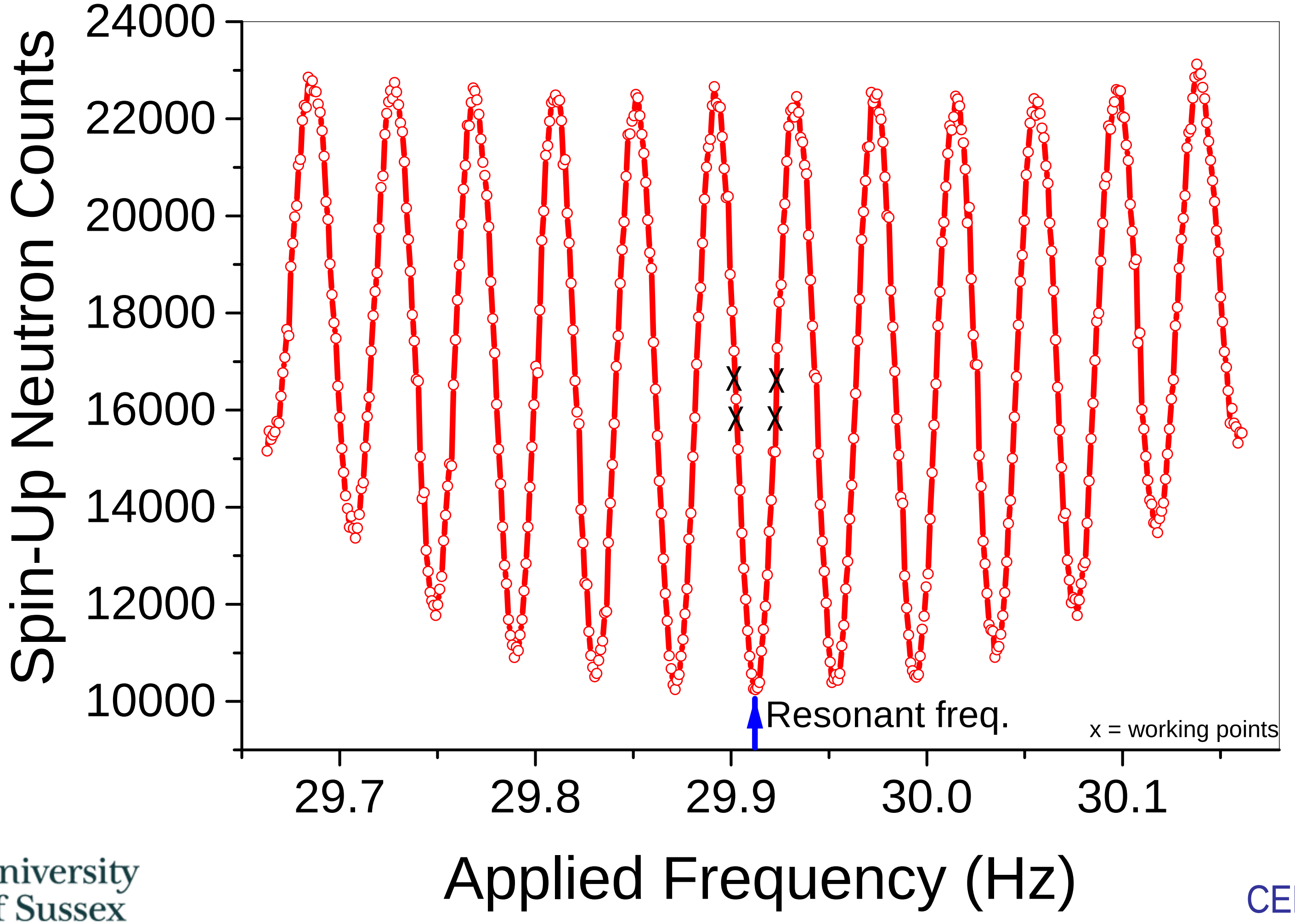
Ramsey resonance

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



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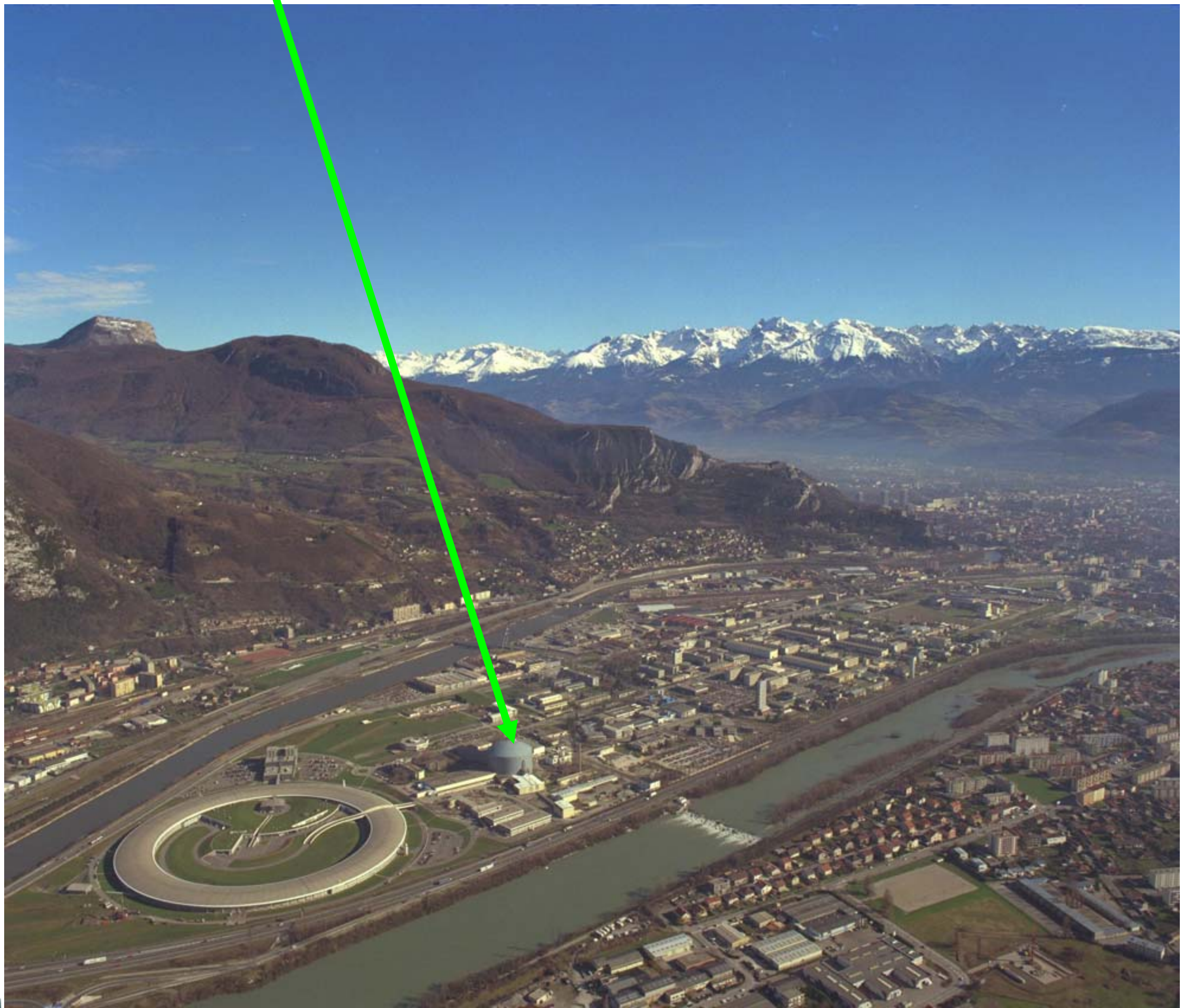
ILL, Grenoble



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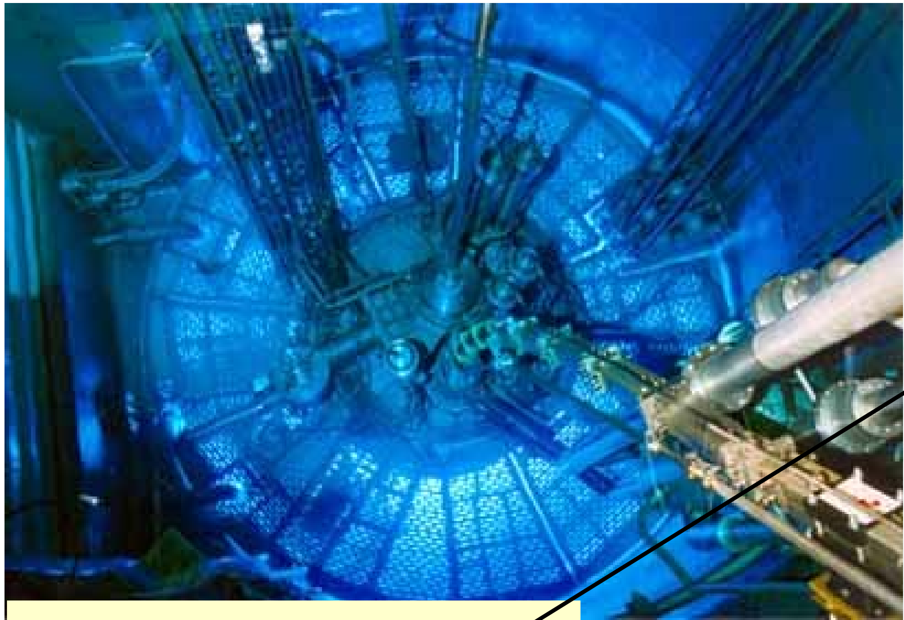
The ILL reactor

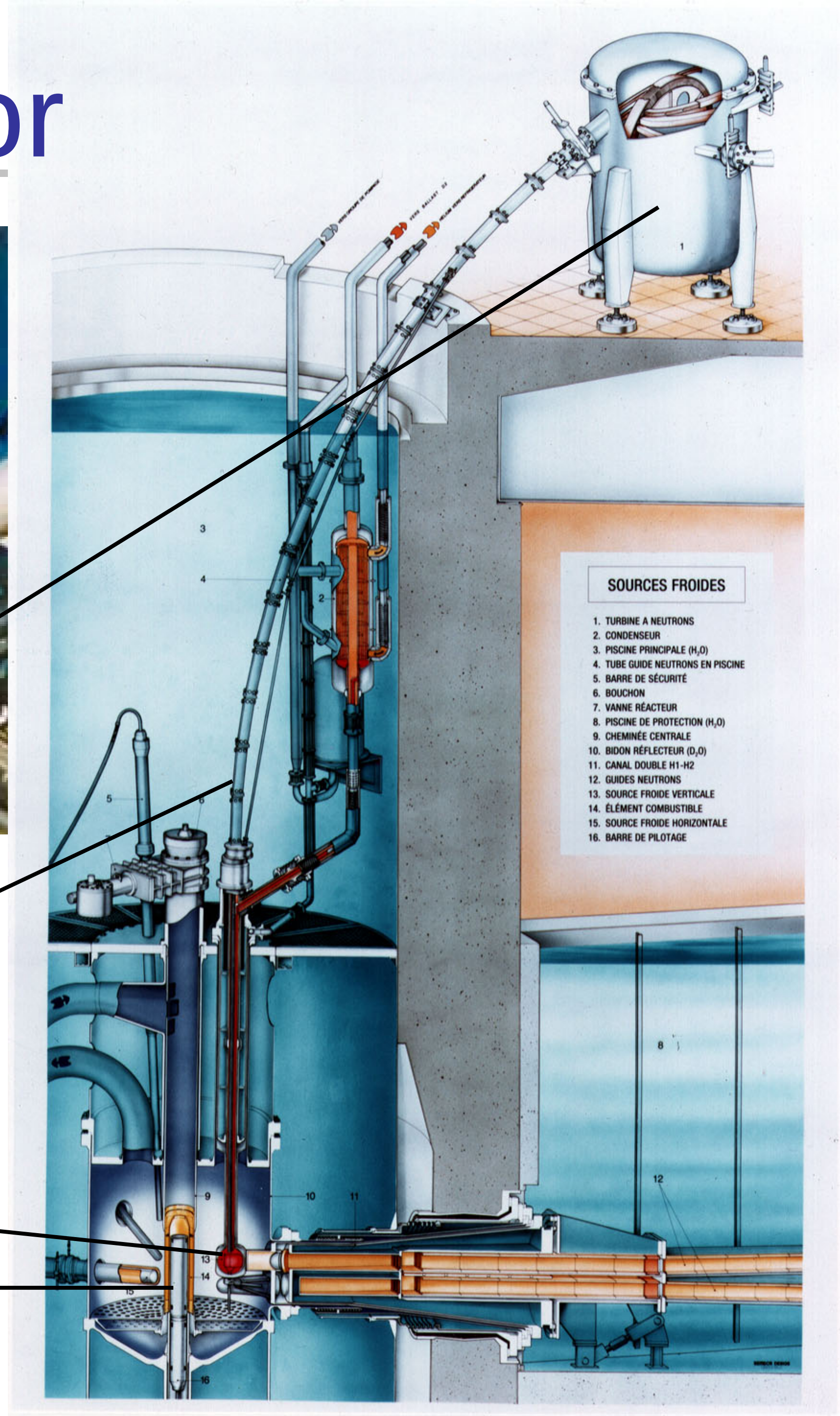


Neutron turbine
A. Steyerl (TUM - 1986)

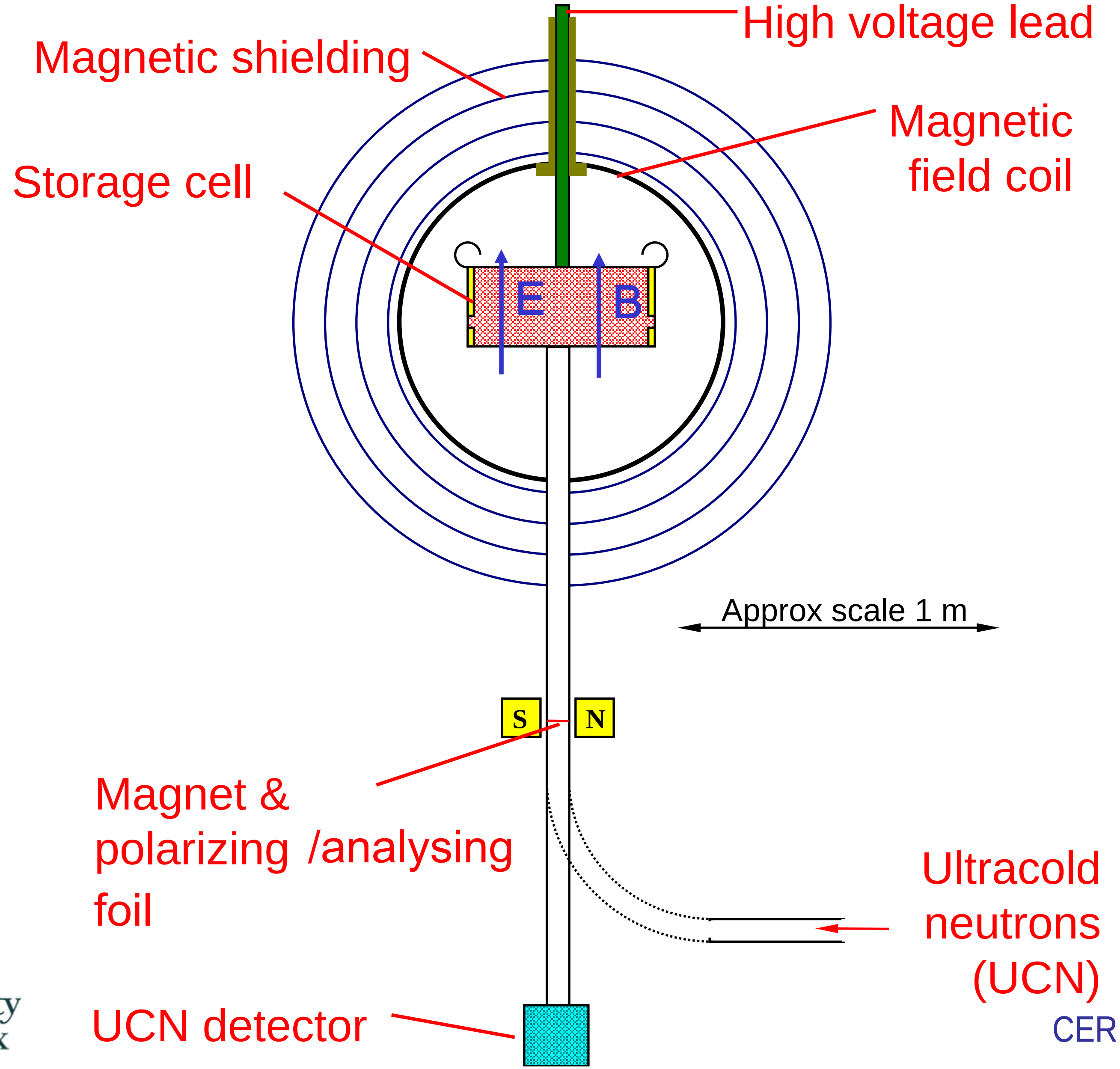
Vertical guide tube

Cold source

Reactor core



Apparatus



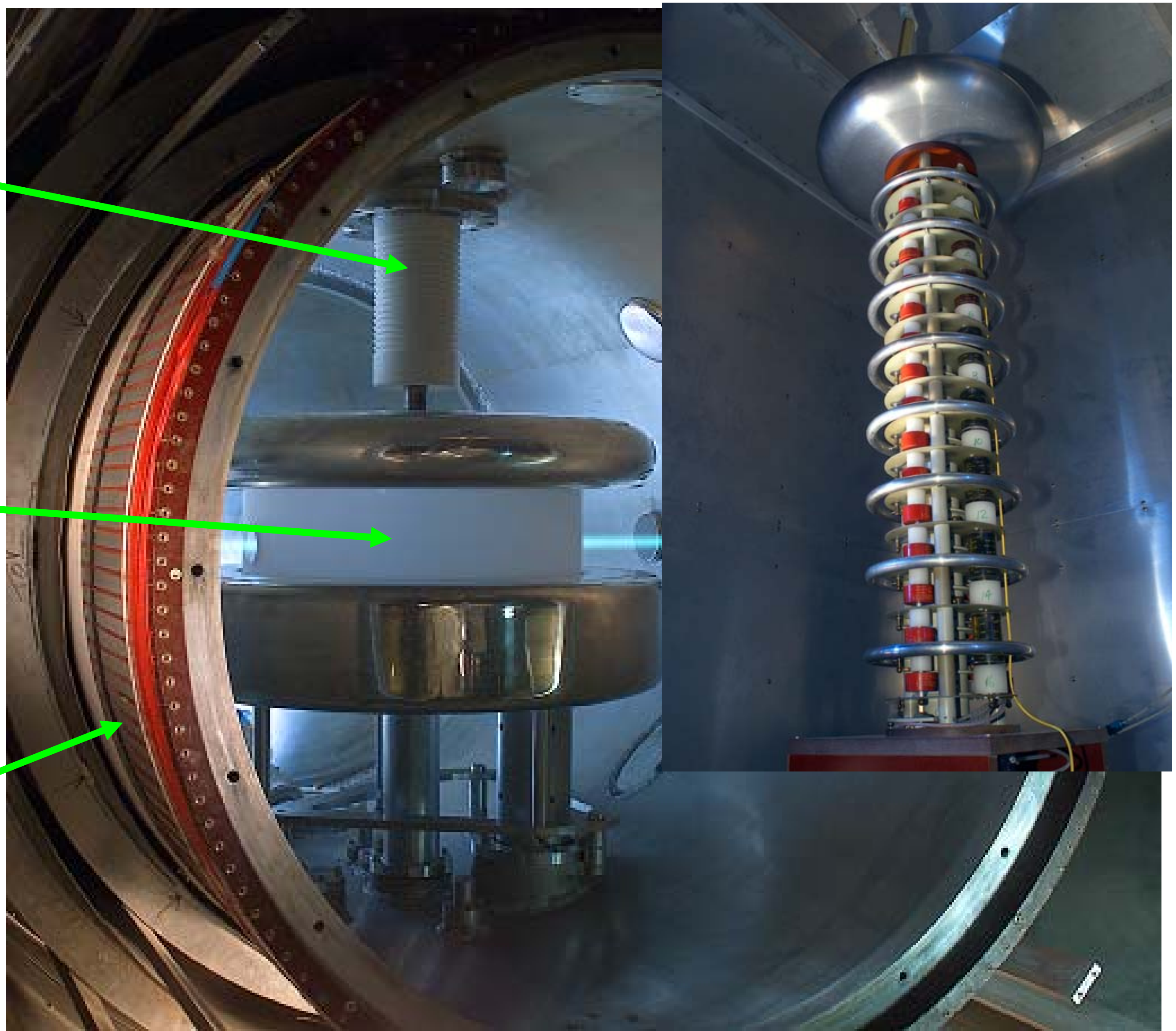
High voltage lead
Magnetic shielding
Magnetic field coil
Storage cell
E
B
Approx scale 1 m
S
N
Magnet & polarizing /analysing foil
Ultracold neutrons (UCN)
UCN detector

Apparatus

HV feedthru

Neutron storage chamber

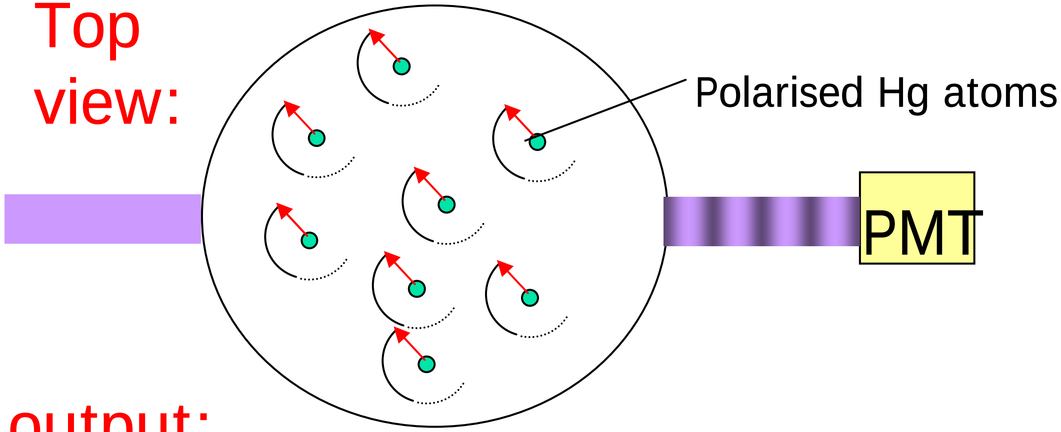
B-field coils



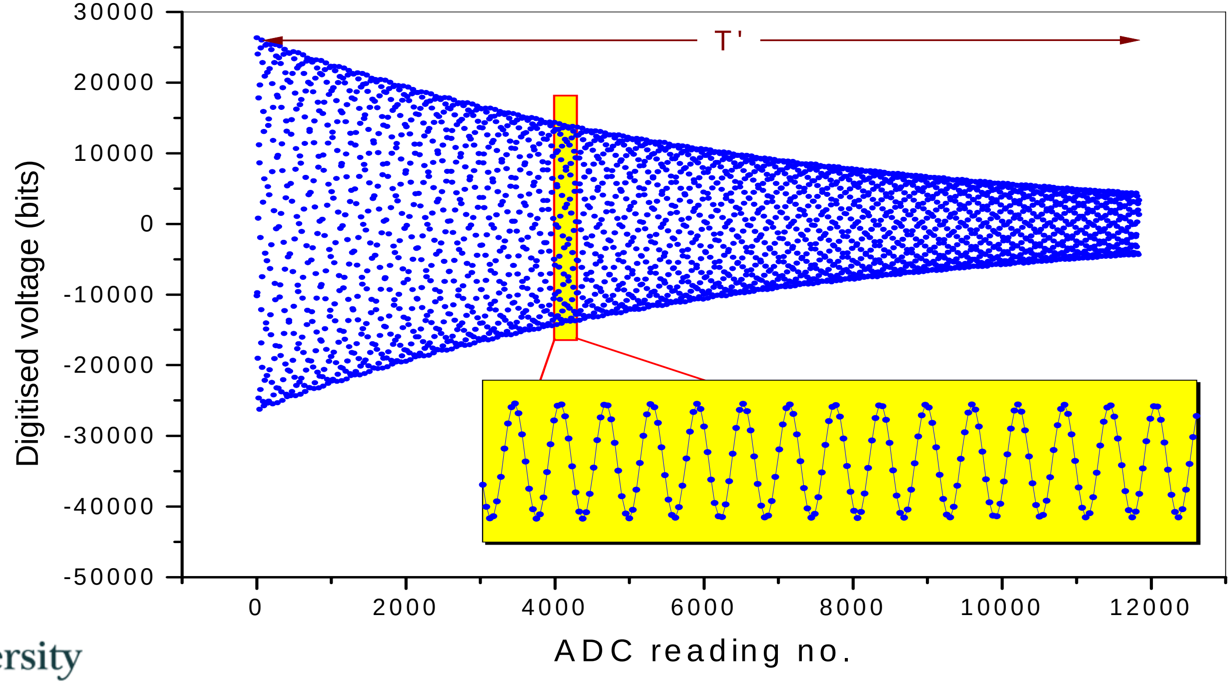
Hg co-magnetometer

$|d_{Hg}| < 2.1 \times 10^{-28}$ *e* cm
[Romalis et al.,
PRL 86 (2001) 8505]

Top view:



PMT output:



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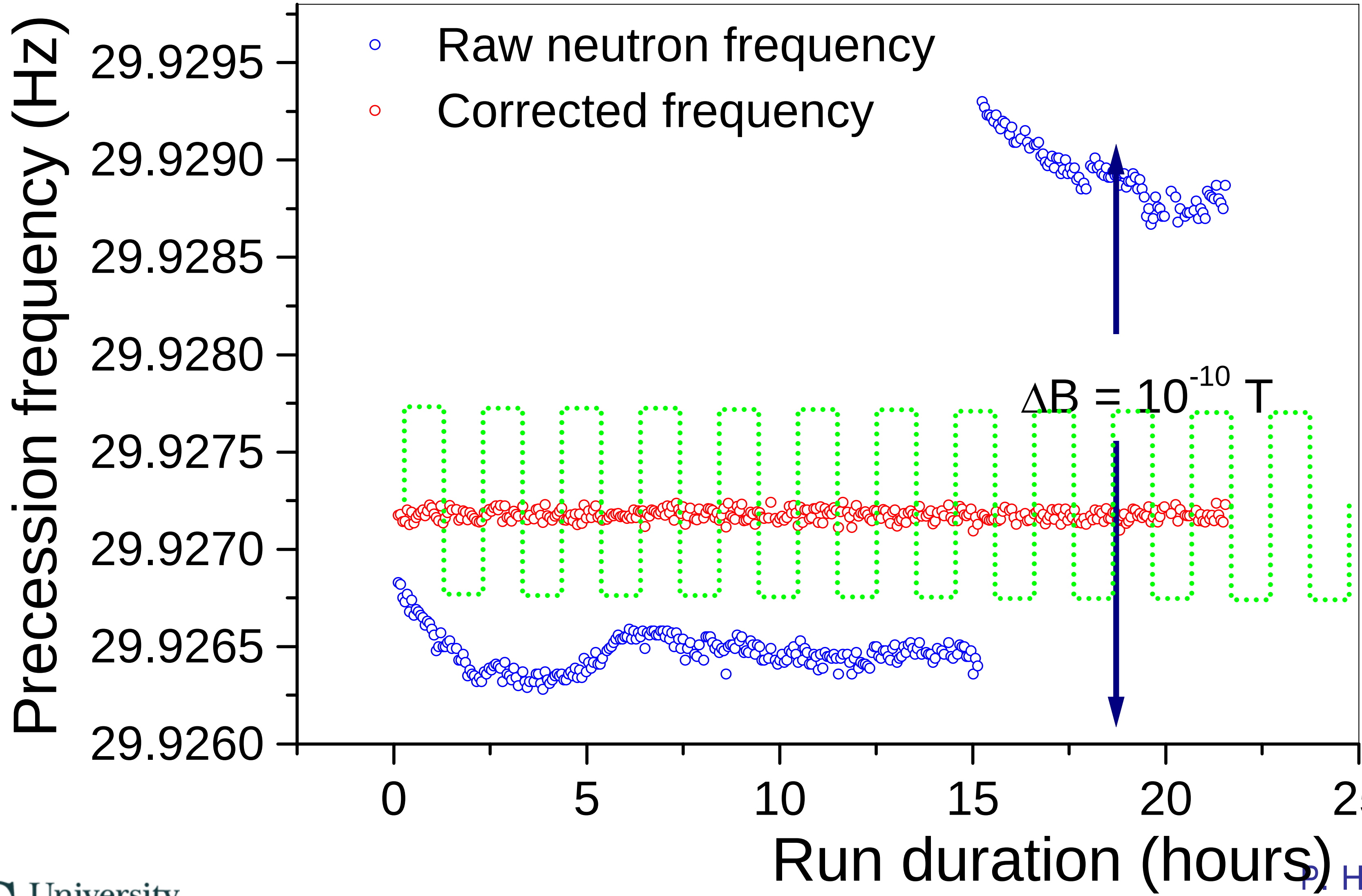
nEDM measurement



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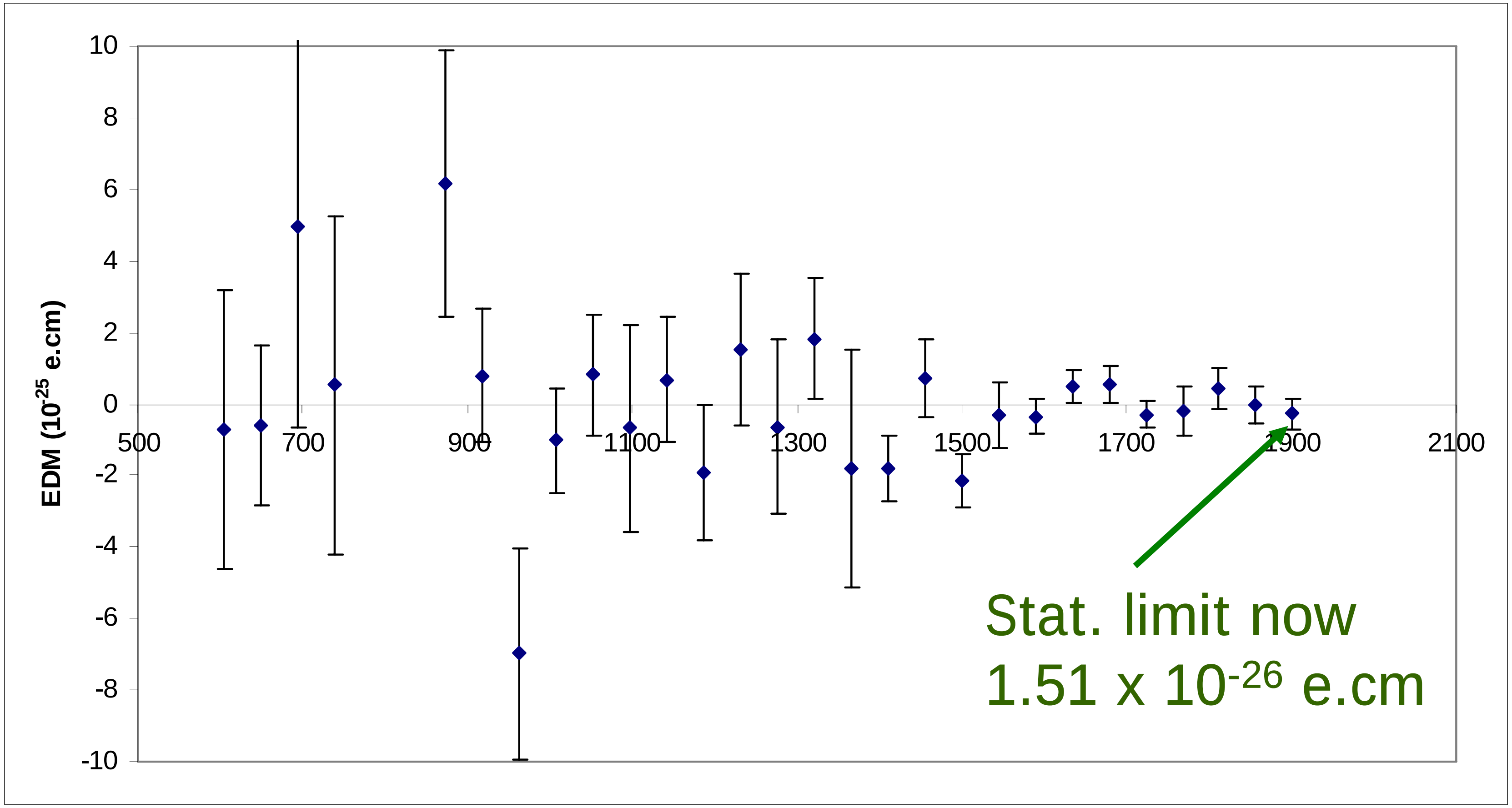
Neutron EDM results (binned)

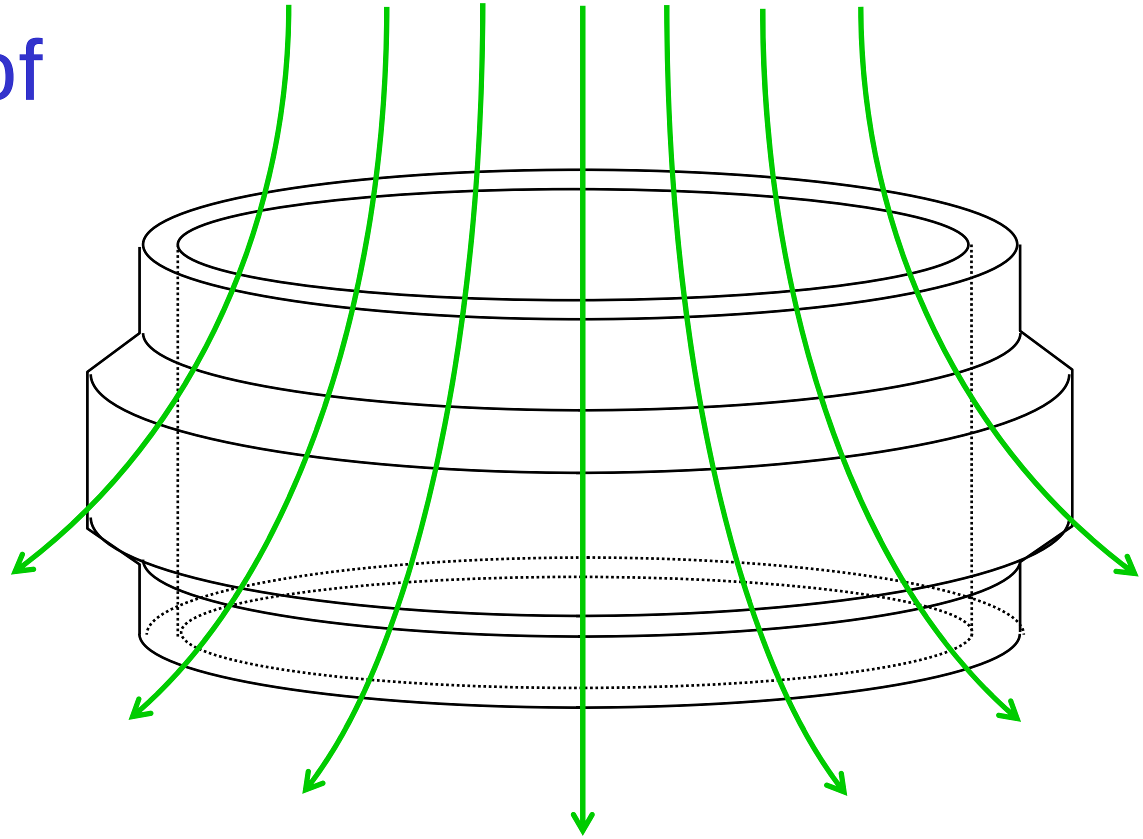


...but B up, B down disagree.

New leading systematic

Combination of 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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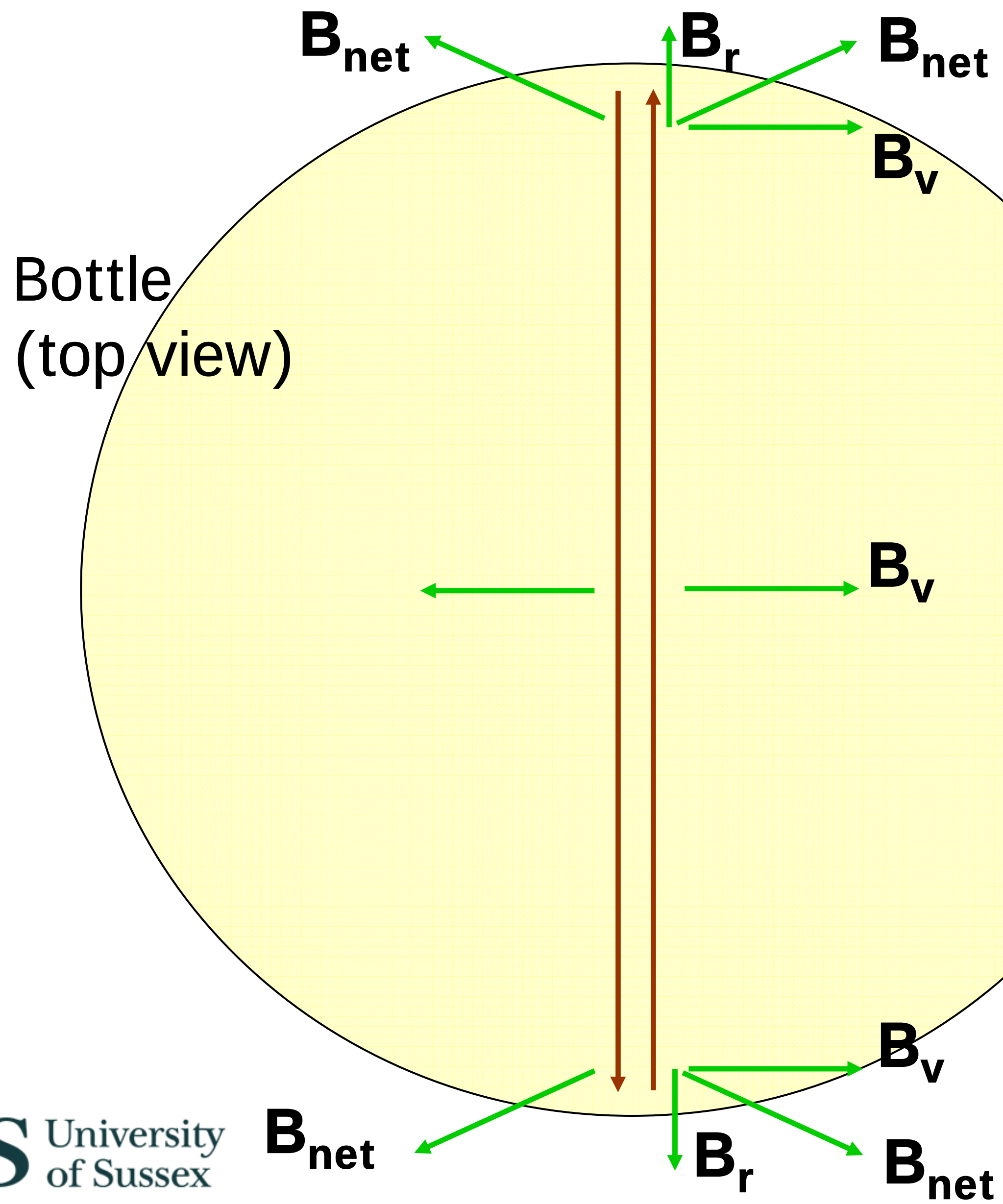
Geometric Phase

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

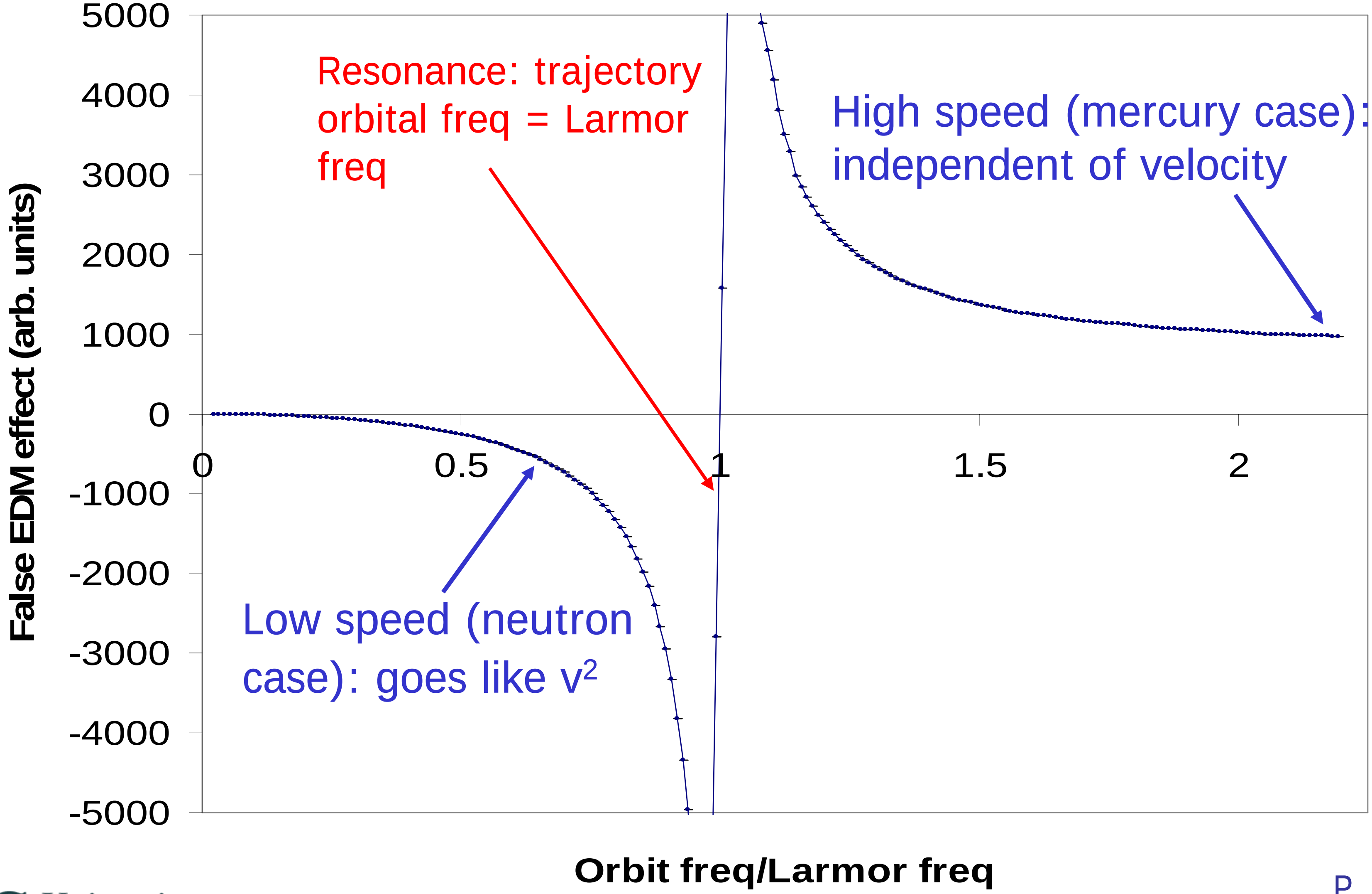


… so particle sees additional rotating field

Frequency shift $\propto$ E

Looks like an EDM, but scales with dB/dz

Geometric Phase Velocity dependence



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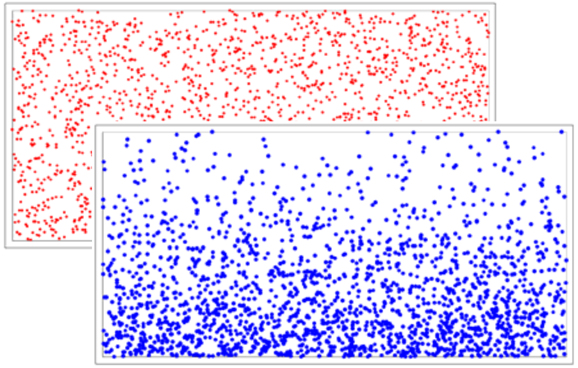
Geometric Phase How to measure it

- 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:

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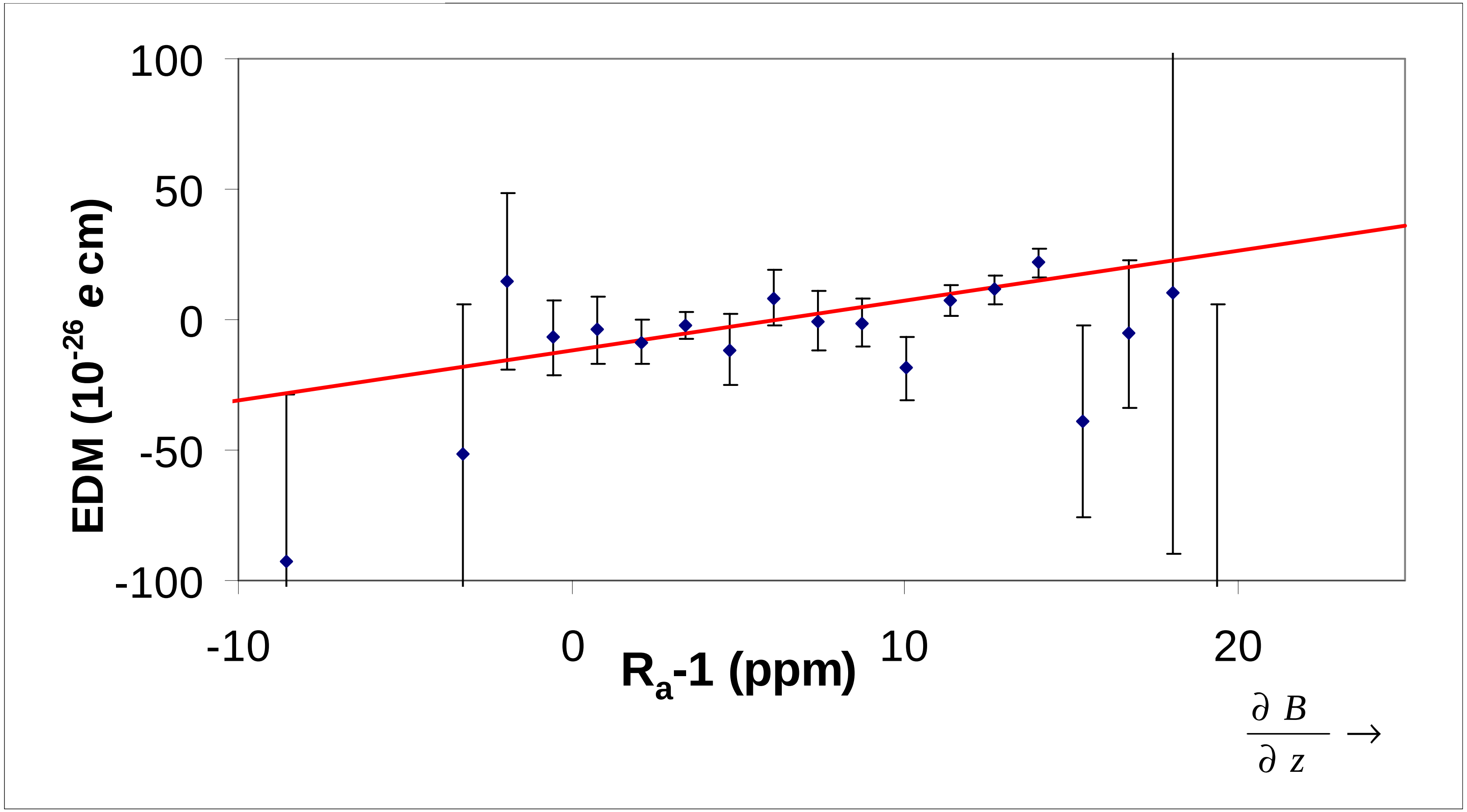
Geometric Phase

Magnetic field down



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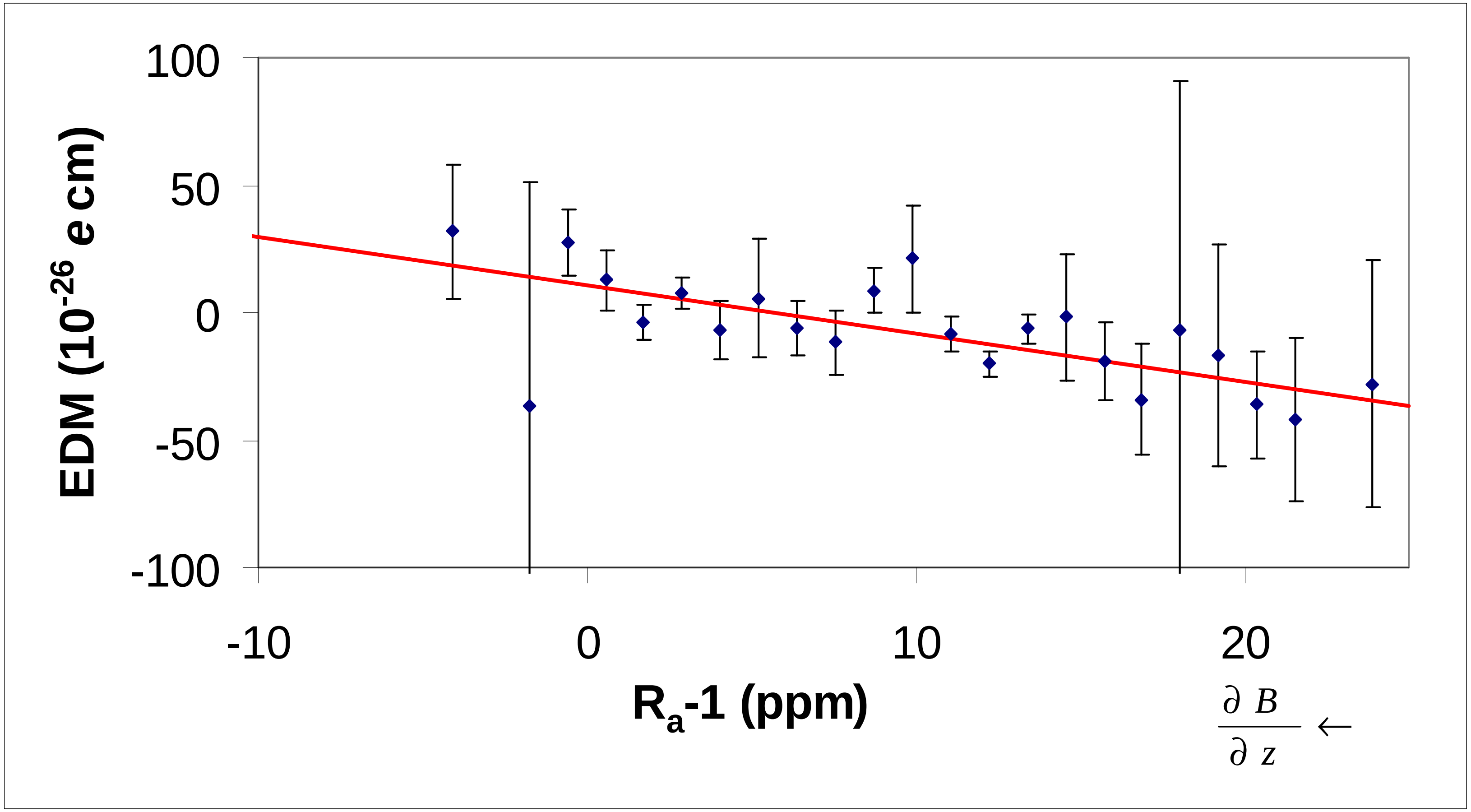
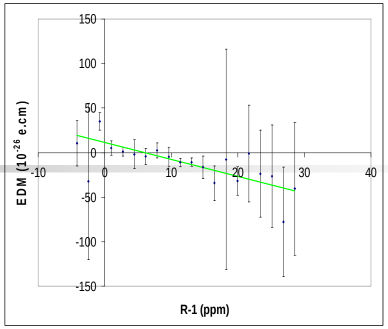
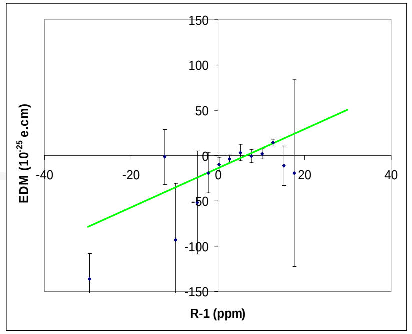
Geometric Phase

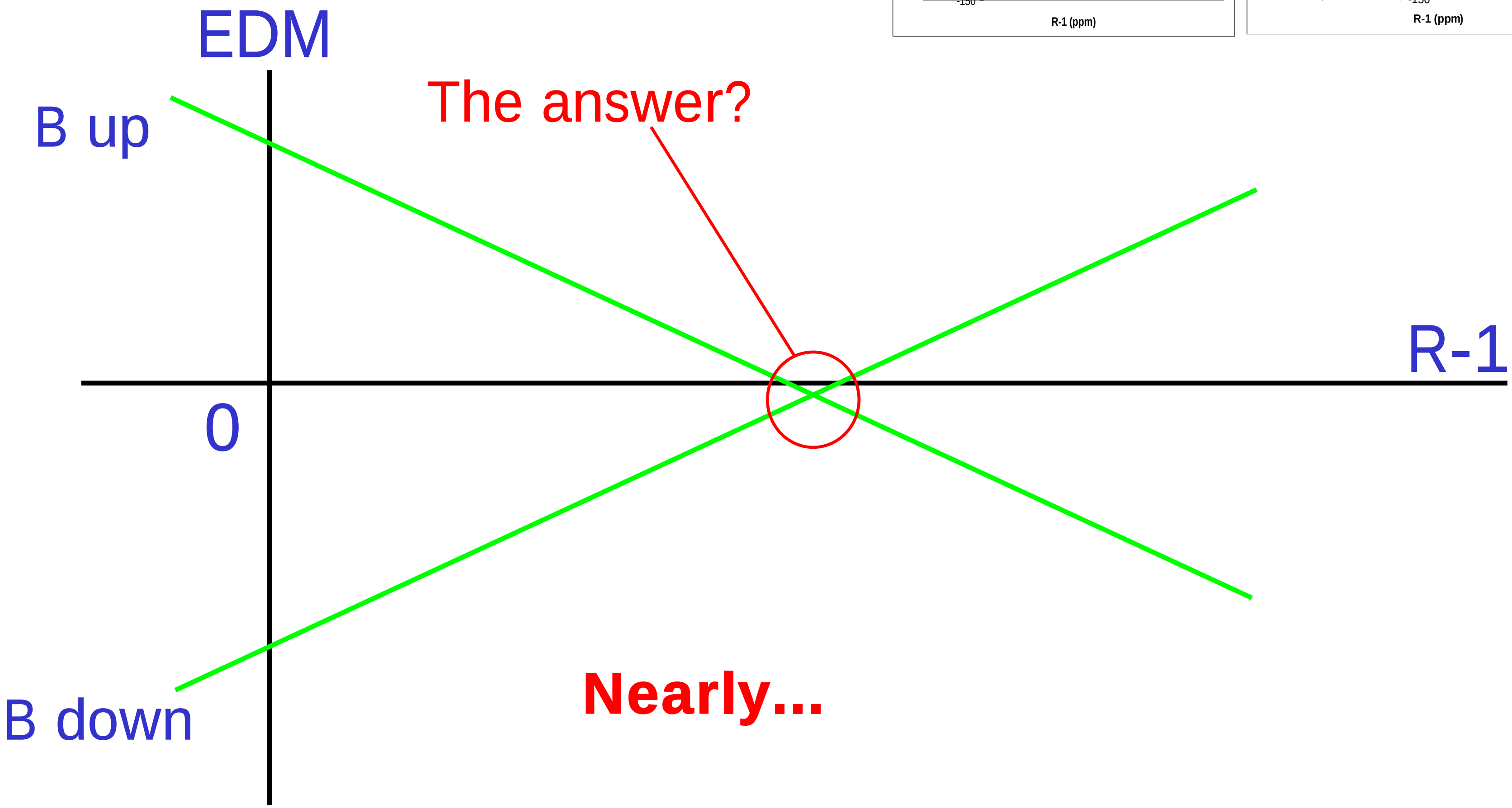
Magnetic field up



Results



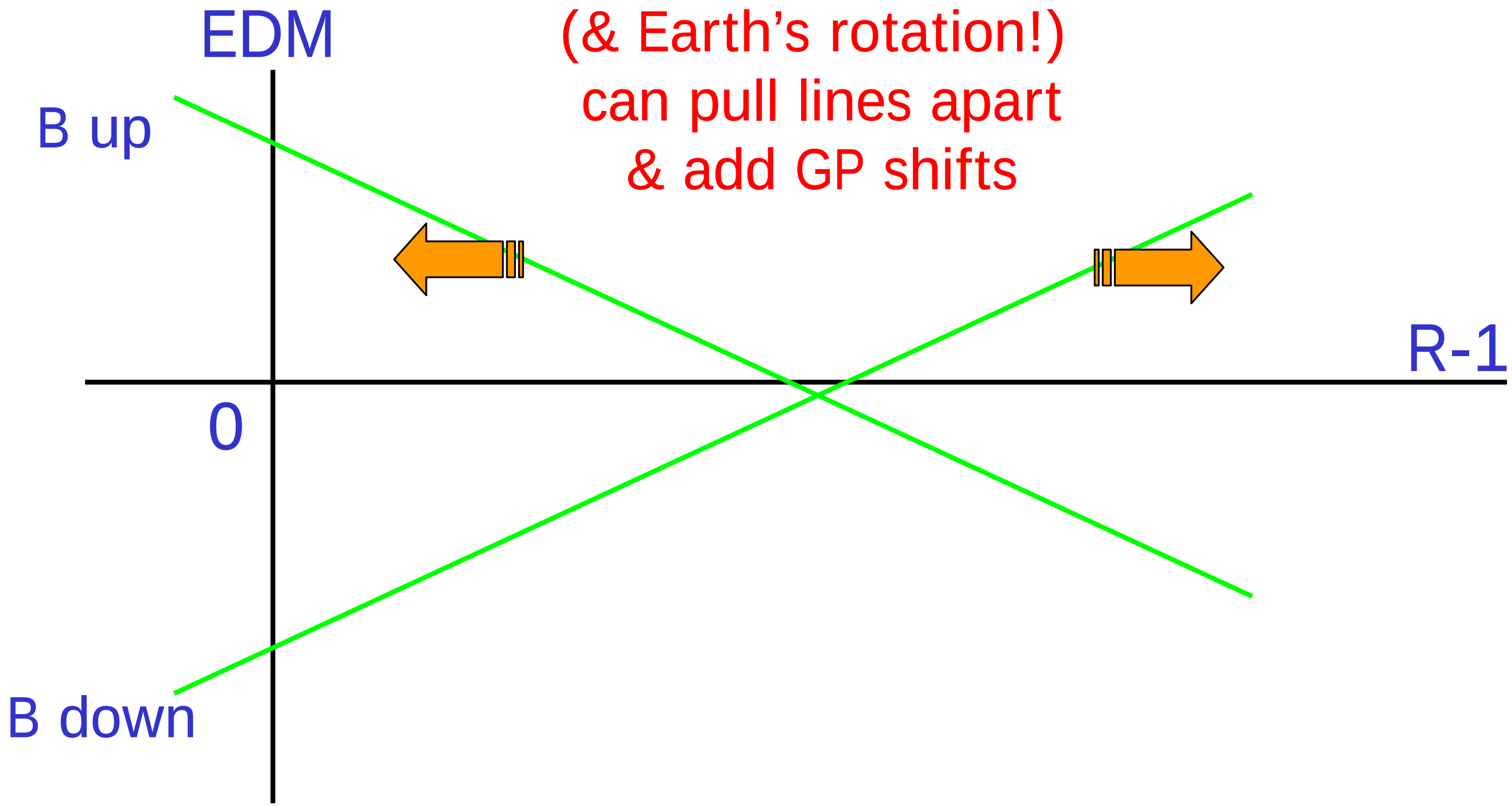




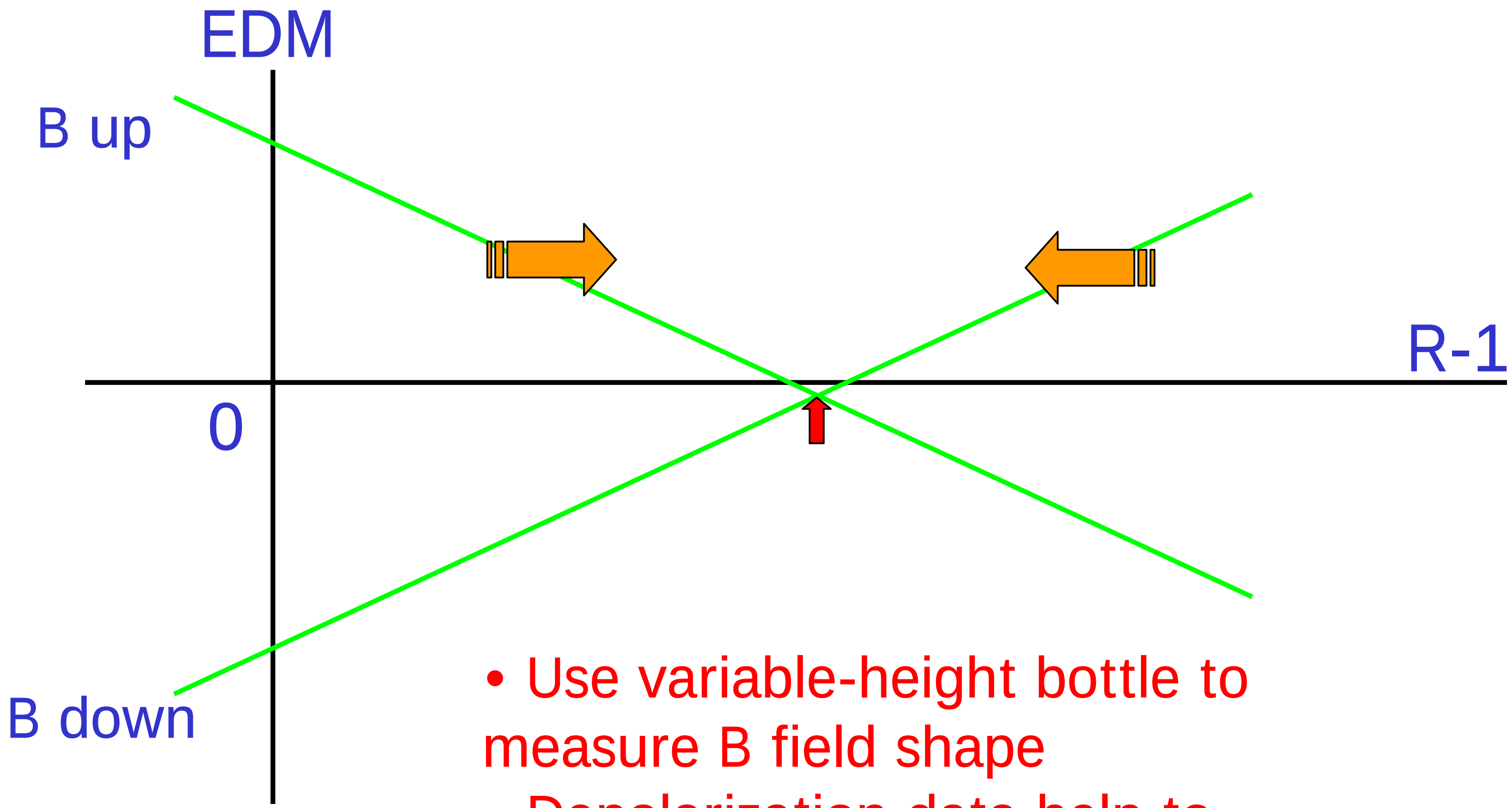
Nearly...

Results

Small dipole/quadrupole fields
(& Earth's rotation!)
can pull lines apart
& add GP shifts



Results



- Use variable-height bottle to measure B field shape
- Depolarization data help to establish separations
- Apply corrections

Final Result

New limit:

$|d_n| < 2.9 \times 10^{-26}$ e.cm (90% CL)

Phys. Rev. Lett. 97, 131801 (2006), hep-ex/0602020

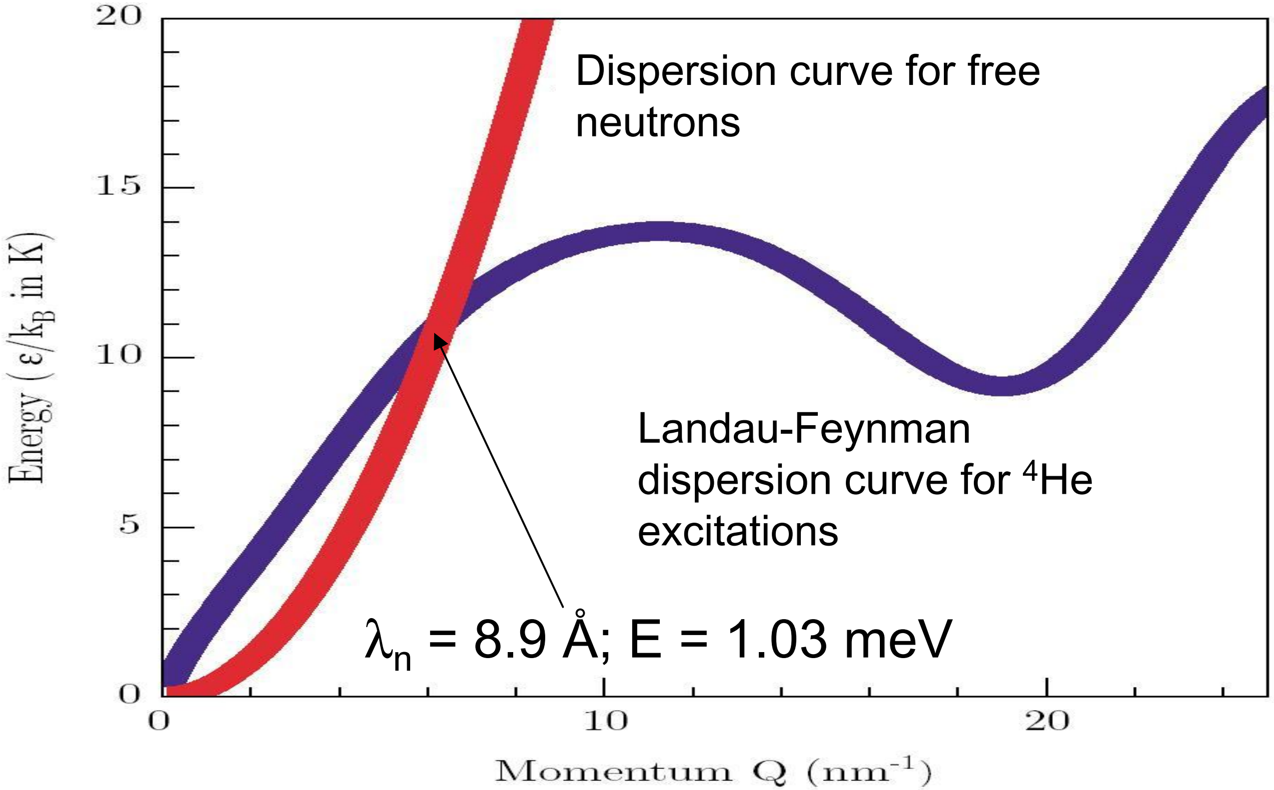
CryoEDM: The Next Generation

New technology:

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

100-fold improvement in sensitivity

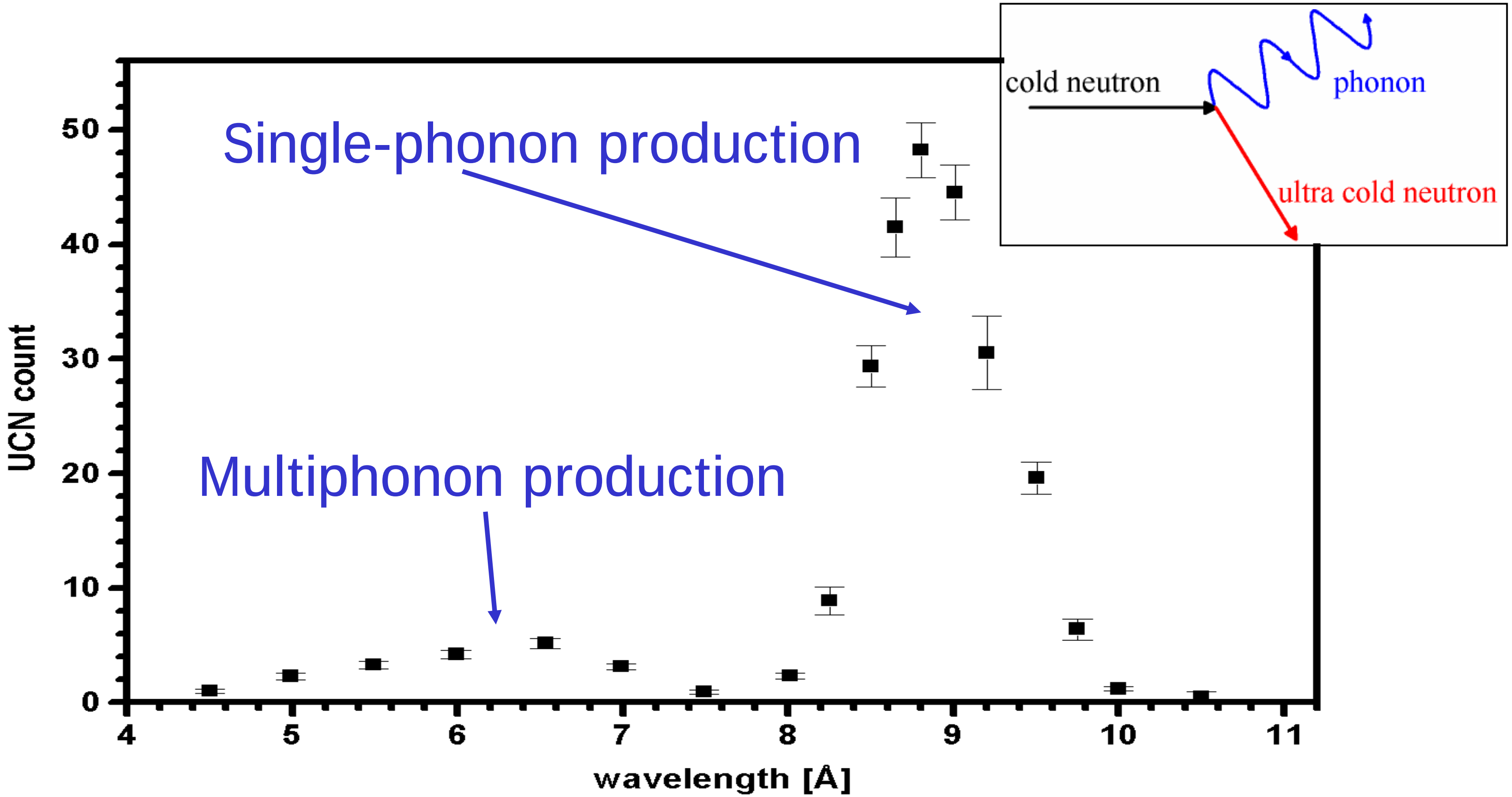
UCN production in liquid helium



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

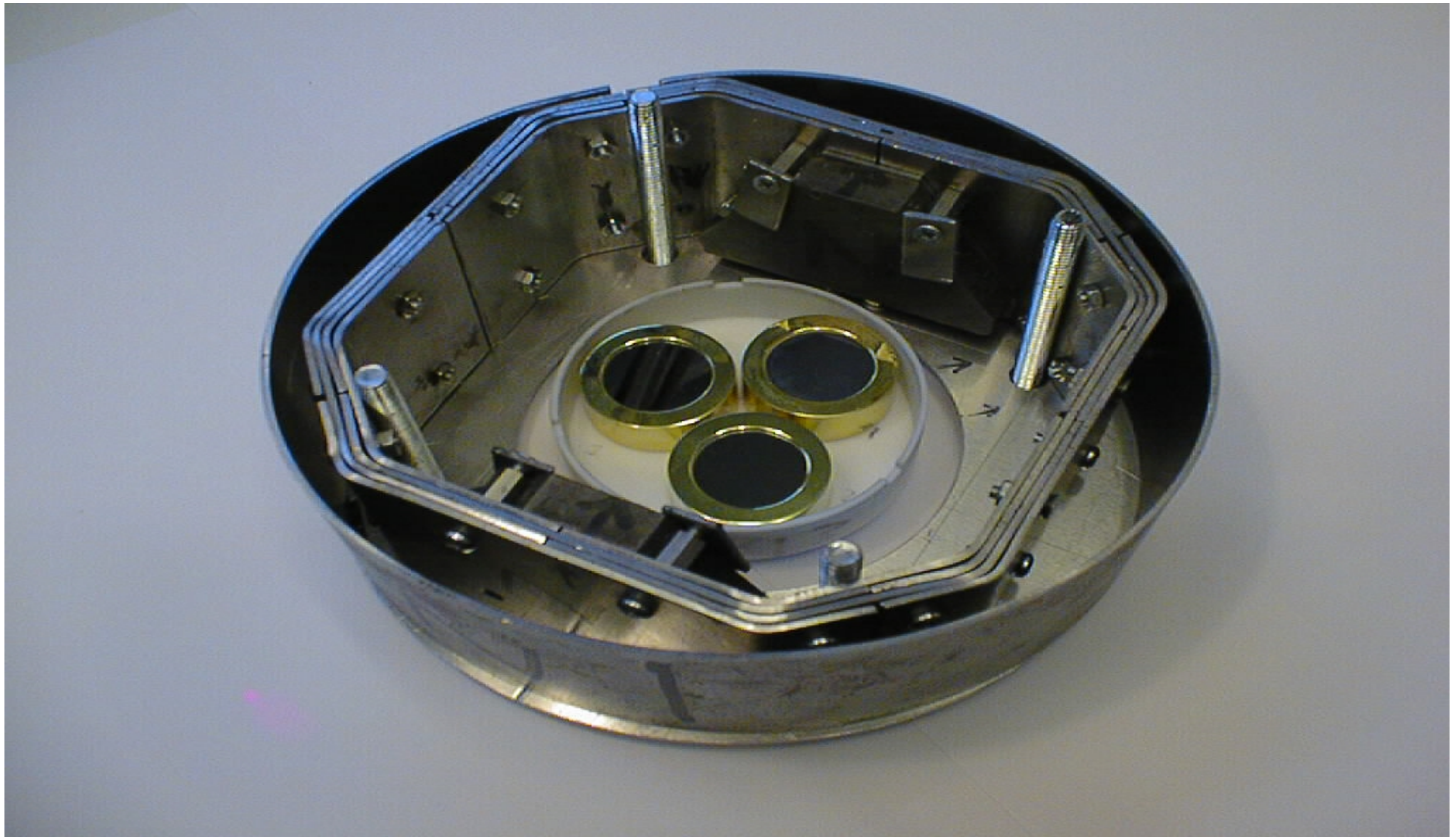
UCN production rate vs λ_n



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

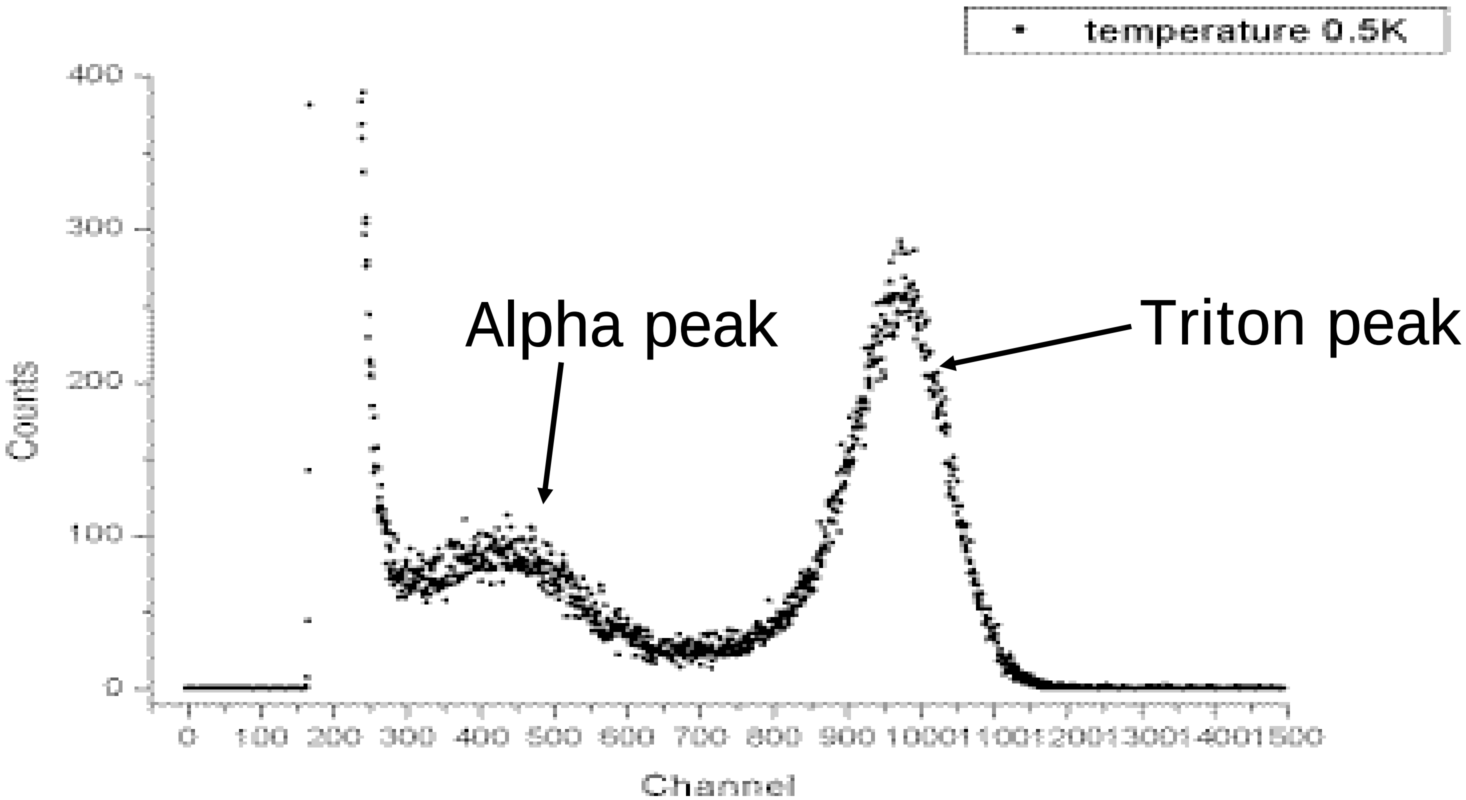
C.A.Baker *et al.*, Phys.Lett. **A308** 67-74 (2002)

UCN detection in liquid helium



- Solid-state detectors developed for use in LHe
- Thin surface film of ^{6}LiF: n + ^{6}Li $\rightarrow$ α + ^{3}H

UCN detection in liquid helium



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

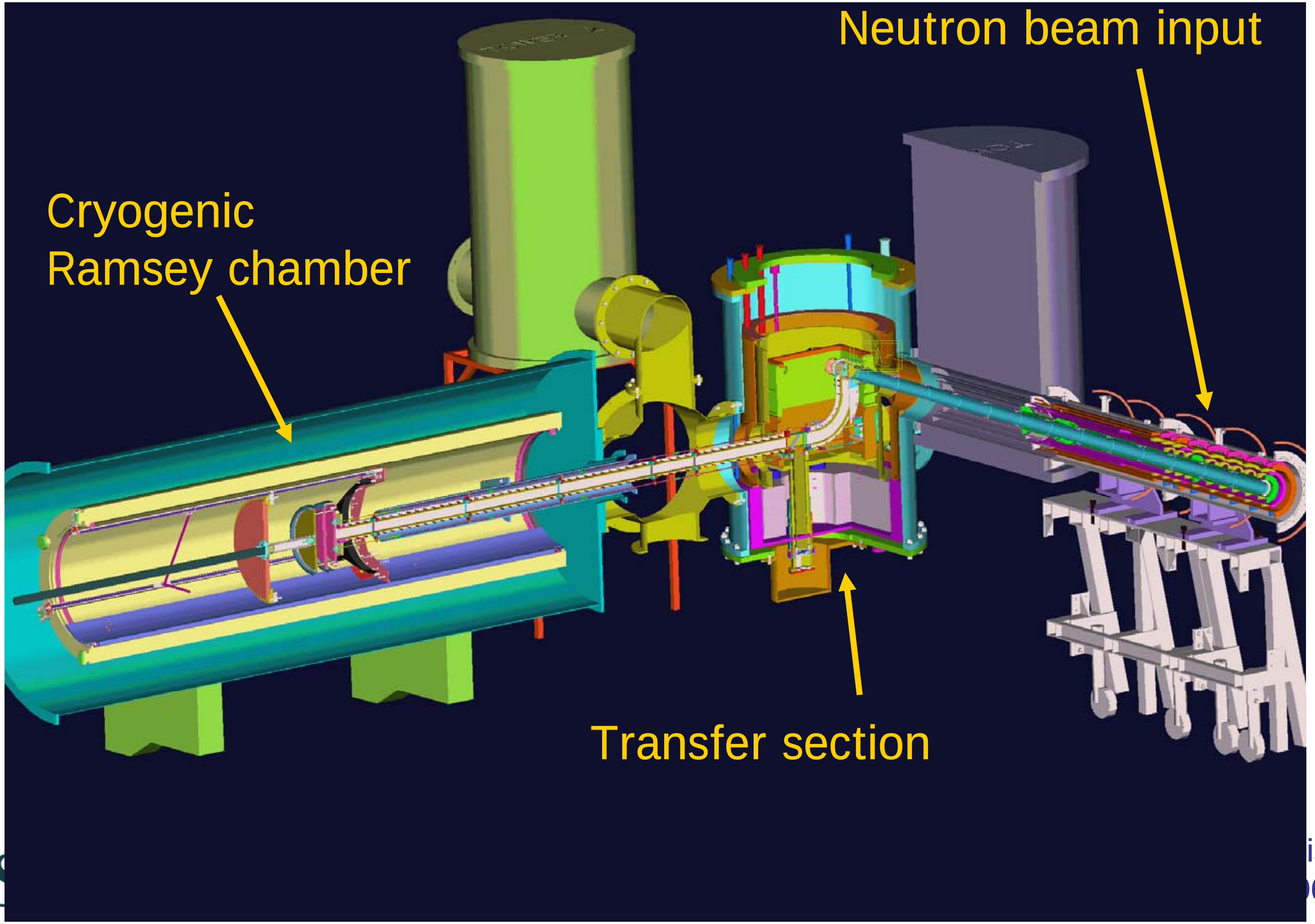
Statistical limits

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

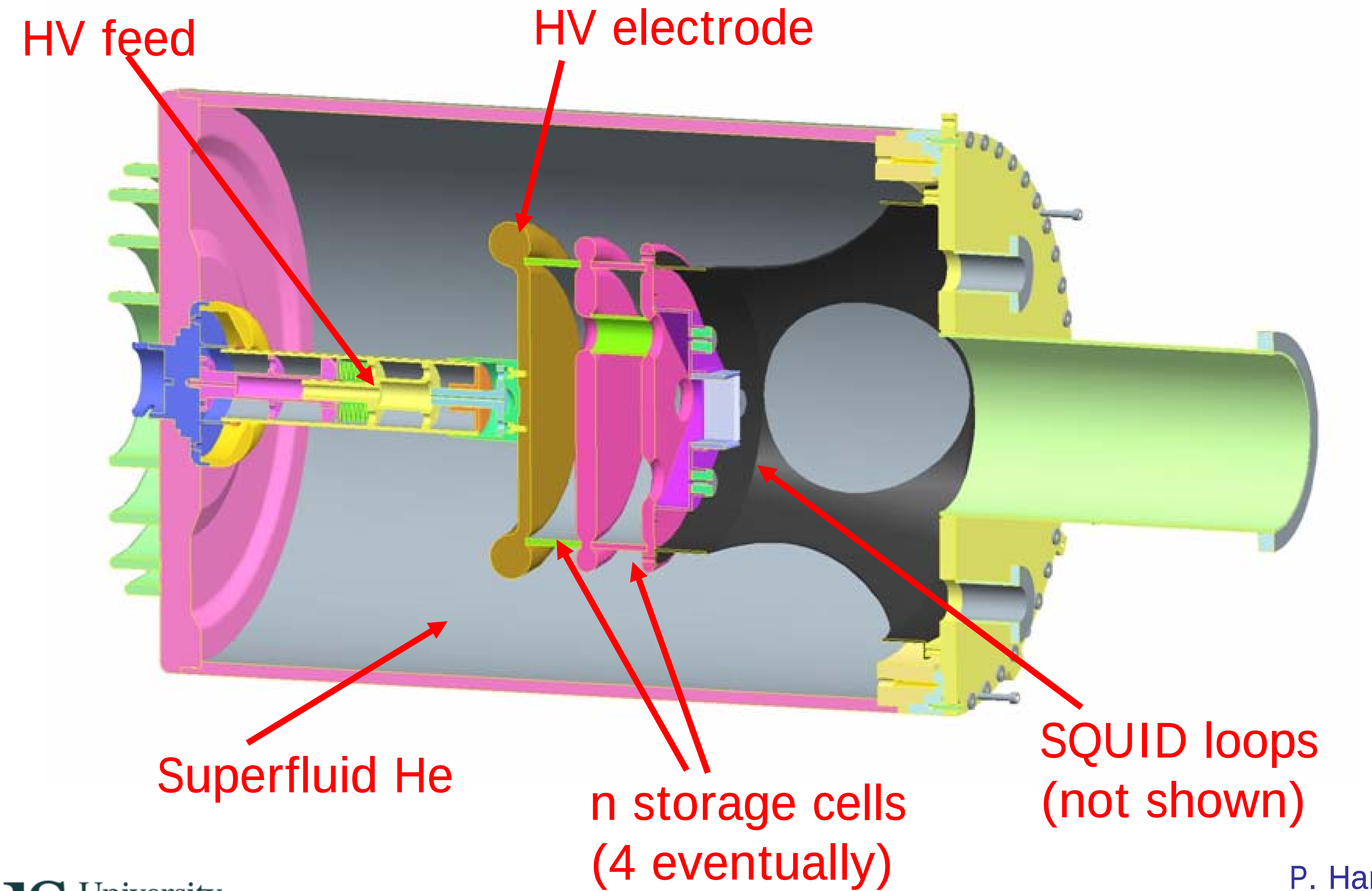
Parameter	Room-tmpr. expt	Sensitivity
Polarisation+detection:	$\alpha = 0.75$	x 1.2
Electric field:	$E = 10^6$ V/m	x 4
Precession period:	$T = 130$ s	x 2
Neutrons counted:	$N = 6 \times 10^6$ /day	x 4.5
(with new beamline)		x 2.6

Total increase approx factor 100

CryoEDM overview



Cryogenic Ramsey chamber



Ramsey cell and HV stack

Systematics

- B-field fluctuations
  - Superconducting solenoid & shield will give much improved field shape and shielding
  - SQUIDs give temporal variation (common-mode)
  - Shielding not optimal at present: improvements foreseen
- Geometric phase
  - n are ~40x less sensitive than Hg
  - $1/B^2$: 5 x increase in B gives 25x protection
  - overall 1000x improvement

Systematics

- Other:
  - **E**x**v**: 3E-29 e.cm
  - Feedback from field coils: <1E-30 e.cm
  - Electrostatic forces: < 1E-28 e.cm
  - Leakage currents: 1 nA $\rightarrow$ 5E-29 e.cm
  - AC fields from HV: < 1E-29 e.cm
- Overall: no show-stoppers...

Current status

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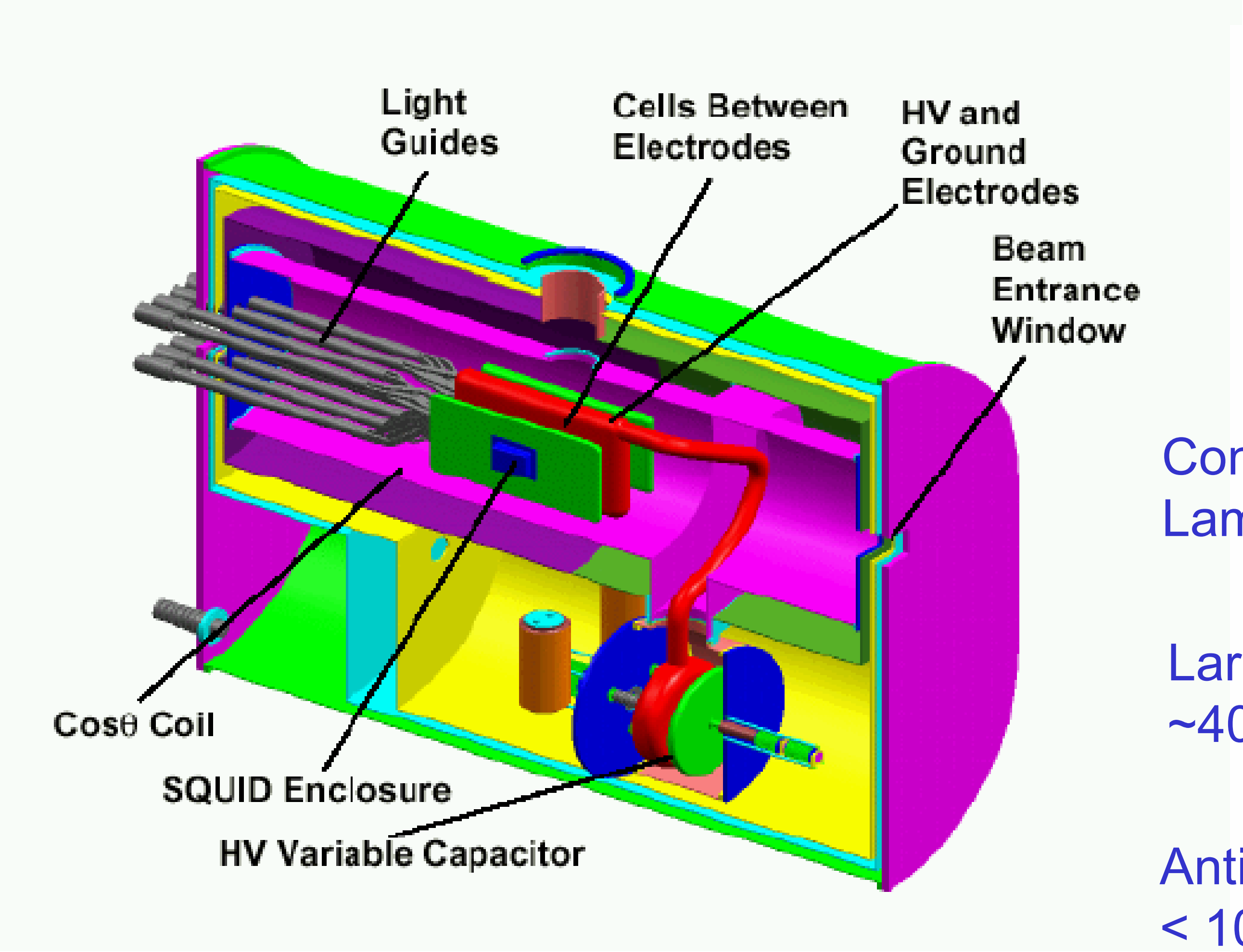
- Final assembly and testing underway
- First neutrons expected autumn 06
- B-field scanning December 06
- High voltage installation spring 07
- **Data taking begins summer 2007**
  - First results ~2009 at ~1E-27 level
  - New beamline ~2009?

CryoEDM at SNS, ORNL



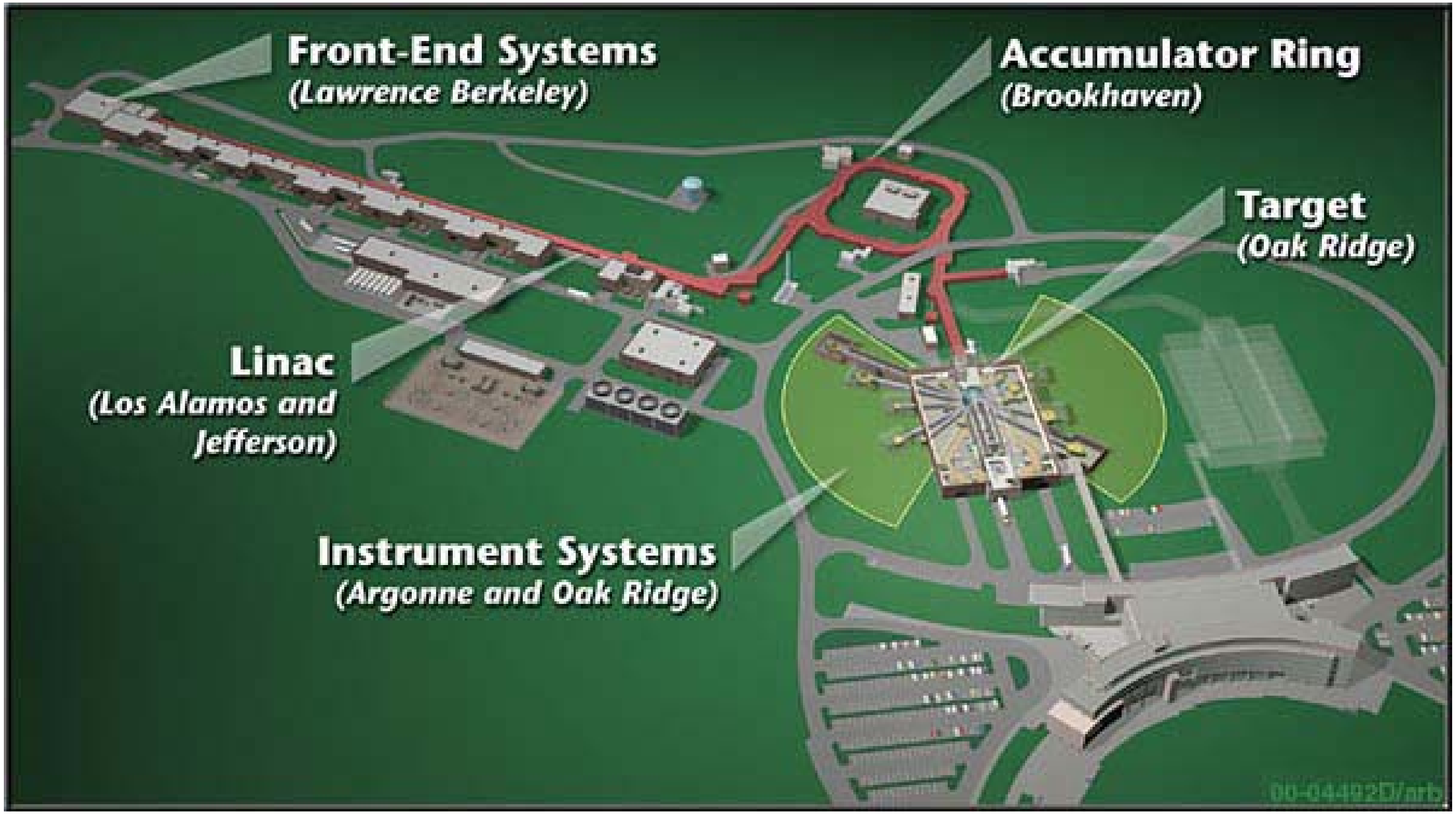
Concept by Golub & Lamoreaux, 1994

Large US collaboration: ~40 people, $16M

Anticipated sensitivity < 10^{-28} e.cm

CryoEDM at SNS, ORNL

1.4 MW (1 GeV proton, 1.4 A) spallation source



First proton beam: April 2006

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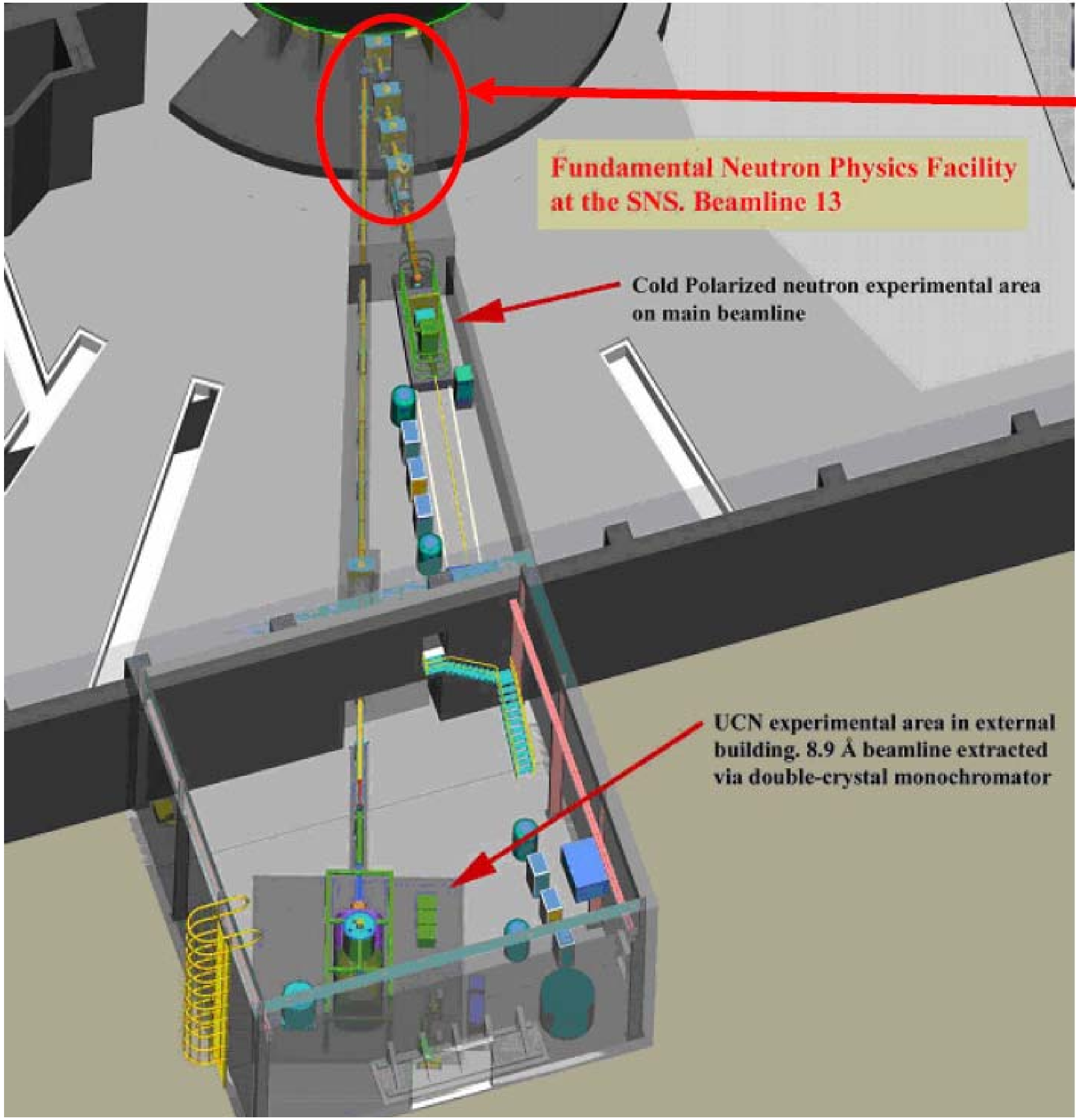
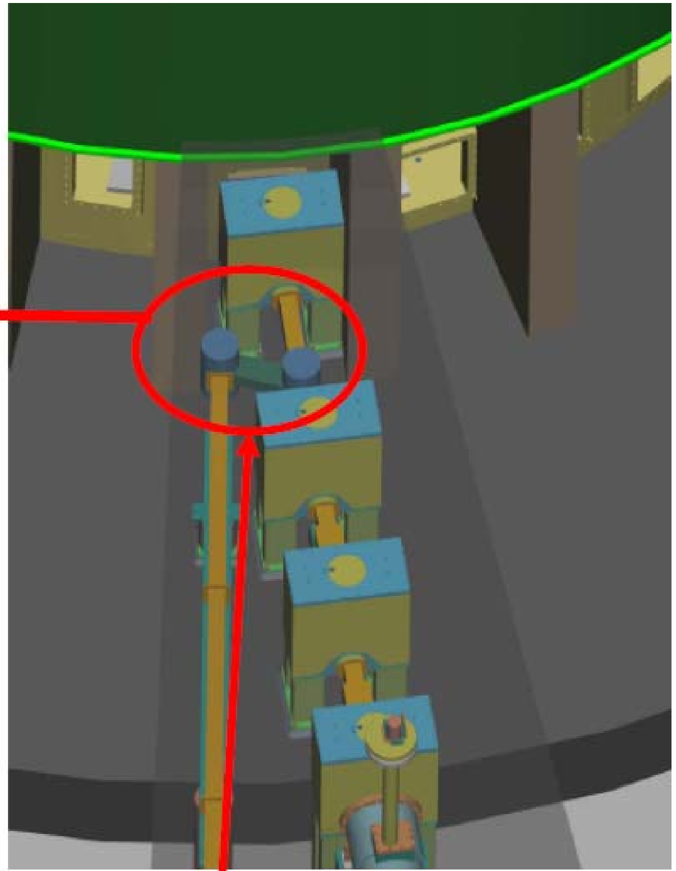
FNPB beamline (2007)





Double monochrometer

Selects 8.9 Å neutrons
for UCN via LHe

Spin precession measurement

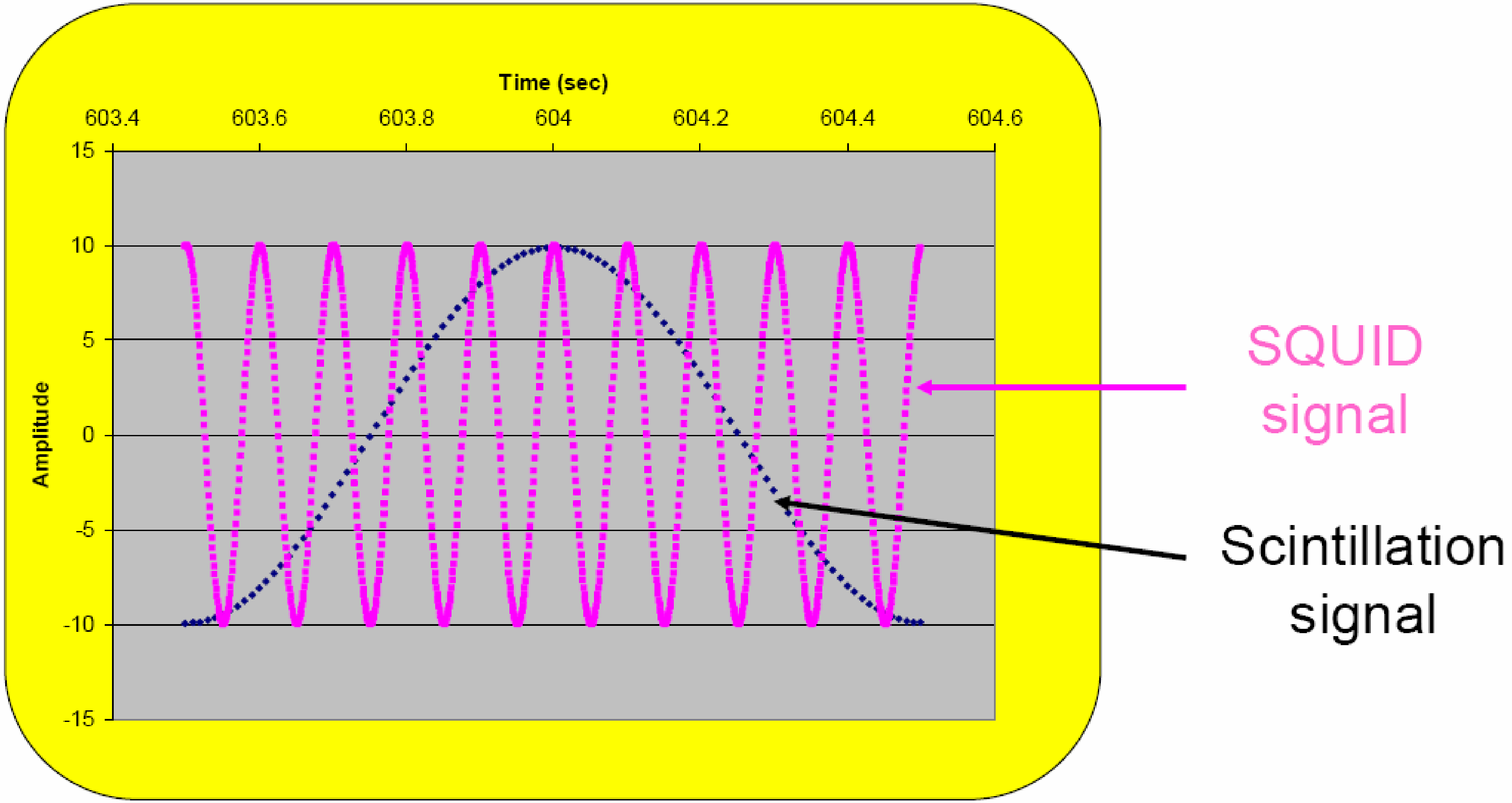
- Add polarized ^{3}He to the bottle
- Strongly spin-dependent n absorption

$$n + {}^3He \rightarrow p + t + 764\,KeV$$

Total spin	σ_{abs} at v = 5m/sec
J = 0	~ 4.8 x 10^6 barns
J = 1	~ 0

- Detect scintillation light from
  $$n + {}^3He \rightarrow p + t$$
- “Beats” with ^{3}He precession

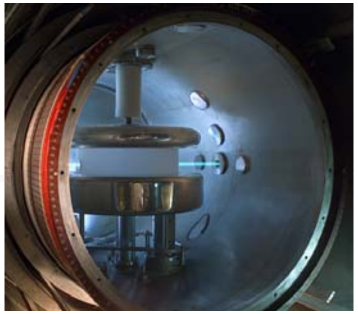
SQUID & scintillator signals



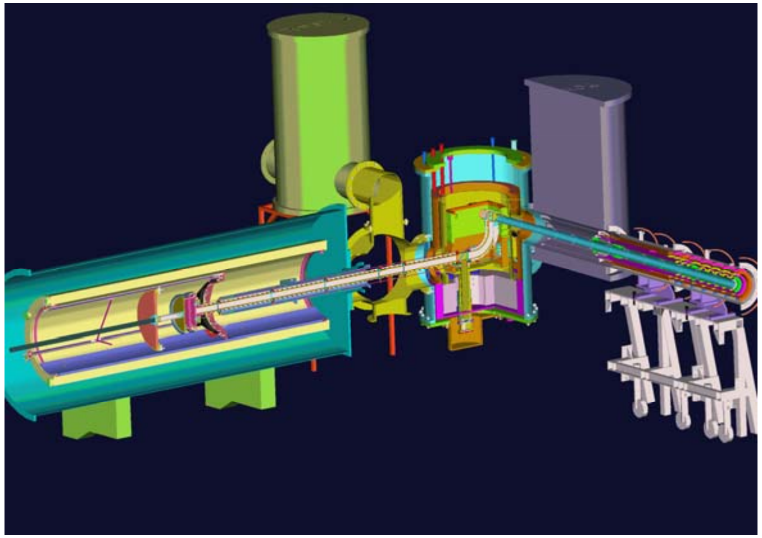
Schedule

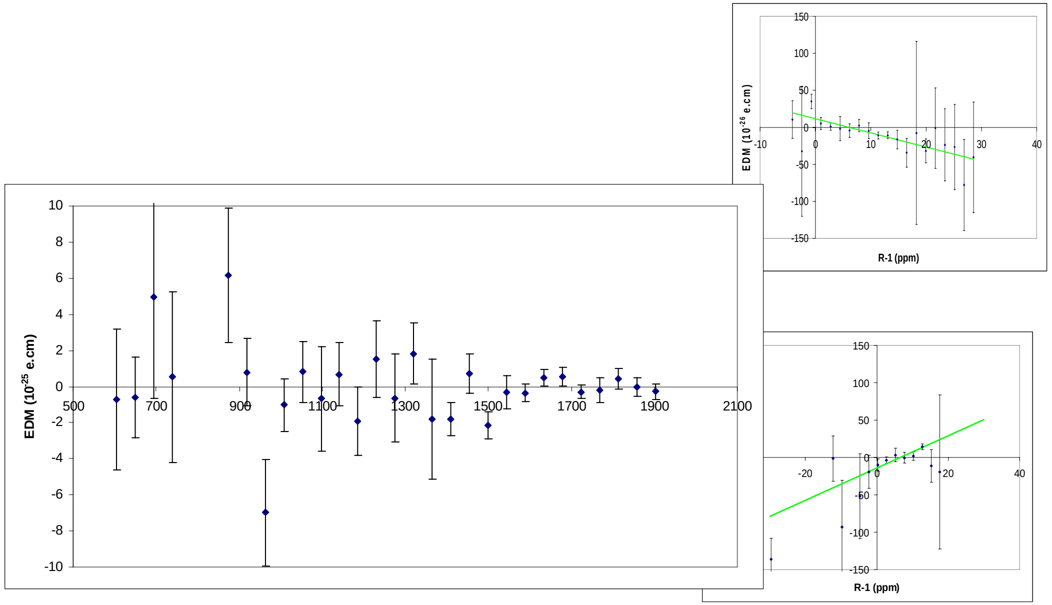
- CD0 Nov. 05
- Various tests underway
  - HV: reached 30 kV/cm so far in He below λ pt
  - Studied ^{3}He diffusion in ^{4}He
  - ^{3}He relaxation time T1 > 3000 s in 1.9 K ^{4}He
- Anticipate CD1 Nov. 06
- Assuming funded, construction could begin 07
- Commissioning anticipated 2012
- Results in....?

Conclusions



- New nEDM limit, 2.9 x 10^{-26} e.cm
- Systematics understood as never before
- CryoEDM coming soon – 100x more sensitive
- SNS CryoEDM: construction to start 2007?
- Watch this space!

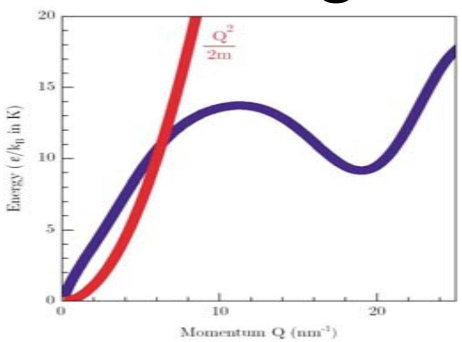




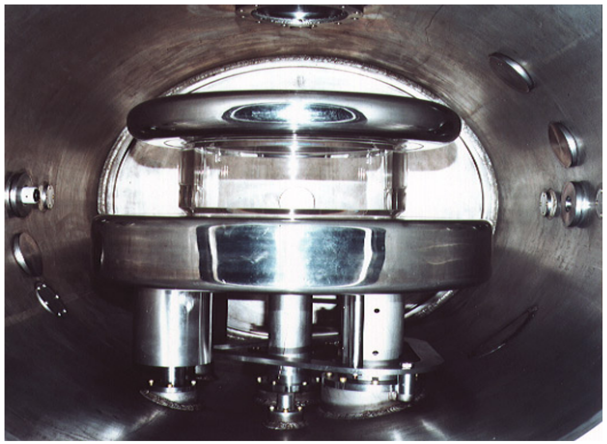
P. Harris
CERN, 9/10/2006

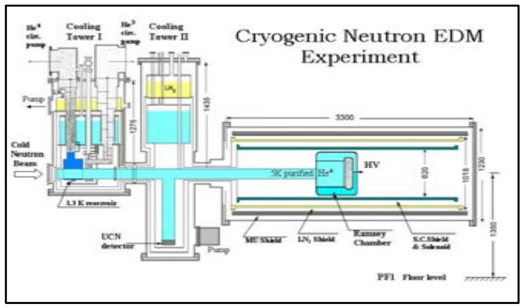
And finally...

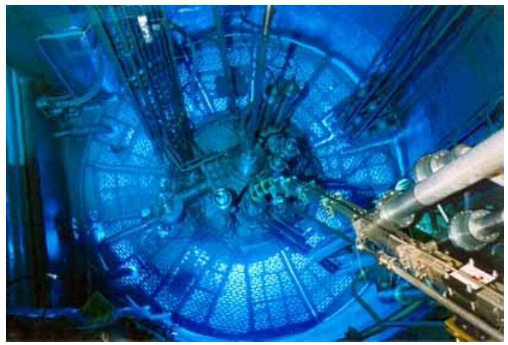
"It may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments... seem to me to offer one of the most exciting possibilities for progress in particle physics."



- S. Weinberg





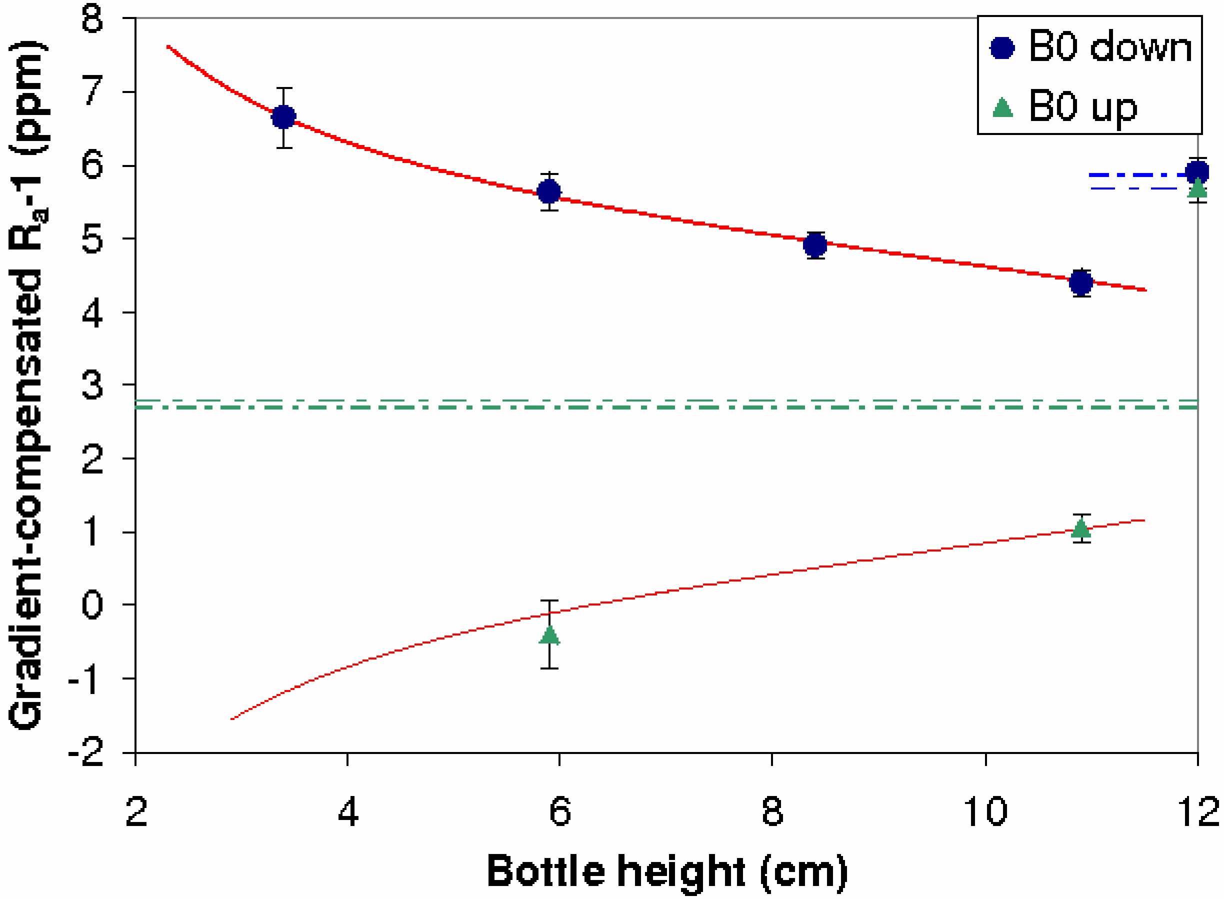


spare slides

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)

Auxiliary bottle measurements



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

Effect	Shift	Uncertainty
Statistical	0	1.51
Door cavity dipole; quadrupole fields	-0.69	0.28
Other GP dipole shifts	0	0.60
(**E** x **v**)/c^2 from translation	0	0.003
(**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	-0.04	0.03
2nd order **E**x**v**	0	0.002
Total	–0.75	1.51 stat, 0.72 sys

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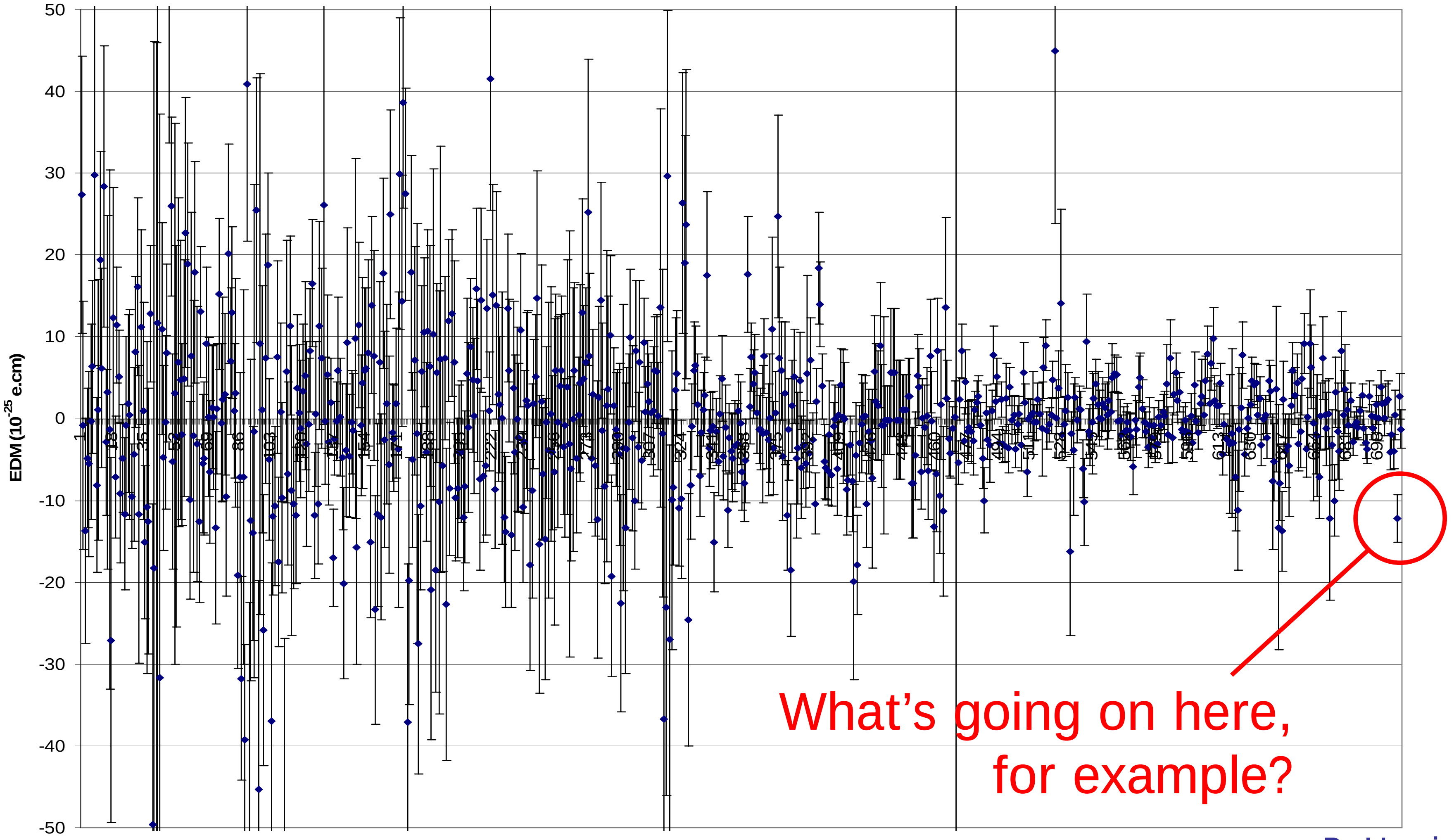
CERN, 9/10/2006

Neutron EDM results (individual runs)



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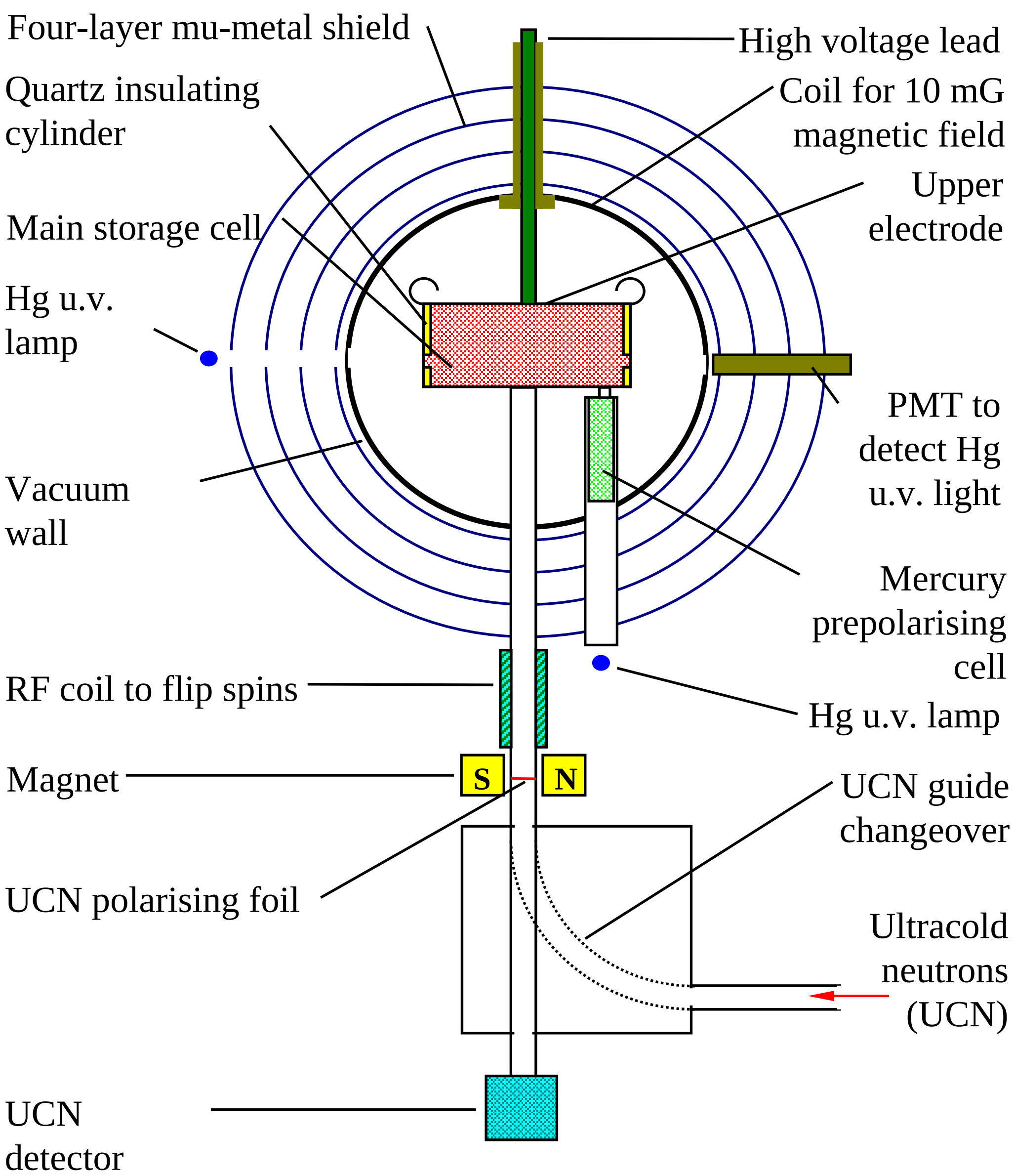
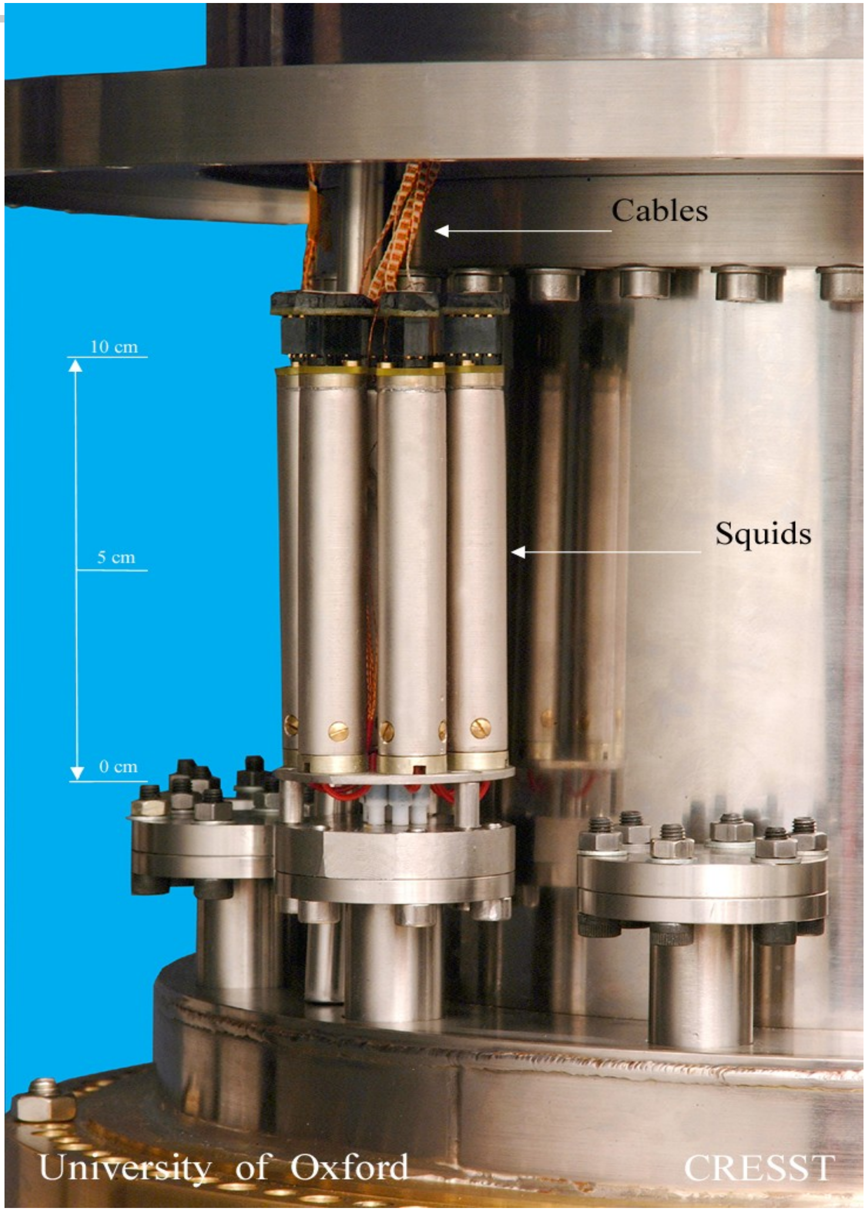
nEDM apparatus



Magnetometry

- SQUID Magnetometers
  - Developed at Oxford for CRESST
  - fT sensitivity:
    adequate to monitor field fluctuations



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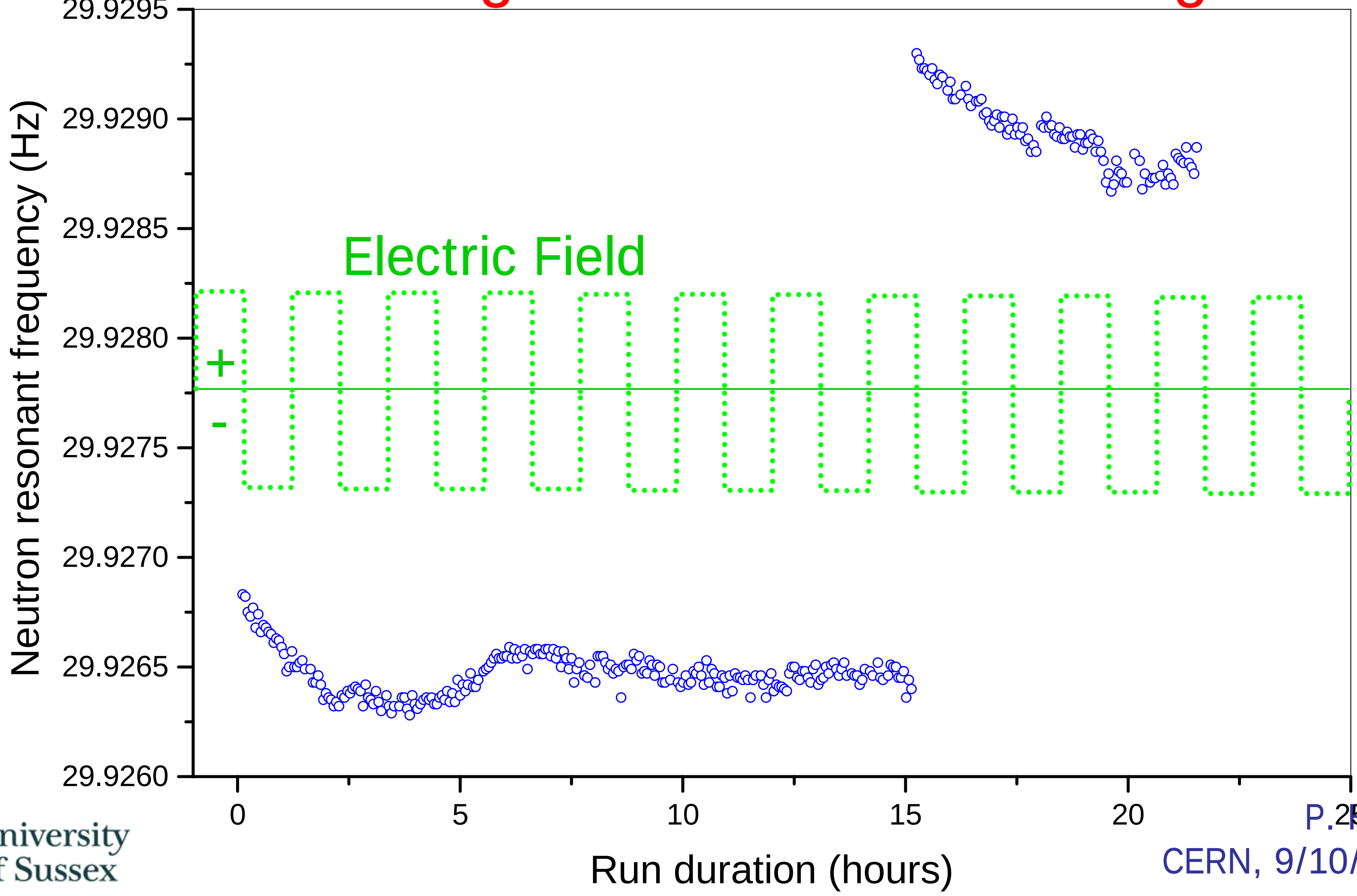
nEDM measurement

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



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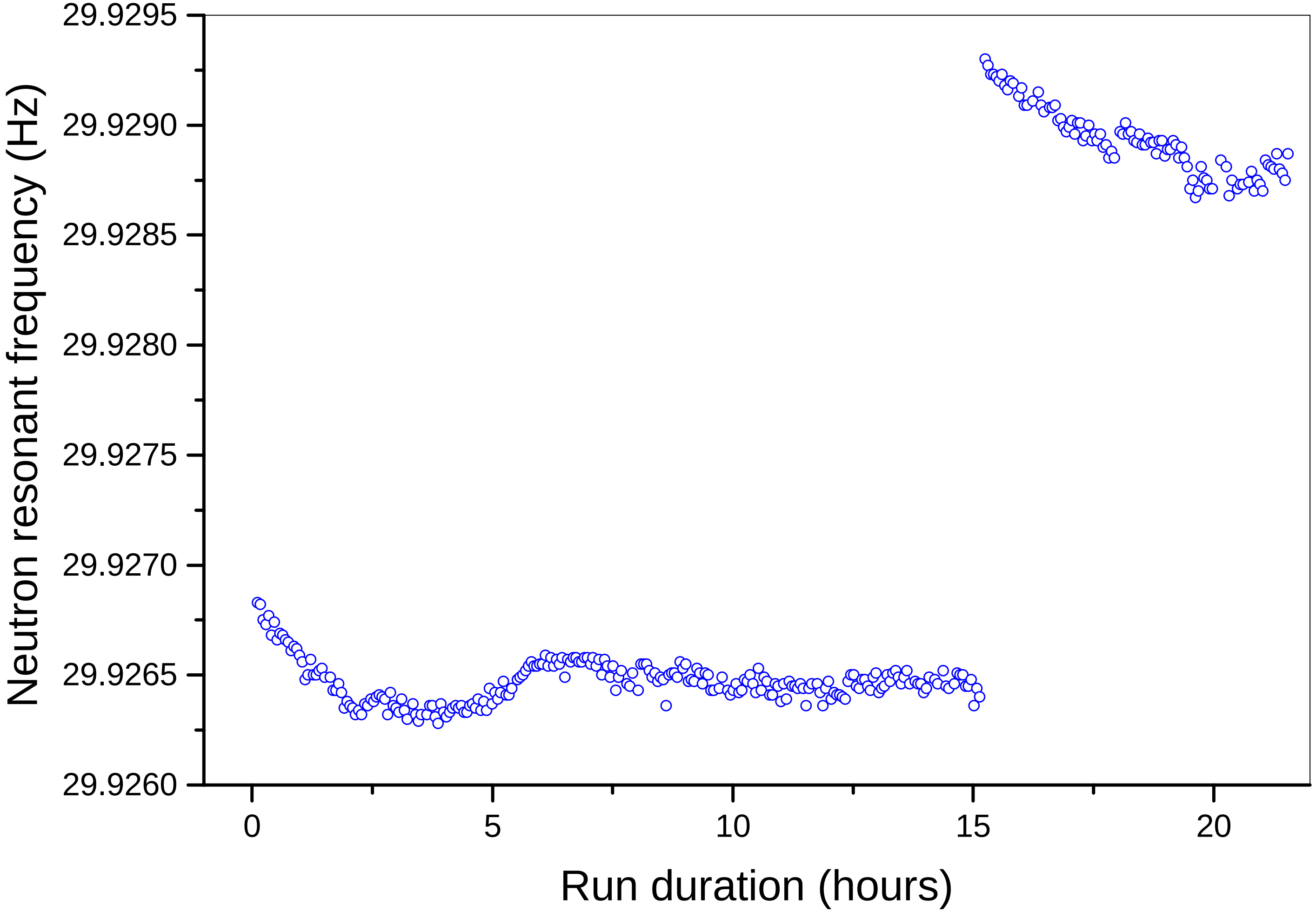
Neutron frequency (from before; 1 day)



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Mercury frequency