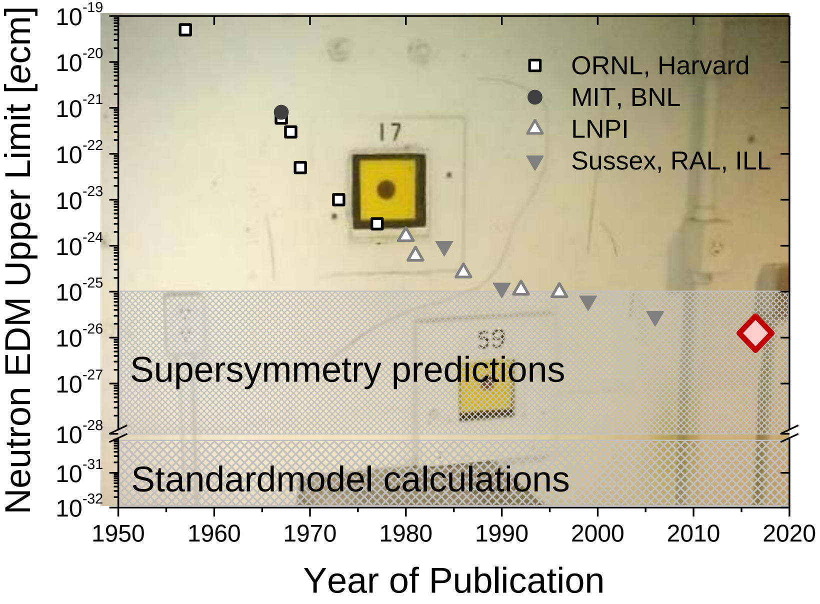
PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

P. Schmidt-Wellenburg, Solvay workshop 29.11-01.12.12, Brussels

Overview and status of neutron EDM experiments

A brief history of nEDM searches



"n-EDM has killed more theories than any other single experiment"

J.M. Pendlebury
1936-2015

First

Smith, Purcell, Ramsey

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

PR 108 (1957) 120

~ 50 years

Last

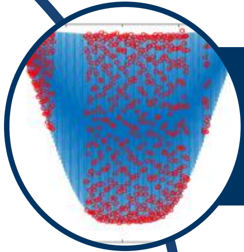
RAL-Sussex-ILL

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

C.Baker et al. PRL(2006) 131801

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

Outline



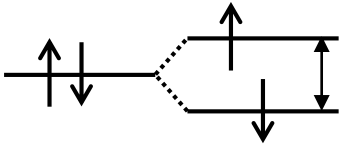
Ultracold neutrons and Ramsey's technique

Worldwide competition

Searches for static and oscillating nEDM at PSI

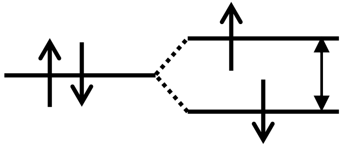
Modified Larmor Frequency

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



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

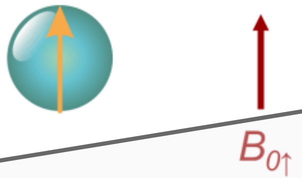
$$\hbar\omega_{\uparrow\uparrow} = \hbar(\omega_L + \omega_{edm}) = 2(\mu_n B + d_n E)$$
$$\hbar\omega_{\uparrow\downarrow} = \hbar(\omega_L - \omega_{edm}) = 2(\mu_n B - d_n E)$$

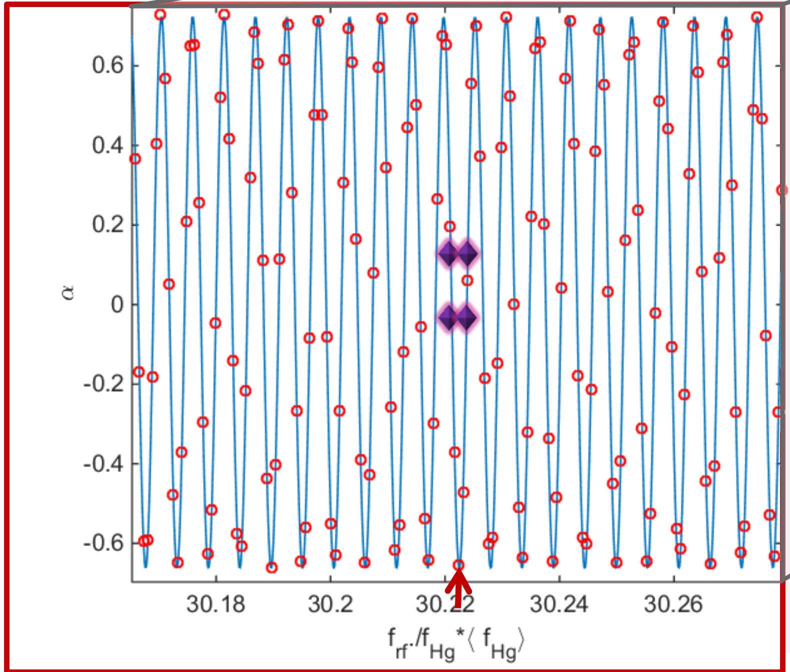
$$\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) = 4\ d_n E$$

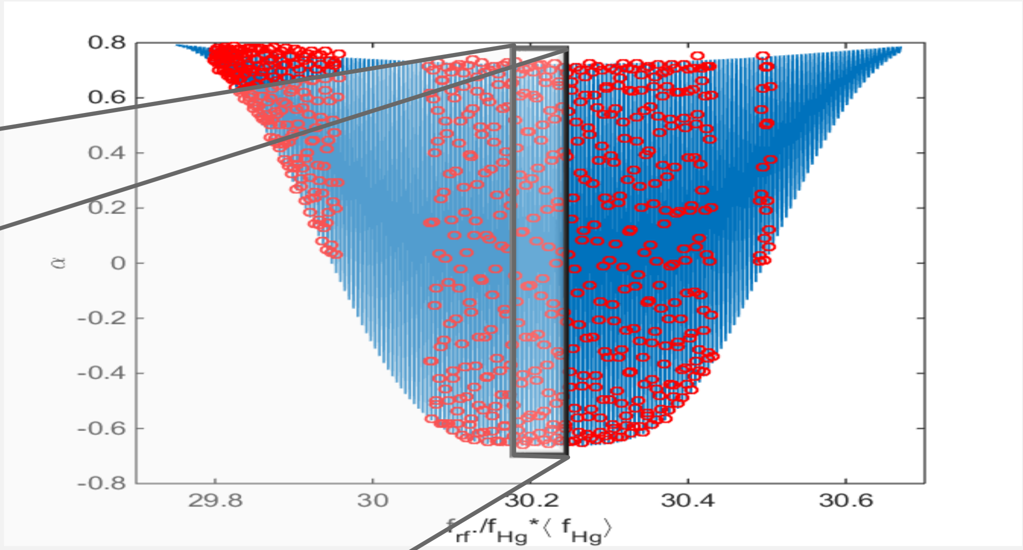
HOW ???

The Ramsey technique

Spin "down" neutron...







Sensitivity:

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

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

The beam searches

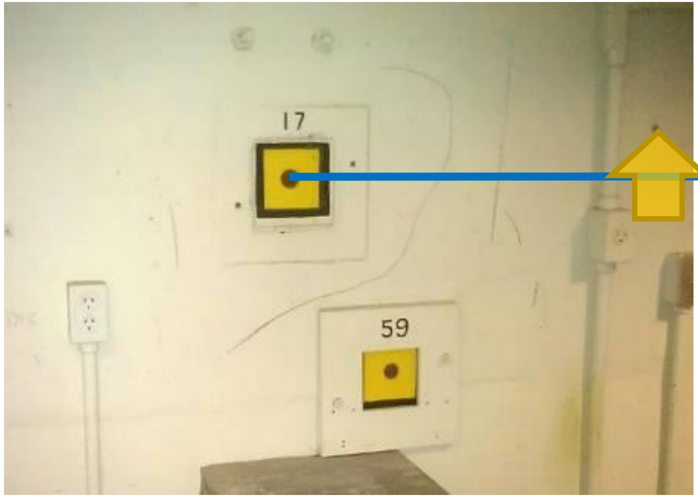
$$\delta(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{\dot N}}\frac{1}{\sqrt{t}}$$

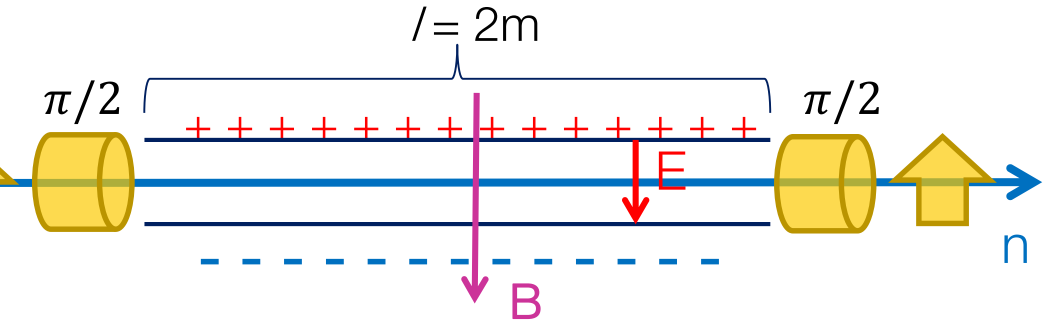
$$T = \frac{l}{v} \approx 0.015\mathrm{s};\ \alpha > 0.9;\ E = \frac{100\mathrm{kV}}{\mathrm{cm}};\ \dot N = 1\times10^{6}\mathrm{s}^{-1}$$

$$=8.7\times10^{-22}\frac{e\mathrm{cm}}{\sqrt{\mathrm{Hz}}}\frac{1}{\sqrt{t}}$$

1 day

$$\sigma = 1\times10^{-24}e\mathrm{cm}$$





Dominant systematic effect:

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

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

final result: $\sigma(d_\mathbf{n}) = 1.5\times10^{-24}e\mathrm{cm}$
due to misalignment of 0.1 mrad

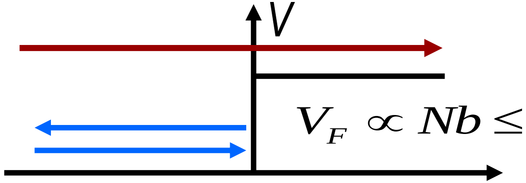
Ultracold neutrons (UCN)

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

$$\boxed{\sigma(d_\mathrm{n}) \propto \frac{1}{\sqrt{NT^{3/2}}}}$$

⇒

Storable neutrons (UCN)



$$V_F \propto Nb \leq 350\,\mathrm{neV}$$

Storage properties are material dependent

Gravity
102 neV/m

Strong
V_F

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

Superthermal UCN production

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

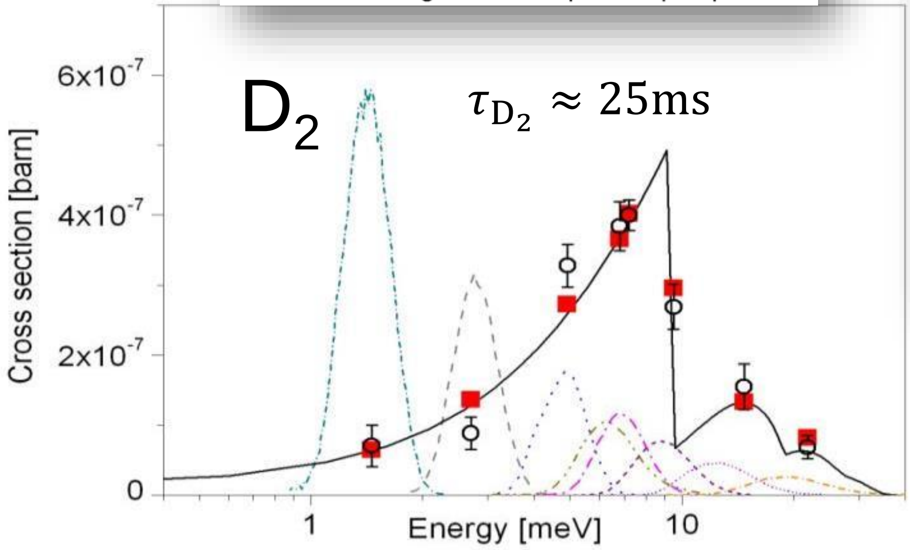
$$\rho = \tau \int \frac{d\Phi}{d\lambda}\Sigma(\lambda)d\lambda$$

macro cross section

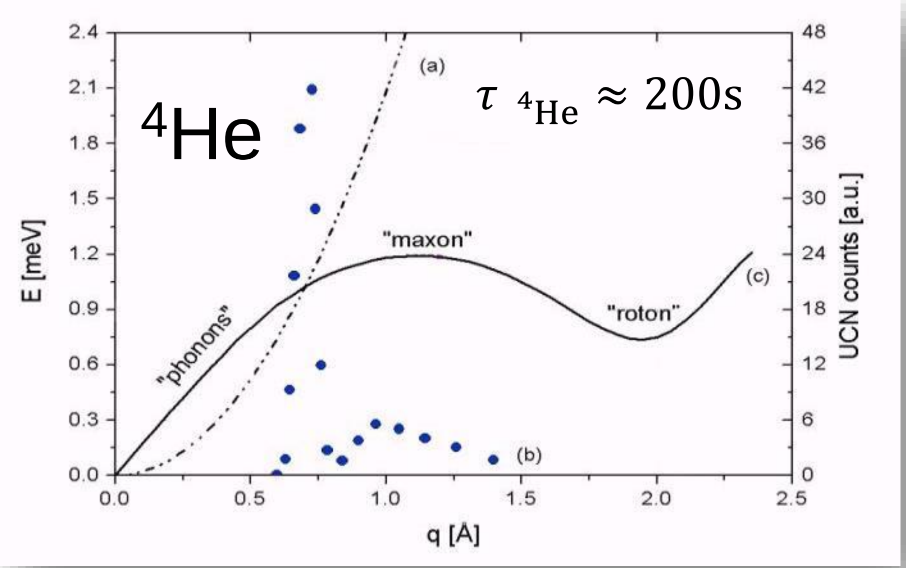
differential flux

UCN lifetime in medium

Cooling machine = phonon pump



F. Atchison et al., PRL99(2007)262502



R. Golub & J.M. Pendlebury, PLA62(1977)338
C.A. Baker et al., PLA308(2003)67
PSW, J. Bossy *et al.*,PRC92(2015)024002

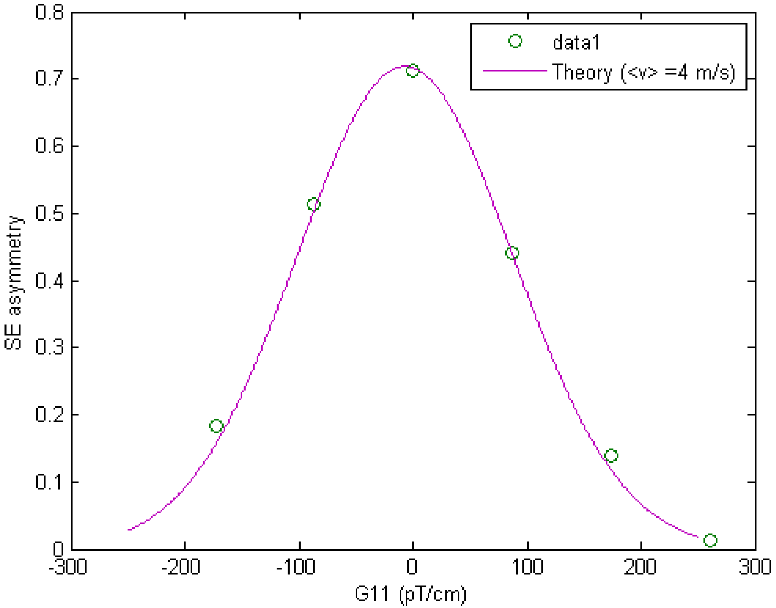
Depolarization

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

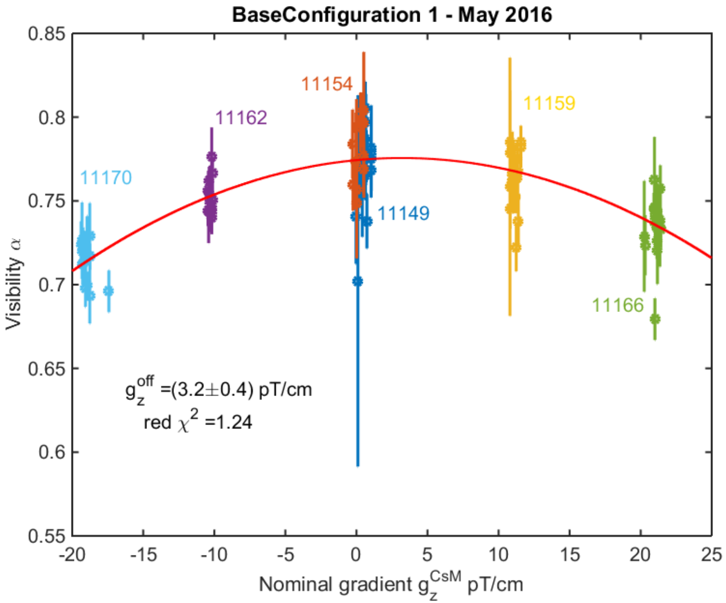
$$\Gamma_2(\epsilon) = a\frac{\gamma_\mathrm{n}^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

$$\alpha(T) = e^{-\Gamma_2 T} - \frac{\gamma_n^2 g_z^2 T^2}{2}\cdot\langle dh^2\rangle_\mathrm{eff}$$

Intrinsic depolarization



Gravitational depolarization

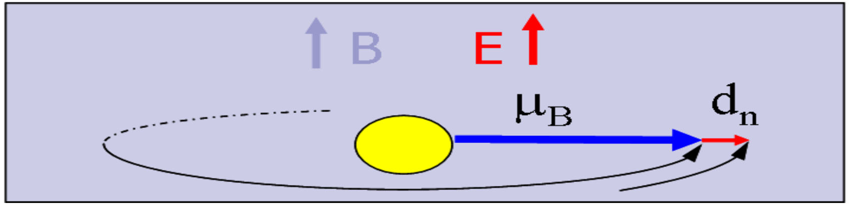


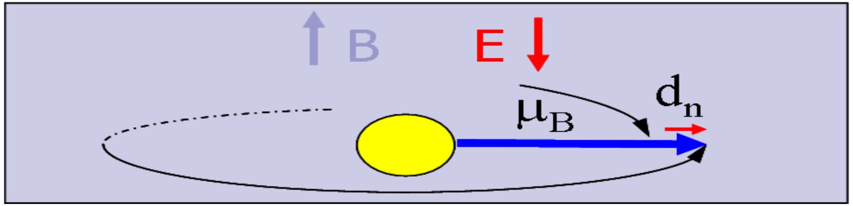
Afach *et al.*,PRD92(2015)052008

Afach *et al.*,PRL115(2015)162502

The measurement technique

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



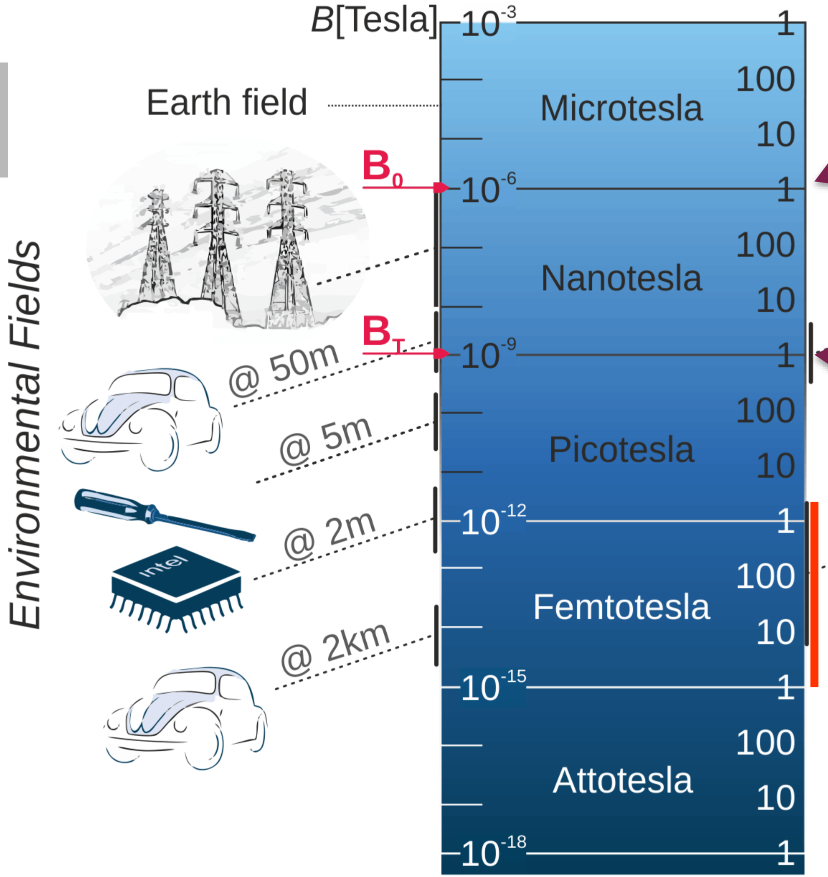


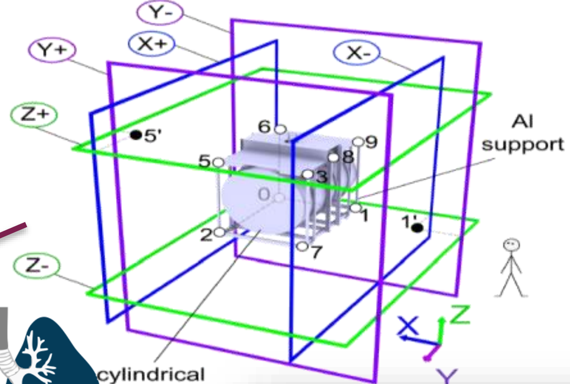
$$\hbar\Delta\omega = 2d_{\mathrm{n}}\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_{\mathrm{n}}\boxed{\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}$$

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

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

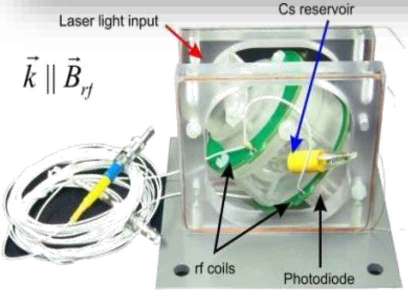
Magnetic fields



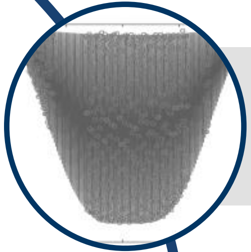


$\delta B < 100\mathrm{fT}$

optical pumped magnetometers (CsM/HgM/XeM…)



Outline



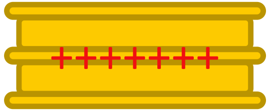
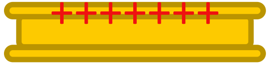
Ultracold neutrons and Ramsey's technique

Worldwide competition

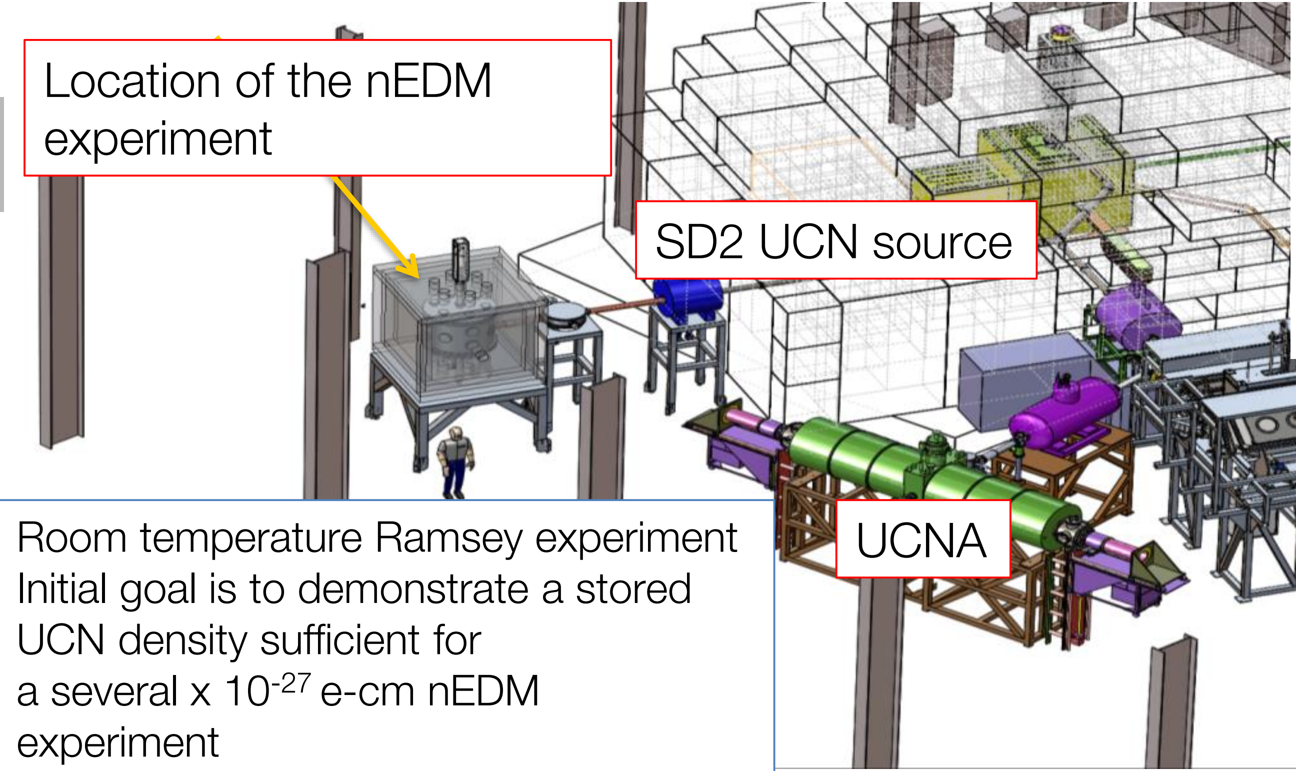
Searches for static and oscillating nEDM at PSI

Principal approaches

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

	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 TRIUMF(2) 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

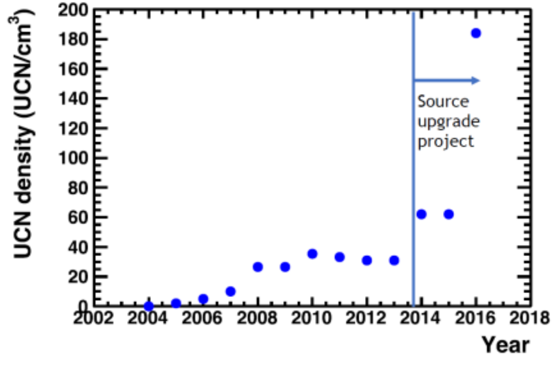


Location of the nEDM experiment

SD2 UCN source

UCNA

UCNτ



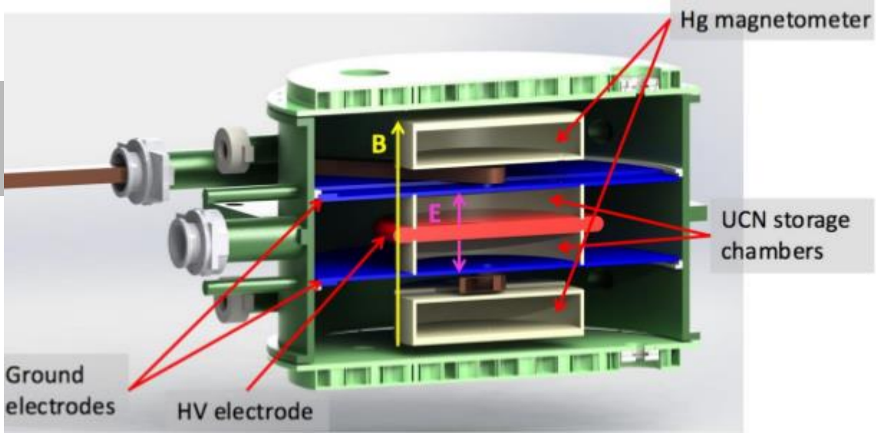
- Room temperature Ramsey experiment
- Initial goal is to demonstrate a stored UCN density sufficient for a several x 10^{-27} e-cm nEDM experiment
- UCN upgrade concluded
- First measurements with Ramsey cell

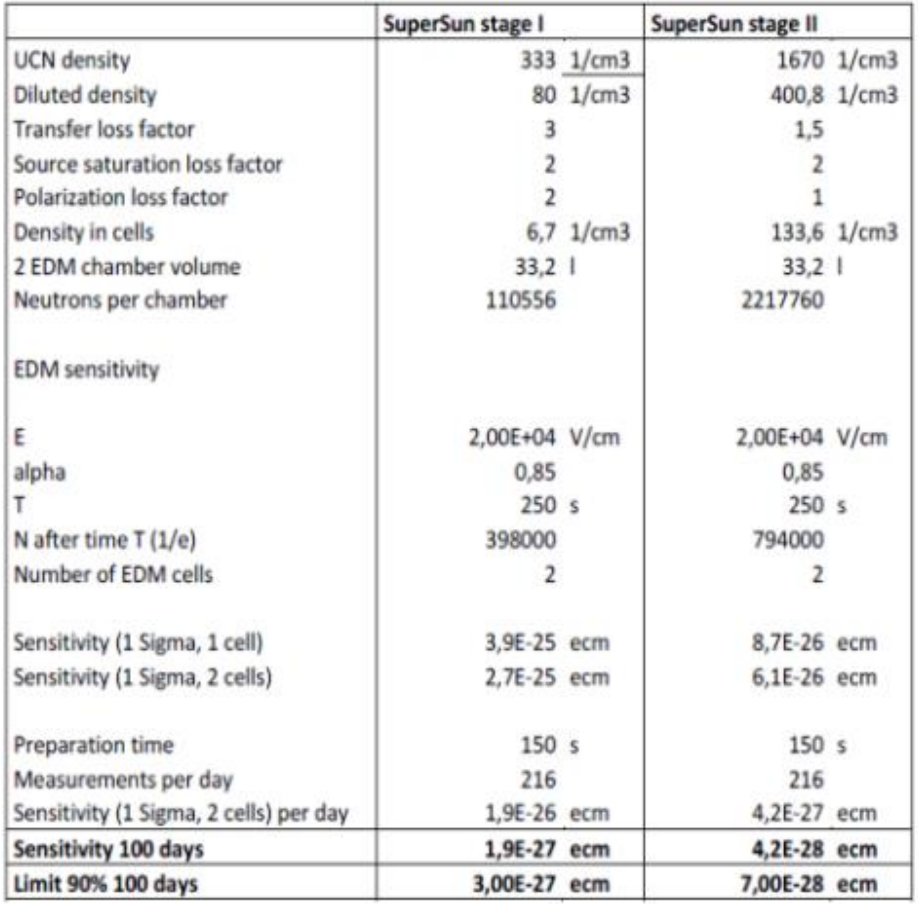
LANL collaboration:

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

courtesy: Ito Takeyasu

ILL / TUM effort





	SuperSun stage I	SuperSun stage II
UCN density	333 1/cm3	1670 1/cm3
Diluted density	80 1/cm3	400,8 1/cm3
Transfer loss factor	3	1,5
Source saturation loss factor	2	2
Polarization loss factor	2	1
Density in cells	6,7 1/cm3	133,6 1/cm3
2 EDM chamber volume	33,2 l	33,2 l
Neutrons per chamber	110556	2217760
EDM sensitivity		
E	2,00E+04 V/cm	2,00E+04 V/cm
alpha	0,85	0,85
T	250 s	250 s
N after time T (1/e)	398000	794000
Number of EDM cells	2	2
Sensitivity (1 Sigma, 1 cell)	3,9E-25 ecm	8,7E-26 ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25 ecm	6,1E-26 ecm
Preparation time	150 s	150 s
Measurements per day	216	216
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26 ecm	4,2E-27 ecm
Sensitivity 100 days	**1,9E-27 ecm**	**4,2E-28 ecm**
Limit 90% 100 days	**3,00E-27 ecm**	**7,00E-28 ecm**

ILL/TUM effort:

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

courtesy: Skyler Degenkolb

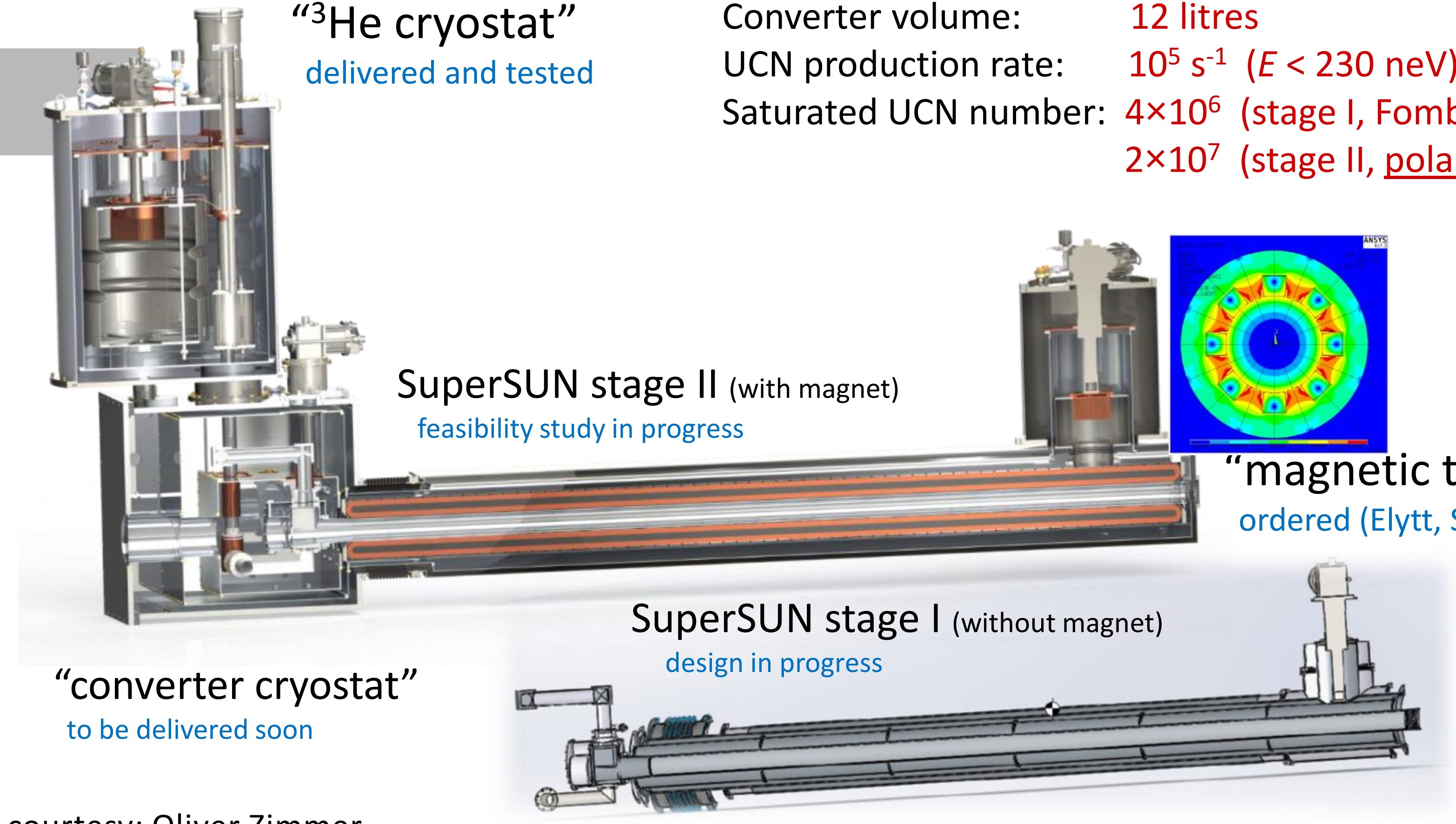
ILL SuperSun

Converter volume: 12 litres

UCN production rate: $10^5\ s^{-1}$ ($E < 230$ neV)

Saturated UCN number: 4×10^6 (stage I, Fomblin spectrum)

2×10^7 (stage II, polarized, $E < 230$ neV)



“^{3}He cryostat”

delivered and tested

SuperSUN stage II (with magnet)

feasibility study in progress

“magnetic trap cryostat”

ordered (Elytt, Spain)

SuperSUN stage I (without magnet)

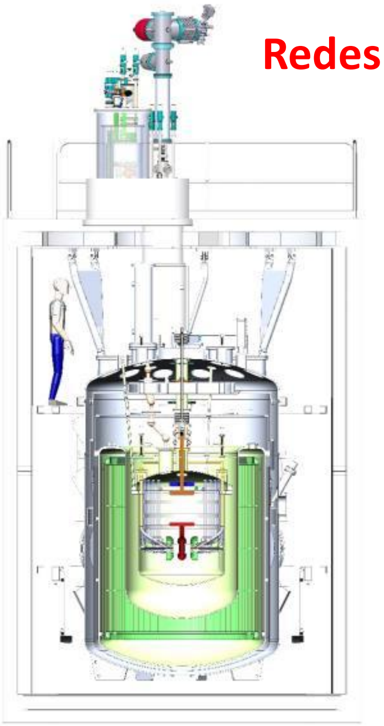
design in progress

“converter cryostat”

to be delivered soon

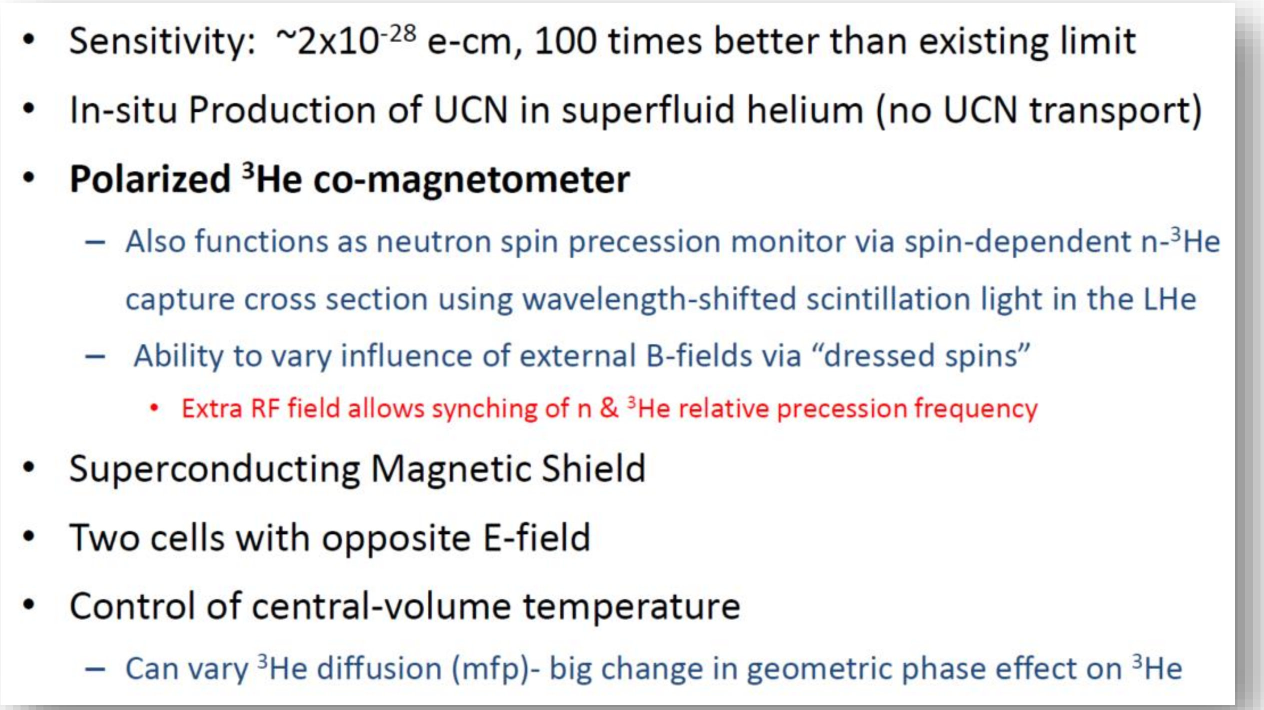
courtesy: Oliver Zimmer

nEDM @ SNS



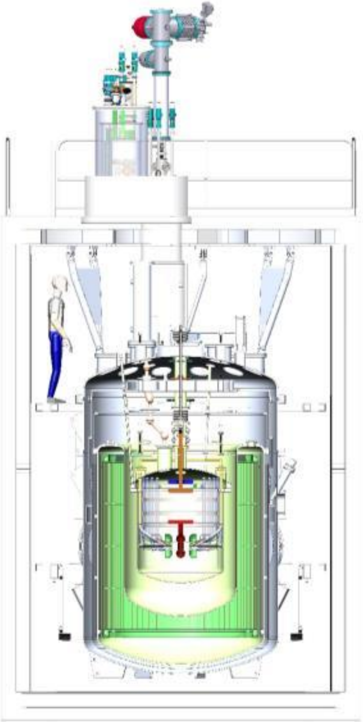
Redesign to reduce costs (7/17)

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



- Sensitivity: ~2x10^{-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

courtesy: Brad Filippone



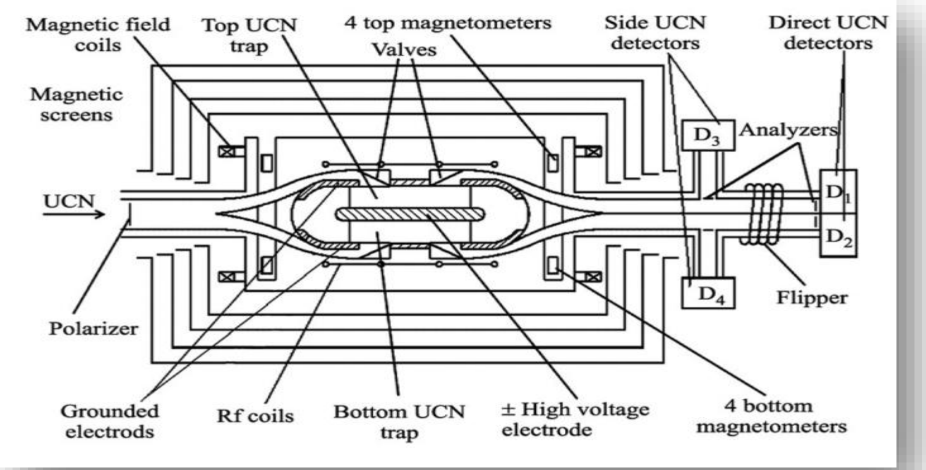
Critical Component Demonstration (1/14-12/17) nearing completion

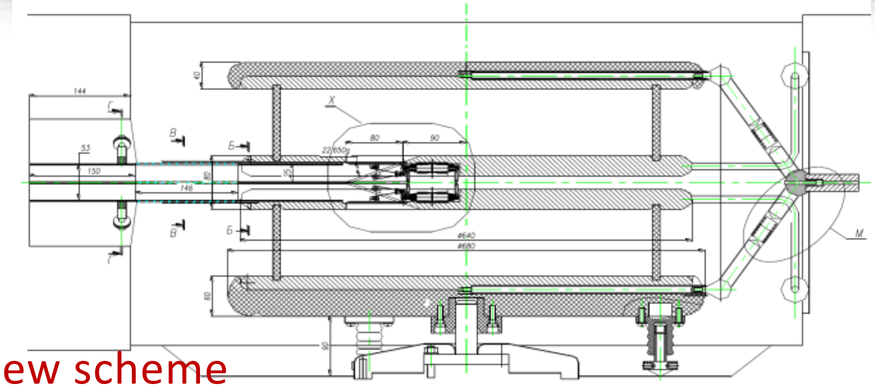
- > 75kV/cm achieved in mid-scale HV system
  - With Cu-coated composite electrodes
  - With closed measurement cell
- ^{3}He transport (phonon heat-flush) demonstrated in large-scale
- Non-magnetic dilution fridge nearly complete
- B-field uniformity (3 ppm/cm in full-scale) achieved in 1/3-scale cryogenic 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

nEDM @ PNPI (&ILL)





new scheme

Current: $d_n < 5.5 \times 10^{-26} e\text{cm}$

Improvement by factor 3
at new position and with new precession cell

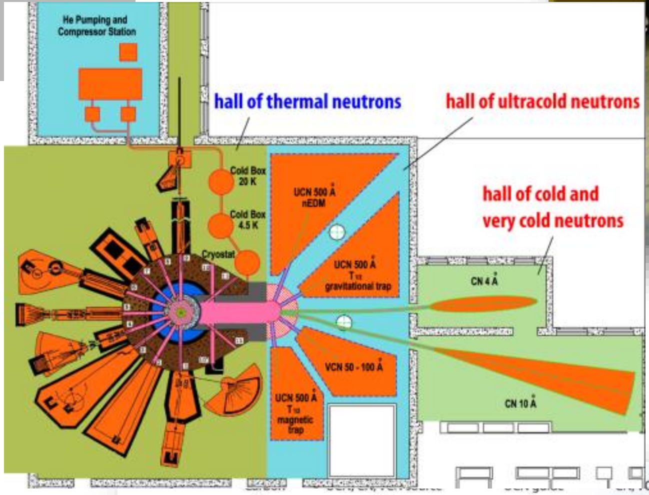
ILL 2020 : $d_n < 2 \times 10^{-26} e\text{cm}$

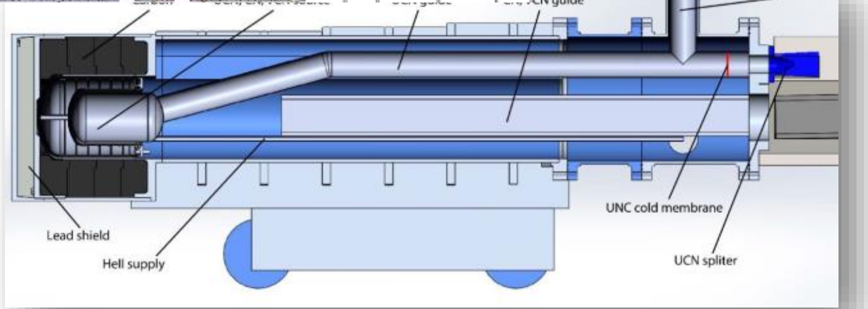
courtesy: Anatolii Serebrov

PNPI UCN source at WWR-M reactor

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

WWR-M reactor



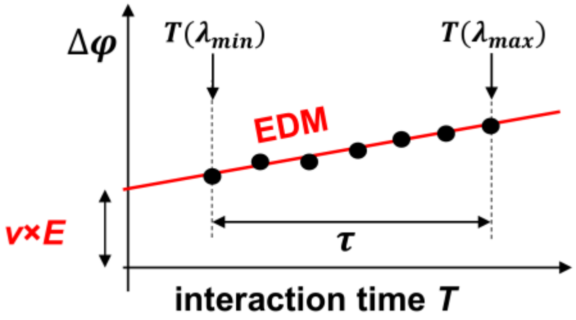


ESS pulsed beam experiment

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

$$\Leftrightarrow$$

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



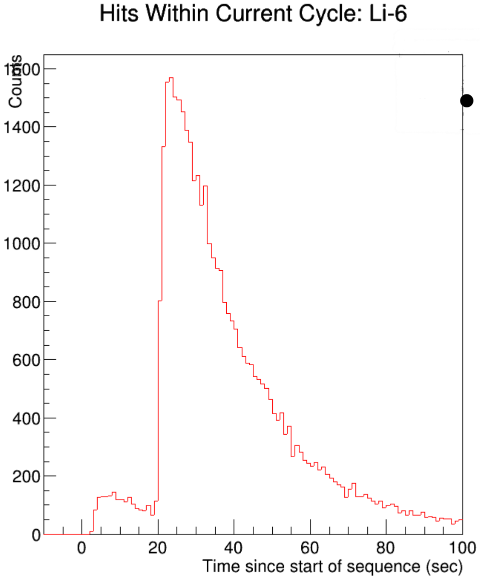
	T	*η*	*E* [kV/cm]	*N*	*M* (no. cycles)	*σ* / day [10^{-26} ecm]
@ PF1b/ILL *	8 ms	0.75	50	2 x 2 MHz	1	~ 800
@ ESS	90 ms	0.75	100	2 x 20 - 200 MHz	1	3 - 10
ILL/RAL /Sussex **	130 s	0.45	8.3	14000 per cycle	360	30

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

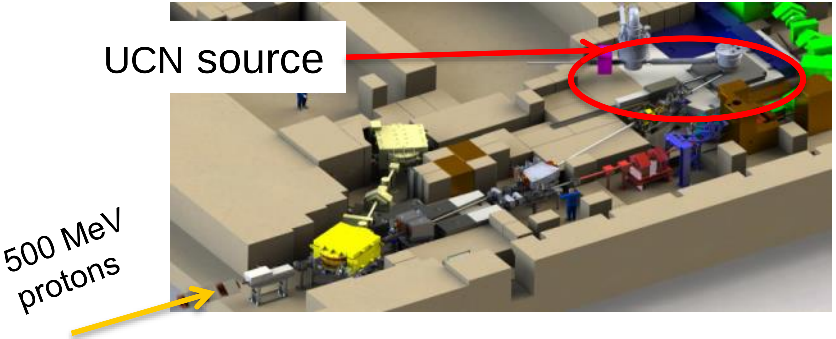
courtesy: F. Piegsa

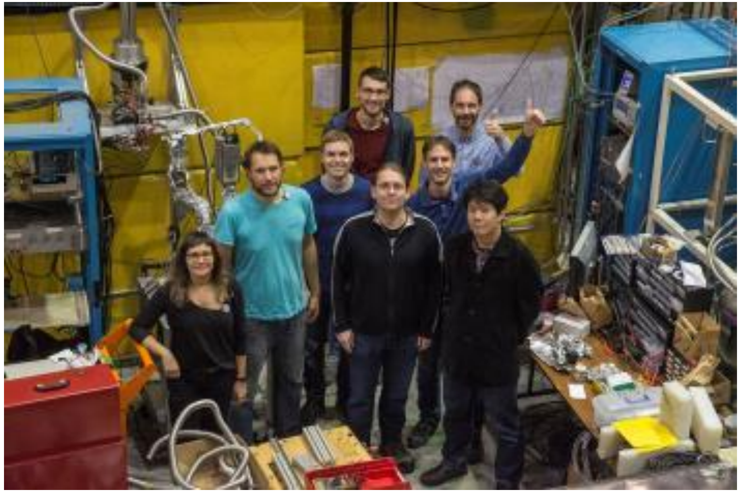
UCN EDM at TRIUMF

- Overview:
  - Japan-Canada collaboration
  - Spallation-driven He-II UCN source connected to RT nEDM experiment.
  - **First UCN Nov 2017! Congratulations**
  - Goal sensitivity (statistics): **$\delta d_n \sim 10^{-27}$ e-cm (2019-2022)**



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



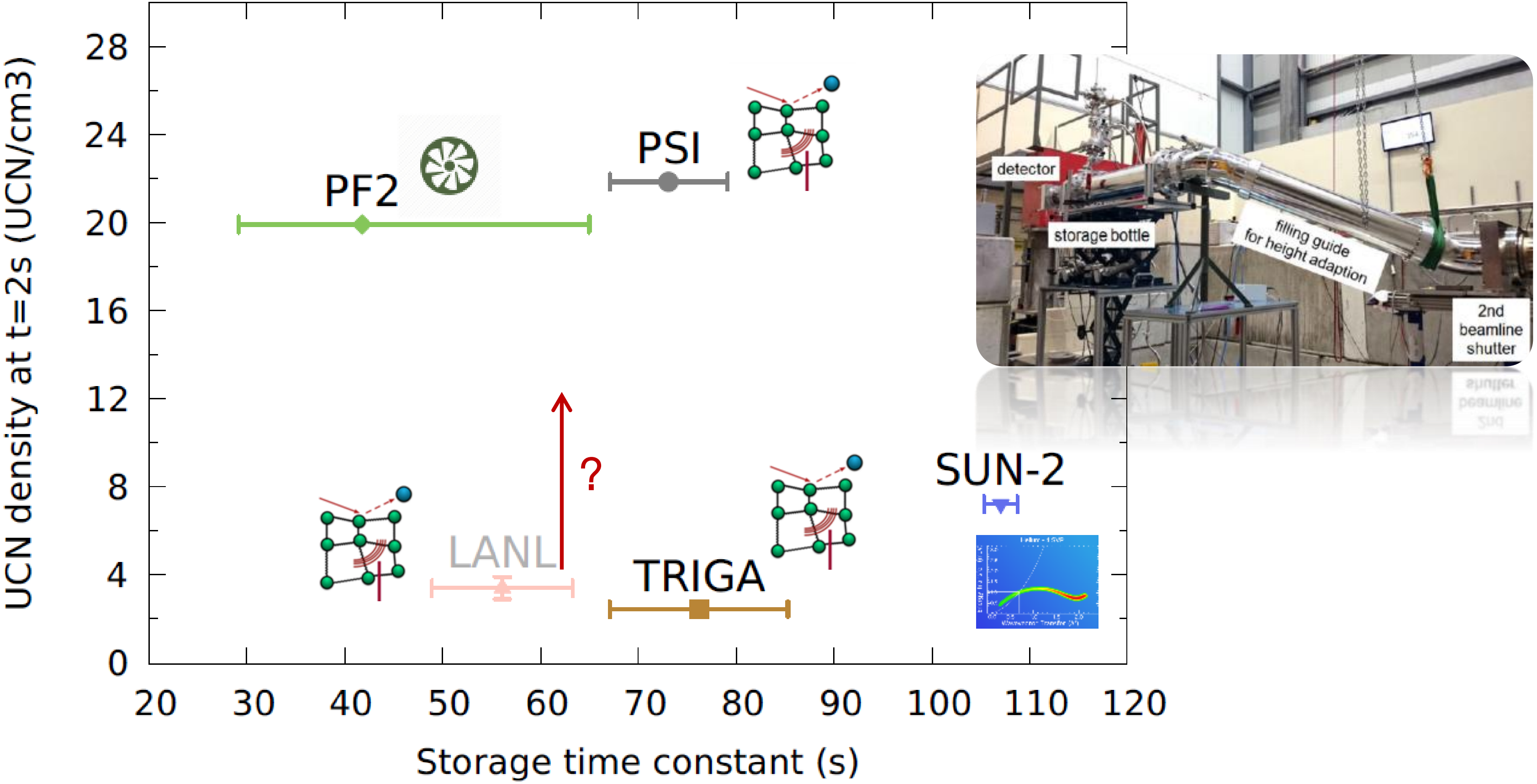


courtesy: Rüdiger Picker

Status & Schedules

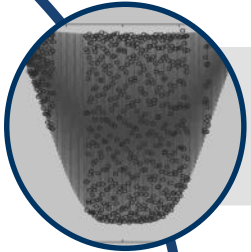
Project	**Status**	**Sensitivity goal (E-27 *ecm*)**	**Schedule (start data-taking)**
LANL	2017:UCN source upgrade finished	UCN density sufficient for O(1)	2019
TUM-ILL	TUM apparatus moves to ILL	O(0.1)	2019
PNPI	At PNPI 2020	PNPI: 0.5	PNPI later
SNS	Critical component demonstration concluded	0.2	2022
TRIUMF	2017: first UCN 2-3 years for experiment	O(1)	2019
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	O(0.1) ?	2025

Worldwide comparison of UCN sources

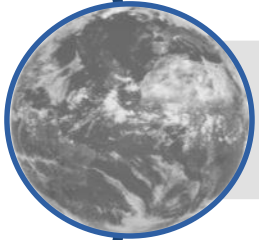


Bison *et al.*, PR C 95(2017)045503

Outline



Ultracold neutrons and Ramsey's technique



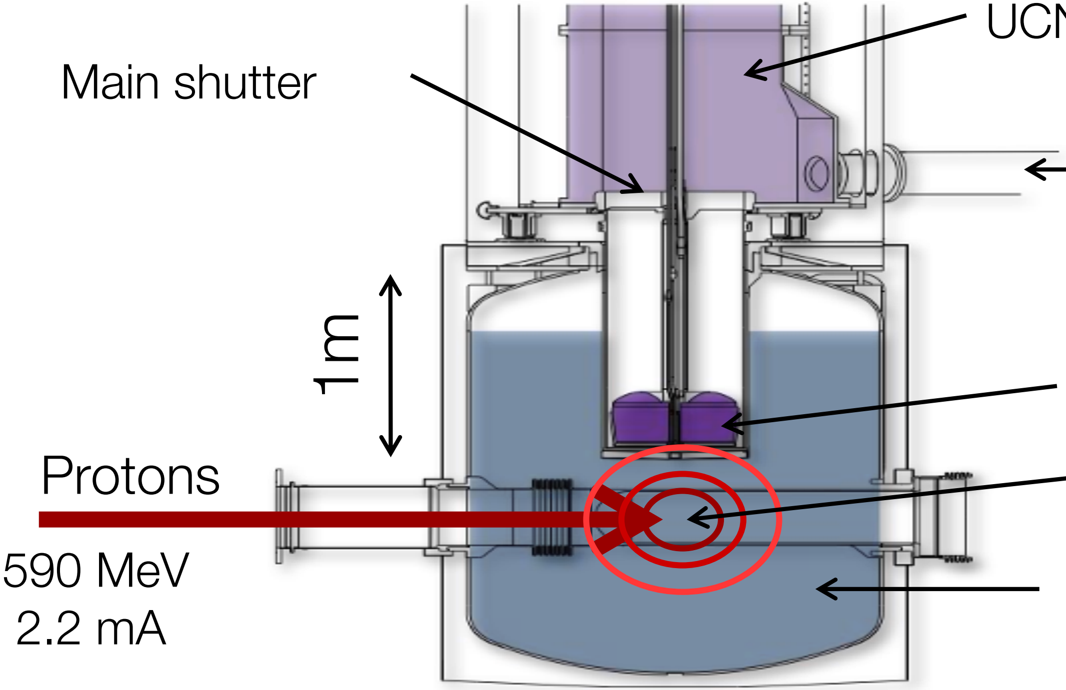
Worldwide competition

Searches for static and oscillating nEDM at PSI

The collaboration

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

PSI UCN source



Main shutter

UCN storage volume

Neutron guide to experiments

UCN convertor (solid D_2 @ 5K)

Protons

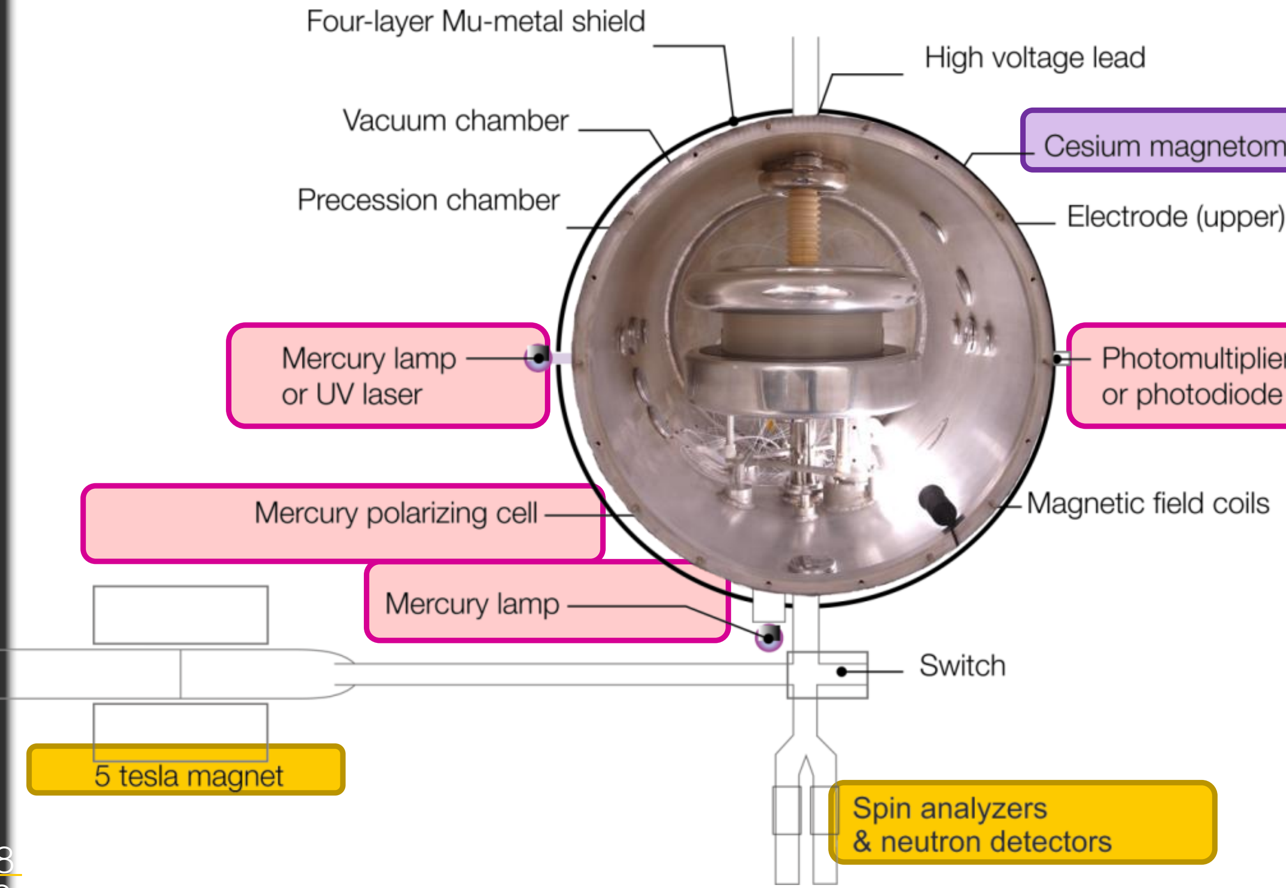
590 MeV
2.2 mA

Spallation target
E_n~MeV

D_2O moderator
Neutrons thermalized to 25 meV

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

The nEDM spectrometer



Four-layer Mu-metal shield

High voltage lead

Vacuum chamber

Cesium magnetometer

Precession chamber

Electrode (upper)

Mercury lamp or UV laser

Photomultiplier or photodiode

Mercury polarizing cell

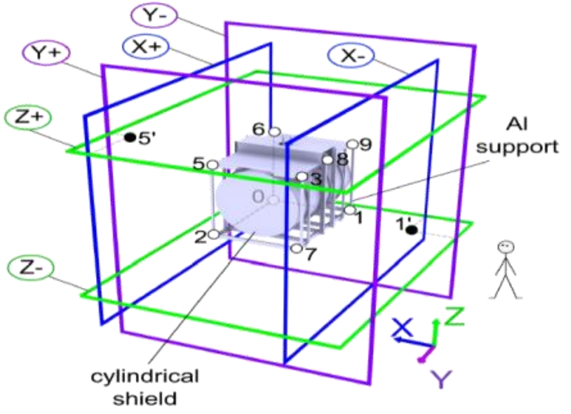
Magnetic field coils

Mercury lamp

Switch

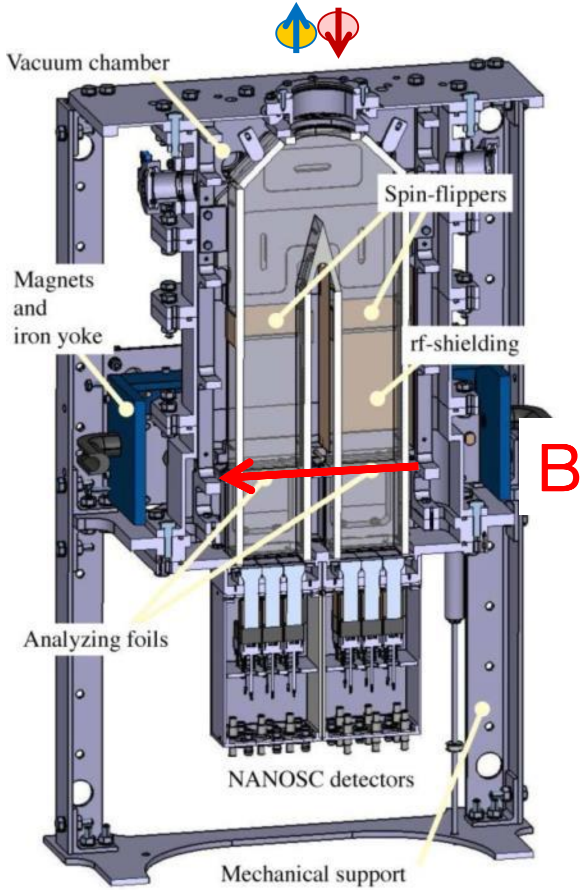
5 tesla magnet

Spin analyzers & neutron detectors

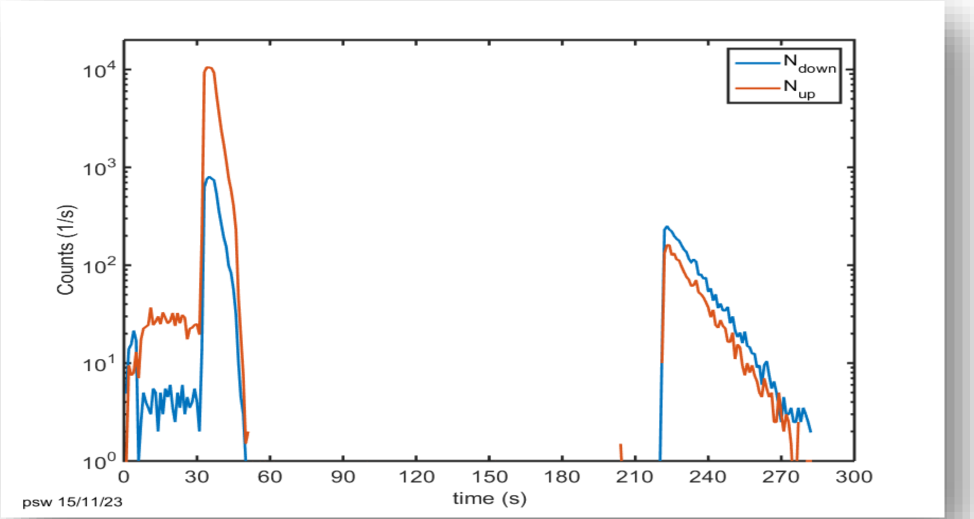


Simultaneous spin detection

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$



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



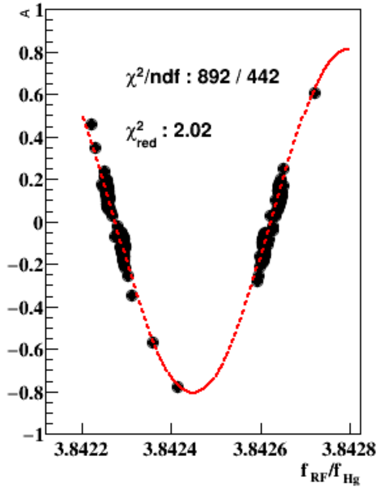
S. Afach *et al.*, EPJA (2015)51: 143

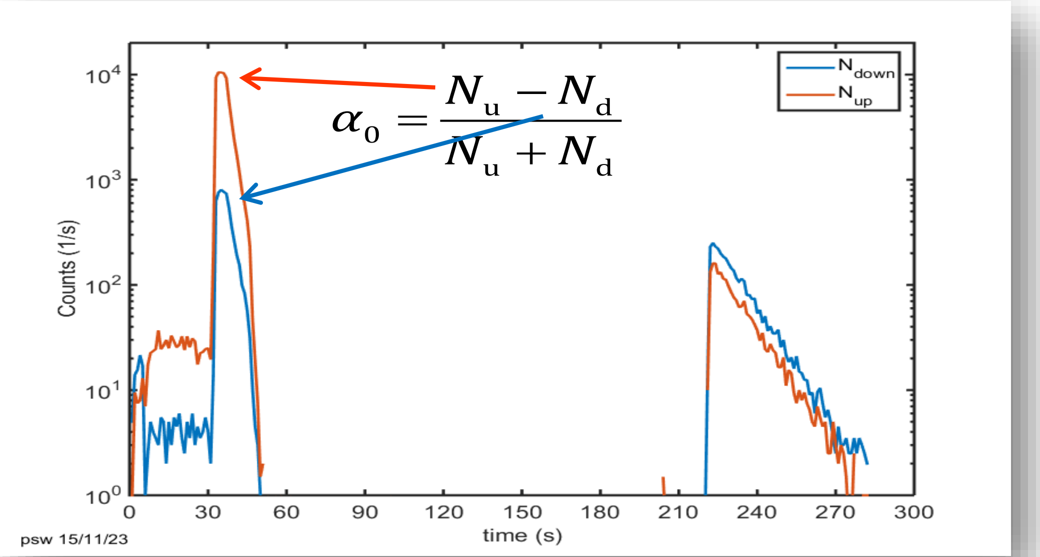
Transverse polarization time

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

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

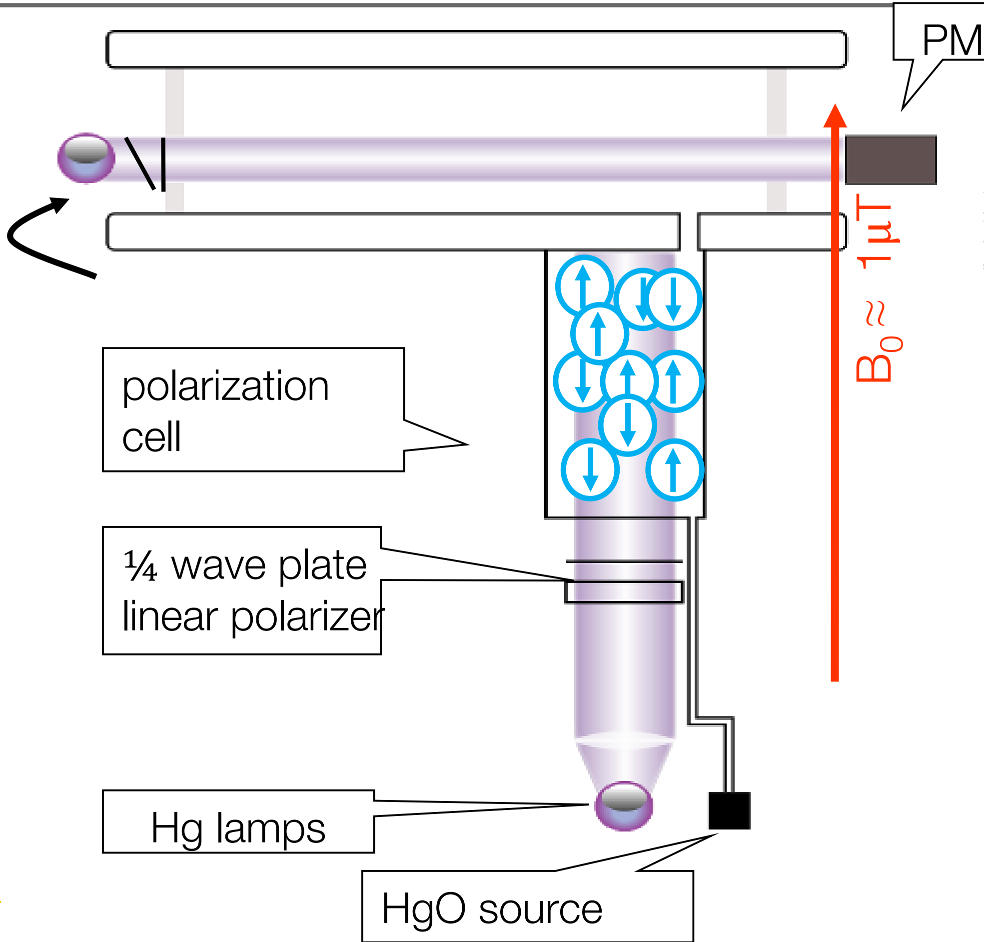
$$T_2^* = t \cdot \ln\left(\alpha(t)/\alpha_0\right) = 2488\text{s}$$

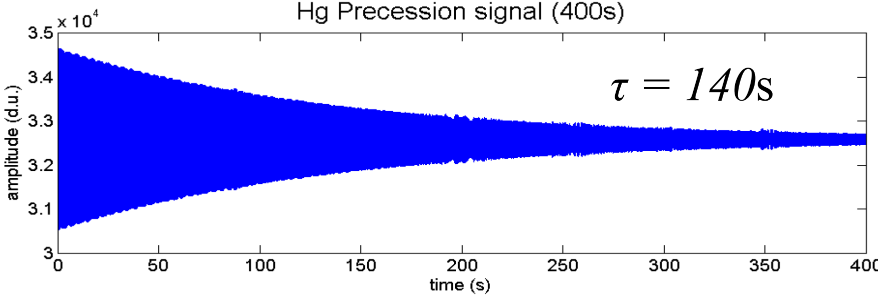




$$\alpha_0 = \frac{N_u - N_d}{N_u + N_d}$$

Mercury co-magnetometer

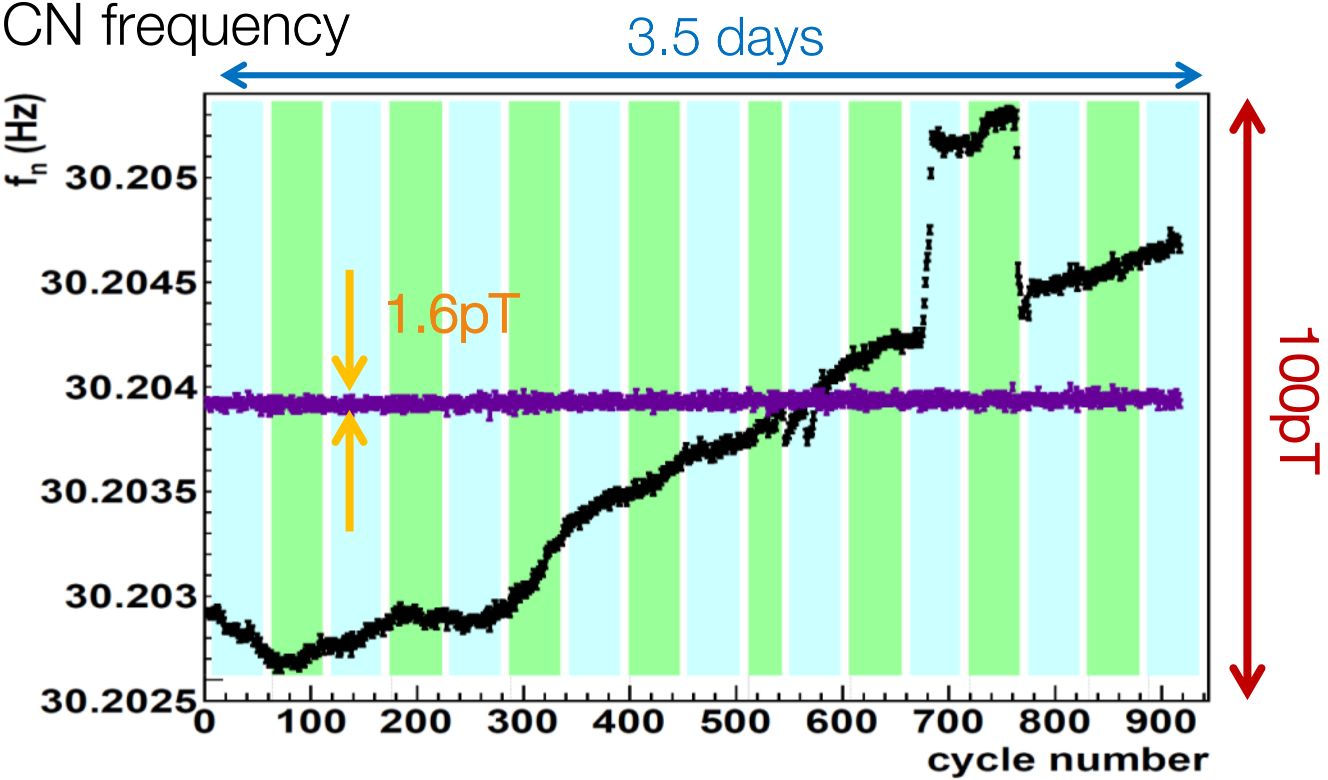




- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with 90s)
- $s/n > 1000$

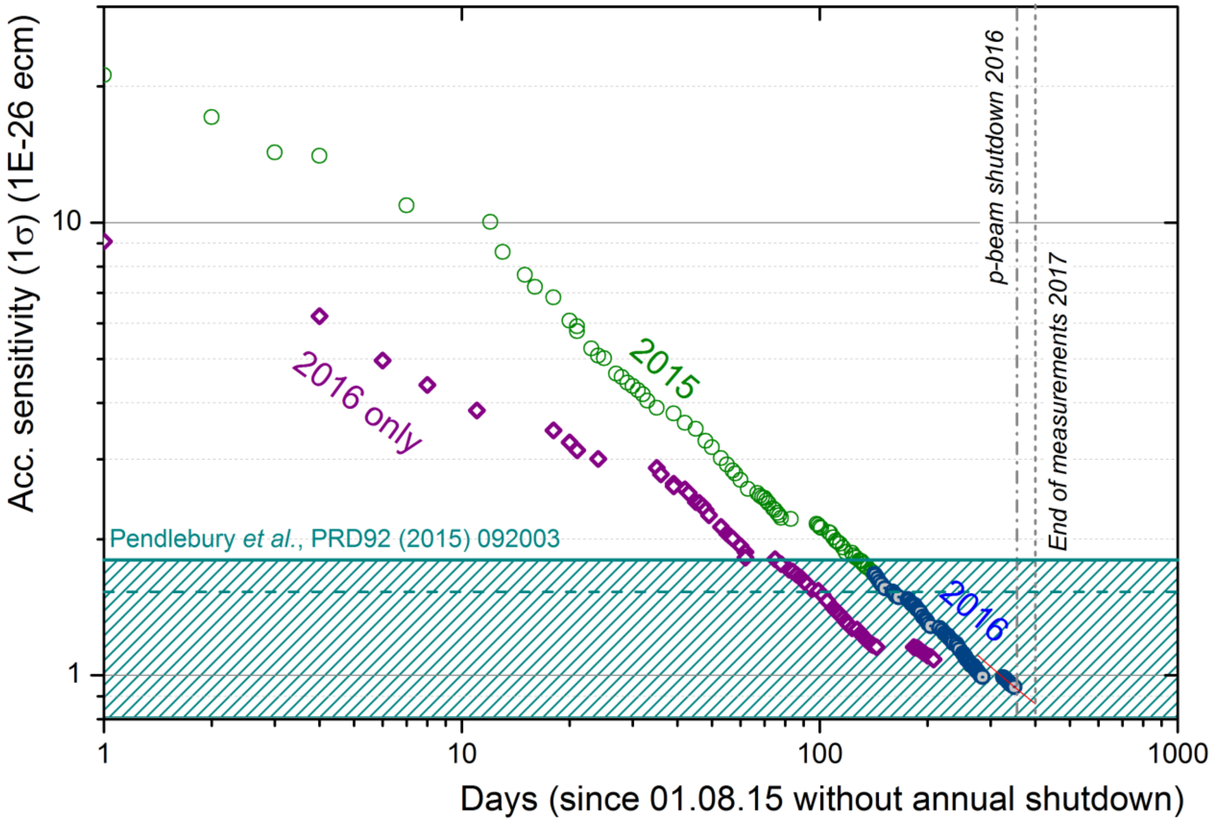
Hg co-magnetometer

Extract B field from Larmor frequency
and correct UCN frequency



Naive statistical sensitivity

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

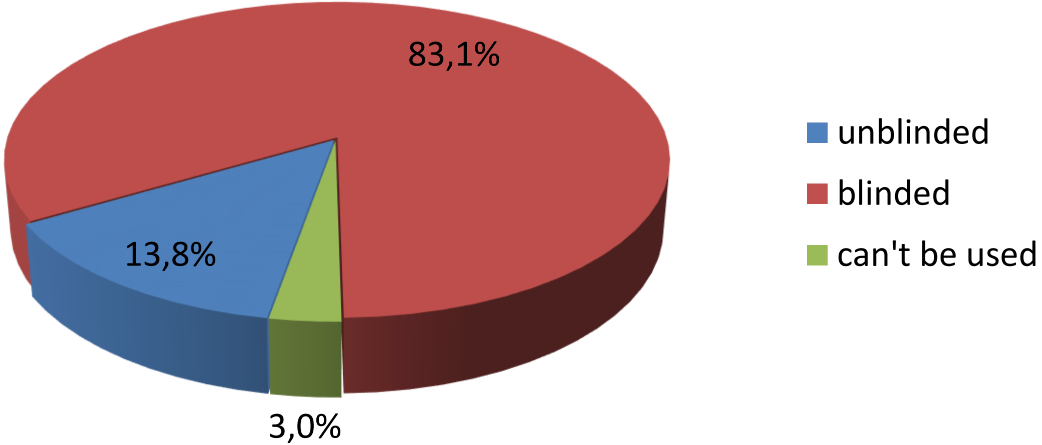


54362 cycles
(exclude runs with issues)

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

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

Analysis

- Two analysis groups prepare a full separately **blinded** 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,

→ Run both codes on fully un-blinded data

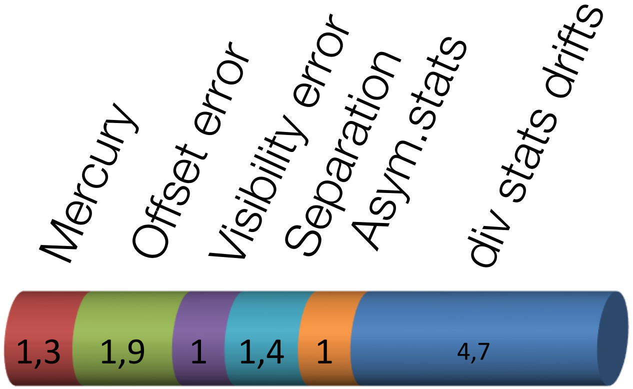
→ publish.

Crossing point analysis

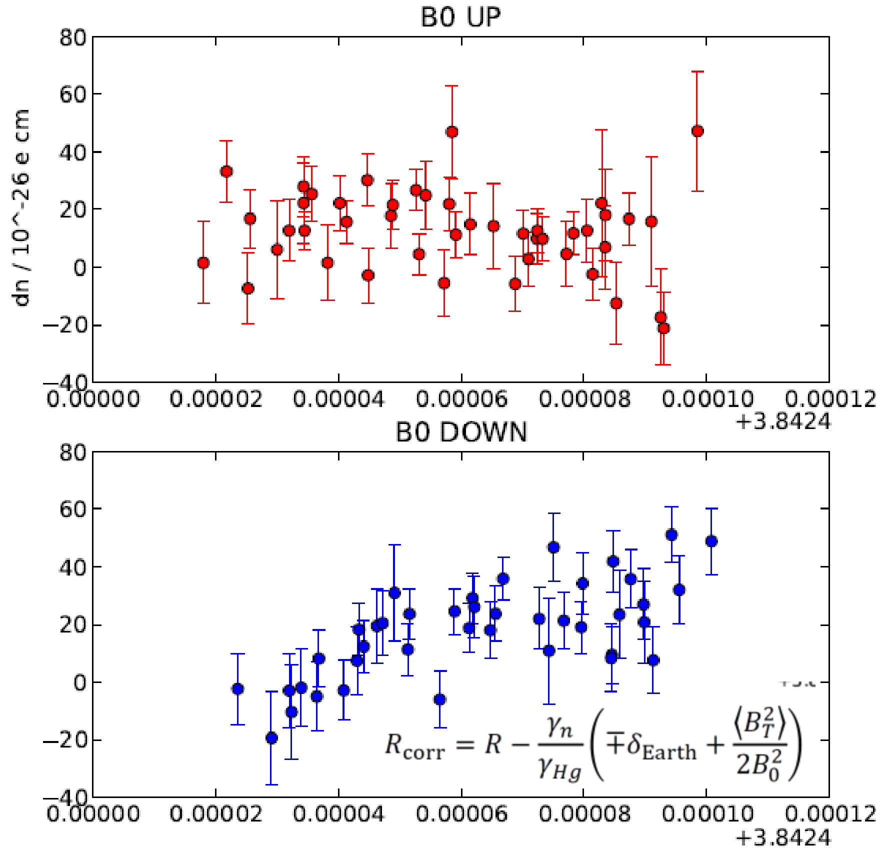
$$d_\times = (14.96 \pm 1.12) \times 10^{-26} e\ \mathrm{cm}$$

$$R_0 = 3.8424521(28)$$

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



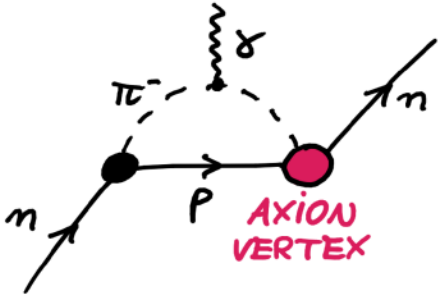
Change in %



$$R_{\mathrm{corr}} = R - \frac{\gamma_n}{\gamma_{Hg}}\left(\mp\delta_{\mathrm{Earth}} + \frac{\langle B_T^2\rangle}{2B_0^2}\right)$$

Searching for axions

- Axions are a proposed solution to strong CP problem (Peccei-Quinn theory)
- It has been proposed that dark matter is really made of ultralight axionlike particles (ALPs) ($m_a \sim 10^{-22}$ eV)
- This would form a coherent classical field throughout the universe
- NB: ALP is generalisation of axion, does not necessarily solve strong CP, but has similar properties



arXiv:1504.07551v2 [hep-ph]
Graham Rajendran
PRD88, 035023 (2013)

gluonic

fermionic

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

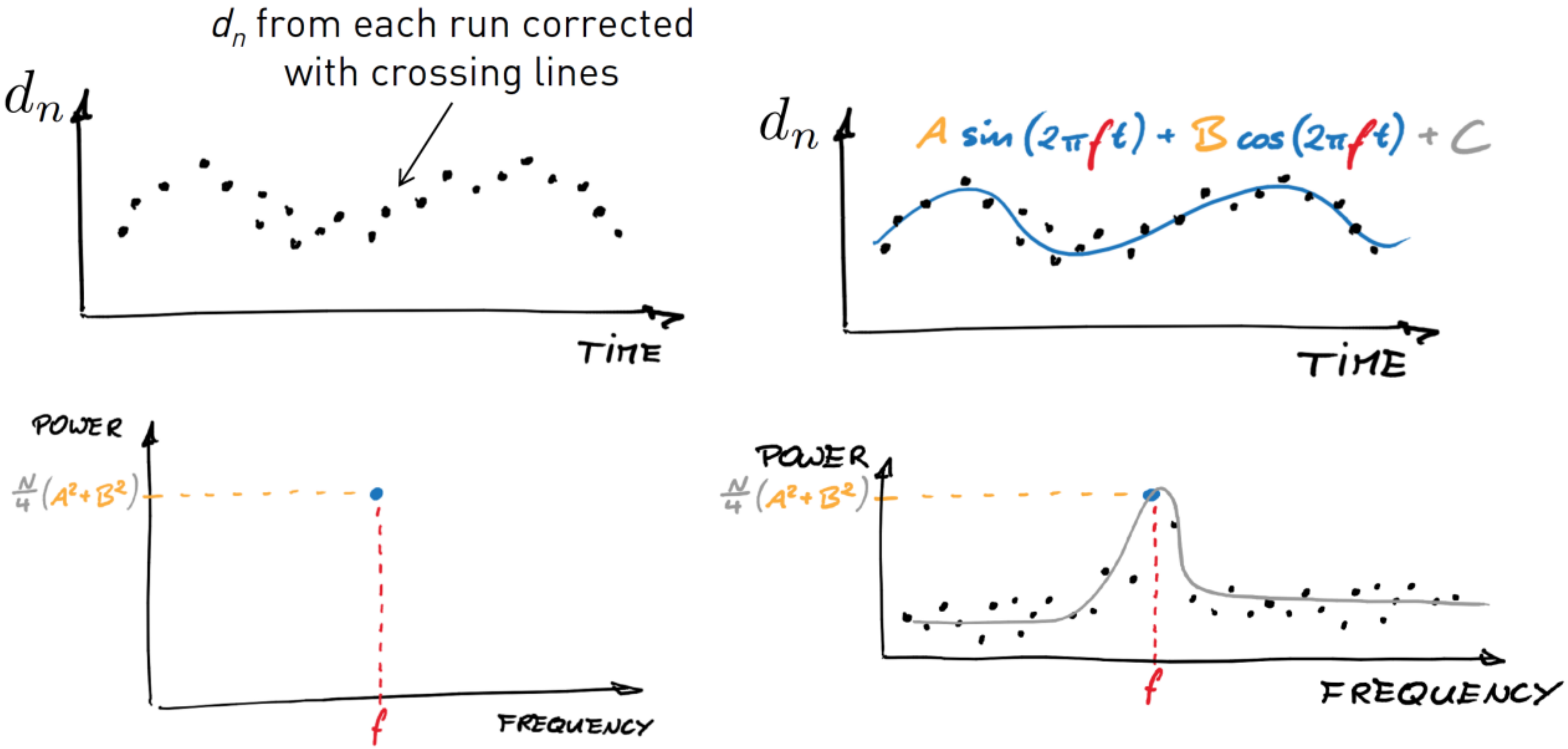
Produces oscillating EDM through same diagrams as θ_{QCD}

Produces oscillations in precession frequency "Axion Wind"

Nick Ayres

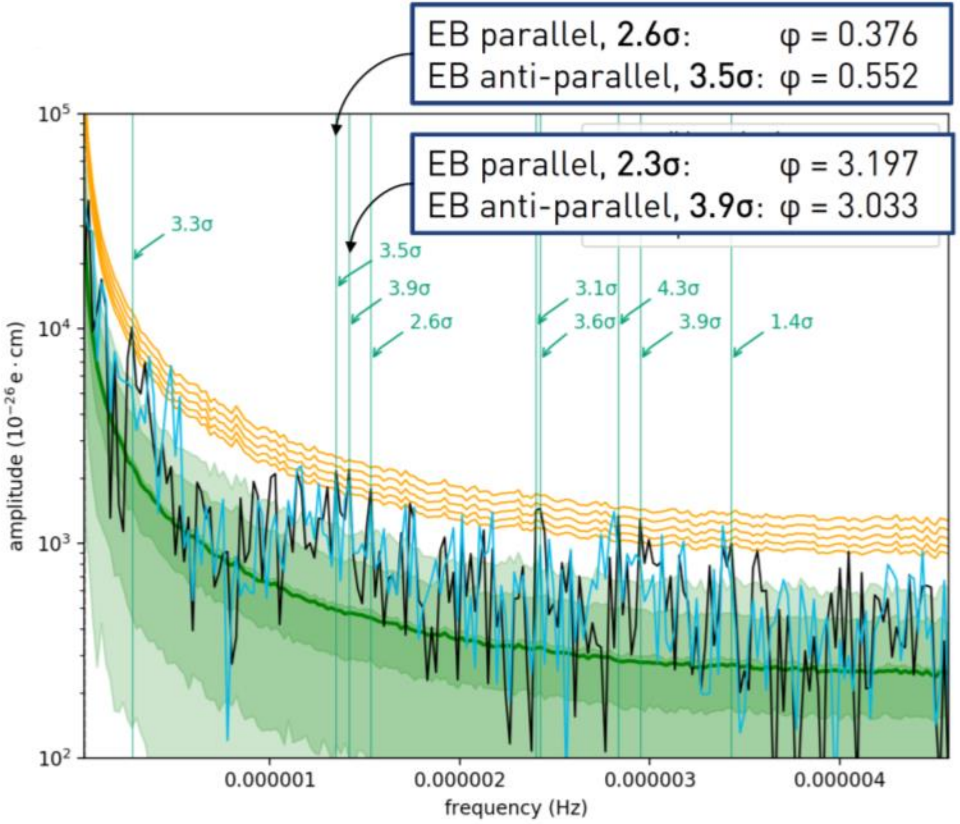
Michal Rawlik

Least square spectral analysis



d_n from each run corrected with crossing lines

Highest peaks



EB parallel, **2.6σ**: φ = 0.376
EB anti-parallel, **3.5σ**: φ = 0.552

EB parallel, **2.3σ**: φ = 3.197
EB anti-parallel, **3.9σ**: φ = 3.033

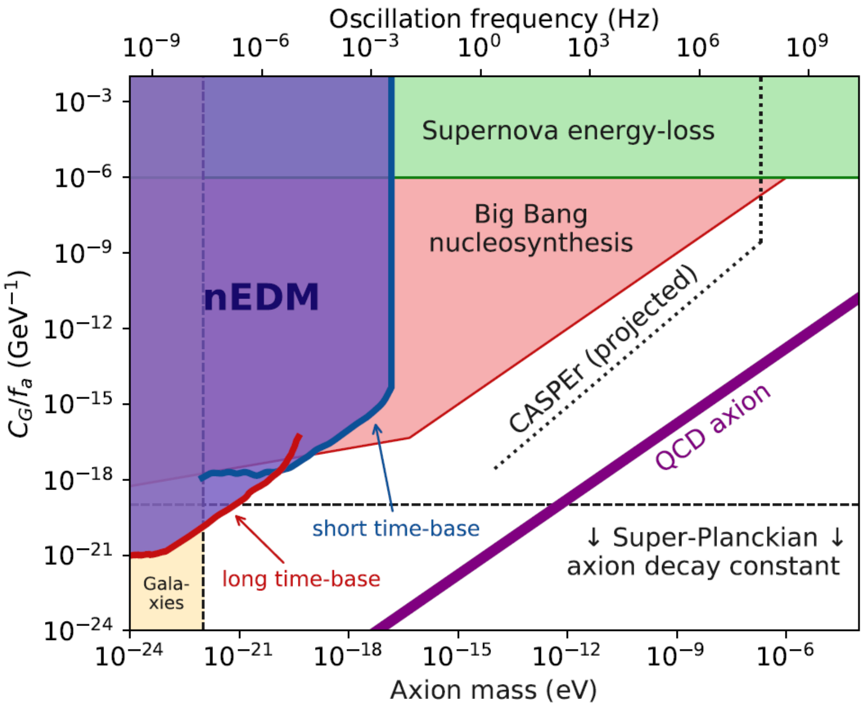
Three "data sets":

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

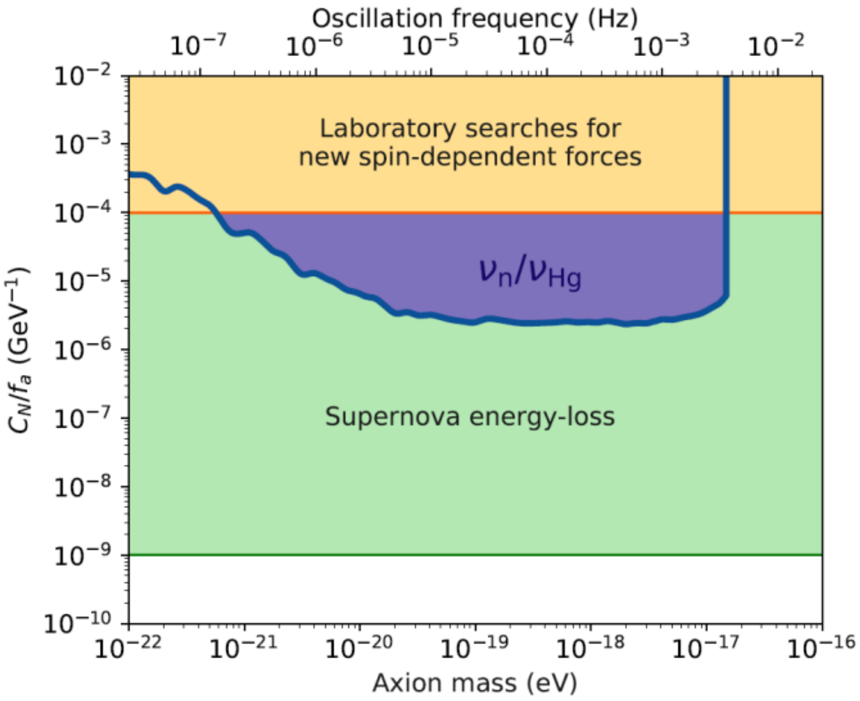
Requirements for signal:

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

Exclusion limits



First experimental limits
on gluonic coupling



40 times better limit
on fermionic coupling

https://PhysRevX.7.041034

A new spectrometer 6-layer Mu

Commissioning 2020

$\sigma(d_{\mathrm{n}}) < 1 \times 10^{-27}$

Summary

- Many groups world wide compete for the next most sensitive nEDM experiement
- The nEDM@PSI collaboration has taken sufficient data for a new result
- Two groups analysis a fully blinded data-set
- Possible unblinding in 2018
- The same data was used for search for an oscillating nEDM, setting first limits on a gluonic and improved limits on a fermionic coupling of the neutron to axions.

Collaboration

🇩🇪	**M. Burghoff, A. Schnabel, J.Voigt**	*Physikalisch Technische Bundesanstalt*, ***Berlin***
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🇬🇧	**C. Abel, N. Ayres, C.W. Griffith, P. Harris, J. Thorne**	*University of Sussex*, ***Brighton***
🇫🇷	**G. Ban , P. Flaux, T. Lefort, Y. Lemiere, O. Naviliat-Cuncic**	*Laboratoire de Physique Corpusculaire*, ***Caen***
🇵🇱	**K. Bodek, D. Rozpedzik, J. Zejma**	*Institute of Physics, Jagiellonian University*, ***Cracow***
🇵🇱	**A. Kozela**	*Henryk Niedwodniczanski Inst. Of Nucl. Physics*, **Cracow**
🇨🇭	**Z. Grujic, A. Weis**	*Département de physique, Université de Fribourg*, ***Fribourg***
🇫🇷	**L. Ferraris, G. Pignol, A. Leredde, D. Rebreyend, R. Virot**	*Laboratoire de Physique Subatomique et de Cosmologie*, ***Grenoble***
🇧🇪	**V. Bondar, P. Koss, N. Severijns, E. Wursten**	*Katholieke Universiteit*, ***Leuven***
🇺🇸	**C. Crawford**	*University of Kentucky*, ***Lexington***
🇩🇪	**W. Heil**	*Inst. für Physik, Johannes-Gutenberg-Universität*, ***Mainz***
🇩🇪	**D. Ries, K. Ross**	*Inst. für Kernchemie, Johannes-Gutenberg-Universität*, ***Mainz***
🇫🇷	**S. Roccia**	*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse*, ***Orsay***
🇨🇭	**G. Bison, P.-J. Chiu[2], M. Daum, N. Hild[2], B. Lauss, P. Mohan Murthy[2], D. Pais[2], P. Schmidt-Wellenburg, G. Zsigmond**	*Paul Scherrer Institut*, ***Villigen***
🇨🇭	**S. Emmenegger, K. Kirch[1], J. Krempel, M. Rawlik**	*Eidgenössische Technische Hochschule*, **Zürich**

also at: [1] *Paul Scherrer Institut*, [2] *Eidgenössische Technische Hochschule*

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.

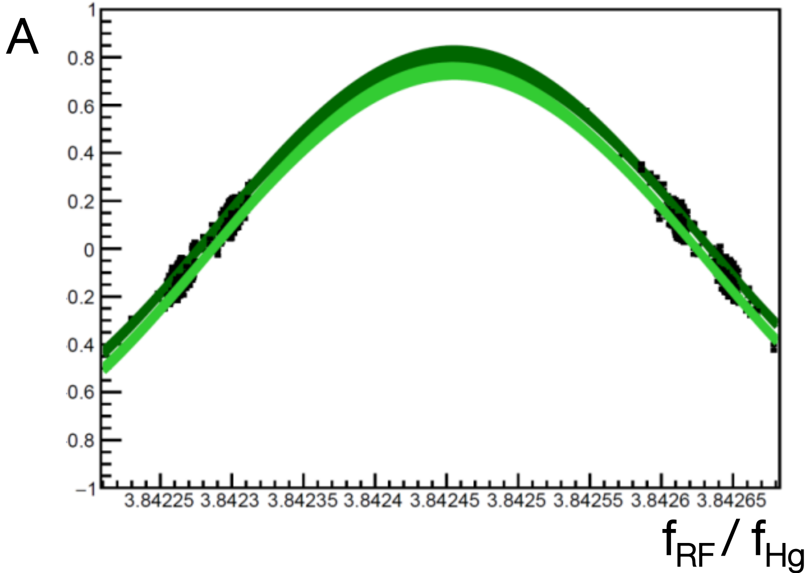
The "Galaxies" bound is dashed. If axions make up all of the dark matter, they need to be heavier than this so that they can reproduce observed distribution of dark matter (rotational curves). If they are only a part of dark matter, they can be lighter.

Ramsey fit procedure

- Split sequence in sub-sequence:

E-field (+ - - +) pattern

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



Ramsey fit with the asymmetry :

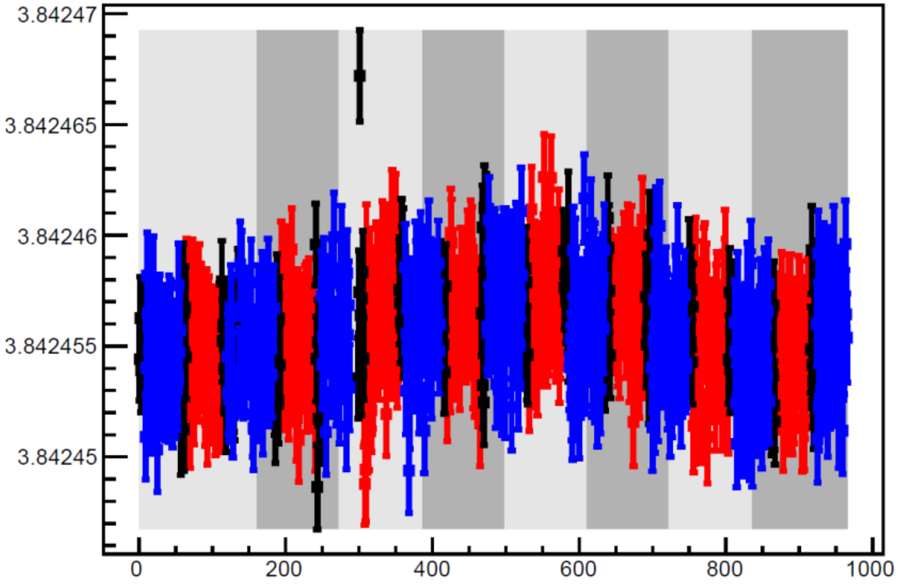
$$A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

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

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

EDM and R-calculation

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



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

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

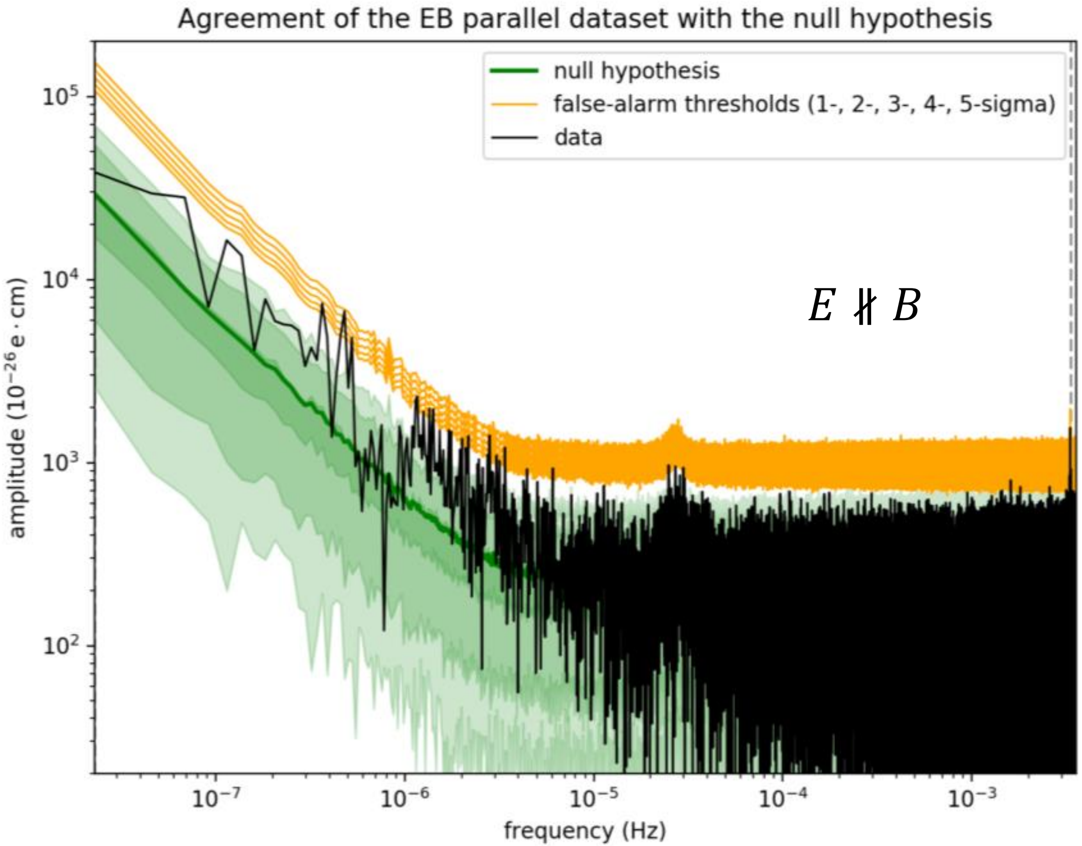
Earth rotation frequency correction :

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

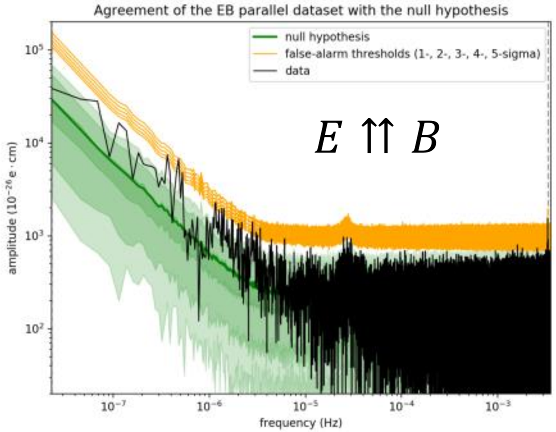
B-gradient fluctuation correction :

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

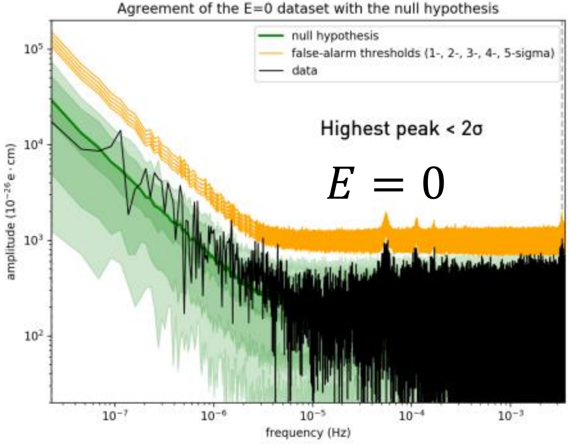
Three Periodograms



$E \nparallel B$



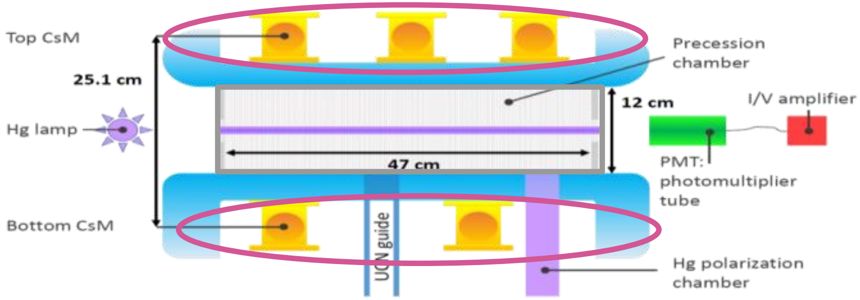
$E \upuparrows B$



Highest peak < 2σ

$E = 0$

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



- Center of mass offset
- Non-adiabaticity

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

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

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

+ further sys.

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

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:

$$|B| = B_0 + \ldots$$

$$+ \frac{\theta v_x}{c^2} E$$

$$+ \frac{(x v_y + y v_x + \theta y v_z)}{2 B_0 c^4} \frac{\partial B_z}{\partial z} E$$

$$+ \frac{v_y{}^2 + \left(v_x - \theta v_z\right)}{2 B_0 c^4} E^2$$

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)

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

50

Dominant systematic

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

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

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

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

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

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

LANL nEDM project

Parameters	Values
E(kV/cm)	12.0
N(per cell)	39 100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year* (10^{-27} ecm) (for double cell)	2.1
90% C.L./year* (10^{-27} ecm) (for double cell)	3.4

Based on the following:

50 cm diameter cell

The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.

The estimate for **N is based** on the actual detected number of UCN from our fill and dump measurement at a **holding time of 180 s.** Further improvements are expected (new switcher and new detector).

* "year" = 365 live days. In practice, it will take 5 calendar years to achieve this with 50% data taking efficiency and nominal LANSCE accelerator operation schedule

Courtesy: Ito Takeyasu

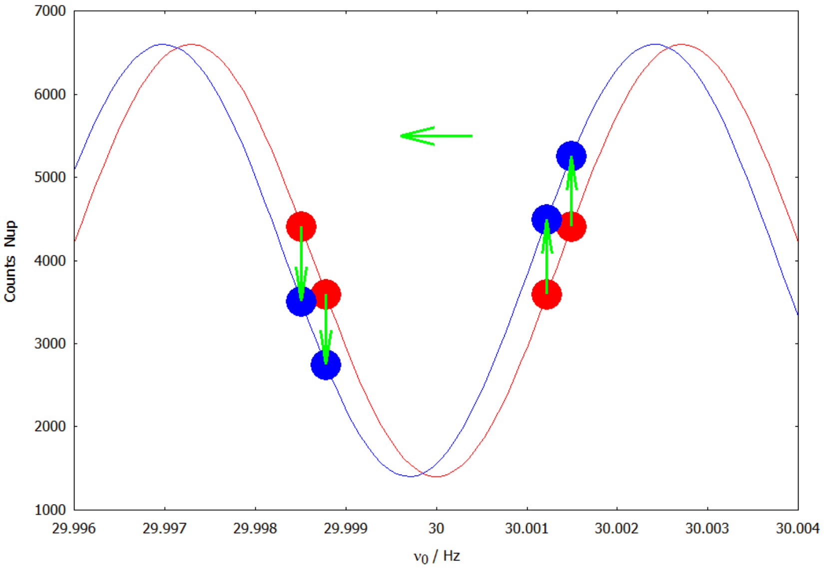
Blinding

How?

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

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

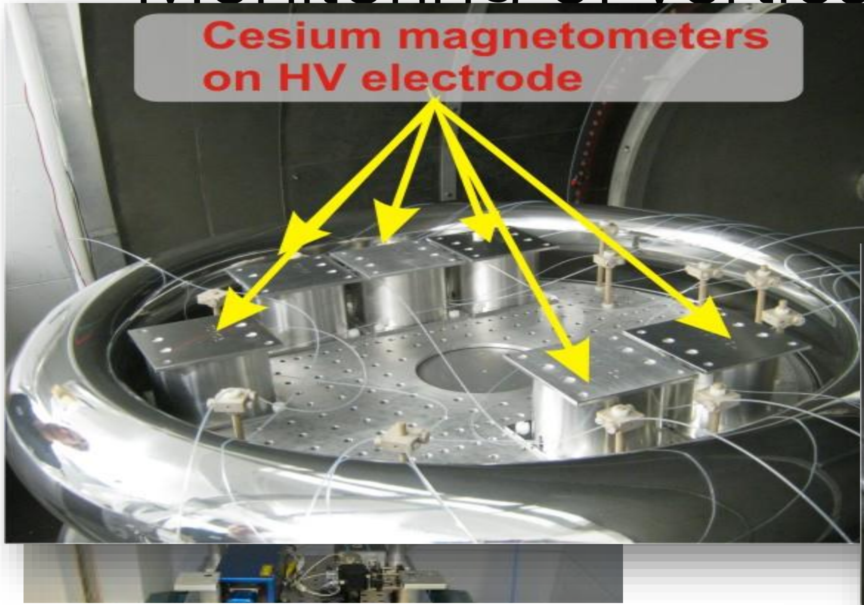
with $$\phi_i = \frac{(\nu_i - \nu_0)}{\Delta\nu}\pi$$

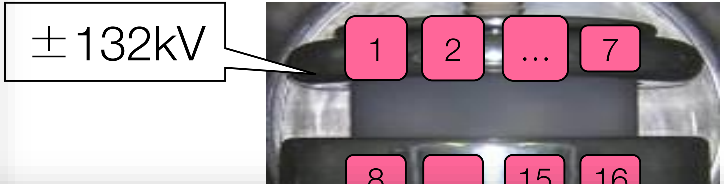


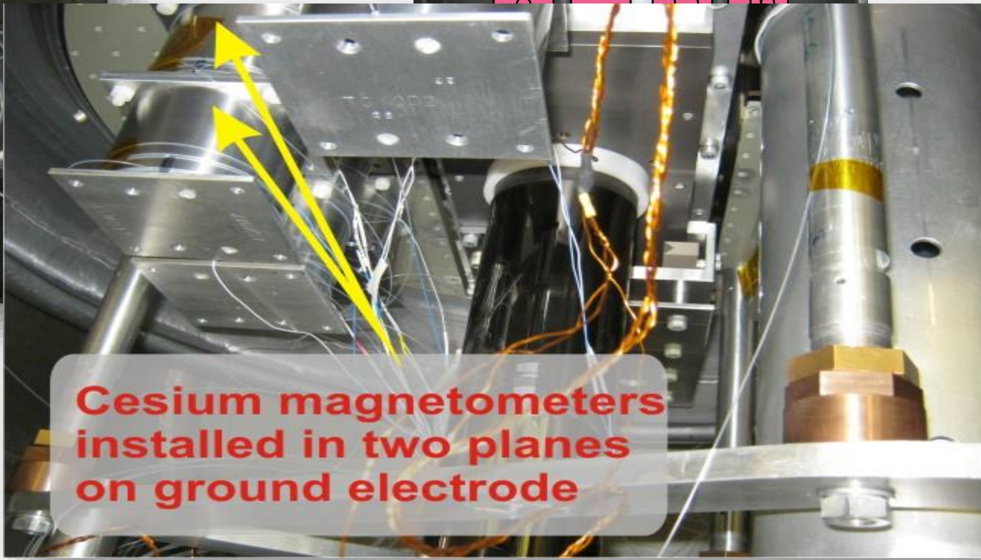
- Keep un-blinded data in a safe place (encrypted)

Cesium gradiometer

Monitoring of vertical magnetic gradients





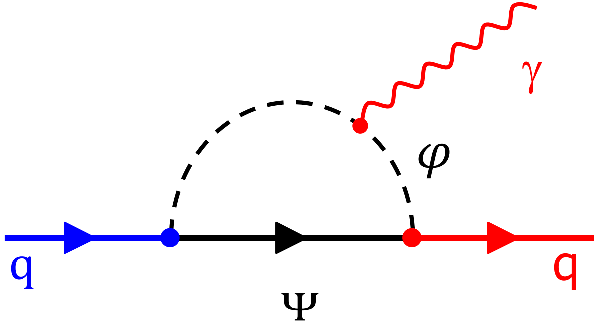


Current accuracy:

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

The value of the nEDM

$$d_\mathrm{n} = \boxed{10^{-16}e\mathrm{cm}} \cdot \left(\theta + \delta_\mathrm{n}^\mathrm{BSM}\right) + d_\mathrm{n}^\mathrm{CKM} < 3 \times 10^{-26} e\mathrm{cm}^*$$



Naive dimensional analysis

- $m_\varphi \sim m_\Psi \sim \Lambda$
- $d_\mathrm{n} \sim e \underbrace{\boxed{\frac{m_q}{\Lambda^2}}}_{\text{dim-6 operator}} \underbrace{\boxed{\frac{\alpha}{4\pi}}}_{\text{loop}} \sin\phi_\mathrm{CP} \underbrace{\boxed{\tilde{F}}}_{f(m_\varphi, m_\Psi)}$

$m_q \equiv v y_q$

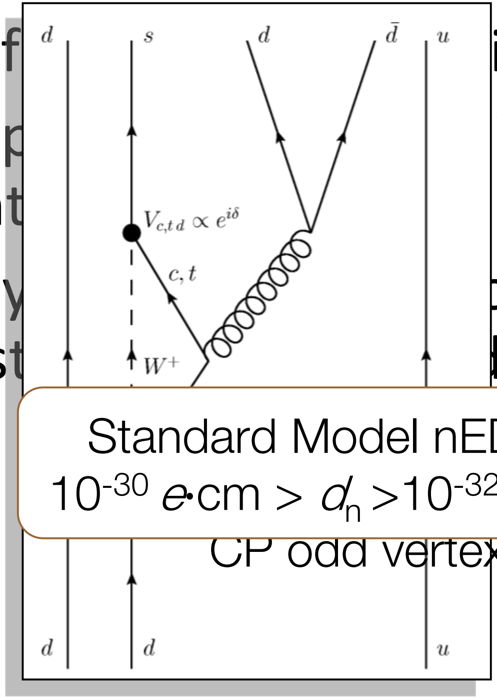
- $d_\mathrm{n} \approx \boxed{\frac{e}{v}\frac{\alpha}{4\pi}} \left(\frac{v}{\Lambda}\right)^2 \sin\phi_\mathrm{CP} \mathrm{y_q} \mathrm{F}$

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

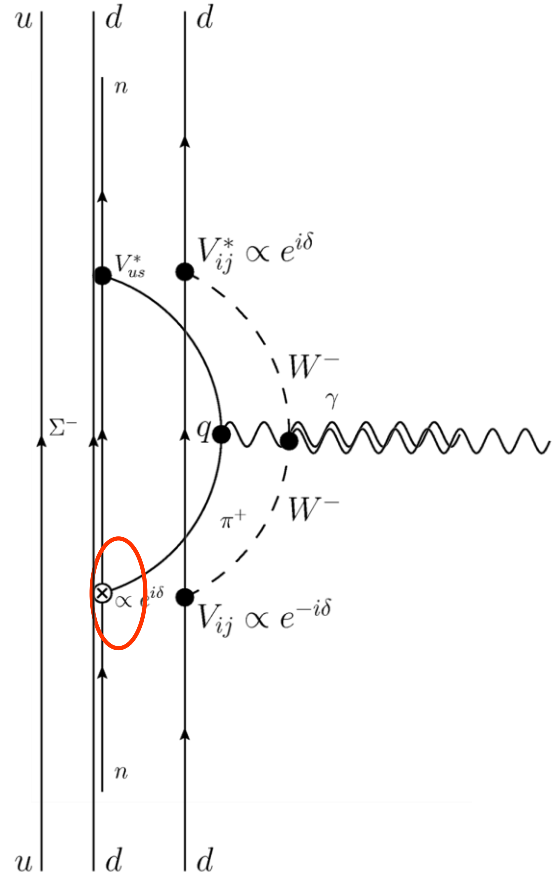
**C.-Y. Seng,PRC(2015)025502

nEDM from CKM Matrix

- No tree level contribution
- No f ion
- No p ion two loop cont
- Only ontribution
  → st d

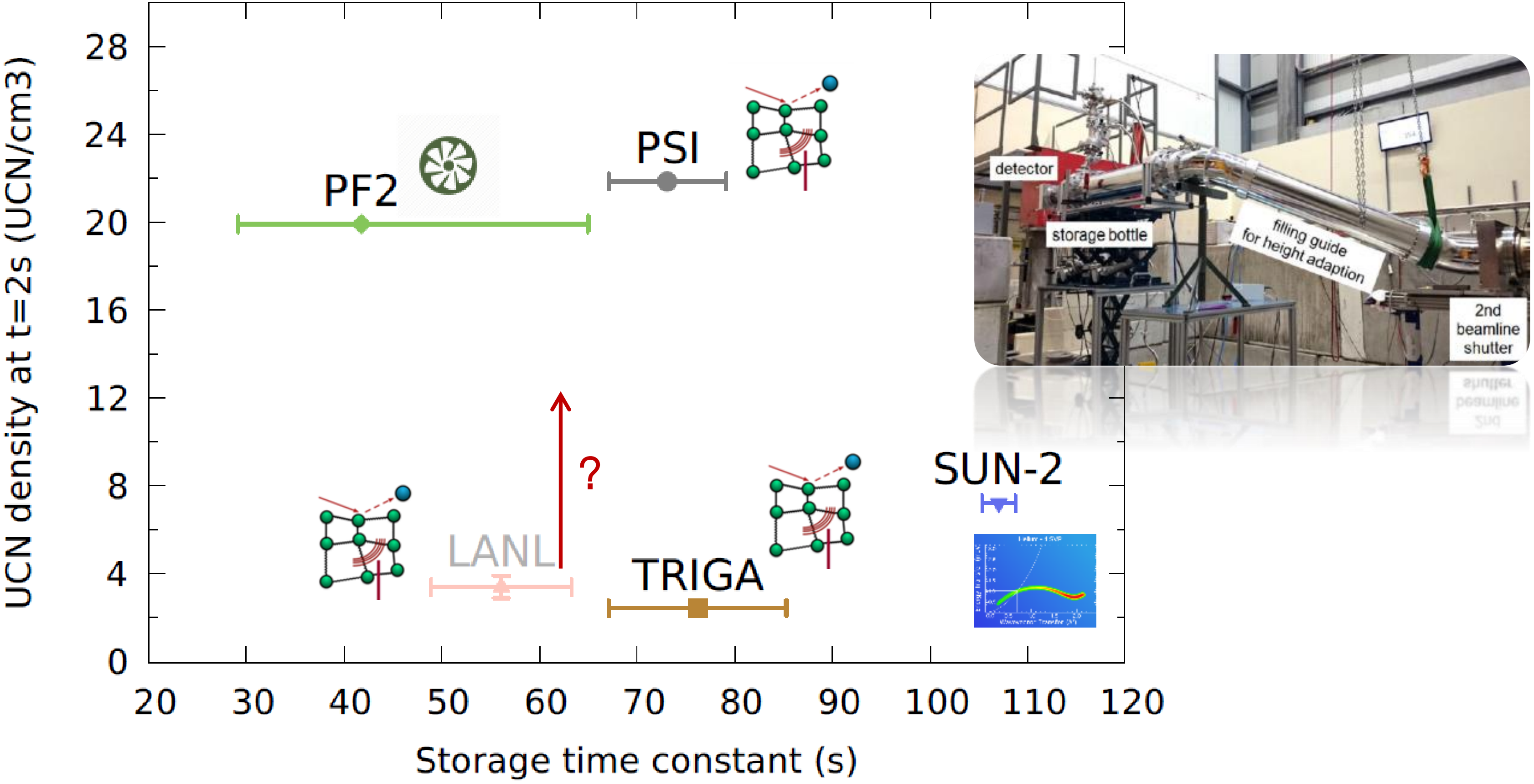


Standard Model nEDM:
$10^{-30}\ e{\cdot}\mathrm{cm} > d_n > 10^{-32}\ e{\cdot}\mathrm{cm}$



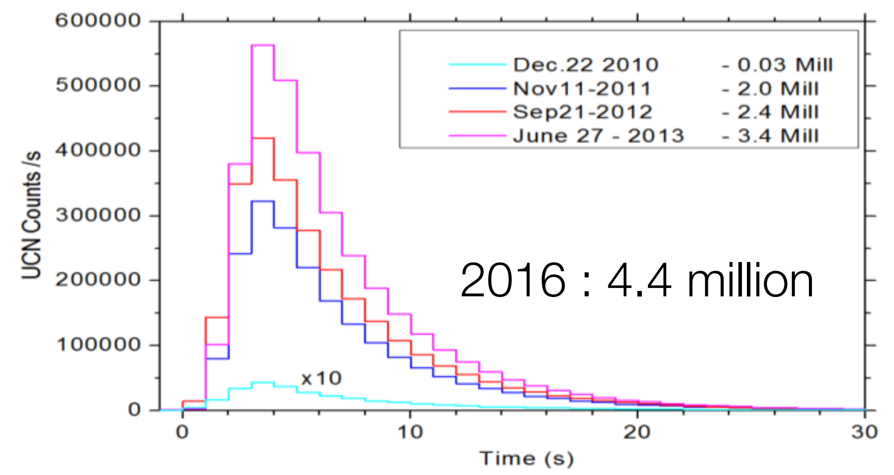
Khriplovich PLB109(1982) & PLB173 (1986)

Worldwide comparison of UCN sources



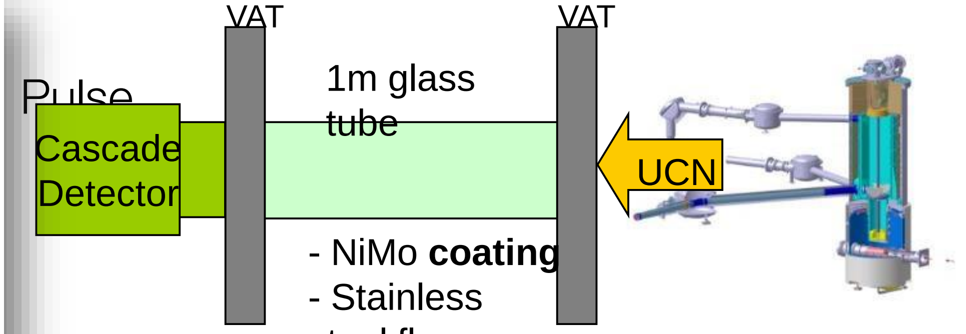
Bison *et al.*, PR C 95(2017)045503

UCN source performance

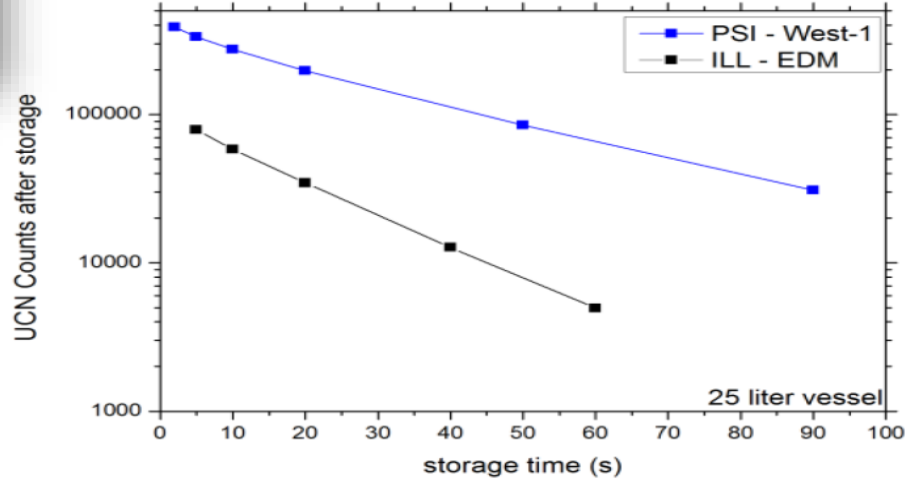


2016 : 4.4 million

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

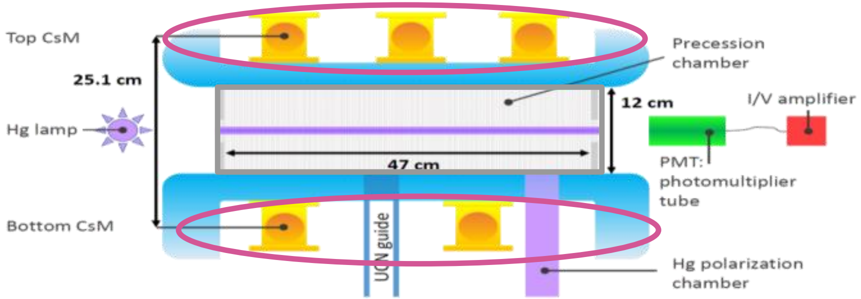


- NiMo **coating**
- Stainless steel flanges
- shutter DLC coated



Frequency ratio R = f_n/f_{Hg}

- Center of mass offset
- Non-adiabaticity



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

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

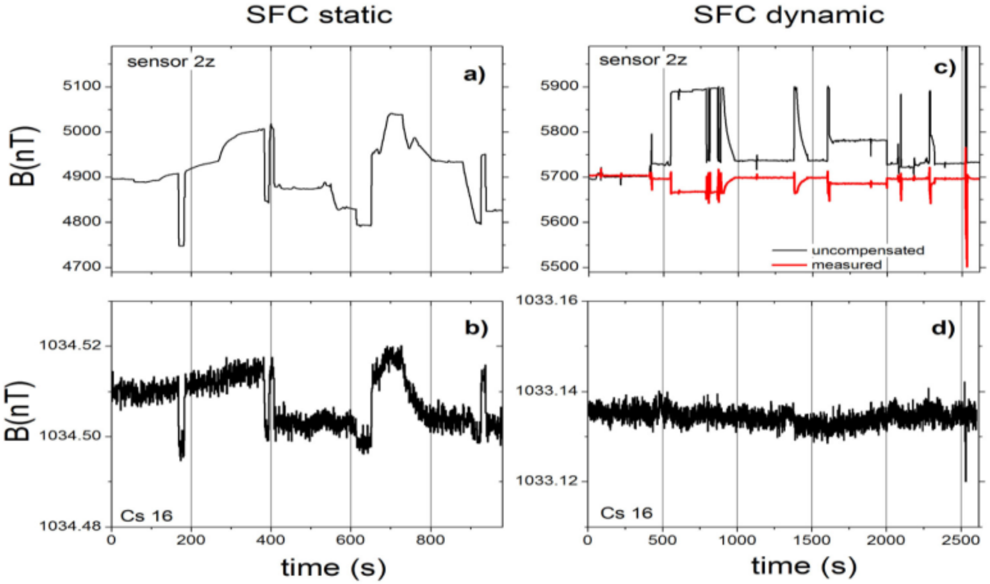
$$\overline{v_{\mathrm{Hg}}} \approx 160\ \mathrm{m/s\ vs.}\ \overline{v_{\mathrm{UCN}}} \approx 3\ \mathrm{m/s}$$

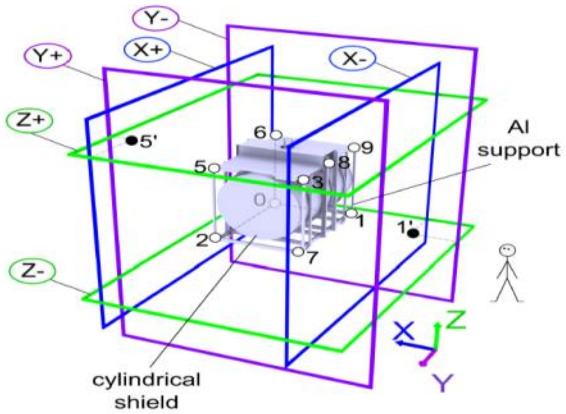
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}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

Measure EDM as function of R & take care of systematics

B-Field stability

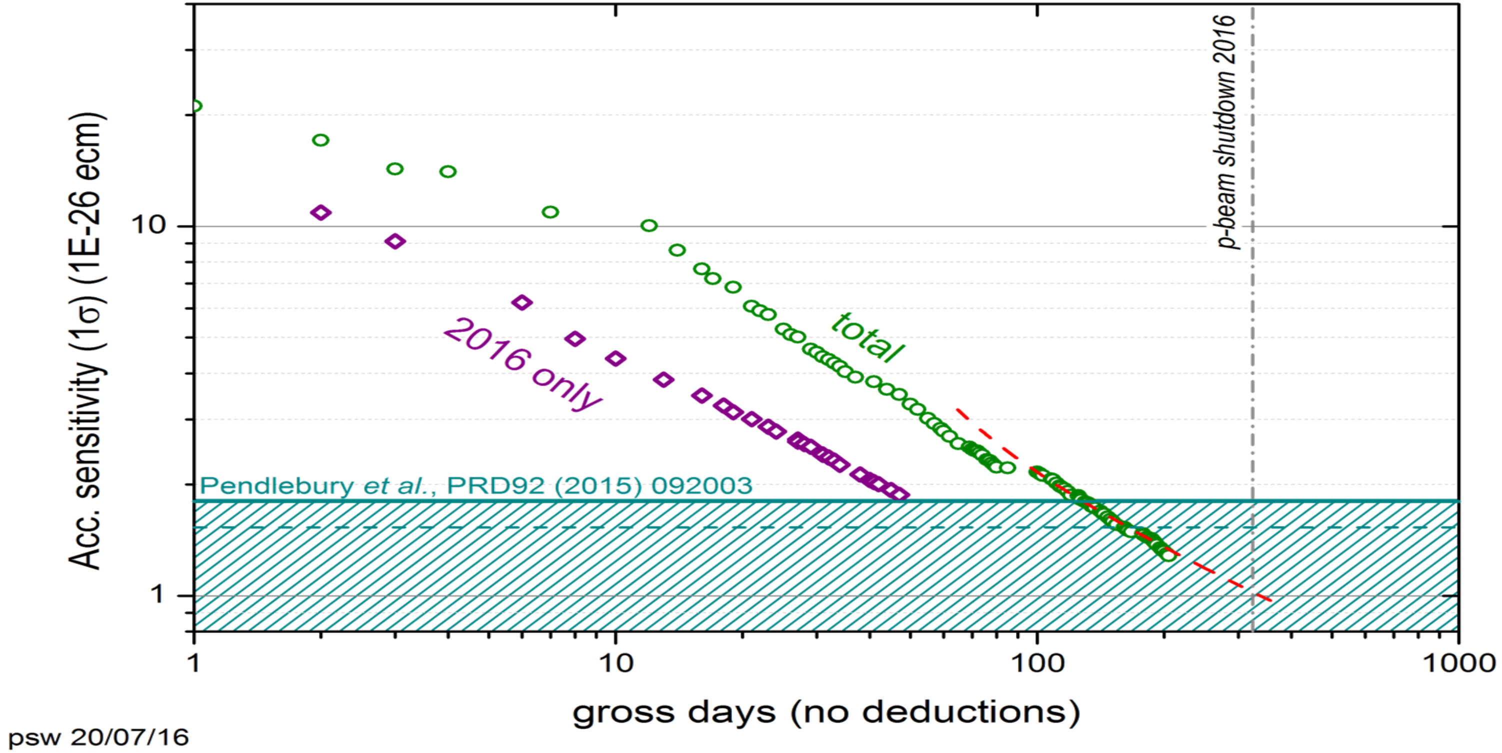
- Excellent stability
  (dynamic SFC & 4 layer magnetic shield)
- Stability (AD) @400s ~ 400fT





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

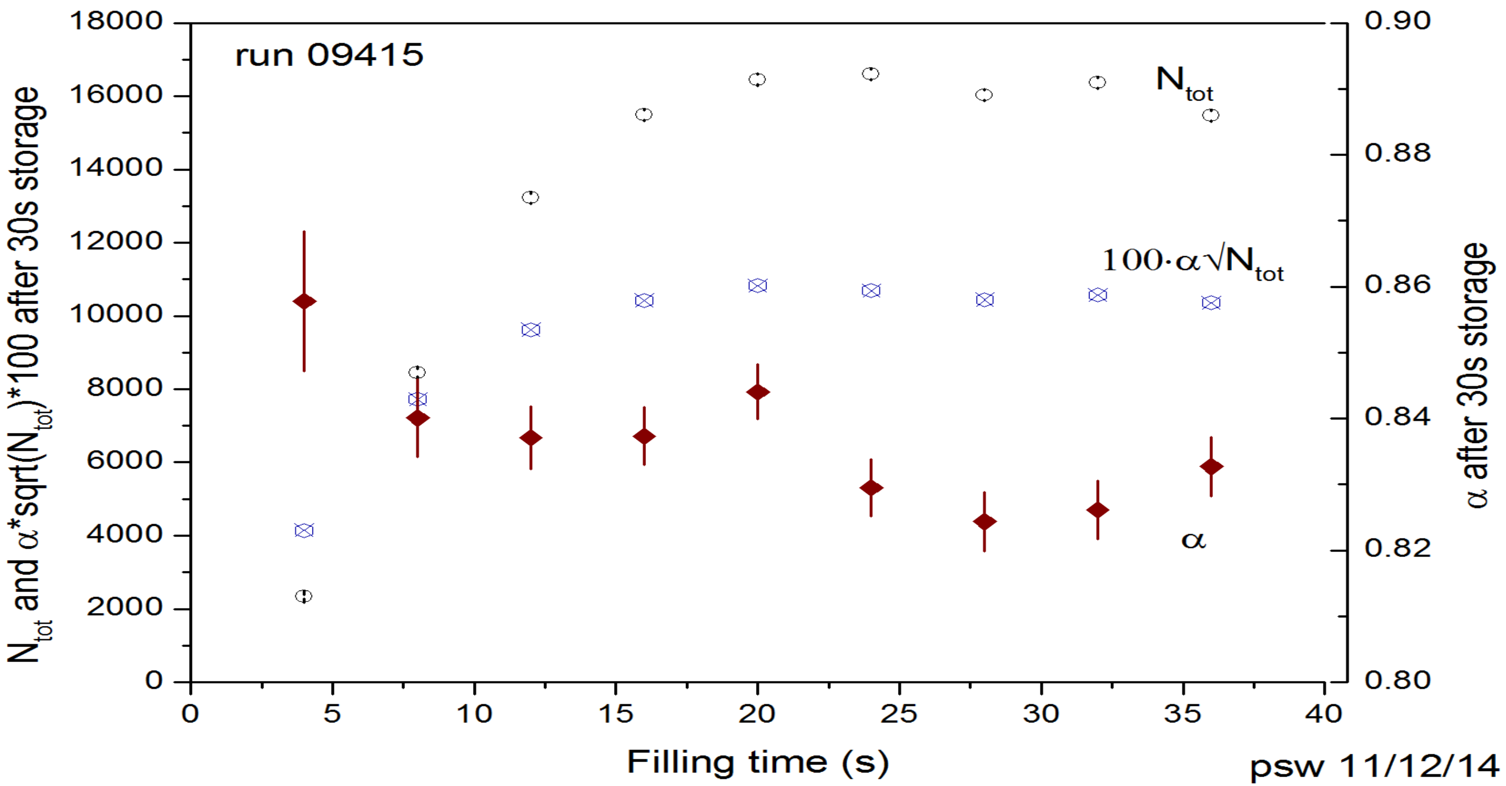
Summary



$$\sigma_d(2016) \approx 1 \times 10^{-26}\ e \cdot \mathrm{cm}$$

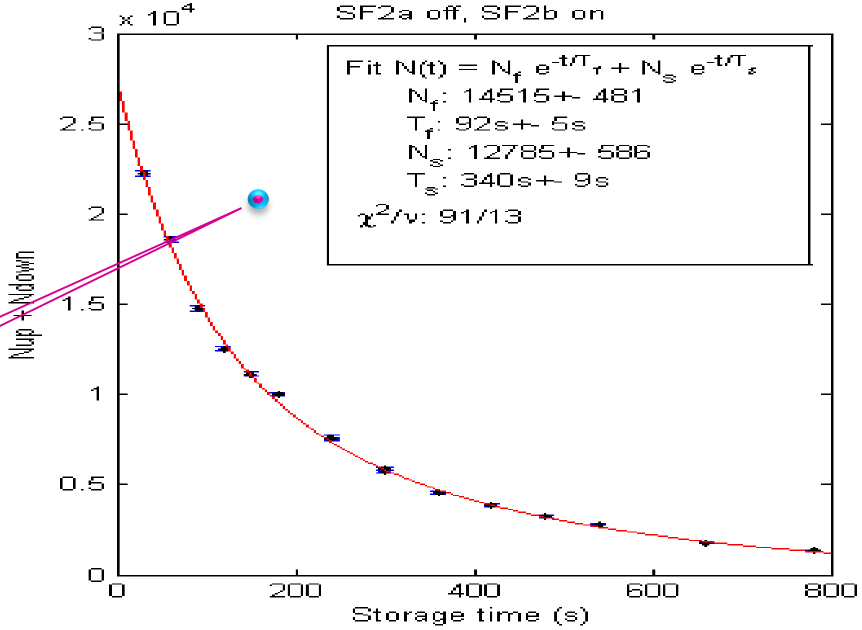
Filling UCN

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



Storage life tim

- 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



Superthermal UCN production

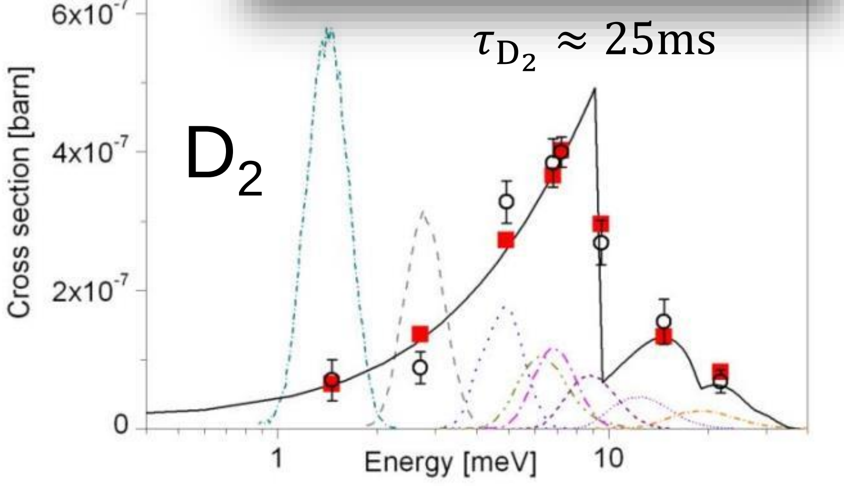
$$\rho = \tau \int \frac{\mathrm{d}\Phi}{\mathrm{d}\lambda} \Sigma(\lambda) \mathrm{d}\lambda$$

macro cross section

differential flux

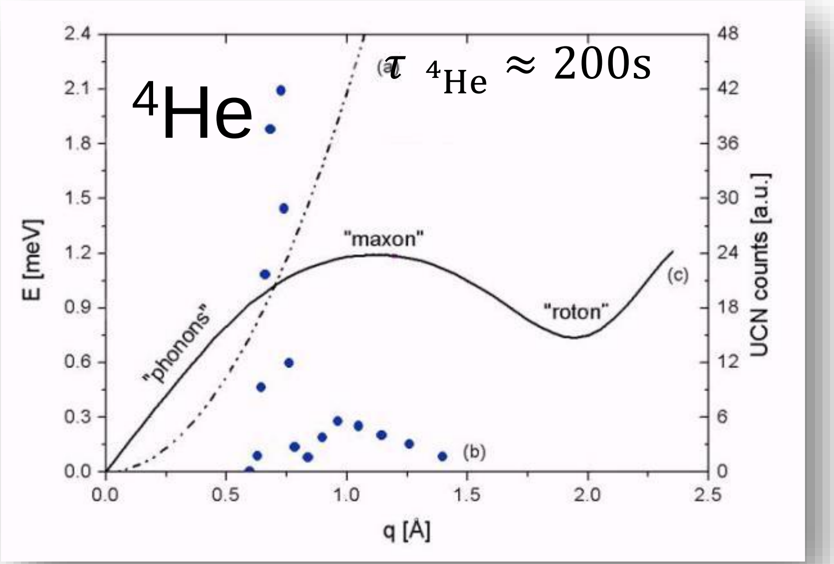
UCN lifetime in medium

Cooling machine = phonon pump



$\tau_{\mathrm{D_2}} \approx 25\mathrm{ms}$

D_2



^{4}He

$\tau_{^4\mathrm{He}} \approx 200\mathrm{s}$

F. Atchison et al., PRL99(2007)262502

R. Golub & J.M. Pendlebury, PLA62(1977)338
C.A. Baker et al., PLA308(2003)67
PSW, J. Bossy *et al.*,PRC92(2015)024002