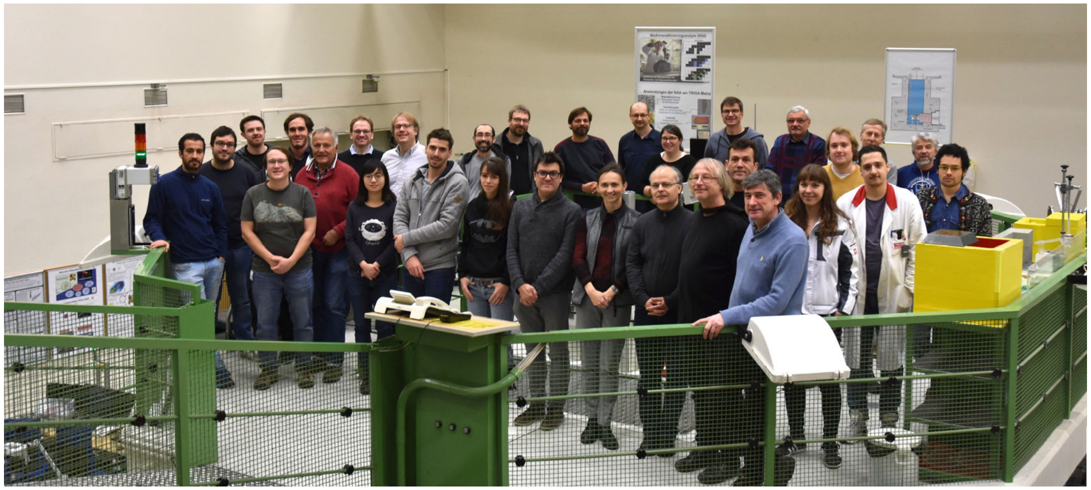
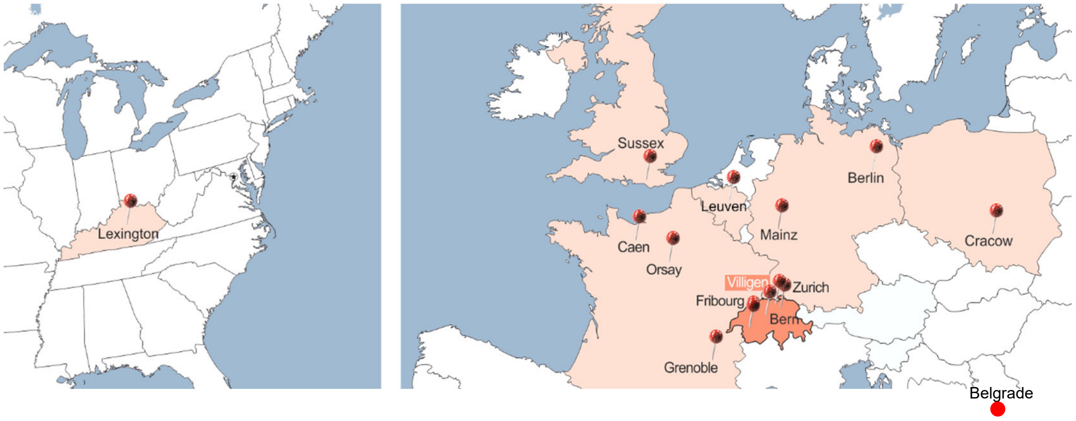
A new limit on the permanent electric dipole moment of the neutron (nEDM)

G. Zsigmond on behalf of the
nEDM collaboration at PSI



Collaboration Meeting, Mainz TRIGA Reactor, November 2019



nEDM collaboration at PSI

- UBel, Institute of Physics, Photonics Center, University of Belgrade, Serbia
- PTB, Physikalisch Technische Bundesanstalt, Berlin, Germany
- AEC, Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- US, University of Sussex, Brighton, United Kingdom
- LPC, Laboratoire de Physique Corpusculaire, Caen, France
- JUC, Jagellonian University, Cracow, Poland
- HNI, Henryk Niedwodniczanski Institute of Nuclear Physics PAN, Cracow, Poland
- FRAP, Université de Fribourg, Fribourg, Switzerland
- LPSC, Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France
- UKY, University of Kentucky, Lexington, USA
- KUL, Katholieke Universiteit, Leuven, Belgium
- GUM, Institut für Physik, Gutenberg Universität, Mainz, Germany
- IKC, Institut für Kernchemie, Gutenberg Universität, Mainz, Germany
- PSI, Paul-Scherrer-Institut, Villigen, Switzerland
- ETHZ, Eidgenössische Technische Hochschule Zürich, Switzerland

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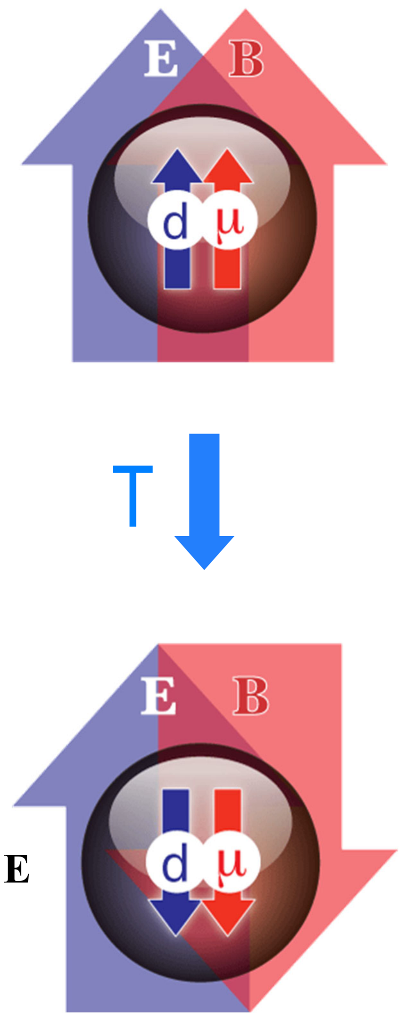
Motivation: CP violation

$$H = -\mu \frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\mathbf{B} - d\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\mathbf{E}$$



$$TH = -\mu\frac{-\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}(-\mathbf{B}) - d\frac{-\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\mathbf{E}$$

A nonzero particle EDM violates T, P and, assuming CPT conservation, also CP

→ A discovery or a highly improved constraint could contribute to our understanding of the baryon asymmetry of the universe.

→ Excellent probe for constraining the parameter space of theory models beyond the Standard Model.

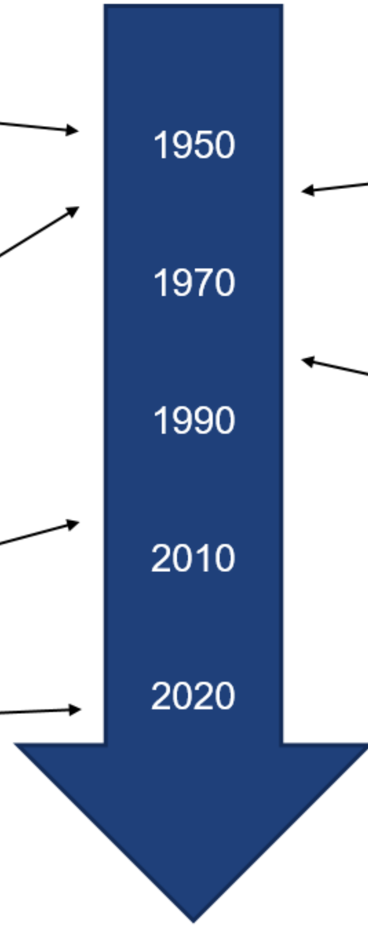
Brief history of nEDM

1950: Suggestion to measure nEDM to test parity [1]

1957: Publication of first dedicated nEDM measurement using magnetic resonance on neutron beams

2006: Last new improvement on nEDM limit

2020: Our newest measurement



1957: Discovery of P violation

1980: First measurement of nEDM using stored ultracold neutrons

So far: always 0

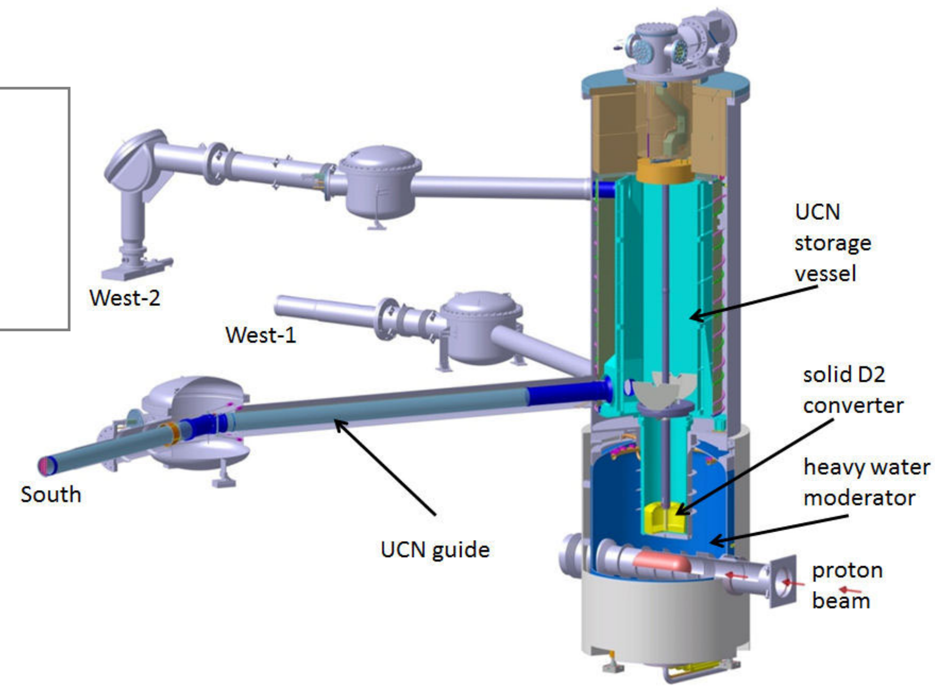
"The neutron EDM has ruled out more theories than any experiment in the history of physics" [2]

[1] E.M. Purcell, N.F. Ramsey, Phys Rev **17,** 807 1950
[2] R. Golub, S. Lamoreaux Phys Rep **237**, 1, 1-62

Ultracold - storable neutrons (UCN)

UCN (< 250 neV)   < 7 m/s   > 500 Å

Total reflection - material dependent
Ni, Ni^{58}, Be, DLC, steel
V_F = 180 - 300 neV
(neutron optical potential)



magnetic

$V_m = -\mu B$

60 neV T^{-1}

gravity

$V_g = m_n g h$

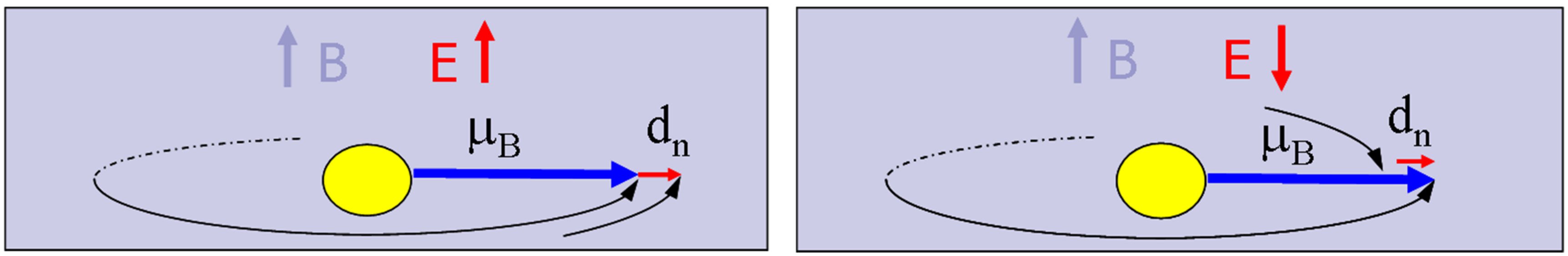
100 neV m^{-1}

PSI UCN Source
Bison et al. EPJ A 56 (2020) 33

Poster I. Rienäcker at PANIC2021

nEDM experiment principle

Difference of UCN precession frequencies in parallel/anti-parallel B and E fields:

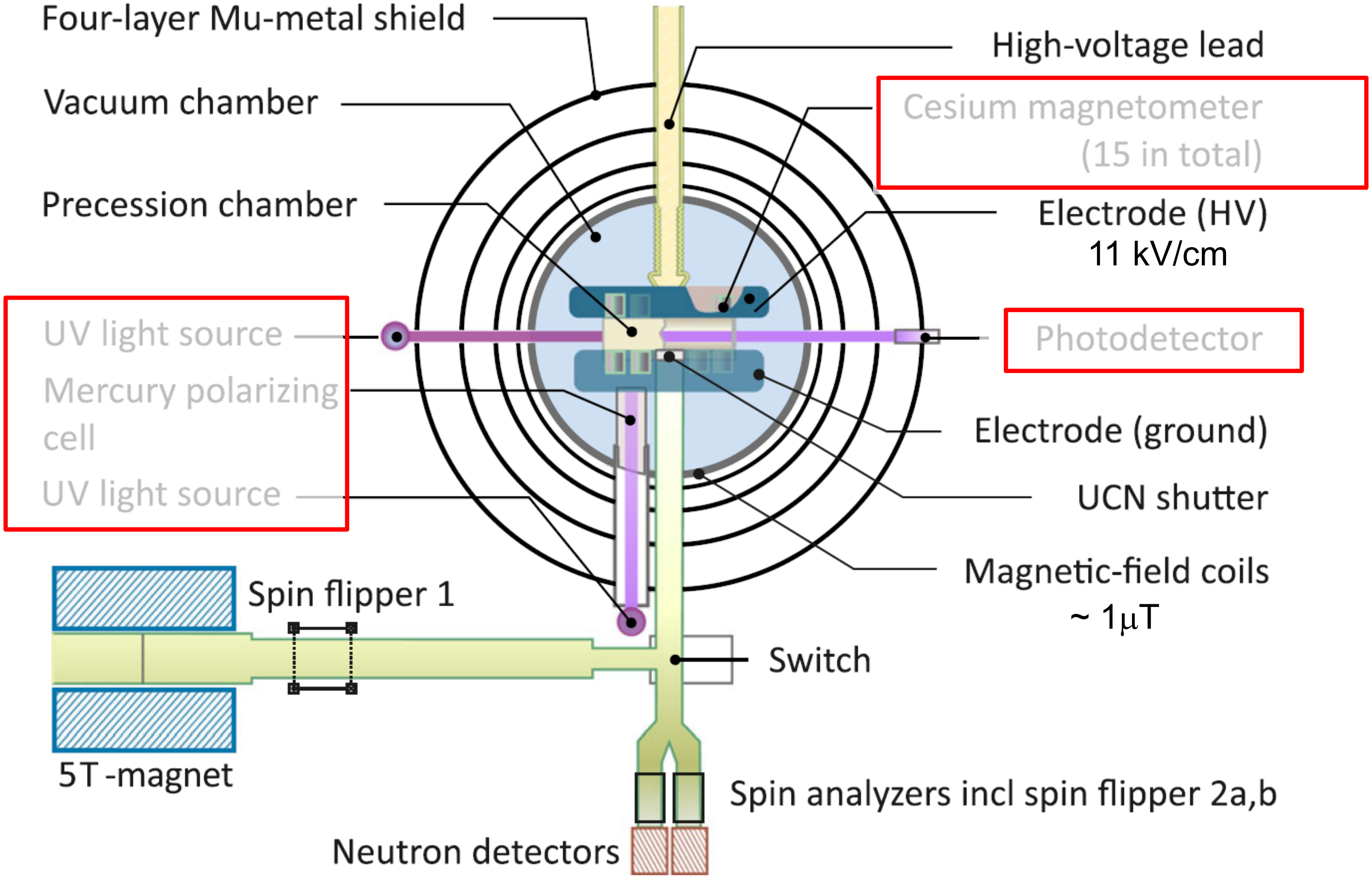


$$h\Delta f = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\cancel{\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}$$

2 measurements example:

$\sigma_{d_n} < 10^{-24}$ e cm → σ_f < 10 μHz at 10 kV/cm → σ_B < 0.2 pT at 1 μT

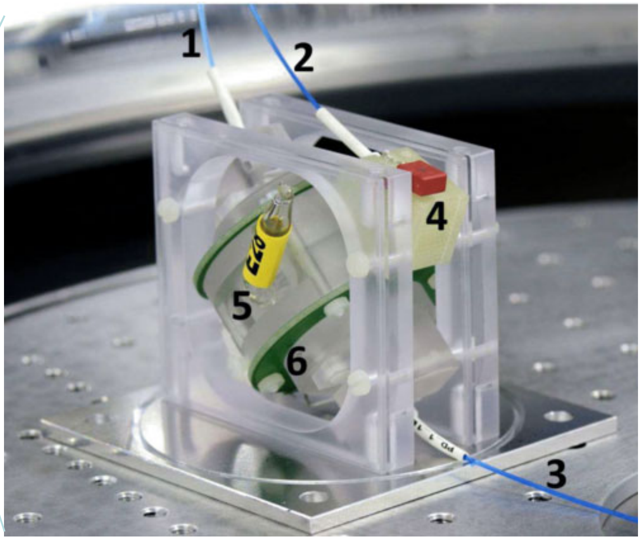
Apparatus


Four-layer Mu-metal shield
High-voltage lead
Vacuum chamber
Cesium magnetometer
(15 in total)
Precession chamber
Electrode (HV)
11 kV/cm
UV light source
Photodetector
Mercury polarizing
cell
UV light source
Electrode (ground)
UCN shutter
Magnetic-field coils
~ 1μT
Spin flipper 1
Switch
5T -magnet
Spin analyzers incl spin flipper 2a,b
Neutron detectors

NEW: Improved magnetometry

- Compensate and correct for magnetic-field changes:
  - ^{199}Hg co-magnetometer
  - array of optically pumped cesium vapor magnetometers
  - offline B-field mapping

  Abel C et al., arXiv: 2103.09039v2 (2021)



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

Magnetic-field uniformity: Abel C et al. Phys. Rev. A 99 (2019) 042112

The Ramsey technique

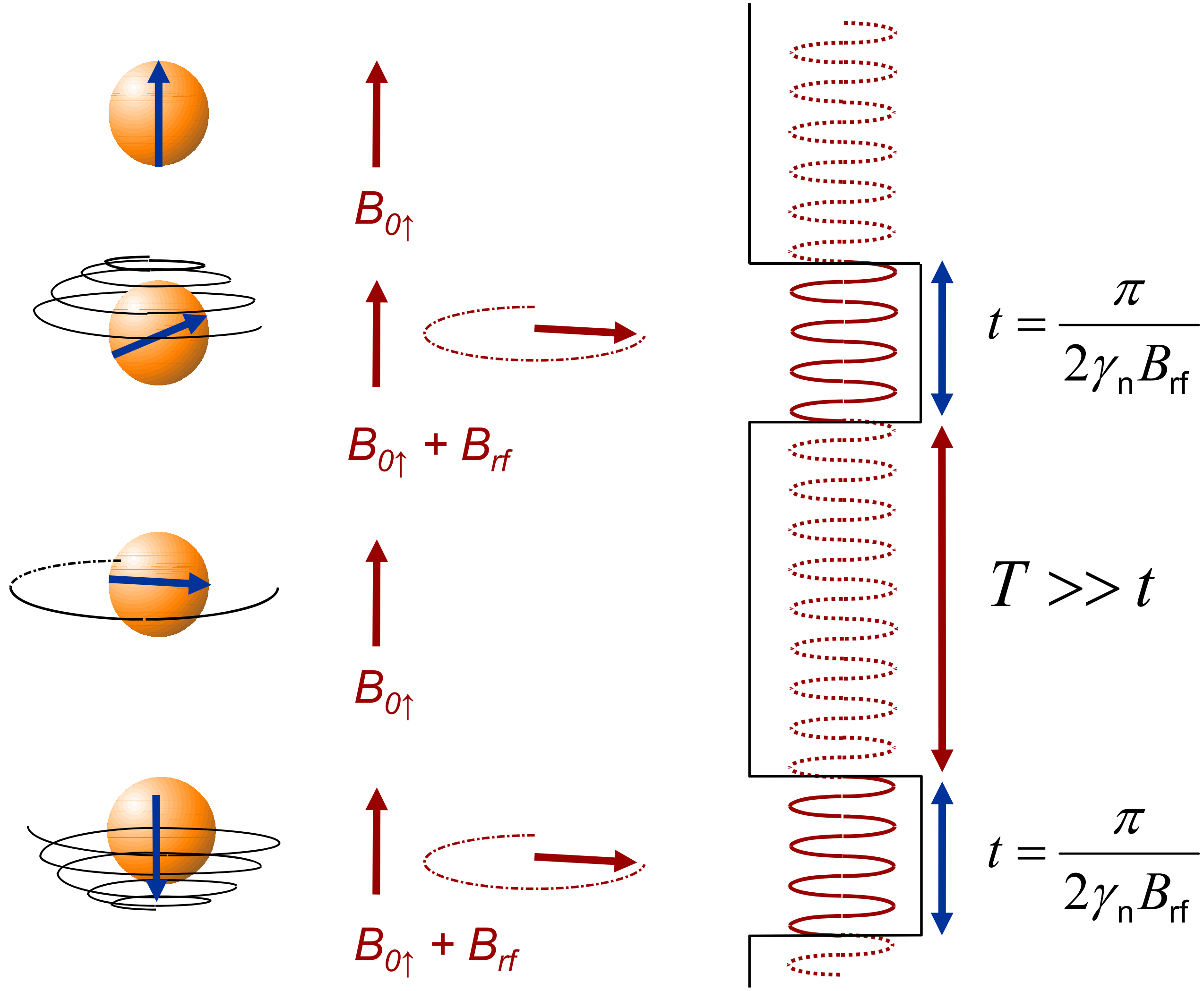
of separated oscillatory fields

"Spin up" neutron

Apply $\pi/2$ spin flip pulse

Free precession at ω_L

Second $\pi/2$ spin flip pulse.



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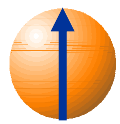
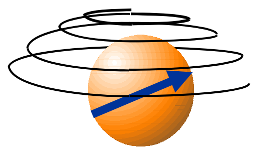
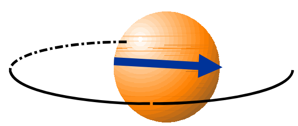


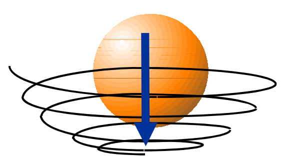
Apply π/2 spin flip pulse



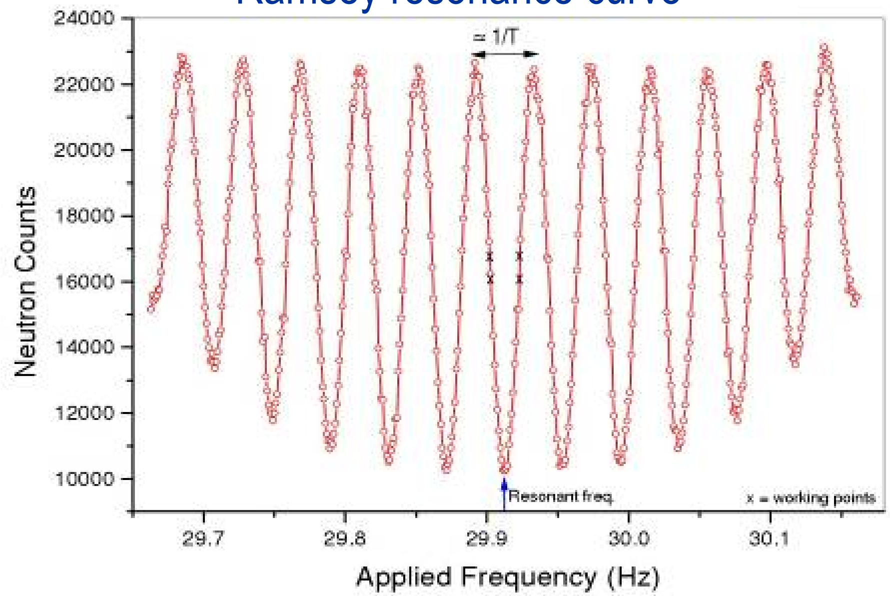
Free precession at ω $_L$



Second π/2 spin flip pulse.



Ramsey resonance curve

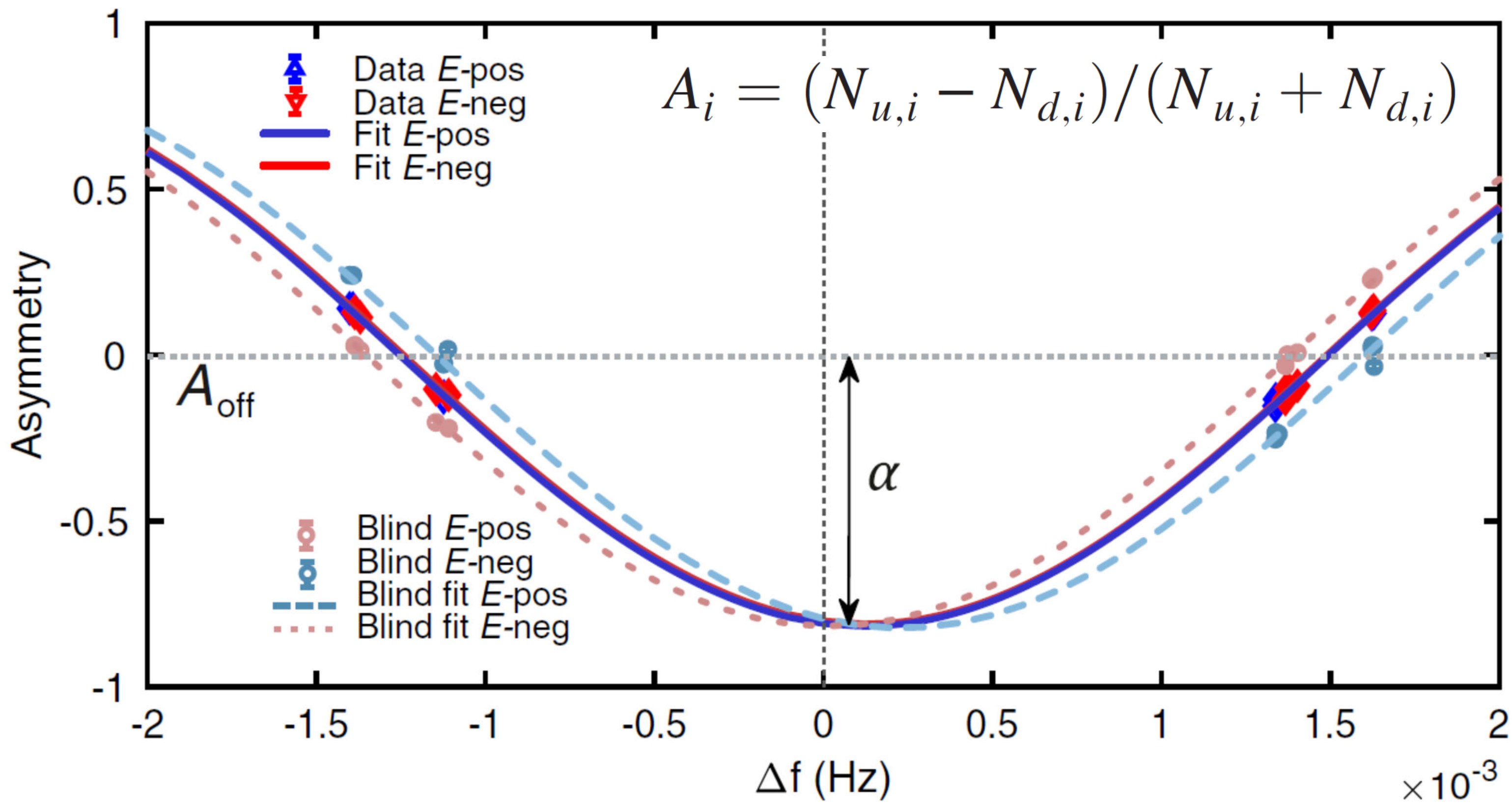


Sensitivity: $$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- α Visibility of resonance
- *E* Electric field strength
- *T* Time of free precession
- *N* Number of neutrons

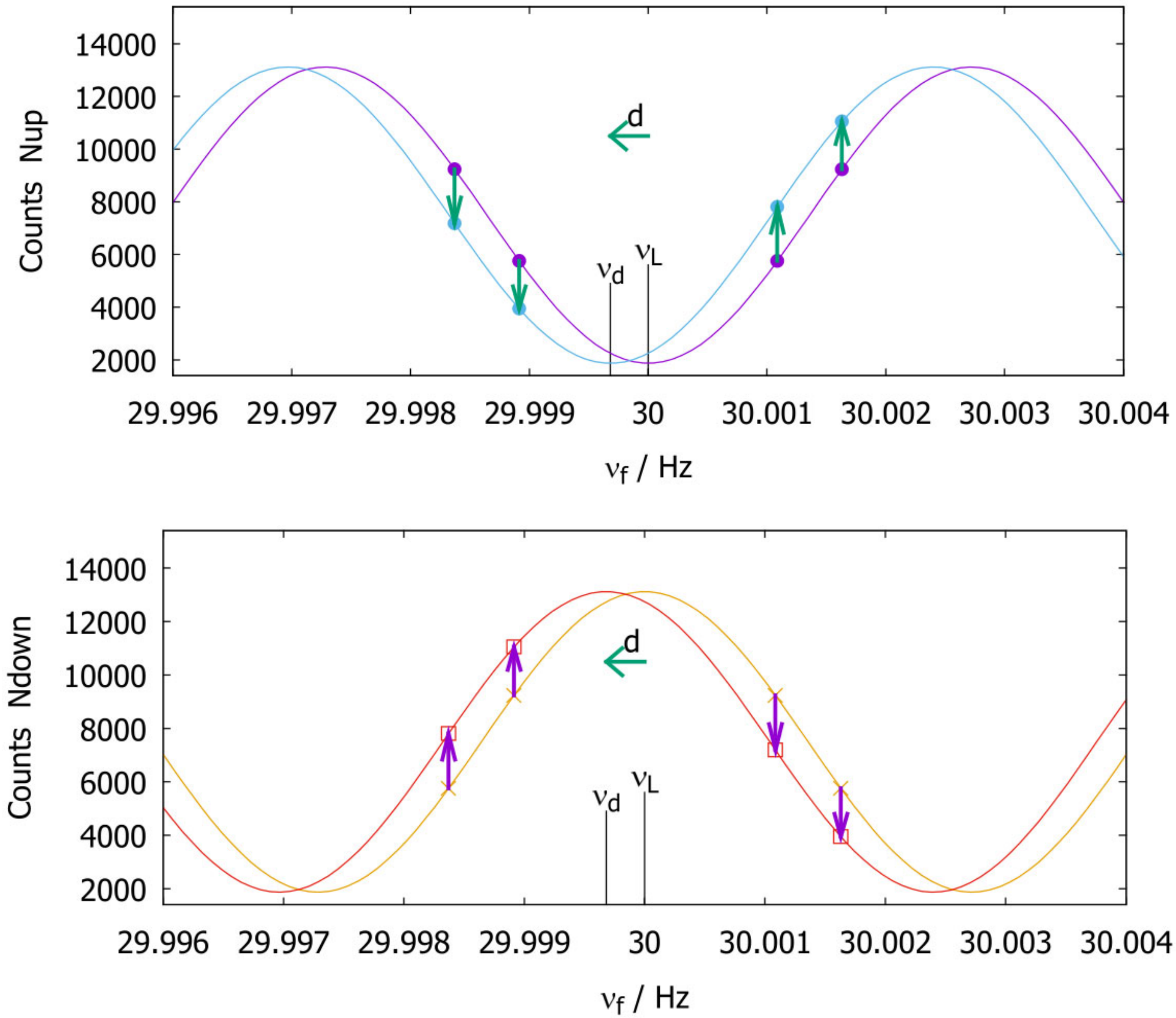
Ramsey pattern analysis

Data taking strategy: Abel C et al. EPJ Web of Conferences **219**, 02001 (2019)



$$A_i = A_{\mathrm{off}} \mp \alpha \cos\left(\frac{\pi \Delta f_i}{\Delta \nu} + \Phi\right)$$

Data-Blinding

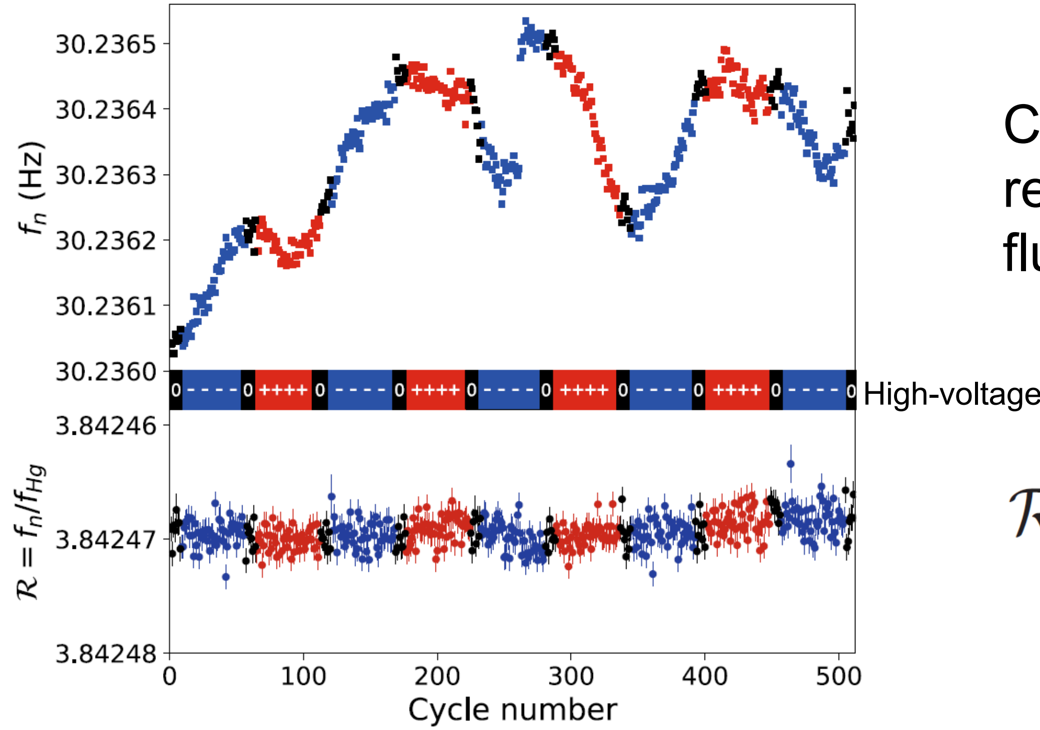


Concept: add an *E*-field dependant shift to the neutron frequency by moving counts between detectors

First nEDM measurement using data blinding

Ayres NJ et al. EPJ A 57 (2021) 152

Compensation and shifts



Compensation for residual magnetic-field fluctuations and drifts

$$\mathcal{R}_i = f_{n,i}/f_{\mathrm{Hg},i}$$

$$\mathcal{R} = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right|\left(1 + \delta_{\mathrm{EDM}} + \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{grav}} + \delta_{\mathrm{T}} + \delta_{\mathrm{other}}\right)$$

$$\delta_{\mathrm{EDM}} = -\frac{2E}{\hbar|\gamma_n|B_0}\left(d_n + d_{n\leftarrow\mathrm{Hg}}\right)$$

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Crossing point analysis

Gravitational shift:

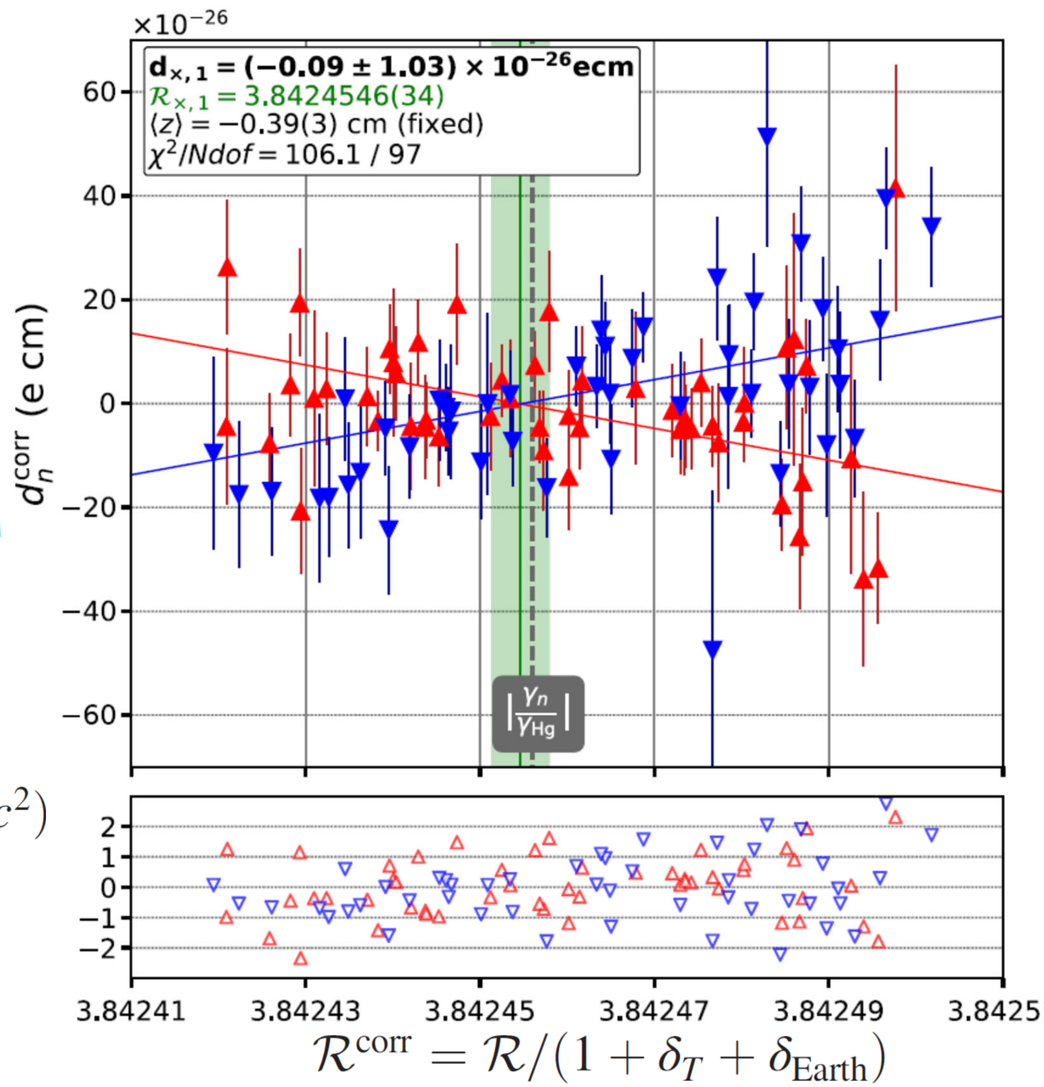
$$\delta_{\mathrm{grav}} = \pm \frac{G_{\mathrm{grav}} \langle z \rangle}{|B_0|}$$

shifts $\mathcal{R}$

$\delta_{\mathrm{EDM}}^{\mathrm{false}}$: v × E contribution

$$d_{\mathrm{n}}^{\mathrm{meas}} = d_{\mathrm{n}}^{\mathrm{true}} + \frac{\hbar}{8c^2} |\gamma_n \gamma_{\mathrm{Hg}}| R^2 (G_{\mathrm{grav}} + \hat{G})$$

$$d_n^{\mathrm{meas}} - \hbar |\gamma_n \gamma_{\mathrm{Hg}}| R^2 \hat{G} / (8c^2)$$



Systematic effects

(x10^{-28} e cm)

Effect	Shift	Error
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

d_x, R_x (first three effects)

Dedicated mapping measurements (Higher-order gradients, Transverse field correction)

Constrained with measurement at PTB Berlin (Local dipole fields)

Cs Magnetometers on HV electrode (Uncompensated G drift)

Not anticipated at design, considered in n2EDM (Inc. scattering ^{199}Hg)

Total systematic error **0.18 x 10^{-26} e cm**

Final result

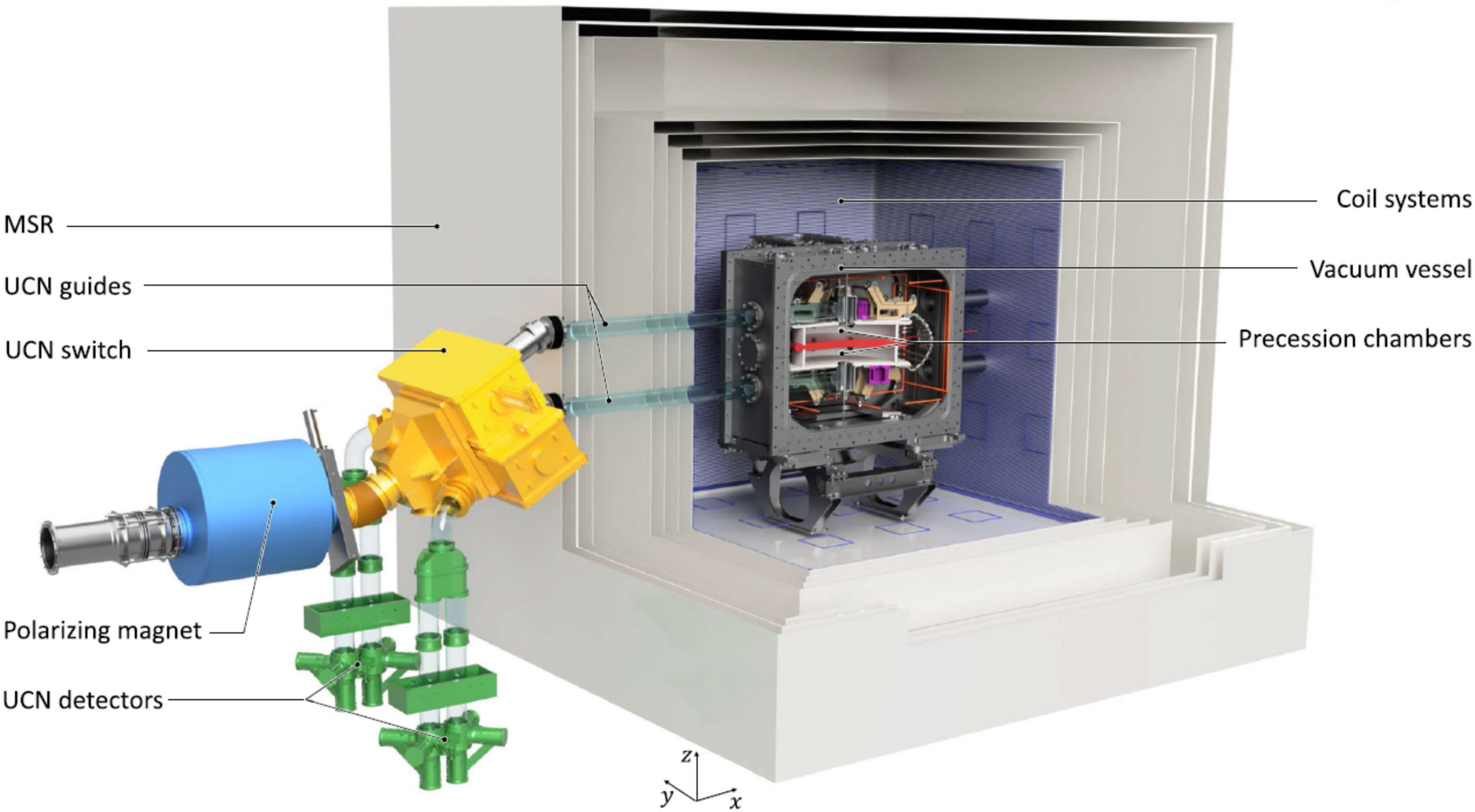
- New measurement:
  - $(0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}$ e cm
  - $|d_n| < 1.8 \times 10^{-26}$ e cm (90% CL)

  C. Abel *et al.* PRL **124**, 081803 (2020)

- Previous measurement:
  - $(-0.2 \pm 1.5_{\mathrm{stat}} \pm 1.0_{\mathrm{sys}}) \times 10^{-26}$ e cm
  - $|d_n| < 3 \times 10^{-26}$ e cm (90% CL)

  J. M. Pendlebury *et al.* Phys. Rev. D **92**, 092003 (2015)

Next: n2EDM for 1×10^{-27} e cm



The design of the n2EDM experiment: Ayres NJ et al. Eur. Phys. J. C 81 (2021) 512

Comparison: nEDM & n2EDM

	nEDM 2016	n2EDM
Chamber	DLC and dPS	DLC and dPS
Diameter D	47 cm	80 cm – two chambers
N (per cycle)	15,000	121,000
T	180 s	180 s
E	11 kV/cm	15 kV/cm
α	0.75	0.8
$\sigma(f_n)$ per cycle	9.6 µHz	3.2 µHz
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm
$\sigma(d_n)$ (final)	9.5×10^{-27} e cm	1.1×10^{-27} e cm

Poster S. Emmenegger PANIC 2021

Conclusion

- The measurement of a permanent electric dipole moment of the neutron, a CP-violating observable, is one of the most important experiments at the low energy frontier of particle physics

- New result of the nEDM collaboration at PSI:
  - $(0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}$ e cm, our systematic error is a factor 5 improvement on previous measurement

- Next phase n2EDM:
  - a sensitivity of 1×10^{-27} e cm will be reached after 500 days of data taking
  - possible future modifications are expected to lead to a sensitivity well within the 10^{-28} e cm range

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Thank you