nEDM @ PSI

Searching for the electric dipole moment of the neutron

XII Rencontres de Vietnam
High Sensitivity Experiments Beyond the Standard Model
July 31st –August 6th, 2016

The collaboration

- 13 Institutions
- 7 Countries
- 48 Members
- 10 PhD students

PSI in Switzerland

Outline

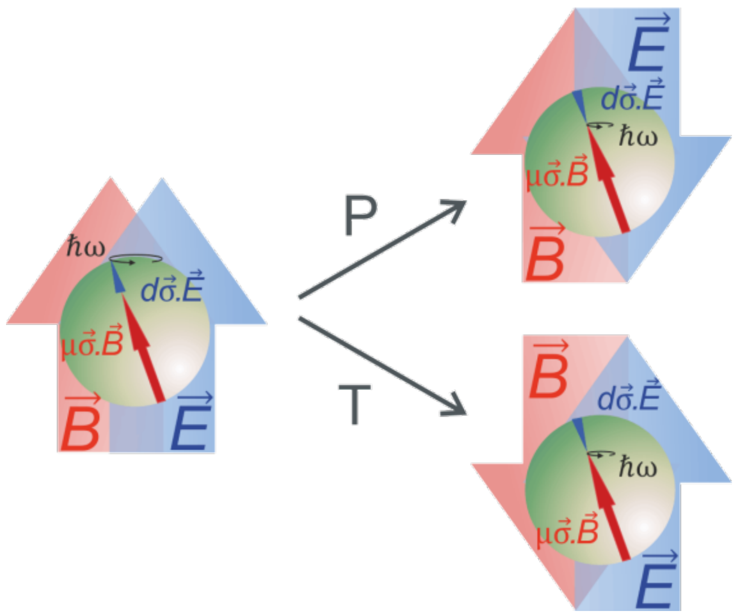
Introduction

- Why search for a neutron EDM?
- How do we search for it?

Status at PSI

- The UCN source
- Statistical sensitivity
- Magnetometry
- Blind Analysis

Reminder: CP violation & nedm



A non-zero particle EDM violates *P*, *T* and, assuming *CPT* conservation, also *CP*.

- Might explain BAU
- Sensitive to QCD –theta term
- Would be first evidence of flavor conserving CP-violation

$$L_{\text{eff}} = L_{\text{QCD}} + \theta \frac{\alpha_s}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

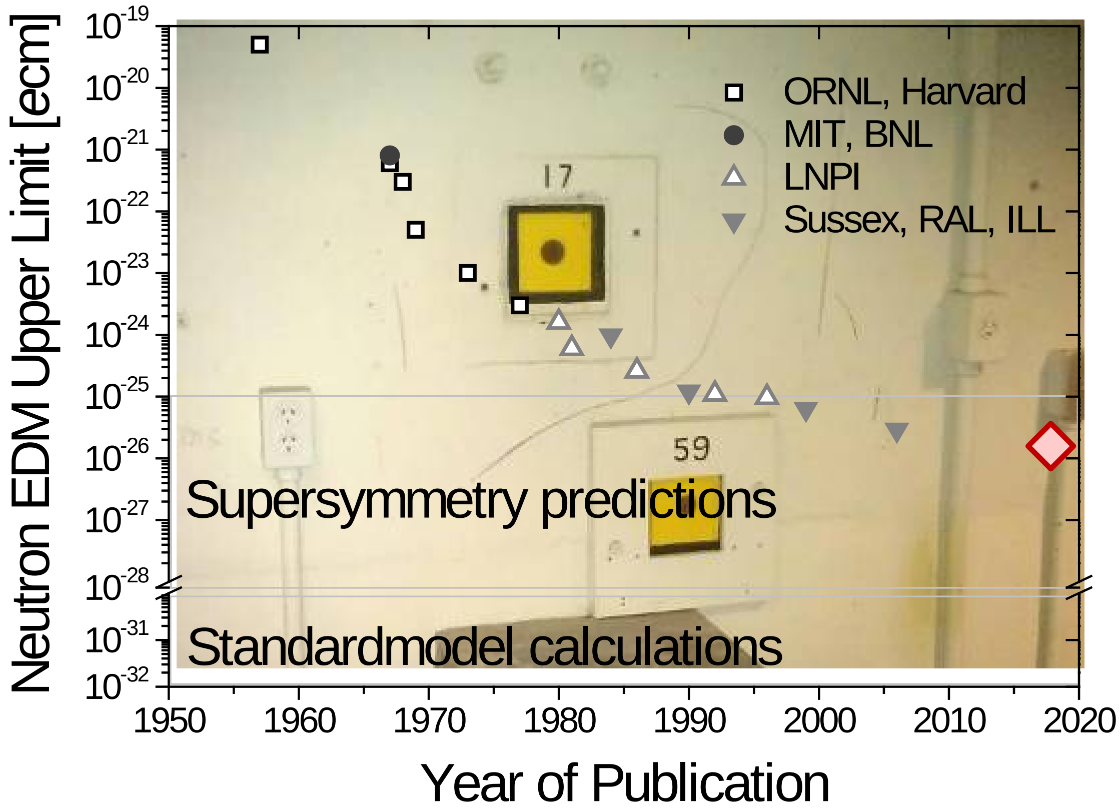
$$d_{\text{n}} \approx \theta \cdot 10^{-16} e \cdot \text{cm}$$

$d_n < 3.0 \times 10^{-26}\ e$ cm*

$\Theta \leq 10^{-9}$
"unnaturally small"

*J.M. Pendlebury et al., PRD 92 (2015) 092003

A brief history of nEDM searches



Aimed at sensitivities at PSI:

Intermediate:

$d_n < 5 \times 10^{-27}$ e cm (95% C.L.)

Final:

$d_n < 5 \times 10^{-28}$ e cm (95% C.L.)

First

Smith, Purcell, Ramsey

$d_n < 5 \times 10^{-20}$ e cm

PR 108 (1957) 120

~ 50 years

Last

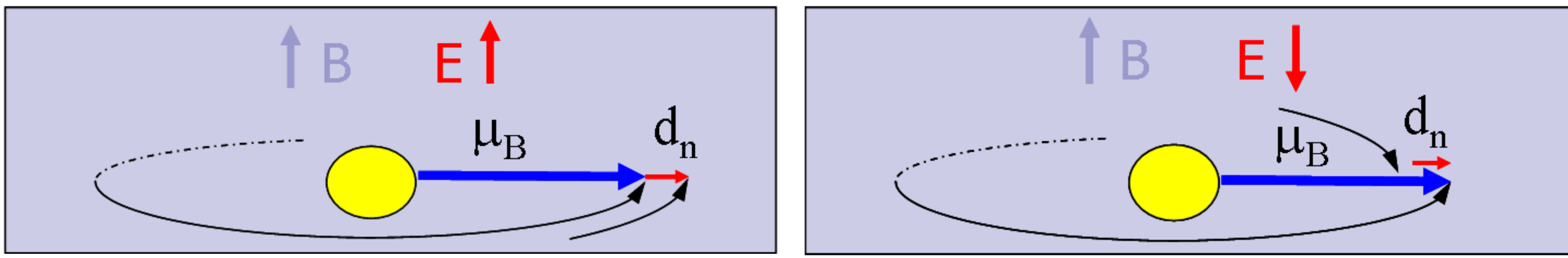
RAL-Sussex-ILL

$d_n < 2.9 \times 10^{-26}$ e cm (90% C.L.)

C.A.Baker et al., PRL 97 (2006) 131801

The measurement technique

Measure the difference of precession frequencies in parallel/anti-parallel fields:



$$\hbar \Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\left(\cancel{B_{\uparrow\uparrow} - B_{\uparrow\downarrow}}\right)$$

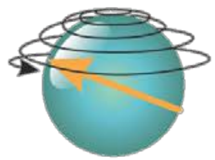
for $d_n < 10^{-26}$ → $\Delta\omega$ < 60 nHz

$\omega_L \approx 30$Hz

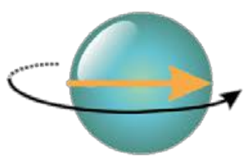
The Ramsey technique

Spin "down" neutron...

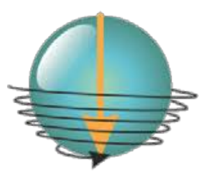
Apply π/2 spin flip pulse...

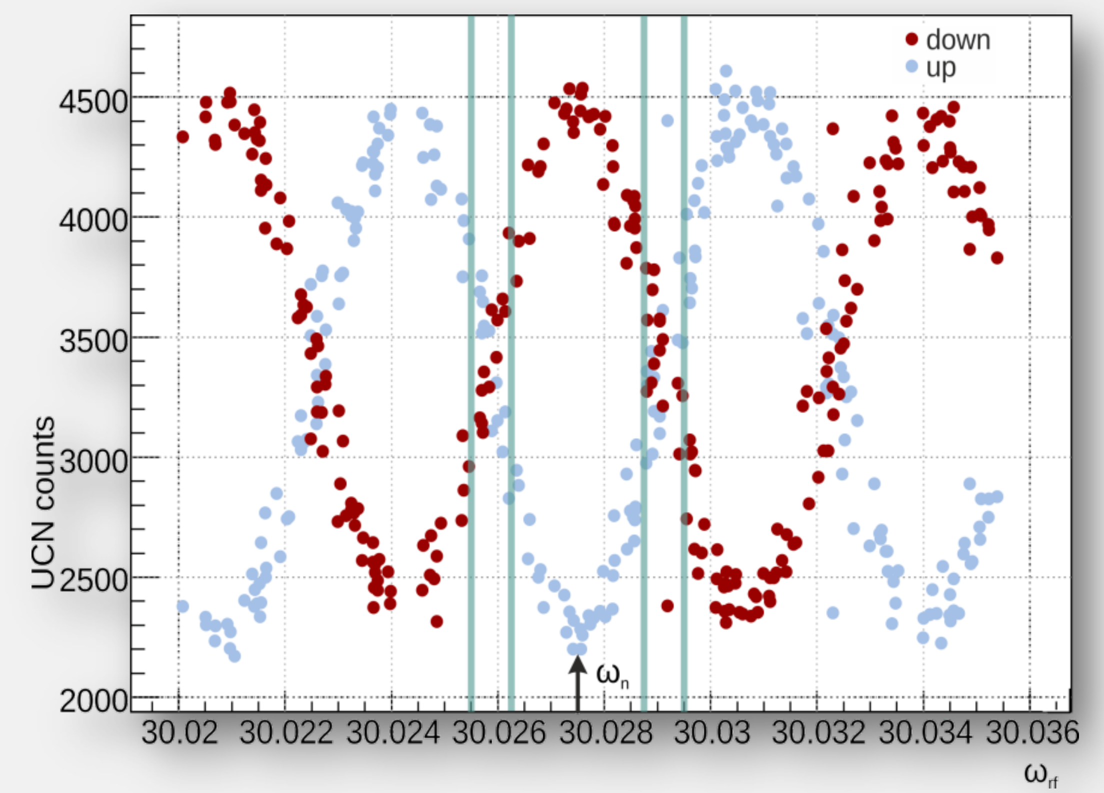


Free precession at ω_L



Second π/2 spin flip pulse.





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

α	Visibility of resonance
T	Time of free precession
N	Number of neutrons
E	Electric field strength

The beam searches

$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{\dot{N}}}\frac{1}{\sqrt{t}}$$

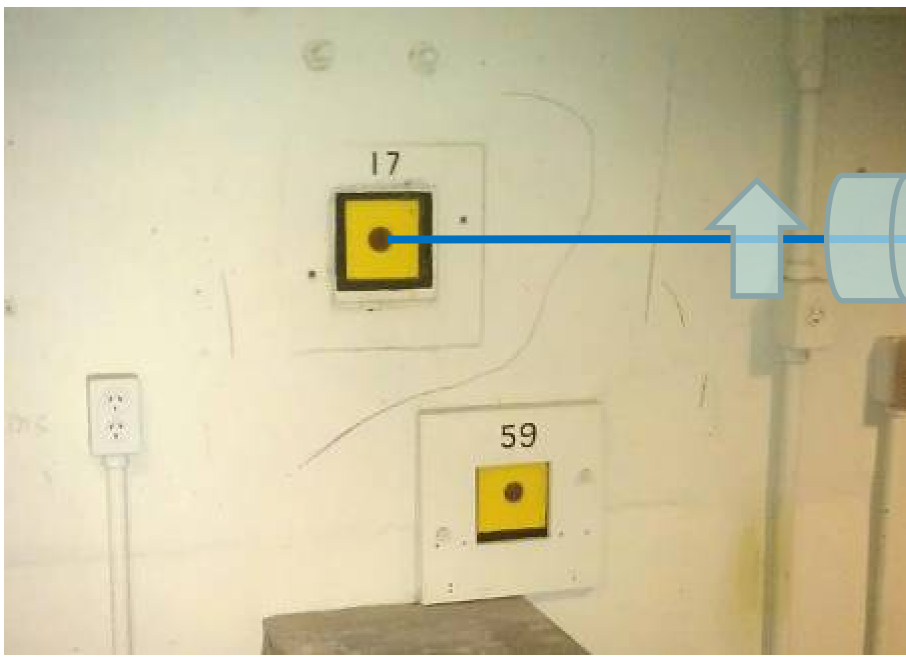
$$= 8.7 \times 10^{-22}\,\frac{e\mathrm{cm}}{\sqrt{\mathrm{Hz}}}\frac{1}{\sqrt{t}}$$

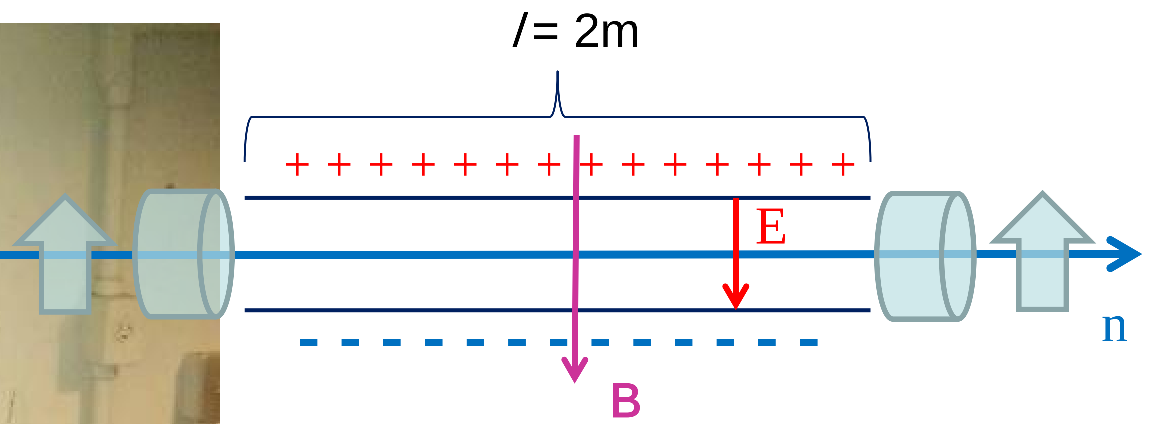
$$T = \frac{l}{v} \approx 0.015\mathrm{s}$$

$$\alpha = 0.8$$

$$E = \frac{100\mathrm{kV}}{\mathrm{cm}}$$

$$\dot{N} = 1 \times 10^{6}\mathrm{s}^{-1}$$





Dominant systematic effect:

$$B_v = -\frac{\boldsymbol{v} \times \boldsymbol{E}}{c^2}$$

final result: $\sigma(d_\mathbf{n}) = 1.5 \times 10^{-24}\,e\mathrm{cm}$
due to misalignment of 15E-6 rad

Dres *et al.*, ***PRD*** 15(**1977**) 9

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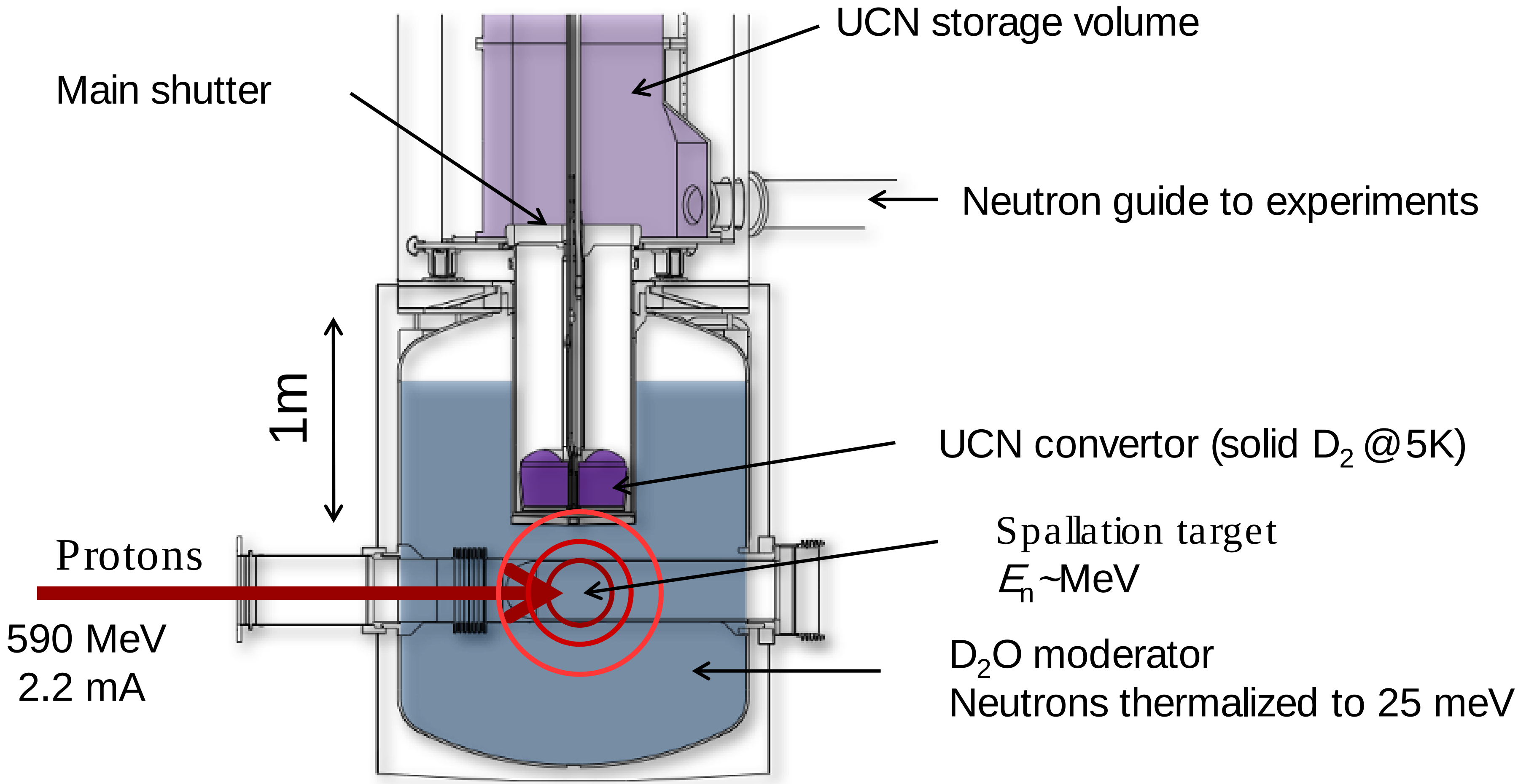
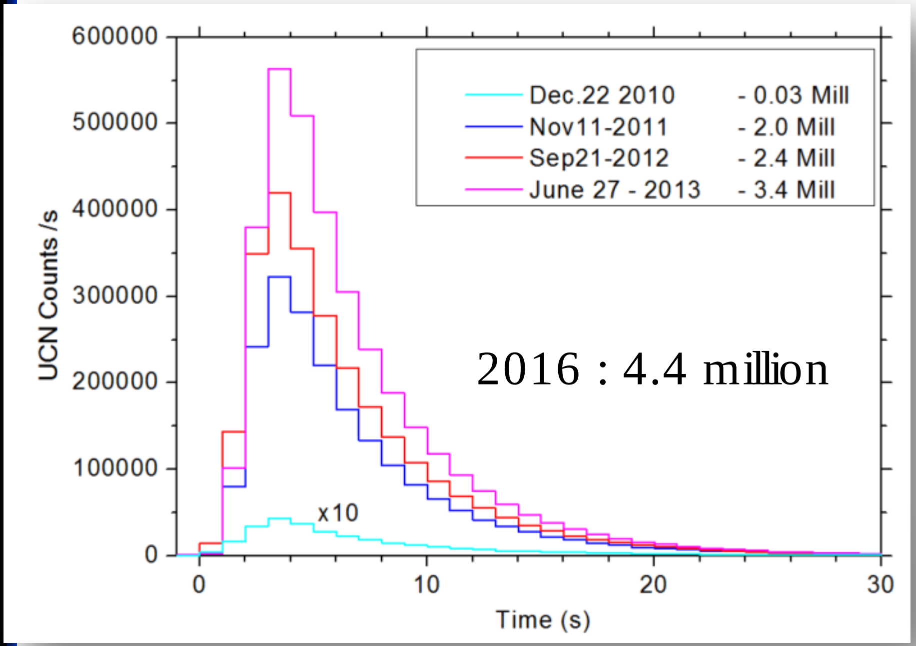
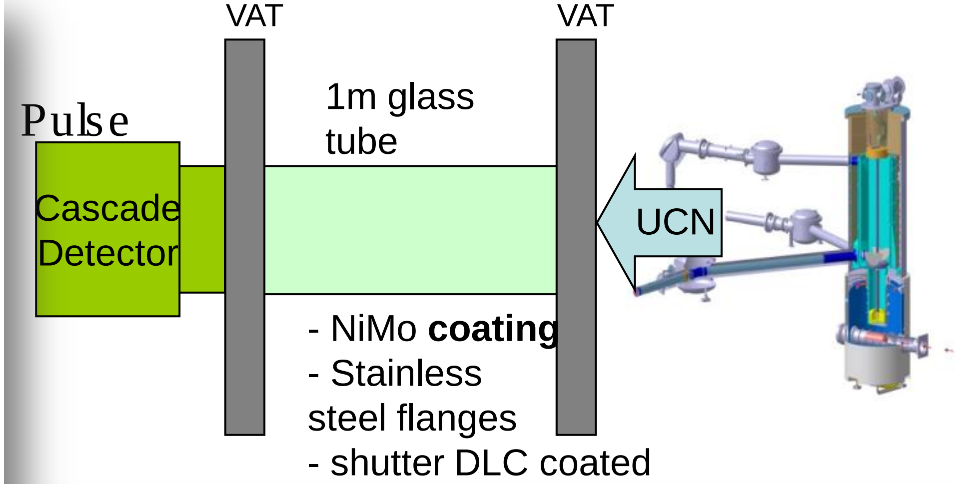
PSI UCN source

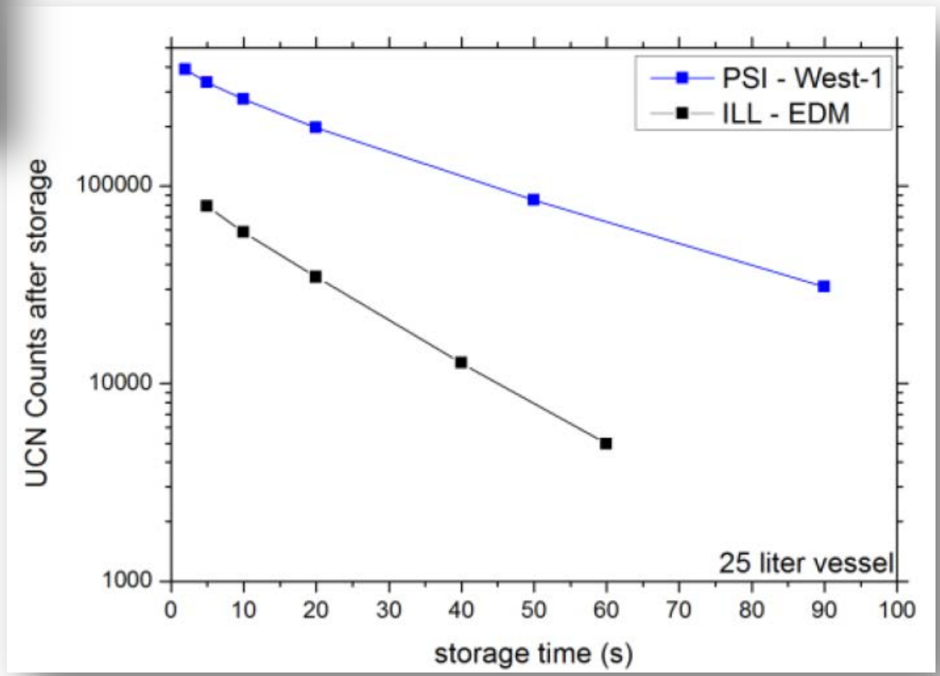


Golub, R. & Pendlebury, J. M
PLA **(1975)**133
Anghel, *et. al*
NIMA **(2009)** 272

UCN source performance

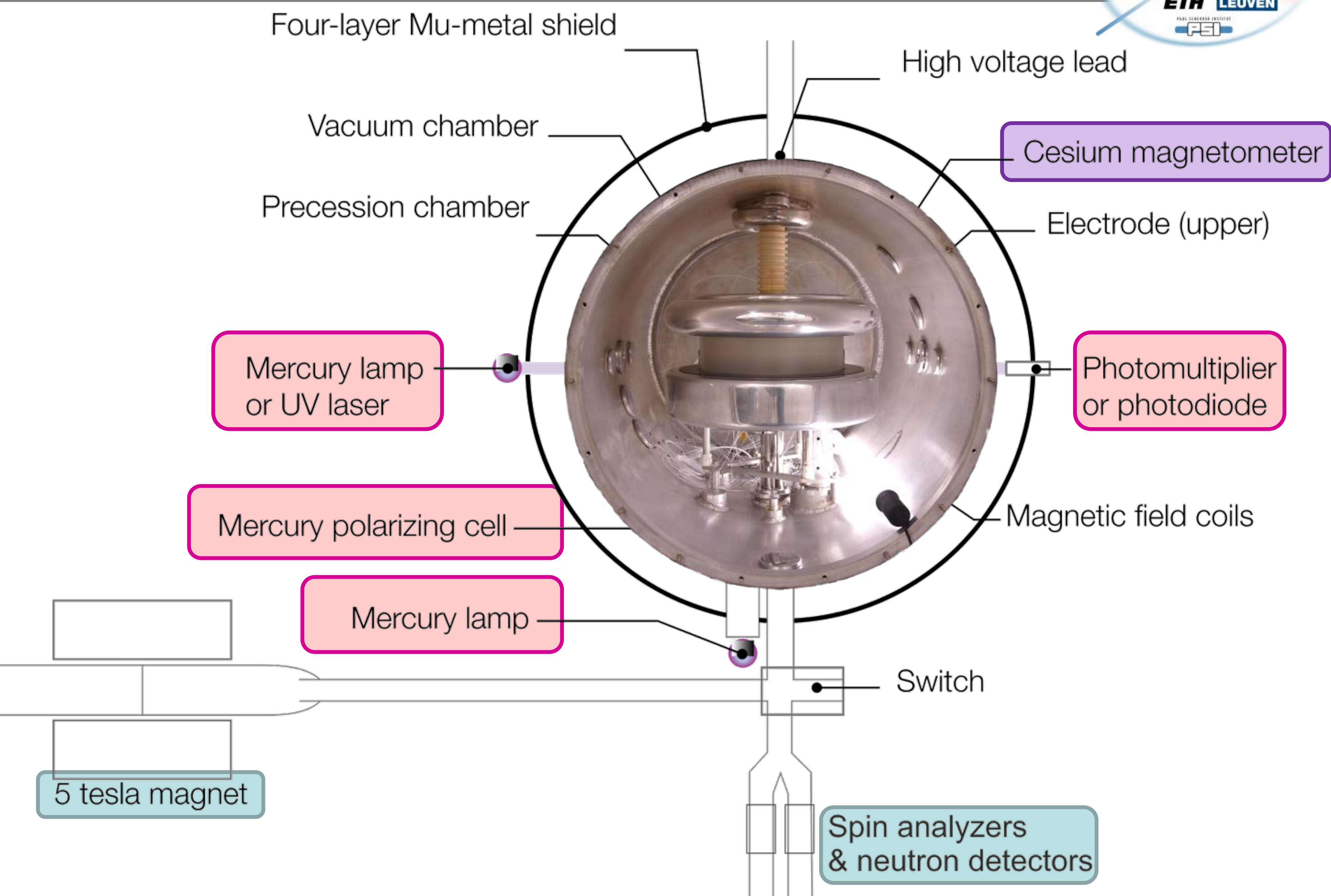






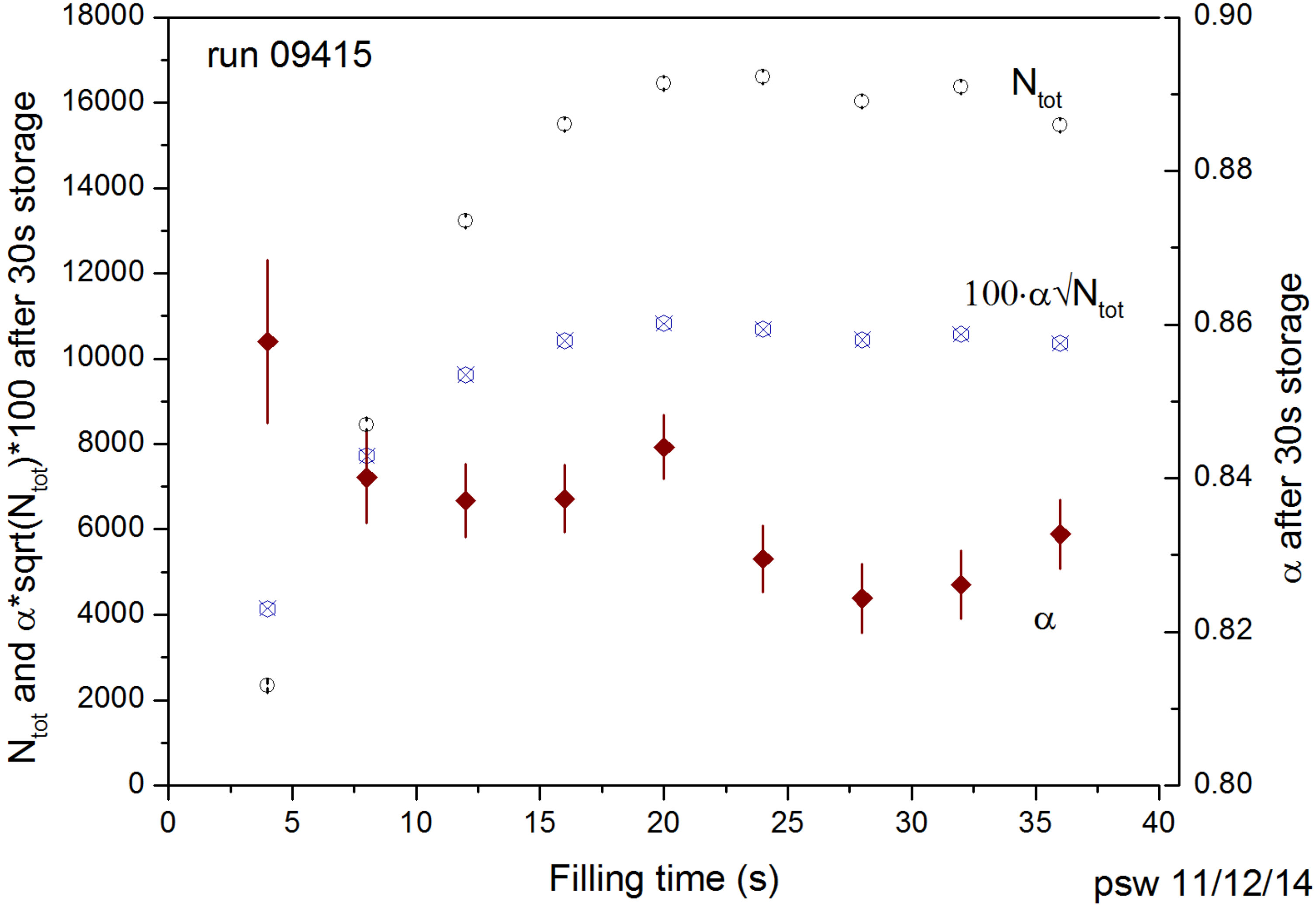
- 30 UCN/cm^3 at beam exit (~550 000 UCN/25 liter)

The nEDM spectrometer



Filling UCN

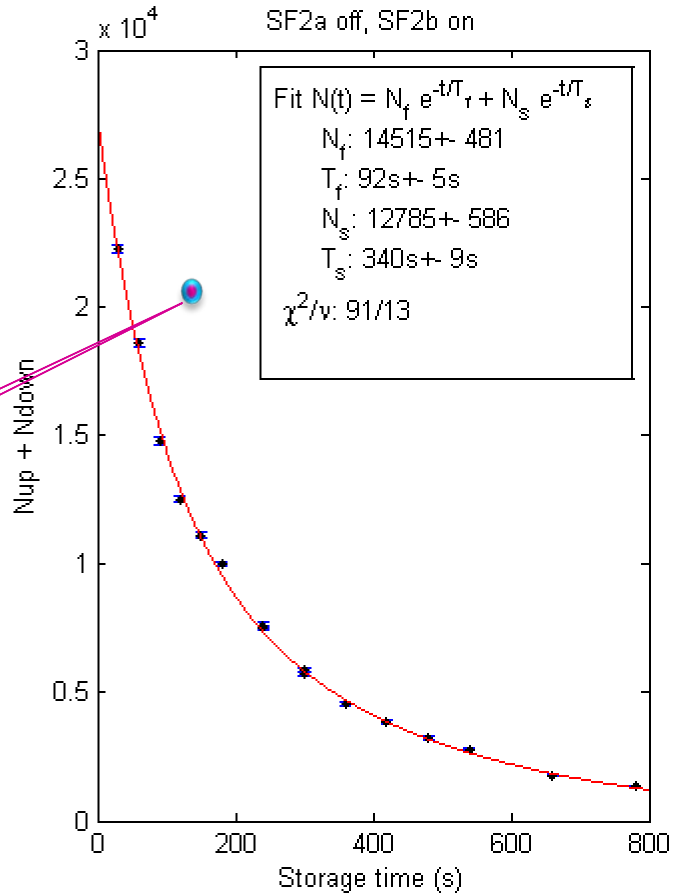
- Optimize product $\alpha\sqrt{N}$



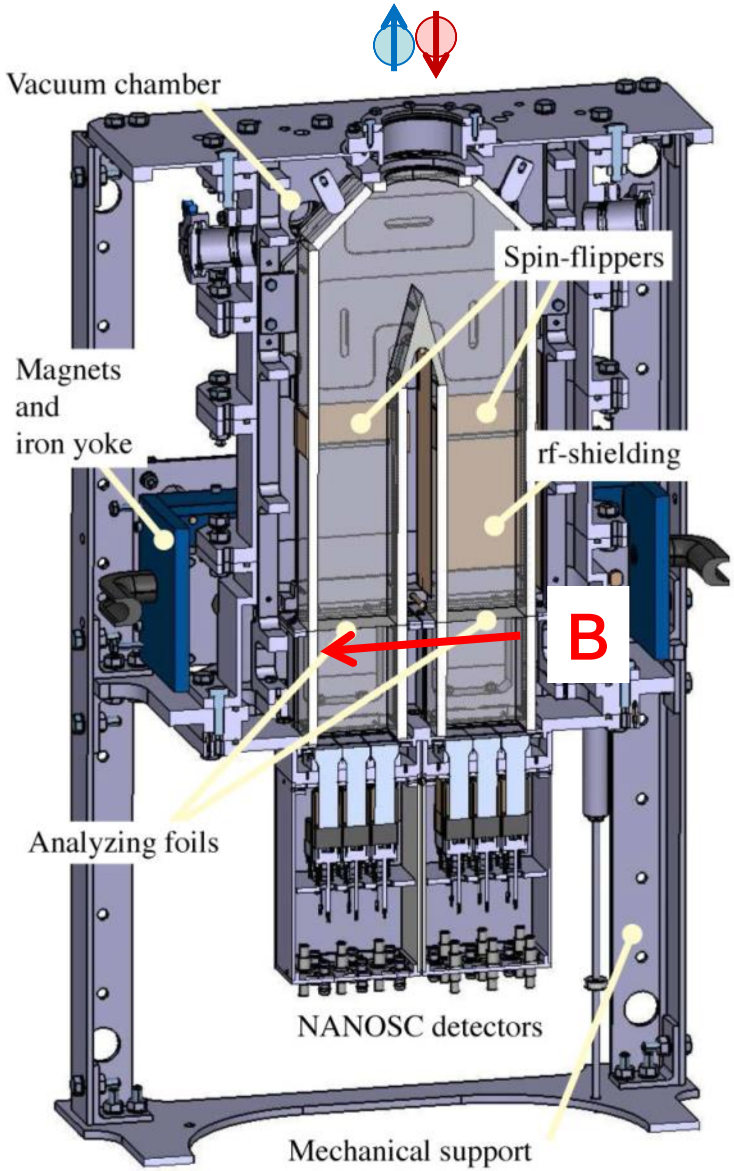
Storage life time

- Chamber made of **dPS** insulator ring and **DLC** electrodes
- Two exp fit:
  t_s~90s
  t_f~340s
- Max number of UCN measured after 180s storage:

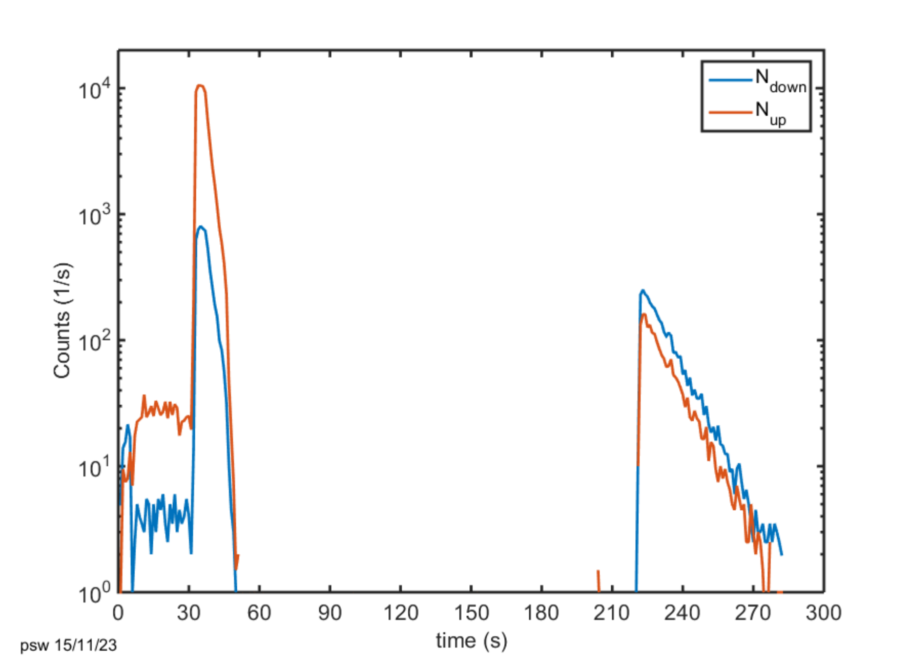
20 800



Simultaneous spin detection

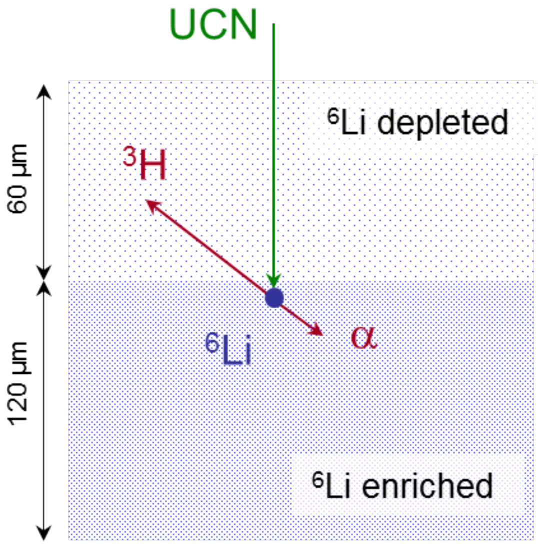


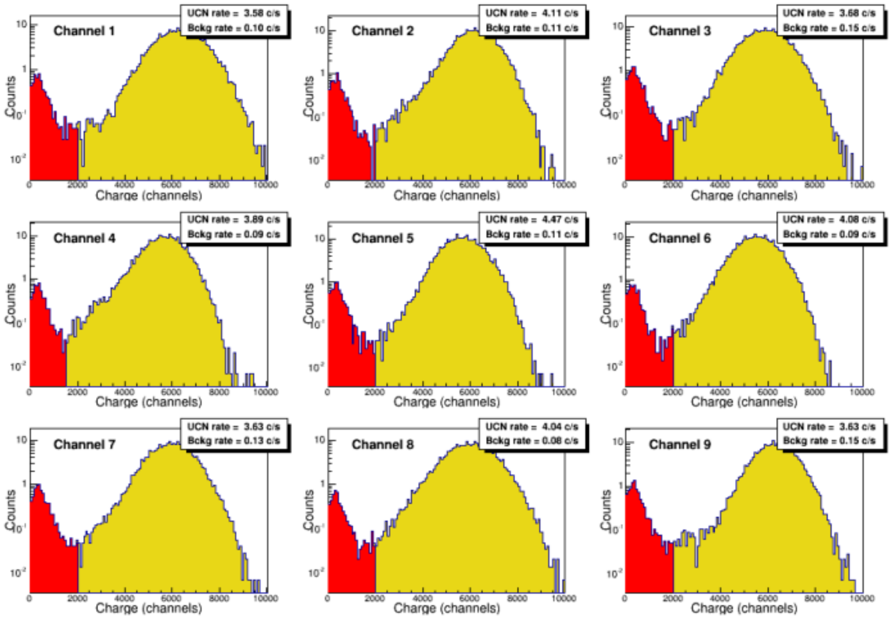
- Spin dependent detection
  - Adiabatic spinflipper
  - Iron coated foil
- ^{6}Li-doped scintillator GS20



S. Afach *et al.*, EPJA (2015)51: 143

Neutron detection





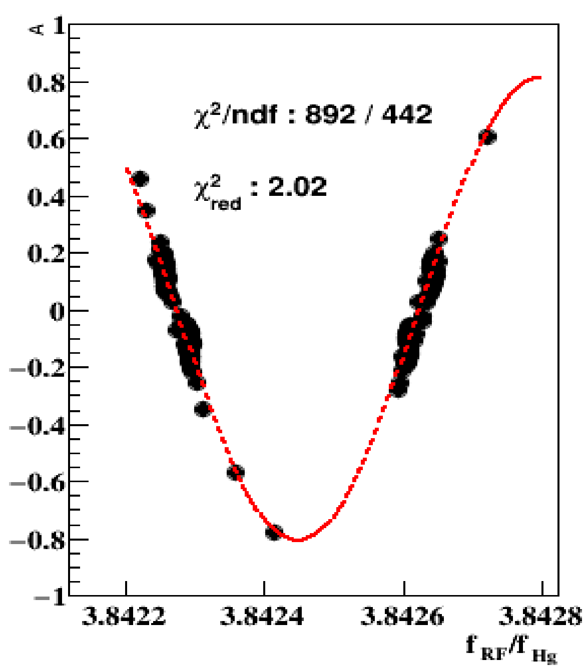
Detection system:

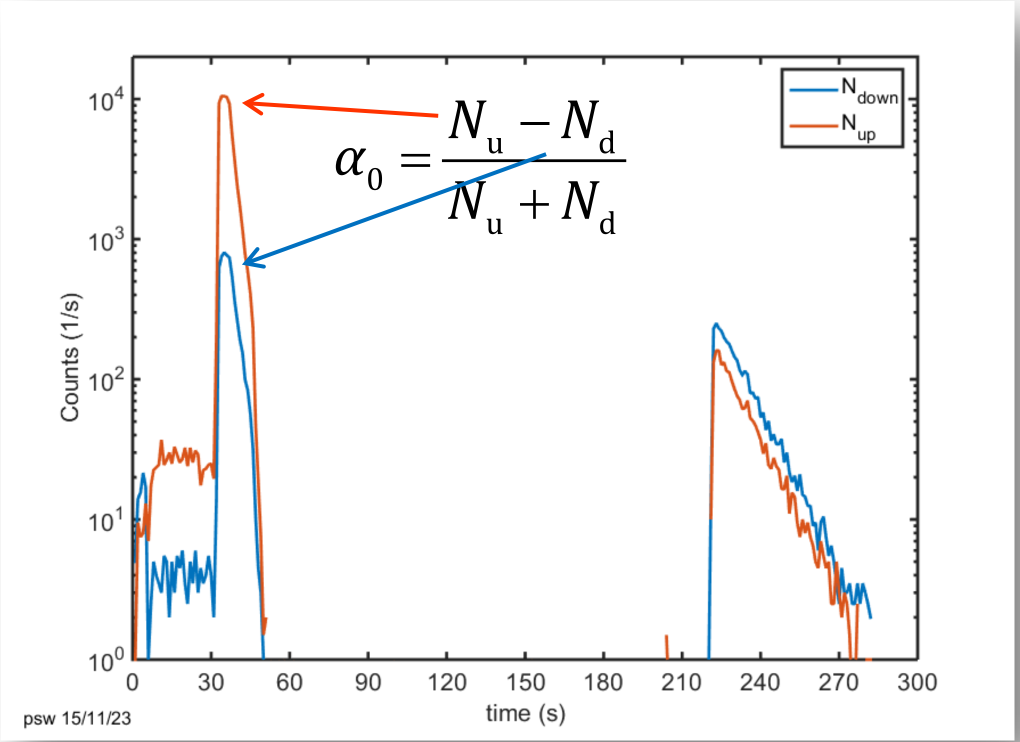
- Two 9-channel scintillation counters
- Reaction:
  $n + {}^{6}Li \rightarrow {}^{3}H + alpha$
- High count rate capable

Transverse polarization time

- Initial polarization α_0 measured with USSA 0.86
- Best polarization after 180s free precession 0.80, average 0.75

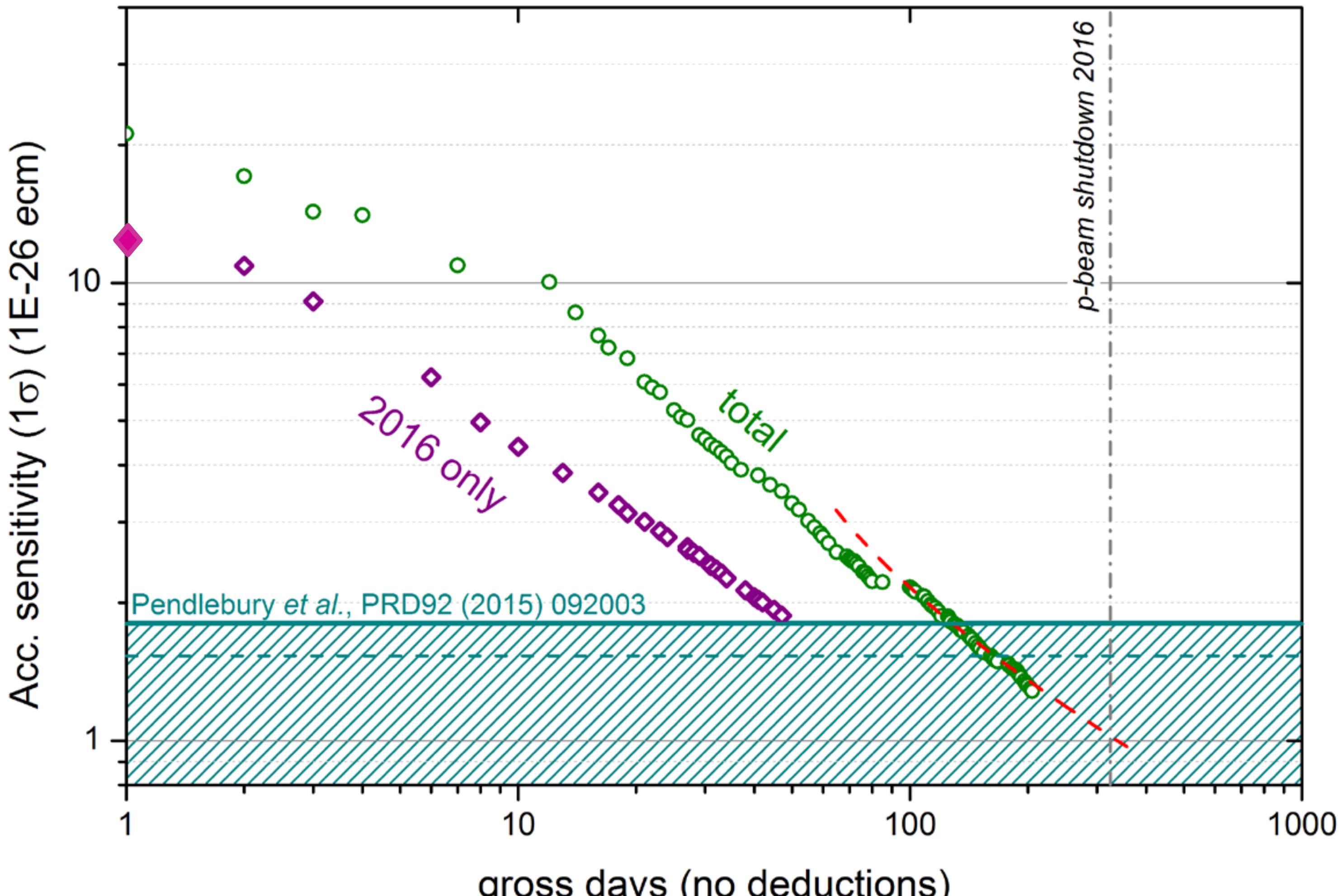
$$T_2^* = T \Big/ \ln\left(\frac{\alpha_0}{\alpha(T)}\right) = 2488\mathrm{s}$$





Current sensitivity

$$\sigma(d_n) = \frac{\hbar}{2\alpha T E\sqrt{\dot{N}}}\frac{1}{\sqrt{t}} = 3.3 \times 10^{-23}\frac{e\mathrm{cm}}{\sqrt{\mathrm{Hz}}}\frac{1}{\sqrt{t}}$$



psw 20/07/16

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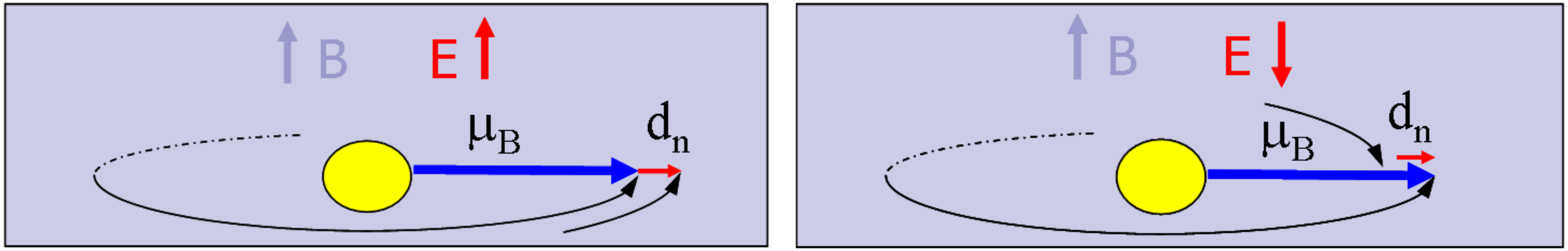
The measurement technique

Measure the difference of precession frequencies in parallel/anti-parallel fields:



$$\hbar \Delta\omega = 2d_{\mathrm{n}}\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_{\mathrm{n}}\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

Statistical accuracy of a magnetometer correcting for a change in B should be better than the neutron sensitivity per cycle:

$$\delta f_{\mathrm{n}} = \frac{1}{2\pi\alpha T\sqrt{N}} \approx 11\,\mu\mathrm{Hz} \xrightarrow{B_0=1\mu\mathrm{T}} \delta B \leq 100\,\mathrm{fT}$$

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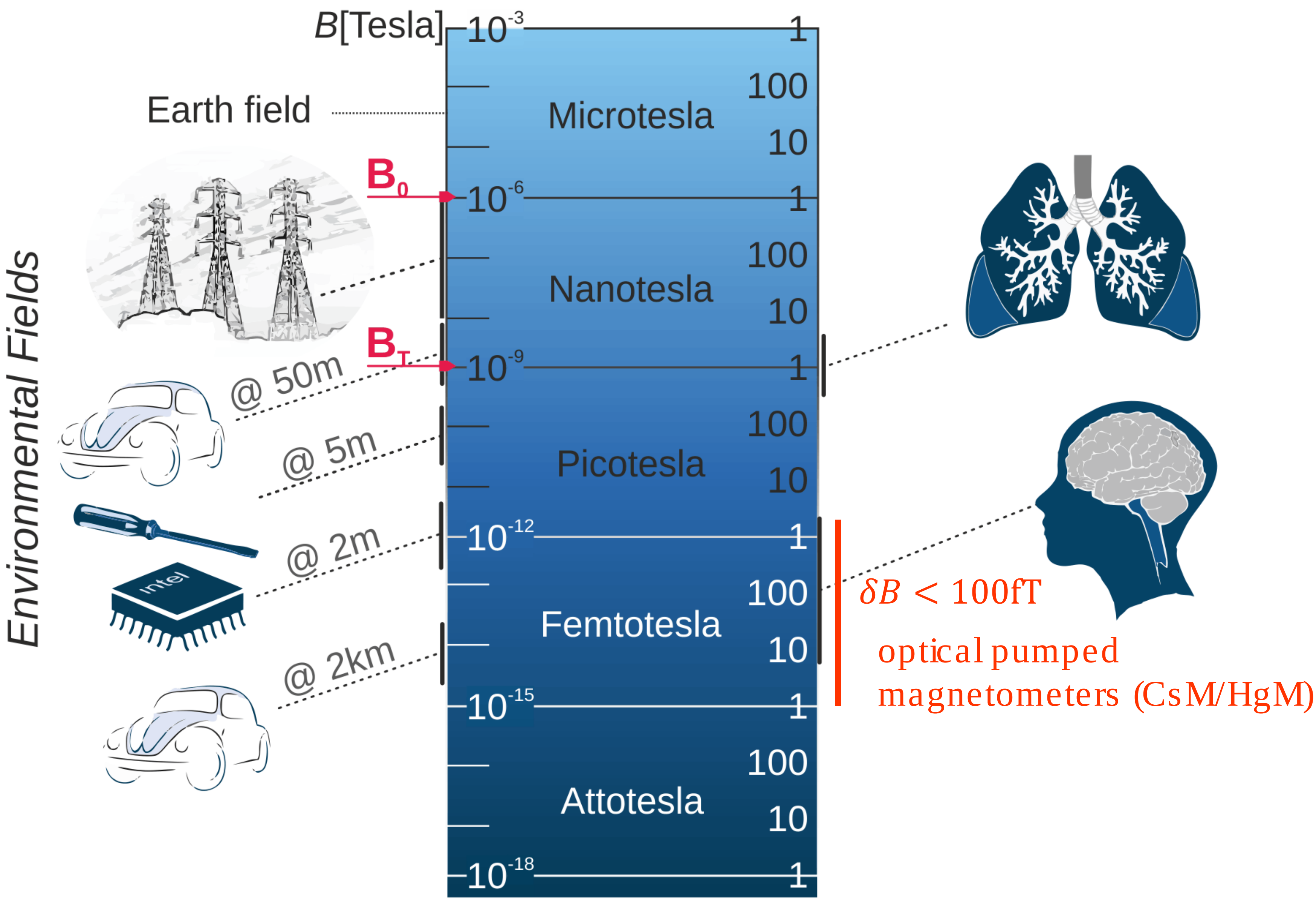
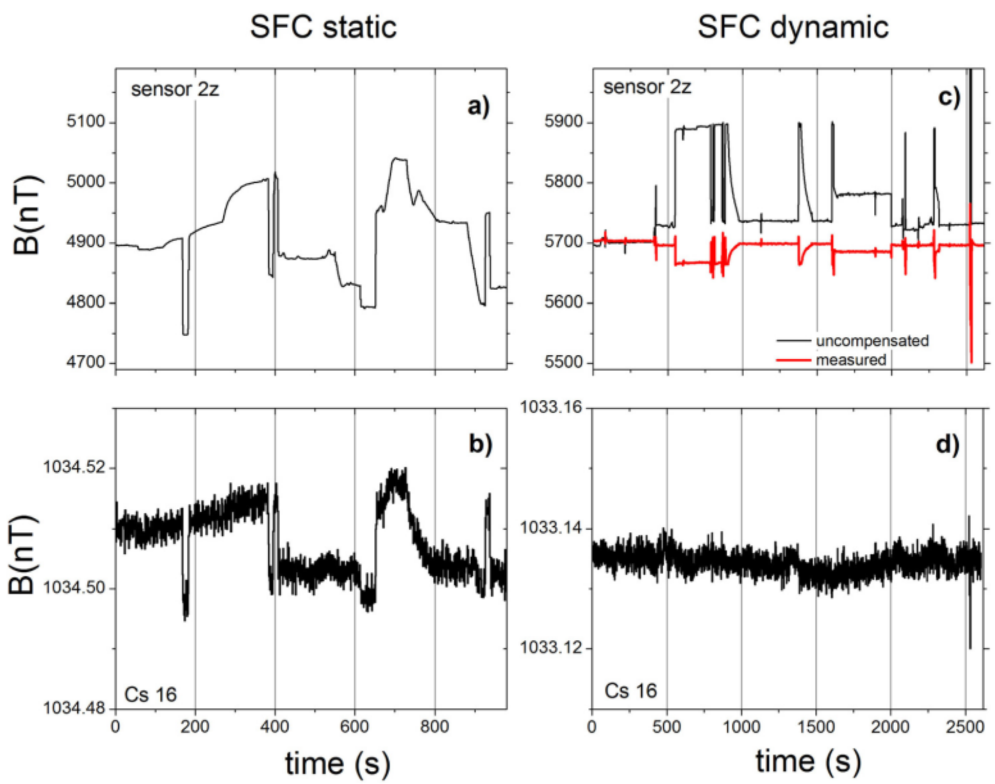
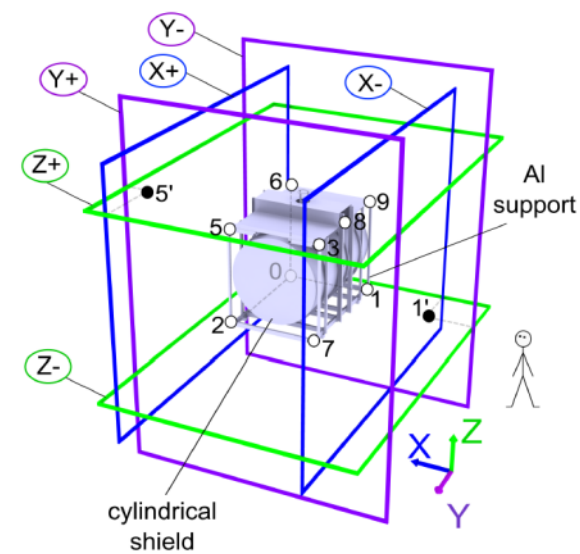
Magnetic fields



B-Field stability

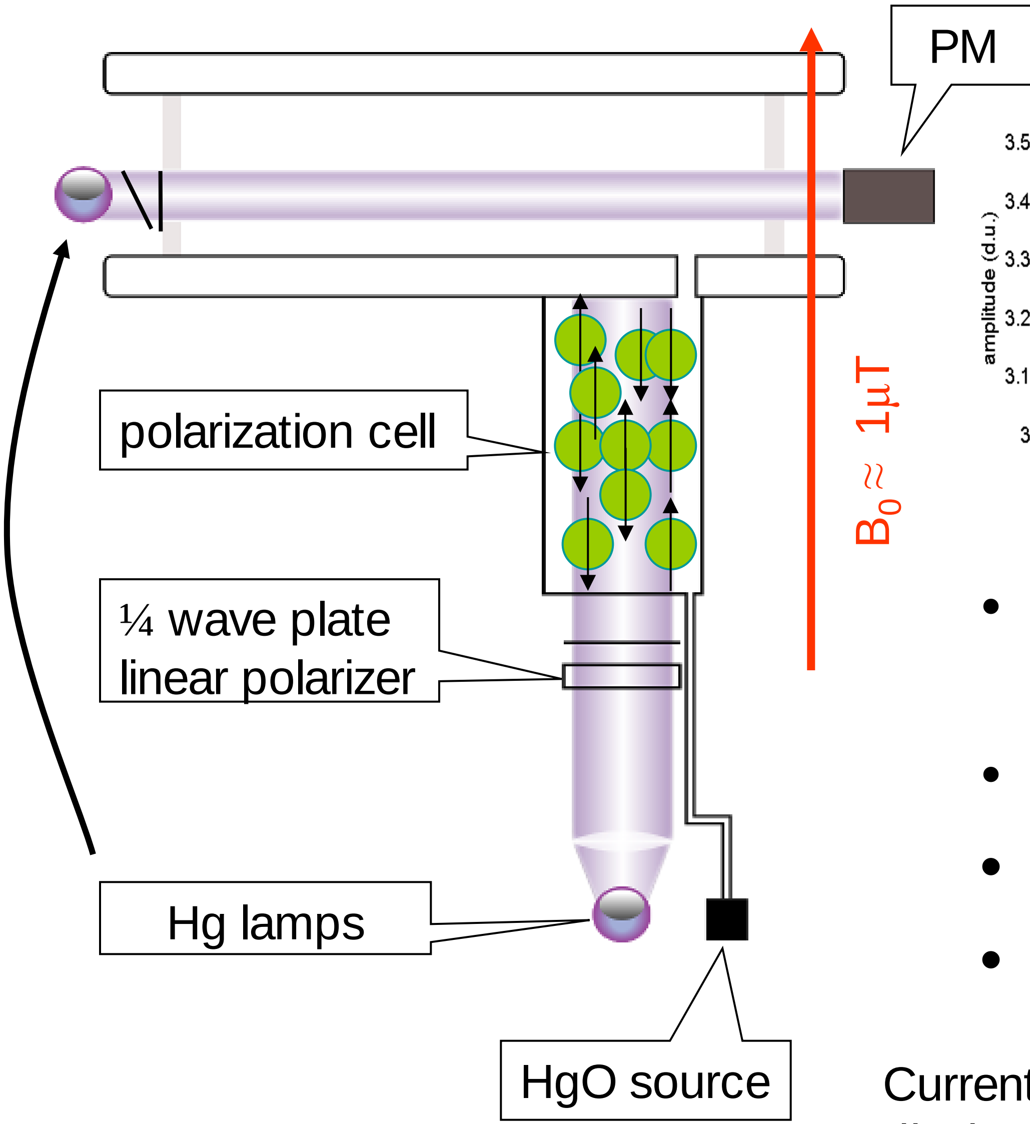
- Excellent stability
  (dynamic SFC & 4 layer magnetic shield)
- Stability (AD) @400s: ~<400fT

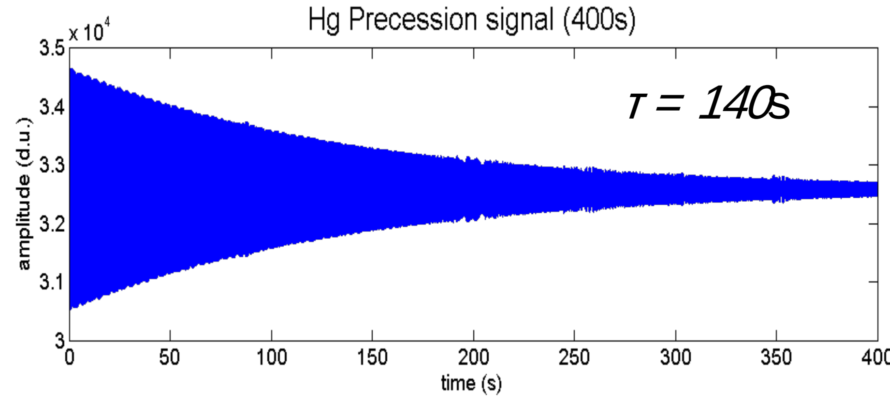




Afach et al., J. Appl. Phys. ***116****, 084510 (2014)*

Mercury co-magnetometer



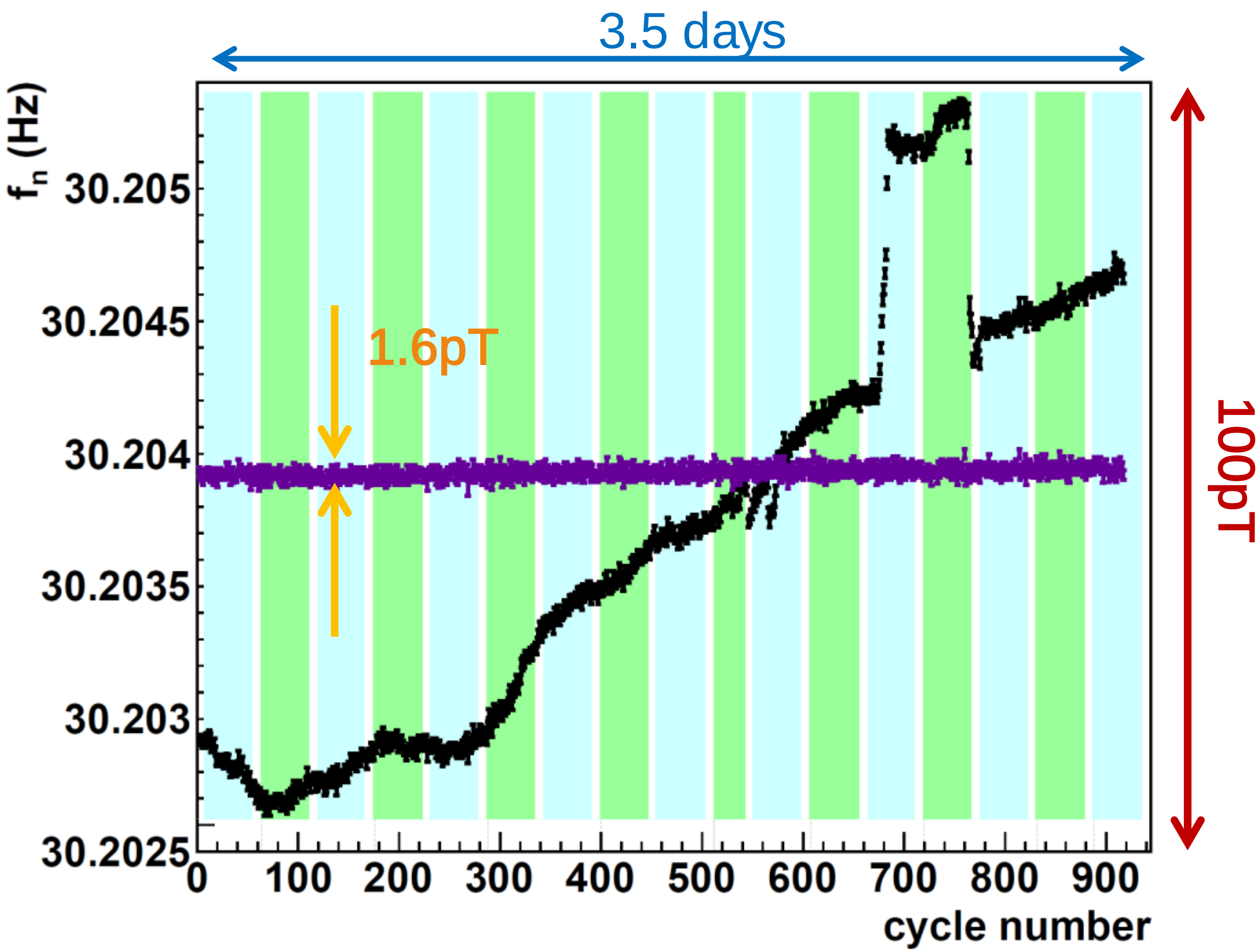


- Average magnetic field (volume and cycle)
- σ_B ~ 100 fT (CR-limit)
- τ > 100 s without HV
- s/n > 500

Currently being improved by replacing discharge lamps with laser: factor 2-3.

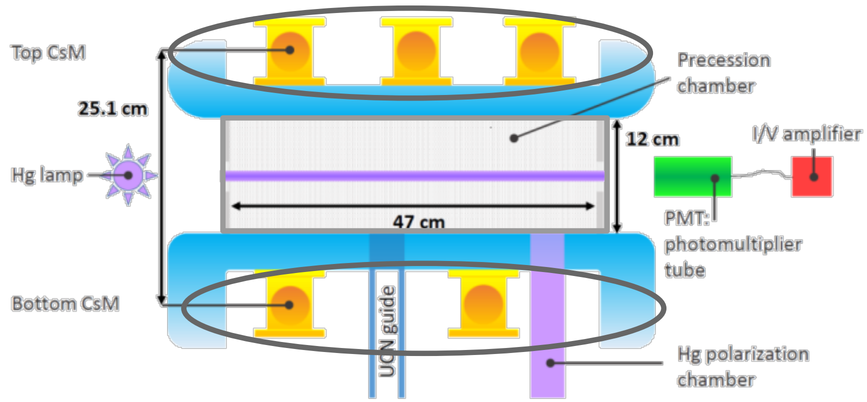
Hg co-magnetometer

Extract B field from Larmor frequency
and correct UCN frequency

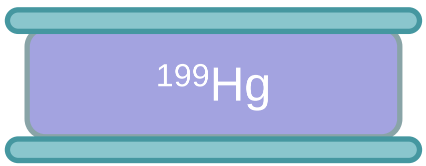


Frequency ratio $R = f_n / f_{Hg}$

- Center of mass offset
- Non-adiabaticity



$\frac{\gamma_{Hg}}{2\pi} \approx 8$ Hz/μT



$\frac{\gamma_n}{2\pi} \approx 30$ Hz/μT

$$\overline{v_{Hg}} \approx 160 \text{ m/s vs. } \overline{v_{UCN}} \approx 3 \text{ m/s}$$

+ further sys.

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{Earth} + \delta_{Hg-lightshift} \right)$$

Dominant systematic

- Motional magnetic field from $B_{\mathrm{m}} = -\frac{v \times E}{c^2}$
- Naively no contribution as $\bar{v} = 0$ for UCN?
- In homogenous B-field and E-field:

$$
\begin{aligned}
|B| &= B_0 + \ldots \\
&+ \frac{\theta v_x}{c^2} E \\
&+ \frac{(x v_y + y v_x + \theta y v_z)}{2 B_0 c^4} \frac{\partial B_z}{\partial z} E \\
&+ \frac{v_y^2 + (v_x - \theta v_z)}{2 B_0 c^4} E^2
\end{aligned}
$$

Result depends on how particle average the magnetic field:

adiabatic (UCN)

$$\delta\omega = \frac{v_{xy}^2 E}{2 B_0 c^2} \frac{\partial B_z}{\partial z}$$

non - adiabatic (Hg)

$$\delta\omega = \frac{\gamma D^2}{16 c^2} \frac{\partial B_z}{\partial z} E$$

Dominant systematic

- Typical B-field gradients: ~10 pT/cm
- Dominant effect from mercury transferred to neutron by correction

$$d_{\mathrm{n}}^{\mathrm{false}} = \frac{\partial B_z}{\partial z} 1.5 \times 10^{-29}\, e \cdot \mathrm{cm} \frac{\mathrm{cm}}{\mathrm{pT}}$$

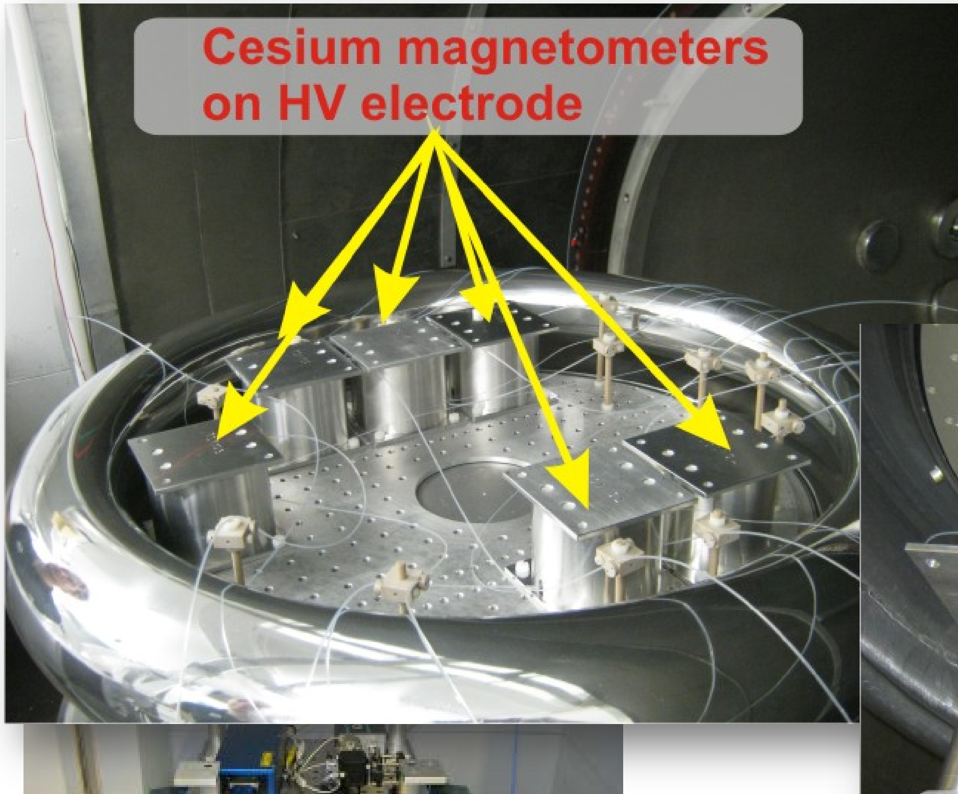
$$d_{\mathrm{Hg}}^{\mathrm{false}} = \frac{\partial B_z}{\partial z} \cdot 1.15 \times 10^{-27}\, e \cdot \mathrm{cm} \frac{\mathrm{cm}}{\mathrm{pT}}$$

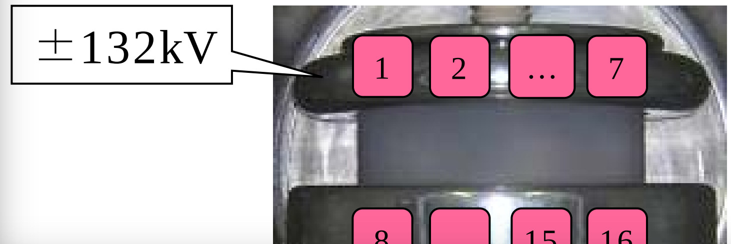
$$d_{\mathrm{Hg}\to\mathrm{n}}^{\mathrm{false}} = -\frac{\partial B_z}{\partial z} \cdot 4.4 \times 10^{-27}\, e \cdot \mathrm{cm} \frac{\mathrm{cm}}{\mathrm{pT}}$$

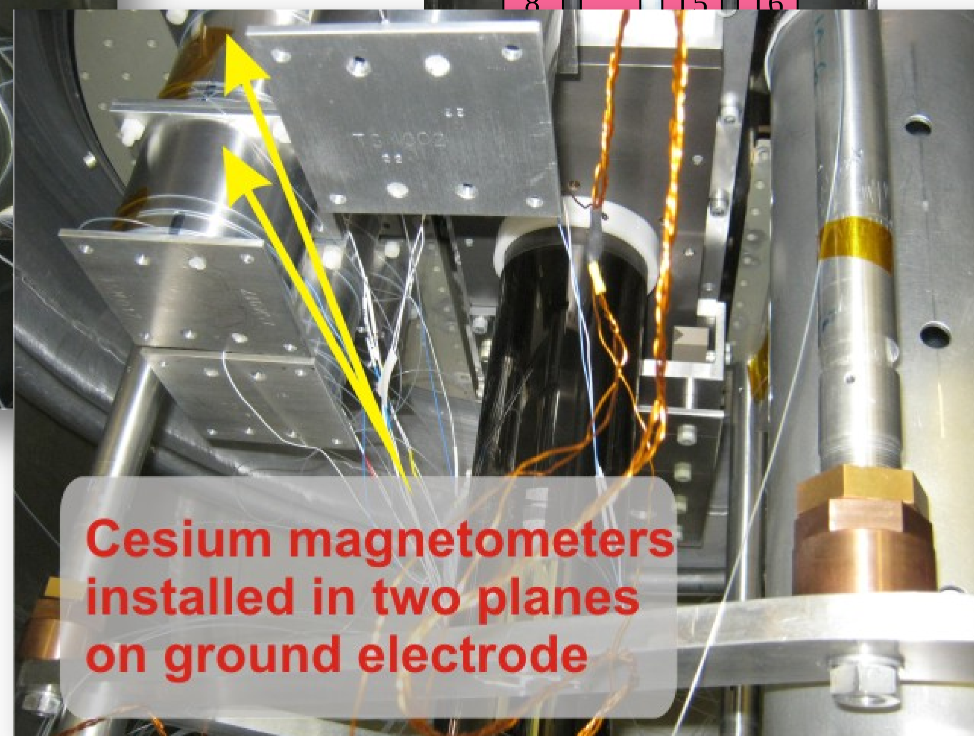
nEDM strategy → Measure nEDM as function of B-Field gradient

Cesium gradiometer

Monitoring of vertical magnetic gradients





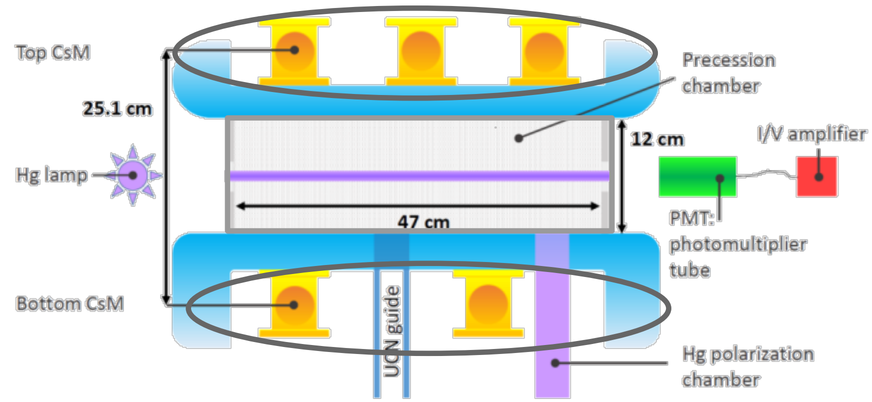


Current accuracy:

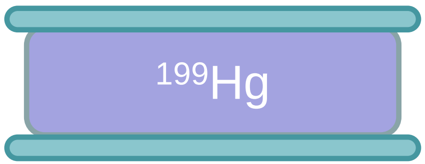
$$\sigma(g_z) \approx 10\text{pT/cm}$$

Frequency ratio $R = f_n/f_{Hg}$

- Center of mass offset
- Non-adiabaticity



$\frac{\gamma_{Hg}}{2\pi} \approx 8$ Hz/μT



$\frac{\gamma_n}{2\pi} \approx 30$ Hz/μT

$$\overline{v_{Hg}} \approx 160 \text{ m/s vs. } \overline{v_{UCN}} \approx 3 \text{ m/s}$$

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{Earth} + \delta_{Hg-lightshift} \right)$$

Measure EDM as function of R & take care of systematics

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Blinding

Why?

- Avoid **psychological** bias during data analysis
    - Experimenter's bias is defined as the unintended influence on a measurement towards prior results or theoretical expectations.
  - Which cut to apply
  - When to stop analysis/searching for bugs

- Outside reputation
  - some secrecy is necessary, simply trusting everybody is not enough.

  Do NOT protect against: Criminal energy, e.g. somebody installing spyware on DAQ computer

JR Klein A Roodman
BLIND ANALYSIS IN NUCLEAR AND PARTICLE PHYSICS
Annual Review of Nuclear and Particle Science 2005
Vol. 55: 141-163 DOI: 10.1146/annurev.nucl.55.090704.151521

Blinding

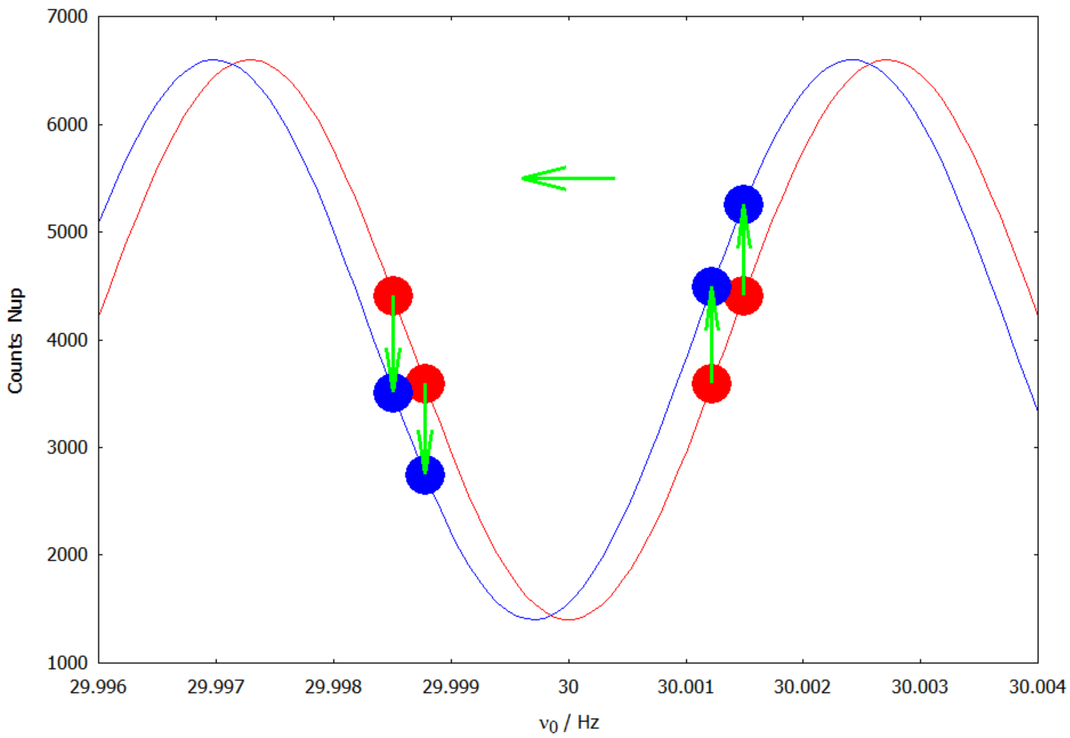
How?

- Shift the central value by adding an unknown offset EDM of -1.5 to 1.5E-25 *e*cm to the data

$$\delta N_{\uparrow,\downarrow;i} = \mp \bar{N} \frac{\pi\alpha}{\Delta\nu} \frac{d \cdot E}{h} \sin\phi_i$$

with $\phi_i = \frac{(\nu_i - \nu_0)}{\Delta\nu}\pi$

- Keep un-blinded data in a safe place (encrypted)



Analysis

- Two analysis groups prepare a full nEDM analysis
- Each group works with a differently blinded data-set
  - Common blinding for all data
  - 2nd blinding differently for each group
- Fully automatized analysis of all blinded data of both groups (+ reference data from August 2015) have to agree statistically
  - Relative un-blinding
    if central values and blinding offset correct,

$\rightarrow$ Run both codes on fully un-blinded data

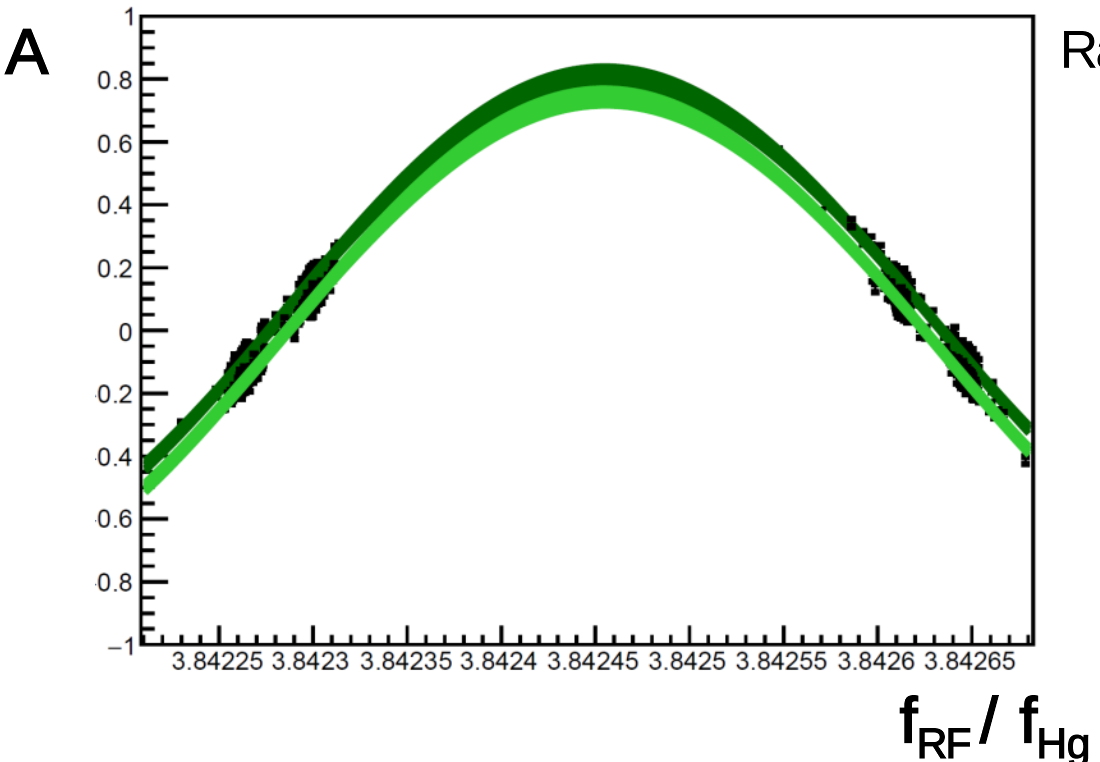
$\rightarrow$ publish.

Ramsey fit procedure

- Split sequence in sub-sequence:

  E-field (+ - - +) pattern

- Split data in two dataset : SF state (↑/↓) discrimination



Ramsey fit with the asymmetry :

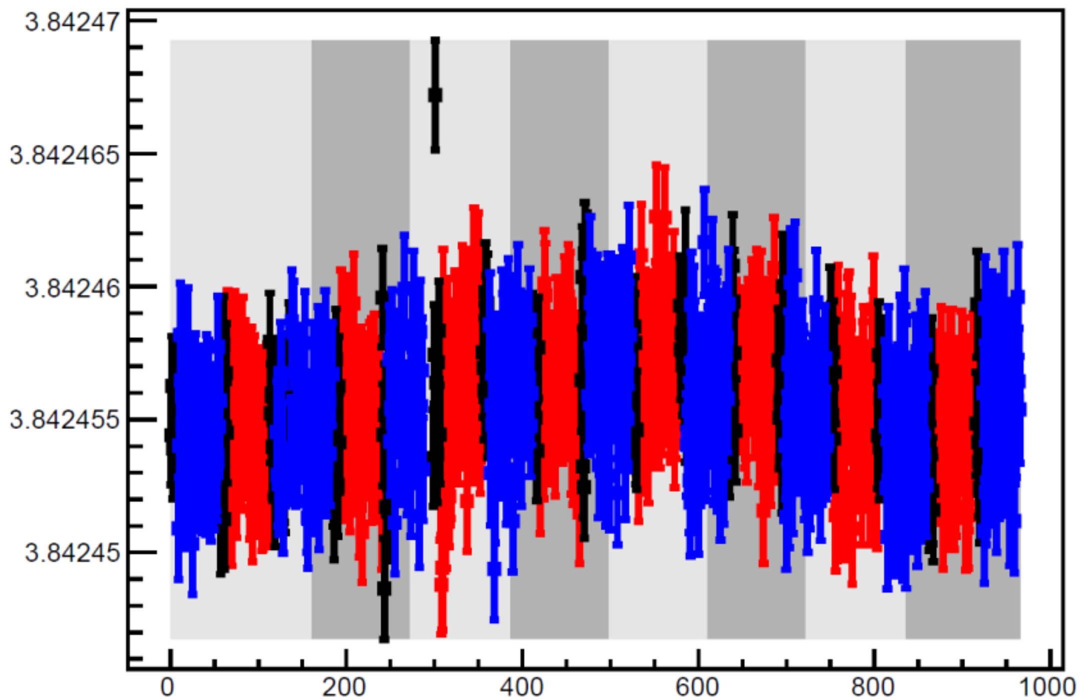
$$A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$\tilde{R} = \frac{f_{\mathrm{RF}}}{f_{\mathrm{Hg}}}$$

$$A^{\uparrow}(\tilde{R}) = \bar{A}^{\uparrow} + \bar{\alpha}\ \cos(\Omega(\tilde{R} - R_0))$$
$$A^{\downarrow}(\tilde{R}) = \bar{A}^{\downarrow} + \bar{\alpha}\ \cos(\Omega(\tilde{R} - R_0))$$

EDM and R-calculation

$$f_{\mathrm{n}}^{i,1(2)} = f_{\mathrm{RF}}^{i} \pm \frac{f_{\mathrm{Hg}}^{i}}{\Omega} \arccos\left(\frac{\bar{A}_{1(2)} - A^{i}}{\bar{\alpha}}\right)$$



$$d_n = \frac{h\left(f_{\mathrm{n}}^{+} - f_{\mathrm{n}}^{-}\right)}{2E}$$

$$R = \frac{f_{\mathrm{n}}^{i}}{f_{\mathrm{Hg}}^{i}}$$

B-gradient fluctuation correction :

$$R_{\mathrm{Gz}}^{\mathrm{corr},i} = R^{i}\left(1 \pm (G_z^{i} - < G_z >)\frac{h}{B_0}\right)$$

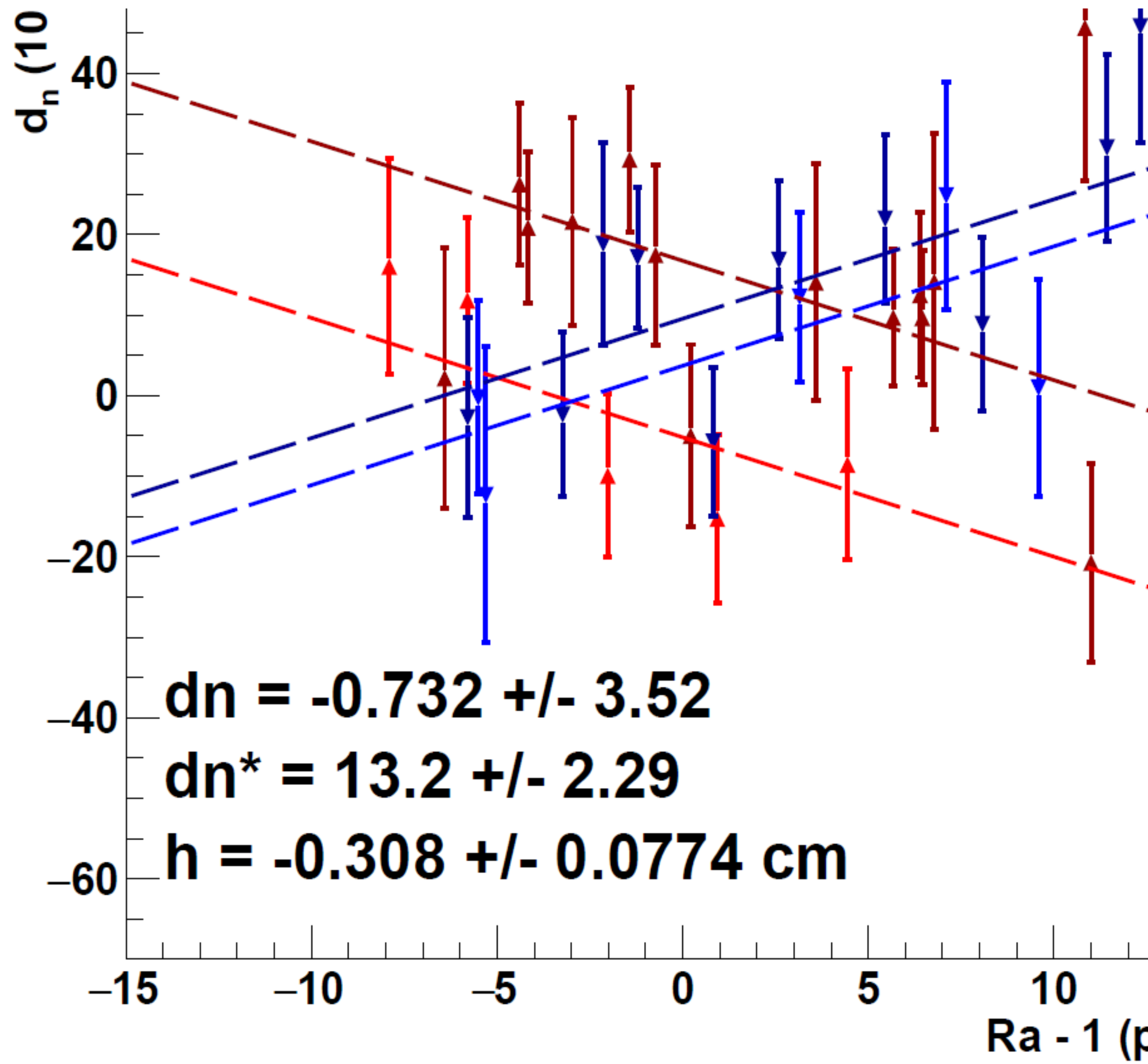
Earth rotation frequency correction :

$$R^{\mathrm{corr}} = R(1 \pm \delta_{\mathrm{earth}}) =< R > (1 + \delta_{\mathrm{gz}})$$

$$(R_a - 1)^{\mathrm{corr}} = \frac{R}{< R >} - 1 \pm \delta_{\mathrm{earth}} = \delta_{\mathrm{gz}}$$

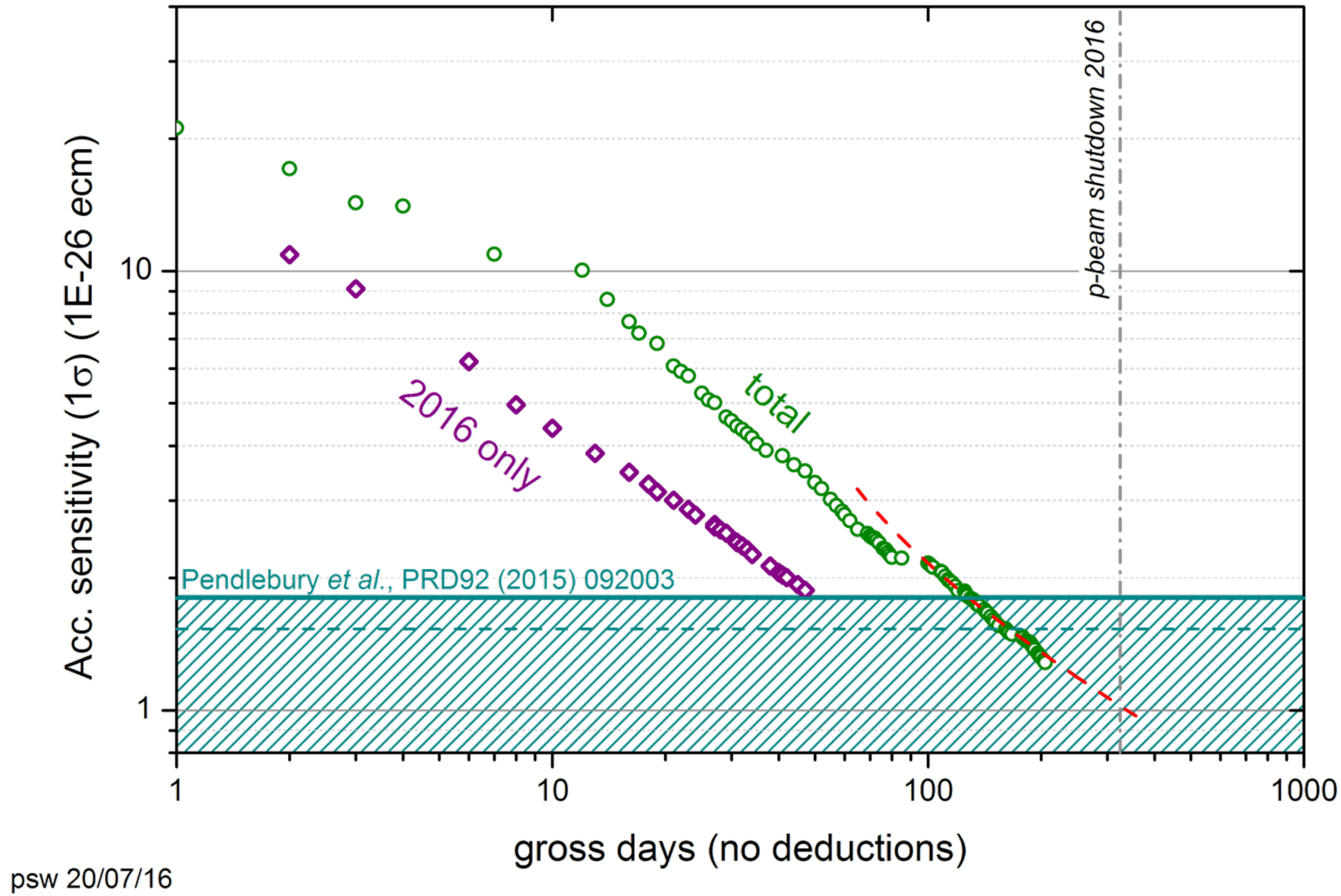
Crossing point analysis

- R corrected for the Earth rotation frequency
- $\chi^2/\nu = 31/29 = 1.06$



$$\sigma_{\text{stat}} d_n = 1.9 \times 10^{-26}\, e\ \text{cm}$$

Summary



$$\sigma_d(2016) \approx 1\times10^{-26}\ e\cdot\text{cm}$$

Schedule for nedm @PSI

- nEDM online sensitivity per day presently approaching $1x10^{-25}$ *e*cm
- nEDM operation will come to an end in 2017
- n2EDM sensitivity will intrinsically be more than 5 times better than that of nEDM, plus additional gains from UCN source improvements
- n2EDM will be installed and commissioned in 2018/19
- n2EDM will start production data taking in 2020 and cut into the low 10^{-27} *e*cm region

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The Neutron EDM Collaboration

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Thank you for your attention.