EXPERIMENTAL RESULT IN EDMs

FPCP 2024
27-31.05.2024

Jacek Zejma on behalf of the nEDM collaboration at PSI

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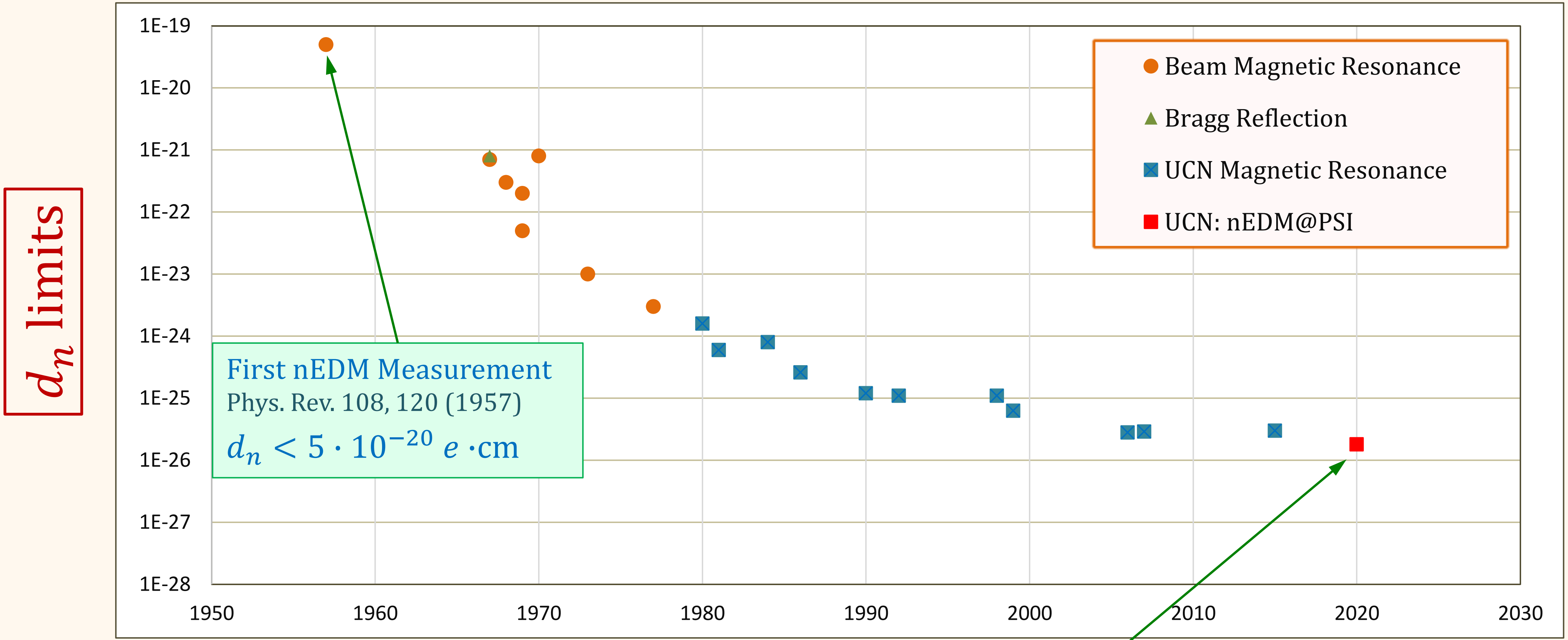
Measurements of the neutron EDM



Result of the nEDM at PSI collaboration Phys.Rev.Lett. 124, 081803 (2020)

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \cdot 10^{-26}\ e\,\cdot\mathrm{cm}$$

$$d_n < 1.8 \cdot 10^{-26}\ e\,\cdot\mathrm{cm}\ (90\%\ \mathrm{C.L.})$$

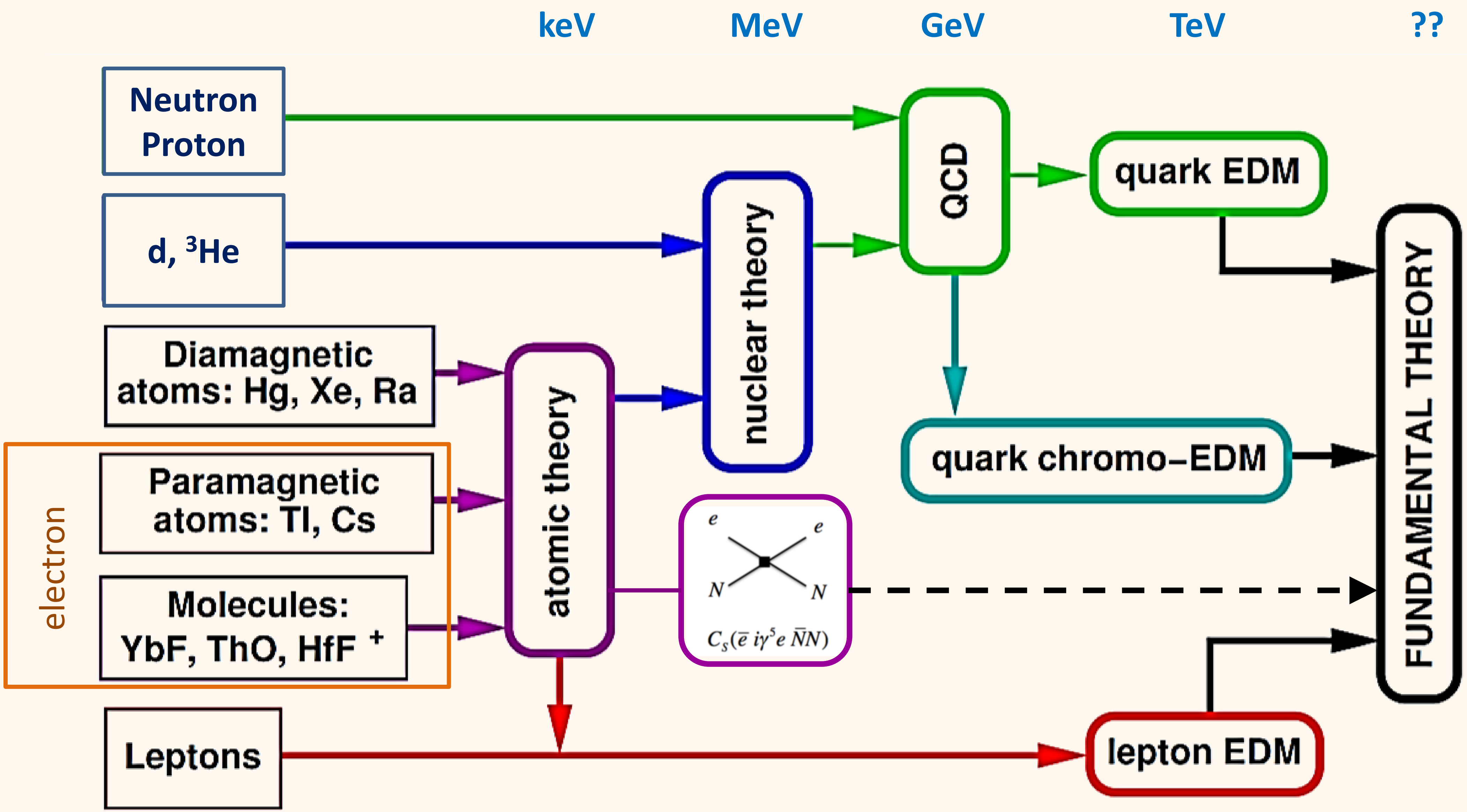
67 years of history - all results are consistent with zero.
Why such stubbornness in measuring the neutron Electric Dipole Moment?

- The non-zero value of Electric Dipole Moment (EDM) will be evidence for the existence of $\mathcal{CP}$ violating processes.

  Electric Dipole Moments of elementary particles are the most sensitive probes in searching for $\mathcal{CP}$ symmetry violating processes.

  This is true only in case of particles or systems of particles, which ground state is not degenerated. Degenerated states (water molecule) can be treated as mirror-image forms of the same object → Parity symmetry is not violated.
- Our Universe is made of matter, not antimatter – both, baryon number and $\mathcal{CP}$ symmetry must be violated – both types of processes must occur outside thermal equilibrium (A. Sacharov postulates).
- EDM - Investigated objects:
  - Neutron – value measured since 1957
  - Electron
  - ^{199}Hg
  - Proton
  - ^{129}Xe
  - Muon
  - Taon

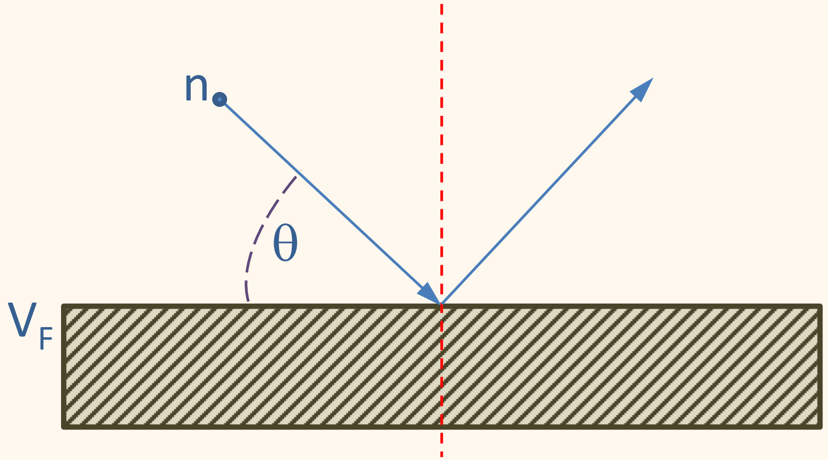
https://www.psi.ch/en/nedm/edms-world-wide


keV
MeV
GeV
TeV
??
Neutron
Proton
d, ³He
Diamagnetic atoms: Hg, Xe, Ra
Paramagnetic atoms: Tl, Cs
Molecules: YbF, ThO, HfF +
electron
Leptons
atomic theory
nuclear theory
QCD
quark EDM
quark chromo–EDM
lepton EDM
FUNDAMENTAL THEORY
e
e
N
N
$C_S(\bar{e}\, i\gamma^5 e\, \bar{N}N)$

Why neutron EDM is particularly interesting?

- Neutron – weak and strong interactions are present
- Nuclear interaction is not present
- Neutron is electrically neutral

- Slow neutrons interact with the Fermi potential of the surface and reflect if $\sin\theta < \sqrt{\frac{V_F}{E_n}}$



If neutron kinetic energy $E_n < V_F$ it always reflects and can be stored in closed vessels. For some materials V_F can reach 250 neV.

Neutrons with energies $E_n < 250$ neV are called “ultracold neutrons.”

Neutrons are stored in (anti-)parallel magnetic and electric fields.

Hamiltonian for neutron in both $\vec{B}$ and $\vec{E}$ fields: $H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$

Spin precession because of acting torque: $\frac{d\vec{J}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$

Frequency of Larmor precession of neutron spin:

$$f_n^+ = \frac{2}{h}(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow}), \text{ if } \vec{B} \uparrow\uparrow \vec{E}.$$

$$f_n^- = \frac{2}{h}(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow}), \text{ if } \vec{B} \uparrow\downarrow \vec{E}.$$

$$\Delta f_n = \frac{2}{h} d_n (E_{\uparrow\uparrow} + E_{\uparrow\downarrow}) + \frac{2}{h} \mu_n (B_{\uparrow\uparrow} - B_{\uparrow\downarrow})$$

$$d_n = \frac{h \Delta f_n}{4E}, \text{ if } E = E_{\uparrow\uparrow} = E_{\uparrow\downarrow} \text{ and } \boldsymbol{B}_{\uparrow\uparrow} = \boldsymbol{B}_{\uparrow\downarrow}.$$

$$\sigma_{d_n} \sim 10^{-27} e \cdot \mathrm{cm} \Longrightarrow \frac{\Delta f_n}{f_n} \sim 3 \cdot 10^{-10} \text{ przy } E = 10 \frac{\mathrm{kV}}{\mathrm{cm}}.$$

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The assumption that the magnetic field value is constant is not fulfilled - we have to measure the field and limit its variations as much as possible.

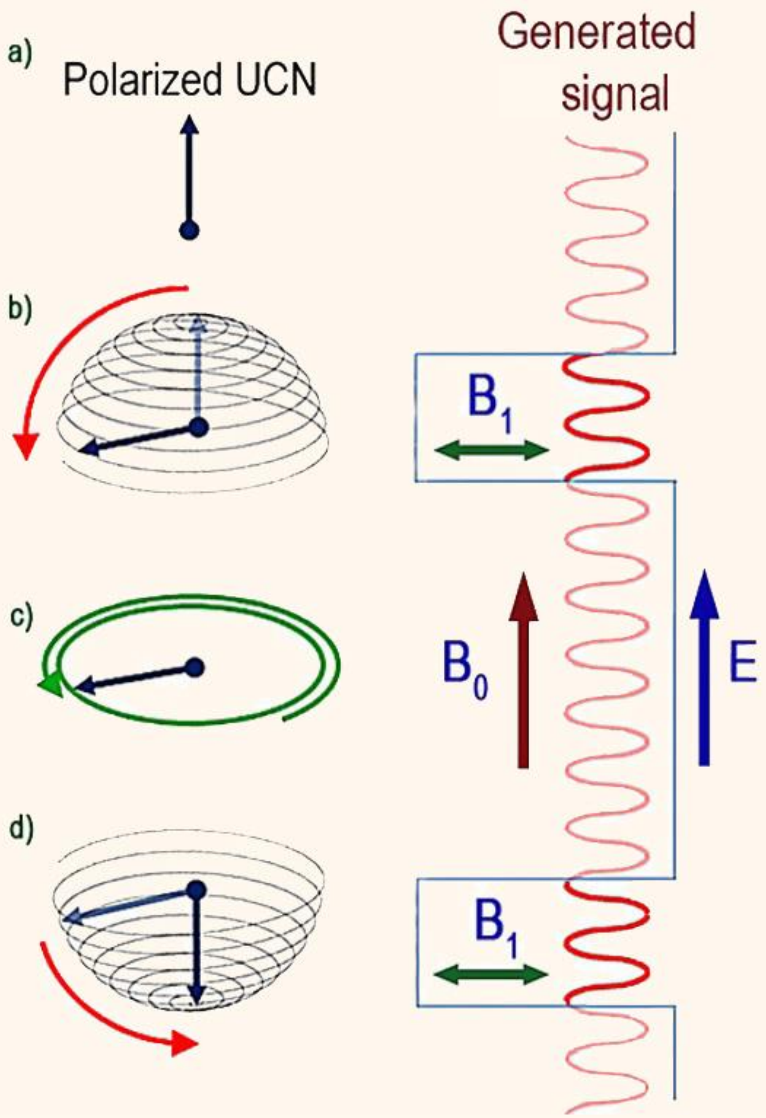
$$d_n = \frac{1}{4E}[h\Delta f_n - \mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})].$$

Most important sources of interferences:

- External devices in the experimental hall.
- Local magnetization of apparatus elements – unperfect homogeneity of the magnetic field.
- Unperfect shape of the magnetic field.

Magnetic field control is crucial to the success of this measurement

Ramsey method of separated oscillating fields



Sample of **polarized neutrons**
parallel $\vec{B}$ (1 μT) i $\vec{E}$ (12 kV/cm) fields.

2s-long pulse of rotating magnetic with $f_{LF} = f_L$ ($\approx$ 30Hz).
Spin rotation by $\pi/2$ to horizontal plane.

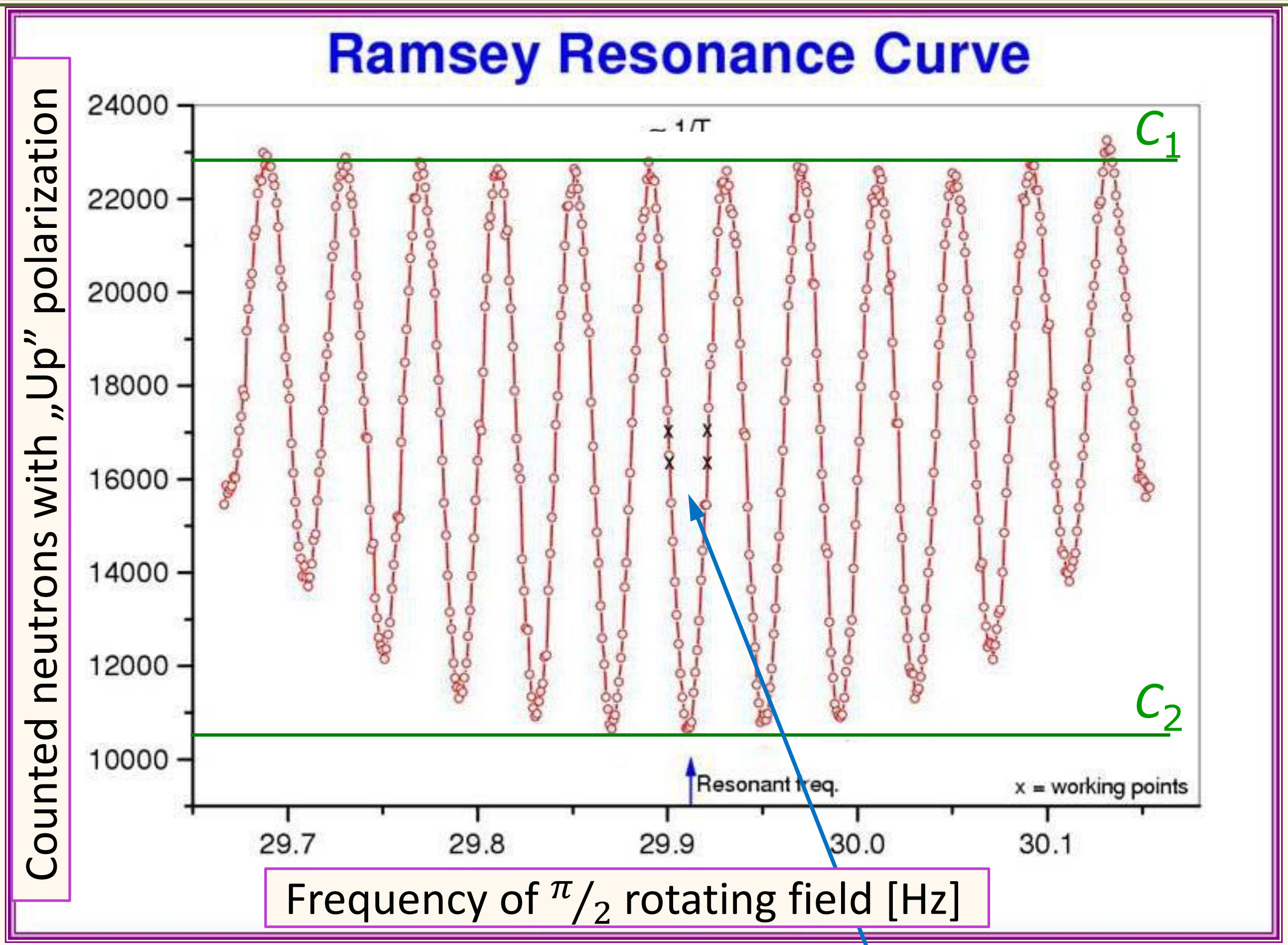
Free precession of neutron spin by about 180 s.
$\vec{B} \uparrow\uparrow \vec{E}$ **or** $\vec{B} \uparrow\downarrow \vec{E}$.

Second 2s-long pulse.
Rotation of spin $\pi/2$ to vertical if d_n=0.

Neutron polarization analysis.

Neutron visibility parameter

$$\alpha = \frac{C_1 - C_2}{C_1 + C_2}$$



4 working points

Paul Scherrer Institut, Villigen, Switzerland

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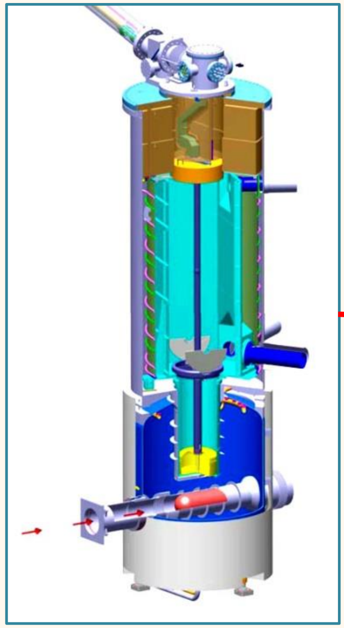
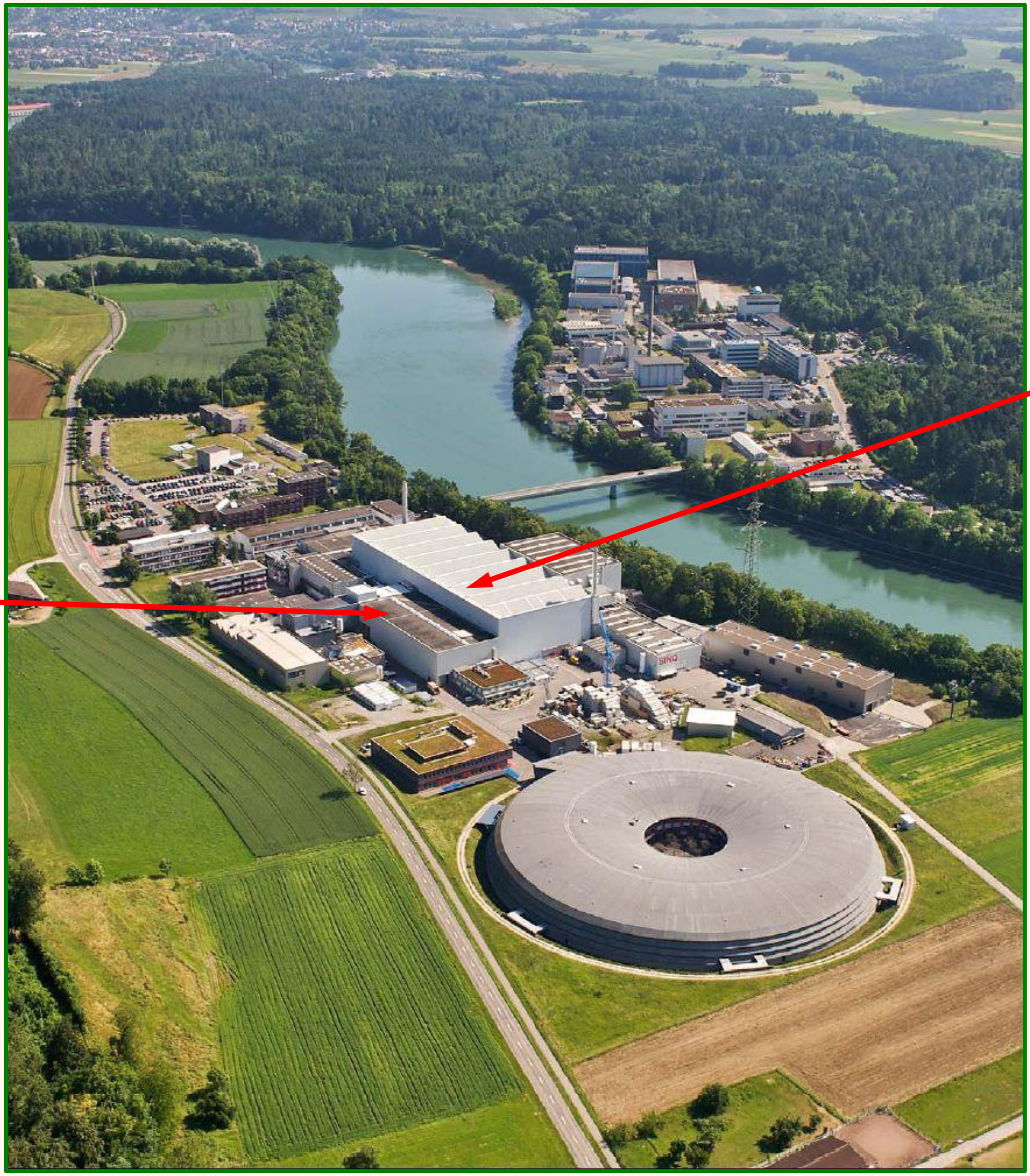
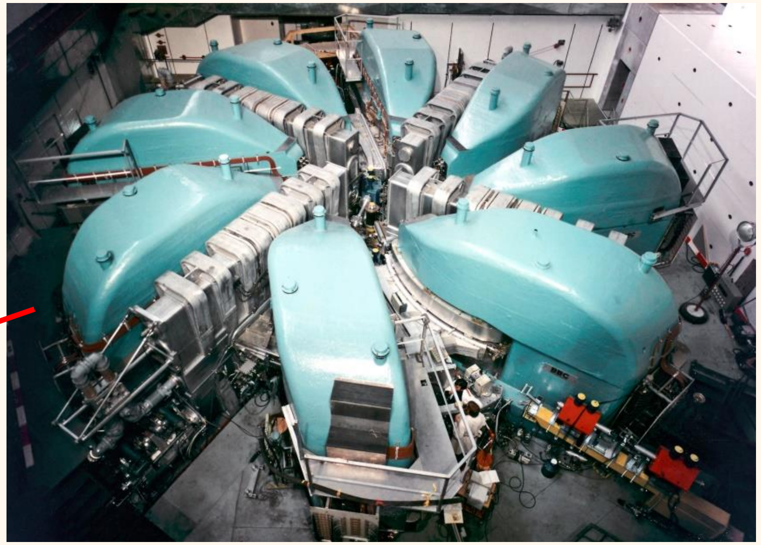


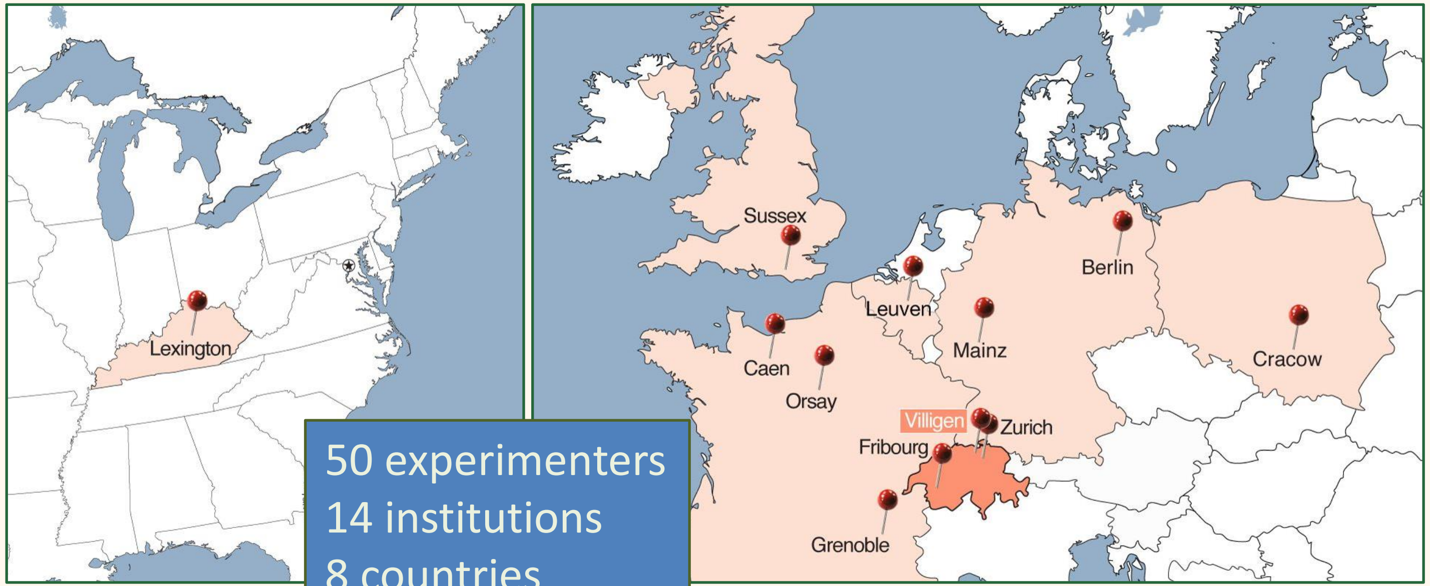
UCN source





Ring cyklotron

$E_p = 590\ \mathrm{MeV}, I = 2.2\ \mathrm{mA}$



50 experimenters
14 institutions
8 countries

nEDM Collaboration

University of Belgrade, ***Belgrade***

Physikalisch Technische Bundesanstalt, ***Berlin***

Universität Bern, ***Bern***

University of Sussex, ***Brighton***

Laboratoire de Physique Corpusculaire, ***Caen***

Institute of Physics, Jagiellonian University, ***Cracow***

Département de physique, Université de Fribourg, ***Fribourg***

Laboratoire de Physique Subatomique et de Cosmologie, ***Grenoble***

Katholieke Universiteit, ***Leuven***

University of Kentucky, ***Lexington***

Inst. für Physik, Johannes-Gutenberg-Universität, ***Mainz***

Inst. für Kernchemie, Johannes-Gutenberg-Universität, ***Mainz***

Paul Scherrer Institut, ***Villigen***

Eidgenössische Technische Hochschule, ***Zürich***

also at: [1]*Paul Scherrer Institut*, [2]*Eidgenössische Technische Hochschule*

PHYSICAL REVIEW LETTERS **124**, 081803 (2020)

Editors' Suggestion | Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

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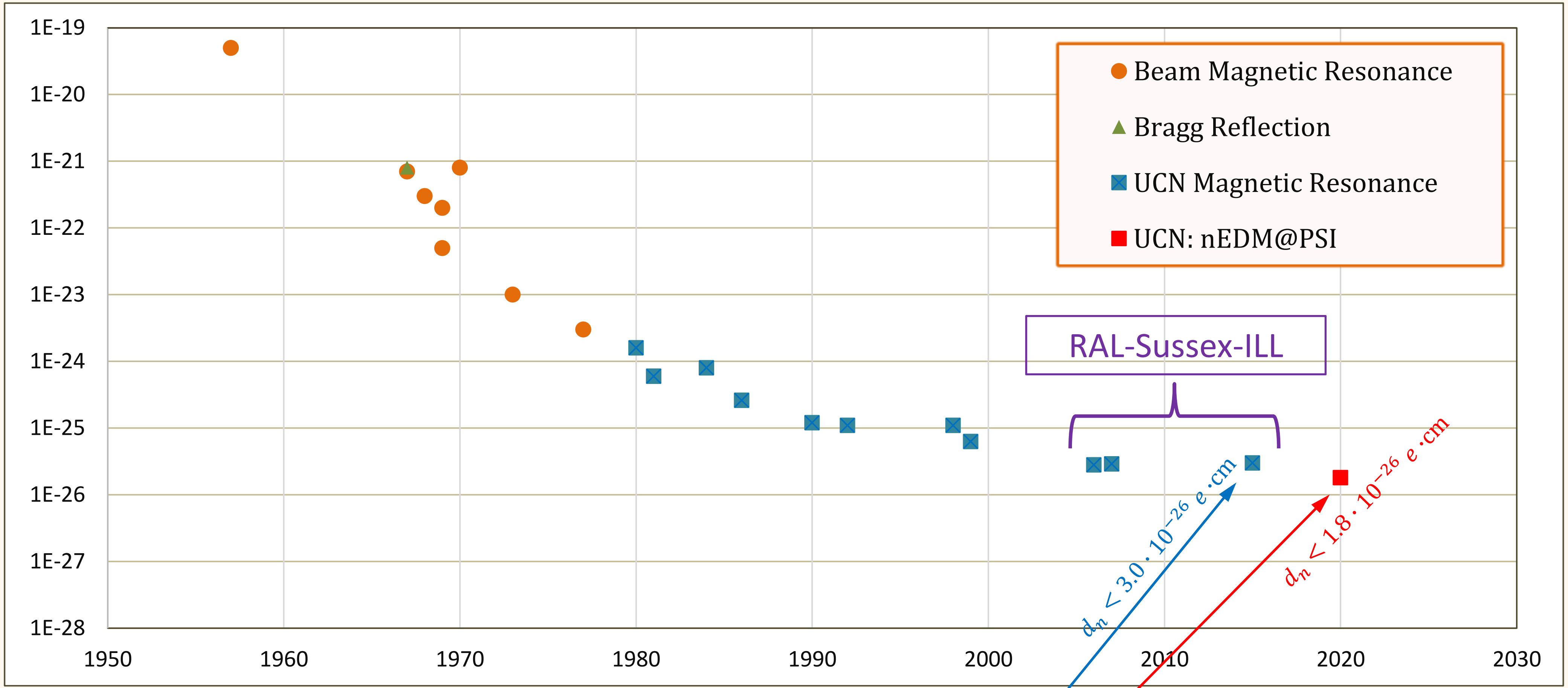
18 Institutions
8 Countries
84 Authors
34 PhD degrees

Measurements of the neutron EDM

d_n limits

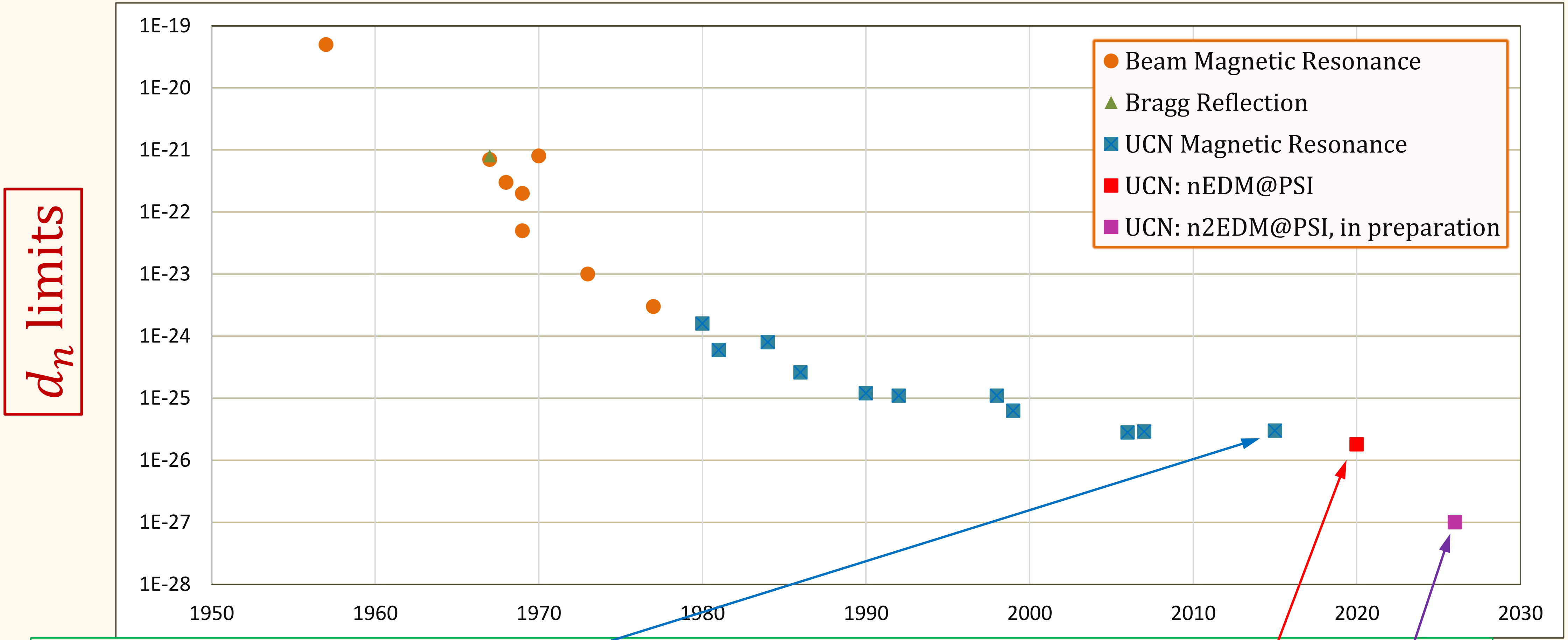


RAL-Sussex-ILL $d_n = (-0.2 \pm 1.5_{\mathrm{stat}} \pm 1.0_{\mathrm{sys}}) \cdot 10^{-26}\ e \cdot \mathrm{cm}$

nEDM at PSI $d_n = (\ 0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \cdot 10^{-26}\ e \cdot \mathrm{cm}$

Fivefold reduction of systematic uncertainties.

Measurements of the neutron EDM

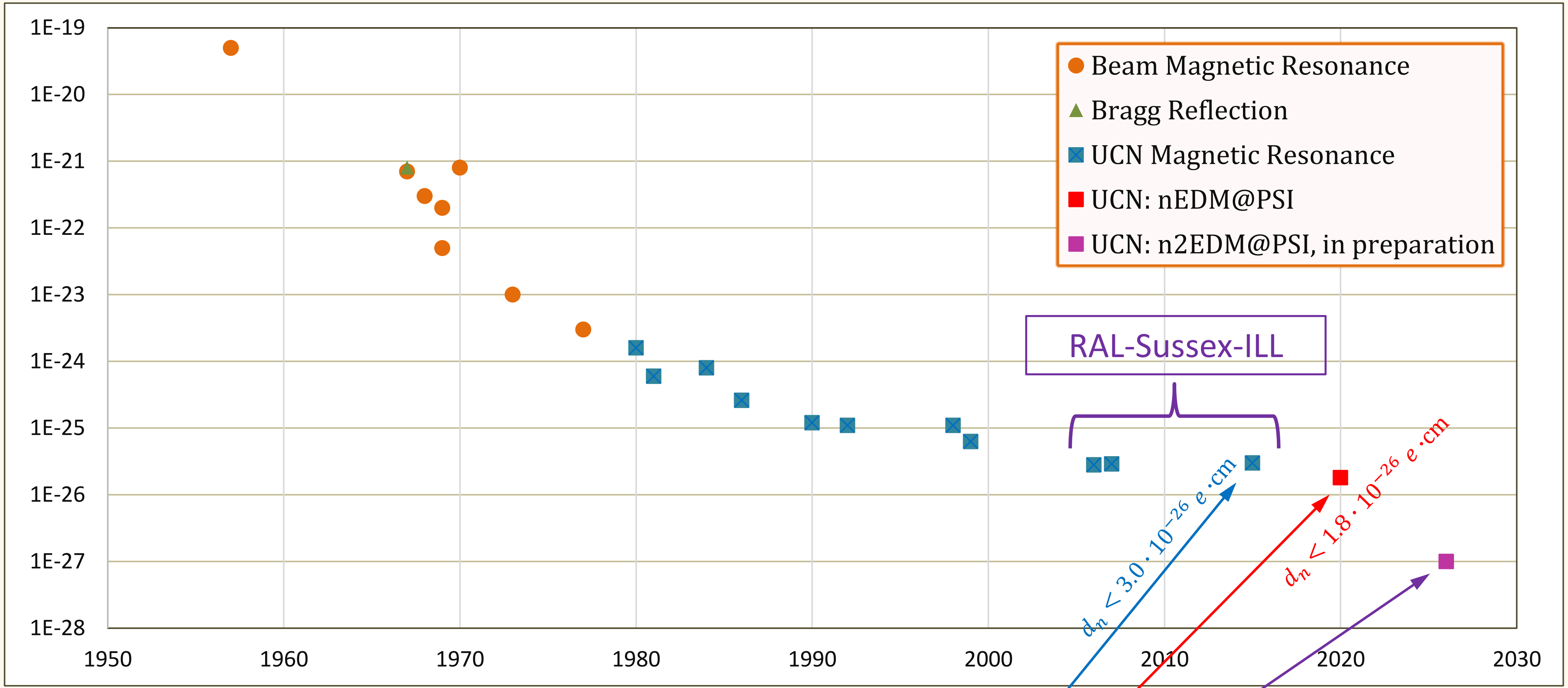


Development scheme:

1. Take the RAL-Sussex-ILL apparatus, upgrade everything but vacuum chamber and passive magnetic shield and add new systems – result published in 2020.
2. Build a completely new apparatus on base of achieved experience – expected future limit.

Measurements of the neutron EDM

d_n limits



RAL-Sussex-ILL $d_n = \left(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{sys}}\right) \cdot 10^{-26}\ e \cdot$cm

nEDM at PSI $d_n = \left(\ 0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}\right) \cdot 10^{-26}\ e \cdot$cm

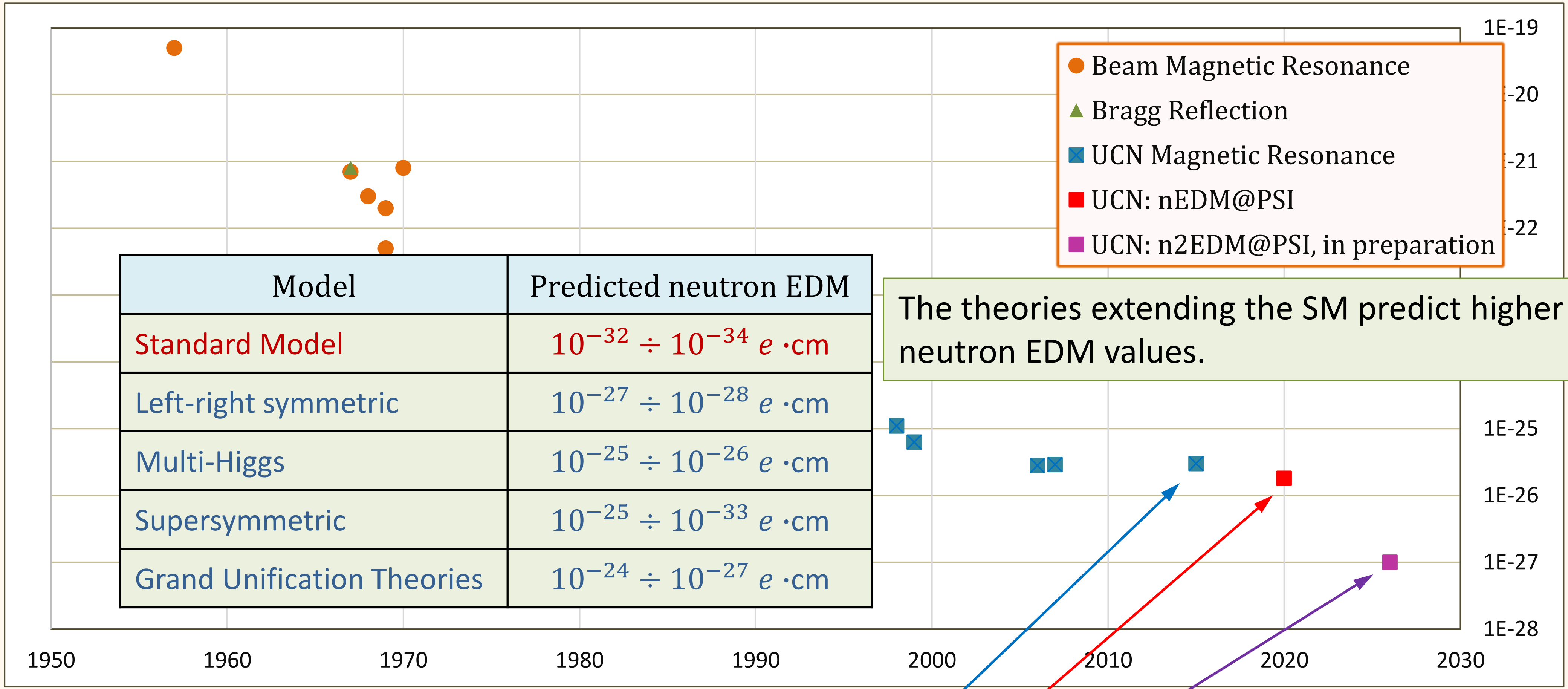
n2EDM at PSI, in preparation $d_n < 1 \cdot 10^{-27}\ e \cdot$cm

Fivefold reduction of systematic uncertainties.

Further reduction of systematic uncert.
Significant reduction of statistical uncert.

Measurements of the neutron EDM

d_n limits



Model	Predicted neutron EDM
Standard Model	$10^{-32} \div 10^{-34}\ e\cdot\mathrm{cm}$
Left-right symmetric	$10^{-27} \div 10^{-28}\ e\cdot\mathrm{cm}$
Multi-Higgs	$10^{-25} \div 10^{-26}\ e\cdot\mathrm{cm}$
Supersymmetric	$10^{-25} \div 10^{-33}\ e\cdot\mathrm{cm}$
Grand Unification Theories	$10^{-24} \div 10^{-27}\ e\cdot\mathrm{cm}$

The theories extending the SM predict higher neutron EDM values.

RAL-Sussex-ILL $d_n < 3.0 \cdot 10^{-26}\ e\cdot\mathrm{cm}$

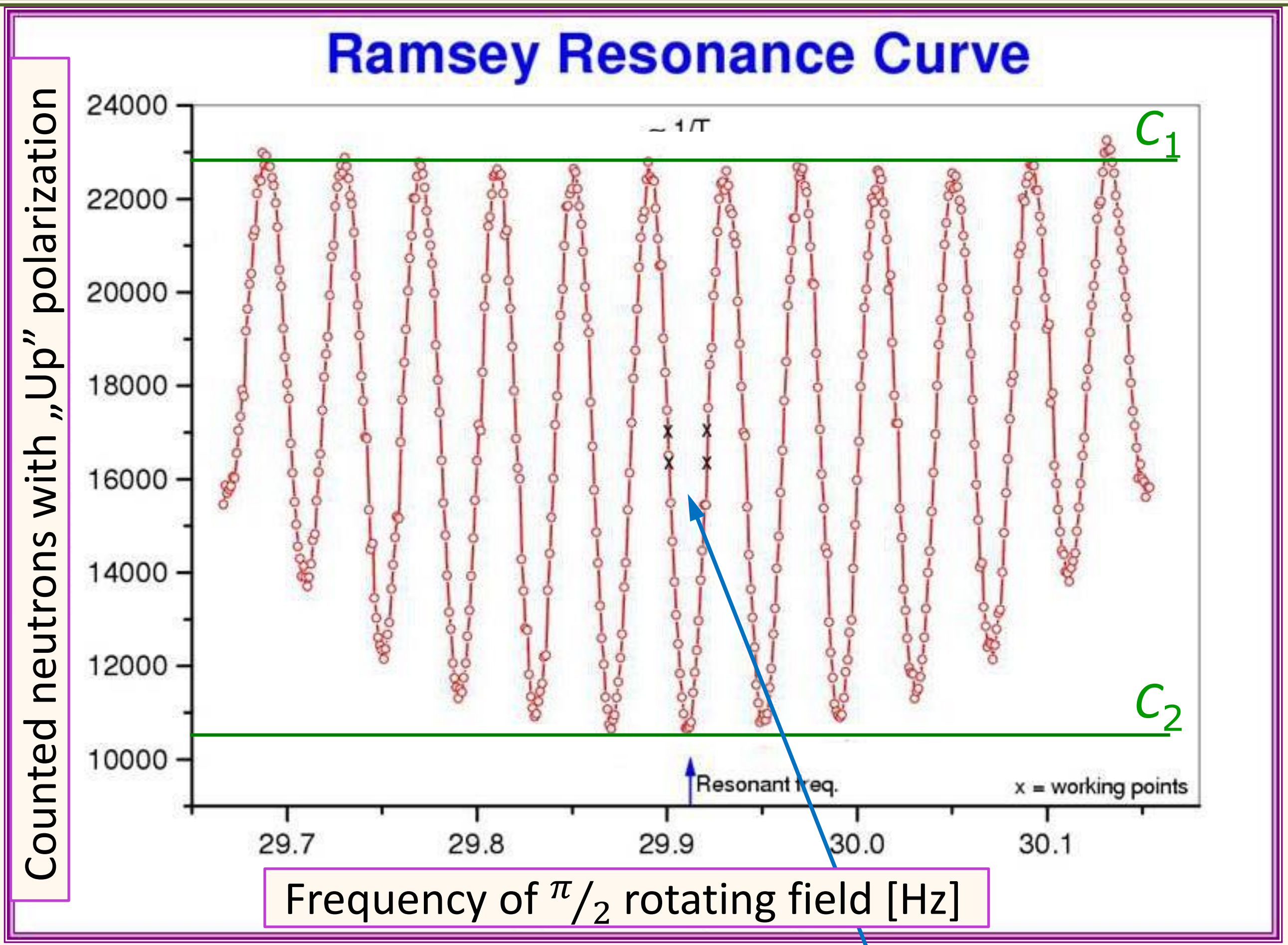
nEDM at PSI $d_n < 1.8 \cdot 10^{-26}\ e\cdot\mathrm{cm}$

n2EDM at PSI, in preparation $d_n \approx 1 \cdot 10^{-27}\ e\cdot\mathrm{cm}$

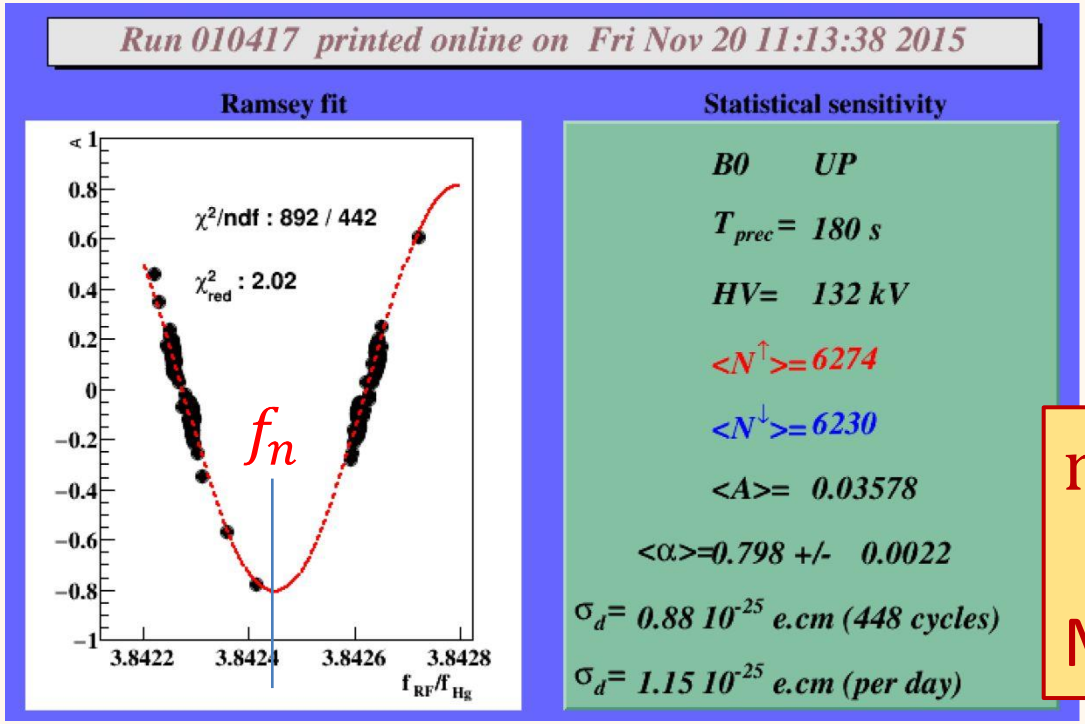
Neutron visibility parameter

$$\alpha = \frac{C_1 - C_2}{C_1 + C_2}$$

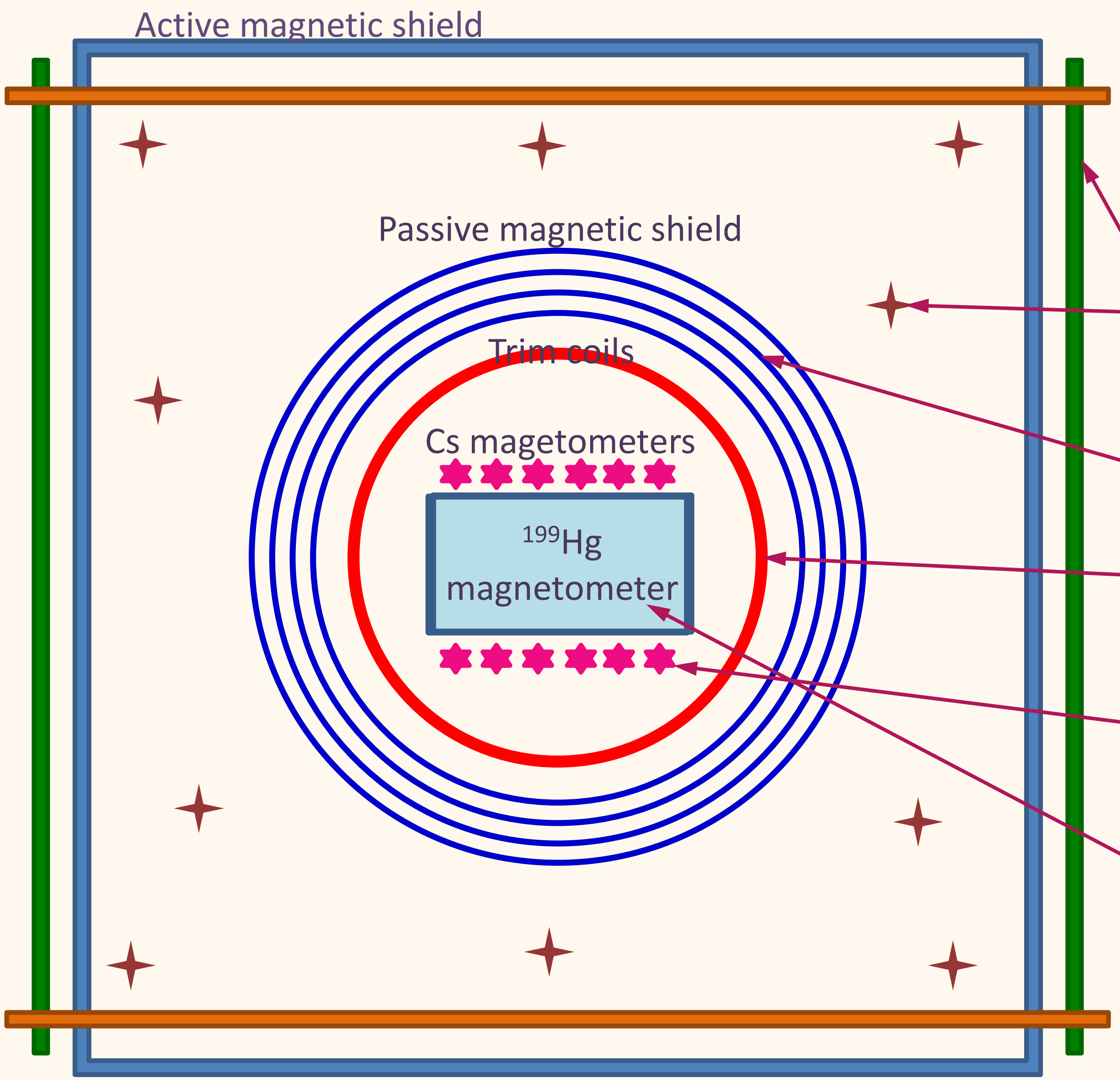
Max w RAL-Sussex-ILL $\alpha = 0.55$



4 working points



nEDM@PSI
$\Leftarrow \alpha \cong 0.8$
Mean value 0.76



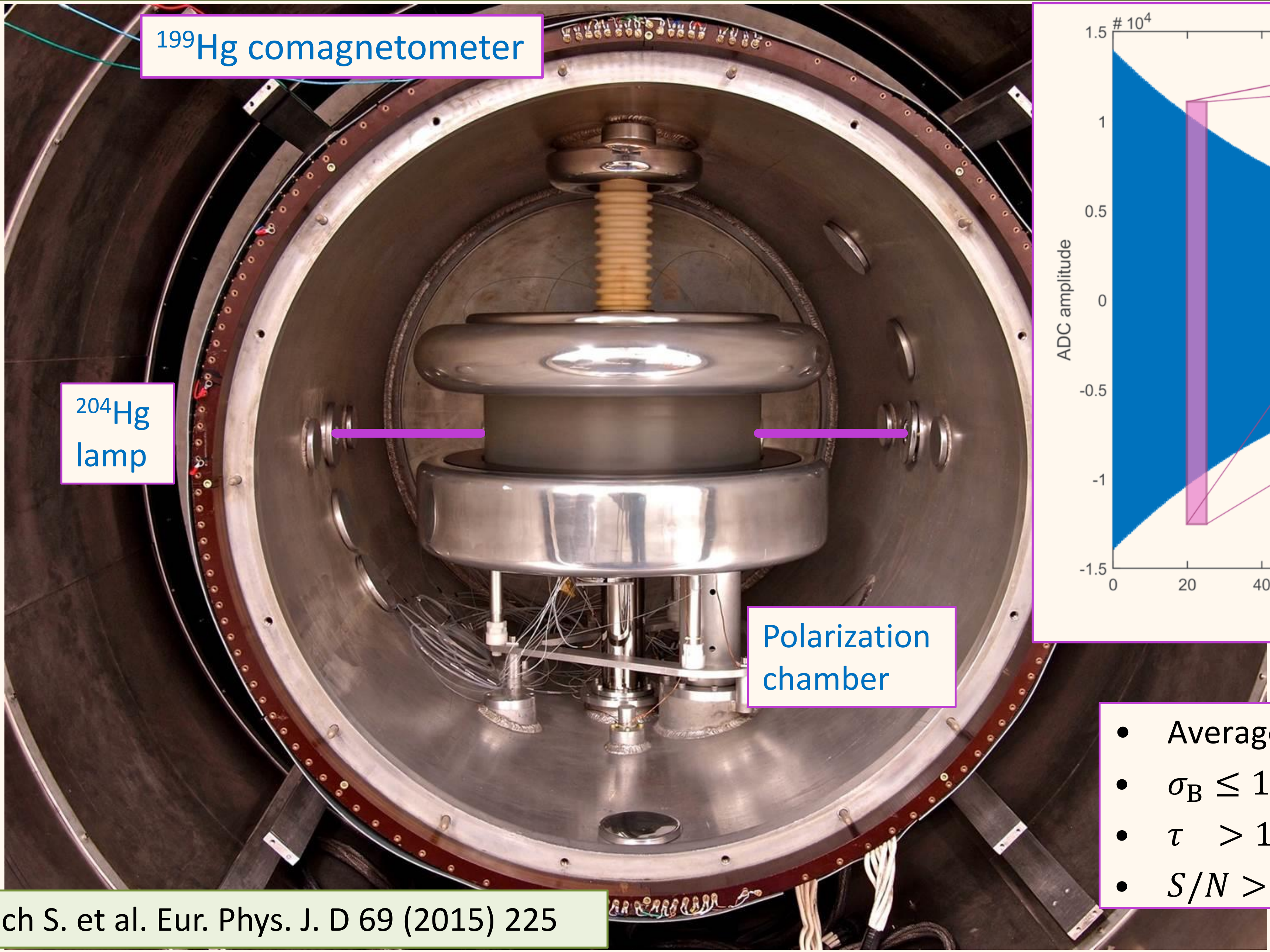
Control of the magnetic field is essential for this measurement

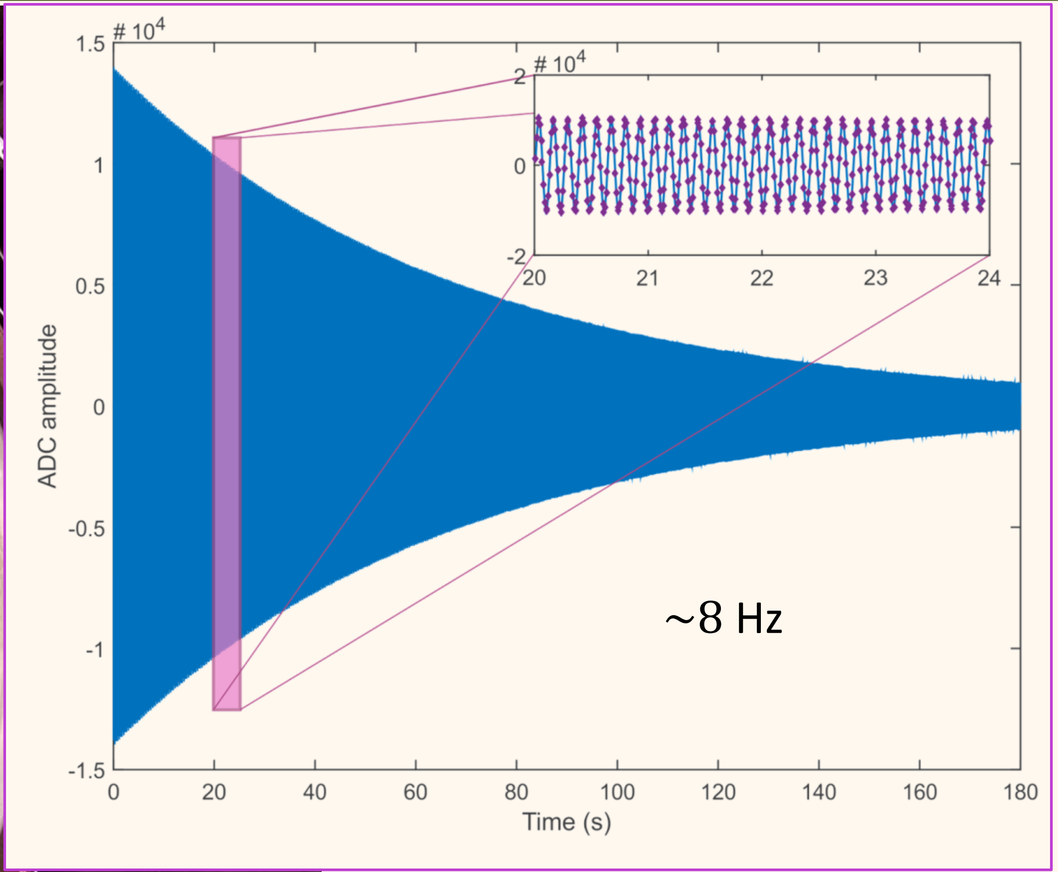
Magnetic filed control and measurement

- 6 coils (x-y-z) and 10 magnetometers for active compensation of changes of the external magnetic field.
- 4 layers of μ-metal for passive magnetic shielding – regularly degaussed.
- 32 trim coils for compensation of local field inhomogeneities and setting UCN polarization holding field.
- 16 cesium magnetometers located above and below storage volume and measuring the magnetic field gradients.
- ^{199}Hg comagnetometer measuring the field inside the storage volume.

Two-level thermo-house

- Top: spectrometer $\Delta T = 0.1°C$.
- Bottom: control room, vacuum system, neutron detector $\Delta T = 1°C$.





- Average magnetic field (volume and cycle)
- $\sigma_{\mathrm{B}} \leq 100$ fT (CR-limit)
- $\tau \quad > 100$ s wo HV (with ~ 90 s)
- $S/N > 1000$

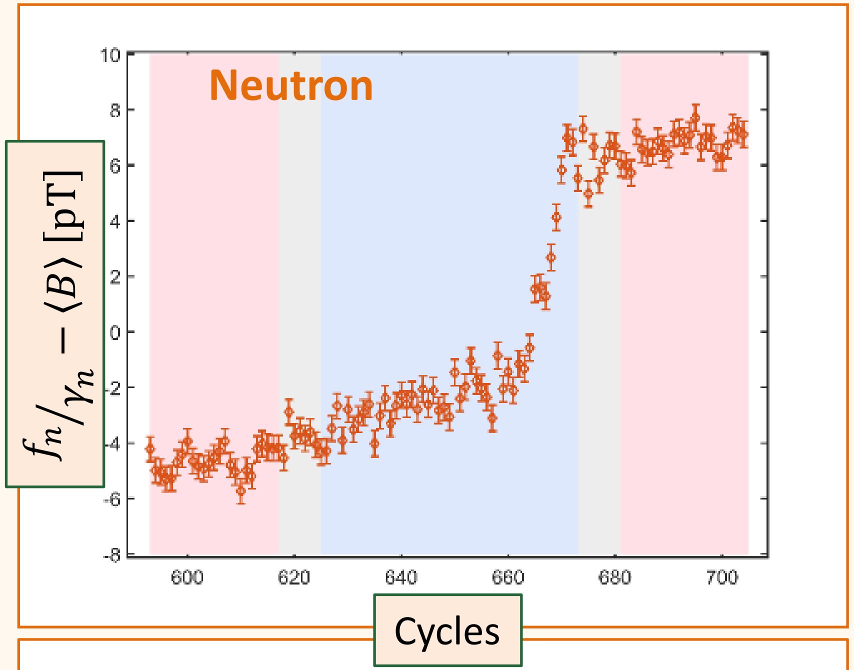
Afach S. et al. Eur. Phys. J. D 69 (2015) 225

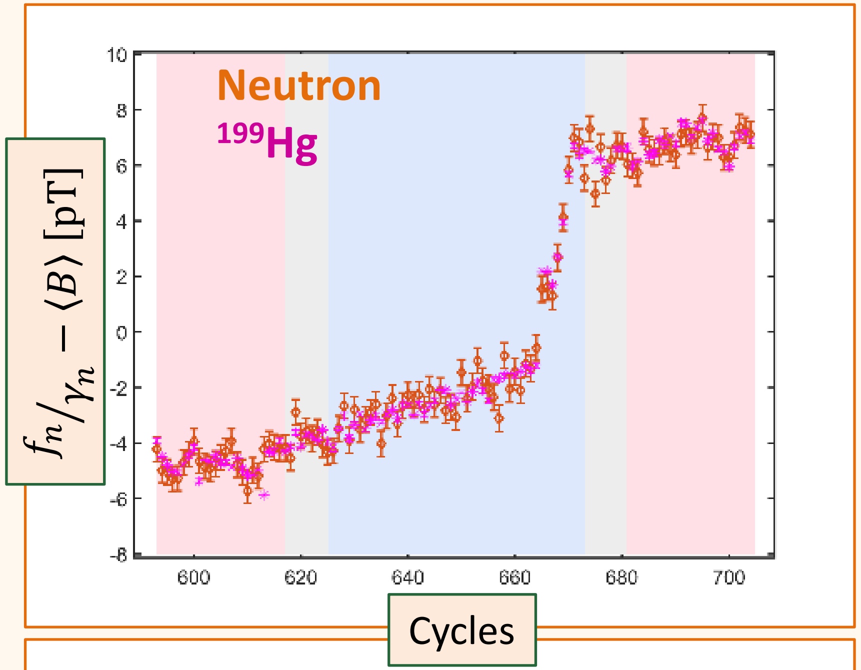
Data analysis

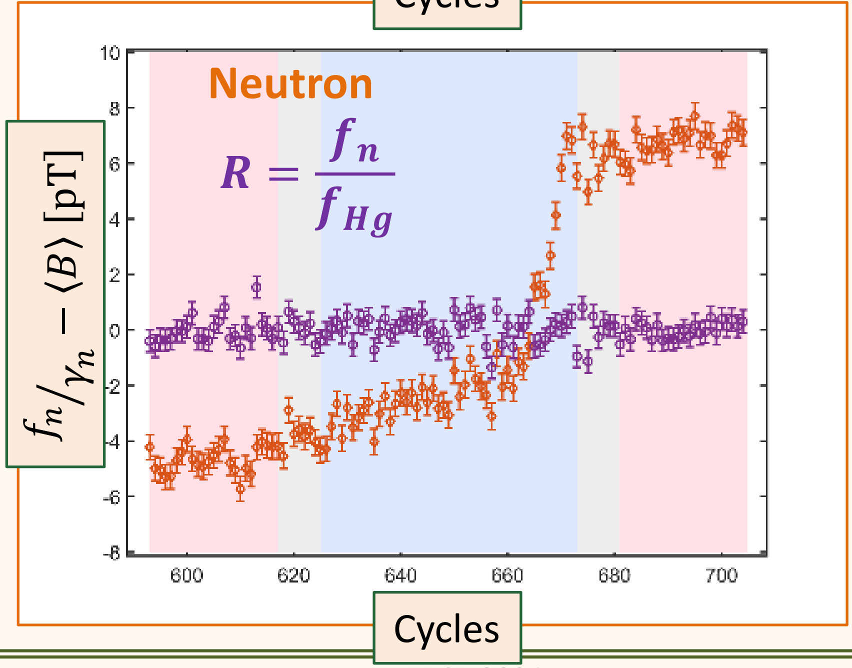
$$d_n = \frac{1}{4E}\left[h\Delta f_n - \mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})\right].$$

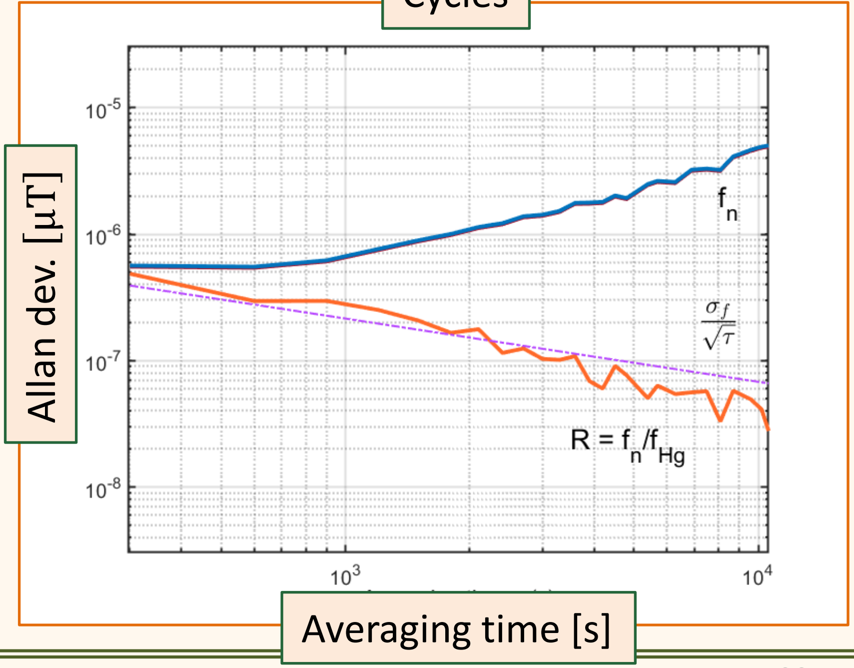
Control of the magnetic field is essential for the experiment success.

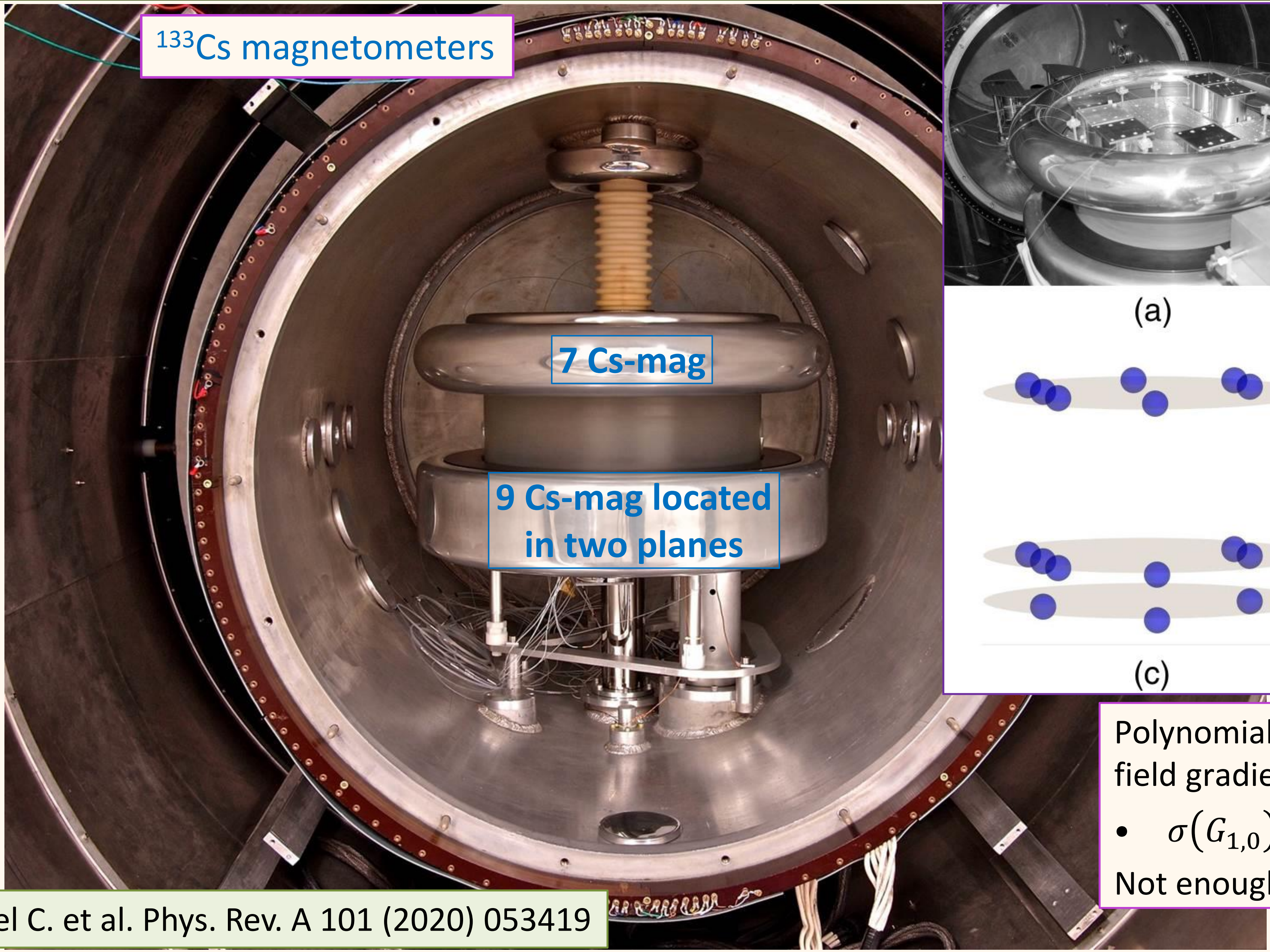
The ratio of frequencies of neutrons and mercury atoms $R = \frac{f_n}{f_{Hg}}$ was used to compensate magnetic field fluctuations.

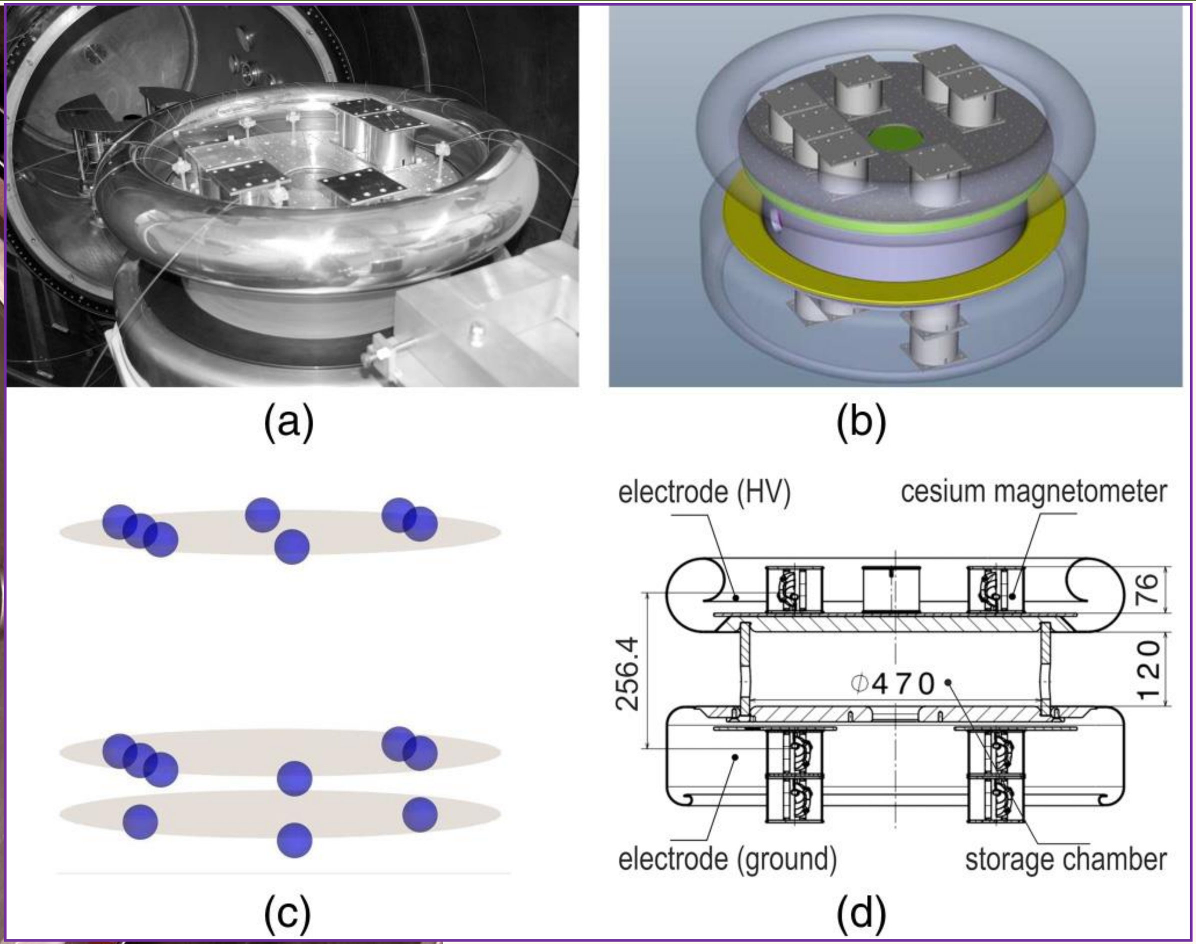












Polynomial decomposition used to calculate field gradients.

- $\sigma(G_{1,0}) \sim 8\ \mathrm{pT/cm}$

Not enough to correct systematic.

Abel C. et al. Phys. Rev. A 101 (2020) 053419

Statistical uncertainty

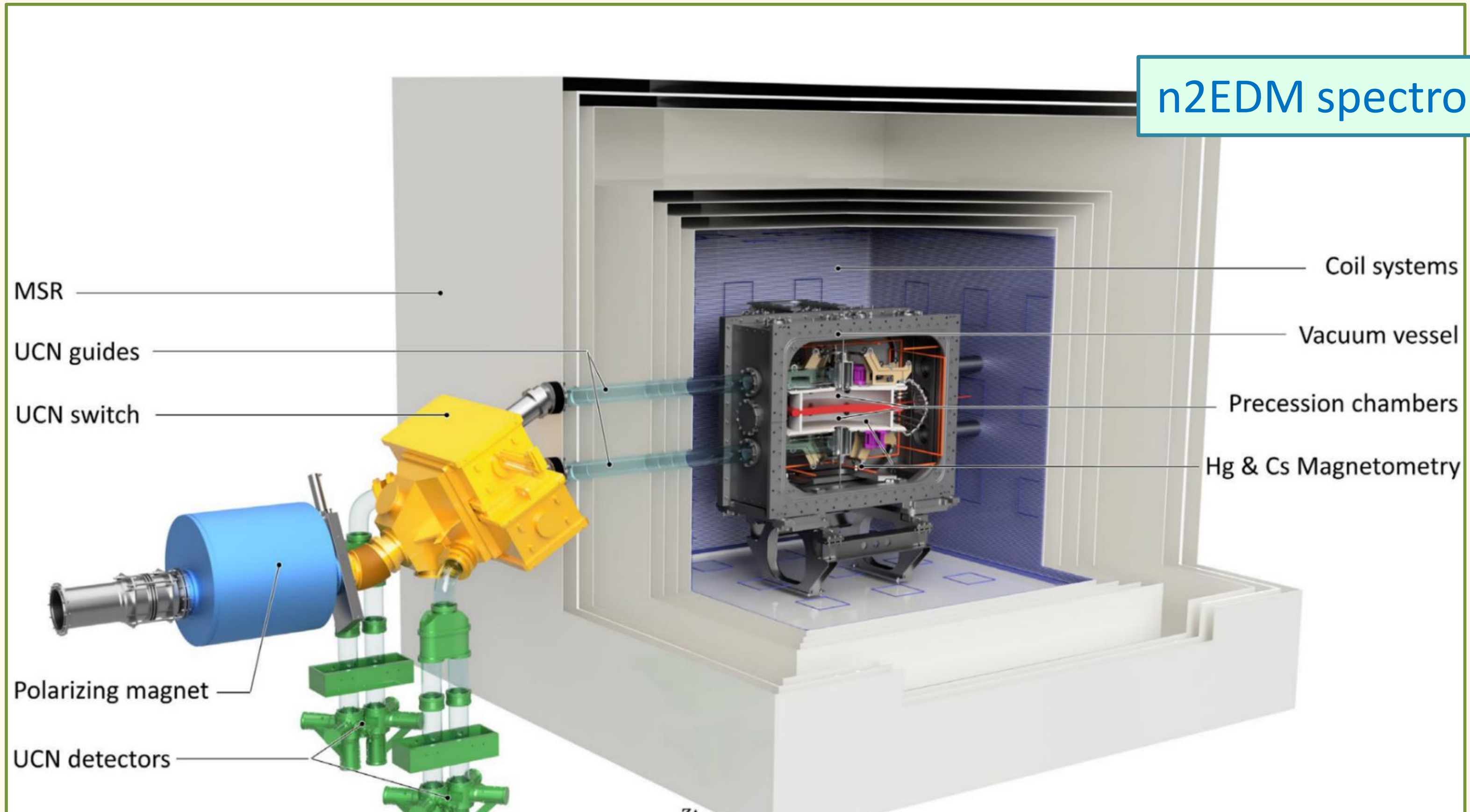
RAL-Sussex-ILL $d_n = (-0.2 \pm 1.5_{stat} \pm 1.0_{sys}) \cdot 10^{-26}\ e \cdot \mathrm{cm}$

nEDM at PSI $d_n = (\ 0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \cdot 10^{-26}\ e \cdot \mathrm{cm}$

n2EDM at PSI, in preparation $d_n \approx 1 \cdot 10^{-27}\ e \cdot \mathrm{cm}$

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

	nEDM single chamber	n2EDM double chamber
α – neutron visibility parameter	0.76	0.80
E – electric field strength	11 kV/cm	15 kV/cm
T – free precession time	180 s	180 s
N – number of counted neutrons	15 000/cycle	121 000/cycle
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm
$\sigma(d_n)$ total	9.5×10^{-27} e cm	1.1×10^{-27} e cm



n2EDM spectrometer

	nEDM	n2EDM
Precession chamber diameter	1 chamber: ϕ47 cm, H = 11 cm	2 chambers: ϕ80 cm, H = 12 cm
Passive magnetic shield	4 layers (10^3-10^4 factor), ϕ2 m	6 layers (10^5 factor), L = 5 m
Active magnetic shield	3 coils	8 coils
Cesium magnetometers	16	112

This ratio is affected by various systematic effects

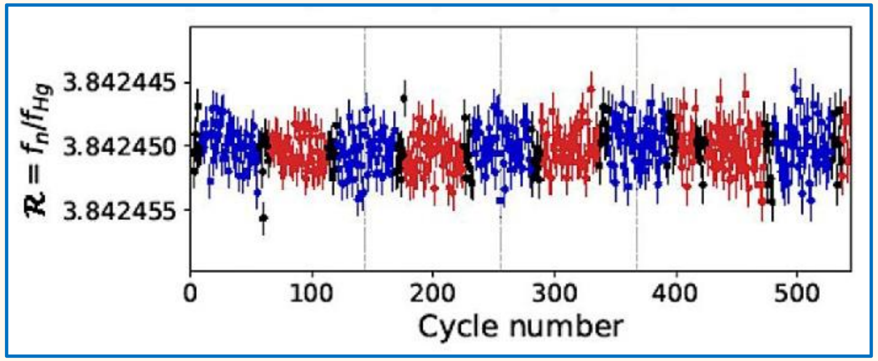
$$R = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| \left(1 + \delta_\mathrm{EDM}^\mathrm{true} \mp \frac{G_z \Delta h}{B_0} + \frac{\langle B_T^2 \rangle}{2B_0^2} + \cdots \right),$$

where

G_z - vertical component of the magnetic field gradient

$\Delta h \approx 3.5$ mm - difference between centers of mass of Hg and UCN clouds.

$\langle B_T^2 \rangle$ - mean square of the transversal component of the field



G_z is extracted from cesium magnetometers.

For other field components the field mapping procedure was performed several times (during cyclotron shutdowns).

Effect	Shift (x10^{-28} e cm)	Error (x10^{-28} e cm)
Error on $\langle z \rangle$	···	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	–0.1	0.1
Local dipole fields	···	4
$v \times E$ UCN net motion	···	2
Quadratic $v \times E$	···	0.1
Uncompensated G drift	···	7.5
Mercury light shift	···	0.4
Inc. scattering ^{199}Hg	···	7
TOTAL	69	18

Dedicated mapping measurements

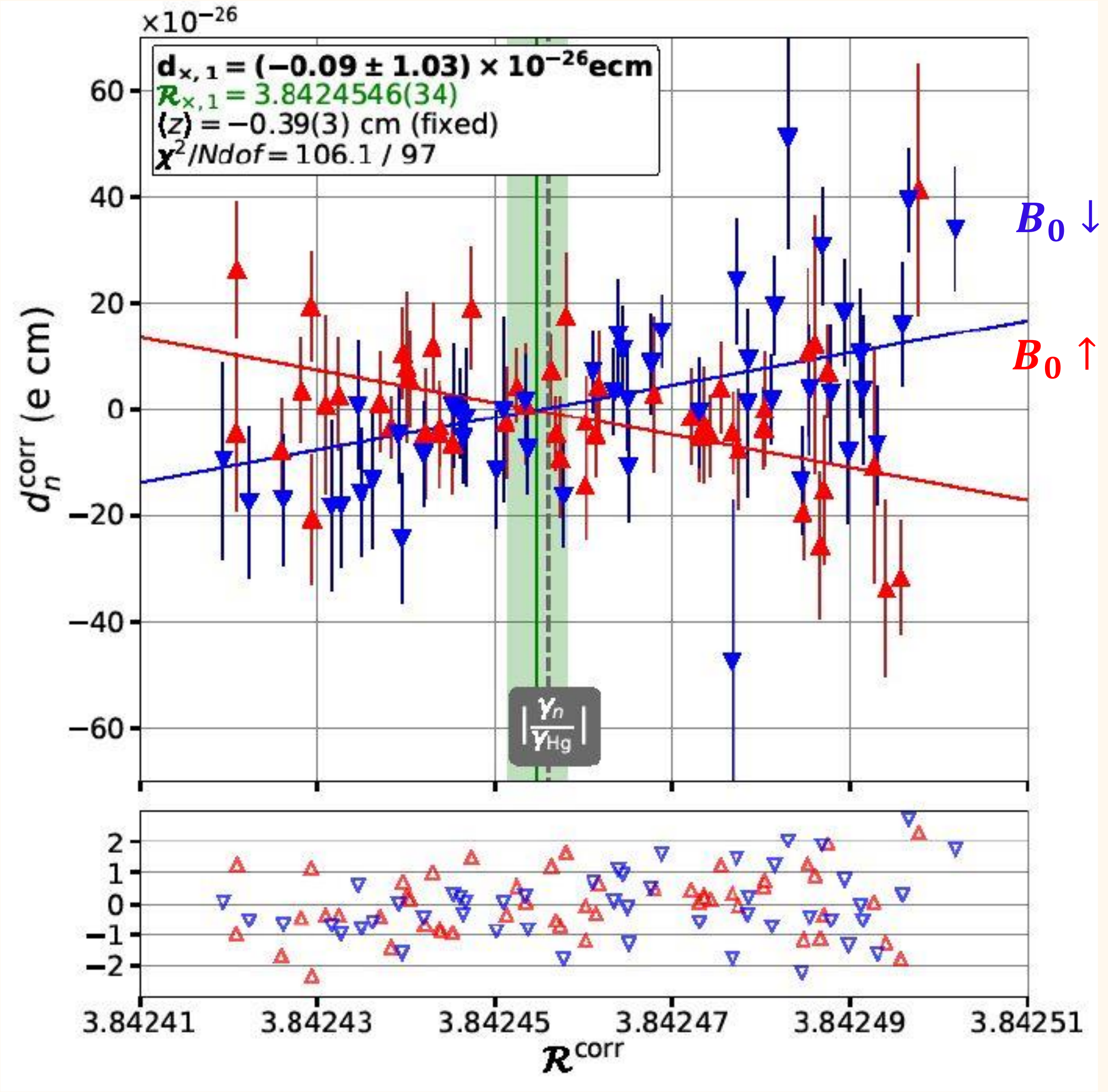
Constrained with measurement at PTB Berlin

Cs Magnetometers

Not anticipated at design, bear in mind for next time

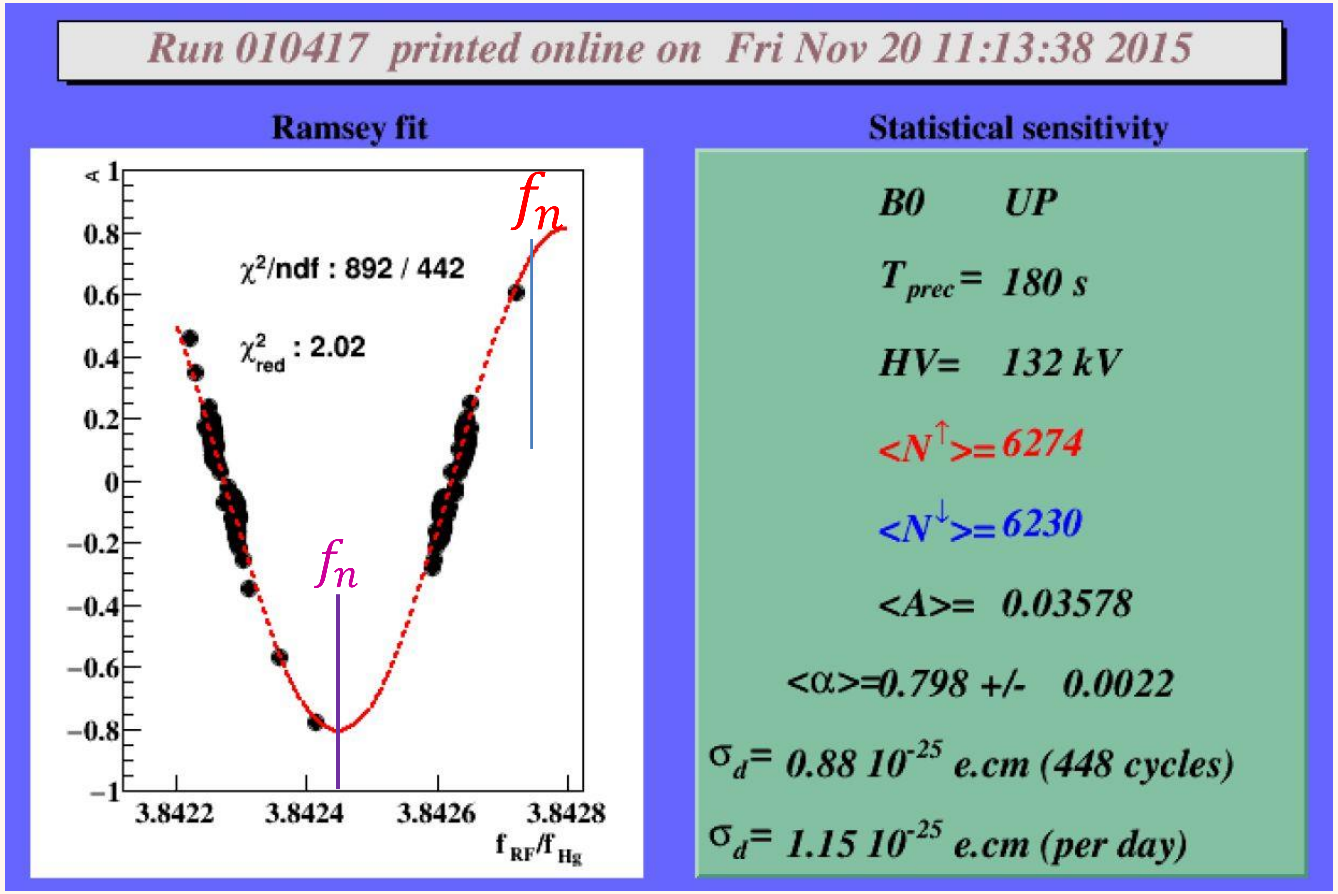
Crossing lines analysis

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \left(1 + \delta_{\mathrm{EDM}}^{\mathrm{true}} \mp \frac{G_z \Delta h}{B_0} + \frac{\langle B_T^2 \rangle}{2B_0^2} + \cdots \right),$$



Analysis scheme

1. During one cycle
   a) Performing of Ramsey cycle in a selected working point.
   b) Counting neutrons with spin up and down
   c) Measuring magnetic field with ^{199}Hg and Cs magnetometers
2. Repeating cycle many times for 4 working points, for a given magnetic and electric field directions.
3. Fitting Ramsey curve
4. Calculation of $R = \frac{f_n}{f_{\mathrm{Hg}}}$ for each cycle.
5. Systematic corrections (field mapping and Cs measurements)
6. Global fit of R versus electric field → neutron EDM.
7. Crossing lines analysis.



Blinding data

Data blinding (first neutron EDM measurement using data blinding method):

- Shifting of neutron frequency f_n by moving counts between “up” and “down” detectors.
- Primary blinding (raw data hidden)
- Analysis performed by two independent groups – two secondary blinding.
- If obtained uncertainties obtained in both analysis groups agree - relative unblinding → Comparison of results.
- If obtained results agree - final unblinding → final result.

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	Result ± Statistical uncertainty ×10-26 e cm	
2 analysis	(1)	(2)
Double blind	15.4 ± 1.1	3.8 ± 1.1
Single blind	6.0 ± 1.1	6.2 ± 1.1
Unblind	-0.1 ± 1.1	0.1 ± 1.1
Result	0.0 ± 1.1	

nEDM at PSI $d_n = (\ 0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \cdot 10^{-26}\ e \cdot \mathrm{cm}$

https://www.psi.ch/en/nedm

- Result of the nEDM at PSI collaboration: Phys. Rev. Lett. 124 (2020) 081803

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \cdot 10^{-26}\ e\cdot\text{cm};$$
$$d_n < 1.8 \cdot 10^{-26}\ e\cdot\text{cm (90\% C.L.)}$$

- Data blinding: EPJ A 57 (2021) 152
- Magnetic field: arXiv:2103.09039v2
  Phys. Rev. A 101 (2020) 053419
  Phys. Rev. A 99 (2019) 042112
  NIM A 896 (2018) 129
  AIP Advances 7 (2017) 035216
- Neutron detection: EPJ A 51 (2015) 143
  EPJ A 52 (2016) 326
- Axion-like dark matter: Phys. Rev. X 7 (2017) 041034
- Neutron to mirror-neutron oscillations: Phys. Lett. B 812 (2021) 135993

And many others at https://www.psi.ch/en/nedm/publications

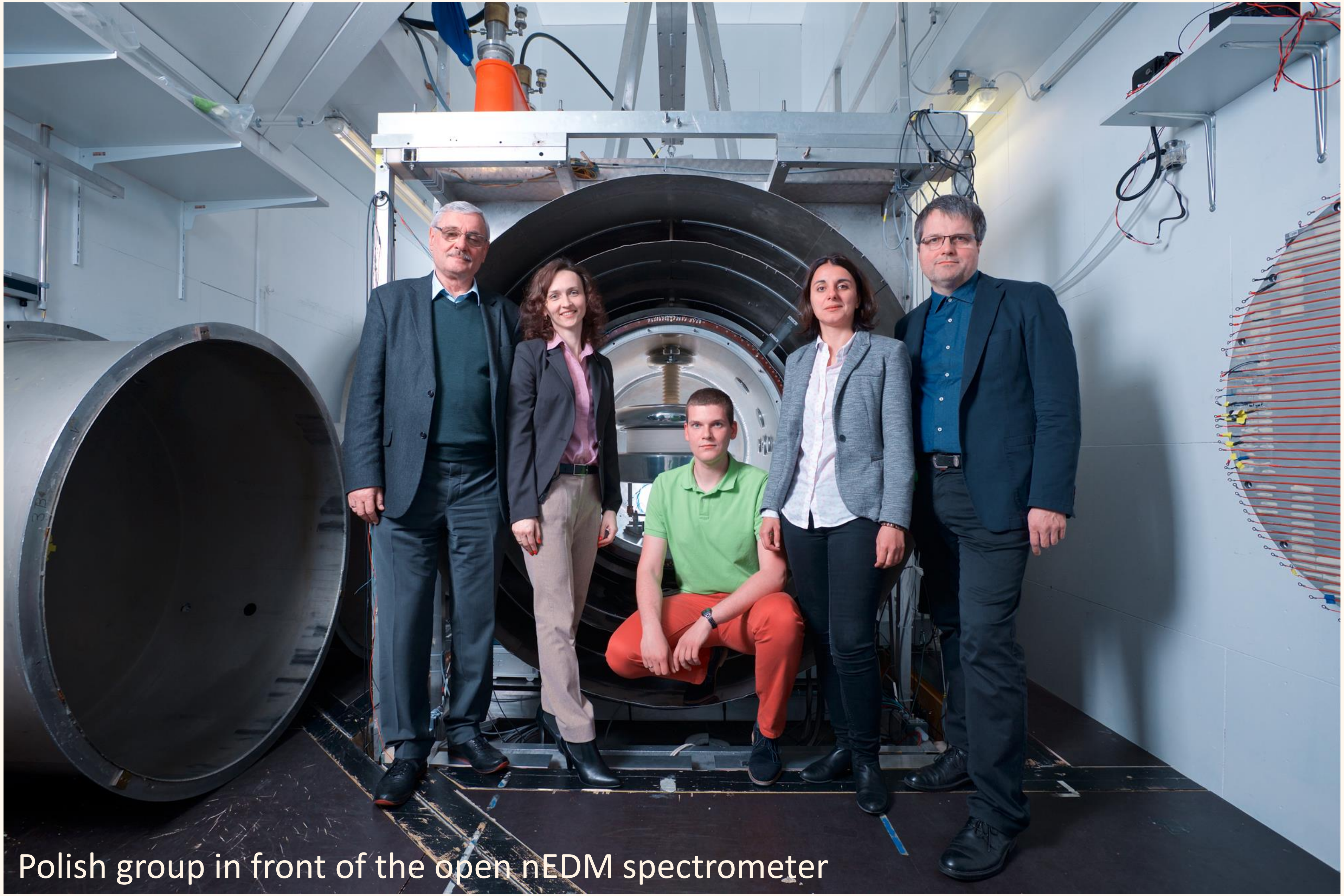
Neutron EDM experiments

https://www.psi.ch/en/nedm/edms-world-wide

- Storage experiments
  - nEDM@PSI – currently starting the next experiment phase.
  - PanEDM @ ILL – with the new SuperSUN UCN source. Double chamber spectrometer equipped with caesium and mercury magnetometers placed around the precession chambers (no comagnetometer is planned) and with both the passive and active magnetic shields. In development.
  - TUCAN@TRIUMF (RCNP in Osaka and the TRIUMF laboratory in Vancouver)- ^{129}Xe comagnetometer, In development.
  - LANL nEDM – similar to PSI but different in details. In development.
- Cryogenic experiment: in Liquid He
  - SNS EDM at Oak Ridge National Laboratory – very ambitious experiment assumes production of UCNs in superfluid helium directly in a double-cell spectrometer with the use of the ^{3}He comagnetometer.
- Pulsed neutron beam experiment
  - neutron beam EDM (to be performed at ESS) - R&D studies of the new concept of using a pulse beam of cold neutrons.

Conclusions

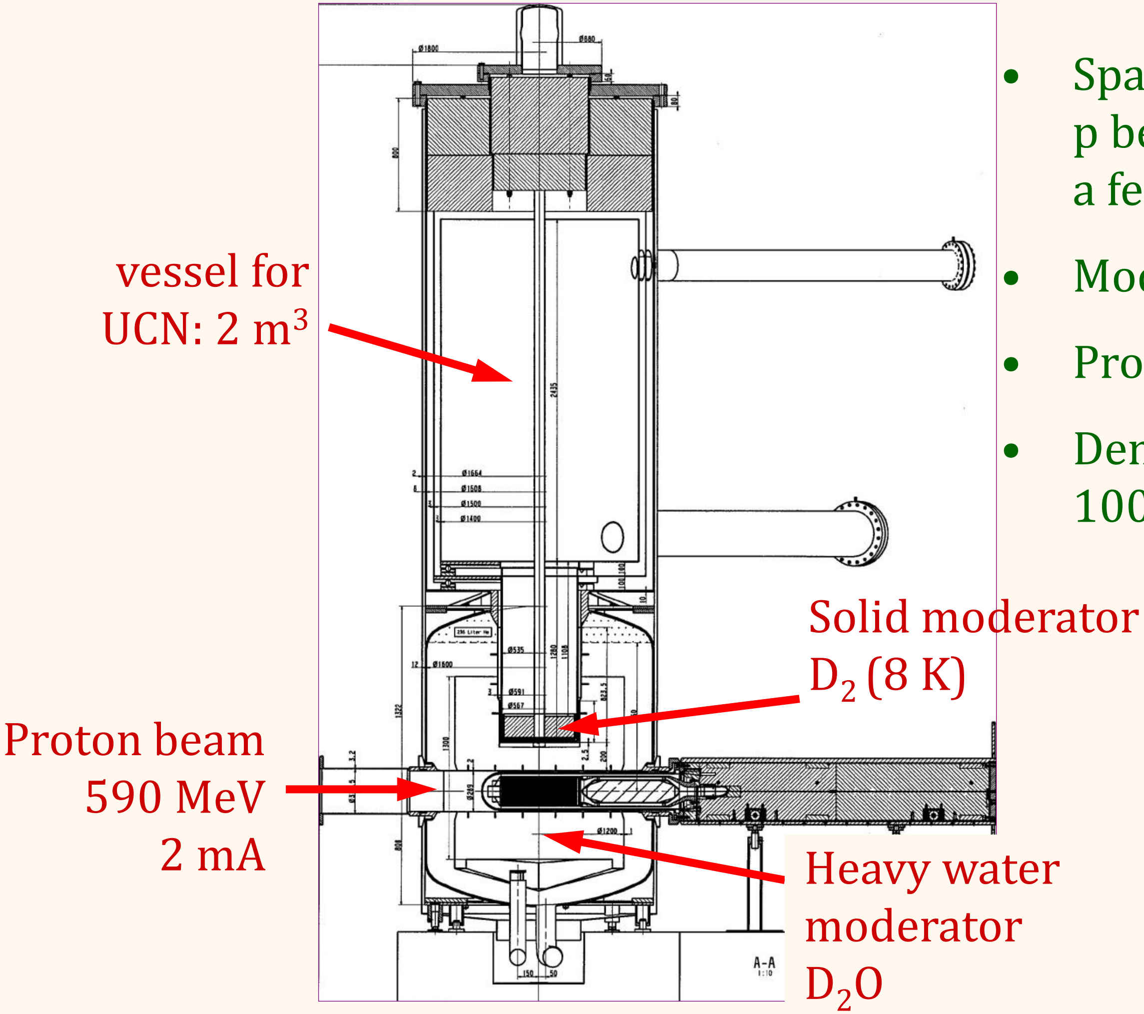
- nEDM @ PSI collaboration has published the most precise result of the neutron EDM measurement.
- The new experiment, n2EDM, is in the process of being launched. Its expected sensitivity of $d_n < 1 \cdot 10^{-27}\ e \cdot \text{cm}$.
- Other neutron EDM measurements needed for complementarity – development under way for at least 5 experiments.
- EDM measurements of other particles are also needed to disentangle source of a possible non-zero EDM value.



Thank you

Spare slides

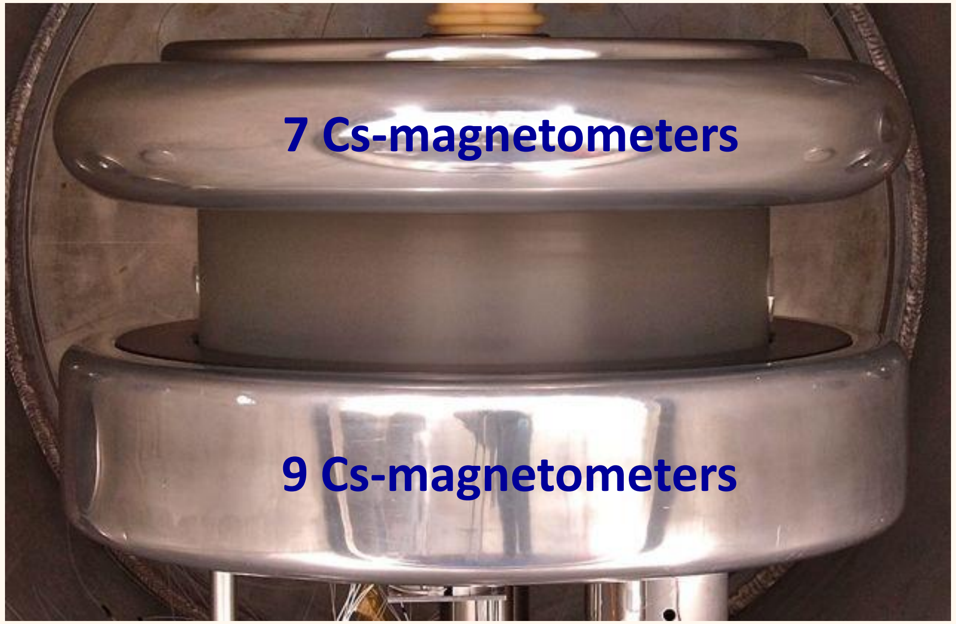
Source of UCN at PSI



- Spallation UCN source: p+Pb
  p beam 590 MeV, 2 mA,
  a few second pulse every 5 minutes.
- Moderator: 30l of solid D_2, 8K.
- Production: $2 \cdot 10^5$ cm^{-3}s^{-1}.
- Density of UCN in the experiment place:
  1000 cm^{-3}.

Centre of mass of ultra cold neutrons is about 3.5 mm lower than that of mercury atoms.

In case of vertical gradient, they experience different mean magnetic field value.



16 Cs magnetometers for field gradient measurements.
Sensitive but not accurate.

Not only vertical gradients are important

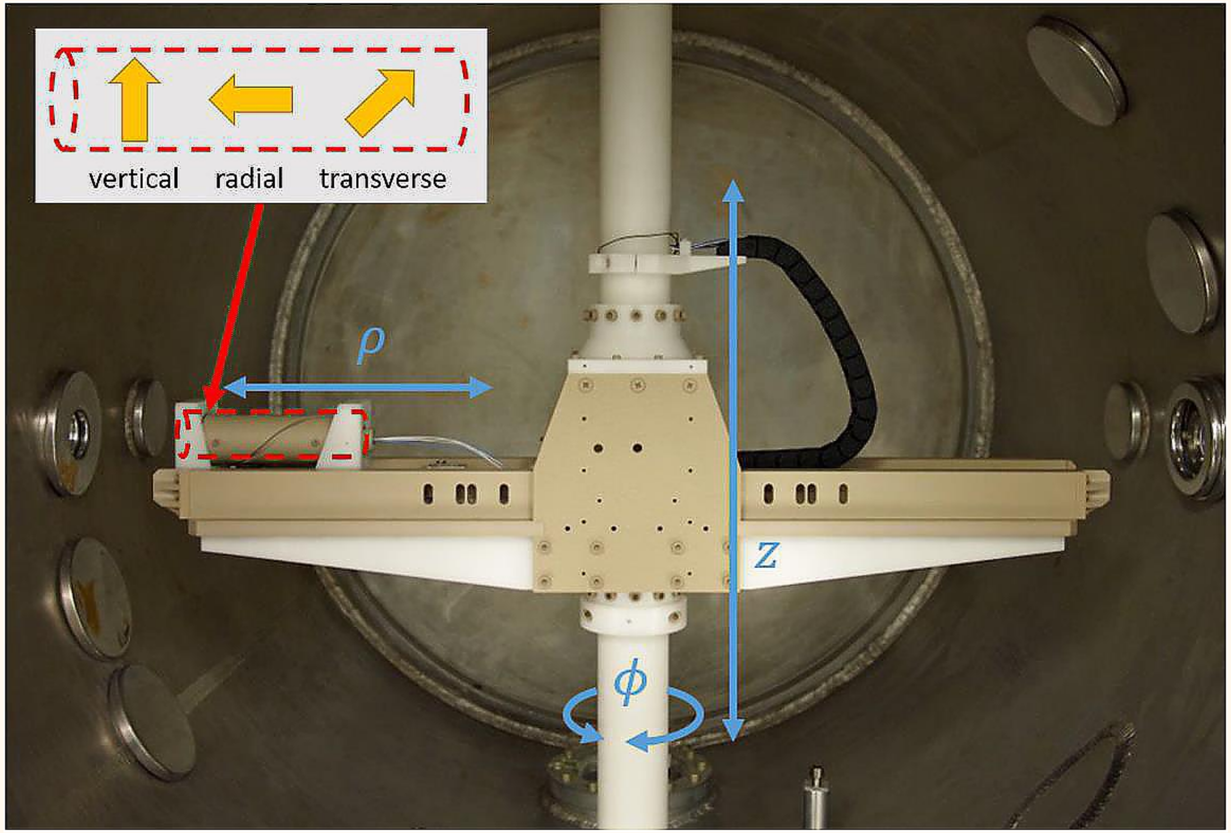
$\frac{\partial B_z}{\partial z}$,

but also transversal components of the field and its gradient

$\frac{\partial B_z}{\partial r}, B_T, \frac{\partial B_T}{\partial r}$.

Magnetic field mapping

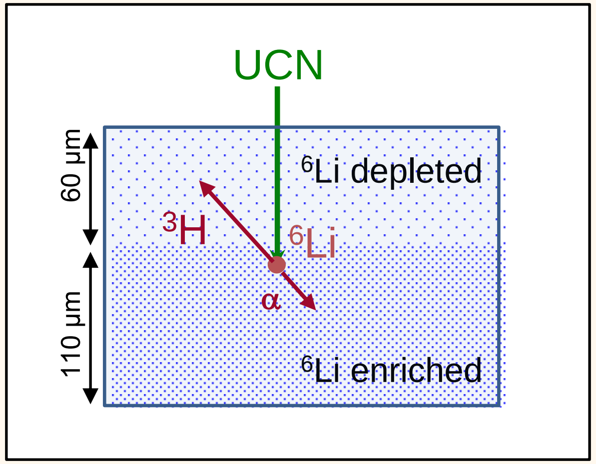
- Measurement performed off-line in thousands of points.
- Decomposition of the field into 63 modes
- Corrected field applied to each run before the actual crossing-lines analysis.

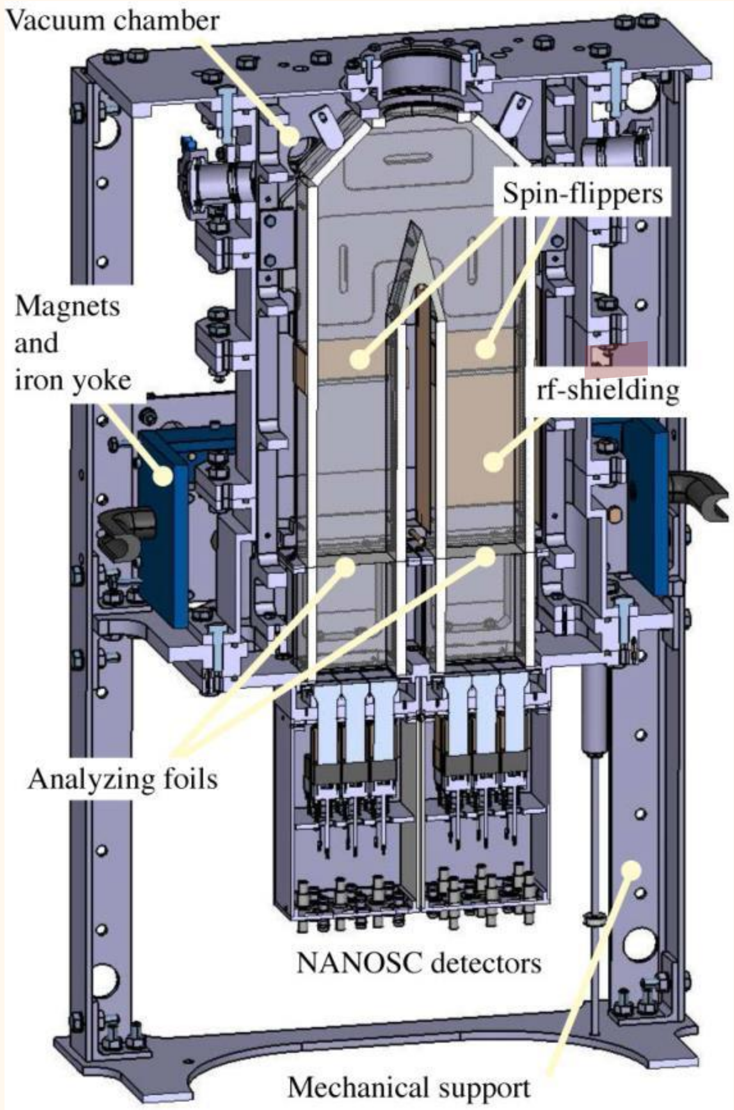


Neutron detection system

Scintillators enriched in ^{6}Li

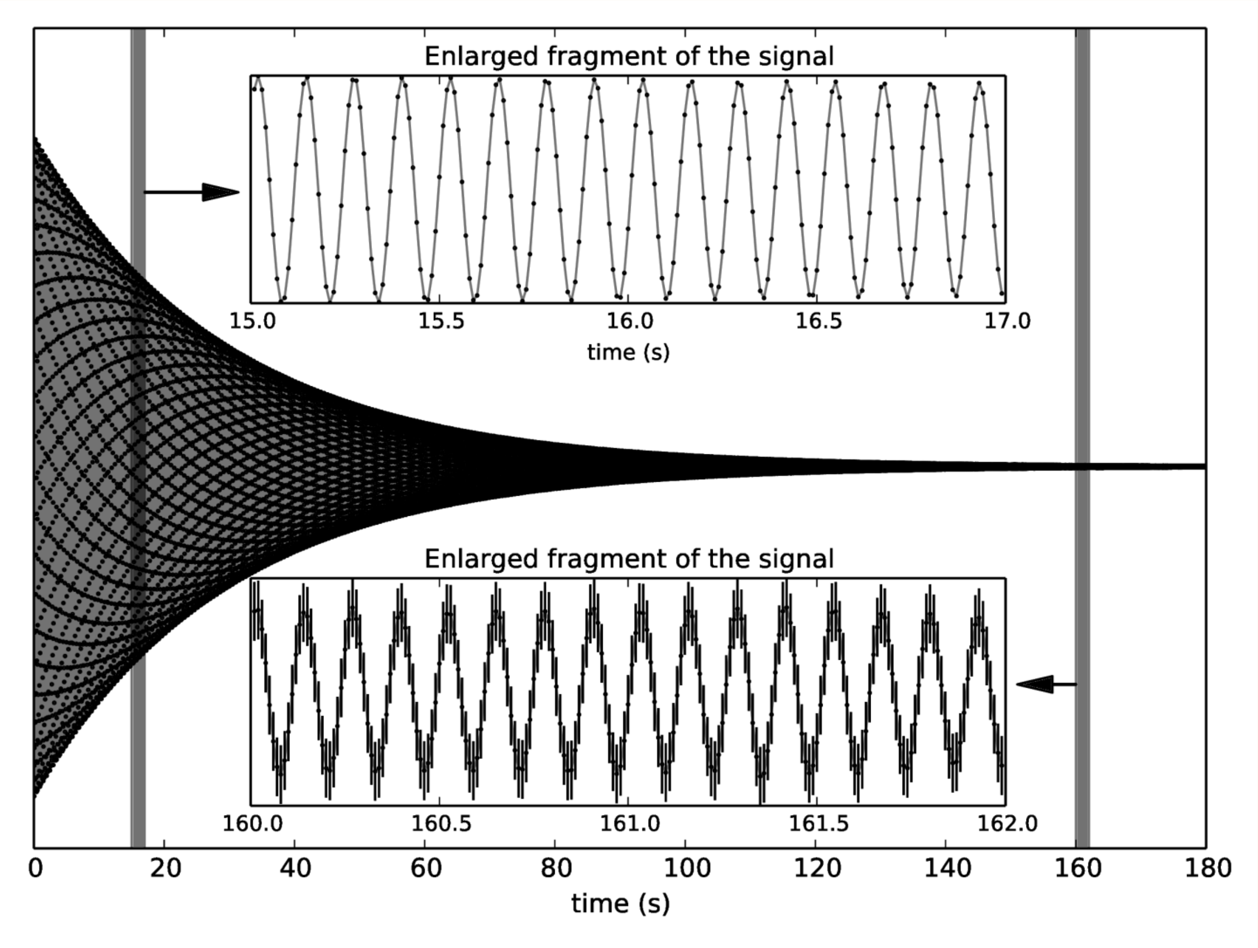
$$n + {}^6Li \rightarrow {}^3H + \alpha$$





Neutron detection systems measures both neutron spin states simultaneously.

Example of a bad signal from ^{199}Hg comagnetometer – short relaxation time.

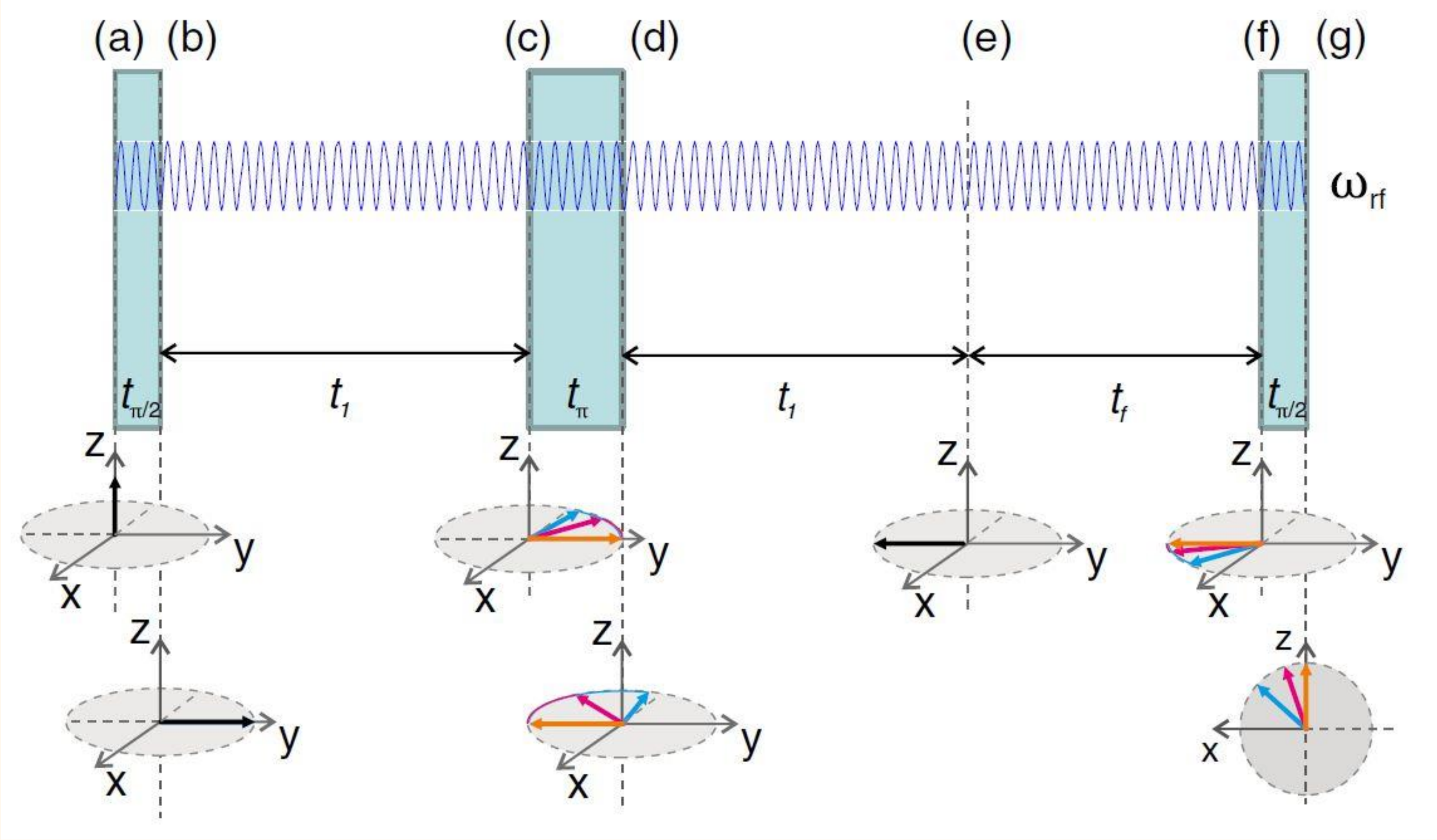


$y(t) = Ae^{-t/\tau}\sin(2\pi f t + \varphi)$- but frequency f is not constant.
We must know the mean frequency, which corresponds to the mean value of the magnetic field B_z.

How to control velocity spectrum of neutrons?

Neutrons with higher energies are captured by the storage volume walls easier

$\Delta h \neq$ const during a cycle → in case of $G_z \neq 0$, the mean magnetic field seen by UCN changes during a cycle.

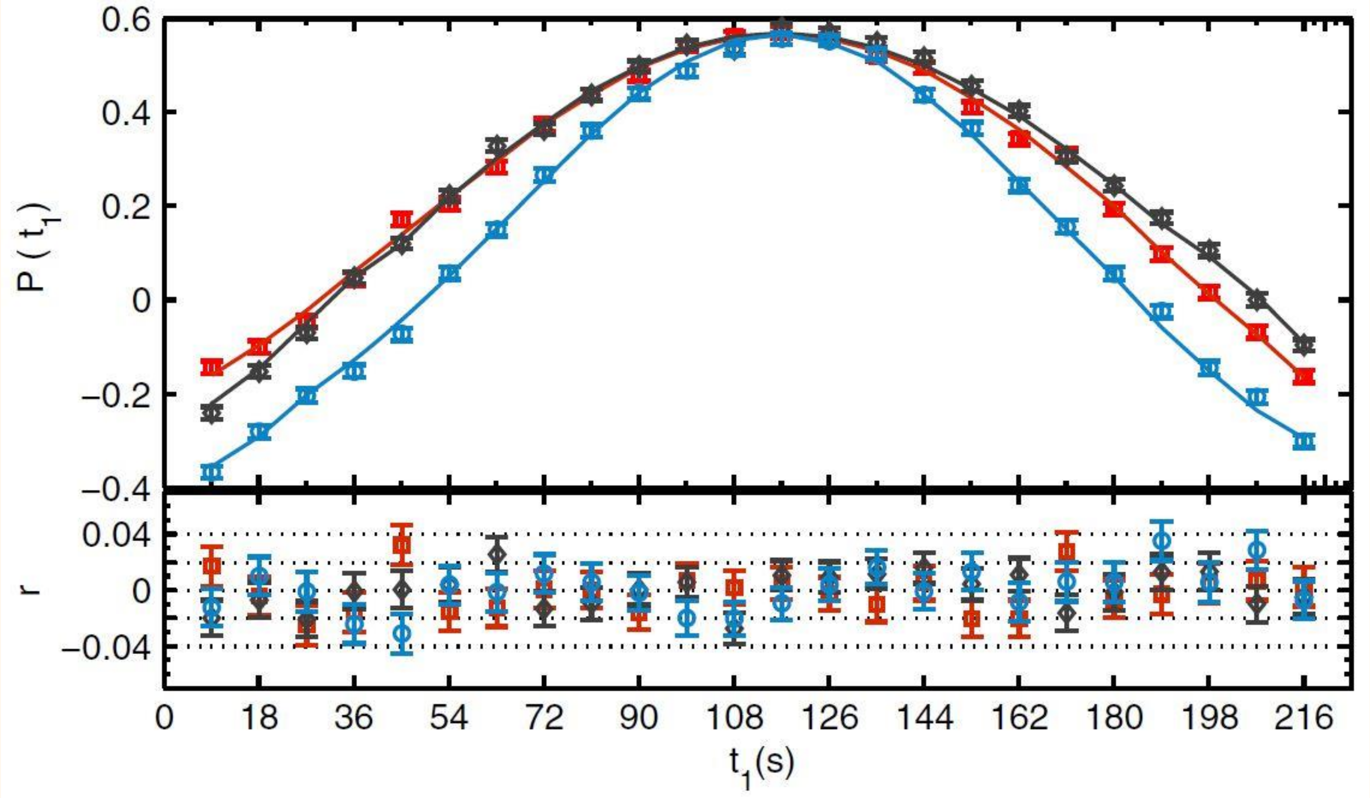


Final polarization depends on neutron velocities.

Final neutron polarization

$$P(t_1) = \int \alpha(T,\epsilon)\cos[\omega_r(\epsilon)(T-2t_1)]p(\epsilon,T)d\epsilon$$

UCN polarization measured for 3 different G_z gradients vs t_1 precession time



$\partial B_z / \partial z =$

10 pT/cm

-18 pT/cm

38 pT/cm

UCN spectra obtained by fitting to the neutron polarization spectra:

- The best fit.
- Spectra for highest and lowest centers of mass of the UCN.
- Spectra for highest and lowest mean energy of the UCN.