JAGIELLONIAN UNIVERSITY
IN KRAKÓW

SEARCH FOR THE NEUTRON ELECTRIC DIPOLE MOMENT AT THE PAUL SCHERRER INSTITUTE

MESON 2021
17-20.05.2021

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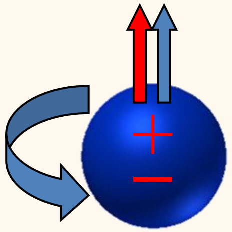
Motivation

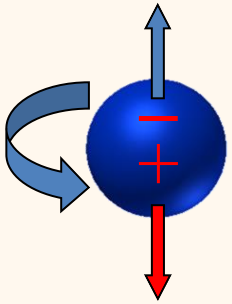
The non-zero value of neutron Electric Dipole Moment (EDM) will be evidence for the existence of $\mathcal{CP}$ violating processes.

Why?

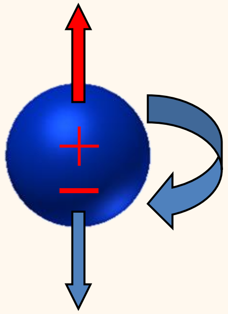
- Neutron is a $\frac{1}{2}$-spin particle → EDM vector must be parallel to particle spin pseudovector by virtue of a cylindrical symmetry $\vec{d} = d \cdot \hat{S}$;



- Parity operation $\mathcal{P}$ changes direction of EDM, but not of spin;



- Time reversal operation $\mathcal{T}$ reverses direction of spin, but not of EDM;



- Violation of both $\mathcal{P}$ and $\mathcal{T}$ symmetries is equivalent to violation of $\mathcal{CP}$ symmetry because of $\mathcal{CPT}$ conservation theorem.

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.

Motivation

Why quest for the $\mathcal{CP}$ violation processes is needed?

1. Baryogenesis – The Universe should be composed of both matter and antimatter. But observed ratio of $\frac{n_{\bar{p}}}{n_p} = (0.1 \div 2) \cdot 10^{-4}$ (energy dependent) is consistent with expected amount of $\bar{p}$ created in $pp \rightarrow pp + p + \bar{p}$ reactions.

2. Alpha magnetic spectrometer AMS-02 installed on the International Space Station limited anti-helium to helium ratio:

$$\frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} < 1 \cdot 10^{-8}$$

3. Annihilation radiation, which should appear as a result of cosmic matter-antimatter collisions, is not observed.

- **Conclusion: Our Universe is made of matter.**

Andrei Sacharov postulates (1967):

- Both, baryon number and $\mathcal{CP}$ symmetry must be violated – both kinds of transitions must perform out of thermal equilibrium.

Motivation

Violation of $\mathcal{CP}$ symmetry has been observed in weak decays (mesons K and B).

Weak interaction distinguishes matter from antimatter:

$$\frac{A(K_L \to \pi^- e^+ \nu_e)}{A(K_L \to \pi^+ e^- \bar{\nu}_e)} > 1, \qquad \frac{A(B^0 \to K^- \pi^+)}{A(B^0 \to K^+ \pi^-)} > 1$$

Is it present in other interactions?

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

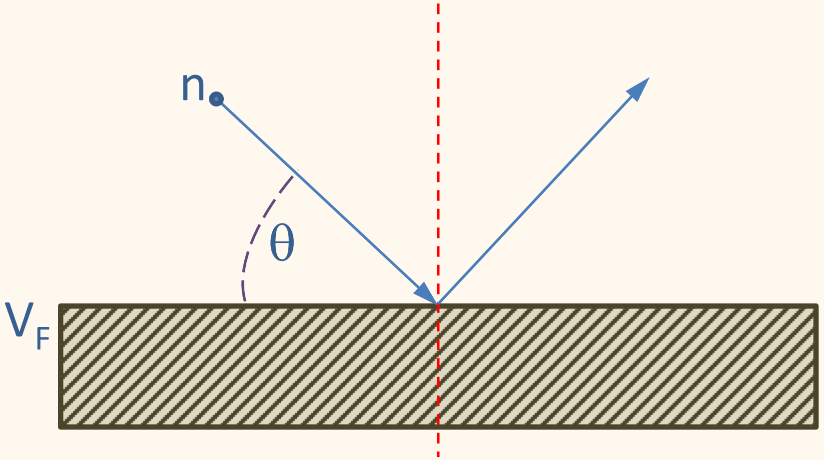
EDM - Investigated objects:

- Electron
- ^{199}Hg
- Proton
- ^{129}Xe
- Muon
- Taon
- **Neutron** – value measured since 1957

Why neutron EDM is particularly interesting?

- Neutron – weak and strong interactions present
- Nuclear interaction not present
- Electrically neutral

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

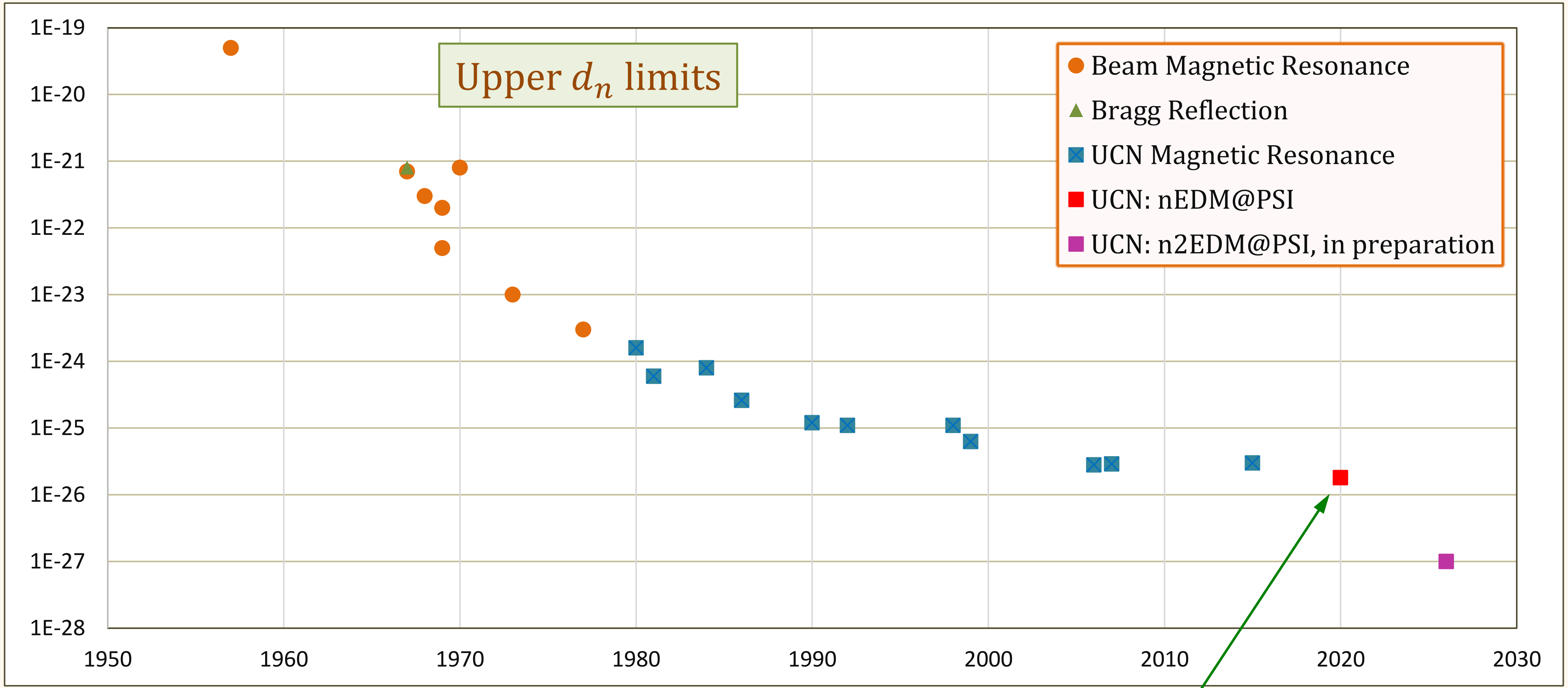


If neutron kinetic energy $E_n < V_F$ it always reflects and can be stored in closed vessels. For some materials V_F can reach 250 neV.

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

Neutron EDM measurements

Measurements of the neutron EDM



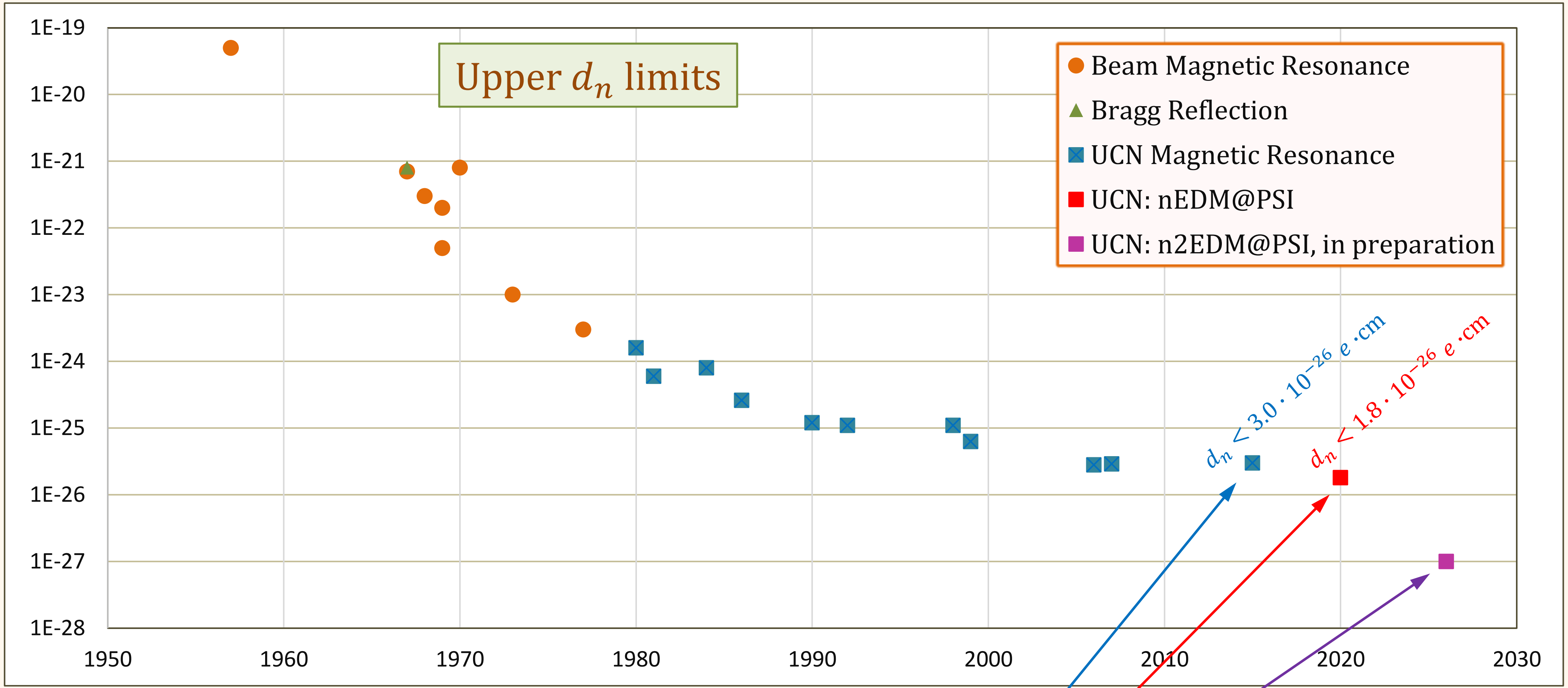
Result of the nEDM at PSI collaboration Phys.Rev.Lett. 124, 081803 (2020)

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

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

Neutron EDM measurements

Measurements of the neutron EDM



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

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

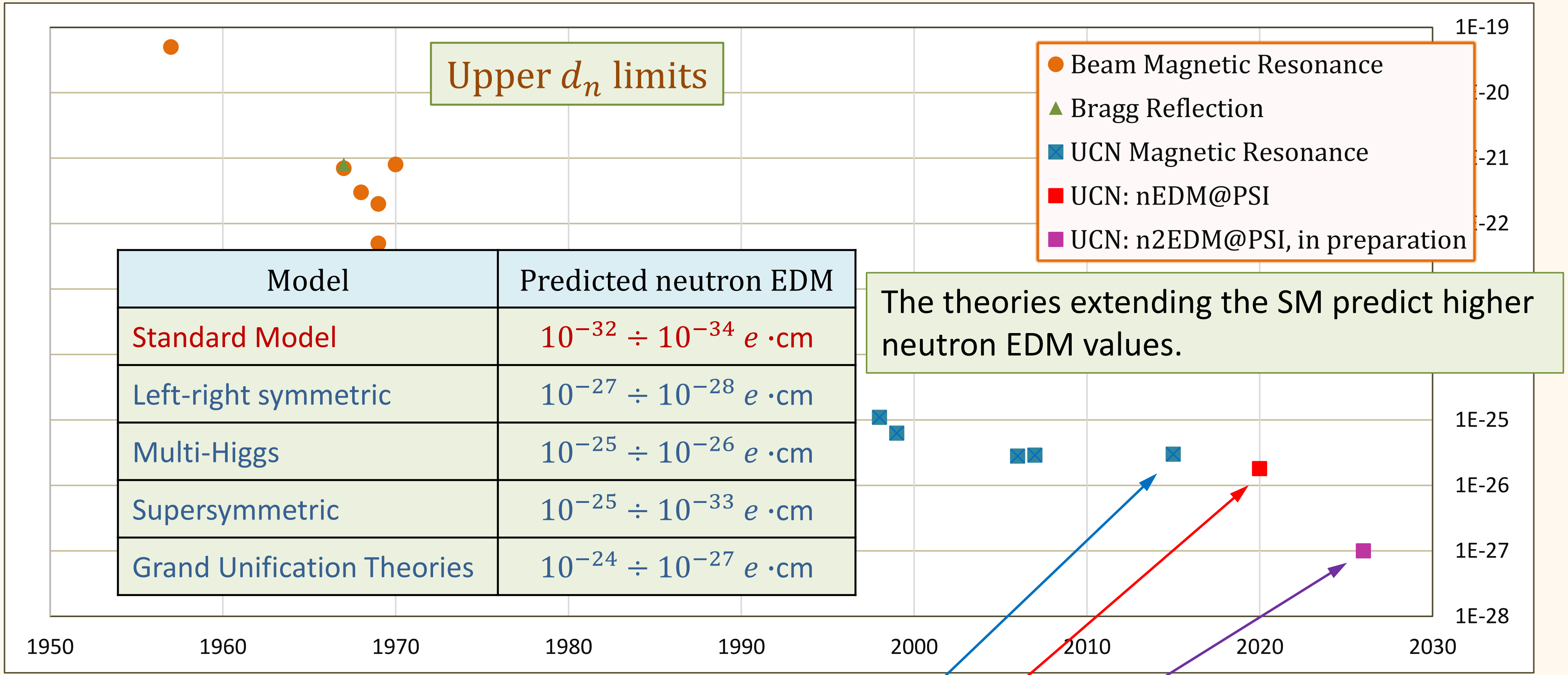
n2EDM at PSI, in preparation $d_n < 1 \cdot 10^{-27}\ e \cdot \mathrm{cm}$

Fivefold reduction of systematic uncertainties.

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

Neutron EDM measurements

Measurements of the neutron EDM



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 $d_n \approx 1 \cdot 10^{-27}\ e \cdot \mathrm{cm}$

Measurement method

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:

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

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

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

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

$$\sigma_{d_n} \sim 10^{-27} \Longrightarrow \frac{\Delta f_n}{f_n} \sim 2 \cdot 10^{-10} \text{ przy } E = 10 \, \frac{\text{kV}}{\text{cm}}.$$

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

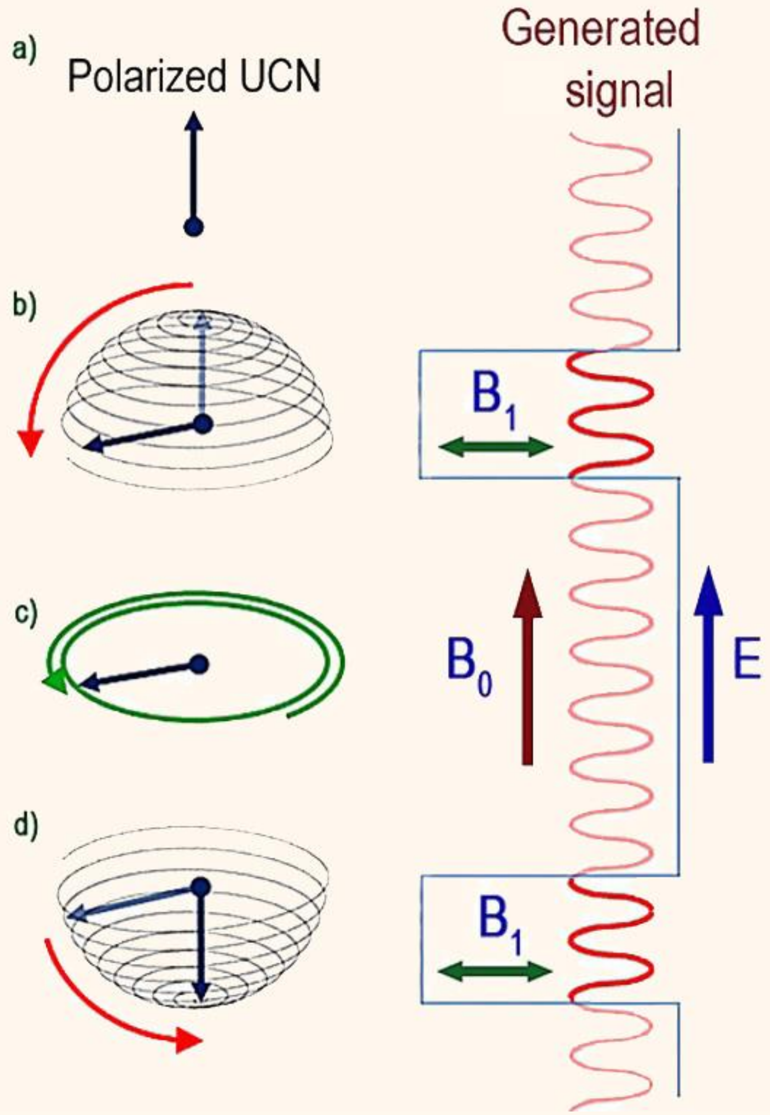
$$d_n = \frac{1}{4E}[h \Delta f_n - \mu_n (B_{\uparrow\uparrow} - B_{\uparrow\downarrow})].$$

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.

Control of the magnetic field is essential for 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 $f_{LF} = f_L$ $(\approx 30\mathrm{Hz})$.
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.

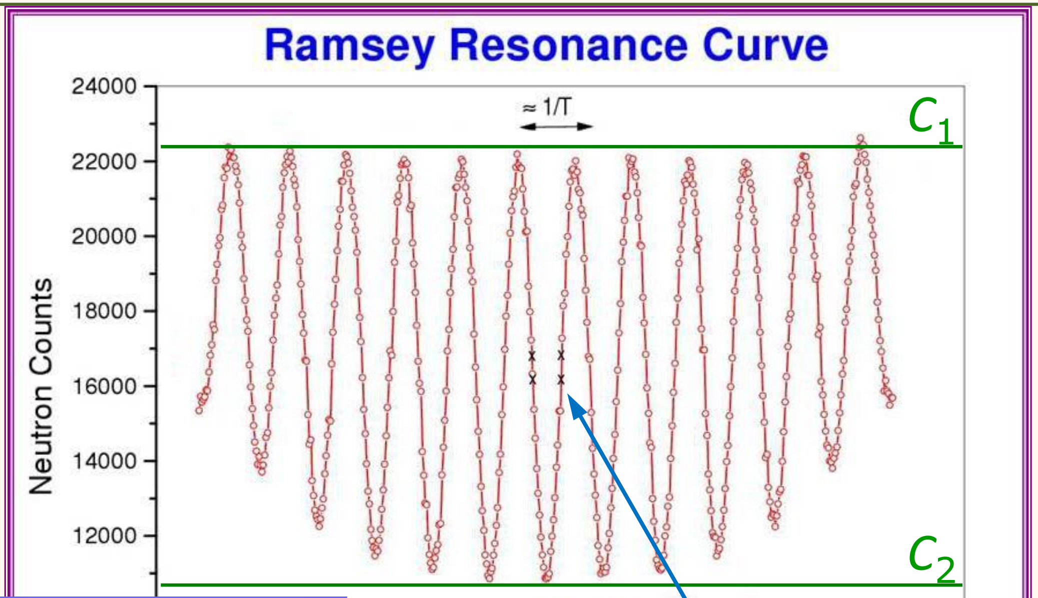
Neutron polarization analysis.

Measurement method

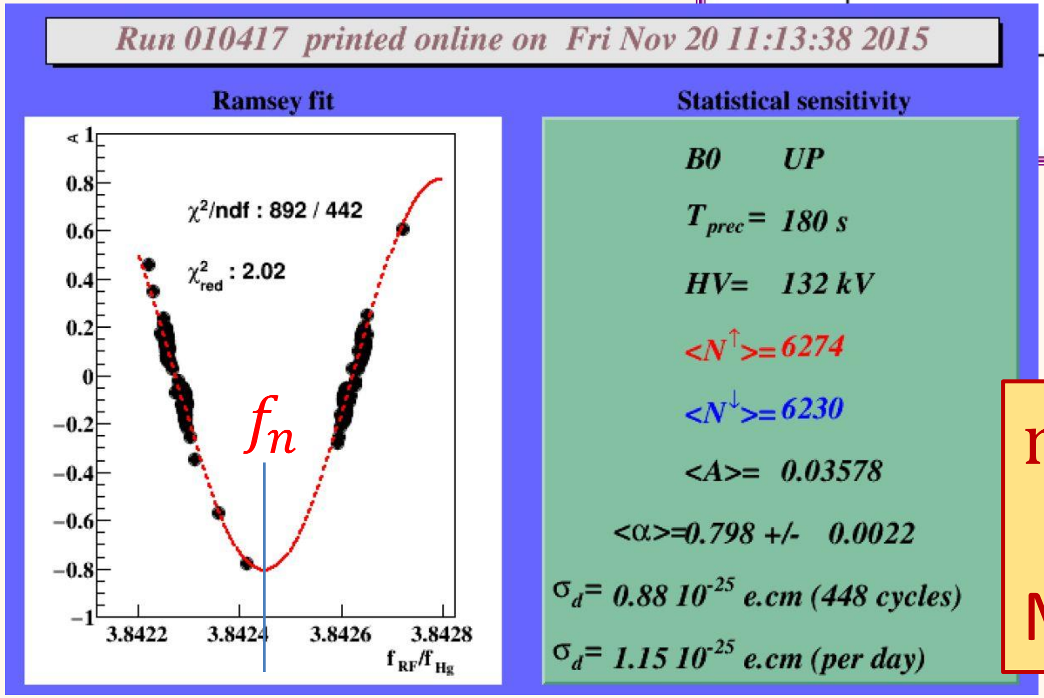
Neutron visibility parameter

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

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



4 working points



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Ramsey fit

Statistical sensitivity

B0 UP

T_{prec} = 180 s

HV= 132 kV

$<N^{\uparrow}>=6274$

$<N^{\downarrow}>=6230$

$<A>= 0.03578$

$<\alpha>=0.798$ +/- 0.0022

$\sigma_d = 0.88\ 10^{-25}$ e.cm (448 cycles)

$\sigma_d = 1.15\ 10^{-25}$ e.cm (per day)

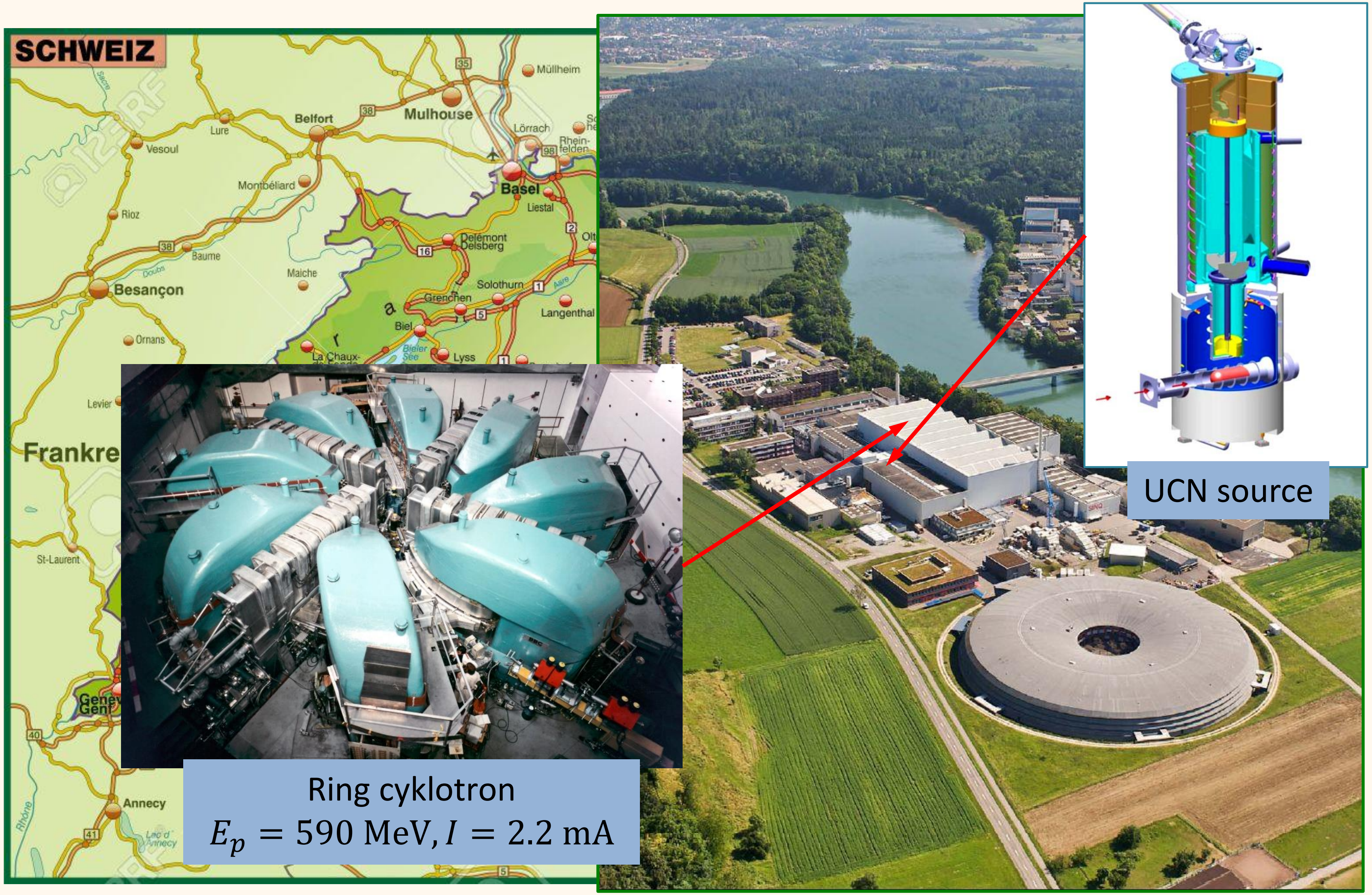
nEDM@PSI

$\Longleftarrow\ \alpha \cong 0.8$

Mean value 0.76

Neutron EDM at PSI

Paul Scherrer Institut, Villigen, Switzerland

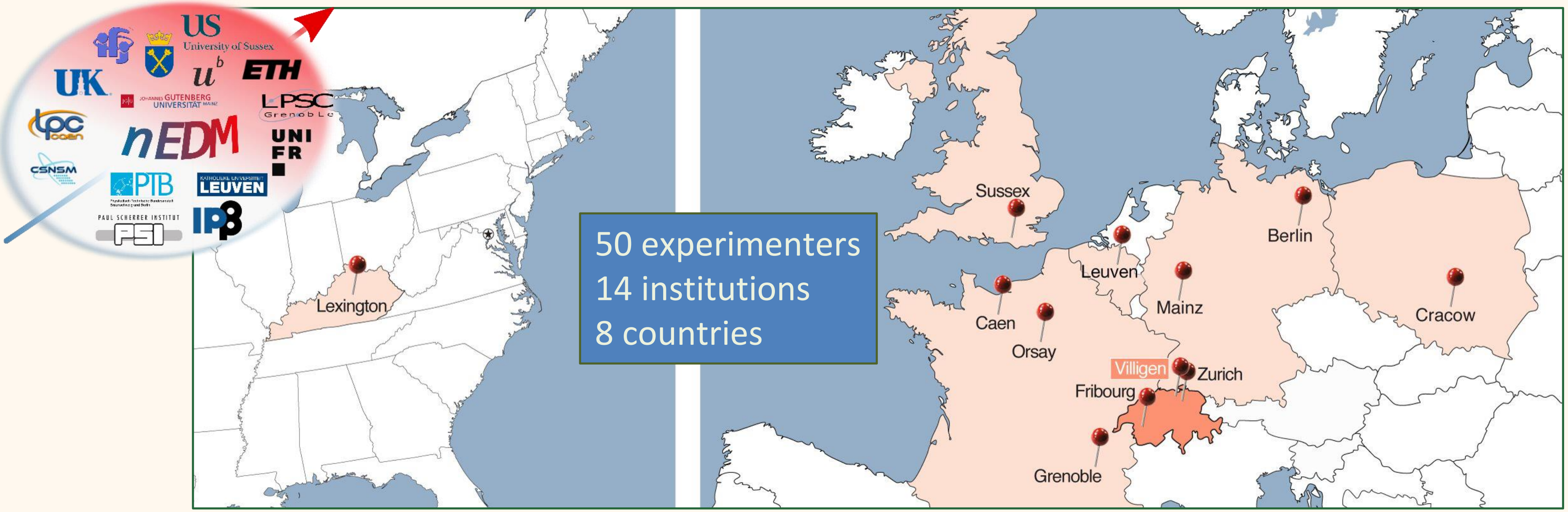


Ring cyklotron

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

UCN source

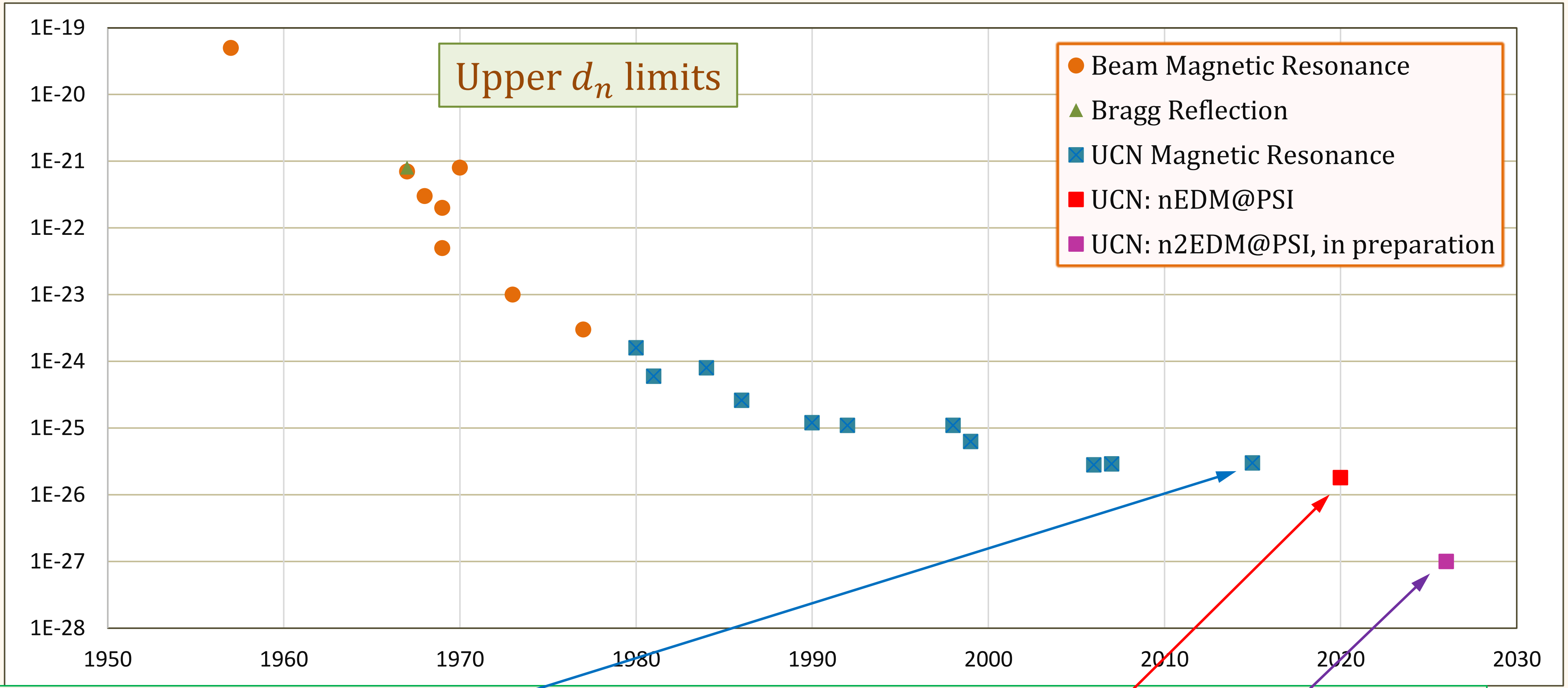
Neutron EDM at PSI



50 experimenters
14 institutions
8 countries

Neutron EDM measurements

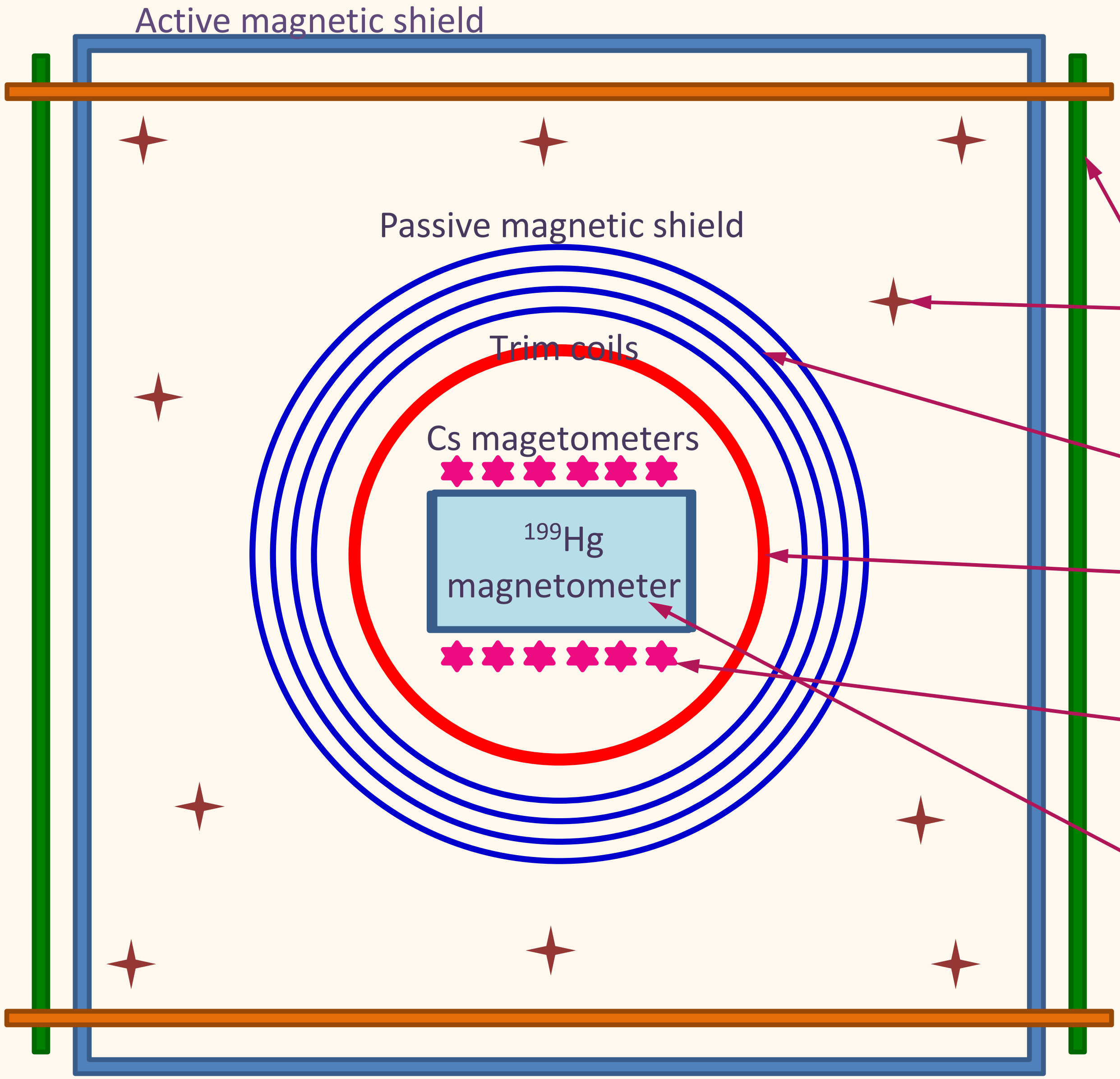
Measurements of the neutron EDM



Development scheme:

1. Take the RAL-Sussex-ILL apparatus, upgrade everything but vacuum chamber and passive magnetic shield and add new systems – first result.
2. Build a completely new apparatus on base of achieved experience – next result(s).

nEDM apparatus



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
- 32 trim coils for compensation of local field inhomogeneities and setting 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

nEDM apparatus

Two-level thermo-house

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

Neutron EDM measurements

Statistical uncertainty

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

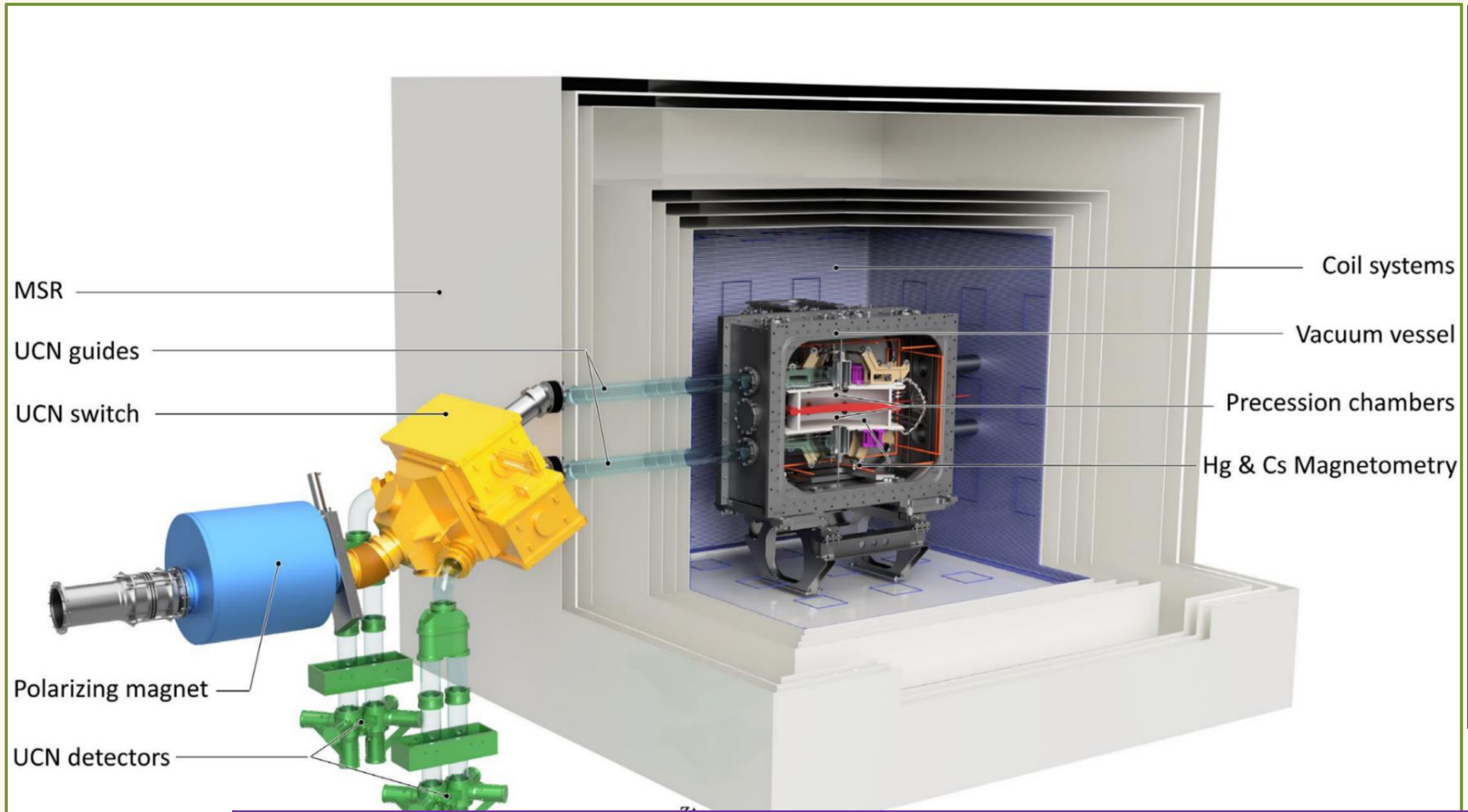
nEDM at PSI $d_n = \left(\ 0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}\right) \cdot 10^{-26}\ e \cdot \text{cm}$

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

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

	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

nEDM apparatus



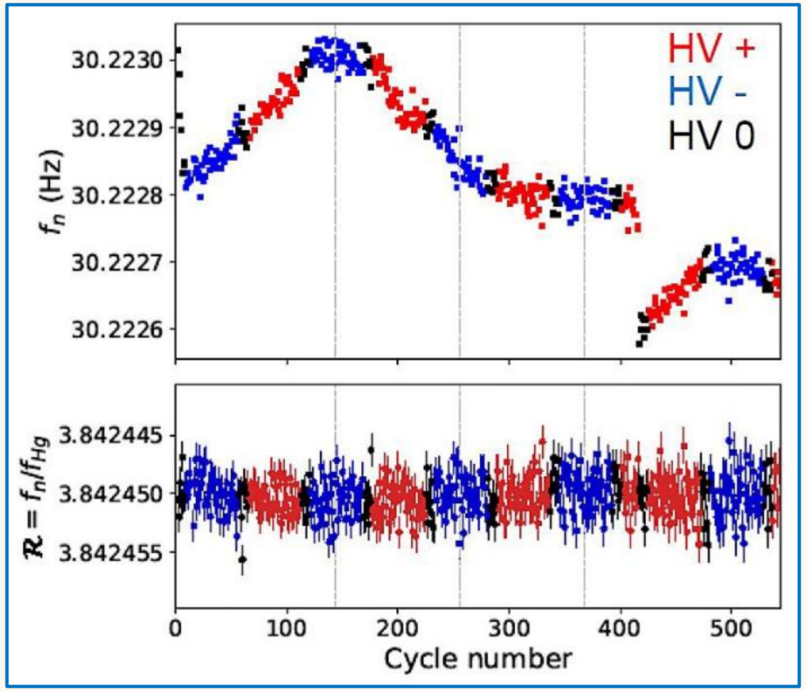
	nEDM	n2EDM
Passive magnetic shield	4 layers (10^3-10^4 factor), ϕ2 m	6 layers (10^5 factor), L = 5 m
Precession chamber diameter	1 chamber: ϕ47 cm, H = 11 cm	2 chambers: ϕ80 cm, H = 12 cm
Active magnetic shield	3 coils	8 coils
Cesium magnetometers	16	112

nEDM – 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 $R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}}$ was used to compensate magnetic field fluctuations.



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).

nEDM – systematic effects

Most important systematic effects introducing EDM error:

- Cs magnetometers are very sensitive but not very accurate. Cs magnetometers and field mapping give $\frac{\partial B_z}{\partial r}, B_T, \frac{\partial B_T}{\partial r}$.

  $$15 \cdot 10^{-28} e \cdot \mathrm{cm}$$

- $\vec{v} \times \vec{E}$ effect – seen as a magnetic field by ^{199}Hg atoms

  $d_{\mathrm{FALSE}} = \frac{G_z}{1\,^{\mathrm{pT}}/_{\mathrm{cm}}} \cdot 4.4 \cdot 10^{-27}\ e \cdot \mathrm{cm}$.

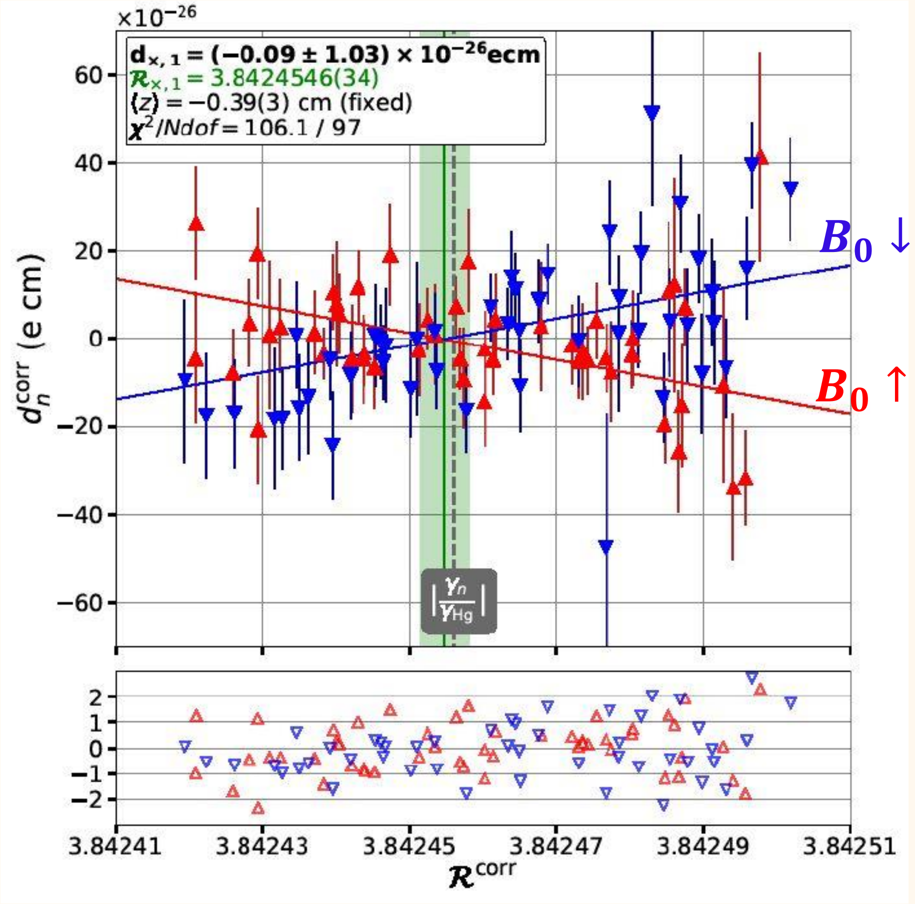
- Local magnetization of electrodes: $d_{\mathrm{FALSE}} < 4 \cdot 10^{-28} e \cdot \mathrm{cm}$
- Influence of $d_{^{199}\mathrm{Hg}} < (8 \pm 12) \cdot 10^{-30} e \cdot \mathrm{cm}$.

Most important systematic effects shifting EDM value:

- Higher order gradients $7 \cdot 10^{-27} e \cdot \mathrm{cm}$ – corrected on base of field mapping.
- Earth rotation shifts R_a ratio by ± 1.33 ppm depending on the $\vec{B}_0$ direction. This effect is considered in the R_a method.

Crossing lines analysis

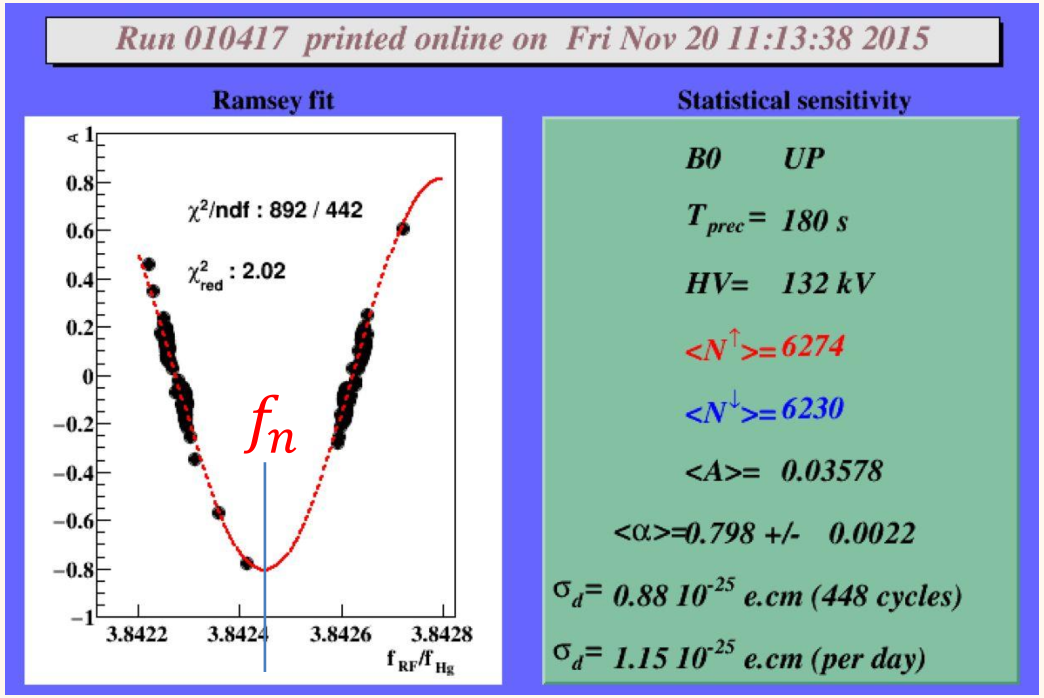
$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \left(1 + \delta_{\mathrm{EDM}}^{\mathrm{true}} \mp \frac{G_z \Delta h}{B_0} + \frac{\langle B_T^2 \rangle}{2 B_0^2} + \cdots\right),$$



nEDM – data analysis

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 $\frac{f_n}{f_{\mathrm{Hg}}}$ for each cycle.
5. Systematic corrections (field mapping and Cs measurements)
6. Global fit of R versus electric field → neutron EDM.



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Ramsey fit

Statistical sensitivity

B0 UP

T_{prec} = 180 s

HV= 132 kV

$\langle N^{\uparrow} \rangle$= 6274

$\langle N^{\downarrow} \rangle$= 6230

<A>= 0.03578

$\langle \alpha \rangle$=0.798 +/- 0.0022

σ_d = 0.88 10^{-25} e.cm (448 cycles)

σ_d = 1.15 10^{-25} e.cm (per day)

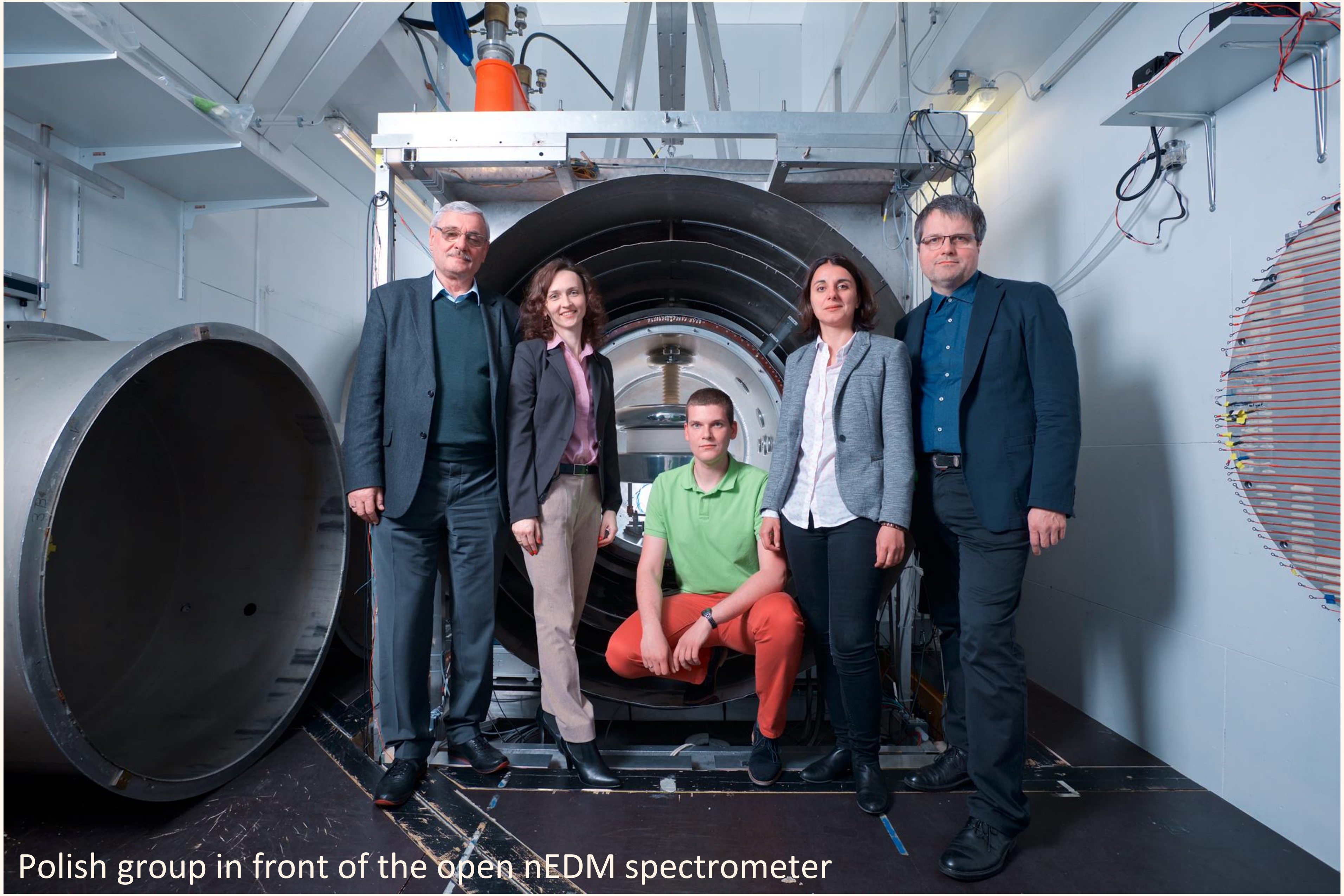
Data blinding (first neutron EDM measurement using data blinding method):

- 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.

If you want to know more about this experiment

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

• Result of the nEDM at PSI collaboration: $d_n = \left(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}\right) \cdot 10^{-26}\ e\ \cdot\text{cm};$ $d_n < 1.8 \cdot 10^{-26}\ e\ \cdot\text{cm}$ (90% C.L.)	Phys. Rev. Lett. 124 (2020) 081803
• 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



Polish group in front of the open nEDM spectrometer

Thank you