PAUL SCHERRER INSTITUT

WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

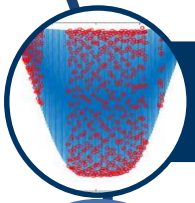
7th international Symposium on symmetries in subatomic physics , 10-15 June 2018, Aachen

Searches for the electric dipole moments of the neutron

Philipp Schmidt-Wellenburg , Paul Scherrer Institute Switzerland

Outline

Complementarity to other EDM searches

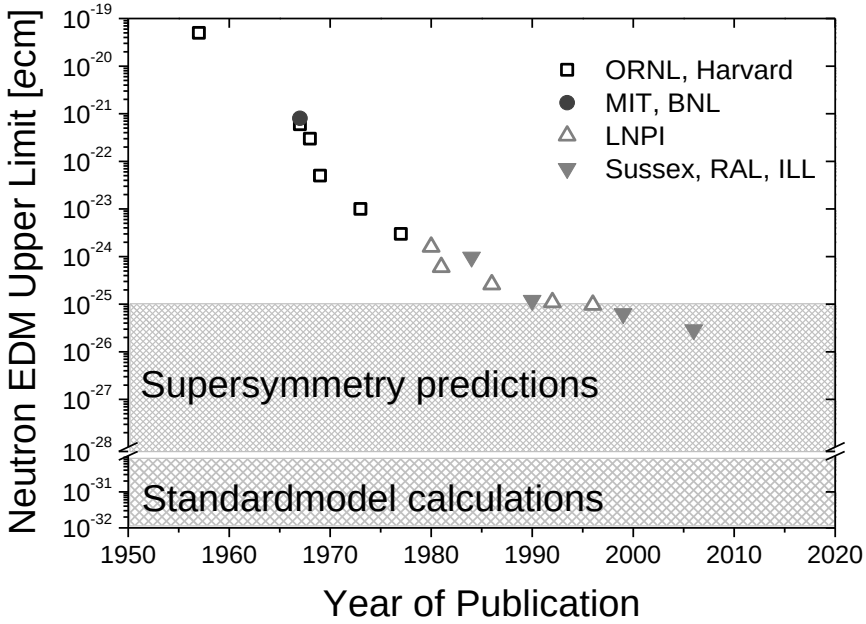


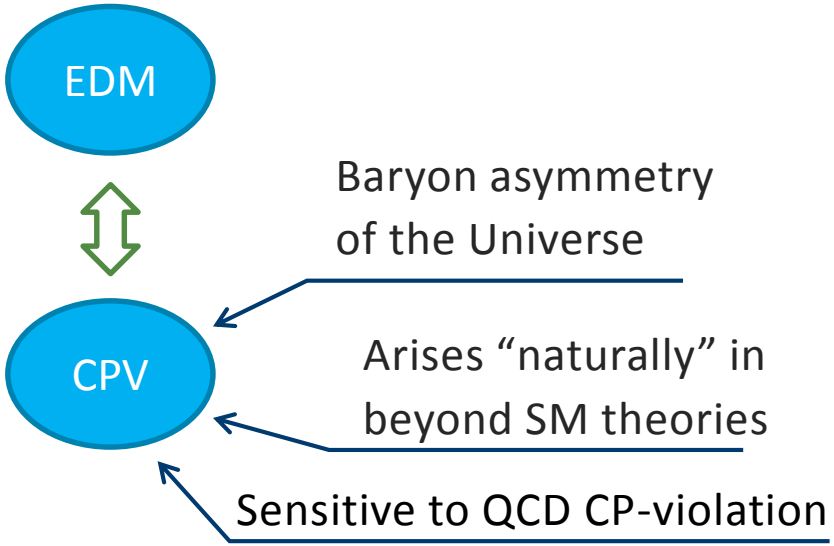
Ultracold neutrons and Ramsey's technique

Worldwide competition

Searches for static and oscillating nEDM at PSI

nEDM searches





First

Smith, Purcell, Ramsey

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

PR 108 (1957) 120

~ 50 years

Last

RAL-Sussex-ILL

$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

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

neutron EDM: complementary to other searches

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

QCD theta term "natural" in neutron, proton

From lattice calculations**

$$\frac{d_n}{\theta} = -3.8(2)(9) \times 10^{-16} e\text{cm} \qquad \frac{d_p}{\bar{\theta}} = +1.1(1.1) \times 10^{-16} e\text{cm}$$

but

$$d_{\text{n}}^{\text{ex}} < 3 \times 10^{-26}\ e\text{cm}^*$$

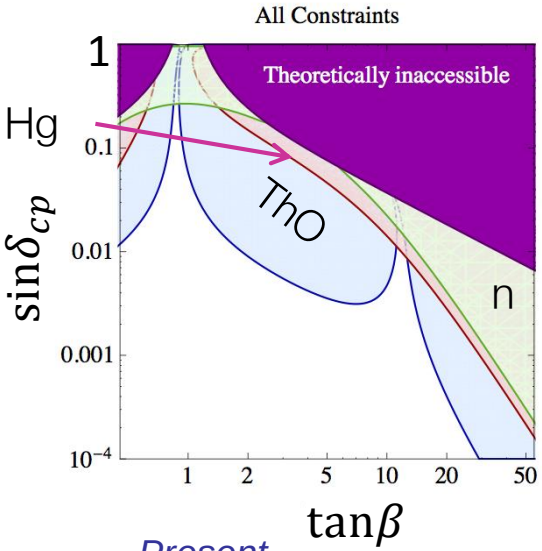
$$\theta < 1 \times 10^{-10}\ e\text{cm}$$

Strongly suppressed in electron

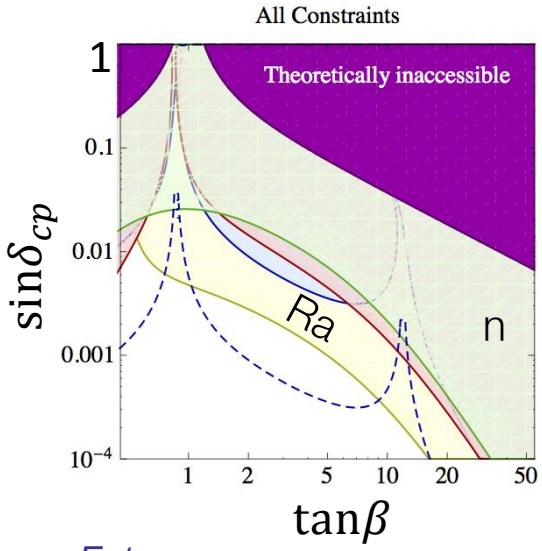
*J.M. Pendlebury et al., **PRD** 92 (2015) 092003
Guo et al., **PRL(2015)062001

Example of complementarity

Higgs Portal CPV *(would also lead to strong first order phase transition)*

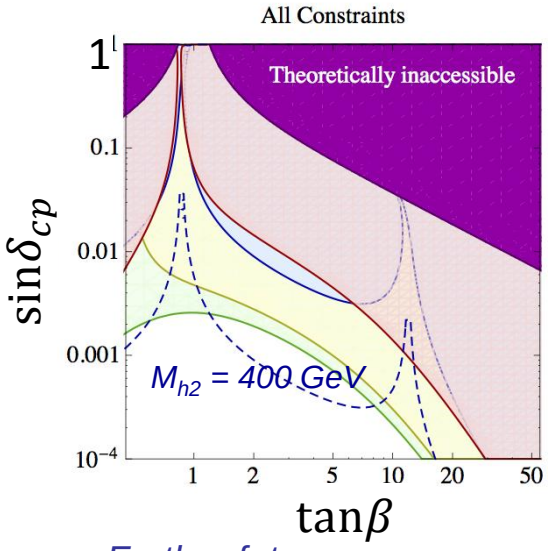


Present



Future:

d_n x 0.1
d_A(Hg) x 0.1
d_{ThO} x 0.1
d_A(Ra)



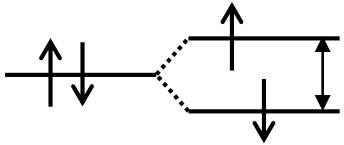
Farther future:

d_n x 0.01
d_A(Hg) x 0.1
d_{ThO} x 0.1
d_A(Ra)

Inoue *et al.*, PRD(2014)115023
Chen *et al*, JHEP06(2015)056

Modified Larmor Frequency

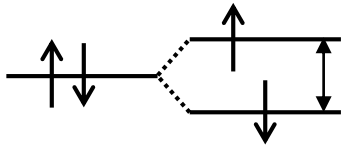
$$V_{\mathrm{mag}} = -\mu_{\mathrm{n}}\vec{\sigma}.\vec{B}$$



$$\Delta E_{mag} = \hbar\omega_L = 2\mu_n B$$

with: $\mu_n = \frac{1}{2}\hbar\gamma_n$

$$V_{\mathrm{edm}} = -d_{\mathrm{n}}\vec{\sigma}.\vec{E}$$



$$\Delta E_{edm} = \hbar\omega_{edm} = 2d_n E$$

For parallel electric and magnetic fields the precession frequencies add up and for anti-parallel fields the frequencies have to be subtracted. The precession frequency difference of the two cases can be measured:

$$\hbar\omega_{\uparrow\uparrow} = \hbar(\omega_L + \omega_{edm}) = 2(\mu_n B + d_n E)$$
$$\hbar\omega_{\uparrow\downarrow} = \hbar(\omega_L - \omega_{edm}) = 2(\mu_n B - d_n E)$$

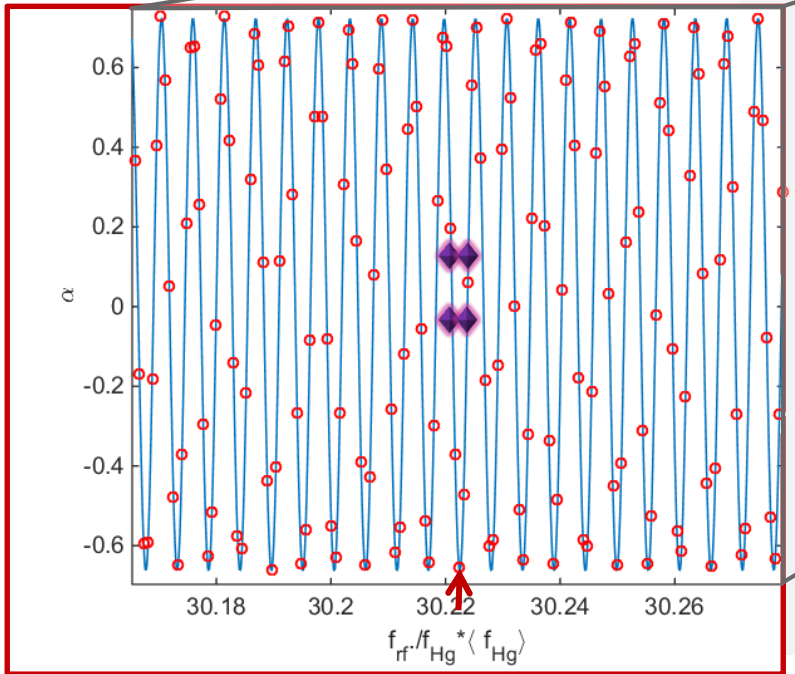
$$\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) = 4\, d_n E$$

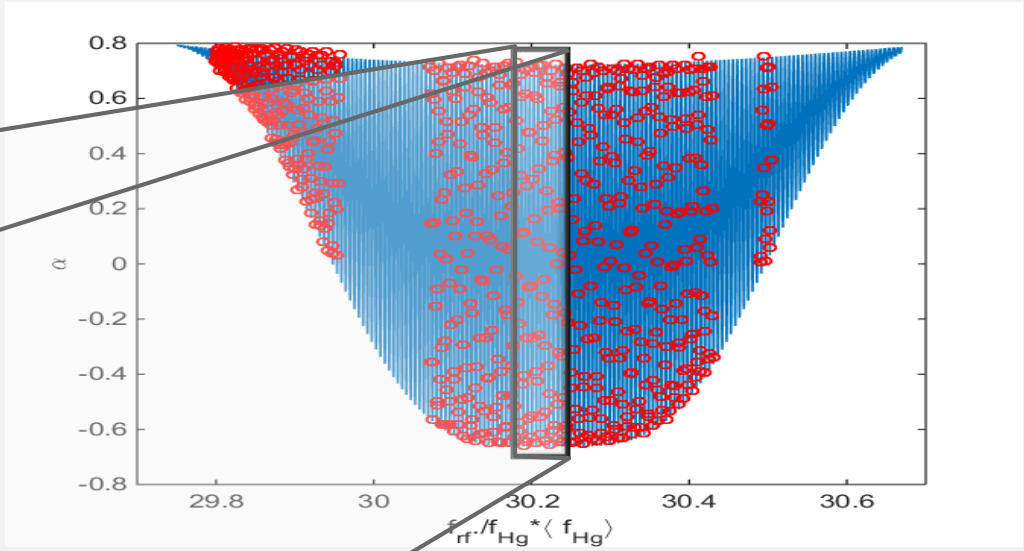
HOW ???

The Ramsey technique

Spin "down" neutron...

$B_{0\uparrow}$





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

How to increase the statistical sensitivity

$$\sigma(d_n) = \frac{\hbar}{2ET\alpha\sqrt{N}} = \frac{\hbar}{2ET\alpha_0 e^{-T/T_2}\sqrt{N_0 e^{-T/\tau_n}}}$$

$E \leq 20\mathrm{kV/cm}$: Limited by insulator

$\alpha \to 1$: Polarization of neutrons

$T \to \tau_n$: Minimize losses

$\sqrt{N_0}$: Limited by transport losses

$T_2 \to \infty$: Magnetic field inhomogeneity

- Make T_2, α large → large high performance magnetically shielded rooms
- Make $\sqrt{N_0}$ large → improve UCN sources
  - better extraction of UCN from converter
  - higher UCN production rates
  - adaptation / improvement of UCN transport

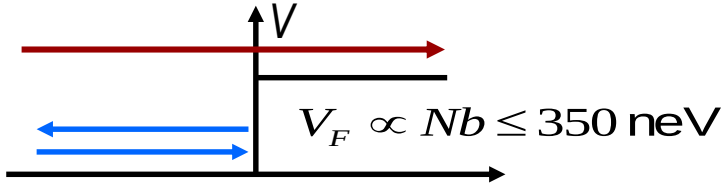
  } Talk :Dieter Ries
- Make $ET\sqrt{N}$ large → cryogenic UCN storage experiment

Ultracold neutrons (UCN)

$$\sigma(d_n) = \frac{\hbar}{2\alpha E\sqrt{NT^{3/2}}}$$

$$\sigma(d_n) \propto \frac{1}{\sqrt{NT^{3/2}}}$$

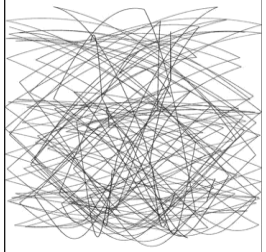
Storable neutrons (UCN)



Storage properties are material dependent

Strong V_F

Gravity 102 neV/m



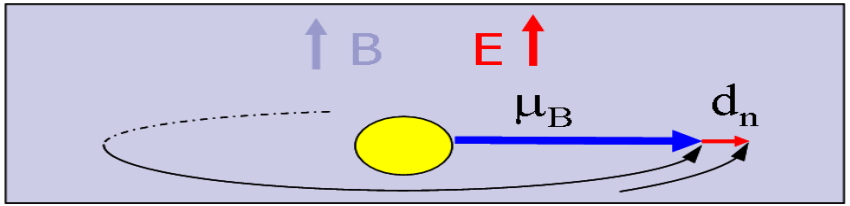
Magnetic ~60 neV/T

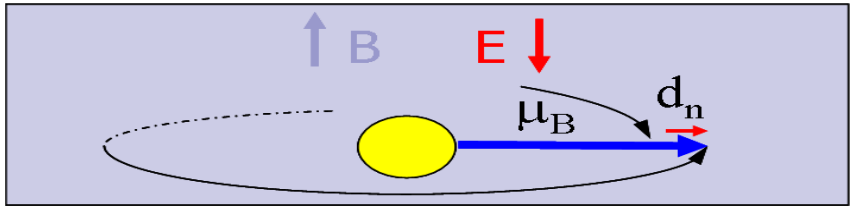
350 neV ↔ 8 m/s ↔ 500 Å ↔ 3 mK

E. Fermi & W.H. Zinn (1946) unpublished,
Y. B. Zeldovich, Sov. Phys. JETP (1959) 389

The measurement technique

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



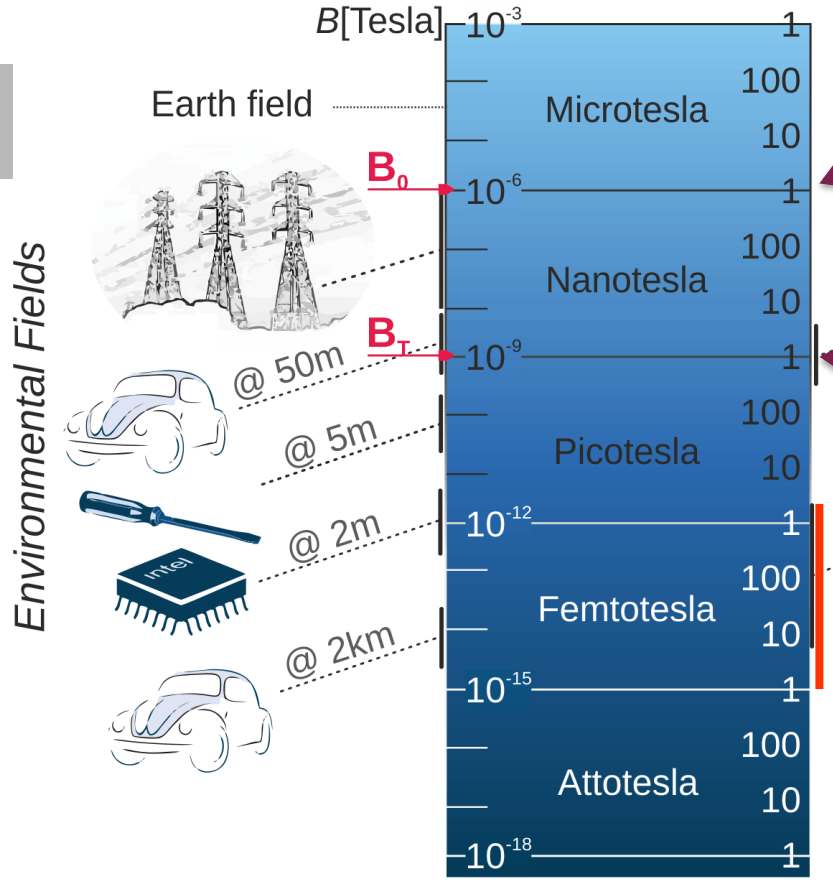


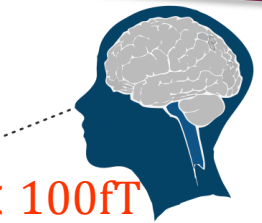
$$\eta \Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

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

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

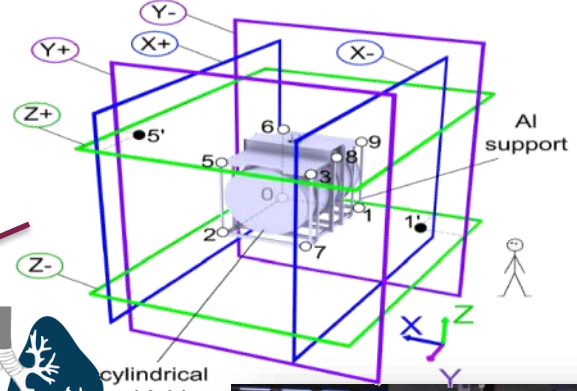
Magnetic fields

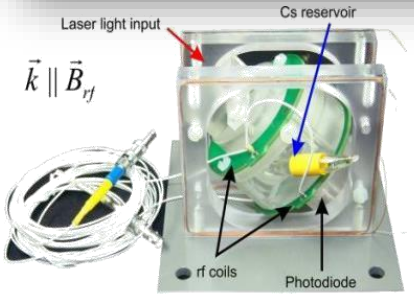




$\delta B < 100\text{fT}$

optical pumped magnetometers (CsM/HgM/XeM…)



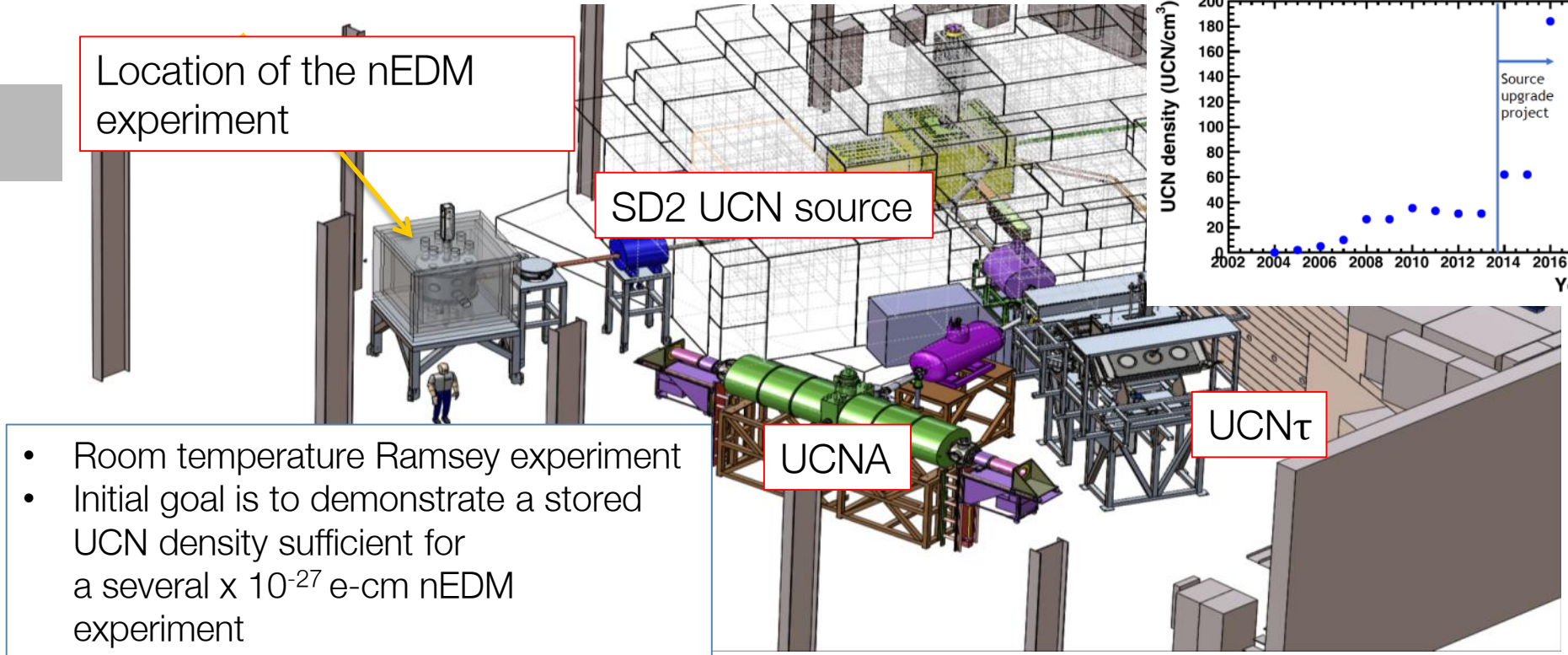


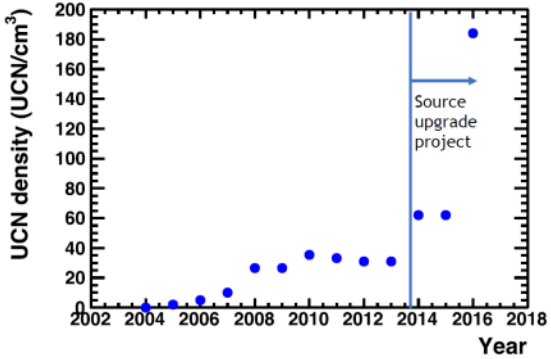
Principal approaches

$$d_{\mathrm{n}} = \frac{\hbar\Delta\omega - 2\mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} - E^{\uparrow\downarrow}\right)} \approx \frac{\hbar\Delta\omega}{4|E|}$$

	Measured simultaneously (n2EDM) 	**Measured as sequence (nEDM)** 
Co-magnetometer (mercury, xenon, ^{3}He)	Corrections for differences of mean magnetic-field gradient	Corrections for changes of the mean magnetic field
Magnetic shield (active, passive)	Minimal residual fields + Stability: higher order gradients	Small residual fields + Stability paramount !!
Efforts	TUM/ILL TRIUMF PNPI PSI(2) SNS LANL(2)	LANL PSI(1) finished TRIUMF(1)
Non-UCN searches	Crystal EDM (ILL&PNPI), beam EDM (F. Piegsa, ESS)	

nEDM Experiment at LANL UCN Source





- Room temperature Ramsey experiment
- Initial goal is to demonstrate a stored UCN density sufficient for a several x 10^{-27} e-cm nEDM experiment
- UCN upgrade concluded
- First measurements with Ramsey cell

LANL collaboration:

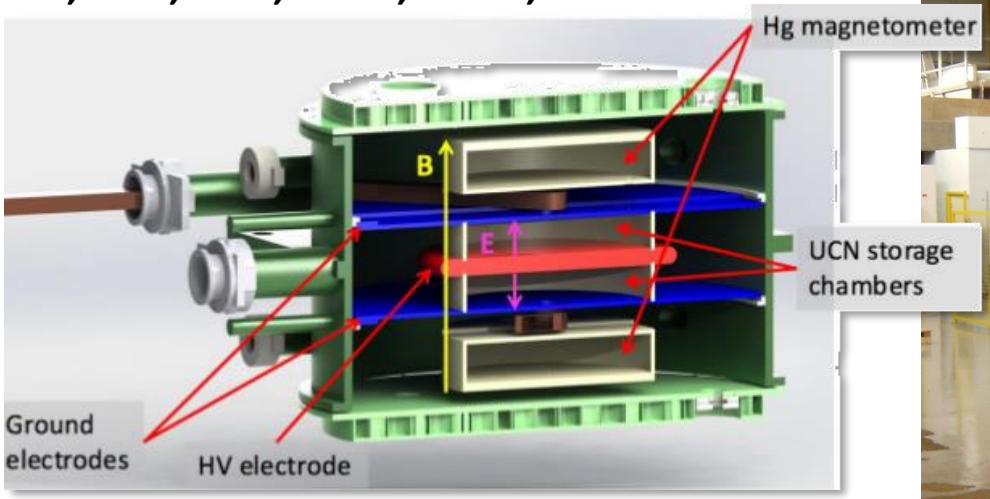
LANL, Indiana Univ., Univ of Kentucky, Univ. of Michigan, Yale Univ., JINR

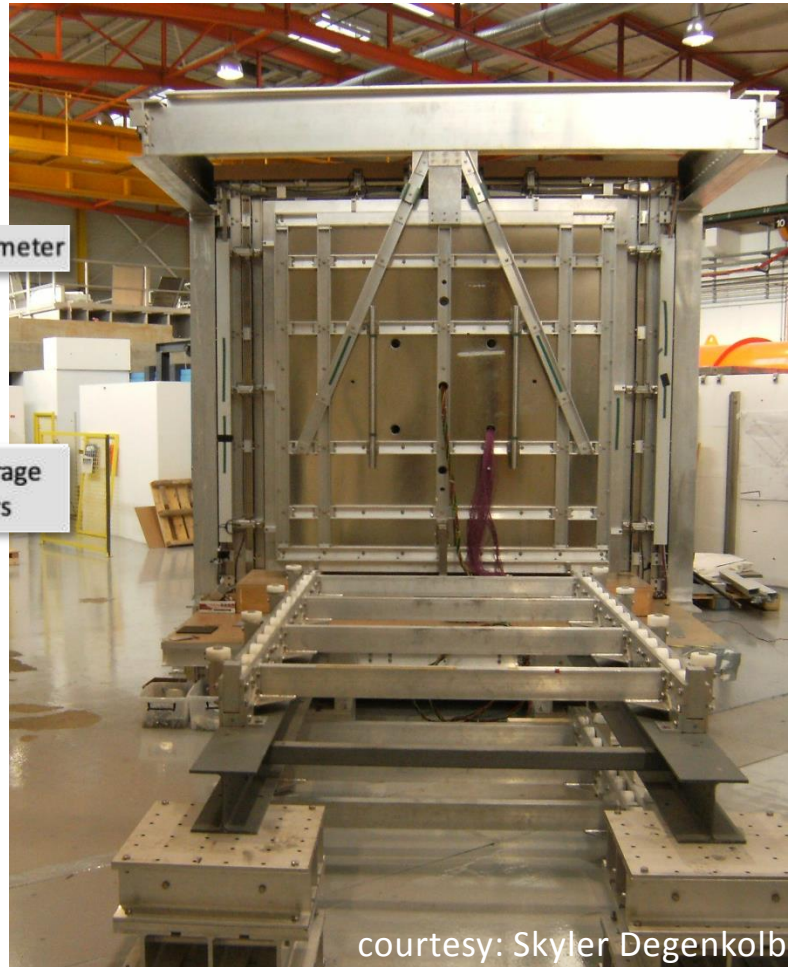
courtesy: Ito Takeyasu

ILL / TUM effort

ILL/TUM effort:

Berkley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM, UIUC, Yale

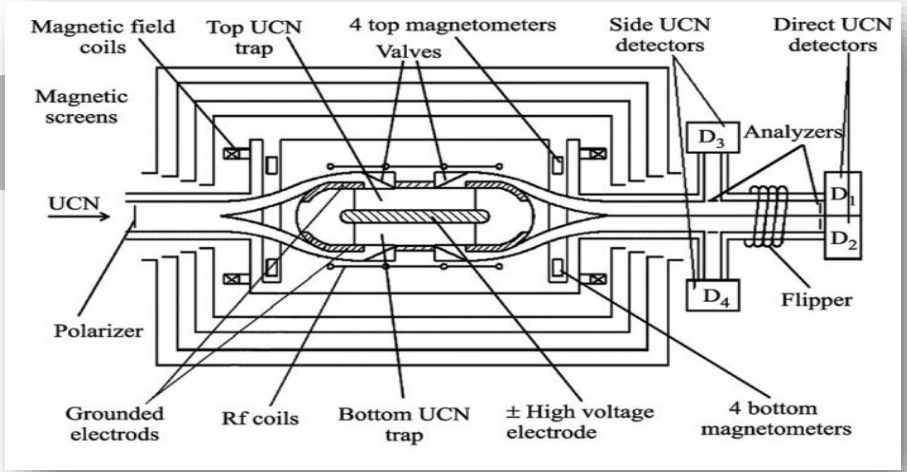




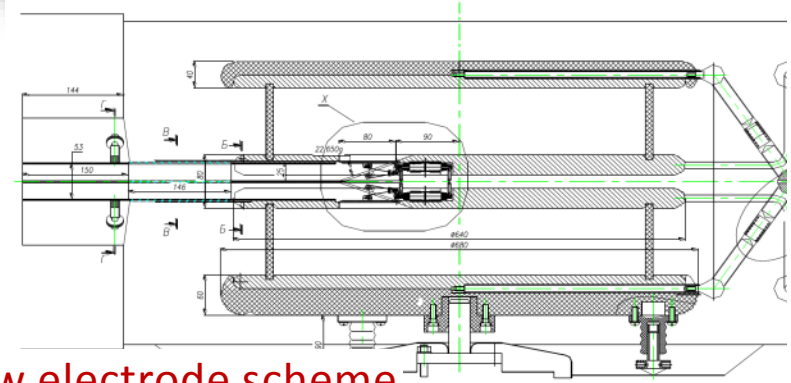
New UCN source based on He-II at ILL

Phase 1 (from 2019)	$1.9 \times 10^{-27} e\mathrm{cm}$
Phase 2 (later)	$4.2 \times 10^{-28} e\mathrm{cm}$

nEDM @ PNPI (&ILL)



courtesy: Anatolii Serebrov



new electrode scheme

Current: $d_n < 5.5 \times 10^{-26} ecm$

Improvement by factor 3

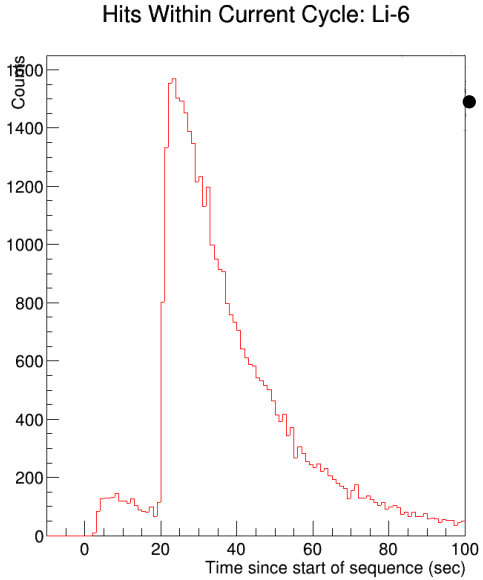
at new position and with new precession cell

ILL 2020: $d_n < 2 \times 10^{-26} ecm$

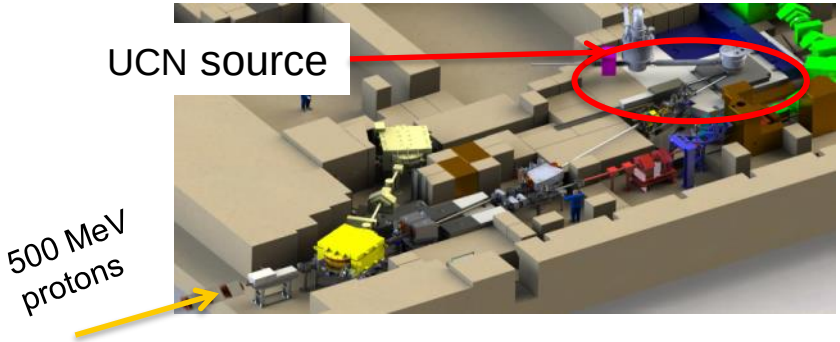
future source at PNPI: $d_n < 1 \times 10^{-27} ecm$

UCN EDM at TRIUMF

- Overview:
  - Japan-Canada collaboration
  - Spallation-driven He-II UCN source connected to RT nEDM experiment.
  - **First UCN Nov 2017! Congratulations**
  - Goal sensitivity (statistics): **δd_n ~ 10^{-27} e-cm (2020-2023)**

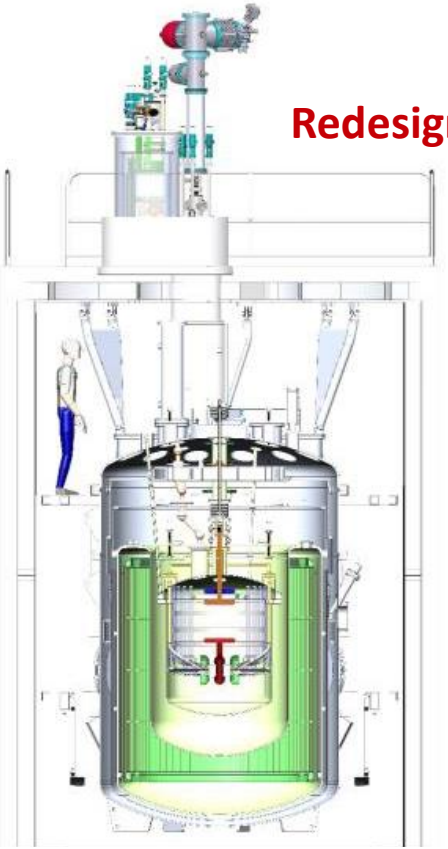


- Features:
  - Unique UCN source technology with world-leading potential.
  - $^{129}Xe/^{199}Hg$ dual-species comagnetometer to cancel false EDM's.



courtesy: Rüdiger Picker

nEDM @ SNS



Redesign to reduce costs (7/17)

- Sensitivity: ~2×10^{-28} e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized ^{3}He co-magnetometer**
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows synching of n & ^{3}He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion (mfp)- big change in geometric phase effect on ^{3}He

Full-scale operation in 2022

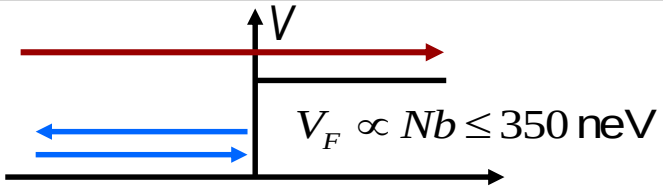
Smaller shield house
Non-modular ^{3}He system
& smaller building

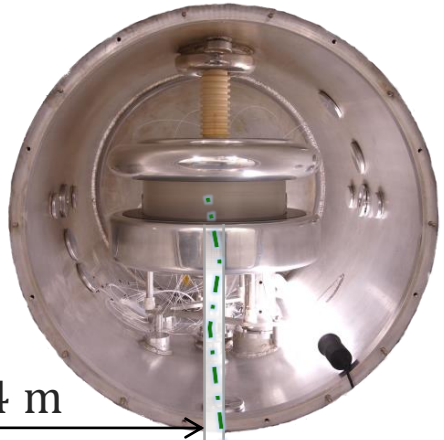
courtesy: Brad Filippone

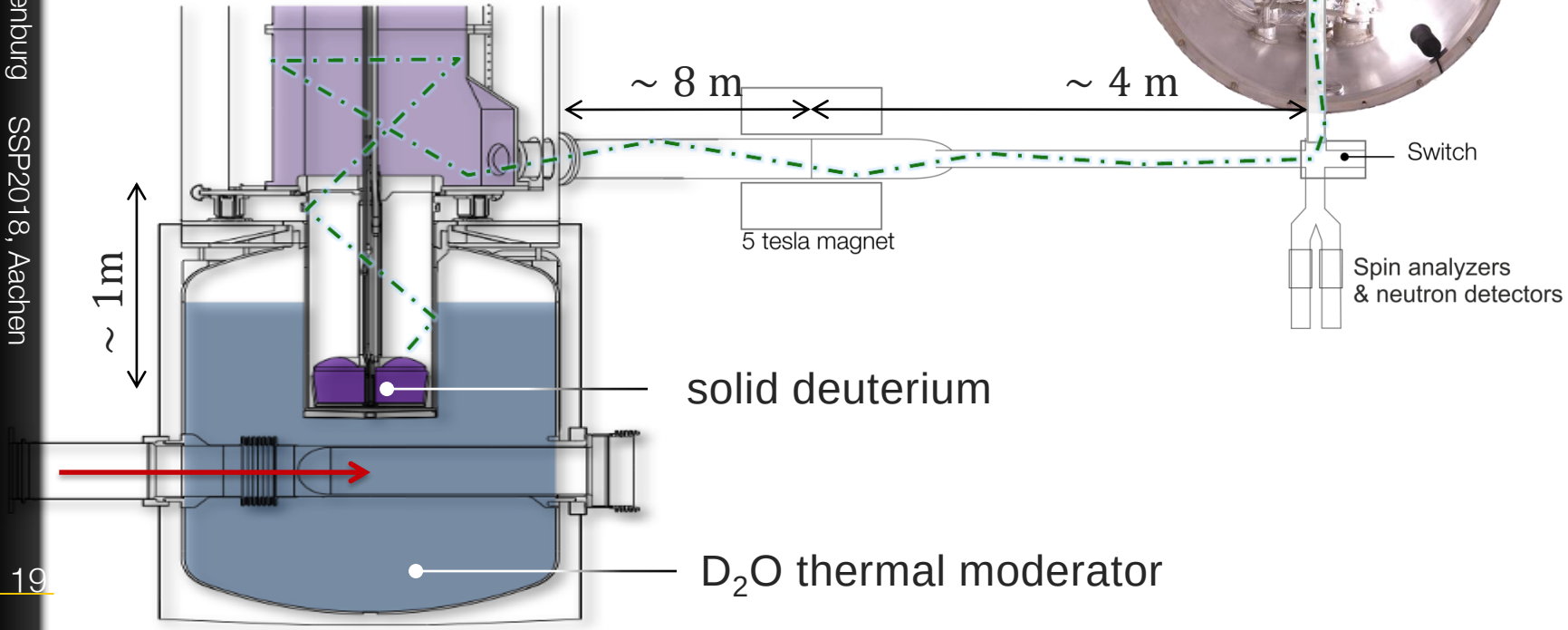
Status & Schedules

Project	Status	Sensitivity goal (E-27 *ecm*)	Schedule (start data-taking)
LANL	2017:UCN source upgrade finished	UCN density sufficient for O(1)	2019
TUM-ILL	TUM apparatus moves to ILL	O(0.1)	2019
PNPI	At PNPI 2020	PNPI: 0.5	PNPI later
SNS	Critical component demonstration concluded	0.2	2022
TRIUMF	2017: first UCN 2-3 years for experiment	O(1)	2020
PSI	Phase(1) data-taking concluded Phase(2) construction	Phase 1: O(10) Phase 2: O(1)	Phase(2): 2020
ESS	Demonstration phase at ILL	?	?
CrystalEDM	Demonstration at ILL successful in 2010	O(1) (at ESS)	?

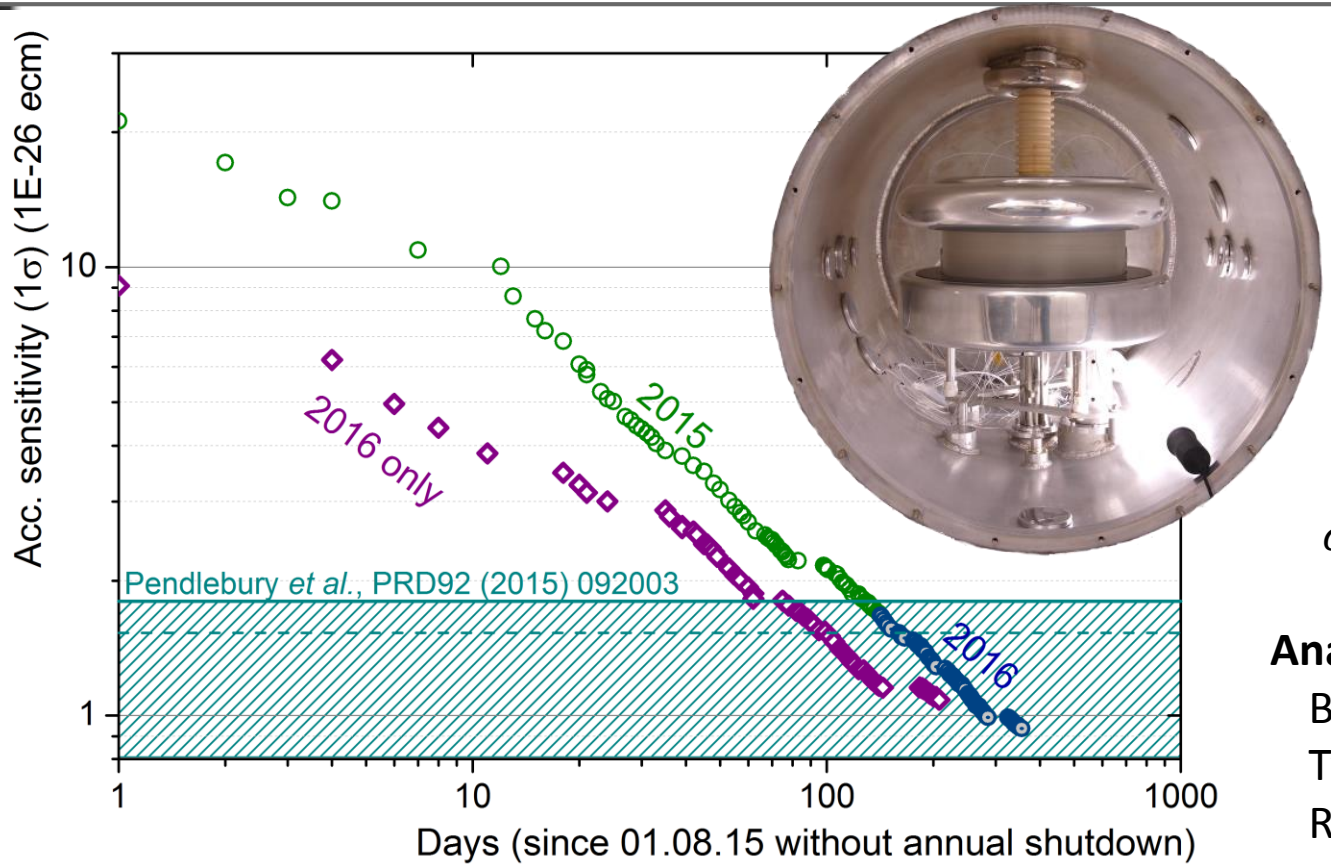
Ultracold neutr







The nEDM spectrometer



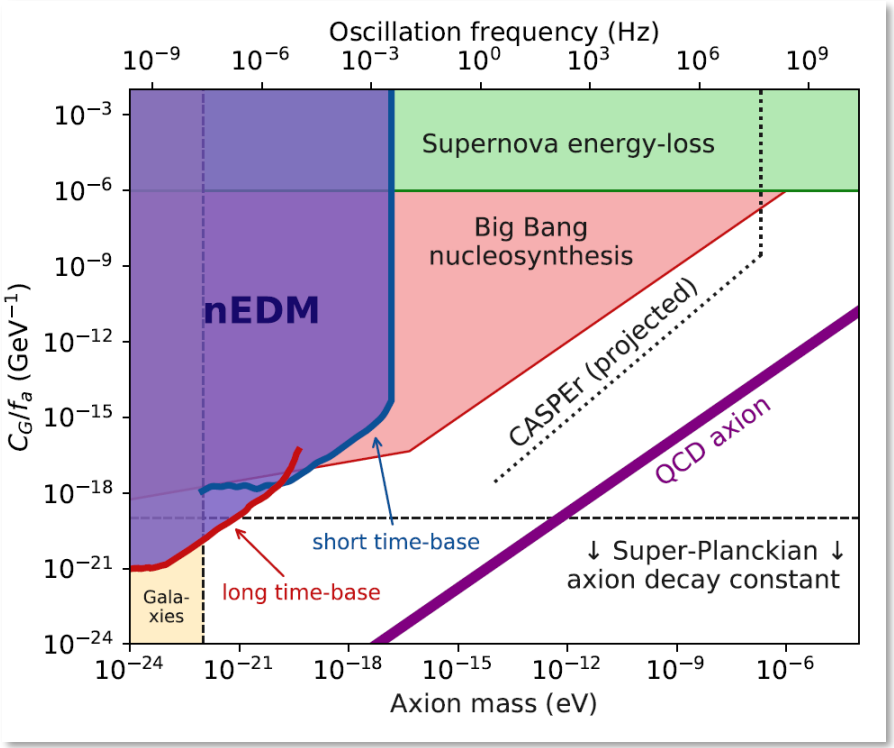
624’364’314 neutrons

$\sigma = 0.94 \times 10^{-26}$ecm

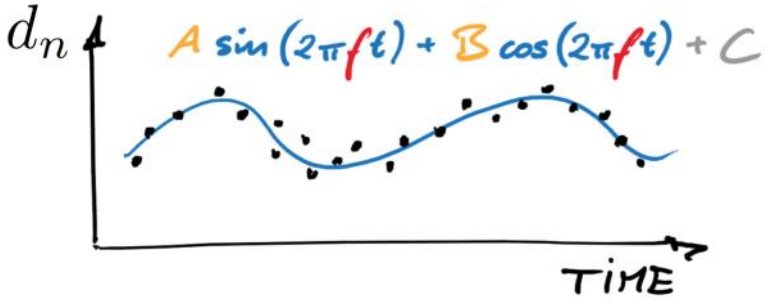
Analysis ongoing:

- Blinded data
- Two groups
- Result planned for 2018

Dark matter limit from the nEDM - search

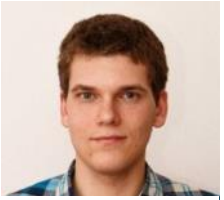


First experimental limits on gluonic coupling



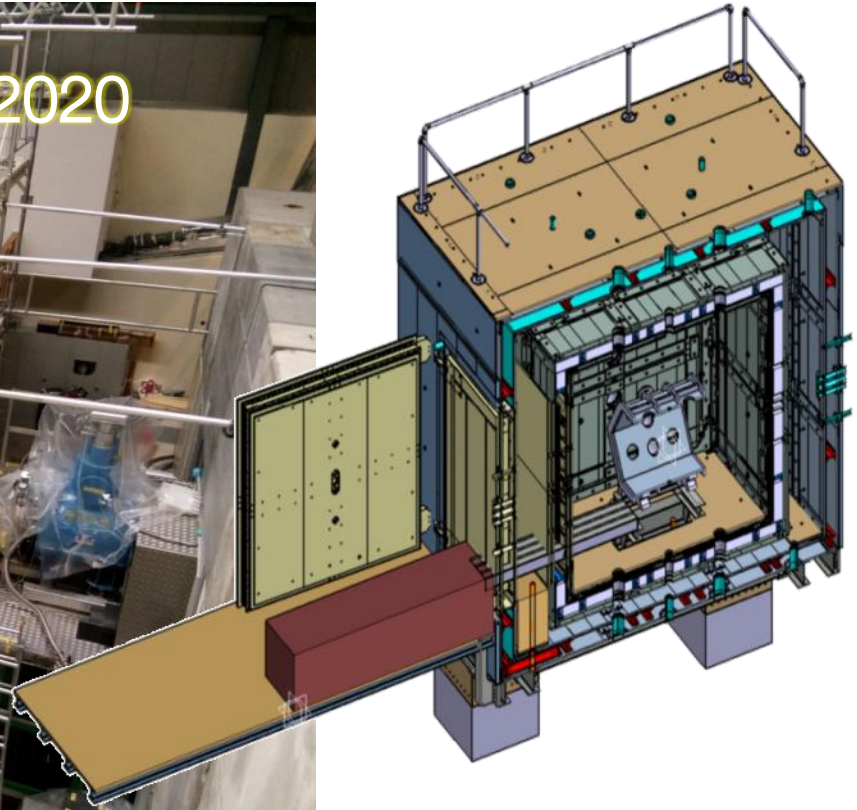
$$\mathcal{L}_{\rm int} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \sum_{f=n,p,e} \frac{C_f}{2f_a}\partial_\mu a\ \bar{f}\gamma^\mu\gamma^5 f$$

Nick Ayres



Michal Rawlik

A new spectrometer 6-layer Mu



$$\sigma(d_n) \approx 1 \times 10^{-27}$$

The collaboration

- 15 Institutions
- 7 Countries
- 48 Members
- 14 PhD students

Summary

- The search for an nEDM is an attractive complementary path for discover of new physics
- Many groups worldwide compete for the next most sensitive nEDM experiment
- The nEDM@PSI collaboration has taken sufficient data for a new result
- Possible un-blinding of the blind analysis still in 2018
- The same data was used for search for an oscillating nEDM, setting first limits on a coupling of the neutron to axions.

Thank you for your attention.

Comsmological limits on axion plot

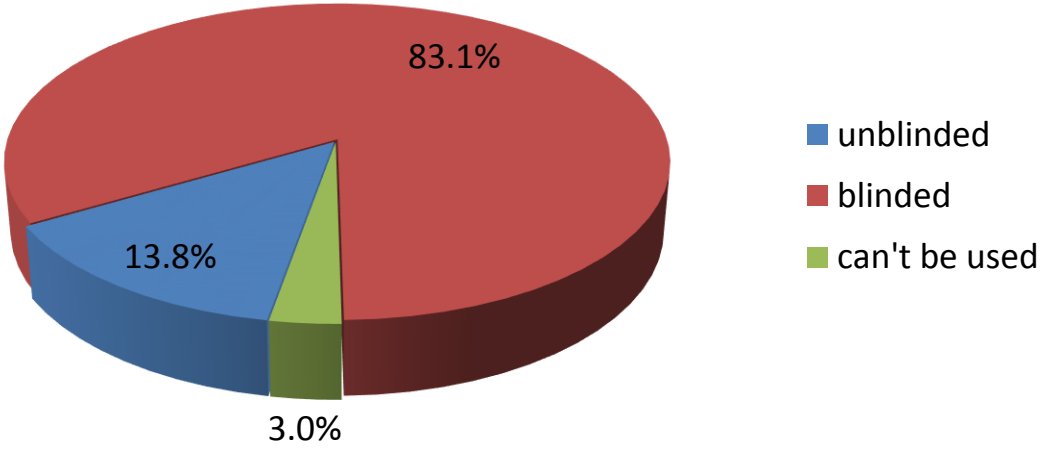
We show that Big Bang Nucleosynthesis (BBN) significantly constrains axion-like dark matter. The axion acts like an oscillating QCD θ angle that redshifts in the early Universe, increasing the neutron–proton mass difference at neutron freeze-out. An axion-like particle that couples too strongly to QCD results in the underproduction of ^{4}He during BBN and is thus excluded. The BBN bound overlaps with much of the parameter space that would be covered by proposed searches for a time-varying neutron EDM. The QCD axion does not couple strongly enough to affect BBN.

The supernova bound arises, as too strong coupling would result in lots of axions produced in supernovae which, in turn, would cause it to cool faster than observed.

The "Galaxies" bound is dashed. If axions make up all of the dark matter, they need to be heavier than this so that they can reproduce observed distribution of dark matter (rotational curves). If they are only a part of dark matter, they can be lighter.

Overview of the data

2.5% Issues which do not allow to use all data
(no HV reversal, too short runs,…)



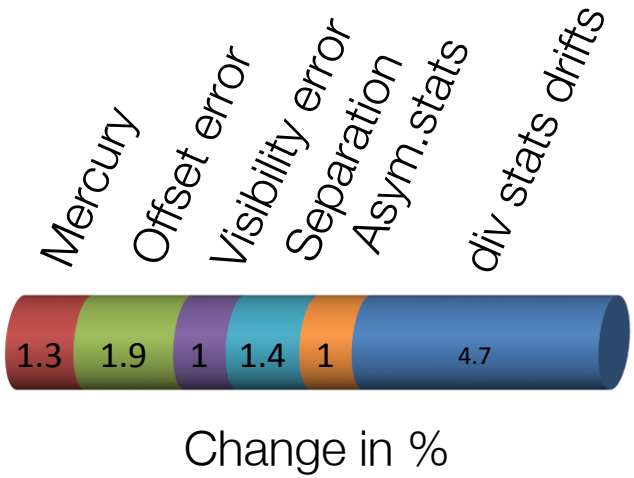
A total of 54333 cycles to analyze

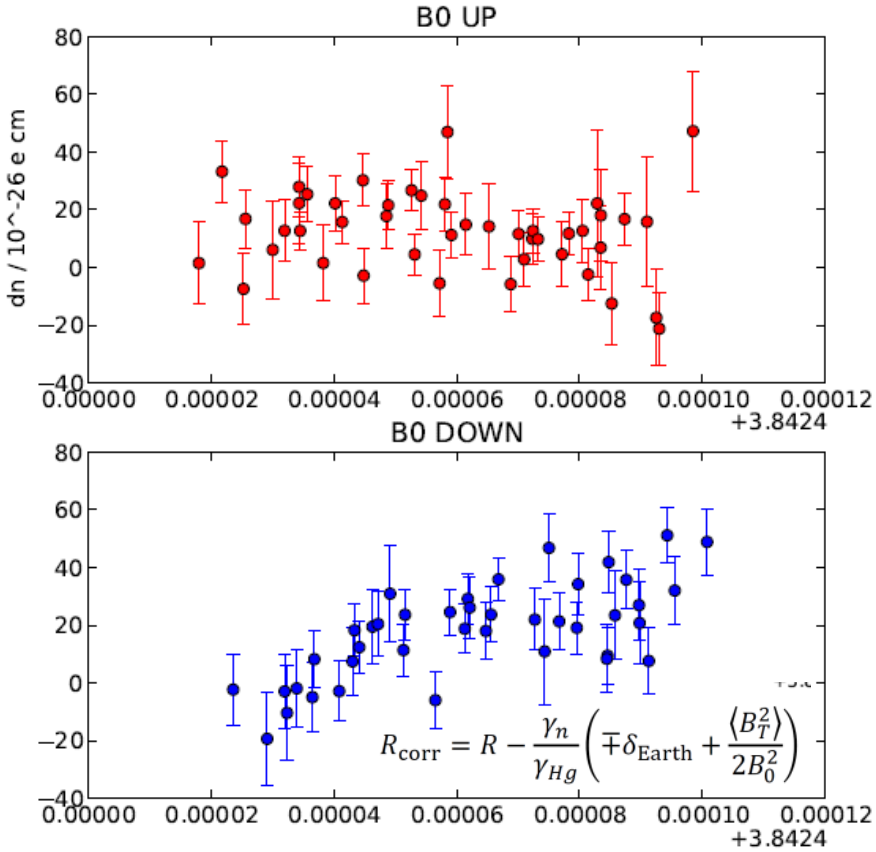
Crossing point analysis

$$d_\times = (14.96 \pm 1.12) \times 10^{-26} e \text{ cm}$$

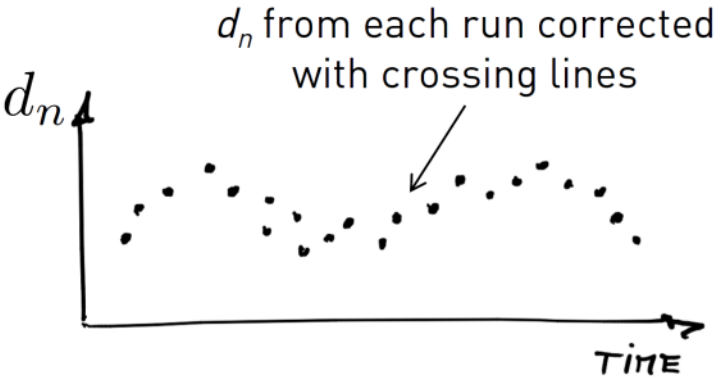
$$R_0 = 3.8424521(28)$$

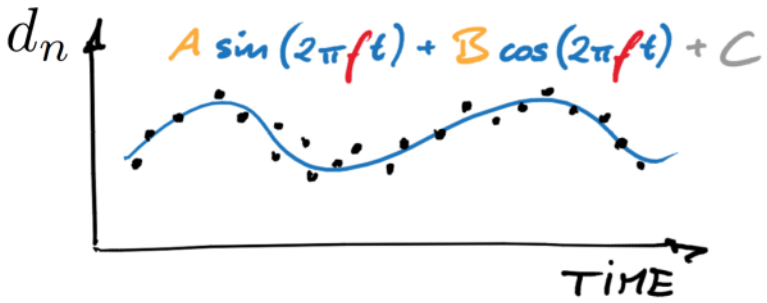
$$\chi^2/NDF = 109/86$$

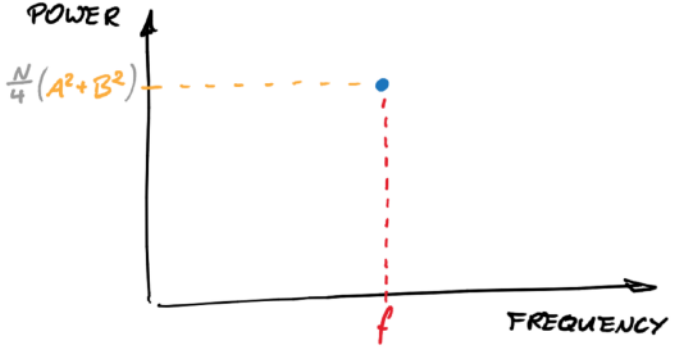


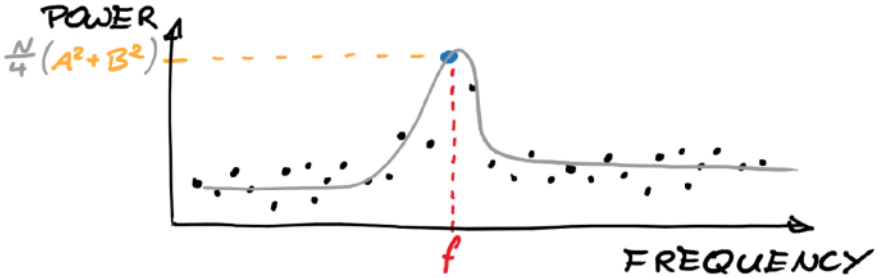


Least square spectral analysis

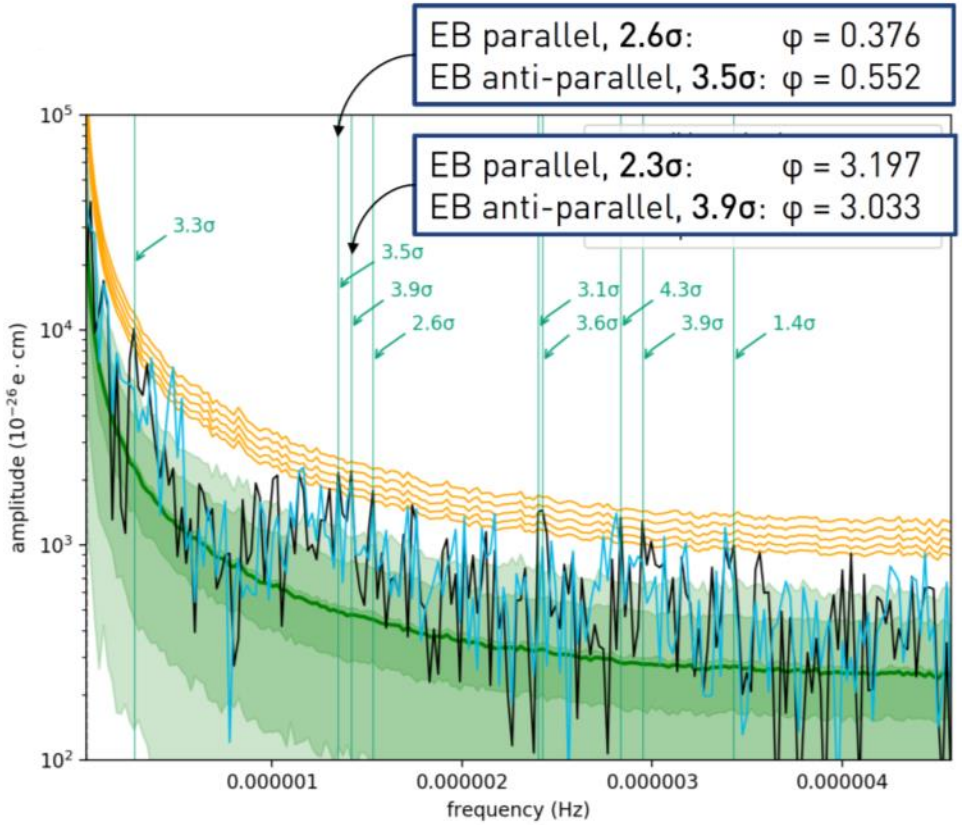








Highest peaks



Three "data sets":

- $E = 0$
- $E \uparrow\uparrow B$
- $E \nparallel B$
  (parallel but pointing in different directions)

Requirements for signal:

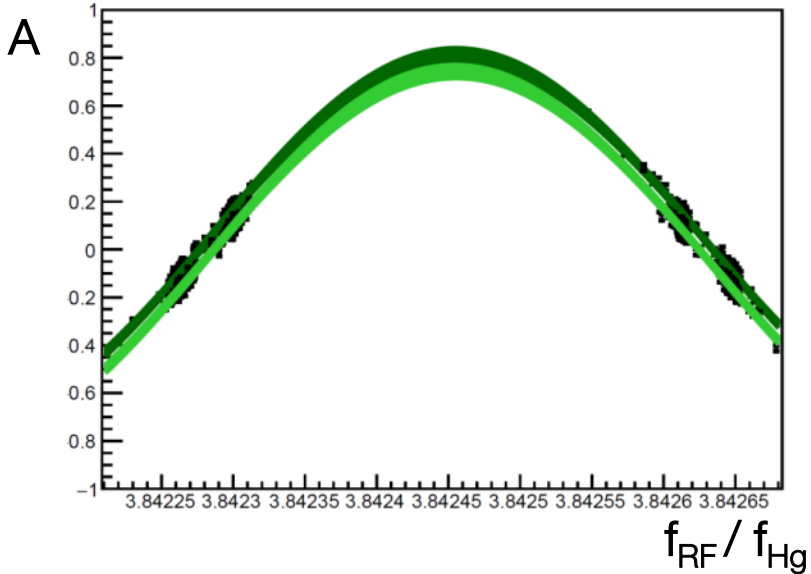
- Five sigma in both $E \neq 0$ and phase shift of π between both set
- No signal in $E = 0$

Ramsey fit procedure

- Split sequence in sub-sequence:

  E-field (+ - - +) pattern

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



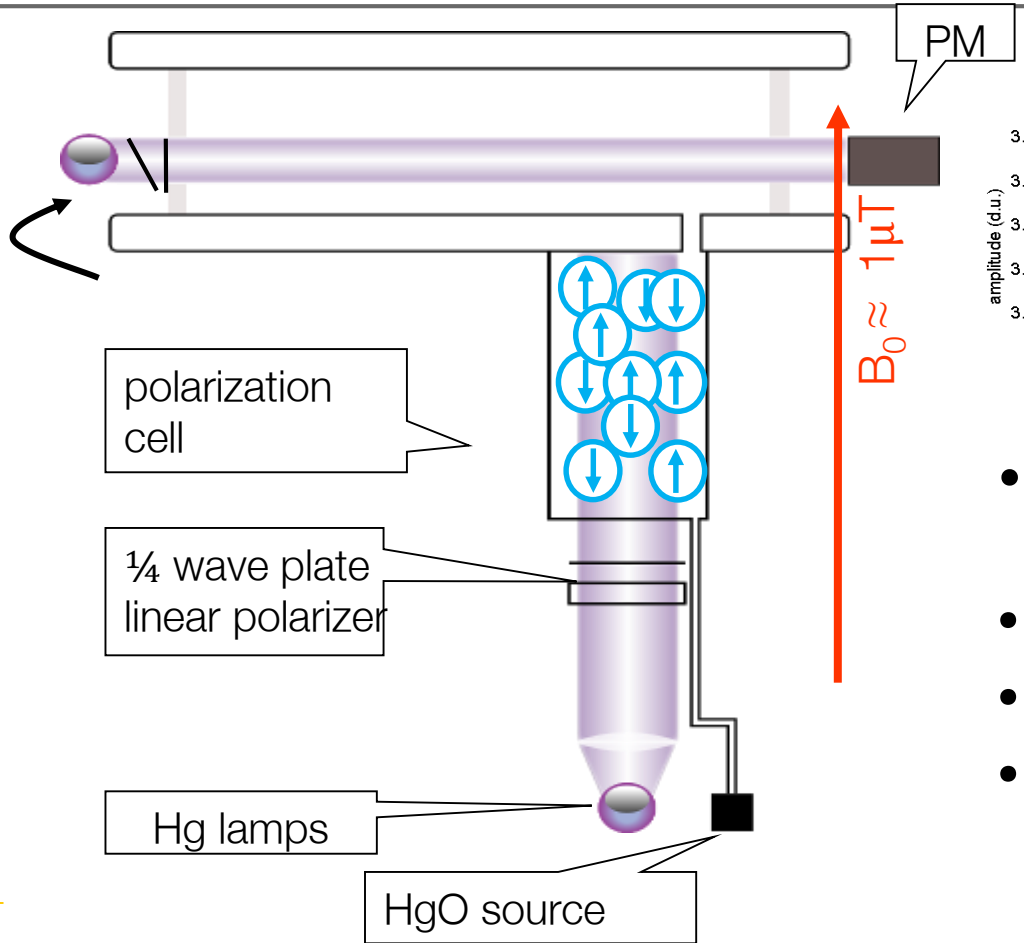
Ramsey fit with the asymmetry :

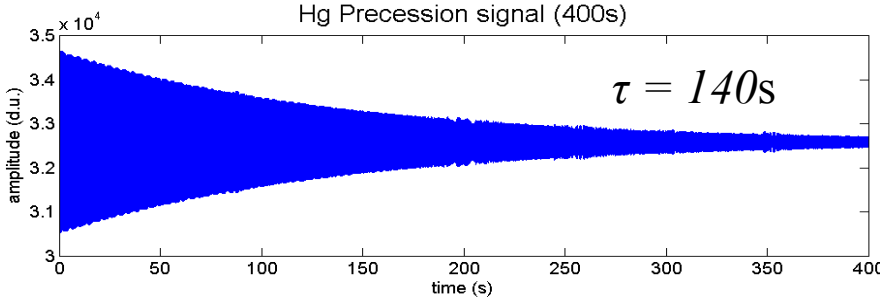
$$A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

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

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

Mercury co-magnetometer

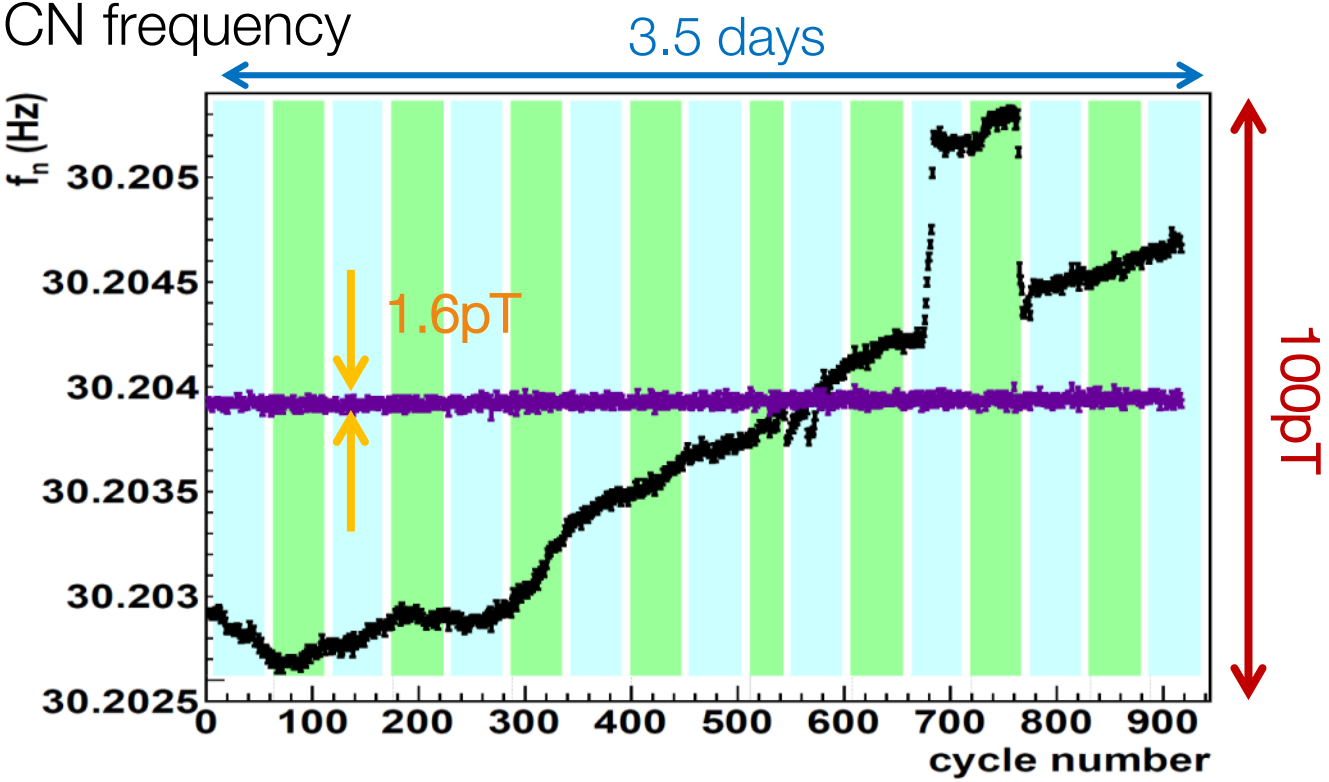




- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with 90s)
- $s/n > 1000$

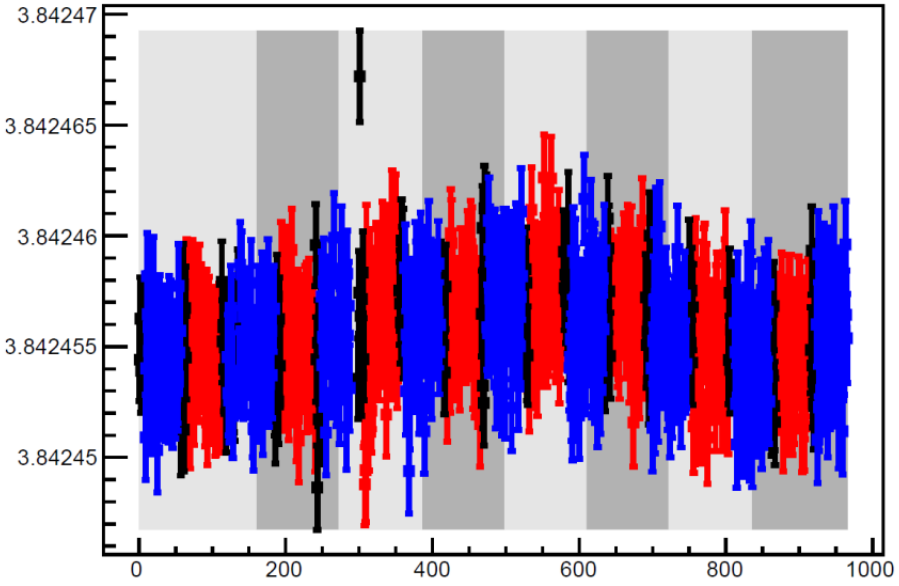
Hg co-magnetometer

Extract B field from Larmor frequency and correct UCN frequency



EDM and R-calculation

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



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

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

Earth rotation frequency correction :

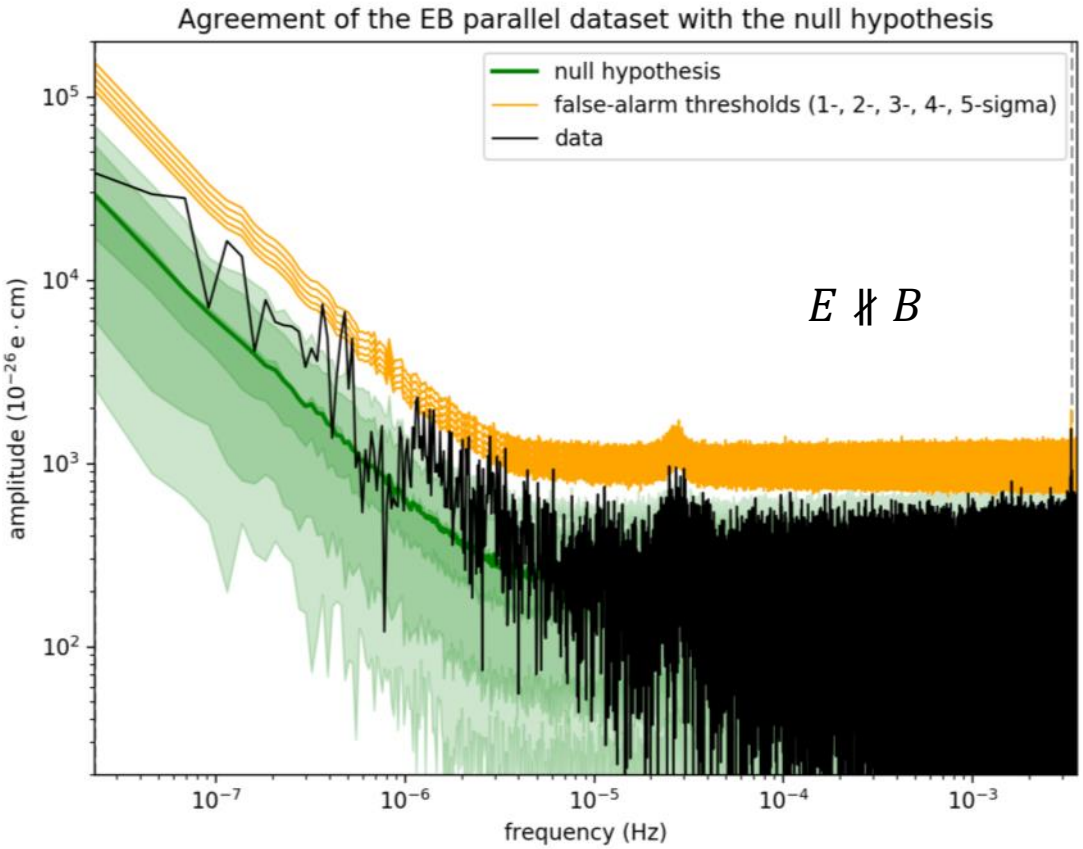
$$R^{\mathrm{corr}} = R(1 \pm \delta_{\mathrm{earth}}) = < R > (1 + \delta_{\mathrm{gz}})$$

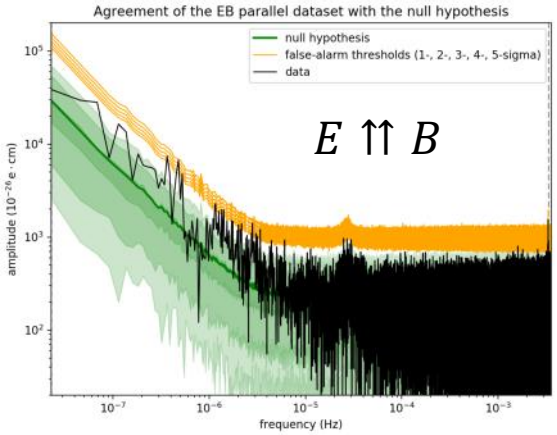
$$(R_a - 1)^{\mathrm{corr}} = \frac{R}{< R >} - 1 \pm \delta_{\mathrm{earth}} = \delta_{\mathrm{gz}}$$

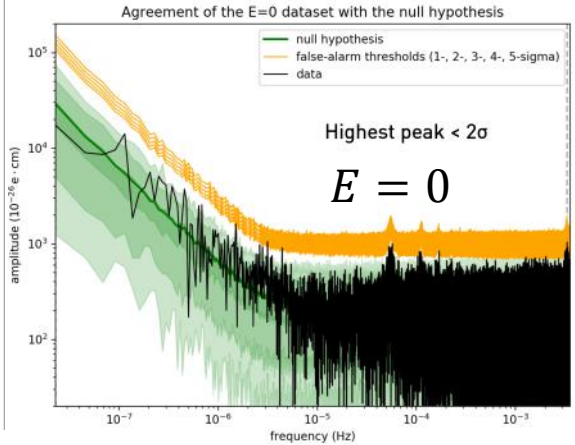
B-gradient fluctuation correction :

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

Three Periodograms

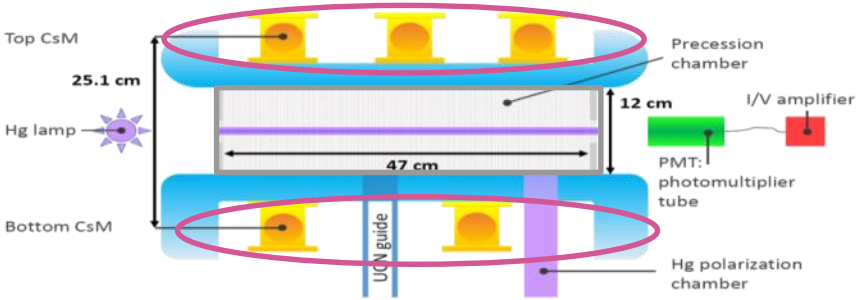




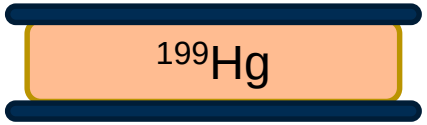


Frequency ratio $R = f_n/f_{Hg}$

- Center of mass offset
- Non-adiabaticity



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



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

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

+ 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

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

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

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

Afach et al., EPJD(2015)69:225

nEDM strategy

Measure nEDM as function of B-Field gradient

Blinding

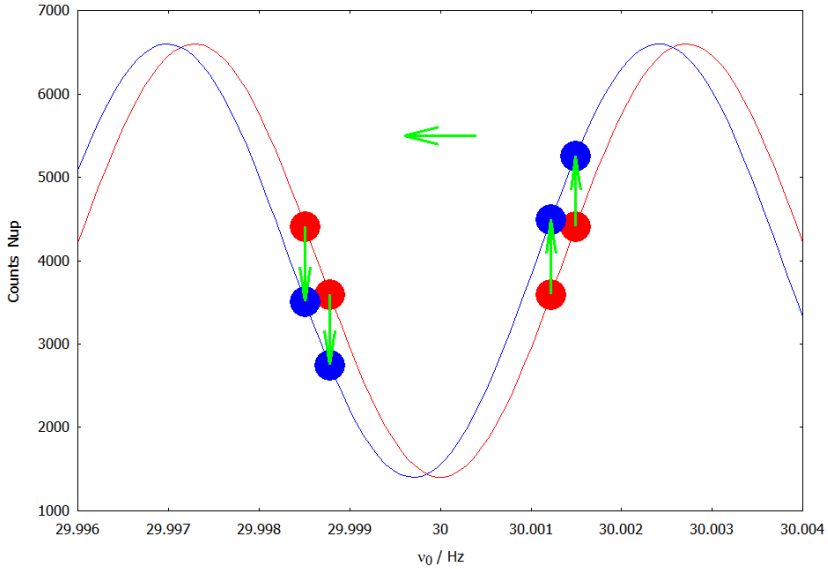
How?

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

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

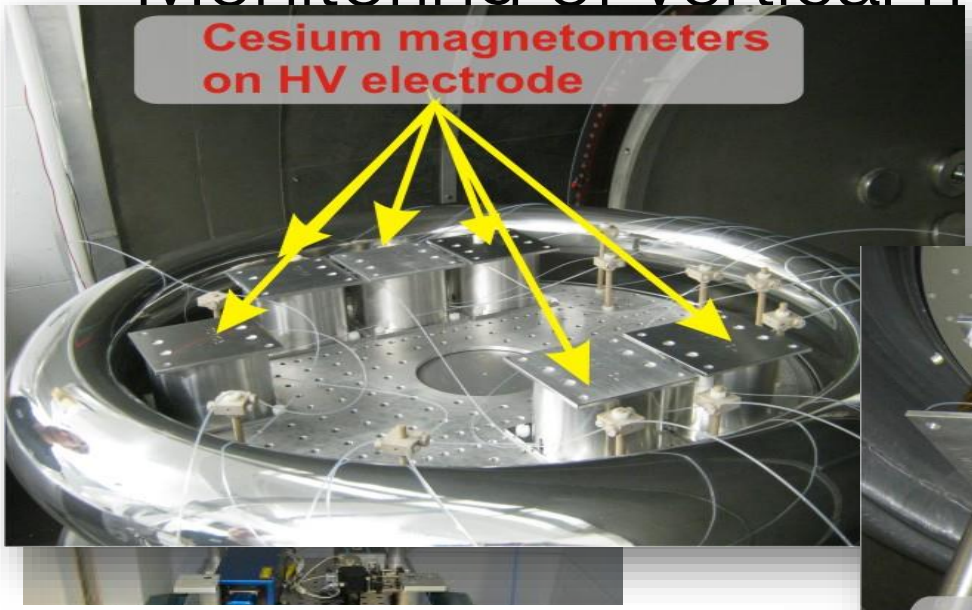
with $$\phi_i = \frac{(\nu_i - \nu_0)}{\Delta\nu}\pi$$

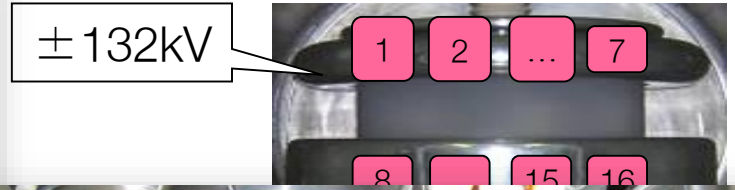
- Keep un-blinded data in a safe place (encrypted)

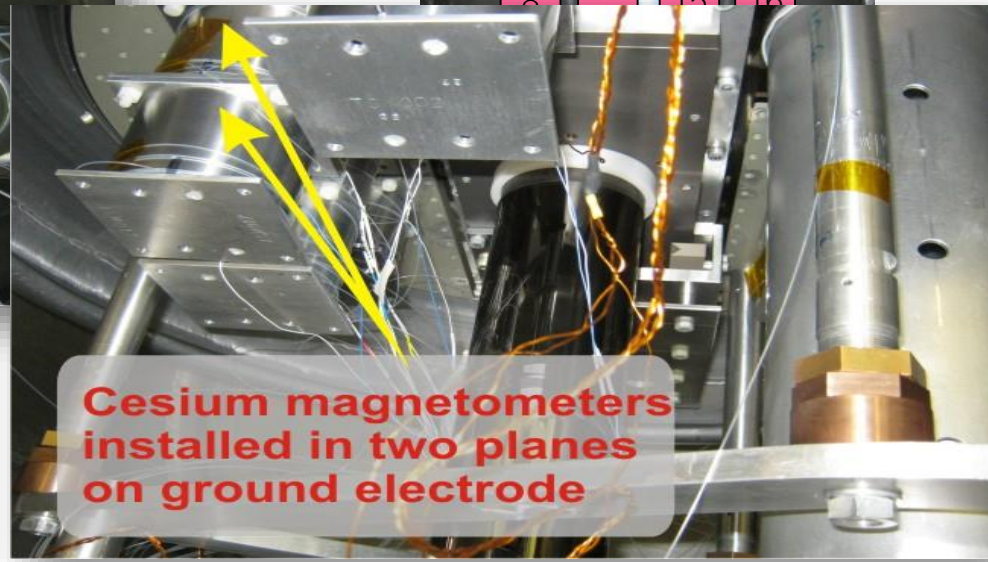


Cesium gradiometer

Monitoring of vertical magnetic gradients

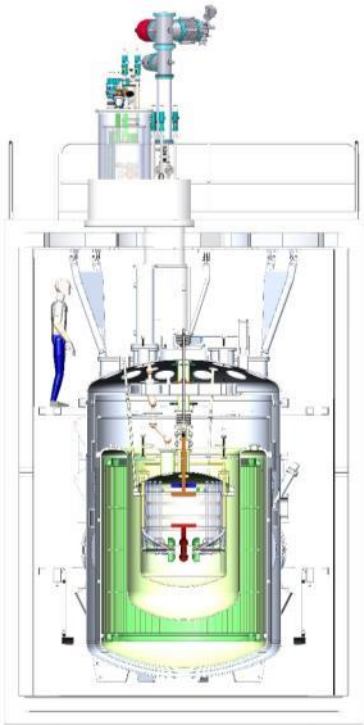






Current accuracy:

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



Critical Component Demonstration (1/14-12/17) nearing completion

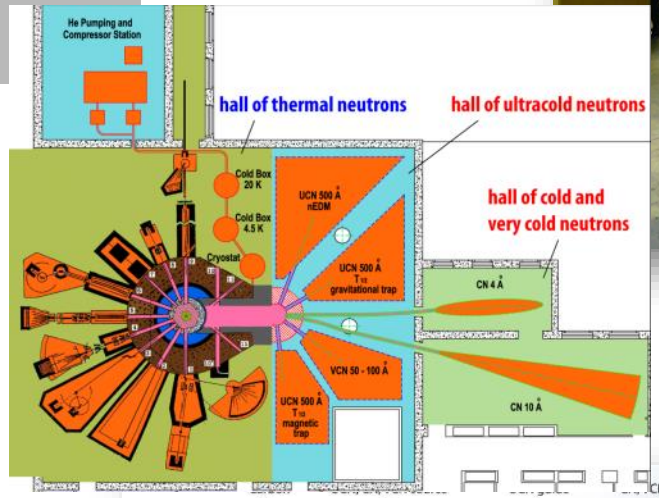
- > 75kV/cm achieved in mid-scale HV system
  - With Cu-coated composite electrodes
  - With closed measurement cell
- ^{3}He transport (phonon heat-flush) demonstrated in large-scale
- Non-magnetic dilution fridge nearly complete
- B-field uniformity (3 ppm/cm in full-scale) achieved in 1/3-scale cryogenic prototype & dressed spin design advanced
- Noise levels sufficient in SQUID system prototype
- 1800s UCN storage time measured in cryogenic cell
- > 18 photo-electrons equivalent observed in cryogenic light collection system with LHe & TBP (need 6 PE at least)

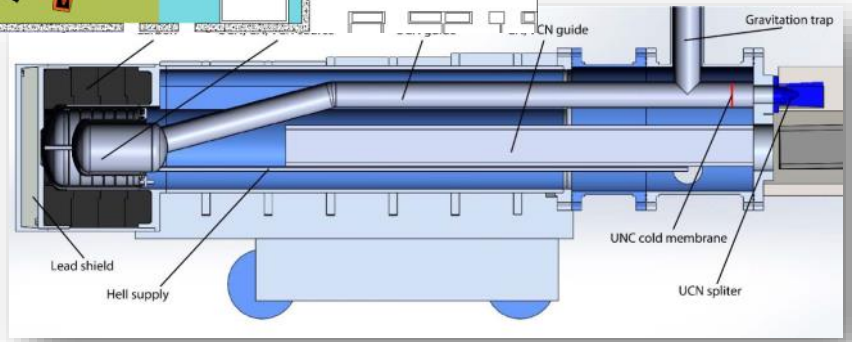
Full-scale operation in 2022

courtesy: Brad Filippone

PNPI UCN source at WWR-M reactor

WWR-M reactor

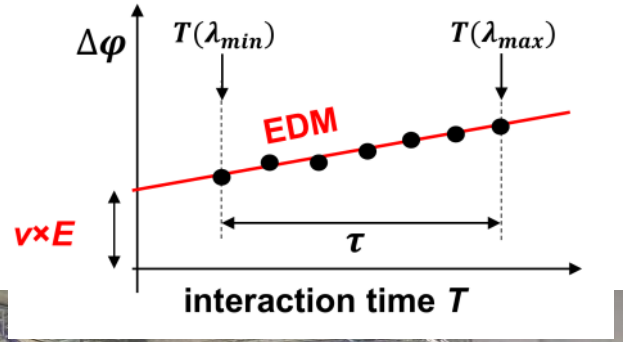




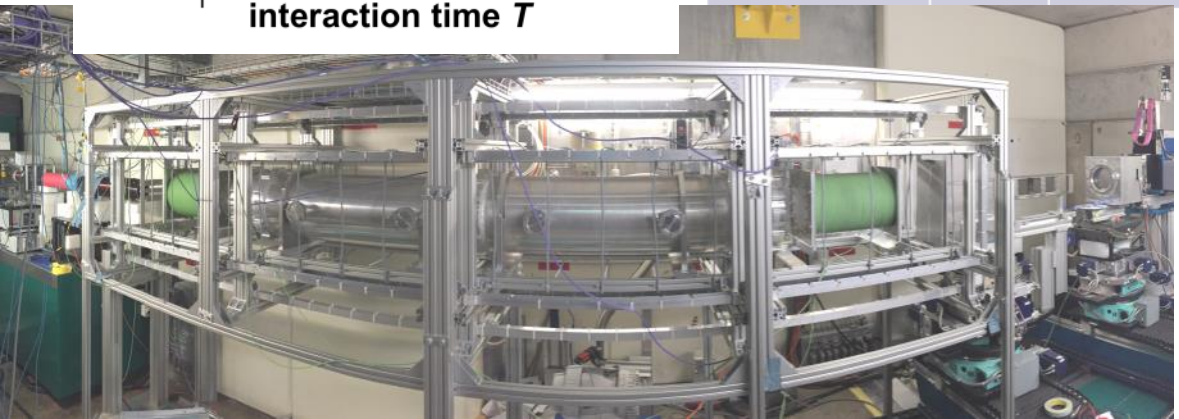
- UCN density >$1 \times 10^5\ \mathrm{cm}^{-3}$
- All hardware exists
- Necessary cooling power test succesfull
- Unclear whether and when WWR-M will get permission to operate

ESS pulsed beam experiment

$$\Delta\omega \propto d_n E + \mu_n E \frac{v}{c^2}\sin(\alpha)$$
$$\Leftrightarrow$$
$$\Delta\varphi = \Delta\omega T \propto d_n E T + \mu_n E \frac{L}{c^2}\sin(\alpha)$$



	T	η	E [kV/cm]	N	M (no. cycles)	σ / day [10^{-26} ecm]
@ PF1b/ILL *	8 ms	0.75	50	2 x 2 MHz	1	~ 800
@ ESS	90 ms	0.75	100	2 x 20 - 200 MHz	1	3 - 10
ILL/RAL /Sussex **	130 s	0.45	8.3	14000 per cycle	360	30



Use neutron source's intrinsic pulses
Fixed installation
Lenght: 50m
$\mathrm{d}N/\mathrm{d}t > 100\ \mathrm{MHz}$

courtesy: F. Piegsa