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

Katia Michielsen, LPSC Grenoble, n2EDM

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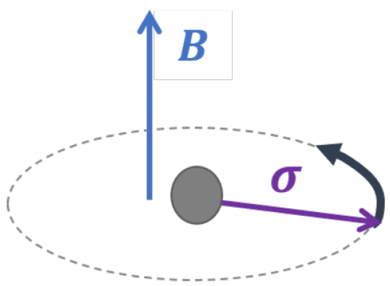
What is the neutron Electric Dipole Moment?

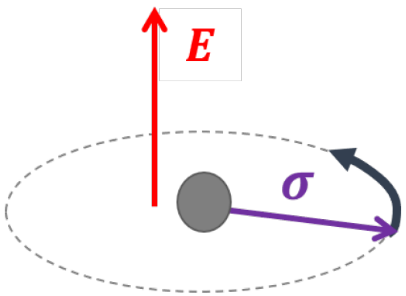
- Spins couple to magnetic fields with strength μ

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

Non-relativistic limit of the fermion-photon interaction:

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





Formation of matter in the early universe: the mystery of **baryon asymmetry**.

3 criteria listed by Sakharov:

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

Subatomic physics AND cosmology?!

Small CP violation in the SM (weak and strong interactions).

- nEDM constrains CP violation in the strong sector.
- Precise measurement constraining a SM parameter to be zero: It is a good probe to new physics.

The neutron EDM probes new physics.

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

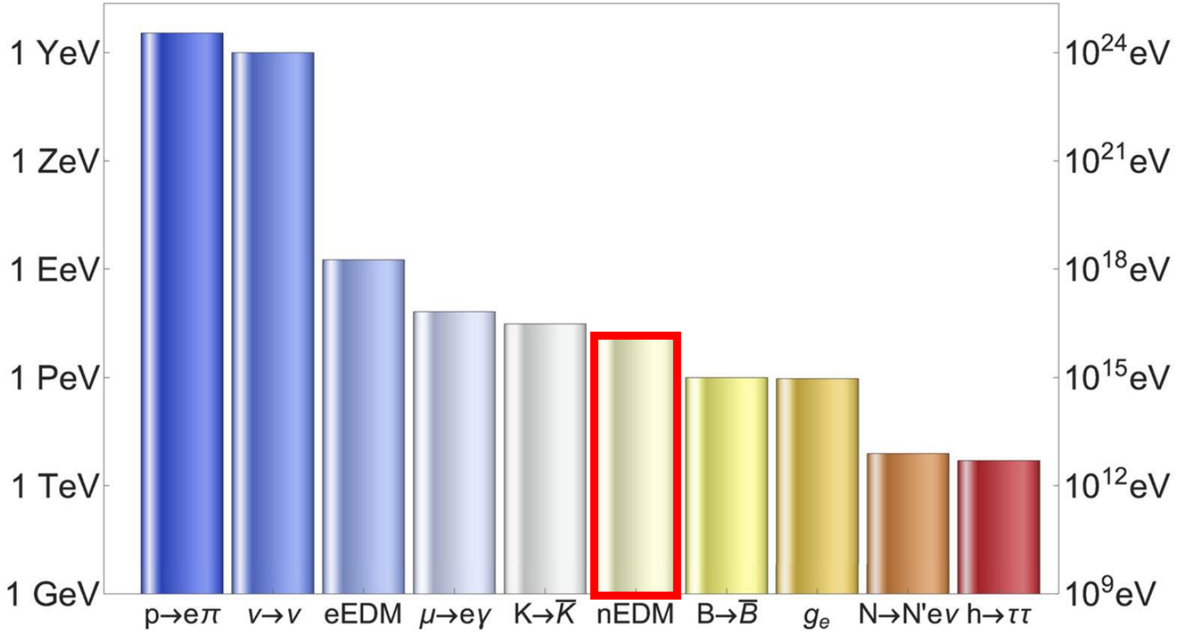
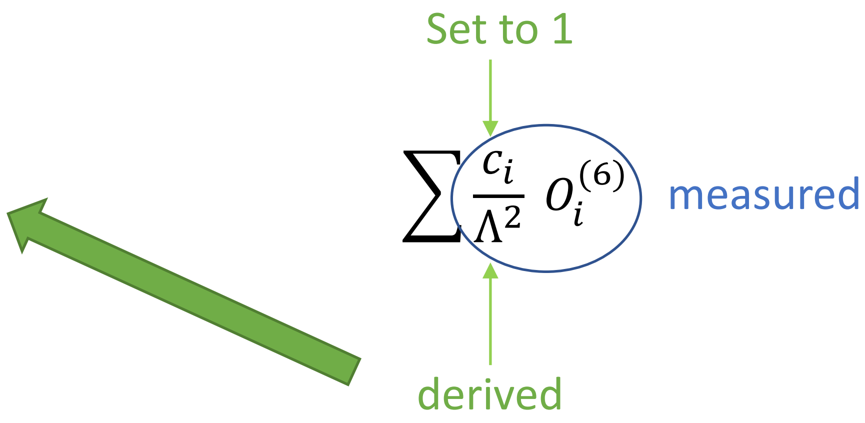


Figure by Adam Falkowski, ***Lectures on SMEFT*** EPJC (2023)

Example: dimension 6 operators



The neutron EDM violates CP

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

Non-relativistic limit of the fermion-photon interaction:

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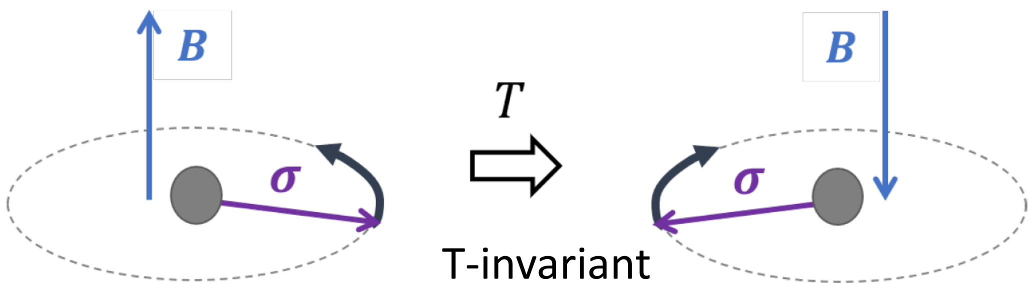

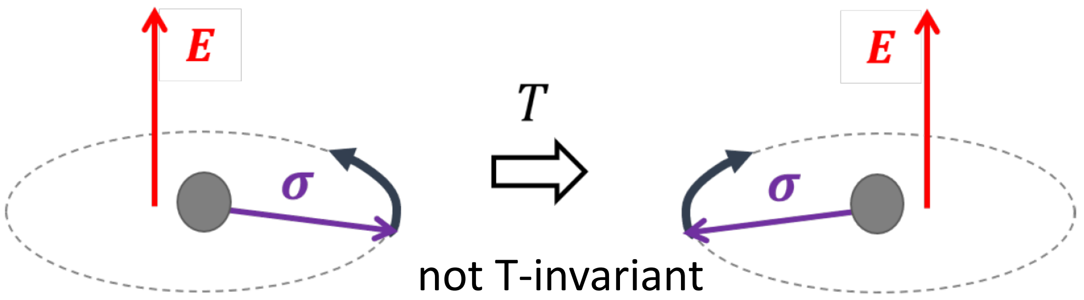

T violation and CPT theorem: CP violation.

Formation of matter in the early universe: the mystery of **baryon asymmetry**.

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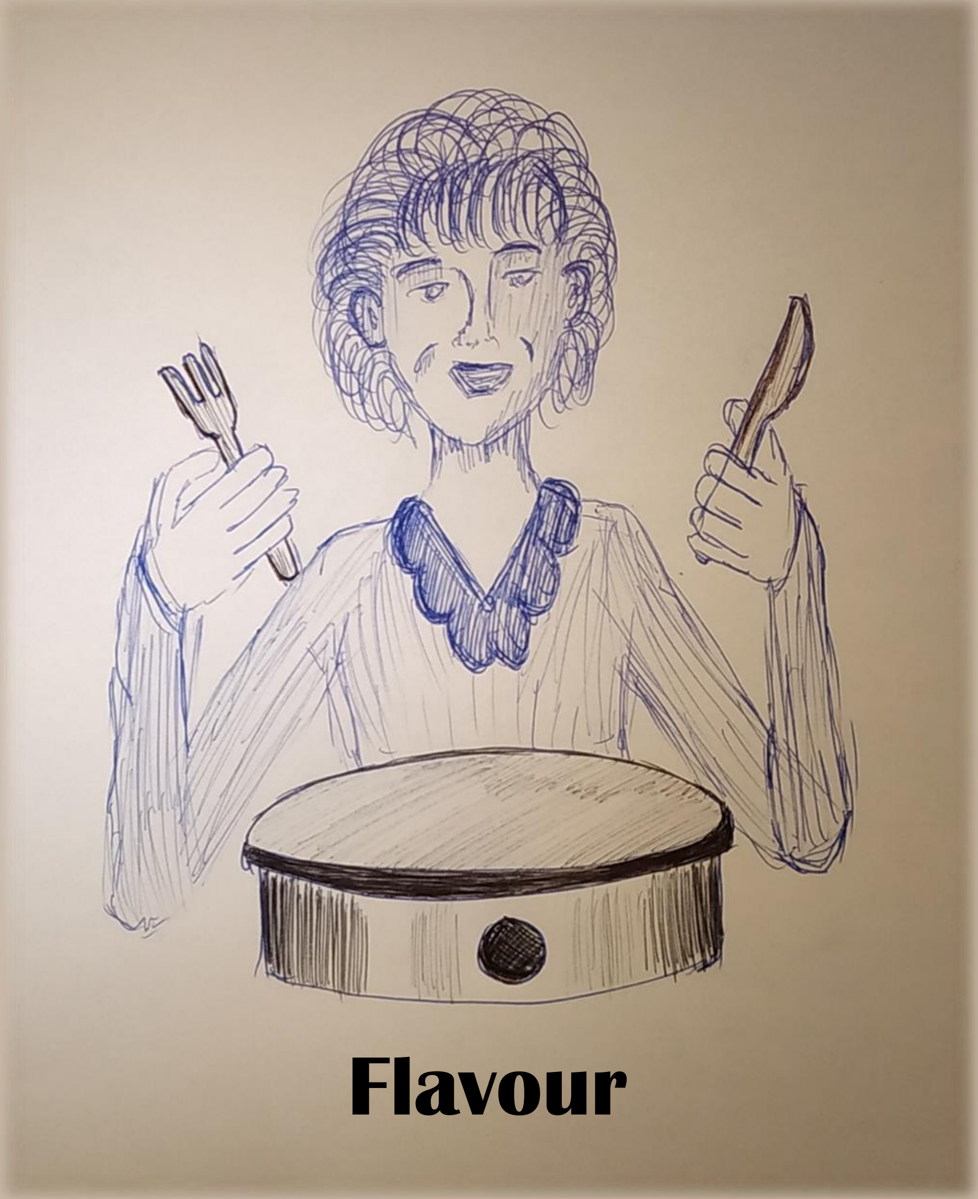
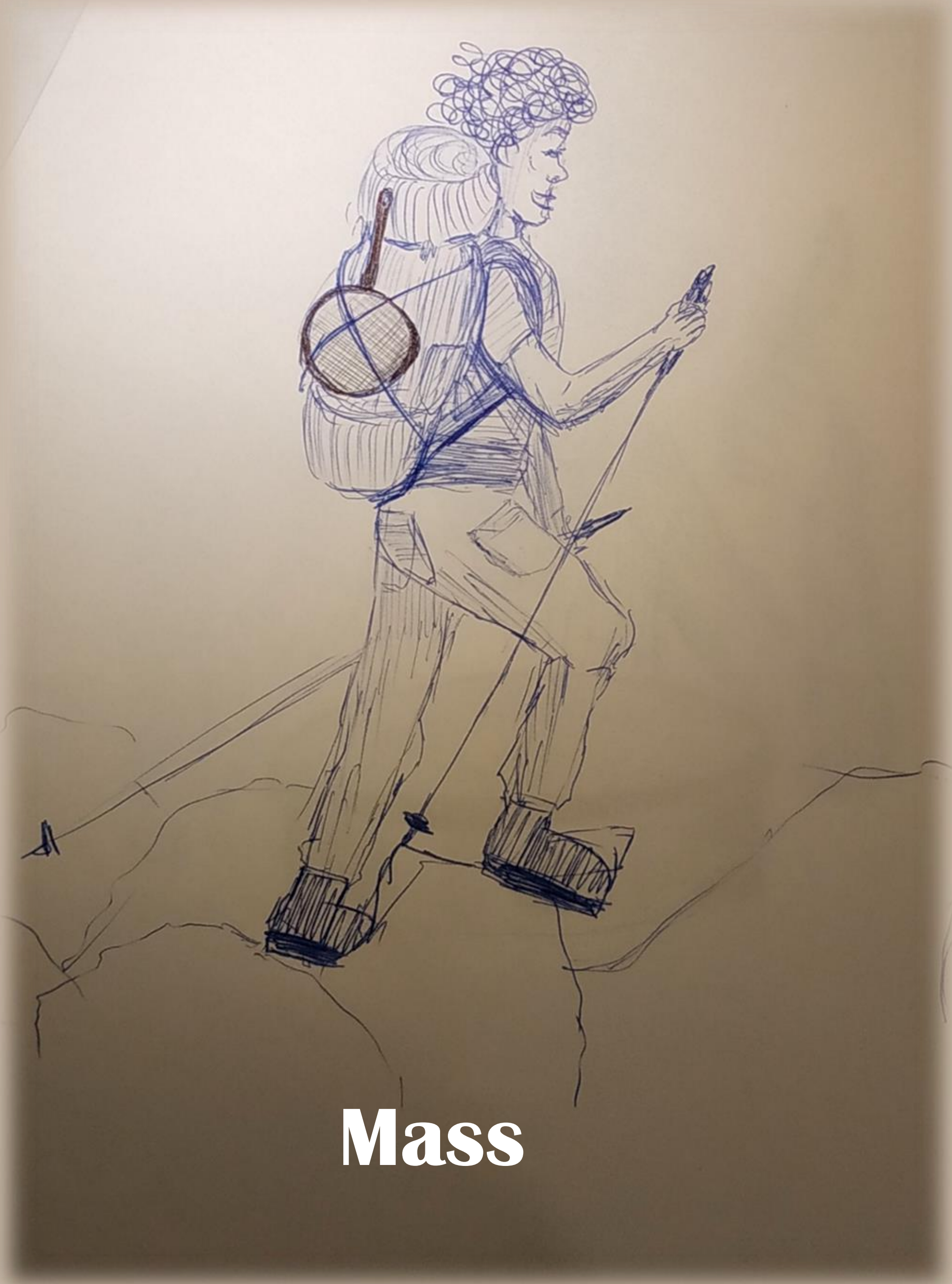
Subatomic physics
AND cosmology?!

What are the relevant parameters that describe a crepe maker?

- Color
- Shape
- Taste of the crepe
- Name

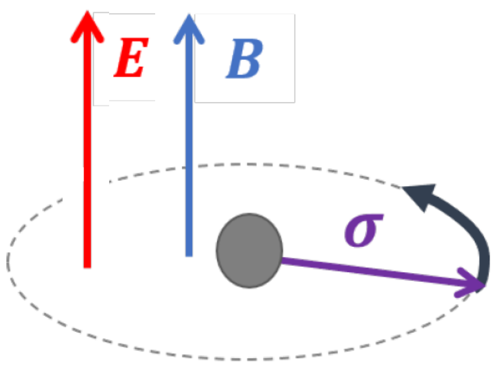


Particle physicist



Cosmologist

How to measure the neutron EDM?



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

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

- Beam measurements (cold neutrons).

A lot of neutrons.

Small **interaction time.**

- Stored **Ultra Cold Neutron** measurements.

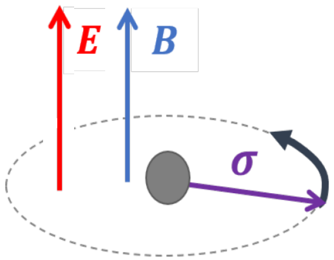
Their kinetic energy is $\sim 100\ neV$ (4mK).
So slow that they bounce against some materials.
Their trajectory is affected by gravity!
(potential energy $\sim 100\ neV/m$)

Less neutrons.

Long **interaction time**: minutes.

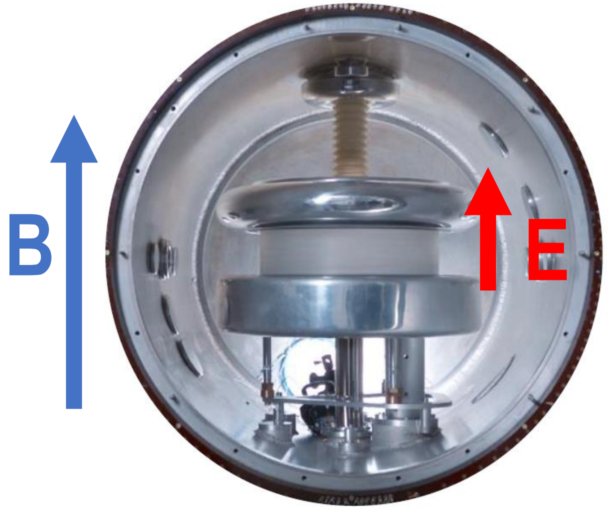
$$\sigma(d_n) = \frac{\hbar}{2\alpha \boldsymbol{E} \boldsymbol{T} \sqrt{N}}$$

Current most sensitive measurement: nEDM at PSI



- *[Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020](#)*
- $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}\ e\ cm$

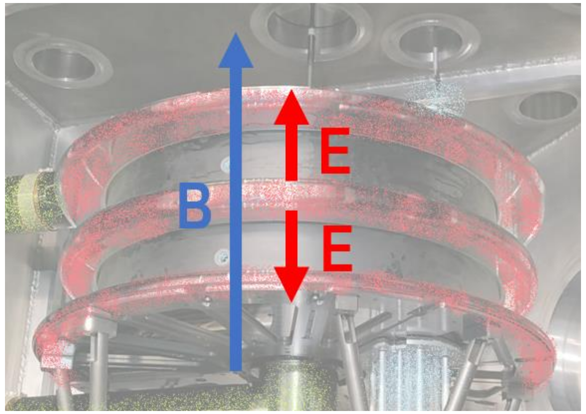
Number of neutrons → stat
Homogeneity of B → syst

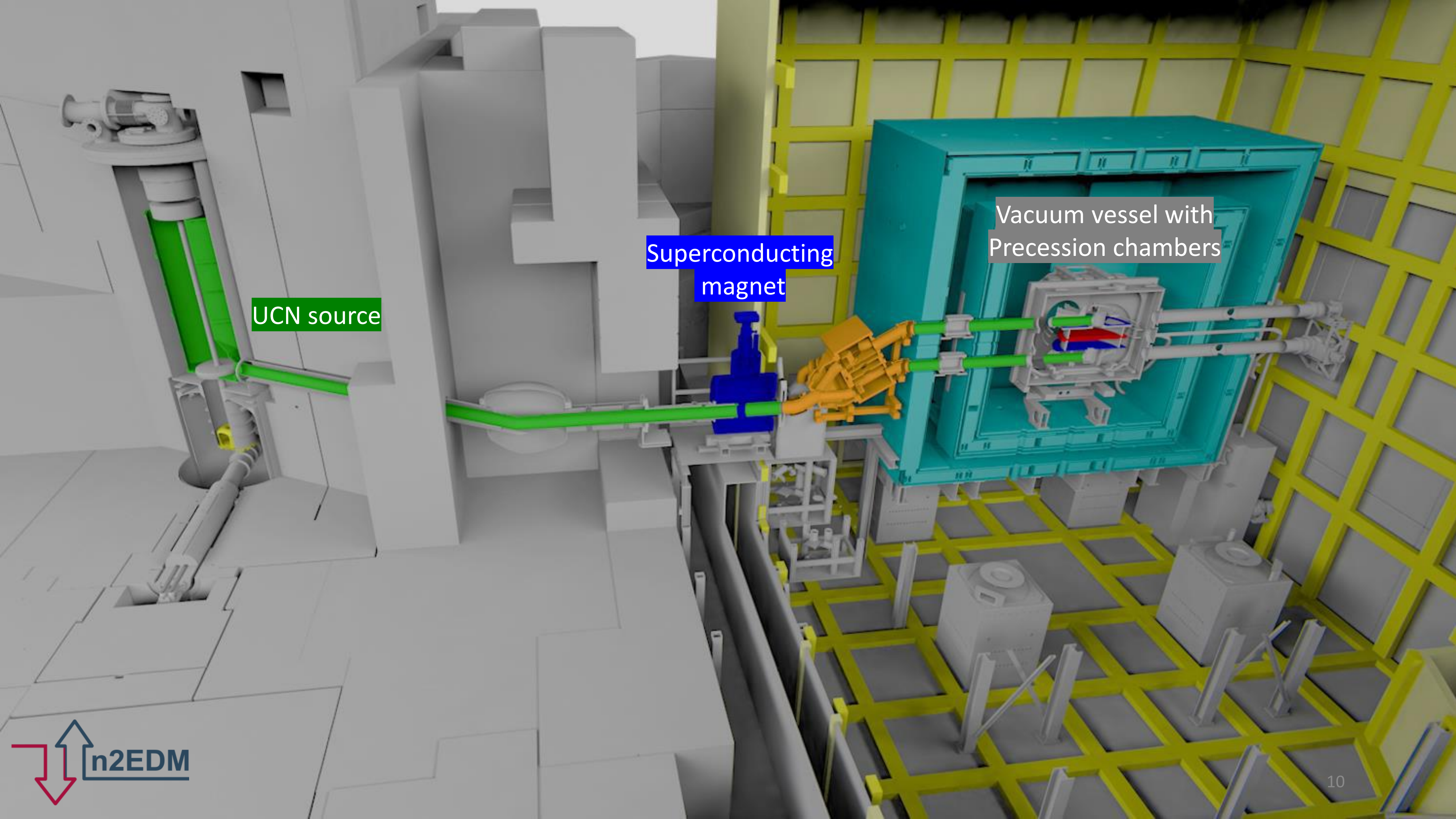


In n2EDM:

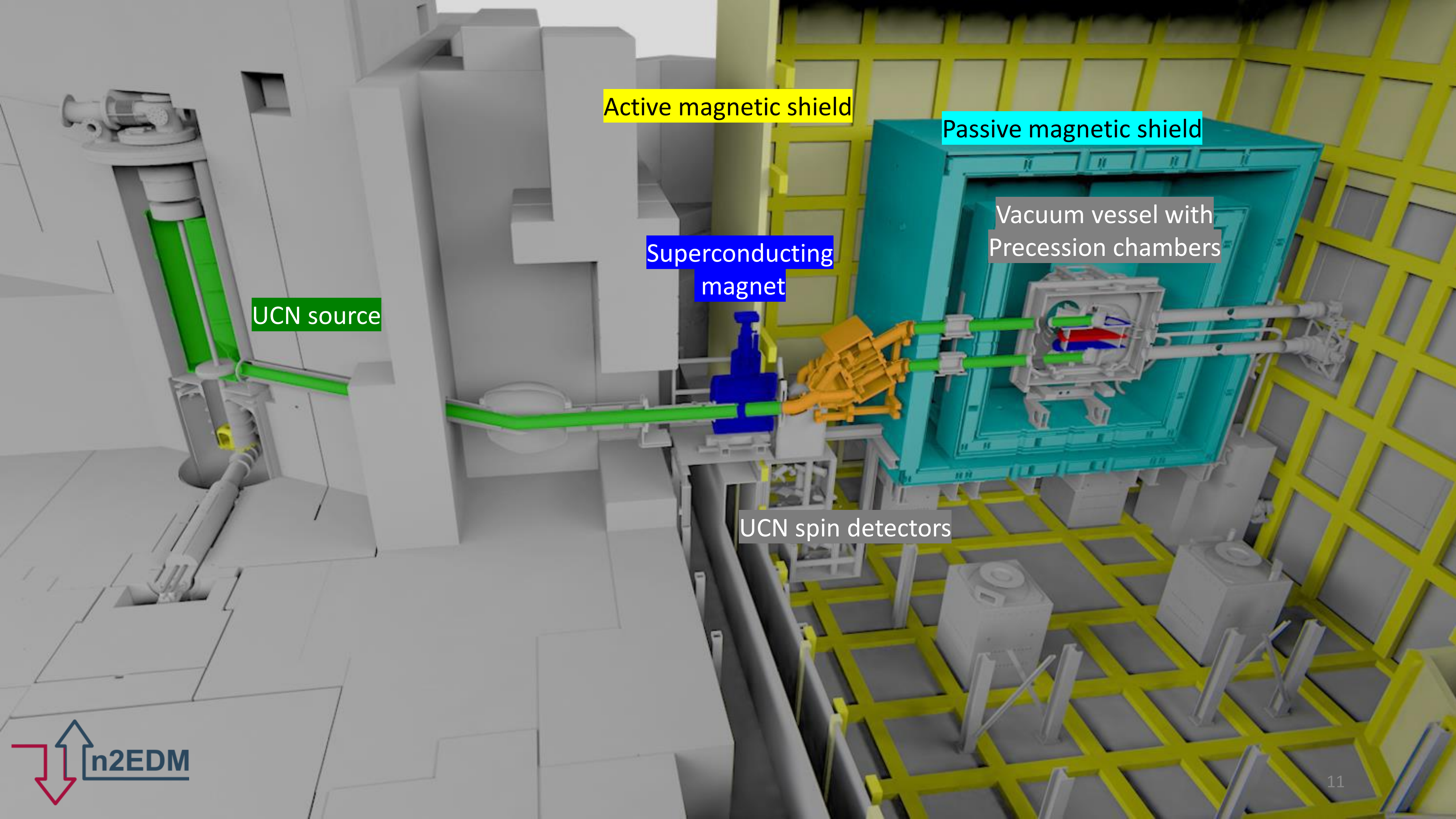
- Increase statistics in larger volume with a better controlled magnetic field: **simultaneous measure is two chambers** for both electric polarities.

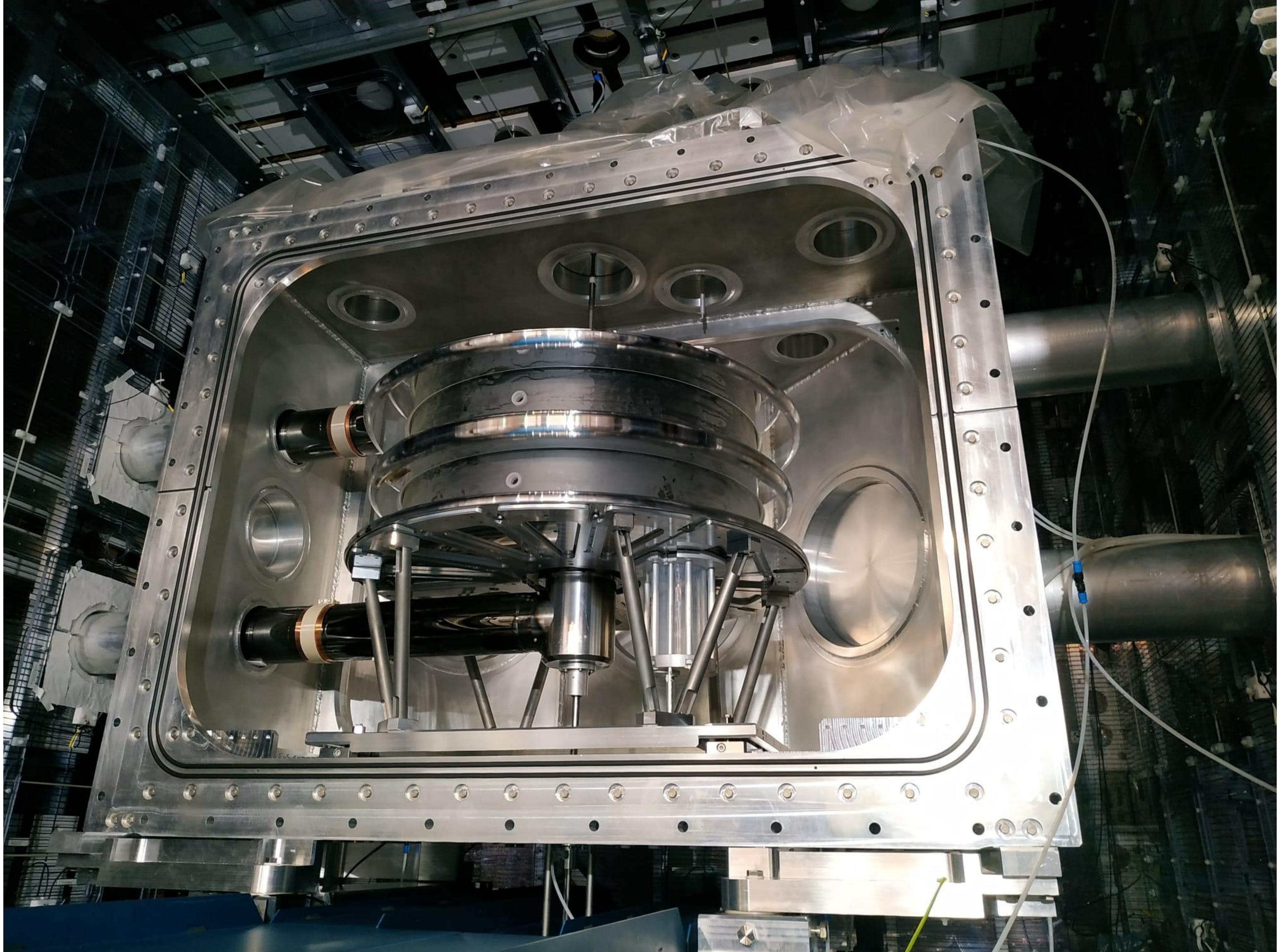
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

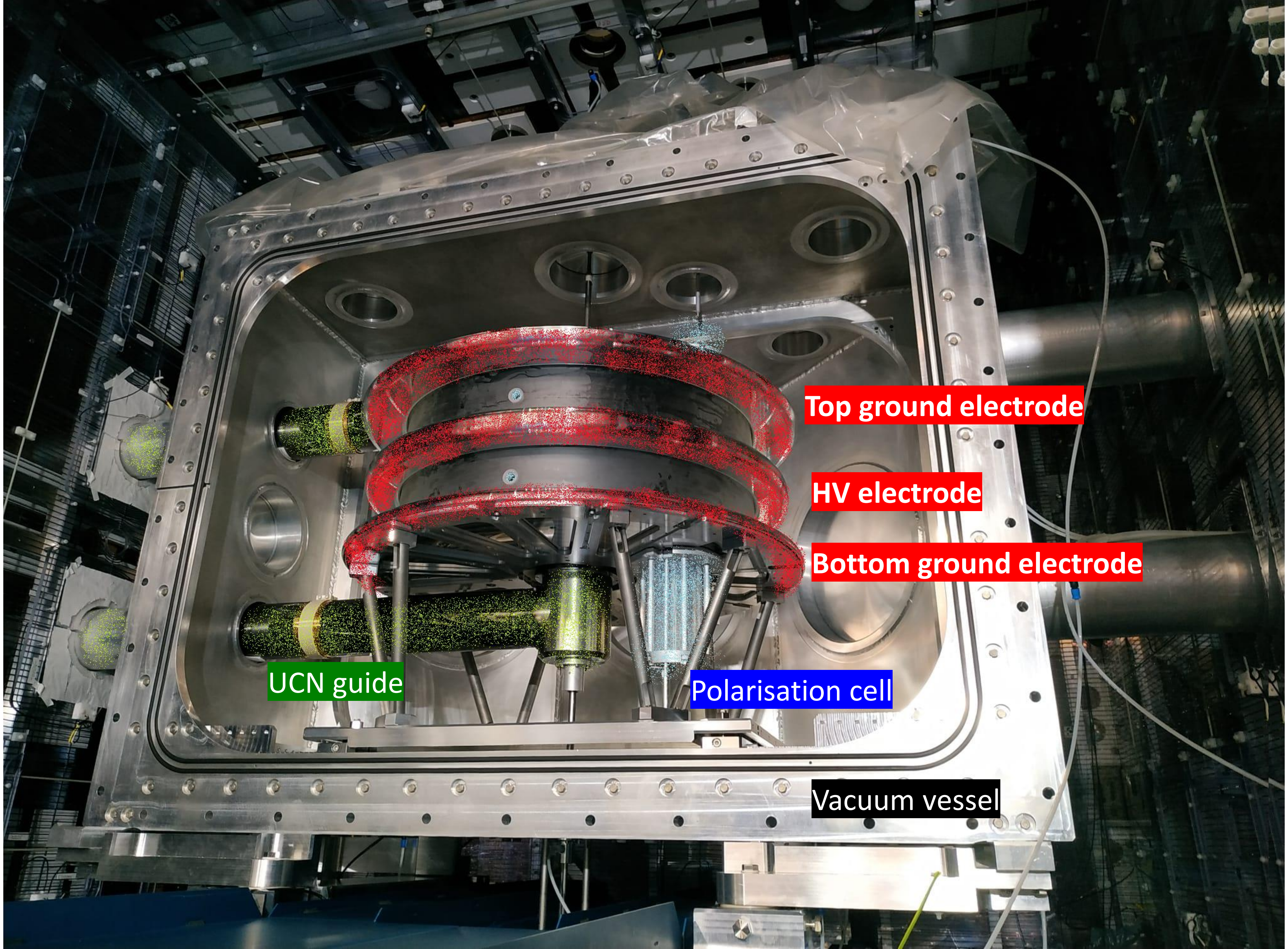


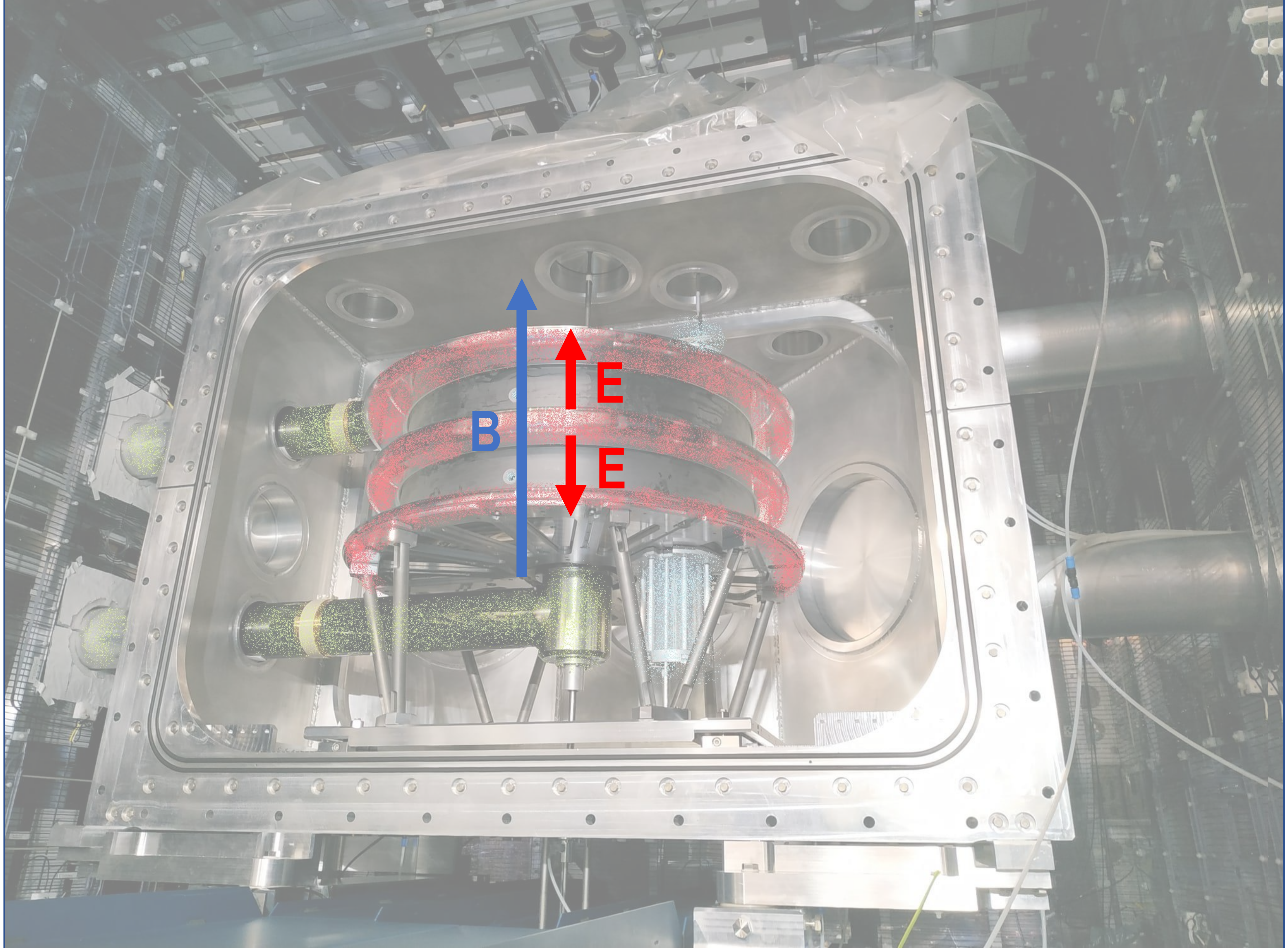

UCN source
Superconducting magnet
Vacuum vessel with Precession chambers

n2EDM


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



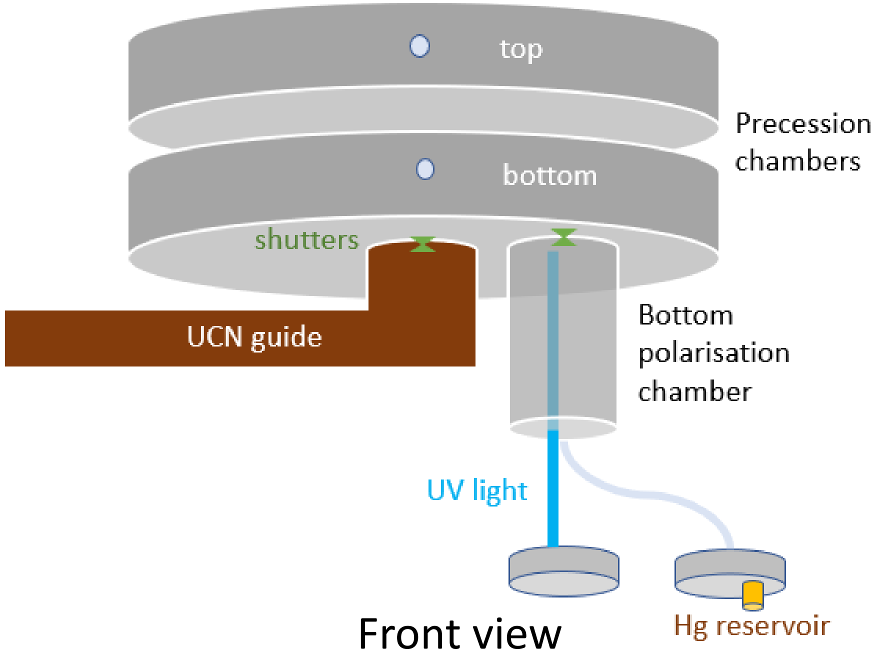

Top ground electrode
HV electrode
Bottom ground electrode
UCN guide
Polarisation cell
Vacuum vessel


E
B
E

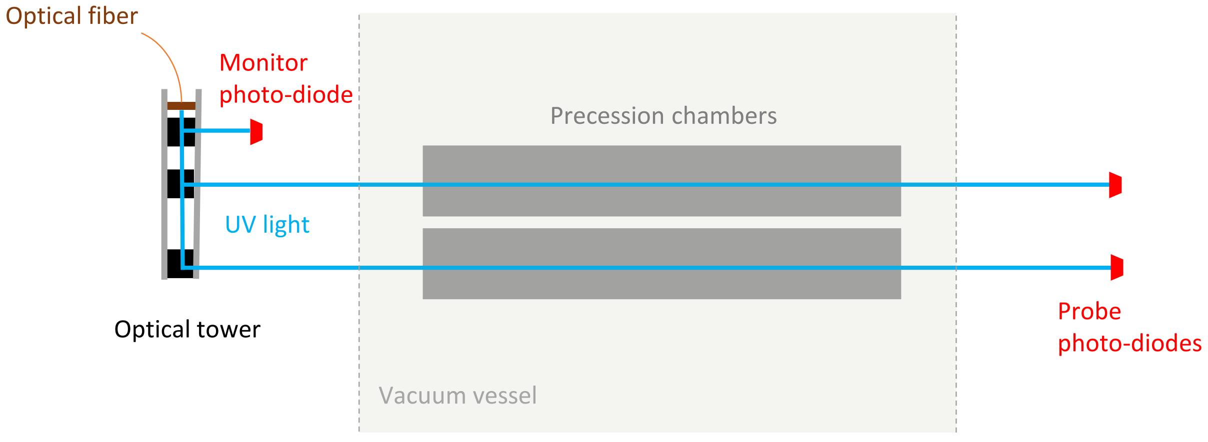
In-situ co-magnetometry.

$$\boxed{f_{\uparrow\downarrow}} - \boxed{f_{\uparrow\uparrow}} = \cancel{\frac{\mu}{\pi\hbar}\left(\mathrm{B}_{\uparrow\downarrow} - \mathrm{B}_{\uparrow\uparrow}\right)} + \frac{d}{\pi\hbar}\left(E_{\uparrow\downarrow} - E_{\uparrow\uparrow}\right)$$

- 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

How to measure the magnetic field: mercury precession

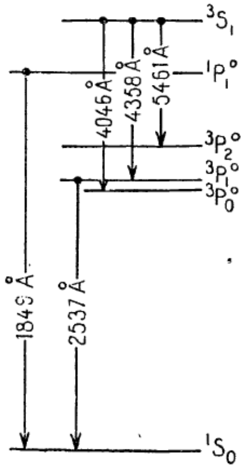
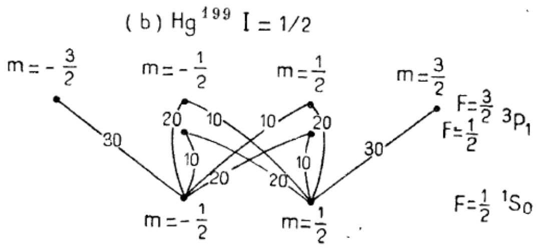
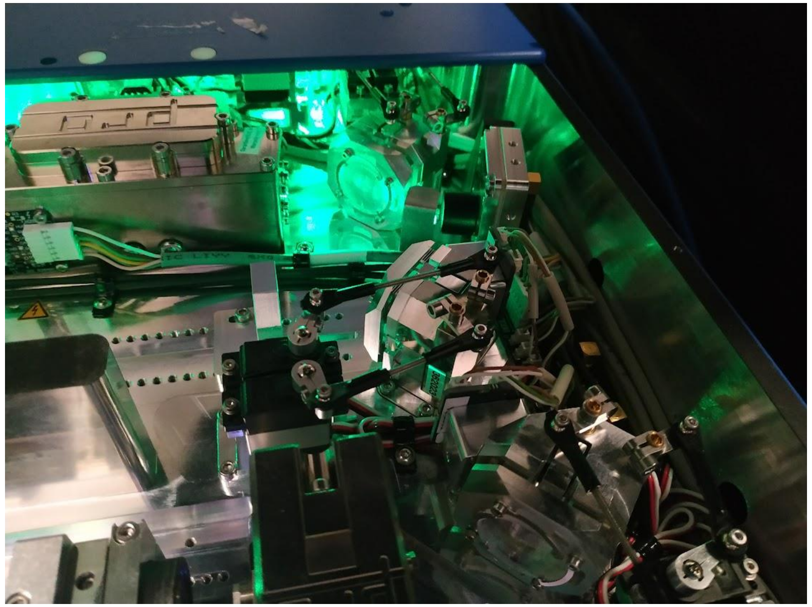
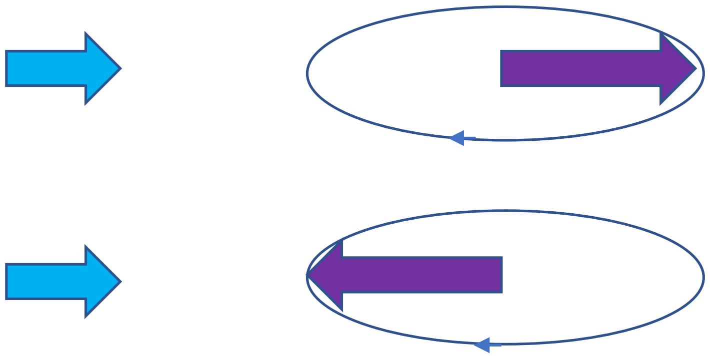


Fig. 1a.





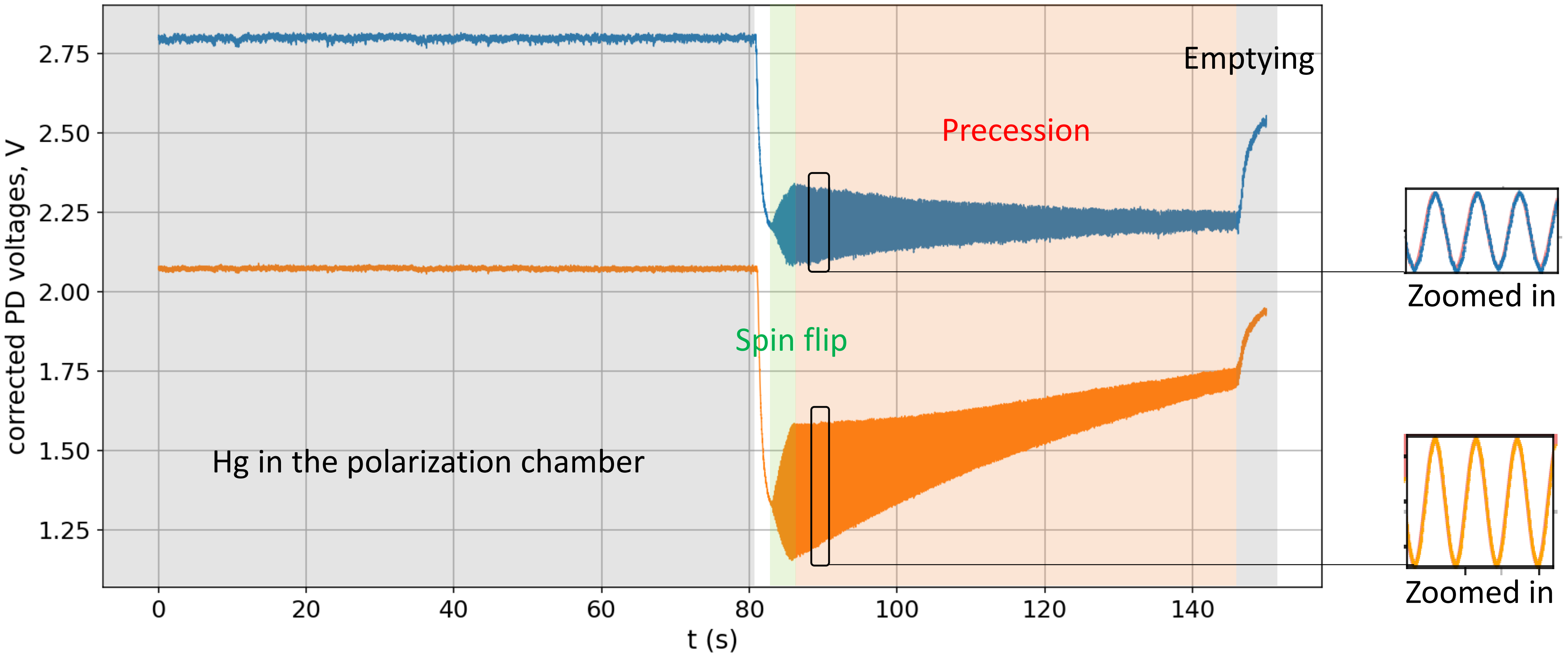


- UV light at 254 nm.
- Transmission is affected by the spin orientation.
- Intensity is oscillating if the spin precesses.
- This frequency is proportional to the magnetic field.

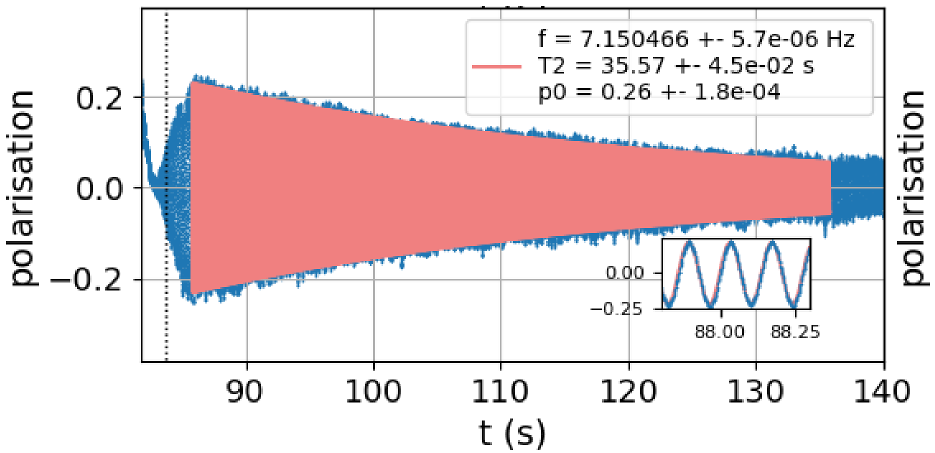
Precession signal: $s_0 e^{-\sigma L n(t)(1-p(t))}$

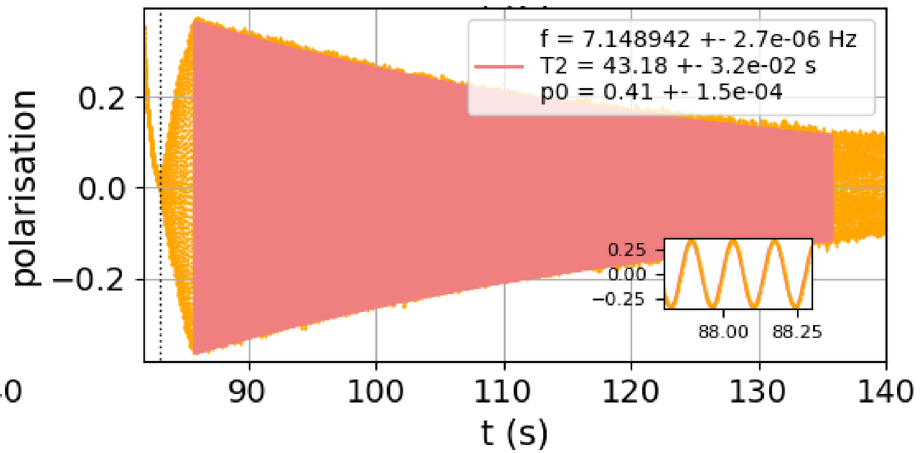
Hg199 density (→ $n(t)$)

Vapor spin polarisation along light propagation axis (→ $p(t)$)



Simultaneous precession signals in the bottom and top storage chambers.

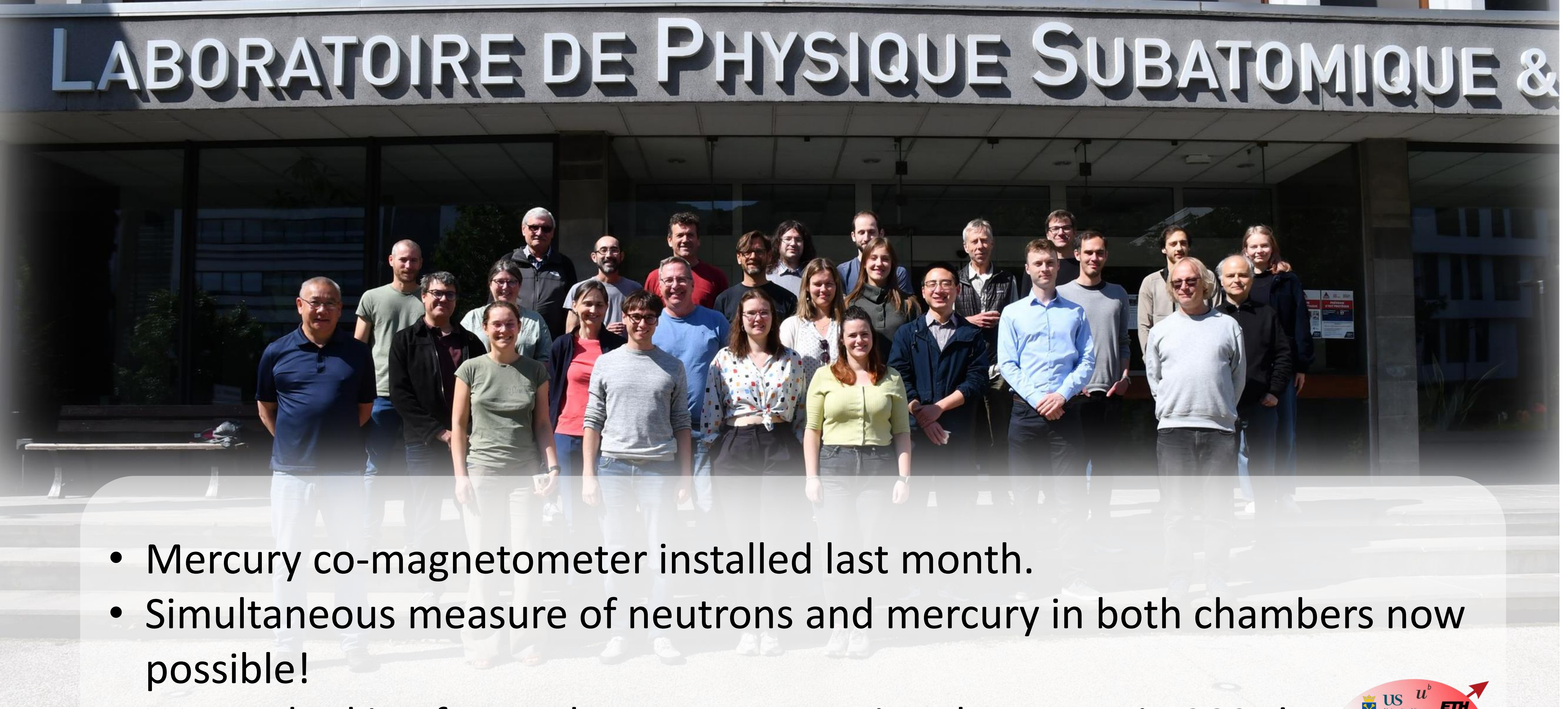




Mercury vapor polarisation as a function of time:

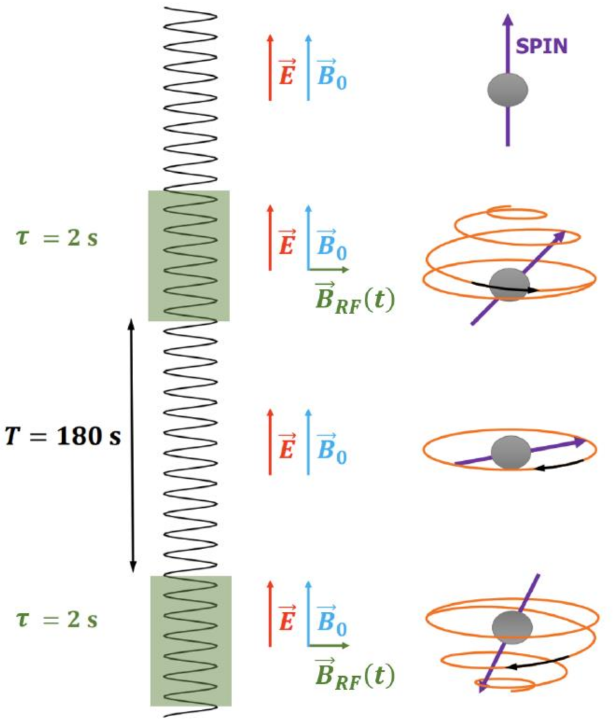
- ➢Initial polarisation p_0
- ➢Depolarisation time T_2
- ➢Precession frequency f_{Hg}

	measured	**goal**
p_0	0.4	1
T_2	80 s	100 s
$\sigma(f_{\mathrm{Hg}})$	~ 5 uHz	0.2 uHz



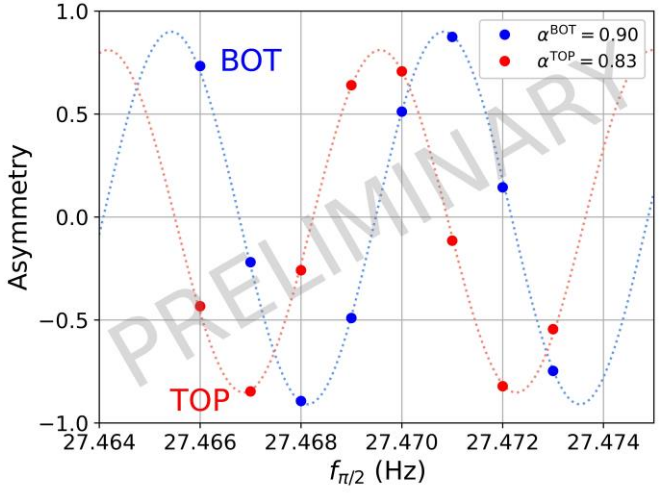
- Mercury co-magnetometer installed last month.
- Simultaneous measure of neutrons and mercury in both chambers now possible!
- We are looking forward to start measuring the nEDM in 2025!

Neutron spin gymnastics: Ramsey.



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

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

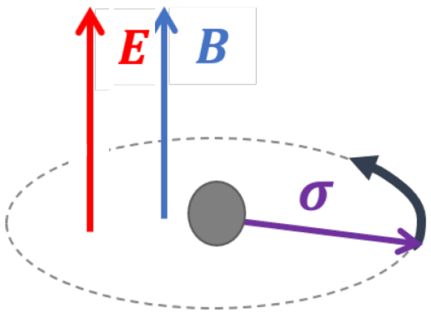


The nEDM is derived from the frequency difference in opposite electric fields.

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

Neutron frequency measurement: magnetic field stability.

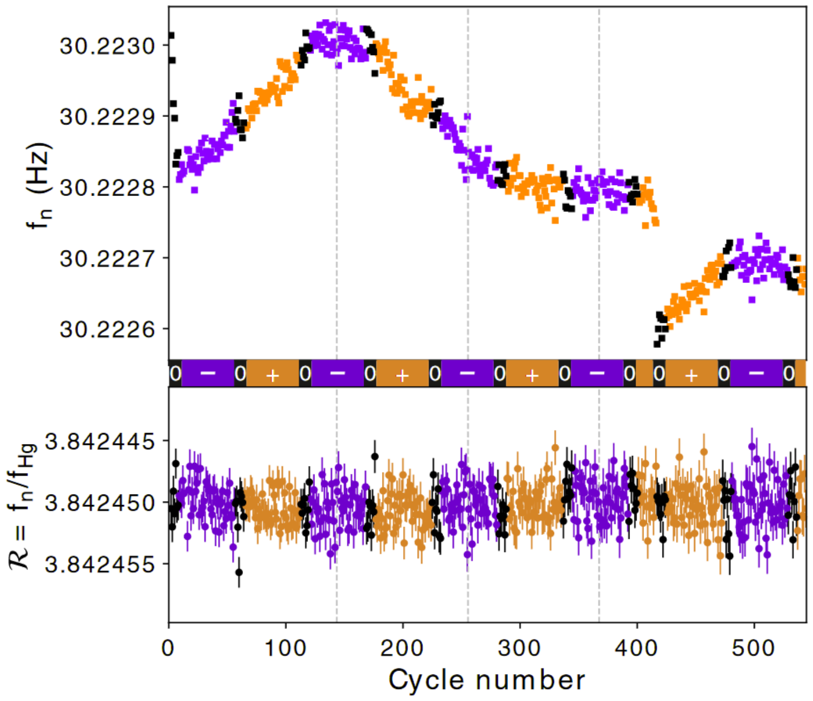
- $f_{\uparrow\downarrow} - f_{\uparrow\uparrow} = \frac{\mu}{\pi\hbar}(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}) + \frac{d}{\pi\hbar}(E_{\uparrow\downarrow} - E_{\uparrow\uparrow})$



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]

Simultaneous precession signals in the top and bottom storage chambers.