Storage of polarized ultracold neutrons

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SPIN 2018, Ferrara, Italy

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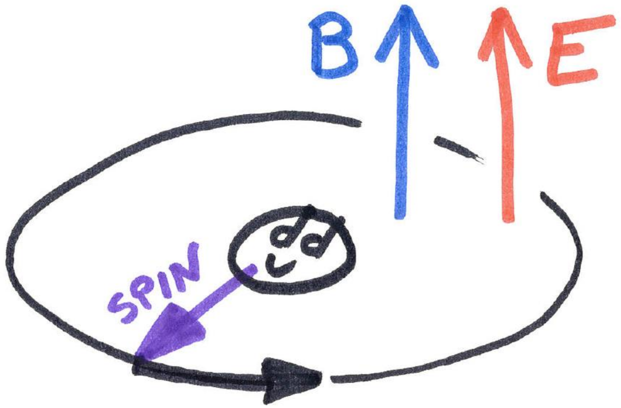
erc European Research Council

Hunting the neutron Electric Dipole Moment (EDM)

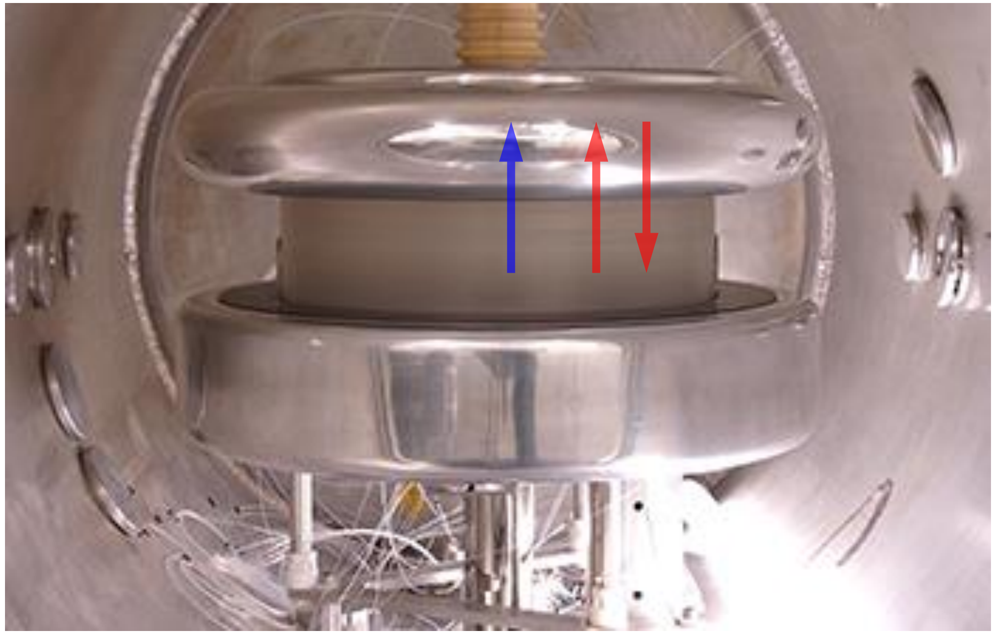


One measures the neutron Larmor precession frequency f_L in weak Bagdetic and strong Electric fields

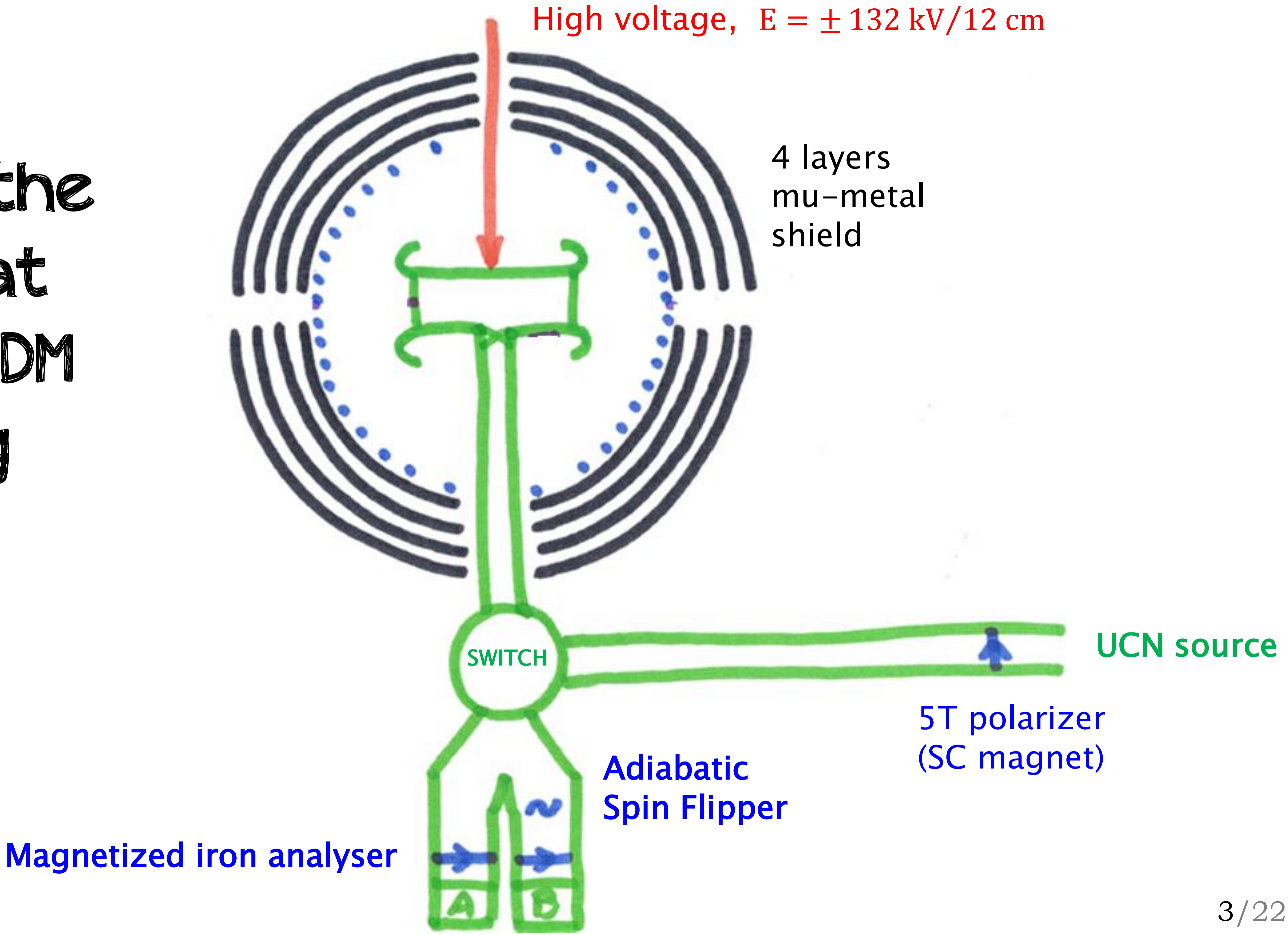
$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi\hbar}\boxed{d_n}E$$

Neutron EDM

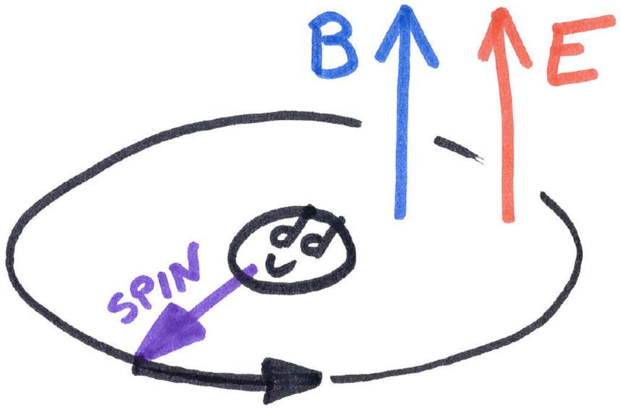
The most sensitive experiments use Ramsey's method with polarized ultracold neutrons stored in a "precession" chamber
Here a cylinder, Ø50 cm, H12 cm.



Scheme of the apparatus at PSI during EDM data-taking 2015-2016



Importance of neutron polarization



Statistical sensitivity:

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

neutron counts

Precession time $\boldsymbol{T} = \mathbf{180\ s}$

Electric field strength
$E = 132\,\mathrm{kV}/12\,\mathrm{cm}$

α = “visibility” = “contrast” =
(final polarization) x (analyzing power)

$\alpha = 0.77$ in average in 2015-2016 PSI nEDM data.

2 modes to study the depolarization in nEDM

Cycle to measure the longitudinal polarization, ***T1 mode***

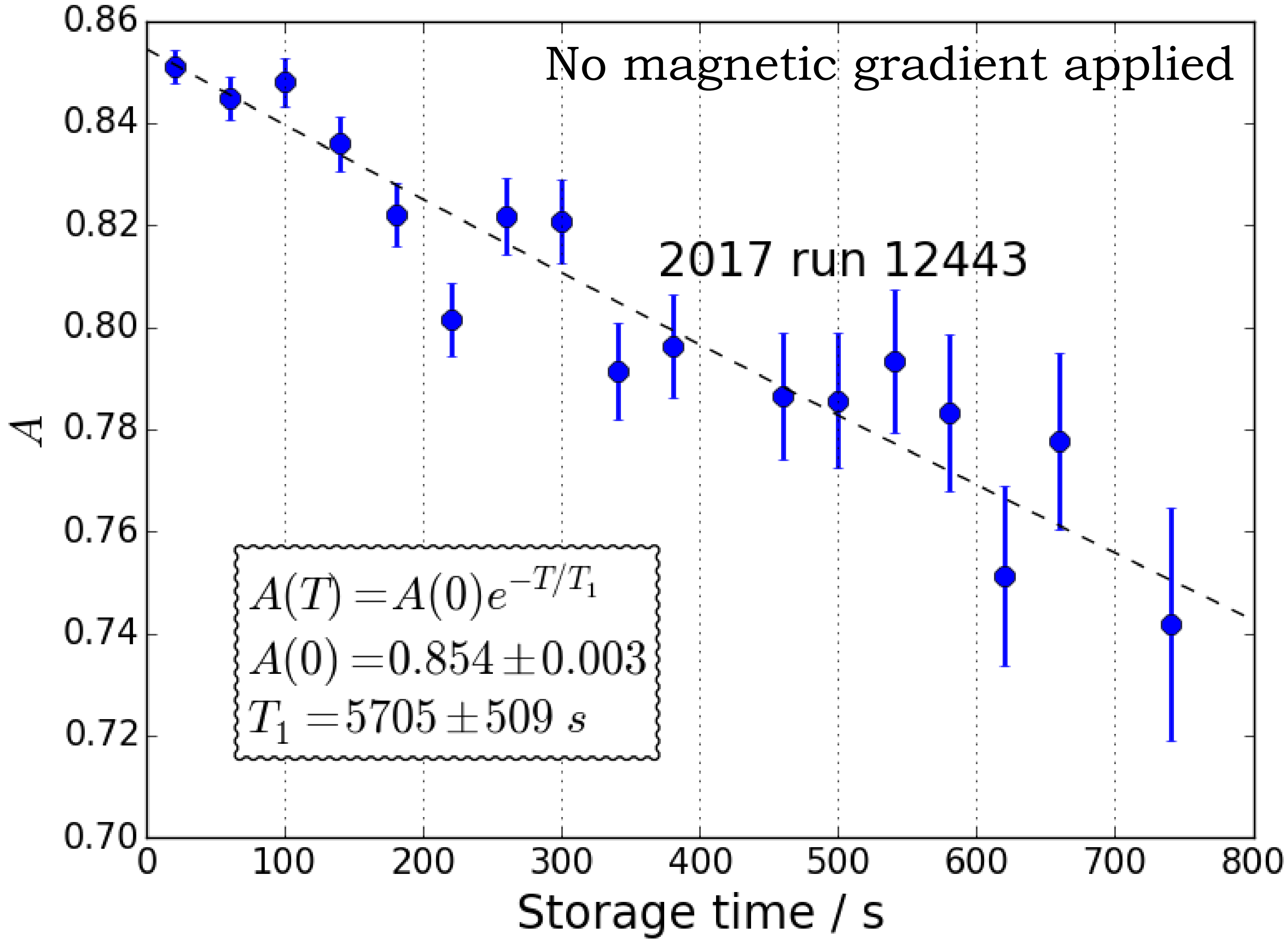
Filling polarized UCNs	Storage period of duration T, UCN spins aligned with $\vec{B}$	Emptying neutrons, counting N_+ and N_-

Cycle to measure the transverse polarization, ***Ramsey mode***

Filling polarized UCNs	$\pi/2$ pulse	Storage period of duration T, UCN spins precessing about $\vec{B}$	$\pi/2$ pulse	Emptying neutrons, counting N_+ and N_-
	(2 s)		(2 s)	

time

Longitudinal depolarization curve



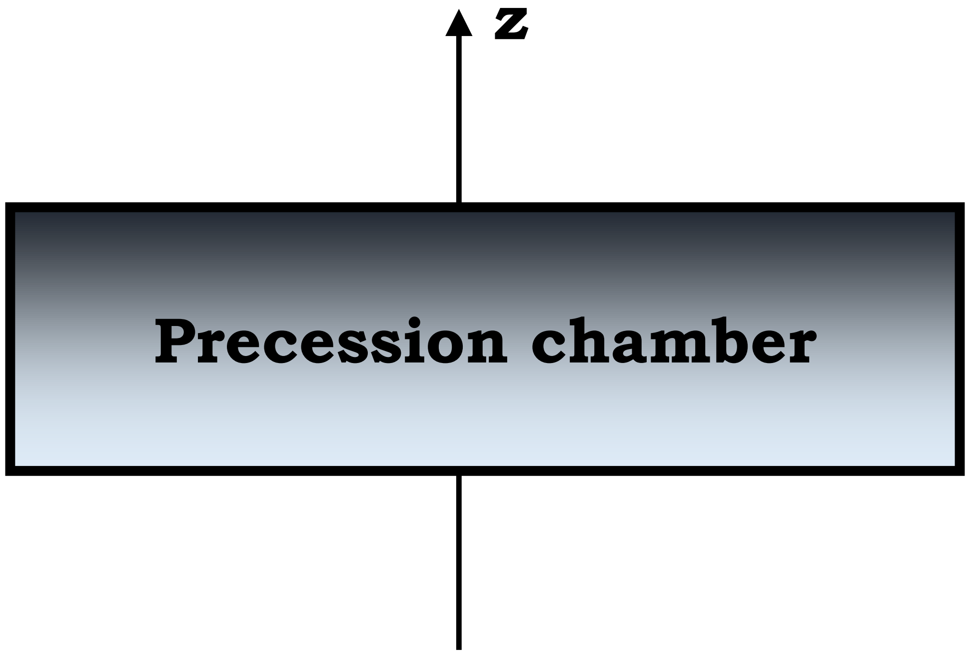
- The initial polarization 0.85 gives the **analyzing power** of the detection system.
- The UCN longitudinal polarization decays due to depolarization at wall collisions.

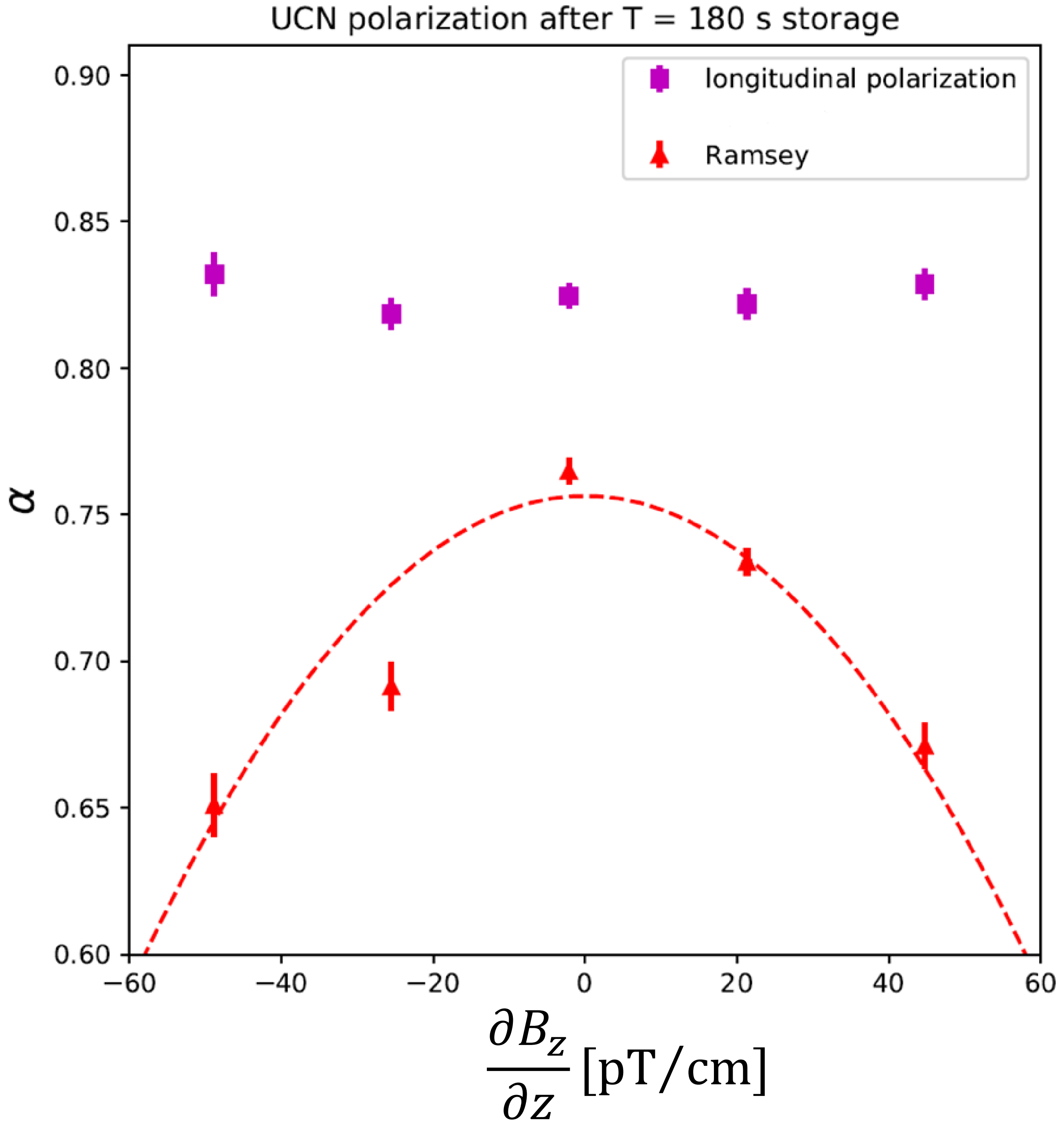
$$\frac{1}{T_1} = \nu\, \beta$$

Rate of wall collisions $\approx 50/s$

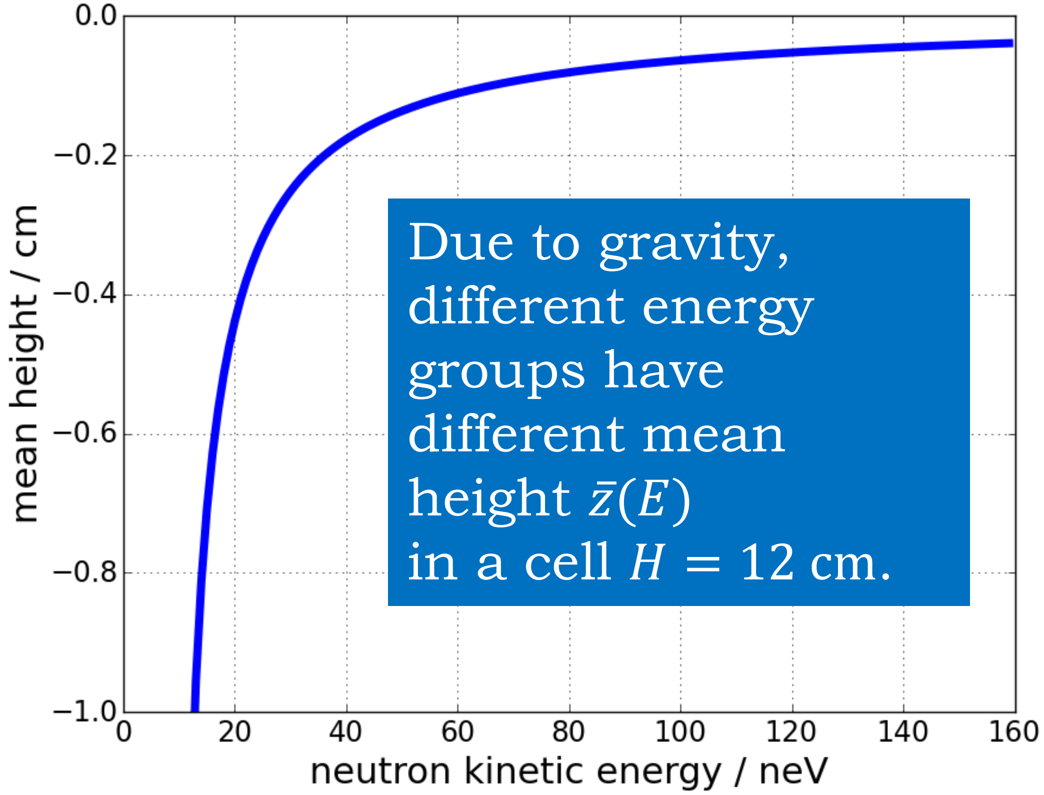
Depolarization probability $\approx 3 \times 10^{-6}$

We scan the vertical field gradient

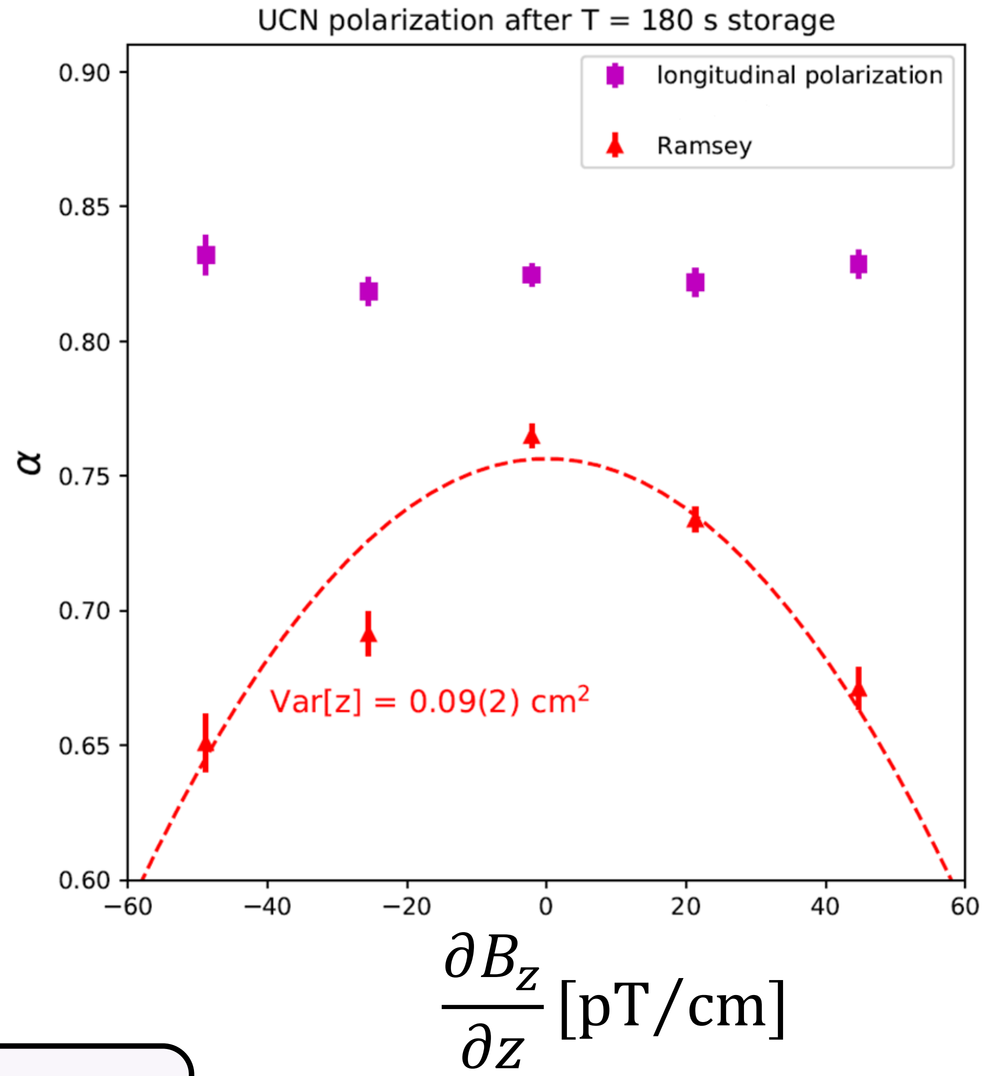




Gravitational depolarization



Due to gravity, different energy groups have different mean height $\bar{z}(E)$ in a cell $H = 12$ cm.



Low energy groups accumulate a phase difference rel. to high energy groups in a vertical gradient.

Theory for small phases:

$$\Delta\alpha = -\frac{1}{2}\gamma_n^2 \left(\frac{\partial B_z}{\partial z}\right)^2 \mathrm{Var}[\bar{z}]\, T^2$$

~~2~~ 3 modes to study the depolarization in nEDM

T1 mode

Filling	Storage UCN spins aligned with $\vec{B}$	Emptying, counting N_+ and N_-

Ramsey mode

Filling	$\pi/2$ pulse	Storage UCN spins precessing about $\vec{B}$	$\pi/2$ pulse	Emptying, counting N_+ and N_-

Spin-echo cycles

Filling polarized UCNs	$\pi/2$ pulse		π pulse		$\pi/2$ pulse	**Emptying, counting N_+ and N_-**
	(2 s)		**(4 s)**		**(2 s)**	

time

Principle of the spin-echo method

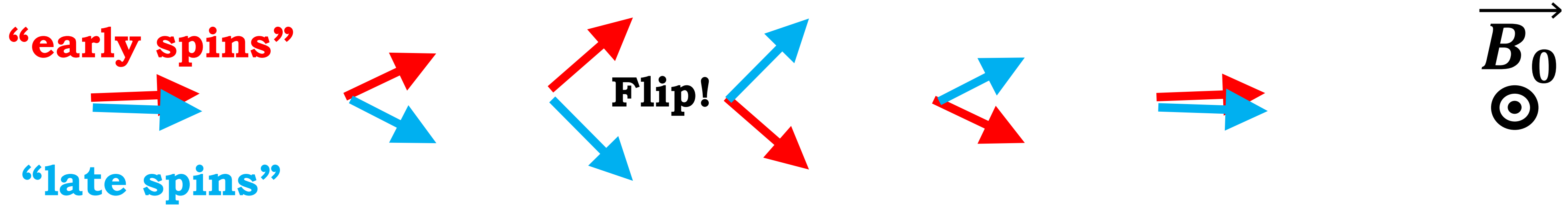
Ramsey cycles

Filling	$\pi/2$ pulse		$\pi/2$ pulse	Emptying neutrons, counting N_+ and N_-

Spin-echo cycles

Filling	$\pi/2$ pulse		π pulse		$\pi/2$ pulse	Emptying neutrons, counting N_+ and N_-

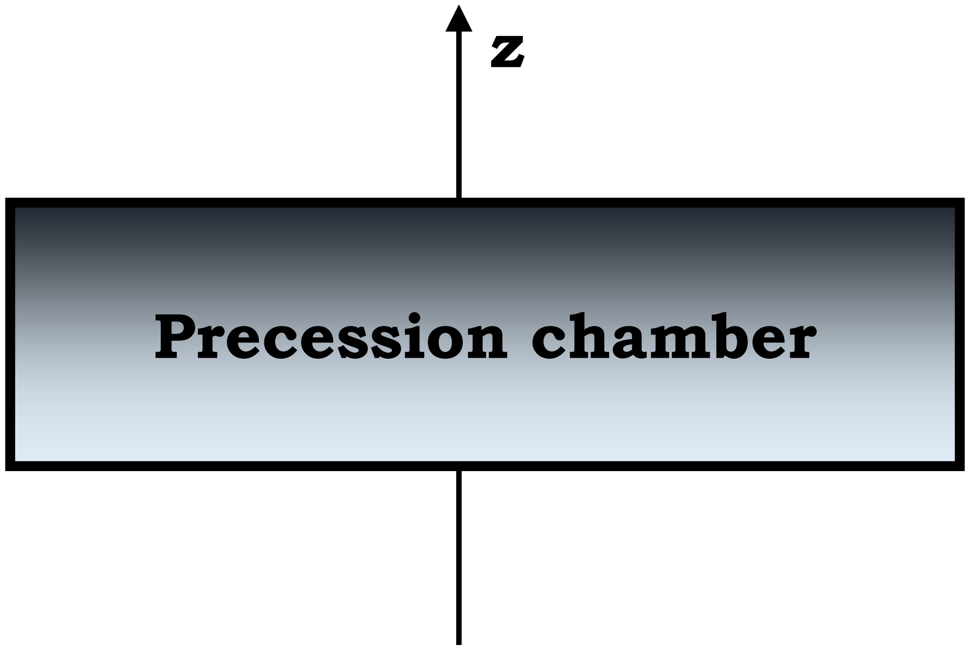
In the rotating frame

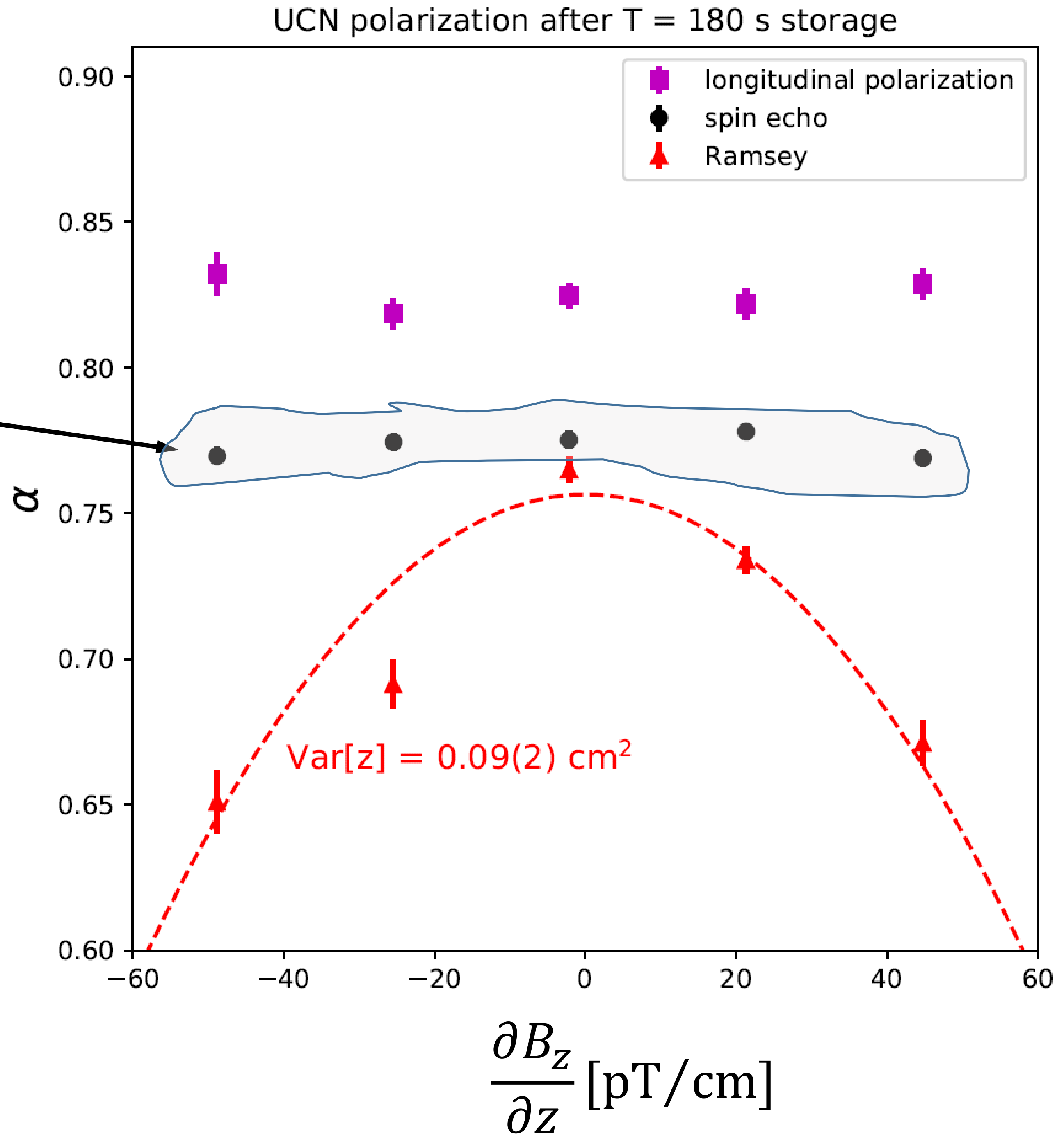


time

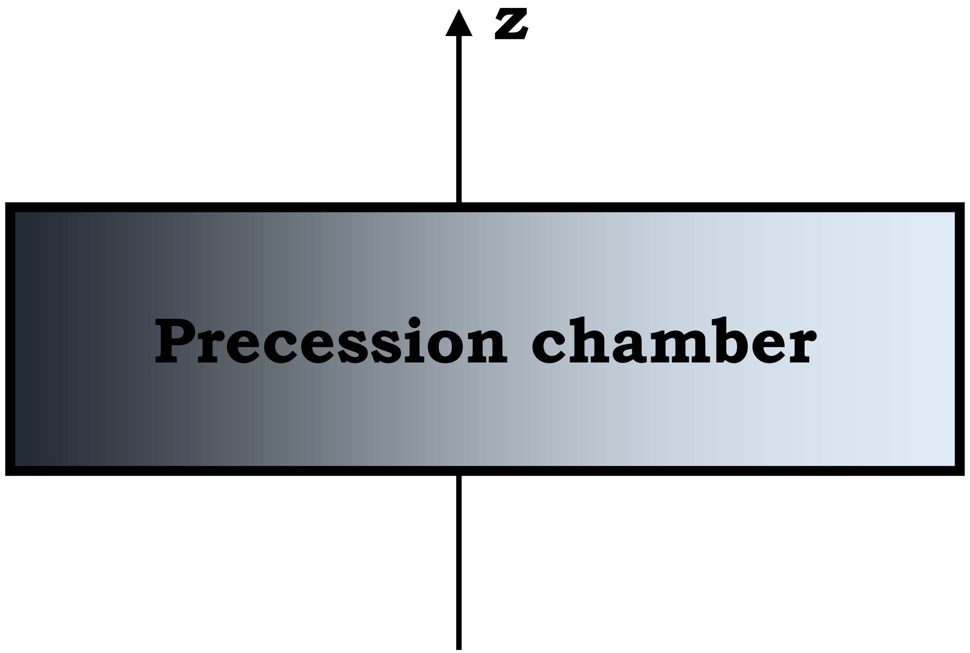
We scan the vertical field gradient

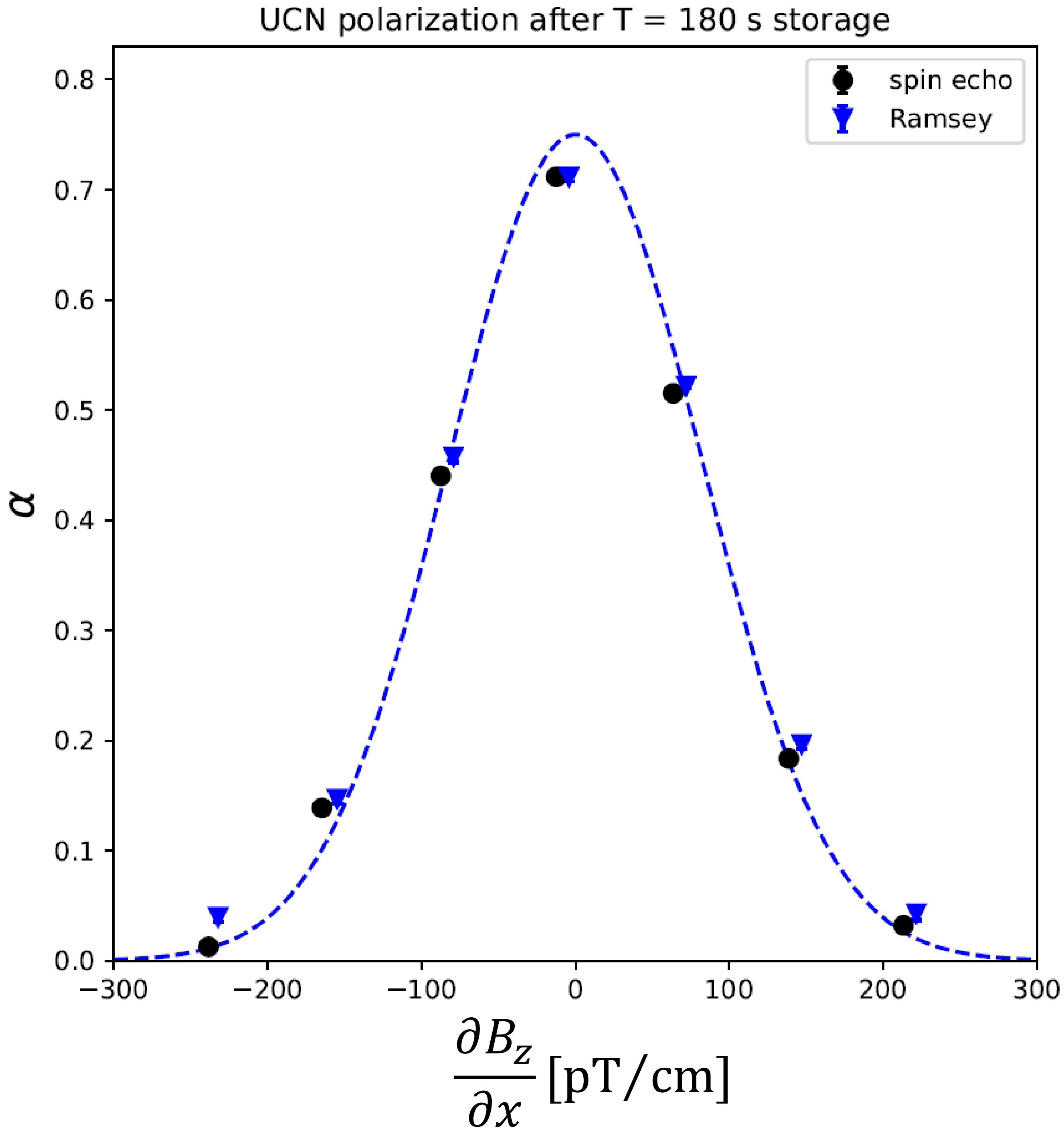
Spin echo cancels the gravitational depolarization.





We scan the horizontal field gradient





Elements of spin-relaxation theory

Intrinsic depolarization =
polarization decay within an energy group due to random motion in a static but non-uniform field.

This is an **irreversible process**

Longitudinal "noise" seen by a neutron $b(t) = B_z(t) - \langle B_z \rangle$.
The spin-relaxation theory says:

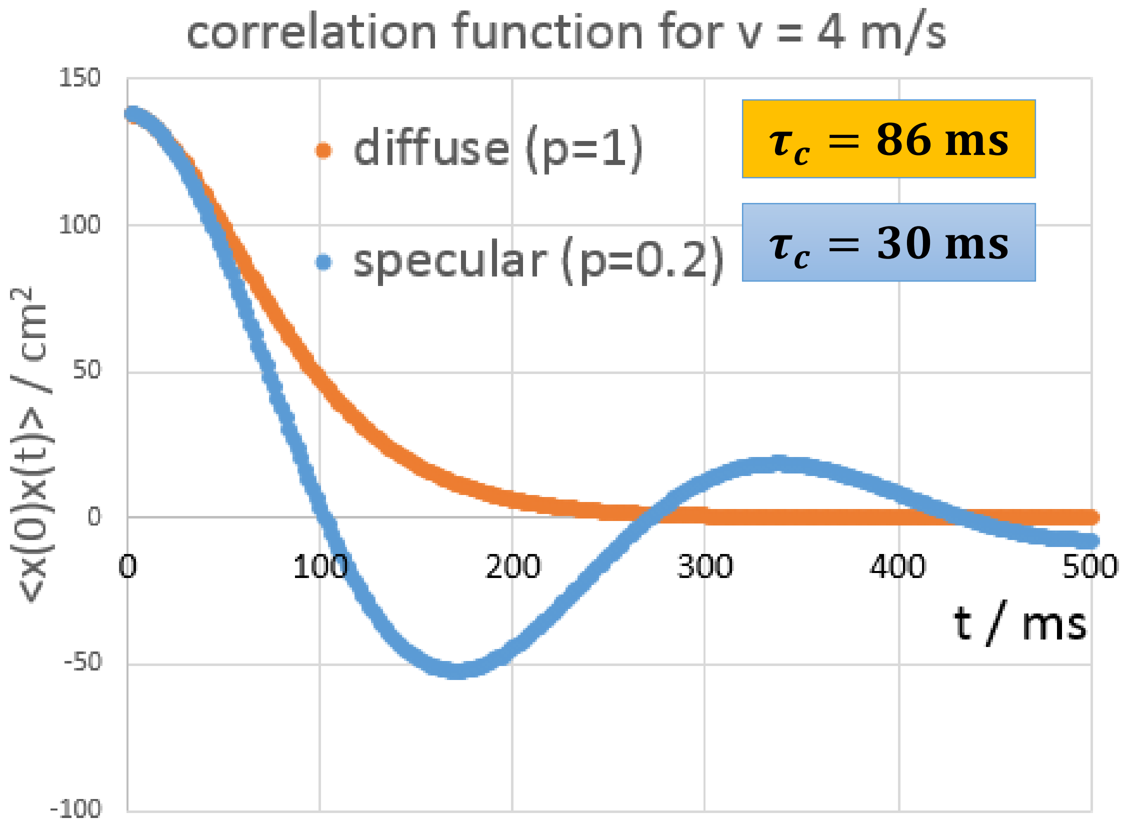
$$\frac{1}{T_2} = \gamma^2 \int_0^\infty \langle b(t) b(t+\tau) \rangle \, d\tau := \gamma^2 \langle b^2 \rangle \, \tau_c$$

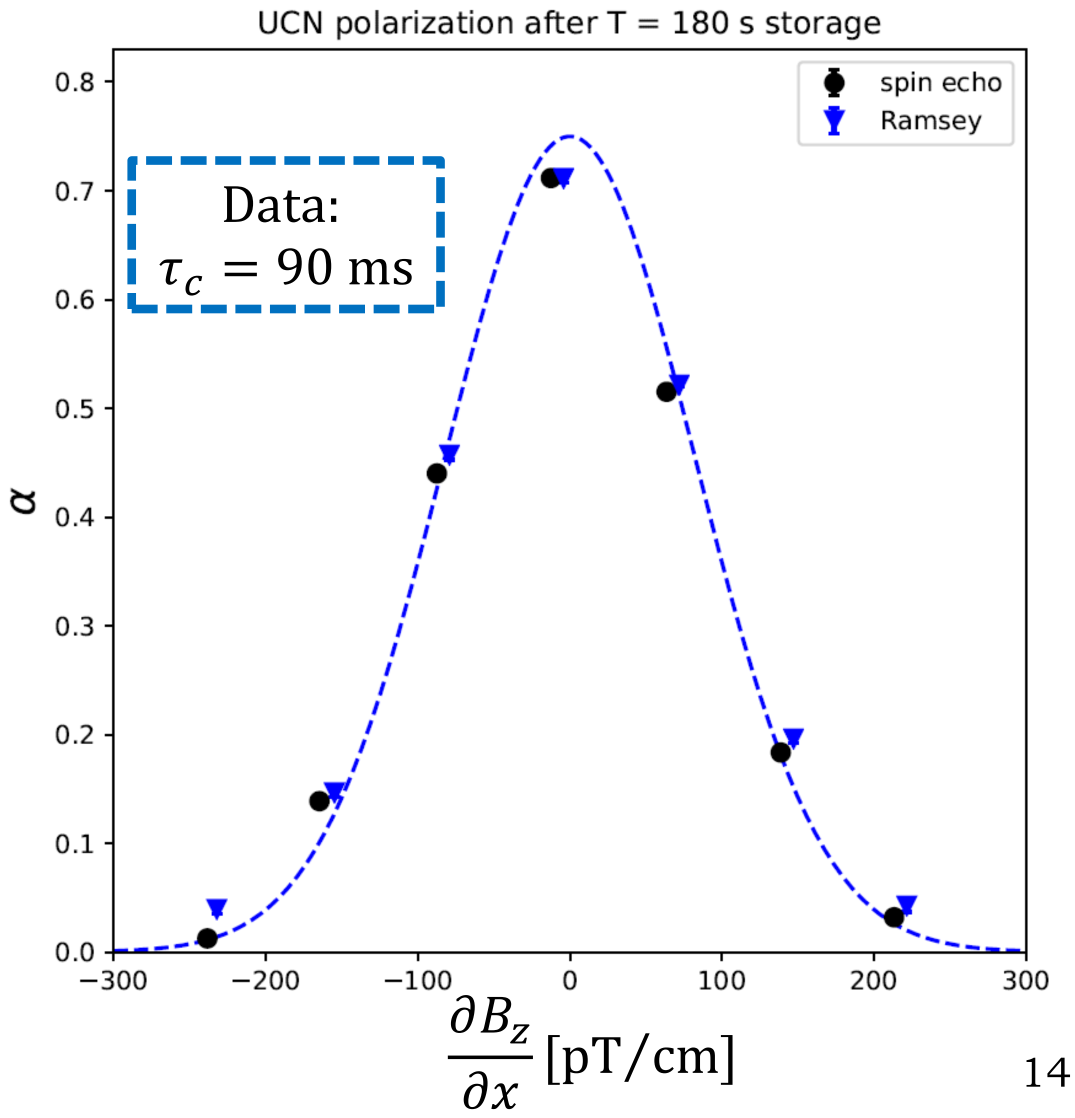
Autocorrelation function of the field

Correlation time, defined by this equation

MC calculation of the correlation time

We calculate $\tau_c = \frac{1}{\langle x^2 \rangle} \int_0^\infty \langle x(0)x(\tau) \rangle \, d\tau$





Summary: UCN transverse depolarization

(during precession)

$$\frac{d\alpha}{dT} = -\frac{\alpha}{T_{\mathrm{wall}}} - \frac{\alpha}{T_{2,\mathrm{mag}}} + \dot{\alpha}_{\mathrm{grav}}$$

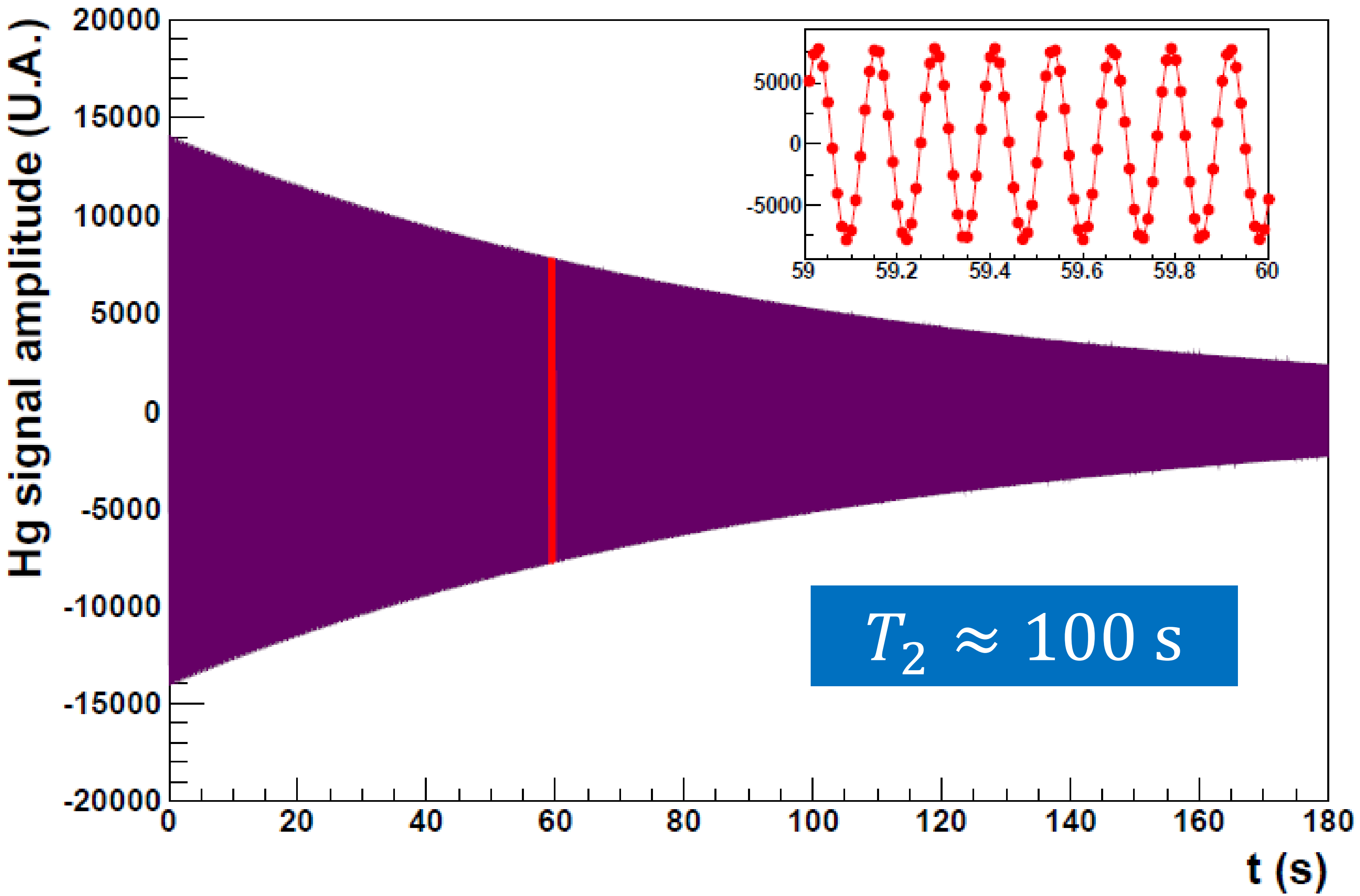
Wall collision
$T_{\mathrm{wall}} = T_1 \approx 5000$ s

Intrinsic depolarization
due to random trajectories in a non-uniform magnetic field

Gravitational depolarization
different energy groups have different height z

- In nEDM@PSI we obtained $\alpha = 0.77$ after T = 180 s of precession
- It is important to understand the magnetic depolarization for the design of n2EDM because we want to increase the size :
  diameter 47 cm in nEDM -> diameter 80 cm in n2EDM

We also store polarized mercury atoms



depolarization at wall collisions.

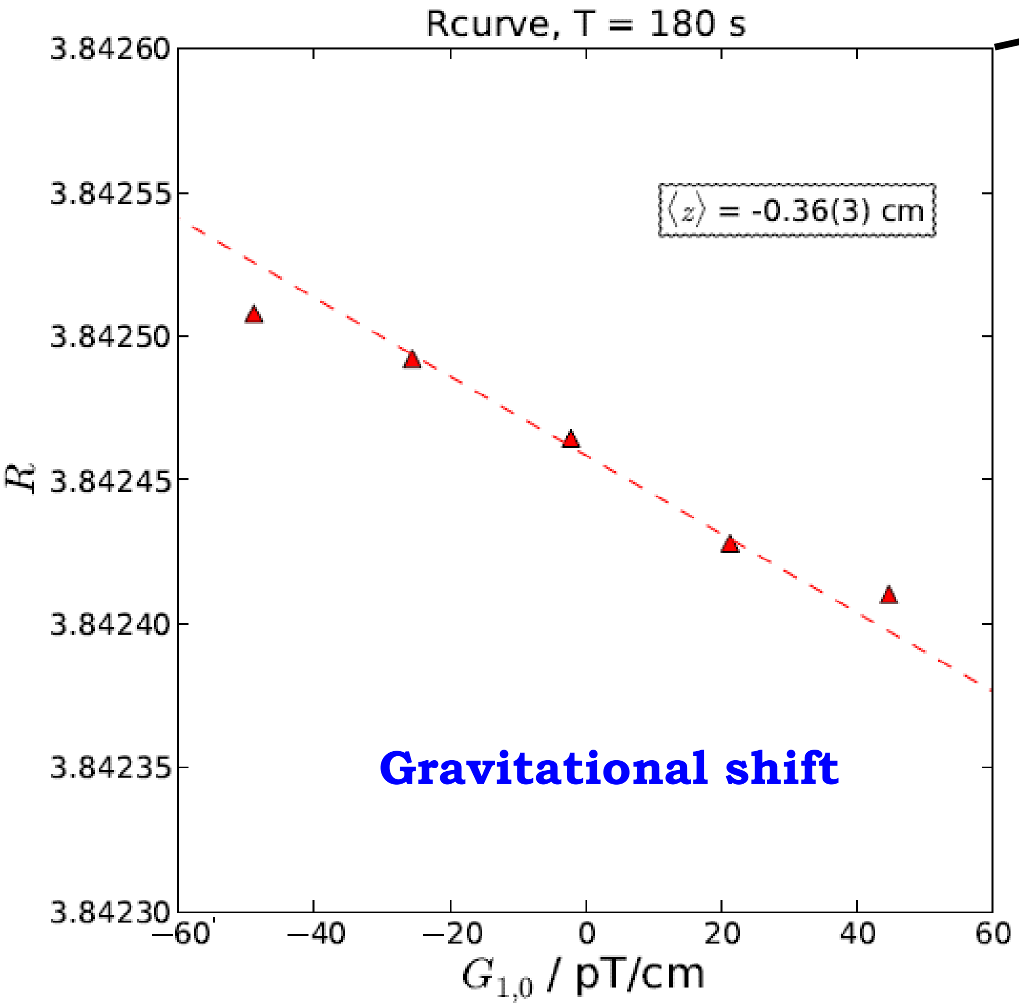
$$\frac{1}{T_1} = \nu\, \beta$$

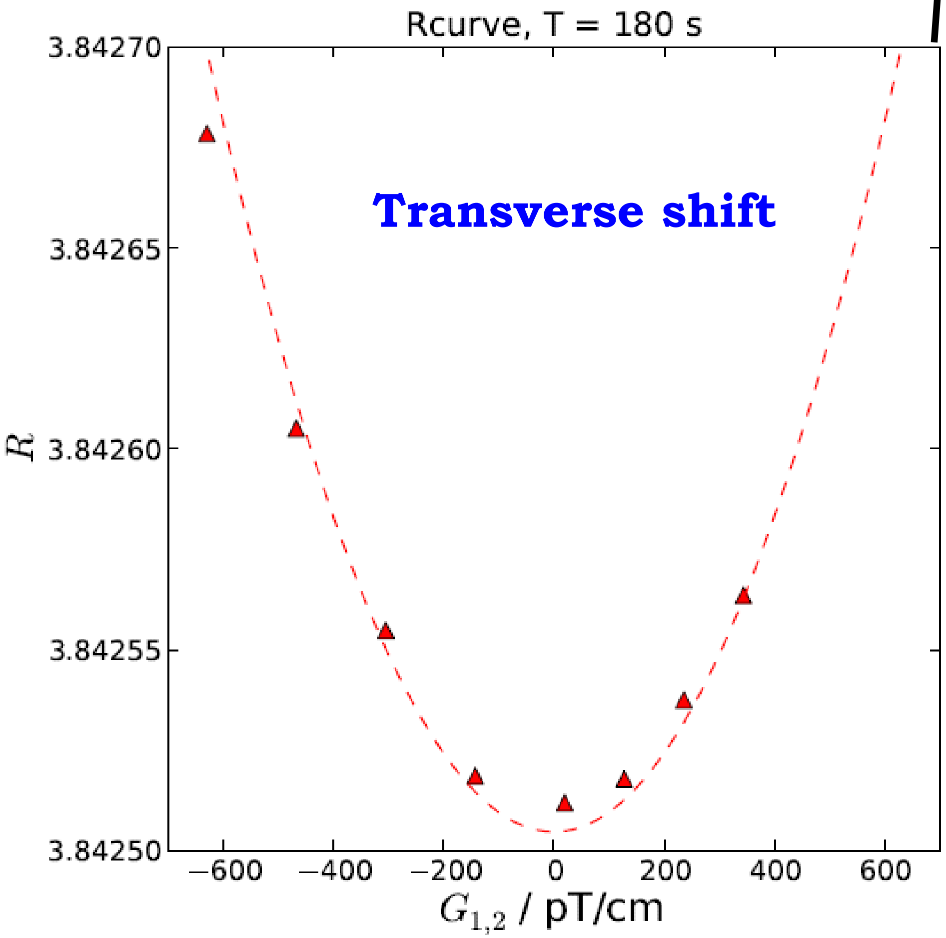
Rate of wall collisions $\approx 1000/s$

Depolarization probability $\approx 10^{-5}$

co-magnetometer equation

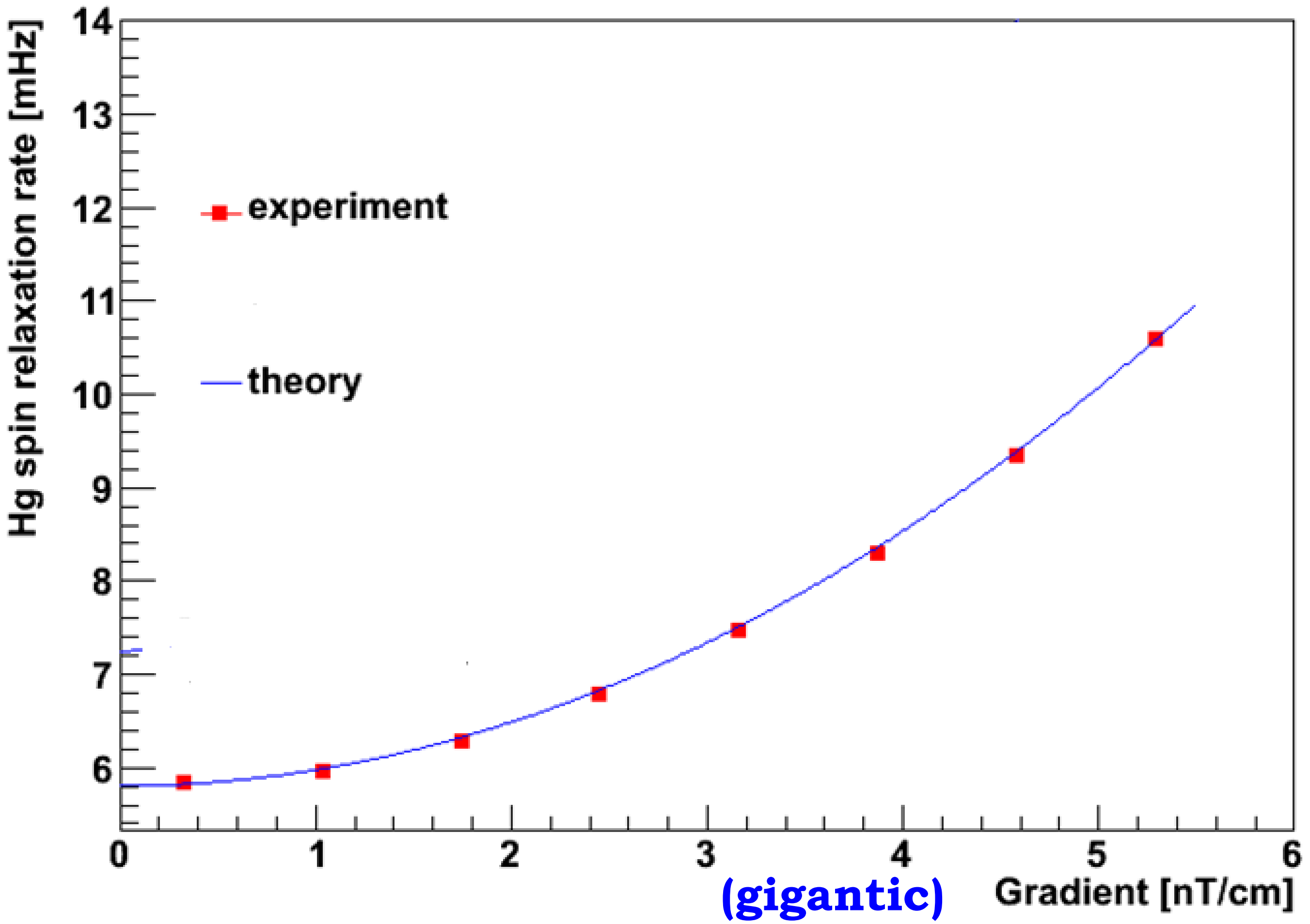
$$\mathcal{R} = \frac{f_n}{f_{\mathrm{Hg}}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\left(1 + \frac{2E}{\pi\hbar f_{\mathrm{Hg}}}\left(d_n^{\mathrm{true}} + d_n^{\mathrm{false}}\right) + \frac{G\langle z\rangle}{B_0} + \frac{\langle B_T^2\rangle}{2B_0^2} + \cdots\right)$$





Magnetic depolarization of mercury?

The mercury is less sensitive to gradients because the correlation time is shorter, $\boldsymbol{\tau_c} = \mathbf{2\ ms}$



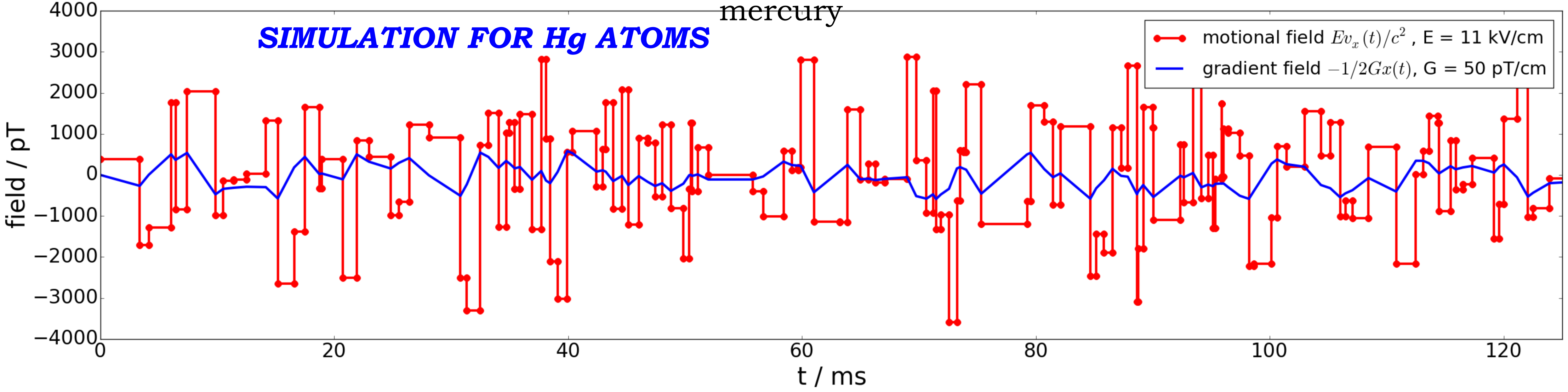
Frequency shift induced by magnetic noise

$$\delta\omega = \frac{\gamma^2}{2}\int_0^\infty \mathrm{Im}\left[e^{i\omega\tau}\langle b^*(t)b(t+\tau)\rangle\right]d\tau$$

motional field

$$b(t) = \left(\vec{B}(t) + \boxed{\frac{1}{c^2}\vec{E}\times\vec{v}(t)}\right)\cdot\left(\overrightarrow{e_x} + i\overrightarrow{e_y}\right)$$

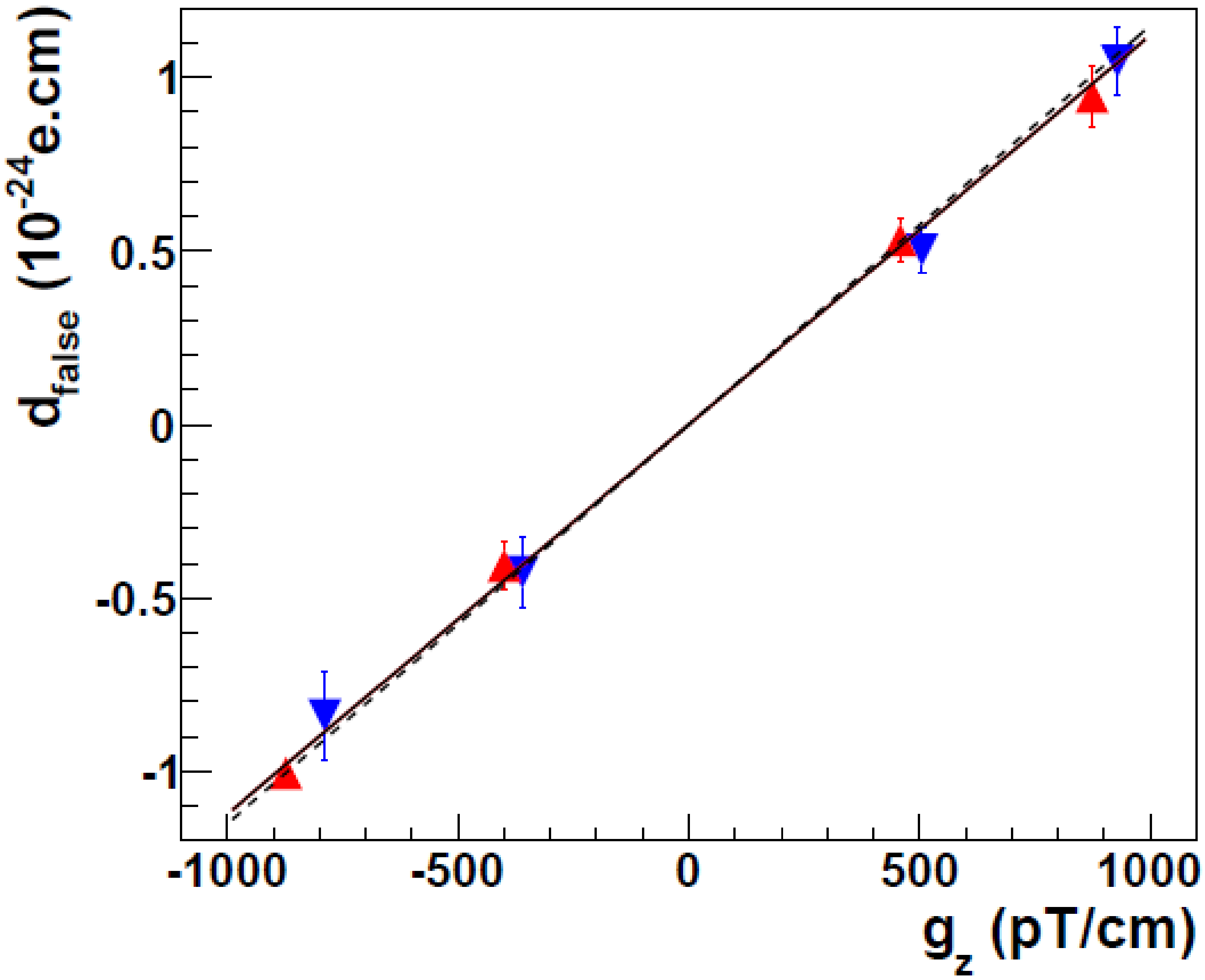
mercury



False motional EDM of mercury

Linear false EDM:

$$d_{\rm Hg}^{\rm false} = \frac{\hbar \gamma_{\rm Hg}^2}{8c^2} R^2 G_{1,0}$$
$$\approx \frac{G_{1,0}}{1\mathrm{pT/cm}} \times 1.15 \times 10^{-27} e\,\mathrm{cm},$$

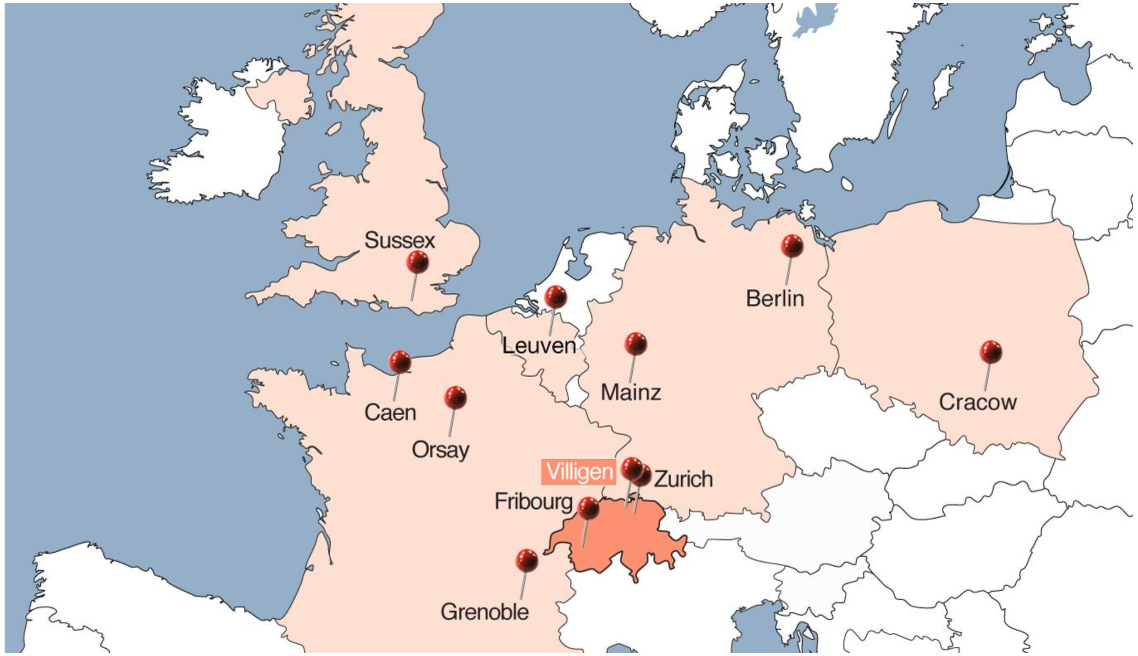


Final remarks on field uniformity
To measure nEDM at the 10^{-27} e cm level

- **B must be uniform**
  otherwise the UCN depolarize too fast
  the requirement on the *field production* is **< 10 pT/cm**

- **B non-uniformities must be controlled**
  otherwise we get a false EDM due to the mercury motional field
  the requirement on the *field measurement* is **< 0.1 pT/cm**

Credits to the n2EDM collaboration



50 physicists
10 PhD students
7 countries
13 laboratories

thank you,

the rest are backup slides

UCNs and magnetic fields

Neutron magnetic moment

$$\mu_n \times (1\ \mathrm{T}) = 60\ \mathrm{neV}$$

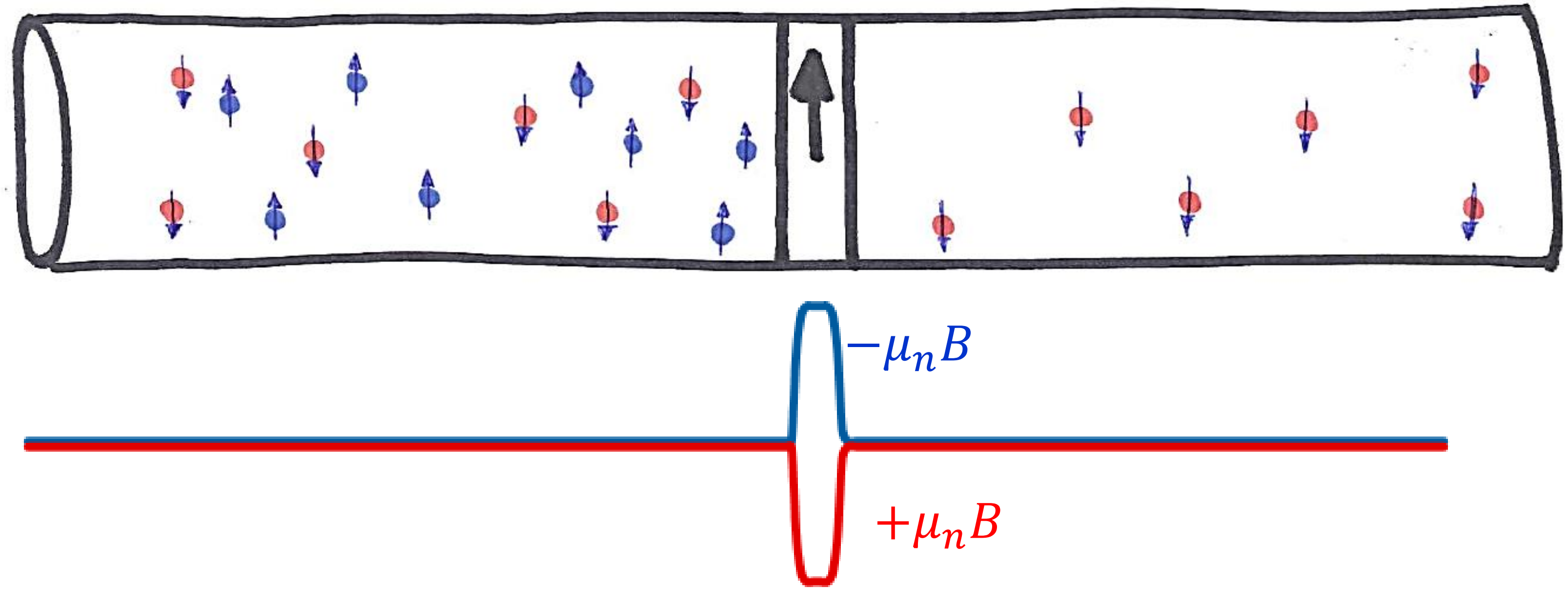
Magnetic fields act on the spin ½ neutron

$$V = -\vec{\mu}_n\,\vec{B}$$

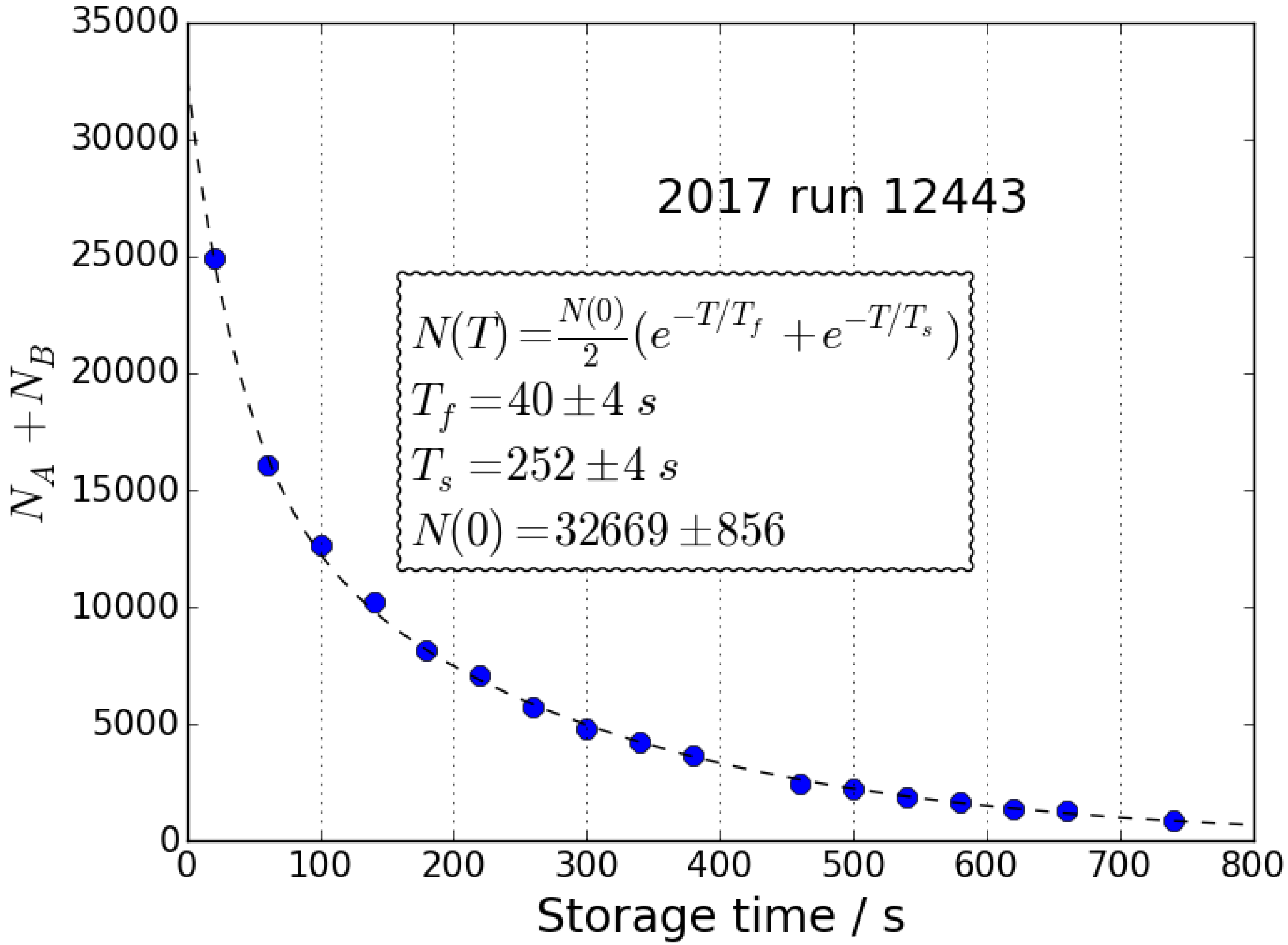
Input: unpolarized UCNs

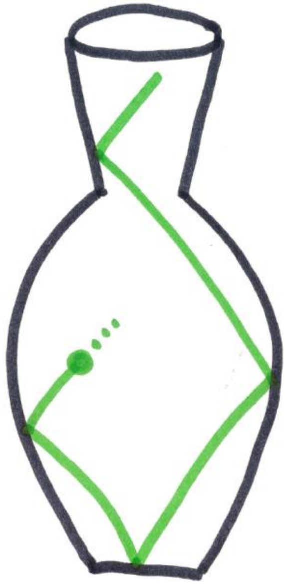
Magnetized foil

Output: polarized UCNs



Storing Ultracold neutrons in the nEDM apparatus





Magic field

$$d_n^{\mathrm{false}} = \frac{\hbar \gamma_n \gamma_{\mathrm{Hg}}}{2c^2} \int_0^\infty \langle B_x(0) v_x(\tau) + B_y(0) v_y(\tau) \rangle \cos \omega\tau \, d\tau.$$

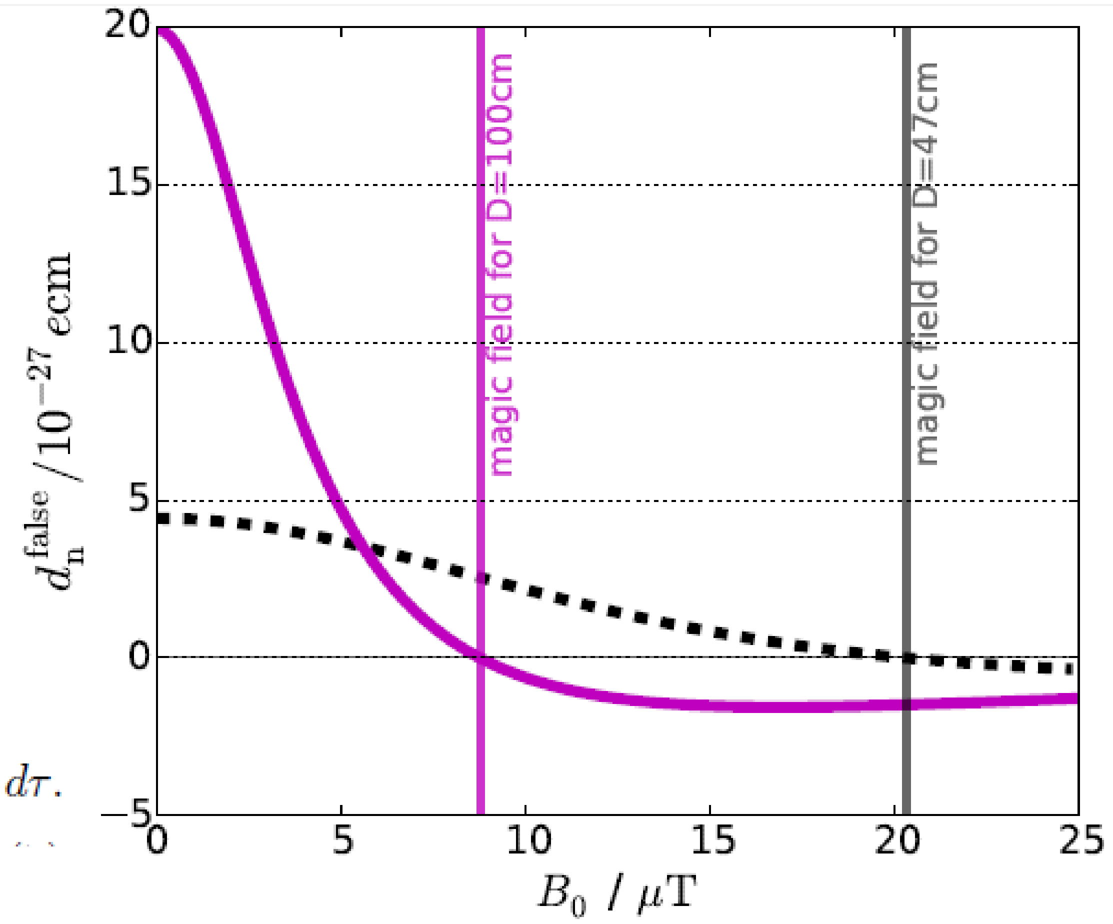


FIG. 3. False motional EDM d_n^{false} induced by a linear gradient of $G_1 = 1$ pT/cm as a function of the magnitude of the holding field B_0 in a cylindrical chamber of height 12 cm and diameter 47 cm (dashed line) or 100 cm (plain magenta line). The vertical lines labeled "magic field" indicate the values of B_0 for which $d_n^{\mathrm{false}} = 0$.