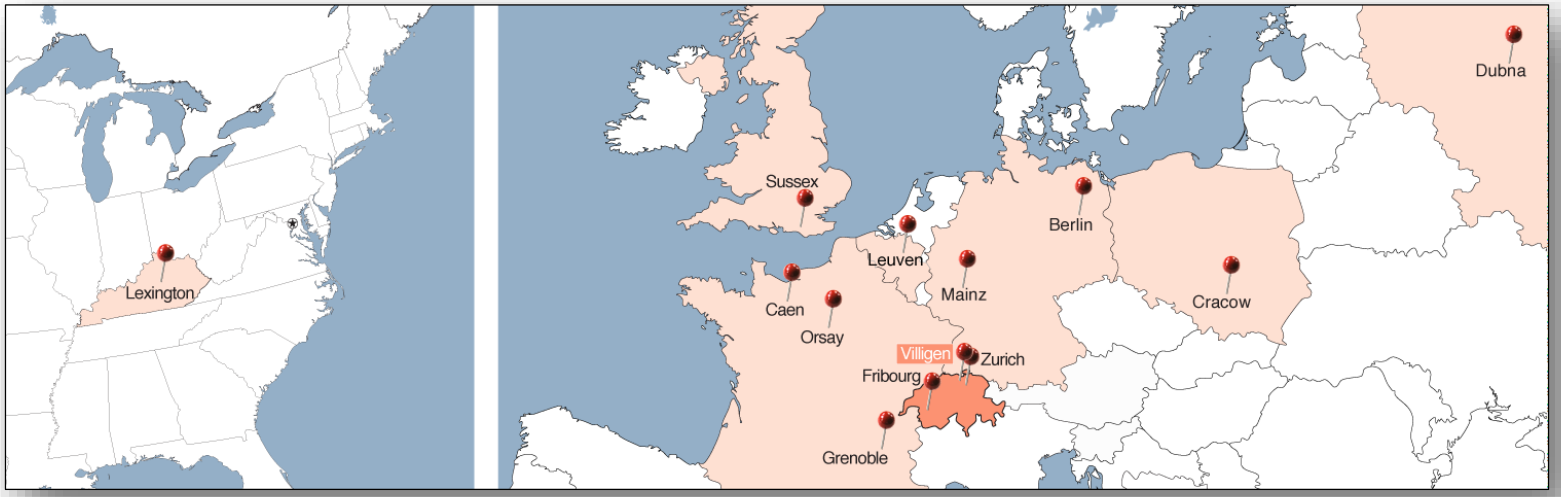
Status of the PSI nEDM Experiment

Matthew Musgrave
University of Sussex
On behalf of the nEDM Collaboration

PSI in Villigen Switzerland

nEDM Collaboration



About 50 members
from 14 institutions
in 8 countries.

Overview

Background

The Experiment

- Method
- Apparatus
- Magnetometry

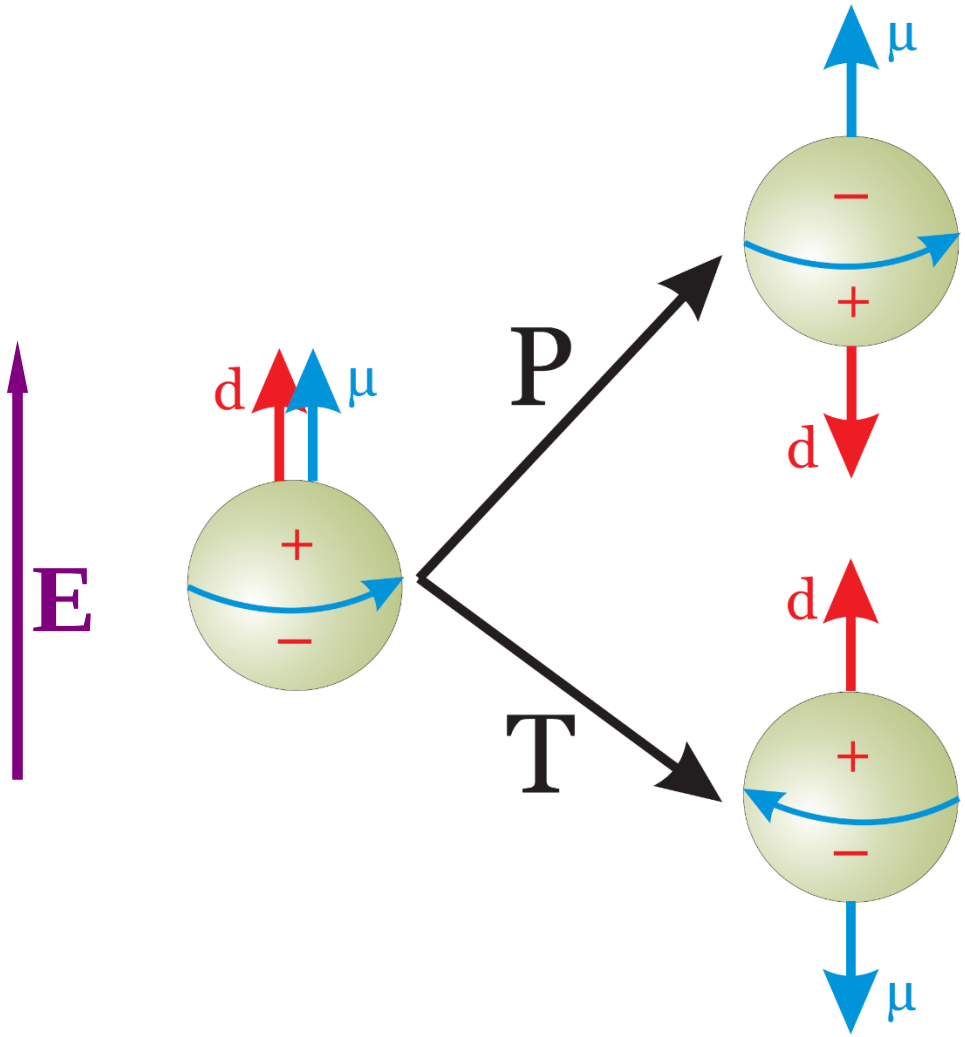
Sensitivity

- Statistical Sensitivity
- Systematic Effects

Status

- Current Successes
- Future Plans

Electric Dipole Moment



Motivation

The Baryon Asymmetry of the Universe

SM Expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

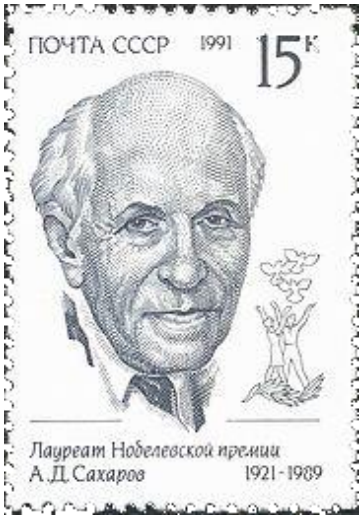
vs.

Observed:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

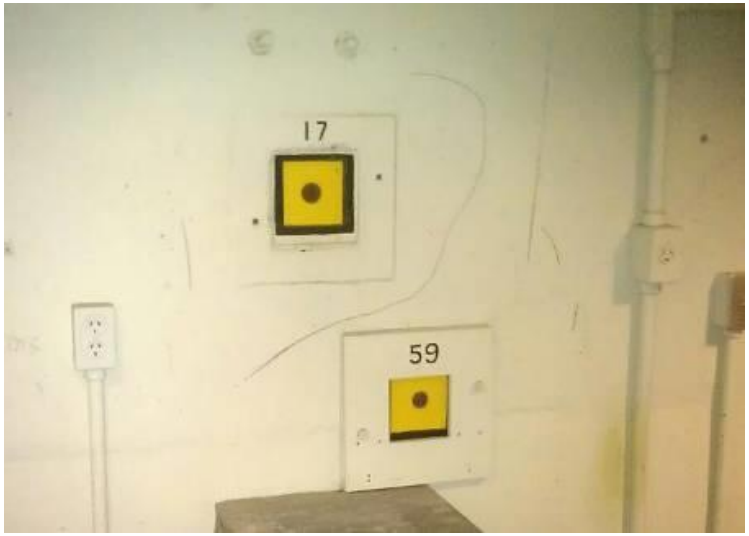
Sakharov criteria

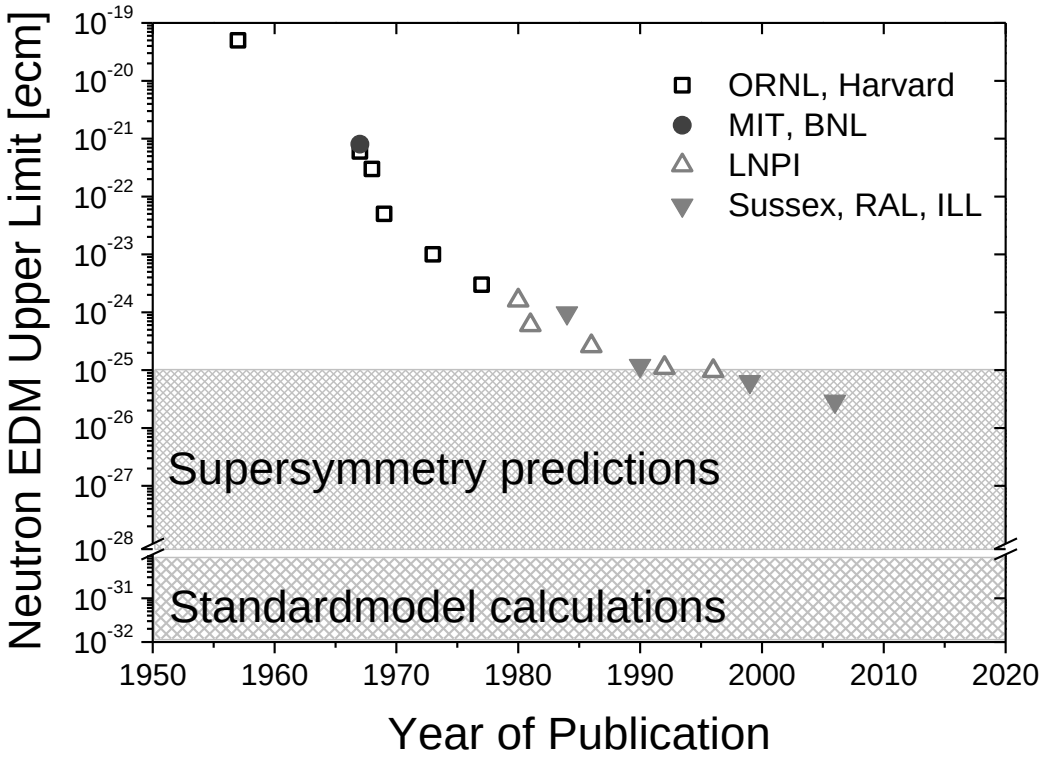
1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*



History of nEDM Searches

Ramsey's Neutron Beamline at Oak Ridge





First Limit

Smith, Purcell, Ramsey

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

PR 108 (**1957**) 120

~ 50 years

Present Limit

RAL-Sussex-ILL

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

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

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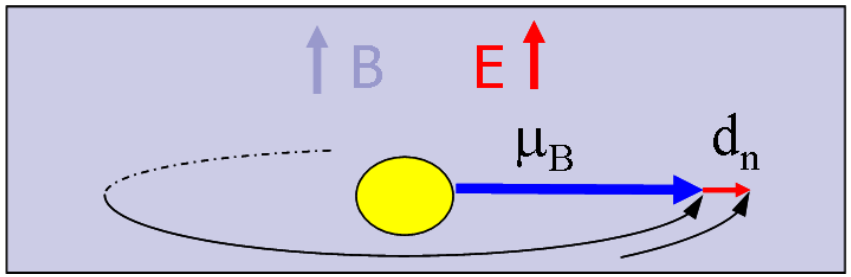
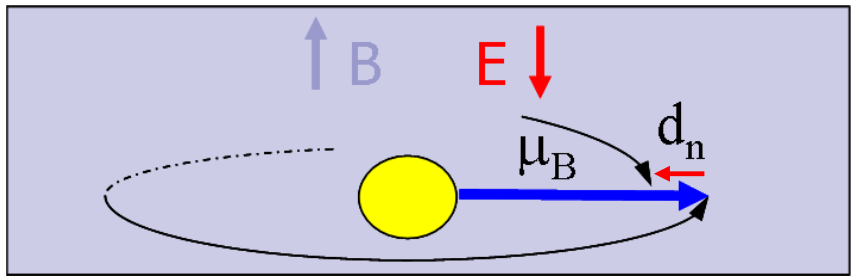
Measurement Technique

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



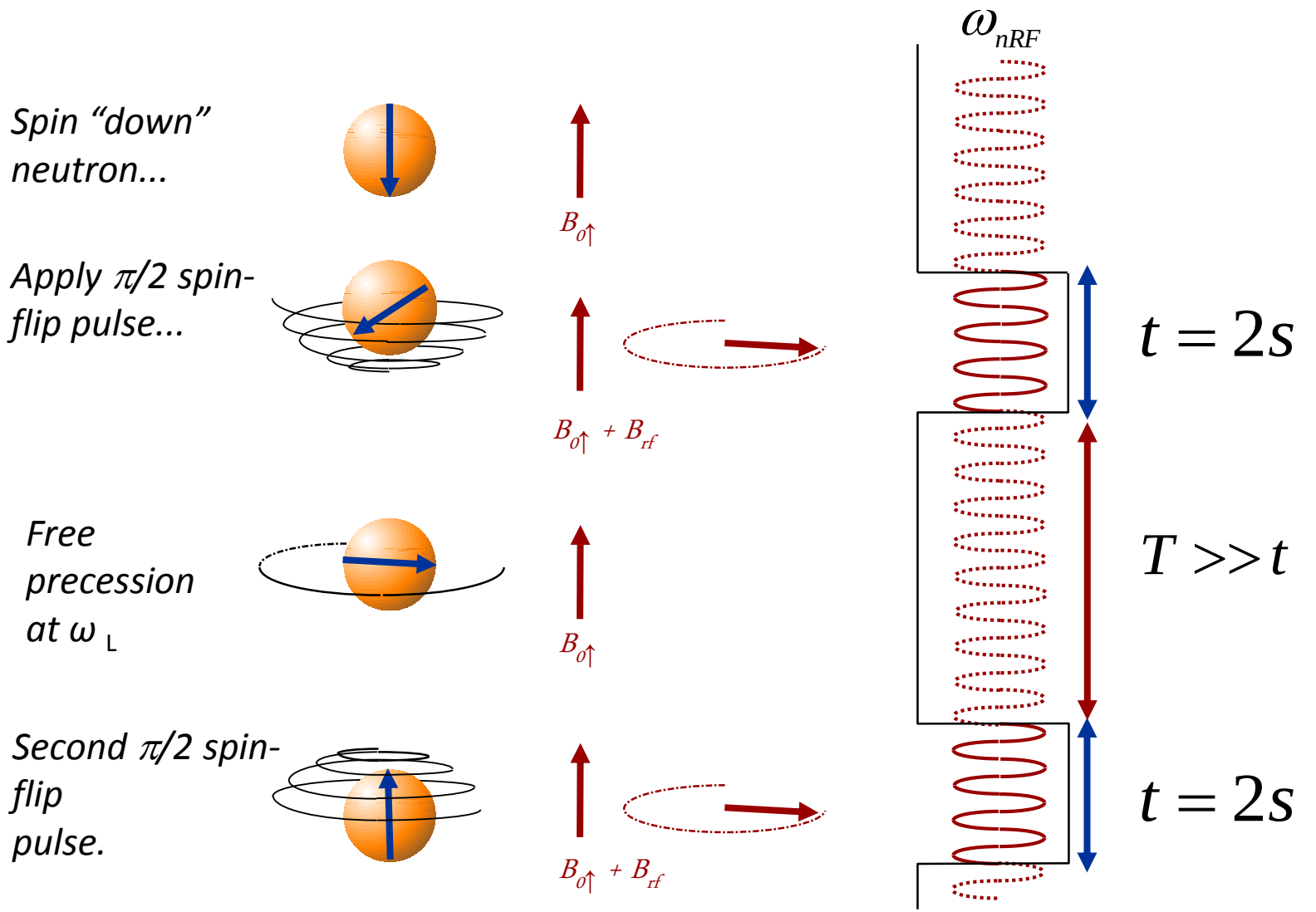


$$\hbar\Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

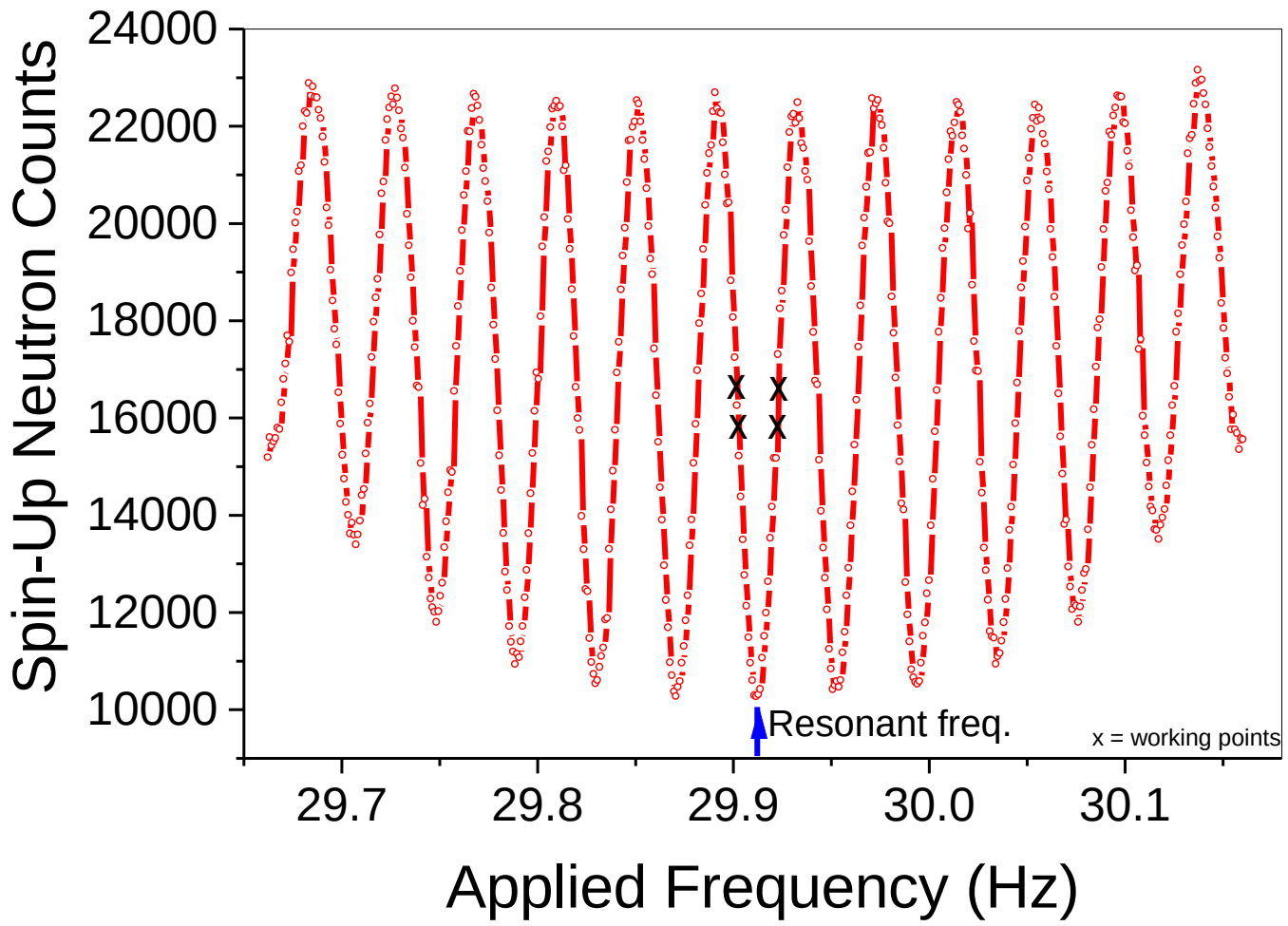
for d_n<10^{-26} & E=10 kV/cm → $\Delta\omega$ < 60 nHz

B=1 μT → $\omega_L \approx 30$Hz

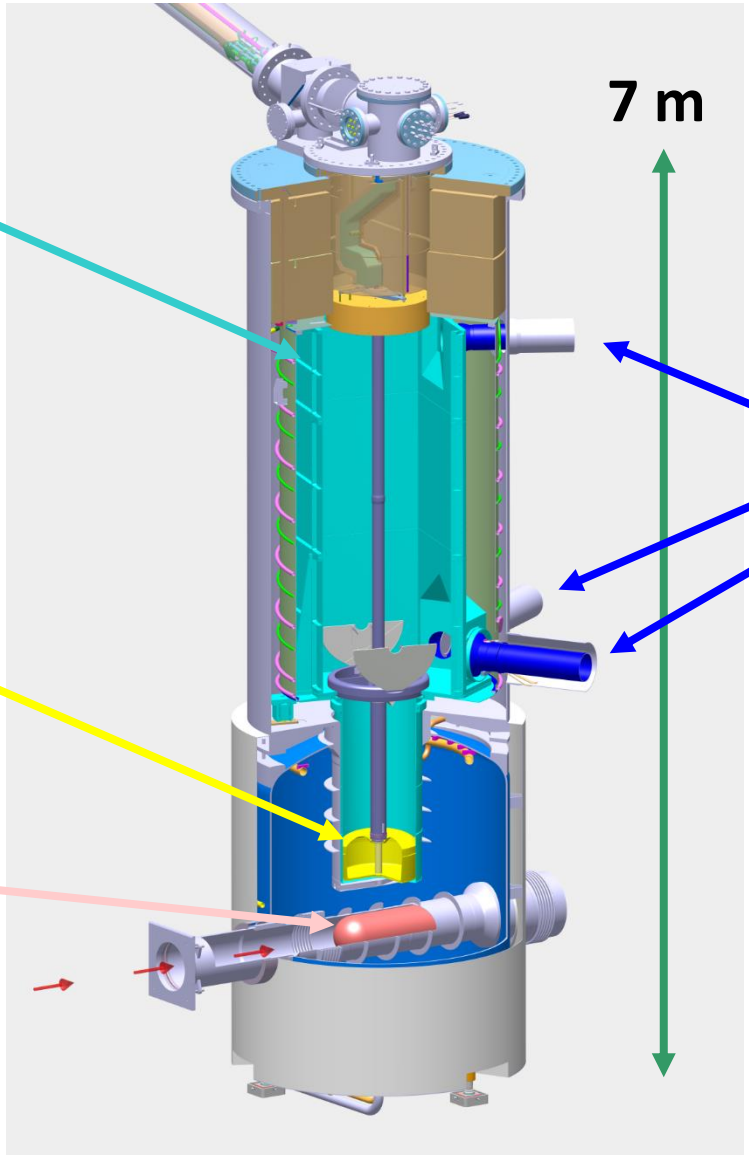
Separated Oscillatory Fields



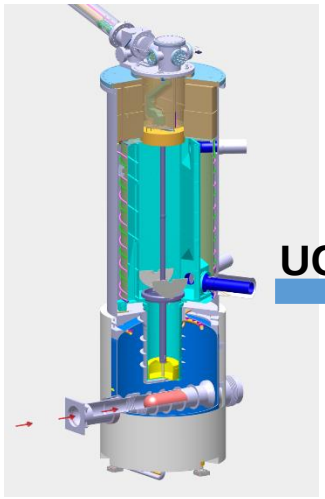
Ramsey Resonance Curve



UCN Source


7 m
UCN storage vessel
UCN guides
Solid D_2
UCN-converter
Spallation target

The nEDM Spectrometer



Passive Magnetic Shielding (4 layers)

Precession Chamber (UCN & Hg)

HV Electrode

~ 2 m

5 T Magnet

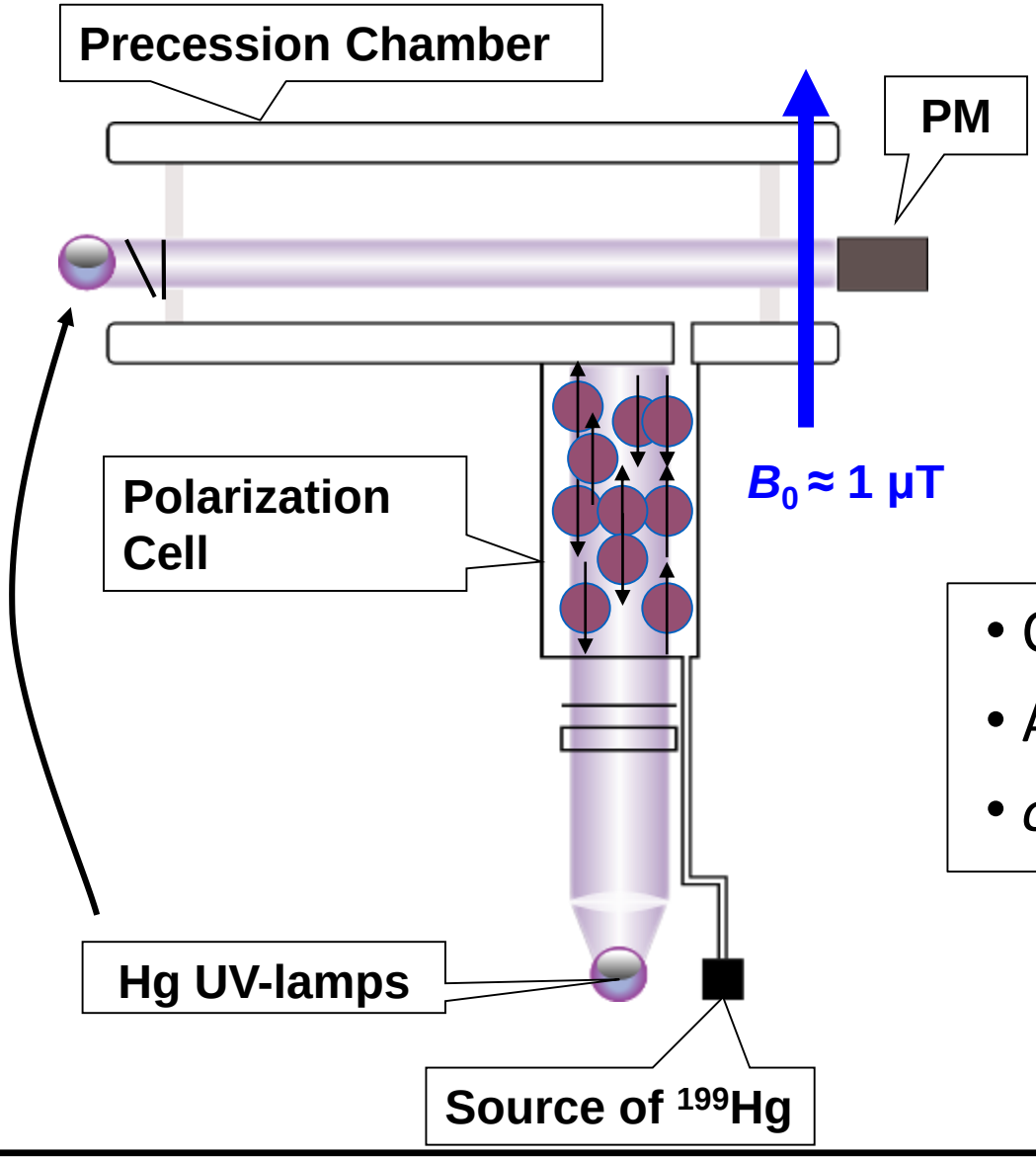
Vacuum Tank

UCN

UCN Switch

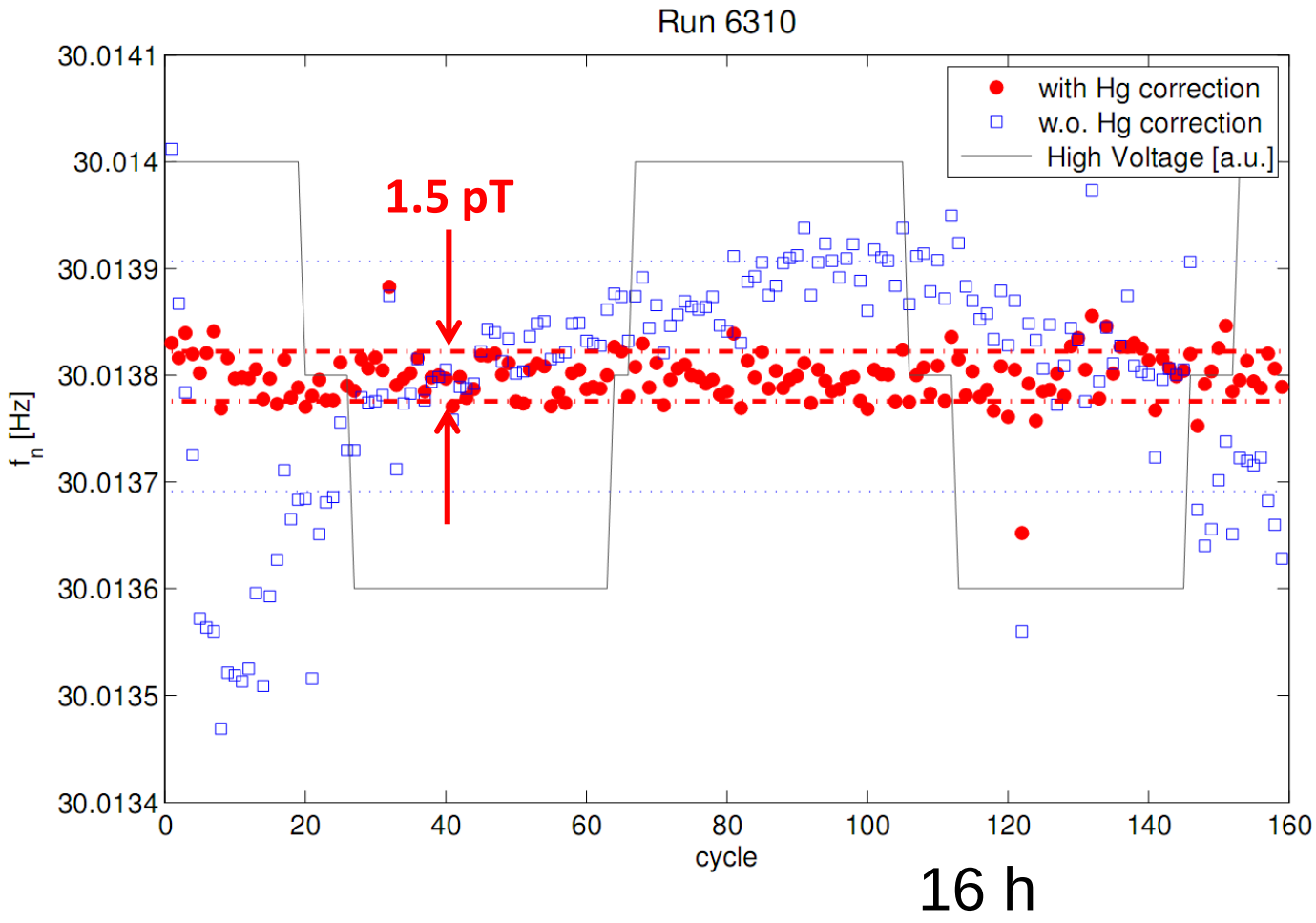
Analyzer(s) & Detector(s)

Hg Co-Magnetometer

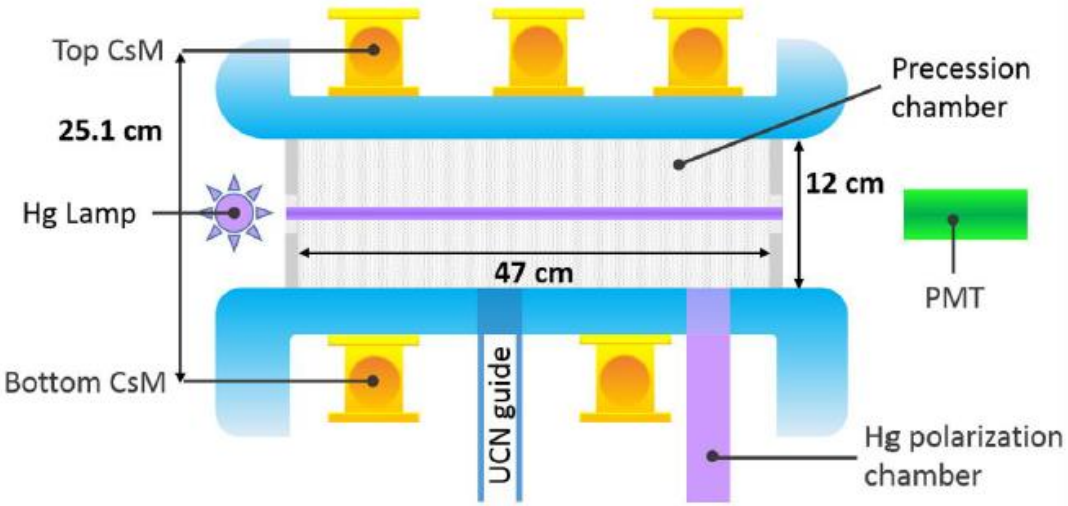


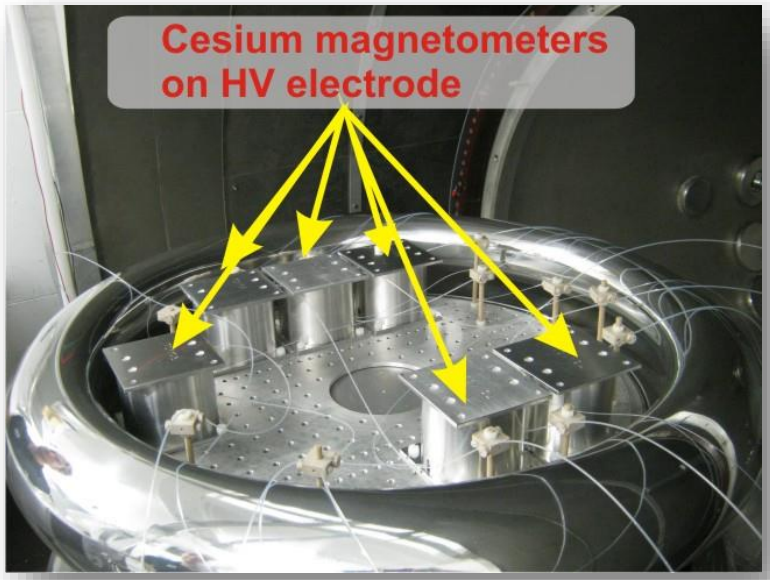
- Corrects UCN frequency
- Average magnetic field
- σ_B ~ *400* fT

Hg Co-Magnetometer



Cs Atomic Magnetometers





- Six HV CsM and ten ground CsM
- Monitors vertical magnetic gradients
- Comparable sensitivity to Hg Co-Magnetometer

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Statistical Sensitivity

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

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

Statistical Sensitivity

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

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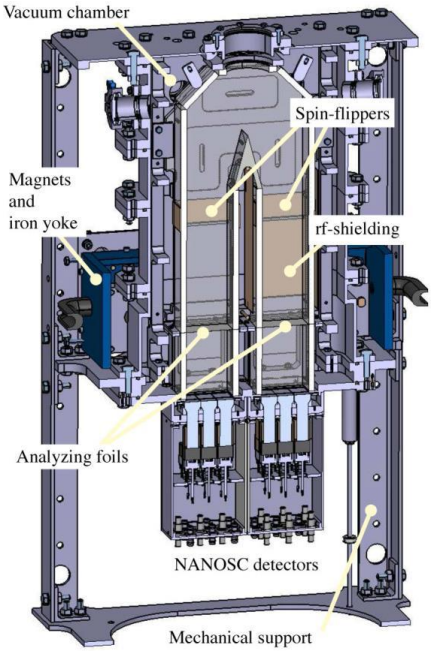
N	Number of neutrons

- Product of polarizer and analyzer efficiency
- ~20% increase in sensitivity with USSA

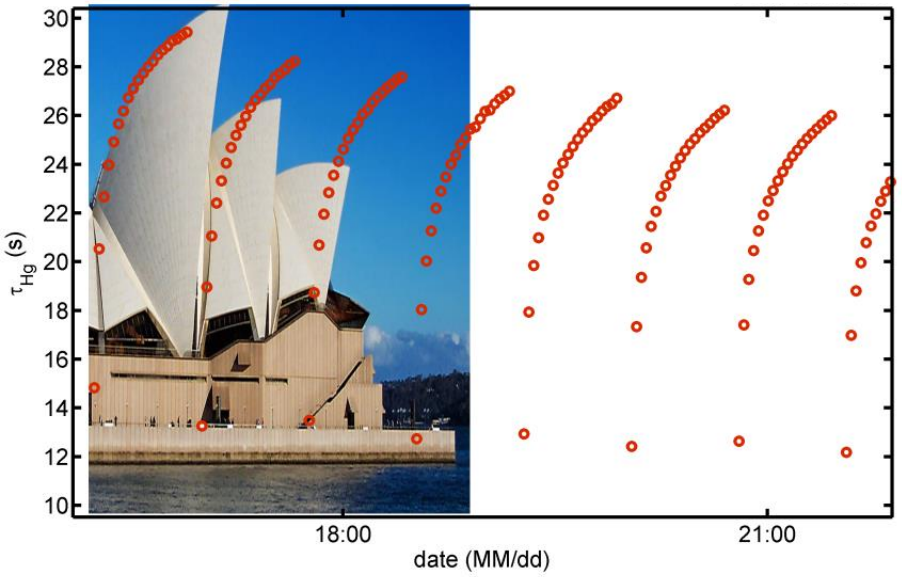


Statistical Sensitivity

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

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

- Currently limited by the Hg depolarization time
- "Opera House" Effect



Statistical Sensitivity

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

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

- Best HV performance 144 kV → 12.0 kV/cm
- Average E-Field while data taking: 10.3 kV/cm

Statistical Sensitivity

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

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

- Expect ~11000 neutron per cycle in 2015
- Storage filling time determined by optimization of $\alpha\sqrt{N}$

Systematic Effects

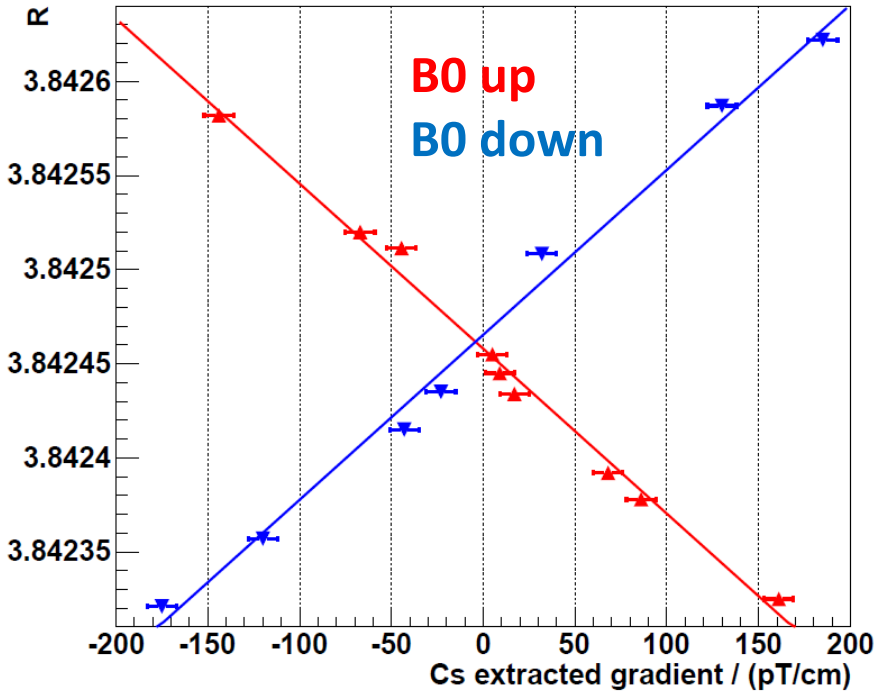
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} \approx \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}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

Geometric Phase Shift

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

Vertical gradients are monitored by Cs magnetometers

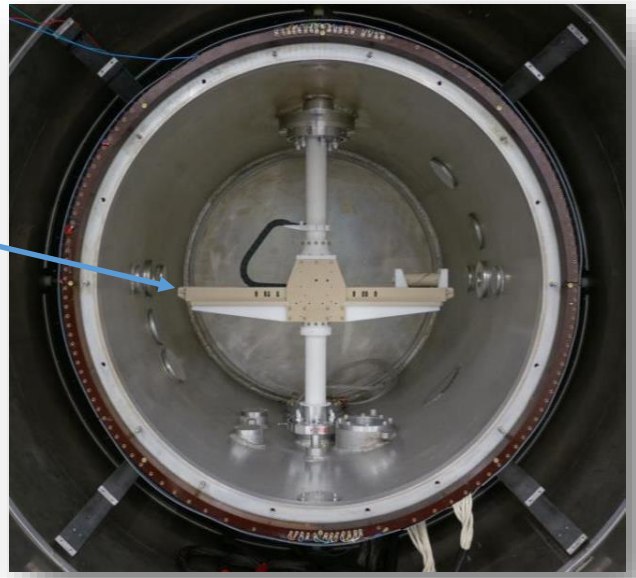
$$\Delta G = 8 \text{ pT/cm}$$



Transverse Fields

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

- Field mapped with fluxgate
- Monitored by Cs magnetometers
- Soon vector Cs magnetometers will be installed



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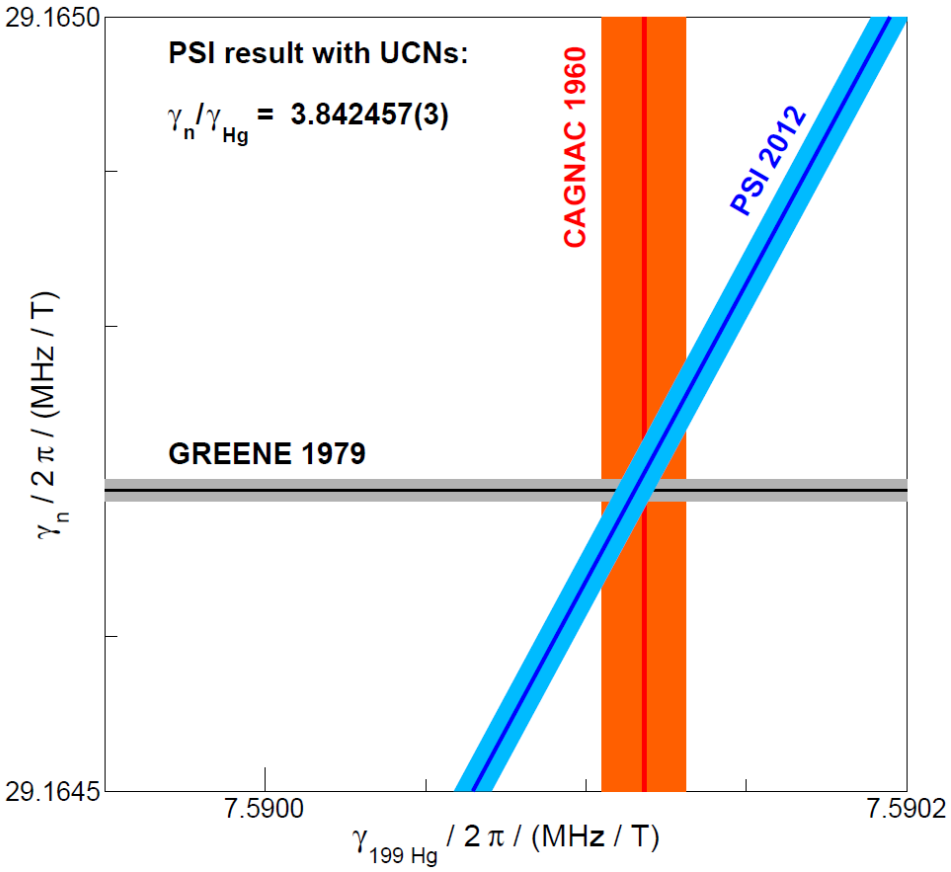
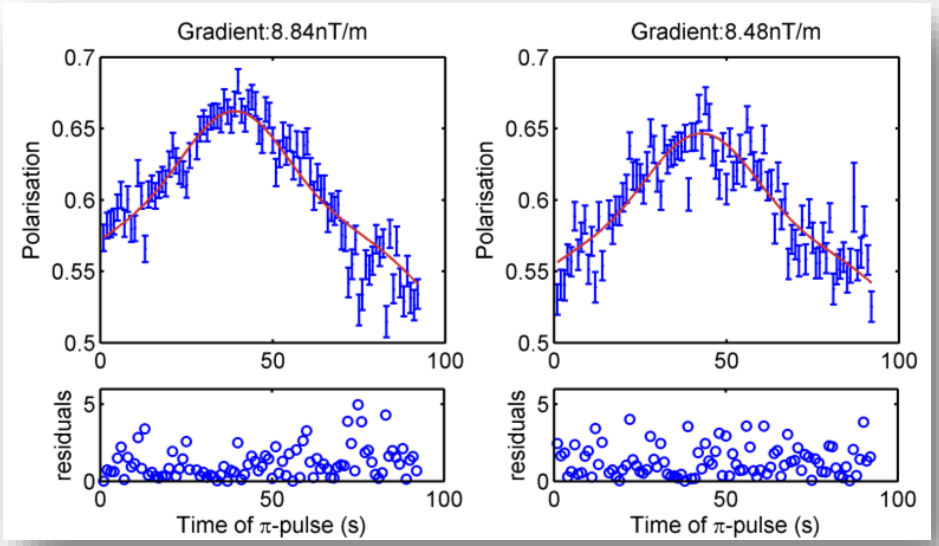
Gyromagnetic Ratio of n & ^{199}Hg

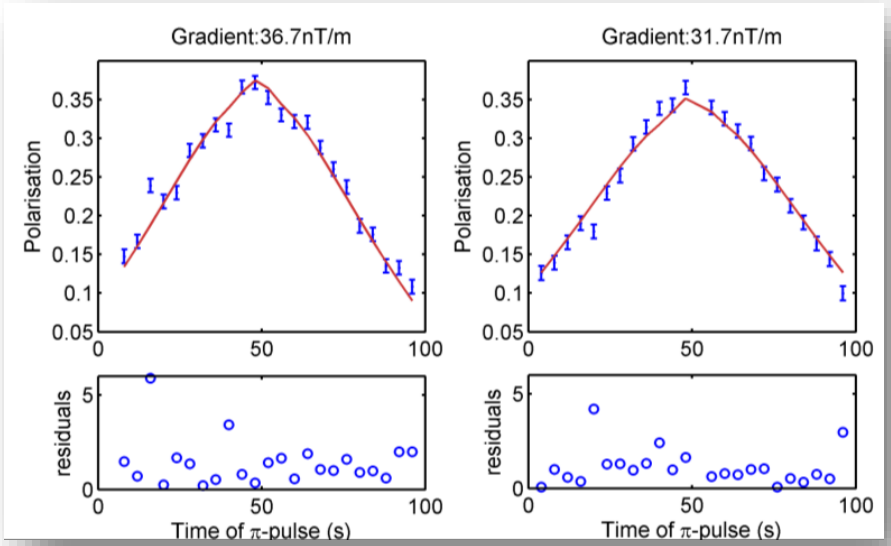
The neutron gyromagnetic ratio was measured relative to the ^{199}Hg gyromagnetic ratio as a test of magnetic field control.



S. Afach, et al. PLB. 739 (2014) 128.

UCN Spin-Echo

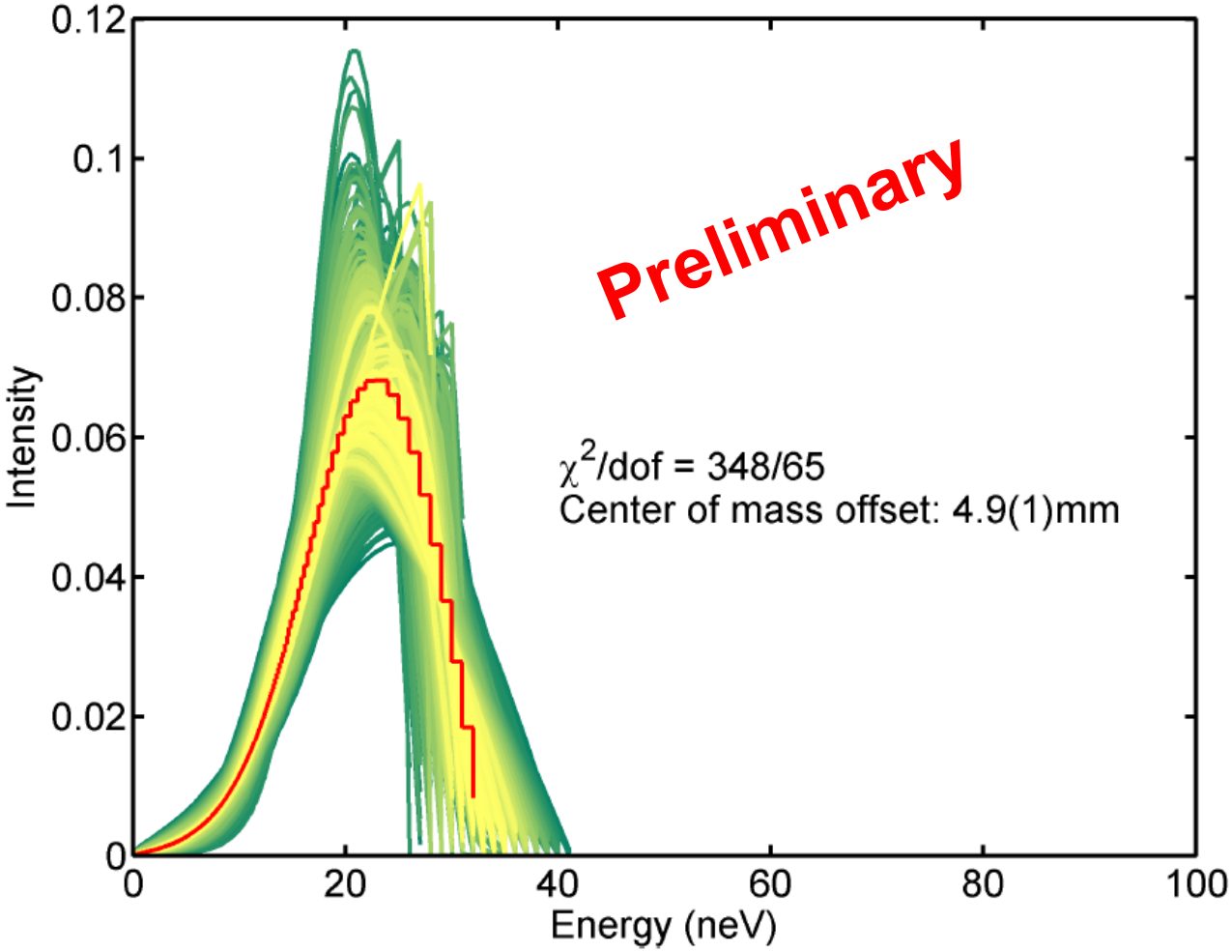




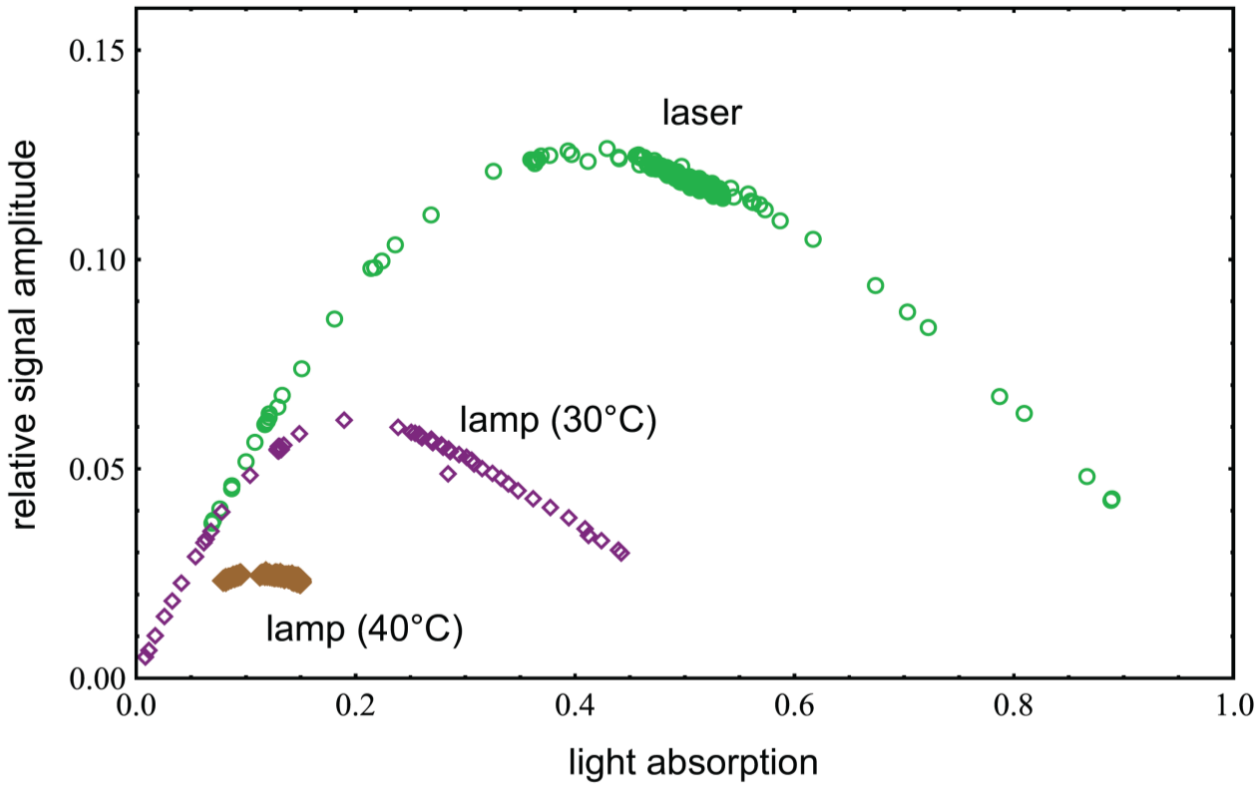
$$\alpha(t_1) = \int_0^\infty \alpha(T,E)\cdot\cos\left[2\pi\gamma_n\left(1+\frac{\partial B_z}{\partial z}\cdot\langle h_{cm}(E)\rangle(T-2t_1)\right)\right]p(E)\,dE,$$

The rate of transverse depolarization in an applied field gradient is dependent of the UCN energy spectrum.

UCN Energy Spectrum



Laser Based Hg Magnetometer



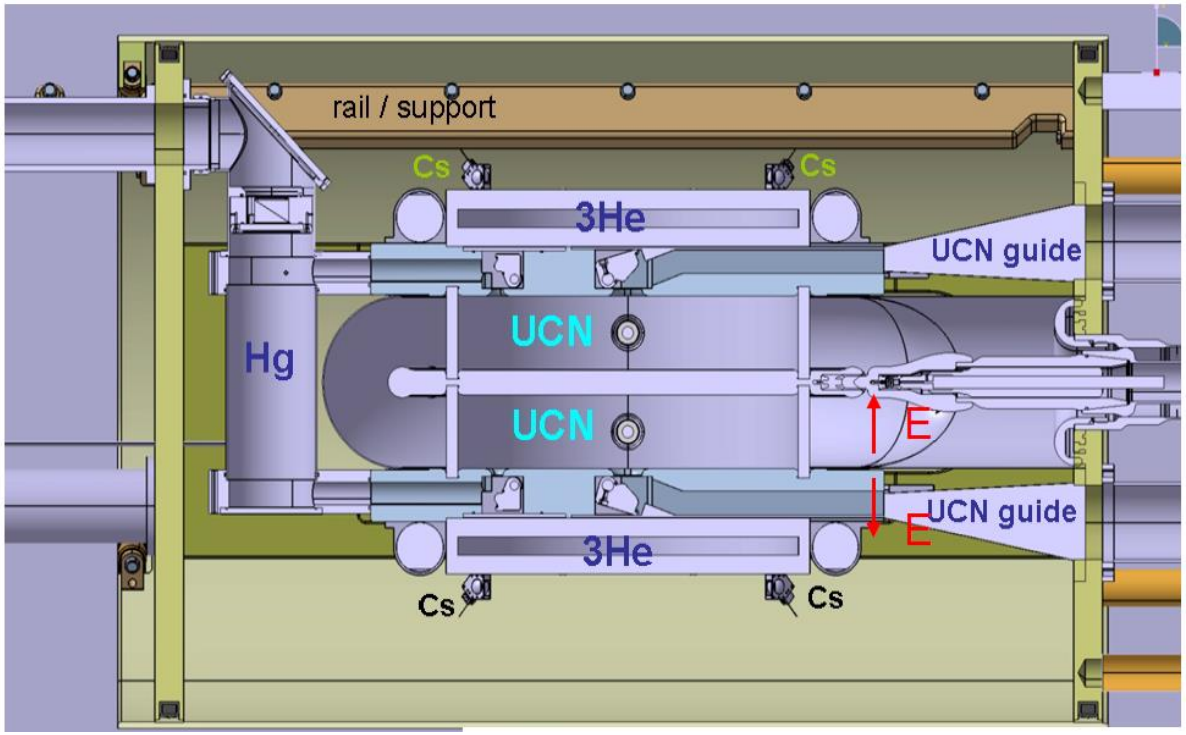
- Improved Hg signal sensitivity
- Reduced Hg light shift effect

Current Status

- The UCN source is delivering sufficient neutrons to reach the statistical goal (when operational).
- Several improvements to increase the sensitivity over the current limit have been implemented.
- New physics results have been obtained such as the gyromagnetic ratio of the neutron and ^{199}Hg and a spin-echo measurement of UCNs.
- We have a sensitivity of 1.6 x 10^{-25}ecm per day and expect 300 data-days through 2016.

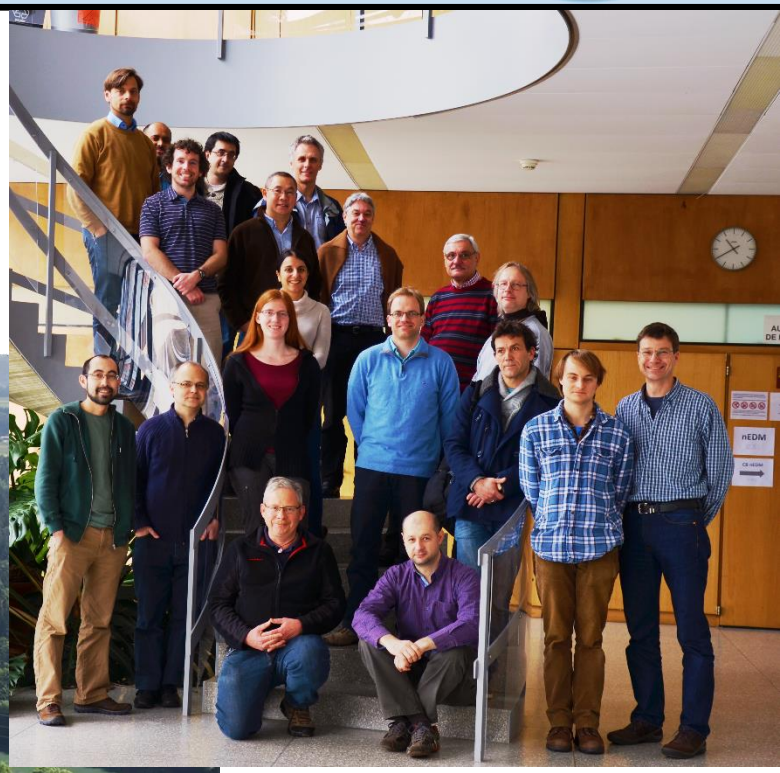
Goal sensitivity: $\boldsymbol{d_n < 5 \times 10^{-27}}$ **e cm (95% C.L.)**

The Nest Phase: n2EMD



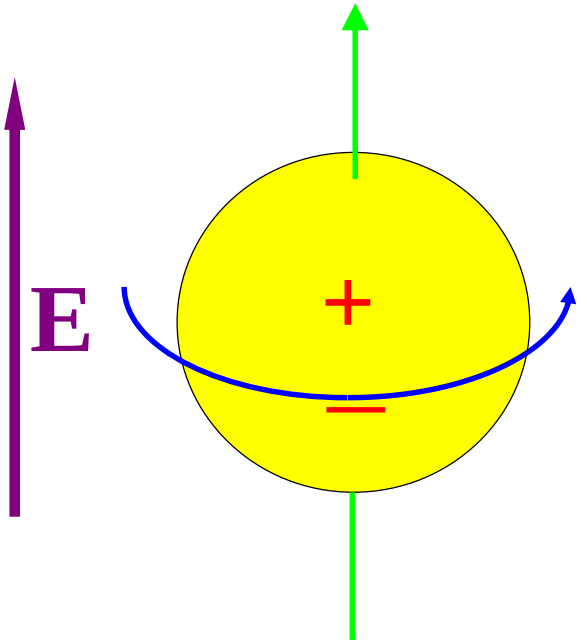
- Two precession chambers
- Improved magnetic shielding
- 3He magnetometers

Thank you for your attention.

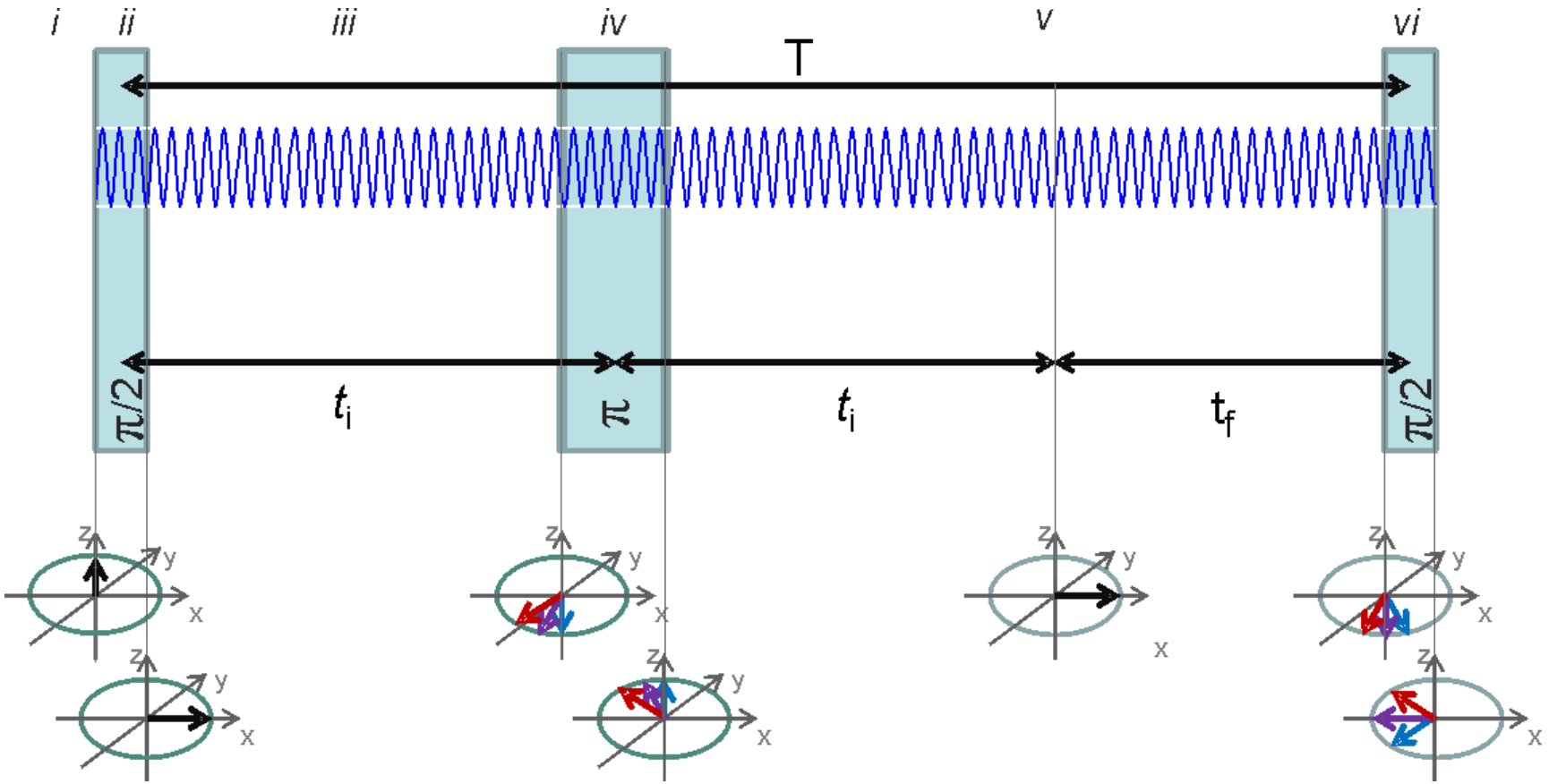


Thanks go to Philipp Schmidt-Wellenburg, Bernhard Lauss, and Florian Piegsa for use of their slides and to Clark Griffith and Philip Harris for guidance.

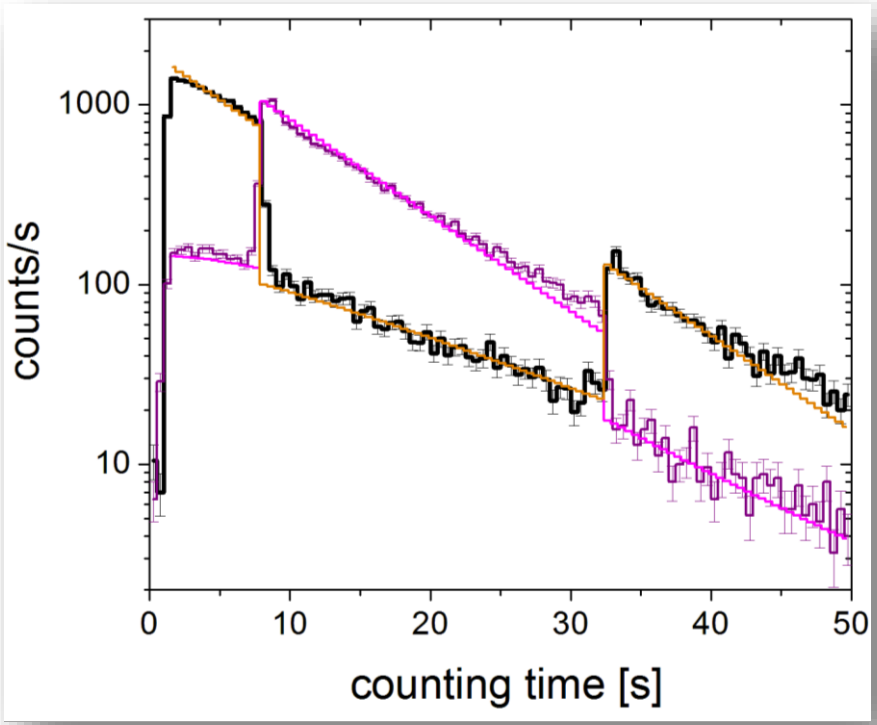
Backup Slides



UCN Spin-Echo

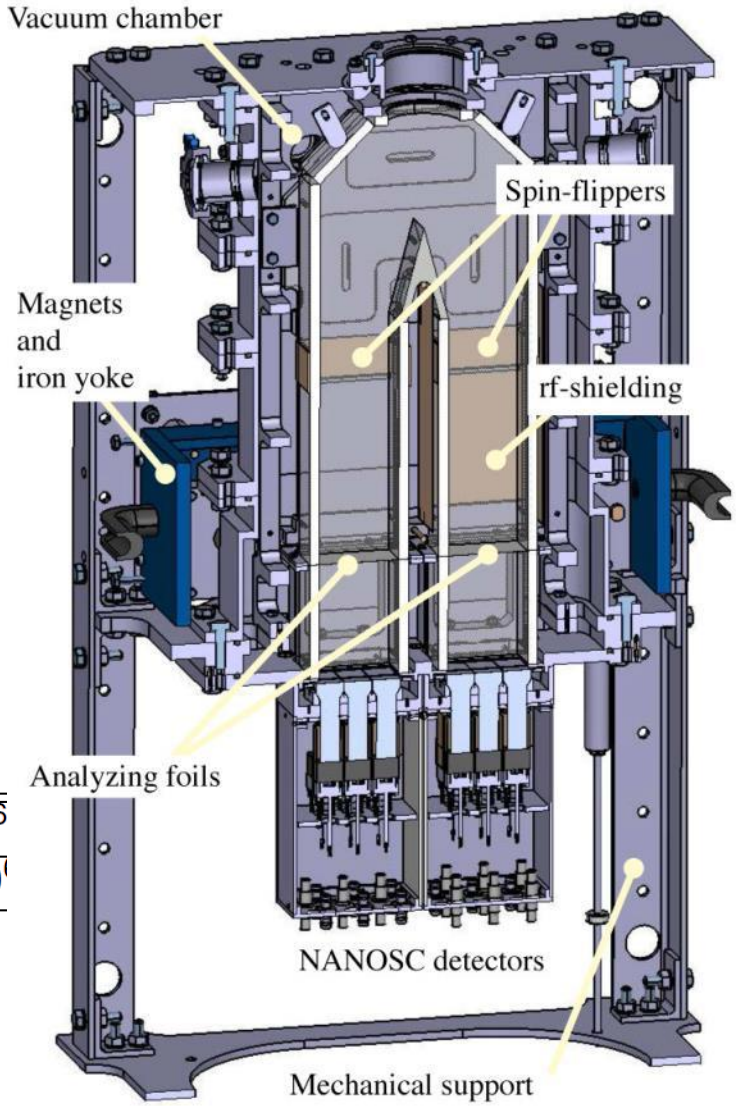


Simultaneous Spin Detection



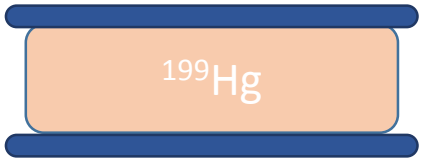
	Visibility α [%]	N_{tot}	N_{West-1}
USSA	63.4 ± 1.8	3791(14)	$1.878(5) \times 10^6$
Sequential	59.7 ± 2.2	2692(15)	$1.651(16) \times 10^$
Ratio	1.062(49)	1.238(10)	

~20% increase in sensitivity



Systematic Effects

$\frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$

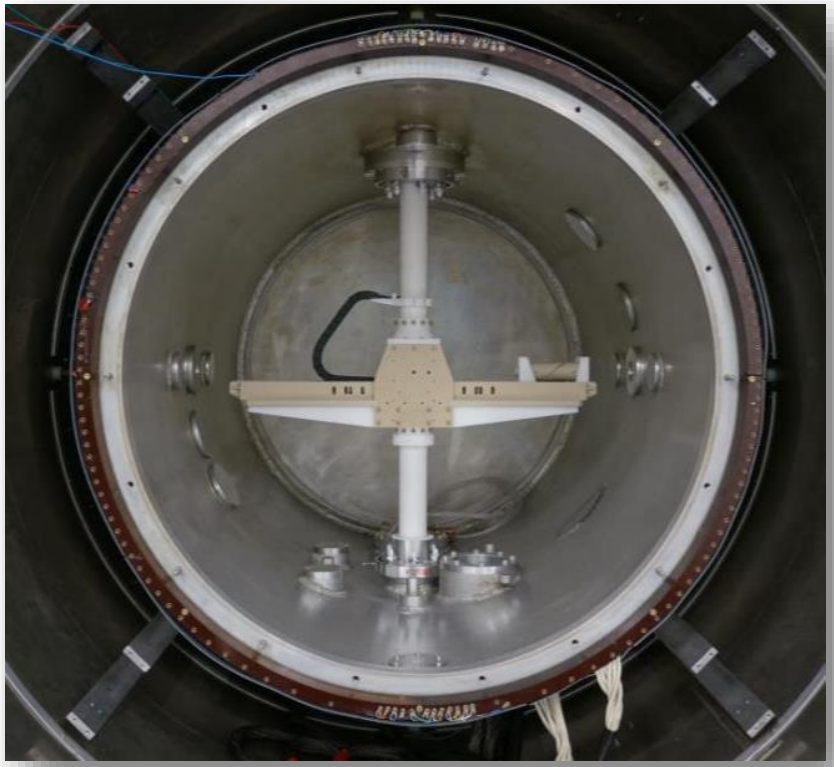


$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$

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

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

Transverse Fields



UCN: Adiabatic regime

$$f_n \propto \langle |\vec{B}| \rangle = B_0 + \frac{\langle B_T^2 \rangle}{2B_0}$$

Mercury: Non-adiabatic regime

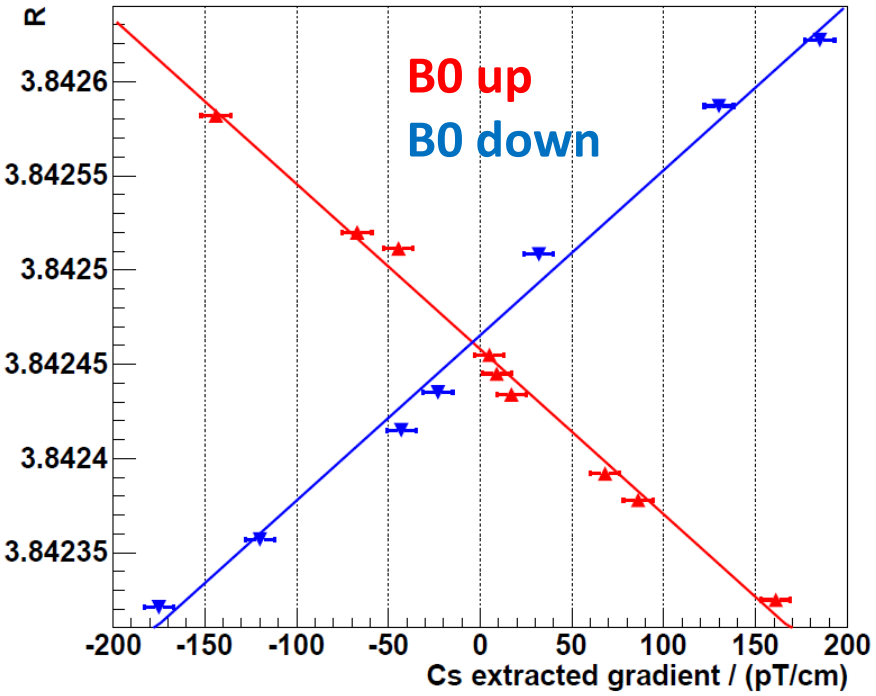
$$f_{\mathrm{Hg}} \propto |\langle \vec{B} \rangle| = B_0$$

- Mapping with fluxgate and vector cesium magnetometer
- -20<z<20, -10<r<30, $\Delta\varphi = 5°$

$$\delta R_{\mathrm{Transverse}} = (3 \pm 1) \times 10^{-6}$$

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

Vertical Field Gradients



- Field parameterized by 9 parameters
- Parameters are adjusted to 12 Cs magnetometers
- Residuals are about 30 pT
- Jackknife procedure used to estimate error of the total gradient G

$$\Delta G = 8 \text{ pT/cm}$$

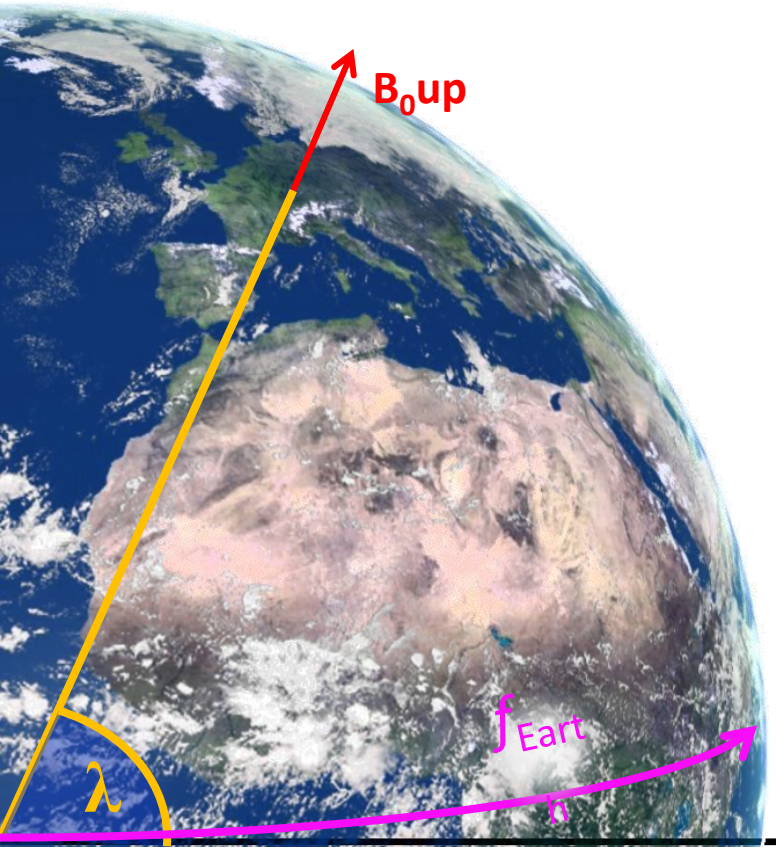
$$\begin{aligned} h &= -0.235(5)\,\text{cm} \\ R_0^{\uparrow} &= 3.8424580(23) \\ R_0^{\downarrow} &= 3.8424653(27) \end{aligned}$$

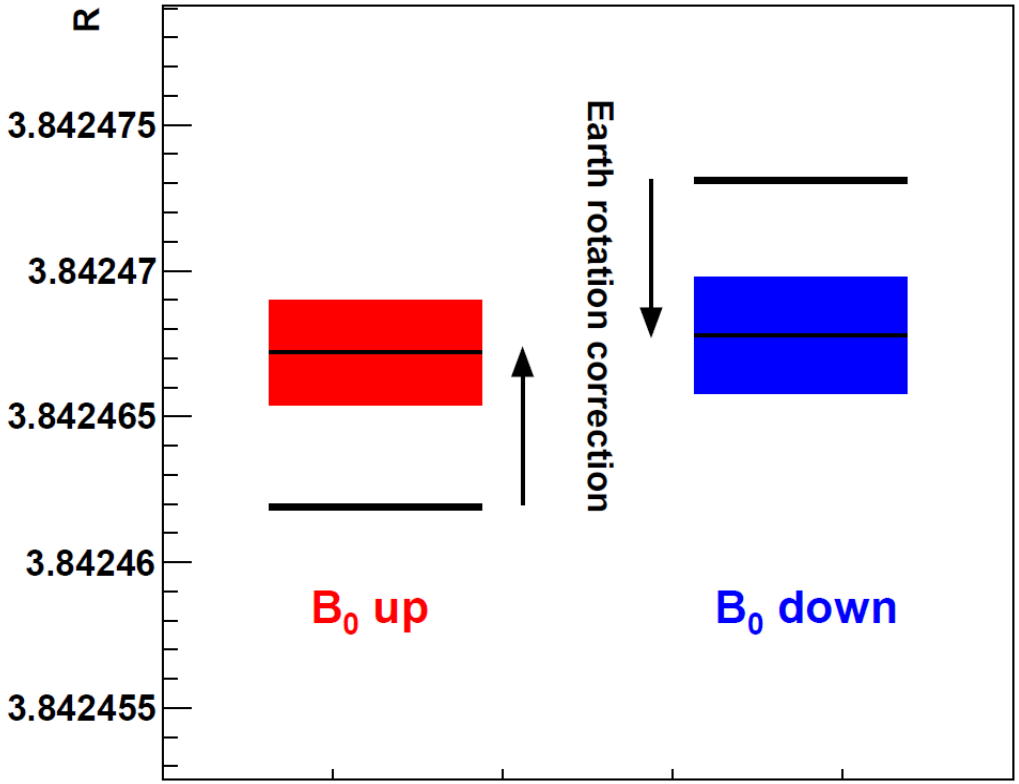
$$R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} \approx \frac{\gamma_{\text{n}}}{\gamma_{\text{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right)$$

Earth Rotation Correction

$$\delta_{\text{Earth}} = \mp \frac{\gamma_n}{\gamma_{Hg}} \left(\frac{f_{\text{Earth}}}{f_n} + \frac{f_{\text{Earth}}}{f_{Hg}} \right) \sin(\lambda)$$

$$= \mp 5.3 \times 10^{-6}$$





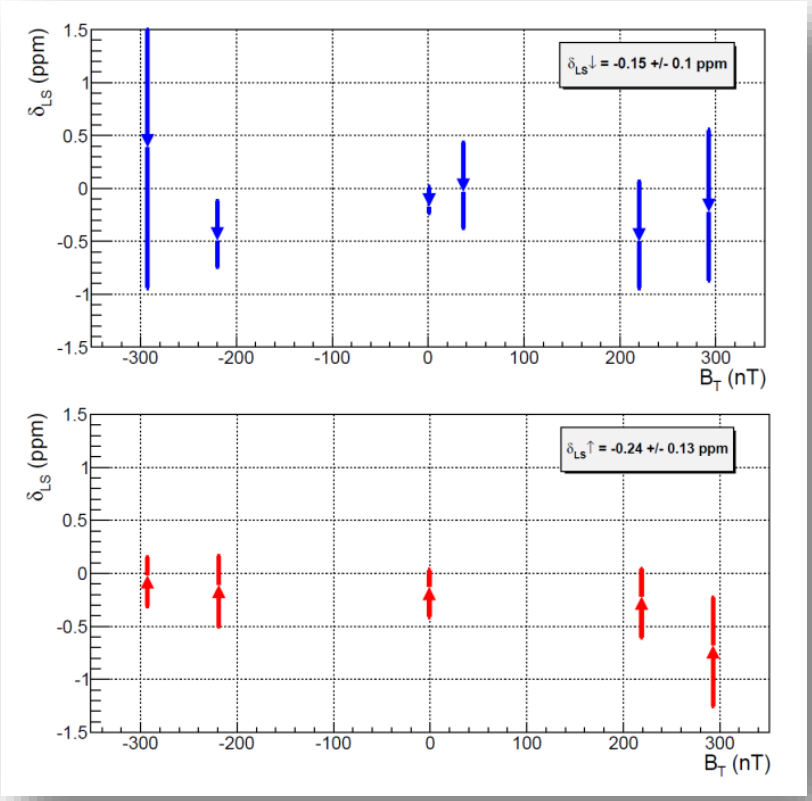
$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} \approx \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_\perp \rangle}{|B_0|^2} \mp \delta_{\text{Earth}} + \delta_{\text{Hg-lightshift}} \right)$$

Hg Light Shift

Hg reading light can create an effective magnetic field that only alters the precession frequency of the Hg atoms.

Effective magnetic field depends on:

- Light intensity
- Light polarization
- Light frequency
- Light beam alignment



$$\delta^{\downarrow}_{\text{Light}} = (0.21 \pm 0.14) \times 10^{-6}$$

$$\delta^{\uparrow}_{\text{Light}} = (0.34 \pm 0.18) \times 10^{-6}$$

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

Current Status

	2015
E-field (kV/cm)	11
Neutrons	11 200
T_{free}	194
T_{duty}	340
α	0.65
$\sigma/d^{-1/2}$ $(10^{-25}$ecm)	1.6

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