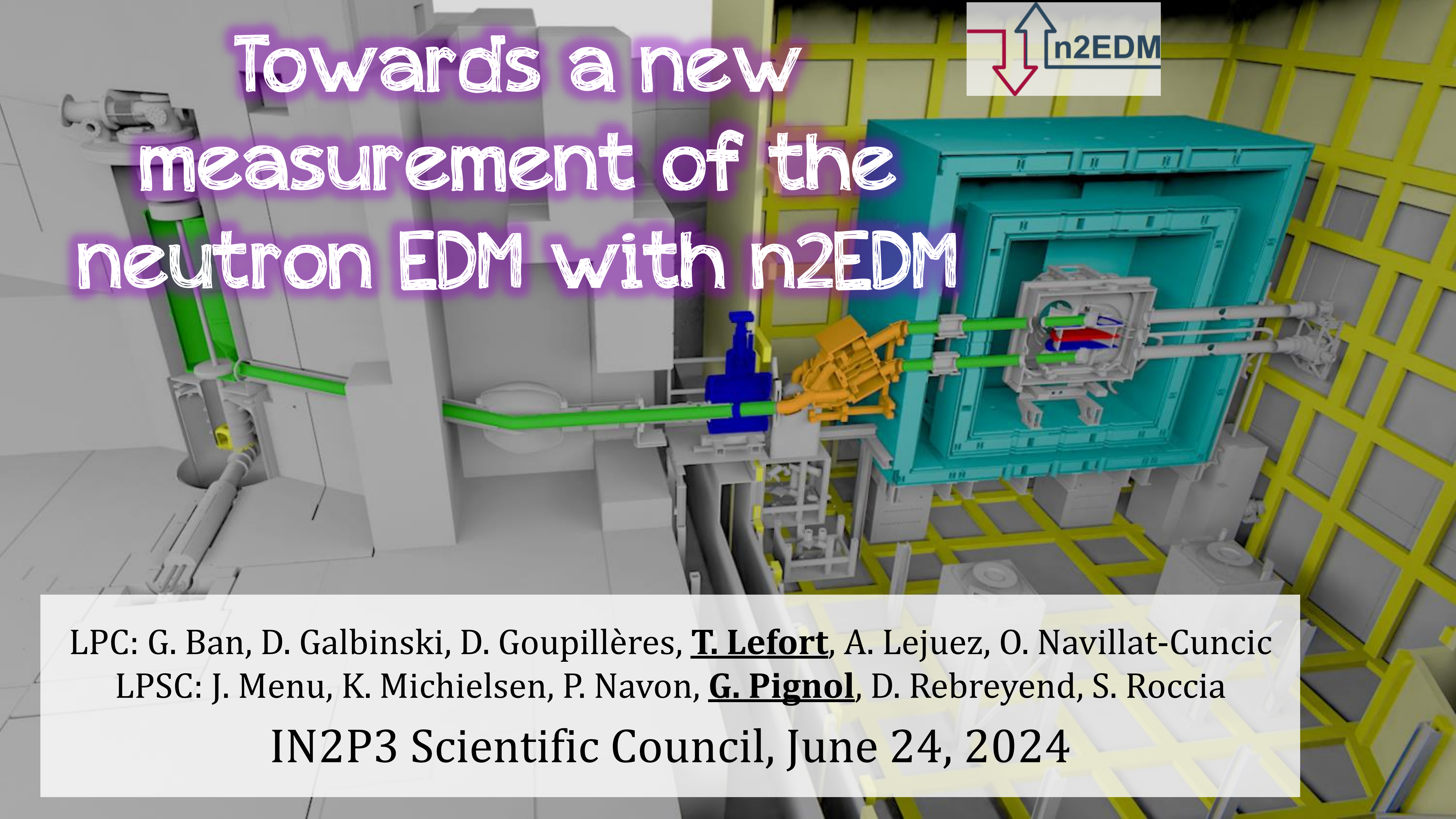


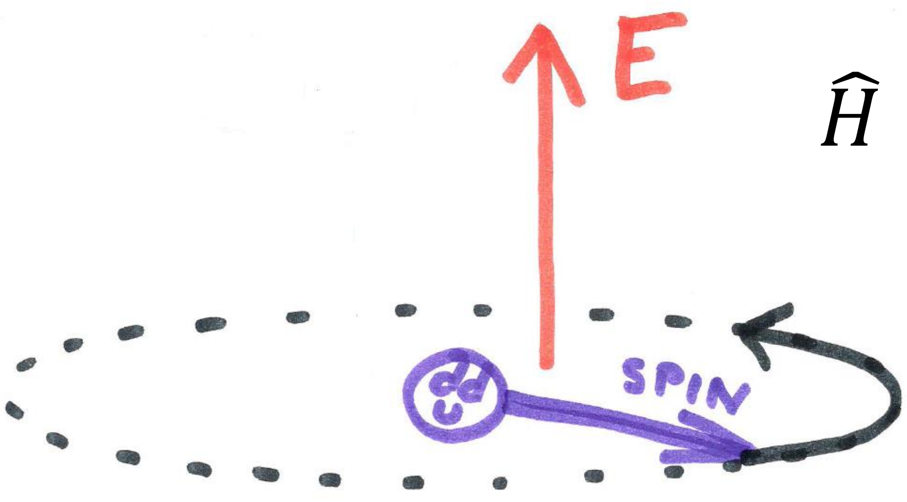
Towards a new measurement of the neutron EDM with n2EDM

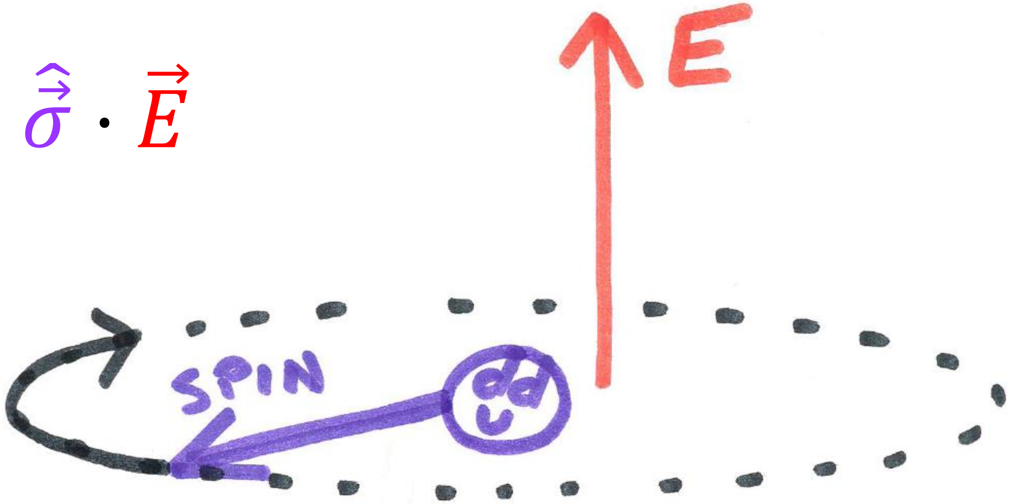
LPC: G. Ban, D. Galbinski, D. Goupillères, **T. Lefort**, A. Lejuez, O. Navillat-Cuncic
LPSC: J. Menu, K. Michielsen, P. Navon, **G. Pignol**, D. Rebreyend, S. Roccia

IN2P3 Scientific Council, June 24, 2024

EDM = coupling between spin and E-field

$$\hat{H} = -d\,\hat{\vec{\sigma}} \cdot \vec{E}$$





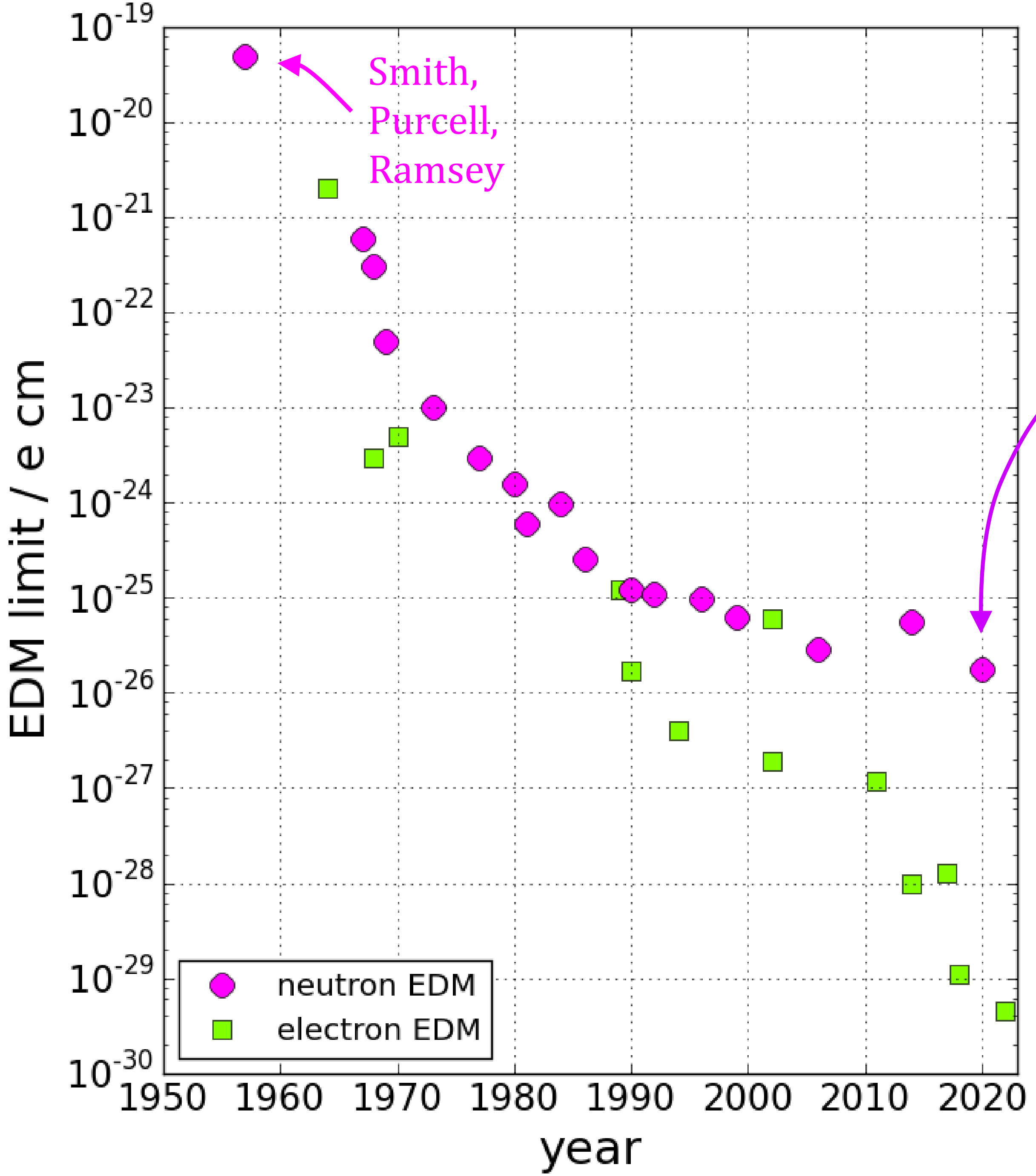
>> PLAY >>

<< REWIND <<

If $d \neq 0$ the process and its time reversed version are different.

Violation of T $\xrightarrow{\text{CPT}}$ **Violation of CP**

EDM limits



Best limit from the nEDM experiment @PSI

$$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm}$$

Abel et al, PRL (2020)

Nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_N}$$

In natural units $|d_n| < 2 \times 10^{-12} \times \mu_N / c$

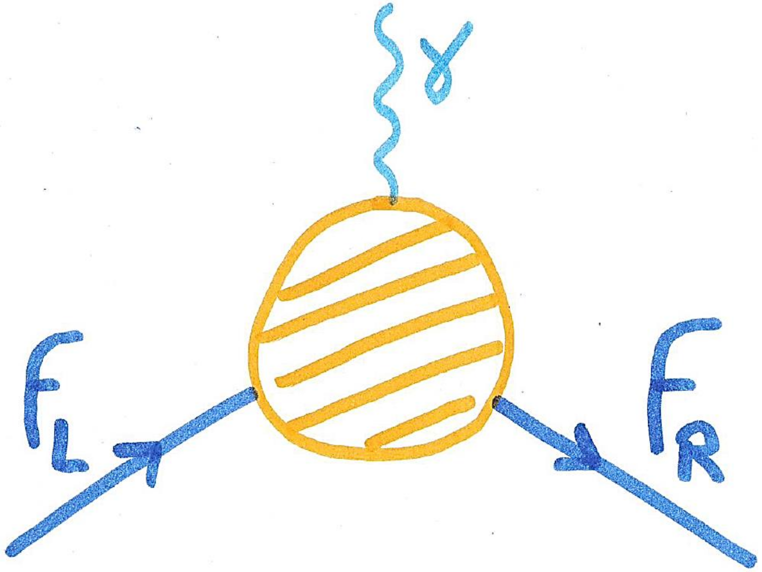
In comparison $\mu_n = -1.9130427(5)\ \mu_N$

Outline

1. Physics case for searching EDMs
2. How to measure nEDM: state of the art
3. Next generation nEDM experiments

4. The design of n2EDM
5. In2p3 contributions
6. Commissioning results
7. Perspectives until 2030 and beyond

the EDM from the point of view of a high energy theorist



Fermion-photon coupling

$$\mathcal{L} = \frac{1}{2}(\boldsymbol{\delta\mu} + i\boldsymbol{d})\bar{f}_L \sigma_{\mu\nu} f_R \, F^{\mu\nu} + h.c.$$

Real part = anomalous magnetic moment

Imaginary part = electric dipole moment

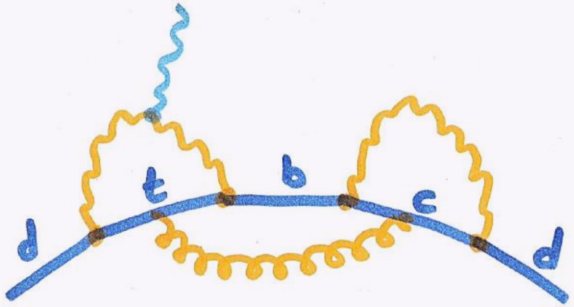
Non-relativistic limit: $\widehat{H} = -\boldsymbol{\mu}\sigma B - \boldsymbol{d}\sigma E$

The neutron EDM is quasi-forbidden

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

Contribution of weak interaction

Leading order
for quark EDMs at 3 loops!
Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-18}\,\mu_N/c$

* The "long distance" contribution dominates over quark EDMs, still super-small.

The neutron EDM is quasi-forbidden
For known reason (CKM)
And unknown reason (strong CP)

The SM QCD theta term $\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$

generates a potentially enormous neutron EDM : $d_n \sim -0.02 \times \bar{\theta}\,\mu_N/c$

→ $|\bar{\theta}| < 10^{-10}$ → « Strong CP problem »

CP violation and EDM in the SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{D=5}} + \mathcal{L}_{\text{D=6}} + \cdots$$

$$\mathcal{L}_{\text{D=6}} = \sum_{a=1}^{3045} \frac{c_a}{\Lambda^2} O_a^{(6)}$$

New physics at high scale would generate these new interactions, many of which are CP-violating and contribute to create EDMs.

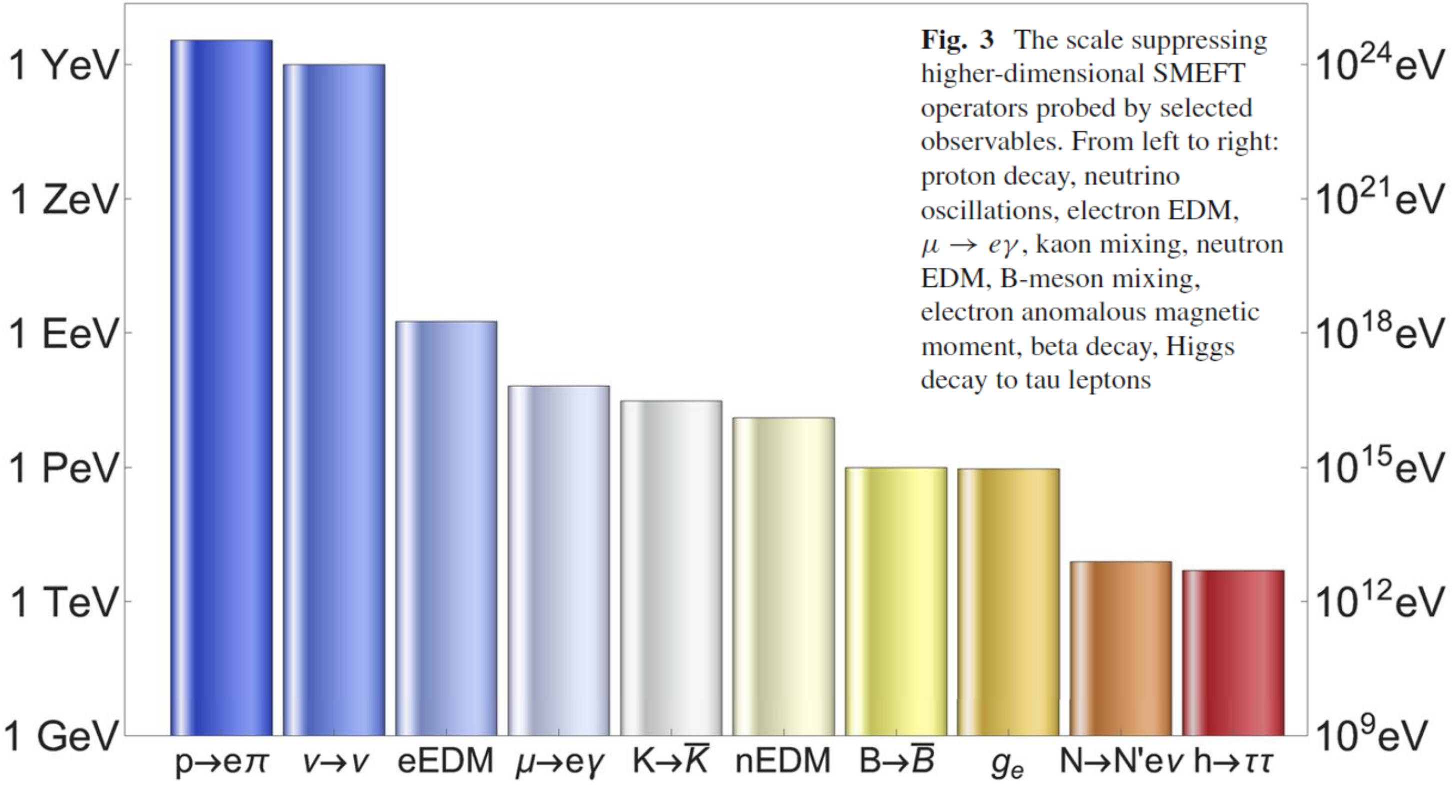


Fig. 3 The scale suppressing higher-dimensional SMEFT operators probed by selected observables. From left to right: proton decay, neutrino oscillations, electron EDM, $\mu \to e\gamma$, kaon mixing, neutron EDM, B-meson mixing, electron anomalous magnetic moment, beta decay, Higgs decay to tau leptons

nEDM probes $\Lambda = 10$ PeV

Figure A. Falkowski, ***Lectures on SMEFT*** EPJC (2023)

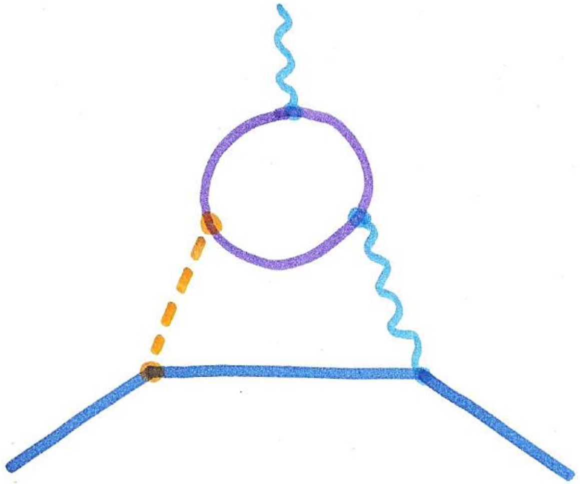
Concrete model: modified Higgs couplings

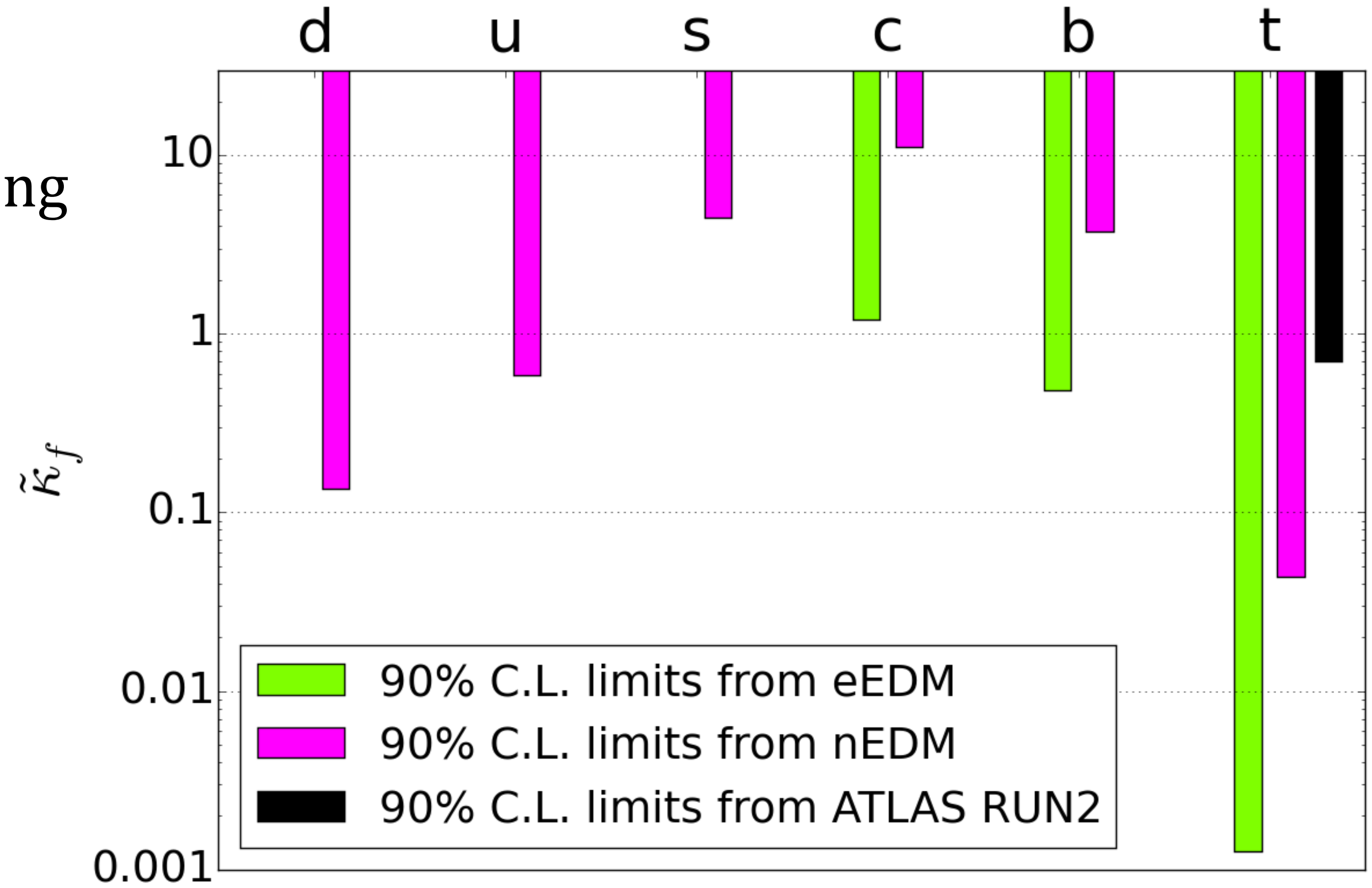
Modified Higgs-fermion Yukawa coupling

$$\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + \boxed{\underset{\textbf{CPV}}{i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h}}\right)$$

Generates EDM at 2 loops

Barr, Zee, PRL 65 (1990)





Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480
ATLAS, PRL 125, 061802 (2020)

Physics case to search for nEDM

1. **Great puzzle**.
   New sources of CPV required to explain baryogenesis (Sakarov).
   A broad class of models "BSM electroweak baryogenesis" predict new CPV physics at the ~TeV scale

2. **Great sensitivity.**
   nEDM probes new CPV physics at the scale $\Lambda = 10$ PeV.
   Next generation experiments will increase the reach by $\sqrt{10}$.
   Note: some concrete models predict $\frac{1}{\Lambda^2} \sim \frac{g^2}{(4\pi)^2} \frac{y_q}{M^2}$ $M \sim 1$ TeV ↔ $\Lambda \sim 10$ PeV

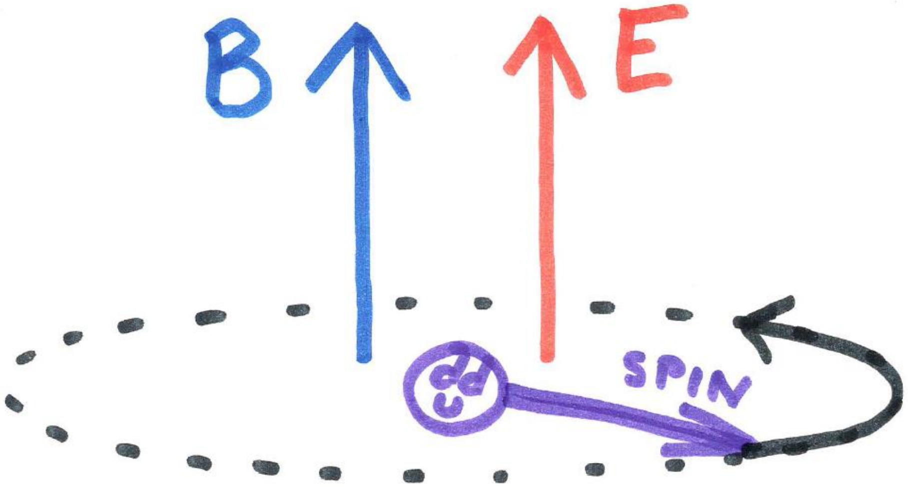
3. **Complementarity**.
   Importance of measuring the EDMs in different systems (neutron, atoms, muons…) to cover the many different possible fundamental sources of CP violation.

Outline

1. Physics case for searching EDMs
2. How to measure nEDM: state of the art
3. Next generation nEDM experiments

4. The design of n2EDM
5. In2p3 contributions
6. Commissioning results
7. Perspectives until 2030 and beyond

Basics of nEDM measurement



Larmor frequency

$\sim 30\ \text{Hz} \ @\ B = 1\ \mu\text{T}$

$$2\pi f = \frac{2\mu_n}{\hbar} B \pm \frac{2d_n}{\hbar} |E|$$

If $d_n \sim 10^{-26}\ e\ \text{cm}$ and $E \sim 10\ \text{kV/cm}$

duration of one full turn ~ 1 year

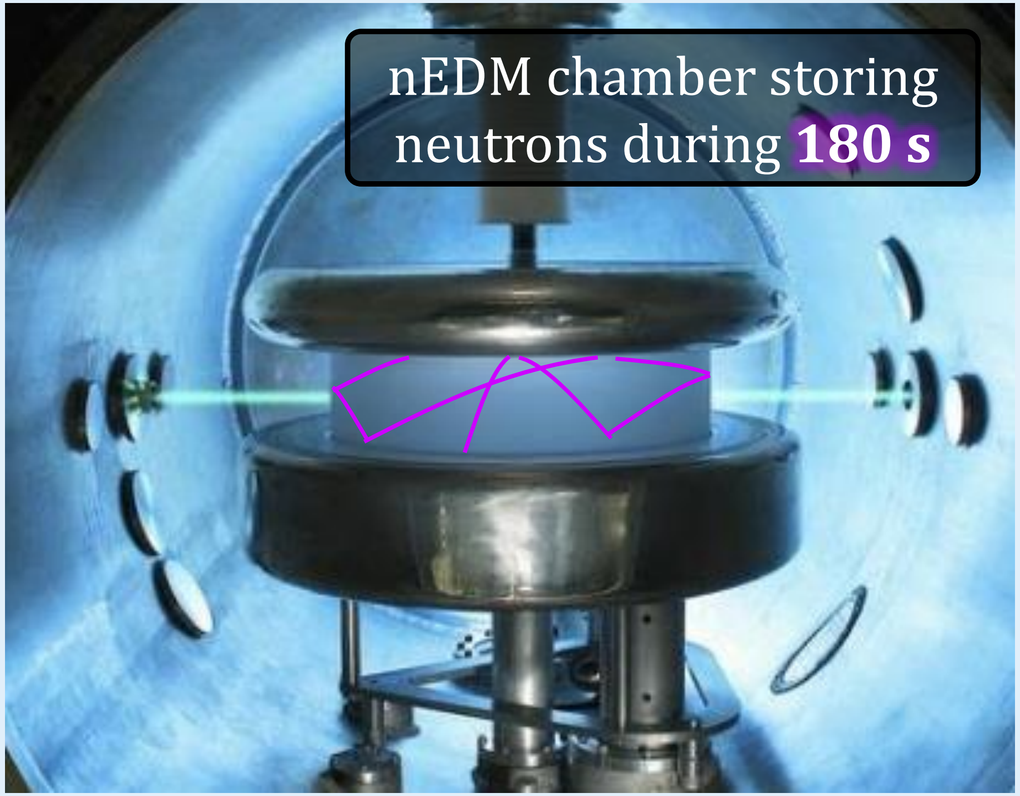
To detect such a minuscule coupling:

- **Long interaction time**
- **High intensity/statistics**
- **Control the magnetic field**

- Long interaction time
- High intensity/statistics
- Control the magnetic field

Use Ultracold neutrons

Neutrons with velocity <5m/s can undergo total reflection and be stored in material "bottles"


nEDM chamber storing neutrons during **180 s**

Use big magnetic shielding

+ Use quantum magnetometry

With mercury and cesium atoms

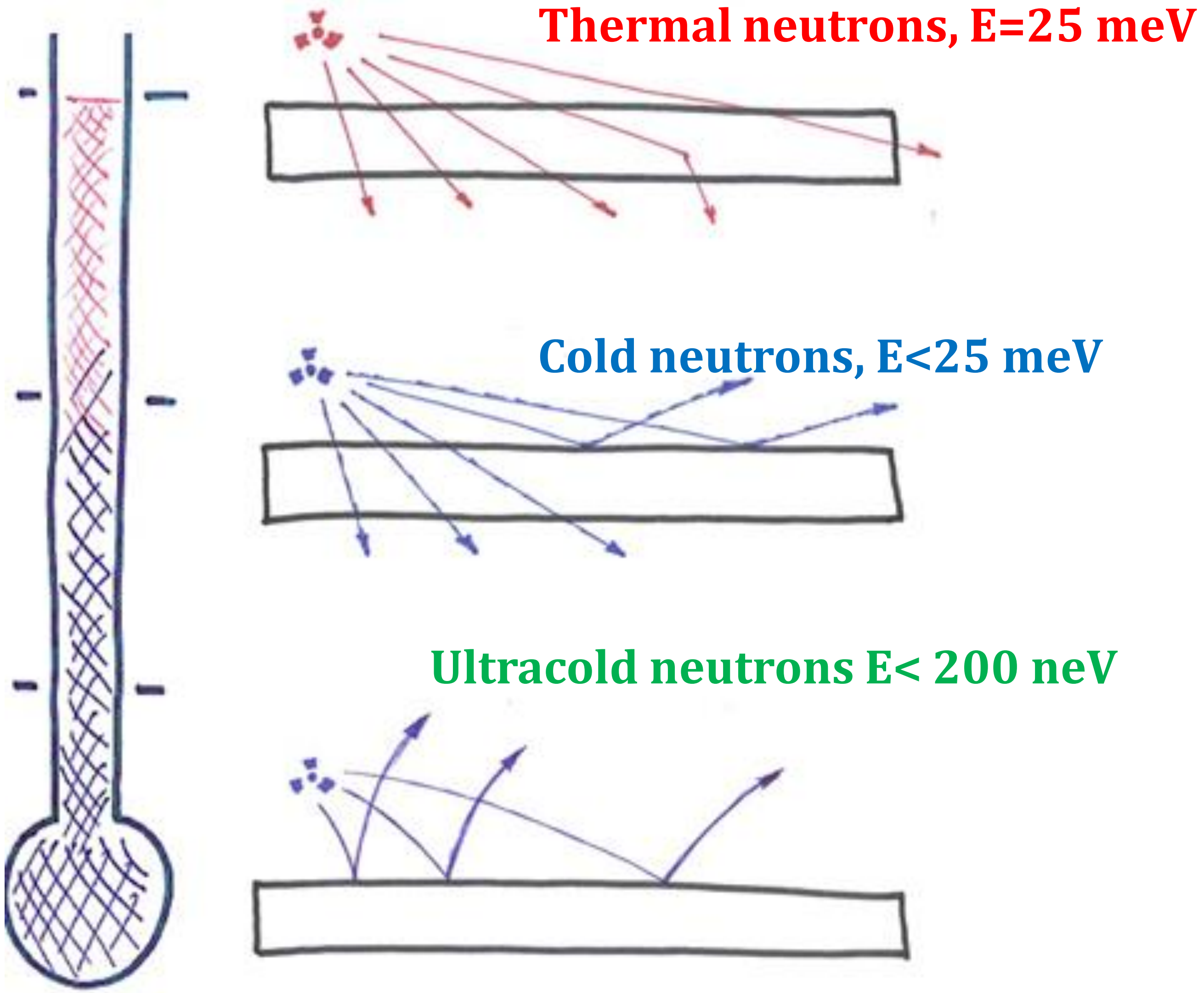
Abel et al, PRL (2020)

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}\ ecm$$

Limited by the number of UCNs (~500 million counts)

Uniformity of the B-field

Ultracold neutrons

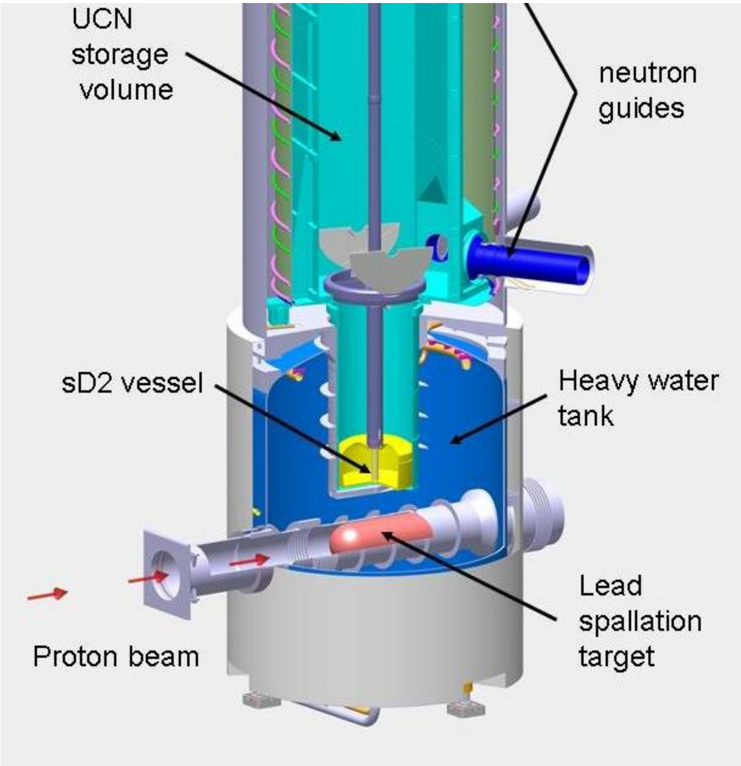


Thermal neutrons, E=25 meV

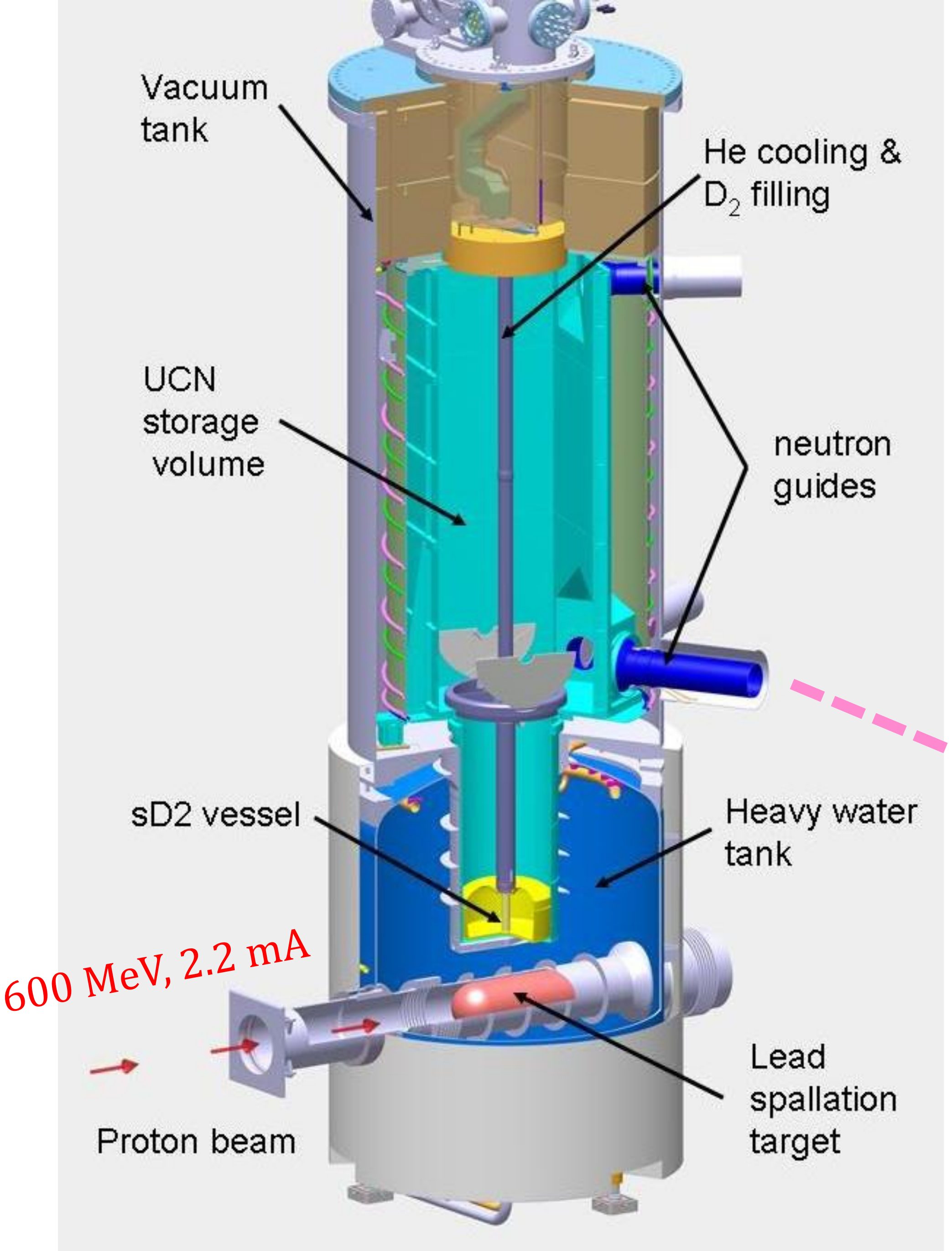
Cold neutrons, E<25 meV

Ultracold neutrons E< 200 neV

To produce UCNs:
convert thermal/cold neutrons to UCNs
- in solid deuterium (PSI, Los Alamos)
- or superfluid helium (TRIUMF, ILL).

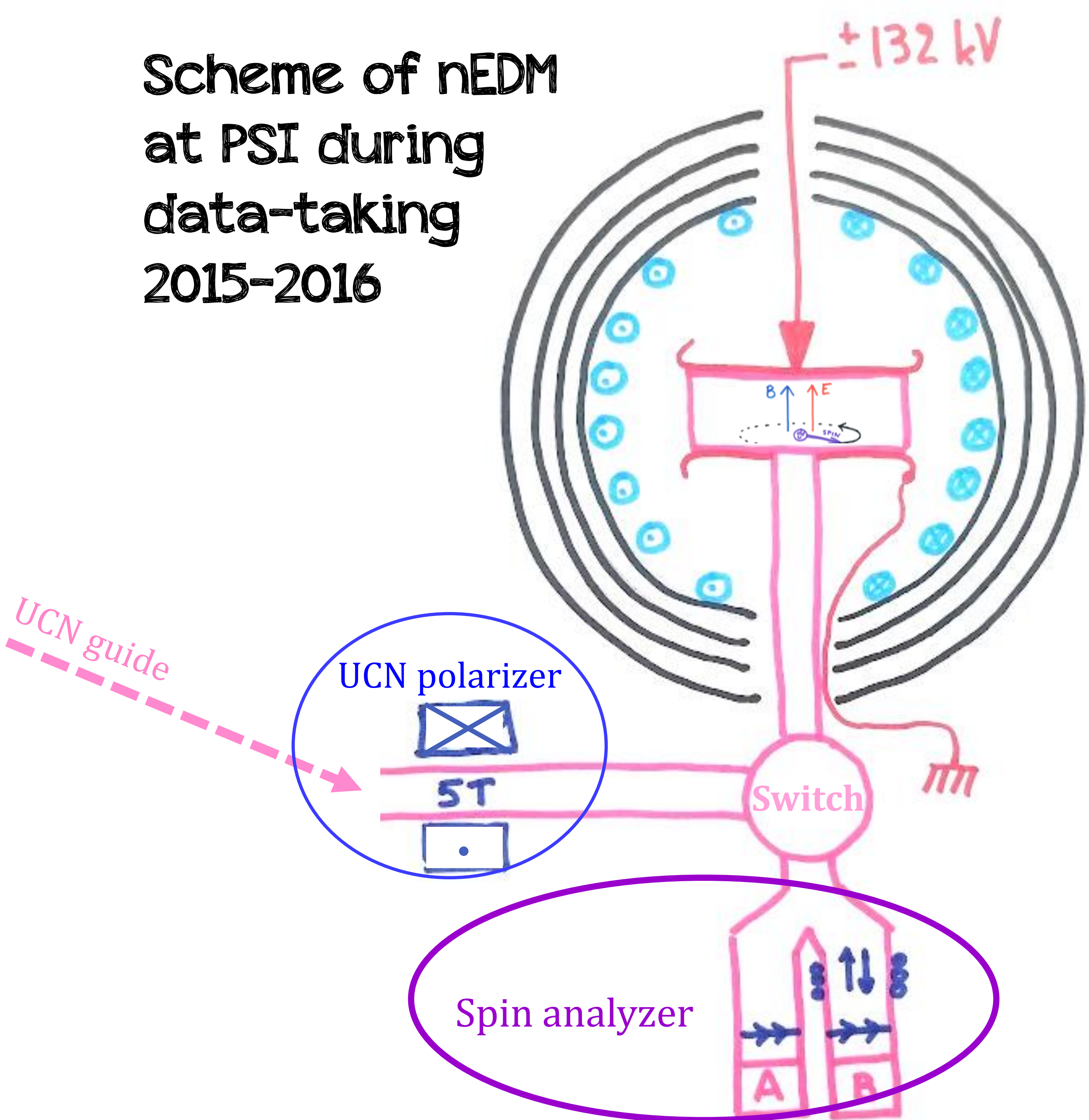


PSI UCN source, since 2011

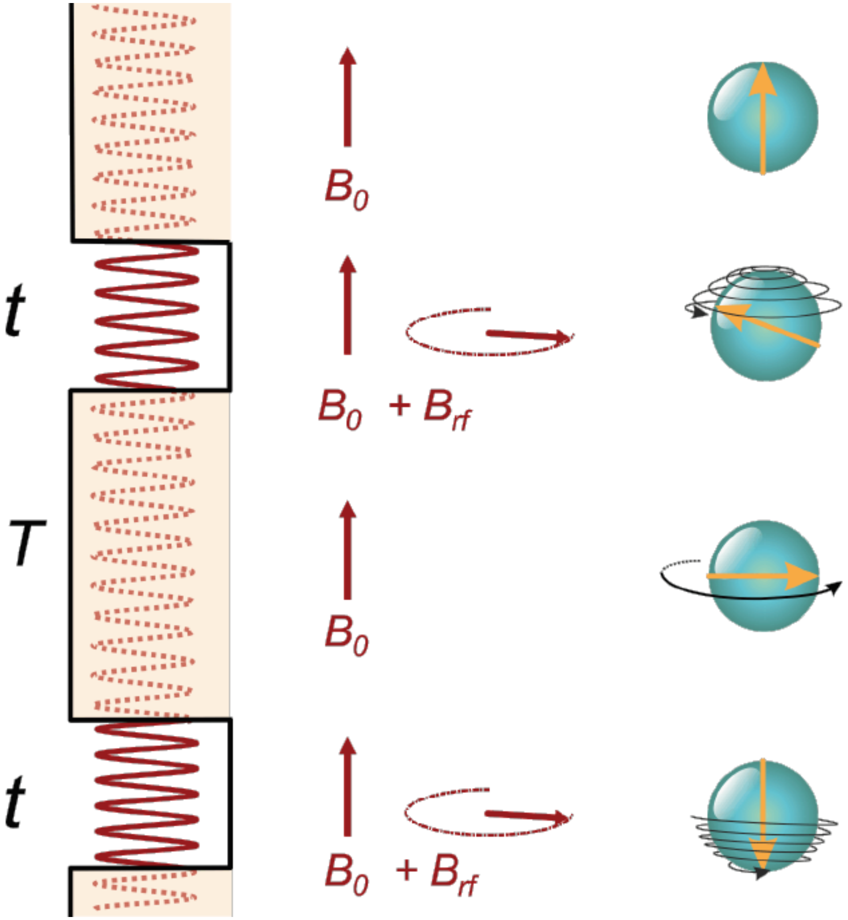


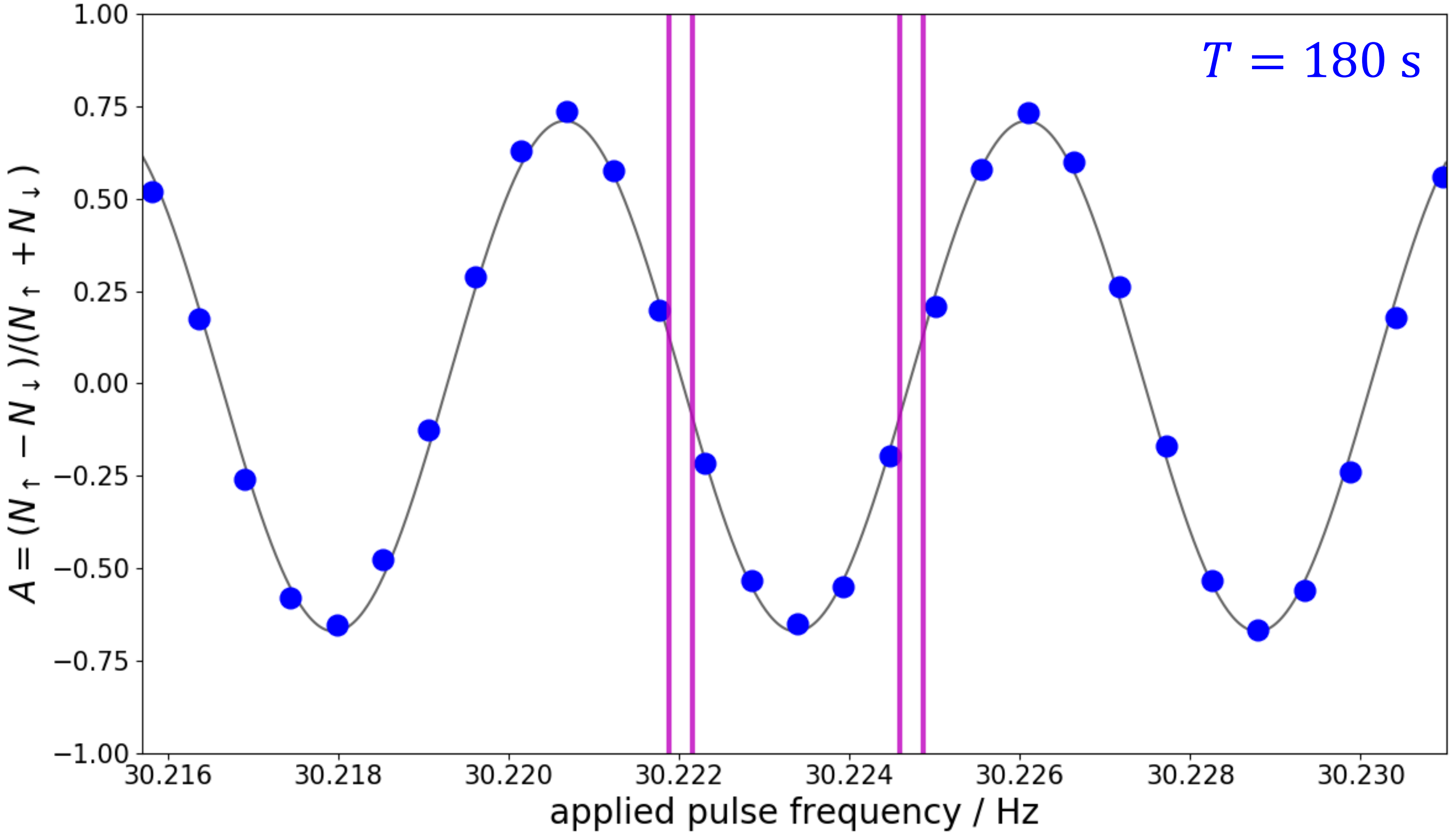
PSI UCN source

Scheme of nEDM at PSI during data-taking 2015-2016



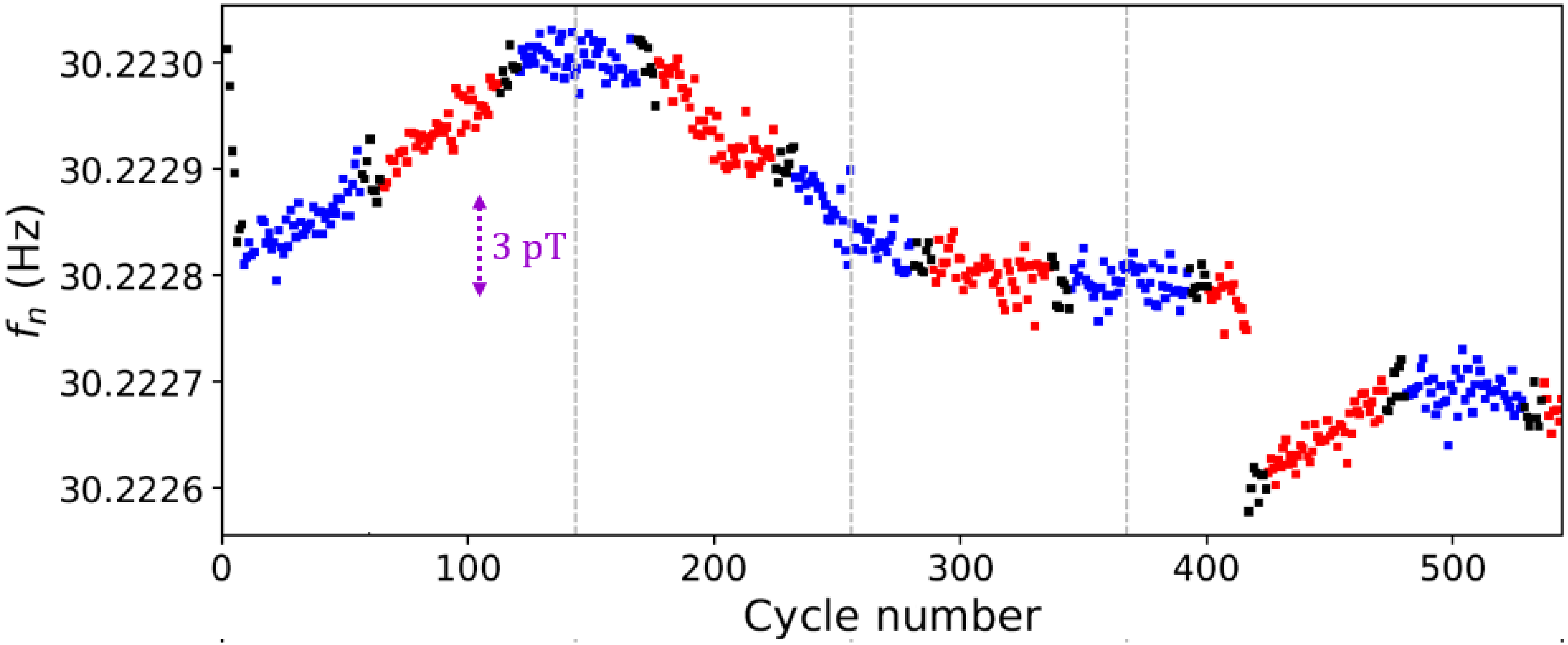
Ramsey's method to measure precession frequency





Statistical sensitivity: $\sigma d_n = \dfrac{\hbar}{2\,\alpha\,E\,T\sqrt{N}}$

nEDM data collected in 2015-2016

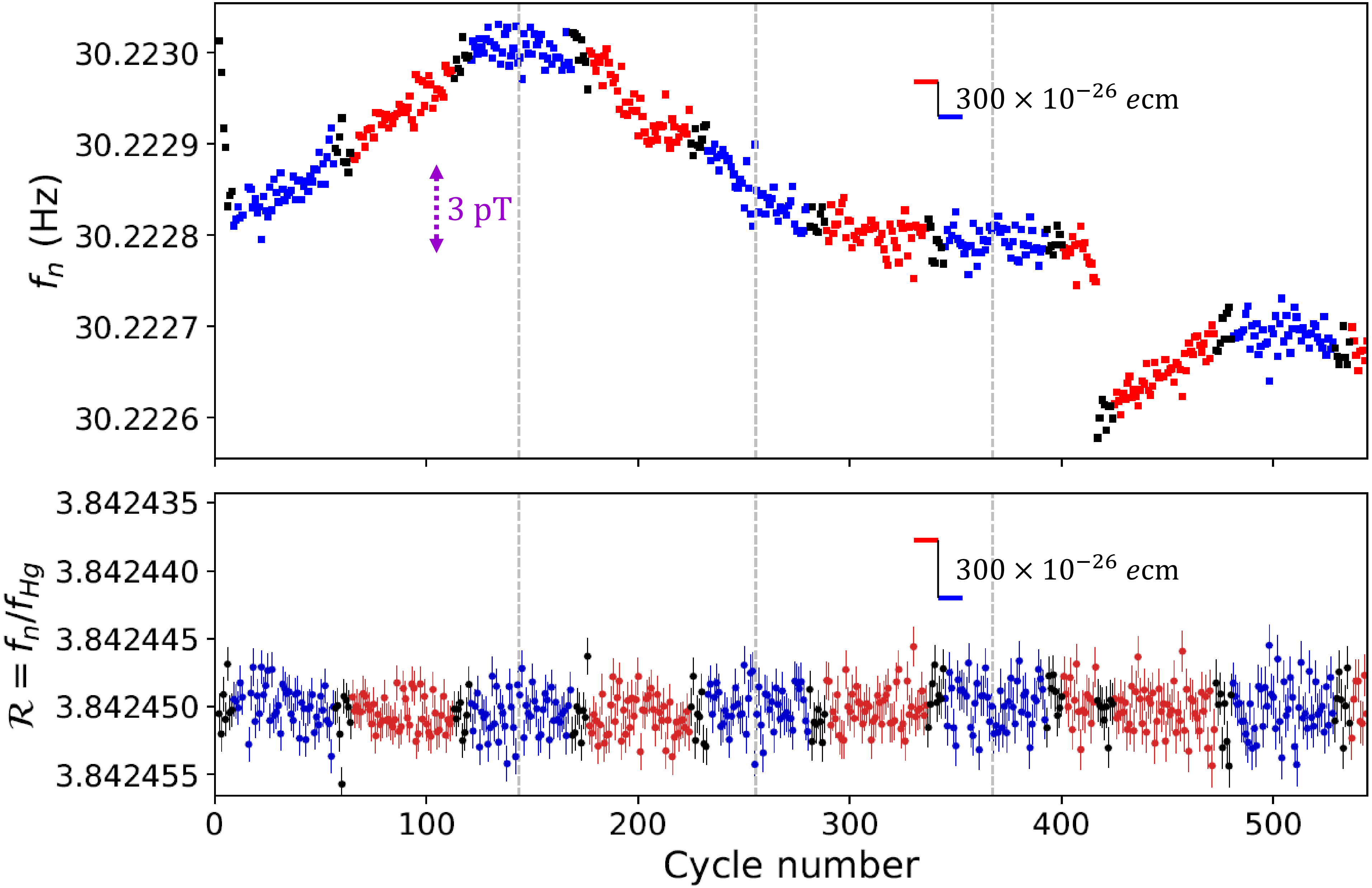


54,068 cycles recorded - one cycle every 5 min,
grouped in 99 sequences,
alternating E field polarity every 48 cycles
11,400 neutrons counted per cycle.

The rescue of the mercury comagnetometer

Magnetic fluctuations (random and correlated with E) are corrected for at each cycle with the Hg magnetometer by measuring

$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$



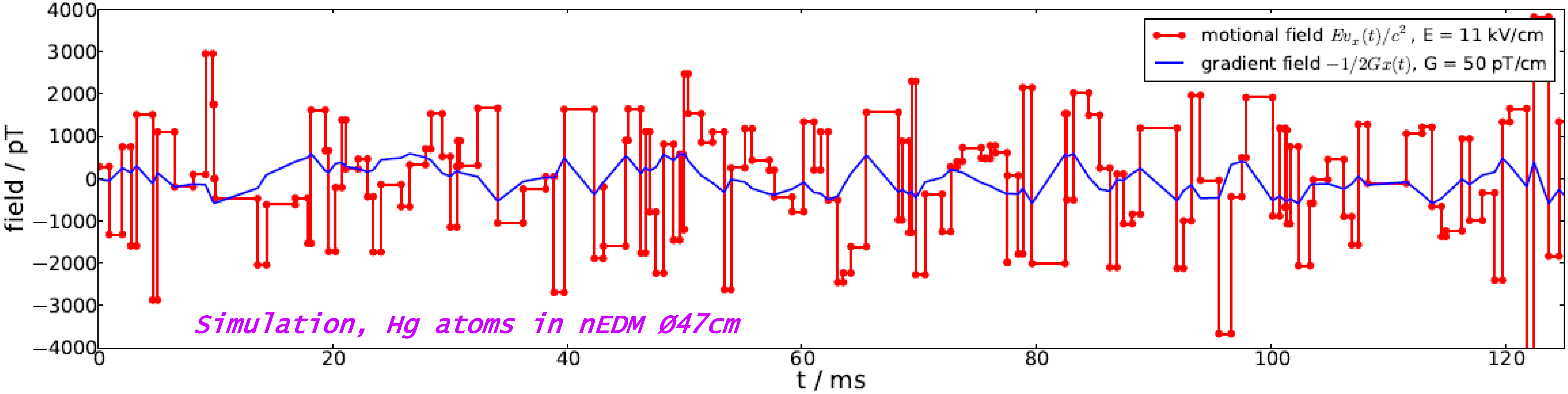
The comagnetometer pitfall: E x v /c^2

Transverse “noise” on
a mercury atom
in random motion

Nonuniform field

relativistic motional field

$$b(t) = \left(\vec{B}(t) + \frac{1}{c^2}\vec{E}\times\vec{v}(t)\right)\cdot\left(\overrightarrow{e_x} + i\overrightarrow{e_y}\right)$$



Simulation, Hg atoms in nEDM Ø47cm

Low frequency limit (Pignol&Roccia 2012): $d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = -\frac{\hbar|\gamma_n\gamma_{\mathrm{Hg}}|}{2c^2}\langle \boldsymbol{x}\boldsymbol{B}_{\boldsymbol{x}} + \boldsymbol{y}\boldsymbol{B}_{\boldsymbol{y}}\rangle$

Budget of systematic errors

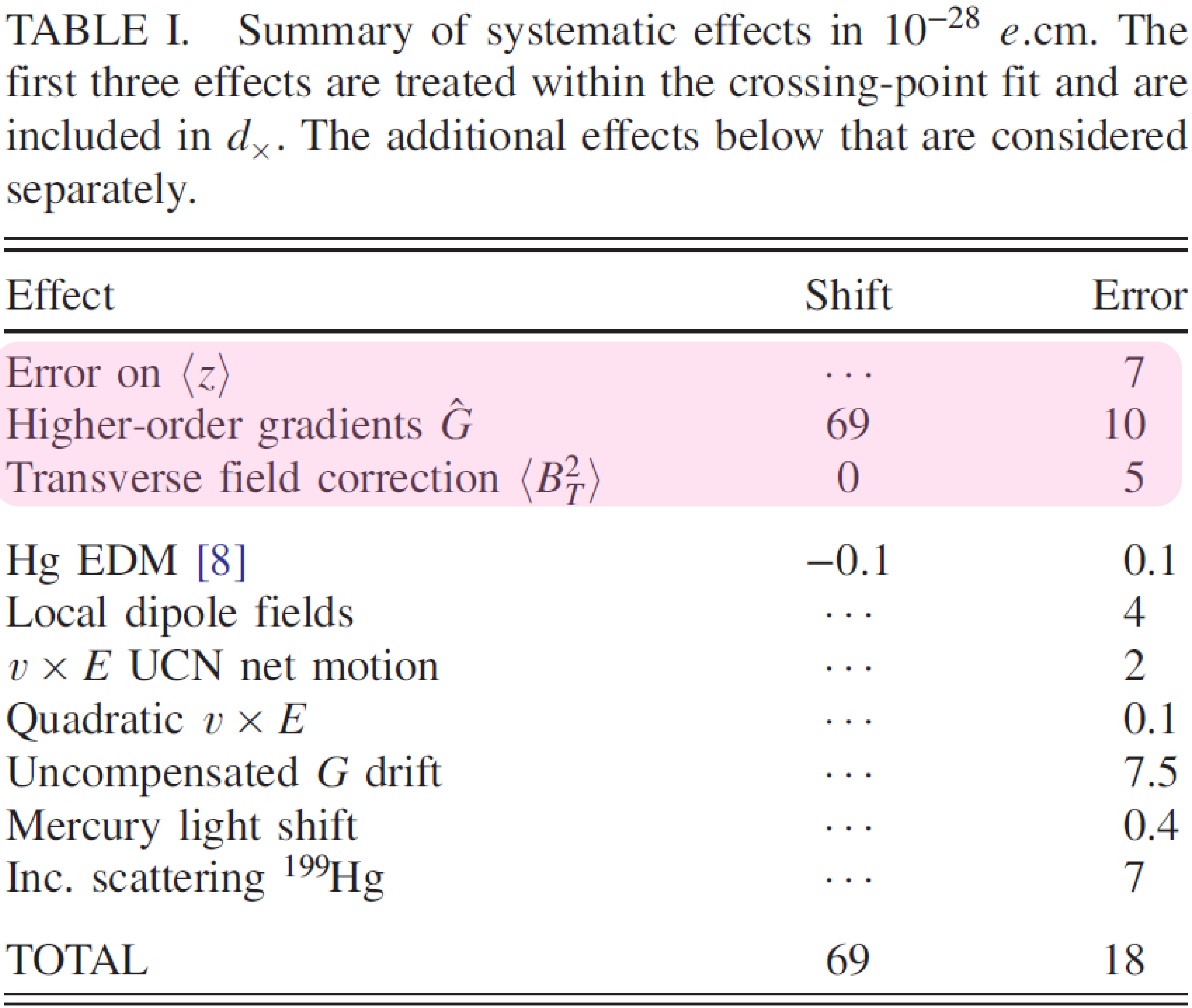
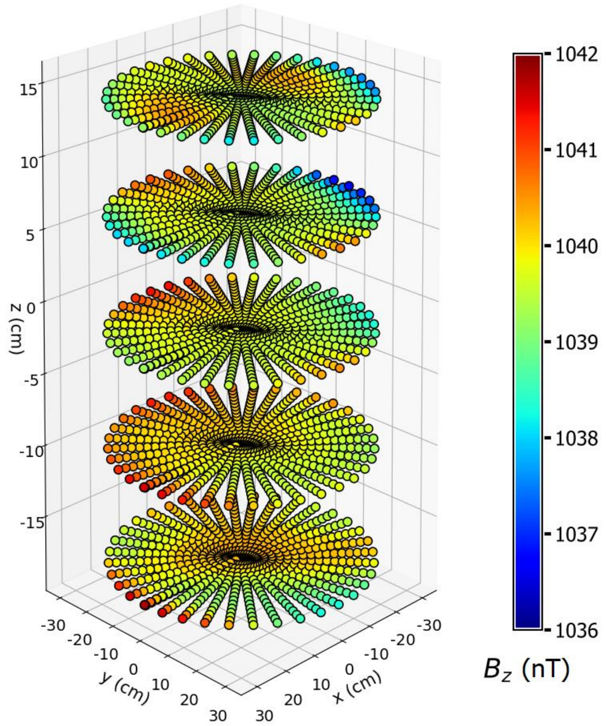


TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

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

Leading systematics associated with B-field uniformity



Field mapping, Quemener et al.

The result

PHYSICAL REVIEW LETTERS 124, 081803 (2020)

Editors' Suggestion | Featured in Physics

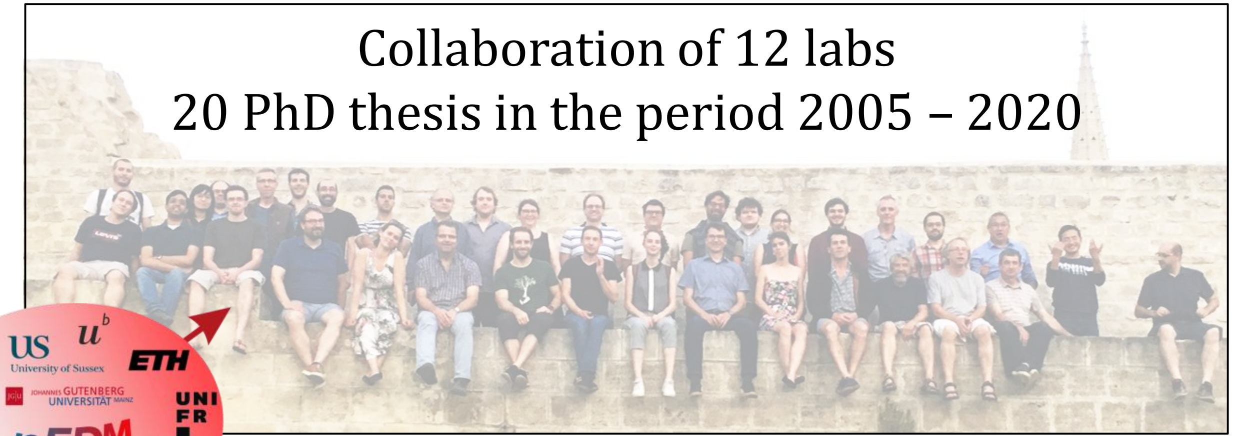
Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

[1]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*
[2]*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[3]*ETH Zürich, Institute for Particle Physics and Astrophysics, CH-8093 Zürich, Switzerland*
[4]*STFC Rutherford Appleton Laboratory, Harwell, Didcot, Oxon OX11 0QX, United Kingdom*
[5]*LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, 14000 Caen, France*
[6]*Marian Smoluchowski Institute of Physics, Jagiellonian University, 30-348 Cracow, Poland*
[7]*Instituut voor Kern- en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium*
[8]*Physikalisch Technische Bundesanstalt, D-10587 Berlin, Germany*
[9]*Laboratory for High Energy Physics and Albert Einstein Center for Fundamental Physics, University of Bern, CH-3012 Bern, Switzerland*
[10]*Université Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38026 Grenoble, France*
[11]*University of Kentucky, 40506 Lexington, Kentucky, USA*
[12]*Institute of Physics, Johannes Gutenberg University Mainz, 55128 Mainz, Germany*
[13]*Institut Laue-Langevin, CS 20156 F-38042 Grenoble Cedex 9, France*
[14]*Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland*
[15]*Institute of Physics Belgrade, University of Belgrade, 11080 Belgrade, Serbia*
[16]*Henryk Niedwodniczanski Institute for Nuclear Physics, 31-342 Cracow, Poland*
[17]*Department of Chemistry - TRIGA site, Johannes Gutenberg University Mainz, 55128 Mainz, Germany*
[18]*CSNSM, Université Paris Sud, CNRS/IN2P3, F-91405 Orsay Campus, France*

(Received 18 December 2019; accepted 3 February 2020; published 28 February 2020)

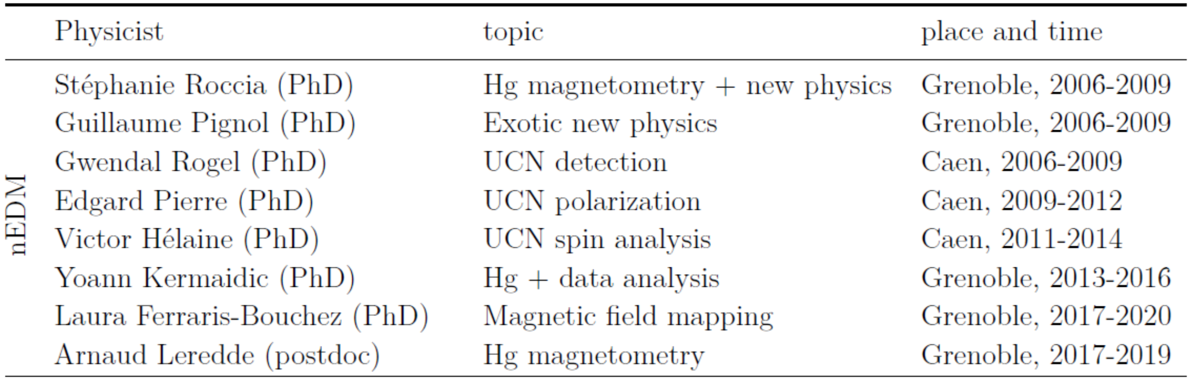
We present the result of an experiment to measure the electric dipole moment (EDM) of the neutron at the Paul Scherrer Institute using Ramsey's method of separated oscillating magnetic fields with ultracold neutrons. Our measurement stands in the long history of EDM experiments probing physics violating time-reversal invariance. The salient features of this experiment were the use of a ^{199}Hg comagnetometer and an array of optically pumped cesium vapor magnetometers to cancel and correct for magnetic-field changes. The statistical analysis was performed on blinded datasets by two separate groups, while the estimation of systematic effects profited from an unprecedented knowledge of the magnetic field. The measured value of the neutron EDM is $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}$ e.cm.



Collaboration of 12 labs
20 PhD thesis in the period 2005 – 2020

IN2P3 labs (LPC and LPSC) contribute since 2004.
Science output during 15 years (2005 – 2020)

- 12 articles with IN2P3 as main author
- 7 PhD thesis related to nEDM



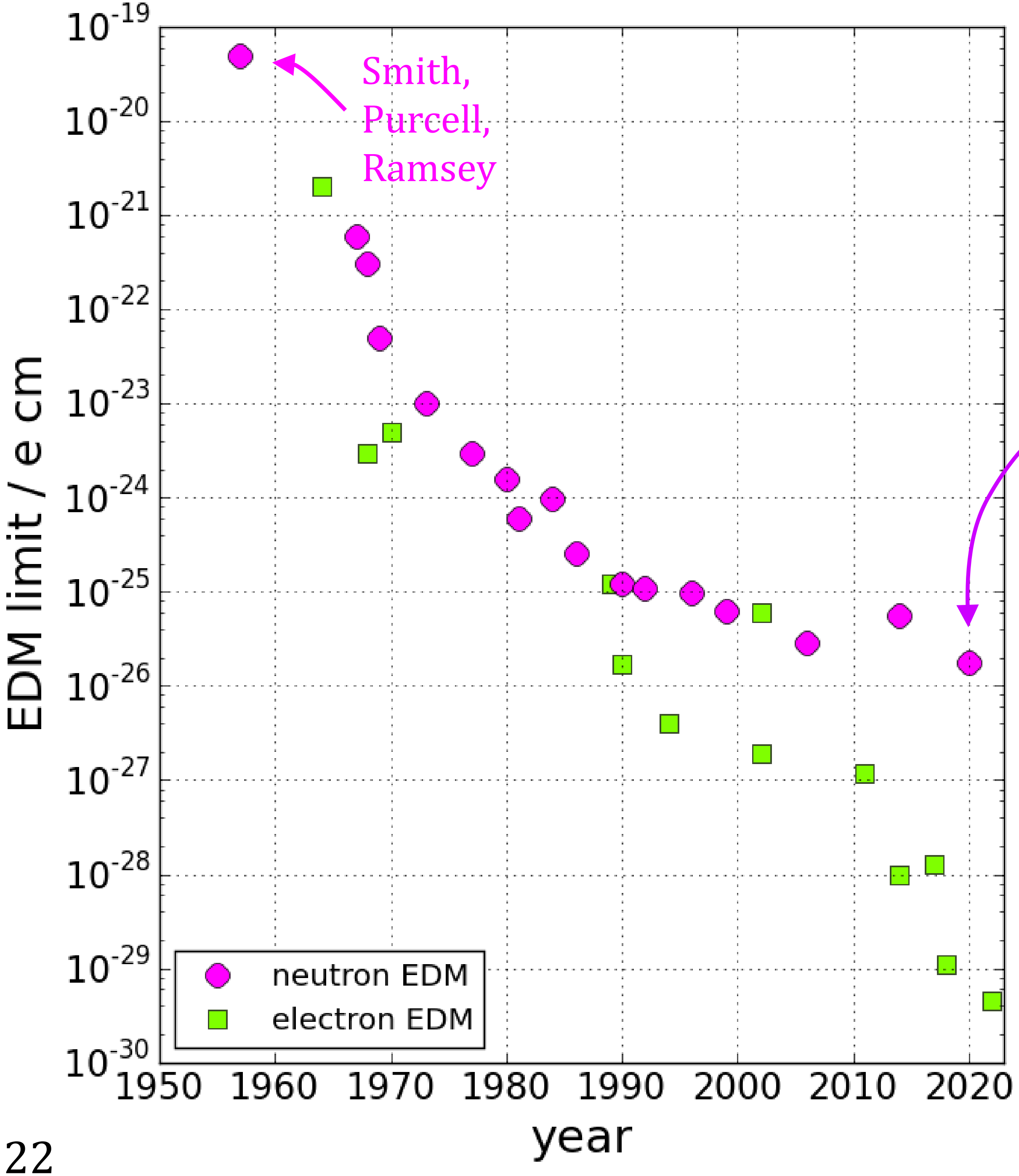
	Physicist	topic	place and time
nEDM	Stéphanie Roccia (PhD)	Hg magnetometry + new physics	Grenoble, 2006-2009
	Guillaume Pignol (PhD)	Exotic new physics	Grenoble, 2006-2009
	Gwendal Rogel (PhD)	UCN detection	Caen, 2006-2009
	Edgard Pierre (PhD)	UCN polarization	Caen, 2009-2012
	Victor Hélaine (PhD)	UCN spin analysis	Caen, 2011-2014
	Yoann Kermaidic (PhD)	Hg + data analysis	Grenoble, 2013-2016
	Laura Ferraris-Bouchez (PhD)	Magnetic field mapping	Grenoble, 2017-2020
	Arnaud Leredde (postdoc)	Hg magnetometry	Grenoble, 2017-2019

Outline

1. Physics case for searching EDMs
2. How to measure nEDM: state of the art
3. Next generation nEDM experiments

4. The design of n2EDM
5. In2p3 contributions
6. Commissioning results
7. Perspectives until 2030 and beyond

Next generation nucleon EDM



Best limit from the nEDM experiment @PSI

$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$ Abel et al, PRL (2020)

Design sensitivity of 4 new experiments:

n2EDM@PSI + panEDM@ILL + LANL + TUCAN@TRIUMF

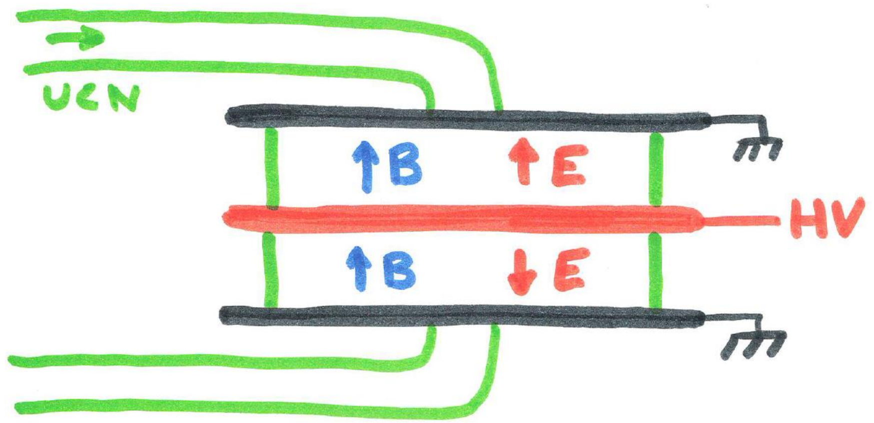
Design sensitivity cryogenic nEDM@SNS

Conceptual reach proton & neutron EDM

CKM background uncertain, possibly 10^{-31} e cm

Concept for the next generation nEDM

Double-chamber UCN @room temperature

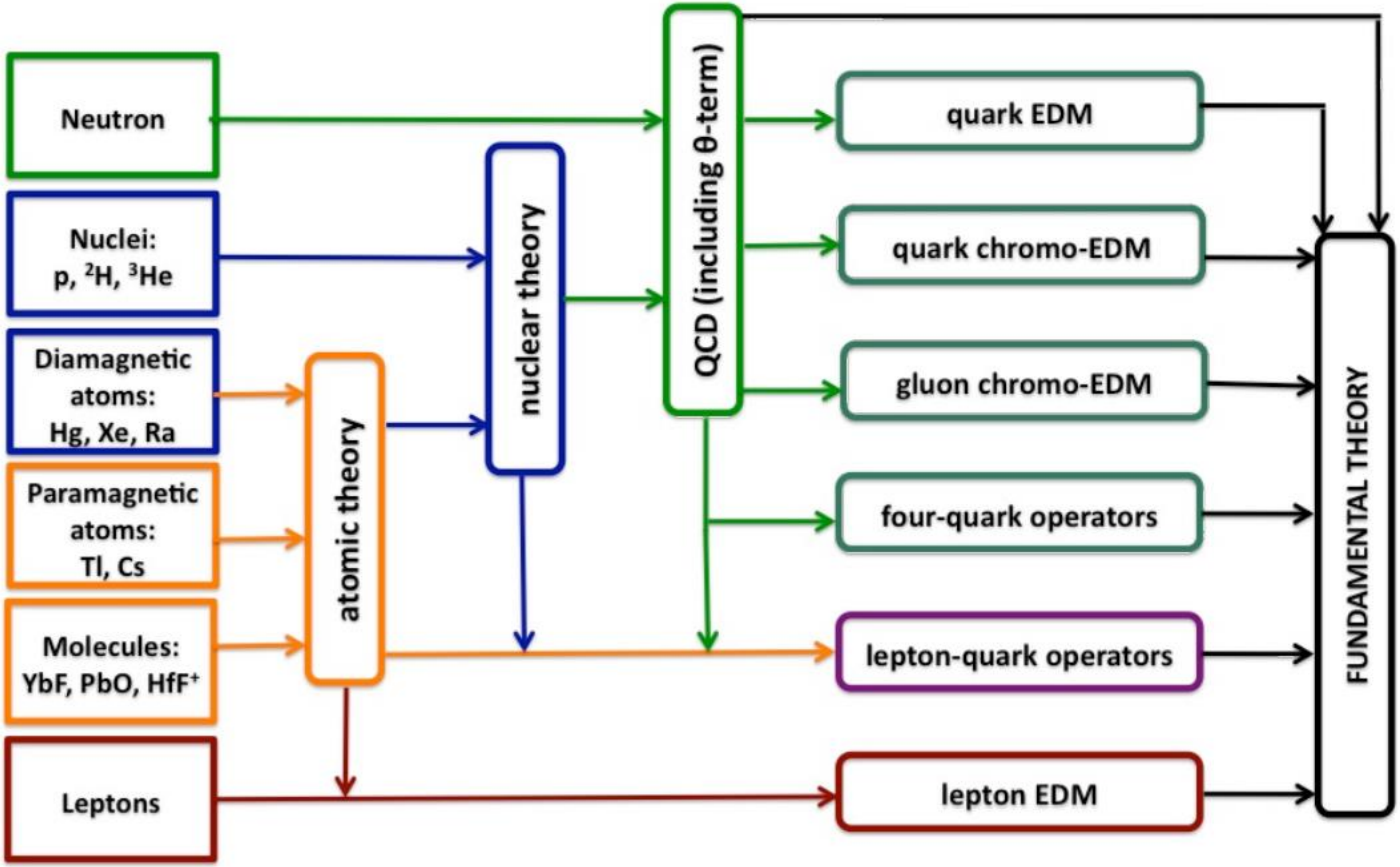


- + atomic co-magnetometry in the UCN cells
- + External magnetometers
- + Complex B0 coil
- + Magnetic Shield

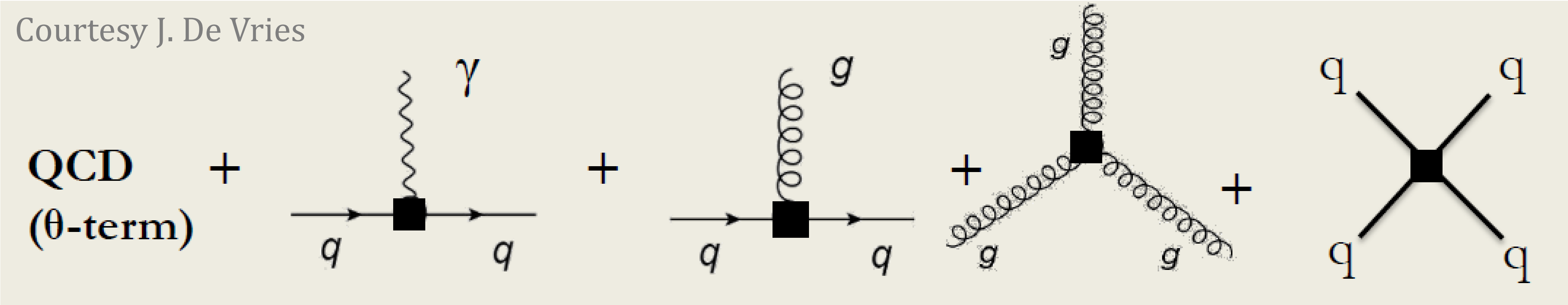
Place	Neutron source	Concept	Stage/Readiness
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber with Hg comagnetometers + Cs mag	Source under construction, experiment under construction
LANL	Spallation + sD2 UCN source	double Ramsey chamber with Hg comagnetometers + commertial OPMs	Source running, experiment under construction
ILL	Reactor + superfluid He UCN source	panEDM: double Ramsey chamber, no comagnetometers + Hg&Cs mag	Source (supersun) commissionning experiment under construction
PSI	Spallation + sD2 UCN source	n2EDM: large double Ramsey chamber with Hg comagnetometers + Cs mag	Source running, experiment almost running

Additional material

EDM metromap (Jordy De Vries)



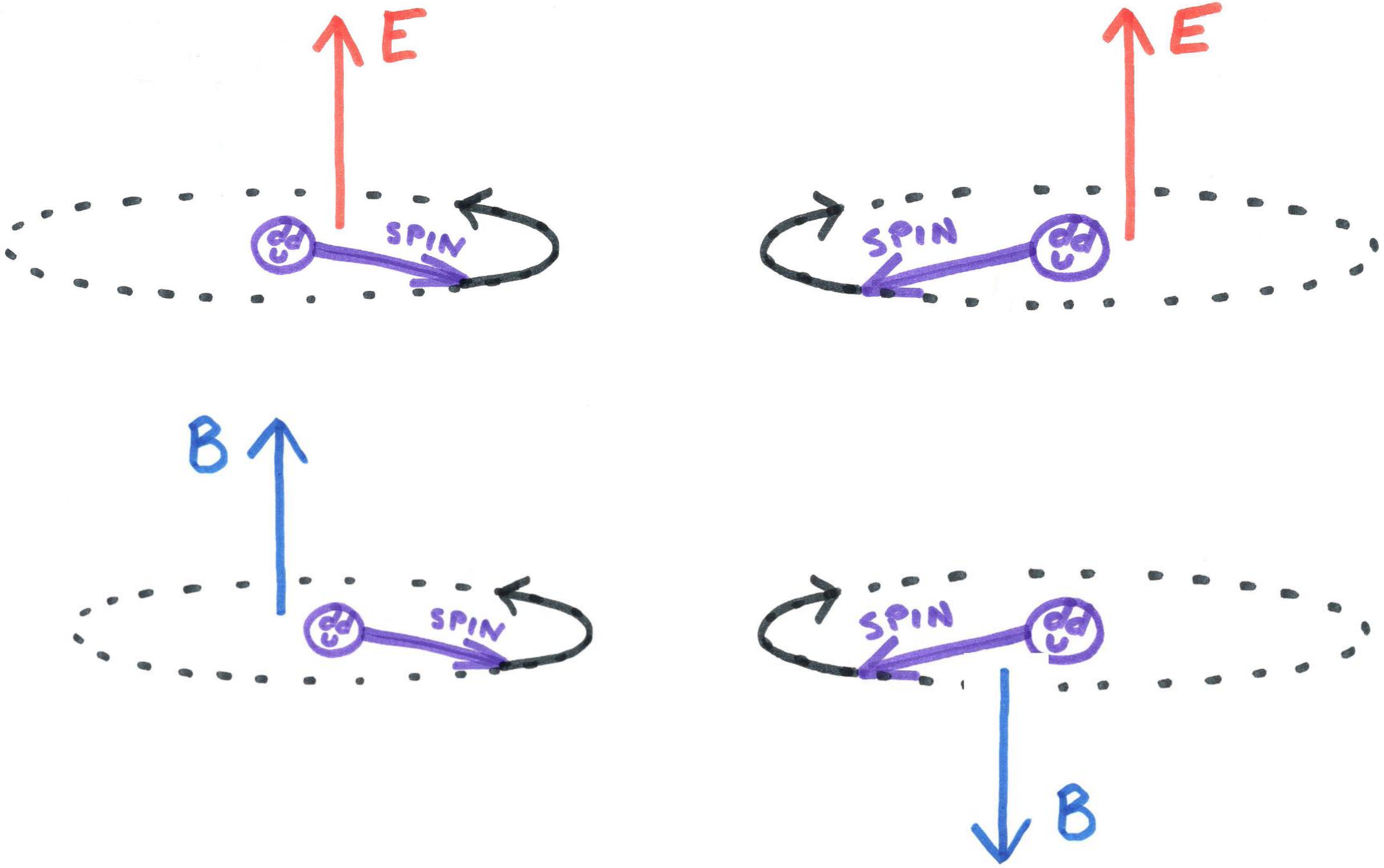
theory bottleneck: Hadronic 1 GeV -> nEDM


Courtesy J. De Vries

$$
\begin{aligned}
d_n = &-(1.5 \pm 0.7) \cdot 10^{-3}\ \bar{\theta}\, e\, \mathrm{fm} \\
&-(0.20 \pm 0.01) d_u \ + \ (0.78 \pm 0.03) d_d \ + \ (0.0027 \pm 0.016) d_s \\
&-(0.55 \pm 0.28) e\tilde{d}_u \ - \ (1.1 \pm 0.55) e\tilde{d}_d \ + \ (50 \pm 40)\ \mathrm{MeV}\, e\, \tilde{d}_G
\end{aligned}
$$

Formula taken from the 2022 review: *Electric dipole moments and the search for new physics*

T-symmetry



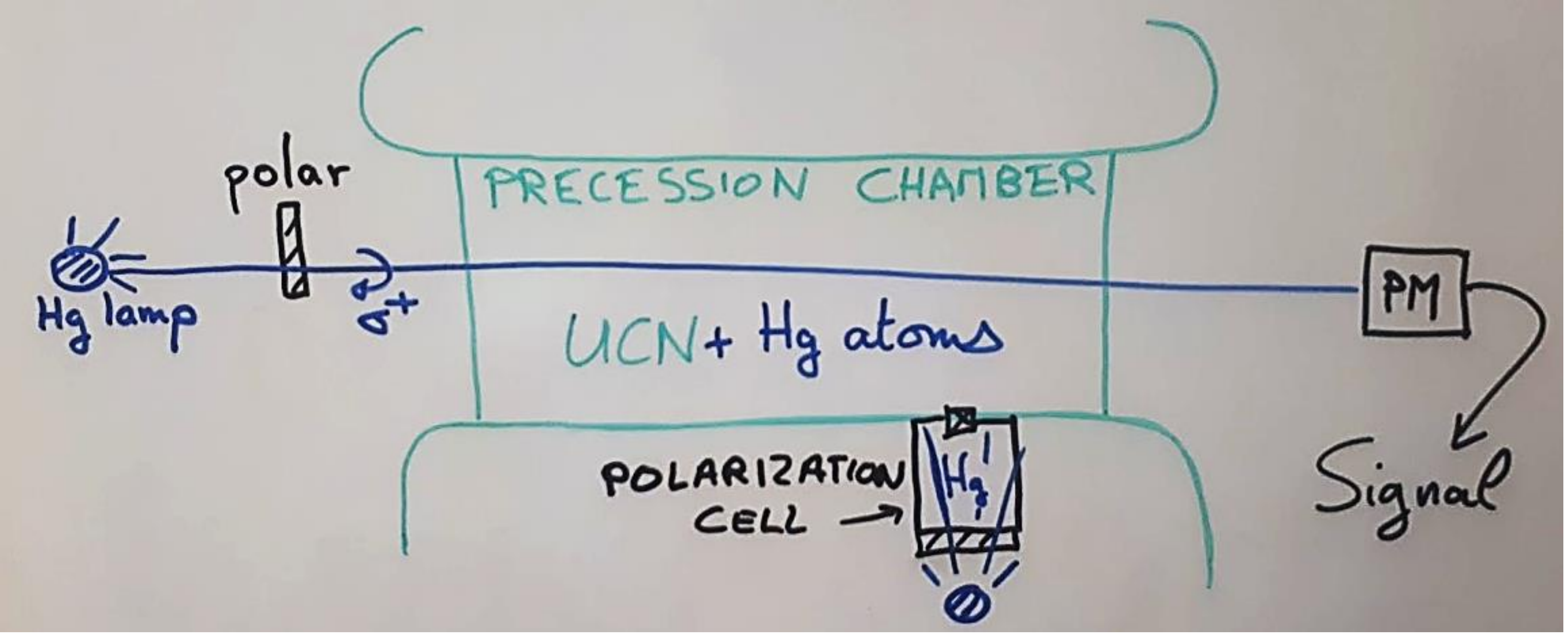
Nonzero EDM
Violates T symmetry

Nonzero MDM
DOES NOT violate T

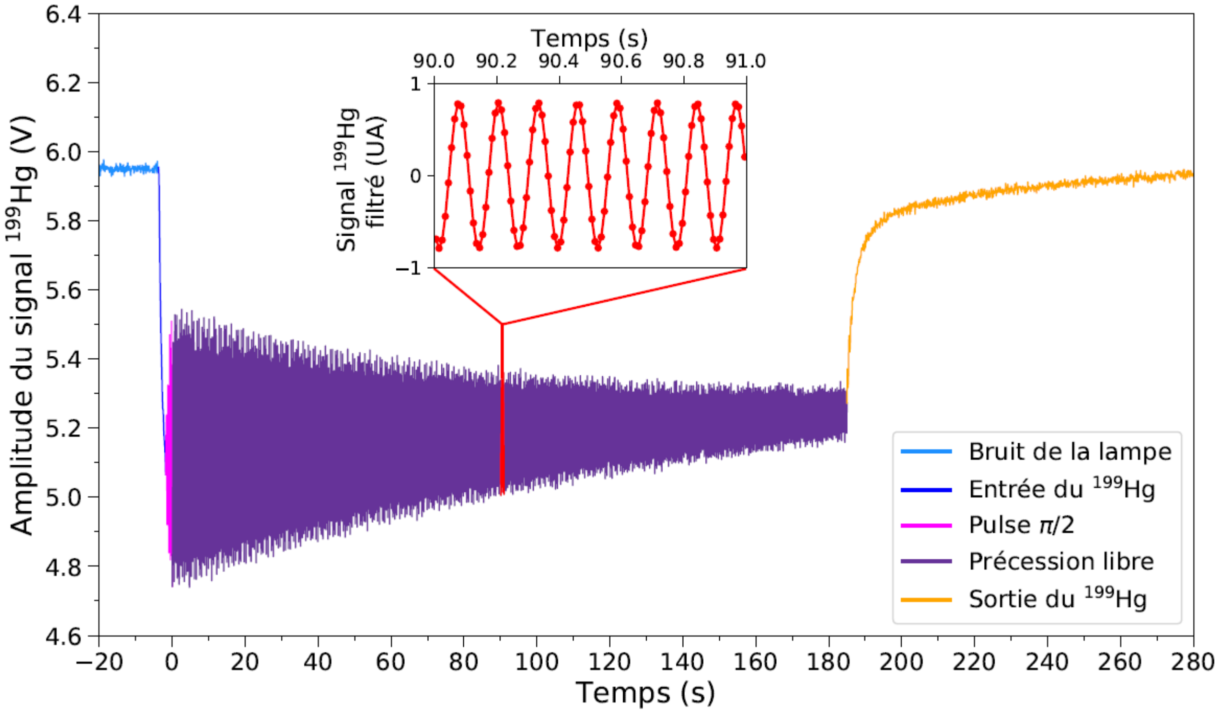
>> PLAY >>

<< REWIND <<

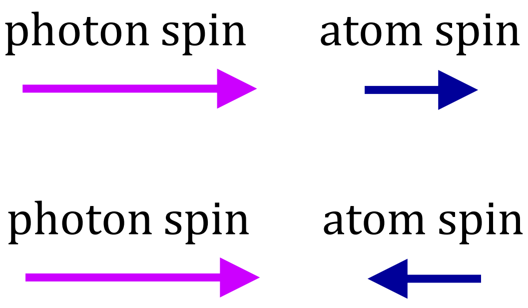
quantum magnetometry with ^{199}Hg



The magnetic field is extracted from the precession frequency of mercury-199 atoms: $f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$



Principle of **optical reading** of the precession:



photon spin → atom spin → absorption of light forbidden by angular momentum conservation

photon spin → atom spin ← absorption of light allowed