EDMs: complementary experiments and theory connections
Trento, March 4-8, 2024

Neutron EDM

Experimental overview

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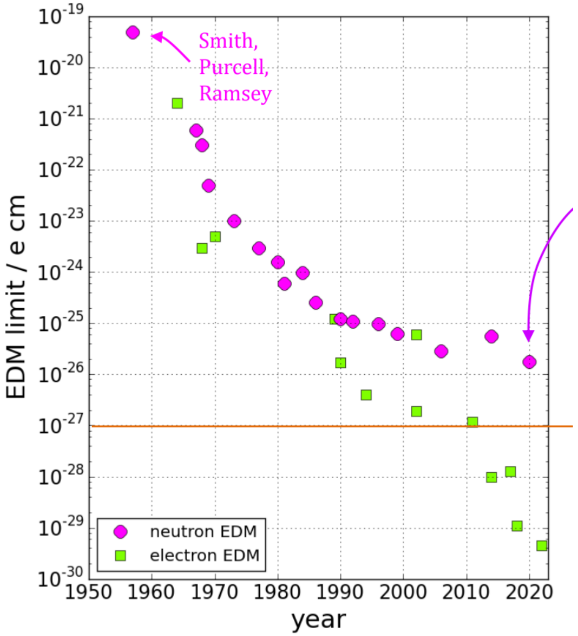
Experiments on Neutron EDM

The nEDM collaboration @PSI


about 50 members
from 8 countries
and 14 institutions



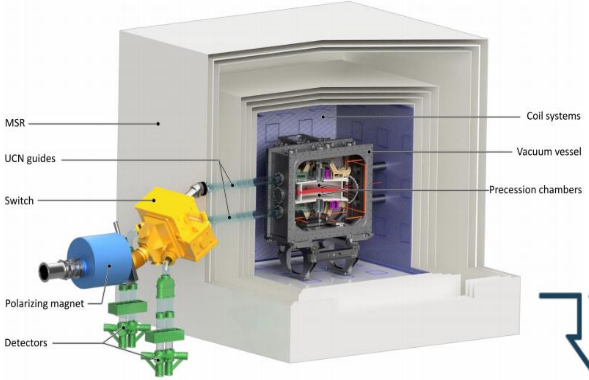
Neutron EDM measured by the nEDM collaboration (2020):

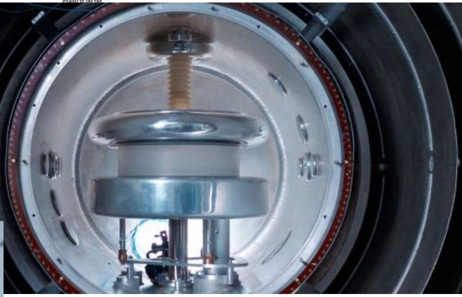
$$d_\mathrm{n} = (0.0 \pm 1.1_\mathrm{stat} \pm 0.2_\mathrm{sys}) \times 10^{-26}\, e\,\mathrm{cm}$$

C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

← The next goal:

n2EDM
PanEDM
LANL
TUCAN





The nEDM apparatus
and the IN2P3 team (FR)
at PSI in 2019

Experiments on Neutron EDM

The nEDM collaboration @PSI

about 50 members
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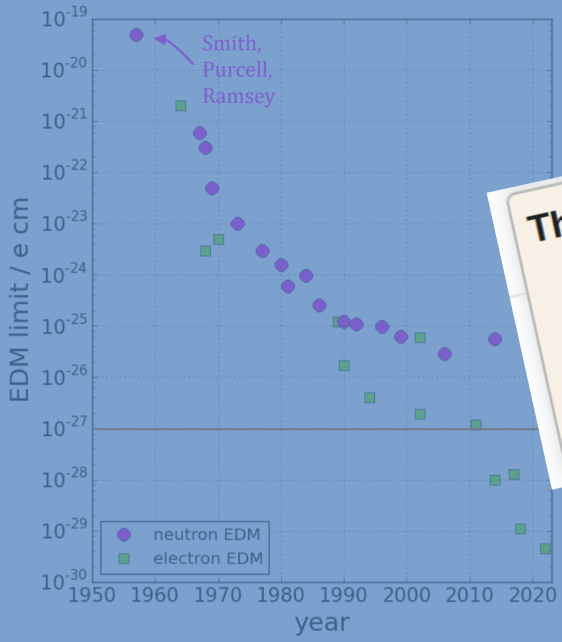


Neutron EDM meas

The n2EDM experiment at PSI

Patrick Mullan

on Friday
March 8

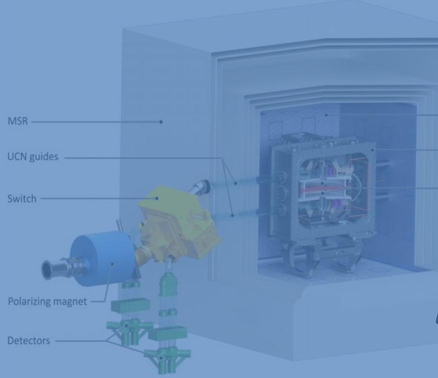
09:45 - 10:30

Aula Renzo Leonardi, ECT*

&

Poster by
Efrain Patrick
Segarra

n2EDM
PanEDM
LANL
TUCAN



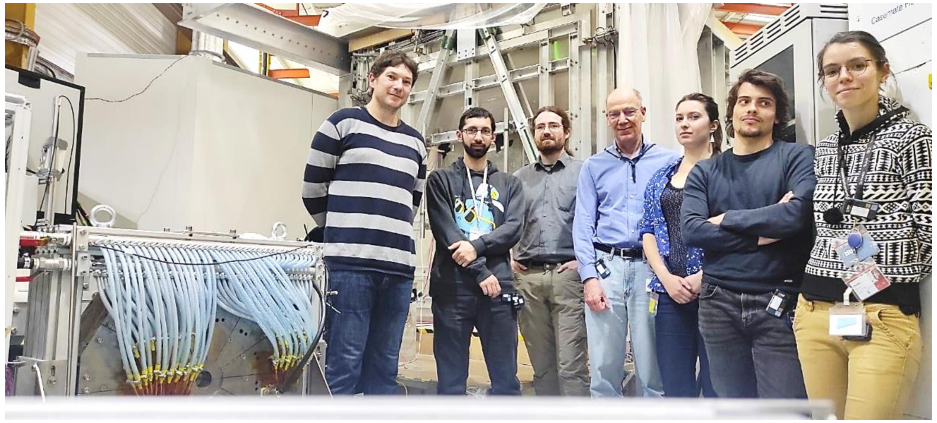
The nEDM apparatus
and the IN2P3 team (FR)
at PSI in 2019

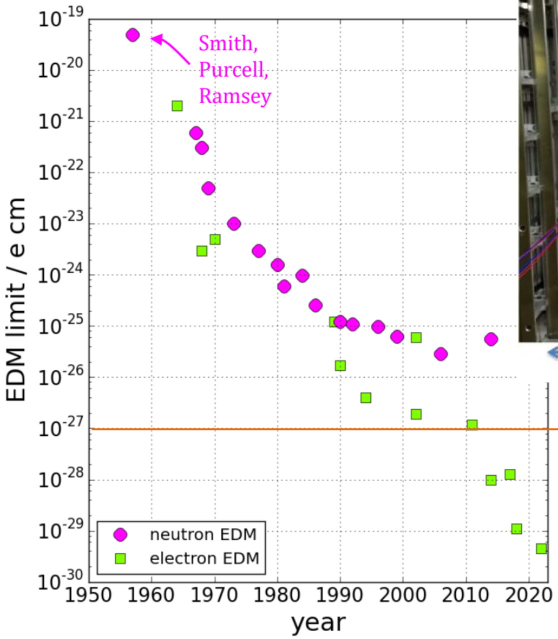
Experiments on Neutron EDM

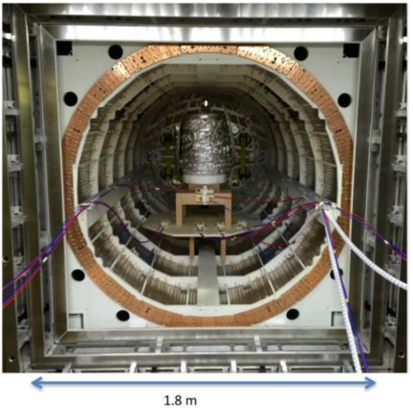
The PanEDM collaboration @ILL, Grenoble

about 25 members
4 countries
8 institutions

Many people contributed,
Over 40 student theses!







← The next goal:

n2EDM
PanEDM
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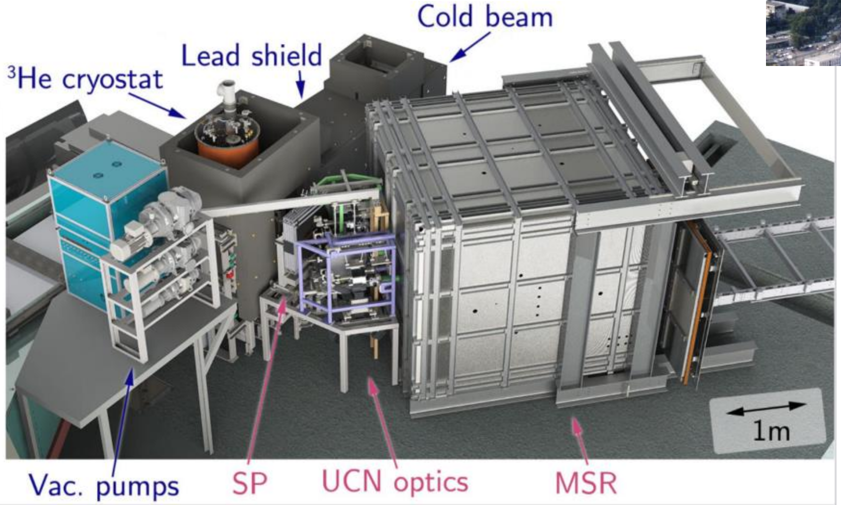
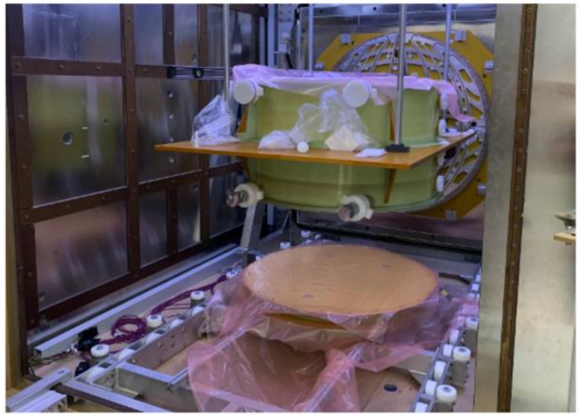
TUCAN

PanEDM experiment at SuperSun UCN source at ILL

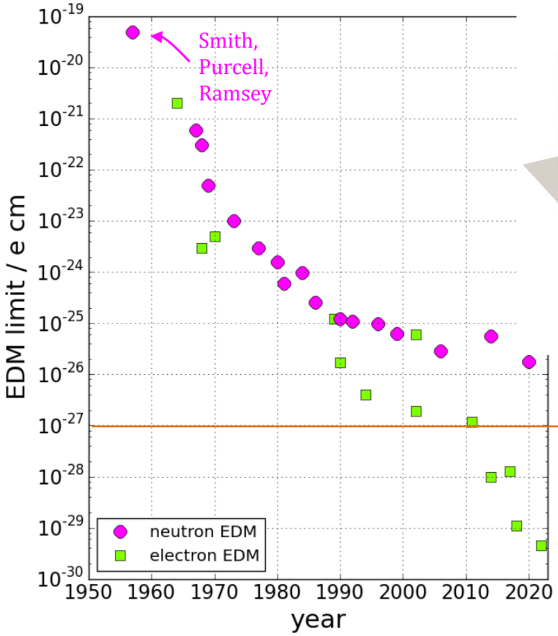




Experiments on Neutron EDM

The Los Alamos National Laboratory nEDM Experiment @LANL UCN facility, USA


about 15 members
5 institutions



← The next goal:

n2EDM
PanEDM
LANL
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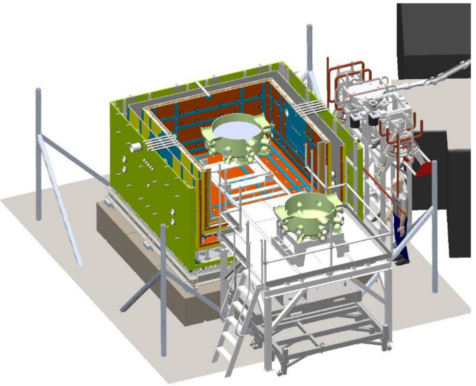
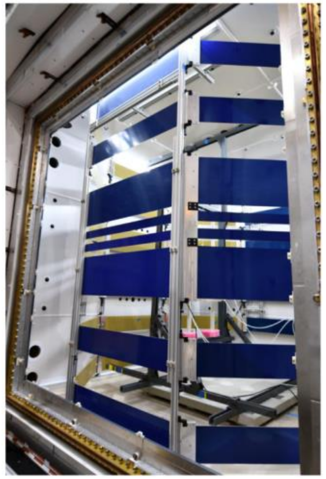
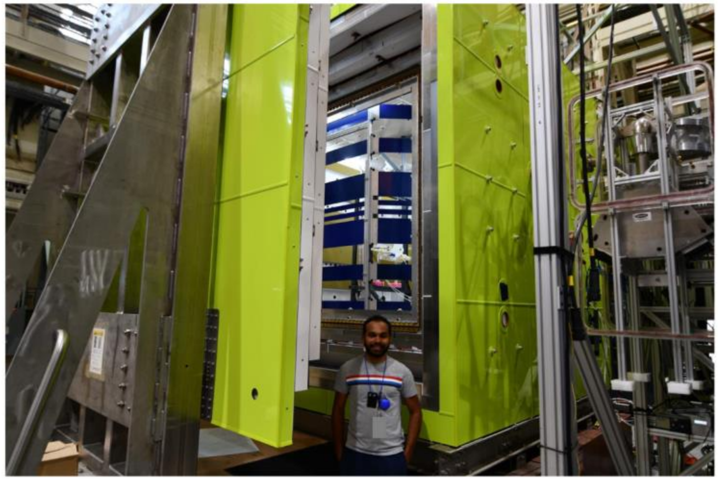
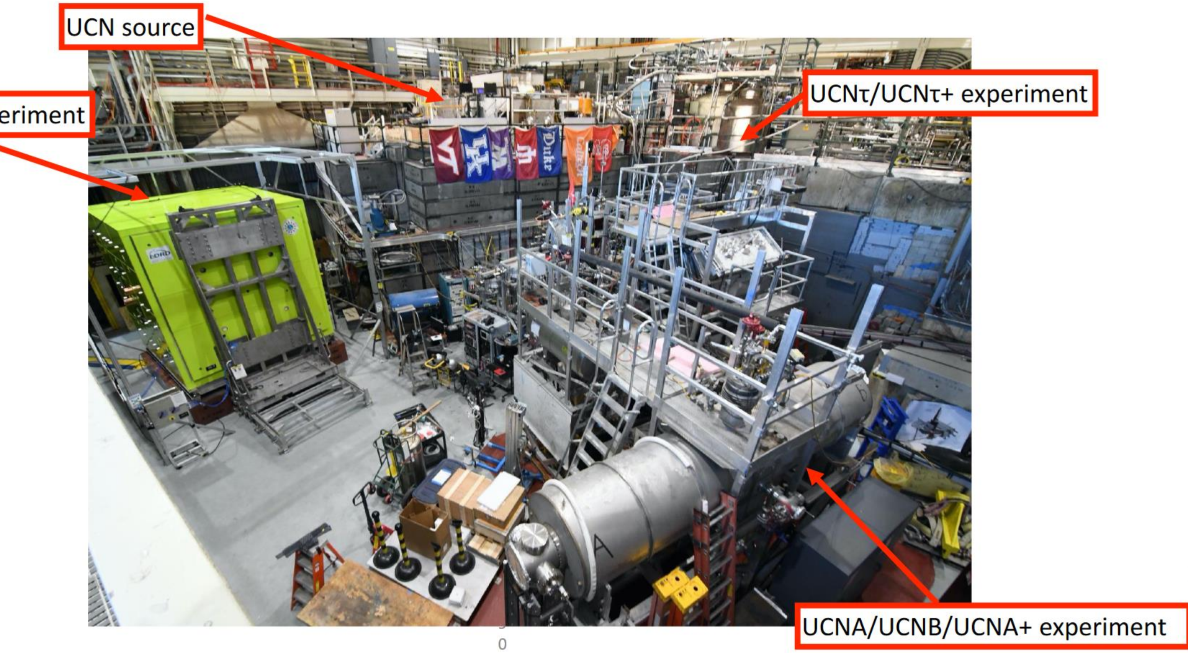


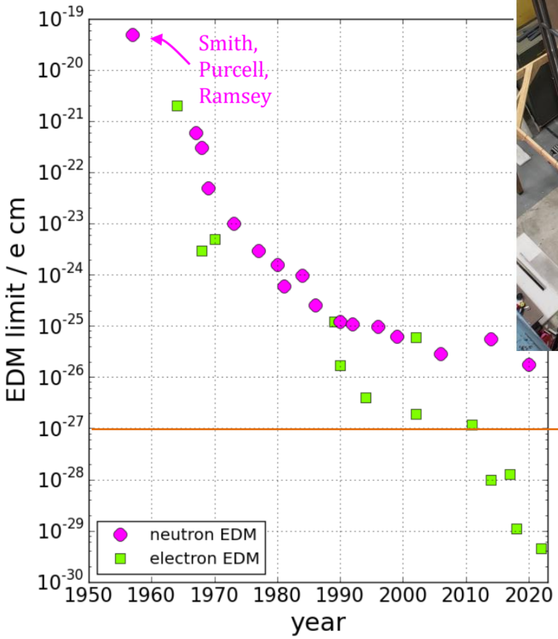






Experiments on Neutron EDM

TRIUMF Ultra-Cold Advanced Neutron (TUCAN) Collaboration, @TRIUMF, Canada

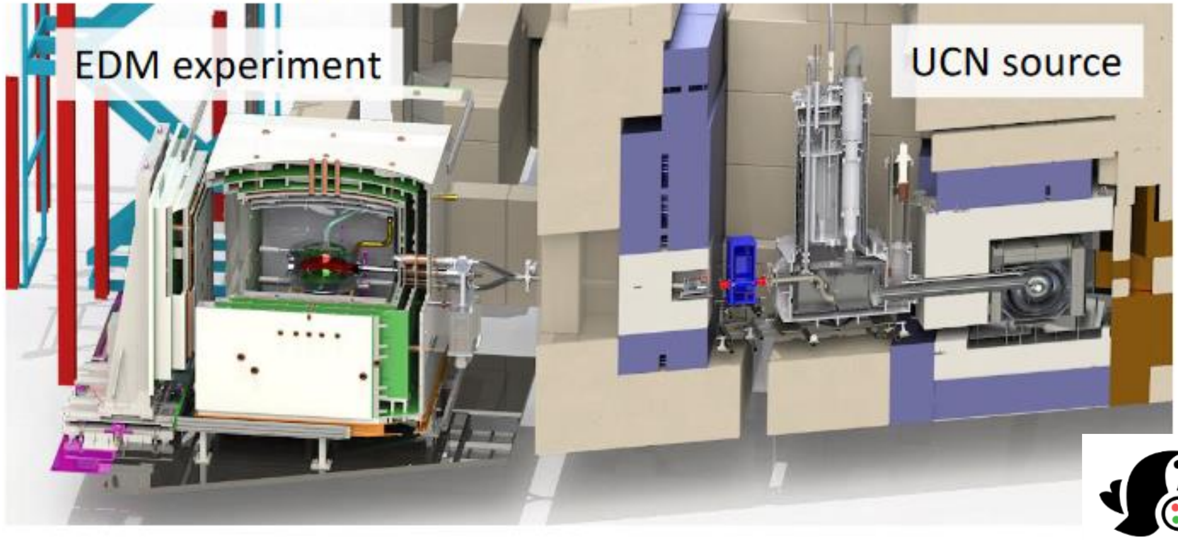


← The next goal:

n2EDM
PanEDM
LANL
TUCAN

12 institutions: Canada & Japan

View of future facility at TRIUMF



How to measure nEDM?

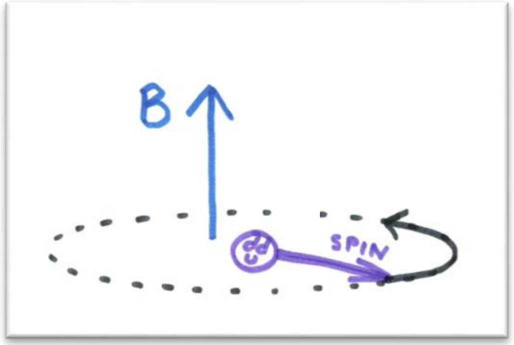
Dipole moments as couplings of the spin to the Magnetic field (MDM) and Electric field (EDM)

$$\hat{H} = -\mu\,\vec{\sigma}\cdot\vec{B}$$

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

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

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



Precession of the spin around $\vec{B}$

How to measure nEDM?

Dipole moments as <u>couplings</u> of the spin to the Magnetic field (MDM) and Electric field (EDM)

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

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

Nuclear magneton

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

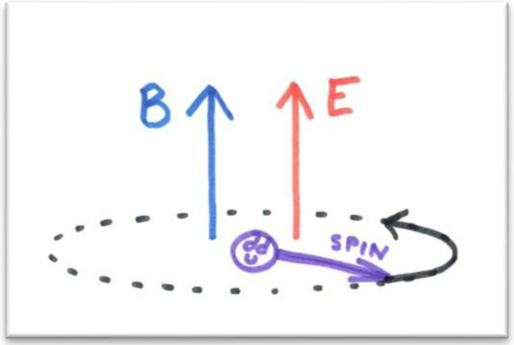
$d = (0 \pm 1) \times 10^{-26}\ e\ \mathrm{cm}$

$= (0 \pm 1) \times 10^{-12} \times \mu_N/c$

$\frac{\mu_N}{c} \approx 0.1\ \mathrm{e\ fm}$

Larmor frequency

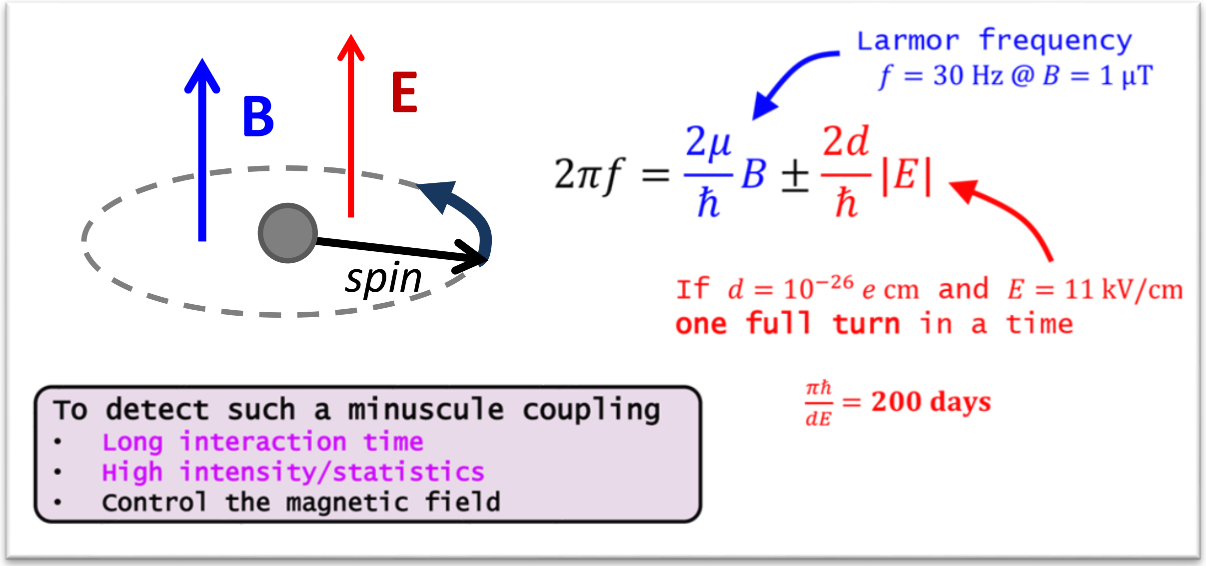
$f = 30\ \mathrm{Hz}\ @\ B = 1\ \mu\mathrm{T}$



Precession of the spin around $\vec{B}$ and $\vec{E}$

How to measure nEDM?

nEDM measurement. The idea:



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

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

If $d = 10^{-26}\,e\,\mathrm{cm}$ and $E = 11\,\mathrm{kV/cm}$
one full turn in a time

$$\frac{\pi\hbar}{dE} = 200\ \text{days}$$

To detect such a minuscule coupling
- Long interaction time
- High intensity/statistics
- Control the magnetic field

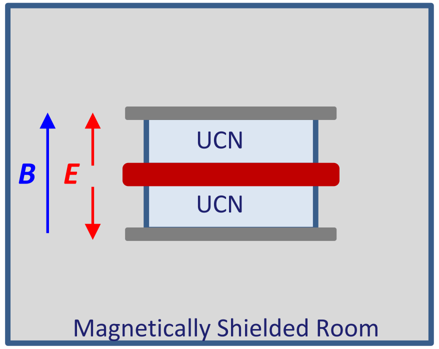
The actual upper limit (2020)

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

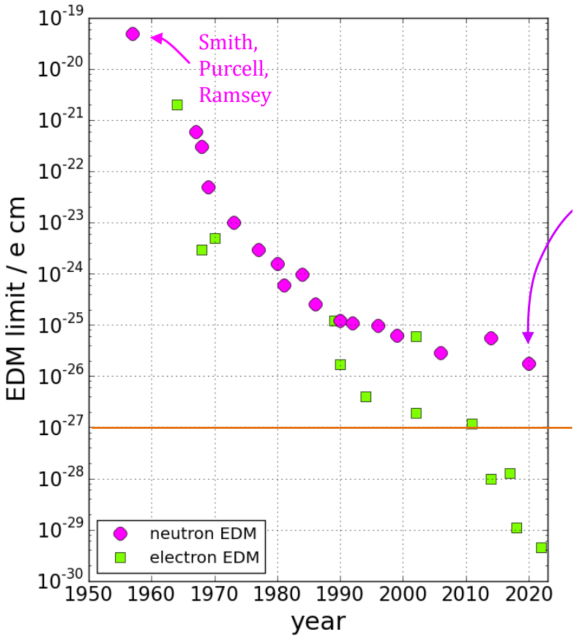
C. Abel et al. Phys. Rev. Lett. 124, 081803

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

$$\boxed{d = \frac{\pi\hbar}{2|E|}\left(f(\uparrow\downarrow) - f(\uparrow\uparrow)\right)}$$



Historical overview: the main milestones



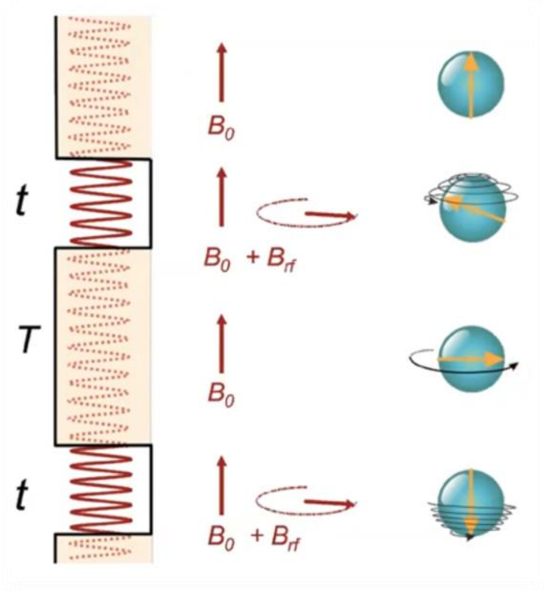
← The next goal

Neutron EDM measured by the nEDM collaboration (2020):

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

C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

Ramsey’s method of separated oscillating fields



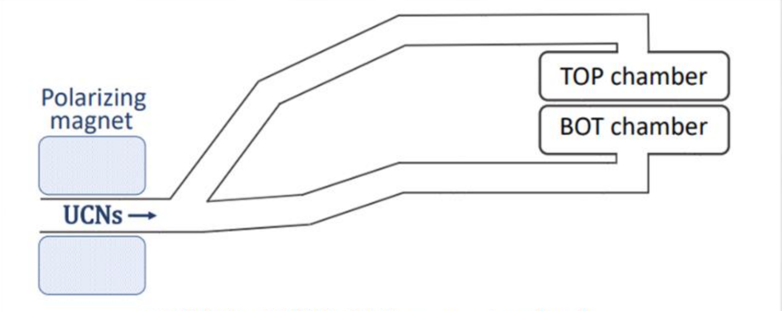
Neutron spin || B_0

Apply oscillating m.field ⊥ B_0

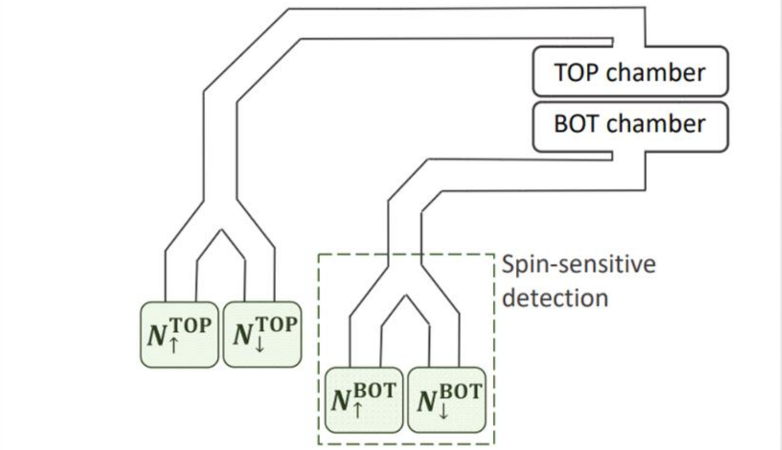
Let precess for 180 s

Again apply oscillating m.field ⊥ B_0

Obtain neutrons with spin either UP or DOWN,
Count the number of each, which depends on f_n



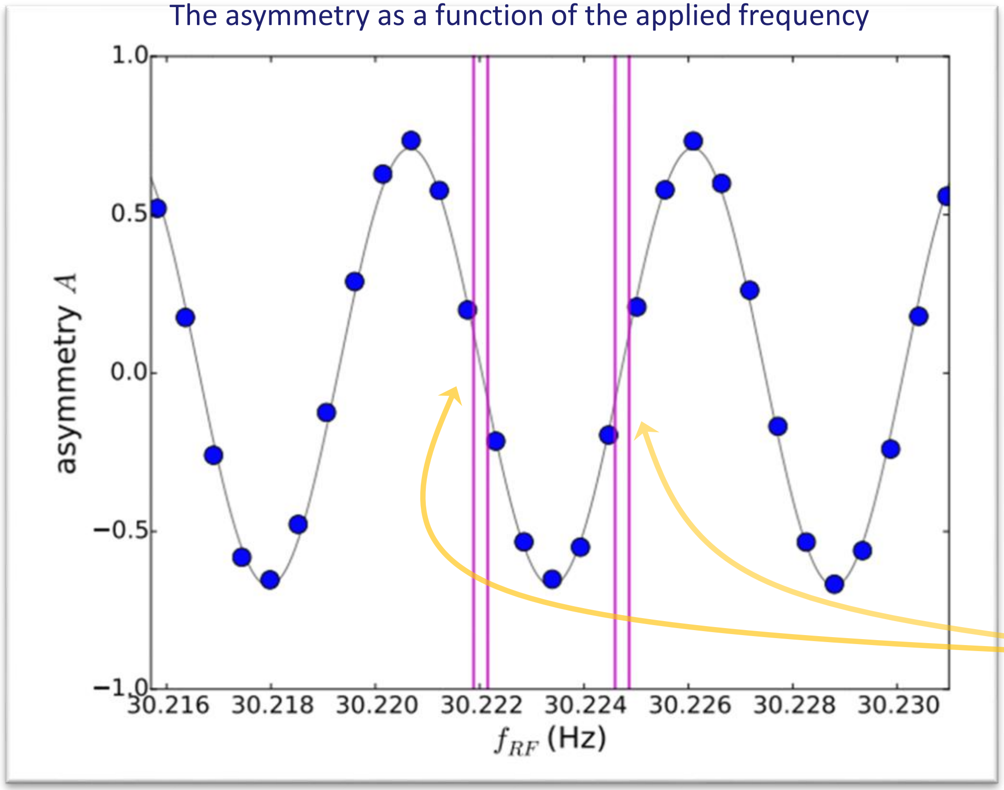
(a) Polarized UCNs fill the precession chambers



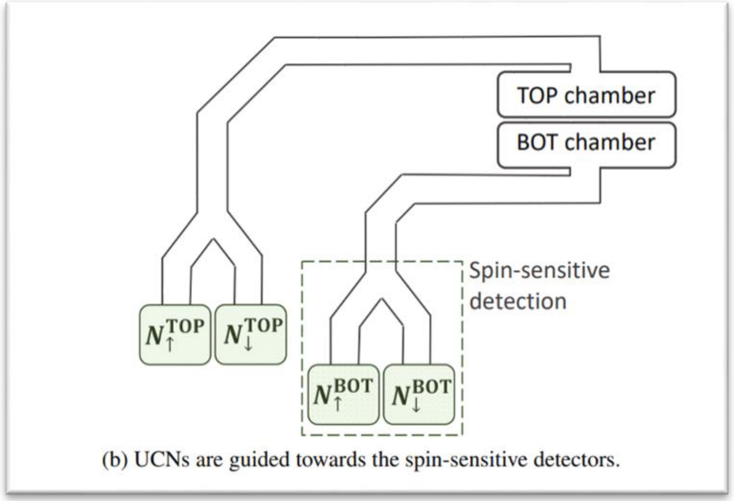
(b) UCNs are guided towards the spin-sensitive detectors.

Ramsey’s method of separated oscillating fields

Asymmetry: $$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$


The asymmetry as a function of the applied frequency

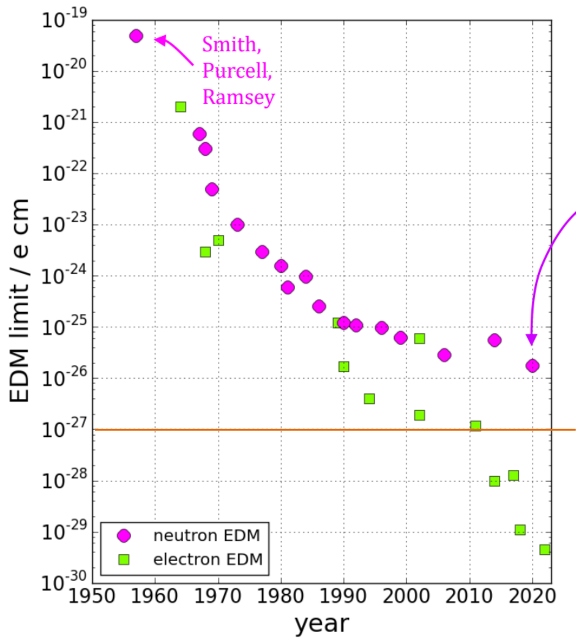
Example, nEDM experimental data (2017):
each point is a measurement cycle with a precession time of T = 180s performed with the nEDM apparatus (single-chamber),
the magnetic field: B0 = 1036.3 nT
which corresponds to a
Larmor precession frequency of 30.2235 Hz.



(b) UCNs are guided towards the spin-sensitive detectors.

The maximal sensitivity is obtained for cycles measured at $A = 0$ where the slope of the resonance curve is highest.

Historical overview: the main milestones



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C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

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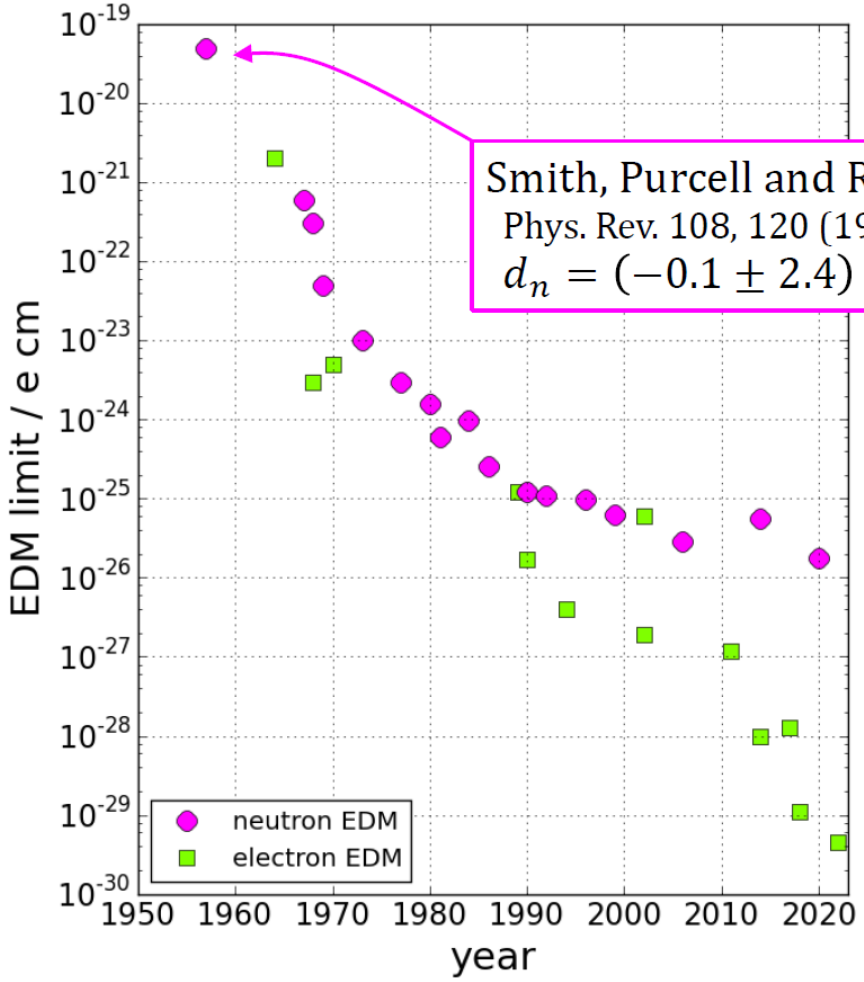
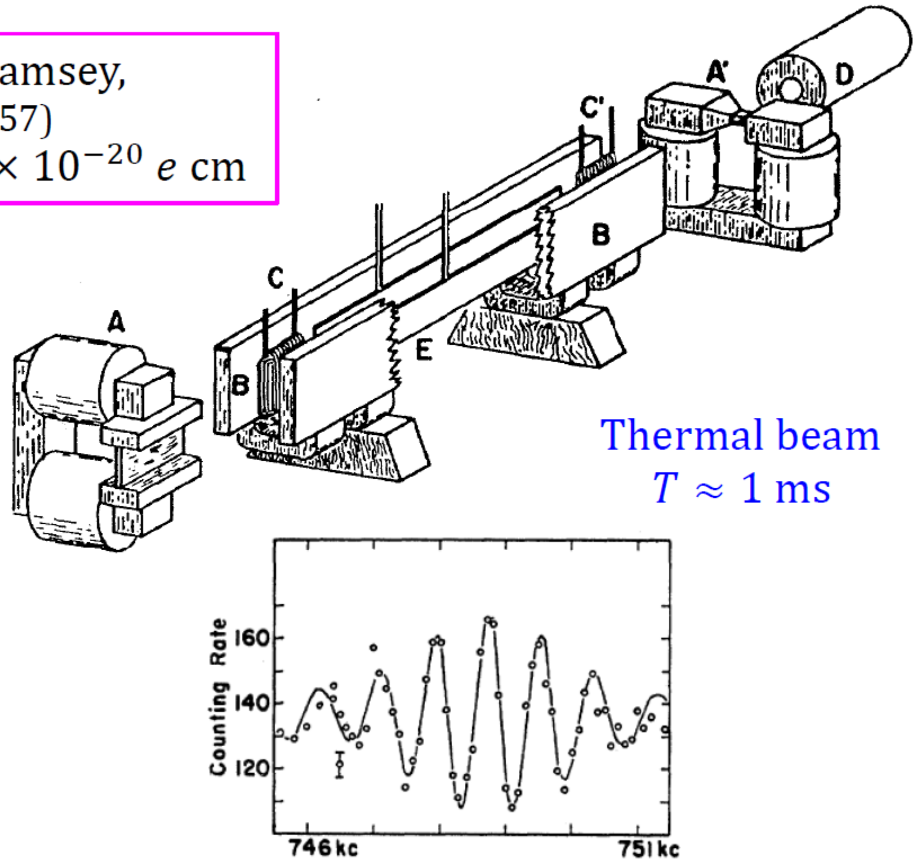


Smith, Purcell and Ramsey,
Phys. Rev. 108, 120 (1957)
$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ e$ cm

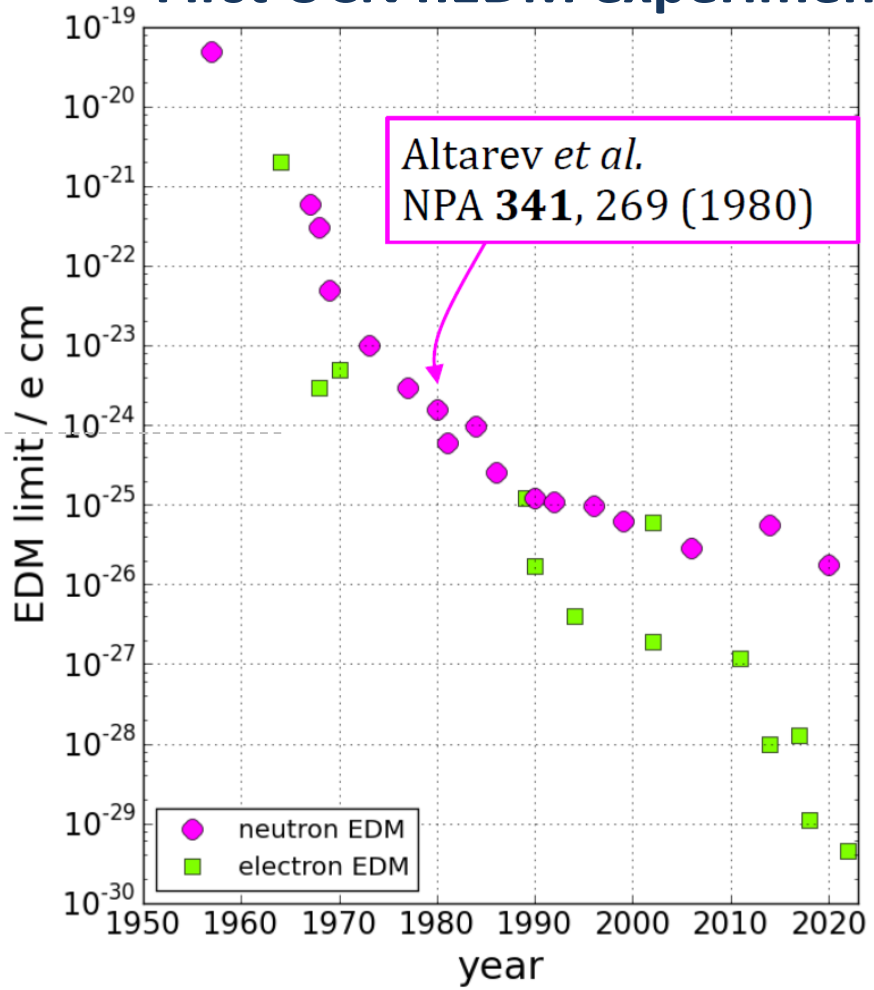
First neutron EDM experiment



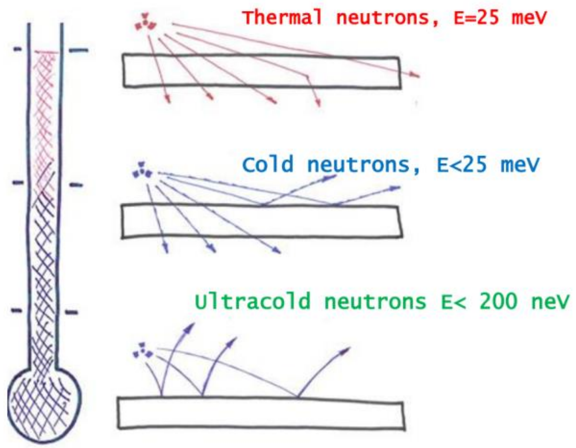
Thermal beam
$T \approx 1$ ms

Historical overview: the main milestones

First UCN nEDM experiment



Altarev *et al.*
NPA **341**, 269 (1980)

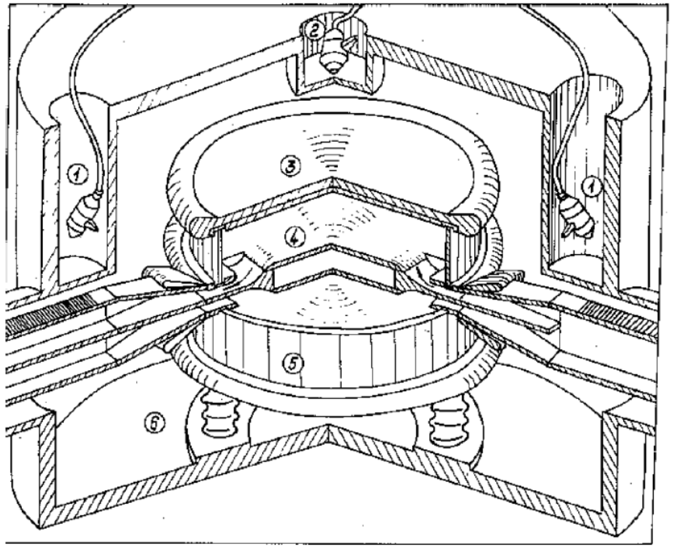


Neutrons with energy < 200 neV, are totally reflected by material walls.

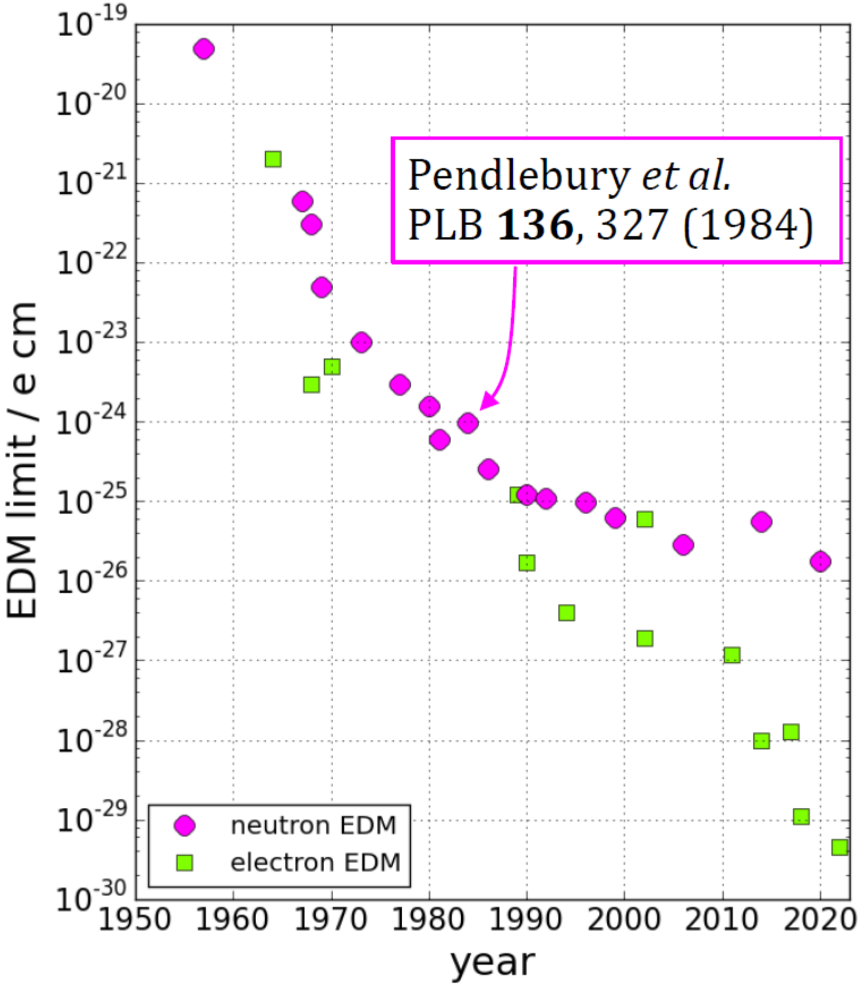
They can be stored in material bottles for long times , up to 15 minutes.

They are significantly affected by gravity.

UCN flow through,
double chamber, $T \approx 5\ s$

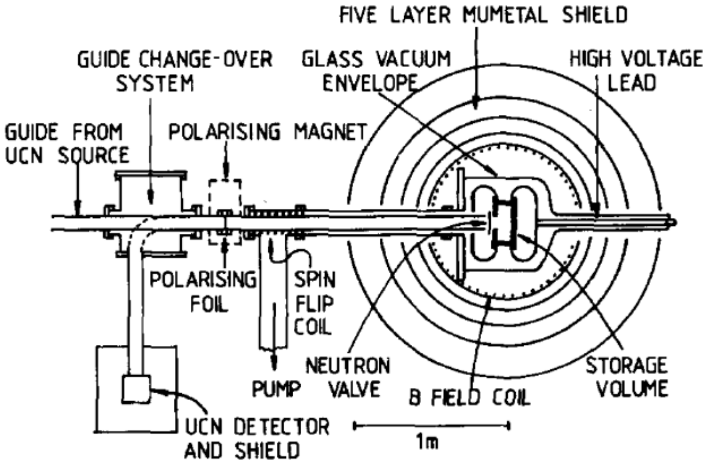


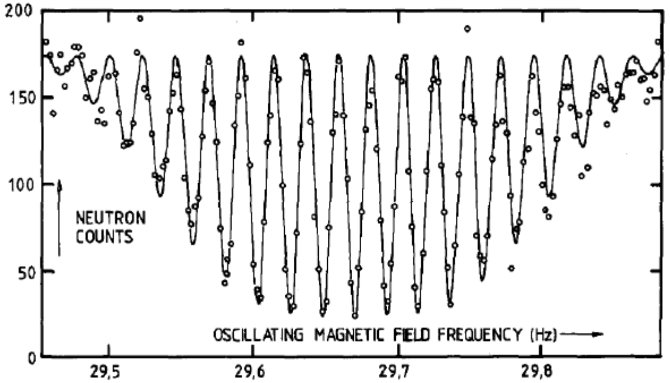
Historical overview: the main milestones



Stored UCN

$T = 60\ s$





Historical overview: the main milestones

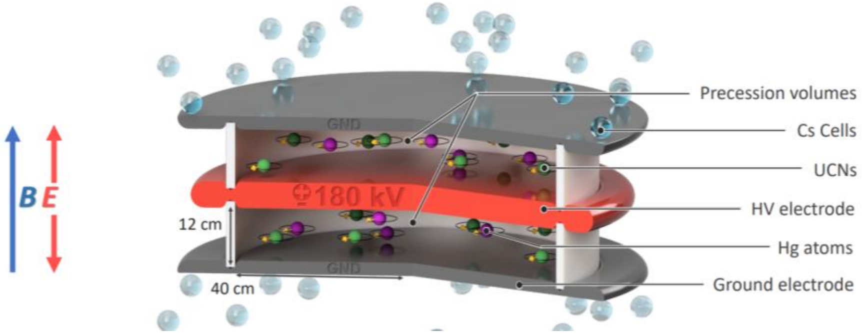
Drift of the magnetic field!

f_n is affected by drifts of the magnetic field!

Solution:

Mercury co-magnetometer

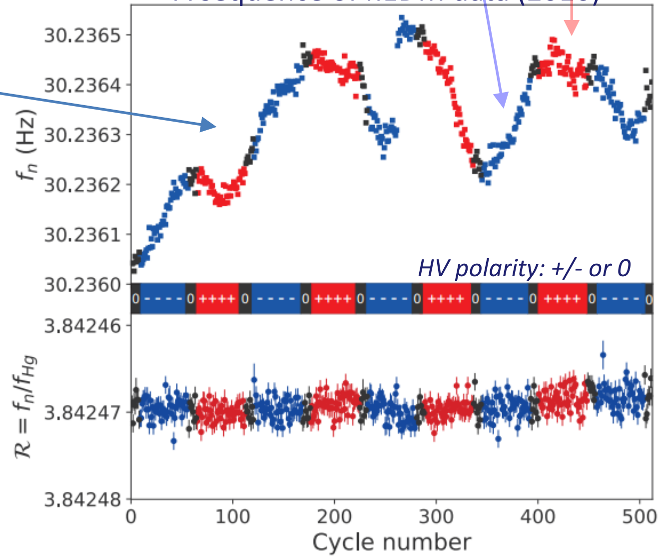
Polarized ^{199}Hg atoms precess in the same chambers



f_{Hg} measurement principle:
a UV probe beam transverses the chambers
→ record the absorbtion of the light (an oscillating signal), extract f_{Hg}

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

A sequence of nEDM data (2016)

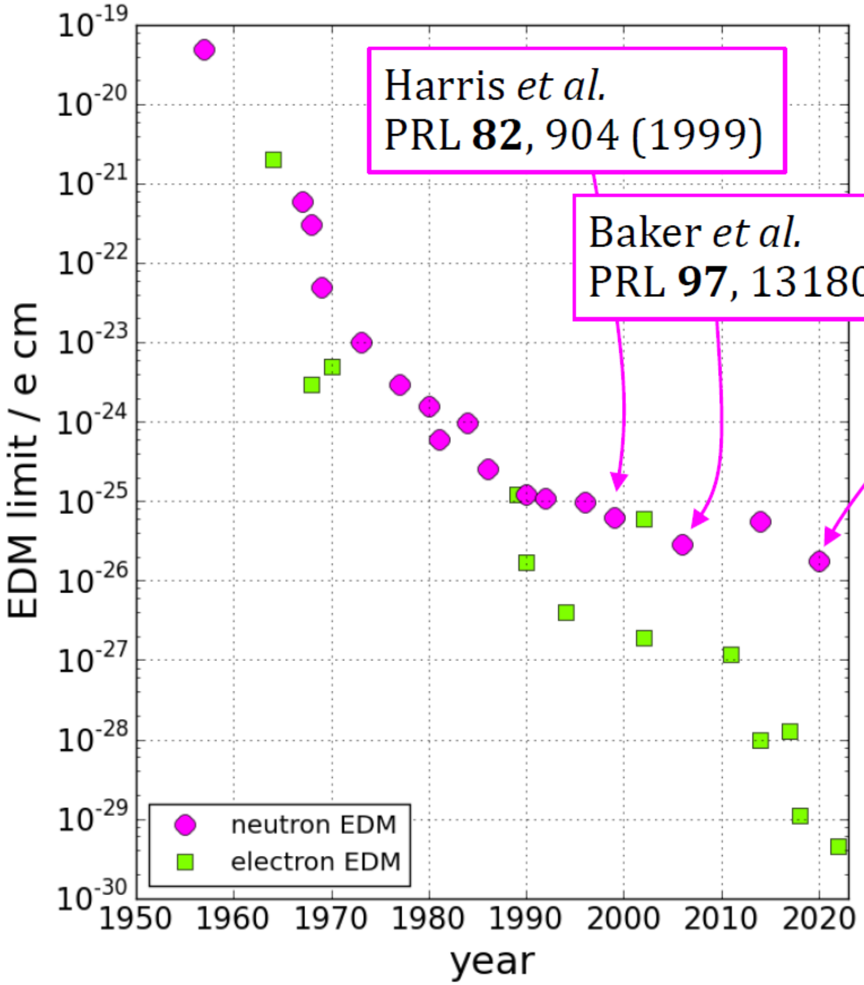


Simultaneous measurement of f_n and f_{Hg}

$$\mathcal{R} \equiv \frac{f_n}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}}$$

$$d_{\mathrm{n}} = \frac{\pi\hbar f_{\mathrm{Hg}}}{4|E|}\left(\mathcal{R}^{\mathrm{TOP}}_{\uparrow\downarrow} - \mathcal{R}^{\mathrm{TOP}}_{\uparrow\uparrow} + \mathcal{R}^{\mathrm{BOT}}_{\uparrow\downarrow} - \mathcal{R}^{\mathrm{BOT}}_{\uparrow\uparrow}\right).$$

Historical overview: the main milestones



Harris *et al.*
PRL **82**, 904 (1999)

Baker *et al.*
PRL **97**, 131801 (2006)

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

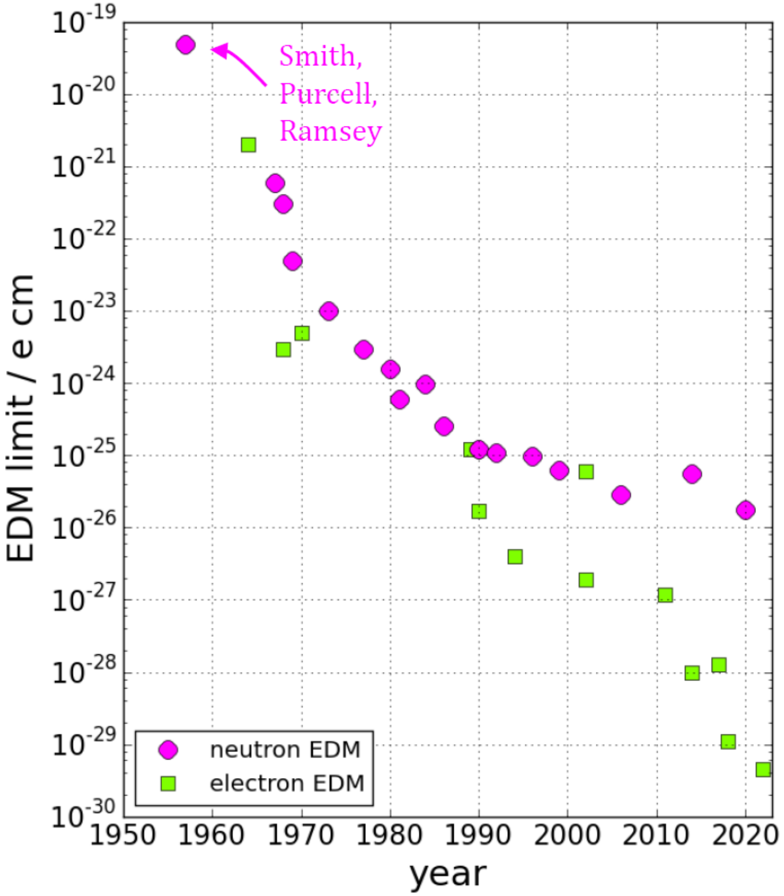
Hg co-magnetometry

Basic principle of co-magnetometry:
2 species in the same volume
to measure simultaneously

$$f_n = \frac{\gamma_n}{2\pi} B \mp \frac{d_n}{\pi\hbar} E$$

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

Towards greater sensitivity



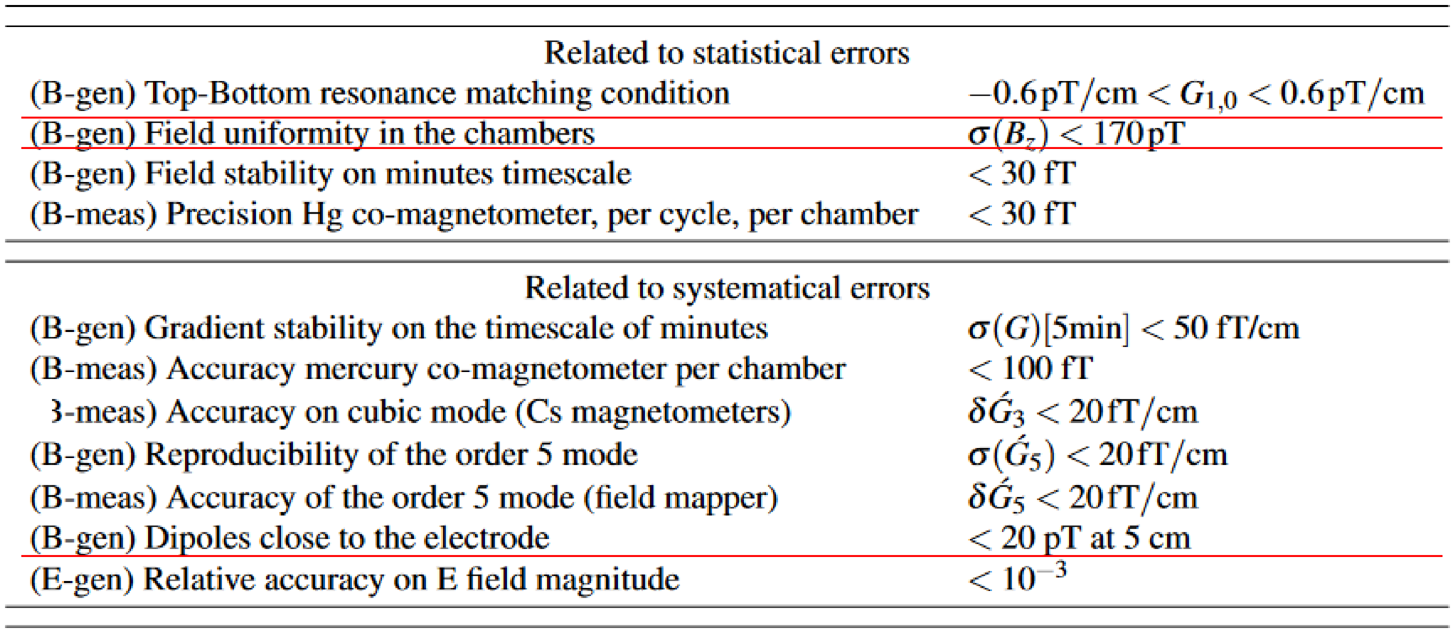
Design sensitivity of 4 new experiments:

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

Design sensitivity cryogenic nEDM@SNS

Experimental challenges (stat and syst)

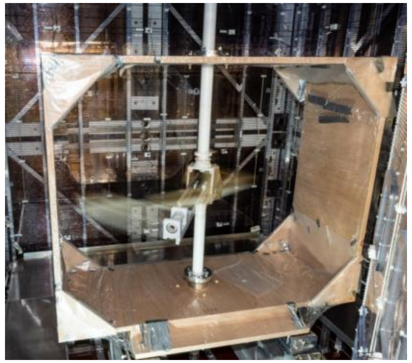
Requirements for the magnetic field for n2EDM as an example



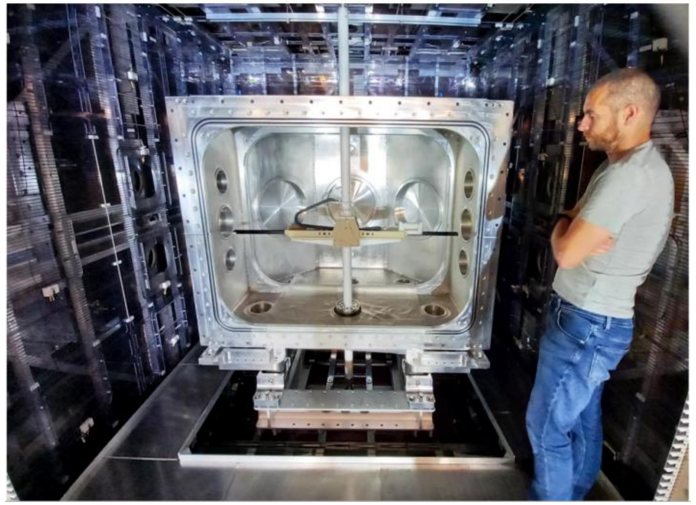
Related to statistical errors	
(B-gen) Top-Bottom resonance matching condition	$-0.6\,\mathrm{pT/cm} < G_{1,0} < 0.6\,\mathrm{pT/cm}$
(B-gen) Field uniformity in the chambers	$\sigma(B_z) < 170\,\mathrm{pT}$
(B-gen) Field stability on minutes timescale	< 30 fT
(B-meas) Precision Hg co-magnetometer, per cycle, per chamber	< 30 fT
Related to systematical errors	
(B-gen) Gradient stability on the timescale of minutes	$\sigma(G)[5\mathrm{min}] < 50$ fT/cm
(B-meas) Accuracy mercury co-magnetometer per chamber	< 100 fT
B-meas) Accuracy on cubic mode (Cs magnetometers)	$\delta \acute{G}_3 < 20\,\mathrm{fT/cm}$
(B-gen) Reproducibility of the order 5 mode	$\sigma(\acute{G}_5) < 20\,\mathrm{fT/cm}$
(B-meas) Accuracy of the order 5 mode (field mapper)	$\delta \acute{G}_5 < 20\,\mathrm{fT/cm}$
(B-gen) Dipoles close to the electrode	< 20 pT at 5 cm
(E-gen) Relative accuracy on E field magnitude	$< 10^{-3}$

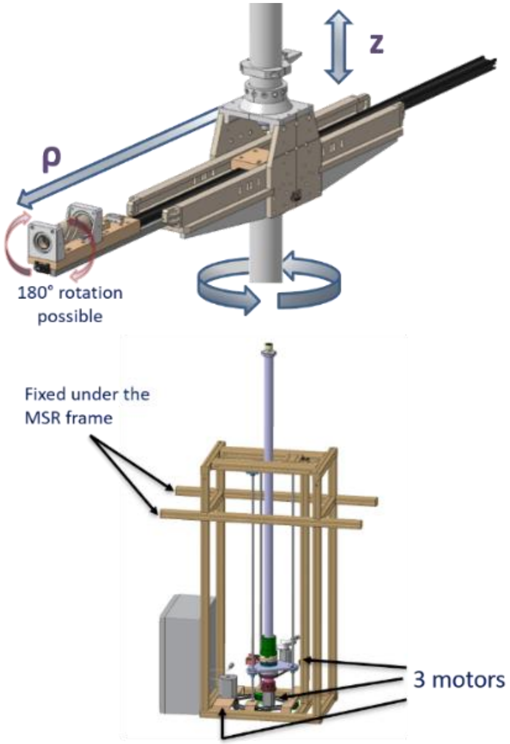
Table 4: Summary of the requirements for the magnetic-field measurement (B-meas), magnetic-field generation (B-gen) and electric-field generation (E-gen) for the n2EDM design.

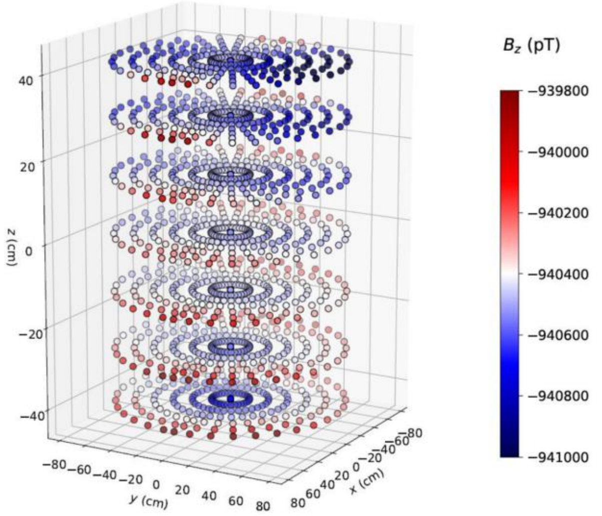
Experimental challenges (stat and syst)



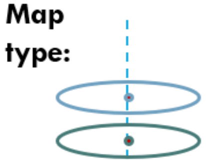
The magnetic field mapper at n2EDM

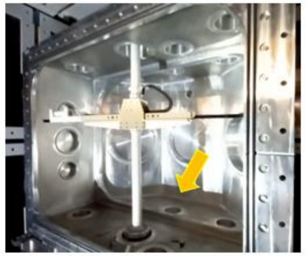




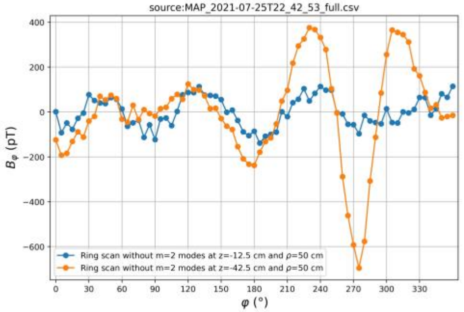


Example illustration (for kids):



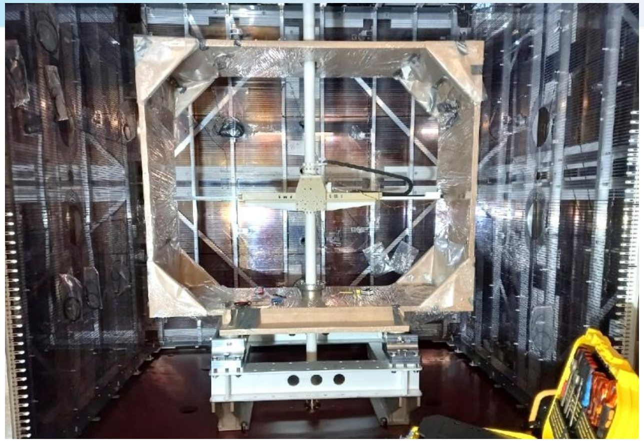


Detected a magnetic piece! (July 2021)
A very clear evidence of a presence of a magnetic element inside the flange located on the bottom surface of the vacuum vessel. The middle and the lowest z-position ring scans.



Experimental challenges (stat and syst)

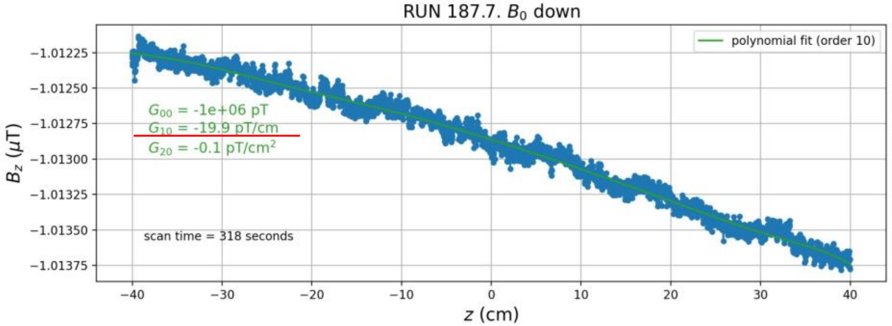
Coil system installation at n2EDM: moving by mm's – tuning pT's !



Map type:

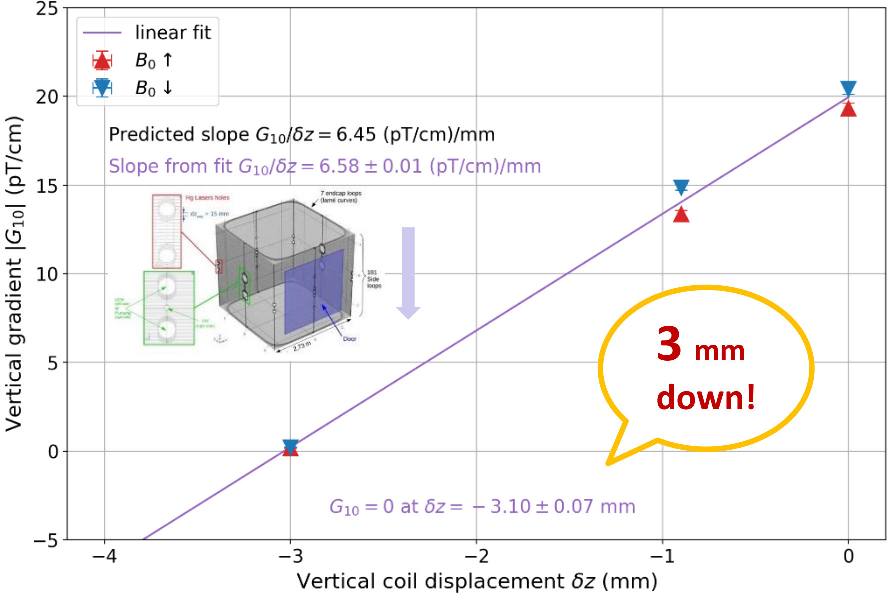
The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $G_{1,0}$.

$G_{1,0} = -19.9\ \mathrm{pT/cm}$ – compatible with a **vertical shift** of the entire coil system with respect to the MSR by $\Delta z = 3\mathrm{mm}$



An example of a vertical scan of the B_z field component in **initial** B_0 coil position.

Evaluation of the vertical shift value in order to get the $G_{1,0}$ gradient within the desired range



The values of $G_{1,0}$ shown for each polarity of the B_0 coil are the averages of the values of $G_{1,0}$ after degaussing in L6 and L6-crossed configurations.

Requirement

on field production (B_0 coil):

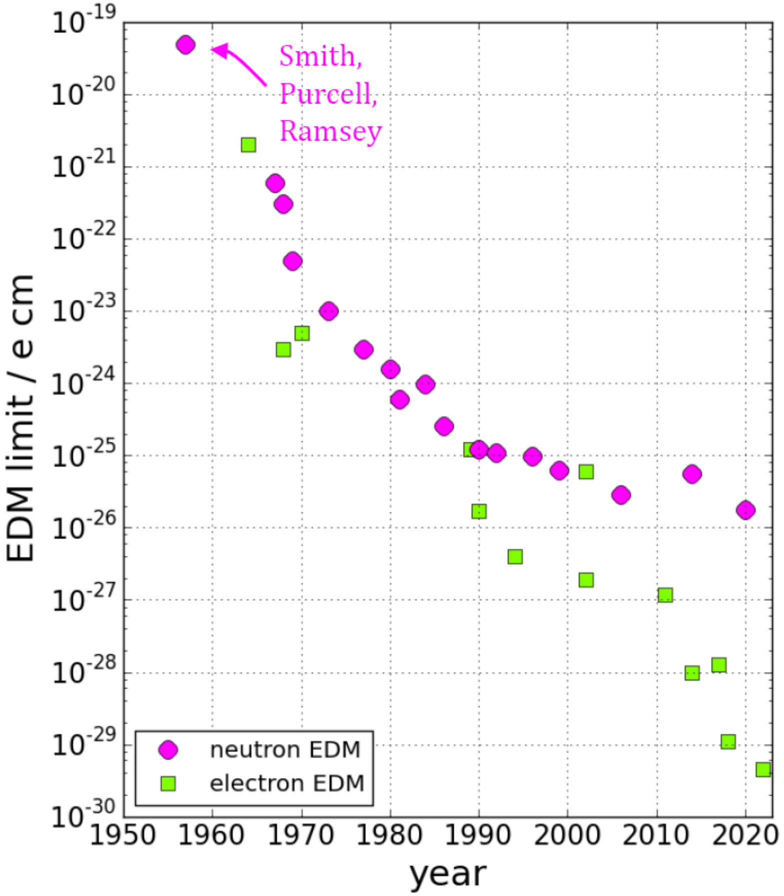
STAT.

$-0.6\ \mathrm{pT/cm} < G_{1,0} < 0,6\ \mathrm{pT/cm}$

"Top-Bottom resonance matching condition"

(maximum permitted vertical gradient of the magnetic field)

Towards greater sensitivity



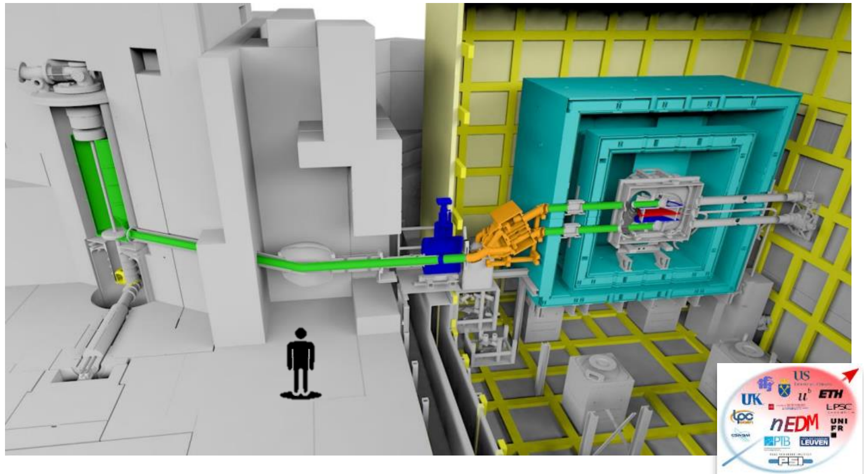
Design sensitivity of 4 new experiments:

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

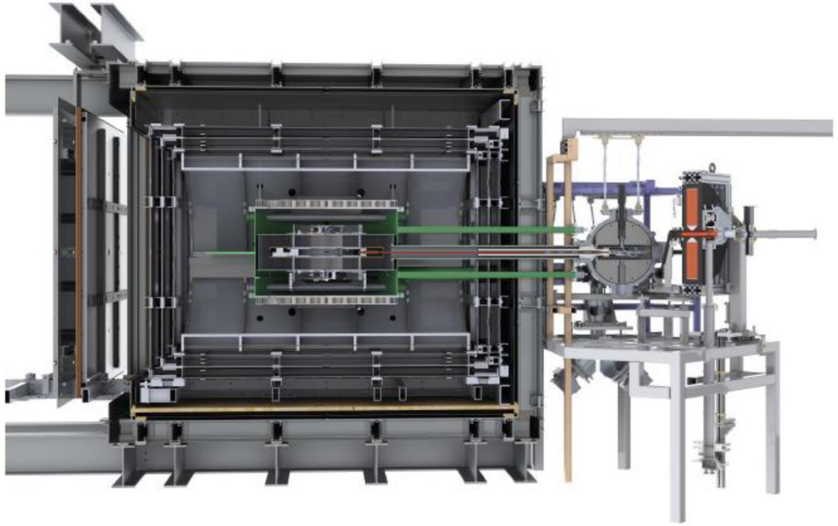
Design sensitivity cryogenic nEDM@SNS

Towards greater sensitivity $\sim 10^{-27} ecm$

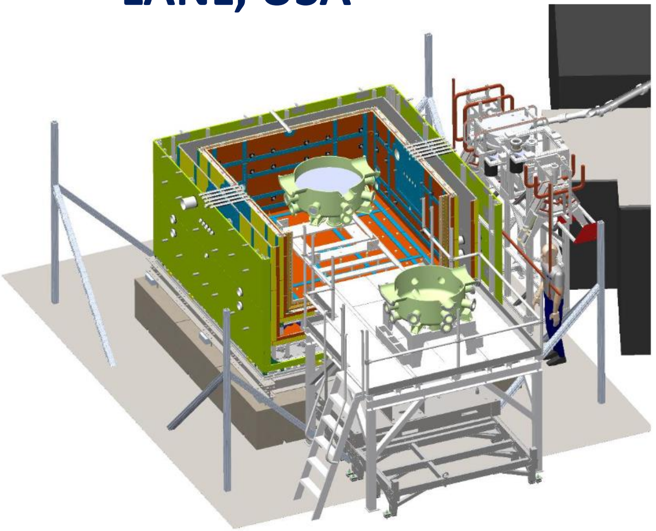
n2EDM@PSI, Switzerland



PanEDM@ILL, France

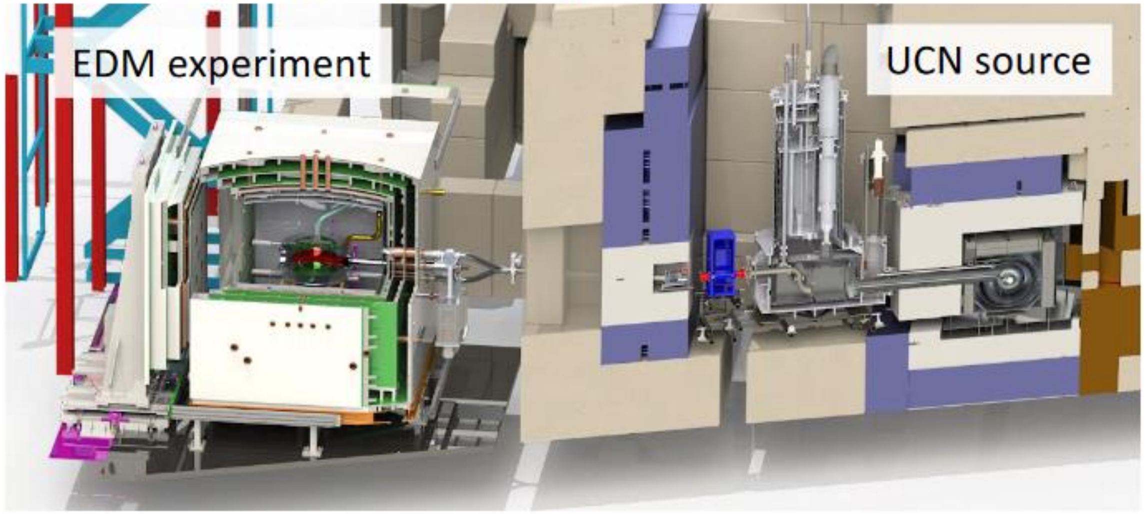


LANL, USA



View of future facility at TRIUMF

TUCAN @TRIUMF, Canada

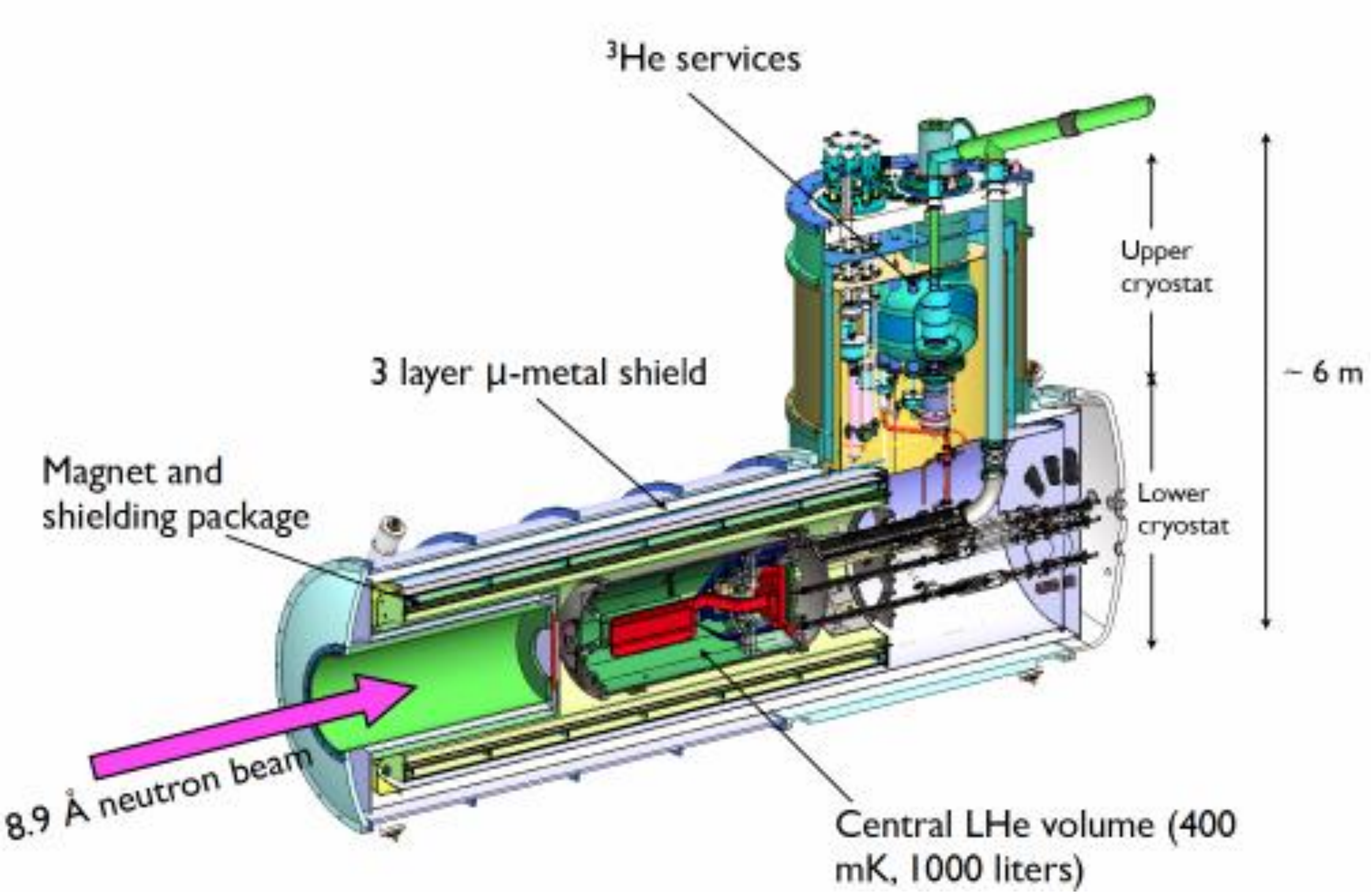


Towards greater sensitivity $\sim 10^{-28} ecm$

nEDM@SNS, USA

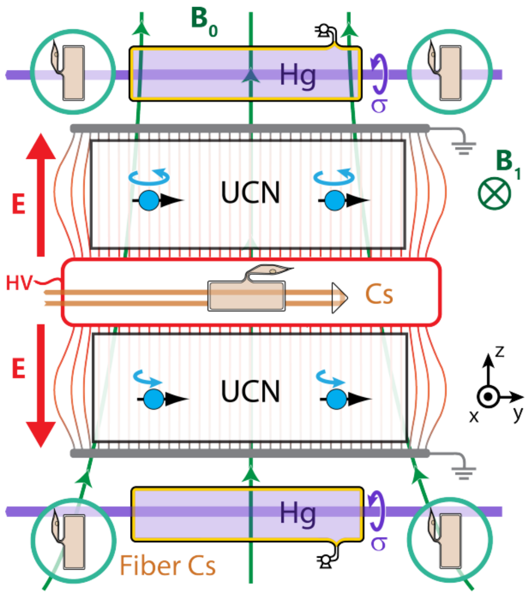
(Spallation Neutron Source
at Oak Ridge National Laboratory)

Concept:
R. Golub & S. K. Lamoreaux,
Phys. Rep. 237, 1 (1994)

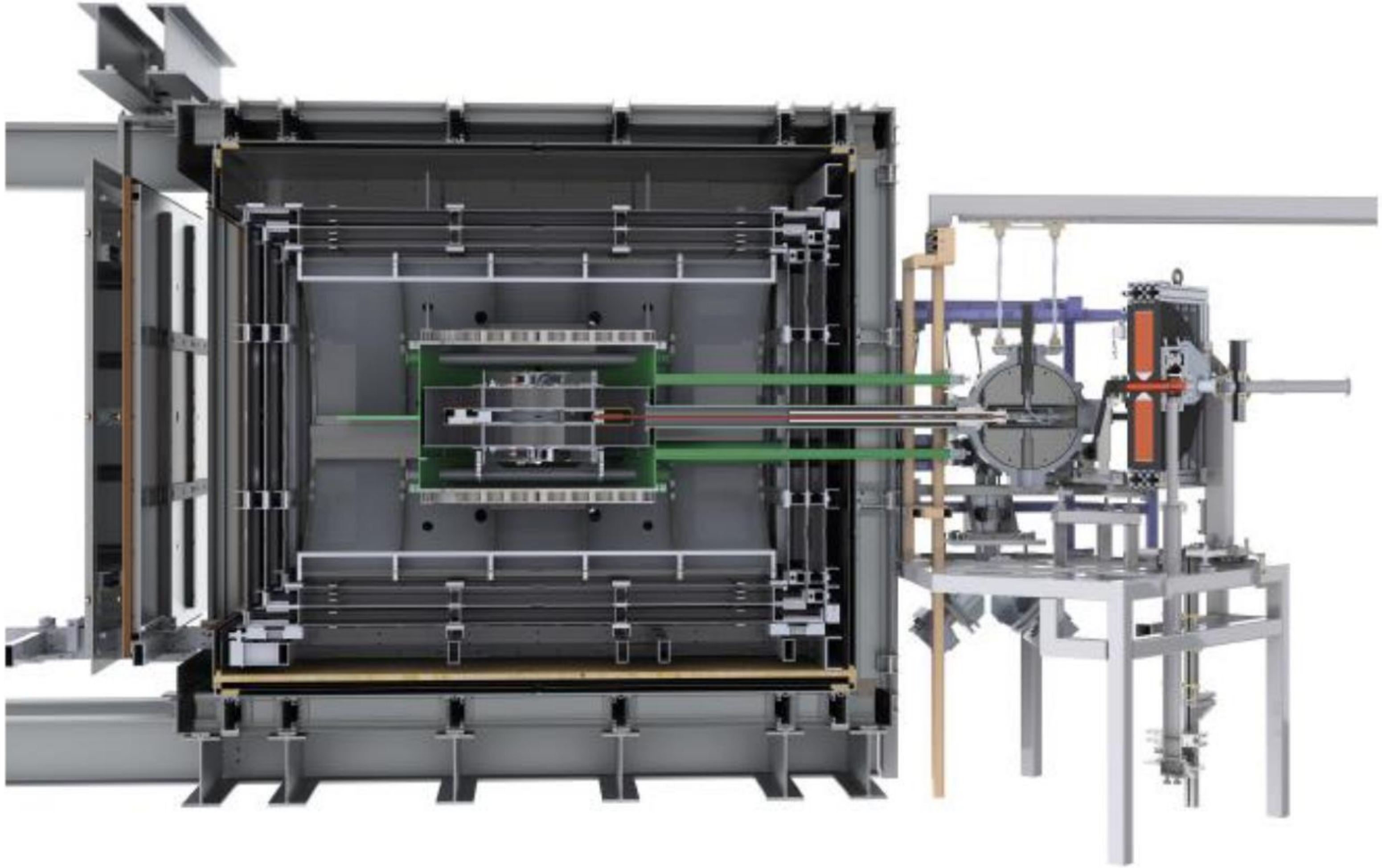


PanEDM@ILL status and outlook

Central part of the PanEDM experiment



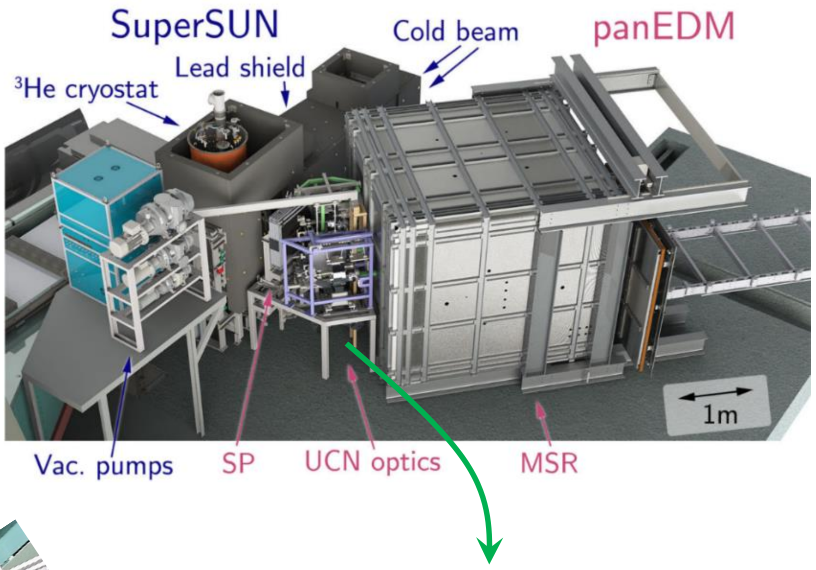
- ✓ Double chamber Ramsey interferometer at room temperature
- ✓ Simultaneous measurement for the “↑↑” and “↑↓” configurations
- ✓ Magnetic shielding: $6{\times}10^6$ @1mHz
- ✓ ^{199}Hg and Cs magnetometers
- ✓ UCNs: 80neV allowing for high statistics



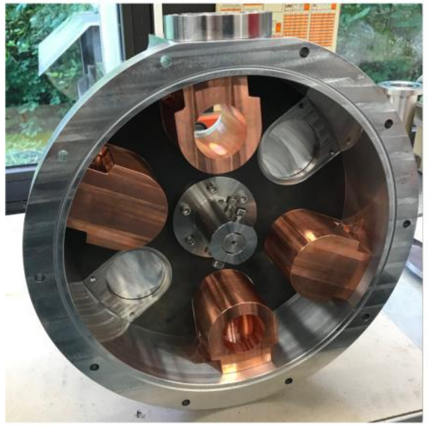
PanEDM@ILL status and outlook

Ongoing installation of parts,
commissioning with UCN in progress since 2023

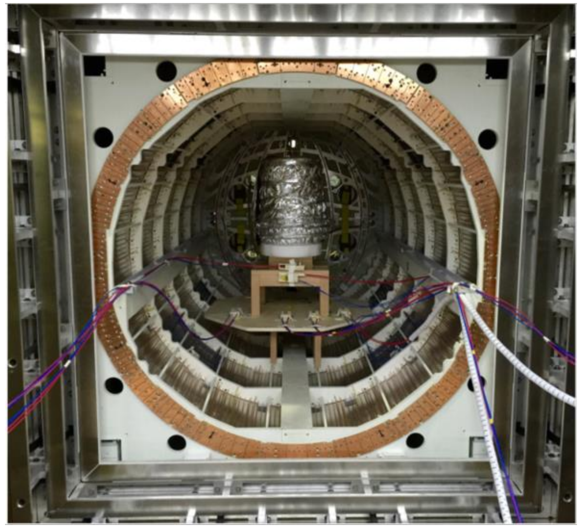
- Characterization of the UCN spectrum: ongoing.
- Neutron guiding system produced and being tested.
- Three-way switch upgrade in progress.
- Magnetic field mapping will be resumed during the reactor shutdown.
- Infrastructure (IT, electrics…) revision.
- New effort on simulations of the UCN transport (Geant4).



Three-way switch

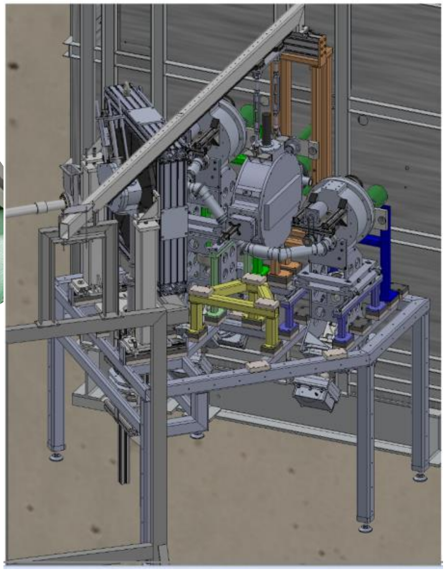


Coil system



Guide Manifold tests at SUN2@ILL

SuperSUN-PanEDM Interface

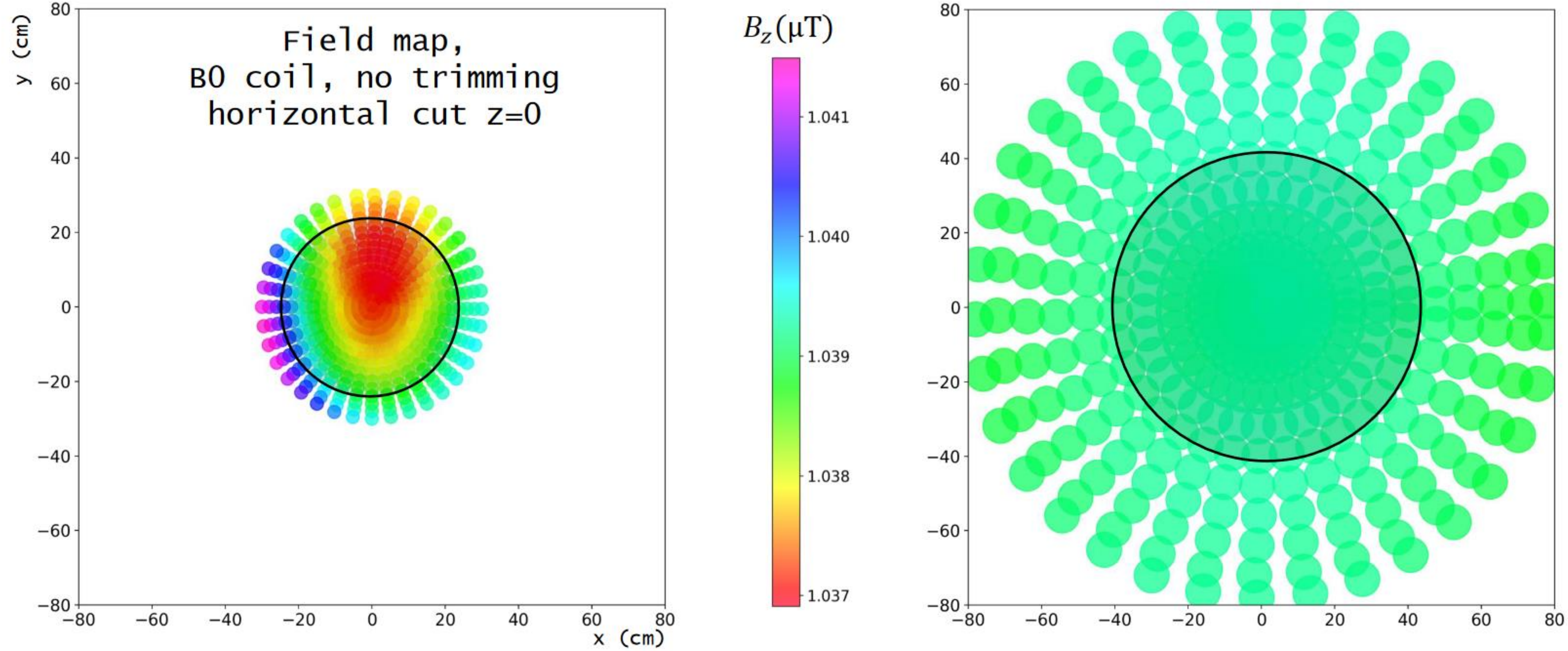


Thank you!

Photos from Trento, Villa Tambosi, March 2024

Uniformity of the vertical B-field

n2EDM



nEDM 2017 $\sigma(B_z) = 860\,\mathrm{pT}$

In the precession chamber ø 47 cm

n2EDM 2022 $\sigma(B_z) = 60\,\mathrm{pT}$

In one chamber ø 80 cm

Thanks – Guillaume Pignol

SuperSUN: High density UCN source

Phase I characterization

Measurement agrees with expectation (48 MW)

cf. EPJ Conf. 219, 02006 (2019)

Total UCN output: 3.8×10^6 (integral of blue peak)
Source density: 270 UCN/cm^3
Long storage times: 126000 UCN remaining after 20min
Expected density in PanEDM: 3.9 UCN/cm^3 (58 MW)
Source characterization, PanEDM commissioning ongoing

Phase II expectation

Peak field: 2.1 T
Source density: 1670 UCN/cm^3 (**x5 gain**)
Density in PanEDM: 40 UCN/cm^3 (**x10 gain**)

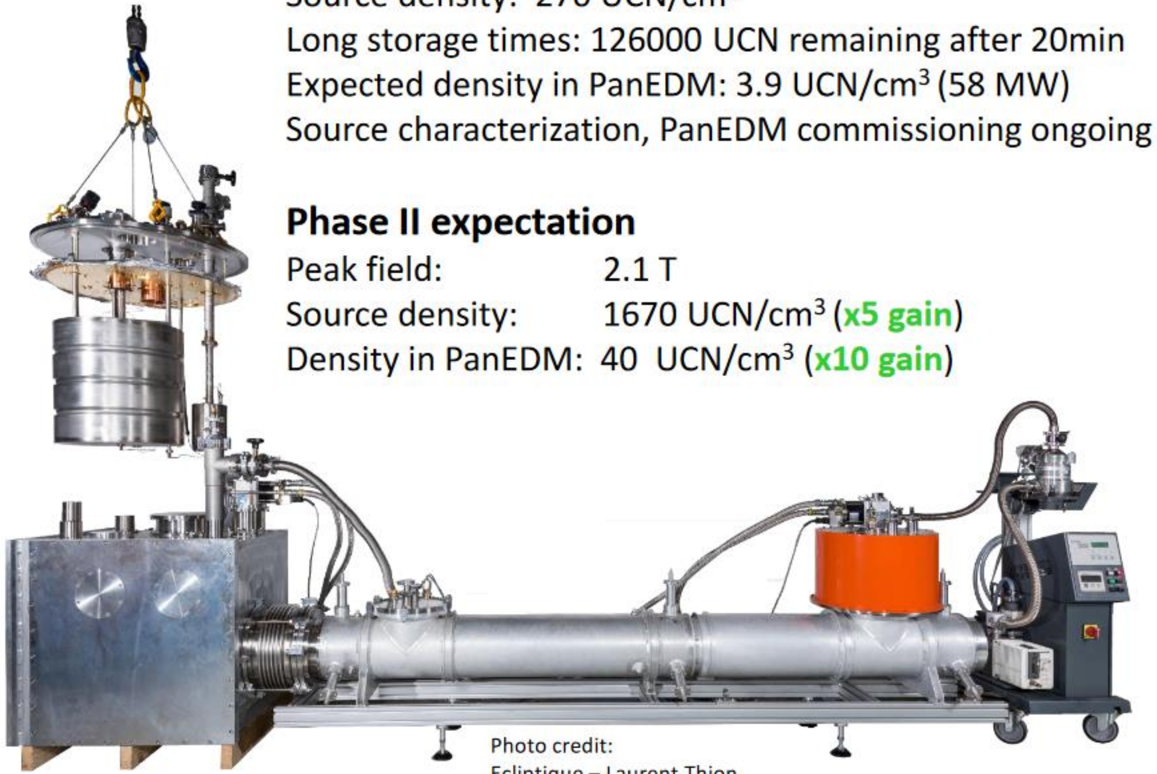
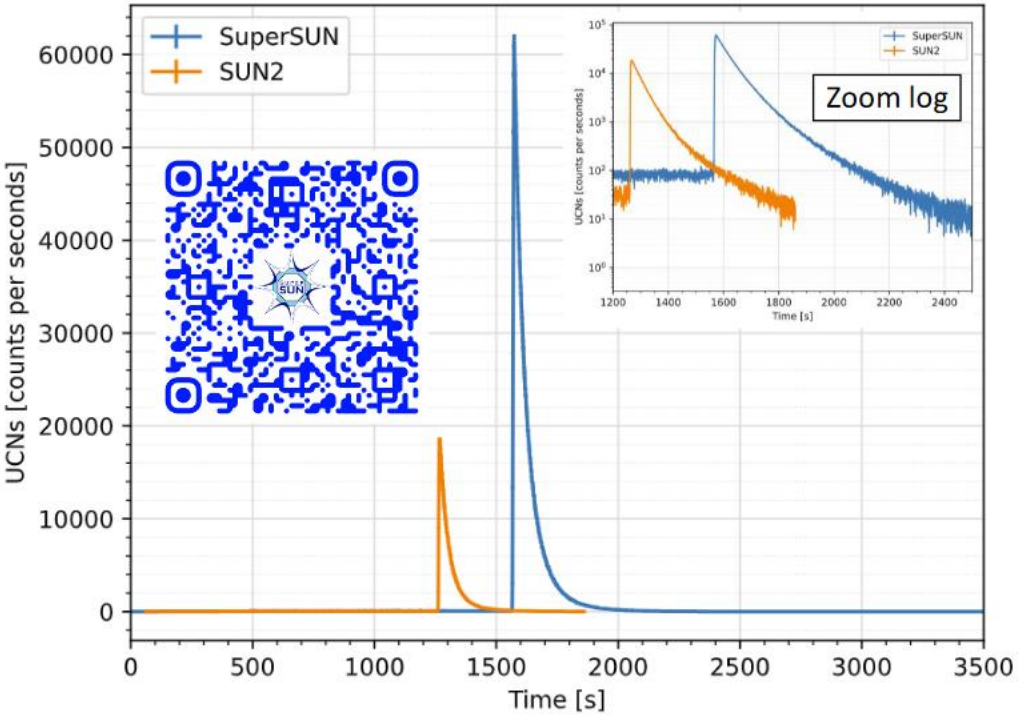


Photo credit:
Ecliptique – Laurent Thion.

Comparison to the prototype source SUN2



SuperSUN: High density UCN source

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

ANR

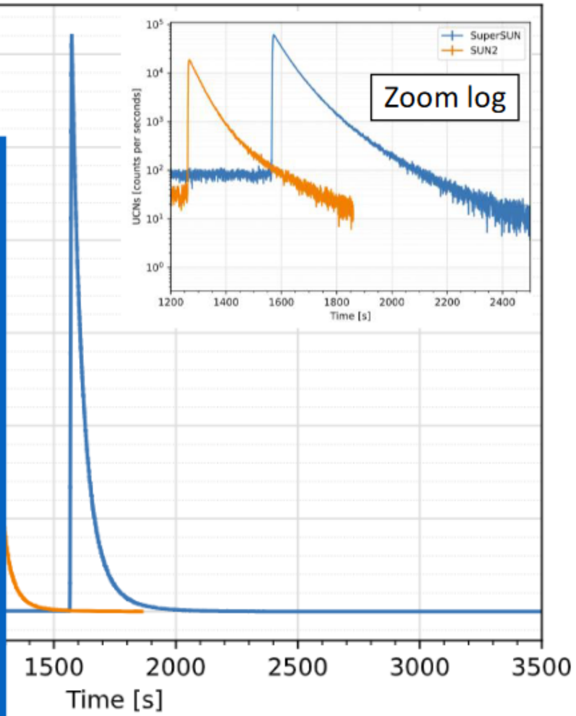
Phase I characterization

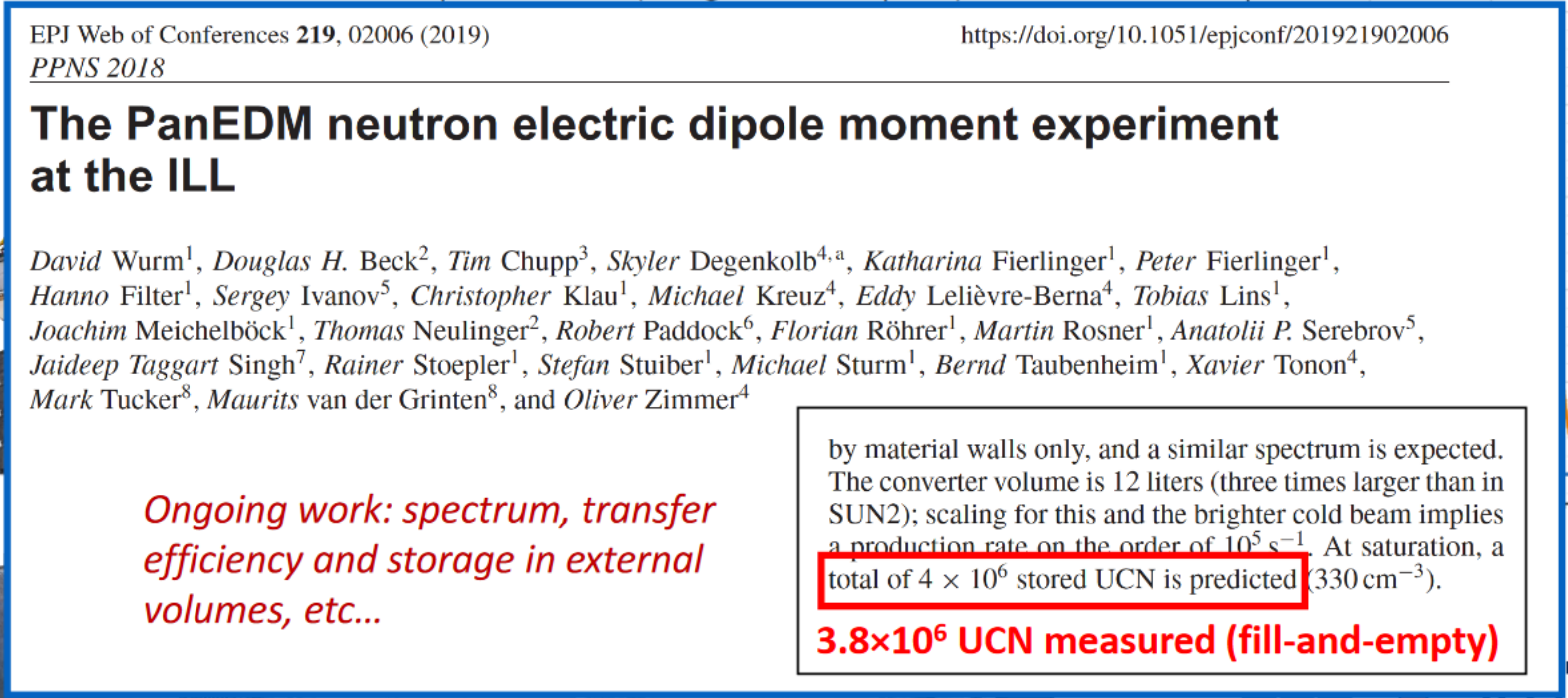
Measurement agrees with expectation (48 MW)

cf. [EPJ Conf. 219, 02006 (2019)](https://doi.org/10.1051/epjconf/201921902006)

Total UCN output: 3.8×10^6 (integral of blue peak)

Comparison to the prototype source SUN2





EPJ Web of Conferences **219**, 02006 (2019) https://doi.org/10.1051/epjconf/201921902006
PPNS 2018

The PanEDM neutron electric dipole moment experiment at the ILL

David Wurm[1], *Douglas H.* Beck[2], *Tim* Chupp[3], *Skyler* Degenkolb[4,a], *Katharina* Fierlinger[1], *Peter* Fierlinger[1], *Hanno* Filter[1], *Sergey* Ivanov[5], *Christopher* Klau[1], *Michael* Kreuz[4], *Eddy* Lelièvre-Berna[4], *Tobias* Lins[1], *Joachim* Meichelböck[1], *Thomas* Neulinger[2], *Robert* Paddock[6], *Florian* Röhrer[1], *Martin* Rosner[1], *Anatolii P.* Serebrov[5], *Jaideep Taggart* Singh[7], *Rainer* Stoepler[1], *Stefan* Stuiber[1], *Michael* Sturm[1], *Bernd* Taubenheim[1], *Xavier* Tonon[4], *Mark* Tucker[8], *Maurits* van der Grinten[8], and *Oliver* Zimmer[4]

Ongoing work: spectrum, transfer efficiency and storage in external volumes, etc…

by material walls only, and a similar spectrum is expected. The converter volume is 12 liters (three times larger than in SUN2); scaling for this and the brighter cold beam implies a production rate on the order of $10^5\ \mathrm{s}^{-1}$. At saturation, a total of 4×10^6 stored UCN is predicted (330 cm^{-3}).

3.8×10^6 UCN measured (fill-and-empty)

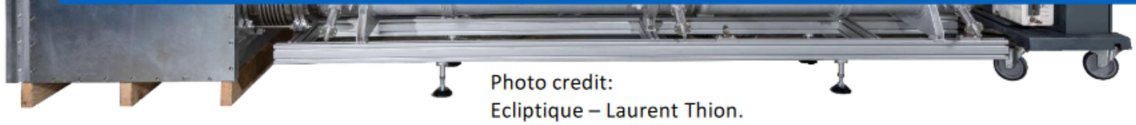


Photo credit:
Ecliptique – Laurent Thion.

NEUTRONS FOR SCIENCE

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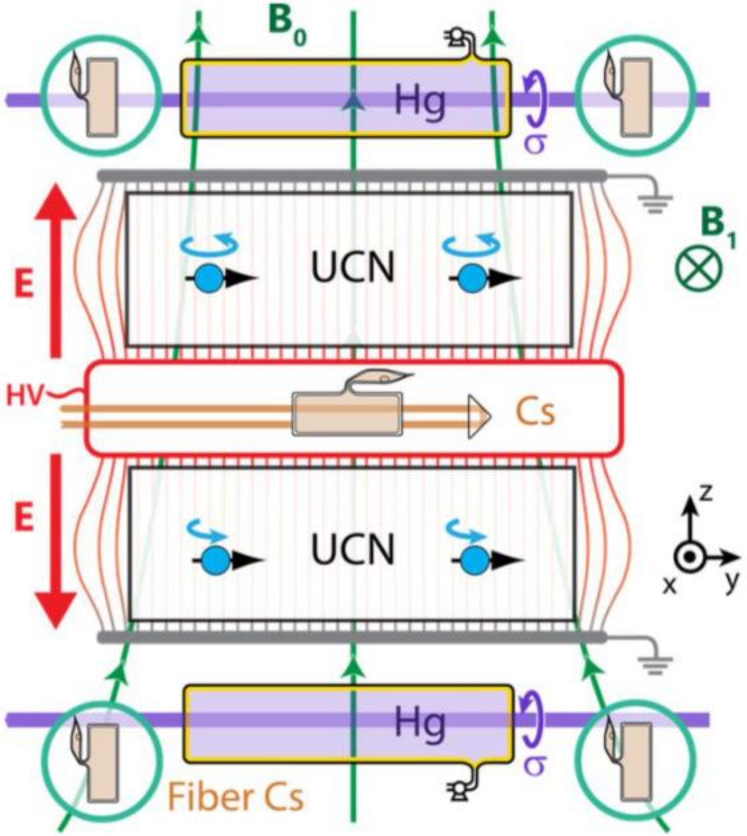
UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

The PanEDM Experiment



Statistical sensitivity:

$$\sigma\left(d_n\right) \gtrsim \frac{\hbar}{2\alpha|\mathbf{E}|T\sqrt{N}}$$

Frequency measurement:

$$|\delta\omega| = \frac{|dE|}{\hbar F}$$

SuperSUN	**Phase I**
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, *e* cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

$$\Delta E \Delta t \geq \hbar/2$$