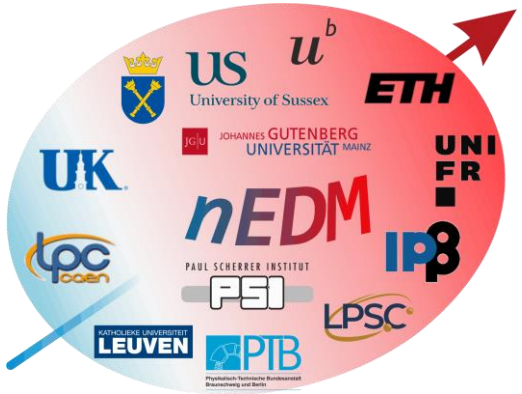
Next-generation nEDM search at PSI

Efrain Segarra, PSI Fellow III-3i

Searching for New Physics at the Quantum Technology Frontier

July 3, 2023



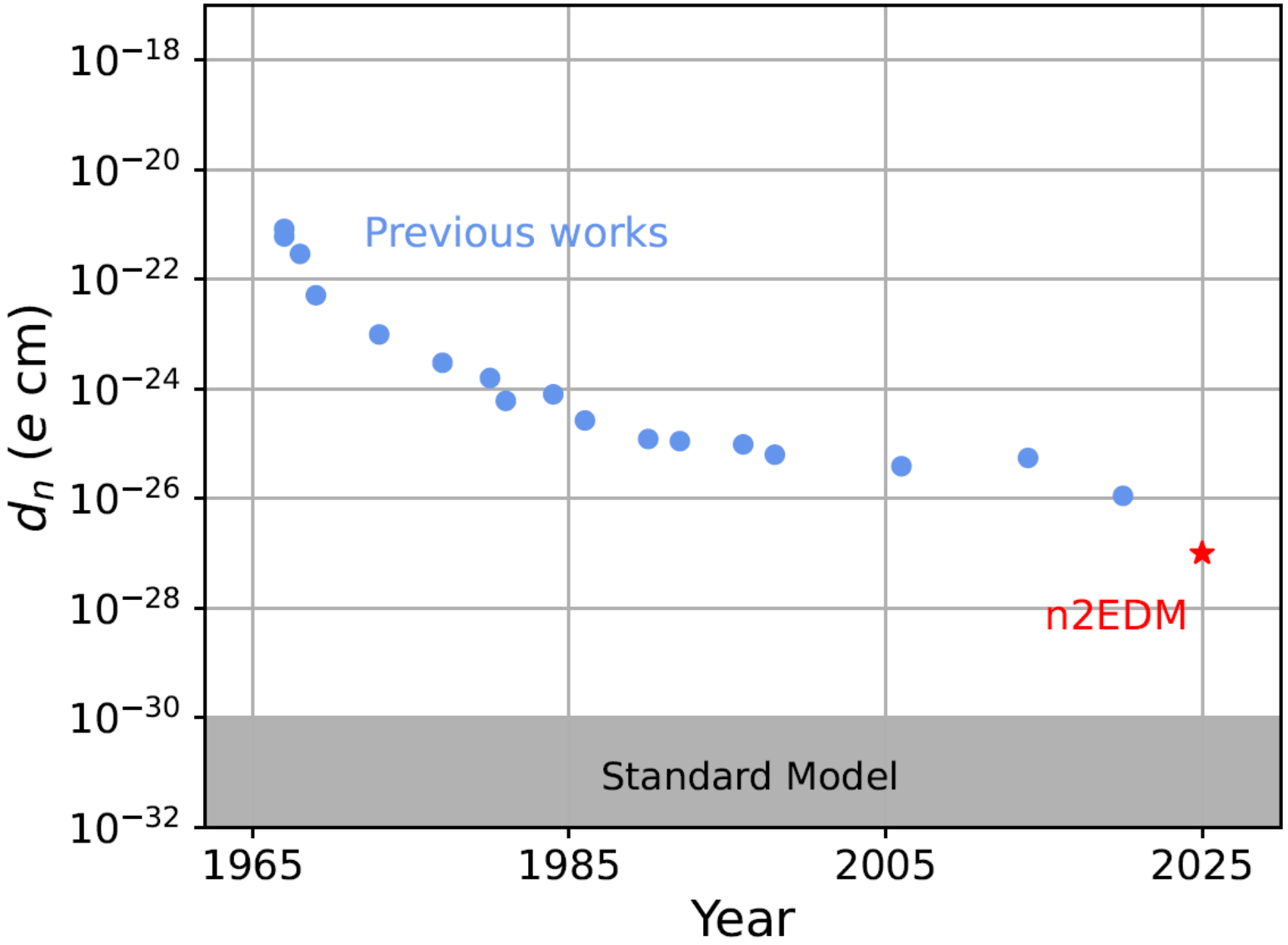
nEDM is interesting because…

- Strong CP problem
- BSM CP violation
- Baryon asymmetry
- Fundamental property of a building block of matter

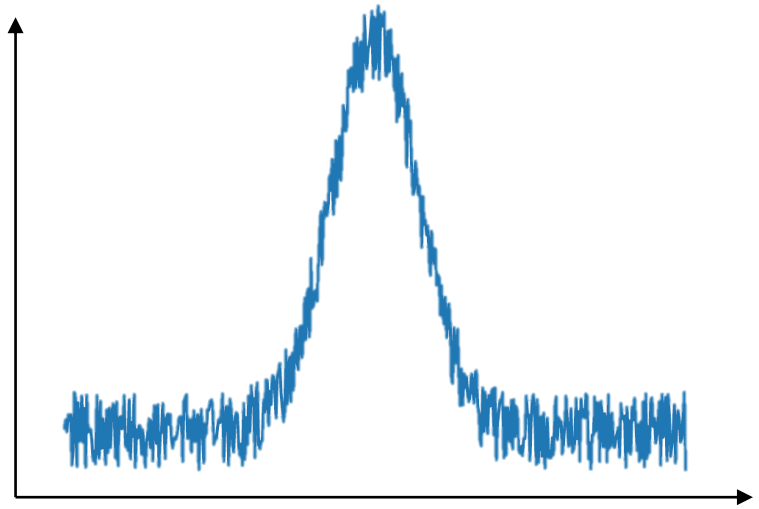
$$d_n \sim 10^{-16}\ (e\ \mathrm{cm})\left[\theta + \delta_n^{\mathrm{BSM}}\right] + 10^{-32}\ (e\ \mathrm{cm})$$

SM expectation

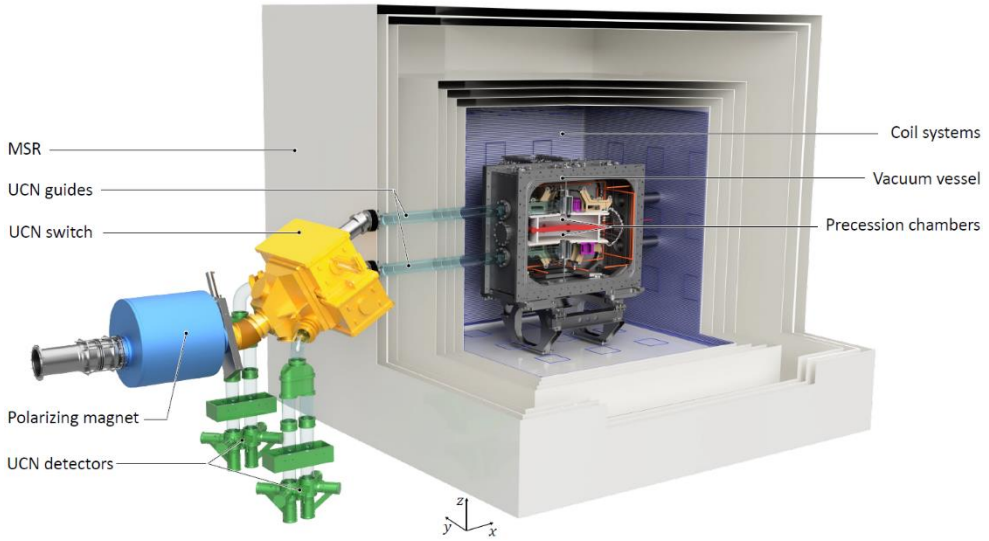
Long history of measuring nEDM



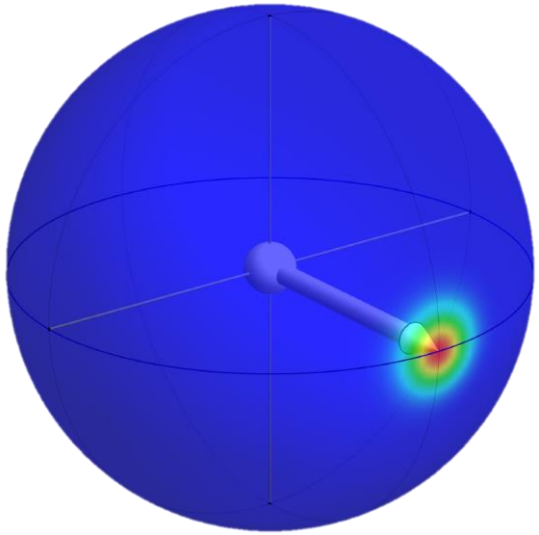
1) Measuring nEDM



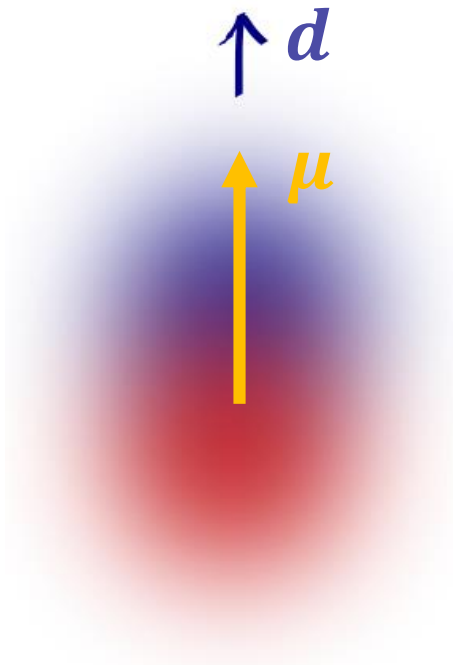
2) n2EDM at PSI



3) Quantum frontier with n3EDM?

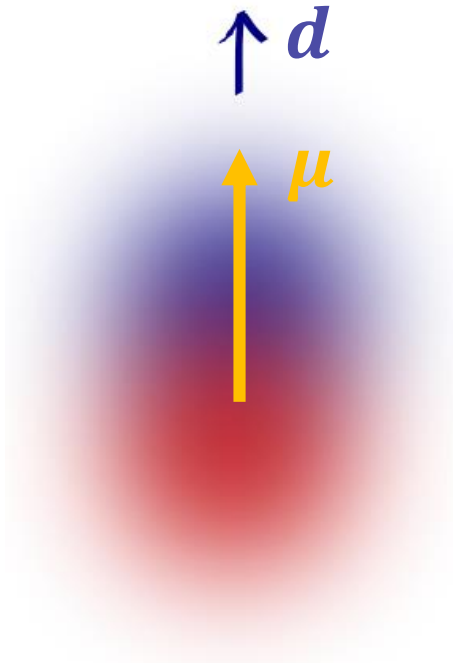


So how can we access the neutron's EDM?



$$H = -\mu_n \frac{\vec{S}}{S} \cdot \vec{B} - d_n \frac{\vec{S}}{S} \cdot \vec{E}$$

Measure the associated transition frequency!



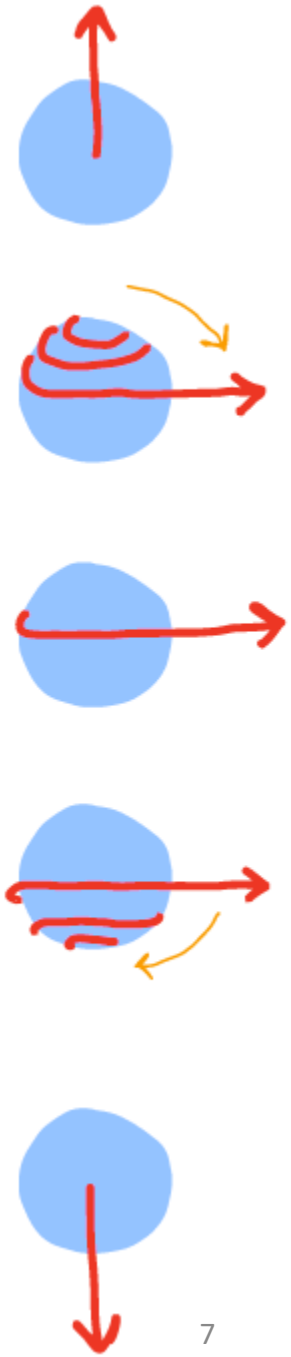
$$hf_{\uparrow\uparrow} = 2(\underbrace{\mu_n B}_{} + \underbrace{d_n E}_{})$$

n2EDM: ≈ 29 Hz ≈ 7 nHz

$$H = -\mu_n \frac{\vec{S}}{S} \cdot \vec{B} - d_n \frac{\vec{S}}{S} \cdot \vec{E}$$

Use Ramsey's technique to measure f

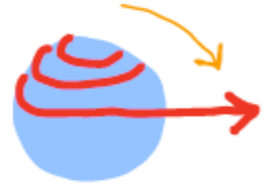
Spin-polarized neutron

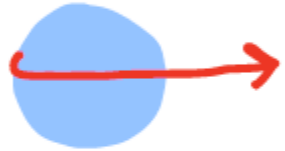


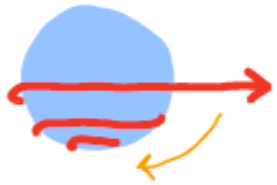
Use Ramsey's technique to measure f

Spin-polarized neutron

Apply "$\pi/2$" spin-flip pulse



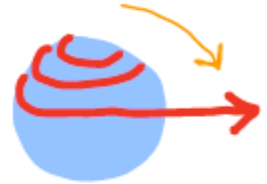




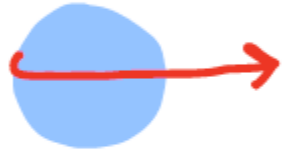
Use Ramsey's technique to measure f

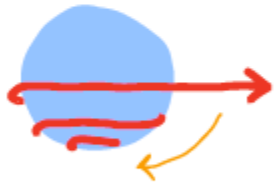
Spin-polarized neutron

Apply "$\pi/2$" spin-flip pulse



Allow free precession at $f_{\uparrow\uparrow}, f_{\uparrow\downarrow}$

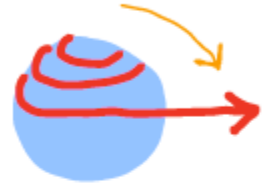




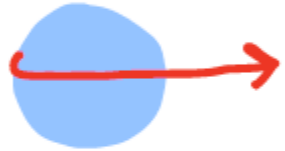
Use Ramsey's technique to measure f

Spin-polarized neutron

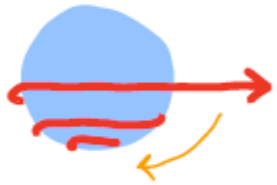
Apply "$\pi/2$" spin-flip pulse



Allow free precession at $f_{\uparrow\uparrow}, f_{\uparrow\downarrow}$



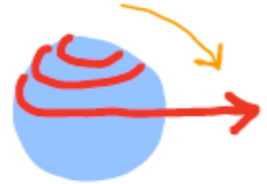
Apply "$\pi/2$" spin-flip pulse



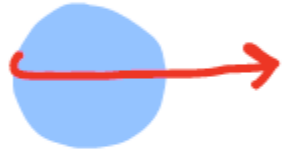
Use Ramsey's technique to measure f

Spin-polarized neutron

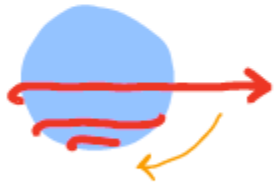
Apply "$\pi/2$" spin-flip pulse



Allow free precession at $f_{\uparrow\uparrow}, f_{\uparrow\downarrow}$

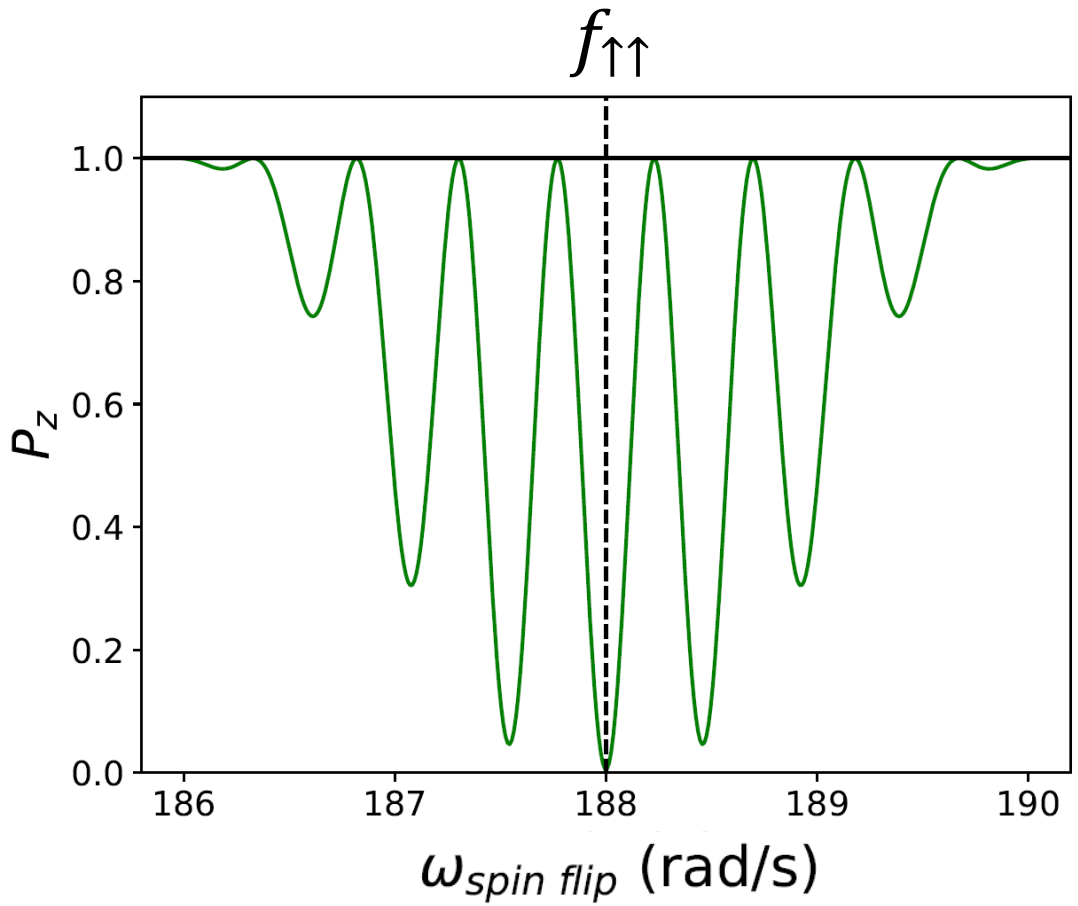


Apply "$\pi/2$" spin-flip pulse



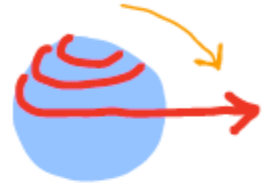
Measure final polarization

Spin-flip pulse sensitive to resonant frequency!

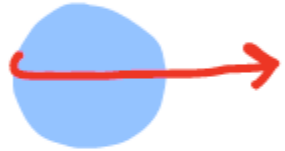


Spin-polarized neutron

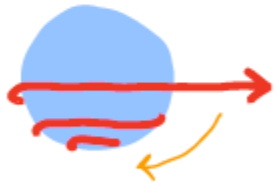
Apply "$\pi/2$" spin-flip pulse



Allow free precession at $f_{\uparrow\uparrow}, f_{\uparrow\downarrow}$



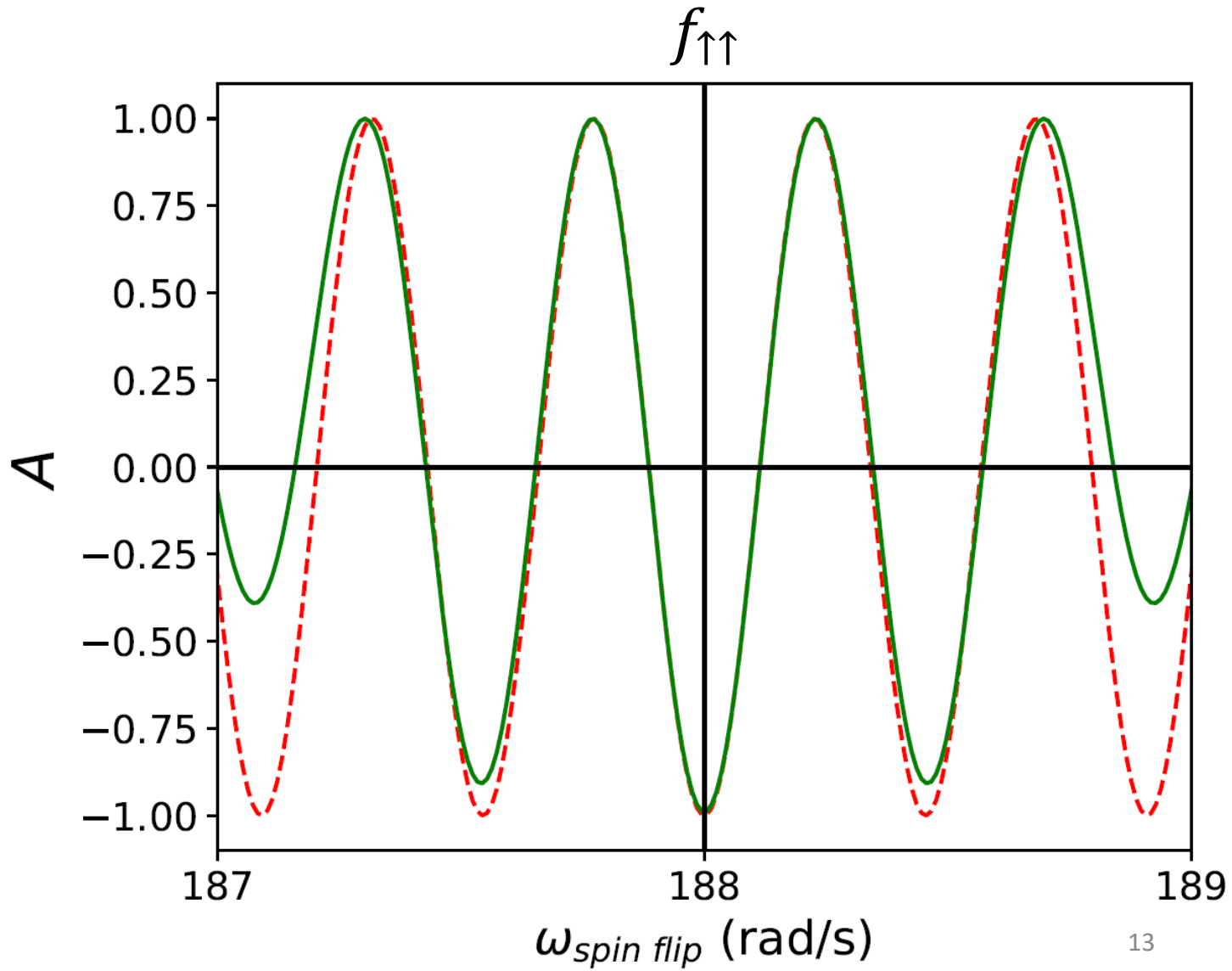
Apply "$\pi/2$" spin-flip pulse



Measure final polarization

…and if we measure both spin-states of UCNs

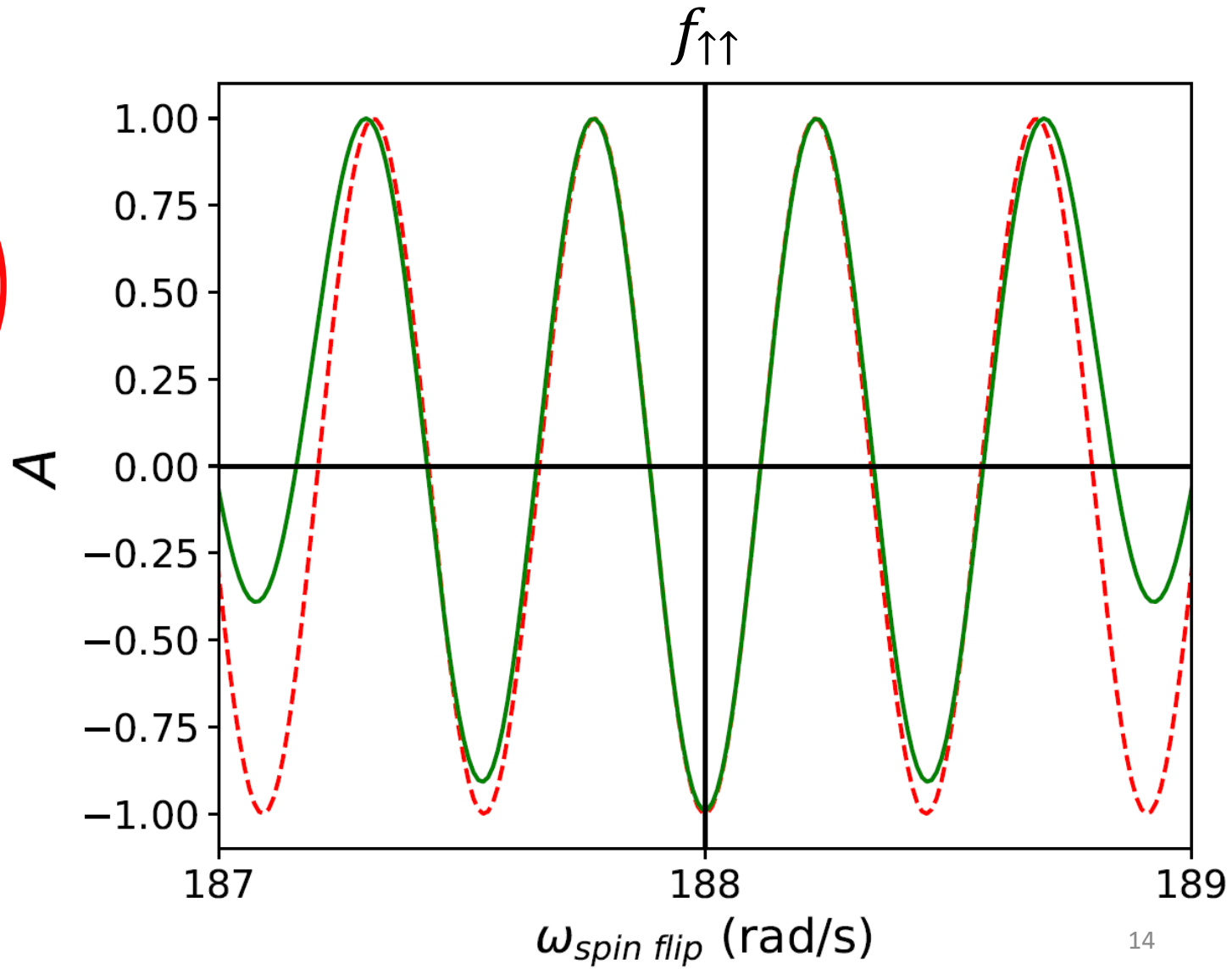
$$A \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



…and if we measure both spin-states of UCNs

$$A \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

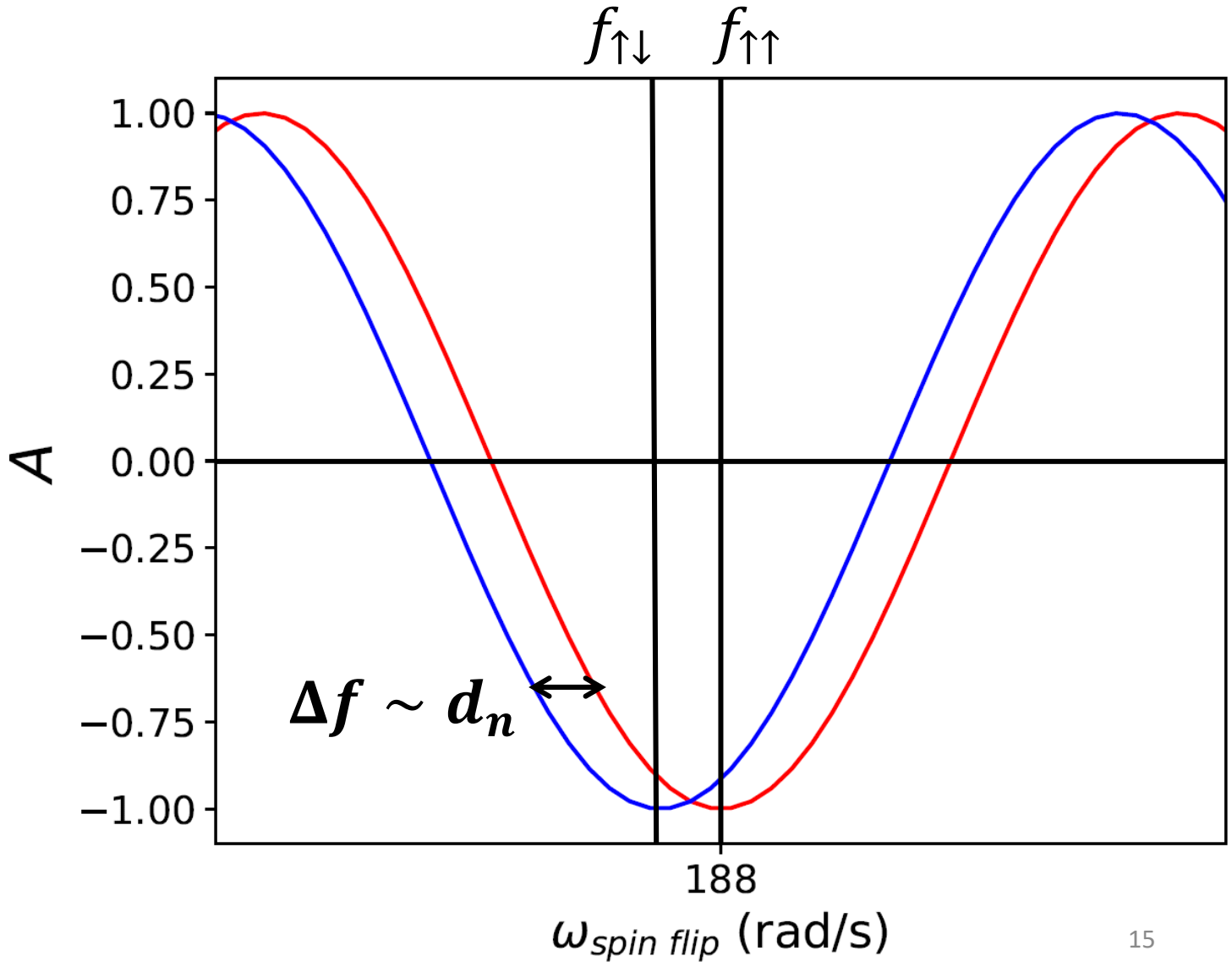
$$\approx -\alpha \cos\left(\pi \frac{f_{\text{spin flip}} - \mathrm{f}_{\uparrow\uparrow}}{v}\right)$$



…and if we flip the electric field, we can access d_n!

$$hf_{\uparrow\uparrow} = 2(\mu_n B + d_n E)$$

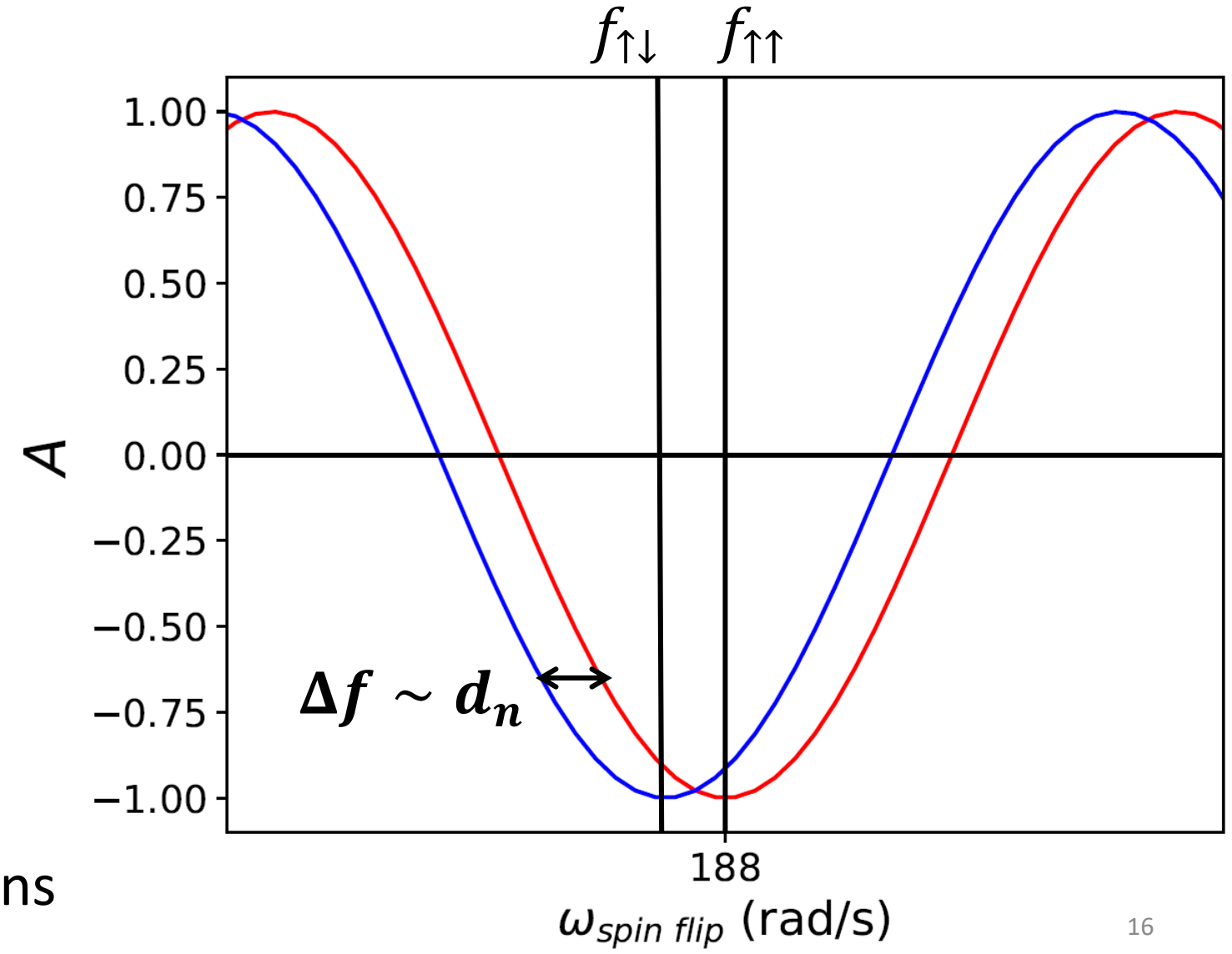
$$hf_{\uparrow\downarrow} = 2(\mu_n B - d_n E)$$



…and if we flip the electric field, we can access d_n!

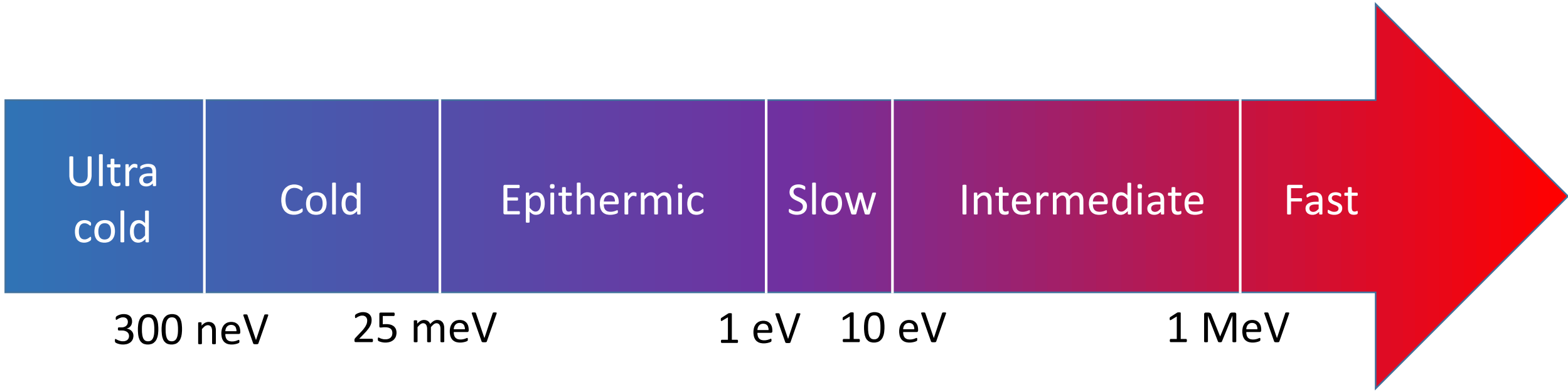
$$hf_{\uparrow\uparrow} = 2(\mu_n B + d_n E)$$

$$hf_{\uparrow\downarrow} = 2(\mu_n B - d_n E)$$

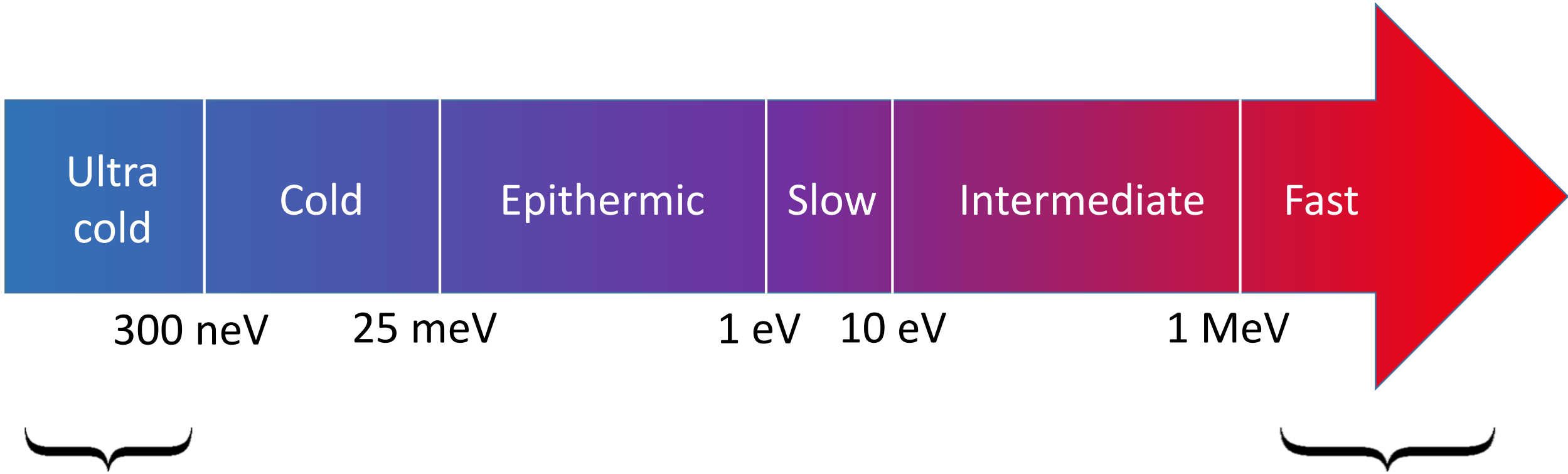


But we need STORABLE neutrons → Ultra cold neutrons

Ultra-**c**old **n**eutrons - UCNs



Ultra-**c**old **n**eutrons - UCNs

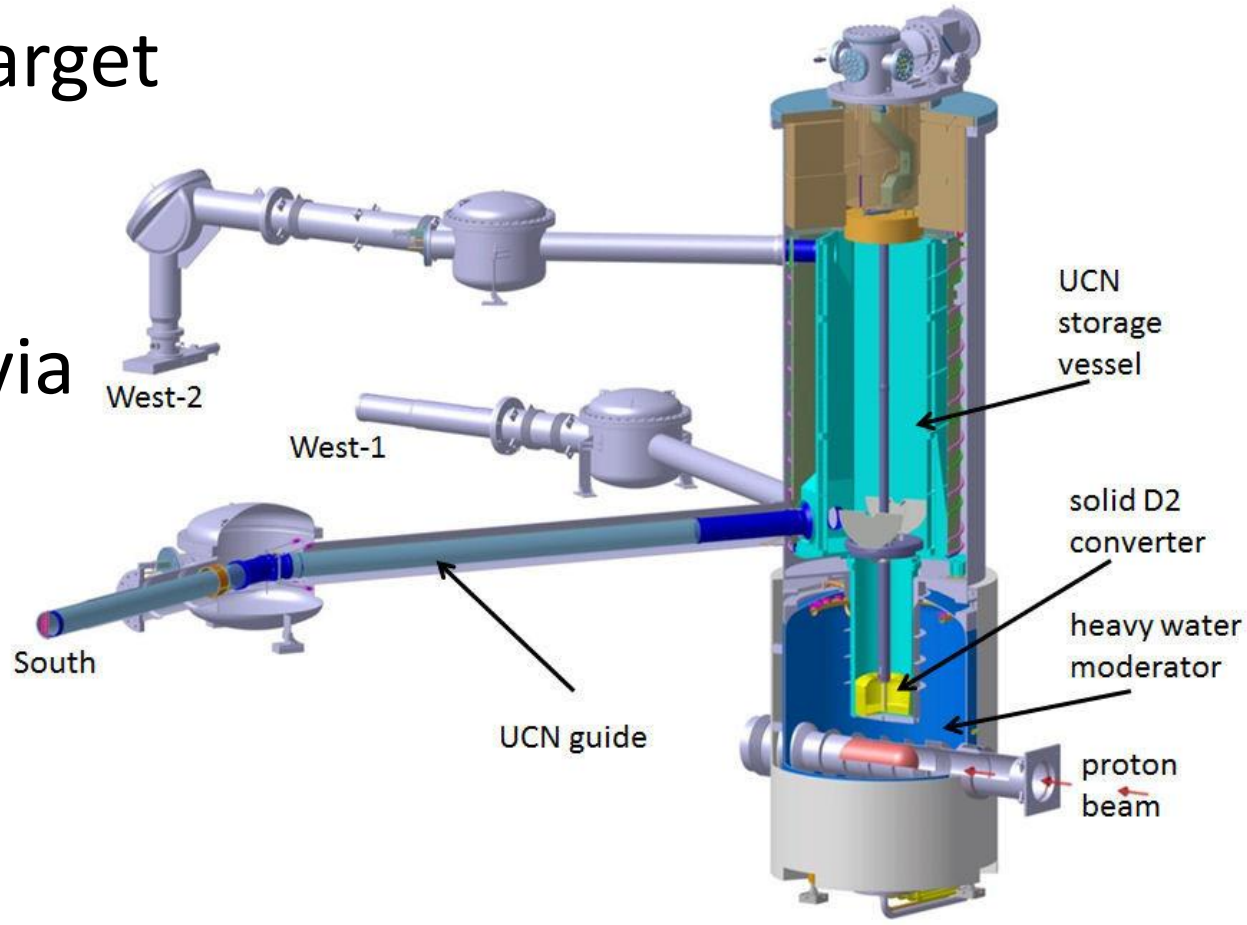


Where we do experiments

Typical production energy

Producing UCNs at Paul Scherrer Institut (PSI)

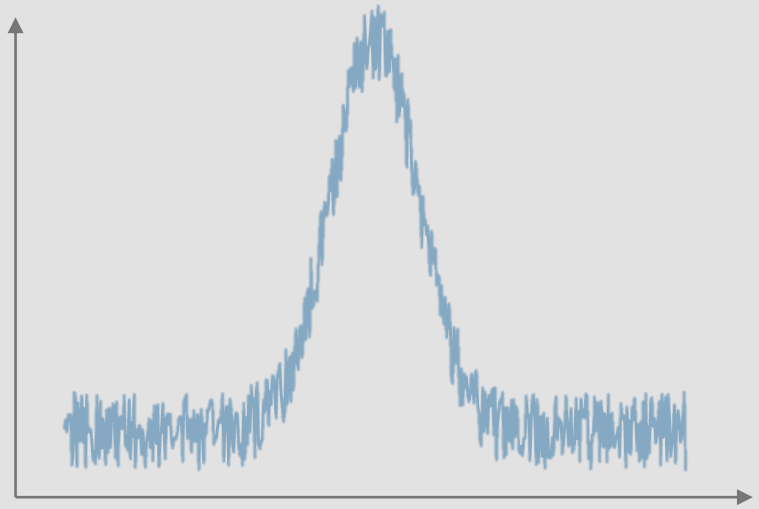
- Proton beam on Pb spallation target (~8 n/p)
- Moderated down to ultra-cold via heavy water & solid D2
- Extracted to experimental hall



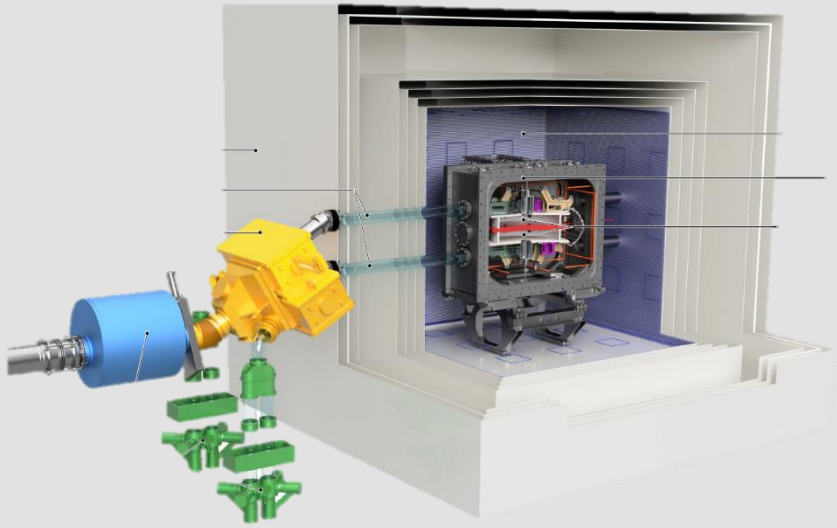
PSI isn't the only one after $10^{-27}\ e\ \mathrm{cm}$

- PanEDM at ILL
- LANL nEDM
- TUCAN at TRIUMF
- nEDM SNS
- BeamEDM at ILL
- J-PARC
- n2EDM@PSI

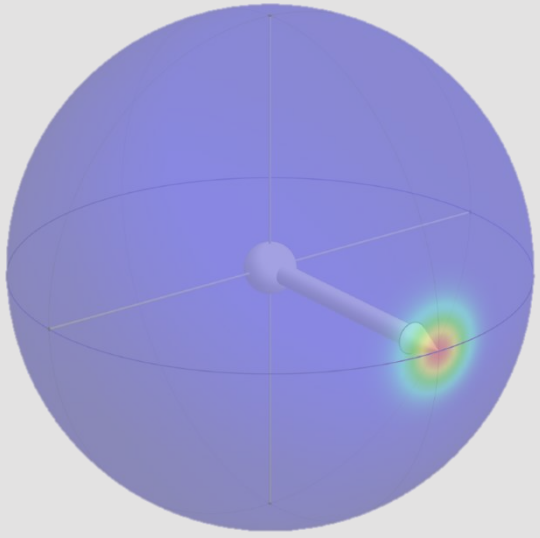
1) Measuring nEDM



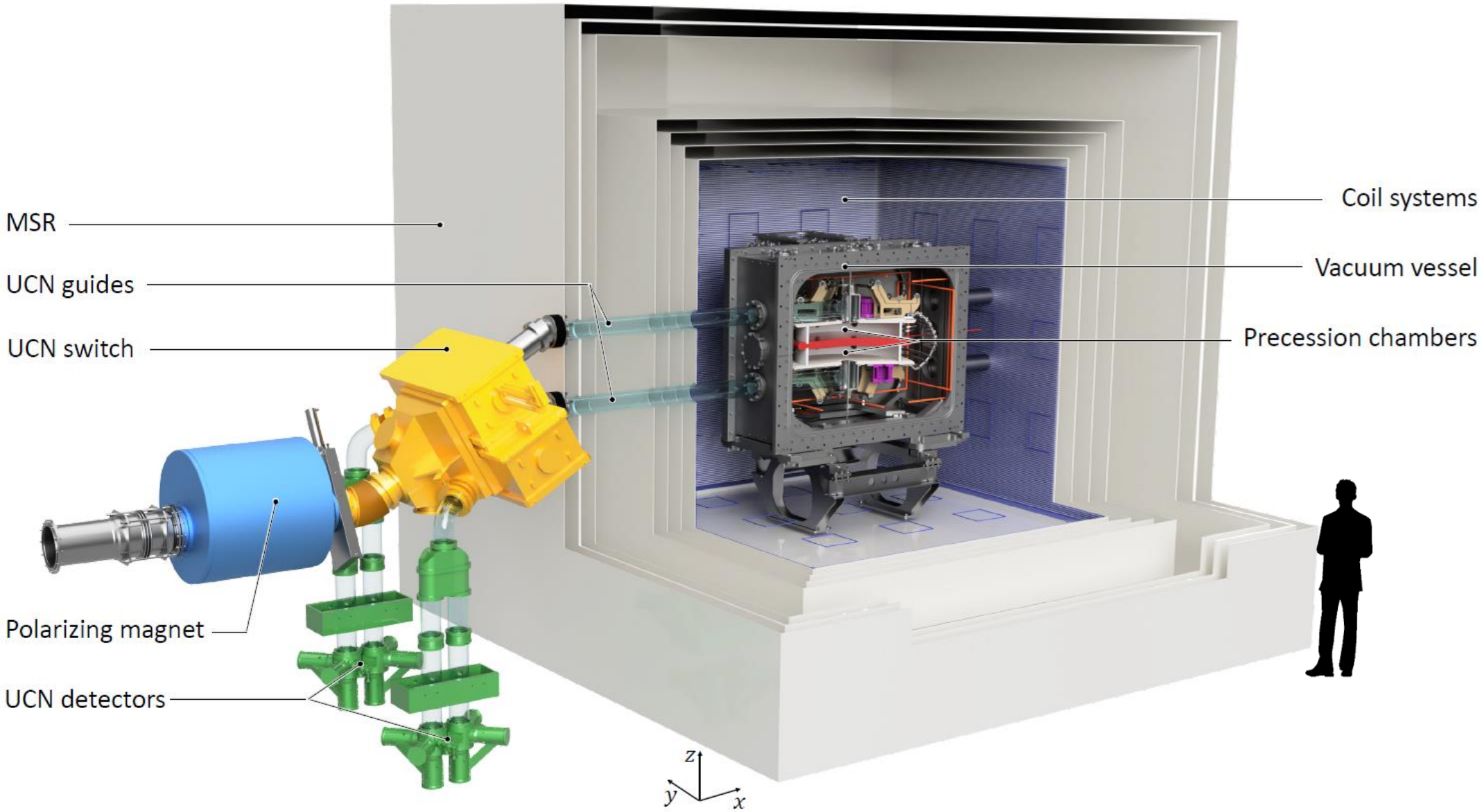
2) n2EDM at PSI



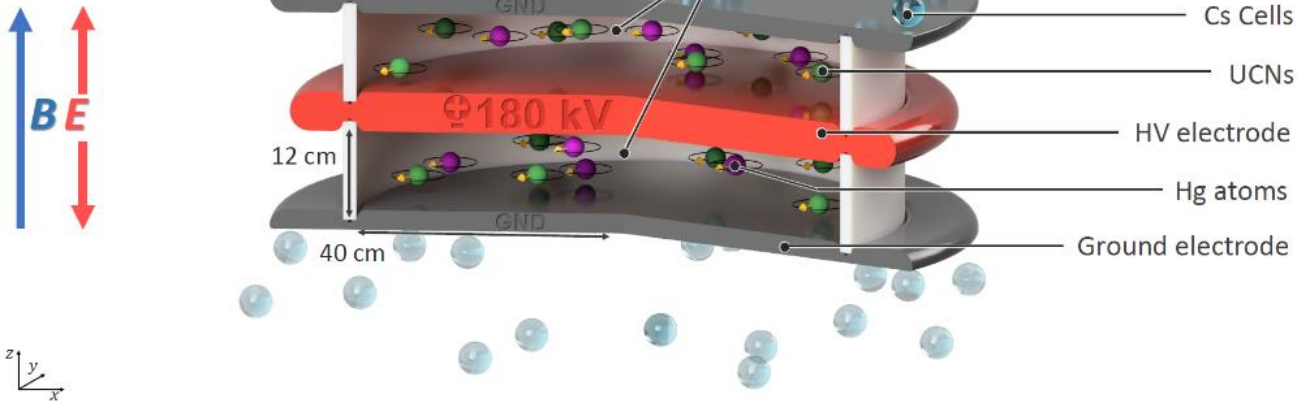
3) Quantum frontier with n3EDM?



n2EDM at PSI


MSR
UCN guides
UCN switch
Polarizing magnet
UCN detectors
Coil systems
Vacuum vessel
Precession chambers
z
y
x

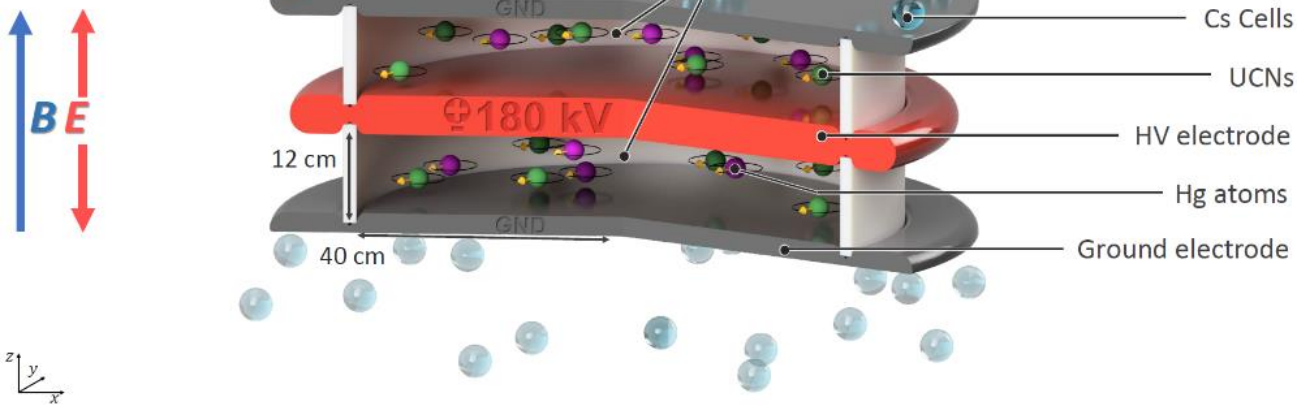
n2EDM at PSI

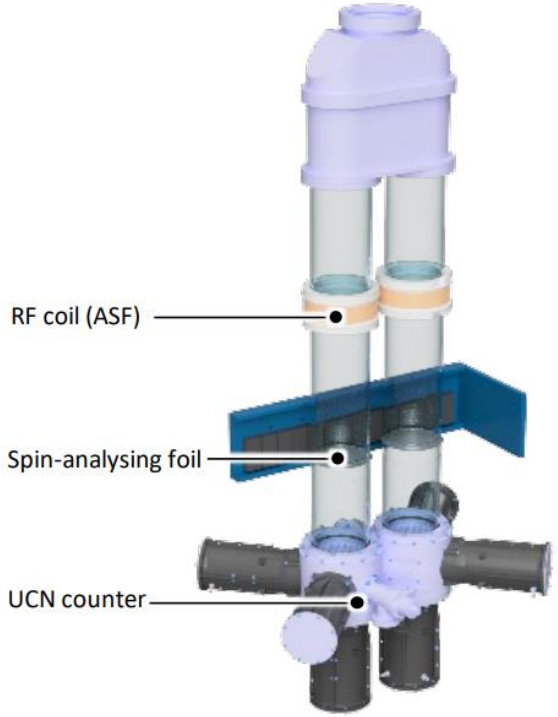


$$hf_{\uparrow\uparrow} = 2(\mu_n B + d_n E)$$
$$hf_{\uparrow\downarrow} = 2(\mu_n B - d_n E)$$

Simultaneous measurement from Top and Bottom chamber

n2EDM at PSI

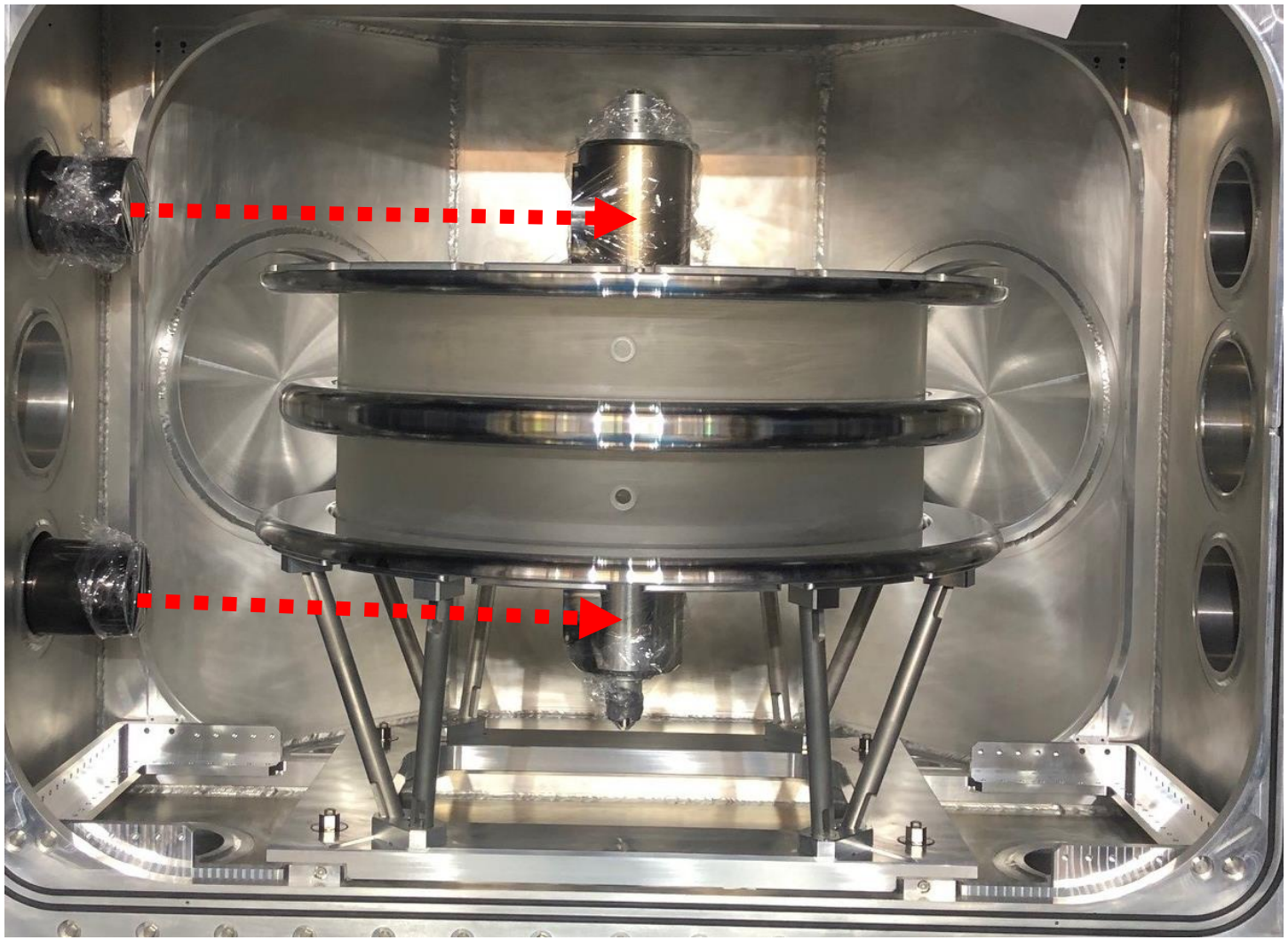




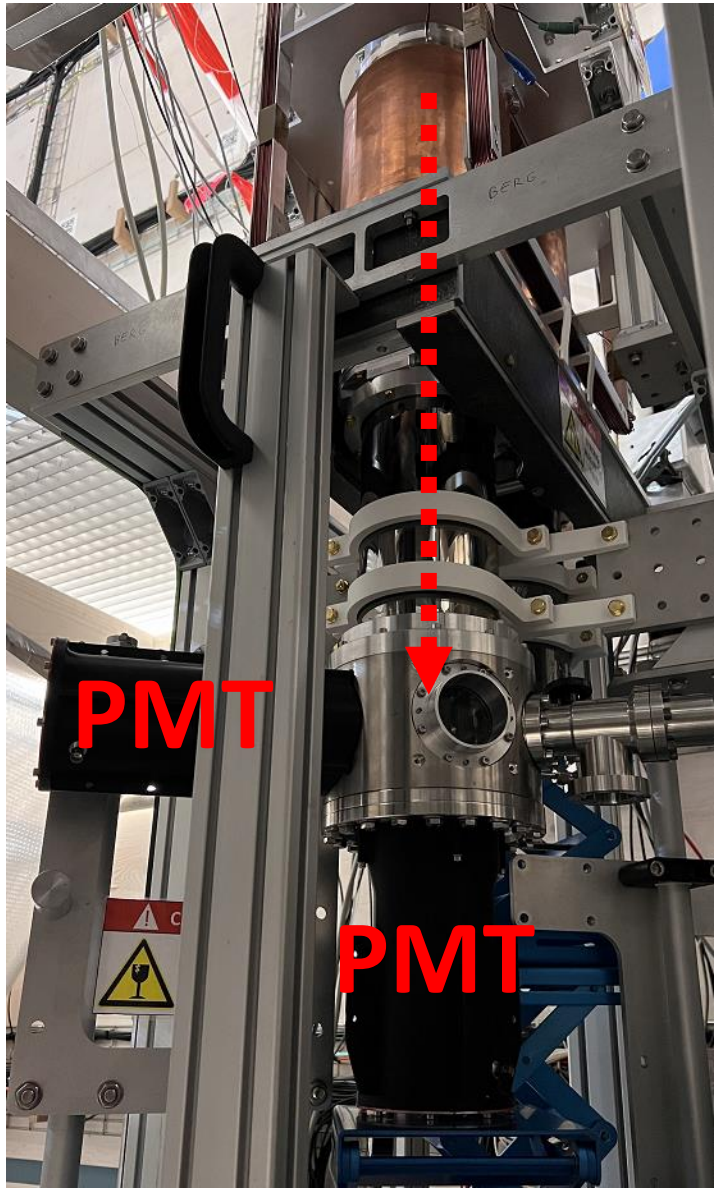
$$hf_{\uparrow\uparrow} = 2(\mu_n B + d_n E)$$
$$hf_{\uparrow\downarrow} = 2(\mu_n B - d_n E)$$

} Simultaneous measurement from Top and Bottom chamber

HV Stack



Spin detector



Actually extracting the nEDM

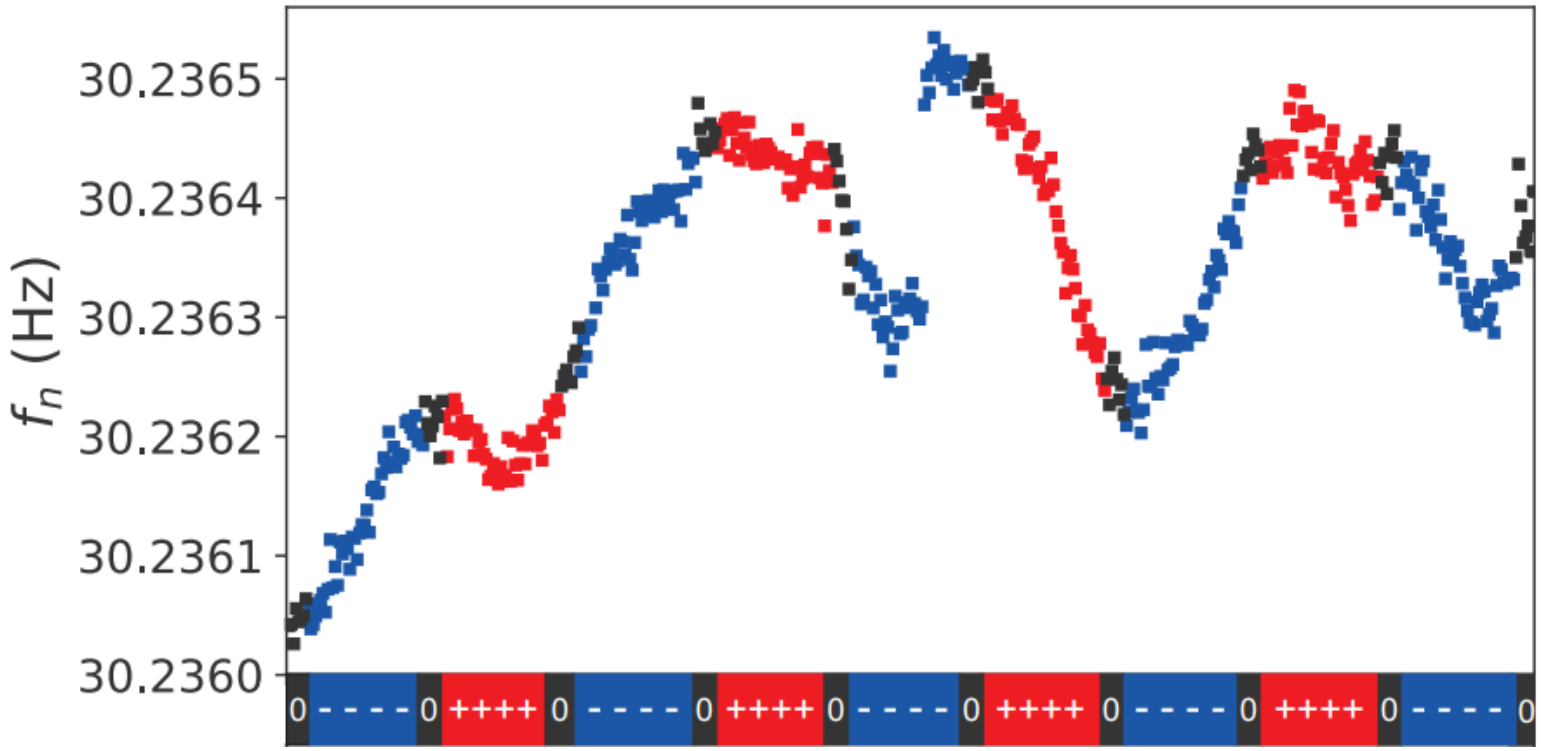
$$f = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} E$$

Even if we take differences of frequencies, drifts still happen!

Actually extracting the nEDM

$$f = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} E$$

Even if we take differences of frequencies, drifts still happen!



Actually extracting the nEDM

$$f = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} E$$

Even if we take differences of frequencies, drifts still happen!

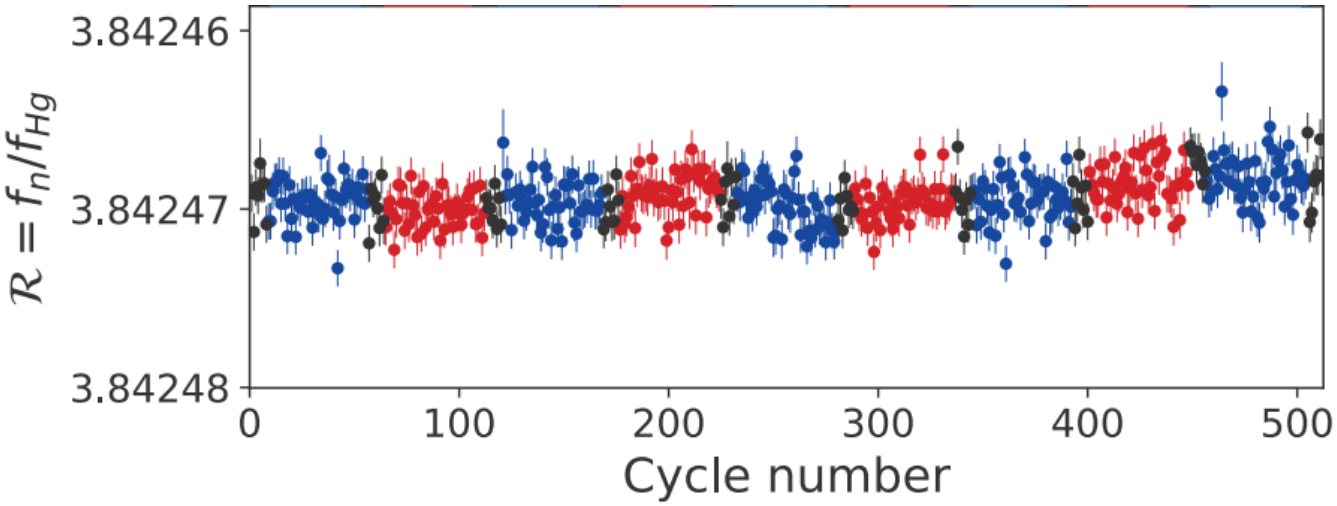
$$R \equiv \frac{f}{f_{\mathrm{Hg}}} = \frac{\mu_n}{\mu_{\mathrm{Hg}}} \pm \frac{2E}{h f_{\mathrm{Hg}}} d_n$$

Take a ratio with a “co-magnetometer”, Hg!

Actually extracting the nEDM

$$f = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} E$$

$$R \equiv \frac{f}{f_{\mathrm{Hg}}} = \frac{\mu_n}{\mu_{\mathrm{Hg}}} \pm \frac{2E}{h f_{\mathrm{Hg}}} d_n$$



Take a ratio with a “co-magnetometer”, Hg!

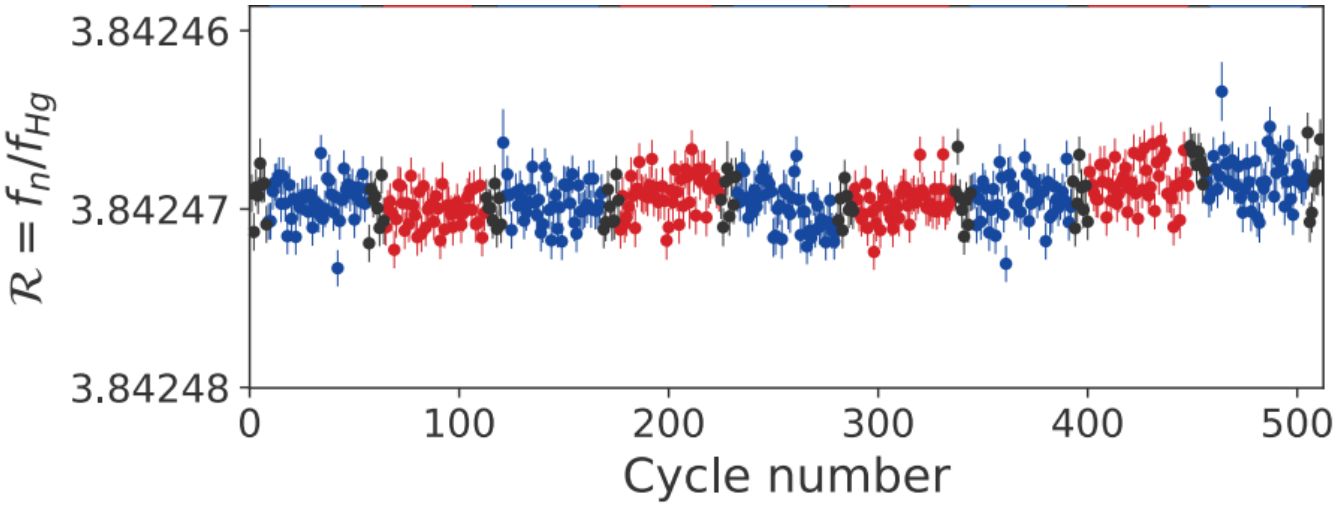
Actually extracting the nEDM

$$f = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} E$$

$$R \equiv \frac{f}{f_{\mathrm{Hg}}} = \frac{\mu_n}{\mu_{\mathrm{Hg}}} \pm \frac{2E}{h f_{\mathrm{Hg}}} d_n$$

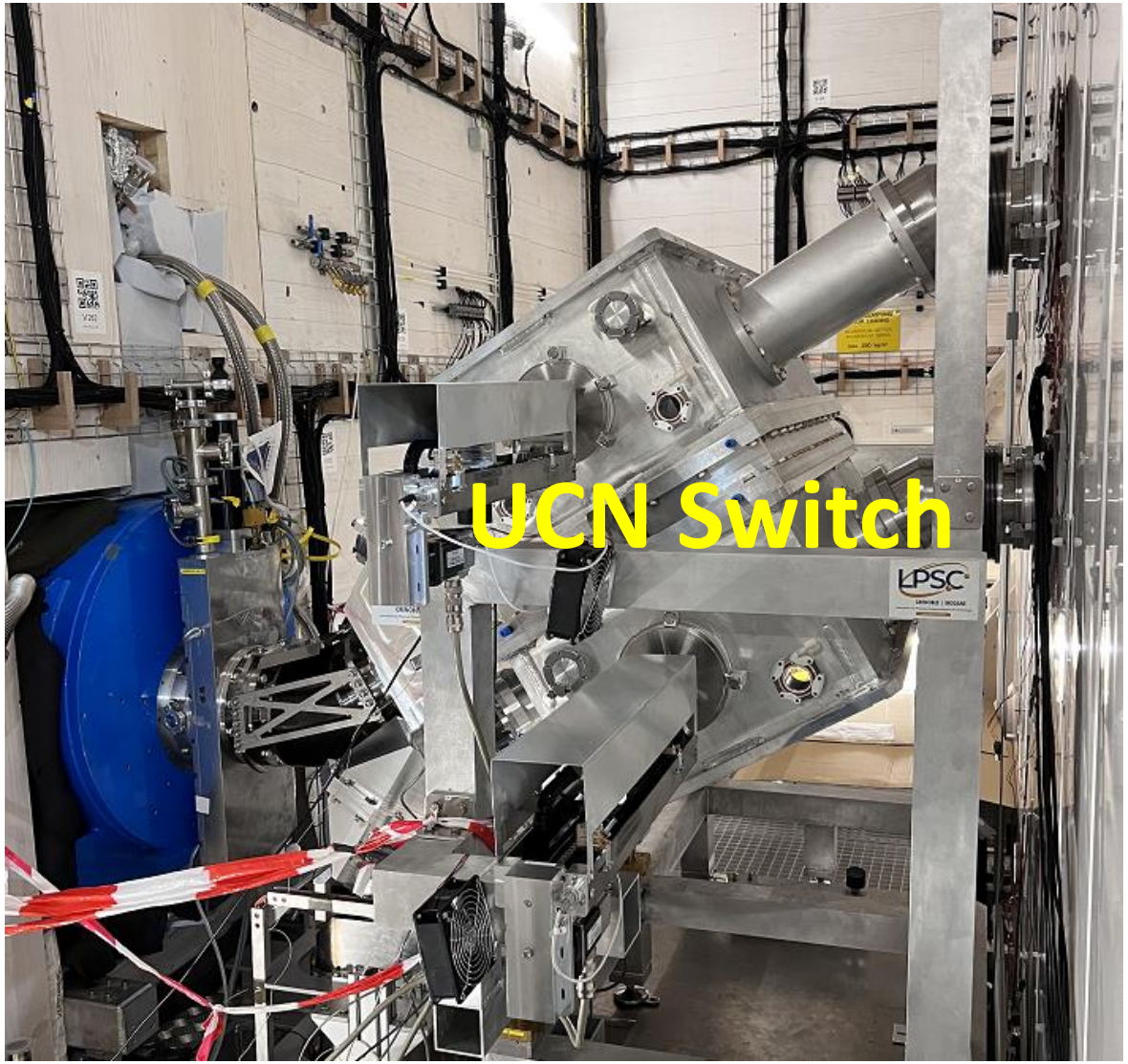
$$d_n = \frac{h f_{\mathrm{Hg}}}{4E} \left(R_{\uparrow\uparrow}^{\mathrm{Top}} - R_{\uparrow\downarrow}^{\mathrm{Bottom}}\right)$$

(can even flip fields on Top/Bottom)



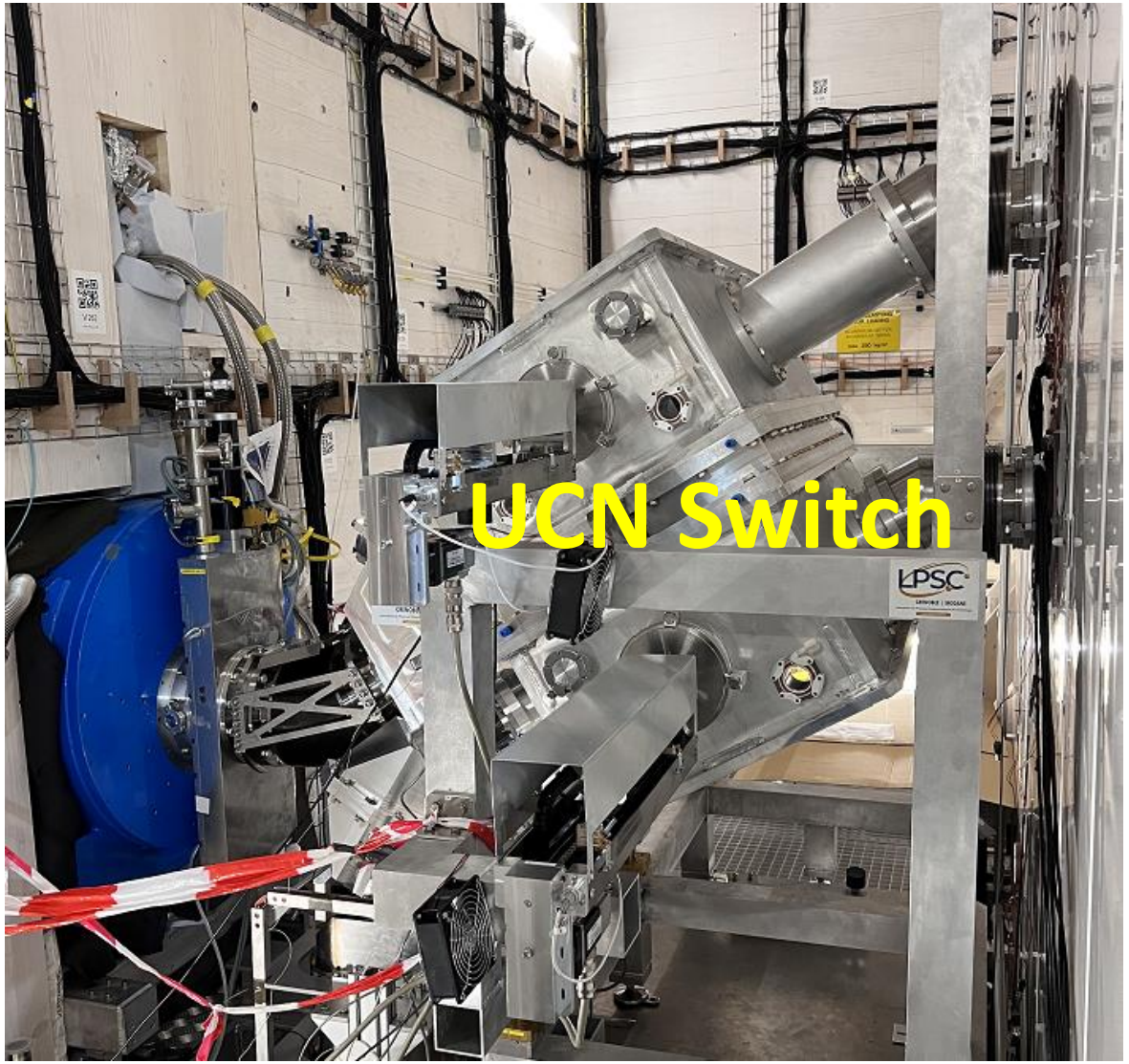
Recent successes

- UCN switch installed
- Spin-analyzing detectors installed
- HV stack installed
- MSR degaussing optimized
- AMS commissioned
- Magnetic field characterized

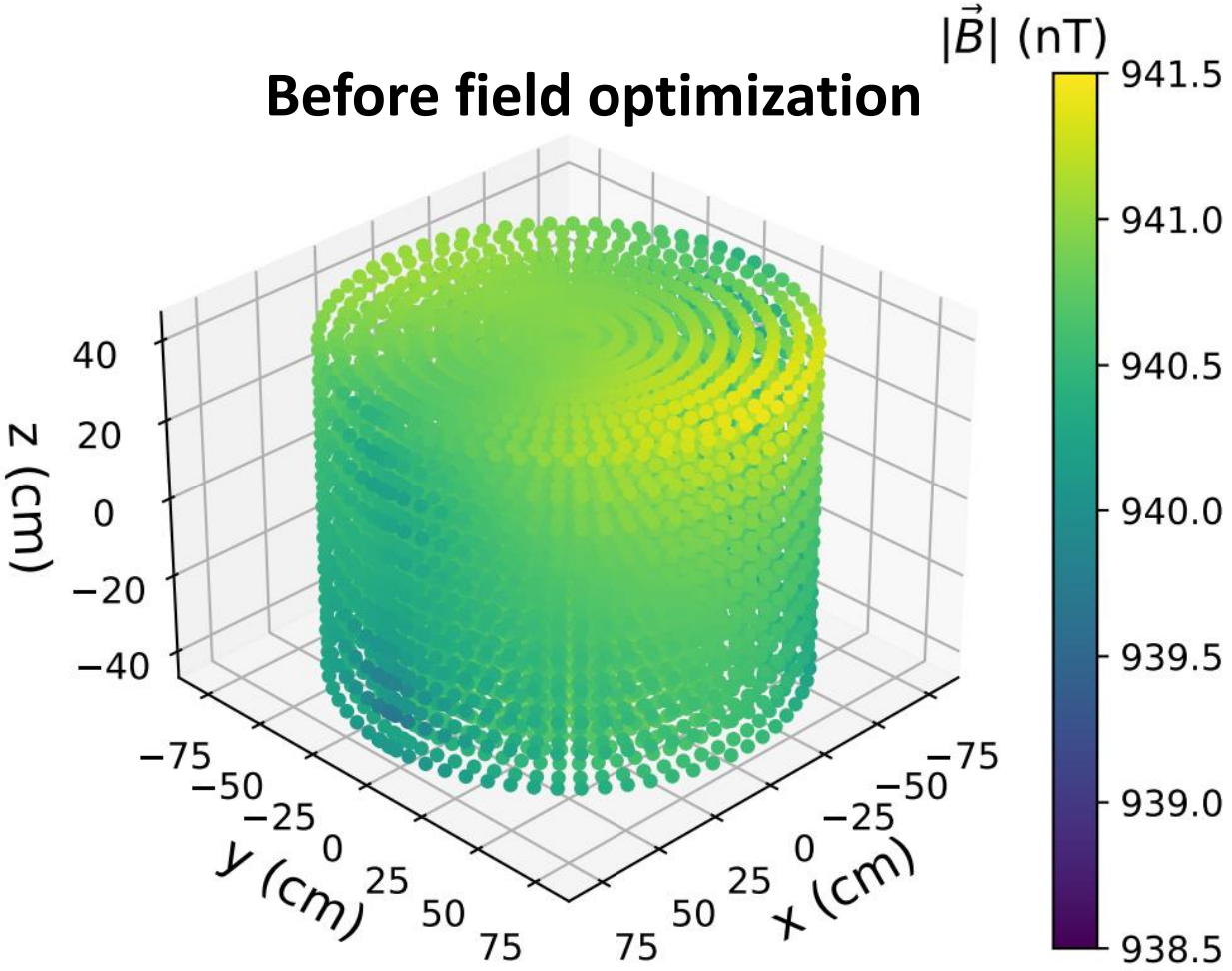


Recent successes

- UCN switch installed
- Spin-analyzing detectors installed
- HV stack installed
- MSR degaussing optimized
- **AMS commissioned**
- **Magnetic field characterized**

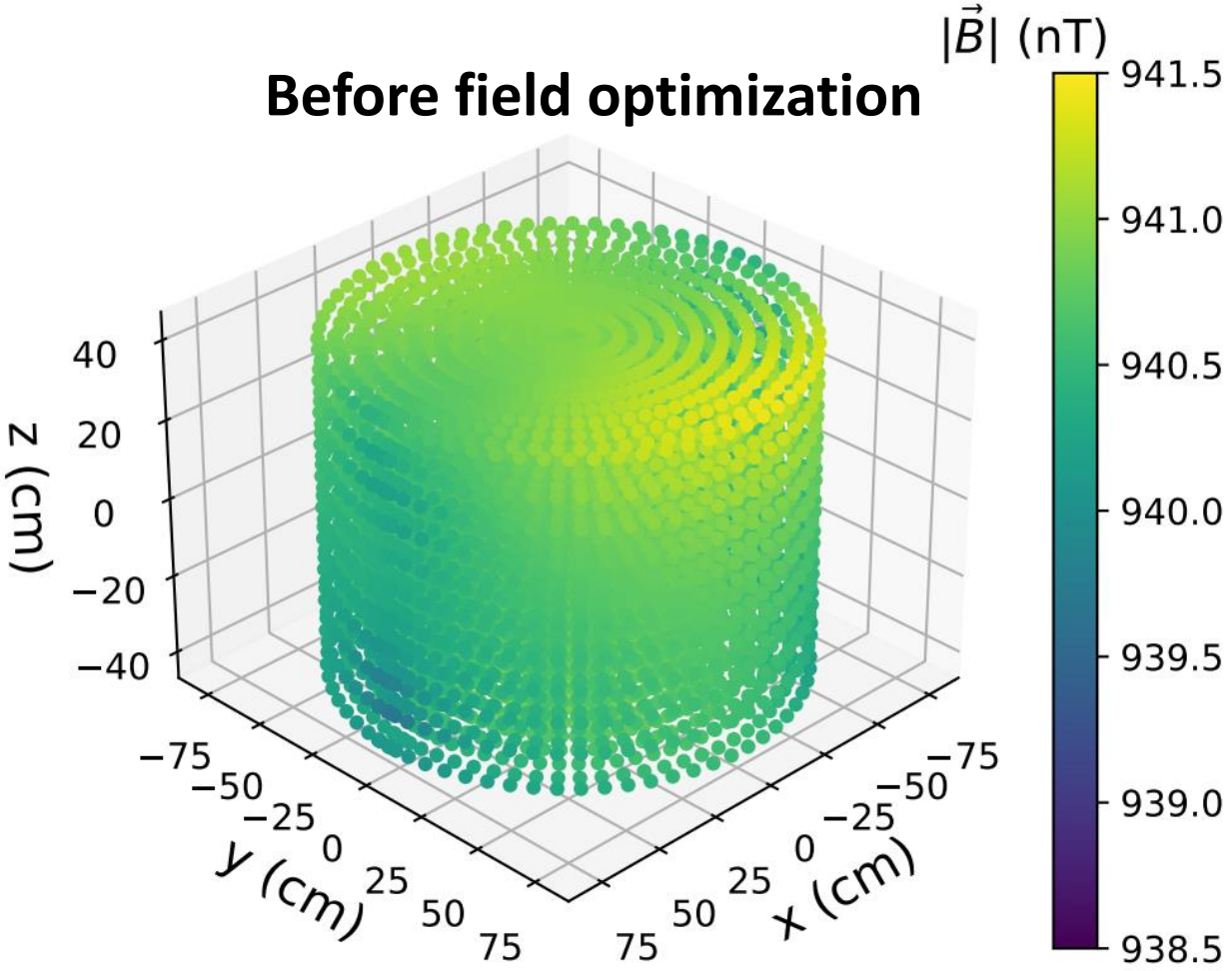


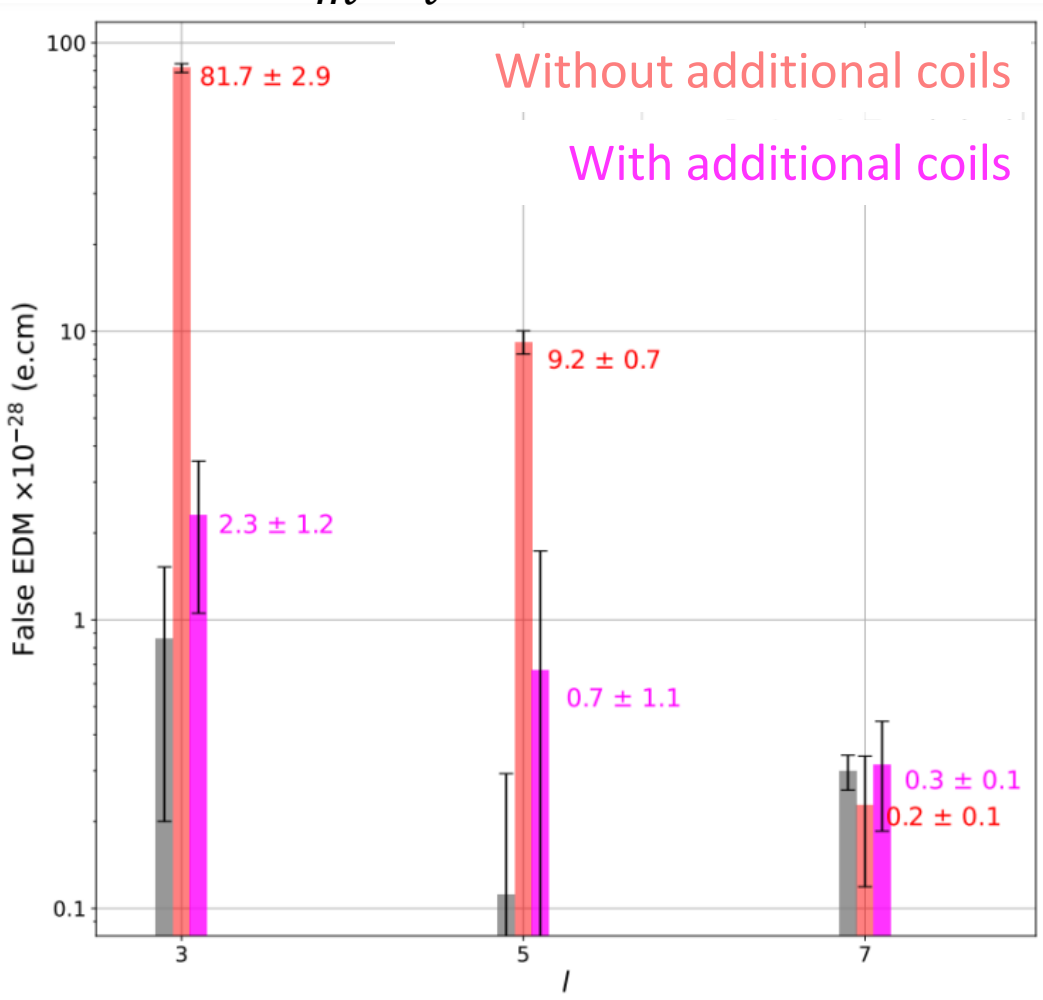
Magnetic field generation



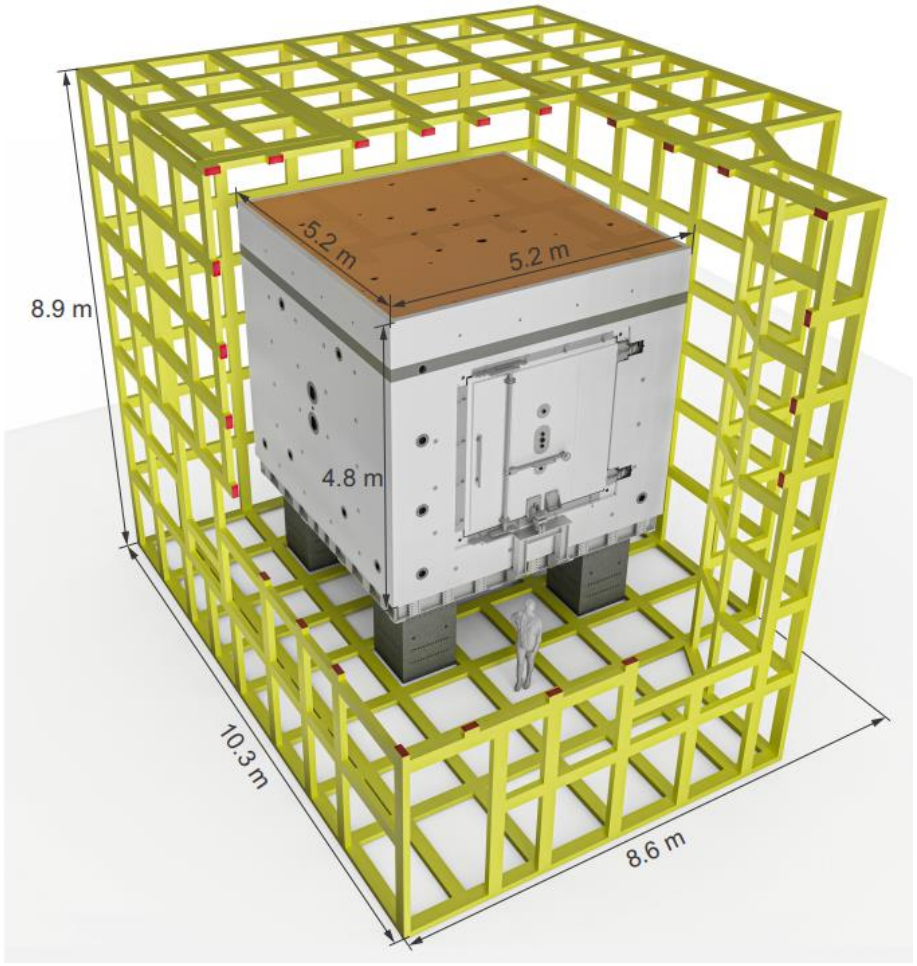
Magnetic field generation

$$B(\rho,\phi,z) \sim \sum_m \sum_l G_{lm}\widehat{\Pi}_{lm}(\rho,z)\cos(m\phi)$$

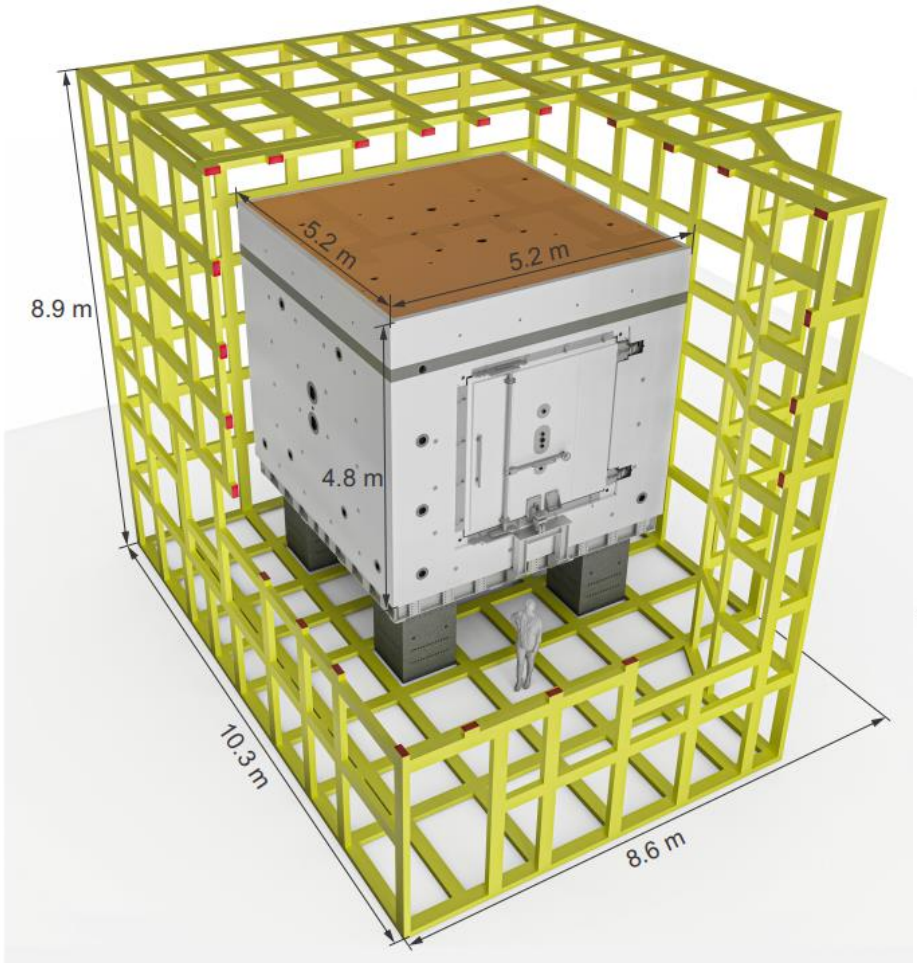




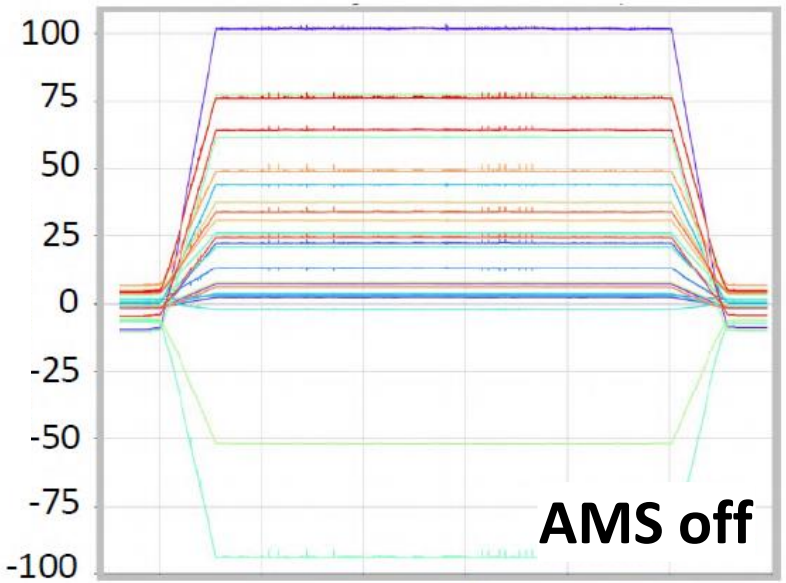
Active magnetic shield (AMS)

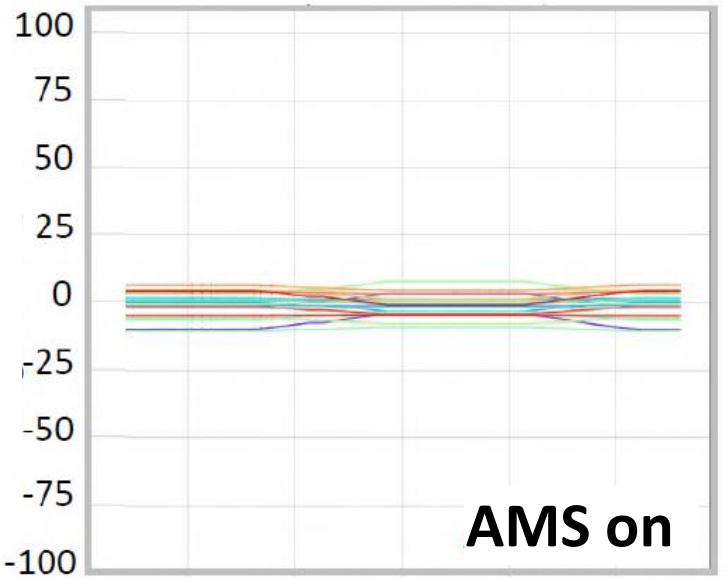


Active magnetic shield (AMS)



$B_{\text{outside MS}R}\ (\mu\text{T})$

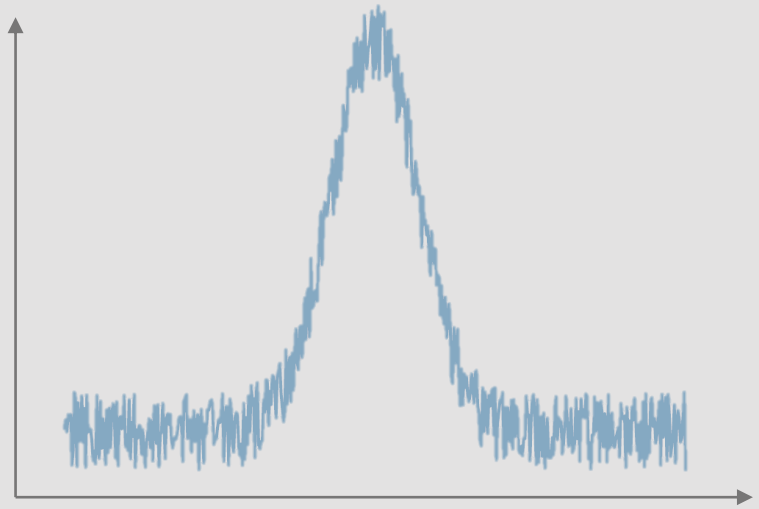




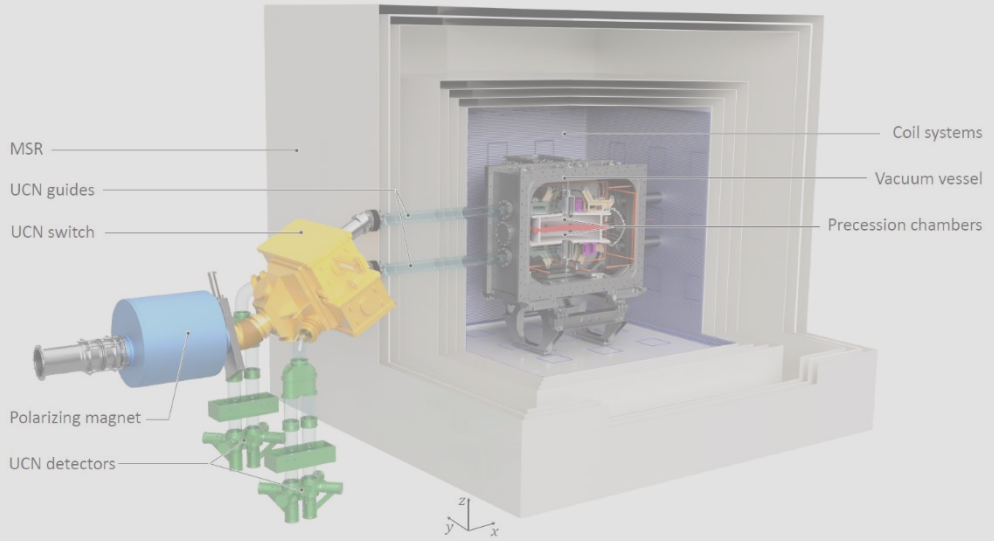
Timeline of n2EDM

- First operation with UCNs later this month
- Spin-polarized UCNs in September
- n2EDM production data next year!

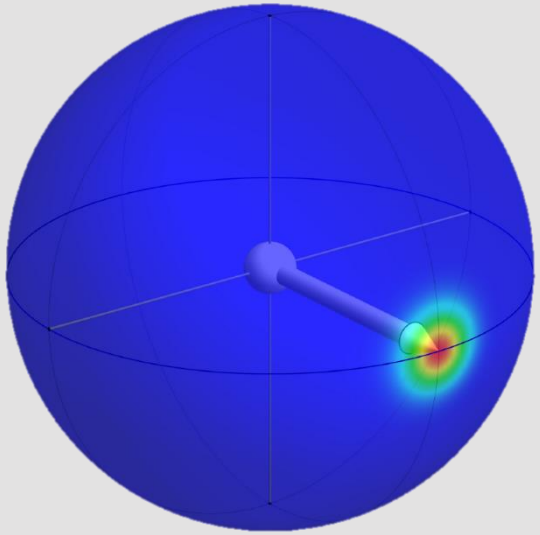
1) Measuring nEDM



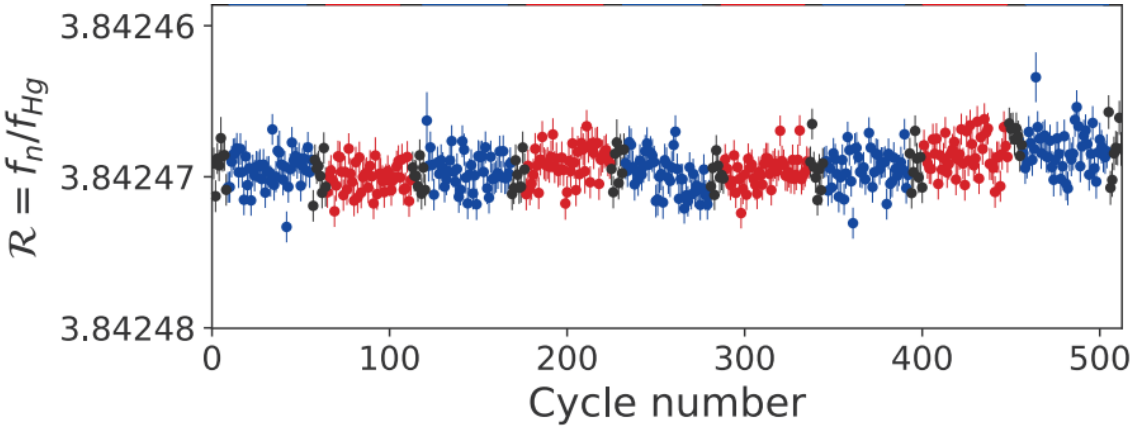
2) n2EDM at PSI



3) Quantum frontier with n3EDM?

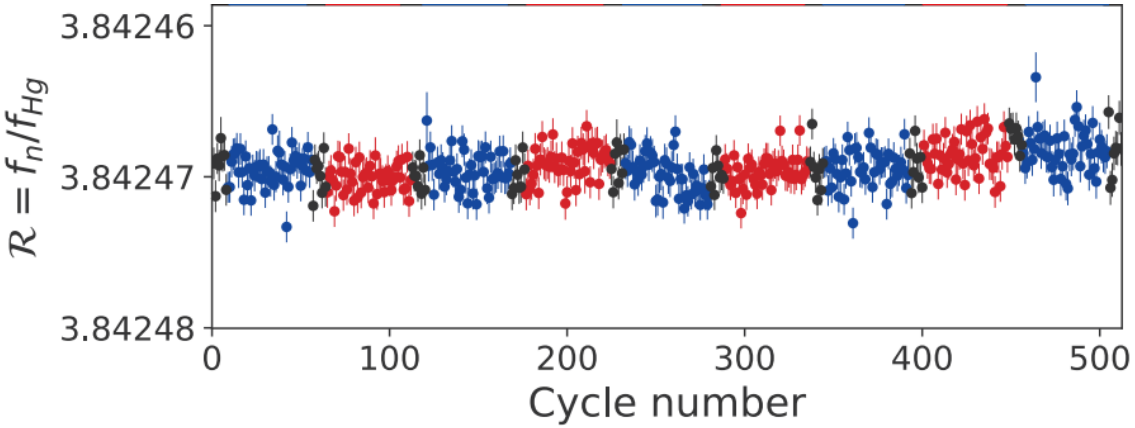


Hg co-magnetometer



Increased sensitivity to B field = increased EDM sensitivity

Hg co-magnetometer



Increased sensitivity to B field = increased EDM sensitivity

- Atomic vapor of Hg polarized by optical pumping
- Hg enters into chamber with UCNs
- $\pi/2$ pulse to start Hg precession
- Photodetector records probe beam absorption → f_{Hg}

Limitations of this approach

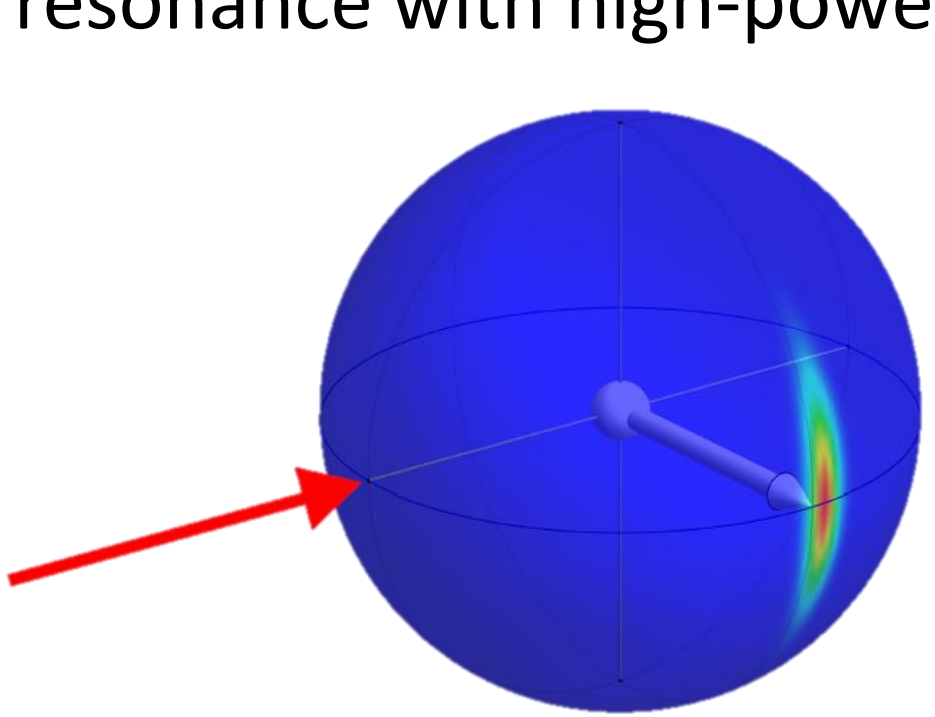
- Low-power of probe beam (long T_2 time but shot-noise limited)

Current shot-noise limit is ~ 8fT in 180s

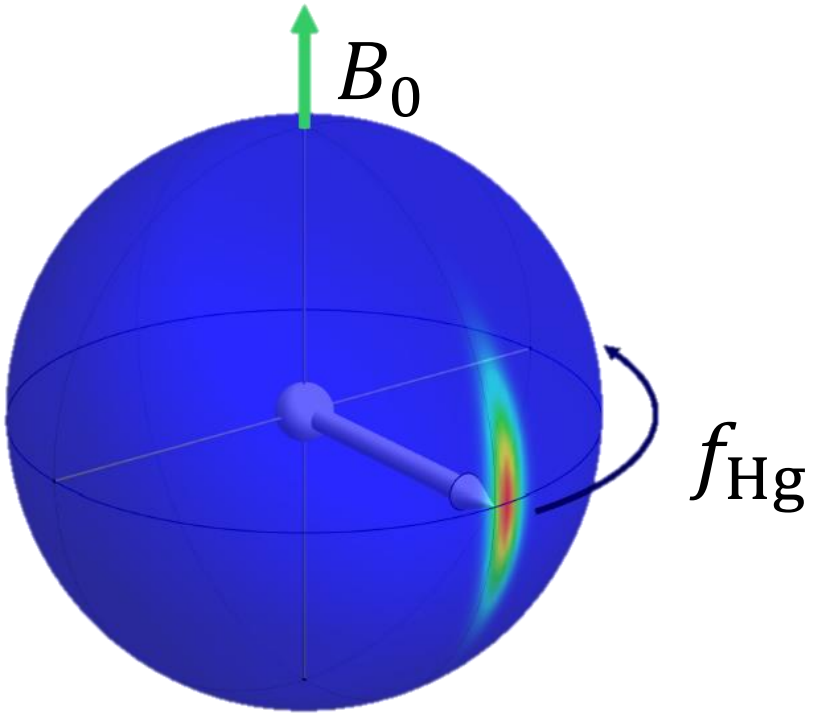
Increased sensitivity to B field = increased EDM sensitivity

Towards spin-projection noise limit

Instead of low-power absorption, measure Faraday rotation far off-resonance with high-power

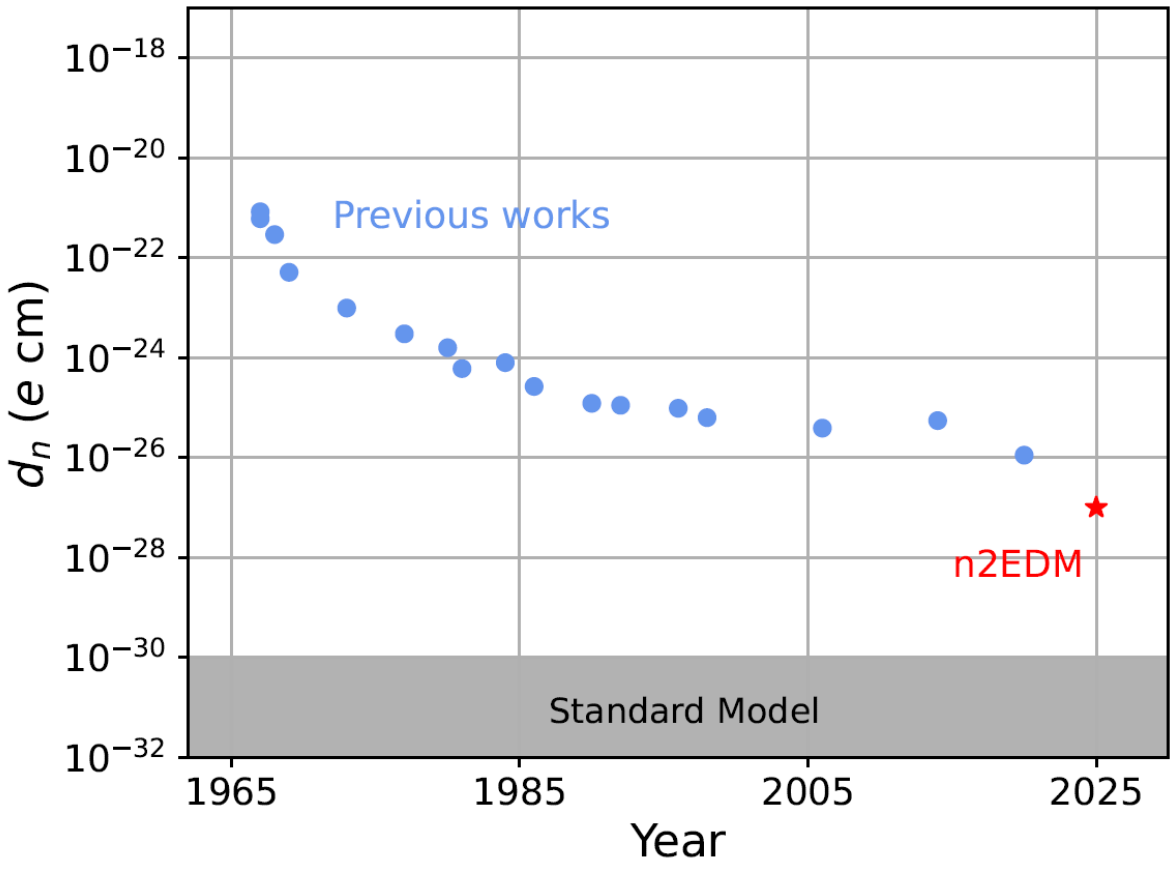


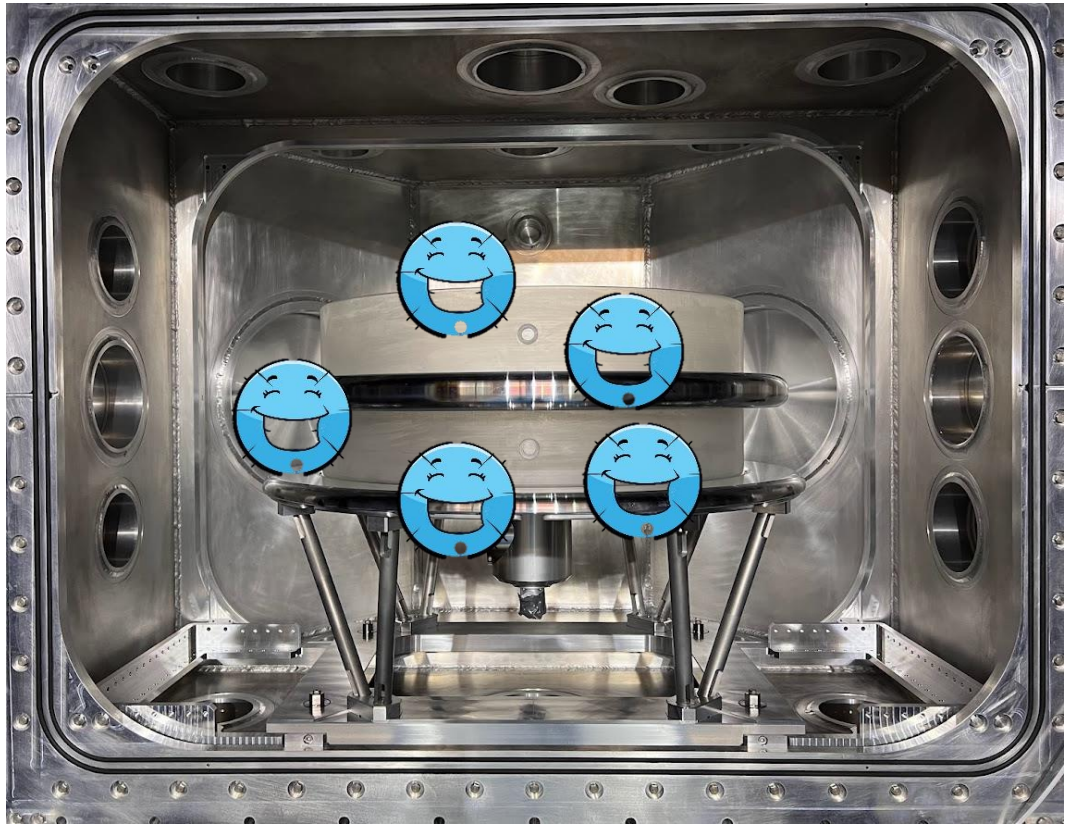
ϕ_1



$\phi_2(t_{\mathrm{precess}})$

But this time, next year, we'll be on our way!





Thanks!

Efrain Segarra

PSI Fellow III-3i

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 884104