EDM Experimental Searches

Maurits van der Grinten
Rutherford Appleton Laboratory
Science & Technology Facilities Council UK

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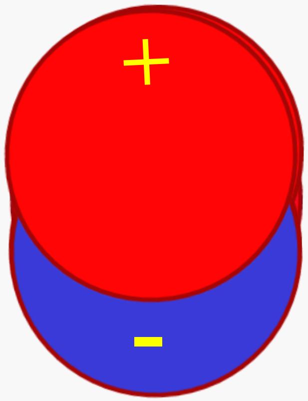
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Outline

- **Physics Motivation**
  - EDM & CP/T violation
  - EDM in physics models
  - restraints by experiments
- **Experimental techniques for nEDM measurements**
  - spin precession frequency & EDM
  - Ramsey Resonance techniques
  - sensitivities
- **Experiments**
  - PSI
  - ILL/ESS
  - SNS
  - …
- **Conclusion/Summary**

EDM CP violation

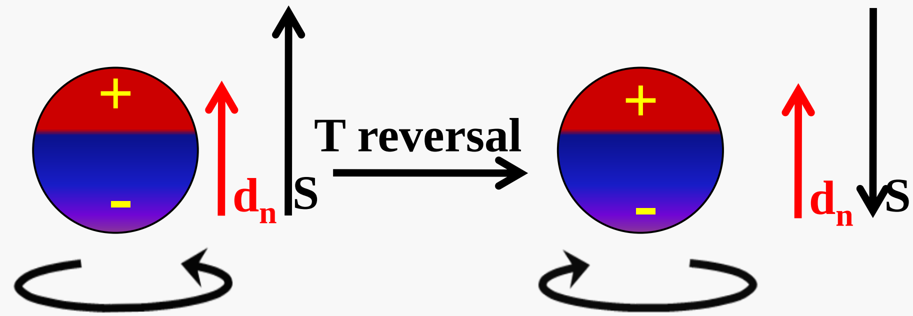


Electric Dipole Moment:

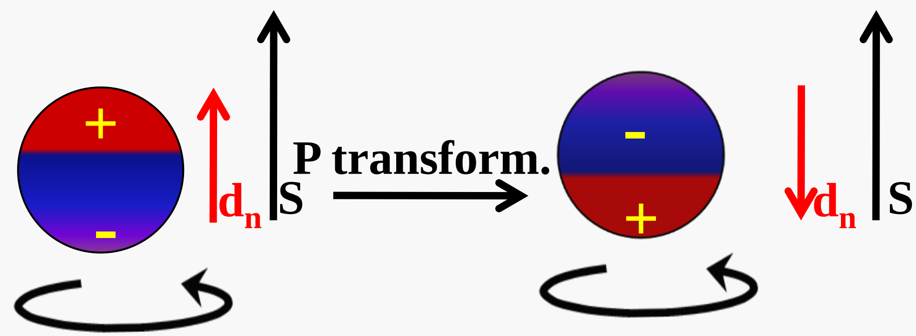
electrically neutral or charged particles

If there is a charge distribution:

EDM



electric dipole moment d_n
spin S



P & T violation

CPT conservation ➔ CP violation

EDM CP violation

The Electric Dipole Moment: d_n

$d_n \neq 0 \quad \Rightarrow \quad P$ and T violation

CP violation observed in K decay, B mesons → $d_n \neq 0$

CP violation, interest

- The study of CP violation to further:
  - Understanding the fundamental laws of physics
  - Understanding the baryon asymmetry of the cosmos
- EDM is a particularly promising laboratory for CP violation
  - The Standard Model contribution is very small
  - Contributions from new physics tend not to be

EDM: systems at hand

Paramagnetic atoms / molecules

- sensitive to d_e, C_S

diamagnetic atoms

- sensitive to $g_{\pi NN}$, d_N, C_S, C_P, C_T, d_e

free neutron

- sensitive to d_n

→ particle EDMs and CP odd interactions

→ fundamental theories

charged systems (muons, ions)

CP violation & nEDM
Standard Model and beyond

Non-trivial structure of vacuum in QCD

Strong

$$|\theta\rangle \equiv \sum_n e^{in\theta} |n\rangle$$

➔ θ-term in the Lagrangian violating CP

$$\mathcal{L}_{QCD} = \mathcal{L}_0 + \mathcal{L}_\theta$$

CP conserving

$$L_0 = -\frac{1}{2g_s^2} Tr\left[F_{\mu\nu}F^{\mu\nu}\right] + \ldots = \vec{E}_a^2 - \vec{B}_a^2 + \ldots$$

$$L_\theta = \theta \cdot \frac{1}{16\pi^2} Tr\left[\tilde{F}_{\mu\nu}F^{\mu\nu}\right] = \vec{E}_a \cdot \vec{B}_a$$

CP violating

$$d_N \sim \bar{\theta} \cdot 2 \times 10^{-16} ecm$$

Electroweak

CKM matrix: three Euler angles and one complex phase δ_{CKM}

$$d_N \propto \ldots c_1 s_1^2 c_2 s_2 c_3 s_3 \sin \delta_{CKM}$$

SUSY

Additional CP violating phases

Φ_A Φ_B

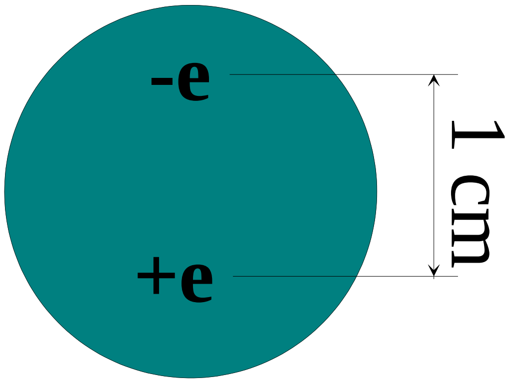
$$d_N \sim 2\left(\frac{100GeV}{\tilde{m}}\right)^2 \sin \Phi_{A,B} \cdot 10^{-23}\ ecm$$

M vd Grinten

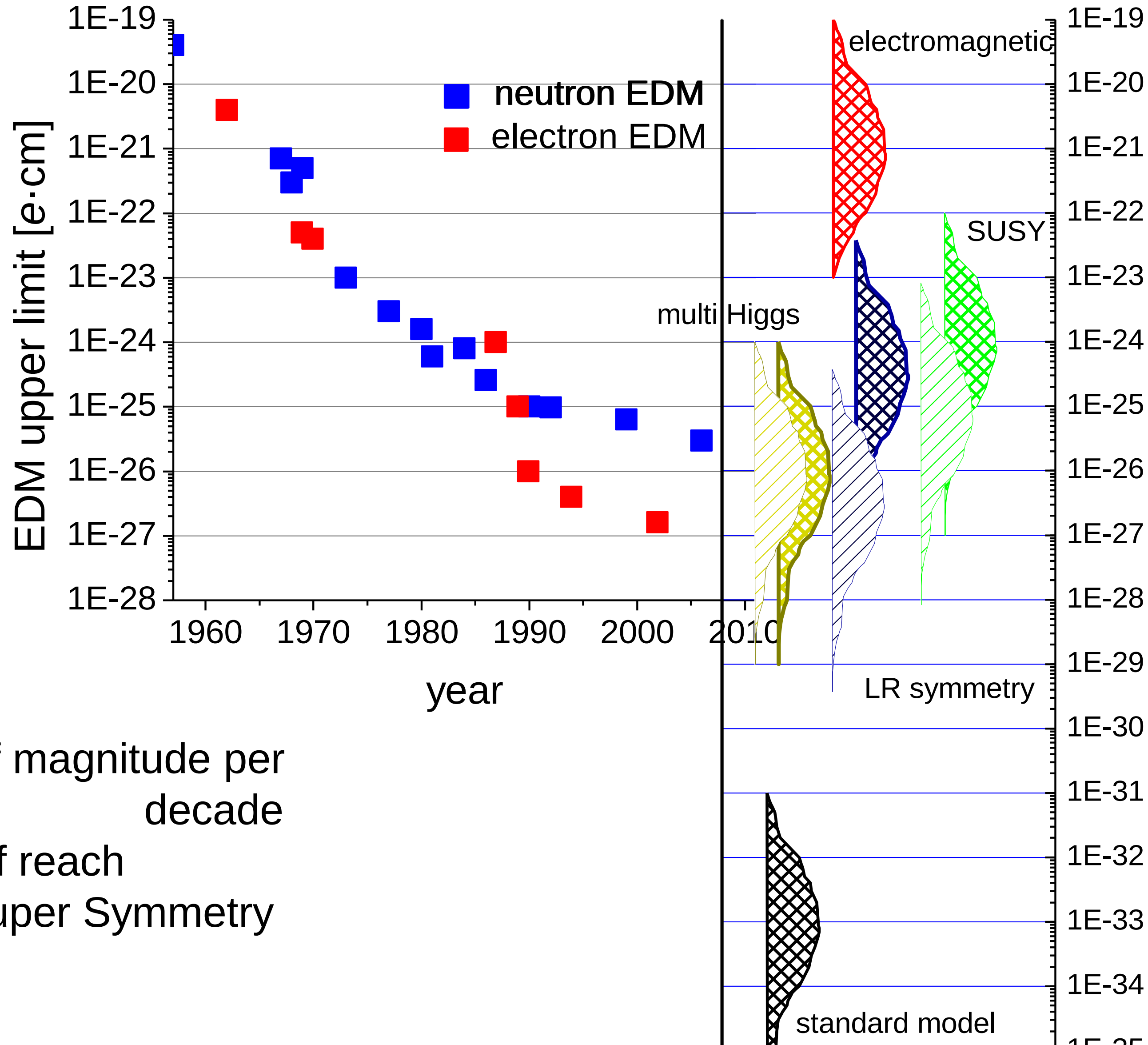
$$d_N < 2.9 \times 10^{-26}\, ecm$$

Strong	$d_N \sim \bar{\theta} \cdot 2 \times 10^{-16}\, ecm$	$\bar{\theta} < 10^{-9}$	*Strong CP problem* ☹
Electroweak	$d_N \propto \ldots c_1 s_1^2 c_2 s_2 c_3 s_3 \sin \delta_{CKM}$	$d_N \sim 10^{-32}\, ecm$	*No problem but what about baryon asymmetry?* 😐
Supersymmetric	$d_N \sim 2 \left(\frac{100 GeV}{\tilde{m}} \right)^2 \sin \Phi_{A,B} \cdot 10^{-23}\, ecm$	$\sin \Phi_{A,B} \sim 10^{-2}$ $\tilde{m} \sim TeV$	*Supersymmetric CP problem* ☹

EDM models - experiment



$d_n = 1\ e{\cdot}cm$



Progress at ~ order of magnitude per decade

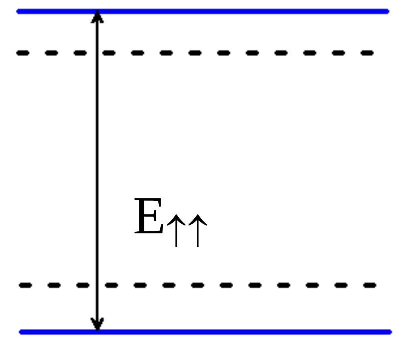
Standard Model out of reach

Constraints on *e.g.* Super Symmetry

nEDM: spin frequency

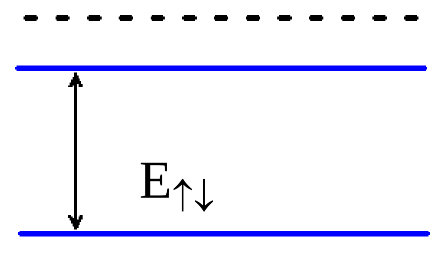
Experiments:
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field

Compare the precession frequency for parallel fields:



$$\nu_{\uparrow\uparrow} = E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$

to the precession frequency for anti-parallel fields



$$\nu_{\uparrow\downarrow} = E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

The difference is proportional to d_n and E:

$$\mathbf{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}) = 4E\, d_n}$$

Need to measure change in Larmor precession frequency to a very high degree : < 1μHz
<1 turn per month!

nEDM: Ramsey Resonance techniques

The difference is proportional to d_n and E:

$$\nu_{\uparrow\uparrow} = E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$
$$\nu_{\uparrow\downarrow} = E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

$$\mathbf{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}) = 4\mathit{E}\, \mathit{d}_n}$$

if B_0 has not changed

Need a magnetometer!

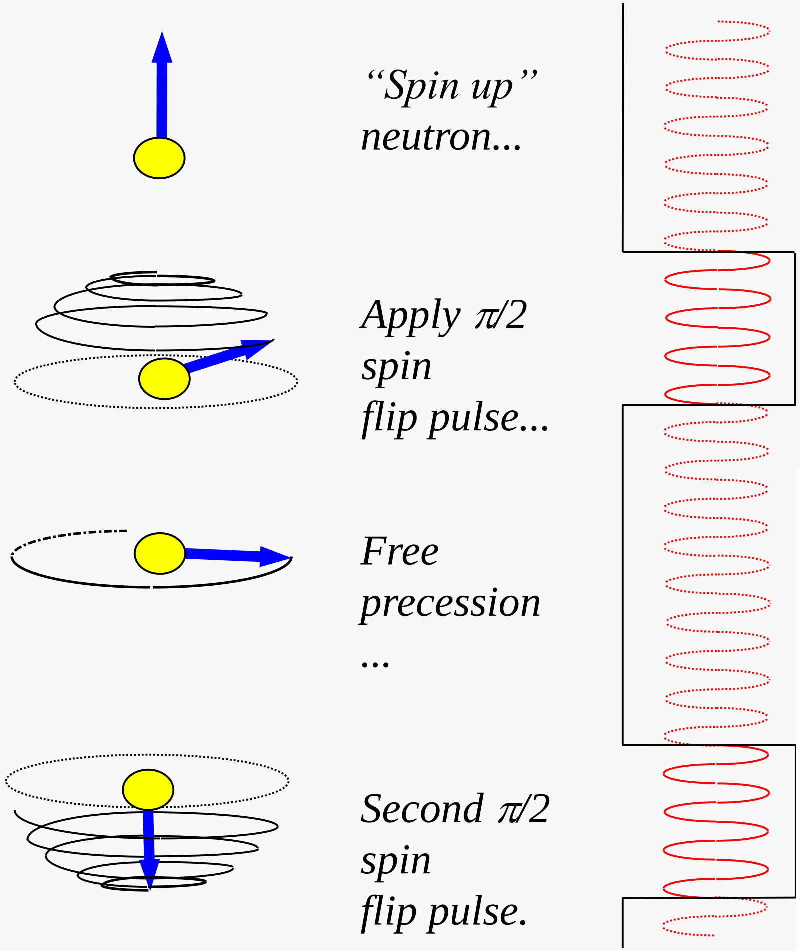
nEDM: Ramsey Resonance techniques

1. *"Spin up" neutron...*

2. *Apply π/2 spin flip pulse...*

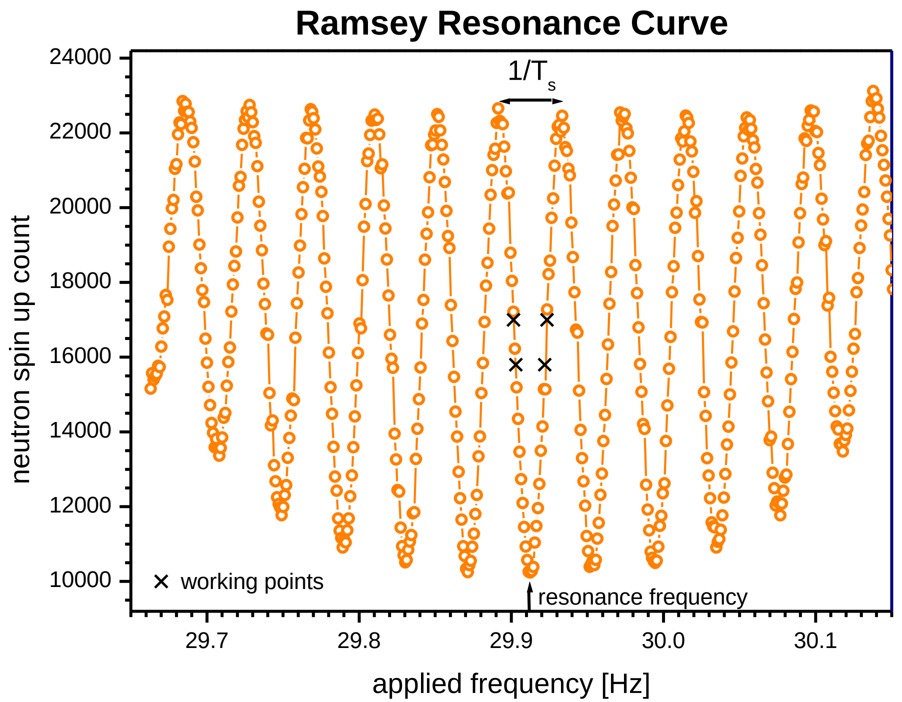
3. *Free precession ...*

4. *Second π/2 spin flip pulse.*



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

α: polarisation product
E: electric field
T: observation time
N: number of neutrons



nEDM: Ramsey Resonance techniques

$$\Delta E \Delta T \approx \hbar$$

Uncertainty in measurement of energy E; (interaction energy between E_{el} and d_n)

Uncertainty in time (*i.e.* width of observation time)

Uncertainty in measurement of E directly related to uncertainty in d_n

$$E = 2 d_n E_{el} \Rightarrow d_n = \frac{E}{2E_{el}}$$

$$\sigma(d_n) = \frac{\hbar}{2\alpha E_{el} T \sqrt{N}}$$

For N measurements with polarisation product $\alpha = P^2$:

neutron EDM Experiments

nEDM: ILL

Institut Max von Laue – Paul Langevin

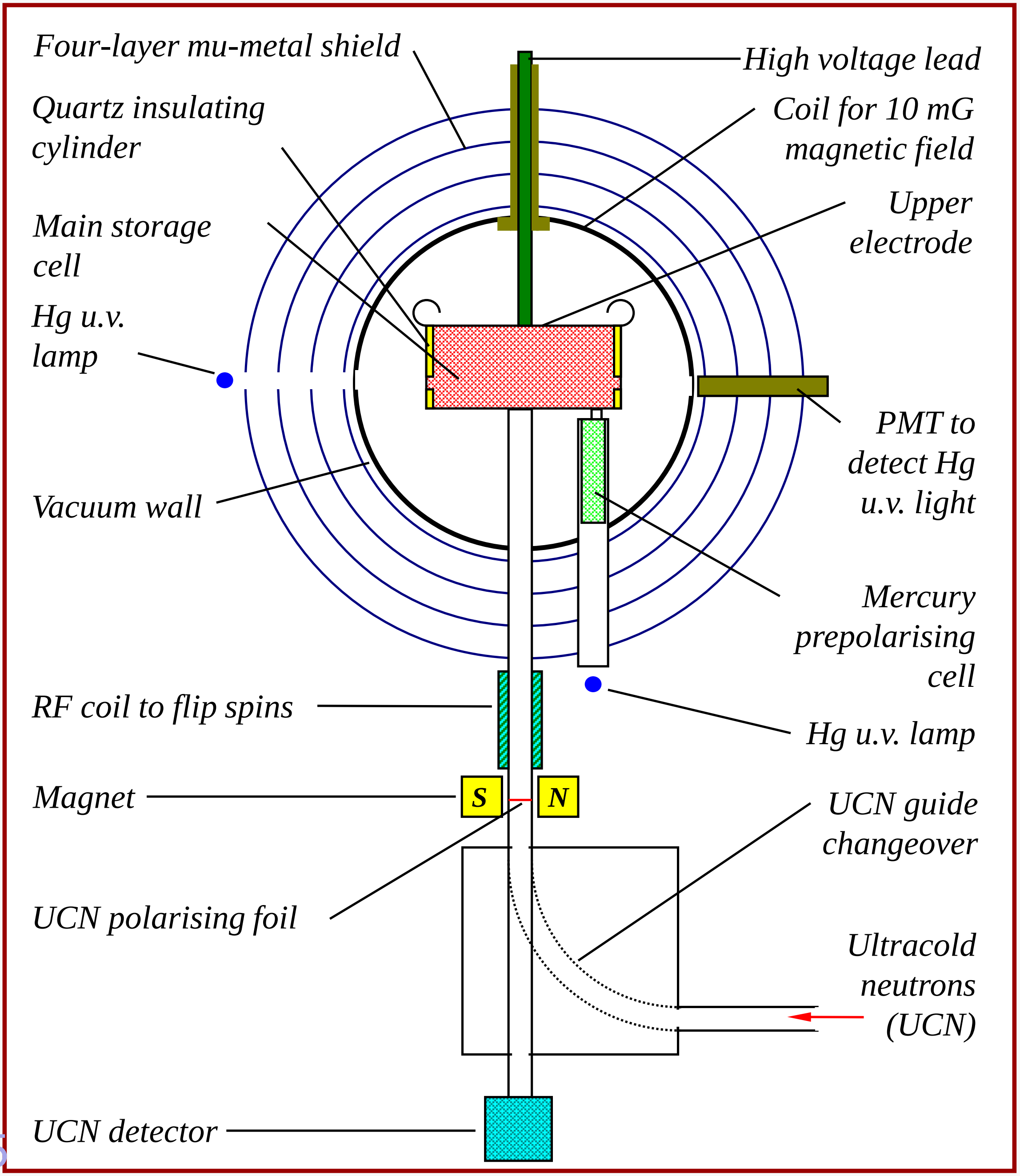
- completed room temperature EDM experiment on UCN source
- cryogenic EDM R&D on cold neutron beam

nEDM: ILL

PF2 beam line

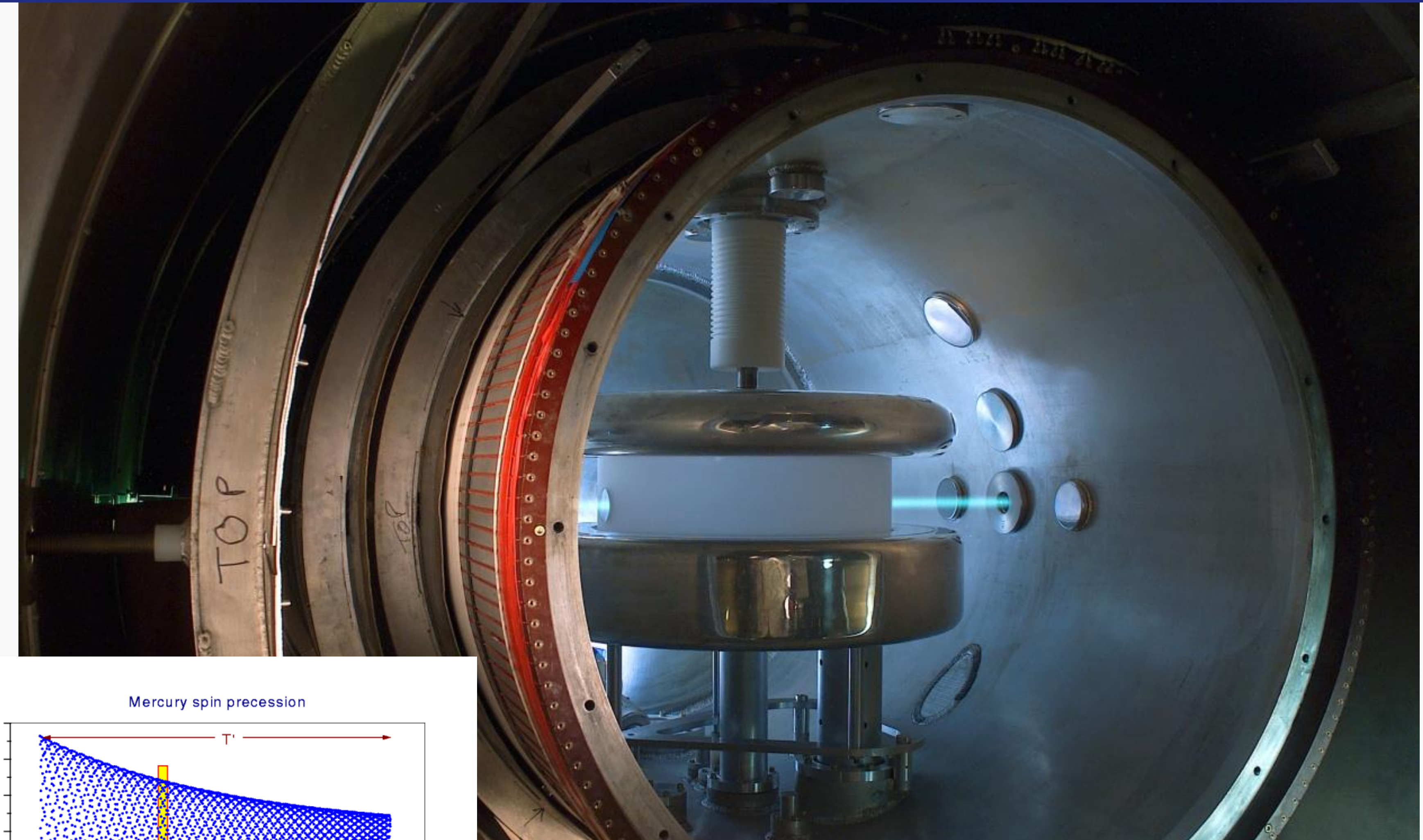
H53 beam line

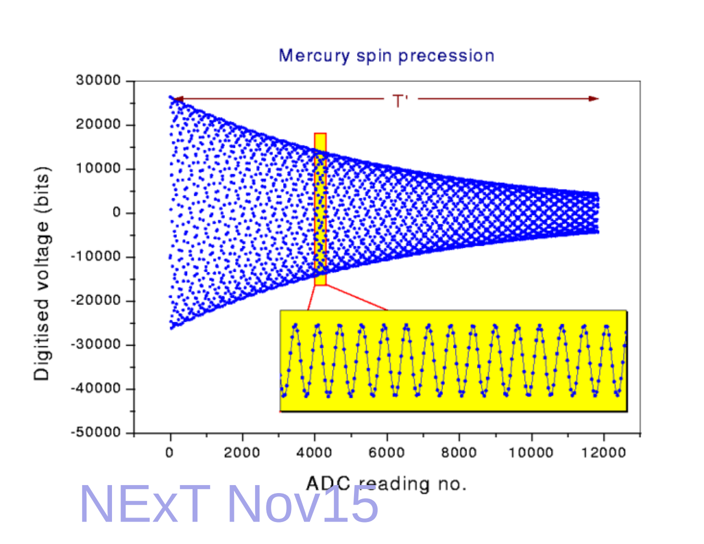
nEDM: ILL



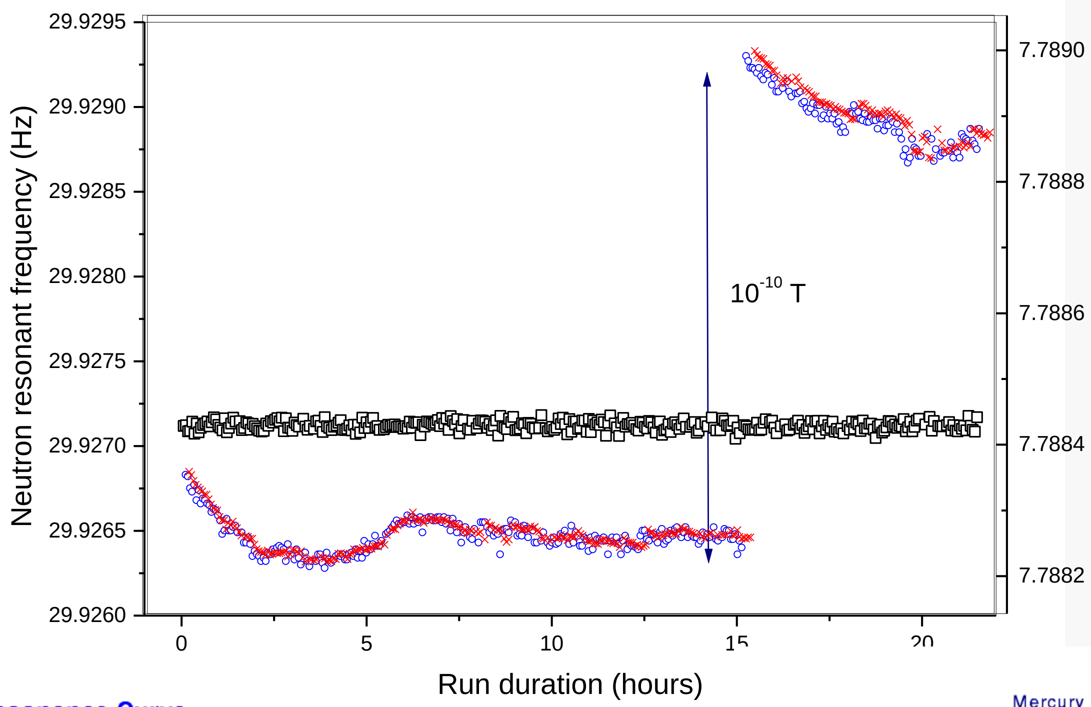
Four-layer mu-metal shield
High voltage lead
Quartz insulating cylinder
Coil for 10 mG magnetic field
Main storage cell
Upper electrode
Hg u.v. lamp
PMT to detect Hg u.v. light
Vacuum wall
Mercury prepolarising cell
RF coil to flip spins
Hg u.v. lamp
Magnet
S
N
UCN guide changeover
UCN polarising foil
Ultracold neutrons (UCN)
UCN detector

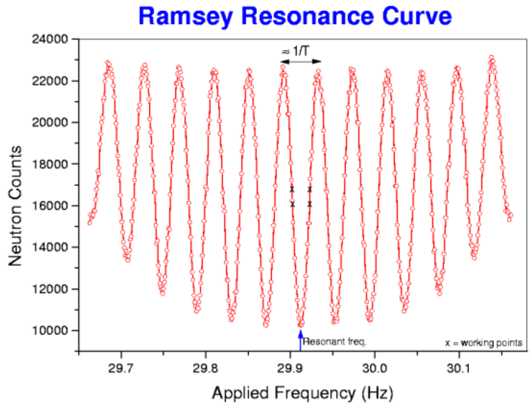
nEDM: ILL

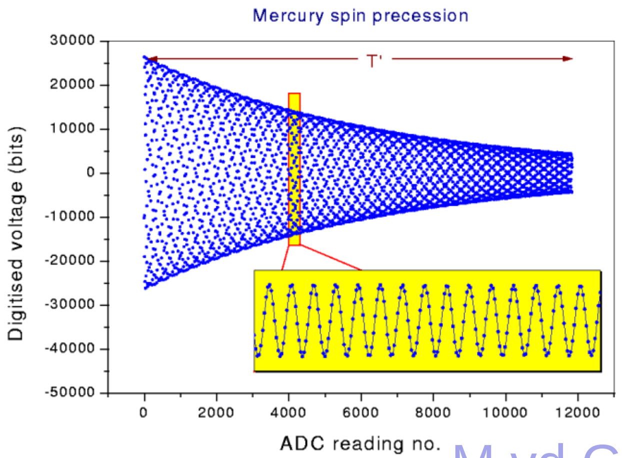


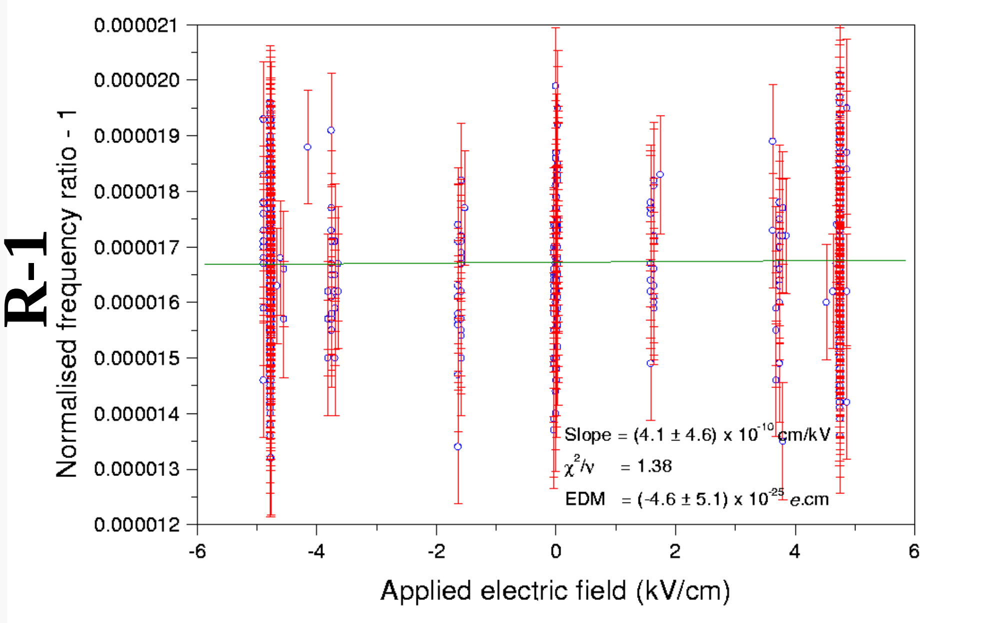

Mercury spin precession
T'
Digitised voltage (bits)
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
0
2000
4000
6000
8000
10000
12000
ADC reading no.

nEDM: ILL

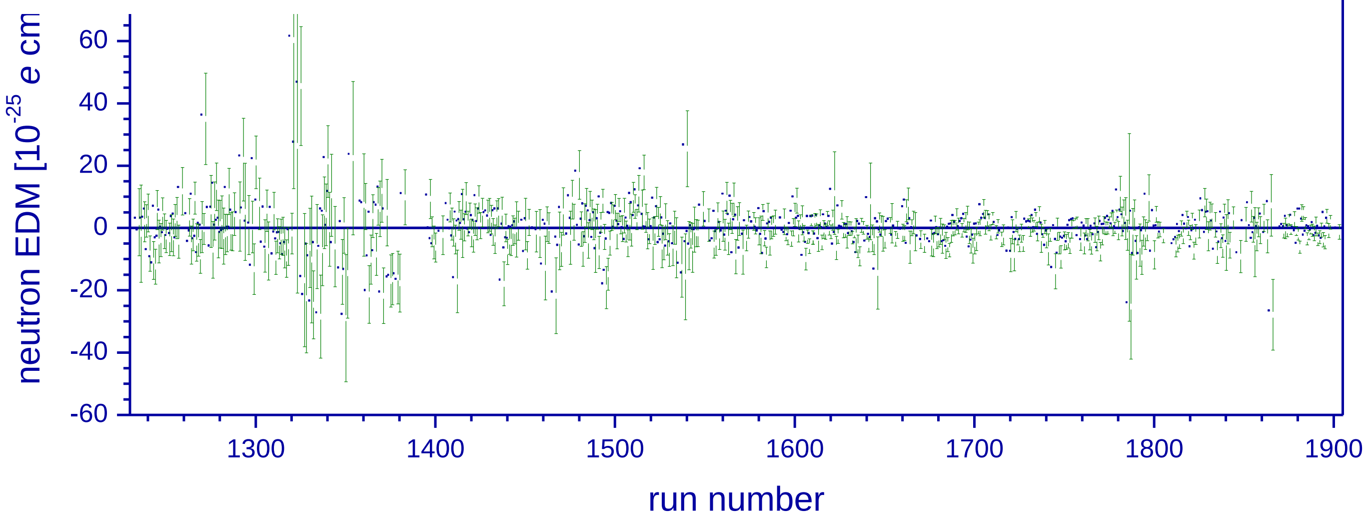

Neutron resonant frequency (Hz)
29.9295
29.9290
29.9285
29.9280
29.9275
29.9270
29.9265
29.9260
7.7890
7.7888
7.7886
7.7884
7.7882
10^{-10} T
0
5
10
15
20
Run duration (hours)


Ramsey Resonance Curve
Neutron Counts
Applied Frequency (Hz)
≈ 1/T
Resonant freq.
x = working points
24000
22000
20000
18000
16000
14000
12000
10000
29.7
29.8
29.9
30.0
30.1


Mercury spin precession
T'
Digitised voltage (bits)
ADC reading no.
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
0
2000
4000
6000
8000
10000
12000



$$R = \frac{\omega_n}{\omega_{Hg}} \frac{\gamma_{Hg}}{\gamma_n}$$



Phys Rev Lett. 97, 131801 (2006)

$d_n < 2.9 \times 10^{-26}$ e·cm

Still the leading limit to date! (>700 citations)

nEDM: cryogenic R&D

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

new superthermal UCN source

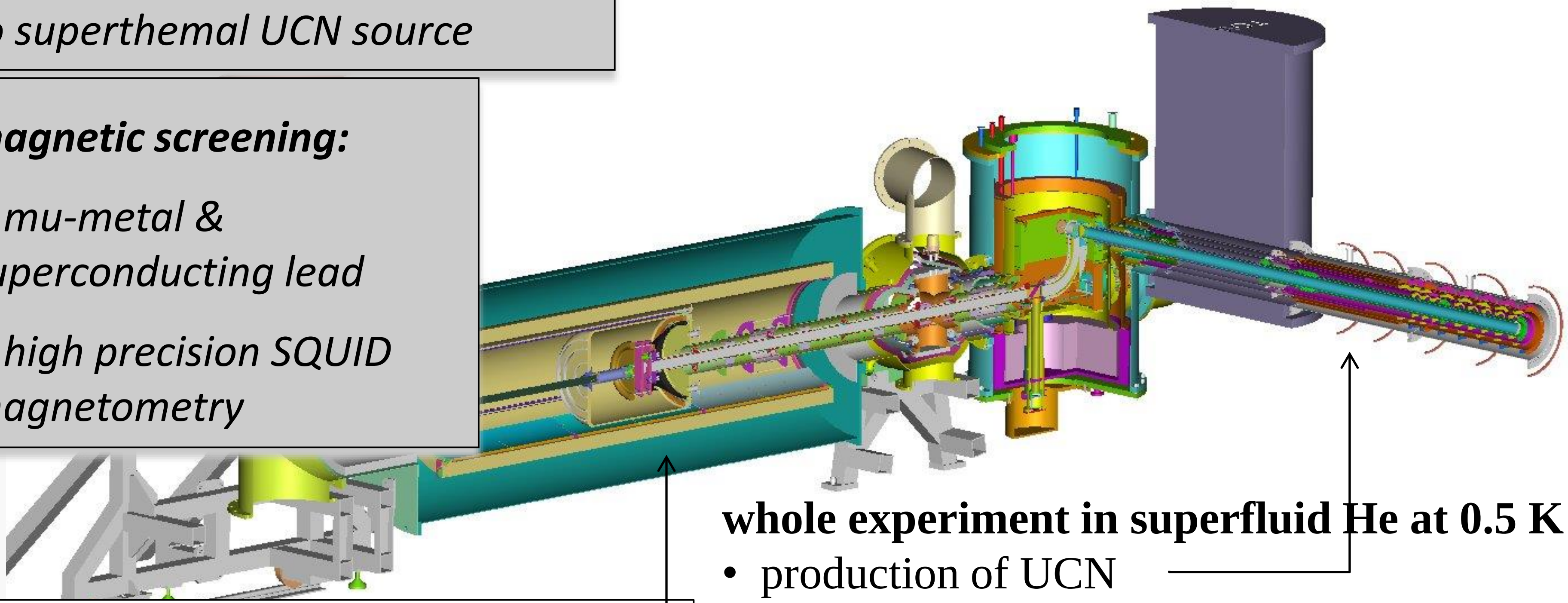
higher electric fields in *l*He

Ultra-cold neutron source:

Strong 9 Å neutron beam coupled to superthemal UCN source

magnetic screening:

- *mu-metal & superconducting lead*
- *high precision SQUID magnetometry*



Alternatively use ^{3}He magnetometry)

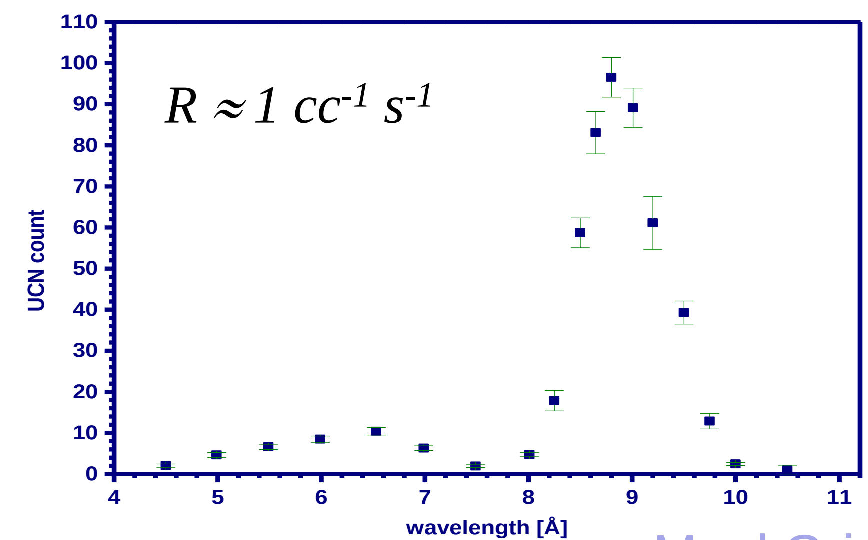
whole experiment in superfluid He at 0.5 K

- production of UCN
- storage & Larmor precession of UCN
- magnetometry
- detection of UCN

nEDM: cryoEDM

Shields & Ramsey cells coupled to UCN source

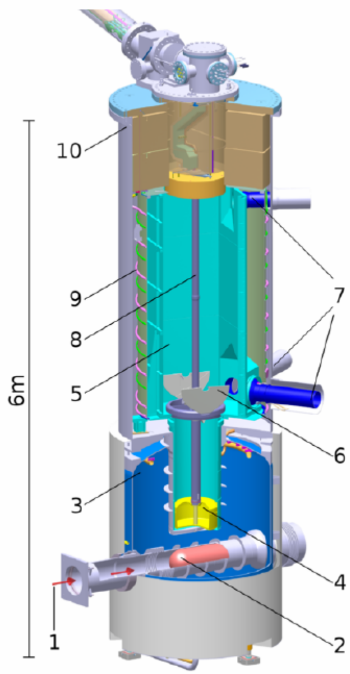
Superthermal UCN source



Paul Scherrer Institut

- **5K sD_2 UCN source**
- use of upgraded RAL/Sussex/ILL apparatus taking data
  expect reaching our limit next year
- construct new apparatus n2EDM
  should probe ω (10^{-27} e·cm) by 2020

The UCN source at PSI



1. PSI proton beam, up to 8 s pulses
2. spallation target (Pb)
3. D_2O vessel
4. 30 dm^3 solid D_2 moderator
5. ~2 m^3 source UCN storage vessel, coating: diamond-like carbon (DLC)
6. source UCN storage vessel shutter
7. UCN guides towards experiments
   - ~ 8 m long
   - coated with NiMo (85/15)
8. He and D_2 supply lines
9. thermal shield
10. vacuum tank

Original design goal: 1000 UCN/cm^3 in a typical external storage volume.

Dieter Ries (nEDM2014) PSI UCN source status November 4, 2014 2 / 22

Paul Scherrer Institut

- 5K sD_2 UCN source
- use of upgraded RAL/Sussex/ILL apparatus taking data
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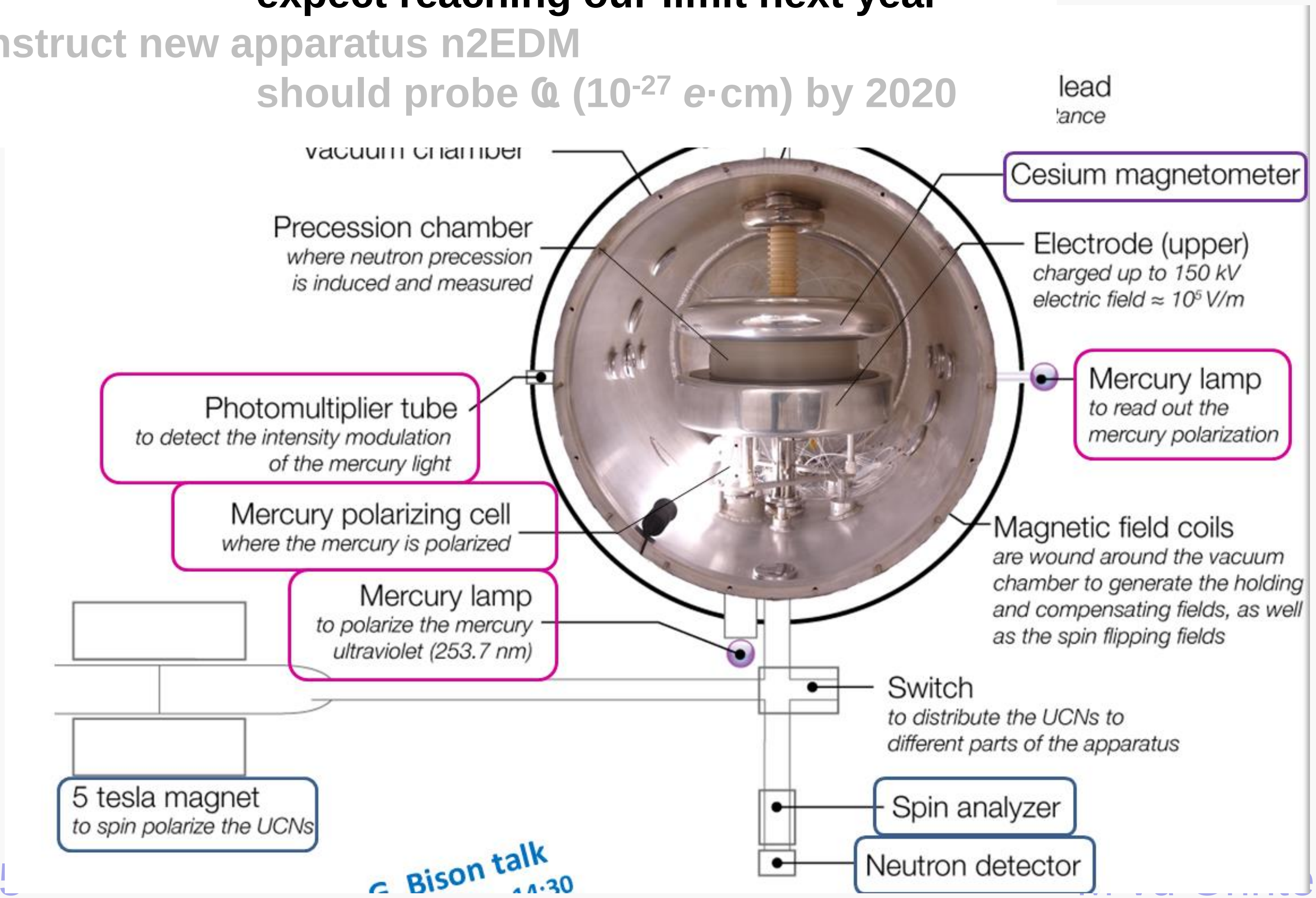
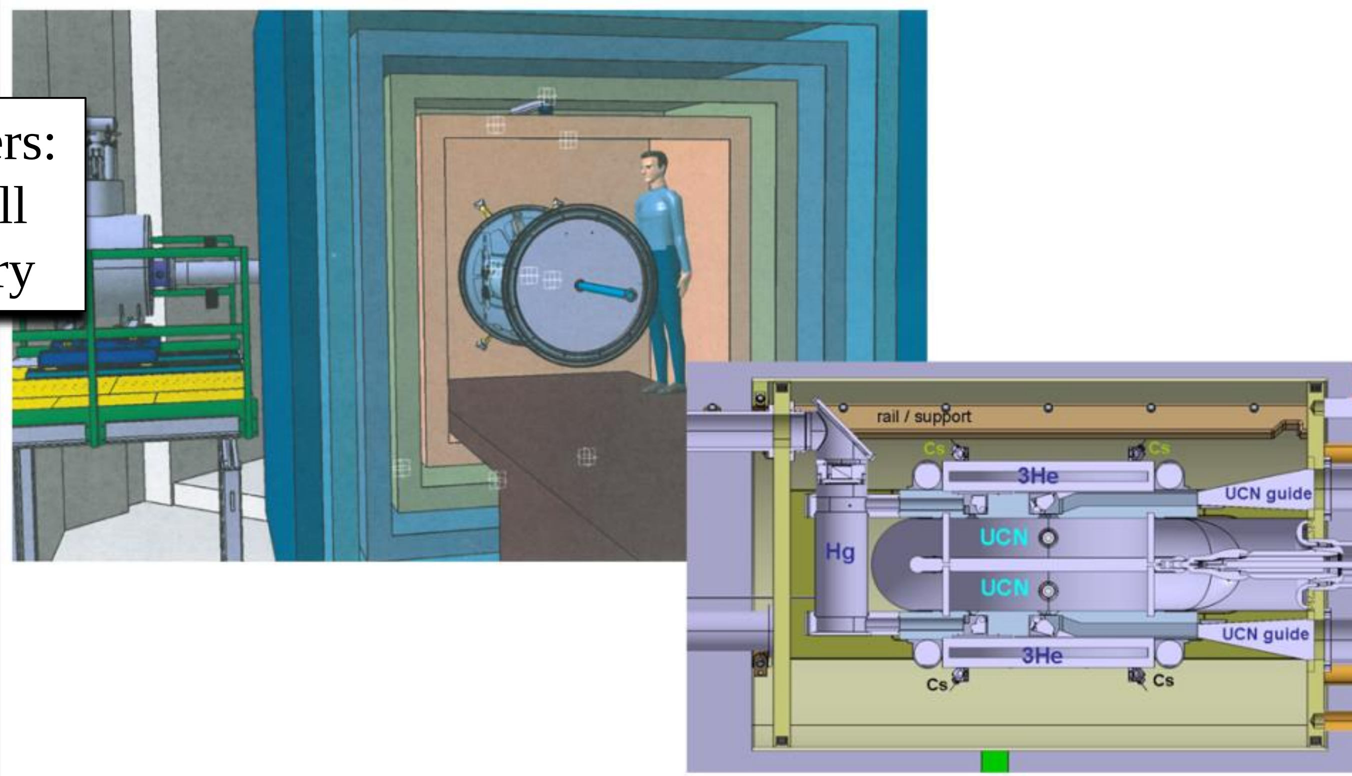
- construct new apparatus n2EDM
  should probe $\mathcal{O}$ (10^{-27} *e*·cm) by 2020



Paul Scherrer Institut

- 5K sD_2 UCN source
- use of upgraded RAL/Sussex/ILL apparatus taking data
  expect reaching our limit next year
- **construct new apparatus n2EDM**
  should probe $\mathcal{O}(10^{-27}\ e\cdot\text{cm})$ by 2020

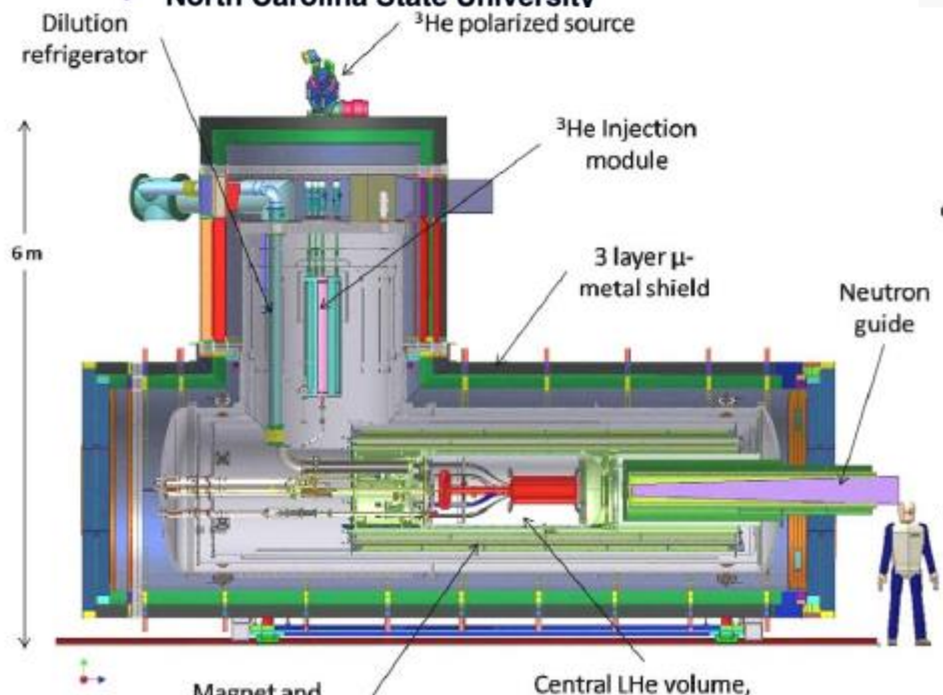
Increase UCN numbers:
- Double storage cell
- Improved geometry



nEDM: SNS

Collaborating Institutions

- Hahn-Meitner Institut, Berlin
- NIST/Gaithersburg
- Harvard
- Simon Fraser University
- Caltech
- University of Illinois
- Los Alamos National Laboratory
- Berkeley
- Duke
- Oak Ridge National Laboratory
- University of Leiden
- University of New Mexico
- North Carolina State University



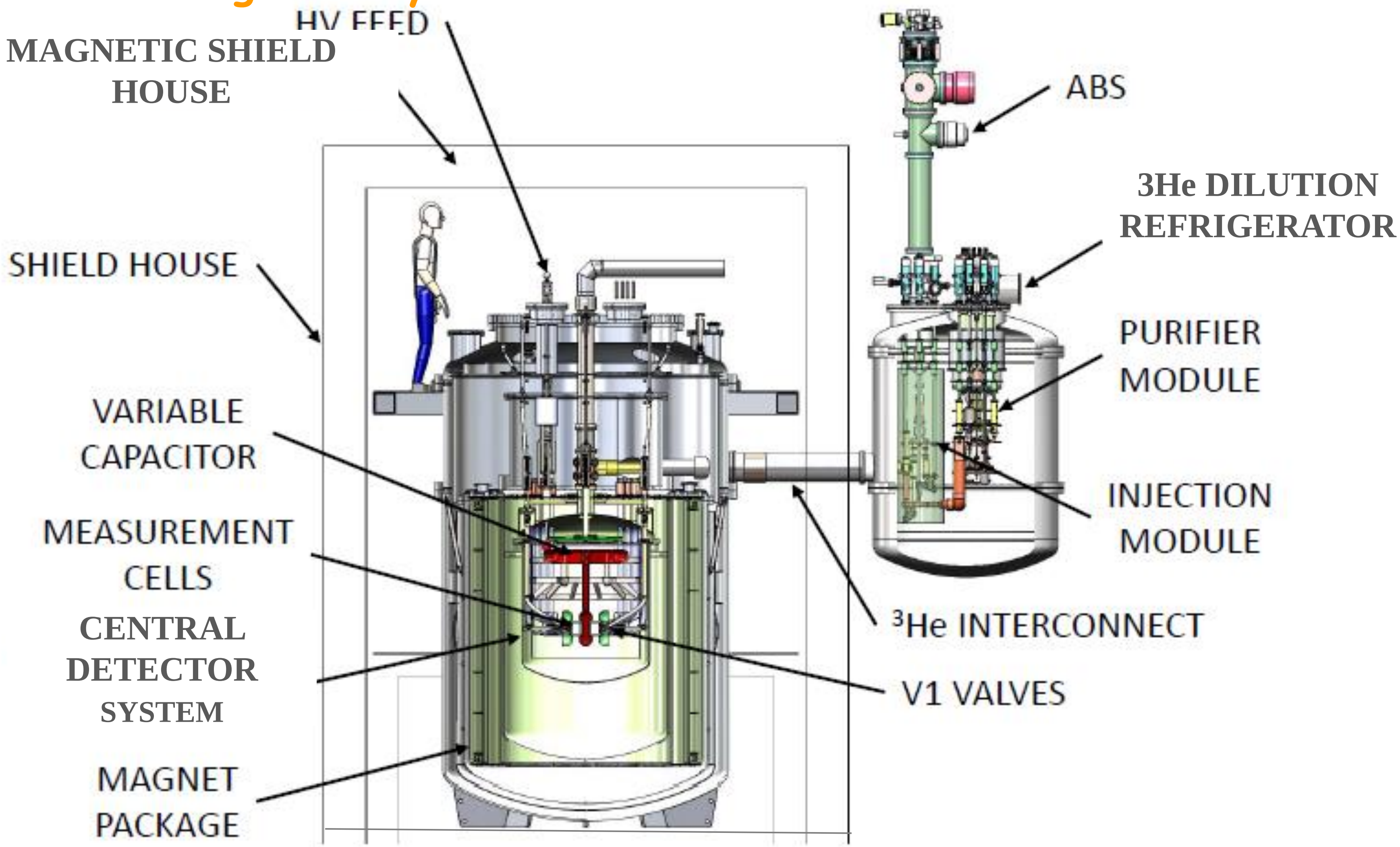
What is Unique About Our Experiment

- Production of ultracold neutrons (UCN) within the apparatus
  – *higher UCN density and longer storage times*
- Use of liquid as a high voltage insulator
  – *higher electric fields*
- Use of a ^{3}He co-magnetometer and superconducting shield
  – *better control of magnetic field systematics*
- Employ two different measurement techniques
  – *oscillation of scintillation rate and dressed spin techniques*

Tackling unknown systematic effects requires unique handles in the experiment that can be varied.

nEDM: SNS

- Key Changes in Alternatives Analysis:
  - Central Detector System & Magnets mounted Vertically
  - Separate functions into modules (Cells/HV, Magnet, ^{3}He)
  - Use Magnetically Shielded House rather than custom "skin"

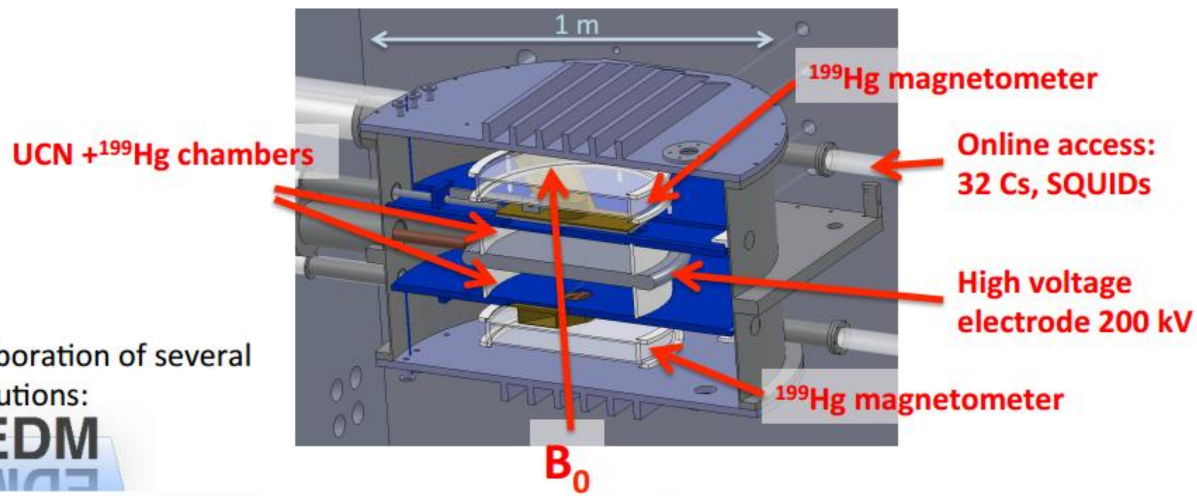


Funding & Schedule for nEDM

- 4-yr NSF proposal for CCD approved ~6.5M$
- Anticipate 4-yr DOE Funding for CCD ~7M$
- Continuation of external Technical Review Committee
- Need additional ~ 25M$ after CCD
- Could complete construction of more conventional systems after additional ~ 2 yrs
- Commissioning underway by 2019-2020

The TUM EDM experiment

- ‚Conventional' Ramsey experiment with UCN stored at room temperature
- Double chamber with co-magnetometers
- ^{199}Hg, Cs, SQUID magnetometers
- Portable setup, including magnetic shielding (demonstrated!)
- Extremely modular design
- Ready for UCN next summer

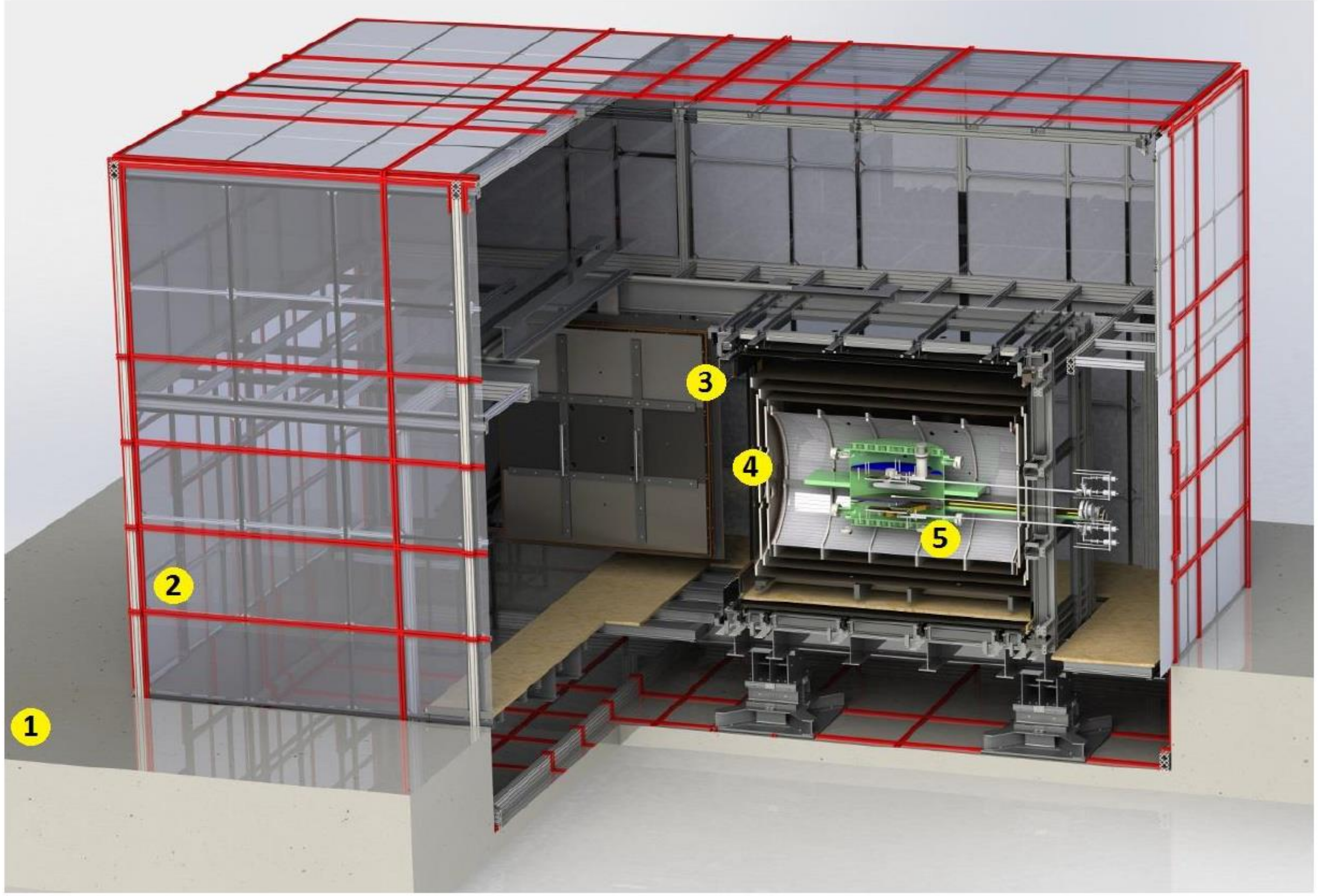


Collaboration of several institutions:

EDM

Measuring at ILL?

Magnetic shield



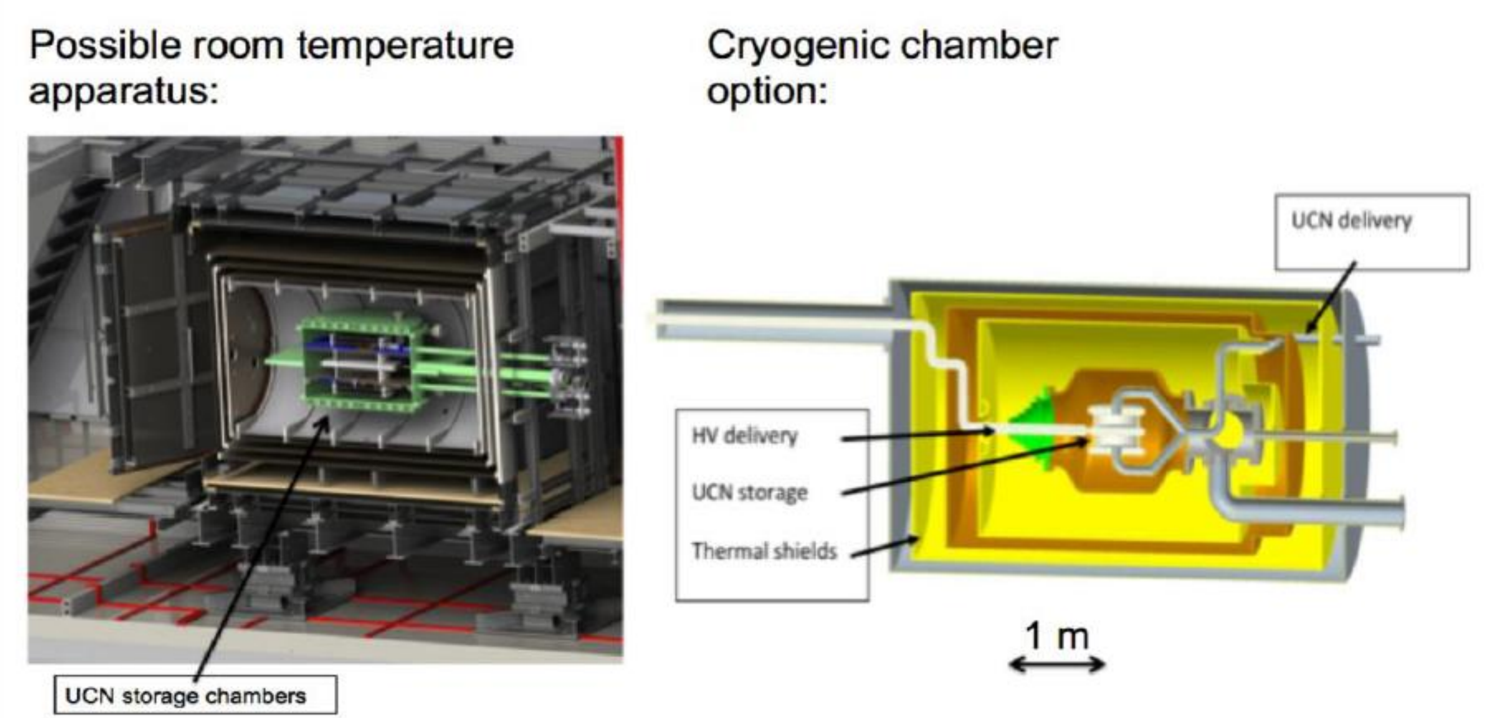


Figure 4: Left: Cut through a possible EDM measurement apparatus with UCN storage volumes at room temperature, placed inside a magnetically shielded laboratory. The conceptual layout of the UCN chambers is comparable to the experiments planned or built at Gatchina, PSI, TUM. Right: A possible cryogenic chamber as upgrade for enhancing the physics reach (design by M. v.d. Grinten et al.)

nEDM 2014

Challenges of the world-wide experimental search for the electric dipole moment of the neutron

2-6 November 2014 *Congressi Stefano Franscini*
Europe/Zurich timezone

PSI:

- Taking data with sensitivity comparable to RAL/Sussex RT expt.
- Aim to upgrade to "n2EDM" with 8 fold increase in sensitivity after 2020.

SNS

- Major overhaul in design
- Aim to be commissioning in 2020
- Sensitivity O(10^{-28} ecm ?)

TUM

- Key parts of equipment (near)ready
- No UCN
- Staged planning ILL/TUM O(10^{-27}-10^{-28} ecm)

LANL

- UCN Source operating, upgrade sought
- "Support" EDM experiment O(10^{-27})

PNPI

- RT result comparable to RAL/Sussex RT expt
- Various future prospects ILL/Russia O(10^{-27})

TRIUMF

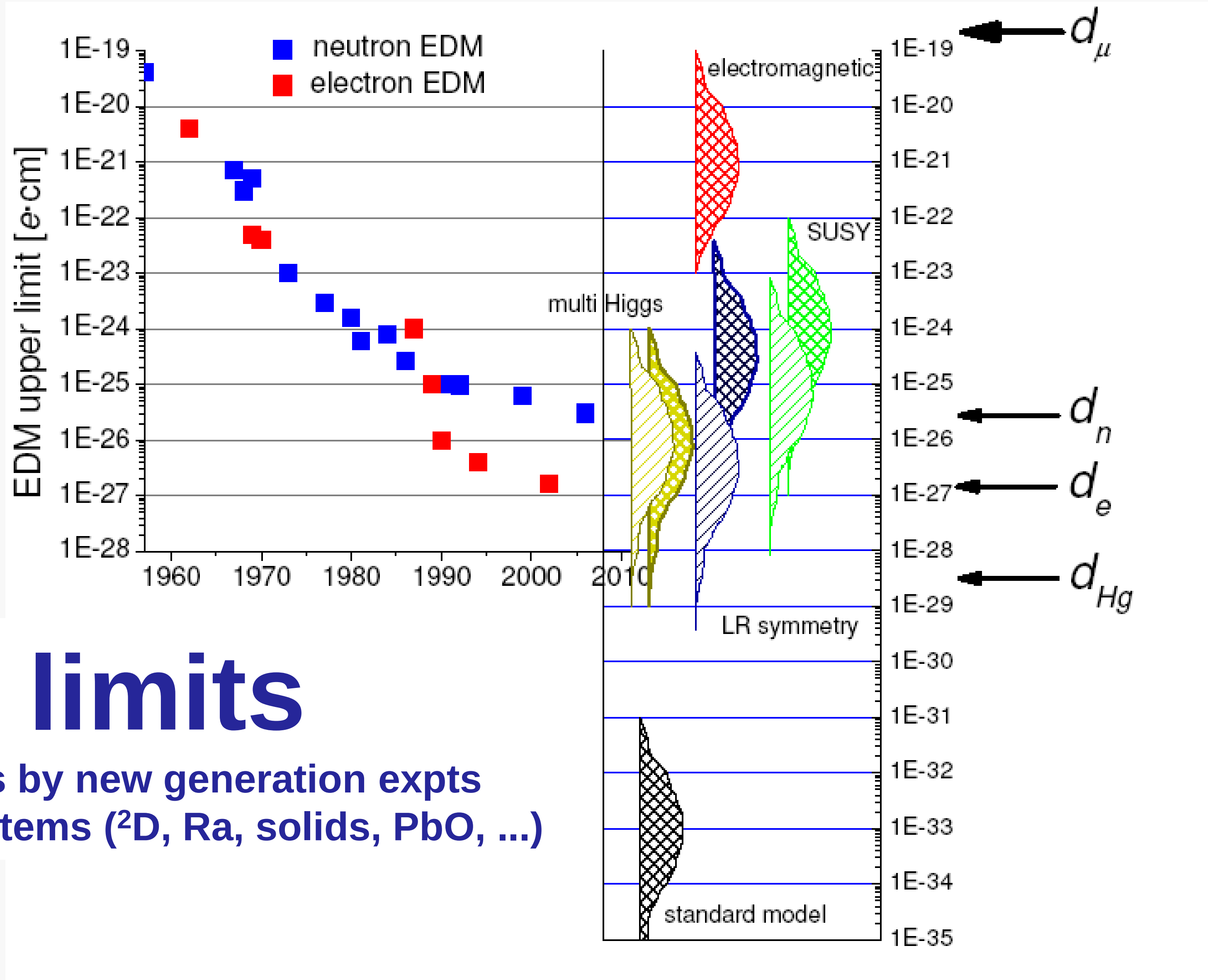
- TRIUMF beam being constructed
- UCN source to be shipped from Osaka
- EDM apparatus to be built
- EDM experiment O(10^{-27}) by 2020

Summary

- nEDM searches probing beyond SM
- World wide interest in pursuing these
- Current generation of experiments will push limits further
- Next generation experiment (2020+) put EDM discovery within reach?

Summary

The END



EDM limits

further limits by new generation expts
different systems (^{2}D, Ra, solids, PbO, ...)