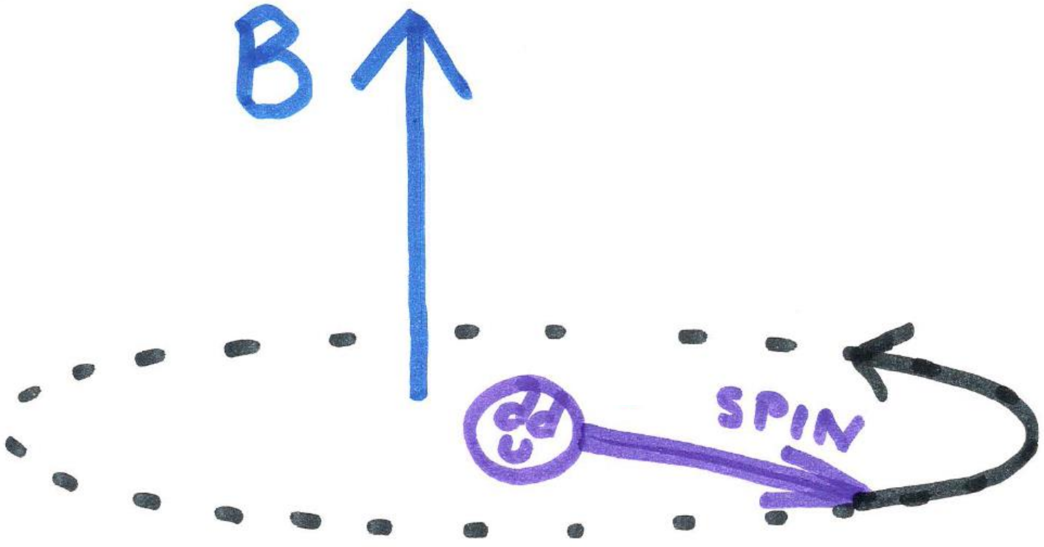
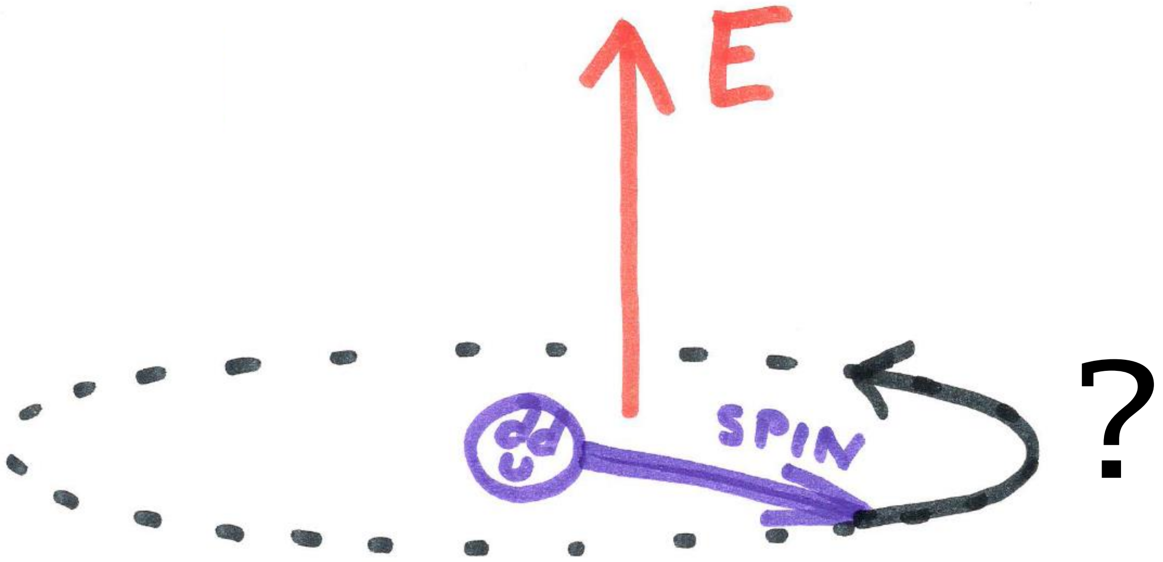
Guillaume Pignol, 02.05.2022
At the MORA Workshop in Jyväskylä

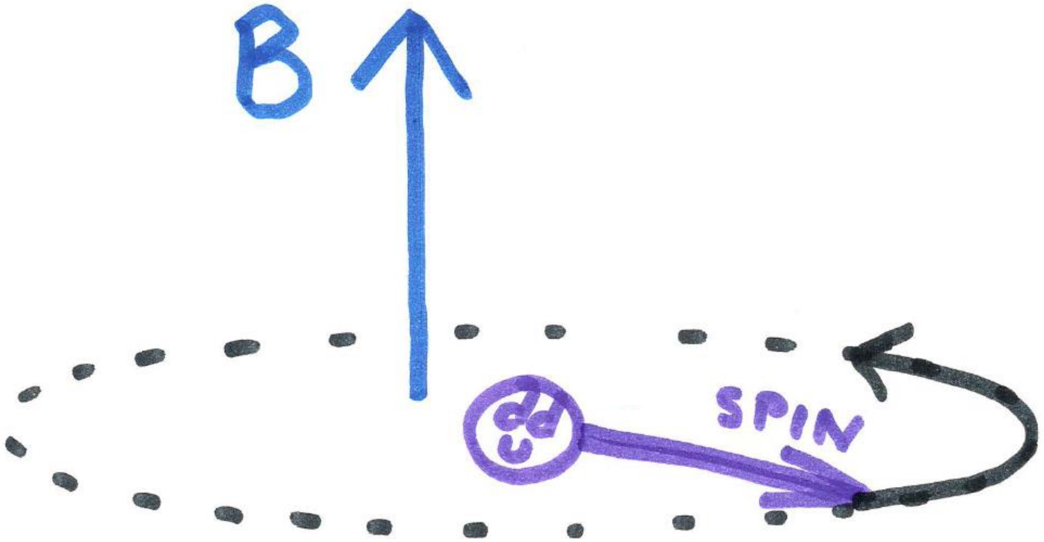
Neutron EDM measurement around the world



- Subatomic particles such as the neutron have a spin ½.
- One can change the orientation with a magnetic field **B**.
- This phenomenon –spin precession– is at the basis of NMR and MRI.

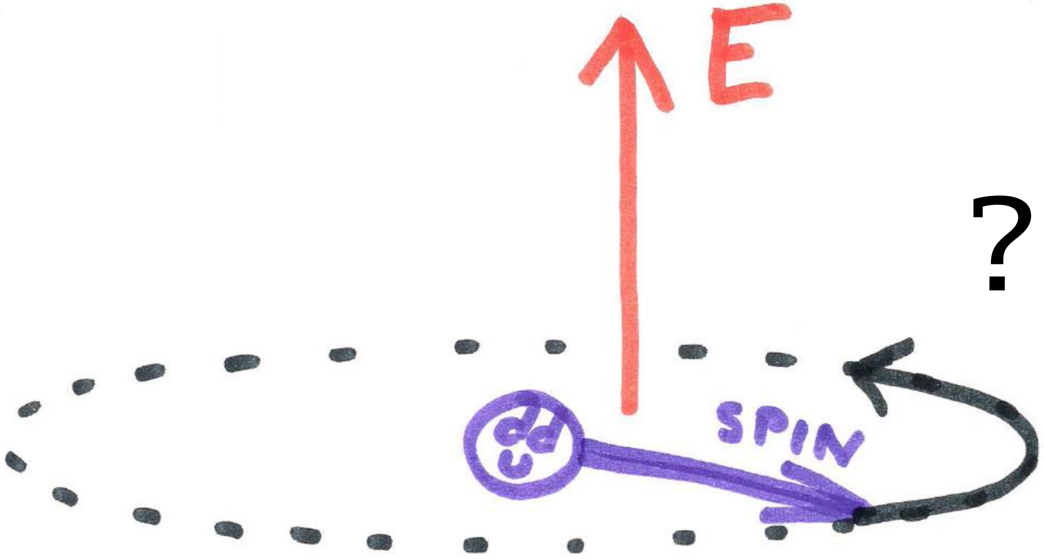


Question: Can we change the spin orientation with an electric field **E** instead?



In B = 1 μT (weak B-field)

Precession frequency ~ 30 /s

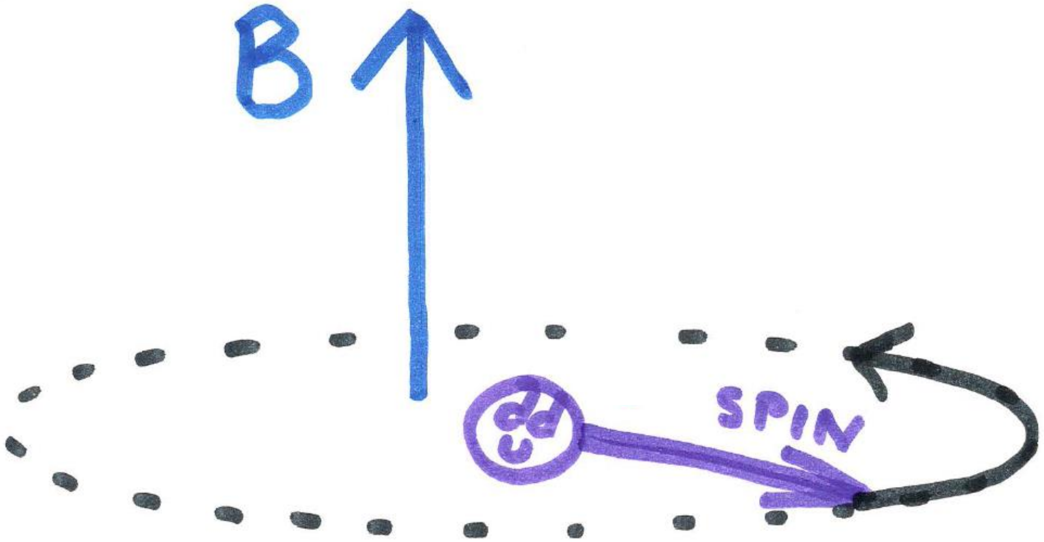


?!

Short answer: no.

In E = 10 kV/cm (strong E-field)

Frequency < 2 /year (!?)

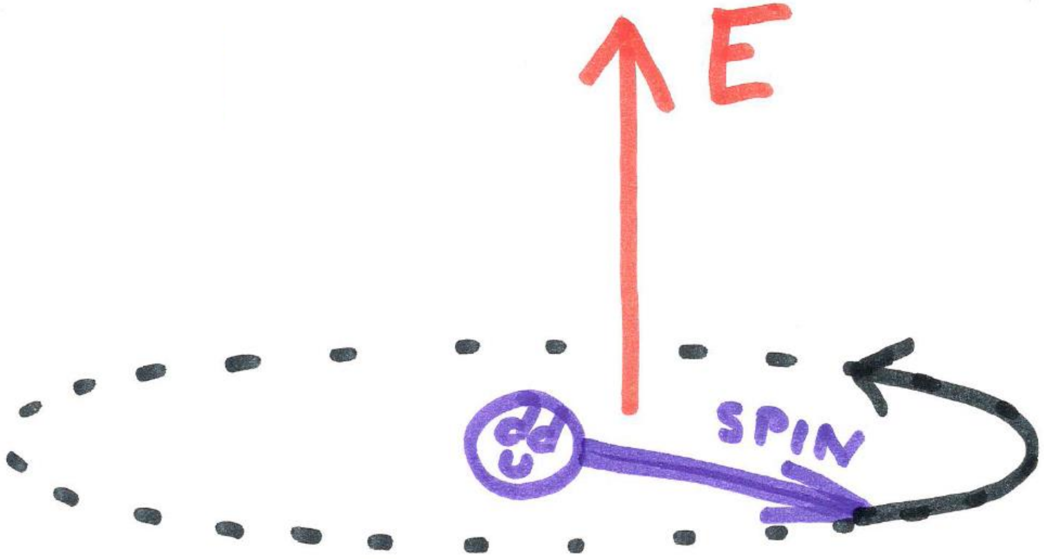


Magnetic Dipole Moment

$$\hbar\omega = 2\,\mu\,B$$

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

$$\mu = -1.913\,042\,7(5)\,\mu_N$$



?

Electric Dipole Moment

$$\hbar\omega = 2\,d\,E$$

$$d = (0 \pm 1) \times 10^{-26}\,e\,\text{cm}$$
$$= (0 \pm 1) \times 10^{-12} \times \frac{\mu_N}{c}$$

Violation of time reversal

>> PLAY >>

<< REWIND <<

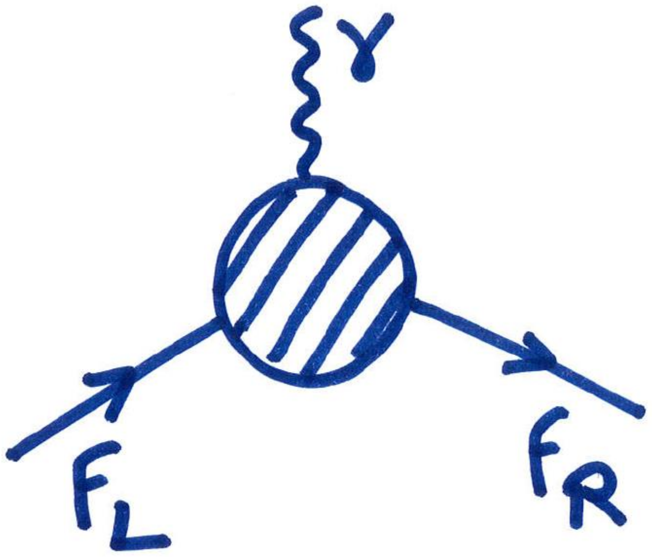
If $d \neq 0$ the process and its time reversed version are different.

Violation of T

CPT

Violation of CP

Electric dipoles & CP symmetry

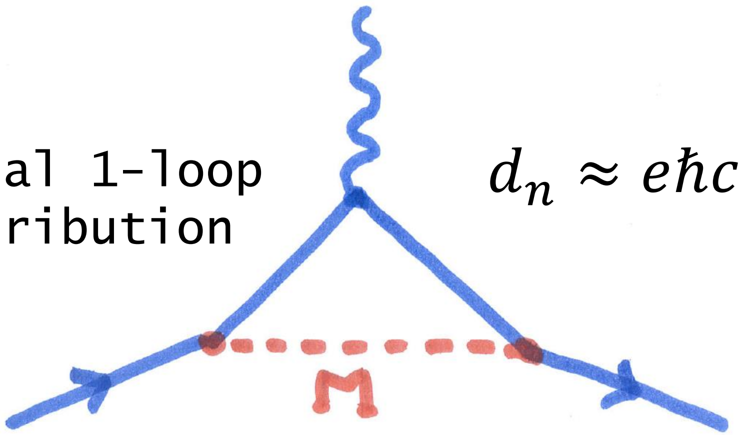


EDM = CP-violating fermion-photon coupling
-imaginary part of the diagram-
generated by radiative corrections

$$\mathcal{L} = -\frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\, F^{\mu\nu}$$

$$\rightarrow \hat{H} = -d\,\hat{\boldsymbol{\sigma}}\boldsymbol{E}$$

Typical 1-loop contribution



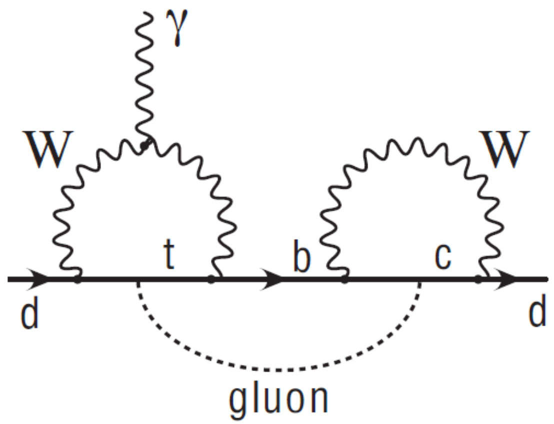
$$d_n \approx e\hbar c\frac{\mathrm{Im}(g^2)}{4\pi}\frac{m_q}{M^2} \approx \frac{\mathrm{Im}(g^2)}{4\pi}\left(\frac{10\ \mathrm{TeV}}{M}\right)^2 \times 10^{-25} e\ \mathrm{cm}$$

Sources of EDMs in the Standard Model

The QCD contribution $\frac{\alpha}{8\pi}\bar{\theta}\, G^{\mu\nu}\widetilde{G_{\mu\nu}}$

Generates a potentially enormous neutron EDM

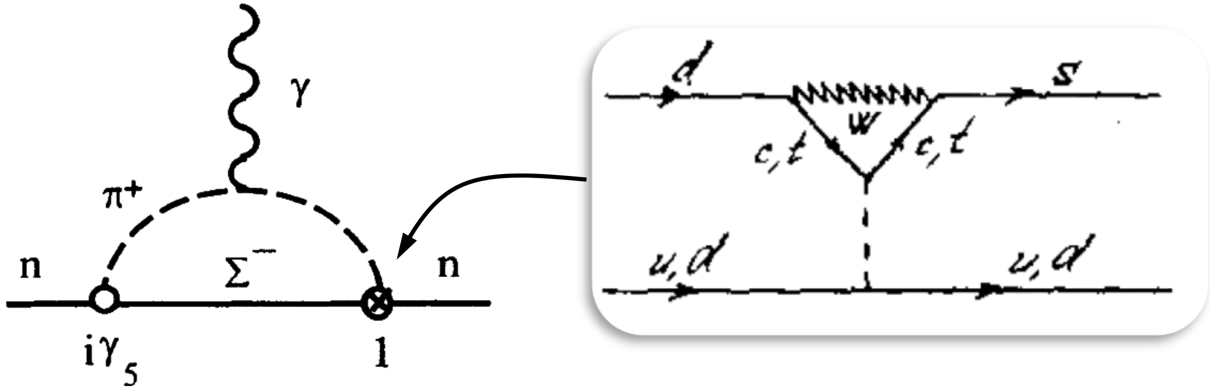
$d_n \approx \bar{\theta} \times 10^{-16}\, e\,\mathrm{cm}$
$\rightarrow \bar{\theta} < 10^{-10}$
« Strong CP problem »



CKM contribution to the quark EDMs: Leading order starts at 3 loops!

Negligible contribution

CKM “long distance” contribution to nEDM



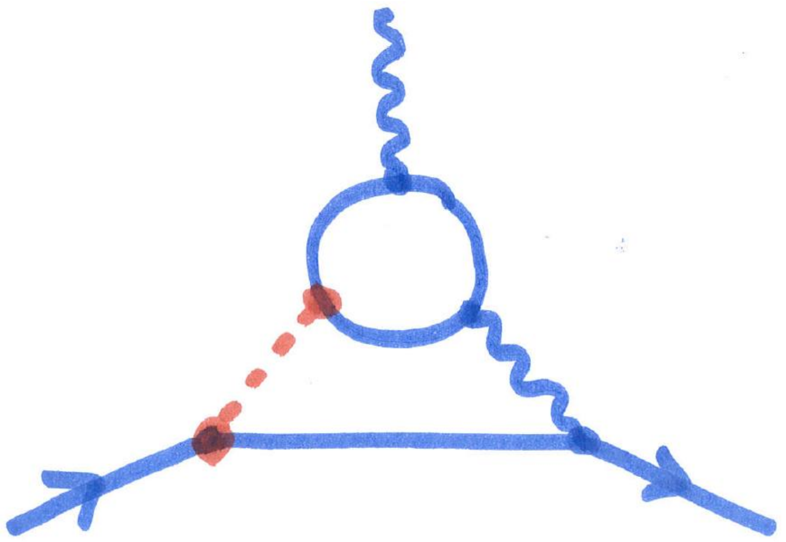
CKM prediction:
$1 \times 10^{-32}\, e\,\mathrm{cm} < |d_n| < 6 \times 10^{-32}\, e\,\mathrm{cm}$
Kobayashi-Maskawa background negligible

EDMs beyond the SM: modified Higgs couplings

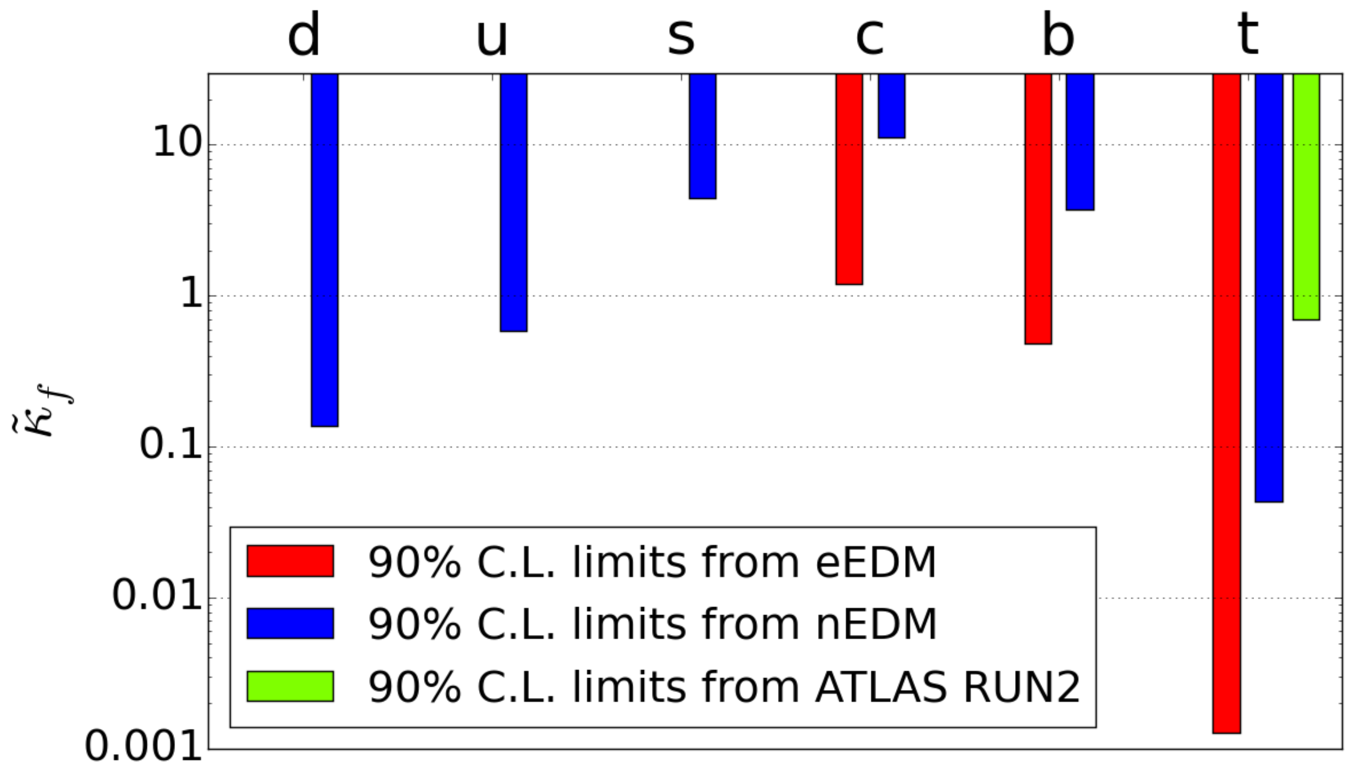
CP violating

Modified Higgs-fermion Yukawa coupling $\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h\right)$

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)

Take home messages

1. **Great sensitivity:** EDMs are very sensitive probes of CP violation beyond the SM – possibly responsible for the baryon asymmetry of the Universe - because
   (i) New physics at the TeV scale (and beyond) predicts generically sizable EDMs
   (ii) CKM contribution to EDMs undetectably small

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

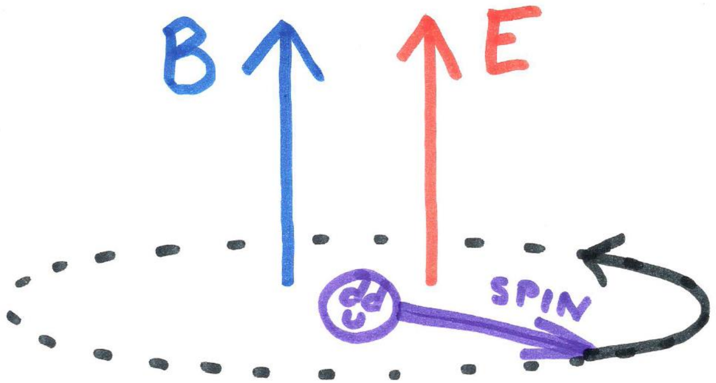
The rest of the talk

1. Basics of nEDM measurement

2. The recent result: $d_n = (0 \pm 1)\ 10^{-26}$ e cm

3. Next generation n2EDM experiments

Basics of EDM measurement



$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

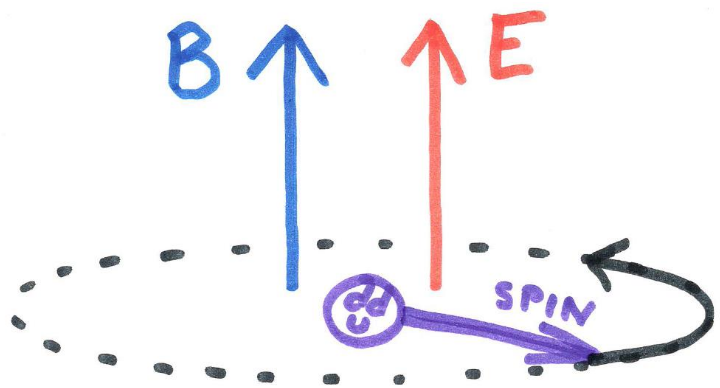
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d\, E$$

Easy!

The trick: measure frequencies*

** Only if you can't, try something else*

Basics of EDM measurement



$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

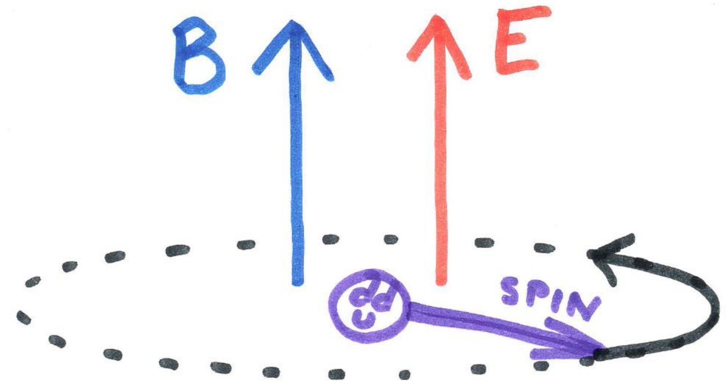
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d\, E$$

~~**Easy!**~~

Larmor frequency
$f = 30\ \mathrm{Hz}$ @ $B = 1\ \mu\mathrm{T}$

If $d = 10^{-26}\ e\,\mathrm{cm}$ and $E = 11\ \mathrm{kV/cm}$
The spin will make **one full turn** in a time
$\frac{\pi\hbar}{dE} =$ **200 days**

Basics of EDM measurement



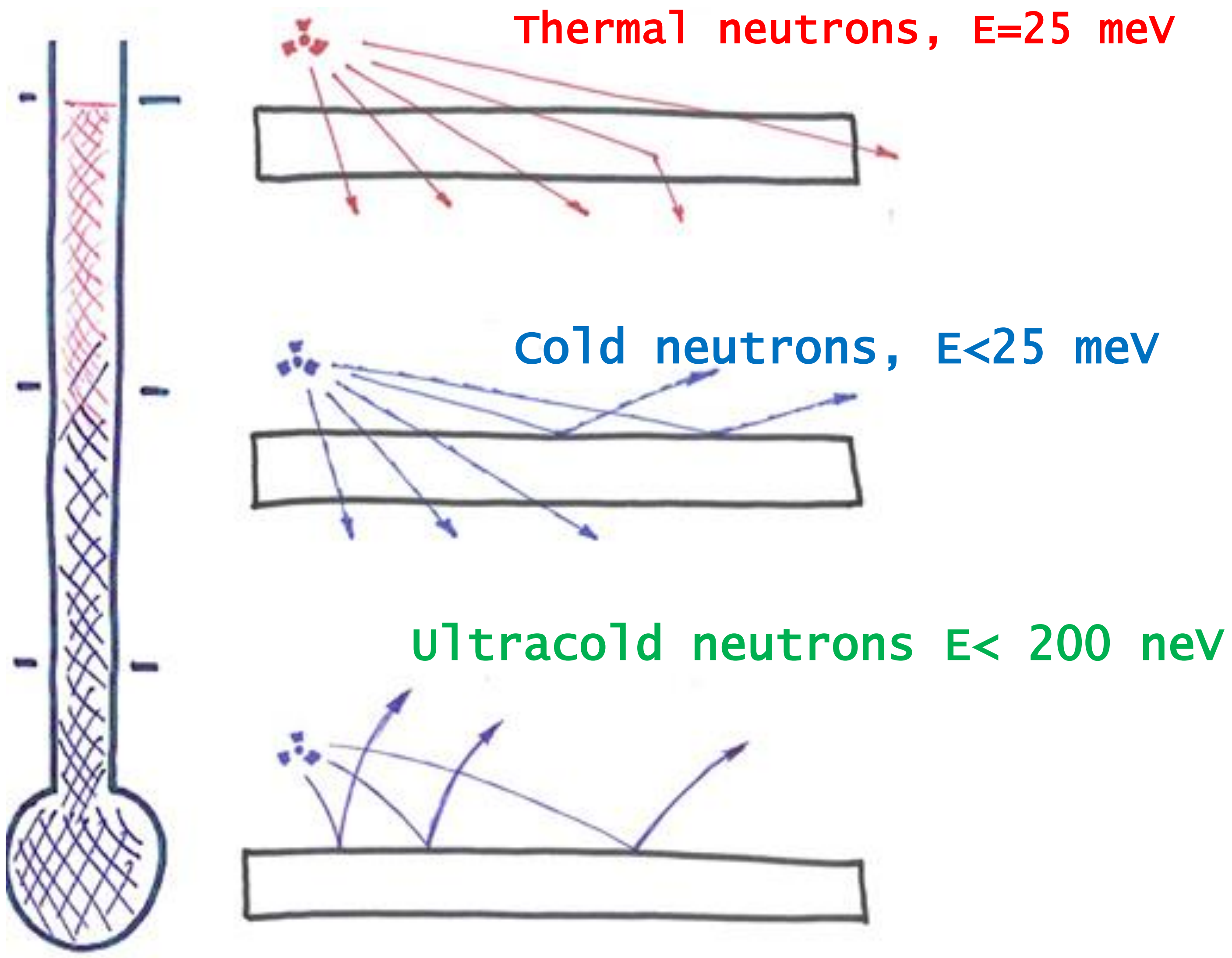
$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

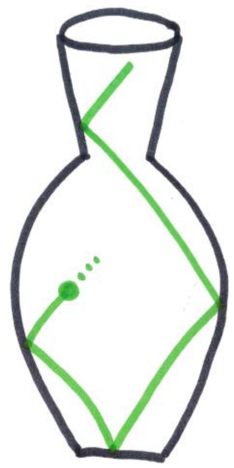
If $d = 10^{-26}\, e\,\text{cm}$ and $E = 11\,\text{kV/cm}$
one full turn in a time $\frac{\pi\hbar}{dE} =$ **200 days**

To detect such a minuscule coupling:

1. Long interaction time
2. High intensity/statistics
3. Control the magnetic field

Neutron optics, cold and ultracold neutrons

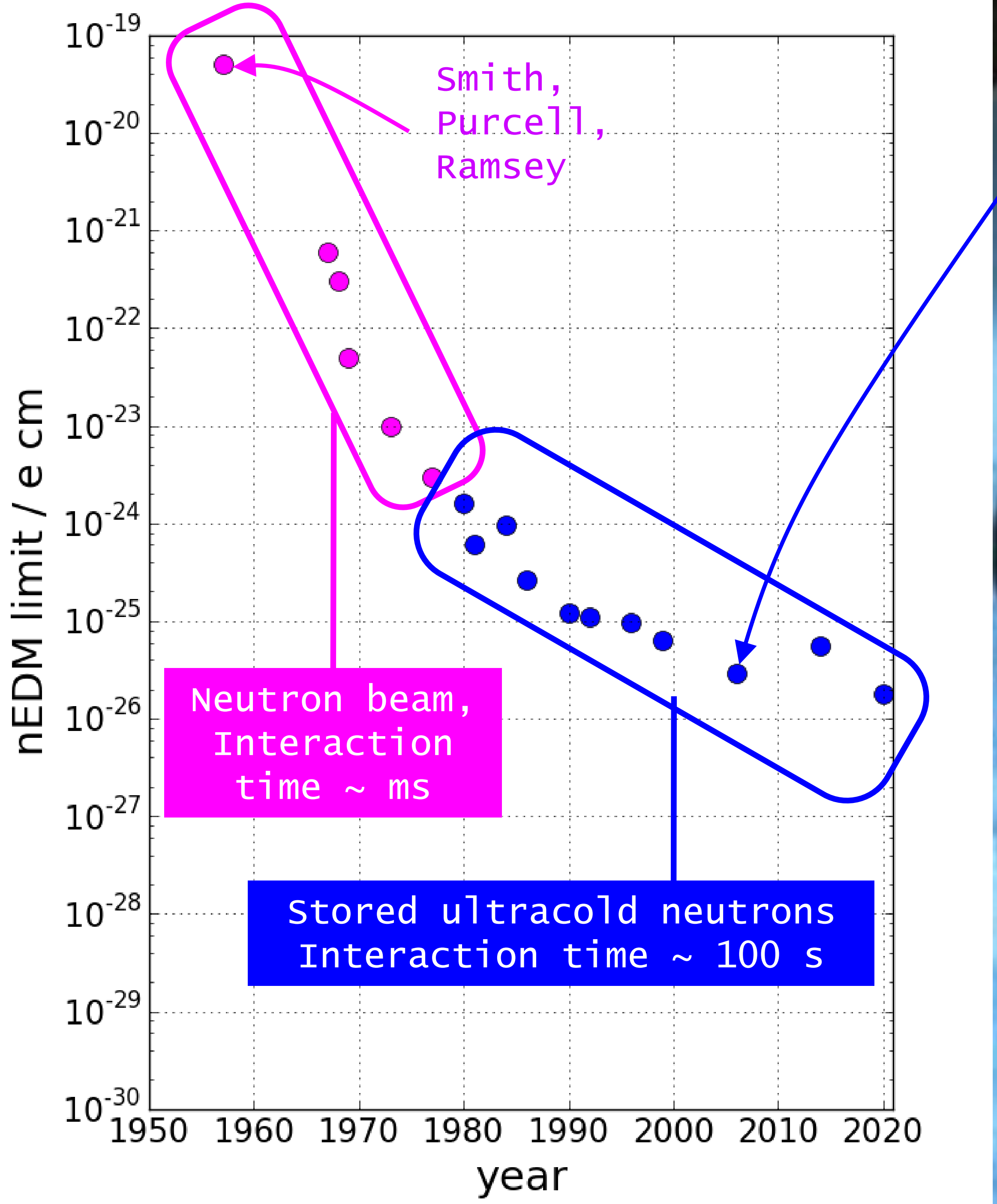


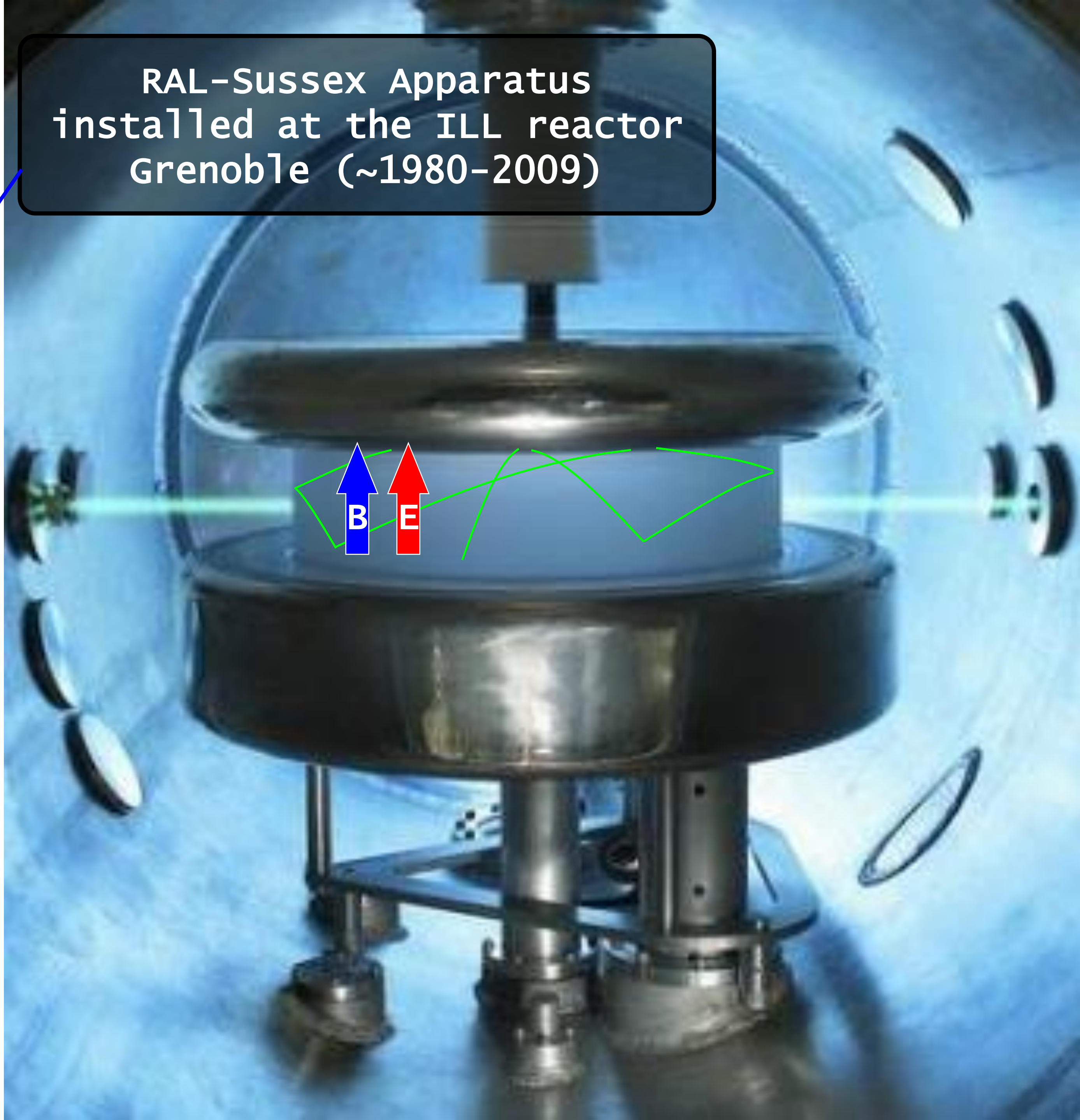


Neutrons with energy < 200 neV, are totally reflected by material walls.

They can be stored in material bottles for long times , up to 15 minutes.

They are significantly affected by gravity.


nEDM limit / e cm
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
1950 1960 1970 1980 1990 2000 2010 2020
year
Smith, Purcell, Ramsey
Neutron beam, Interaction time ~ ms
Stored ultracold neutrons Interaction time ~ 100 s


RAL-Sussex Apparatus installed at the ILL reactor Grenoble (~1980-2009)
B
E

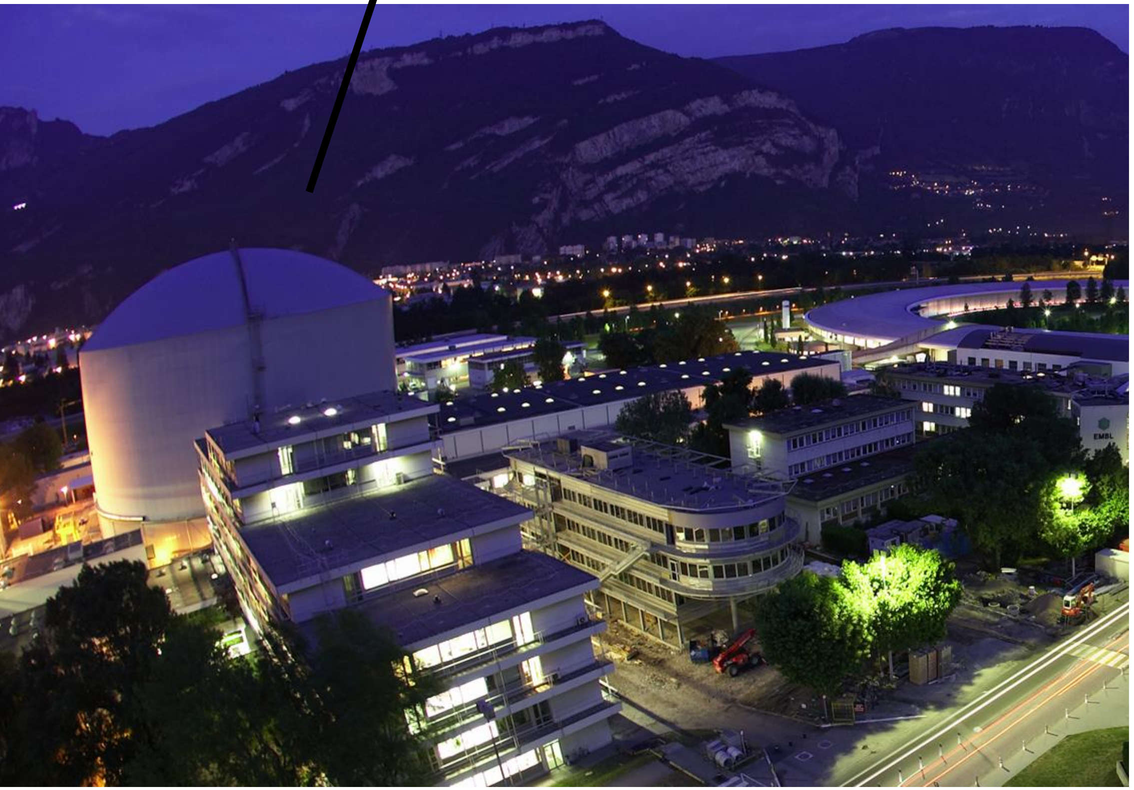
Recent history of the single-chamber apparatus

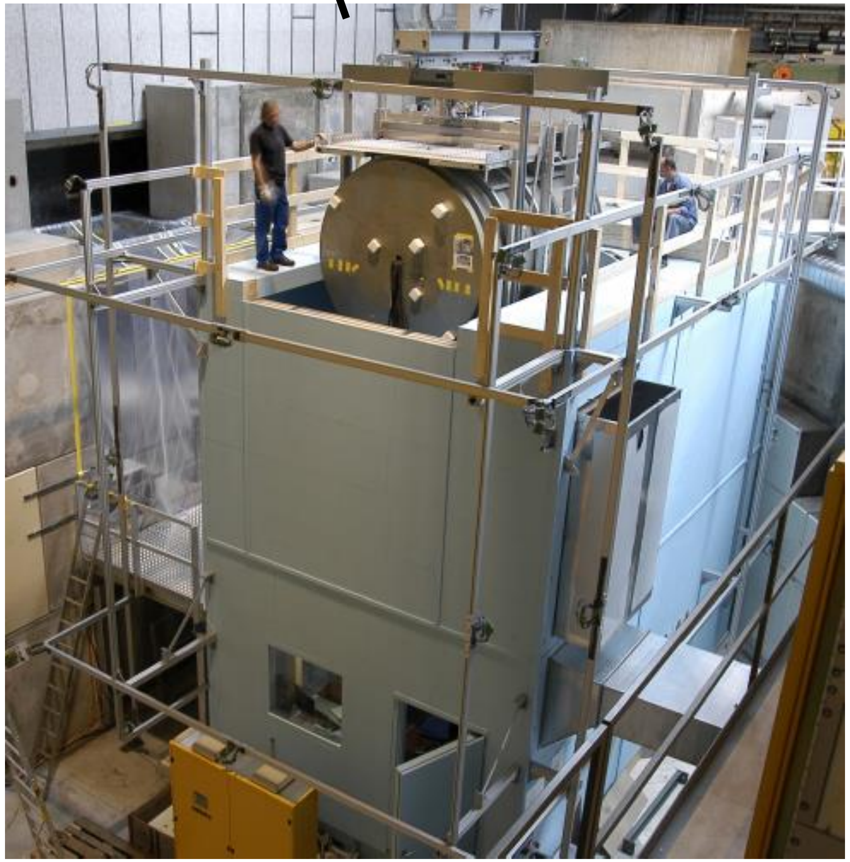
1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

ILL data production

UCN source startup
& nEDM upgrade

PSI data





Dismantling nEDM
Installing n2EDM

Move of the apparatus at the
Paul Scherrer Institute

The rest of the talk

1. Basics of nEDM measurement

2. The recent result: $d_n = (0 \pm 1)\ 10^{-26}$ e cm

3. Next generation n2EDM experiments

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

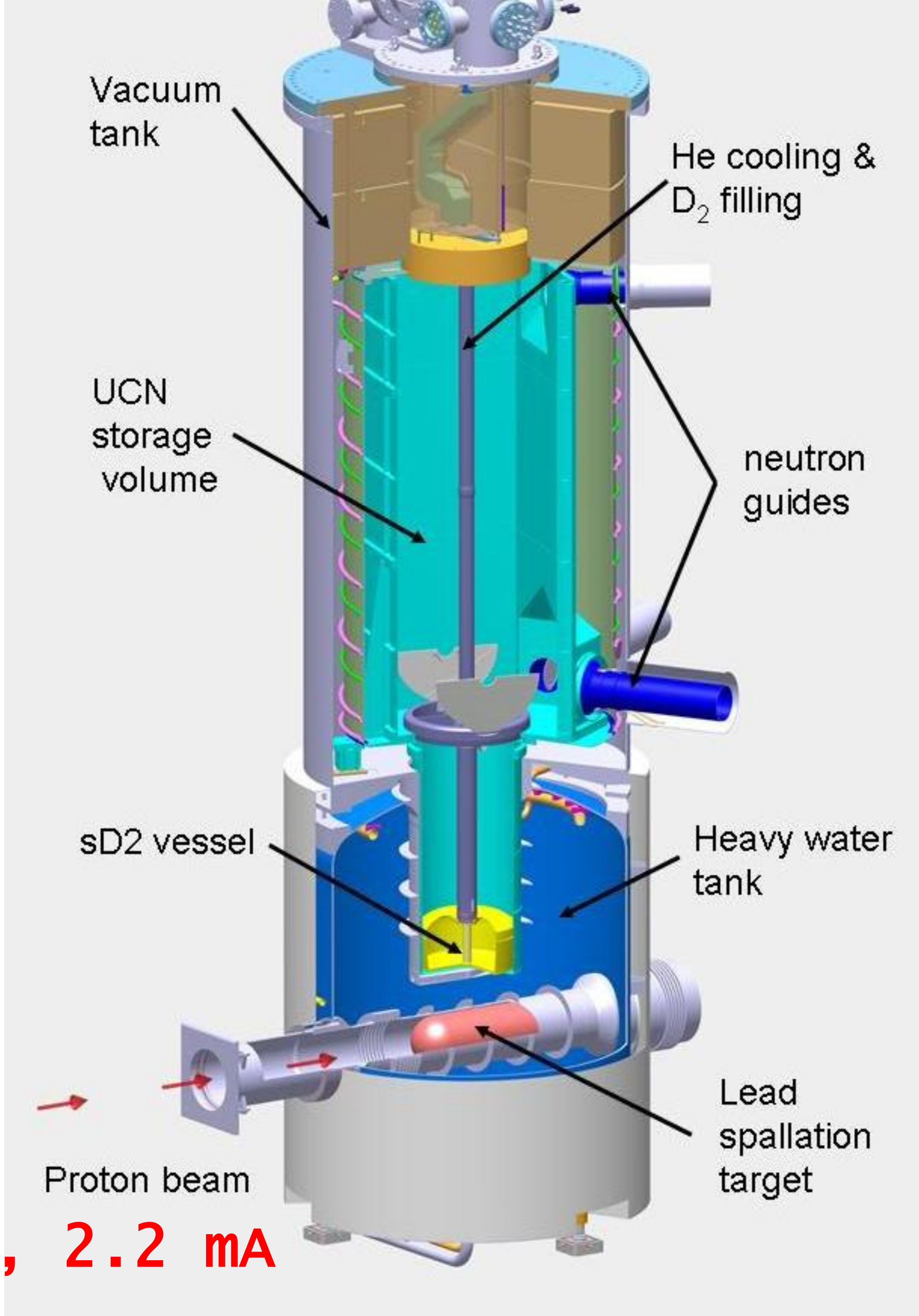
Editors' Suggestion **Featured in Physics**

Measurement of the Permanent Electric Dipole Moment of the Neutron

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

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

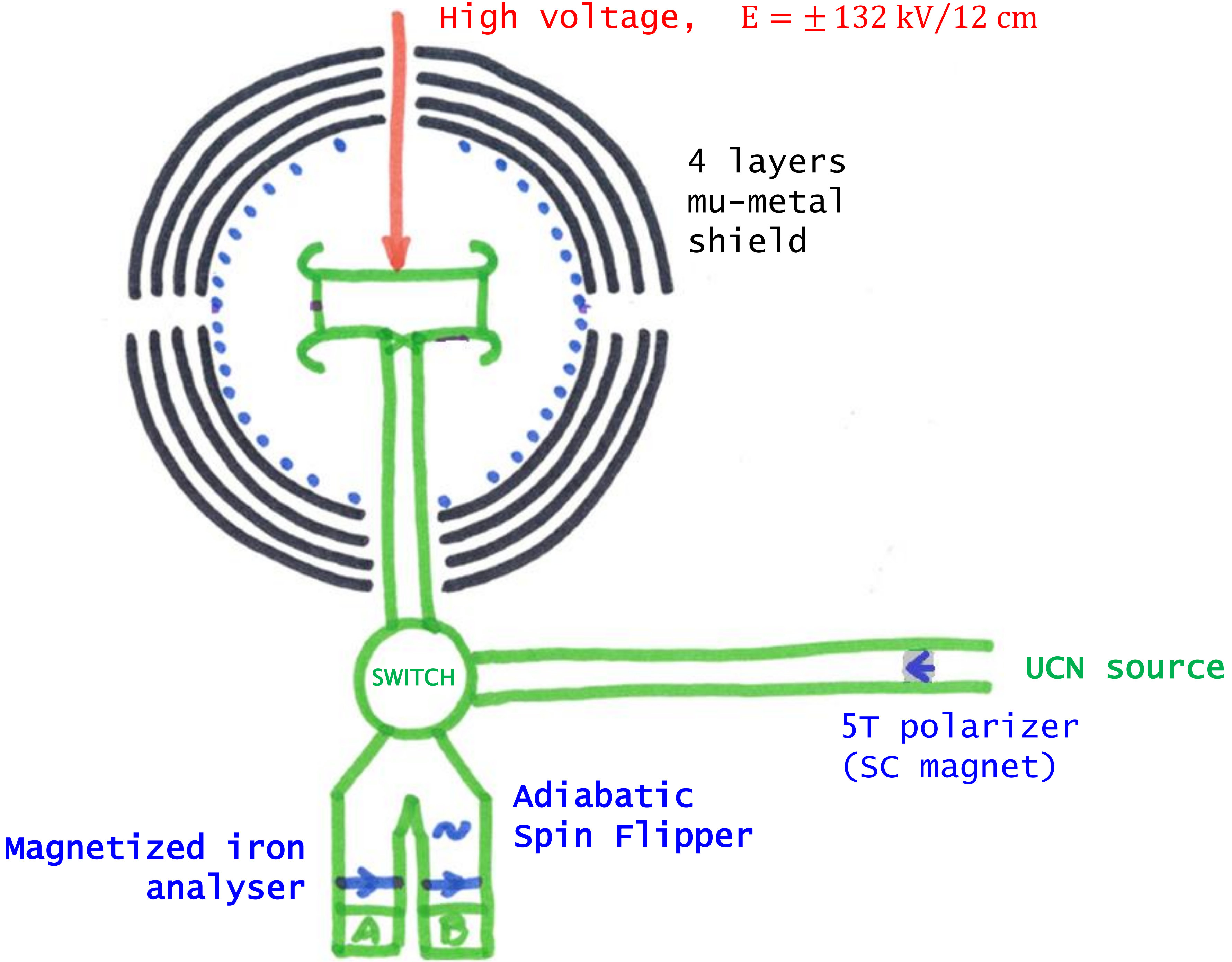
UCN source at the Paul Scherrer Institute



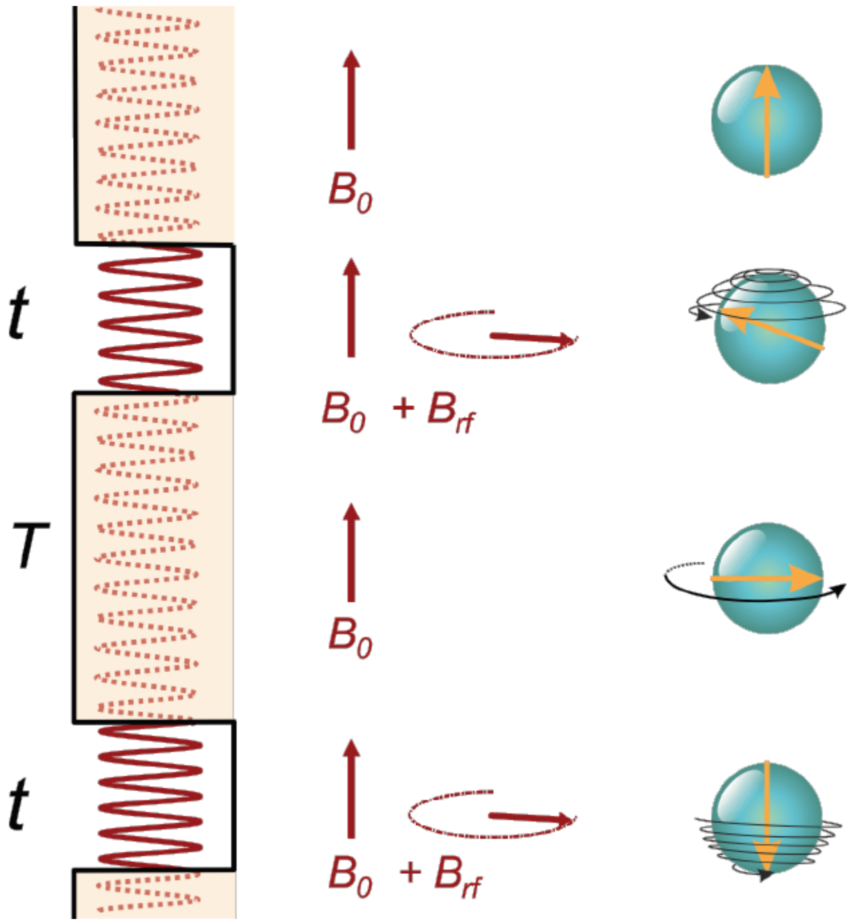
pulsed UCN source
One kick per 5 min
online since 2011

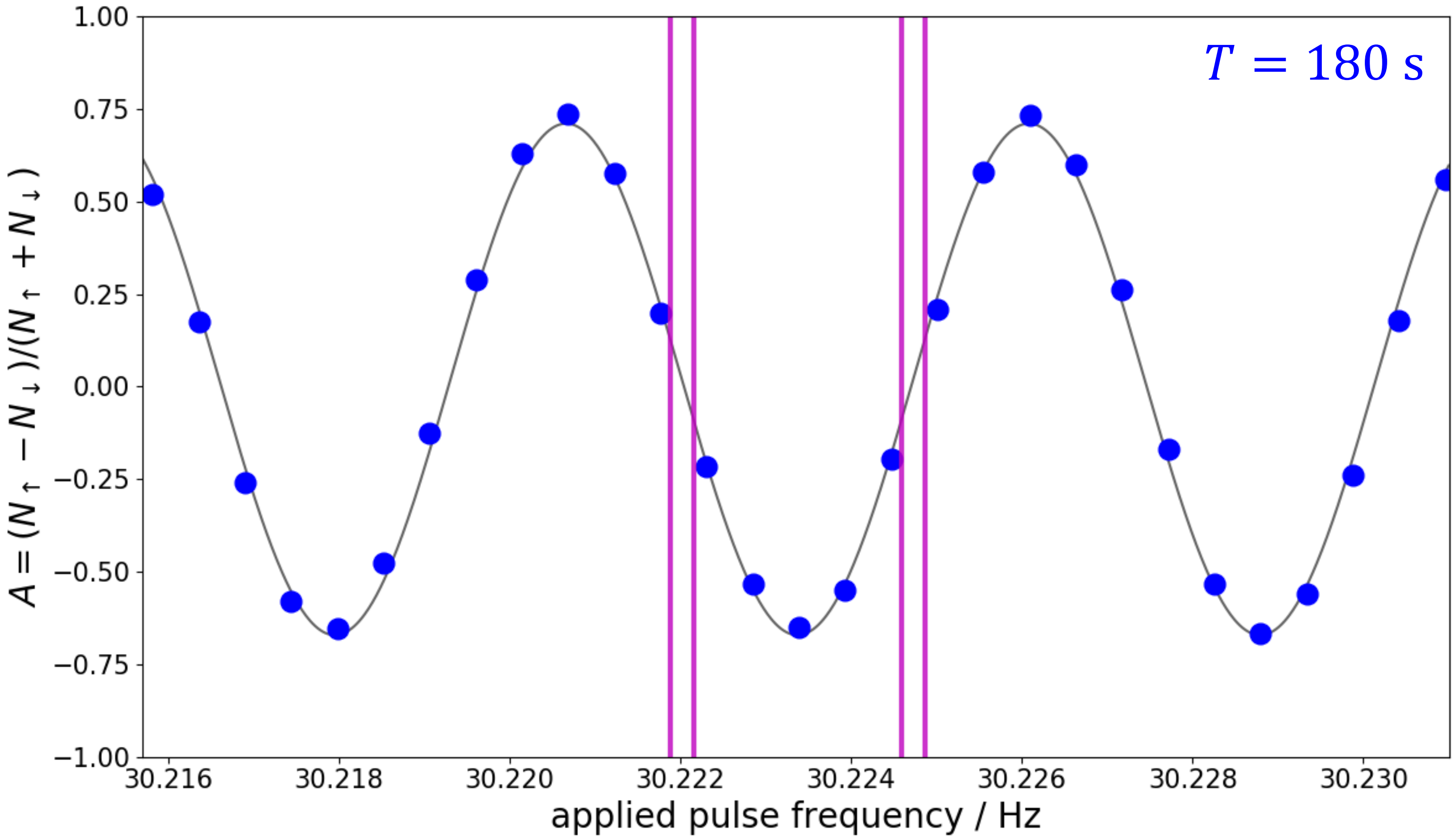
600 MeV, 2.2 mA

Scheme of the apparatus at PSI during EDM data-taking 2015-2016



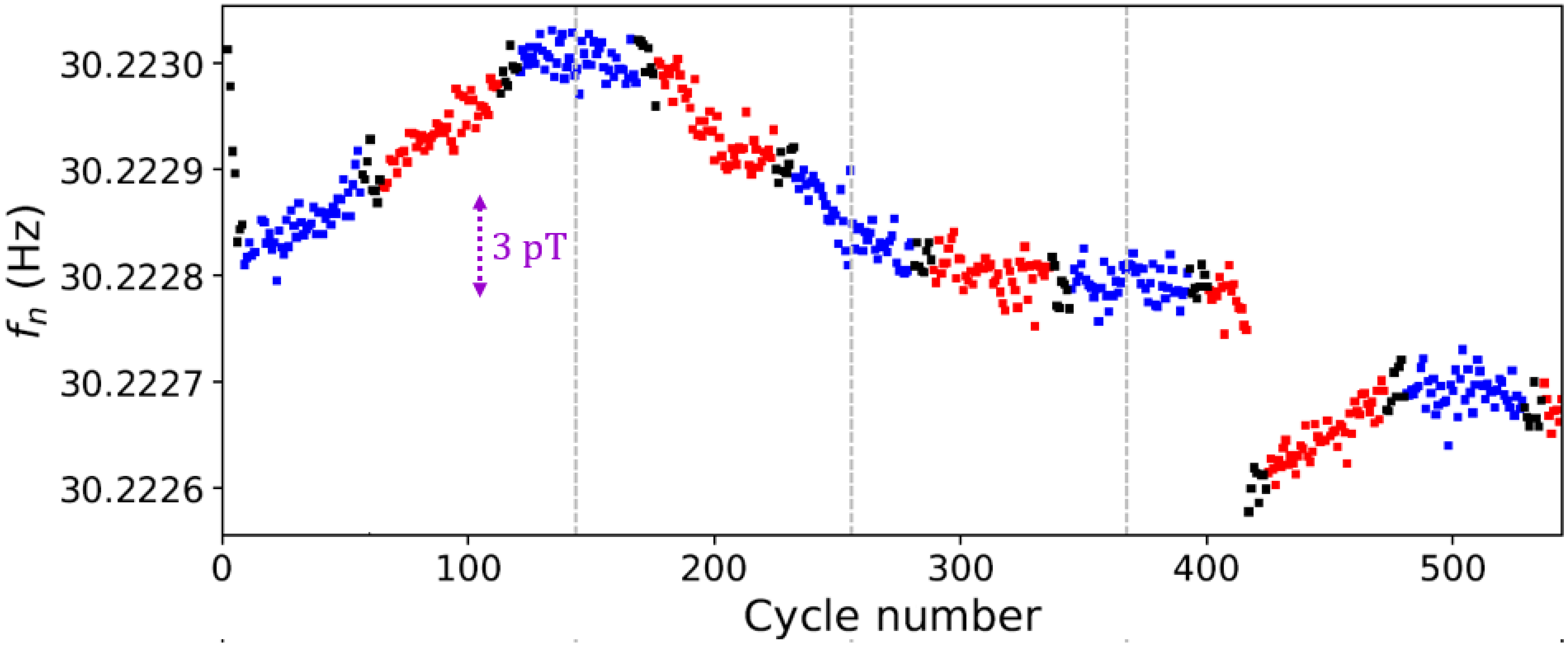
Ramsey's method





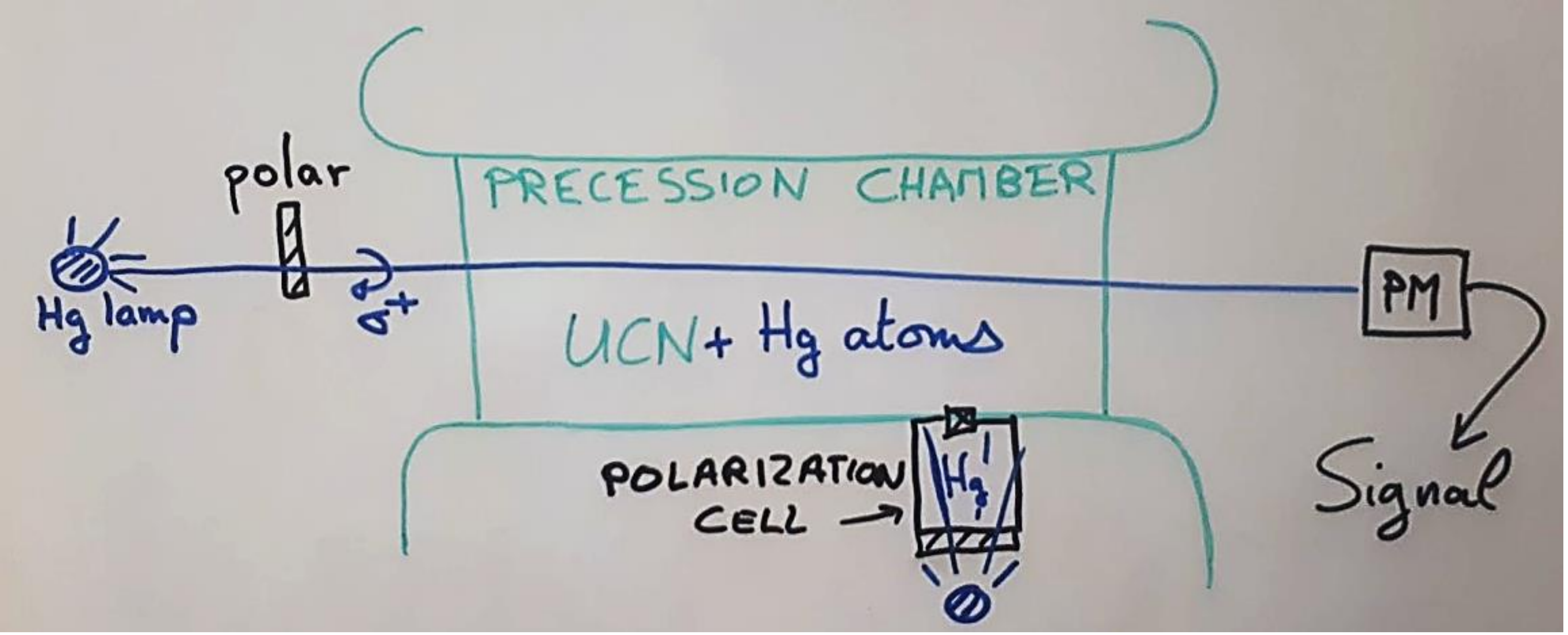
Statistical sensitivity: $\sigma d_n = \dfrac{\hbar}{2\,\alpha\,E\,T\sqrt{N}}$

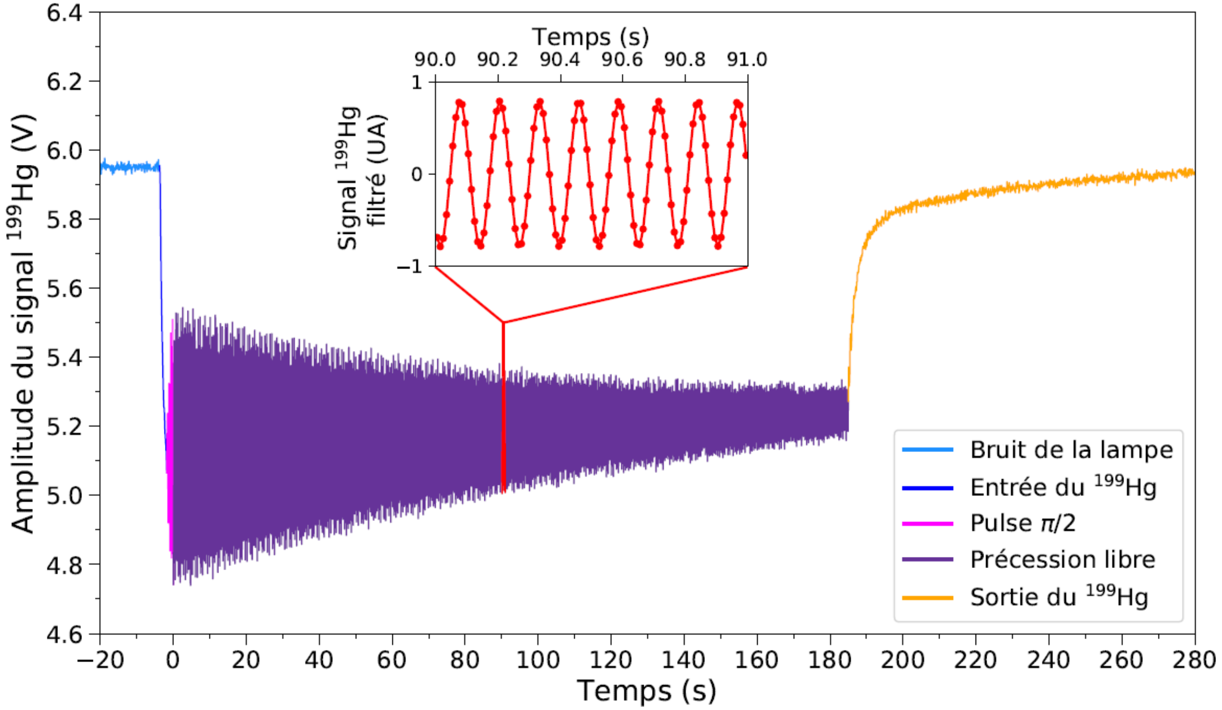
nEDM data collected in 2015-2016



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

Atomic comagnetometry with ^{199}Hg





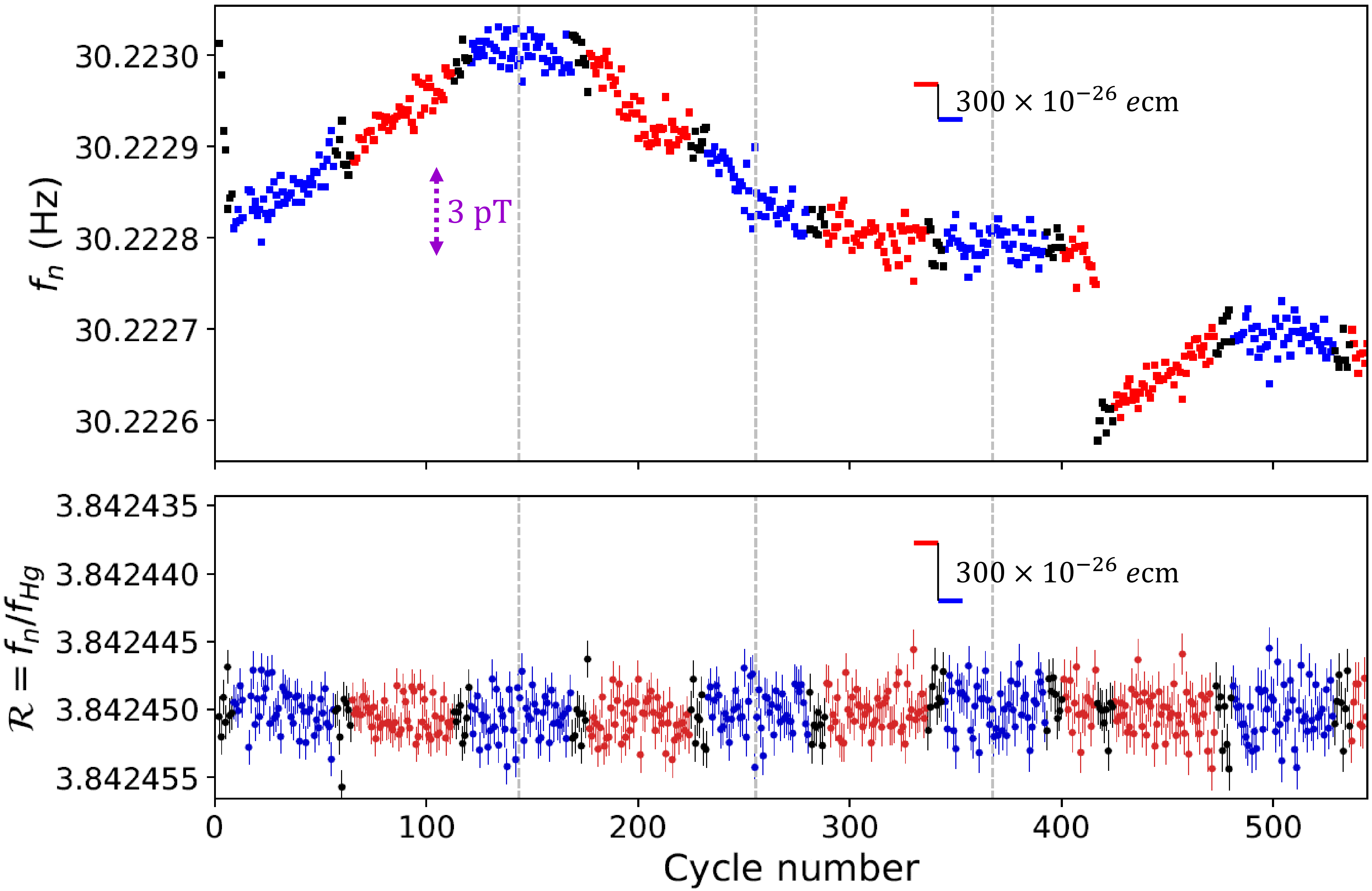
The magnetic field is extracted from the precession frequency of mercury-199 atoms:

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

A sequence of cycles (nEDM data)

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

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



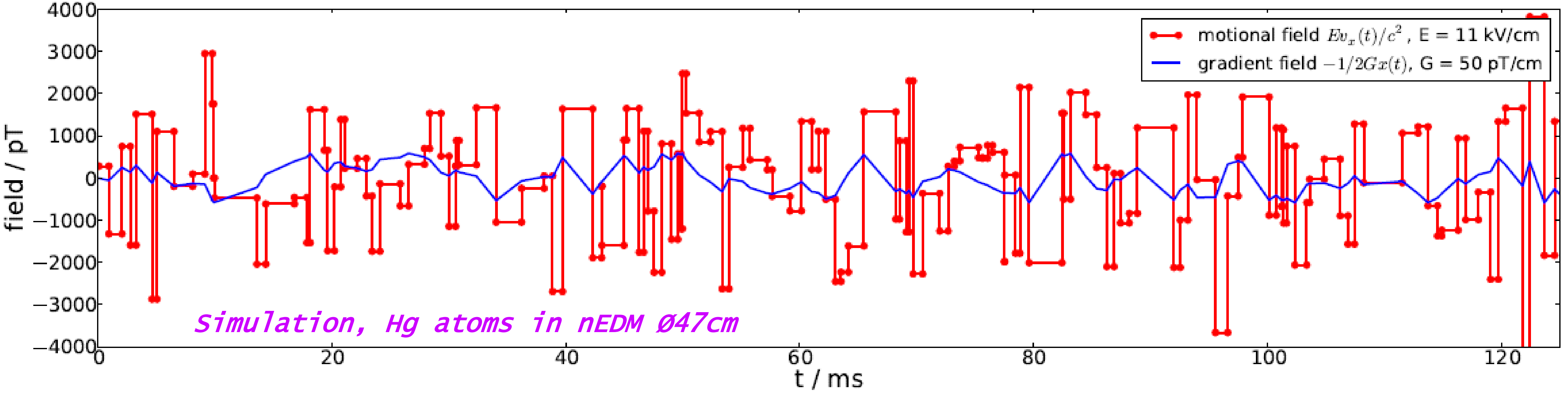
The co-magnetometer problem: Exv/c²

Nonuniform field

relativistic motional field

Transverse “noise”
on a mercury atom
in random motion

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



False EDM (low frequency limit): $d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = -\frac{\hbar|\gamma_n \gamma_{\mathrm{Hg}}|}{2c^2} \langle \boldsymbol{x B_x} + \boldsymbol{y B_y} \rangle$

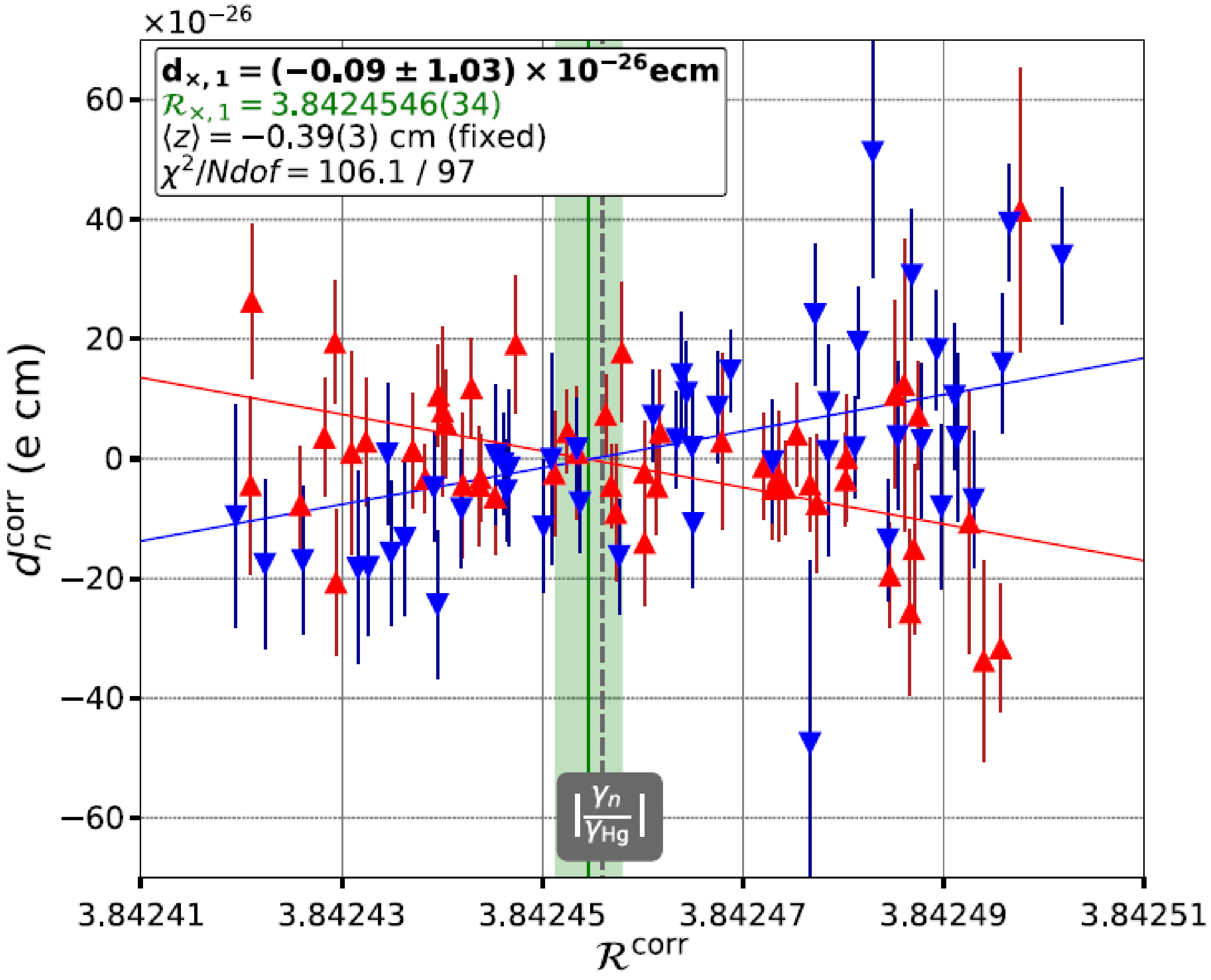
Budget of systematic errors

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.

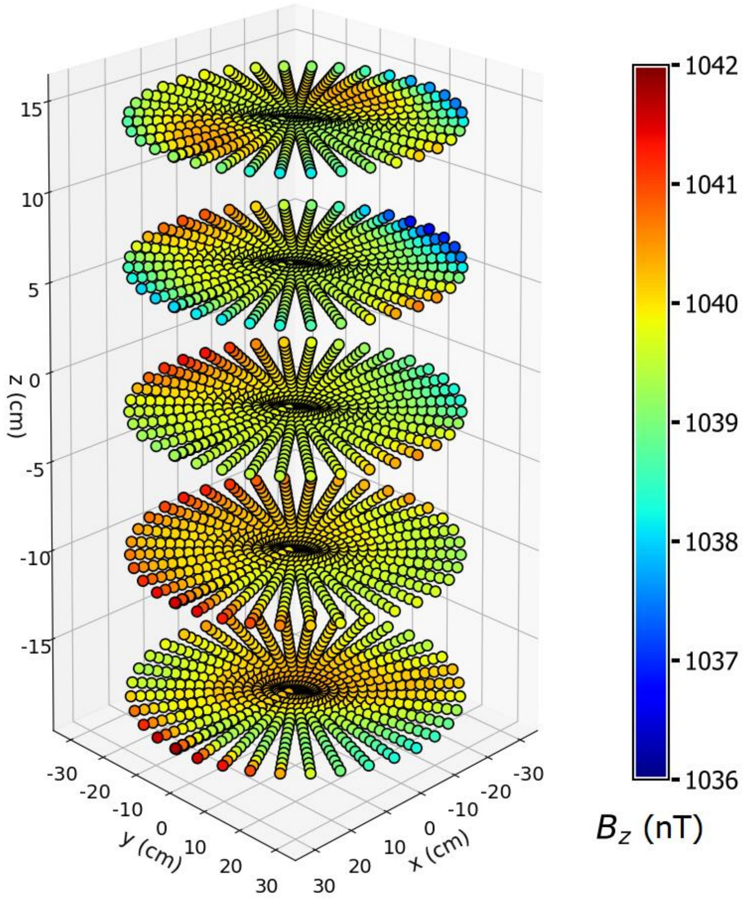
Effect	Shift	Error
Error on $\langle z \rangle$	···	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	–0.1	0.1
Local dipole fields	···	4
$v \times E$ UCN net motion	···	2
Quadratic $v \times E$	···	0.1
Uncompensated G drift	···	7.5
Mercury light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

Leading systematics associated with B-field uniformity

Systematics due to B-field non-uniformities



"online" correction based on the gravitational shift



"offline" correction based on magnetic field mapping

The rest of the talk

1. Basics of nEDM measurement

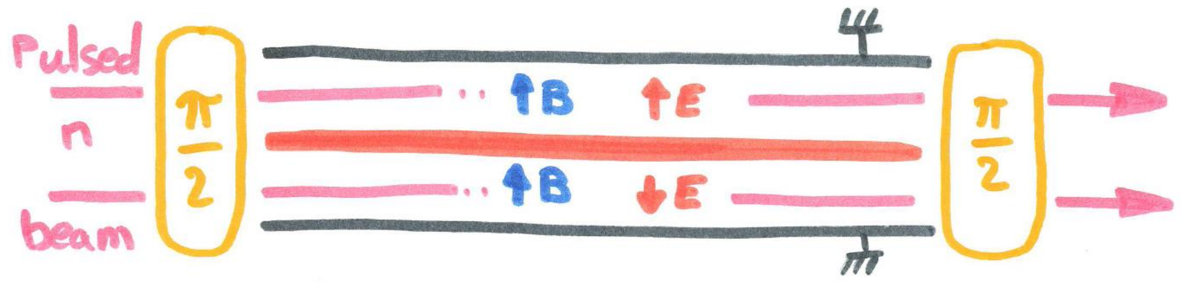
2. The recent result: dn = (0±1) 10-26 e cm

3. **Next generation n2EDM experiments**

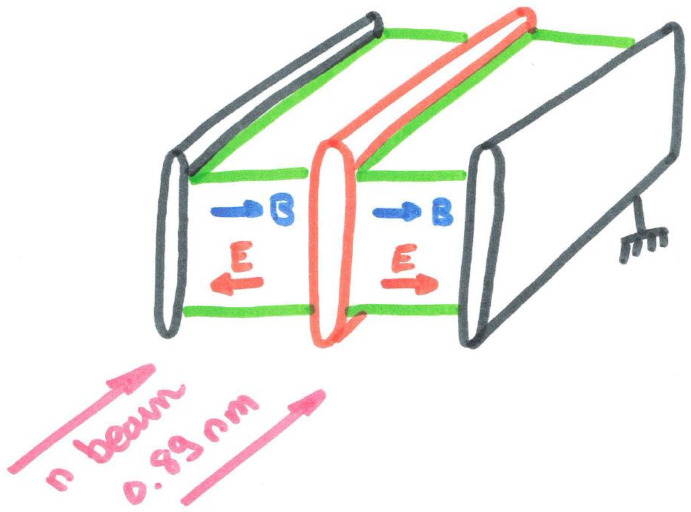
Next generation nEDM experiments

Topics discussed at the nEDM2021 workshop

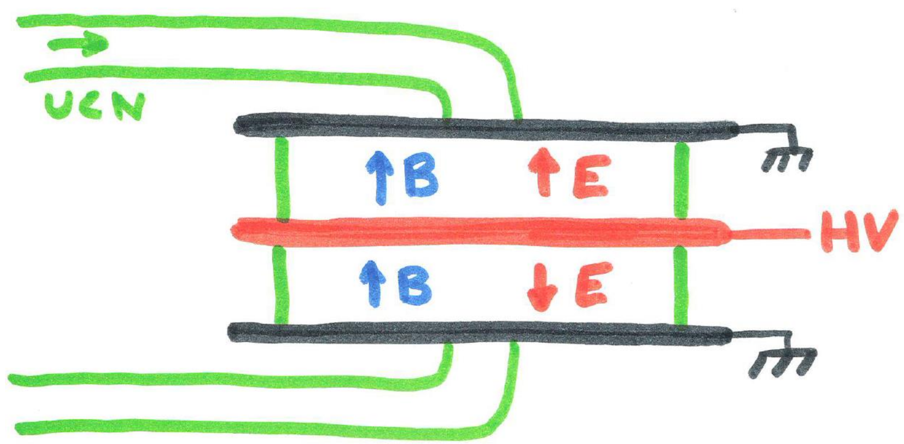
Revival of nEDM with a neutron beam



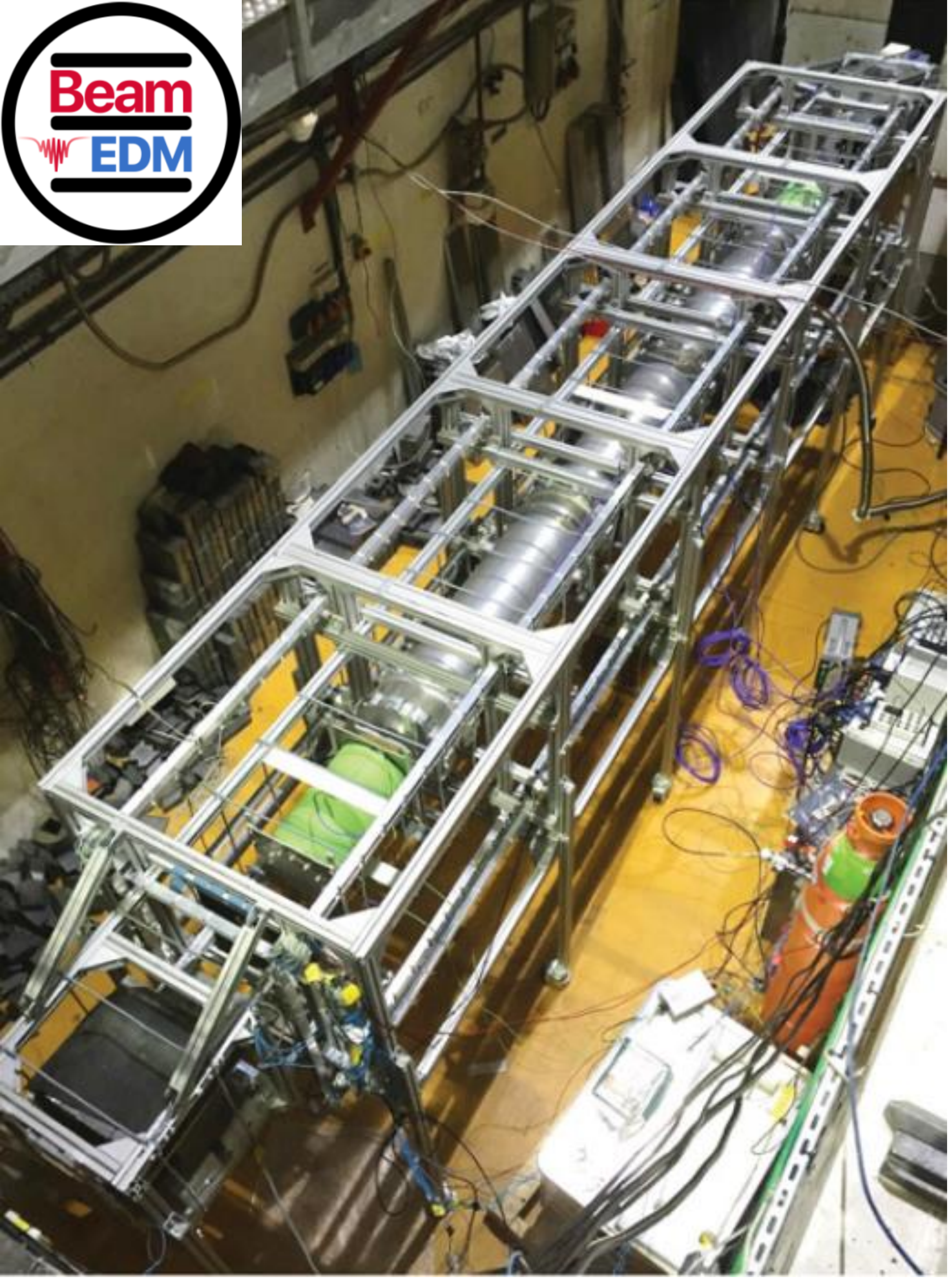
nEDM in superfluid helium



Double-chamber UCN @room temperature

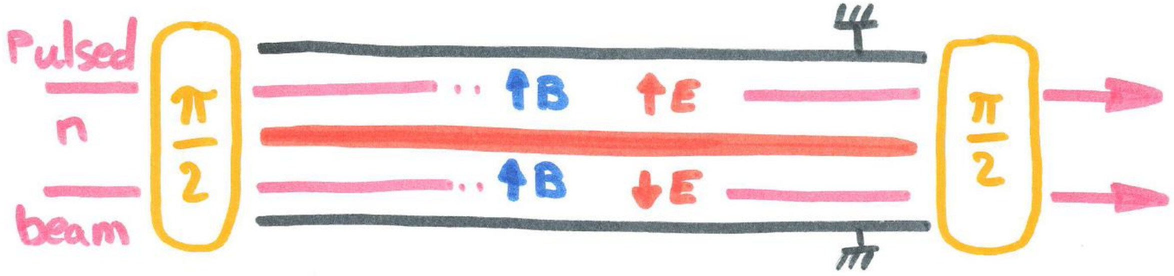


BeamEDM project



4 m long apparatus at ILL

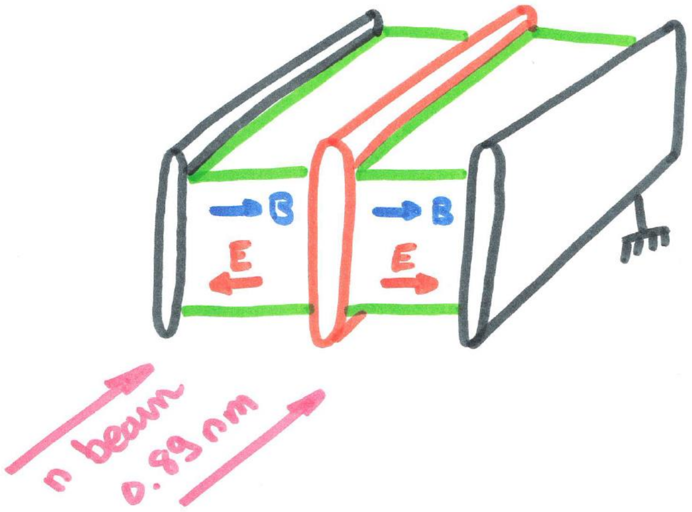
Revival of nEDM with a neutron beam



- Proof of principle measurements have been performed at the PSI, and at the ILL in Grenoble.
- Projected sensitivity at the ESS with a 50 m long apparatus: 5×10^{-26} e cm in one day of measurement.

E. Chanel et al. EPJ Web Conf., 219, 2004 (2019)

nEDM in superfluid helium



Golub-Lamoreaux concept:

- In-situ UCN production in superfluid helium-4 @ 0.5K
- Precession of polarized neutrons and helium-3 in the cells
- Measure the scintillation light of $^3\mathrm{He}(n,p)t$ which is spin-dependent

nEDM @SNS

Collaboration ~95 members

Precision goal of 2×10^{-28} e cm

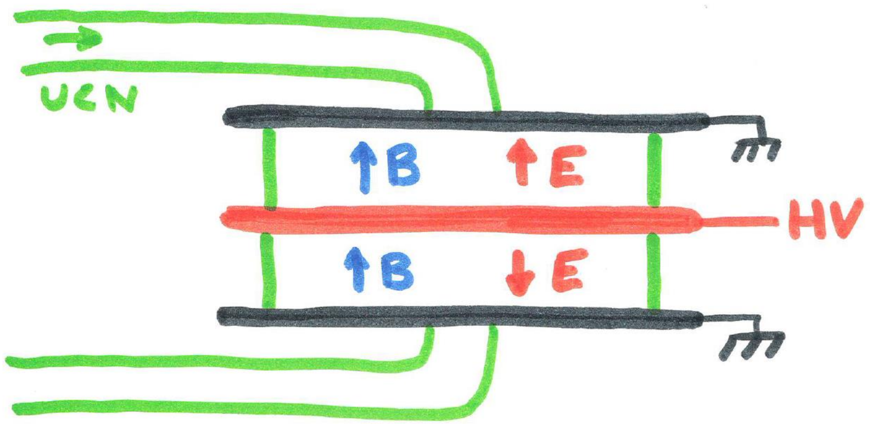
Baseline start date 2028

M.W. Ahmed et al, J. Inst., 14, P11017 (2019)

Some large final components

One concept, four competing projects

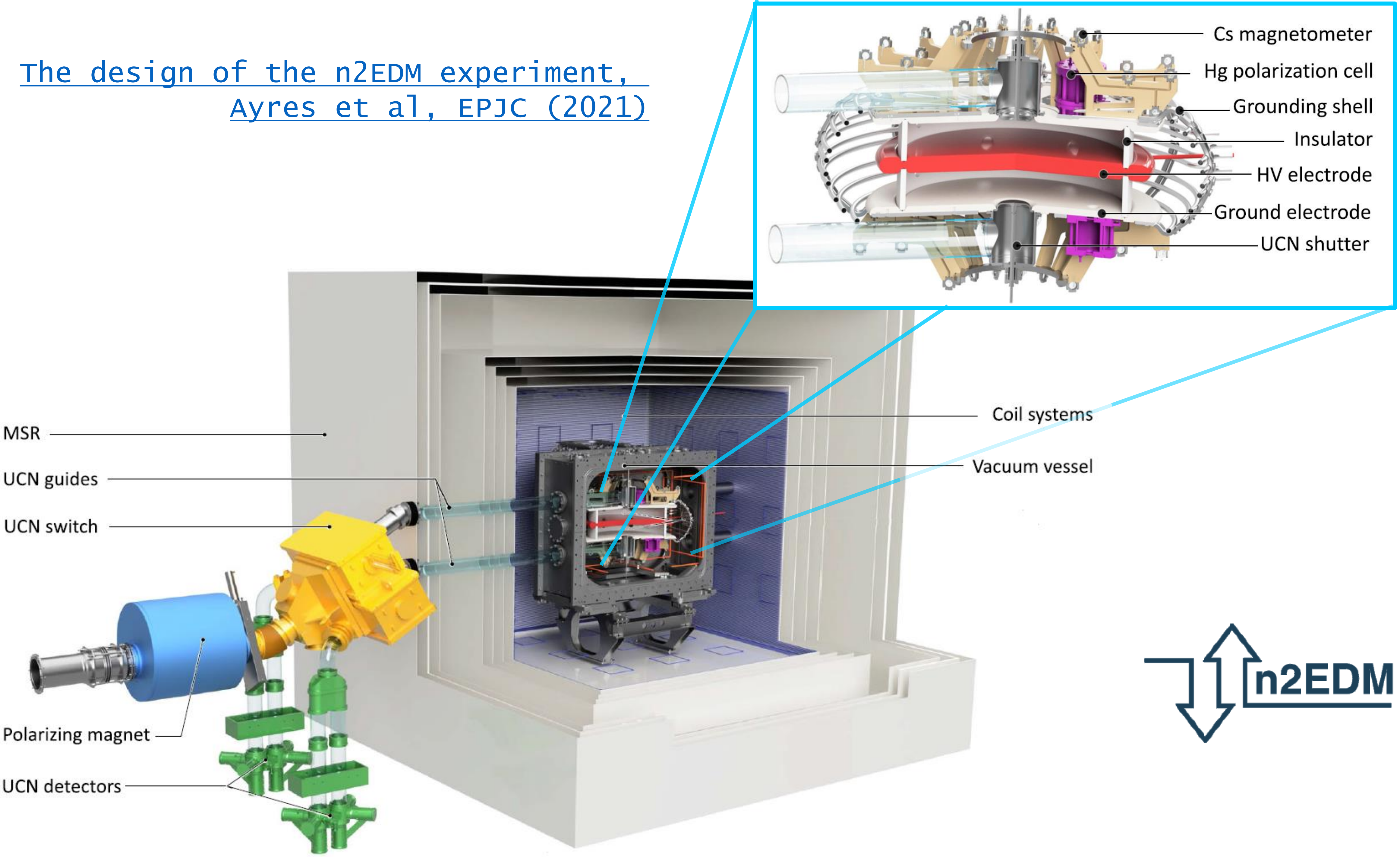
Double-chamber UCN @room temperature



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

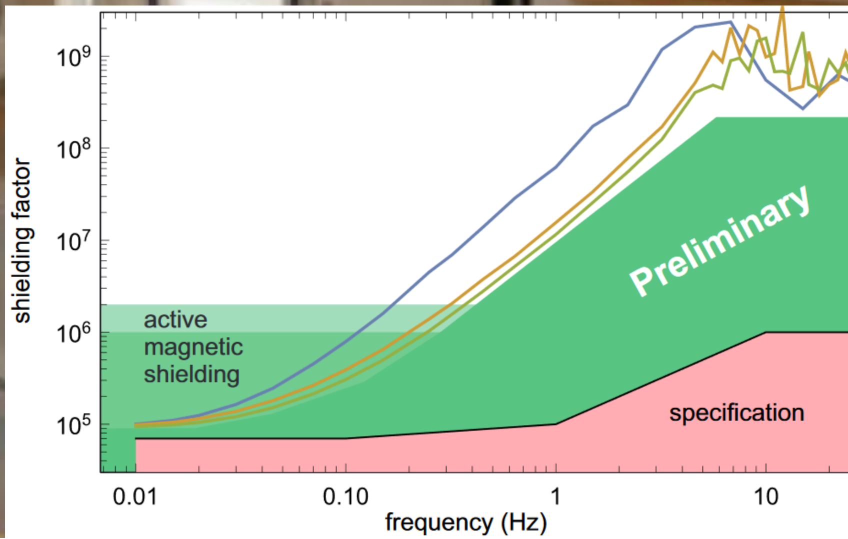
Place	Neutron source	Concept	Stage/Readiness
TRIUMF	Spallation + superfluid He UCN source	double Ramsey chamber with Hg comagnetometers + Cs mag	Source under construction, experiment in design phase
LANL	Spallation + sD2 UCN source	double Ramsey chamber with Hg comagnetometers + commertial OPMs	Source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

[The design of the n2EDM experiment, Ayres et al, EPJC (2021)]

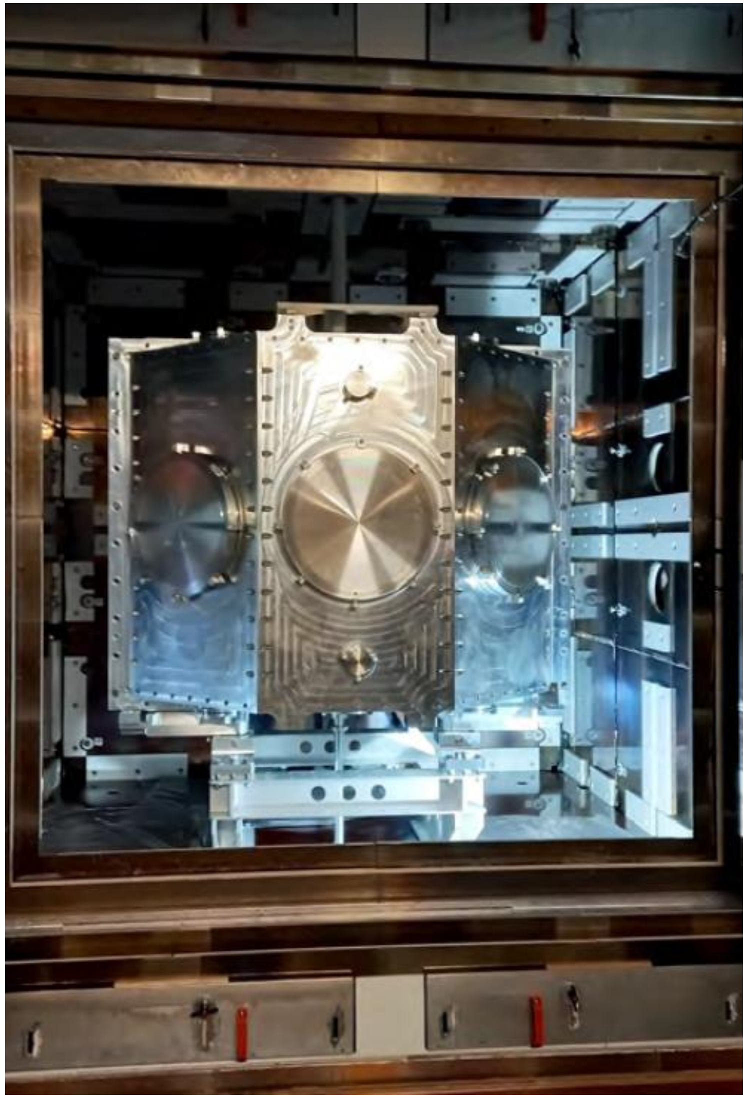


n2EDM


AMS:
active shield
50 km of wires
MSR: passive shield
6 layers mumetal


shielding factor
10^9
10^8
10^7
10^6
10^5
0.01
0.10
1
10
frequency (Hz)
active
magnetic
shielding
Preliminary
specification

n2EDM progress in 2021

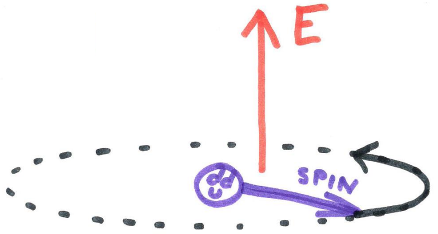


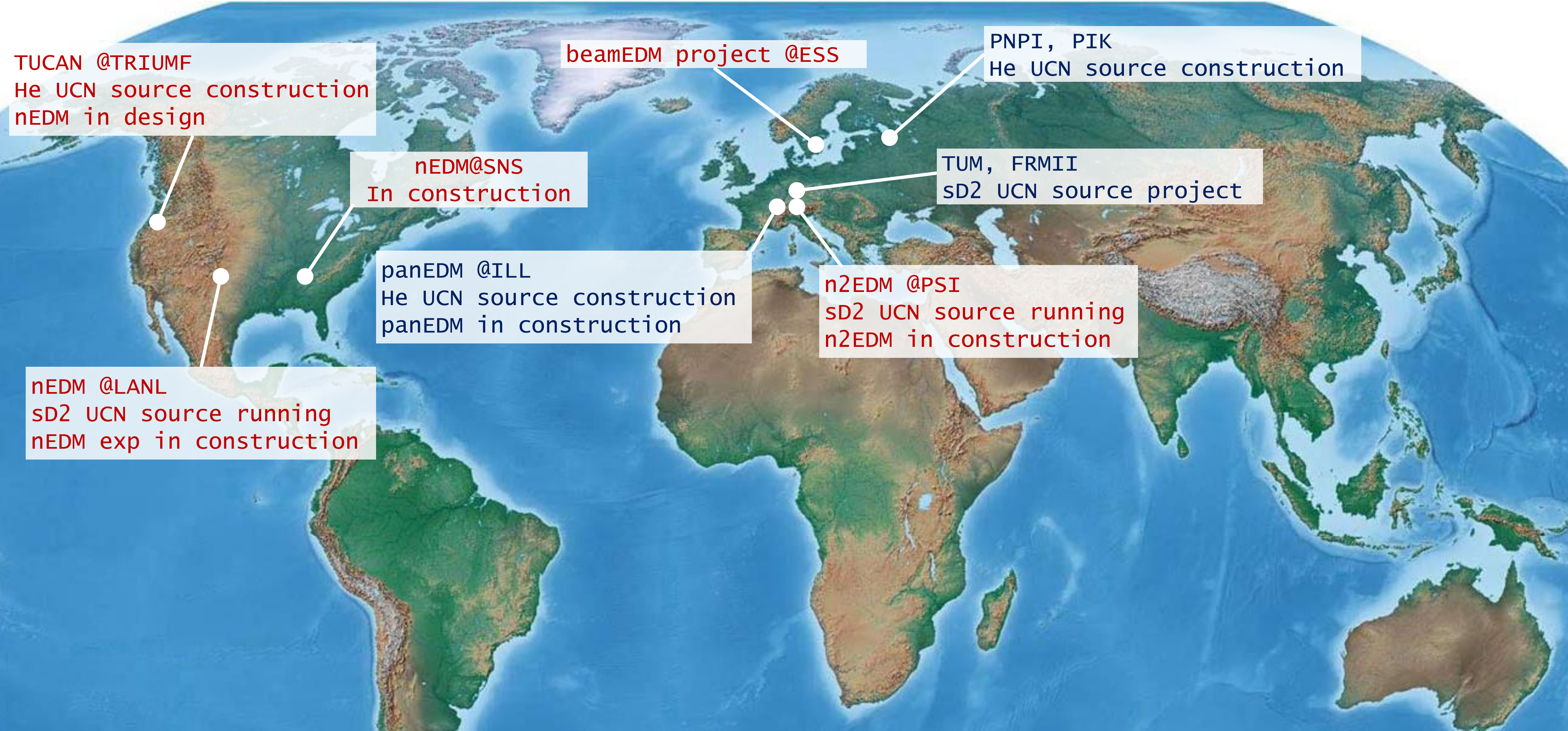
Vaccum tank within the shield

Magnetic mapper inside the tank

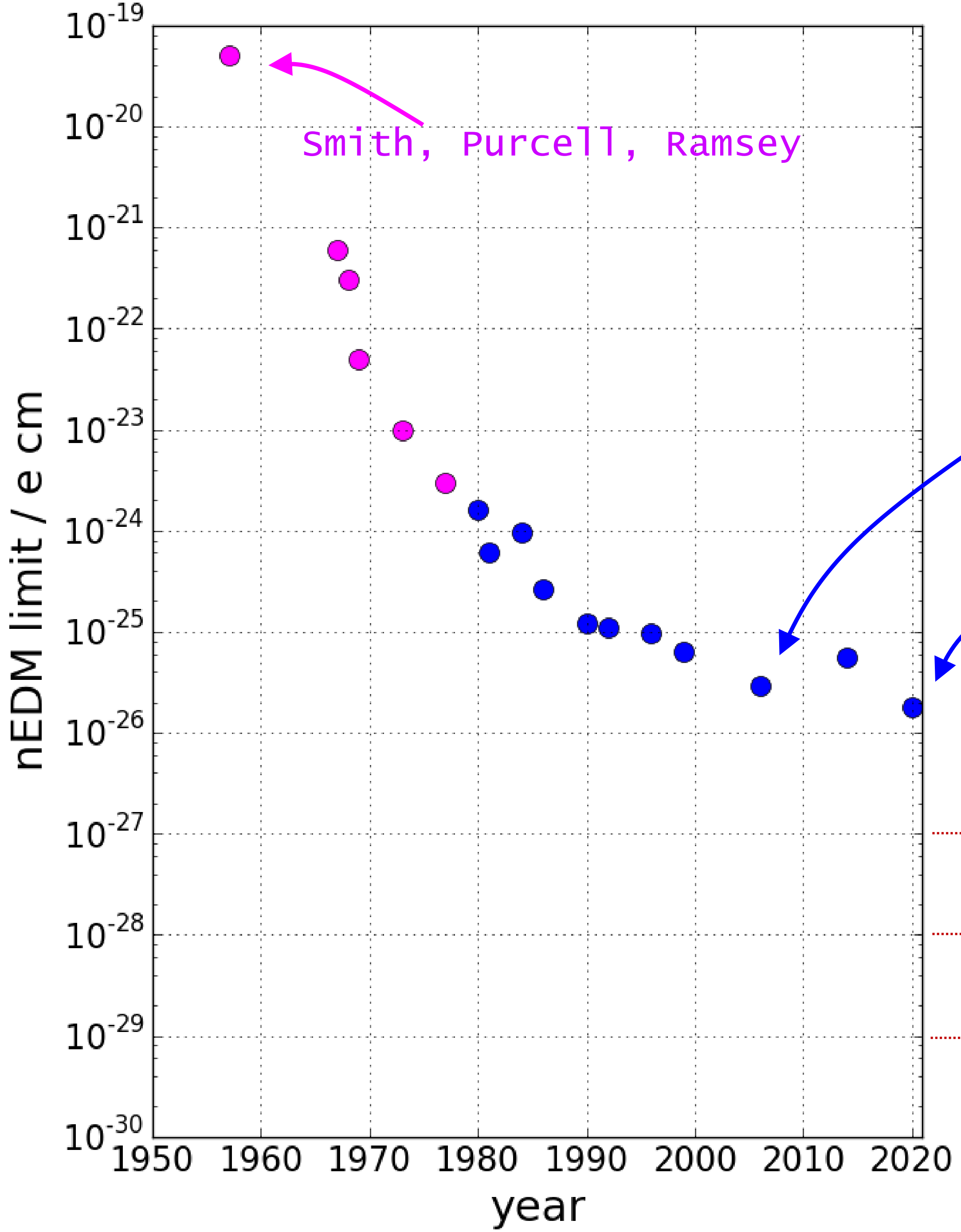
Large B0 coil installed

Neutron EDM around the world





Conclusion/perspectives...



Previous best result (@ILL, Grenoble)
Pendlebury et al, PRD **92**, 092003 (2015)

New best limit (@PSI)
Abel et al, PRL **124**, 081803 (2020)

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

Design sensitivity range of 4 experiments
n2EDM(@PSI), panEDM(@ILL), LANL EDM, tucan(@TRIUMF)
under construction now

Design sensitivity EDM@SNS, starting 2028

~Statistical reach of present neutron sources

CKM background