Measuring the **neutron Electric Dipole Moment** for CP violation searches with the n2EDM experiment

Katia Michielsen, LPSC Grenoble, neutrons ultra froids

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Outline

I. Context
II. Overview of the n2EDM experiment
III. Hg co-magnetometer
IV. n2EDM status and outlook

I- Context

What is the **Electric Dipole Moment** ?

- a **CP-violation** probe
- a **new physics** probe

Shakarov criteria for matter-antimatter asymmetry during baryogenesis

- C and **CP violation**
- Baryon number violation
- Out of equilibrium

One can quantify the sensitivity of observables to new physics using Effective Field Theories (EFT).

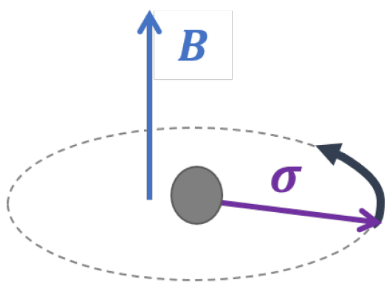
What is an Electric Dipole Moment?

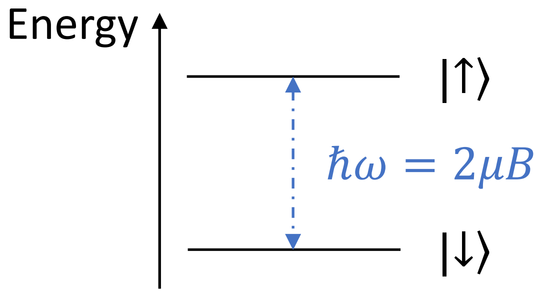
- Spins couple to magnetic fields. *Magnetic moment* is the coupling strength μ

- Spins couple to electric fields. EDM is the coupling strength d

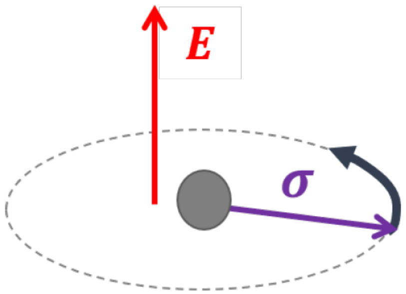
Non-relativistic limit of the fermion-photon interaction:

$$H = -\mu\,\sigma B \; - d\,\sigma E$$





Larmor precession of a spin in a magnetic field at frequency $f = \frac{\mu B}{\pi\hbar}$



d not T invariant
→ not CP invariant

Larmor precession of a spin in an electric field at frequency $f = \frac{dE}{\pi\hbar}$

What do we know about the nEDM?

Theory: $d_n = 10^{-32} e\text{ cm} + \bar{\theta} \cdot 10^{-16}\, e\text{ cm} + \underbrace{\quad}$

weak interaction | strong interaction | new physics?

Current limit: $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst})\mathbf{10^{-26}} e\text{ cm}$

n2EDM sensitivity goal: $\mathbf{10^{-27}} e\text{ cm}$

Measurement compatible with zero:

Contrains either:

- **CP violation** in the strong sector $\bar{\theta} < 10^{-10}$ "strong CP problem" led to the introduction of the **axion**

- CP violating **new physics**
with mass scale of >1 PeV (EFT).

Non-zero measurement:

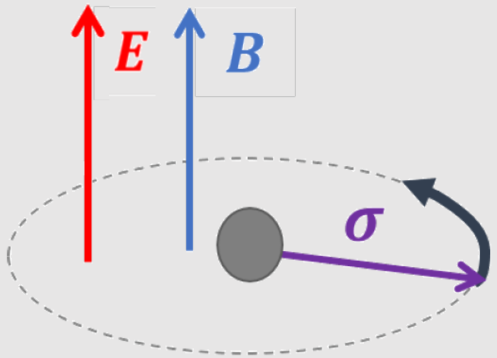
But where from??

Complementary EDM measurements required: proton, electron, muon EDM

Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

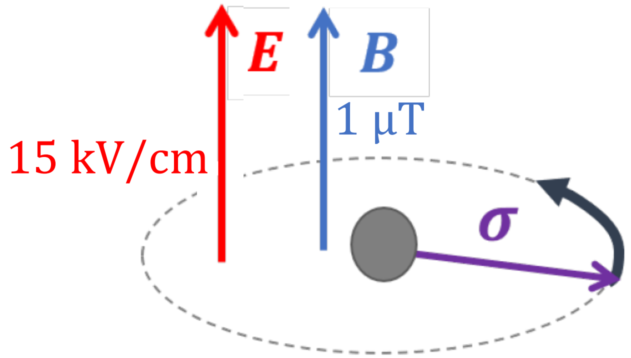
II- **How** do we measure the neutron EDM at PSI

1. Measurement concept



nEDM measurement concept

Larmor precession frequency measurement.
in a *weak* magnetic field and *strong* electric field.



$$f_n = \frac{\mu_n}{\pi\hbar} B + \frac{d_n}{\pi\hbar} E$$

In n2EDM, electric/magnetic term $\approx 10^{-9}$
→ any magnetic drift is prohibitive!

We measure the neutron spin at the end of a precession duration of 3 min.

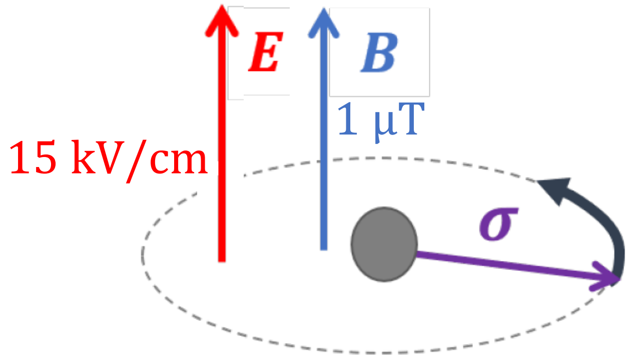
$$\sigma(\boldsymbol{f}) = \frac{1}{2\pi\alpha \boldsymbol{T}\sqrt{N}} \sim 10^{-6}\ \mathrm{Hz}$$

Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

nEDM measurement concept

Larmor precession frequency measurement.

in a *weak* magnetic field and *strong* electric field.



$$f_n = \frac{\mu_n}{\pi\hbar} B + \frac{d_n}{\pi\hbar} E$$

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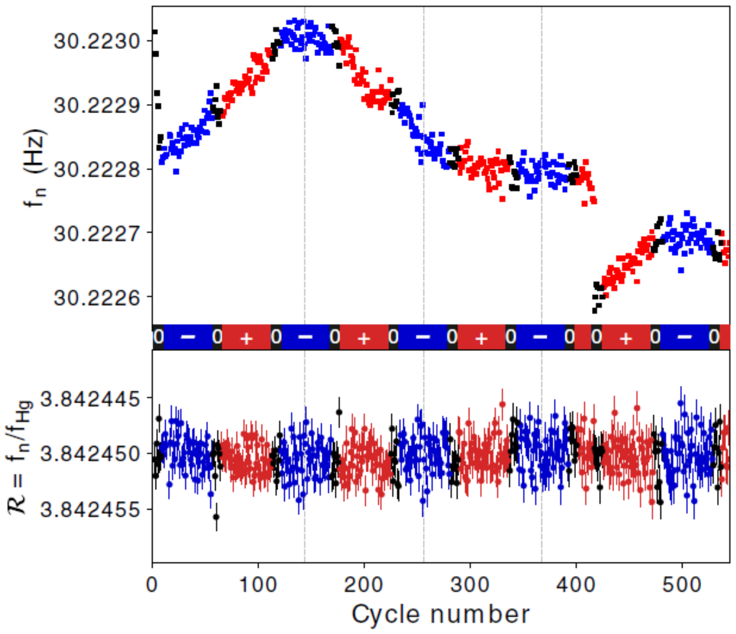


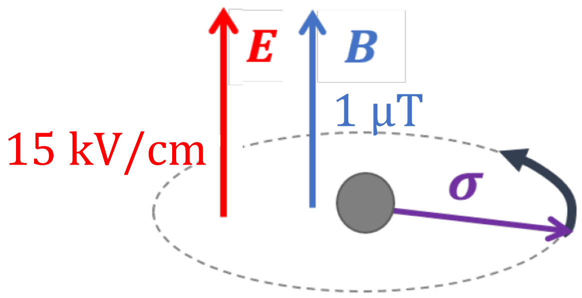
f_n affected by magnetic drift

f_n after correction

Effect of the magnetic field drift in the nEDM experiment

Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

Measure the neutron EDM: frequency ratio



$$f_{\mathrm{n}} = \frac{\mu_{\mathrm{n}}}{\pi\hbar} B + \frac{d_{\mathrm{n}}}{\pi\hbar} E$$

$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B$$

Hg co-magnetometer

Measurement:

(destructive) spin asymmetry

continuous optical reading

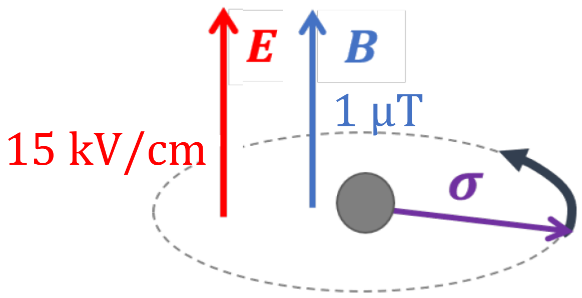
Ratio R

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \frac{\mu_{\mathrm{n}}}{\mu_{\mathrm{Hg}}} \frac{B}{B} + \frac{d_{\mathrm{n}}}{\pi\hbar} \frac{E}{f_{\mathrm{Hg}}}$$

$$\approx 0 + \frac{d_{\mathrm{n}}}{\pi\hbar} \frac{E}{f_{\mathrm{Hg}}}$$

*Reduced limit on the permanent electric dipole moment of Hg 199. Graner, Brent, et al. PRL (2016) :*Hg EDM $|d_{Hg}| < 7{,}4 \ 10^{-30} \ e$ cm

Measure the neutron EDM: frequency ratio



$$f_n = \frac{\mu_n}{\pi\hbar} B + \frac{d_n}{\pi\hbar} E$$

$$f_{Hg} = \frac{\mu_{Hg}}{\pi\hbar} B$$

Hg co-magnetometer

Measurement:

(destructive) spin asymmetry

continuous optical reading

Ratio R

$$R = \frac{f_n}{f_{Hg}} = \frac{\mu_n}{\mu_{Hg}} \frac{B}{B} + \frac{d_n}{\pi\hbar} \frac{E}{f_{Hg}}$$

$$\approx 0 \quad + \frac{d_n}{\pi\hbar} \frac{E}{f_{Hg}}$$

But neutrons and mercury do not see the same magnetic field…

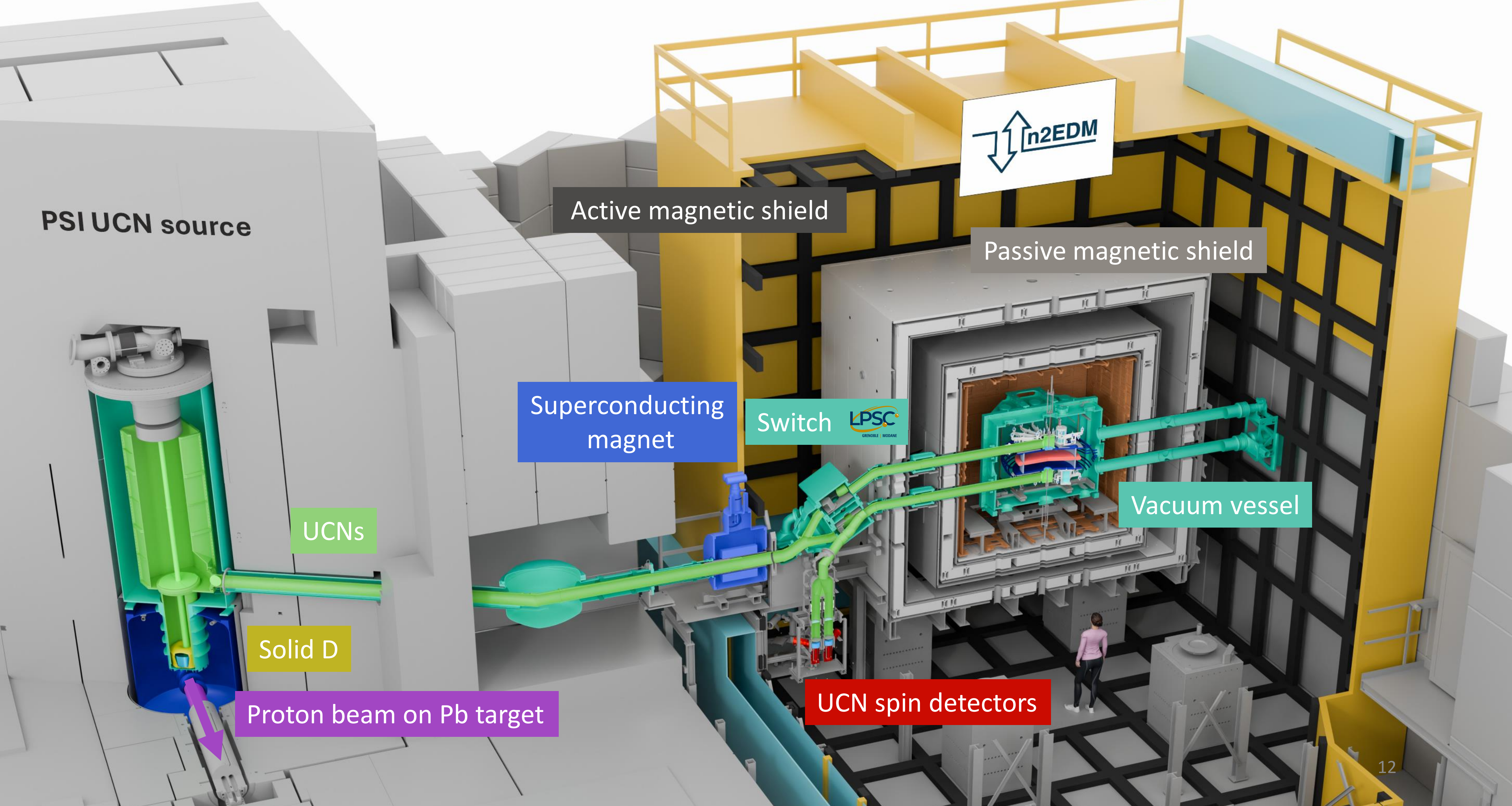
→ study of the systematic effects affecting R is ongoing (Morgan Ferry)

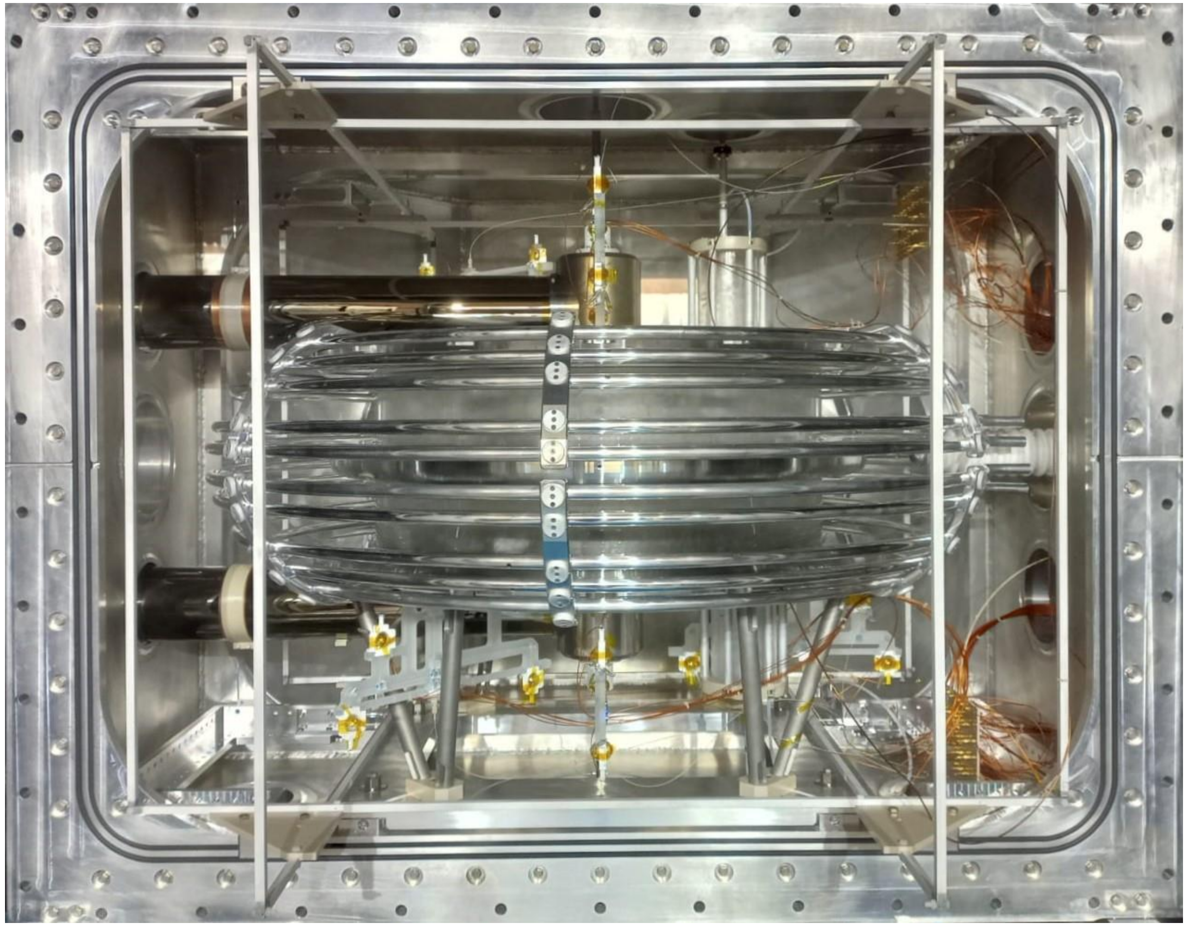
Reduced limit on the permanent electric dipole moment of Hg 199. Graner, Brent, et al. PRL (2016) :Hg EDM $|d_{Hg}| < 7{,}4 \ 10^{-30}\ e$ cm

II- **How** do we measure the neutron EDM at PSI

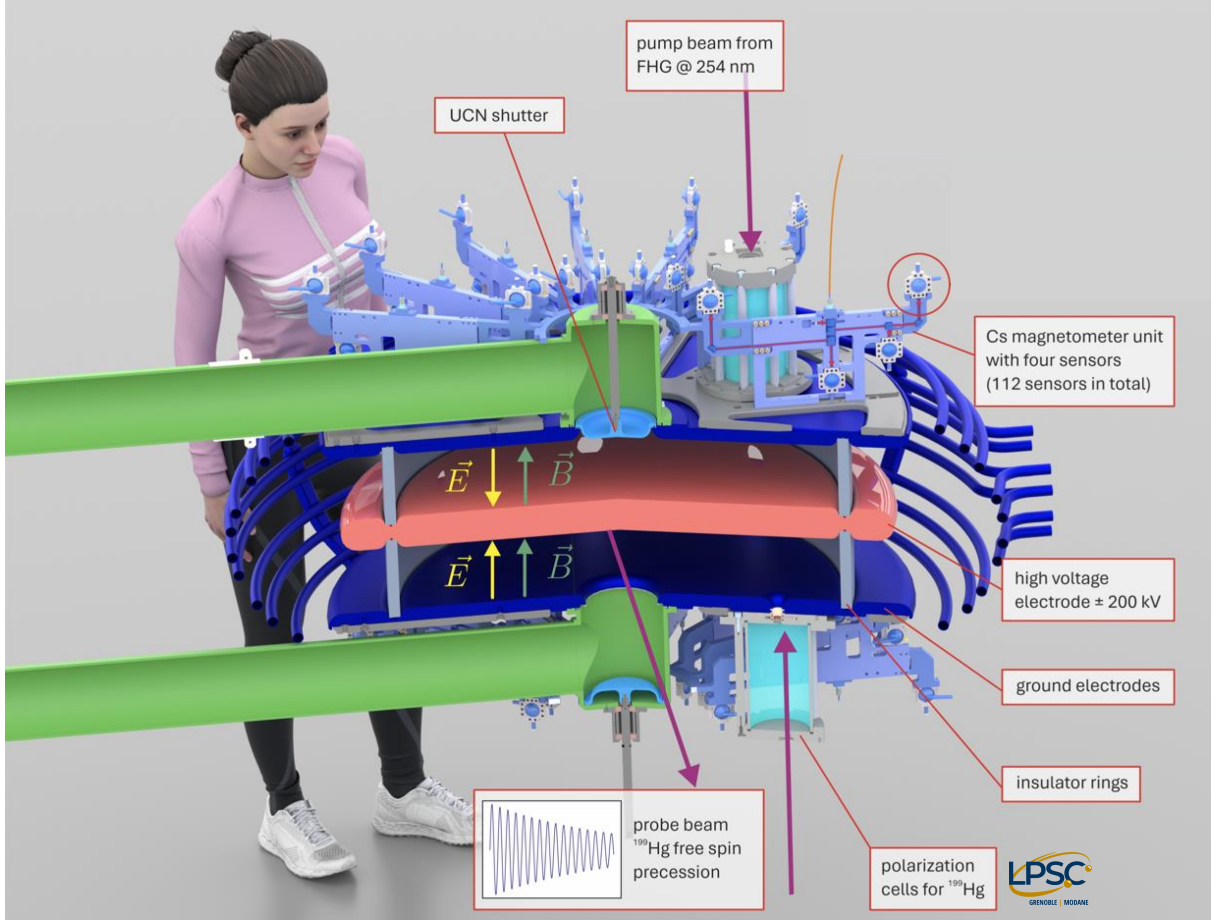
2. Experimental setup

n2EDM


PSI UCN source
Active magnetic shield
n2EDM
Passive magnetic shield
Superconducting magnet
Switch
LPSC
Vacuum vessel
UCNs
Solid D
Proton beam on Pb target
UCN spin detectors



Photograph of the n2EDM precession chambers , october 2025

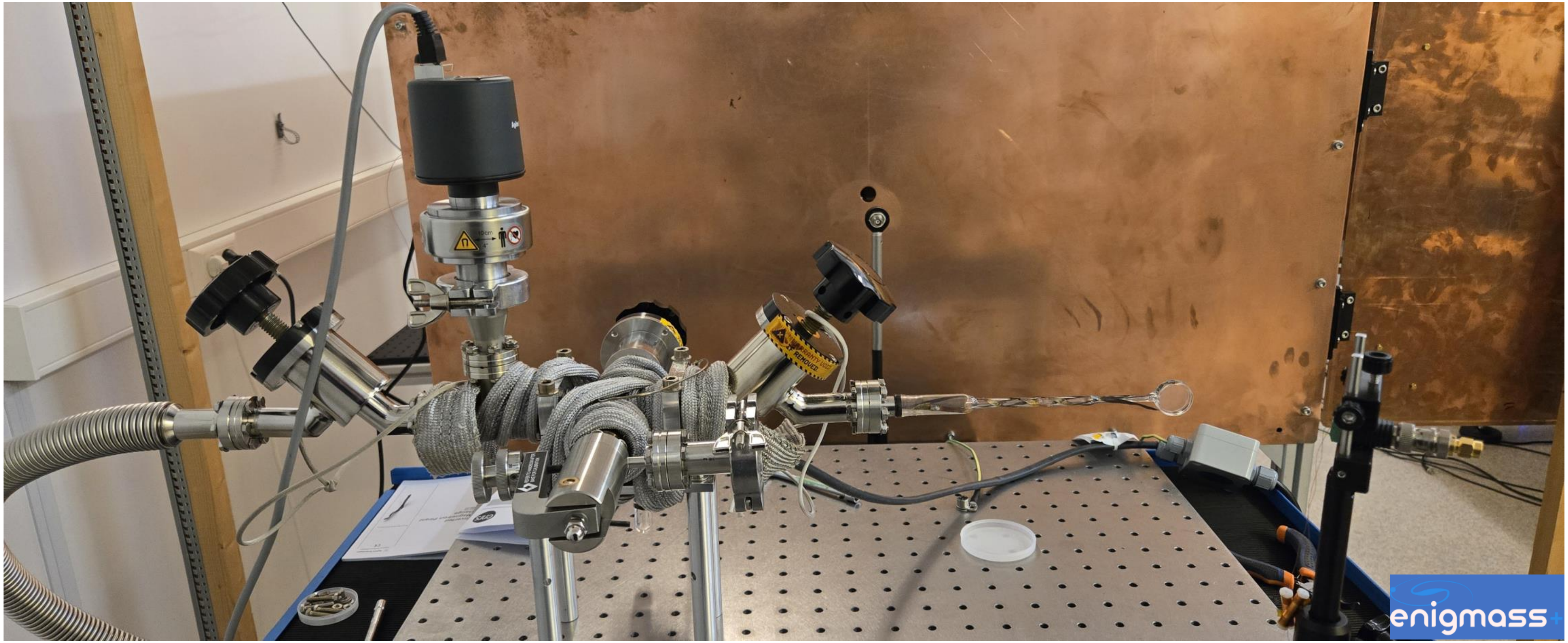


n2EDM precession chambers design scheme with subsystems.

LPSC contributions

- Switch (UCN guiding)
- Hg polarisation chambers
- Hg injection system
- Hg spectroscopy cells
- Magnetic field mapper
- Data Monitoring Interface

Enriched ^{199}Hg spectroscopy cell (L4M, LPSC)

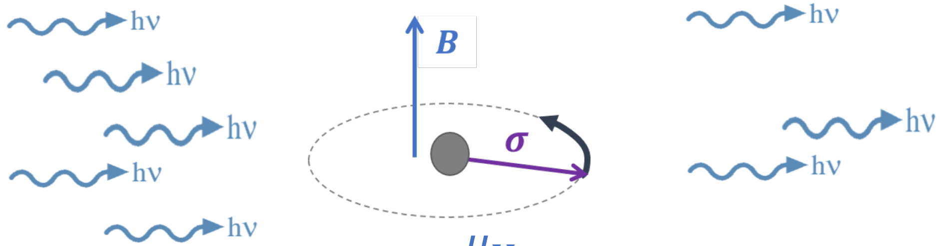


III- The Hg co-magnetometer

Concept, setup and performances.

Measuring magnetic fields with Hg vapour

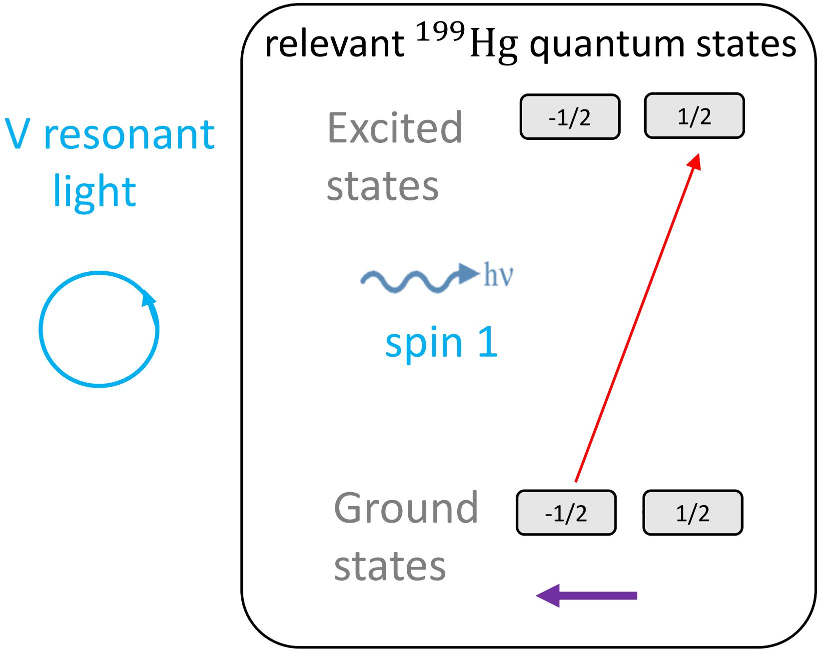
Hg precession



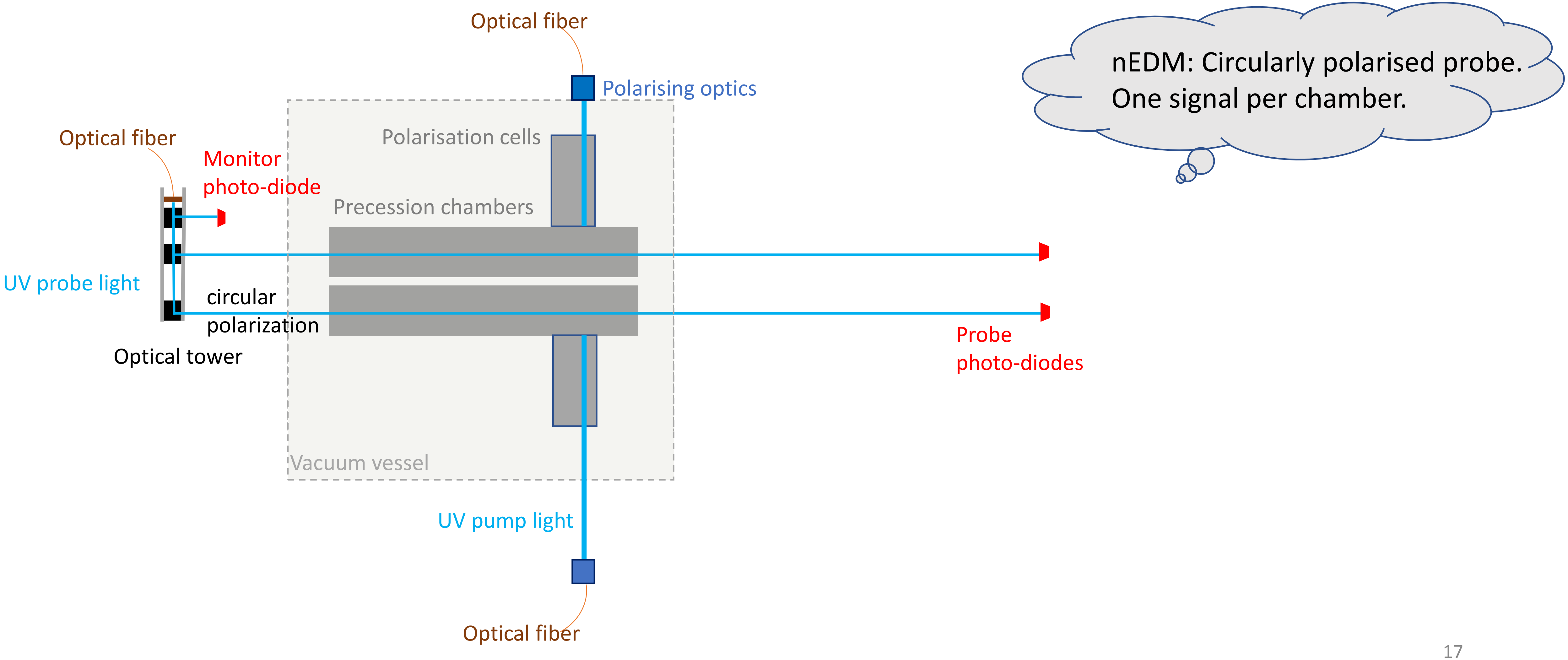
Transmitted light modulated at f_{Hg}

$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B$$

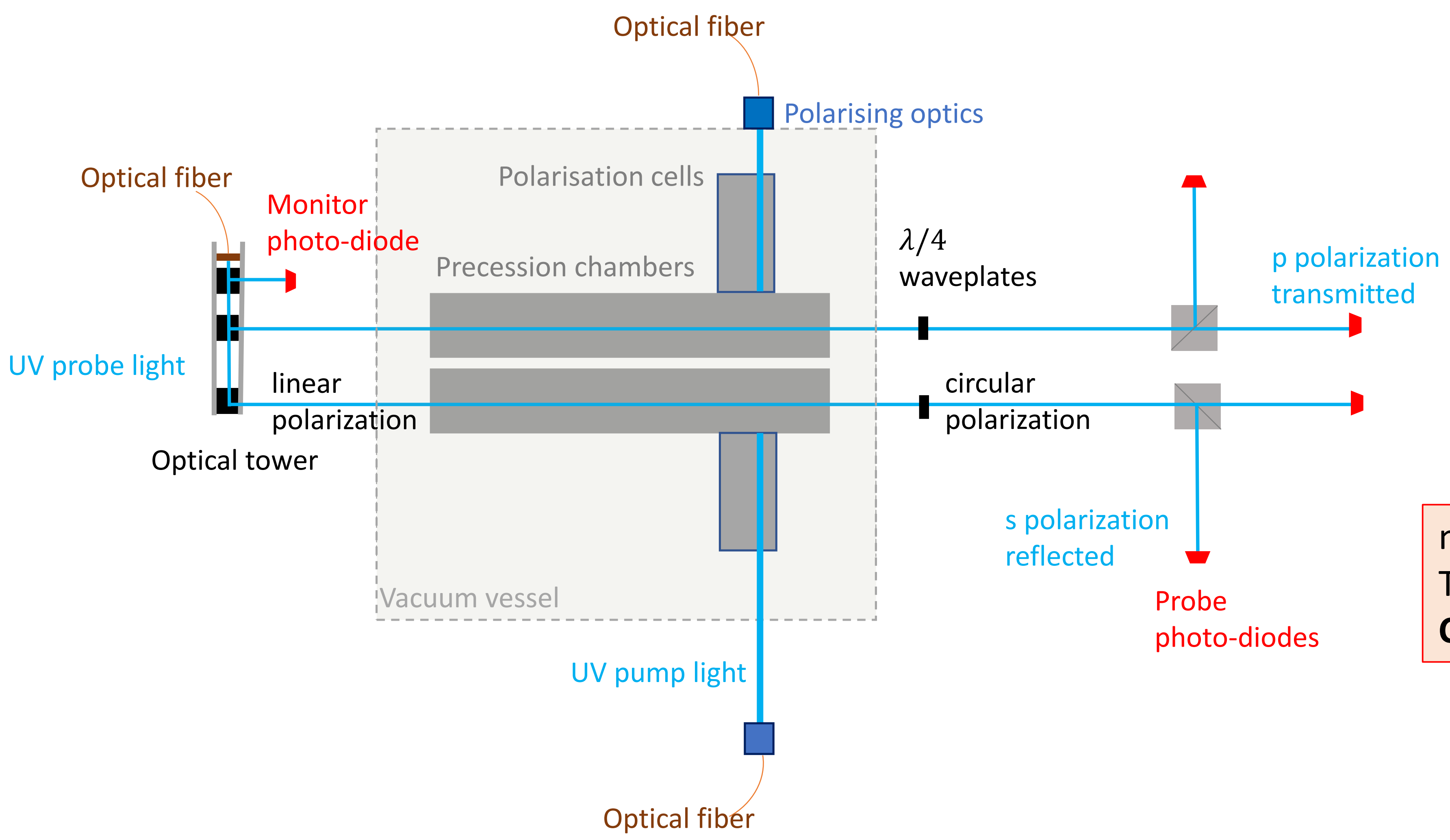
UV resonant light



Optical reading of Hg precession in n2EDM

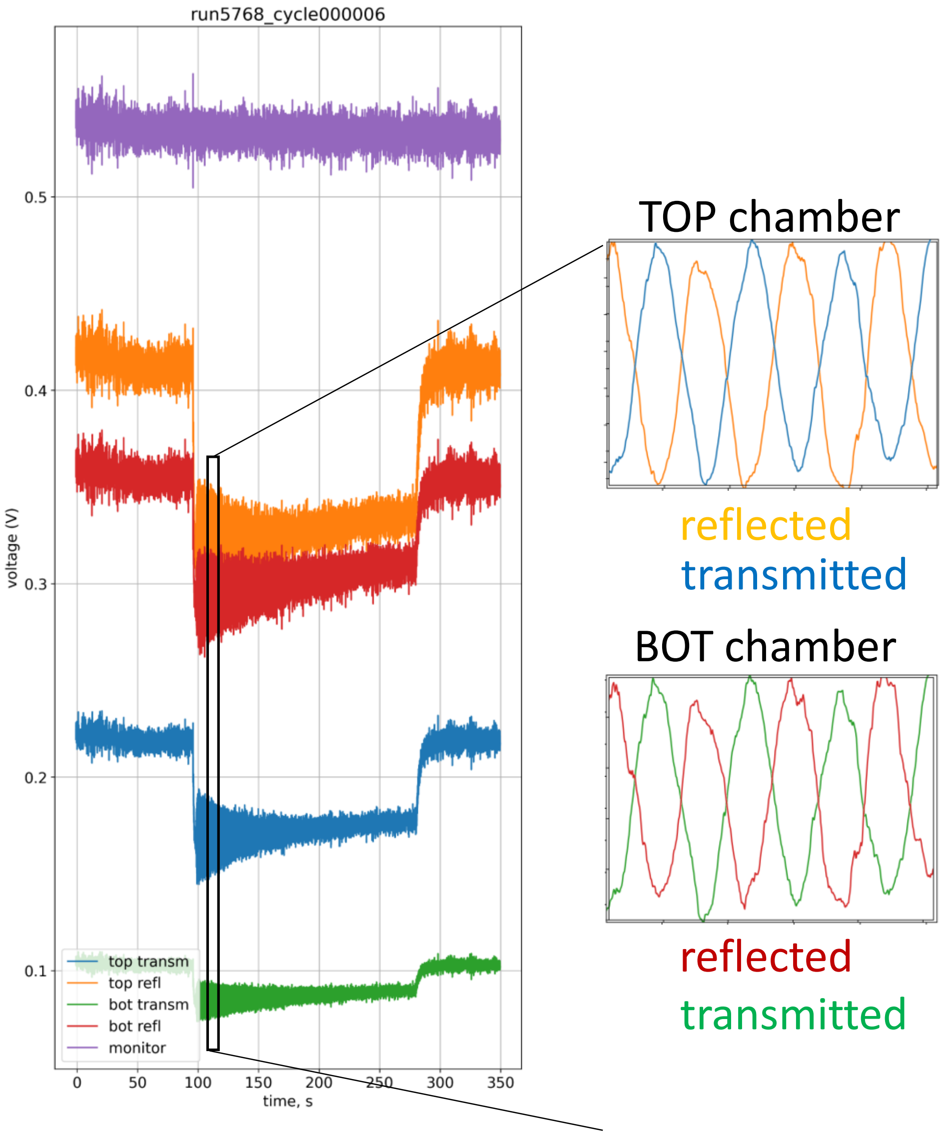


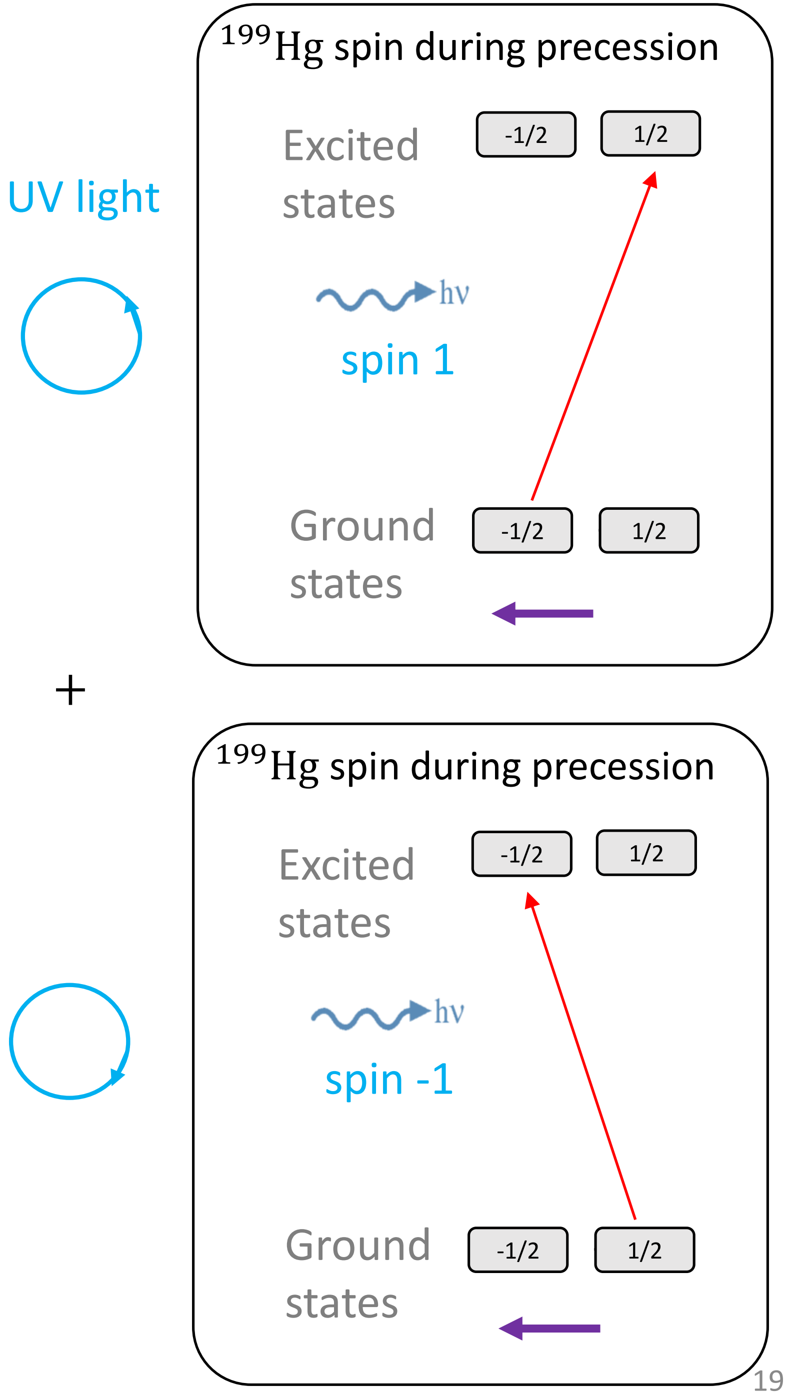
Optical reading of Hg precession in n2EDM



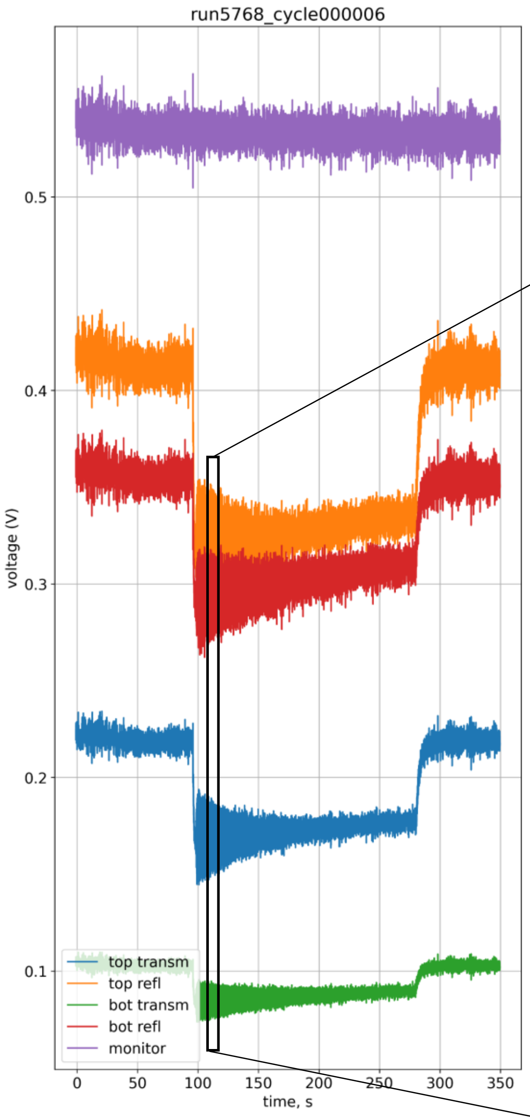
n2EDM: linearly polarised probe.
Two signals for each chamber.
Cancellation of common noise.

Probe photo-diode signals

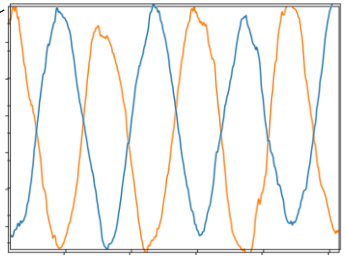




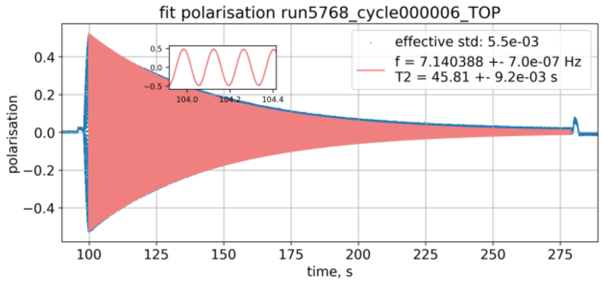
Probe photo-diode signals



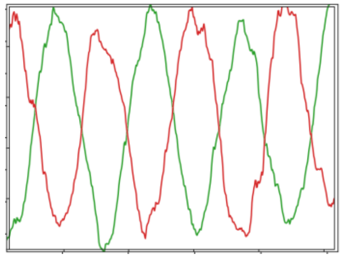
TOP chamber



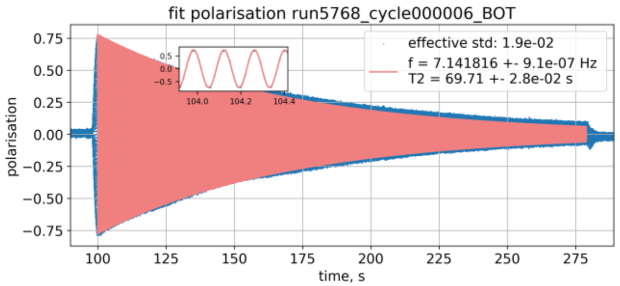
reflected
transmitted



BOT chamber

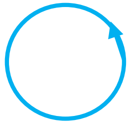


reflected
transmitted



Linearly polarised probe lowered the uncertainty by a factor 3.

UV light



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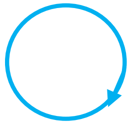
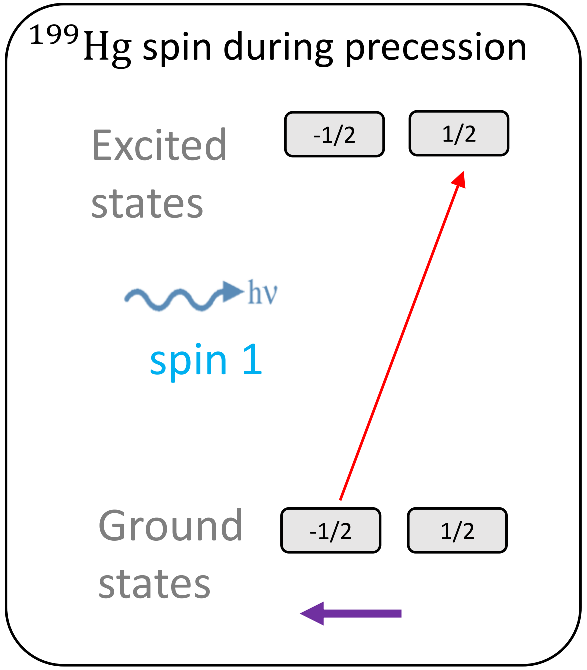
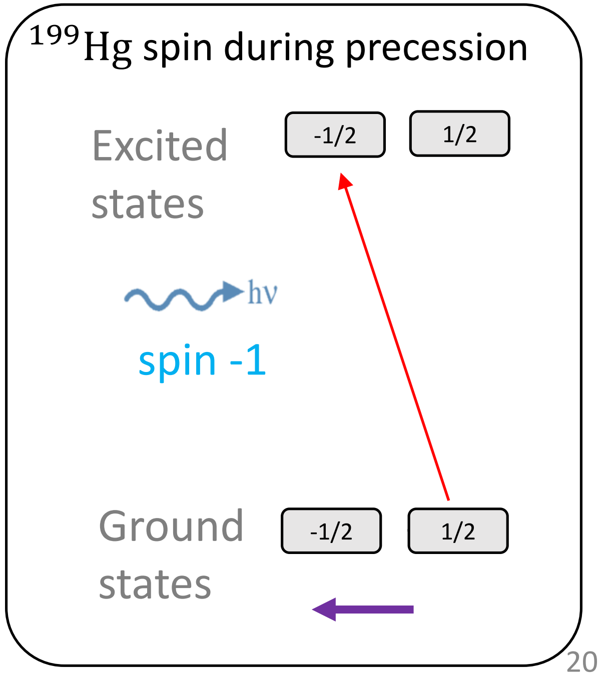






Performance of the Hg magnetometer

Precision:

- TOP chamber $\frac{\sigma(f_{\mathrm{Hg}})}{f_{\mathrm{Hg}}} = 7 \times 10^{-8}$ $\frac{\sigma(f_{\mathrm{n}})}{f_{\mathrm{n}}} = 2 \times 10^{-7}$
- BOT chamber $\frac{\sigma(f_{\mathrm{Hg}})}{f_{\mathrm{Hg}}} = 4 \times 10^{-8}$ $\frac{\sigma(f_{\mathrm{n}})}{f_{\mathrm{n}}} = 2 \times 10^{-7}$

Accuracy: unbiaised estimator?

- effect of non-white noise,
- magnetic field drifts within one cycle

status
✓
ongoing

n2EDM status and outlook

- UCN production, detection, polarization, spin transport ✓
- Magnetic shielding and characterization ✓
- Magnetic field generation and characterization ✓
- Electric field ✗
- Hg co-magnetometer injection, polarization, optical reading ✓
- Cs magnetometers installation, polarisation & optical reading ✗

✓ Operational
✗ Not yet operational

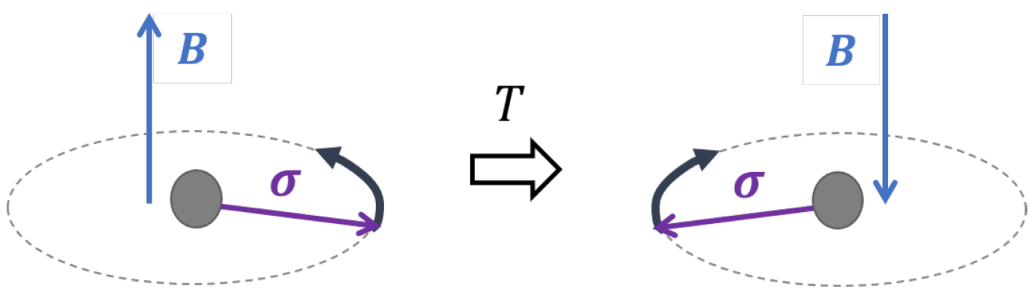
2025 n and Hg | Today | 2025 EDM test run | 2026 systematics | 2026 EDM | 2027-2028 Accelerator shutdown | 2029- Magic EDM

Neutrons available
Neutrons unavailable

Thank you for your attention!
Questions?

Additional slides

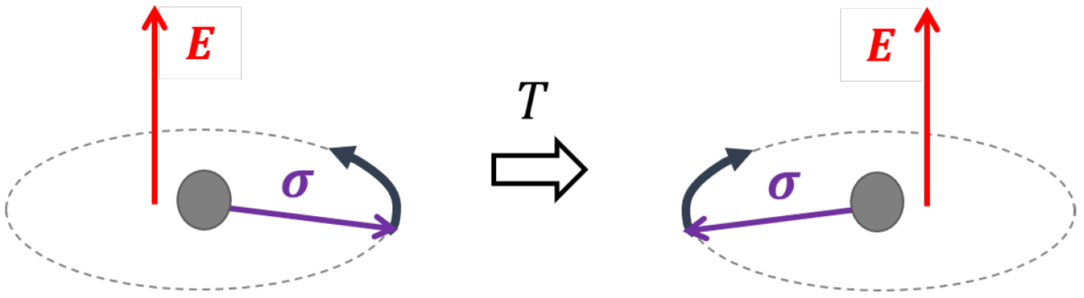
An EDM violates Charge Parity symmetry.



Observable = magnetic moment μ

$\mu > 0$ $\mu > 0$

T-invariant



Observable = electric moment d

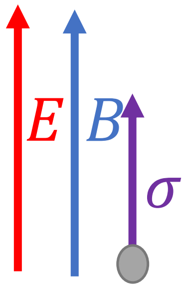
$d > 0$ $d < 0$

not T-invariant

CPT symmetry ↔ Lorentz invariance of the Standard Model.
T violation ↔ CP violation

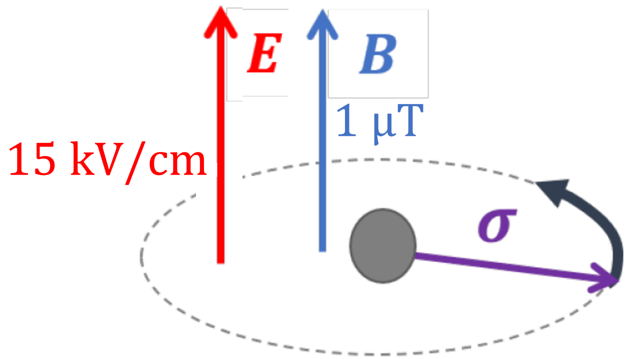
Measure the neutron EDM: Ramsey method of oscillatory fields

Larmor precession frequency measurement.
in a *known* magnetic field and *strong* electric field.



$\frac{\pi}{2}$ spin flip

f_{RF}

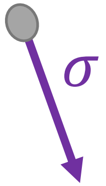


$$f_n = \frac{\mu_n}{\pi\hbar} B + \frac{d_n}{\pi\hbar} E$$

In n2EDM, electric/magnetic term $\approx 10^{-9}$
→ any magnetic drift is prohibitive!

$\frac{\pi}{2}$ spin flip

f_{RF}



Spin asymmetry

$$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = -\alpha \cos[\frac{(f_{RF} - \boldsymbol{f}_n)}{\Delta\nu}]$$

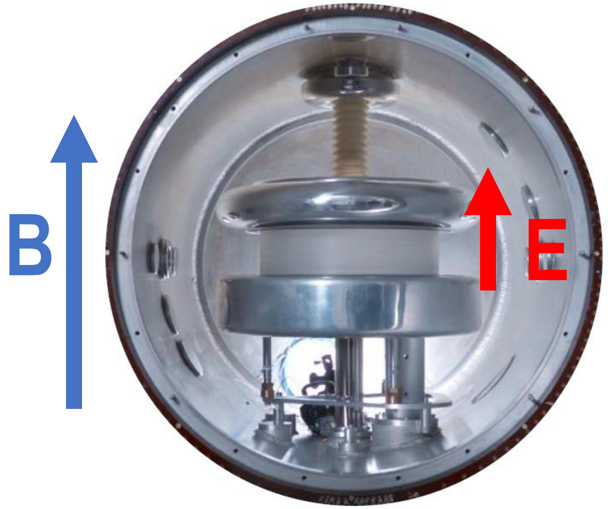
$$\sigma(\boldsymbol{f}) = \frac{1}{2\pi\alpha \boldsymbol{T}\sqrt{N}} \sim 10^{-6}$$

Current most sensitive measurement: nEDM at PSI

Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

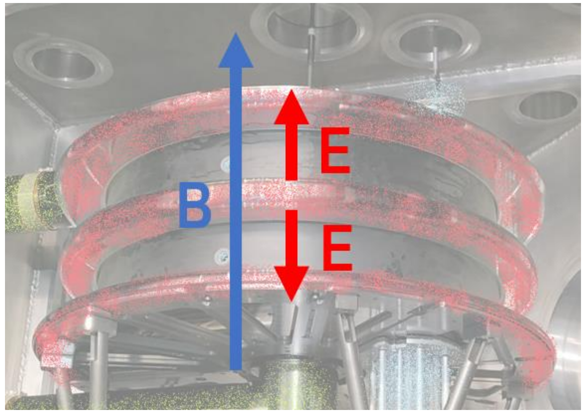
$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-26}\ e\ cm$$

Number of neutrons   Homogeneity of B

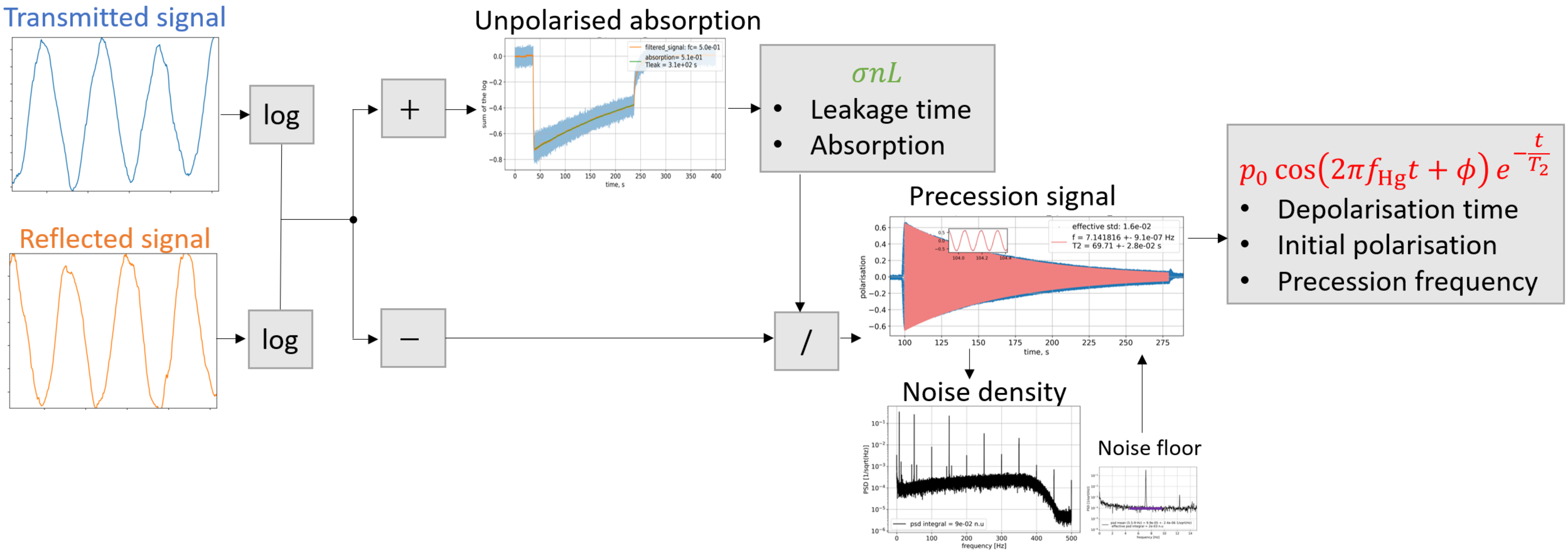


In n2EDM:

- Increase satistics in larger volume with a better controlled magnetic field: **simultaneous measure is two chambers** for both electric polarities.
- Same principle of co-magnetometry: Hg and Cs.



The mercury co-magnetometer



Linearly polarised light: two signals oscillating with opposite phase

$$\Pi_t = a\,\Pi_0 e^{-\sigma n L(1+p)}$$

$$\Pi_r = (1-a)\Pi_0 e^{-\sigma n L(1-p)}$$

$$\Pi_r \Pi_t = a(1-a)e^{-2\sigma n L}$$

Derive $\sigma n_0 e^{-t/T_{leak}} L$

$$\frac{\Pi_r}{\Pi_t} = e^{-2\sigma n L p}$$

Derive p knowing $\sigma n L$

σ unpolarised cross section
n mercury density
L length of the precession volume
p polarisation of the mercury vapour
Transmission/reflection factors:
ideally $a = 1 - a = \frac{1}{2}$

$$-\frac{1}{2\sigma n L}\ln\left(\frac{\Pi_r}{\Pi_t}\right) = p_0 \cos\left(2\pi f_{\mathrm{Hg}} t + \phi\right) e^{-\frac{t}{T2}}$$

1st fit provides
- Absorption
- Leakage time of precession chamber

2nd fit provides
- Polarisation of mercury vapour p_0
- Depolarisation time $T2$
- Noise spectrum
- Precession frequency f_{Hg}

nEDM, one of the most sensitive probes to CP-violating new physics

Comparison of the sensitivity of different observables with the Standard Model Effective Field Theory: all coupling constants to one.

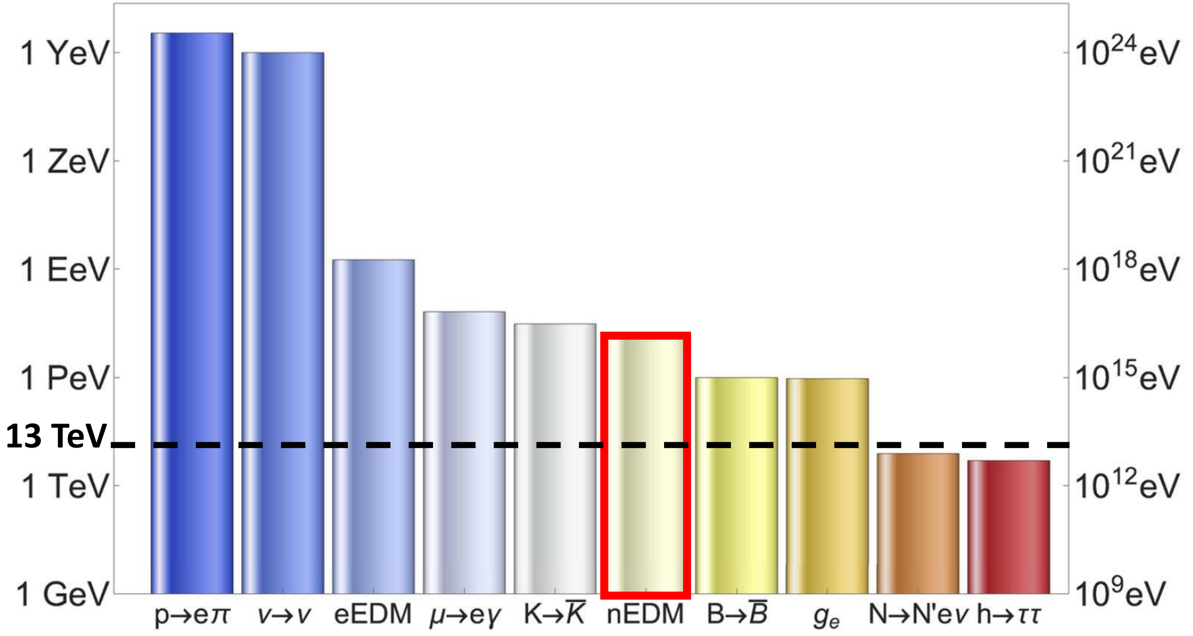
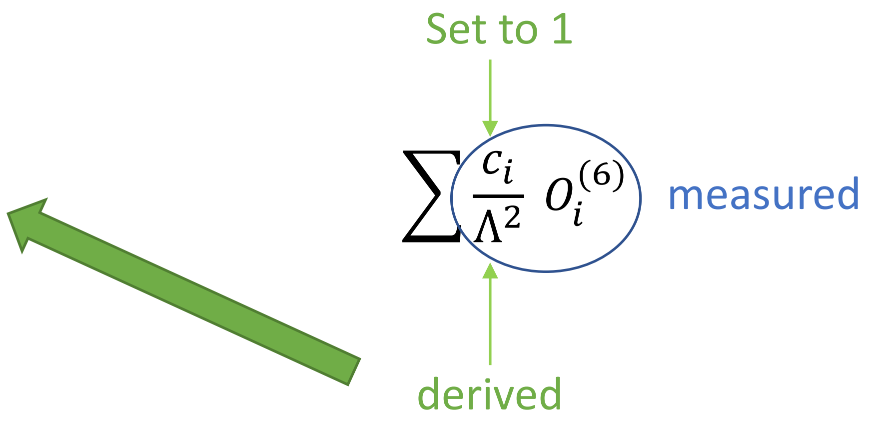


Figure by Adam Falkowski, ***Lectures on SMEFT*** EPJC (2023)

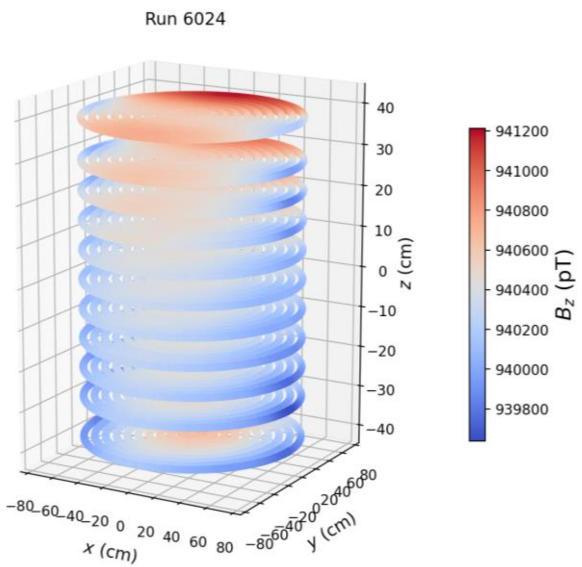
Example: dimension 6 operators



$$\sum \frac{c_i}{\Lambda^2} O_i^{(6)}$$

2. Offline control of the magnetic field: mapping

- Fluxgate moving in cylindrical coordinates provides B_ρ, B_ϕ, B_z.
- Composed of non-magnetic parts to measure the remnant field, and the generated B_0.

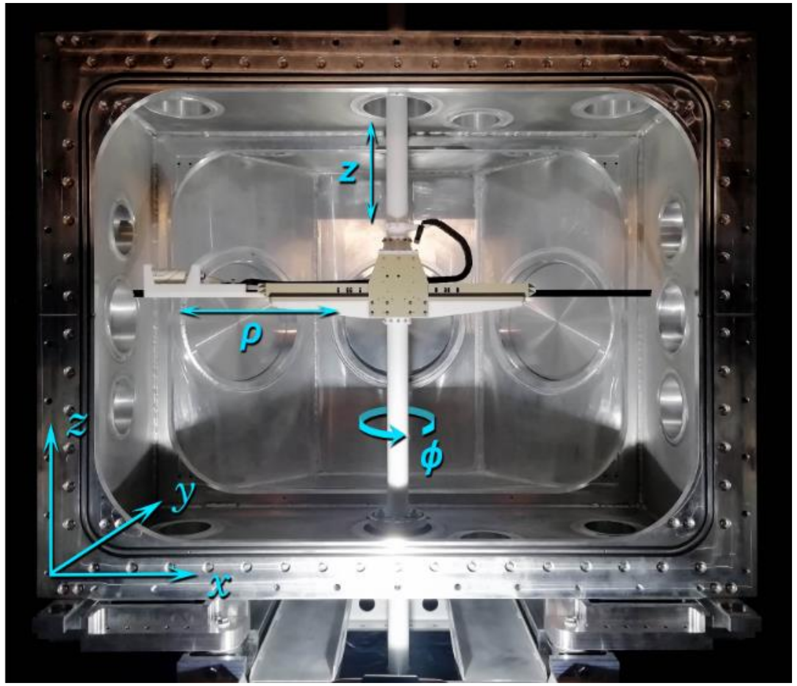


G_{lm} [fT/cm]	2025 optimized*
G_{10}	144 ± 220
G_{20}	59.2 ± 25.4
G_{30}	12.5 ± 30.9
G_{40}	-22.0 ± 8.4
G_{50}	-4.9 ± 11.2
G_{60}	-21.4 ± 3.3
G_{70}	-1.10 ± 2.93

$\delta G_1 > 25\ pT$

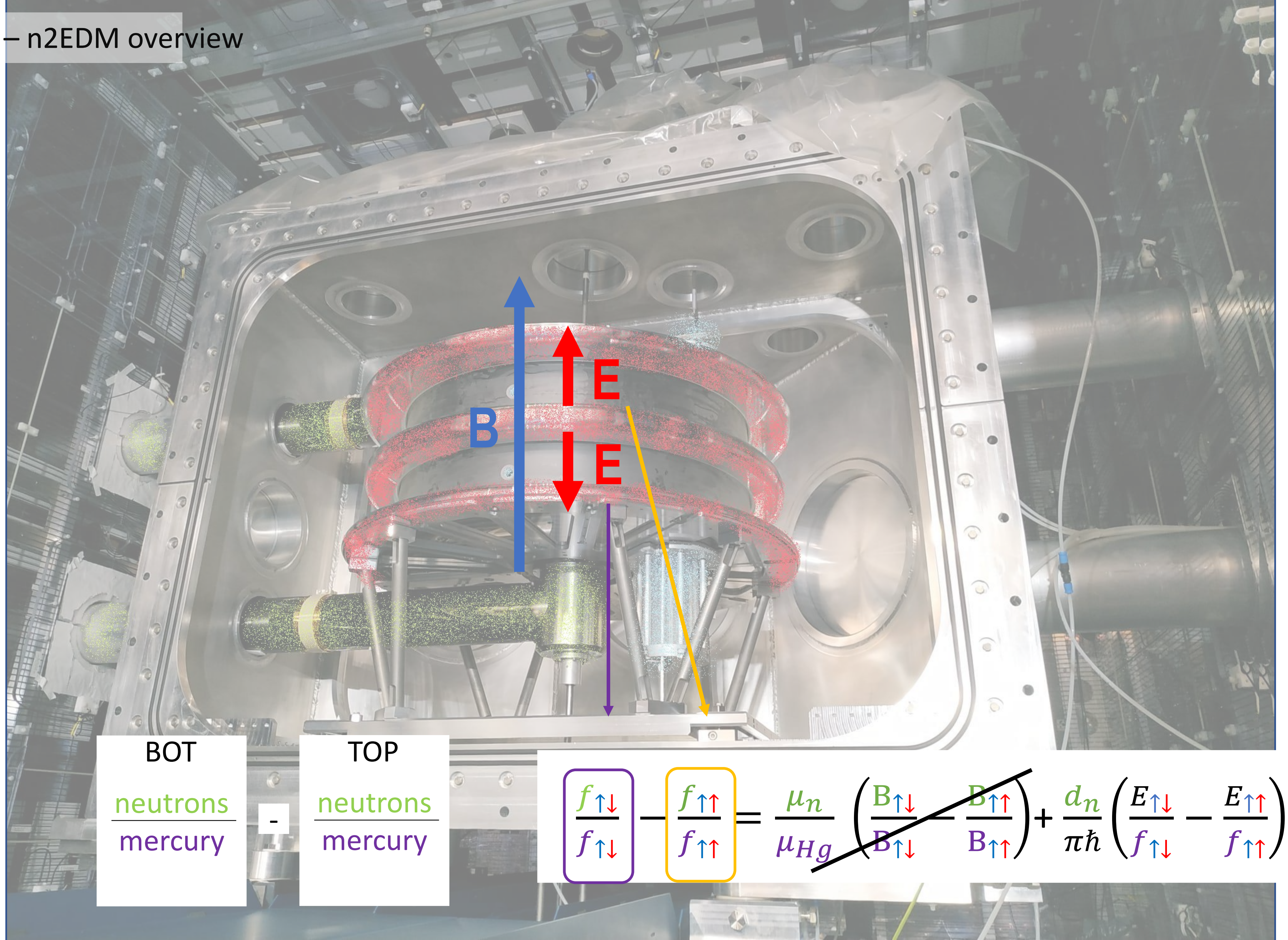
$\delta G_3 > 20\ pT$

$\delta G_5 < 20\ pT$



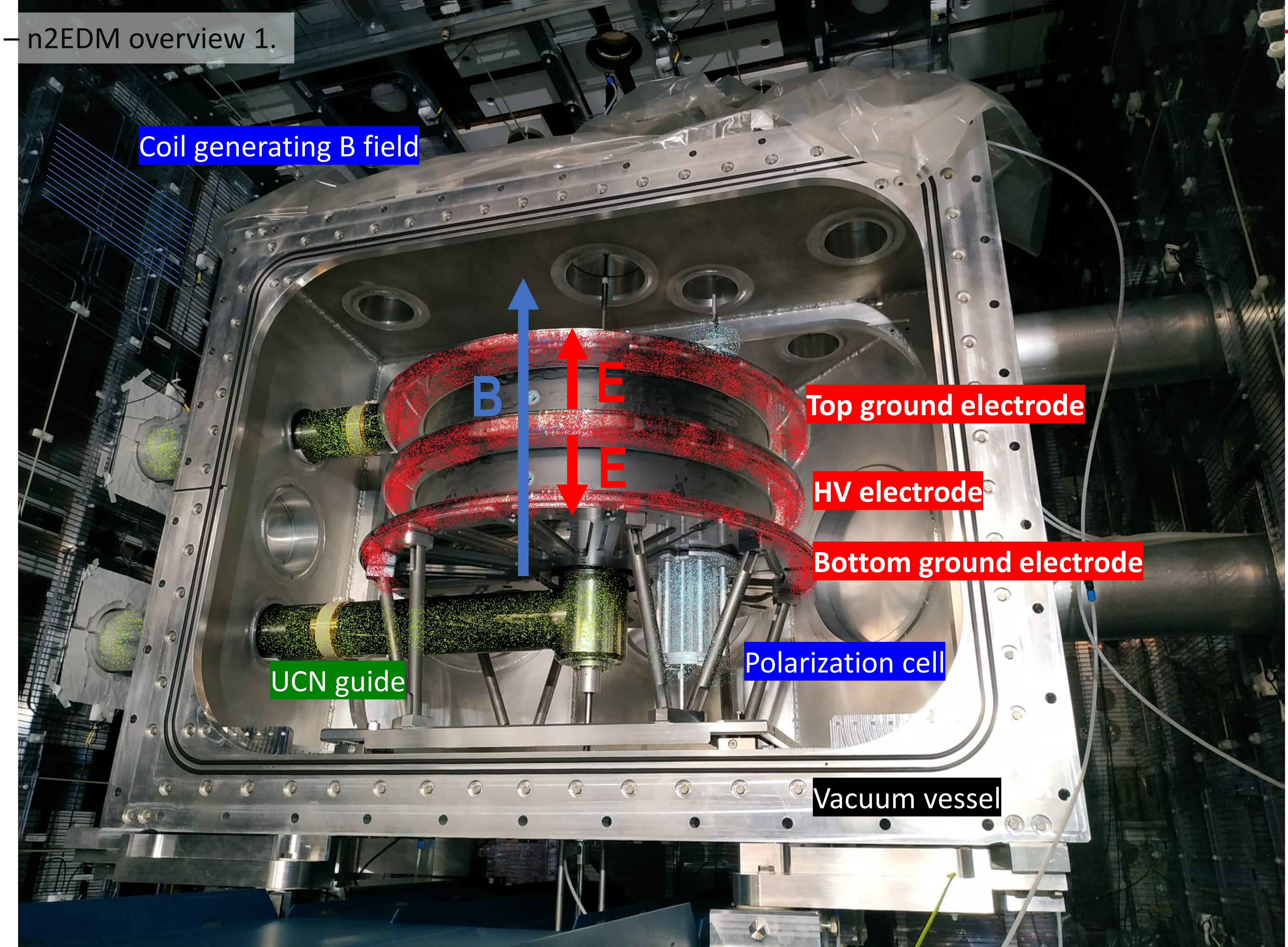
French technical contribution

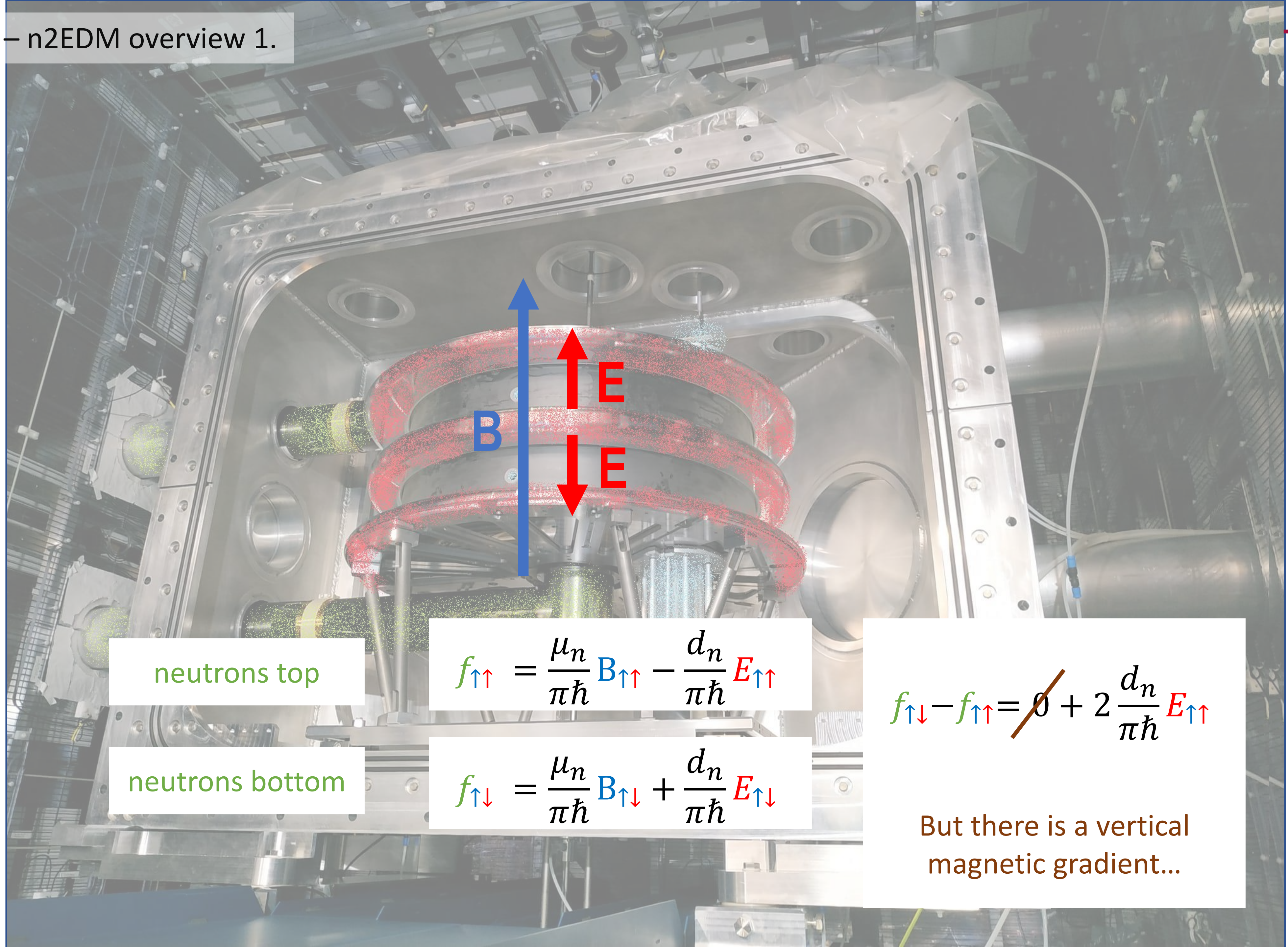
LPSC GRENOBLE | MODANE   LPC CAEN



BOT		TOP
neutrons / mercury	-	neutrons / mercury

$$\frac{f_{\uparrow\downarrow}}{f_{\uparrow\downarrow}} - \frac{f_{\uparrow\uparrow}}{f_{\uparrow\uparrow}} = \frac{\mu_n}{\mu_{Hg}}\left(\frac{B_{\uparrow\downarrow}}{B_{\uparrow\downarrow}} - \frac{B_{\uparrow\uparrow}}{B_{\uparrow\uparrow}}\right) + \frac{d_n}{\pi\hbar}\left(\frac{E_{\uparrow\downarrow}}{f_{\uparrow\downarrow}} - \frac{E_{\uparrow\uparrow}}{f_{\uparrow\uparrow}}\right)$$


Coil generating B field
B
E
E
Top ground electrode
HV electrode
Bottom ground electrode
UCN guide
Polarization cell
Vacuum vessel



neutrons top

$$f_{\uparrow\uparrow} = \frac{\mu_n}{\pi\hbar} B_{\uparrow\uparrow} - \frac{d_n}{\pi\hbar} E_{\uparrow\uparrow}$$

neutrons bottom

$$f_{\uparrow\downarrow} = \frac{\mu_n}{\pi\hbar} B_{\uparrow\downarrow} + \frac{d_n}{\pi\hbar} E_{\uparrow\downarrow}$$

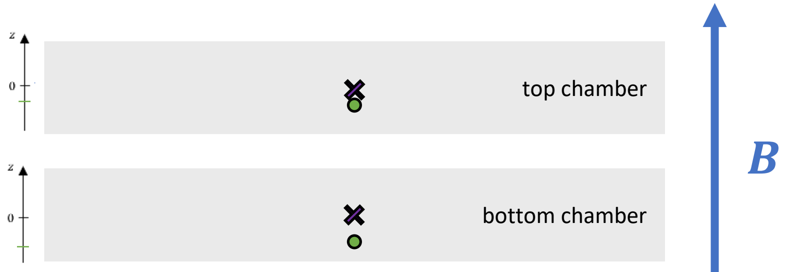
$$f_{\uparrow\downarrow} - f_{\uparrow\uparrow} = \cancel{0} + 2\frac{d_n}{\pi\hbar} E_{\uparrow\uparrow}$$

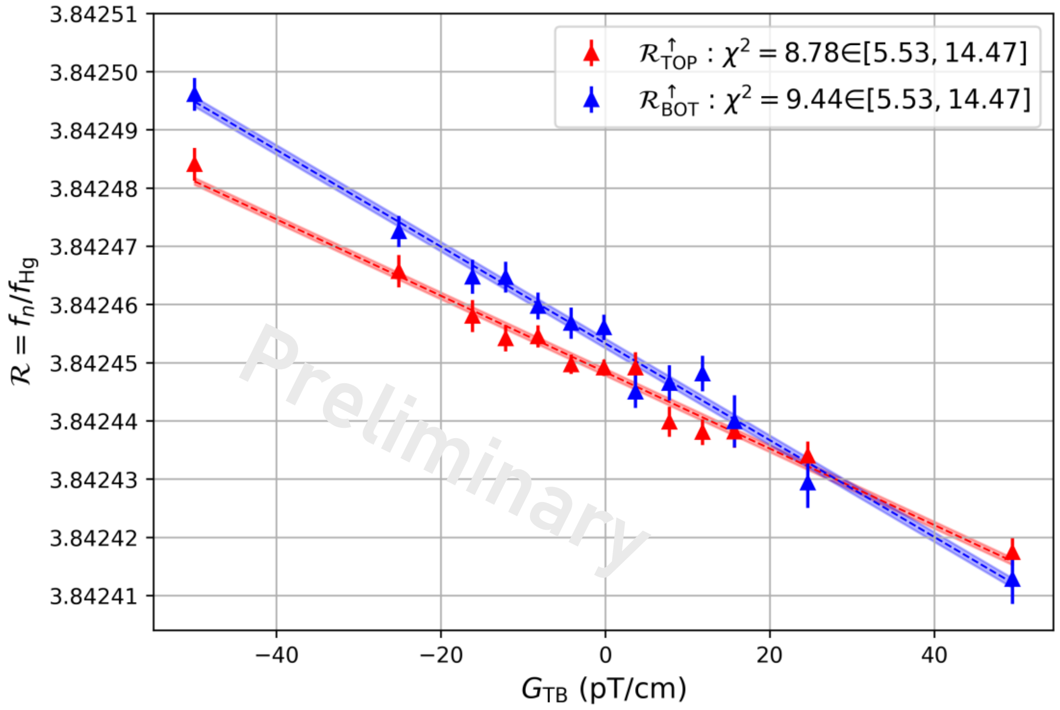
But there is a vertical magnetic gradient…

Observation of gravitational shift on $R = \frac{f^n}{f^{Hg}}$

- Neutrons have a lower center of mass than Hg atoms because of gravity

→ R slightly depends on the vertical gradients G_{TB}





Susceptibility to vertical gradient

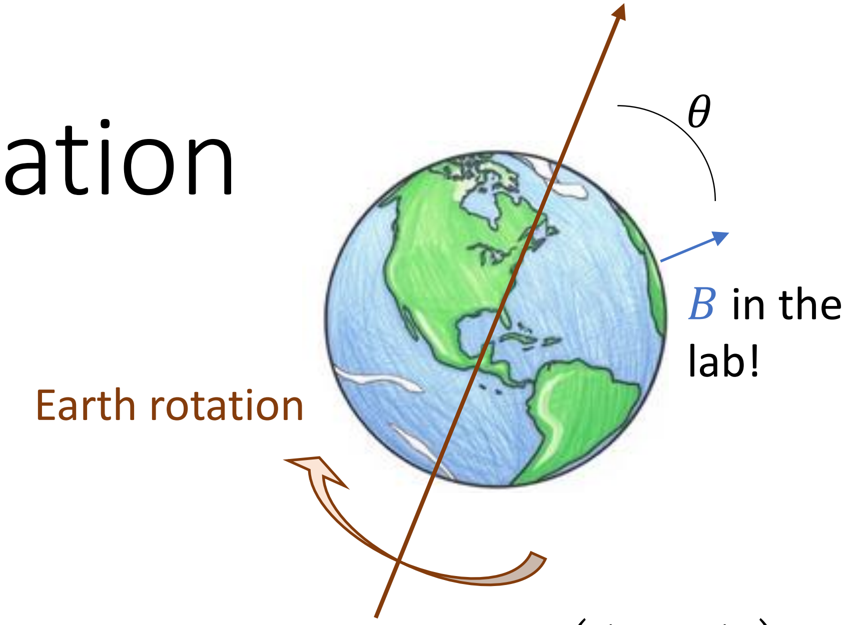
$$\frac{dR_{T,B}}{dG_{TB}} = R_0 \frac{< z_{T,B} >}{< B >}$$

Result:

$$< z_T > = -0.161(4)\ \text{cm}$$
$$< z_B > = -0.214(6)\ \text{cm}$$

Provides information of the energy spectrum of neutrons!

R- curve: sensitivity to earth rotation



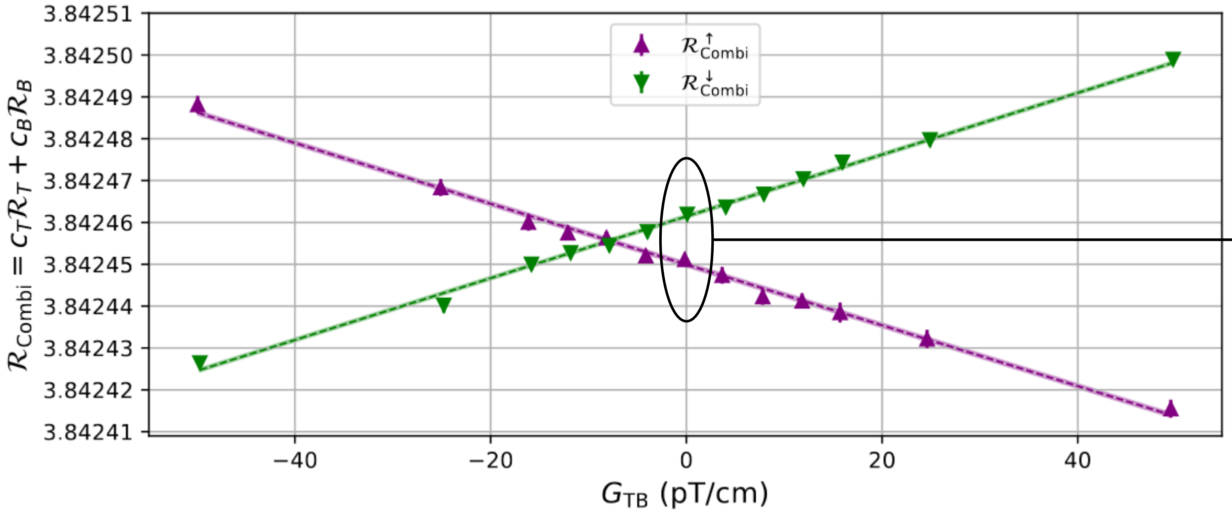
- $\mu_{Hg} > 0$ and $\mu_n < 0$ Measured period: 24 ± 1 hours
- Laboratory referential is rotating (earth rotation)
- Depending on B one frequency is enhanced, the other is diminished.

$$R = \frac{f_n}{f_{Hg}} = \left|\frac{\mu_n}{\mu_{Hg}}\right|(1 \pm \delta_{earth})$$

$$\delta_{earth} = f_{earth} cos(\theta) \left(\frac{1}{f_n} + \frac{1}{f_{Hg}}\right) \approx 10^{-6}$$

Magnetic field up

Magnetic field down



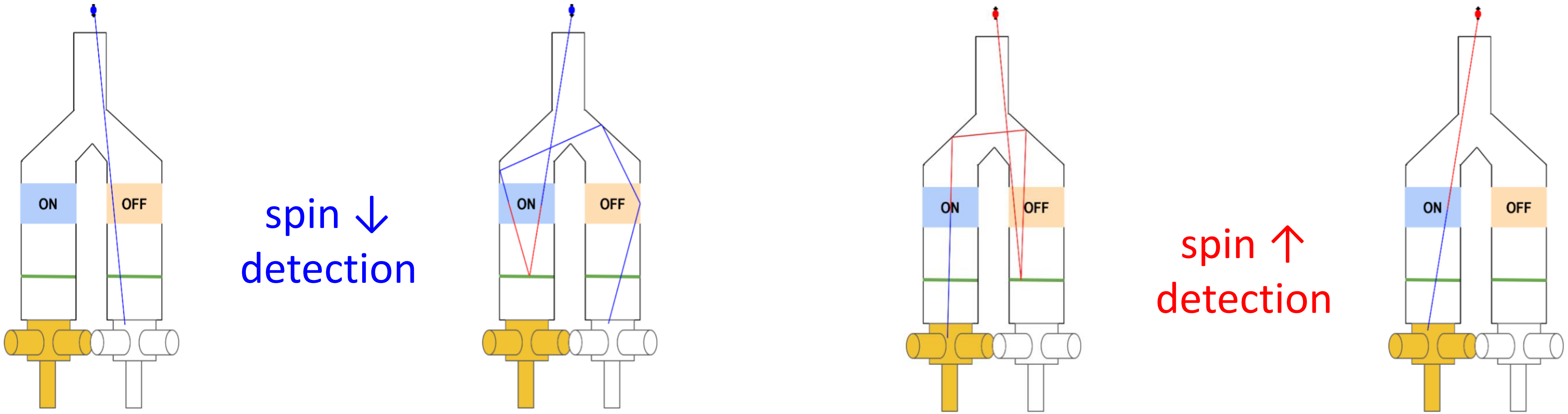
Result:
Rotation period
24 ± 1 hour

1. Neutron Spin Analyzer: measure $\frac{N_{up} - N_{down}}{N_{up} + N_{down}}$

Simultaneous detection of both spin components in gaseous detector:

- **Analyzing foil**: spin down transmitted (spin up reflected).
- Two arms: - one with a **spin flipper**: detects spin up neutrons

  - one without: detects spin down neutrons



2. Magnetic field specifications

- Expansion in harmonic modes :

$$B(x,y,z) = \sum_{l,m} G_{lm} \Pi_{l,m}(x,y,z)$$

Gradient terms (G_{lm}) — Legendre polynomials ($\Pi_{l,m}$)

  - G_{00} : Uniform vertical magnetic field
  - G_{10} : vertical gradient
  - G_{lm} $l \geq 2$: non uniformities

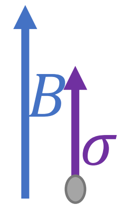
- Non uniformities (modes $l \geq 1$) affect the frequency ratio R.
- **Odd-modes** result in an EDM-like signal

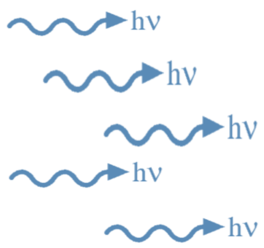
Specifications	fT/cm	Measured by…
Mode 1 of the magnetic field	$\delta G_1 < 25$	Hg, online
Mode 3 of the magnetic field	$\delta G_3 < 20$	Cs, online
Mode 5 of the magnetic field	$\delta G_5 < 20$	Mapper, offline

The design of the n2EDM experiment. nEDM Collaboration, EPJ C, 2021

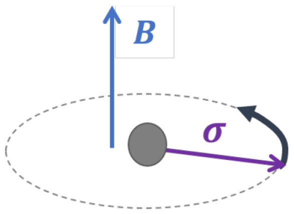
Measuring magnetic fields with Hg vapour

Polarized Hg

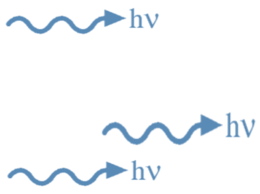




Hg precession



$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B$$



Transmitted light modulated at f_{Hg}

$$S = S_0 e^{-\kappa\sigma \underbrace{p_0 \cos(2\pi f_{\mathrm{Hg}} t+\phi)}_{\text{Vapour spin polarization}}}$$

UV resonant light