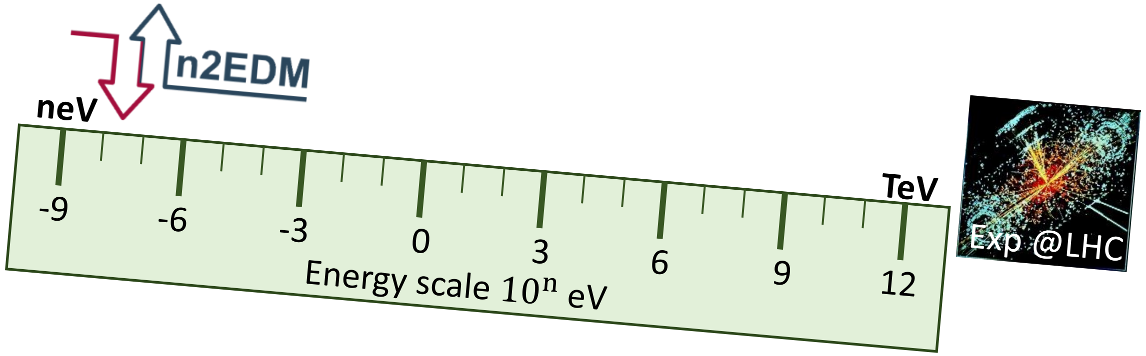
The n2EDM experiment

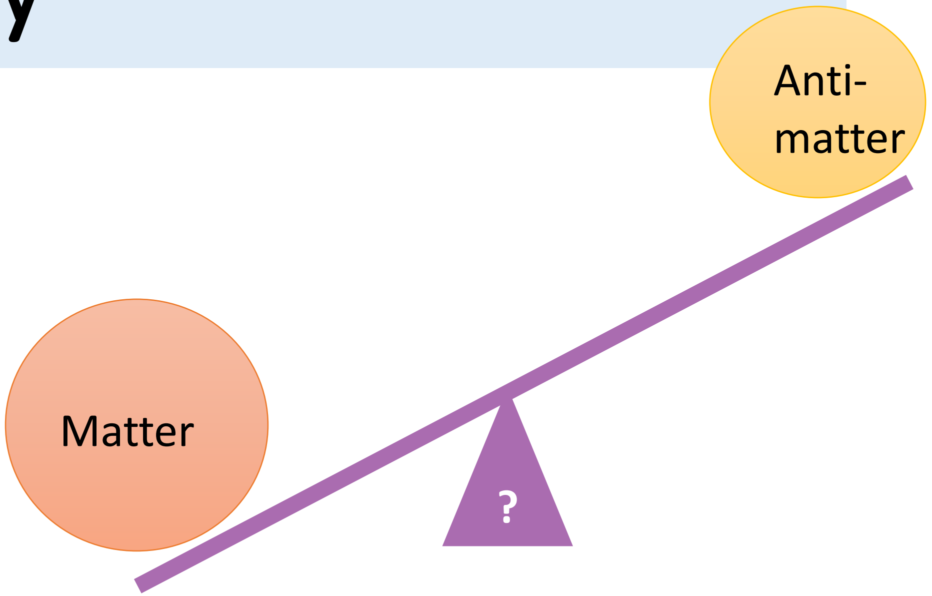
A search for new physics at the precision frontier

2024.09.11, SPS annual meeting 2024

Wenting Chen, on behalf of the nEDM collaboration



Big Puzzel: Baryon Asymmetry



Expect (derived from SM): $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$

But observed asymmetry: $\eta \approx 6 \cdot 10^{-10}$?!

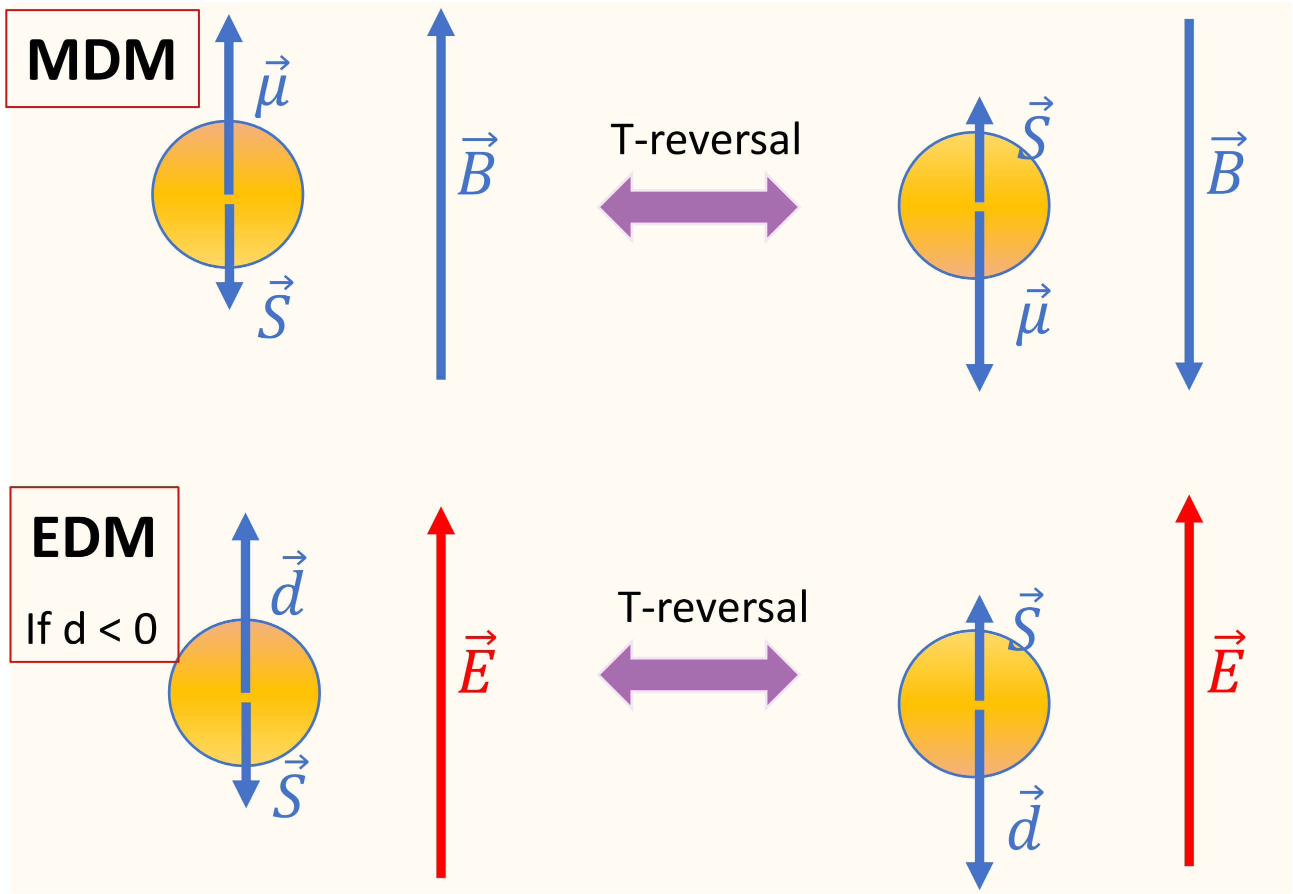
Sakharov conditions

- Baryon number violation
- C & CP-symmetry violation
- Thermal equilibrium

Start from Big bang:
$\eta = 0$

Now:
$\eta \approx 6 \cdot 10^{-10}$

Electric dipole moment violates CP symmetry



In non-relativistic regime:

$$H_{\mathrm{mag}} \sim \vec{\mu} \cdot \vec{B} \sim \mu \left(\vec{S} \cdot \vec{B}\right)$$

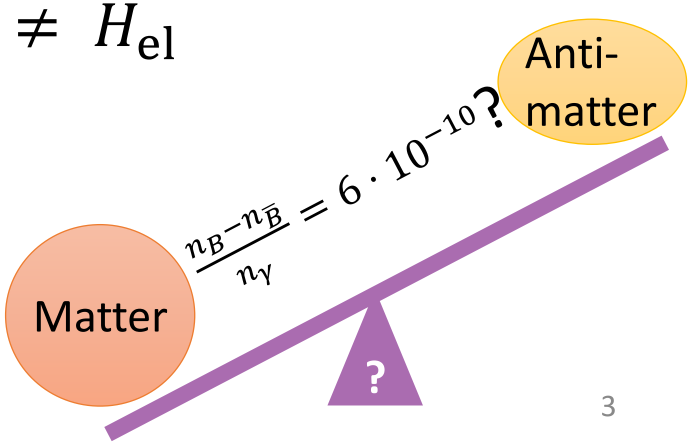
$$T H_{\mathrm{mag}} = H_{\mathrm{mag}}$$

$$H_{\mathrm{el}} \sim \vec{d} \cdot \vec{E} \sim d \left(\vec{S} \cdot \vec{E}\right)$$

$$T H_{\mathrm{el}} \neq H_{\mathrm{el}}$$

If $d \neq 0$

Violation of T — CPT theorem — Violation of CP — Baryon Asymmetry



(Potential) Sources of EDM

SM:

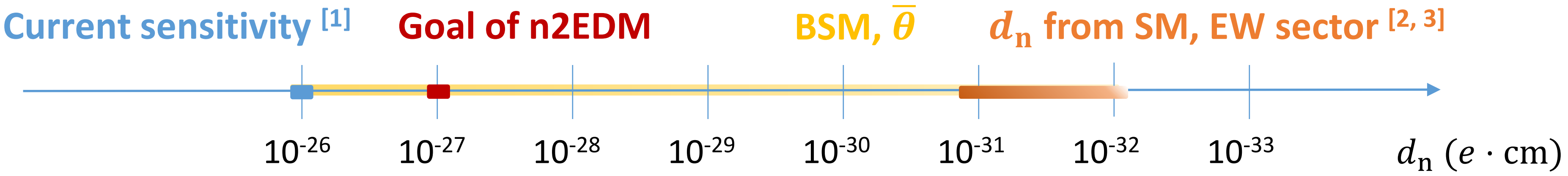
- CKM contribution → $d_{\mathrm{n}} \sim 10^{-32}\ e \cdot \mathrm{cm}$ [2, 3]
- QCD $\bar{\theta}$ - term

$d_{\mathrm{n}} \sim \bar{\theta} \cdot 10^{-16}\ e \cdot \mathrm{cm}$
$|d_{\mathrm{n}}| < 10^{-26}\ e \cdot \mathrm{cm}$ [1]

→ $\bar{\theta} < 10^{-10}$, very small
→ "Strong CP problem"

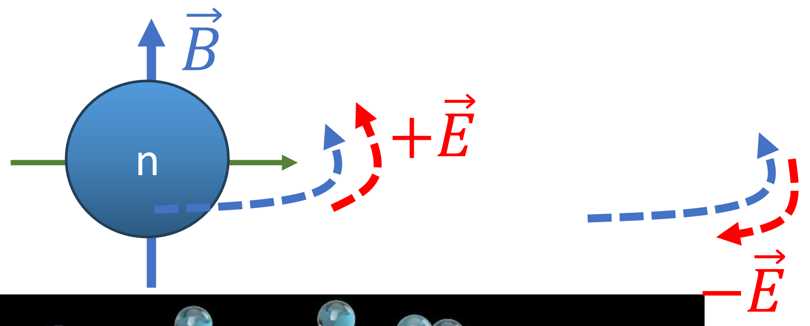
BSM:

- New physics models @ TeV scale predict sizable EDMs.
  (SUSY [4], 2Higgs [5] …)

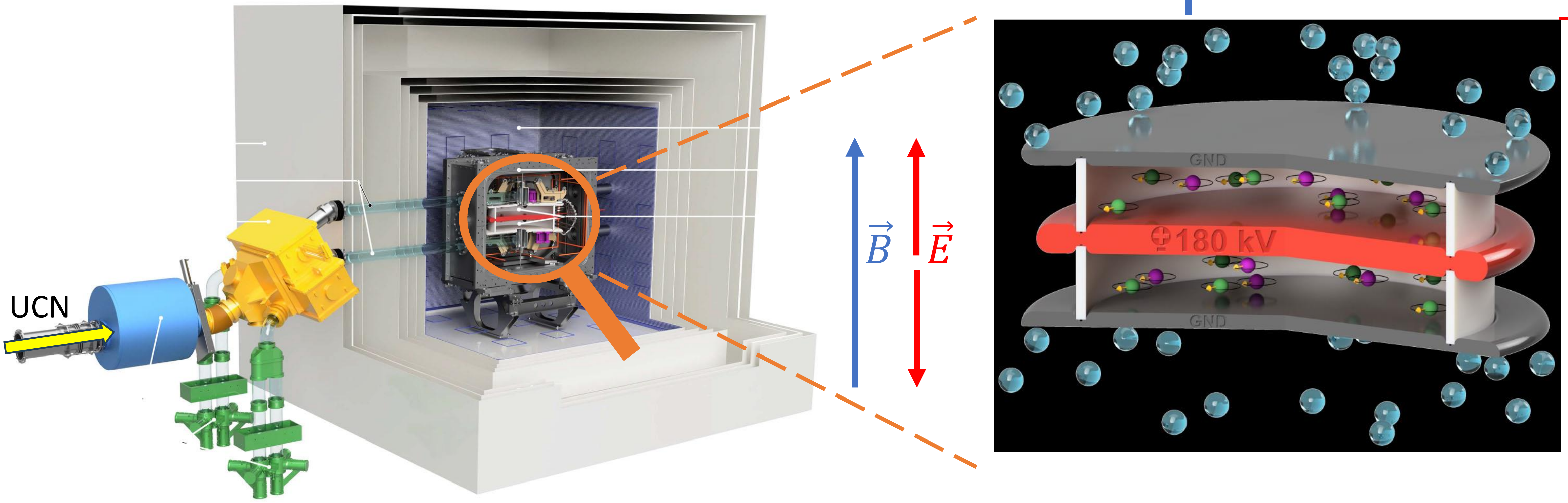


[1] C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
[2] C-Y. Seng, Phys. Rev. C 91, 025502 (2015)
[3] M. Pospelov, A. Ritz, Annals of Physics 318 119-169 (2005)
[4] S A. Abel and O. Lebedev, JHEP01(2006)133
[5] K. Cheung et al, Phys. Rev. D 102, 075029 (2020)

How to measure d_n: measure f_n

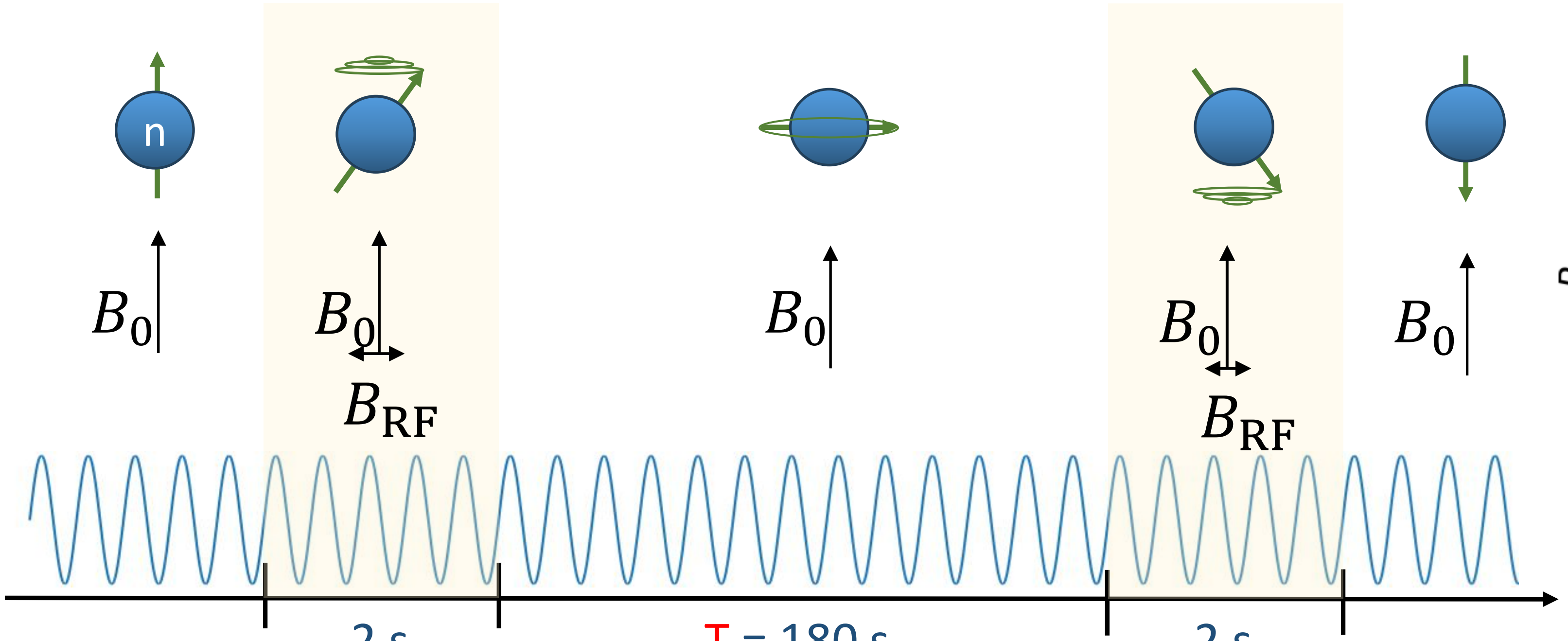


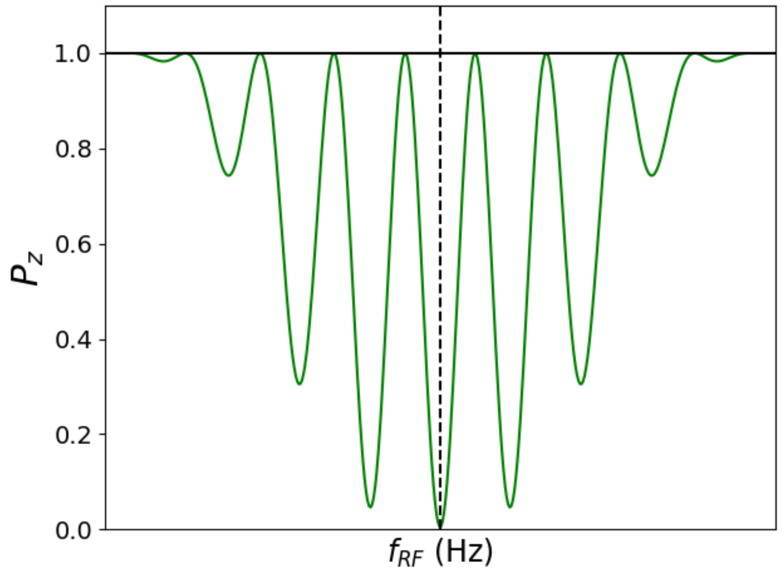
Frequency as observable → $f_\mathrm{n} = \frac{\mu_\mathrm{n}}{\pi\hbar} B \pm \frac{d_\mathrm{n}}{\pi\hbar} E$



Two design figures: N.J. Ayres et al., Eur. Phys. J. C 81, 512 (2021)

How to measure d_n: Ramsey method





Initially polarized neutrons

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

Free precession of neutrons

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

Spin down if $f_{RF} = f_n$

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

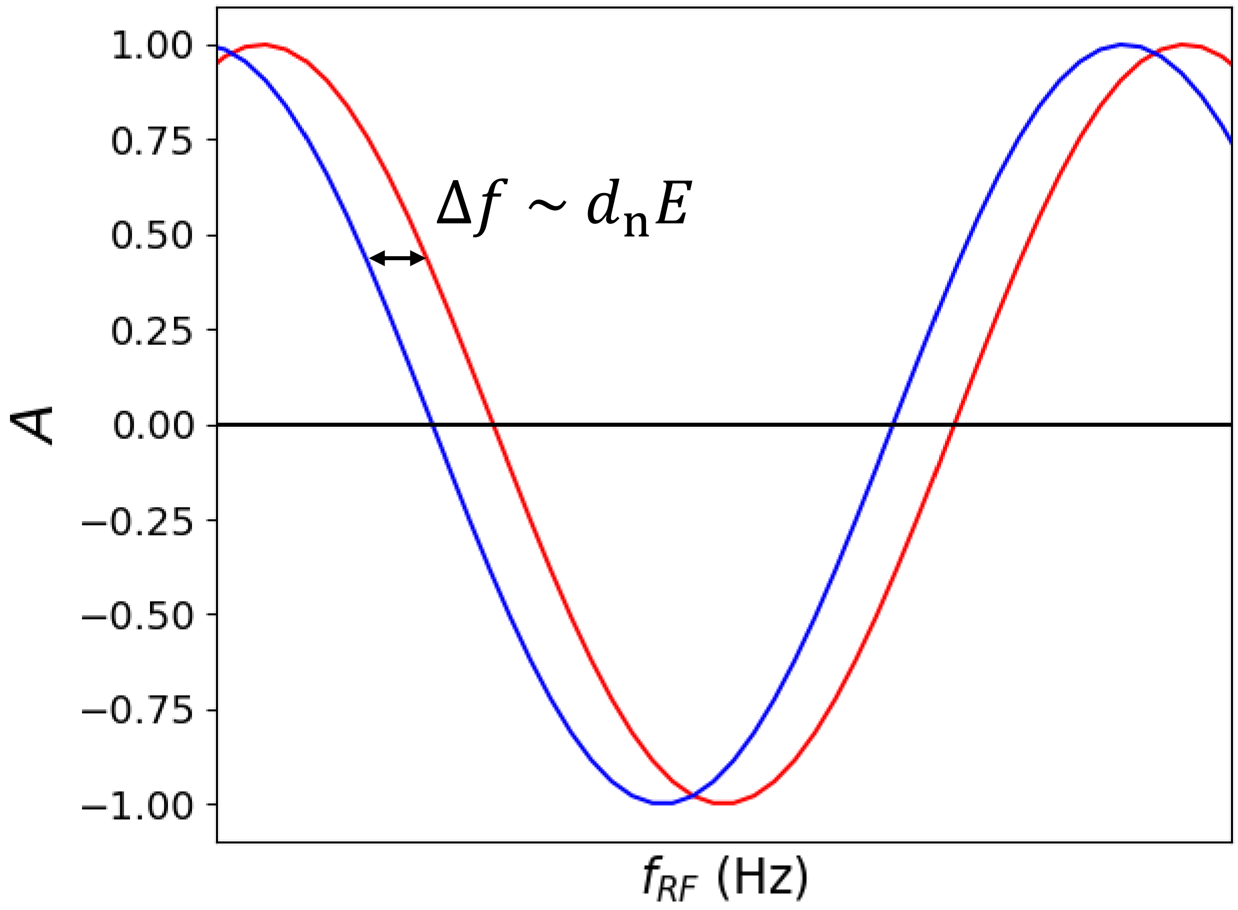
Ramsey Asymmetry Plot

Counting $N_\uparrow$, $N_\downarrow$ and get asymmetry:

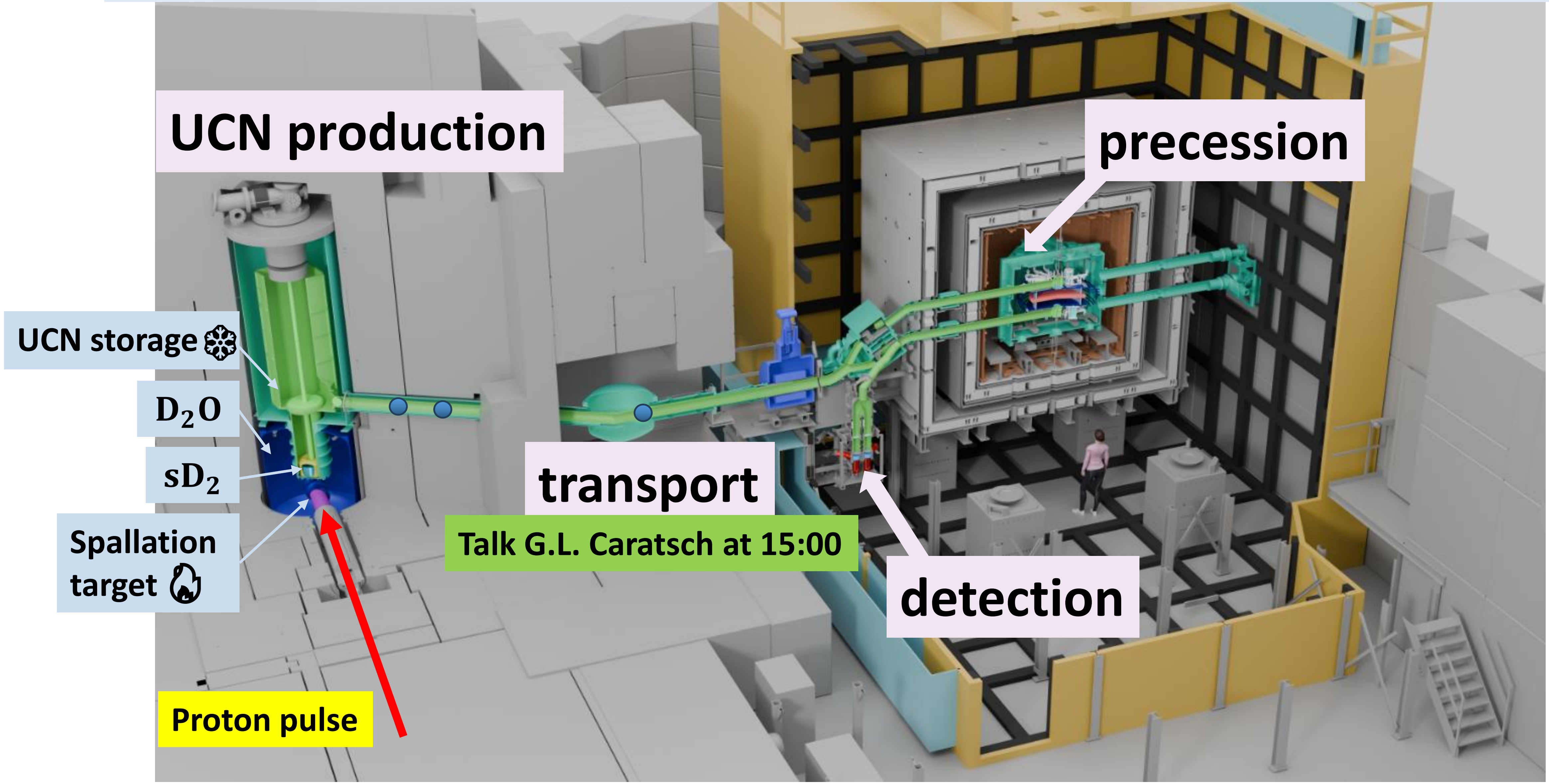
$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

as a function of applied RF frequency f_{RF} ($\Delta\nu = \frac{1}{2T + 8t_{\mathrm{RF}}/\pi}$):

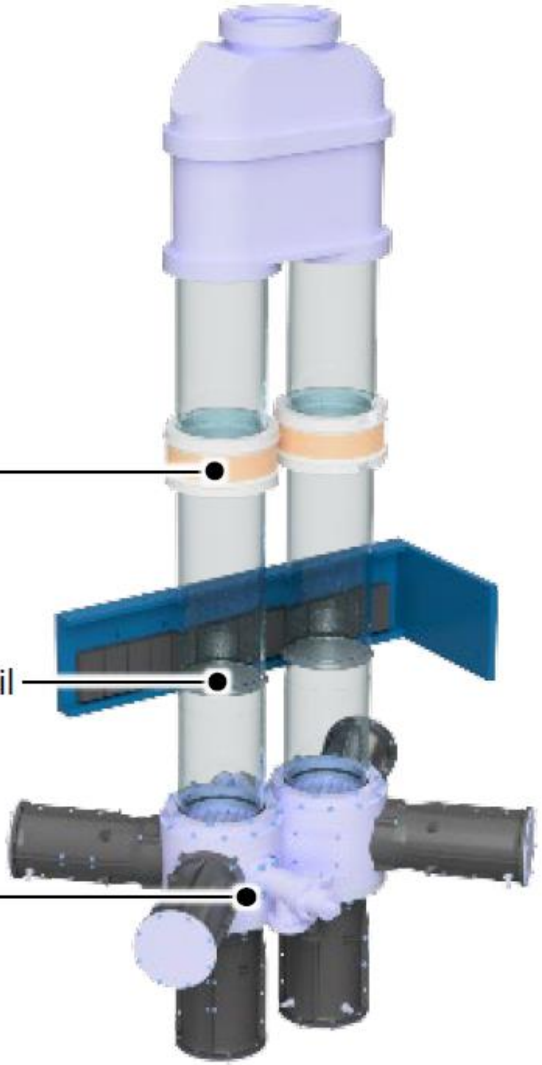
$$A \approx -\alpha \cos\left[\pi \frac{f_{\mathrm{RF}} - f_{\mathrm{n}}}{\Delta\nu}\right]$$



The journey of UCNs



The journey of UCNs: detection



- Spin-analysis: Magnetized foils filter out polarized neutrons.
- UCN counted by 4 detectors filled with ^{3}He & CH_4 gas.

$$n + {}^{3}He \rightarrow p + {}^{3}H$$

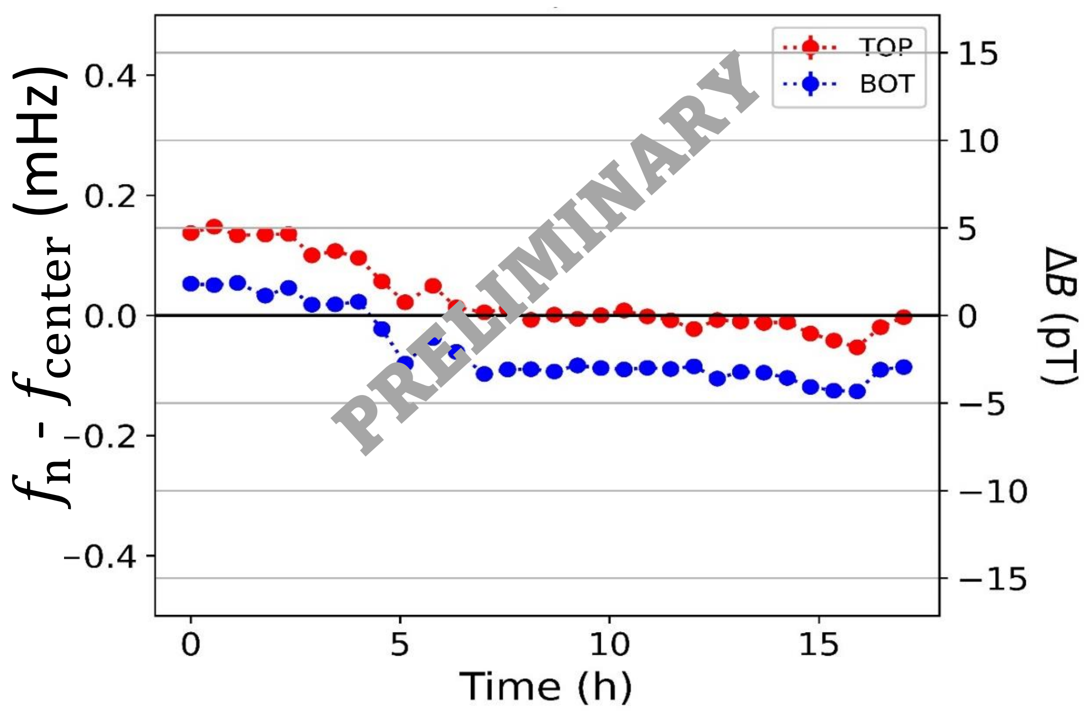
causes scintillation of CH_4

Light detected by PMTs

Magnetic field stability

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

Small, stable $B \sim 1\ \mu\text{T}\ (f_{n,B} \sim 27\ \text{Hz})$!



Stable magnetic field

Magnetic field control

Reduce $\vec{\boldsymbol{B}}_{\mathbf{bkg}}$ using passive and active methods

- MSR shields $\vec{B}_{\mathrm{bkg}}$:
  Size: $4.2 \times 5.2 \times 5.2\ \mathrm{m}^3$
- AMS compensates $\delta\vec{B}_{\mathrm{bkg}}$ using actively-controlled coils.
  $\vec{B} = M\,\vec{I} + \vec{B}_{bkg}$

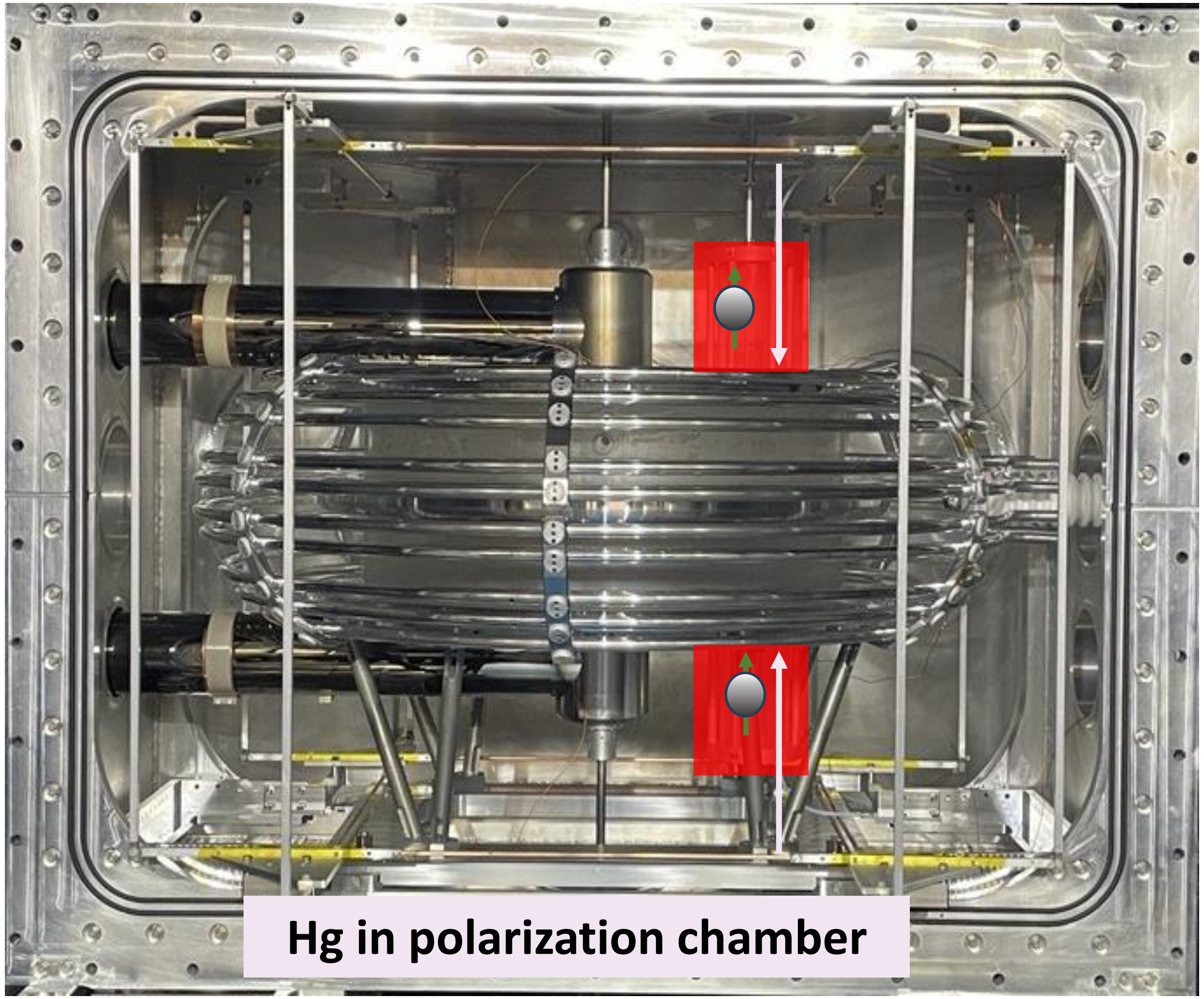
Monitor $\vec{\boldsymbol{B}}$ with magnetometers:

- ^{199}Hg co-magnetometer
- Cs magnetometers

Talk V. Kletzl at 15:15

Talk S. Ermakov at 14:45

Monitor $\vec{B}$ & $\Delta\vec{B}$: ^{199}Hg co-magnetometer



An optically pumped magnetometer using ^{199}Hg

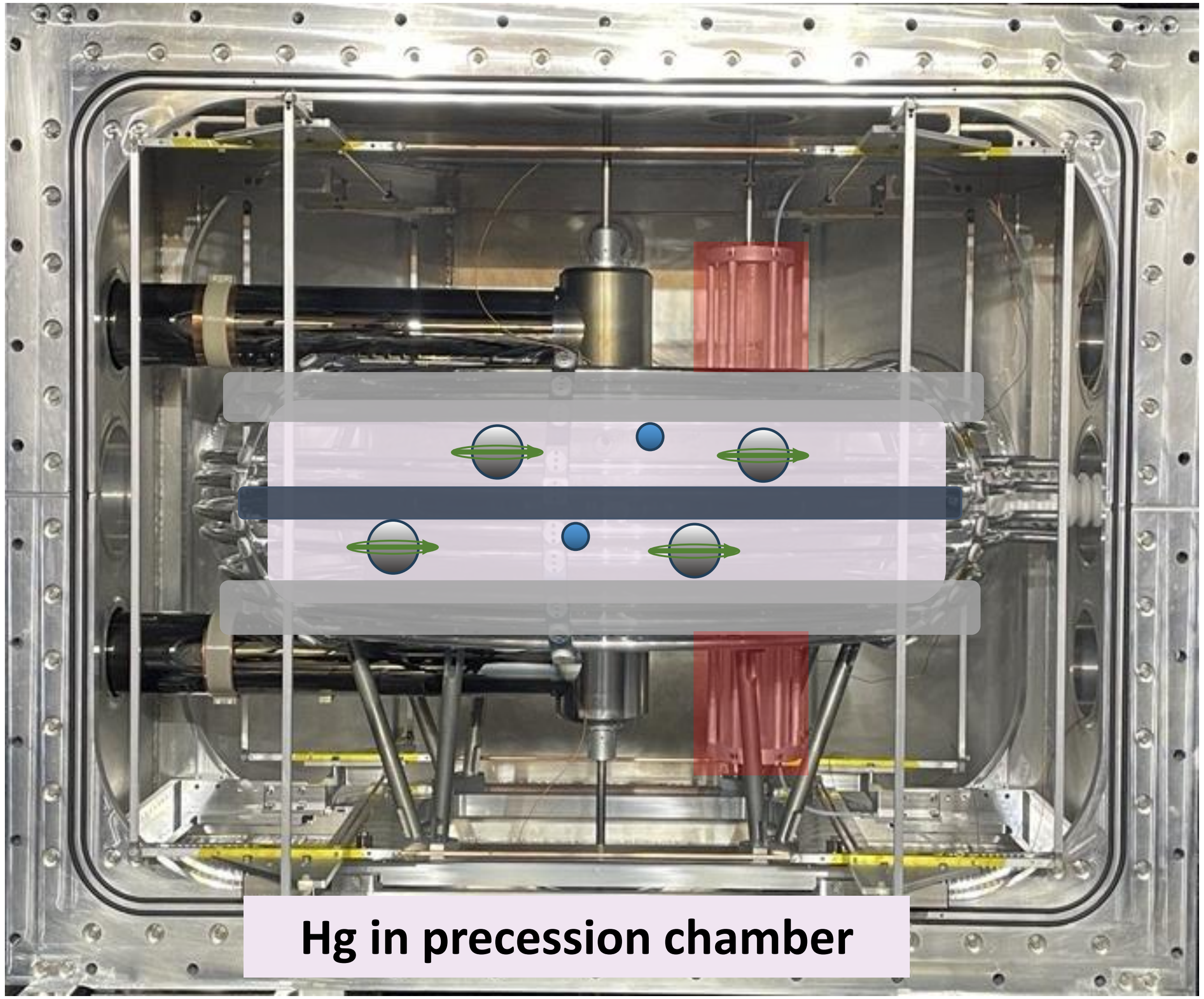
$|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}\ e \cdot \mathrm{cm}$ [1]

$$f_{\mathrm{Hg}} = \left|\frac{\gamma_{\mathrm{Hg}}}{2\pi} B\right| \sim 7\ \mathrm{Hz}$$

Polarize Hg atoms using UV light

[1] B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016)

Monitor $\vec{B}$ & $\Delta\vec{B}$: ^{199}Hg co-magnetometer



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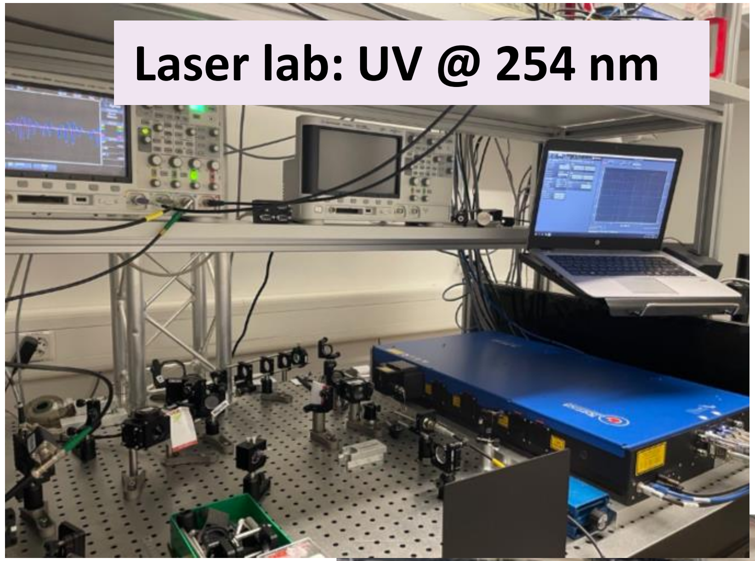
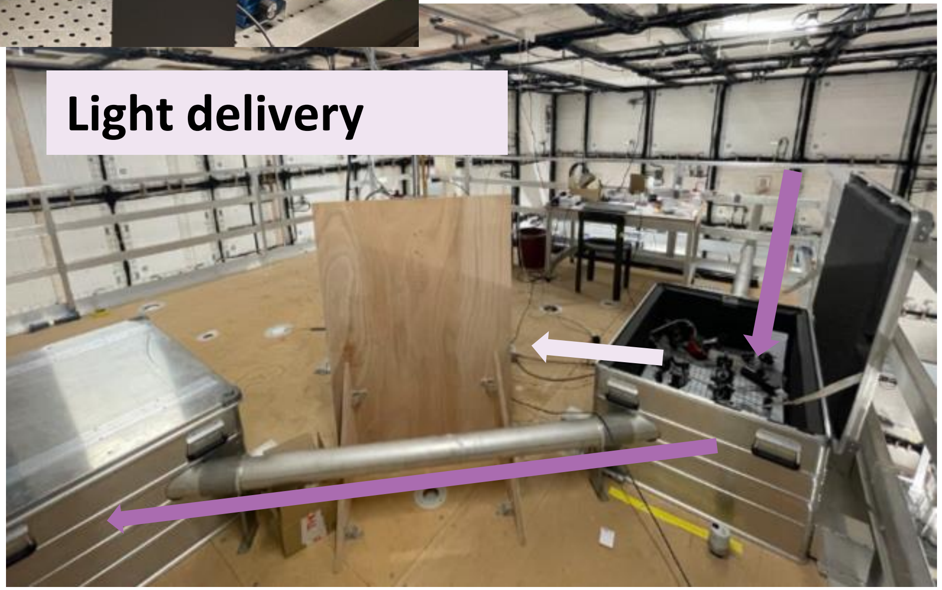
Probe Hg spin precession with UV light

[1] B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016)

Monitor $\vec{B}$ & $\Delta\vec{B}$: ^{199}Hg co-magnetometer





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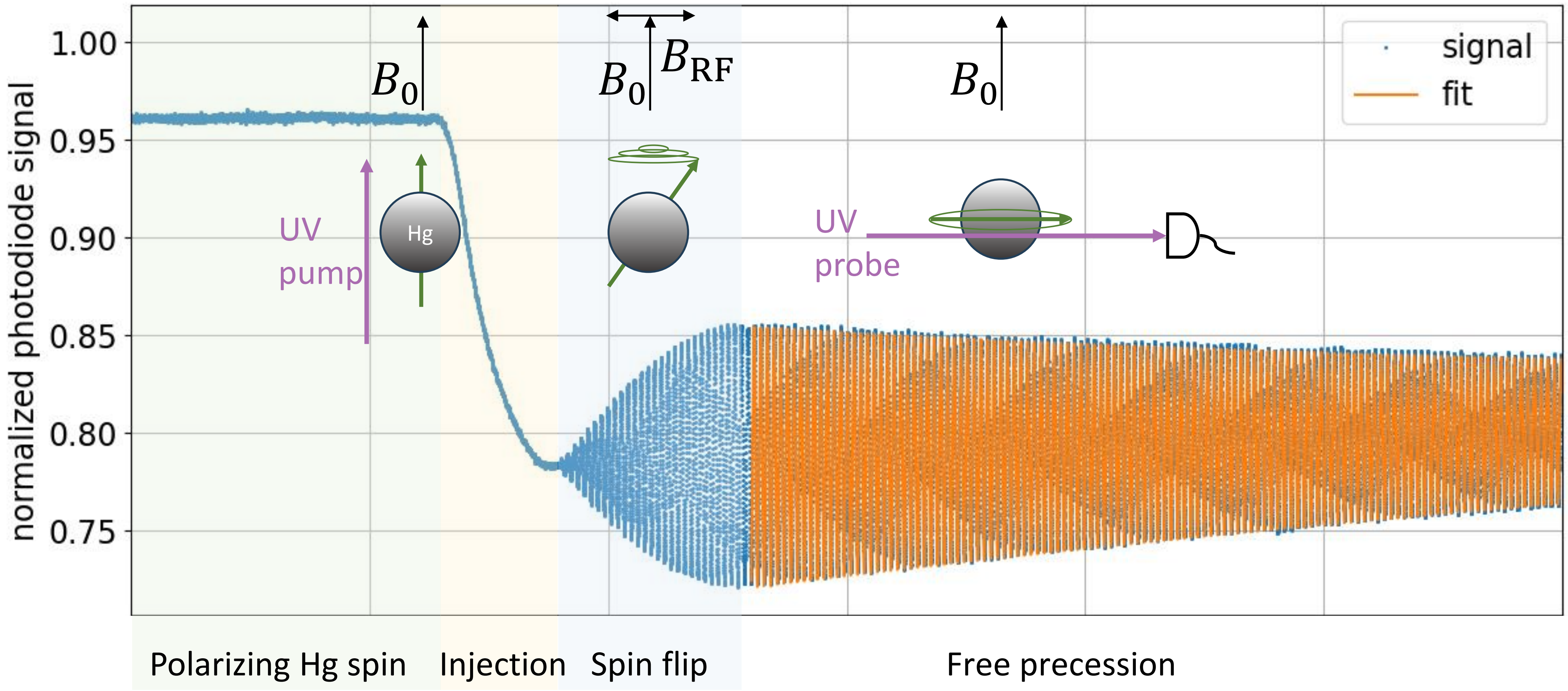
Challenge: require > 30 m of UV delivery (free-space + fiber)

[1] B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016)

Monitor $\vec{B}$ & $\Delta\vec{B}$: ^{199}Hg co-magnetometer

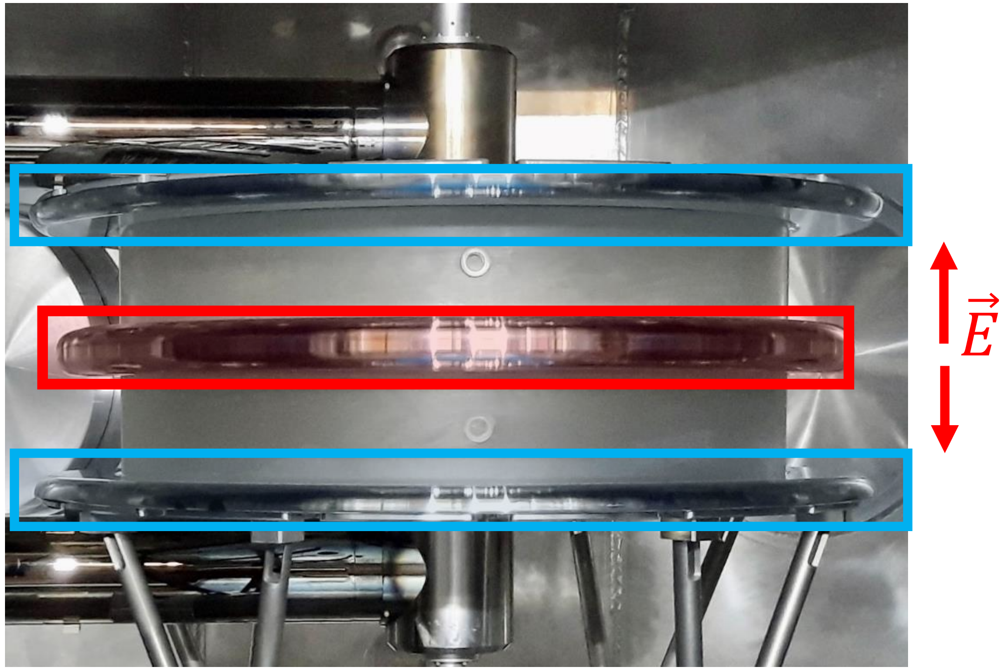
f_{Hg} extracted by fitting or through demodulation analysis



Provide $\boldsymbol{E}$: approaching 180 kV!

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

	n2EDM requirements
$\sigma(d_{\mathrm{n}})$ final	$1.1 \times 10^{-27}\ e \cdot \mathrm{cm}$
N (per cycle)	12100
α	0.8
T	180 s
E	15 kV/cm

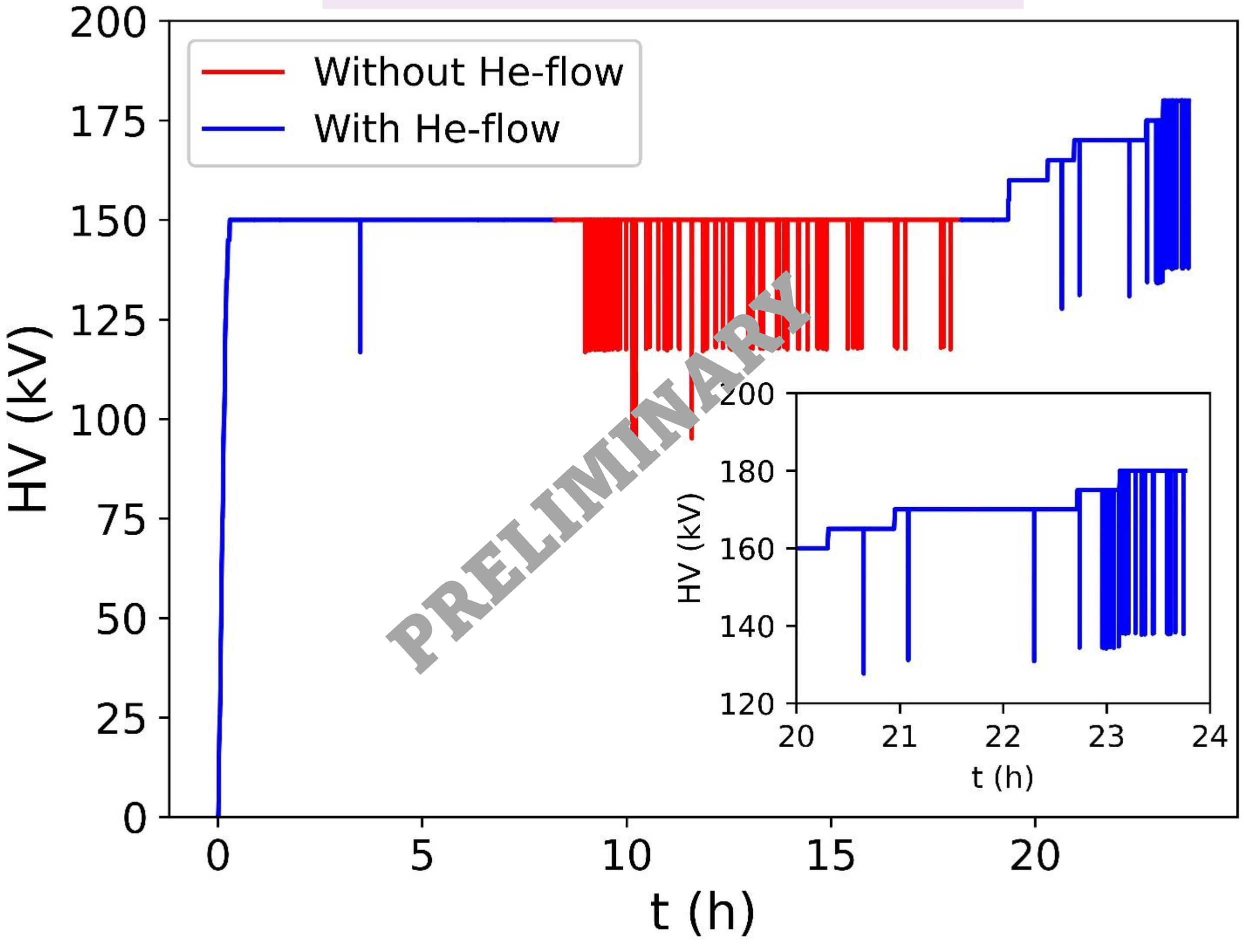


requires $E \sim 15\ \frac{\mathrm{kV}}{\mathrm{cm}} \sim \frac{\mathbf{180\ kV}}{12\ \mathrm{cm}}$!

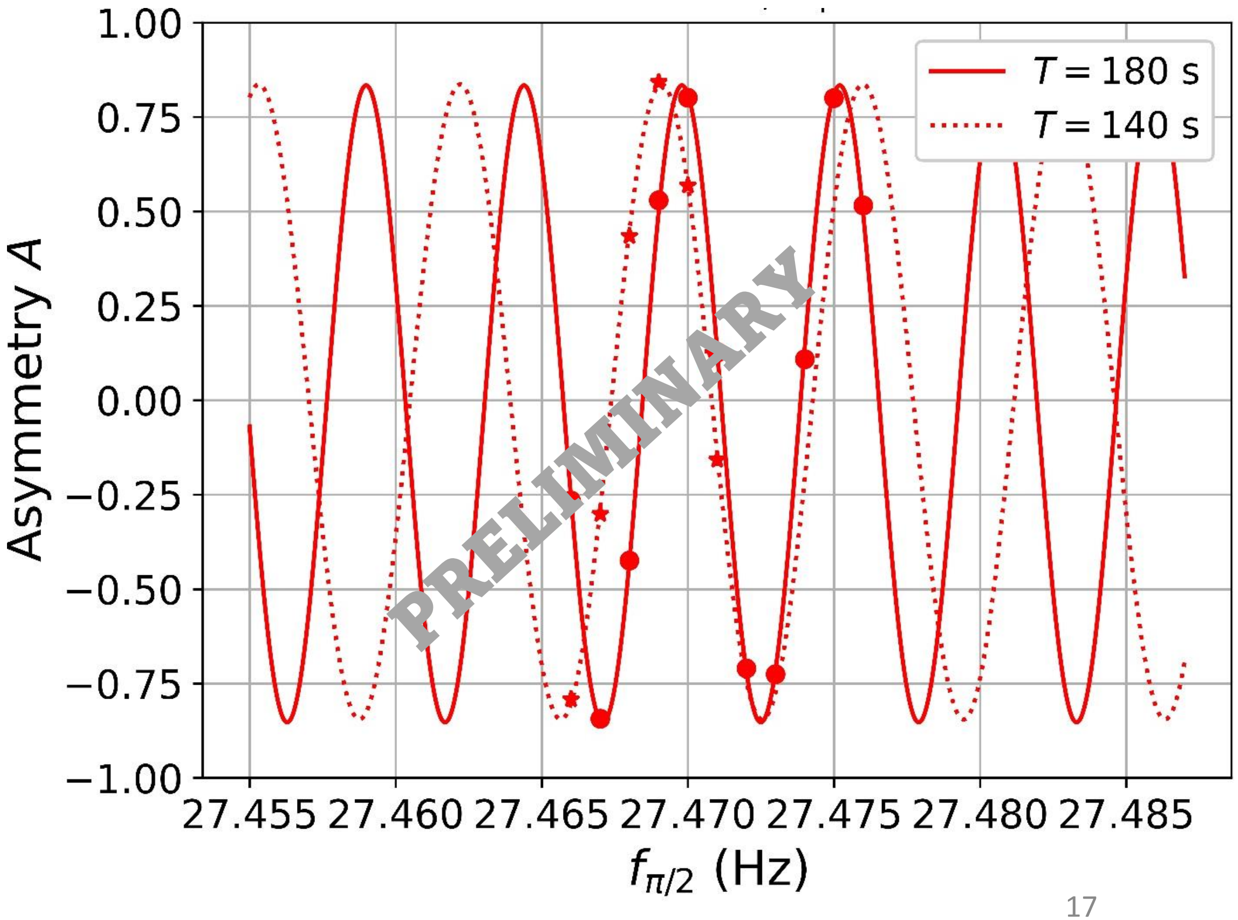
Recent achievements

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

E approaches 15 kV/cm!



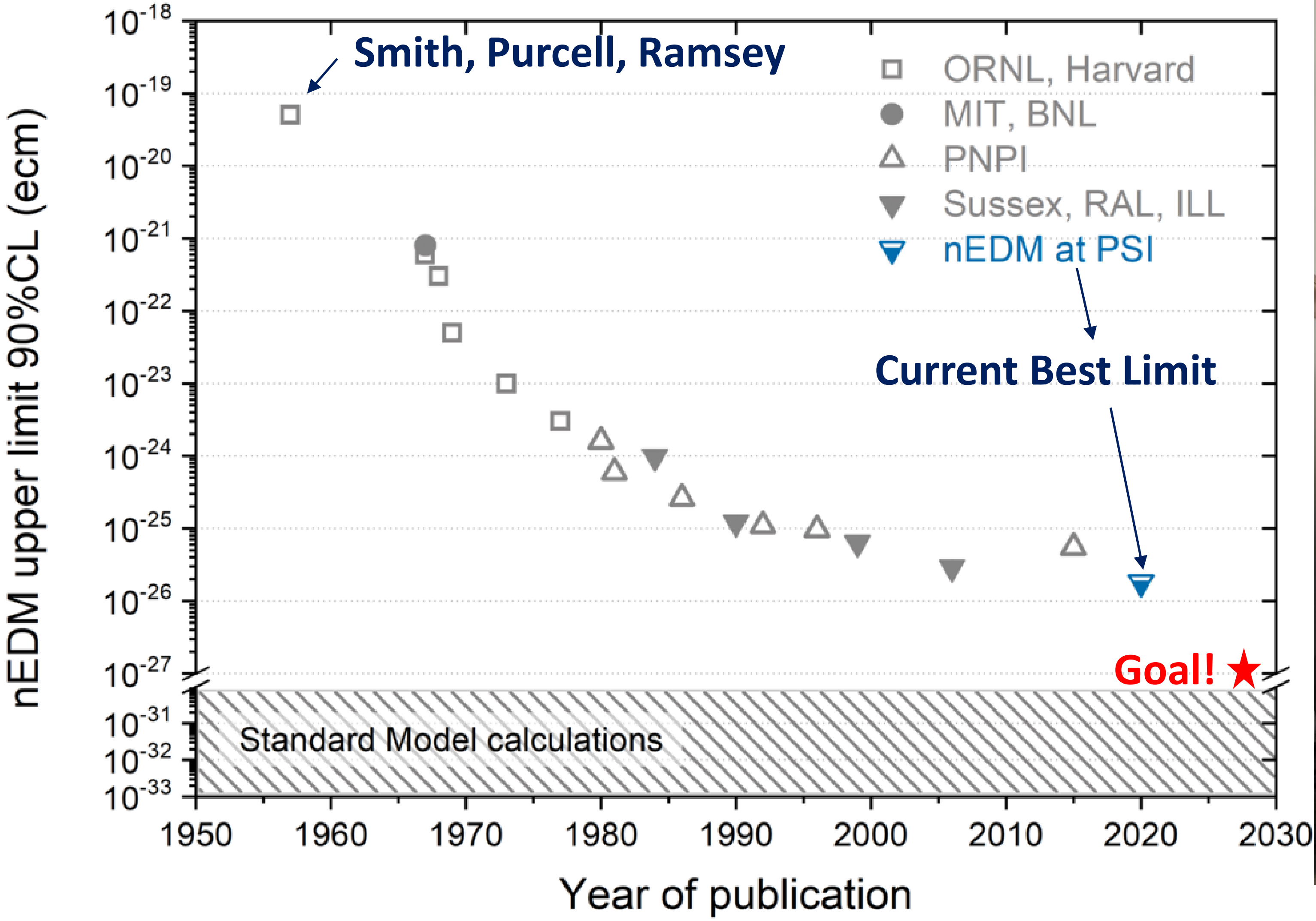
Ramsey pattern with $\alpha \sim 0.9$



PSI

Thanks for your attention!

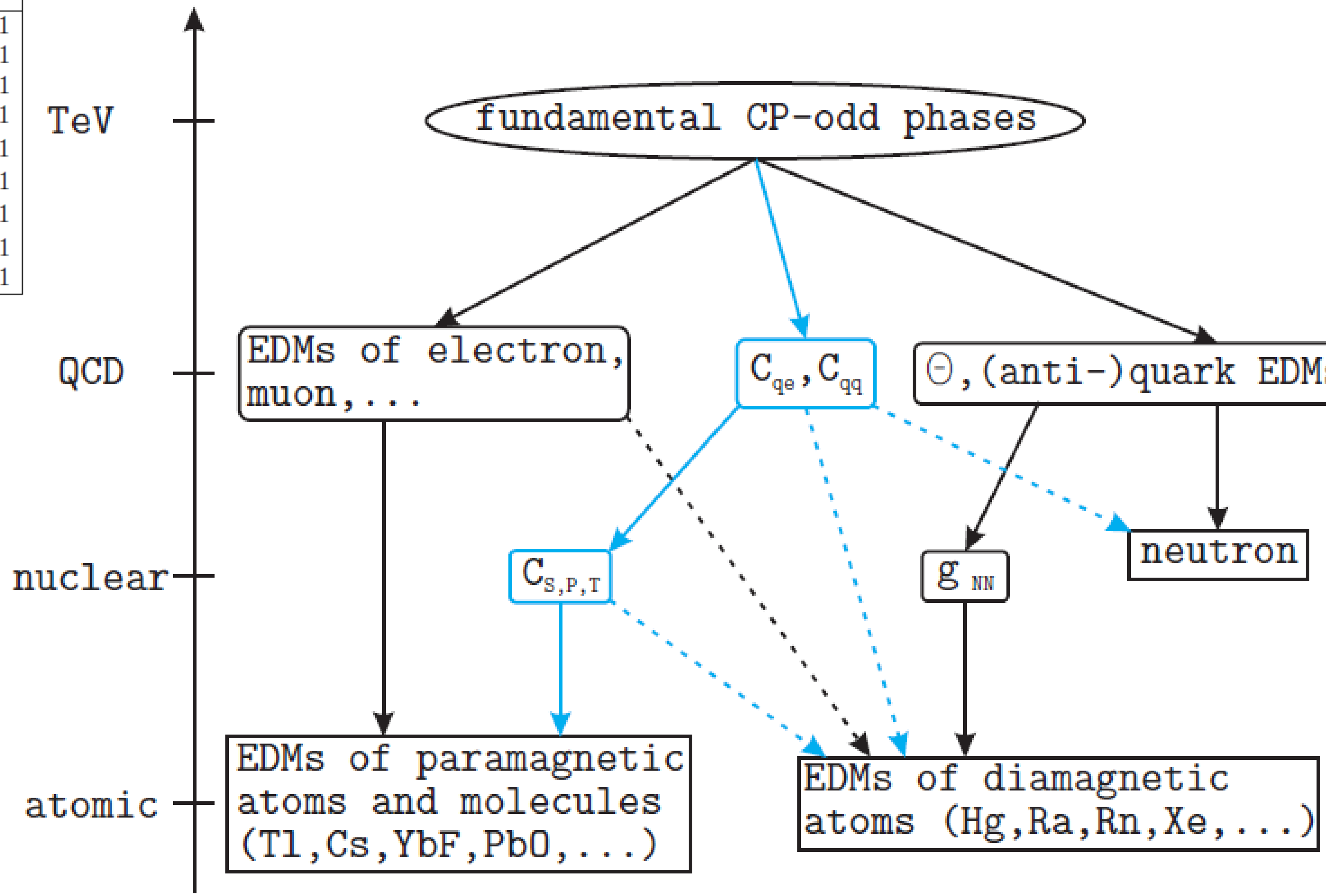
n2EDM



Backup

CP violation sources and EDMs

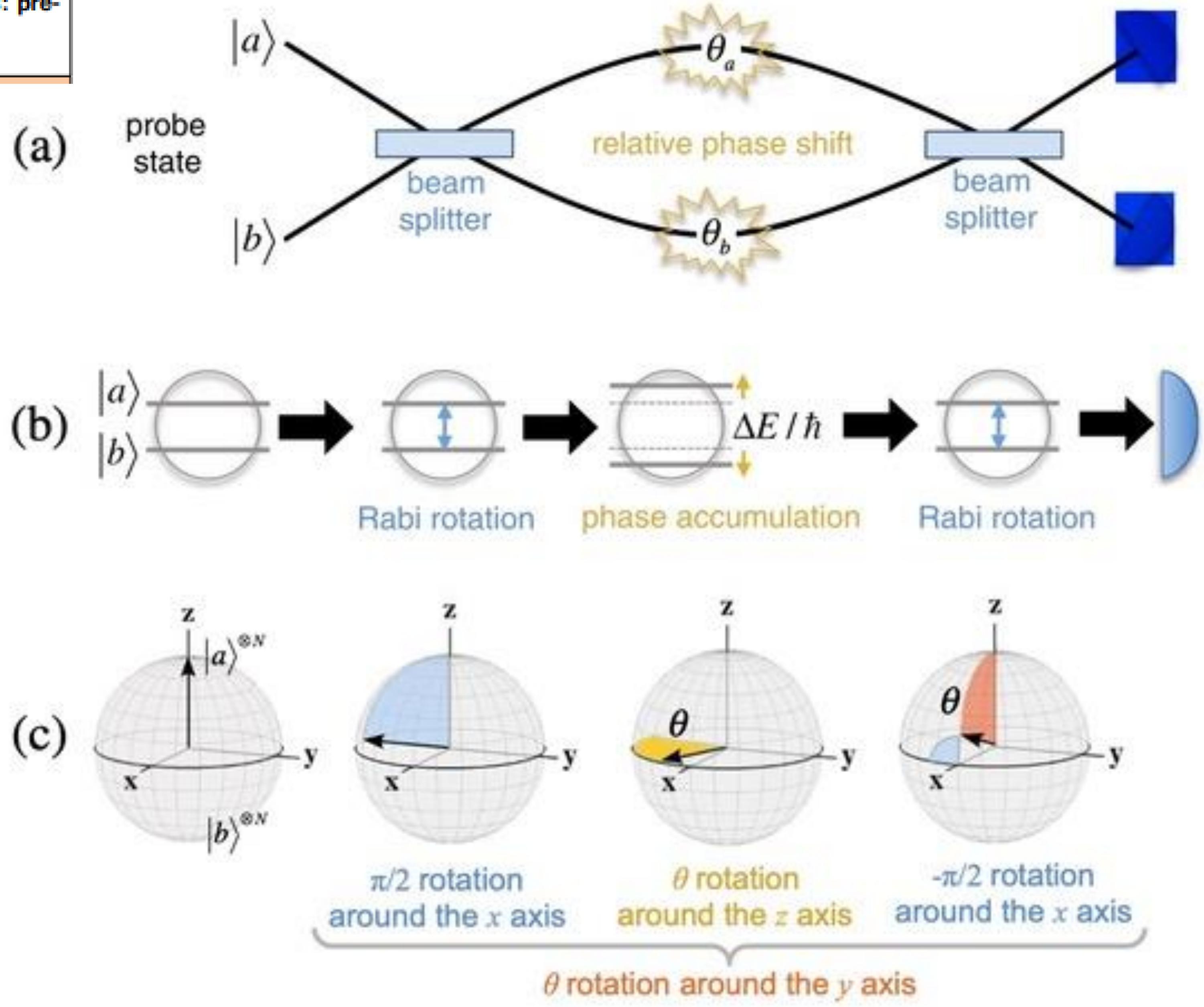
Quantity	Notation	P	C	T
Position	$\vec{r}$	-1	$+1$	$+1$
Momentum (Vector)	$\vec{p}$	-1	$+1$	-1
Spin (Axial Vector)	$\vec{\sigma} = \vec{r} \times \vec{p}$	$+1$	$+1$	-1
Helicity	$\vec{\sigma}.\vec{p}$	-1	$+1$	$+1$
Electric Field	$\vec{E}$	-1	-1	$+1$
Magnetic Field	$\vec{B}$	$+1$	-1	-1
Magnetic Dipole Moment	$\vec{\sigma} \cdot \vec{B}$	$+1$	-1	$+1$
Electric Dipole Moment	$\vec{\sigma} \cdot \vec{E}$	-1	-1	-1
Transverse Polarization	$\vec{\sigma} \cdot (\vec{p_1} \times \vec{p_2})$	$+1$	$+1$	-1



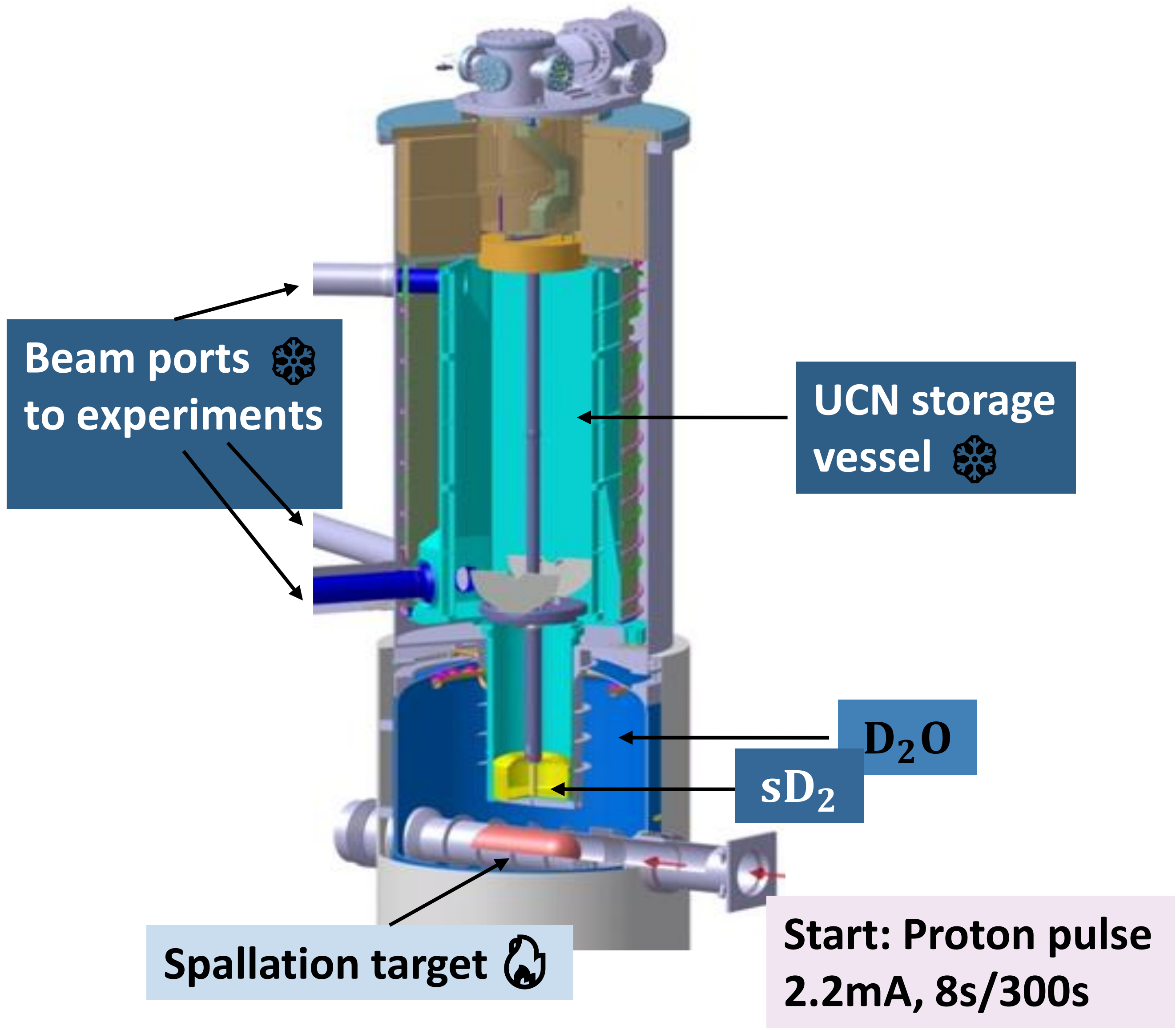
Time	ID	*Chair: Michel Calame, Empa & Universität Basel*
16:30	8	**Wave-particle duality in atom interferometers: precision measurements at the quantum limit** *Philipp Treutlein (p)*

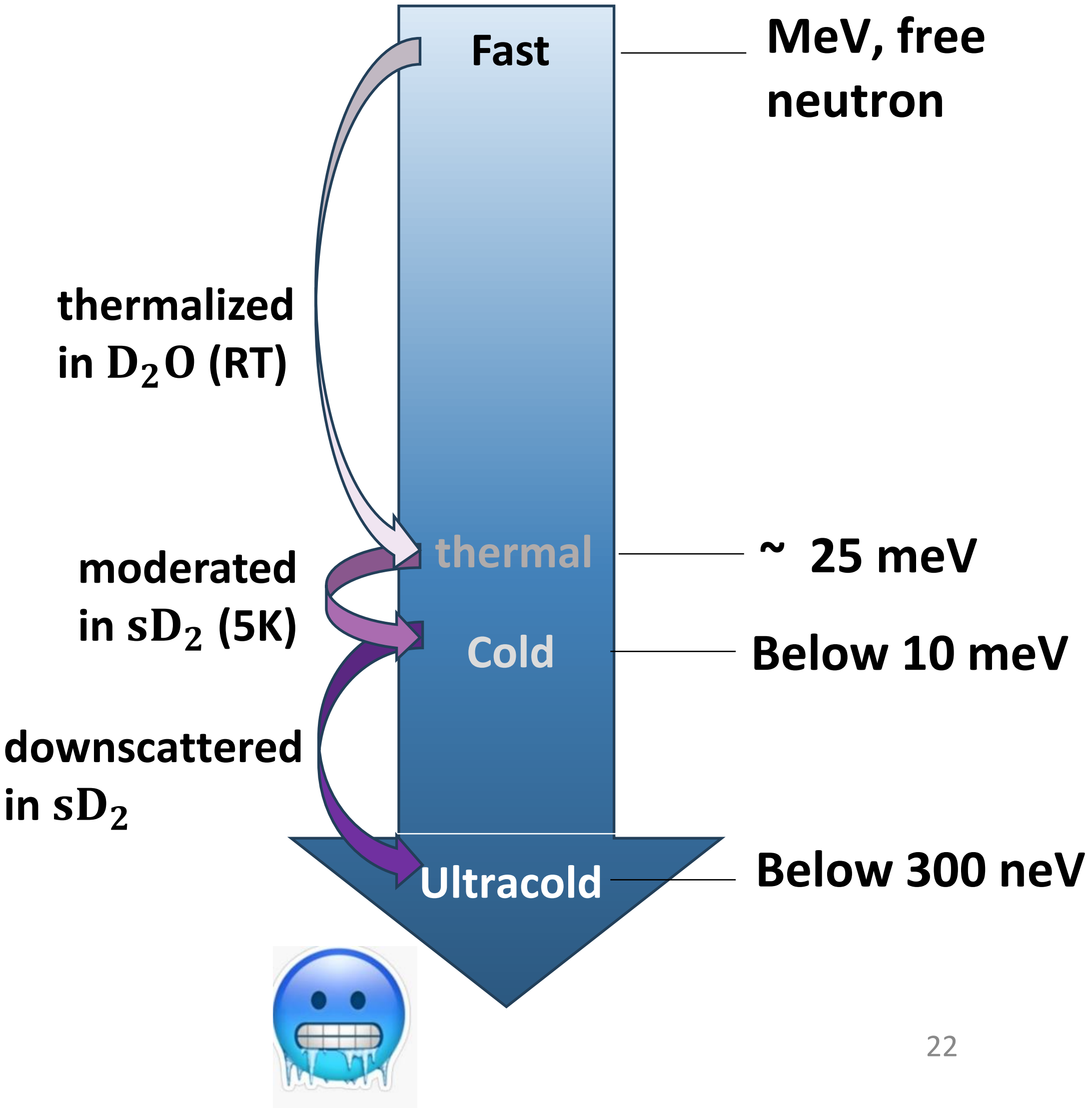
Ramsey Interferometers

[1] L. Pezzè et al, Rev. Mod. Phys. 90, 035005 (2018)

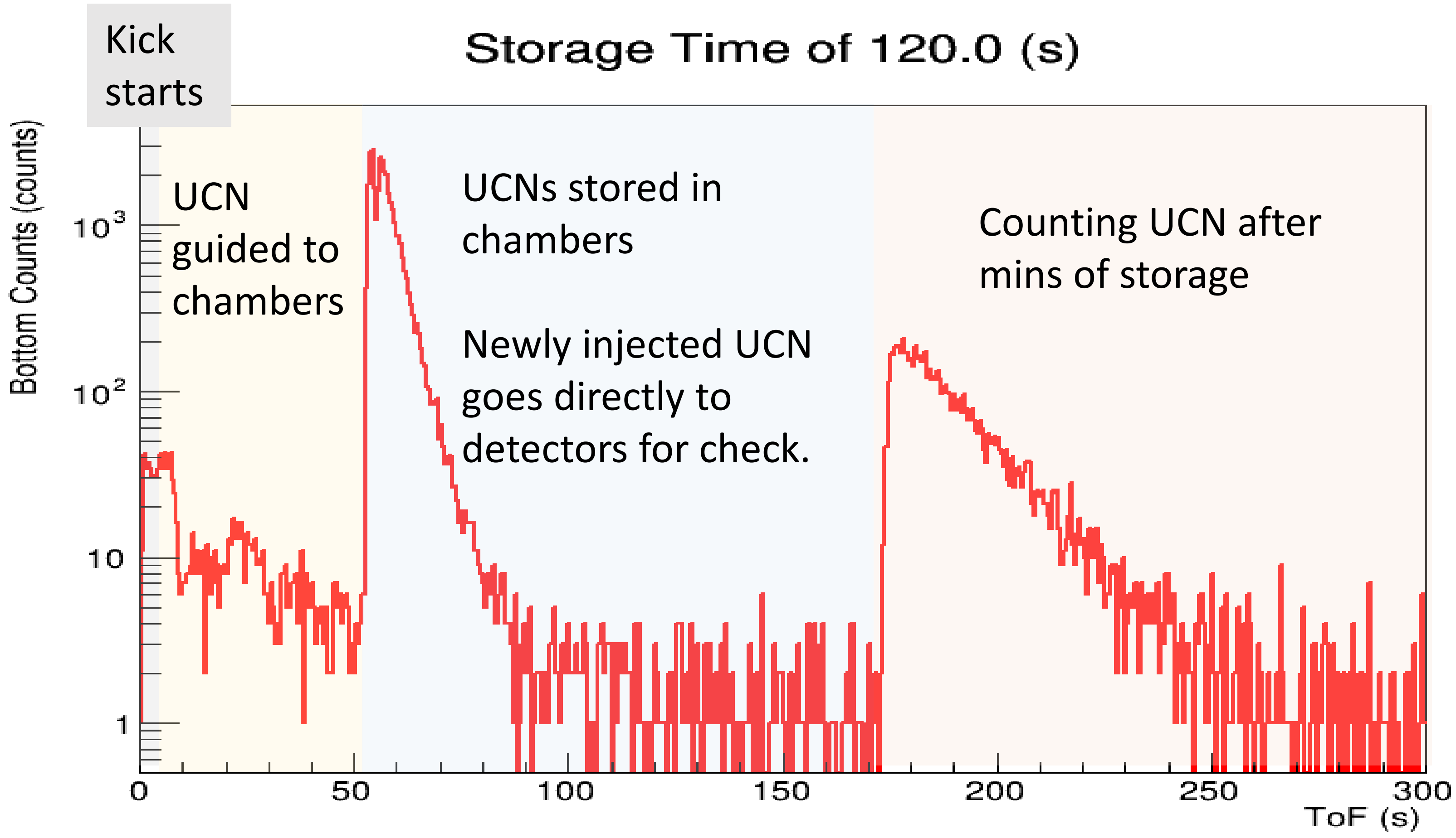


The journey of UCNs: production



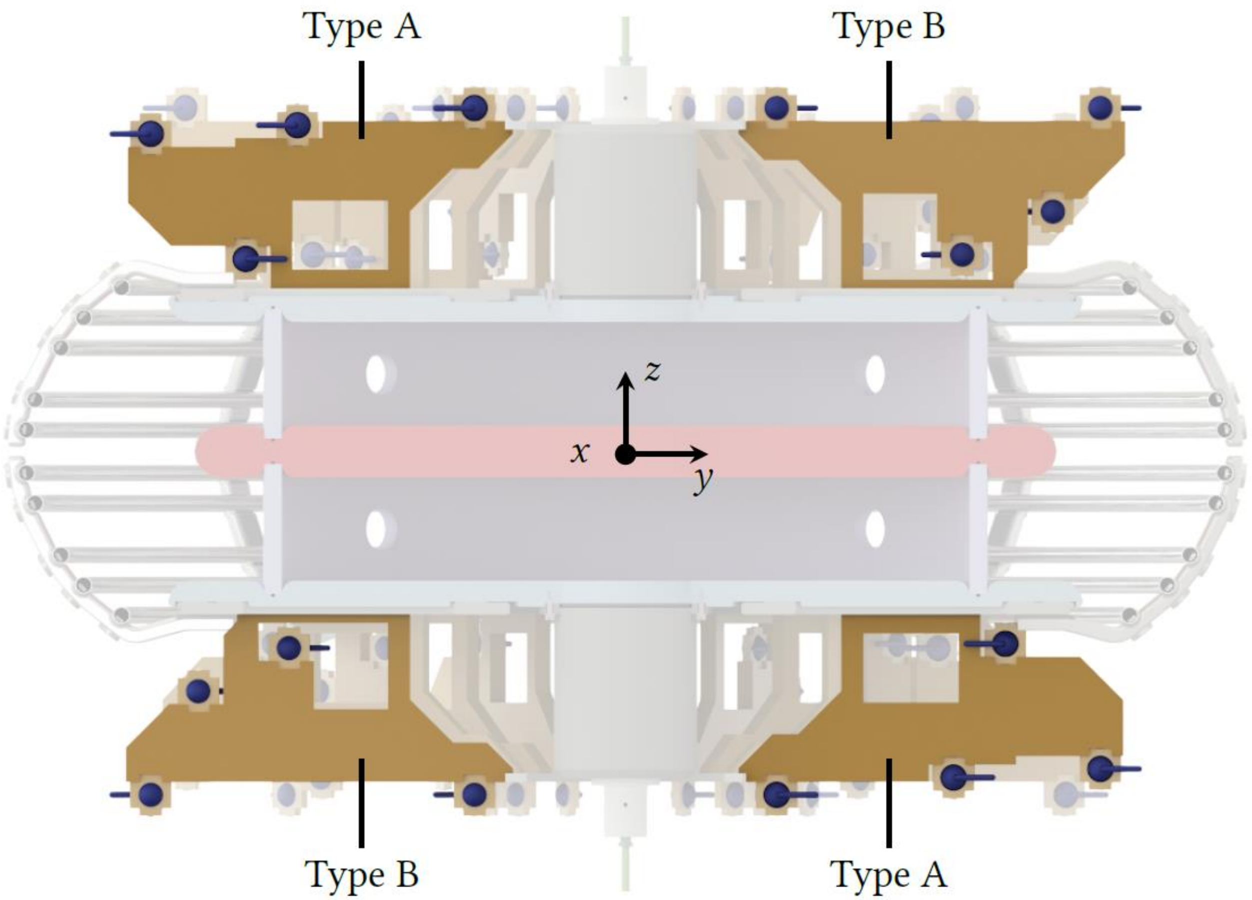


The journey of UCNs: detection



Monitor $\vec{B}$ and more gradients: Cs magnetometer

Talk V. Kletzl at 15:15



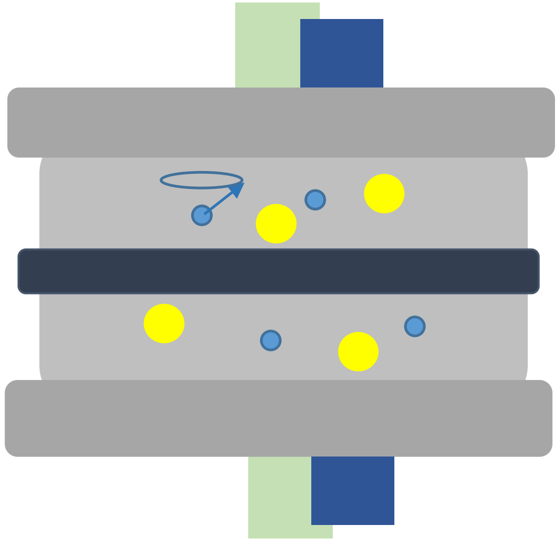
Cs cell production

Plan to mount an array of 112 Cs cells on plates

Hg magnetometer: motivation

Hg atoms also precess: $f_{\mathrm{Hg}} = \left|\frac{\gamma_{\mathrm{Hg}}}{2\pi} B_0\right|$ (electric term negligible)

$\Rightarrow$ allow us to cancel the magnetic field drifts!



Use a ratio $R_{\mp} = \frac{f_{\mathrm{n},\mp}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}}$

Then extract $d_n = \frac{\pi\hbar < f_{\mathrm{Hg}} >}{2|E|}(R_+ - R_-)$

Hg magnetometer: data extraction

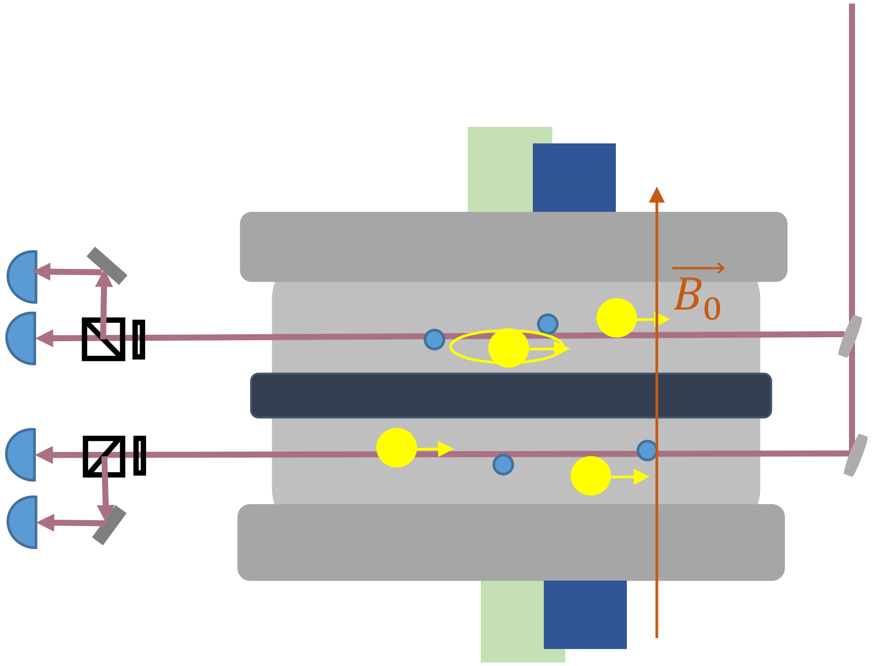
Use UV laser to spin-polarize the ^{199}Hg atoms.

Release the polarized atoms into precession chambers.

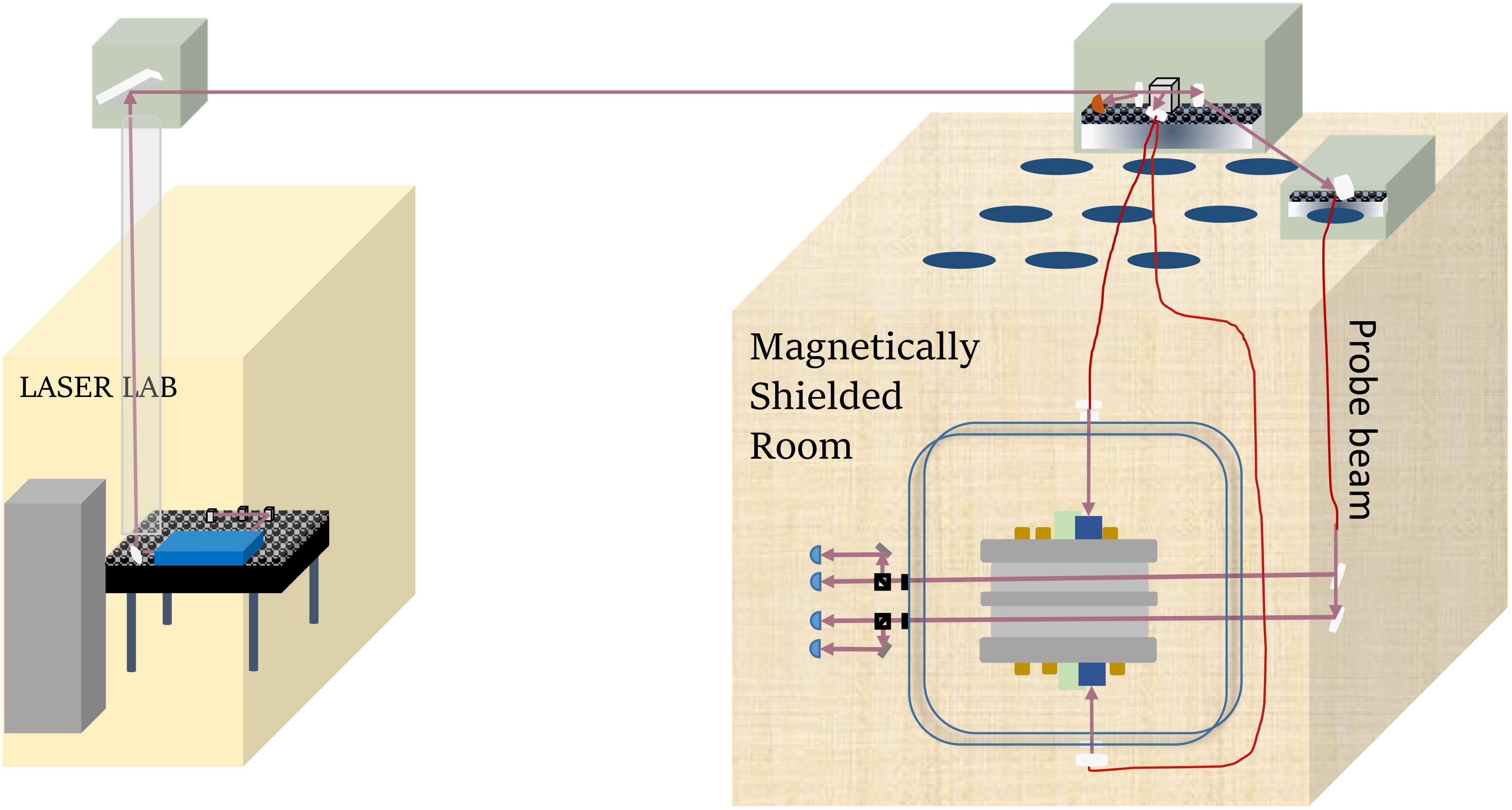
Apply oscillating field $\overrightarrow{B_{xy}}$ to flip the ^{199}Hg spin by 90°.

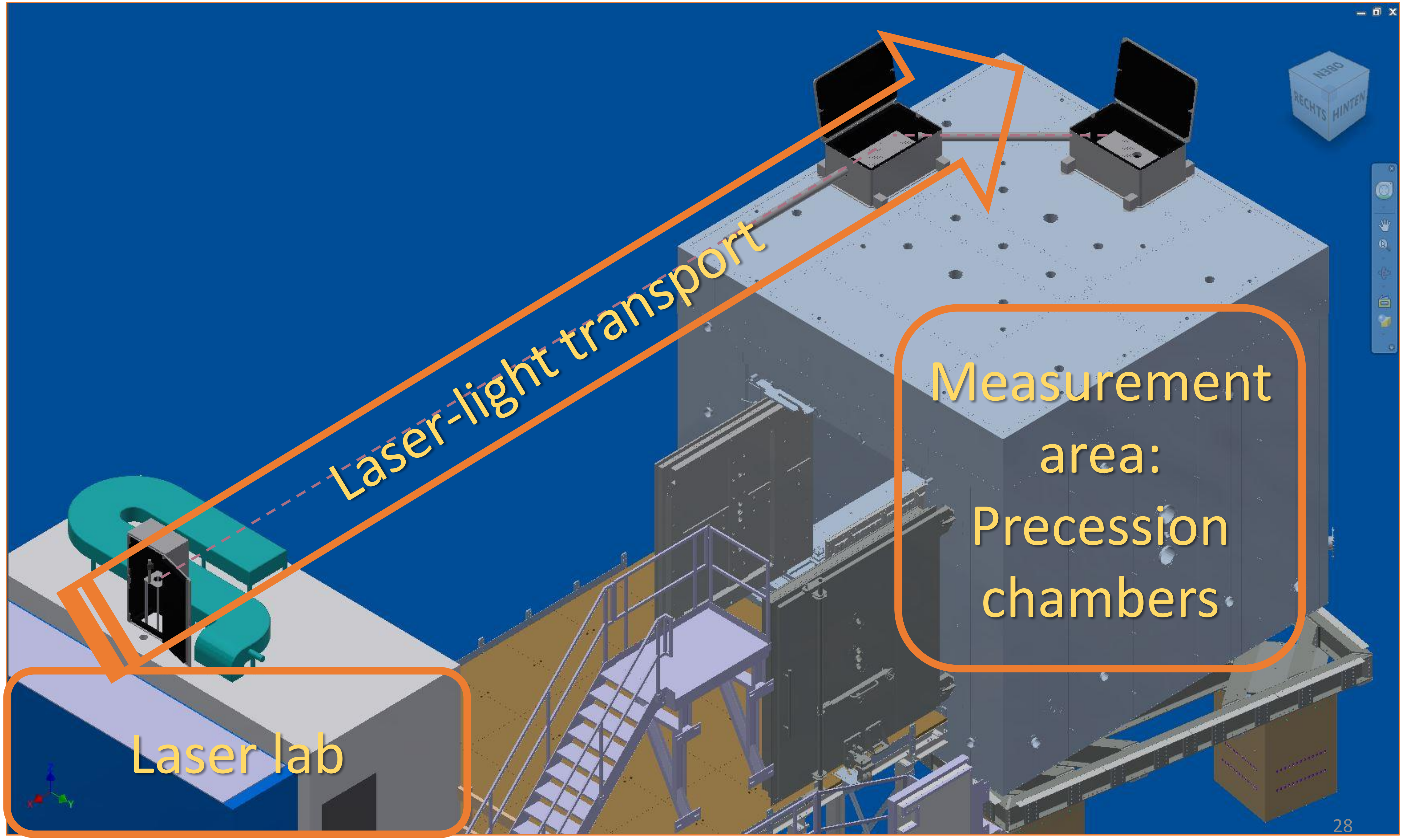
Probe the precession of ^{199}Hg atoms by laser.

Light absorption cross-section depends on the orientation of ^{199}Hg spin and the light propagation.



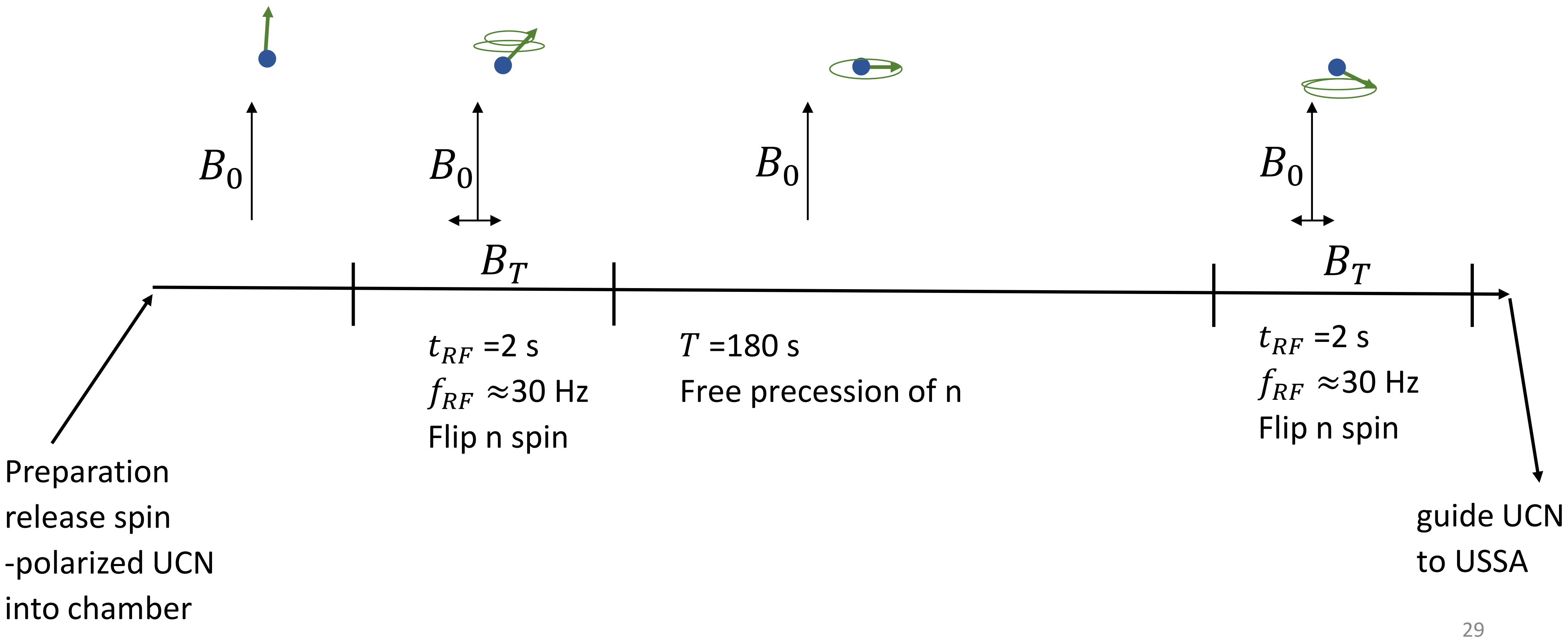
Hg magnetometer: beam delivery





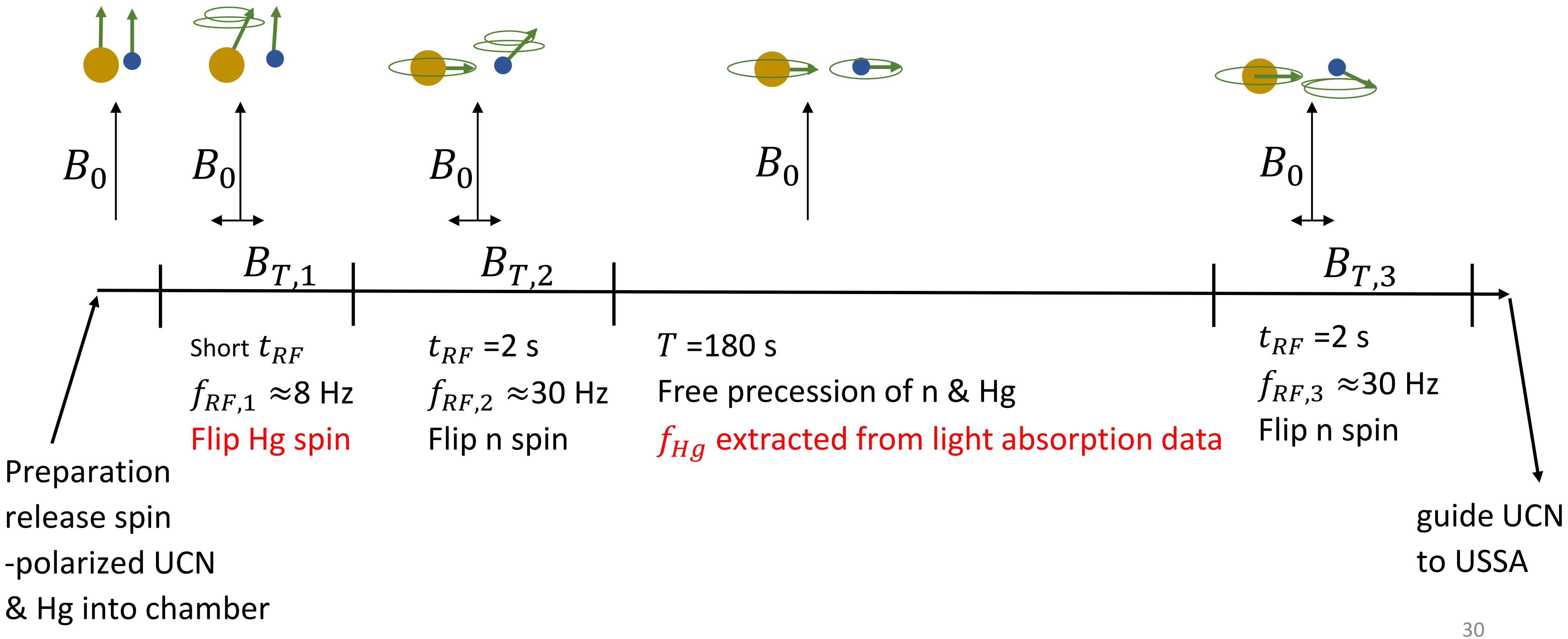
Laser-light transport
Measurement area: Precession chambers
Laser lab
OBEN
RECHTS
HINTEN

One cycle for UCN



One cycle for UCN & Hg

Use Ramsey method to measure $f_{n,\uparrow\uparrow}$, $f_{n,\uparrow\downarrow}$



Field stability – chamber difference

The drift of magnetic field difference

$f_{\mathrm{n}}^{\mathrm{top}} - f_{\mathrm{n}}^{\mathrm{bot}}$ over 17h