Laboratoire de Physique
Subatomique et de Cosmologie

^{199}Hg co-magnetometry study in the nEDM experiment at the Paul Scherrer Institute (Switzerland)

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Séminaire des doctorants

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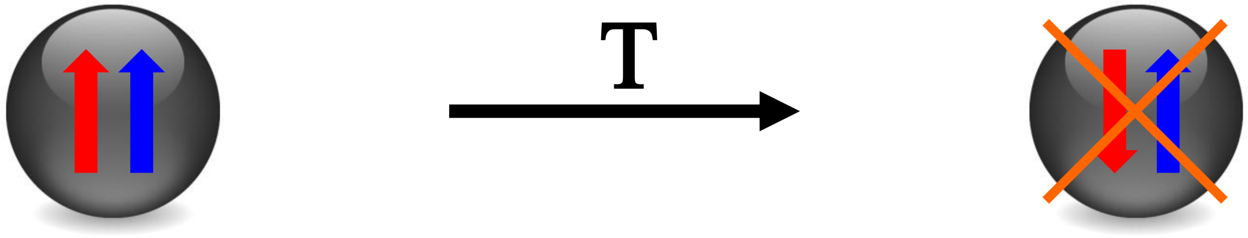
MOTIVATION

Scientific motivations

- The neutron states are only defined relatively to its spin $\vec{\boldsymbol{\sigma}}$
- Any spin $\vec{\boldsymbol{\sigma}}$ couples to: to $\vec{B}$ via $\boldsymbol{\mu}$ ← magnetic moment
  to $\vec{E}$ via $\boldsymbol{d}$ ← electric dipole moment
- $\mathrm{T}\,|\mu\rangle = -|\mu\rangle$ $\mathrm{T}\,|d\rangle = +|d\rangle$
- If $\boldsymbol{d}_{\mathbf{n}}$ is not zero, T (CP) symmetry is violated



Scientific motivations

Experimental upper bound: $|d_\mathrm{n}|_{exp} < 3.10^{-26}\ e.\mathrm{cm}$ [Ral-Sussex-ILL, 2006]

1. SM predicts $|d_\mathrm{n}| \sim 10^{-32}\ e.\mathrm{cm}$ ⟵ weak CPV (δ_{CKM} @ 2 loops)

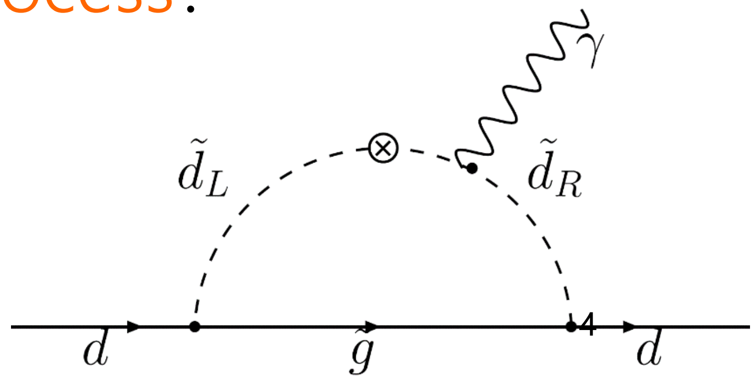
[Khriplovitch, 1981]

2. Additional CPV sources from BSM models constrained by $|d_\mathrm{n}|_{\mathrm{exp}}$

3. How sensitive to new physics we are to 1 loop process?

$$d_\mathrm{n} \approx 10^{-25} e.\mathrm{cm} \times \sin(\varphi^{CP}) \times \left(\frac{1\ TeV}{M_{NP}}\right)^2$$

[Pospelov & Ritz, 2005]



International context

- **PSI** nEDM collaboration at the Paul Scherrer Institute (Switzerland)
  8 countries (Switzerland, Germany, France, UK, Poland, Belgium, USA, Russia)
  48 members / 11 PhD students

- **SNS** nEDM collaboration — Oak Ridge (USA)
- **PNPI-ILL** nEDM experiment — Grenoble (France)
- **TRIUMF** nEDM collaboration — Vancouver (Canada)
- **LANL** nEDM collaboration — Los Alamos (USA)

- And others…

The nEDM experiment

The measurement principle

- Hamiltonian of the problem:

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

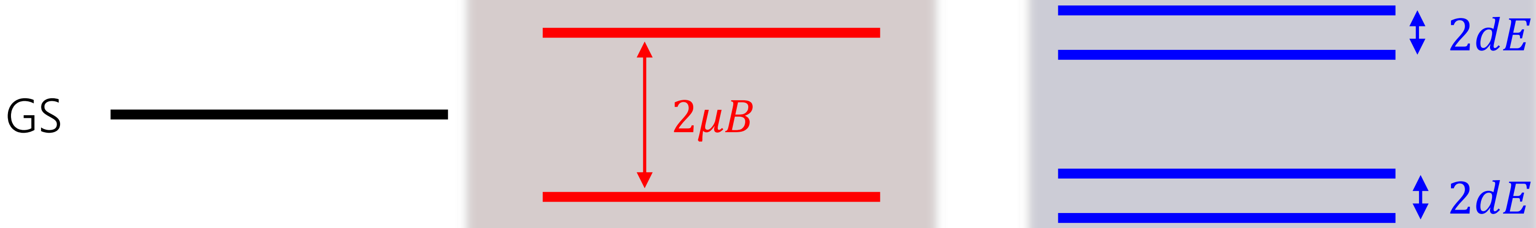
- Energy level splitting:

$\boldsymbol{\Delta E_{\mathrm{B}} = 6.10^{-14}}$ **eV**

$\boldsymbol{B = 1\ \mu\mathrm{T}}$

$\boldsymbol{\Delta E_{\mathrm{E}} < 3.10^{-22}}$ **eV**

$\mathbf{E = 10\ kV/cm}$

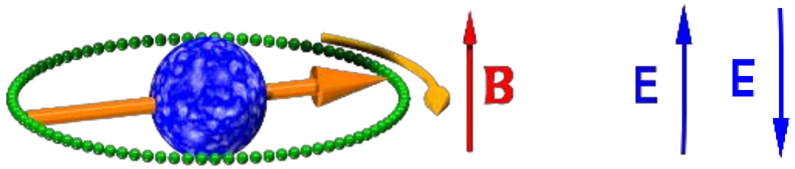


The measurement principle

- Hamiltonian of the problem:

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

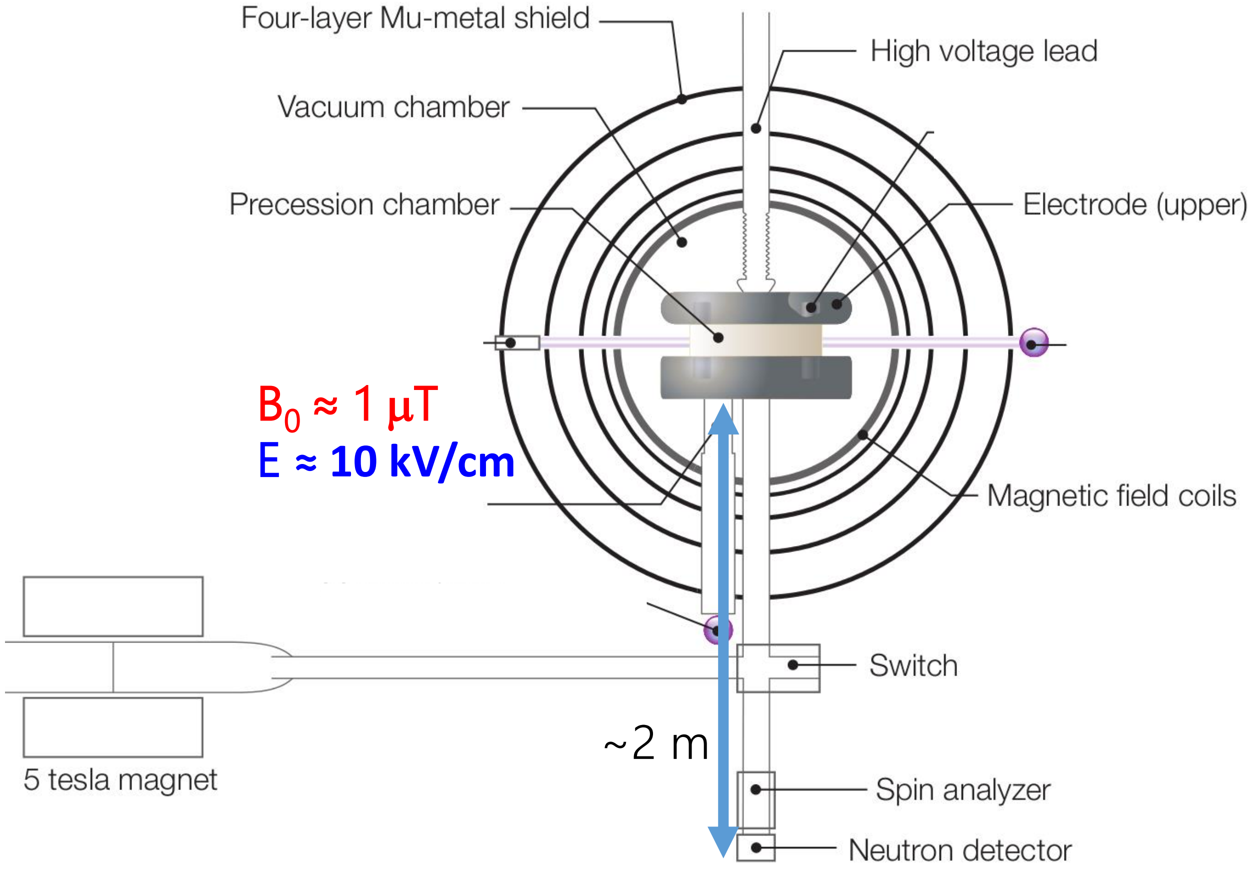
- Measure a neutron spin precession frequency shift proportional to an applied electric field!

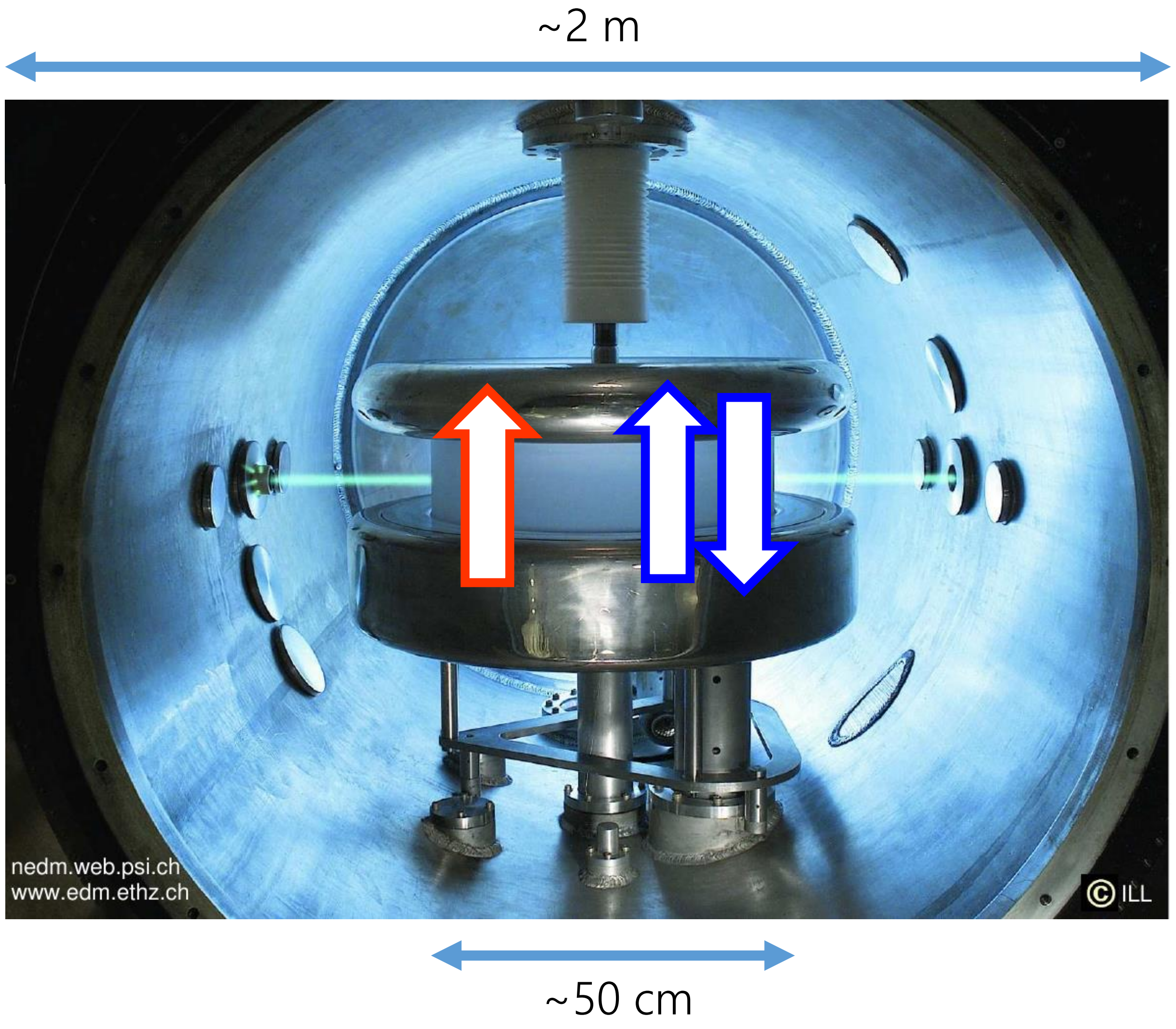


$$\left.\begin{aligned} \frac{h\nu^{\uparrow\uparrow}}{2} &= -\mu B^{\uparrow} - dE^{\uparrow} \\ \frac{h\nu^{\uparrow\downarrow}}{2} &= -\mu B^{\uparrow} + dE^{\downarrow} \end{aligned}\right\} \qquad |\boldsymbol{d}| = \left|\frac{\boldsymbol{h}\,(\boldsymbol{\nu}^{\uparrow\uparrow} - \boldsymbol{\nu}^{\uparrow\downarrow})}{\boldsymbol{4E}}\right|$$

True only if $\boldsymbol{B}^{\uparrow} = \boldsymbol{B}^{\uparrow}$!

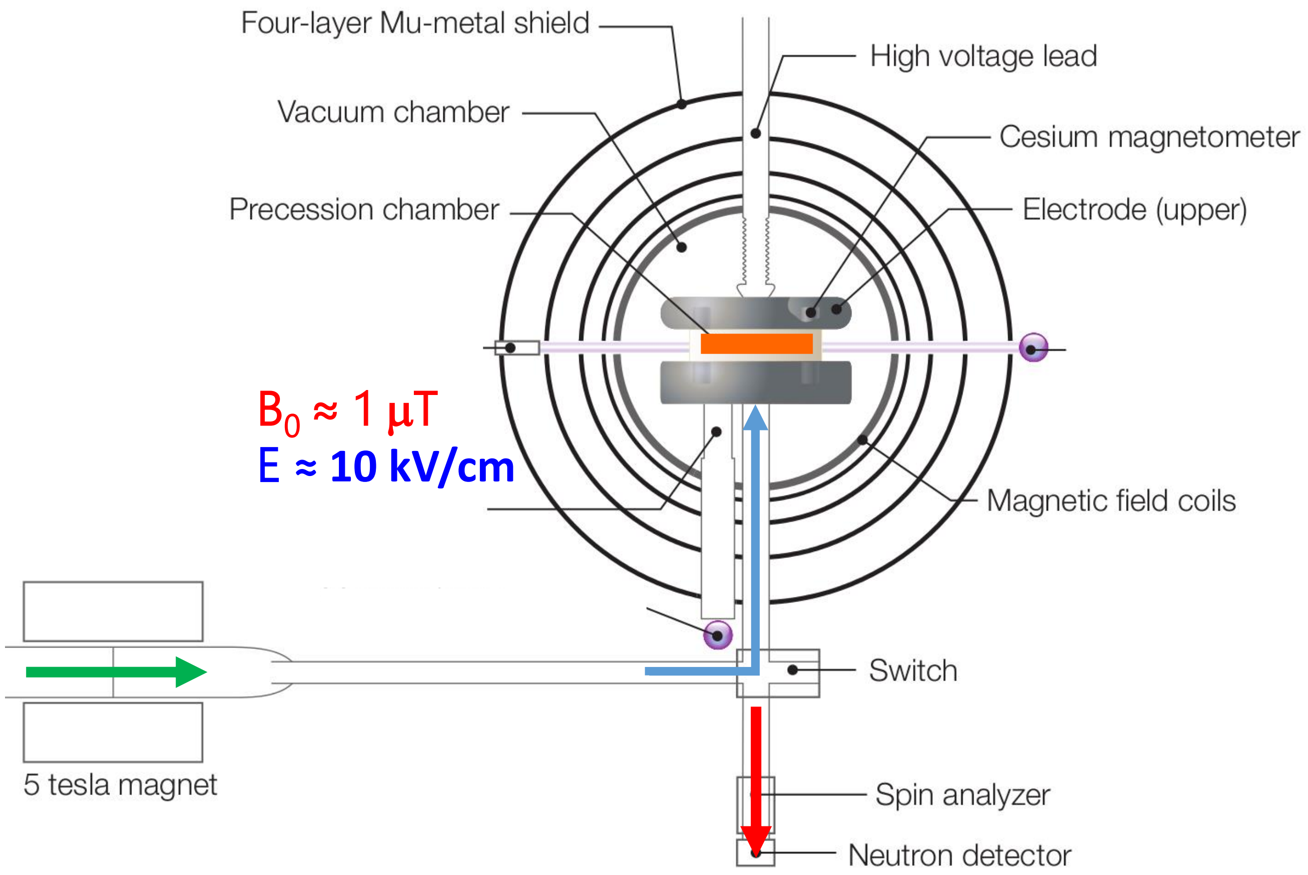
Experimental setup





NB: Upgraded RAL-Sussex spectrometer

Experimental setup



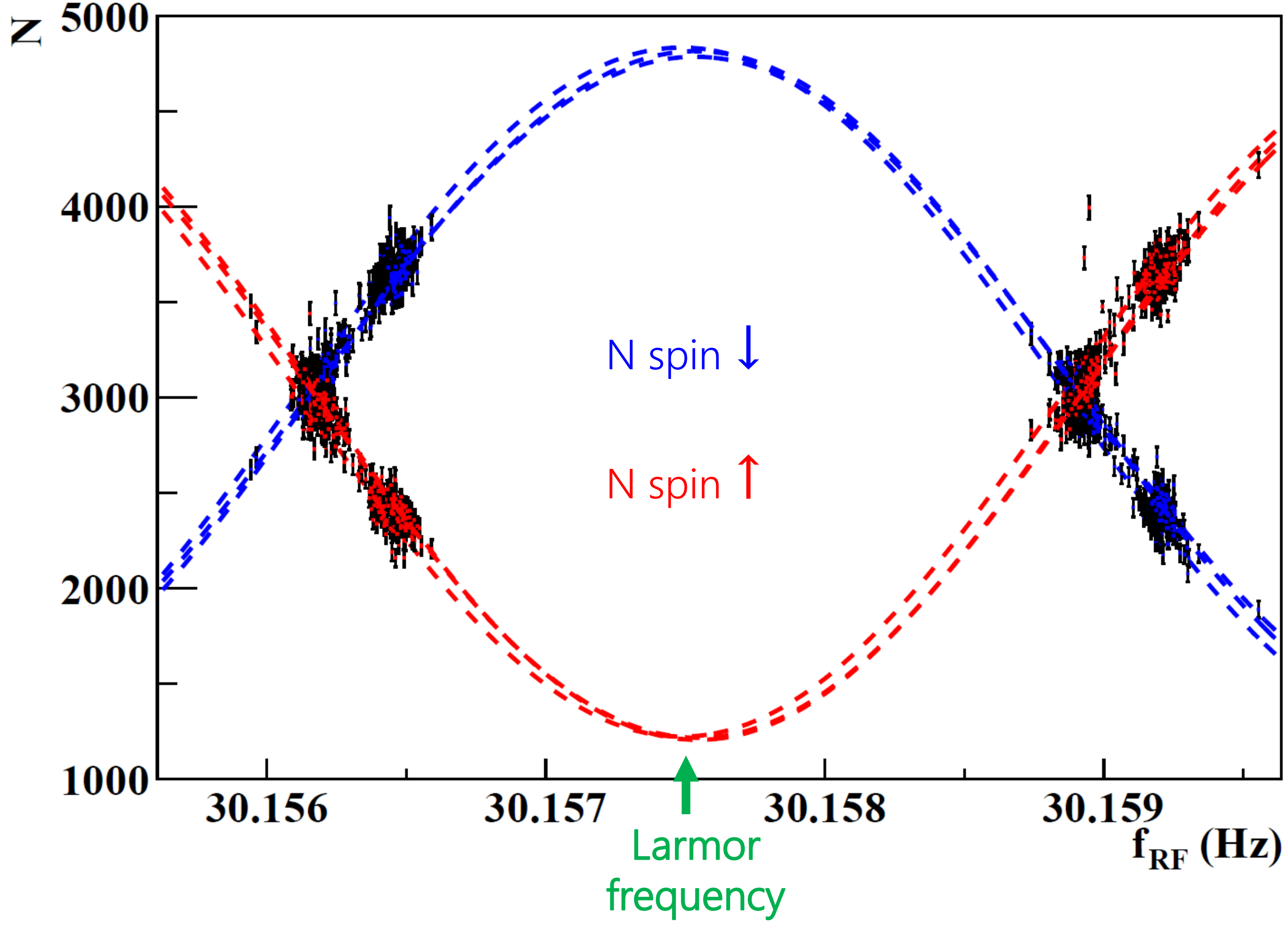
1. Production of Ultra Cold Neutrons (UCN) in the new PSI UCN source
$$E_{\mathrm{UCN}} \sim \mathbf{100\ neV}$$
2. UCN are spin-polarized ↑ with a 5T magnetic field
3. Fill the precession chamber
4. Store UCN for 200 s with (E, B) parallel or antiparallel
    1. Apply $\frac{\pi}{2}$ pulse (2s)
    2. Spin freely precess (200s)
    3. Apply $\frac{\pi}{2}$ pulse (2s)

[Ramsey, 1956]

5. Measure neutron counts with spin Up & Down

The Ramsey method

Fit to the central Ramsey fringe (2013 data)



$\frac{\pi}{2}$ pulse = oscillating magnetic field

→ $B_1(t) = B_1[\cos(\omega_{RF}\, t)\vec{x} + \sin(\omega_{RF}\, t)\vec{y}]$

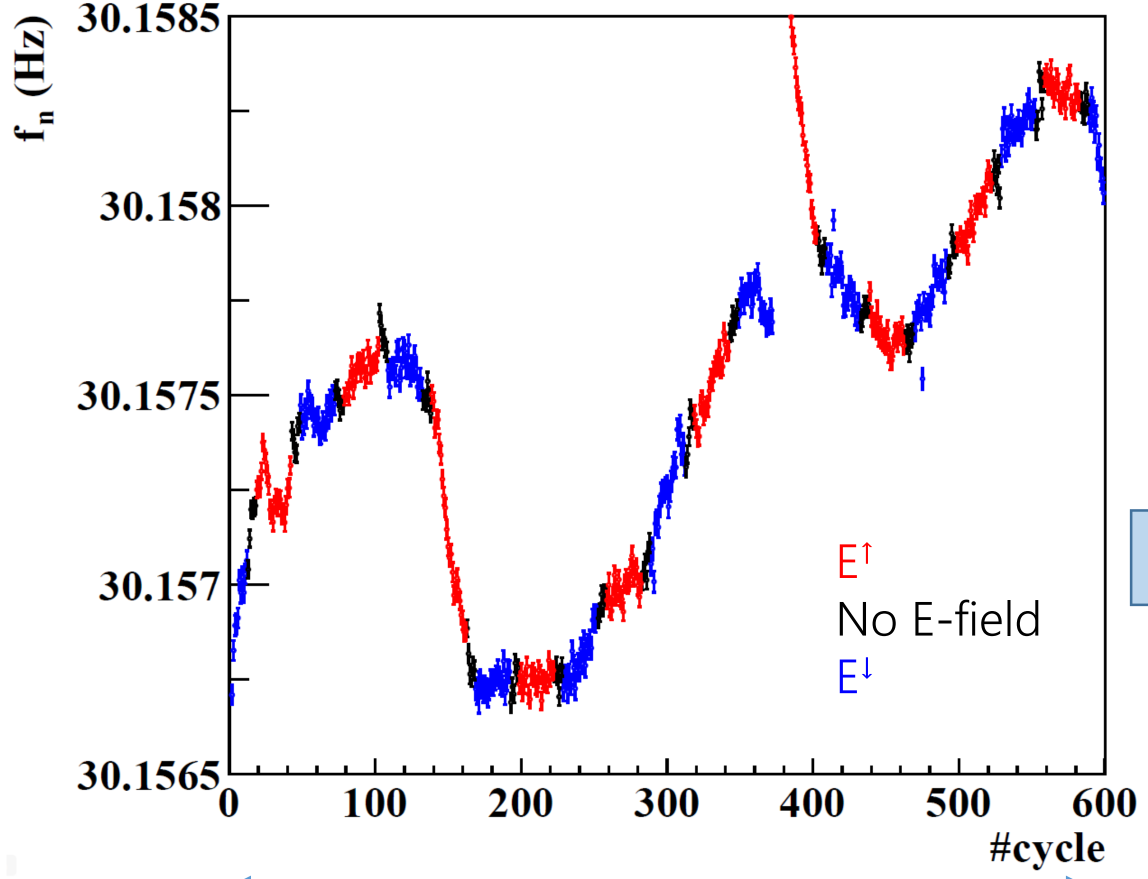
$$\boldsymbol{P}(\uparrow\to\downarrow) \propto \cos\left(\frac{f_{RF} - f_L}{\Delta\nu}\right)$$

$\boldsymbol{P}(\uparrow\to\downarrow)$ maximized if $\boldsymbol{f}_{RF} = \boldsymbol{f}_L = \frac{\gamma_n}{2\pi}\boldsymbol{B}_0$

Experimental challenges

Reminder: Earth magnetic field ≈ 50 µT = 50.10^6 pT

Neutron frequency (run 7650)



3 days

ORDER OF MAGNITUDE OF MAGNETIC FIELD FLUCTUATIONS:

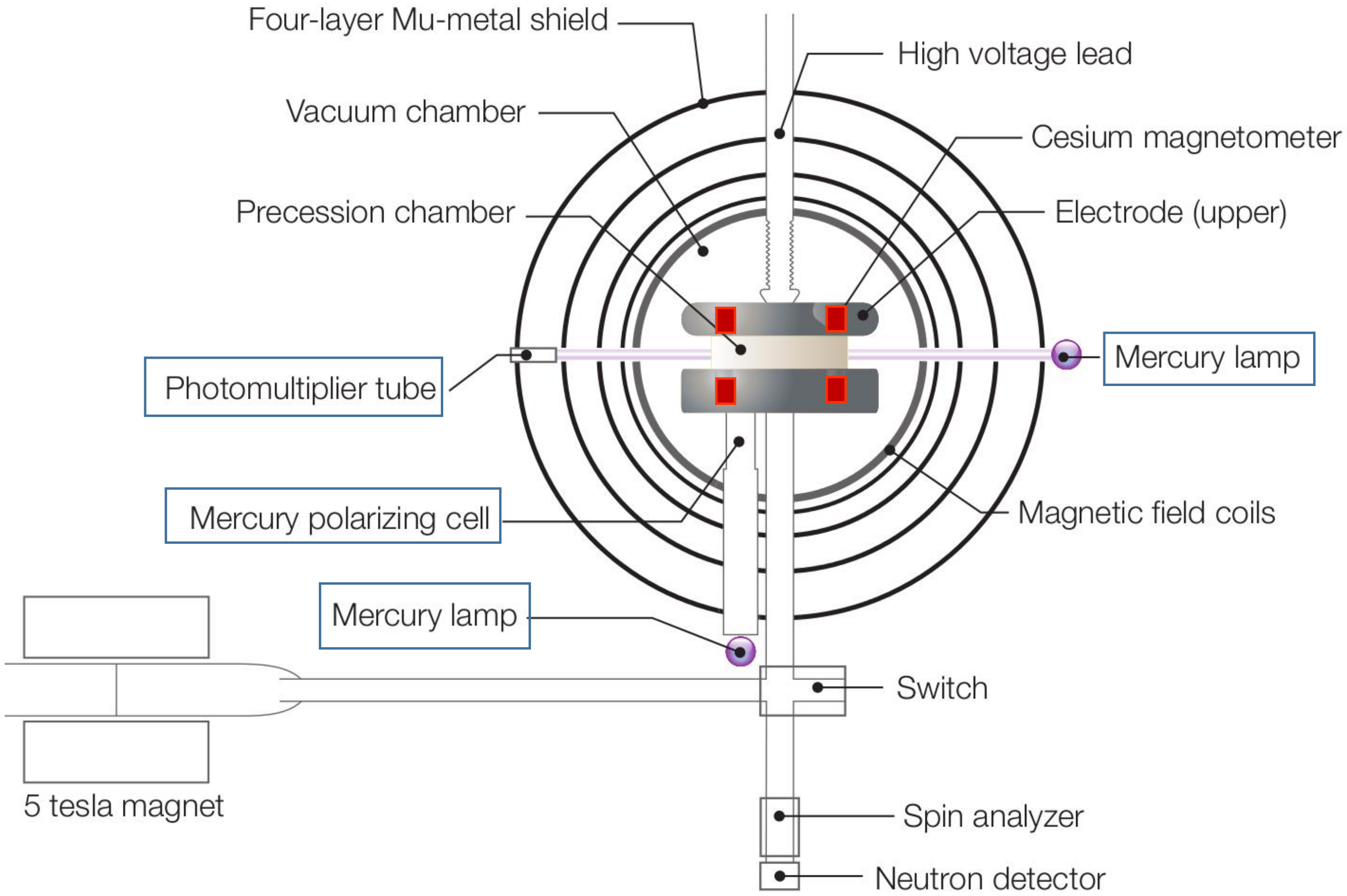
- E^+ to E^-: $\Delta B \sim 7$ pT $\sigma_{d_n} \sim 2.10^{-23}$ e.cm (1970)
- Cycle: $\Delta B \sim 0.5$ pT $\sigma_{d_n} \sim 1.10^{-24}$ e.cm (1980)
- nEDM: $\Delta B \sim 5$ fT $\sigma_{d_n} \sim 1.10^{-26}$ e.cm

How can we achieve a 5 fT magnetic field sensitivity?

^{199}Hg co-magnetometry

Functioning principle

Need to correct for magnetic field drift every cycle with a 100 fT precision



[Ral-Sussex-ILL, 1997]

^{199}Hg atomic magnetometry

=

Same sampled volume

during the same integrated time

as UCN

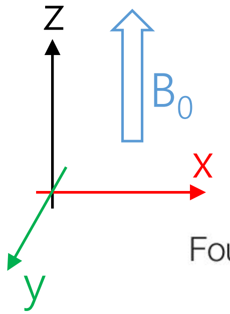
[Bison, 2006]

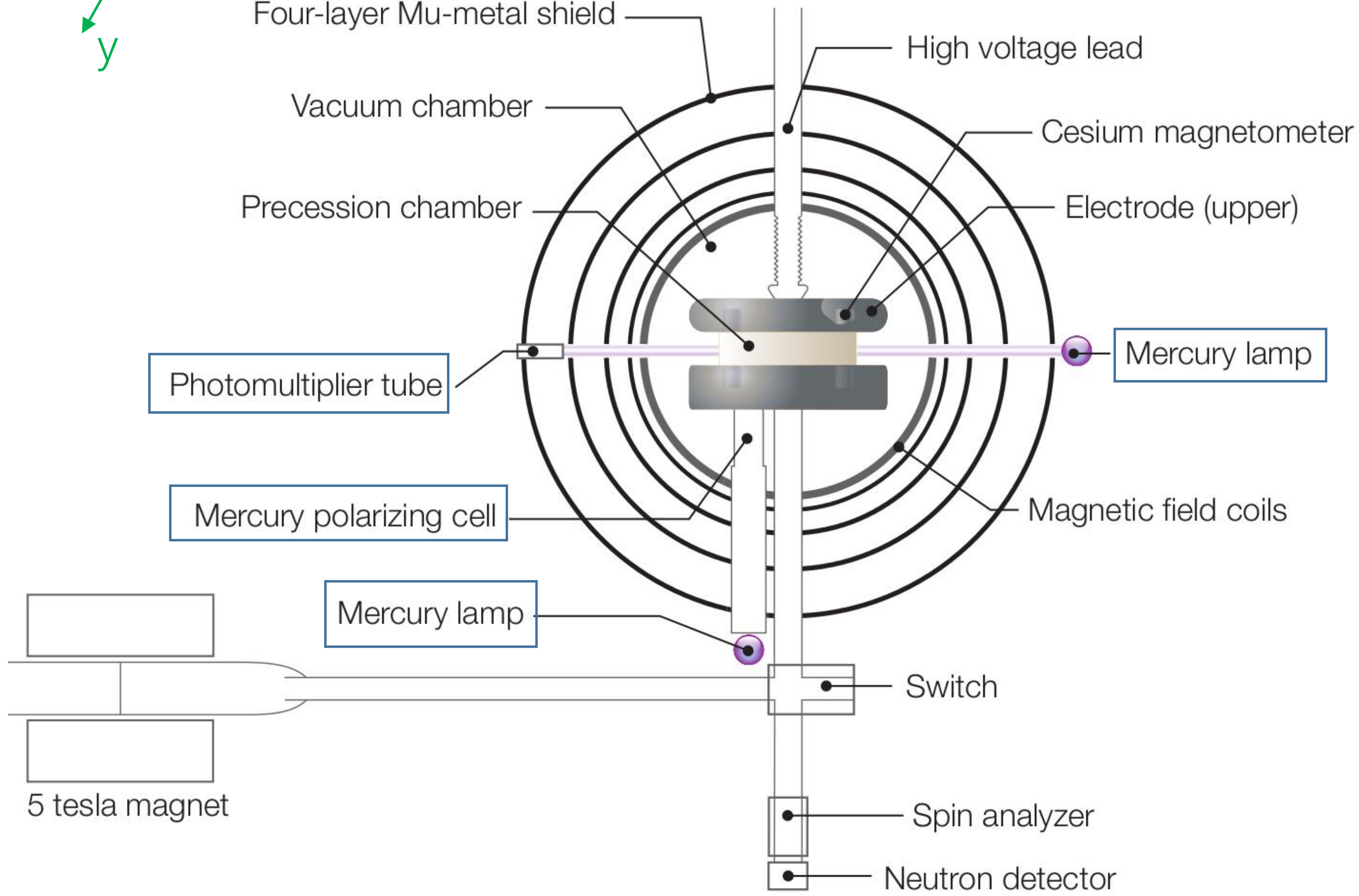
^{133}Cs atomic magnetometry

=

Spatial magnetic field distribution

Functioning principle



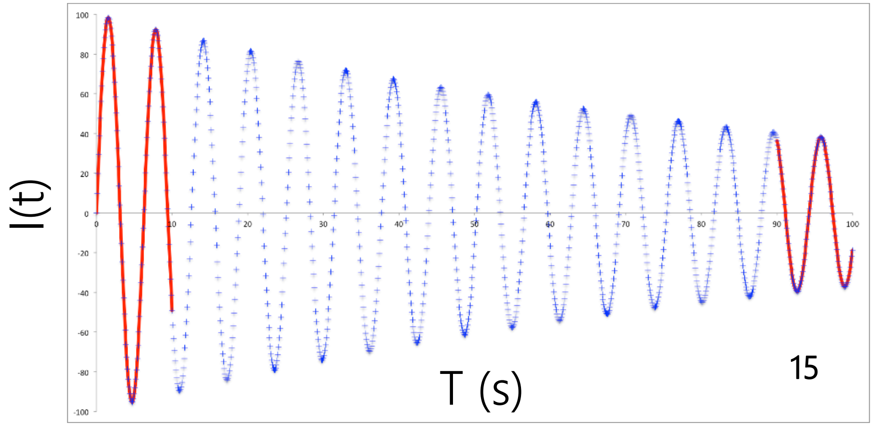


- ^{199}Hg atoms are spin polarized by optical pumping (40s)
- Apply a $\frac{\pi}{2}$ **pulse** (2s)
- Free precession in (x, y) plane (200s)

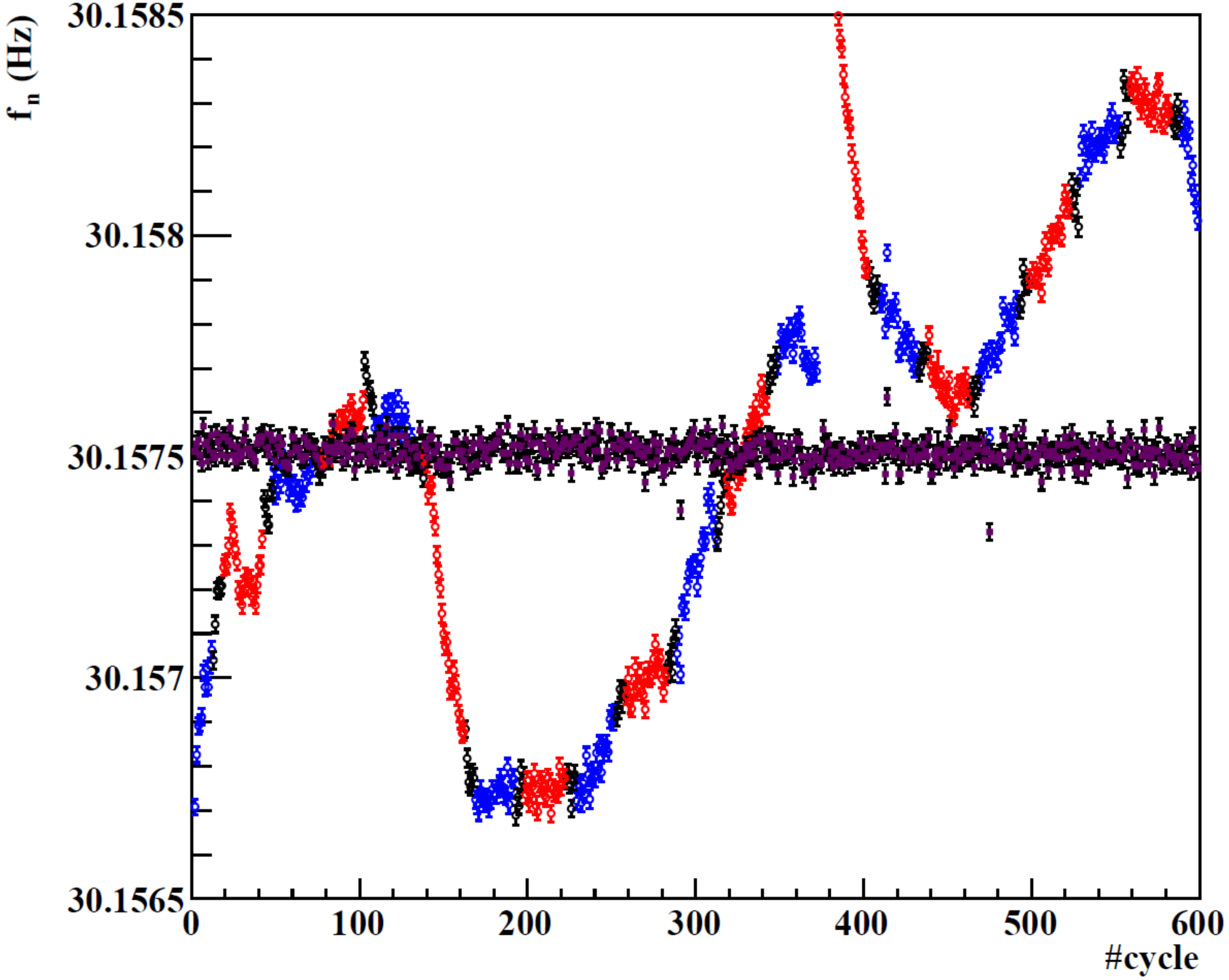
$$I(t) = Ae^{-\frac{t}{\tau}} \sin(\omega_L t + \varphi)$$

Relaxation time constant due to wall collision ≈ 100 s

Oscillating phase @ Larmor frequency $f_L = \gamma_{Hg} B_0 \approx 8$ Hz



Correction of magnetic field drift



$$\frac{\sigma_{f_n}}{f_n} = \frac{1}{2\pi\, T_p\, \alpha \sqrt{N_{UCN}}} \approx 0.5\ \mathrm{ppm}$$

x 7

$$\frac{\sigma_{f_{Hg}}}{f_{Hg}} = \frac{3}{2}\frac{1}{\mathrm{SNR}\, T_p \sqrt{N_{fit}}}\sqrt{1+e^{2T_p/\tau}} \approx 0.07\ \mathrm{ppm}$$

- The co-magnetometry allows to be only statistically limited by UCN

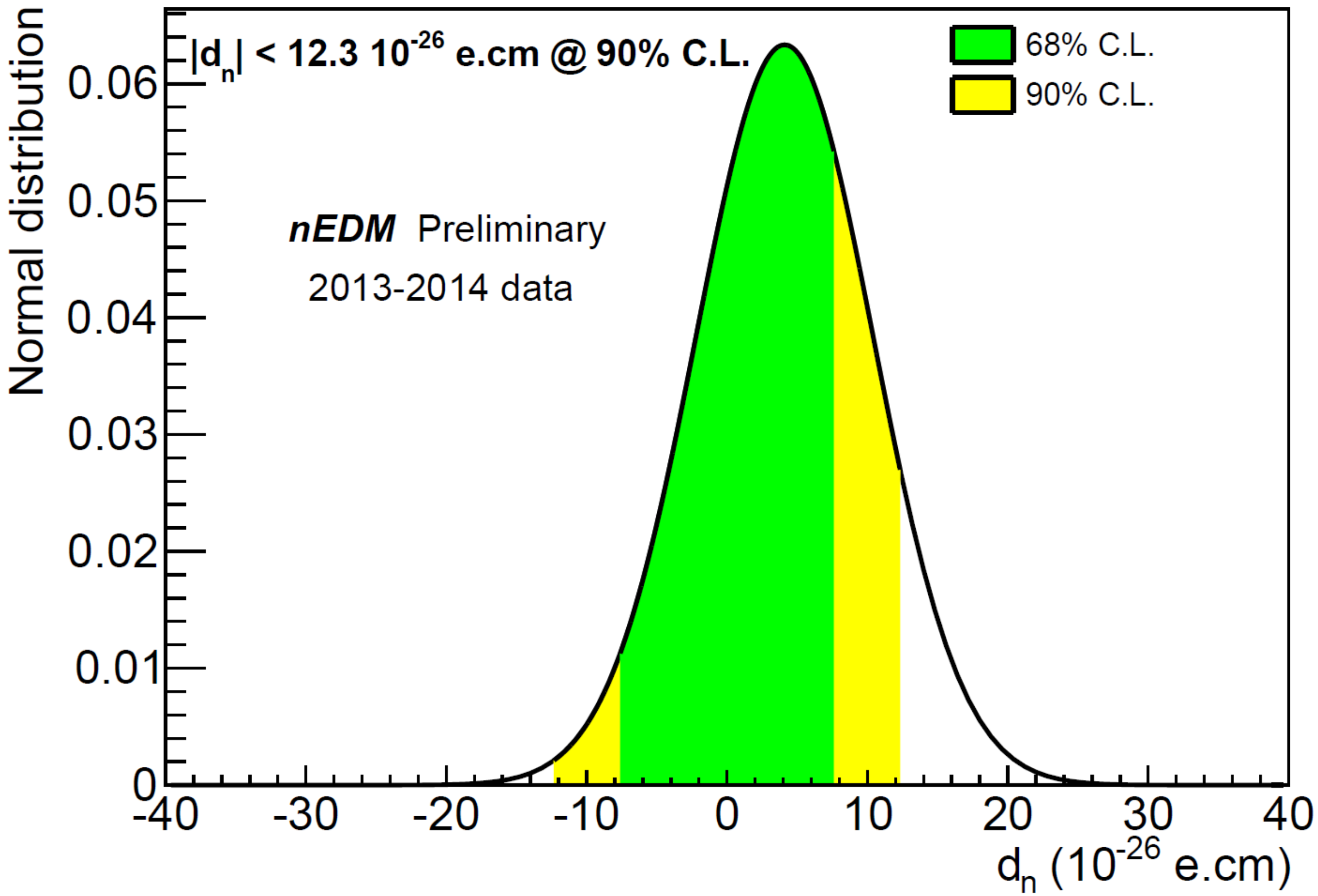
→ $\sigma_d/\mathrm{cycle} = 1.10^{-24}\ e.\mathrm{cm}$

- Need to repeat X cycles to reach the $10^{-26}\ e.\mathrm{cm}$ level, with $X \to \infty$!!

(Actually ~ 10 000 = months)

Current statistical sensitivity

$|d_{\mathrm{n}}| < 12.3 \times 10^{-26}\ e.\mathrm{cm}$ (2 months full time)



- nEDM data analysis software
  → EDMA
- Expected sensitivity in 2-3 years
  → $\sigma_d = 1 - 2.10^{-26}\ e.\mathrm{cm}$
- Control of systematics?

Current control of systematics

Effect	Status [$\times 10^{-27}$ e.cm]
Direct effects	
Uncompensated B-Drifts	-0.7 ± 1.1
Leakage current	0.00 ± 0.05
$v \times E$ UCN	0 ± 0.1
Electric forces	0 ± 0
Hg EDM	0.02 ± 0.06
Hg direct light shift	0 ± 0.008
Indirect effects	
Hg Light Shift	0 ± 0.05
Quadrupole difference	1.3 ± 2.4
Dipoles	
At surface	0 ± 0.4
Other dipoles	0 ± 3
Total	0.2 ± 4.0

Motional ^{199}Hg false EDM **40 ± 40** ← correction of this effect

Motional ^{199}Hg induced false EDM

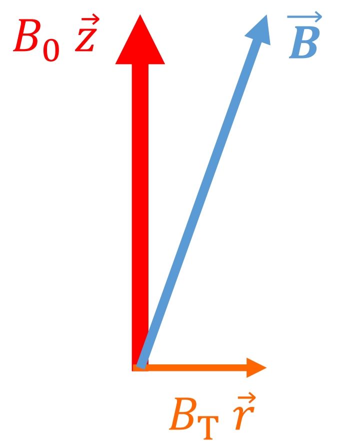
- Reminder: $$|d| = \left|\frac{\hbar\,(\omega^{\uparrow\uparrow} - \omega^{\uparrow\downarrow})}{4E}\right|$$

- The motional ^{199}Hg induced false EDM arises from transverse magnetic field :

Vertical magnetic field gradient — Position in the transverse plane

$$\left.\begin{aligned}\tilde{B}_{\nabla B}(t) &\approx \frac{\partial B_z}{\partial z}\, r(t)\\ \tilde{B}_{\vec{v}\times\vec{E}}(t) &\approx \frac{E_z}{c}\, v_{xy}(t)\end{aligned}\right\}\quad \delta\omega \propto \left(\tilde{B}_{\nabla B}(t) + \tilde{B}_{\vec{v}\times\vec{E}}(t) + \cdots\right)^2$$

Longitudinal electric field — Speed in the transverse plane



- Different ^{199}Hg frequency shift source arise: $\delta\omega = \delta\omega_{B^2} + \delta\omega_{BE} + \delta\omega_{E^2} + \cdots$

Motional ^{199}Hg induced false EDM

- Reminder: $$|d| = \left|\frac{\hbar\,(\omega^{\uparrow\uparrow} - \omega^{\uparrow\downarrow})}{4E}\right|$$

- Different ^{199}Hg frequency shift source arise: $\delta\omega = \delta\omega_{B^2} + \delta\omega_{BE} + \delta\omega_{E^2} + \cdots$

- Hypothesis: Uniform vertical magnetic field gradients in a cylindrical cell

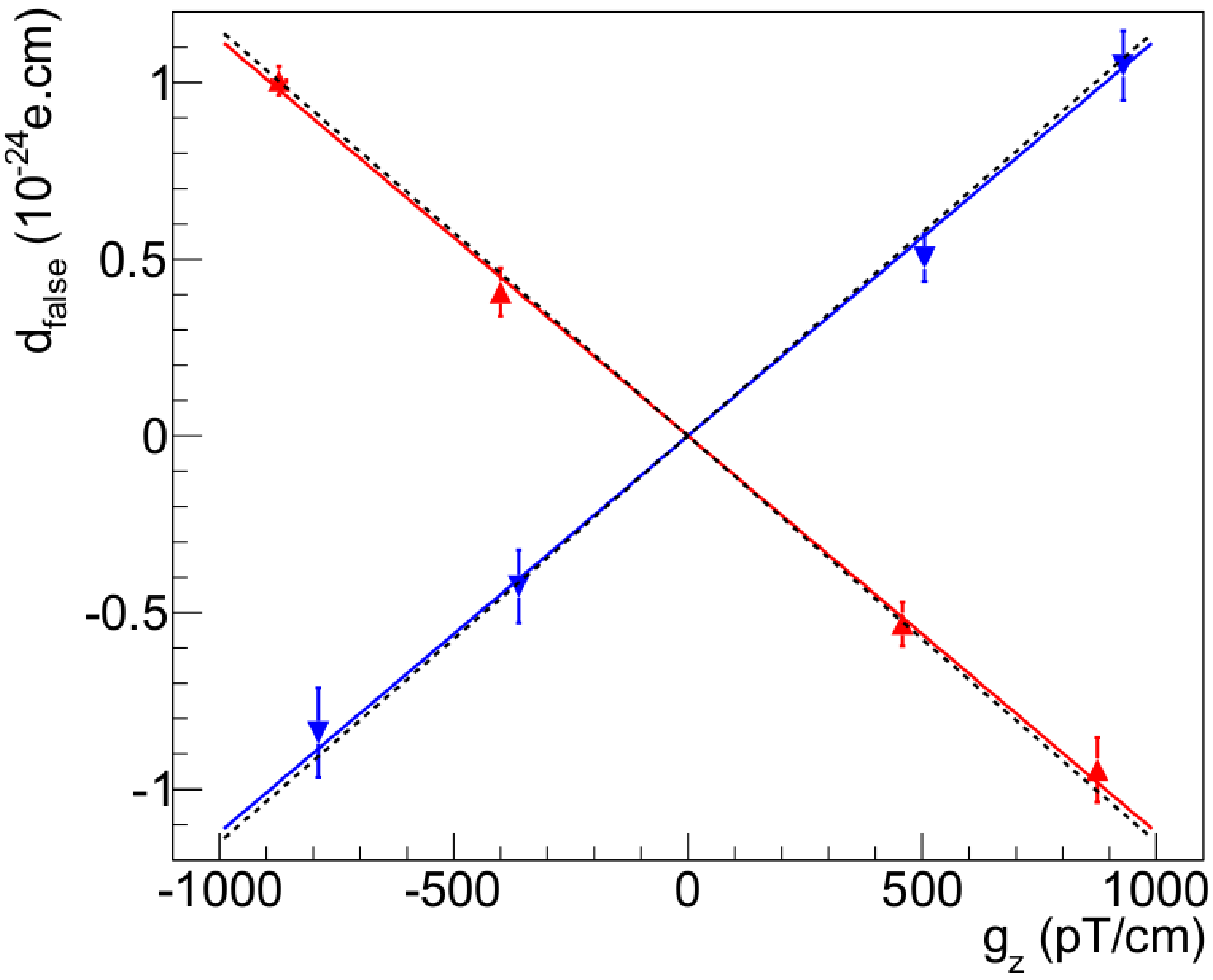
[Pendelbury, 2006]

[Pignol, 2012]

- Theoretical expression: $\delta\omega_{BE} = \pm\frac{\gamma^2 D^2}{8\,c^2} E \frac{\partial B_z}{\partial z}$ which leads to:

$$\boldsymbol{d_{\mathrm{Hg}}^{\mathrm{false}} = \pm\frac{\hbar\gamma^2 D^2}{32\,c^2}\frac{\partial B_z}{\partial z}}$$

Motional ^{199}Hg induced false EDM



Data B_0 down

Data B_0 up

Best fit to the data: $d_{\mathrm{Hg}}^{\mathrm{false}}(g_z) = |a| \,.\, g_z$

Theoretical slope

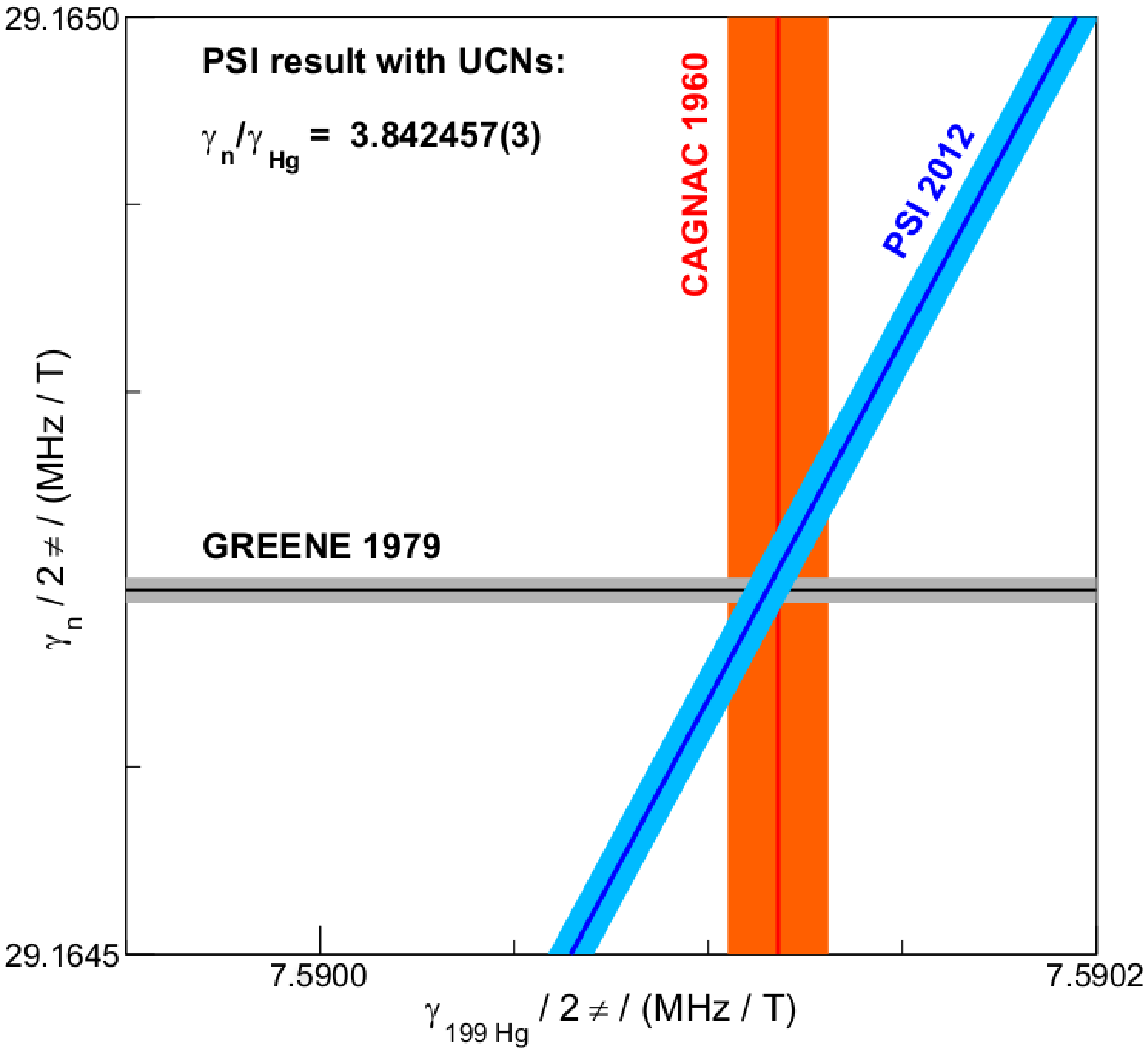
Result: $\boldsymbol{|a_{\mathrm{exp}}| = 1.122(35) \times 10^{-27}\, e.\mathrm{cm}/\frac{\mathrm{pT}}{\mathrm{cm}}}$

$\boldsymbol{|a_{\mathrm{th}}| = 1.148 \times 10^{-27}\, e.\mathrm{cm}/\frac{\mathrm{pT}}{\mathrm{cm}}}$

Available: arxiv:1410.8259

"Measurement of a false electric dipole moment signal from ^{199}Hg atoms exposed to an inhomogeneous magnetic field"

Neutron to ^{199}Hg magnetic moment ratio



Larmor frequency definition: $f_L = \frac{\gamma}{2\pi} B_0$

The gyromagnetic ratio of the two species reads:

$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{earth} + \delta_{grav} + \cdots)$$

$$\frac{\gamma_n}{\gamma_{Hg}} = 3.8424574(30)\ \ [0.78\ \mathrm{ppm}]$$

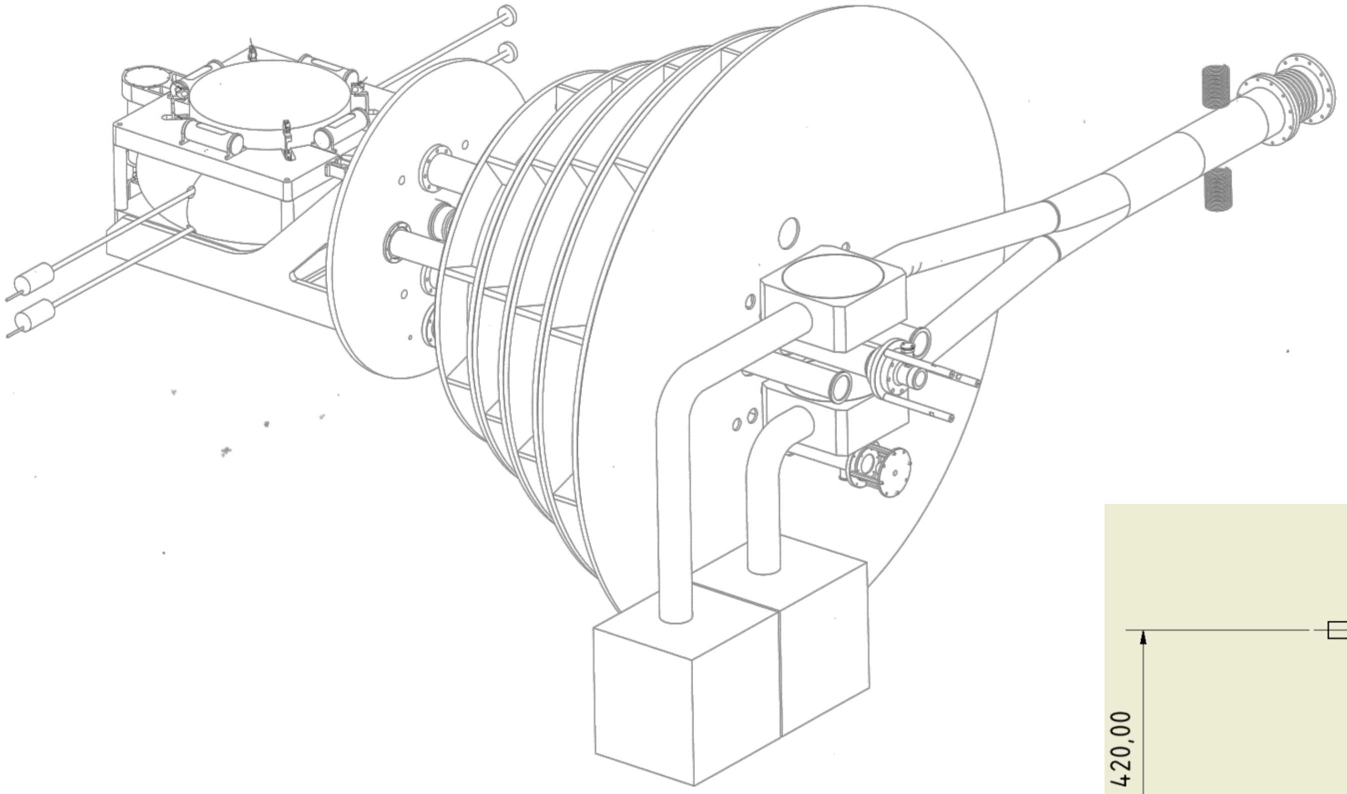
Interpretation as a new measurement of whether γ_n or γ_{Hg} at the ppm level

Results in agreement with previous measurement

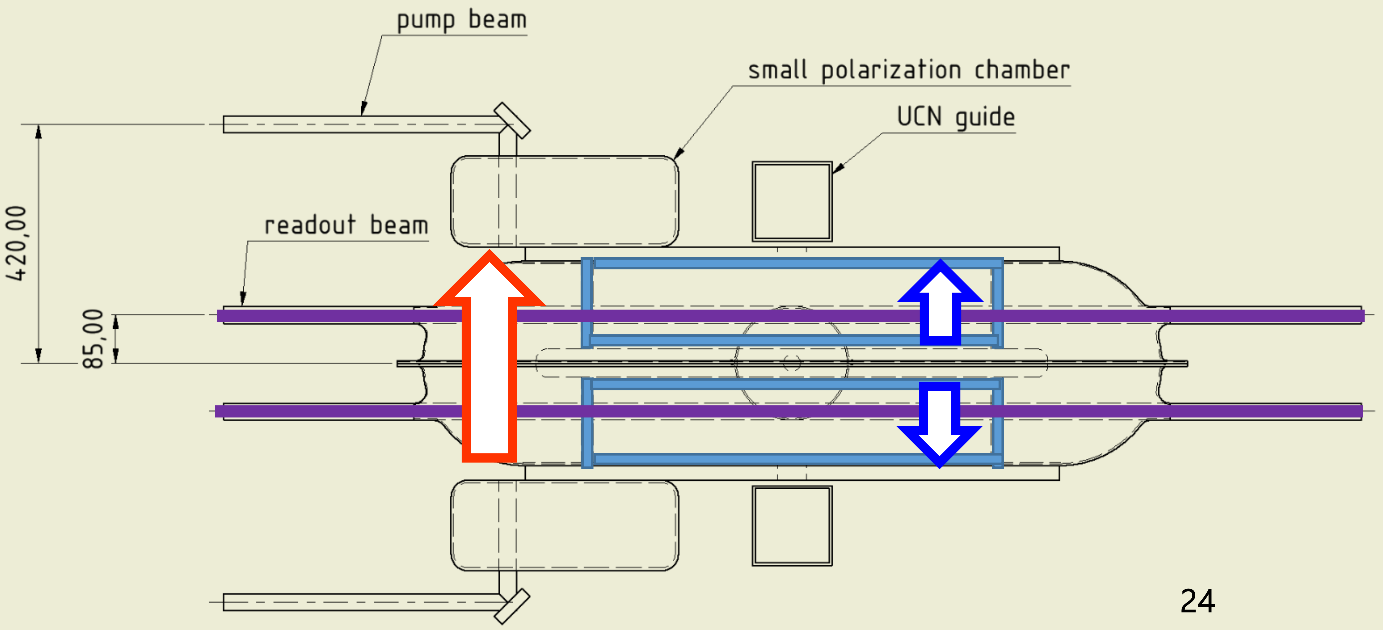
Available: Physics Letters B 739, 128-132 (2014)

Toward n2EDM

n2EDM project



- 2 precession chambers
- Optimized geometry to increase N_{UCN}
- Keep ^{199}Hg co-magnetometry
- Sensitivity: $\sigma_d = 5.10^{-27}\ e.\text{cm}$



Now	2017-2020	2025	
R&D	Data taking		
10^{-25}	10^{-26}	5.10^{-27}	(e.cm)

^{199}Hg test bench @ LPSC

- Goal is to study properties of ^{199}Hg co-magnetometer

- Increase number of UCN/cycle = increase in co-mag. sensitivity!

- Sensitivity depends on: $$\frac{\sigma_{f_{\mathrm{Hg}}}}{f_{\mathrm{Hg}}} \propto \frac{1}{\mathrm{SNR}\, T_{\mathrm{p}} \sqrt{N_{\mathrm{fit}}}} \sqrt{1 + e^{2T_{\mathrm{p}}/\tau}}$$

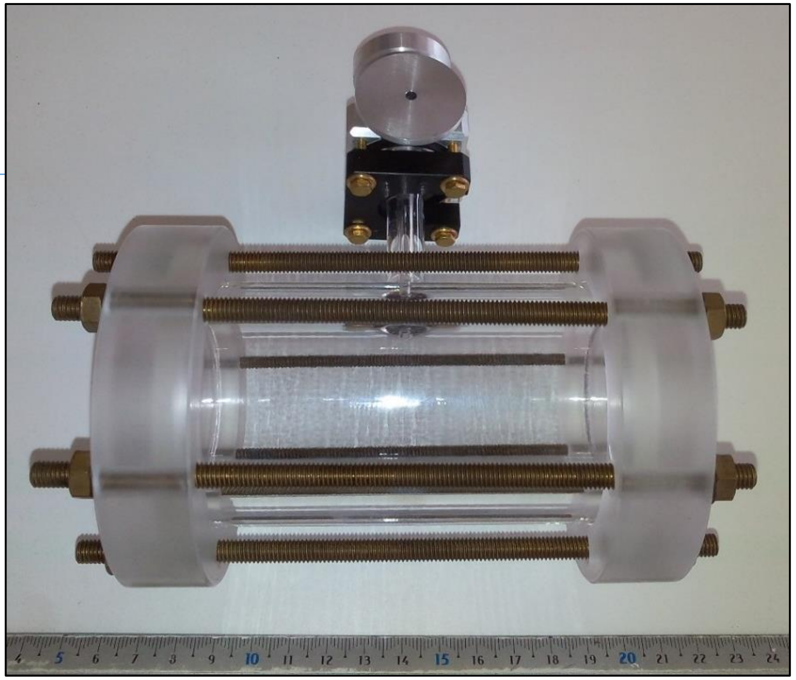
  Input polarization -> Signal to Noise Ratio

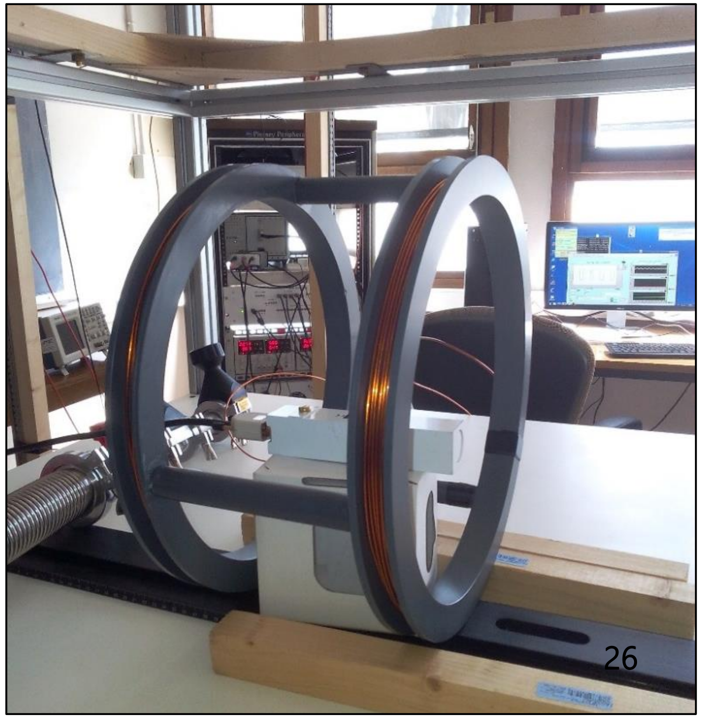
  Depolarization time -> Coherence time of the signal τ

  → Surface state dependent

- Contribution of LPSC technical groups & ILL glass ware

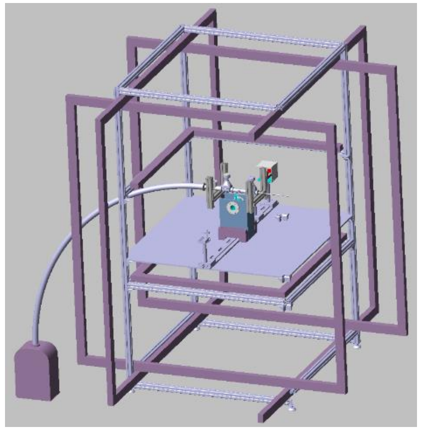
^{199}Hg test bench @ LPSC



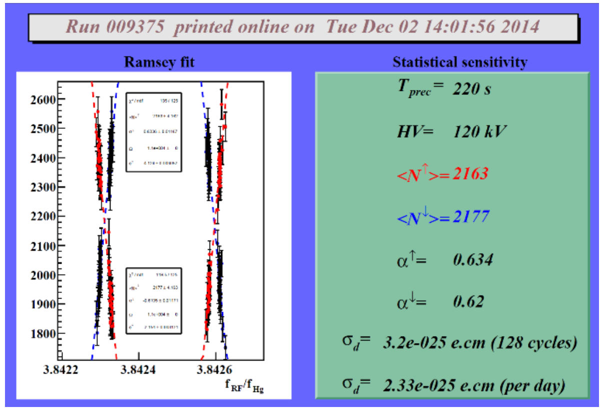


Perspectives

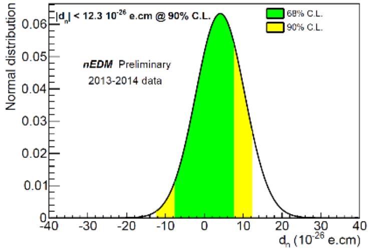
- Finalize the ^{199}Hg test bench construction
- Take physics data with the ^{199}Hg test bench end of spring
- Participate to the n2EDM ^{199}Hg co-mag. Design



- Maintain online data quality software
- Continue developing my offline data analysis software: EDMA
- Improve pyAMI database integration in the collaboration



- Get the best upper limit on d_n ??



Thank you for your attention