Quantum magnetometry for the search of the neutron electric dipole moment at PSI

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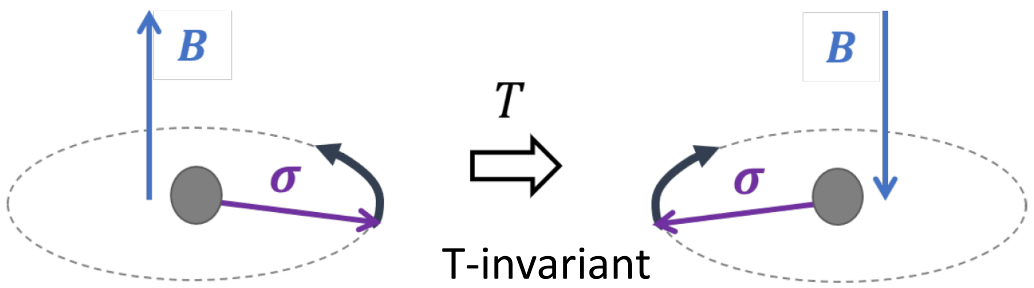
The neutron EDM, source of CP violation

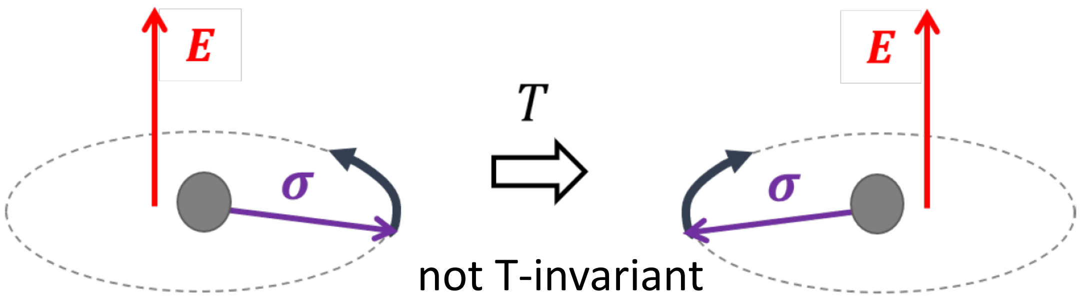
- Spins couple to magnetic fields with strength μ

- Spins could couple to electric fields. The electric dipole moment (EDM) is this coupling strength d.

Non-relativistic limit of the fermion-photon interaction:

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





T violation and CPT theorem: CP violation.

But also one of the most sensitive probes to new physics

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

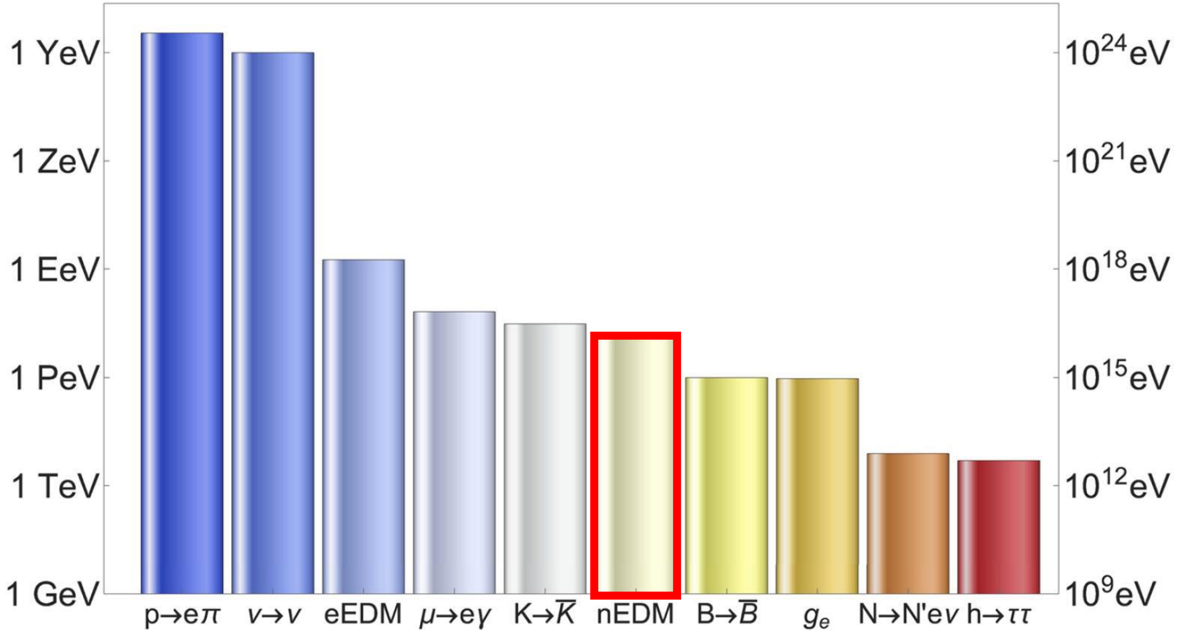
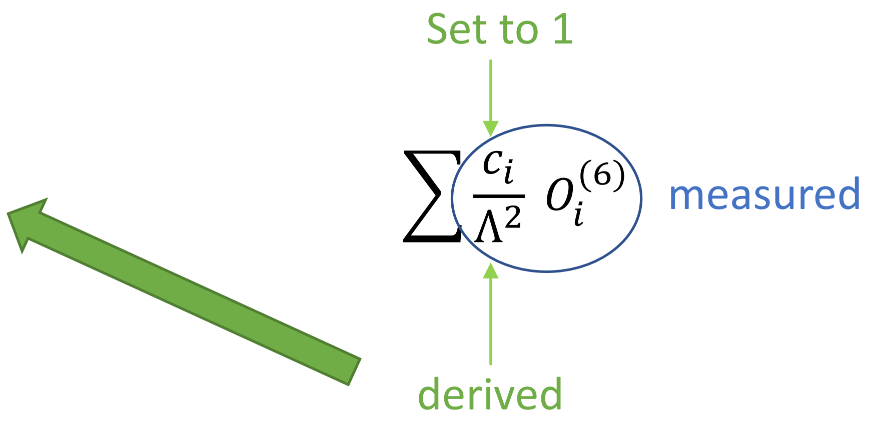
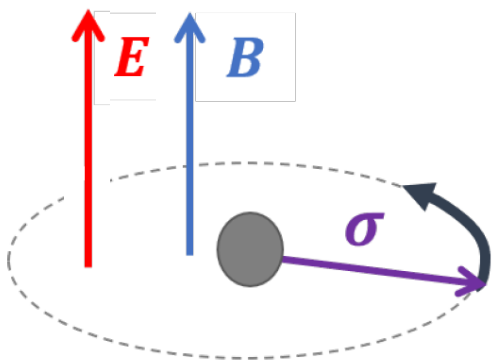


Figure by Adam Falkowski, ***Lectures on SMEFT*** EPJC (2023)

Example: dimension 6 operators



How to measure the neutron EDM?



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

- Beam measurements (cold neutrons).

A lot of neutrons.

Small interaction time.

- Stored Ultra Cold Neutron measurements.

Less neutrons.

Long interaction time: minutes.

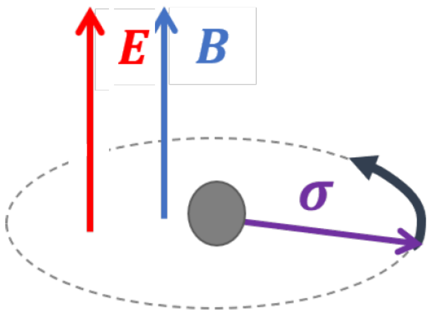
- Stored Ultra Cold Neutron measurements in superfluid helium

Higher neutron density.

Long interaction time: minutes.

Neutron frequency measurement: magnetic field stability.

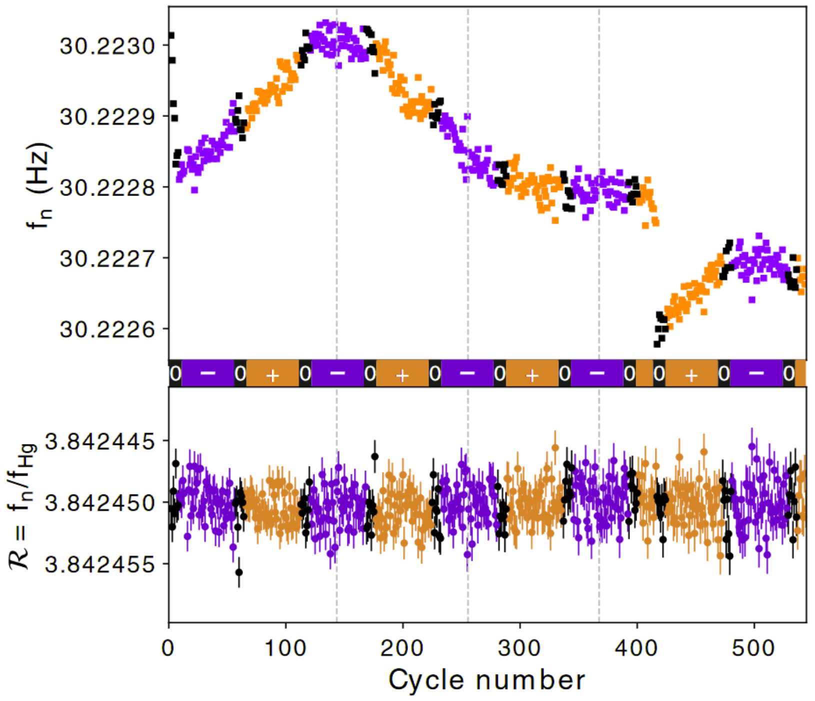
- $f_{\uparrow\downarrow} - f_{\uparrow\uparrow} = \frac{\mu}{\pi\hbar}(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}) + \frac{d}{\pi\hbar}(E_{\uparrow\downarrow} - E_{\uparrow\uparrow})$



Co-magnetometry technique to correct for **magnetic field fluctuations**, mercury.

Neutron: **destructive** spin measurement.

Mercury: non destructive spin measurement.



Measurement of the Permanent EDM of the Neutron, 2020

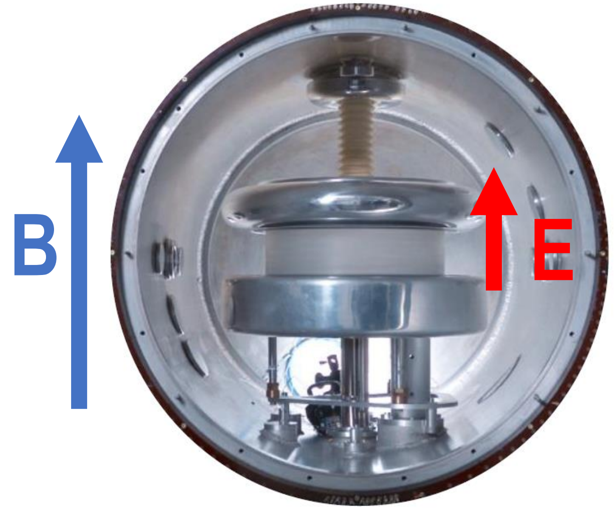
Current most sensitive measurement: nEDM at PSI

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

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

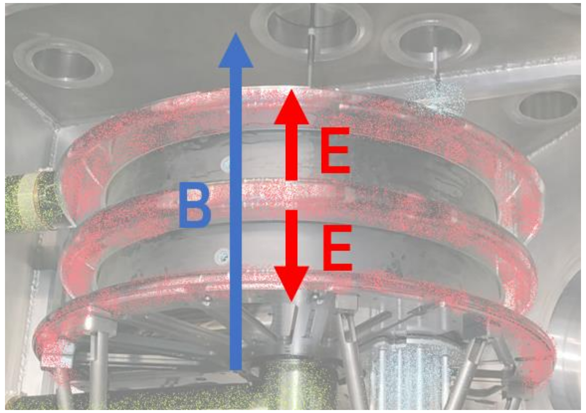
Number of neutrons ↗ (stat)

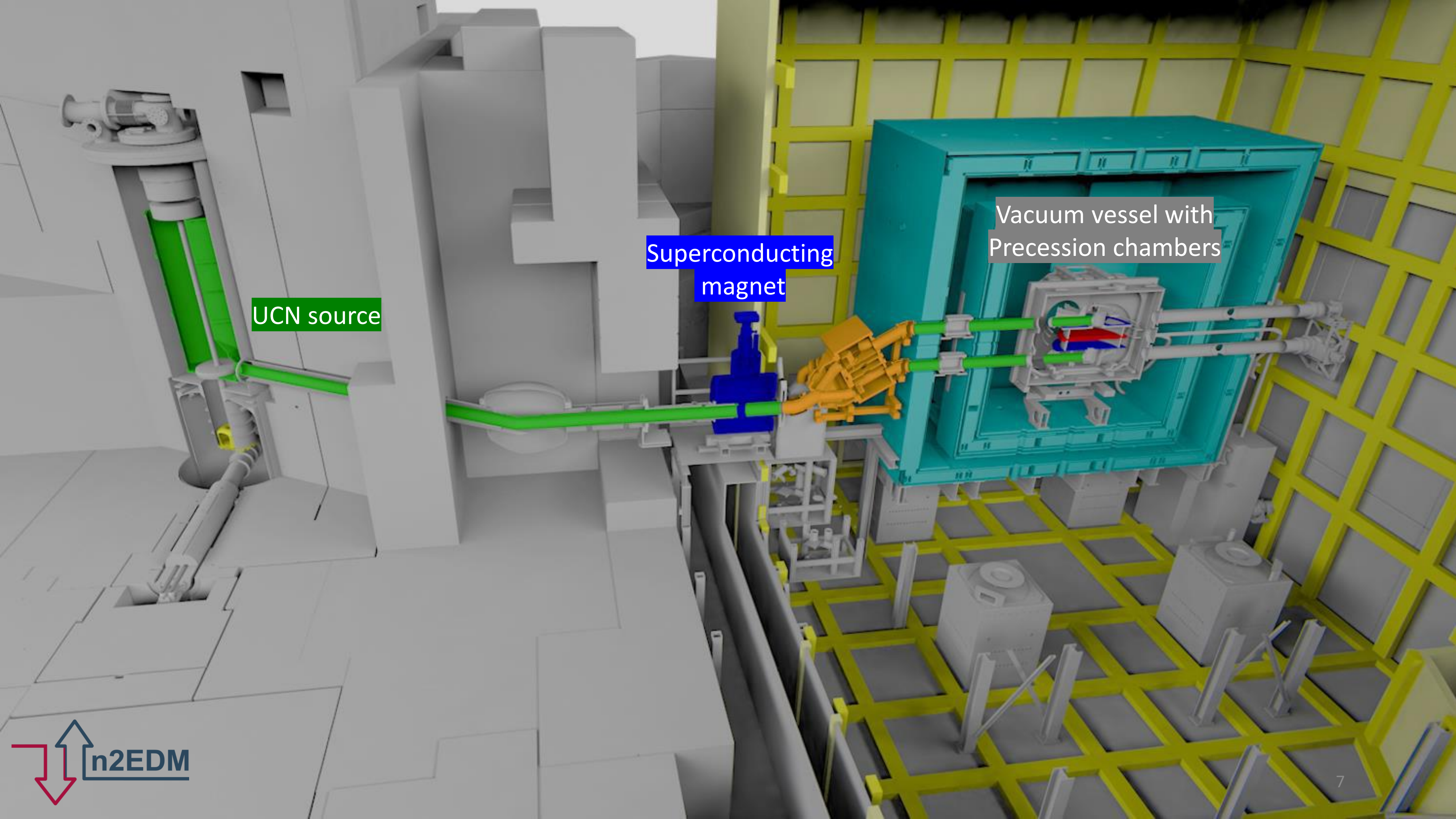
Homogeneity of B ↖ (syst)



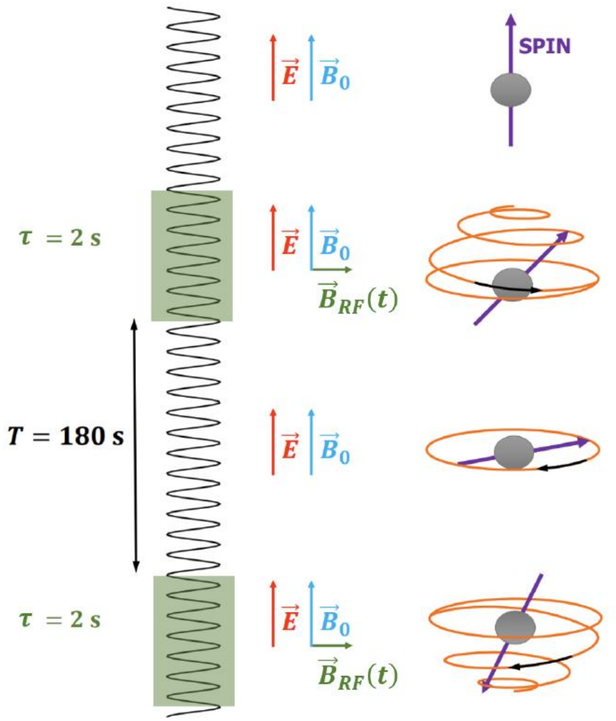
In n2EDM:

- 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.



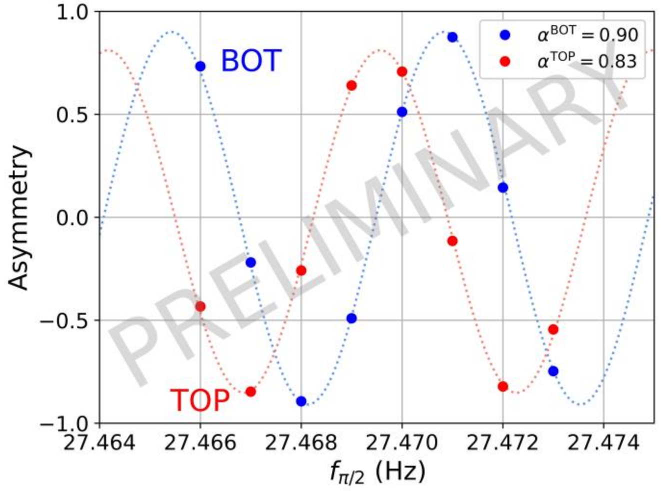

UCN source
Superconducting
magnet
Vacuum vessel with
Precession chambers
n2EDM

Neutron spin gymnastics: Ramsey.



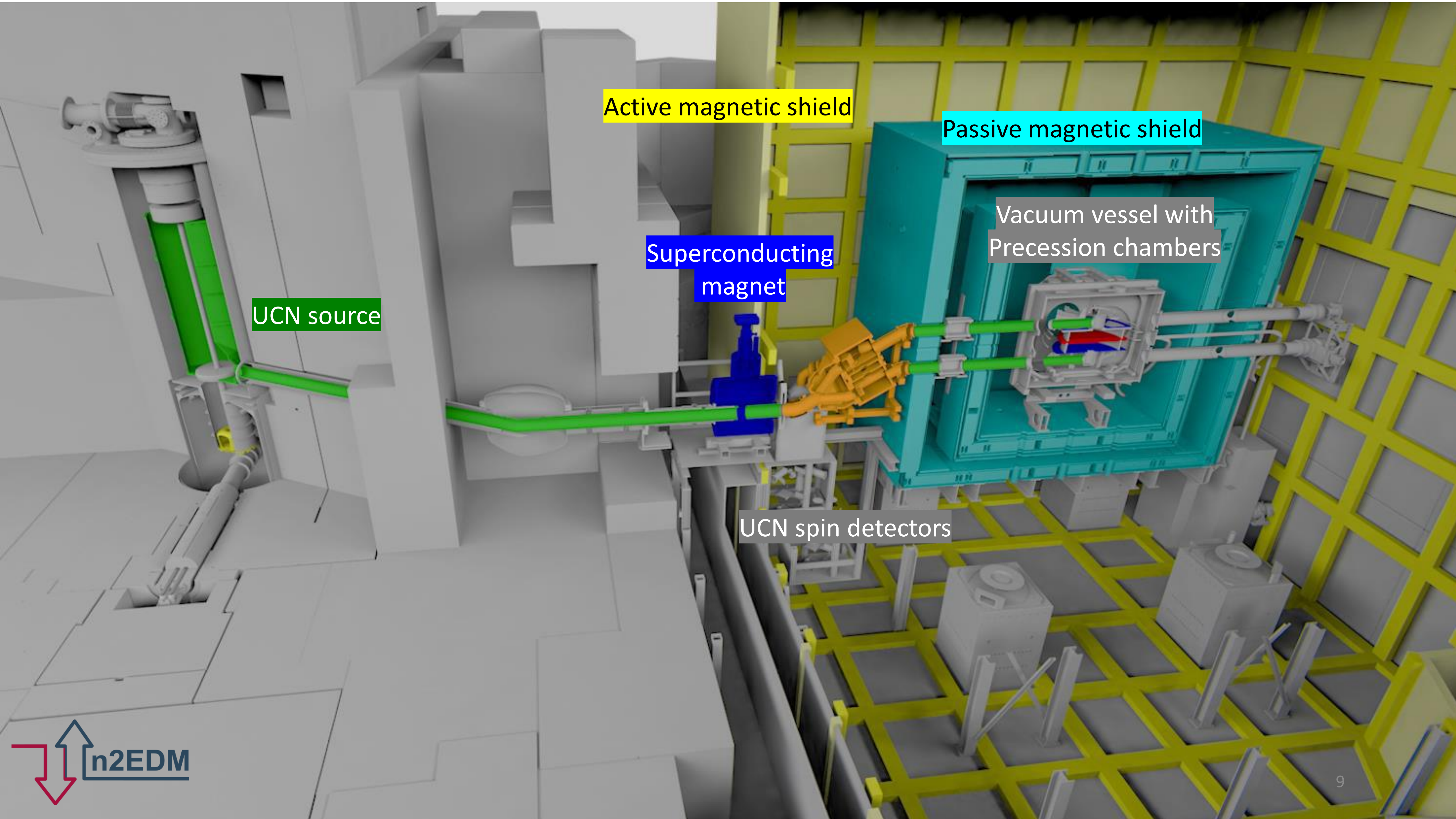
Ramsey method of oscillatory fields, counting spin up and down to derive the precession frequency:

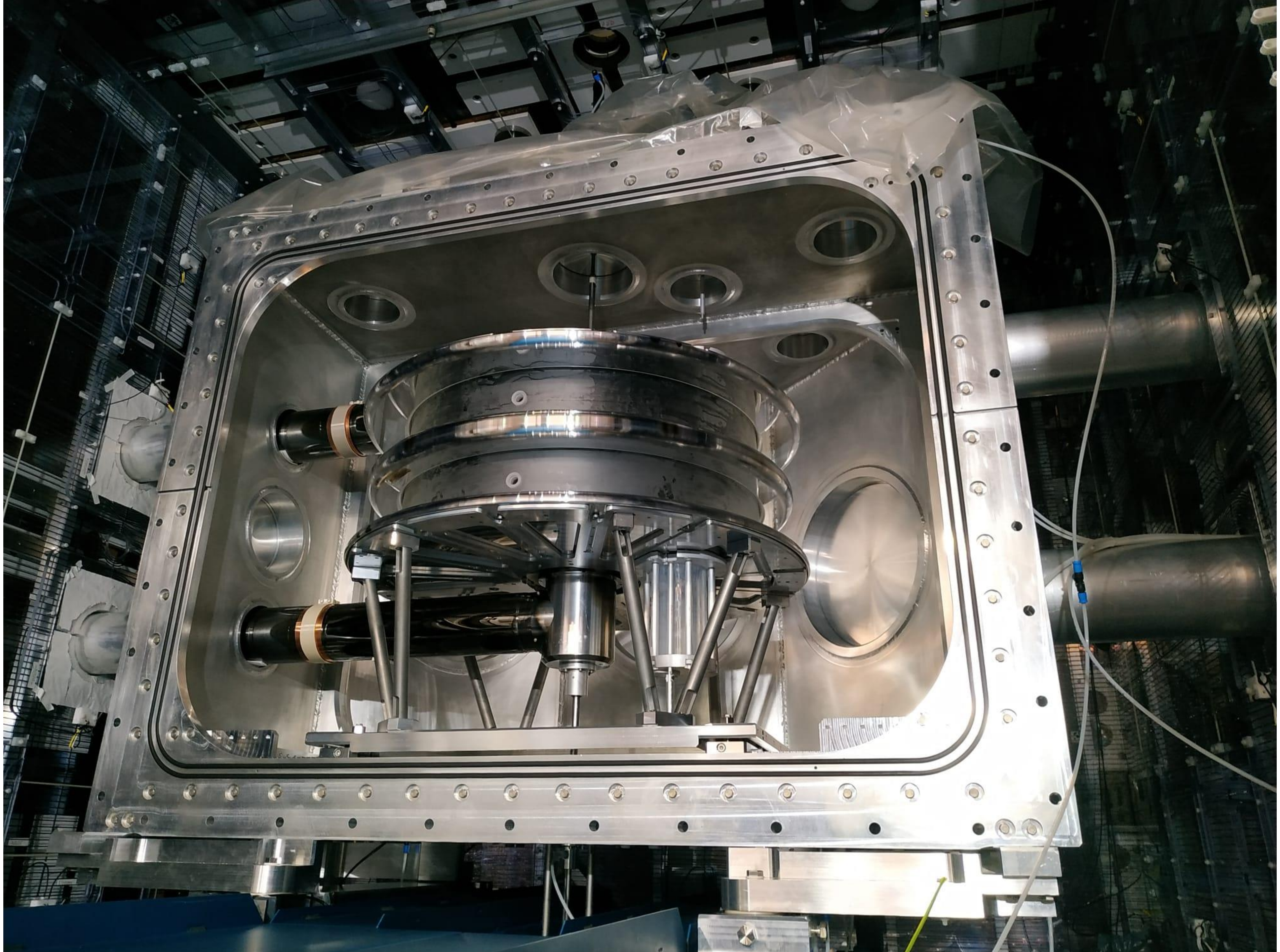
$$\frac{N_{up} - N_{down}}{N_{up} + N_{down}} = -\alpha\cos[\pi(f_{RF} - \boldsymbol{f})\left(2\boldsymbol{T} + \frac{8\tau}{\pi}\right)]$$

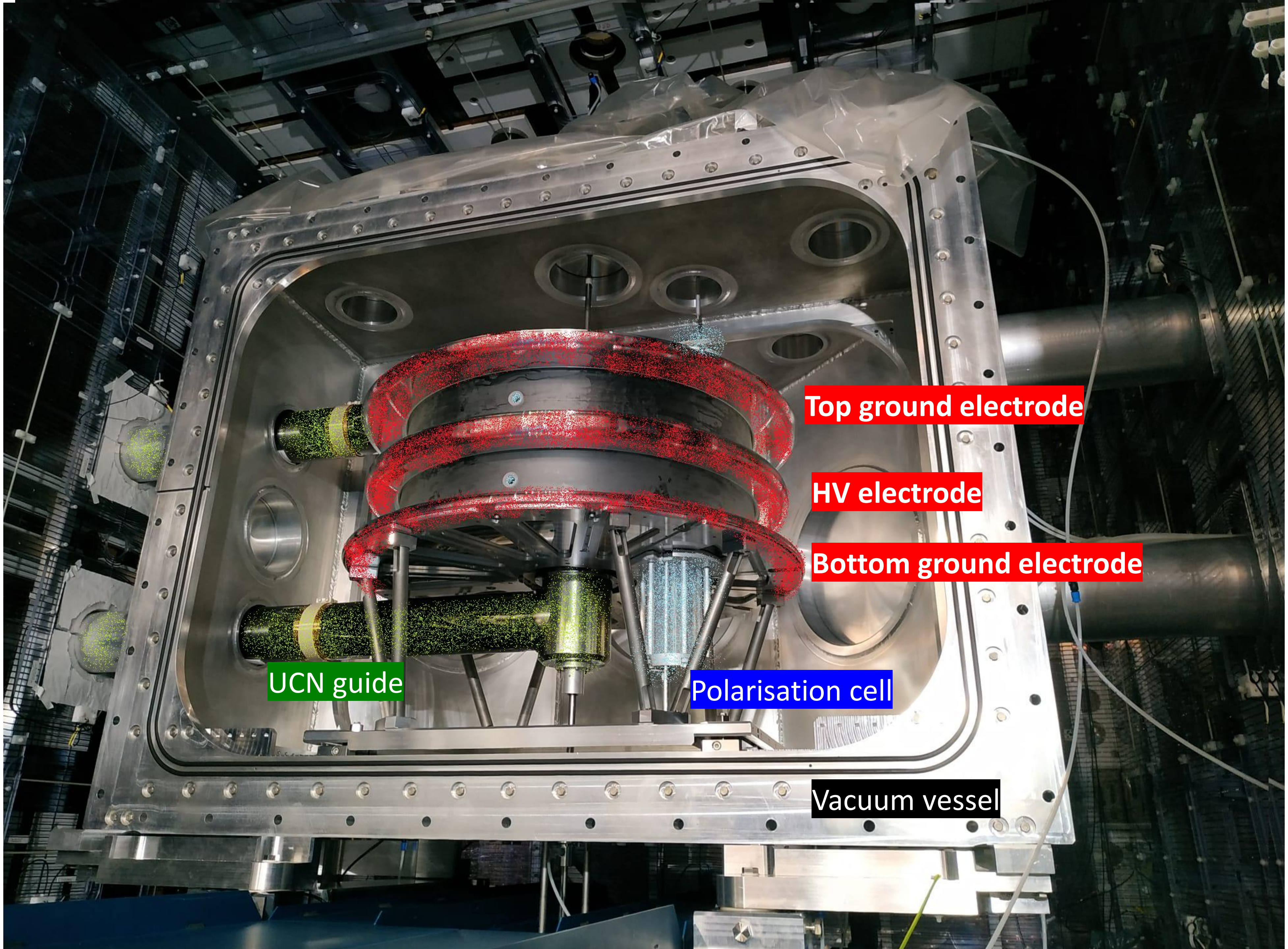


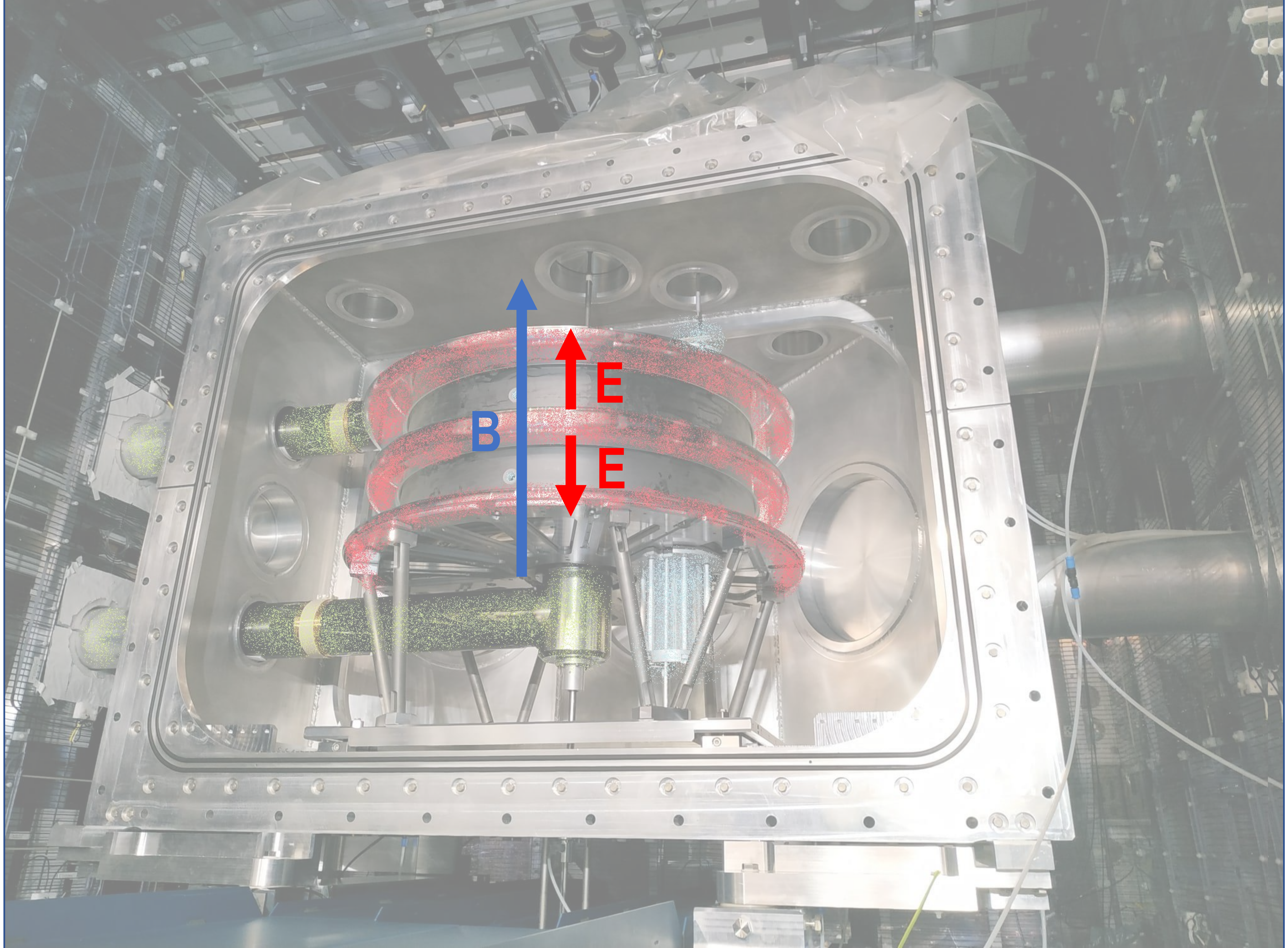
The nEDM is derived from the frequency difference in opposite electric fields.

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


Active magnetic shield
Passive magnetic shield
Vacuum vessel with
Precession chambers
Superconducting
magnet
UCN source
UCN spin detectors
n2EDM

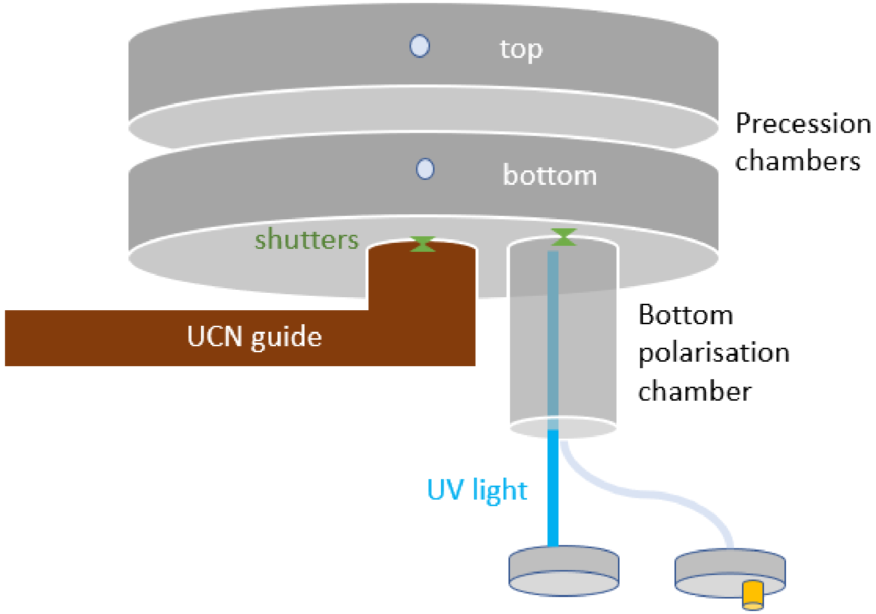



Top ground electrode
HV electrode
Bottom ground electrode
UCN guide
Polarisation cell
Vacuum vessel

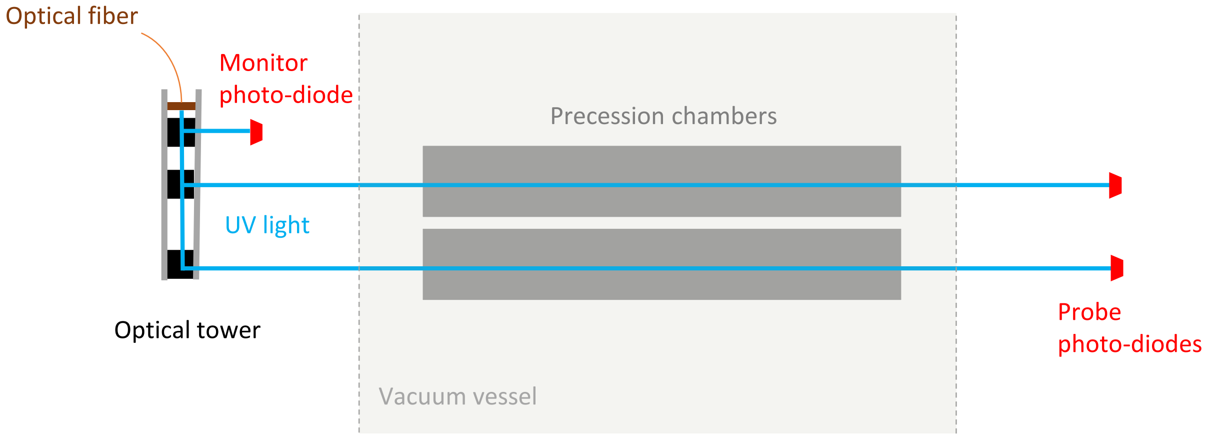

E
B
E

In-situ co-magnetometry.

- Larmor precession of the spin of **mercury** (better limit on its EDM).
- **Continuous reading** of the mercury spin precession 254 nm laser light.
- Neutrons and mercury are stored in the same volume, at the same time.



Front view

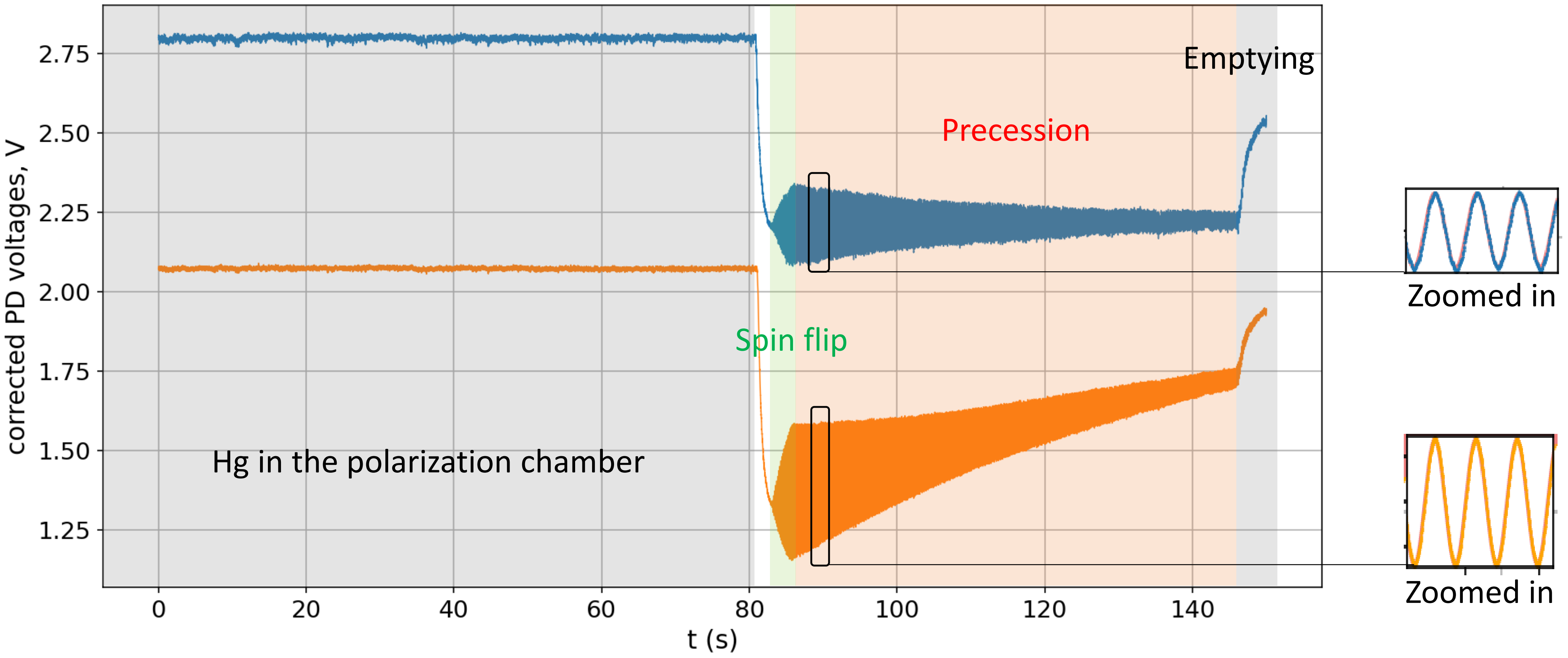


Side view

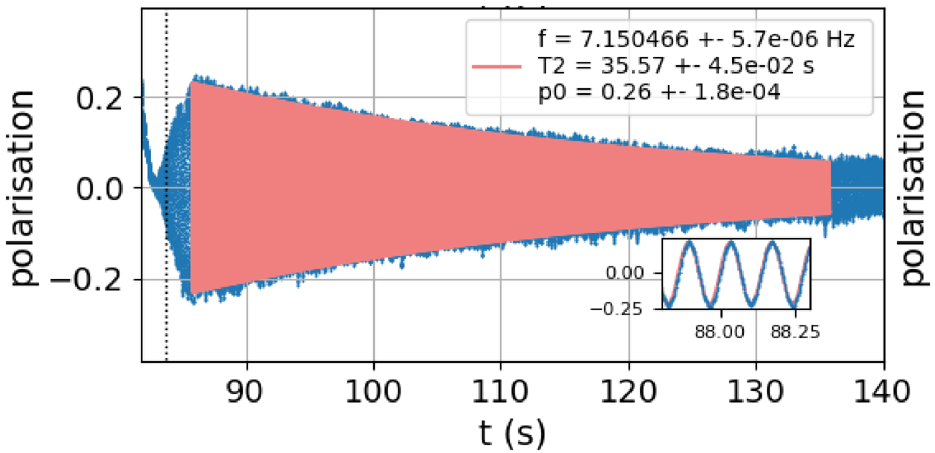
Precession signal: $s_0 e^{-\sigma L n(t)(1-p(t))}$

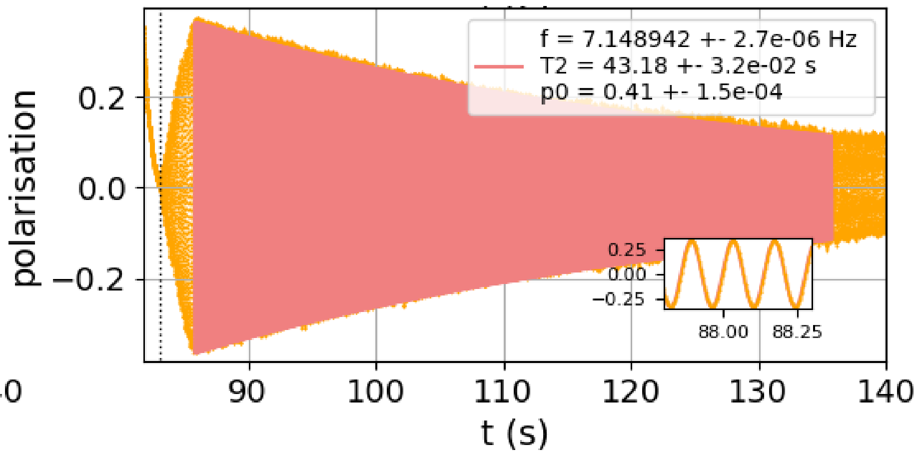
Hg199 density

Vapor spin polarisation along light propagation axis



Simultaneous precession signals in the bottom and top storage chambers.

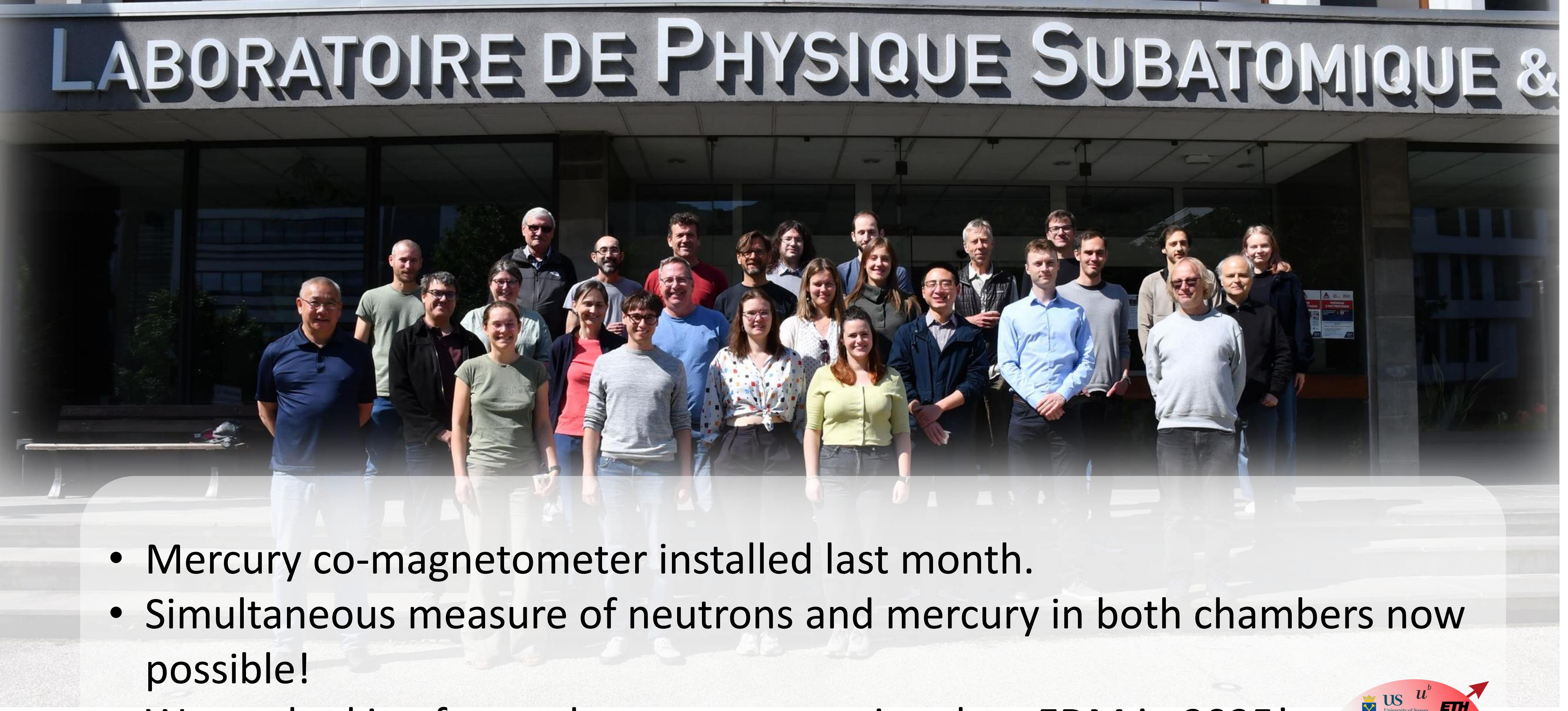




Mercury vapor polarisation as a function of time:

- Initial polarisation p_0
- Depolarisation time T_2
- Precession frequency f_{Hg}

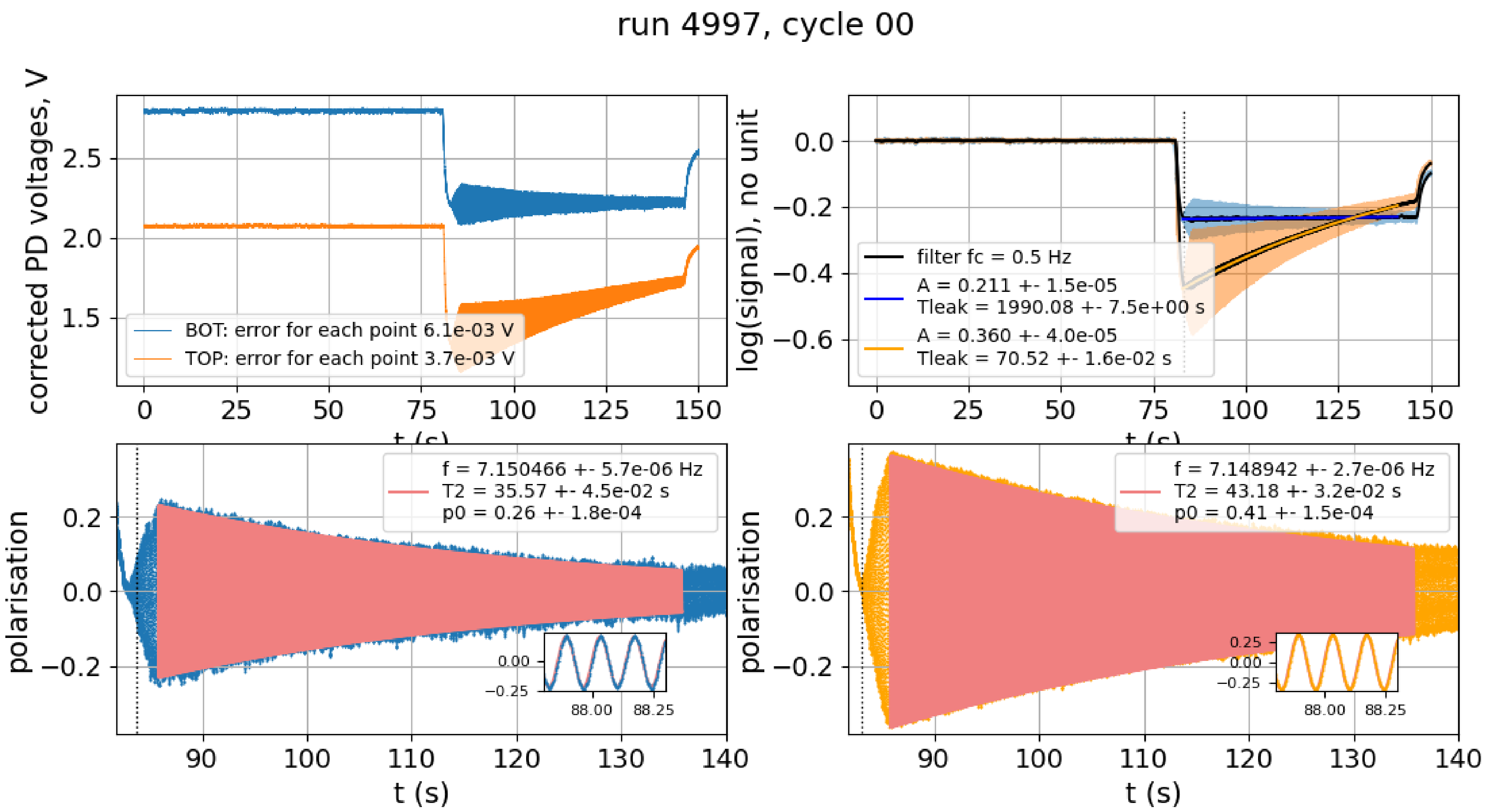
	measured	**goal**
p_0	0.4	1
T_2	60 s	100 s
$\sigma(f_{\mathrm{Hg}})$	~ 5 uHz	0.2 uHz

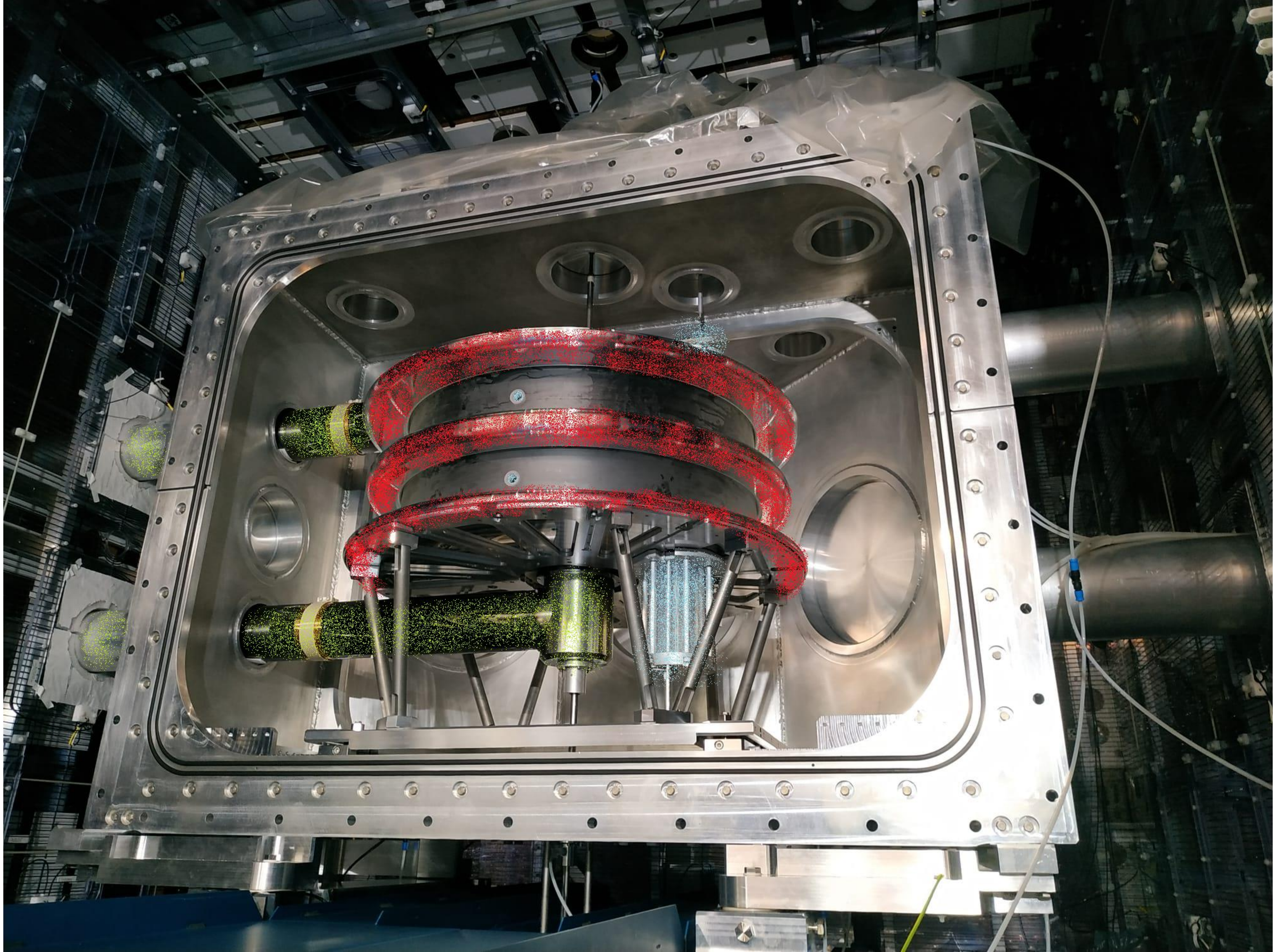


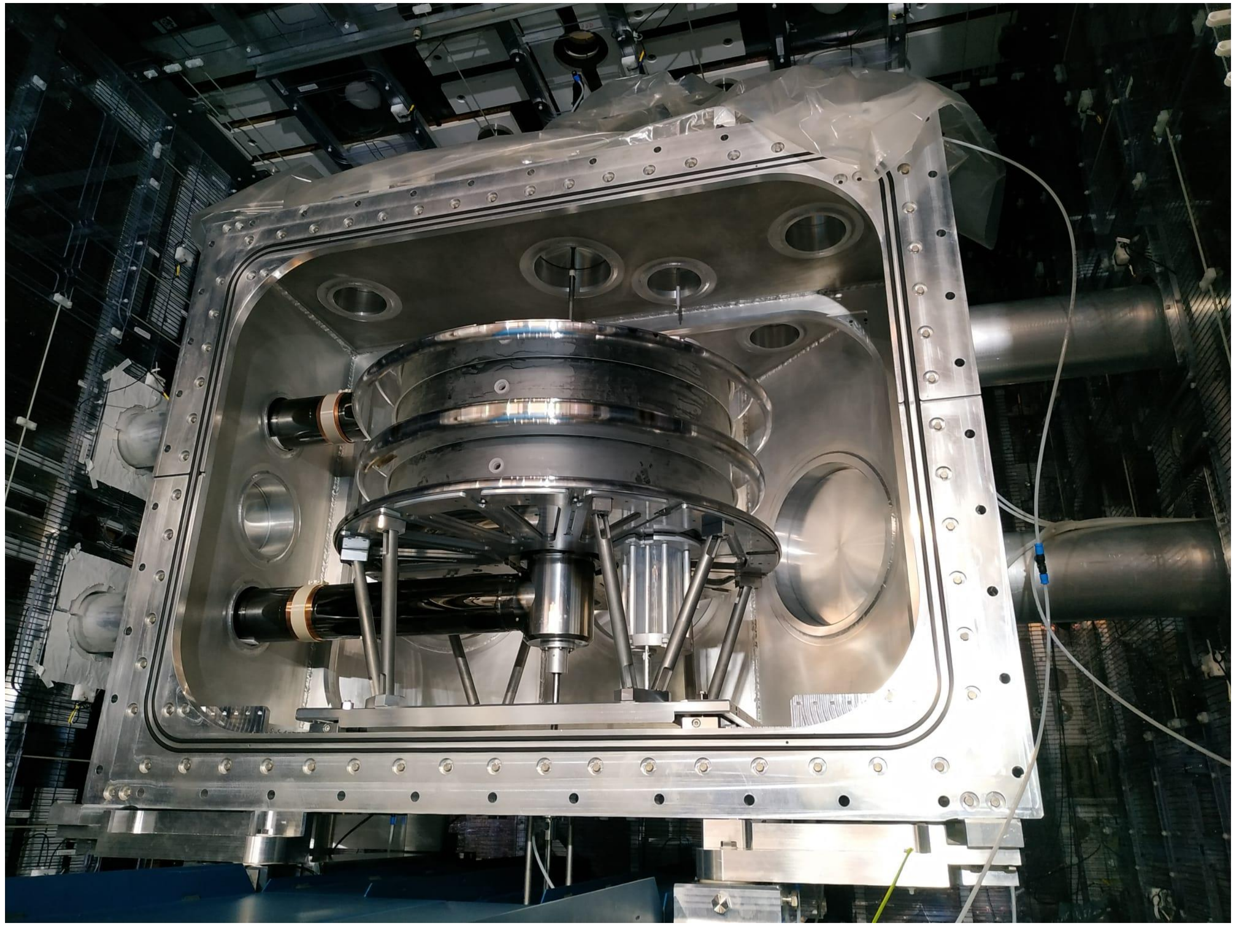
- Mercury co-magnetometer installed last month.
- Simultaneous measure of neutrons and mercury in both chambers now possible!
- We are looking forward to start measuring the nEDM in 2025!

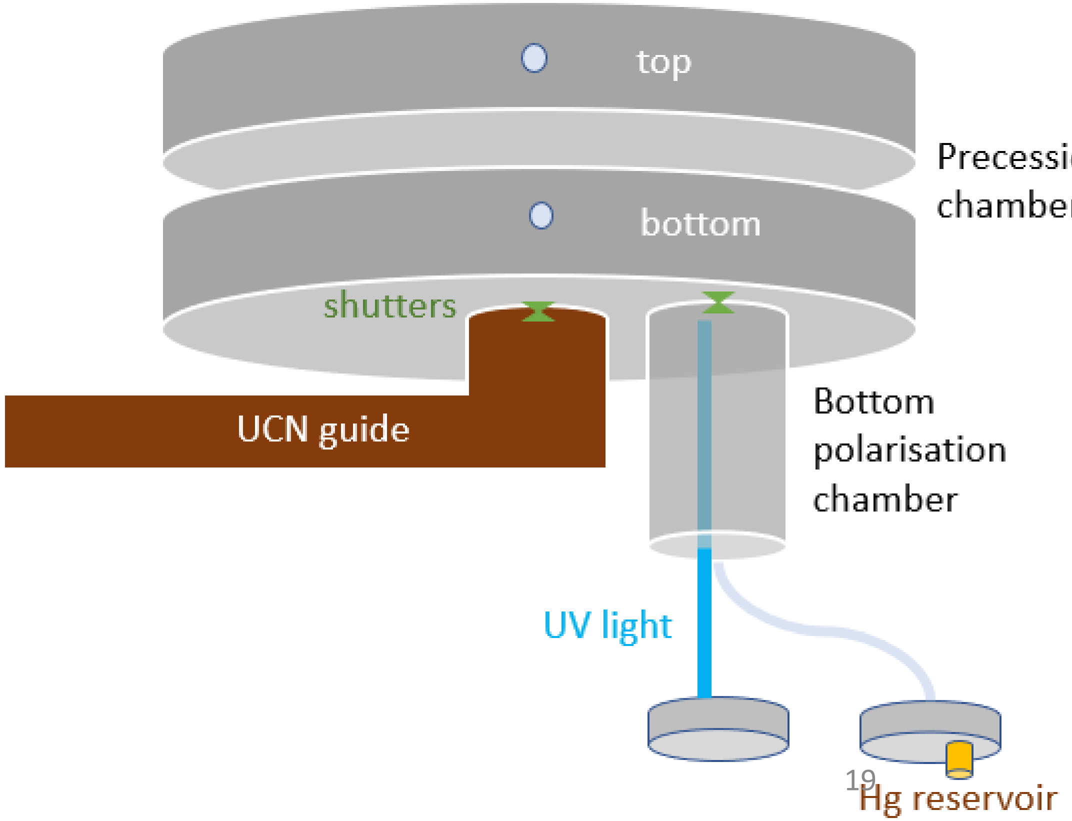
Credits to Thomas Bouillaud for illustrations from his PhD thesis.

Simultaneous precession signals in the top and bottom storage chambers.








top
bottom
Precessi
chambe
shutters
UCN guide
Bottom
polarisation
chamber
UV light
Hg reservoir