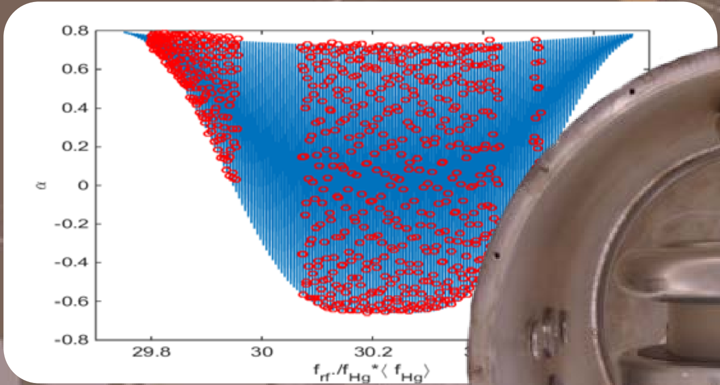
Reduced Limit on the Permanent Electric Dipole Moment of the Neutron



PHYSICAL REVIEW LETTERS **124,** 081803 (2020)

Editors' Suggestion | Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

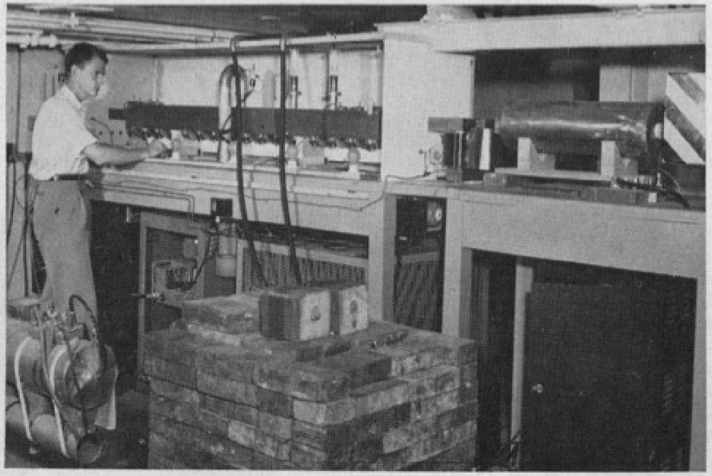
C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

PSI
LTP Colloquium
2020/10/08
P. Schmidt-Wellenburg

THE OAK RIDGE NATIONAL LABORATORY NEWS

A Publication by and for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

Vol. 3—No. 13 OAK RIDGE, TENNESSEE Friday, September 29, 1950

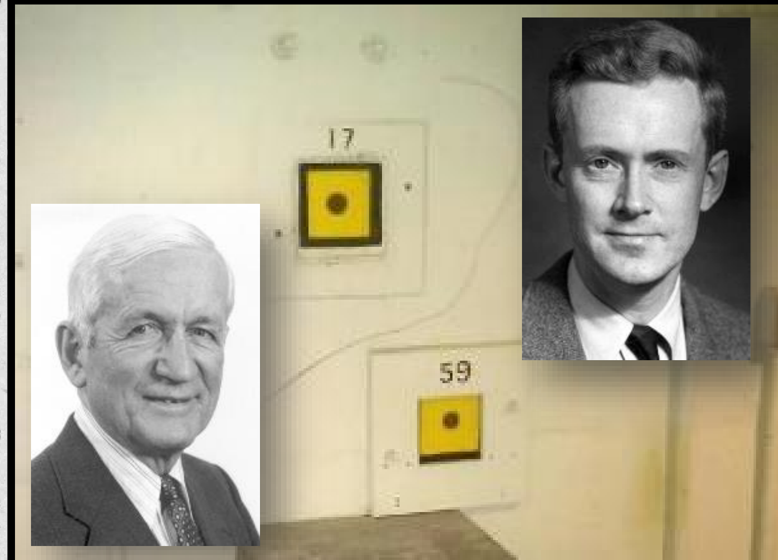


HARVARD UNIVERSITY SPONSORS PROGRAM HERE — *James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.*

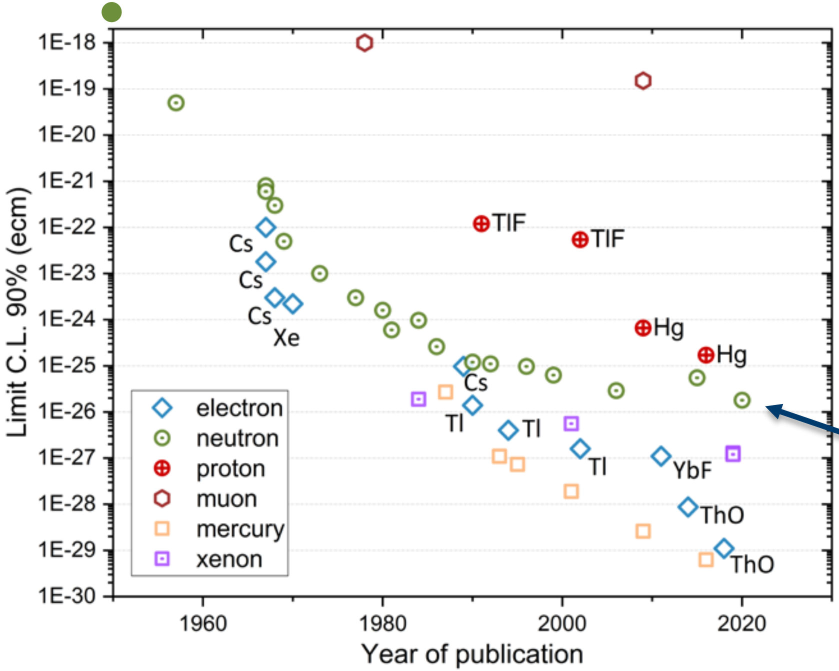
Harvard University Conducts Important Research at ORNL

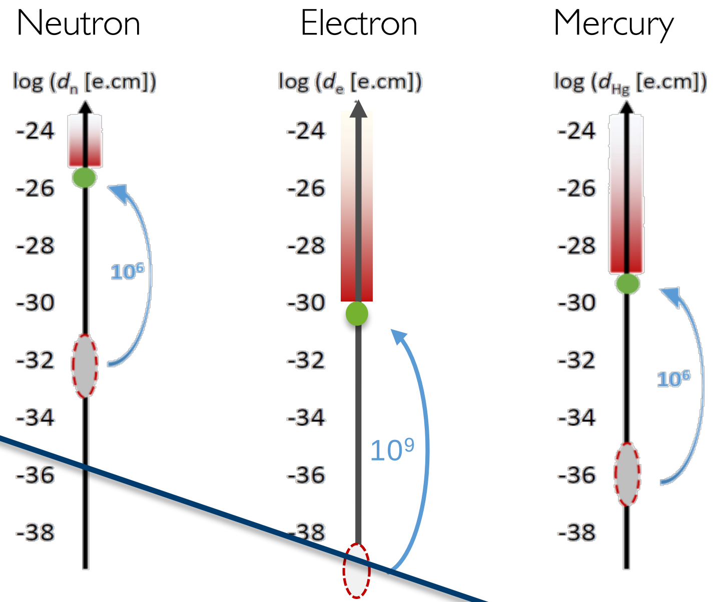
The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a



A brief history of EDM searches





First

Smith, Purcell, Ramsey

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

PR 108 (1957) 120

~ 60 years

This talk

PSI

$d_n < 1.8 \times 10^{-26}$ e cm (90% C.L.)

Abel C. et al. PRL124 (2020) 081803

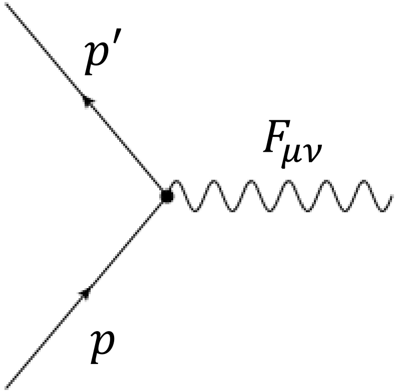
An EDM is…

… just a form factor of the electromagnetic interaction of fermions:

magnetic-dipole　　　　　　　　　Anapole - moment

$$\langle p' | J_\mu^{\mathrm{EM}} | p \rangle = \overline{\Psi}(p') \left[F_1 \gamma_\mu + \boxed{\frac{iF_2}{2M} \sigma_{\mu\nu} q^\nu} + \boxed{\frac{iF_3}{2M} \sigma_{\mu\nu} \gamma_5 q^\nu} + \frac{F_4}{M^2} \left(q^2 \gamma_\mu - \gamma^\mu q_\mu q_\mu \right) \gamma_5 \right] \Psi(p)$$

charge　　　　　　　　　electric-dipole

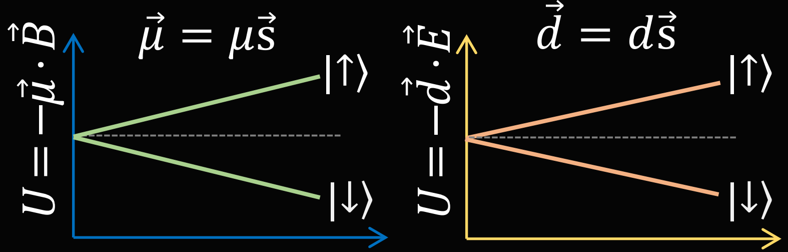


non-relativistic

$$H = -2 \left(\mu \boxed{\vec{\sigma} \cdot \vec{B}} + d \boxed{\vec{\sigma} \cdot \vec{E}} \right)$$

P,T conserving　　　　　P,T violating

CP violation & EDM



PAUL SCHERRER INSTITUT PSI

Insufficient CP-violation to explain origin of matter

The **CP**-violating phase of the CKM matrix cannot explain the observed baryon asymmetry of the Universe.

Additional sources of CP-violation beyond the standard model are needed.

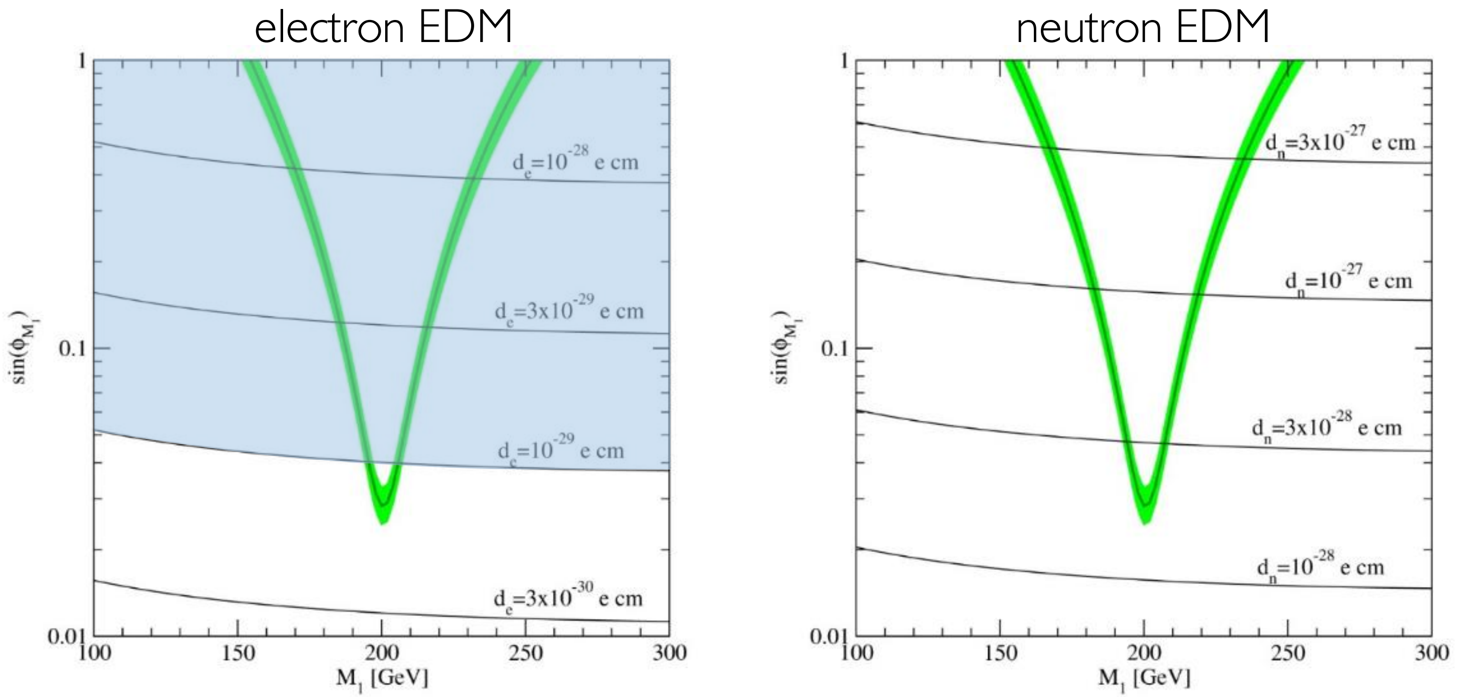
Sakharov criteria*

	Standard model	beyond SM
1. *Baryon number violation*	✓	✓
2. *C and CP violation*		✓
3. *Thermal non-equilibrium*		✓

⇨ Search for EDMs

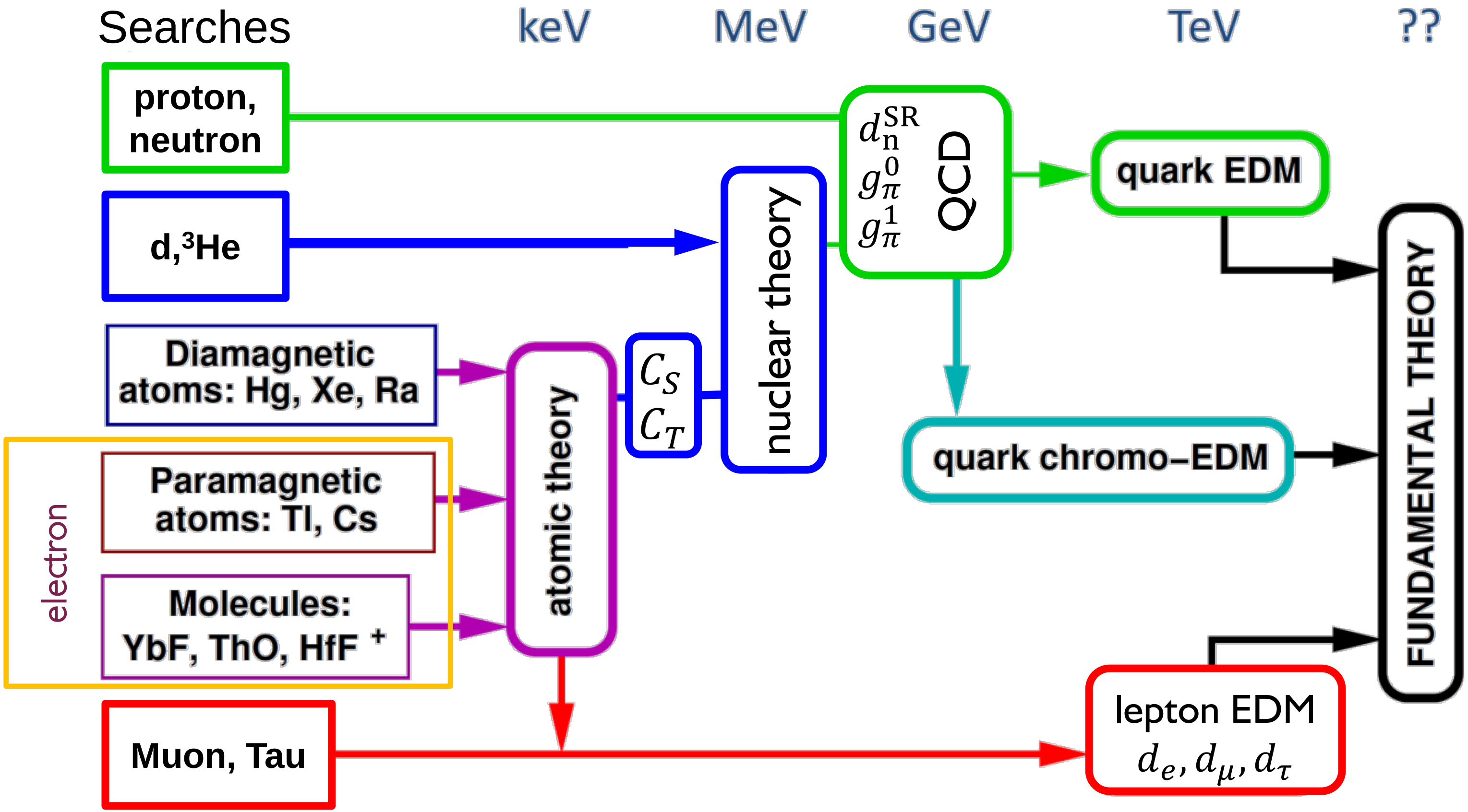
*[A. D. Sakharov, JETP 5 (1967), 32]

Testing electro-weak baryogenesis



Y. Li, S. Profumo, M. Ramsey-Musolf PLB673(2009)95
Andreev et al. (ACME), Nature562(2018)355

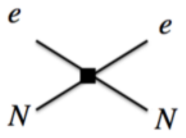
Complementarity of EDM searches



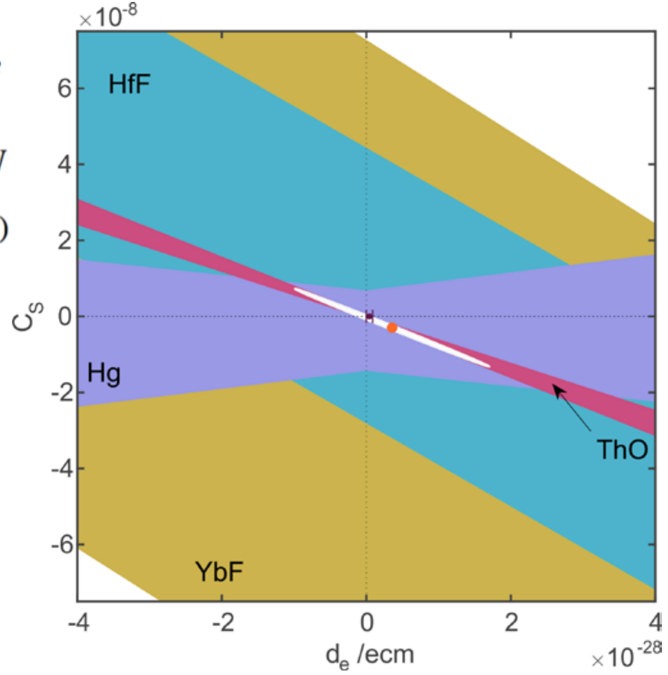
Scheme: adapted from Rob G. E. Timmermans

Electron EDM

- Several measurement of the electron EDM have different sensitivities to different CPV terms
- Adding the mercury EDM which by itself is hardly sensitive to the eEDM constraints the C_s-eEDM correlation.



$C_S(\bar{e}\, i\gamma^5 e\, \bar{N}N)$



K. Kirch and PSW, EPJ WoC 234 (2020) 01007

nucleon EDM and the QCD θ-term

$$\delta L^{\mathrm{QCD}}_{\mathrm{CPV}} = \boxed{\theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

QCD theta term "natural" in neutron, proton and nuclei

e.g. from chiral perturbation theory*

$$\frac{d_n}{\theta} \approx 2\times 10^{-16} e\mathrm{cm} \qquad \frac{d_p}{\bar{\theta}} = 2.4\times 10^{-16} e\mathrm{cm} \qquad \frac{d_d}{\bar{\theta}} = 1.4\times 10^{-17} e\mathrm{cm}$$

but

$$d^{\mathrm{ex}}_{\mathrm{n}} < 1.8\times 10^{-26}\ e\mathrm{cm}^{**}$$

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

Strong CP problem

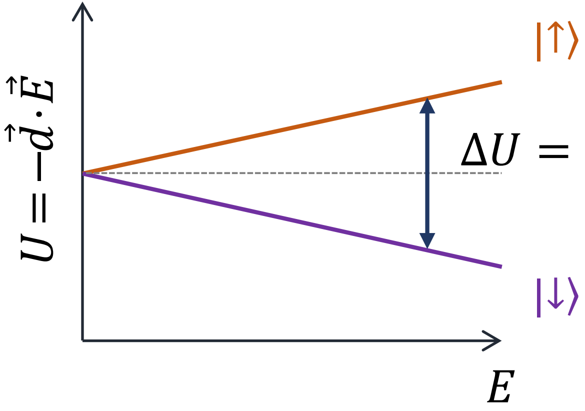
Might be solved by introducing a new chiral symmetry $U(1)_{PQ}$***,which is spontaneously broken and gives rise to the **Axion,** a viable DM candidate.

*E. Mereghetti et al., **PLB** 696 (2011) 97
Abel C. et al., **PRL 124 (2020)081803
*** R.D. Peccei and H. R. Quinn, **PRL** 38 (1977) 1440

EDM measurement basics

Measure the energy splitting

Best to measure the associated frequency ω_e



$$\Delta U = \hbar\omega_e = 2dE$$

$$f_e = \frac{2dE}{h} \approx 53\mathrm{nHz}$$

Corresponds to
1 turn in about 1 year

Systematic effect:
classical Larmor precession

$$f_L = \frac{2\mu B}{h} \approx 0.1\mathrm{mHz}$$

Corresponds to
1 turn in 2.5 h
in the best MSR

Use a magnetic field as reference

I $\quad f^{\uparrow} = \frac{2}{h}(\mu B + dE)$

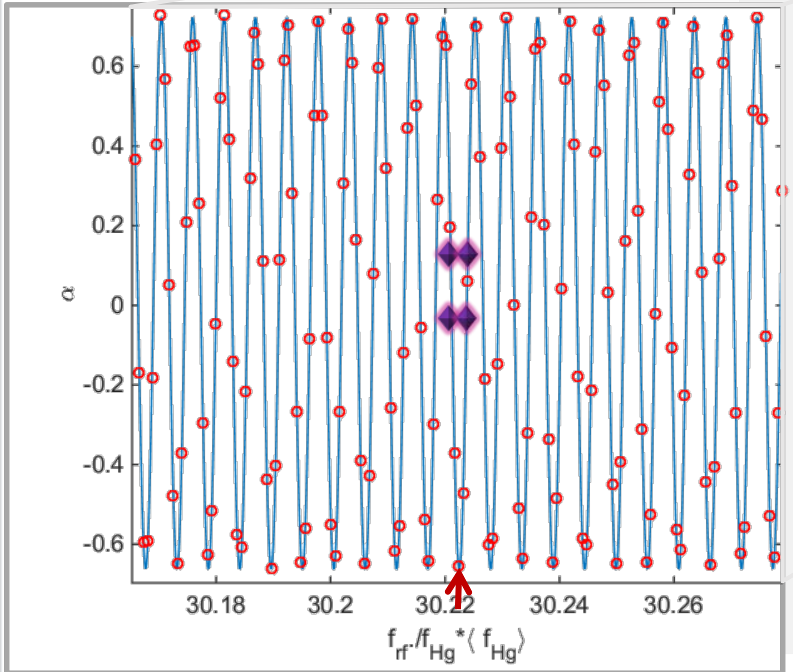
II $\quad f^{\downarrow} = \frac{2}{h}(\mu B - dE)$

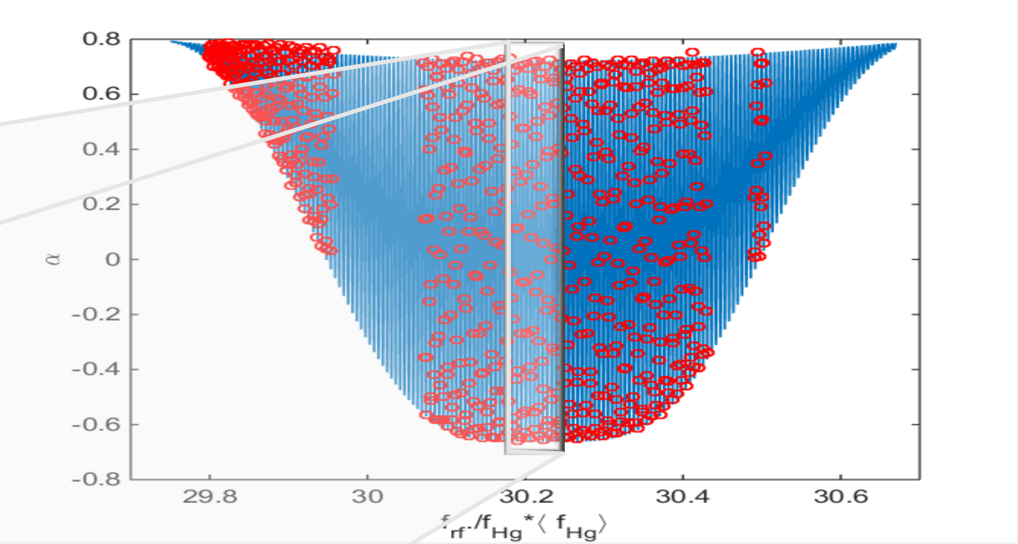
II-I $\quad \Delta f = \frac{2}{h}(\mu \Delta B - 2dE)$

$$d = \frac{h\Delta f}{4E}$$

Ramsey's technique to measure f

Spin "down" neutron...



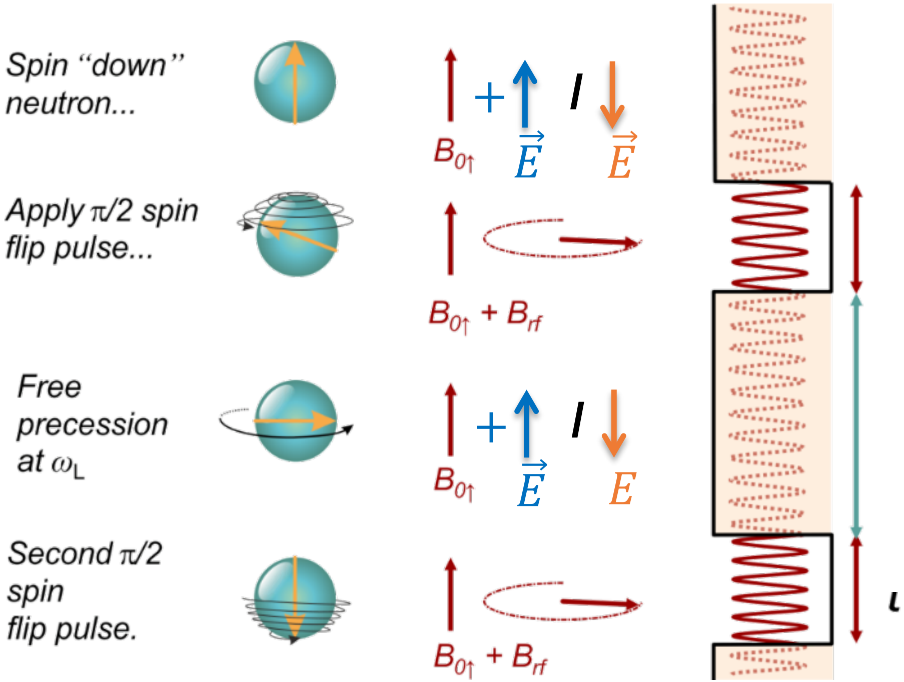


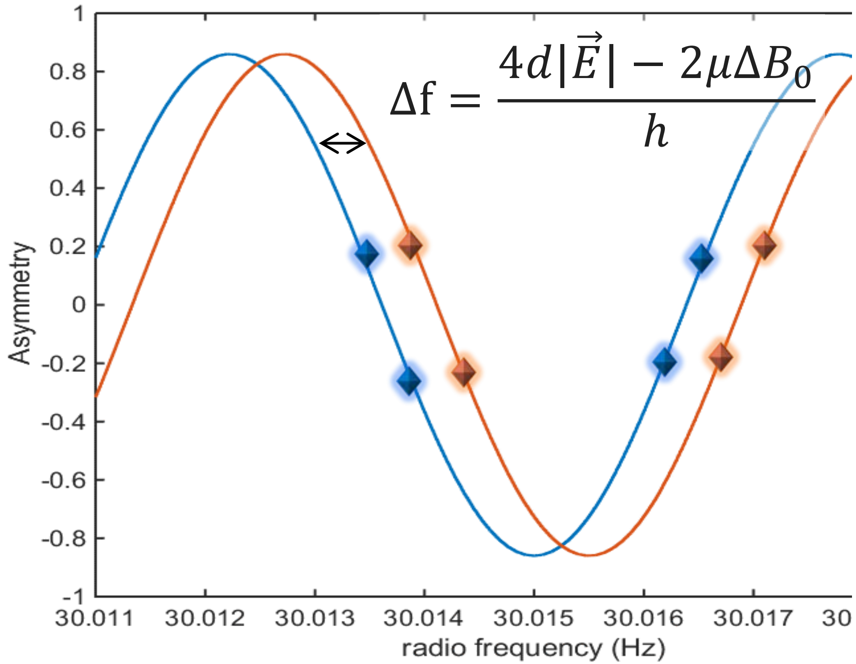
Sensitivity:

$$\sigma(\omega_n) = \frac{1}{\alpha T \sqrt{N}}$$

α	Visibility of resonance
T	Time of free precession
N	Number of neutrons

Coupling of the spin to an electric field





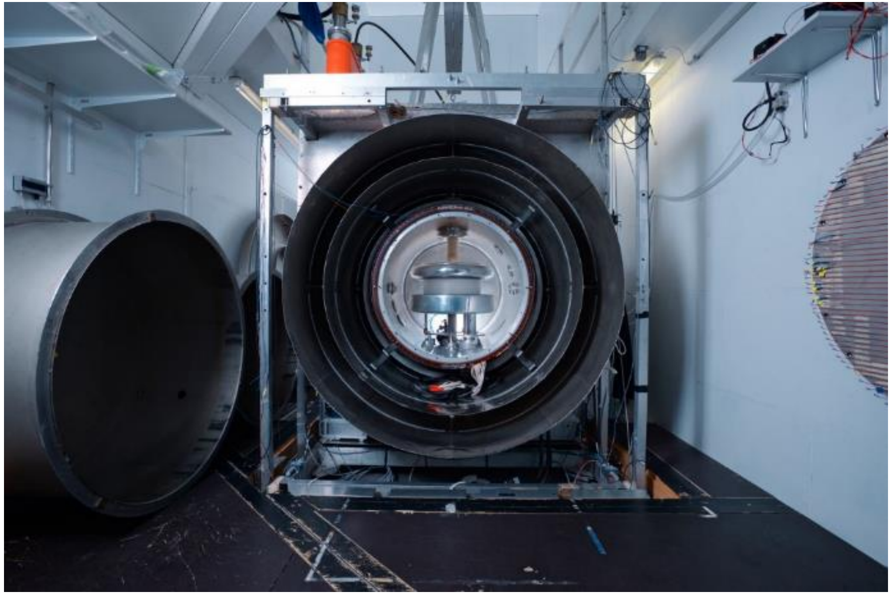
$$\Delta f = \frac{4d|\vec{E}| - 2\mu\Delta B_0}{h}$$

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

The hardware:

A historical interlude

The history of the Sussex tin can



The history of the Sussex tin can

1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997

Last beam result

Setup of tin can

1st result u. UCN

Move to turbine

2nd result

Installation of HgM

Move to the Paul Scherrer Institute

1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

ILL data taking

3rd result

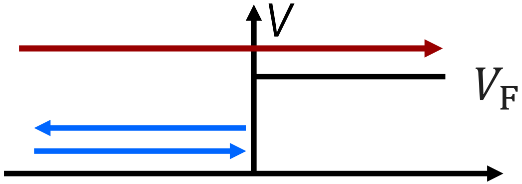
4th result

UCN source startup & nEDM upgrade

PSI data

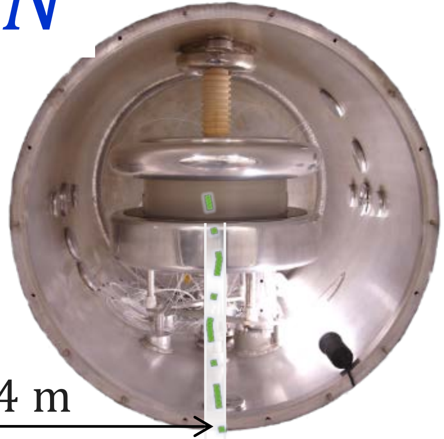
Dismantling nEDM
Installing n2EDM

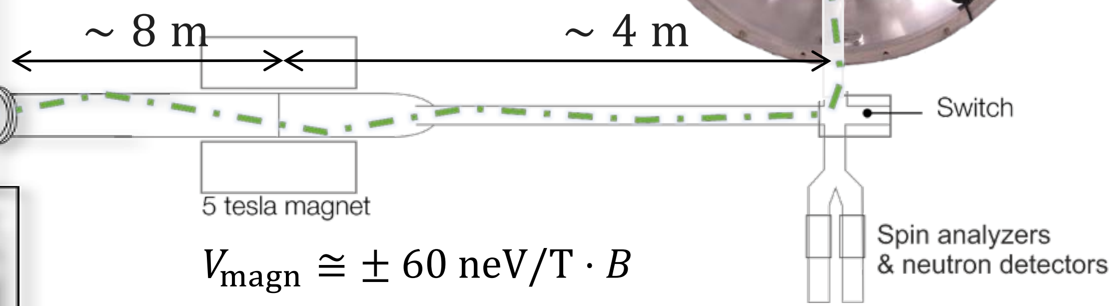
Ultracold neutrons: good for $T\sqrt{N}$



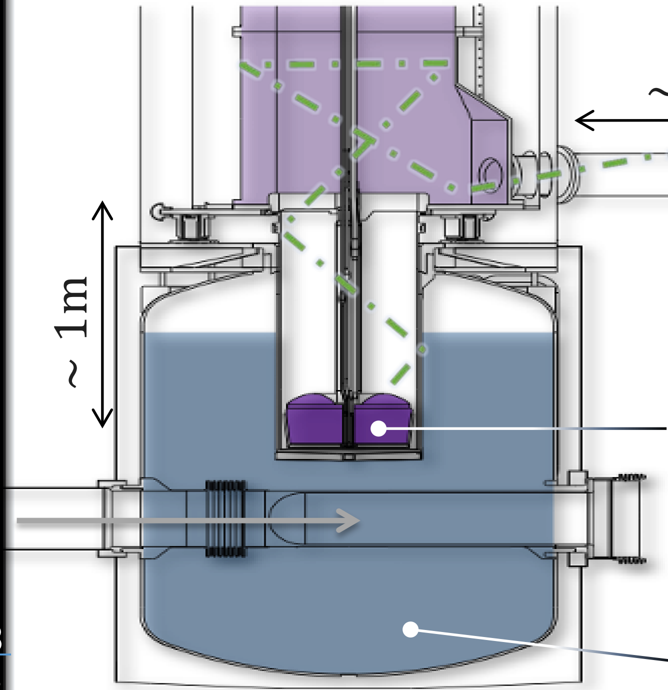
$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m_{\mathrm{n}}} bN \leq 350\mathrm{neV}$$

$$(8\mathrm{m/s},\ 3\mathrm{mK})$$





$$V_{\mathrm{magn}} \cong \pm 60\ \mathrm{neV/T} \cdot B$$



solid deuterium
(phonon excitation
→ UCN conversion)

D_2O thermal moderator

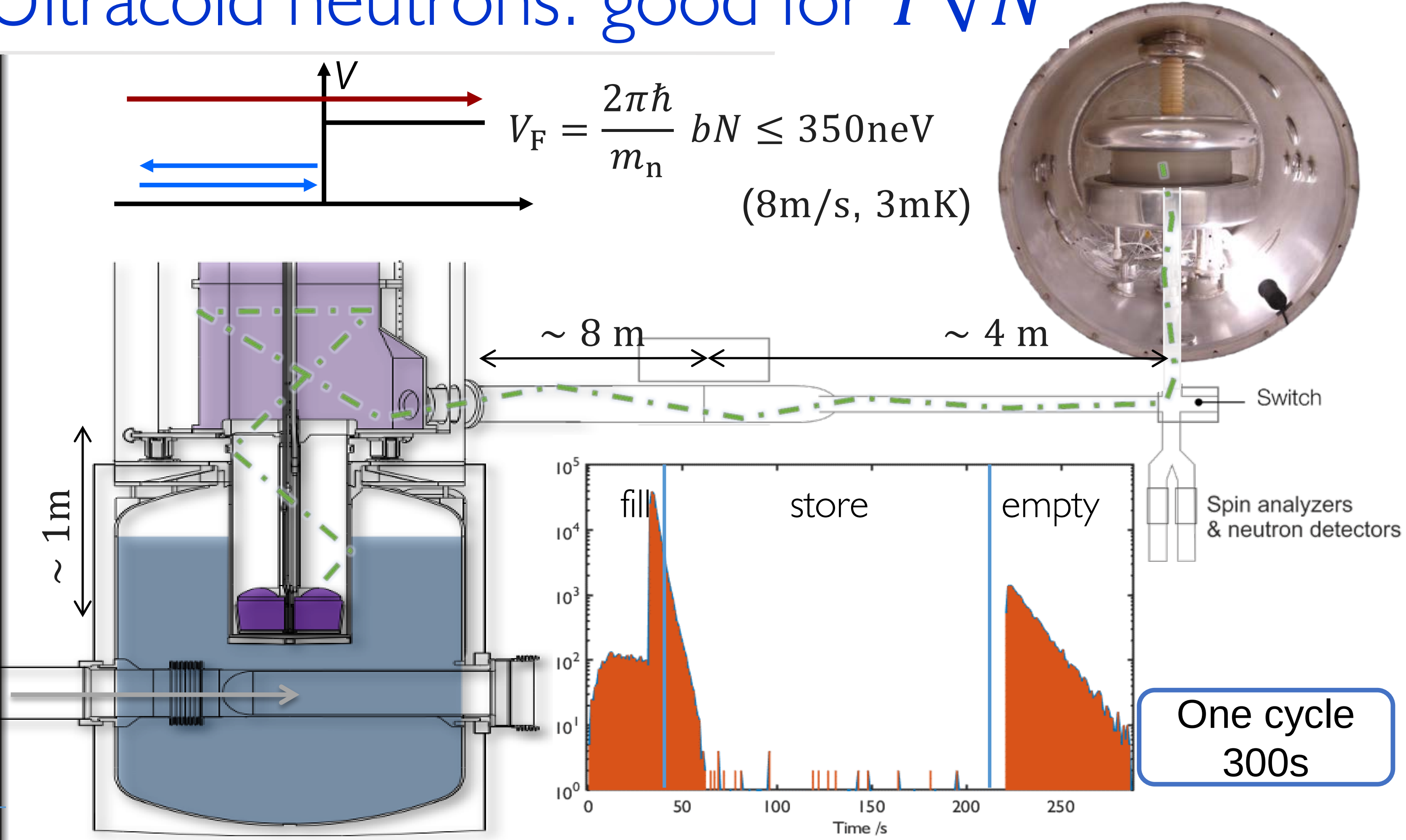
Materials used at PSI:

DLC	230neV
NiMo	220neV
dPS	165neV

Ultracold neutrons: good for $T\sqrt{N}$

$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m_{\mathrm{n}}} bN \leq 350\mathrm{neV}$$

$(8\mathrm{m/s},\ 3\mathrm{mK})$



One cycle 300s

G. Bison et al., EPJA (2020) 56:33

Increasing sensitivity

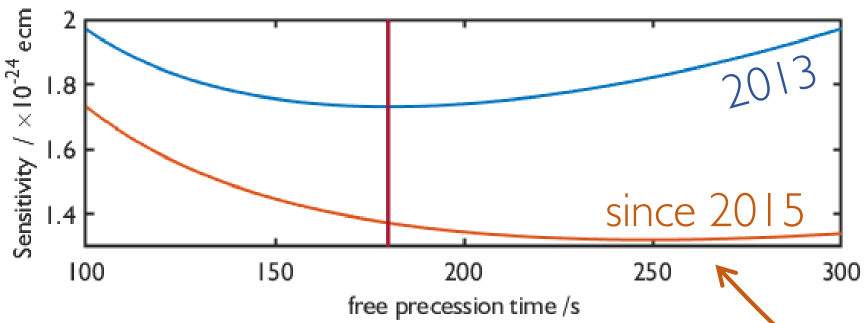
One cycle
300s

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

Many cycles
of 300s

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

$$\sigma(d_n) = \frac{\hbar}{E T \alpha_0 e^{-T/T_2} \sqrt{2 N_0 \left(e^{-T/\tau_f} + e^{-T/\tau_s}\right)}}$$



$N = 20000$, $N(180s) = 11400$

$\tau_{f,s} = 80\mathrm{s}, 180\mathrm{s}$

$E = 11\ \mathrm{kV/cm}$

$\alpha_0 = 0.76$

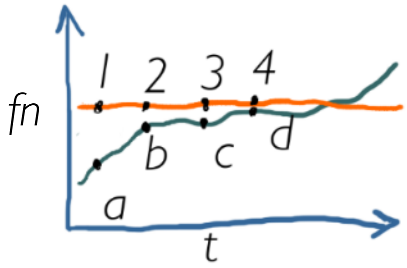
$T = 500\mathrm{s}, \boxed{1300\mathrm{s}}$

C. Abel et al., PRL 124 (2020) 081803

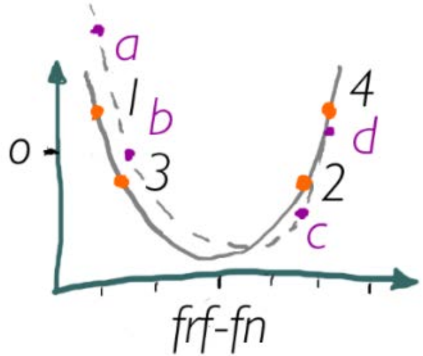
Sensitivity versus field drifts

- Sensitivity for many cycles ideal case:

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



- Only if magnetic field is stable enough.
(Good fit with orange,
bad fit with purple)

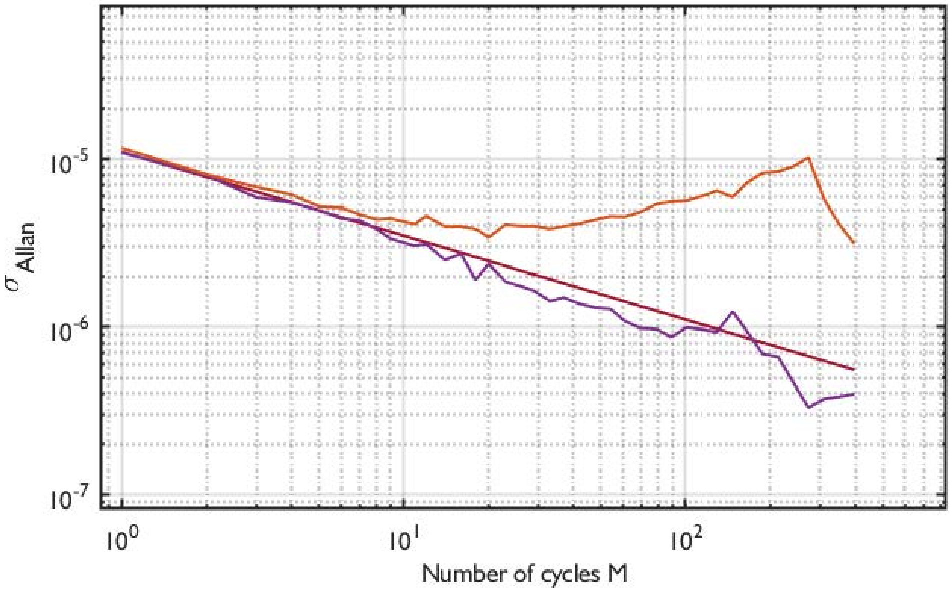


Stability and changing E-fields

$$\Delta f = \frac{4d_n|\vec{E}| - 2\mu\Delta B_0}{h}$$

Options with field changes:

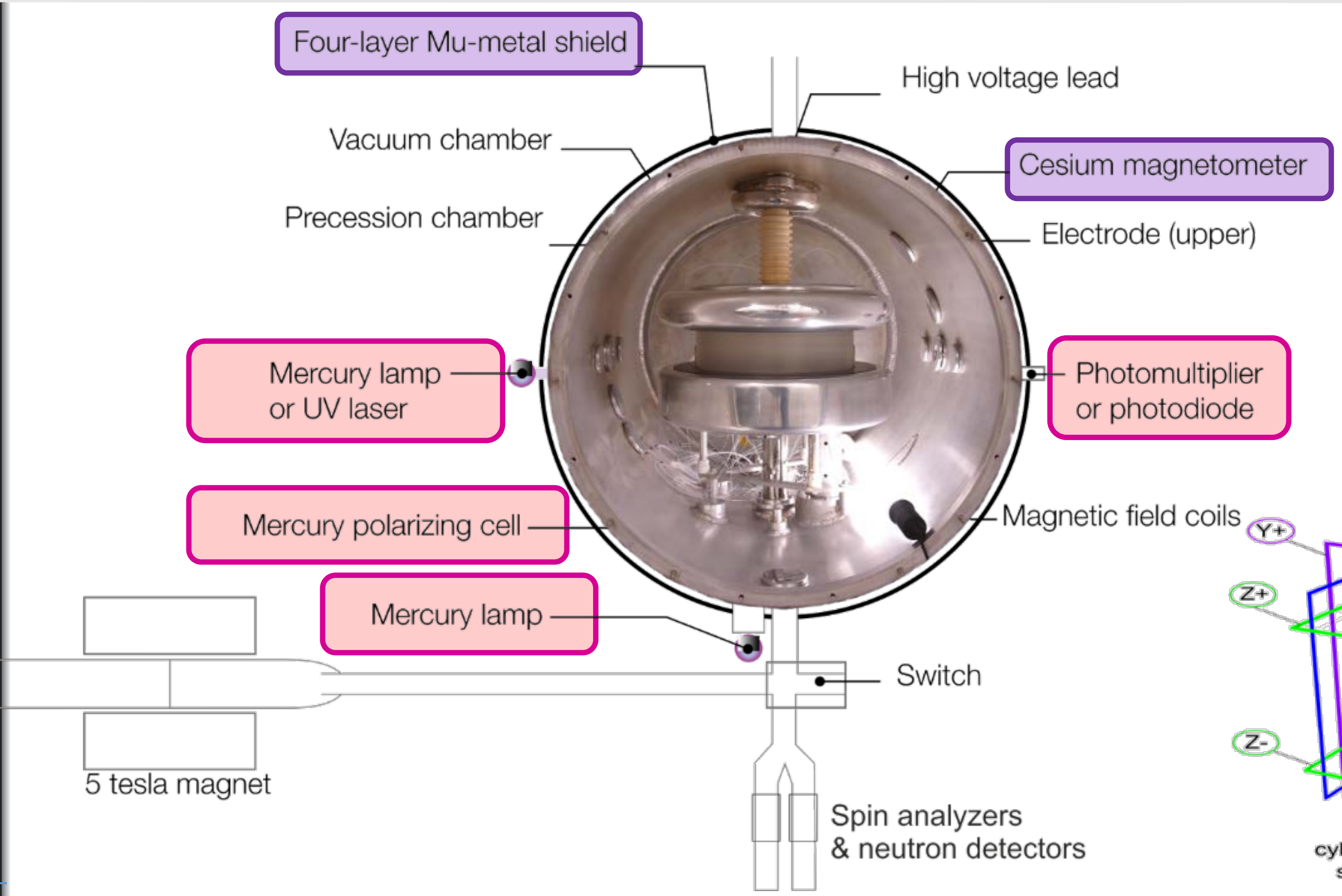
- Change E-field with adequate period (e.g. every 10 cycles) (loose time due to E ramps)
- Use a stack of two neutron precession chambers
- Use a comagnetometer



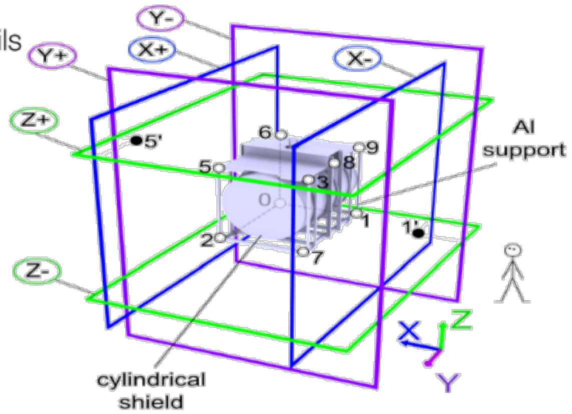
Gatchina's double chamber design

Sussex's co-magnetometer

The nEDM spectrometer

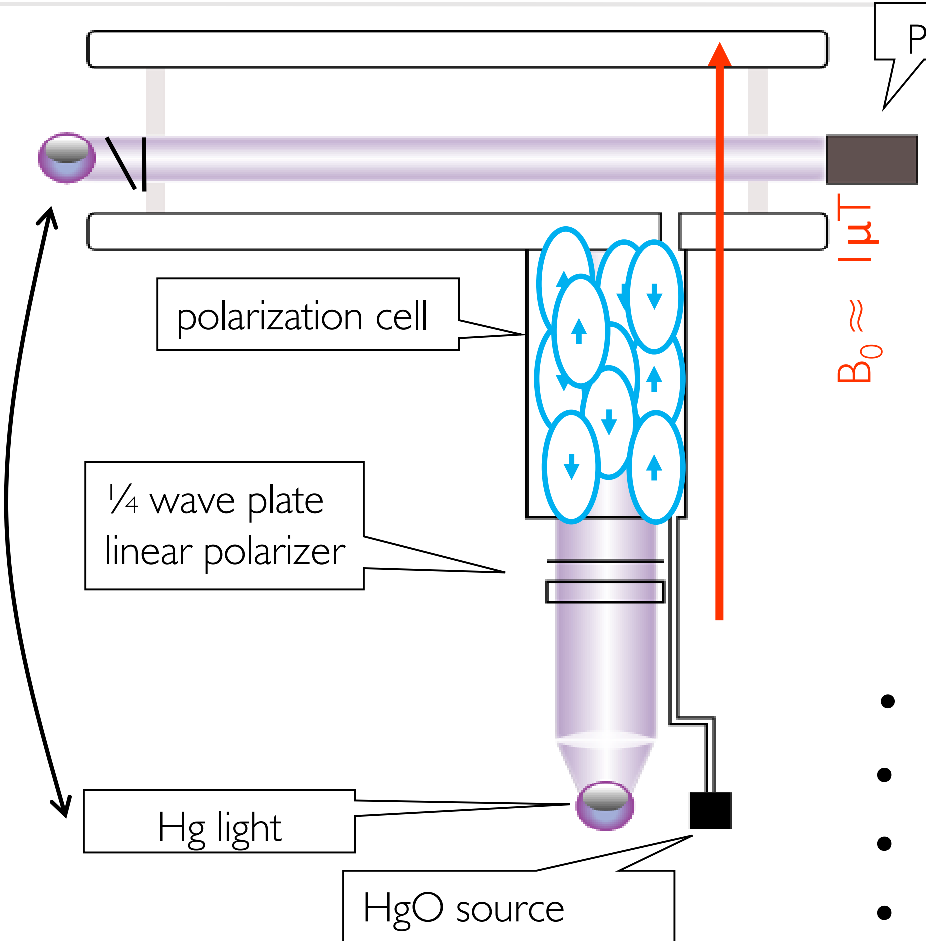


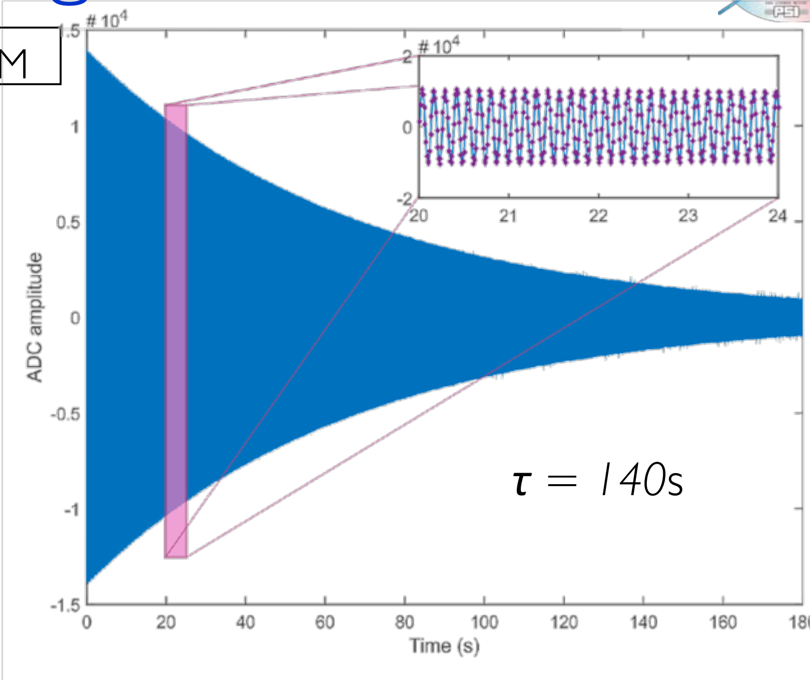
Active magnetic shield



S. Afach et al., JAP 116 (2014) 084510

Mercury comagnetometer

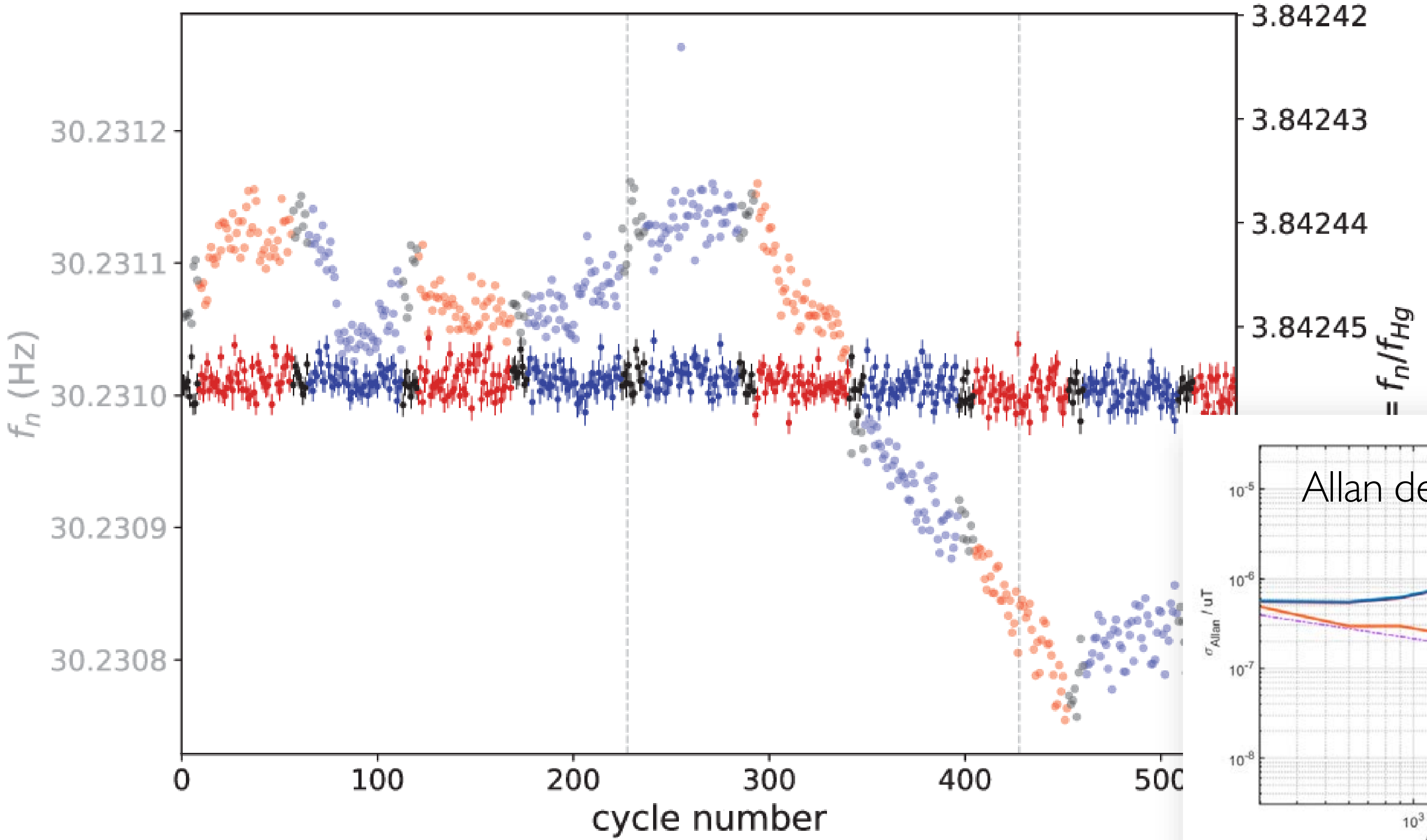


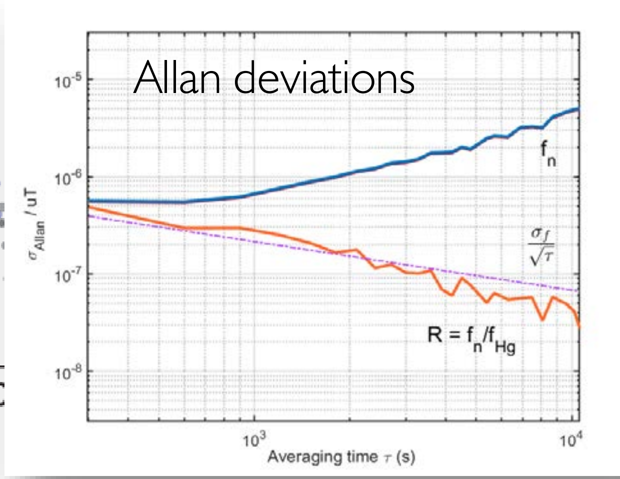


- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with ~ 90 s)
- $s/n > 1000$

K. Green et al., NIMA 404 (1998) 381
G. Ban et al., NIMA 896 (2018) 129

Real data example (stability)





Systematic effects (no free meals)

Express EDM with ratios:

$$d_{\mathrm{n}} = \frac{\hbar\langle\omega_{\mathrm{Hg}}\rangle}{4E}(R_{+} - R_{-})$$

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \Big(1 \underbrace{\pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}}}_{\text{E-field}} \underbrace{+\delta_{\mathrm{G}} + \delta_{\mathrm{T}}}_{\text{B-field}} \underbrace{+ \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}}_{\text{Secondary effects}}\Big)$$

- nEDM
- HgEDM

Linear effect ($v \times E$)

- "geometric phase"
- Ordered motion

Quadratic effect (neutron and Hg, random motion)

ll E-

n all

Secondary effects cancel unless correlated with E-field.

$v \times E$ the 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 non-uniform B-field and E-field:

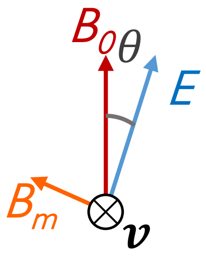
Rabi: Spin rotation due to oscillating horizontal field. This leads to a shift (Ramsey, Bloch, Siegert) of the resonance frequency by

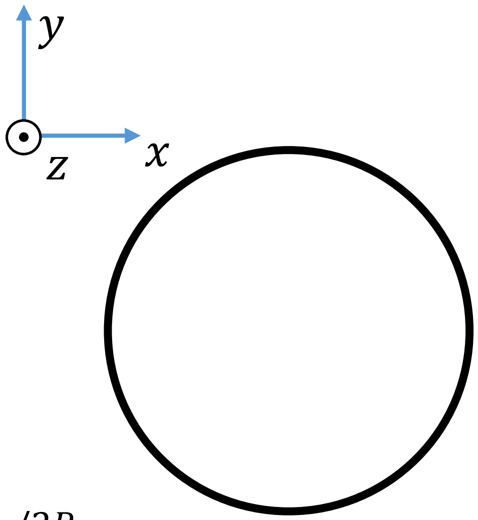
$$\Delta\omega = \frac{(\gamma_n B_\perp)^2}{2(\gamma_{\mathrm{n}} B_0 - \omega_r)}$$

with

$$B_\perp = \frac{\partial B_z}{\partial z}\frac{r}{2} + \frac{v_r E}{c^2}$$

and the oscillation ω_r is a result of rapidly changing trajectories, e.g. $\omega_r = v_r/2R$





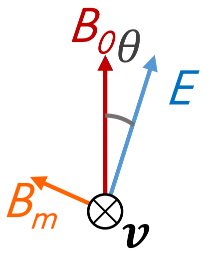
J.M. Pendlebury et al., **PRA** 70 (2004) 032102
G. Pignol and S. Roccia, **PRA** 85 (2012) 042105

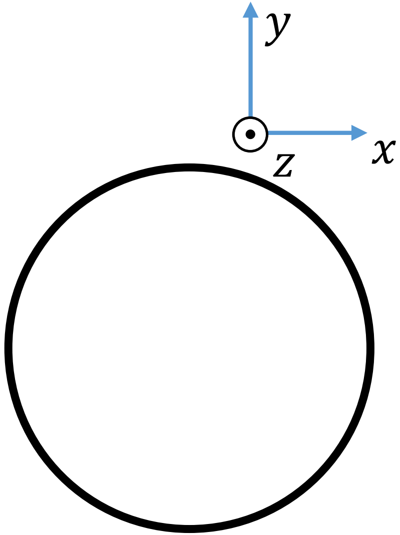
$v \times E$ the dominant systematic

- Motional magnetic field from $B_{\mathrm{m}} = -\frac{v \times E}{c^2}$
- In non-uniform B-field and E-field:

$$B_{\perp}^2 = \left(\frac{\partial B_z}{\partial z}\frac{r}{2}\right)^2 + r\frac{\partial B_z}{\partial z}\frac{v_r E}{c^2} + \left(\frac{v_r E}{c^2}\right)^2$$

- The term linear in E will lead to a electric field induced shift of precession frequency, **an EDM like signal.**





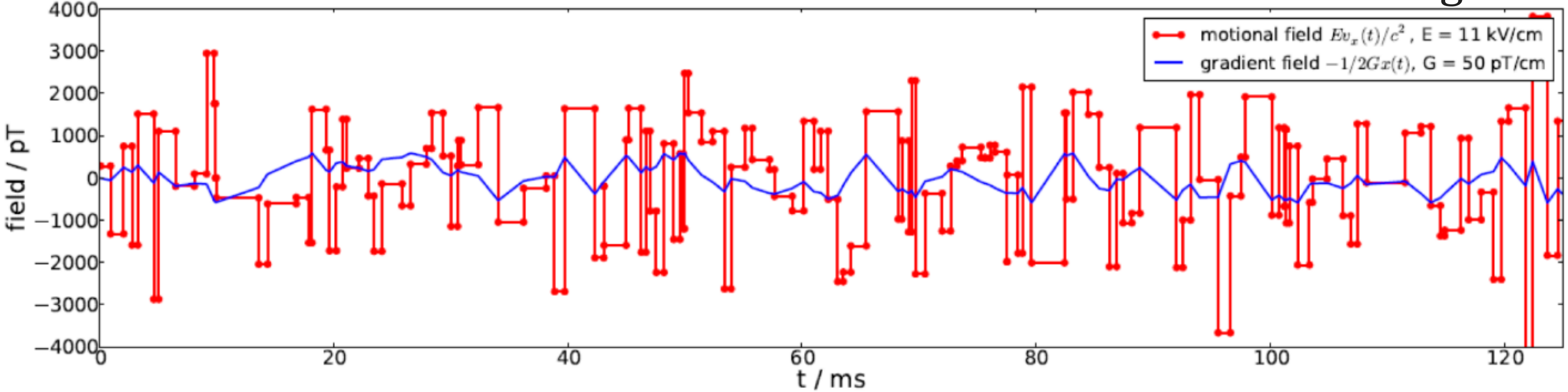
$$\Delta\omega_{\mathrm{f}} = r\frac{\partial B_z}{\partial z}\frac{v_r E}{2c^2(\gamma_{\mathrm{n}} B_0 - \omega_r)}$$

Different for neutrons (adiabatic), and mercury (ballistic/non-adiabatic)

J.M. Pendlebury et al., **PRA** 70 (2004) 032102

Motional false effect from ^{199}Hg

The dominant effect is transferred from ^{199}Hg to neutron: $d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}}$



$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar\gamma_{\mathrm{n}}\gamma_{\mathrm{Hg}}}{2c^2}\langle xB_x + yB_y\rangle = \frac{\hbar\gamma_{\mathrm{n}}\gamma_{\mathrm{Hg}}}{32c^2}D^2 G_{1,0}$$

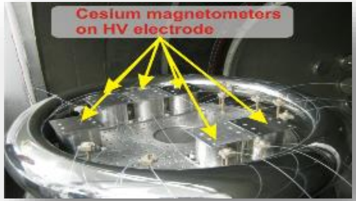
with
D = 47cm

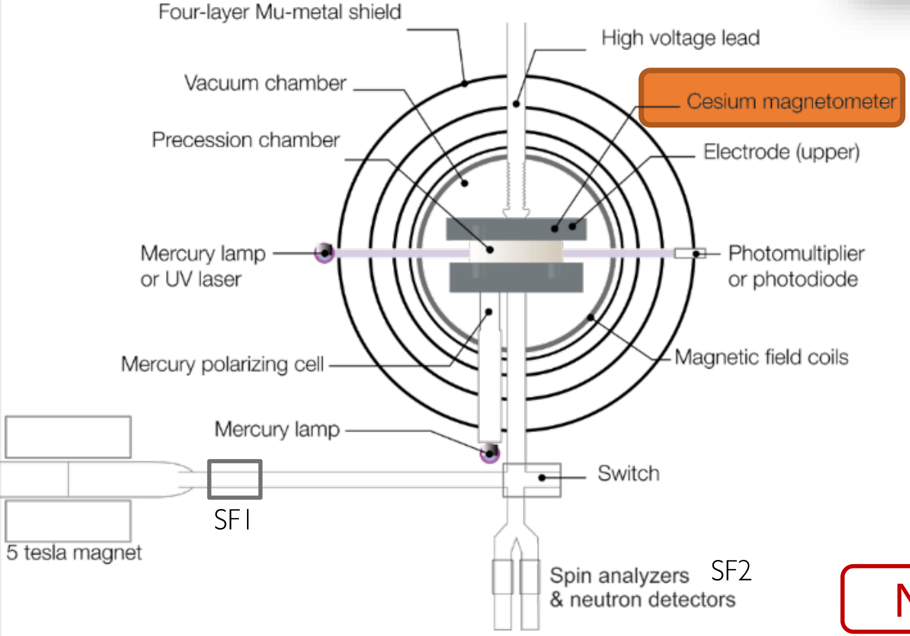
$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = G_{1,0}\, 4.4\times 10^{-27} e\,\frac{\mathrm{cm}^2}{\mathrm{pT}}$$

G. Pignol and S. Roccia, **PRA** 85 (2012) 042105
Guillaume Pignol, **PLB** 793 (2019) 440

Measure EDM vs $G_{1,0}$

- Cesium magnetometer array for field gradients





Use polynomial decomposition to calculate non-uniform field

$$\vec{B}(\vec{r}) = \sum_{l,m} G_{l,m} \begin{pmatrix} \Pi_{x,l,m}(\vec{r}) \\ \Pi_{y,l,m}(\vec{r}) \\ \Pi_{z,l,m}(\vec{r}) \end{pmatrix}$$

$$\sigma(G_{1,0}) \approx 8\ \mathrm{pT/cm}$$

Not sufficient to correct for systematic

C. Abel et al., PRA 99 (2019) 042112
C. Abel et al., PRA 101 (2020) 053419

Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right|\left(1 \pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}} + \delta_{\mathrm{G}} + \delta_{\mathrm{T}} + \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}\right)$$

$\frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$ $^{199}\mathrm{Hg}$ UCN $\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$

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

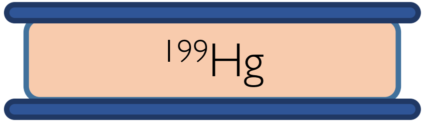
$$R \cdot \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| - 1 = \delta_{\mathrm{G}} = \pm \frac{\langle z \rangle G_{1,0}}{B_0}$$

Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_{\pm} = \frac{f_{\rm n}}{f_{\rm Hg}} = \left|\frac{\gamma_{\rm n}}{\gamma_{\rm Hg}}\right| \left(1 \pm \delta_{\rm EDM} \pm \delta_{\rm EDM}^{\rm false} + \delta_{\rm Q} + \delta_{\rm G} + \delta_{\rm T} + \delta_{\rm E} + \delta_{\rm LS} + \delta_{\rm I} + \delta_{\rm P} + \delta_{AC}\right)$$

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



$\frac{\gamma_{\rm n}}{2\pi} \approx 30$ Hz/μT

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

$$R \cdot \left|\frac{\gamma_{\rm n}}{\gamma_{\rm Hg}}\right| - 1 = \delta_{\rm G} + \delta_{\rm T} = \pm \frac{\langle z \rangle G_{1,0}}{B_0} + \frac{\langle B_{\rm T}^2 \rangle}{2B_0^2}$$

Needs to be known for each measurement

Maximize field uniformity

- Use variometer method field information
- Use known sensitivity of each CsM to changes of any of 30 trim coils
- Use field information from offline field maps for $\langle B_{\mathrm{T}}^2 \rangle$

Initial polarization (prior $\pi/2$ flip)

$$\alpha_0 = 0.86$$

Best polarization after **180 s** free precession

$$\alpha_{180} = 0.81$$

Average:

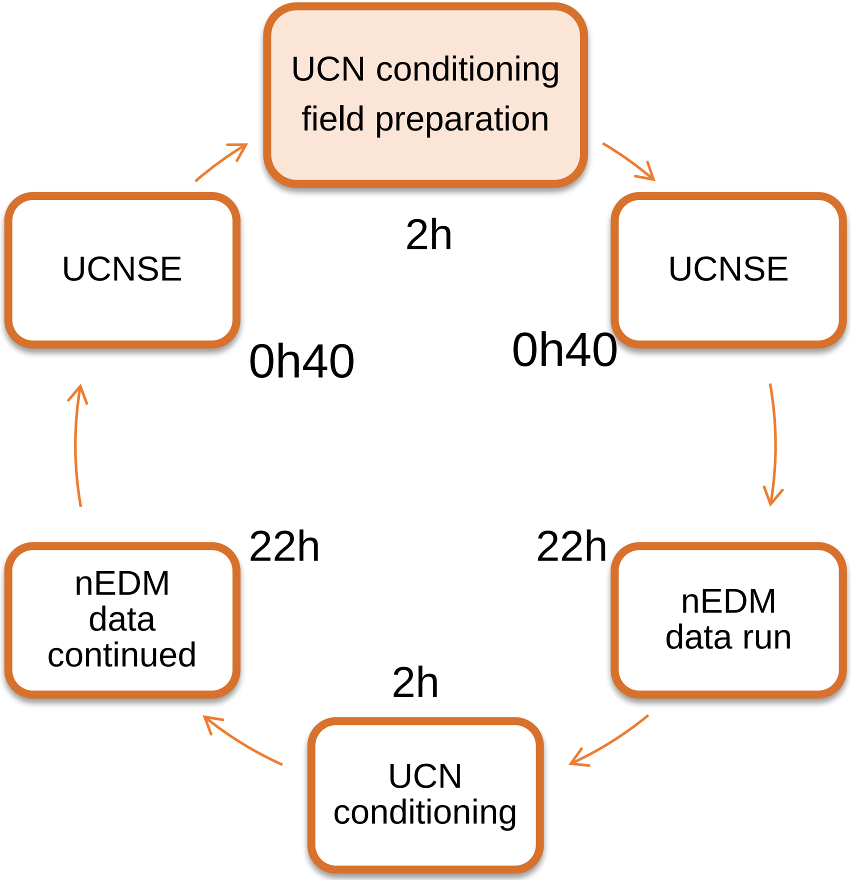
$$\overline{\alpha_{180}} = 0.76$$

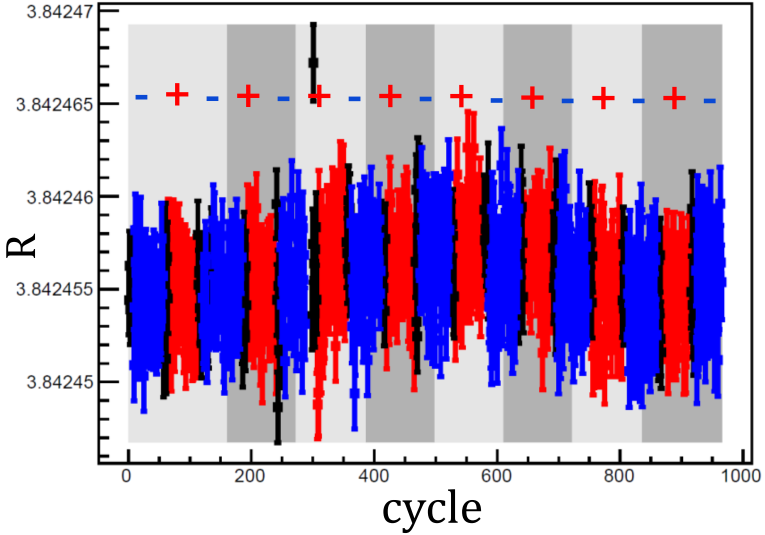
$$\mathrm{T}_2 = -180\mathrm{s} \,/\, \ln\left(\frac{\alpha_{180}}{\alpha_0}\right) = 3000s$$

$$\overline{T_2} = -180\mathrm{s} \,/\, \ln\left(\frac{\overline{\alpha_{180}}}{\alpha_0}\right) = 1315s$$

C. Abel et al., PRA 101 (2020) 053419

Data taking





$$d_n = \frac{\hbar \langle \omega_{Hg} \rangle}{4E}(R_+ - R_-)$$

with $R = f_n / f_{Hg}$

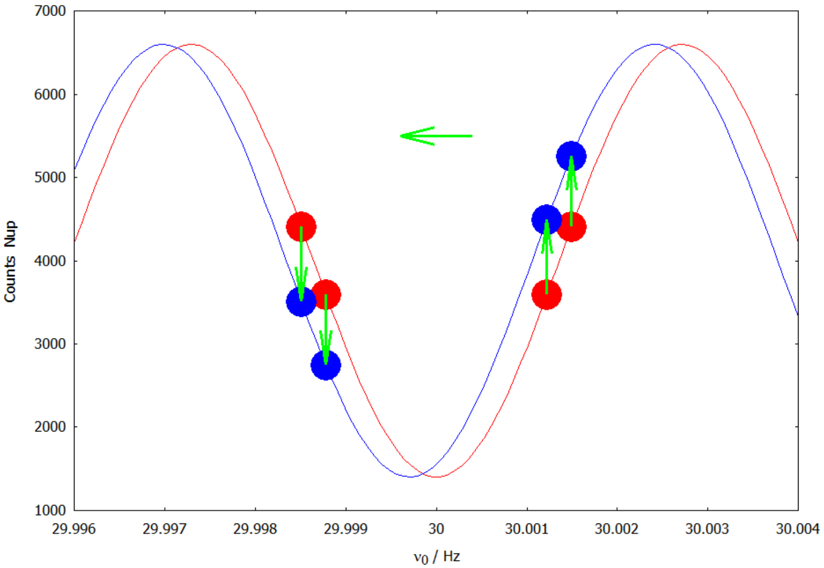
Blinding

- Shift the central value by adding an unknown offset EDM of **-1.5** to **1.5E-25** ecm 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)
- Two blinding levels
  - Primary blinding same for both analysis groups
  - Secondary blinding layer different for both groups



N.J. Ayres et al. arXiv:1912.09244

Path to a new result (PSI)

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = \left(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{syst}}\right) \times 10^{-26}\, e\text{cm}$$

$$d_n = \left(?_{3} \pm ?_{1}\,\text{tat} \pm ?_{2}\,\text{yst} \right) \times 10^{-26}\, e\text{cm}$$

99 sets
54068 cycles
11400 neutrons counted per cycle

Divide data into sets

- Each set has one fixed gradient (typically 48h long)
- Each set is subdivided into subsets with at least two E-field reversals (ABBA) with $A = \pm E$ and B inverse
- Length of typical subset approximately 112 cycles
- SF1 at entrance was flipped every 112 cycles

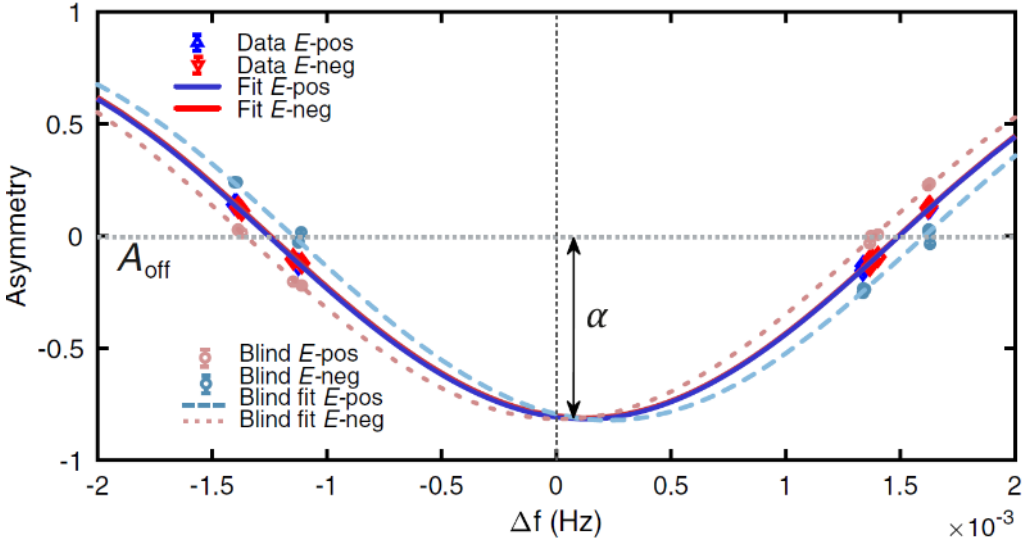
0AA0BB0AA0BB0AA0BB0A

0AA0BB0AA0BB0AA0BB0AA0B

SF1	0	1	0	1

Single Ramsey fit

- One fit per subsequence: combine all E-field states SF2 and SF1 states
   - A total of 8 fit parameters
   - Parameter errors are small due to high number of **dof.**



$$A_i = \underbrace{A_{\mathrm{off}(1-4)}}_{4} - \underbrace{\alpha}_{2} \cos\left(\frac{\omega_{\mathrm{rf}} - \omega_{\mathrm{cor}}}{\Delta\nu} - \Phi_1 - E\frac{\mathrm{d}\phi_2}{\mathrm{d}E}\right)$$

depends on SF1 and SF2 state

one for each SF1

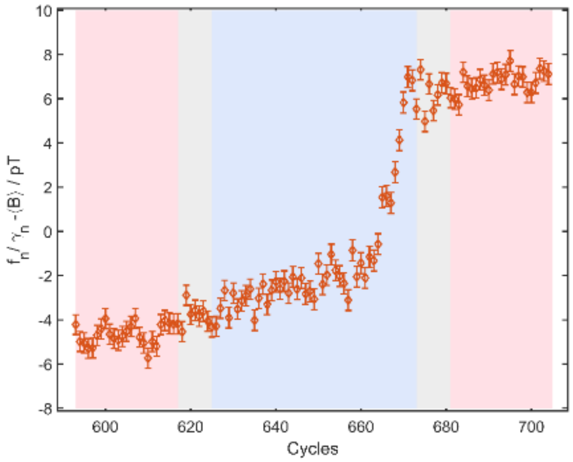
blinding

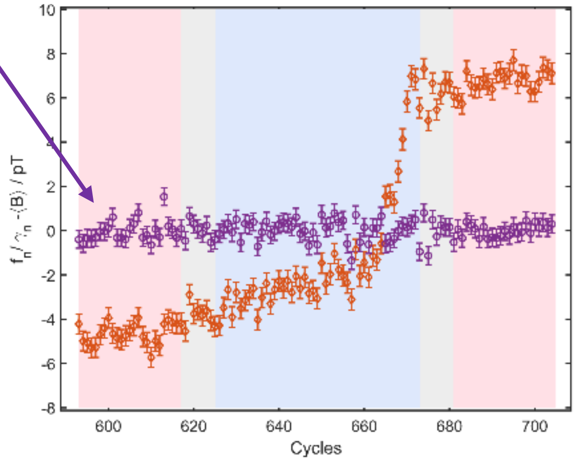
Single point fit to obtain f_n

- Fix all parameters of the fix but ϕ_1^i for each cycle *i*, and solve cosine equation for ϕ_1^i.

$$\Rightarrow f_n^i = \frac{\phi_1^i}{2\pi T'} \Rightarrow \boxed{R^i = \frac{f_n^i + \langle z \rangle \Delta g}{f_{Hg}^i}}$$

- As we use the same parameters from the original Ramsey fit for each cycle, a full covariant error propagation is required in the next step.

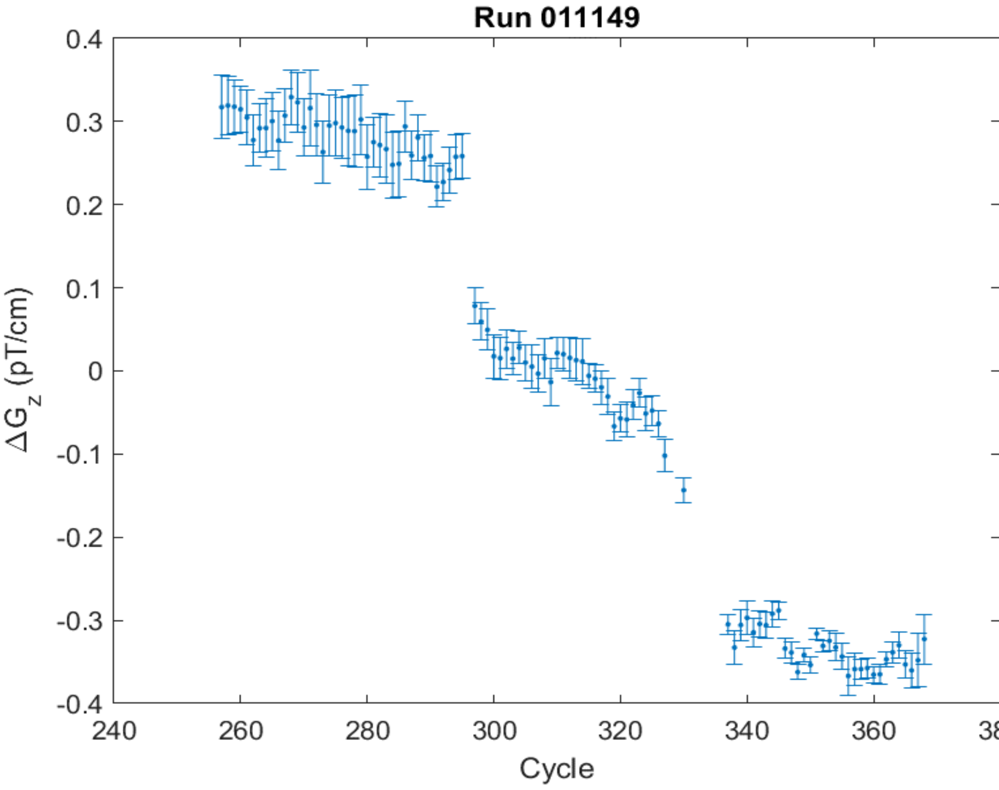




Gradient drift correction

For each subset a relative gradient Δg was calculated:

- Exclude sensors at high voltage
- Use 9 ground CsM and HgM
- Subtract mean value of each sensor for entire subset
- Polynomial expansion up to second order
- Use G_{10} and error for correction



Obtain d_{n} from R

Remaining drifts in R required to employ an R vs (t, E) fit:

Minimize

$$(R - Ax)^{-1} C^{-1} (R - Ax)$$

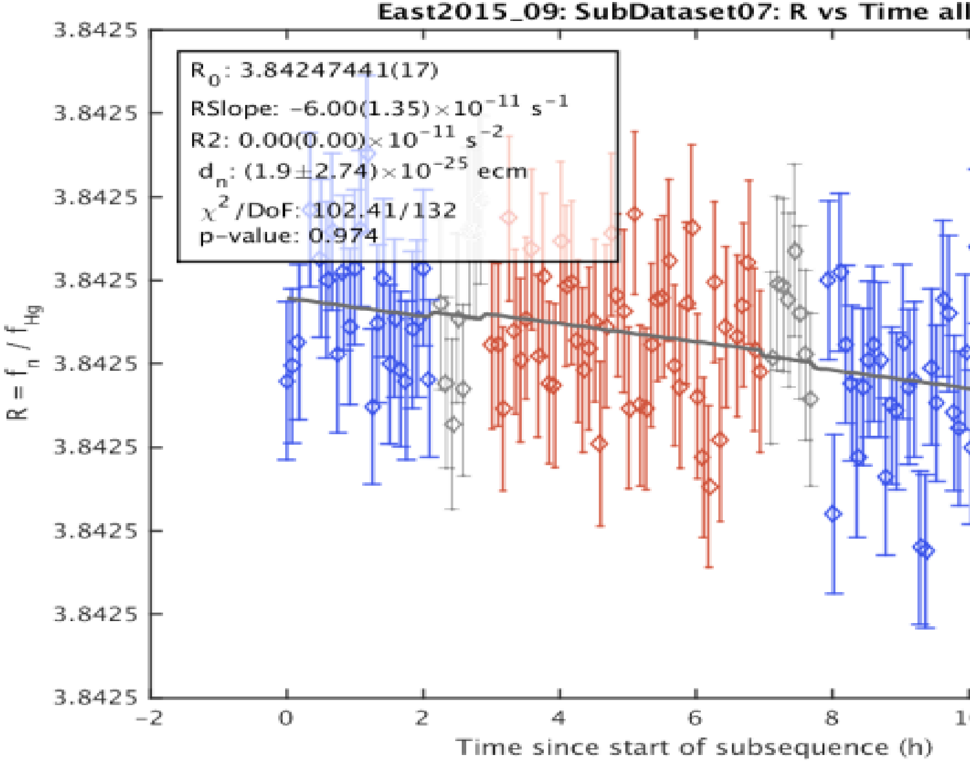
with

$$Ax = \begin{bmatrix} 1 & t_1 - \langle t \rangle & E_1 \\ 1 & t_2 - \langle t \rangle & E_2 \\ \vdots & \vdots & \vdots \\ 1 & t_n - \langle t \rangle & E_3 \end{bmatrix} \begin{pmatrix} R_{\mathrm{sub}} \\ \mathrm{d}R/\mathrm{d}t \\ a \end{pmatrix}.$$

From a we deduce the EDM for each subset:

$$d_{\mathrm{n}} = \mp a \frac{h}{\langle f_{\mathrm{Hg}} \rangle}$$

$$R(t) = \frac{\mathrm{d}R}{\mathrm{d}t}(t - \langle t \rangle) + E(t) \cdot a + R_{\mathrm{sub}}$$



Analysis flow diagram:

ABBA division → Ramsey fit → R-value per cycle → Gradient correction → Fit time series $\rightarrow d_{\mathrm{n}}, R$ → Average d_{n}, and R for each gradient → 99 sequences (d_{n}, R)

New Result (PSI)

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = \left(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{syst}}\right) \times 10^{-26}\ ecm$$

$$d_n = \left(\ ?_{3} \pm\ ?_{1}\,\text{tat} \pm\ ?_{2}\,\text{syst}\right) \times 10^{-26}\ ecm$$

99 sequences
54068 cycles
11400 neutrons counted per cycle

Systematic effects

Table I: Summary of systematic effects in 10^{-28} $e$cm. The first three effects are treated within the crossing-point fit and are included in $d_{\times}$. The additional effects below the line are considered separately.

	Effect	shift	error
False Hg EDM	Error on $\langle z \rangle$		
	Higher order gradients $\hat{G}$		
	Transverse field correction $\langle B_T^2 \rangle$		
Other effects	Hg EDM[8]		
	Local dipole fields		
	$v \times E$ UCN net motion		
	Quadratic $v \times E$		
	Uncompensated G drift		
	Mercury light shift		
	Inc. scattering ^{199}Hg		
	TOTAL		

Field mapping

Effect of higher order gradients

$$R_\pm = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| \left(1 \pm \delta_\mathrm{EDM} \pm \delta_\mathrm{EDM}^\mathrm{false} + \delta_\mathrm{Q} + \delta_\mathrm{G} + \delta_\mathrm{T} + \delta_\mathrm{E} + \delta_\mathrm{LS} + \delta_\mathrm{I} + \delta_\mathrm{P} + \delta_{AC}\right)$$

$$\delta_\mathrm{G} = \pm\frac{\langle z\rangle G_{1,0}}{|B_0|}$$

and

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^\mathrm{false} = \frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2} D^2 G_{1,0}$$

is not the full story, but…

… neither.

But instead:

$$\delta_\mathrm{G} = \frac{\langle z\rangle G_\mathrm{g}}{|B_0|}$$

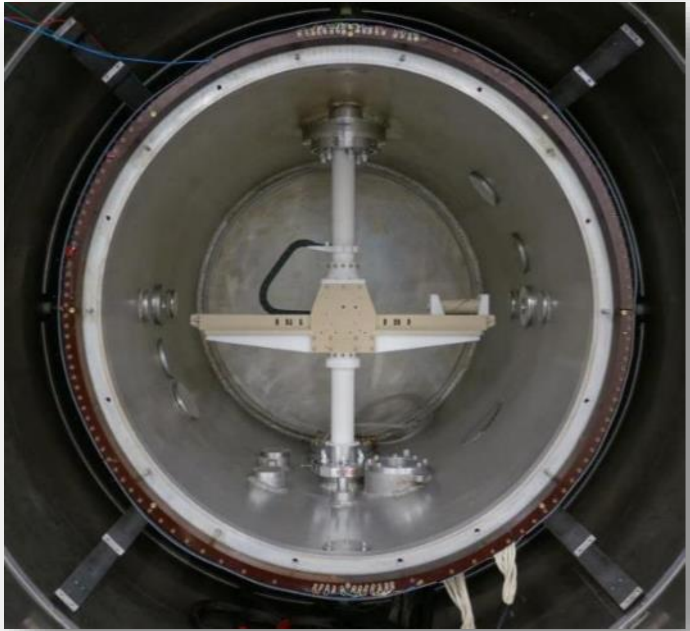
with

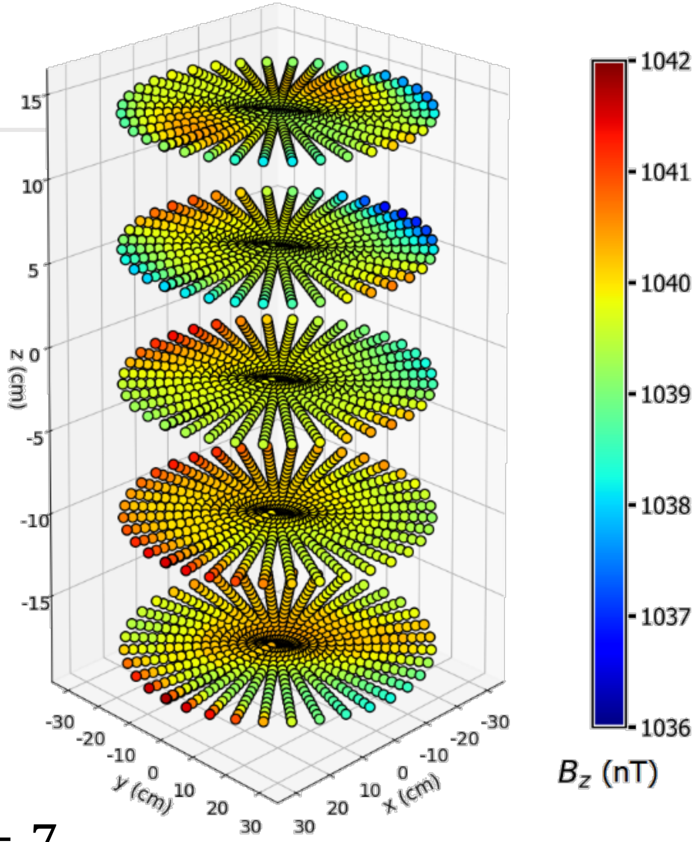
$$G_\mathrm{g} = \mathrm{G}_{10} + \mathrm{G}_{30}\left(\frac{3H^2}{20} - \frac{3D^2}{16}\right) + \cdots$$

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^\mathrm{false} = -\frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2}\sum_{l\ \mathrm{odd}} G_{l0}\langle\rho\Pi_{\rho lm}\rangle$$

$$= \frac{\hbar\gamma_\mathrm{n}\gamma_\mathrm{Hg}}{32c^2} D^2 \left[G_{10} - G_{30}\left(\frac{D^2}{8} - \frac{H^2}{4}\right)\right.$$

Magnetic field maps



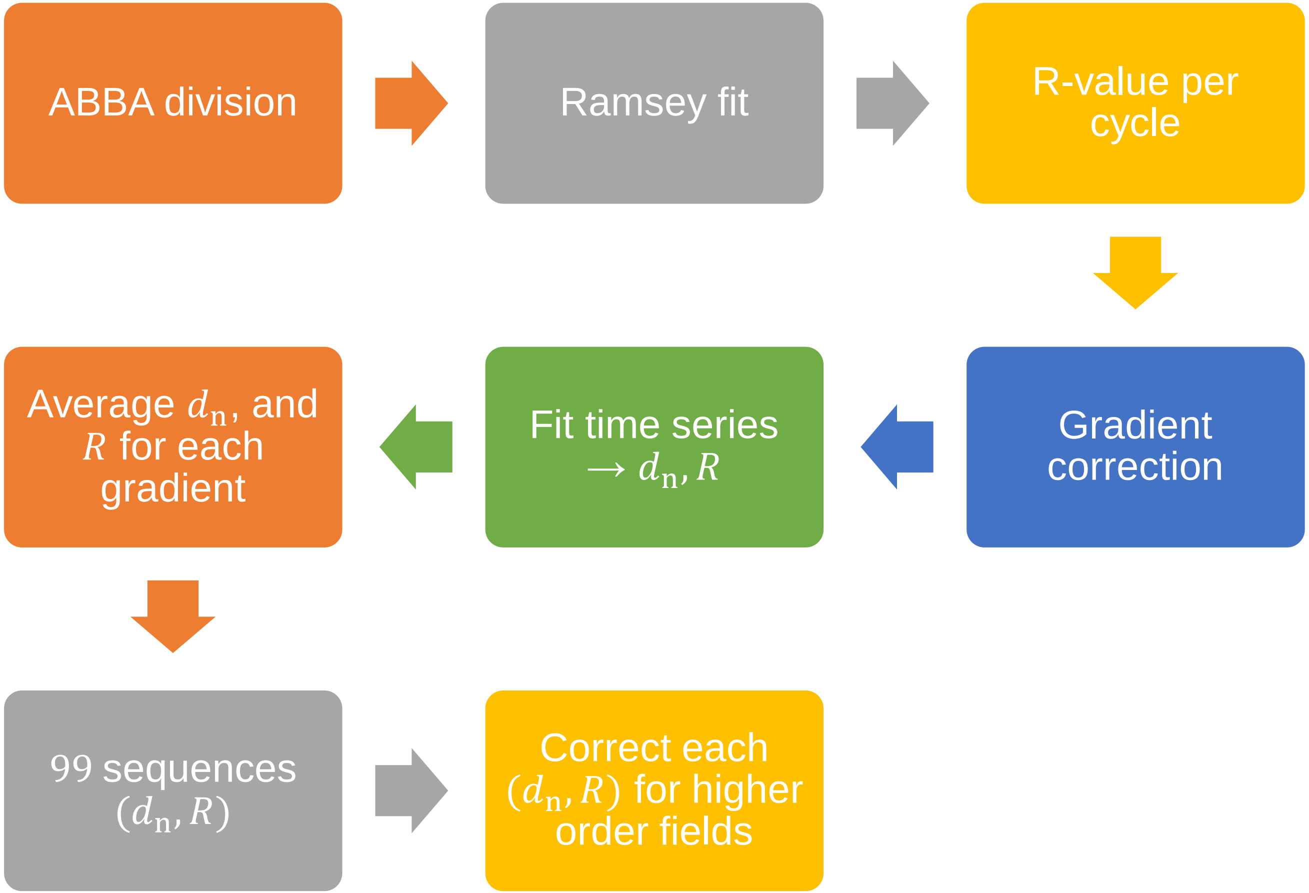


Mapping with fluxgate

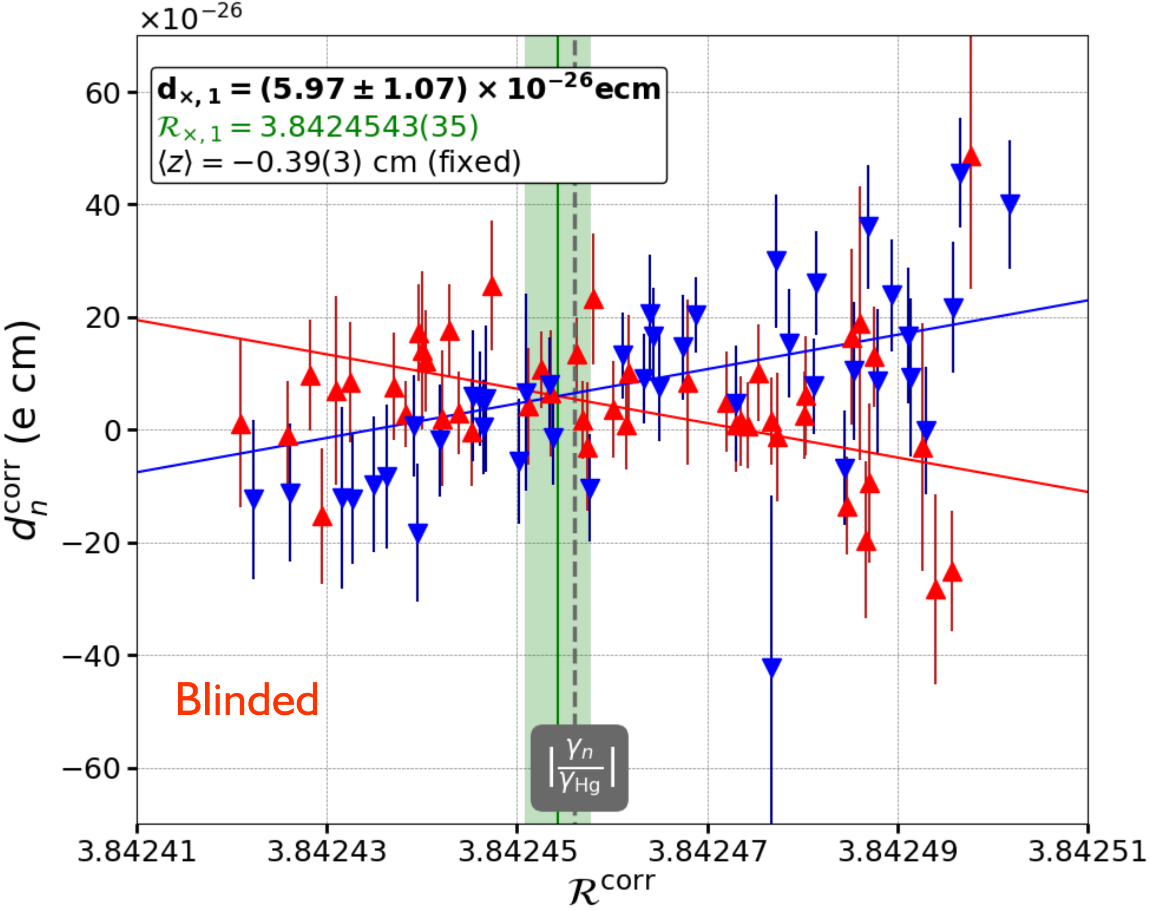
- -20<z<20,
- -10<r<30,
- $\Delta\phi = 5°$

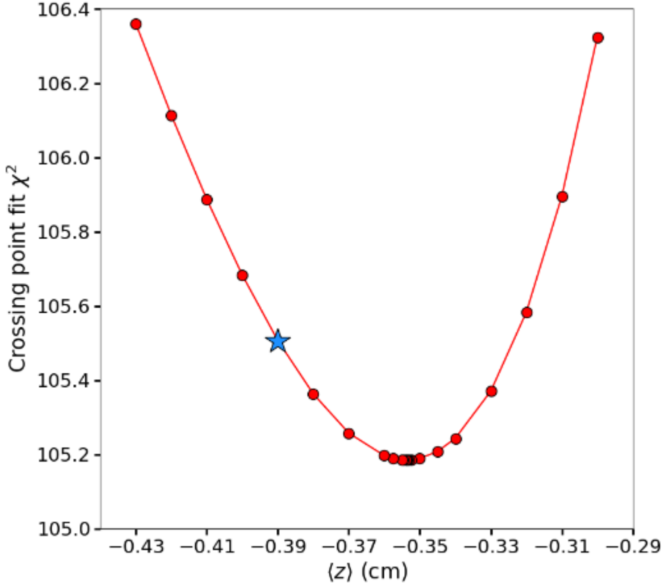
- Fit to order $l = 7$
- Extract $\langle B_T^2 \rangle$ for each base configuration
- Extract $\delta_G(\hat{G})$ for each base configuration

Analysis flow diagram:



Crossing point analysis





Correcting systematic by G_g and $\hat{G}$

The crossing point analysis takes care of a large part of the motional false EDM:

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar\gamma_{\mathrm{n}}\gamma_{\mathrm{Hg}}}{32c^2} D^2 \left[G_g + \underbrace{G_{30}\left(\frac{D^2}{16} + \frac{H^2}{10}\right) + G_{50}\left(\frac{H^4}{28} - \frac{D^2H^2}{96} - \frac{5D^4}{256}\right)}_{\hat{G} := \hat{G}_{30} + \hat{G}_{50}} \right]$$

Corrected by crossing point fit

$$\hat{G} := \hat{G}_{30} + \hat{G}_{50}$$

Corrected set for set using map analysis

Systematic effects

Table I: Summary of systematic effects in 10^{-28} $e$cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below the line are considered separately.

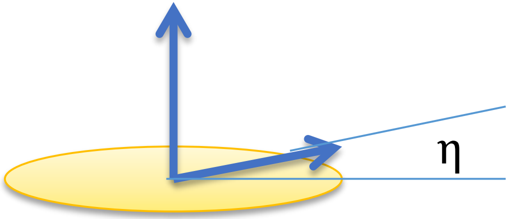
	Effect	shift	error
False Hg EDM	Error on $\langle z \rangle$	-	7
	Higher order gradients $\hat{G}$	69	10
	Transverse field correction $\langle B_T^2 \rangle$	0	5
Other effects	Hg EDM[8]	-0.1	0.1
	Local dipole fields	-	4
	$v \times E$ UCN net motion	-	2
	Quadratic $v \times E$	-	0.1
	Uncompensated G drift	-	7.5
	Mercury light shift	-	0.4
	Inc. scattering ^{199}Hg	-	7
	TOTAL	69	18

Field mapping

← was not anticipated… therefore poorly controlled

Pseudo magnetic field from incoherent scattering length b_i of mercury

$$B^* = -\frac{4\pi\hbar}{m_\mathrm{n}\gamma_\mathrm{n}}\, n b_i P \sqrt{\frac{I}{I+1}}$$

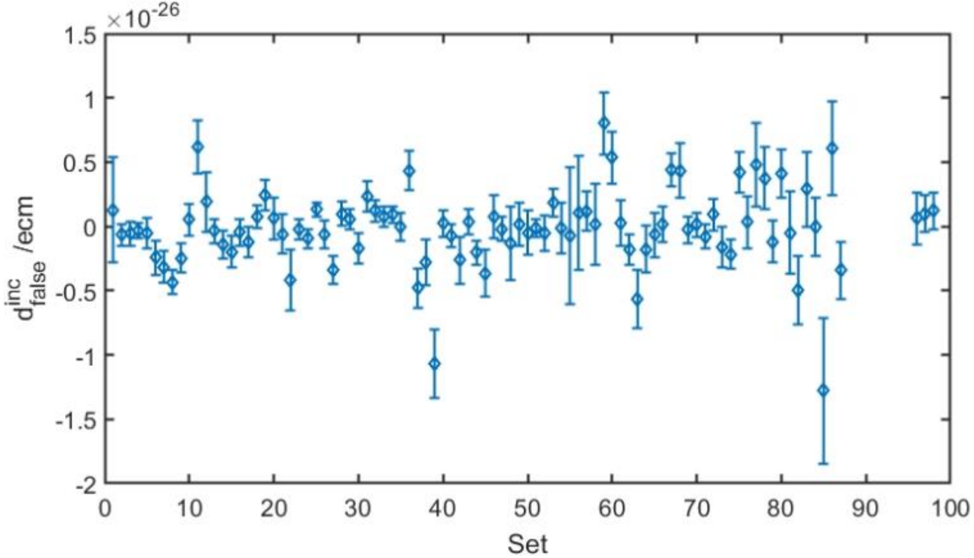


$$\delta\eta = \eta(+E) - \eta(-E)$$

- $I = 1/2$ *nuclear angular momentum*
- $b_i = \pm 15.5\ \mathrm{fm}$
- nP (^{199}Hg × polarization) extracted from data cycle by cycle

$$d_\mathrm{n}^\mathrm{false} = \hbar \frac{\gamma_\mathrm{n}}{4E} B^* \cdot \delta\eta$$

$$< 7 \times 10^{-28} ecm$$



New Result (PSI)

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = \left(-0.2 \pm 1.5_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}\right) \times 10^{-26}\ e\mathrm{cm}$$

$$d_n = \left(\ ?\ \pm\ 1.1_{\mathrm{stat}}\ \pm\ 0.2_{\mathrm{syst}}\right) \times 10^{-26}\ e\mathrm{cm}$$

Systematic error reduced by a factor of 5

$d_{\times}$ $(10^{-26}\ e\text{cm})$	THE WEST	THE EAST
DOUBLE BLIND	15.4 ± 1.1	3.8 ± 1.1
SINGLE BLIND		
UNBLIND		

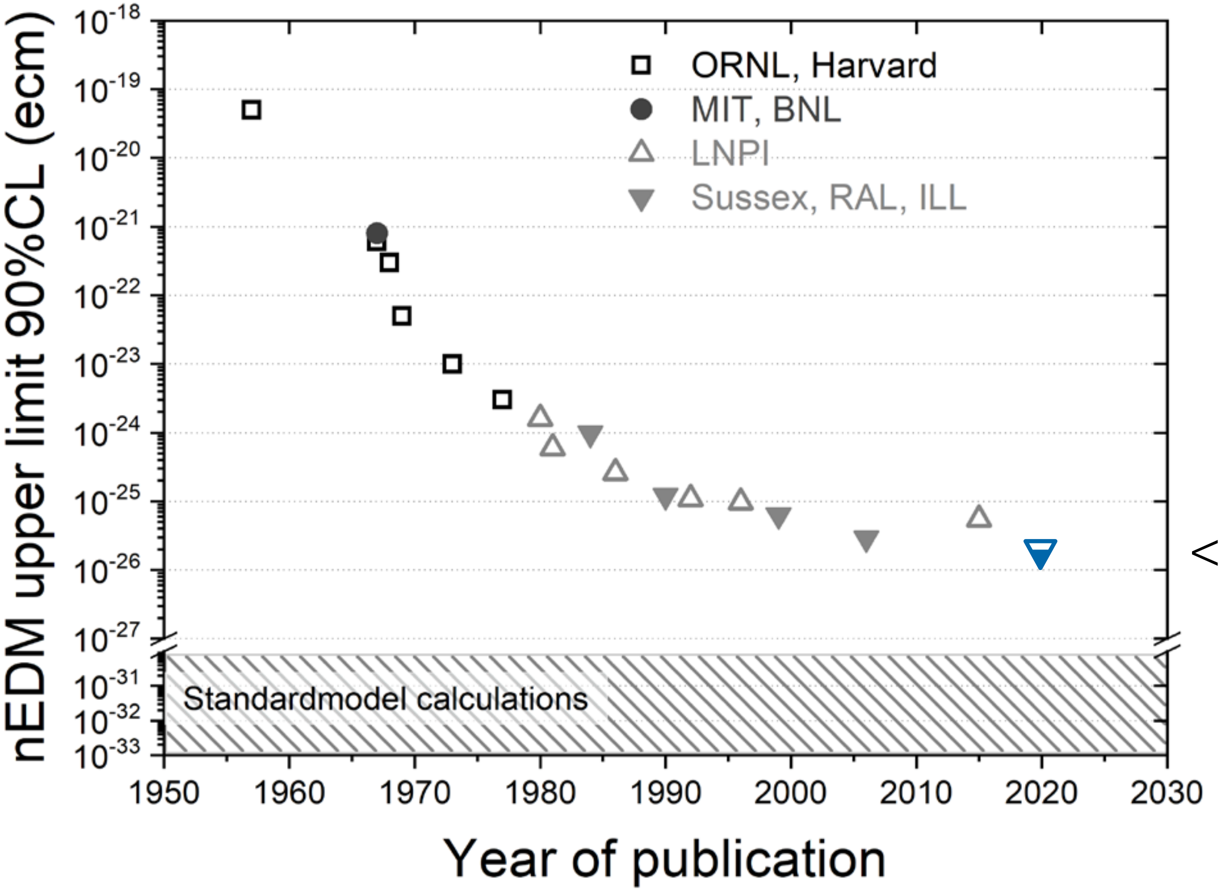
New Result (PSI)

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = (-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{syst}}) \times 10^{-26}\ ecm$$

$$d_n = (\ 0.0\ \pm\ 1.1_{\text{stat}}\ \pm\ 0.2_{\text{syst}}) \times 10^{-26}\ ecm$$

The new limit



$< 1.8 \times 10^{-26} e\text{cm}$

Global limit on theta

Different EDM searches have different sensitivities to the θ-term and other underlying effective parameters.

In general one can describe any EDM as

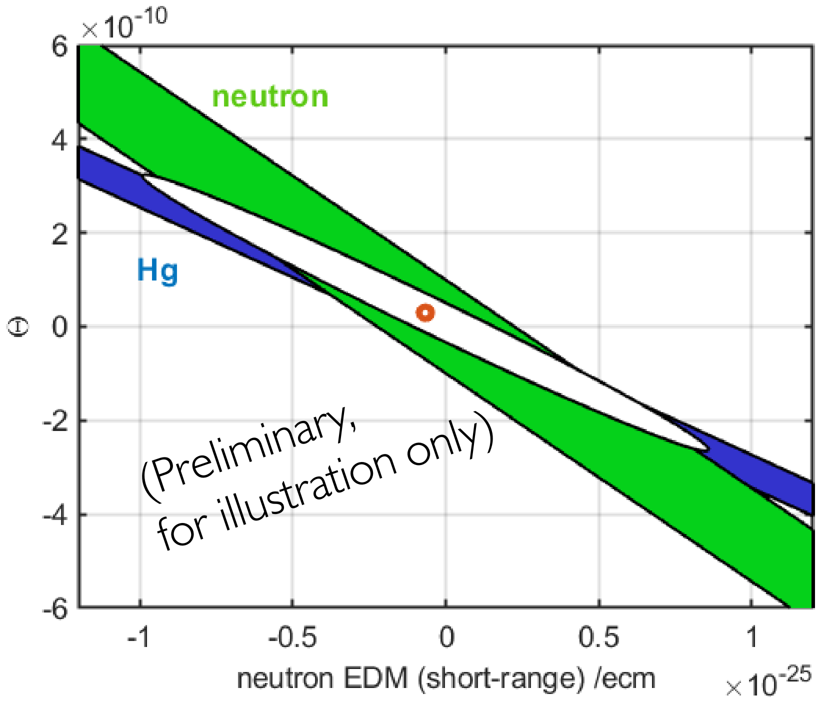
$$d_i = \sum \alpha_{ij} C_j$$

where α_{ij} is the sensitivity to the EFT parameter C_j for a specific EDM d_i.

Unconstraint fit to all EDM limits using all nucleon parameters $(C_T, g_\pi^0, g_\pi^1, d_n^{SR})$:

$$-9 \times 10^{-8} < \theta < 0.2 \times 10^{-8}$$

(Global d_e and C_s subtracted.)



Constraint fit of d_n^{SR} and $\theta = g_\pi^0 / 0.015$ to $d_n, d_{Hg}, d_{Xe}, d_{TlF}$, and d_{Ra}.

based on T. Chupp et al., RMP 91 (2019) 016001

Thank you all!

- 16 Institutions
- 8 Countries
- 84 authors
- 34 PhD degrees

Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

58

Backup

Correcting systematic by G_g and $\hat{G}$

The crossing point analysis takes care of a large part of the motional false EDM:

$$d_{n\leftarrow Hg}^{false} = \frac{\hbar \gamma_n \gamma_{Hg}}{32c^2} D^2 \left[G_g + \underbrace{\boxed{G_{30}\left(\frac{D^2}{16} + \frac{H^2}{10}\right)} + \boxed{G_{50}\left(\frac{H^4}{28} - \frac{D^2H^2}{96} - \frac{5D^4}{256}\right)}} \right]$$

Corrected by crossing point fit

$$\hat{G} := \hat{G}_{30} + \hat{G}_{50}$$

Corrected set for set using map analysis

Ingredients needed for baryon genesis

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

Anomalous B-violating processes

SM Sphalerons:

$$\Gamma(\mathrm{A}+\mathrm{B}\rightarrow\mathrm{C})\neq\Gamma(\bar{\mathrm{A}}+\bar{\mathrm{B}}\rightarrow\bar{\mathrm{C}})$$

EDMs

SM CKM CPV:

Prevent washout by inverse processes

LHC: scalars

SM EWPT:

(Requires Higgs mass <80meV)

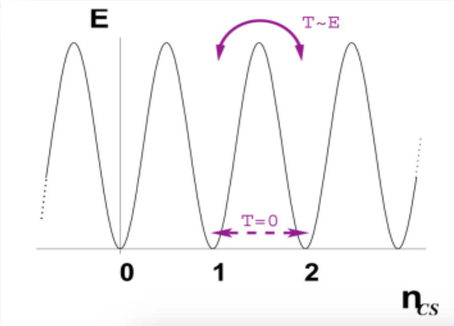
Ingredients for EW baryogenesis

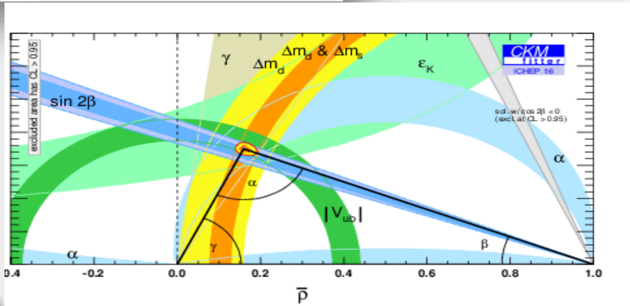
1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

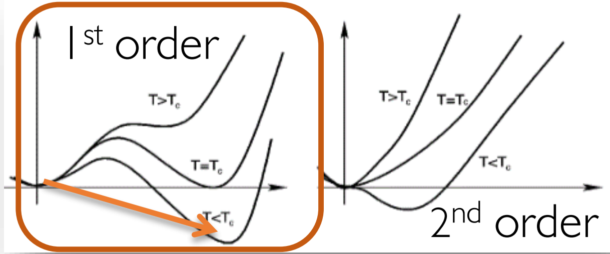
possible

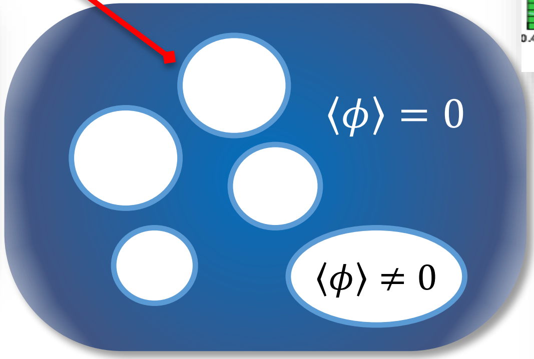
too weak

Higgs too heavy





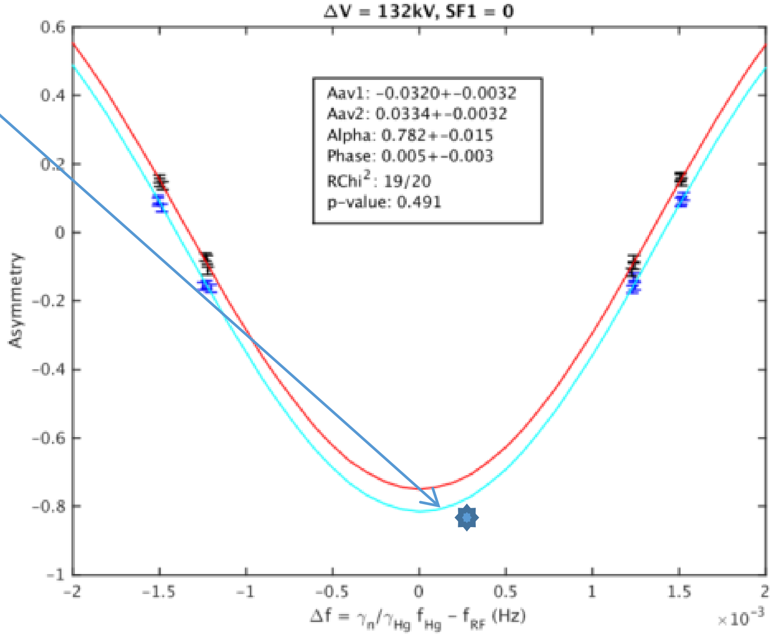




Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

Frequency for each cycle

- Single point fits to avoid loss of cycles
  (same equation, but all parameters know but ϕ_1)
- In the end the relative change of frequency is relevant for the nEDM analysis the global parameter are all covariant.



Data point below cosine: $A_i < (A_{\mathrm{SF2}} - \alpha)$

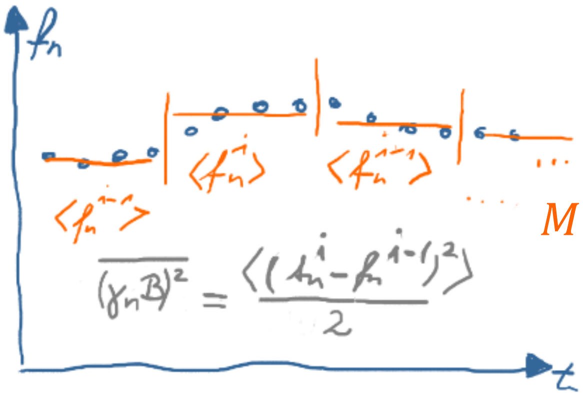
Sensitivity versus Stability

- Sensitivity for many cycles ideal case:

$$\sigma_{\mathrm{stat}}(B) = \frac{1}{\gamma_{\mathrm{n}} \alpha T \sqrt{NM}}$$

- Requires:

$$\overline{\Delta B} \leq \sigma_{\mathrm{stat}}$$



$M = 4$

Allan deviation:

$$\sigma_{AD}(M) = \sqrt{\frac{\left\langle \left(f_i(M) - f_{i-1}(M) \right)^2 \right\rangle}{2}}$$

Choose M such that:

$$\sigma_{\mathrm{stat}}(M) \geq \sigma_{AD}(M)$$

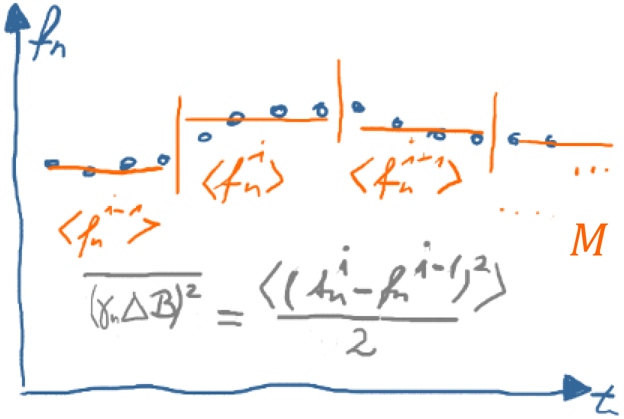
Sensitivity versus Stability

- Many cycles sensitivity ideally:

$$\sigma_{\mathrm{stat}}(B) = \frac{1}{\gamma_{\mathrm{n}} \alpha T \sqrt{NM}}$$

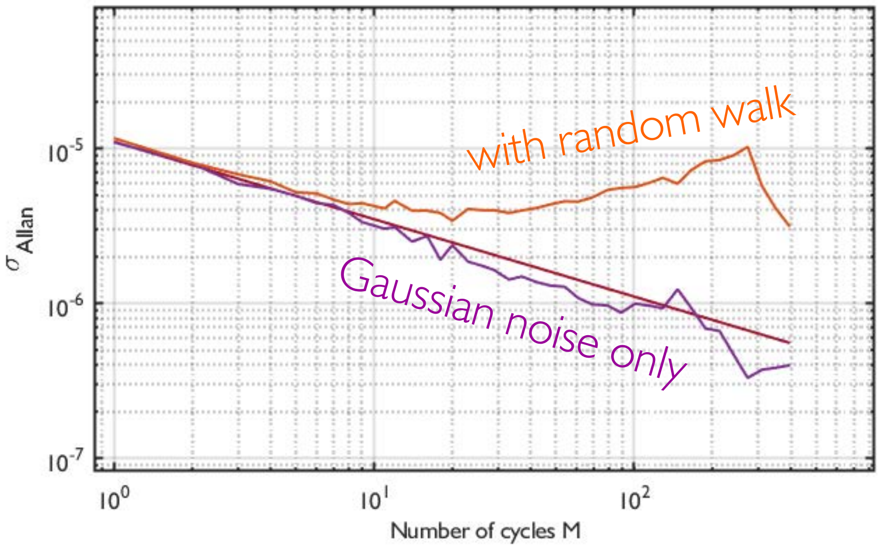
- Require:

$$\sigma_{\mathrm{stat}} \geq \overline{\Delta B}$$



Allan deviation:

$$\sigma_{AD}(M) = \sqrt{\frac{\left\langle \left(f_i(M) - f_{i-1}(M)\right)^2 \right\rangle}{2}}$$



The full covariant matrix C

$$A_i = A_{\mathrm{av}} - \alpha\cos\left(\frac{\omega_{\mathrm{rf}} - \omega_{\mathrm{cor}}}{\Delta\nu} + \phi\right) \rightarrow \quad f = \frac{\Delta\nu}{\pi}\left[\mathrm{acos}\left(\frac{(A_{\mathrm{av}} - A_i)}{\alpha}\right) + \phi\right]$$

$$C = C_\alpha + C_{A_i} + C_{A_{av}} + C_\phi$$

$$C_{A_{\mathrm{av}},ij} = \frac{\mathrm{d}f}{\mathrm{d}A_{\mathrm{av},i}} \cdot \frac{\mathrm{d}f}{\mathrm{d}A_{\mathrm{av},j}} \cdot \delta A_{\mathrm{av},i}\,\delta A_{\mathrm{av},j}$$

$$= \frac{\Delta\nu^2 \delta A_{\mathrm{av},i}\,\delta A_{\mathrm{av},j}}{\pi^2}\left(\alpha^2 - \left(A_{\mathrm{av},i} - A_i\right)^2\right)^{-1/2}\left(\alpha^2 - \left(A_{\mathrm{av},j} - A_j\right)^2\right)^{-1/2}$$

Remember there are four different A_{av}

The full covariant matrix C

$$A_i = A_{\mathrm{av}} - \alpha \cos\left(\frac{\omega_{\mathrm{rf}} - \omega_{\mathrm{cor}}}{\Delta\nu} + \phi\right) \rightarrow \ f = \frac{\Delta\nu}{\pi}\left[\operatorname{acos}\left(\frac{(A_{\mathrm{av}} - A_i)}{\alpha}\right) + \phi\ \right]$$

$$C = C_\alpha + C_{A_i} + C_{A_{av}} + C_\phi$$

$$C_{\alpha,ij} = \frac{\mathrm{d}f}{\mathrm{d}\alpha_i} \cdot \frac{\mathrm{d}f}{\mathrm{d}\alpha_j} \cdot \delta\alpha^2 = \frac{\Delta\nu^2\delta\alpha^2}{\alpha^2\pi^2} \frac{\left(A_{\mathrm{av},i} - A_i\right)}{\sqrt{\alpha^2 - \left(A_{\mathrm{av},i} - A_i\right)^2}} \frac{\left(A_{\mathrm{av},j} - A_j\right)}{\sqrt{\alpha^2 - \left(A_{\mathrm{av},j} - A_j\right)^2}}$$

$$C_{\phi,ij} = \frac{\mathrm{d}f}{\mathrm{d}\phi_i} \cdot \frac{\mathrm{d}f}{\mathrm{d}\phi_j} \cdot \delta\phi\delta\phi = \frac{\Delta\nu^2\delta\phi^2}{\alpha^2\pi^2}$$

Remember there are four different A_{av}

R value and error on R

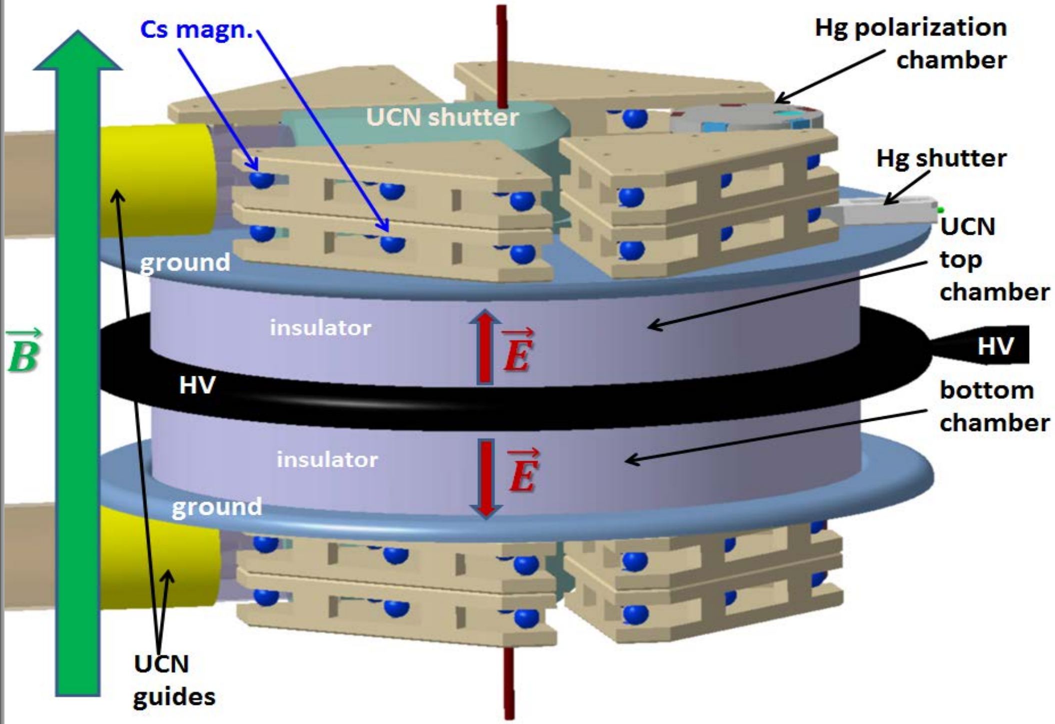
- Calculate R
- Divide covariance matrix by matrix $f'_{\mathrm{Hg},ij}$ (element for element)
- Add diagonal matrix with statistical error for each R value

$$R = \frac{f_\mathrm{n} \mp \gamma_n/2\pi\langle z\rangle g_z}{f_\mathrm{Hg}}$$

$$f_{\mathrm{Hg},ij} = f_{\mathrm{Hg},i} \cdot f_{\mathrm{Hg},j}$$

$$\sigma_R^2 = \frac{\sigma_{f_\mathrm{n}}^2}{f_\mathrm{Hg}^2} + \left(\frac{\gamma_n/2\pi\langle z\rangle\,\delta g_z}{f_\mathrm{Hg}}\right)^2 + \left(\frac{\sigma_\mathrm{Hg}\cdot(f_\mathrm{n}\mp\gamma_n/2\pi\langle z\rangle\,\delta g_z)}{f_\mathrm{Hg}^2}\right)^2$$

Main features of the new instrument



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

Inspired by Gatchina double-chamber setup
I.Altarev et al. JETP Lett.44(1986)460
and based on **years of experience with** our **own operating experiment:**

- 2 neutron precession chambers

- Hg co-magnetometer in both chambers with laser read out

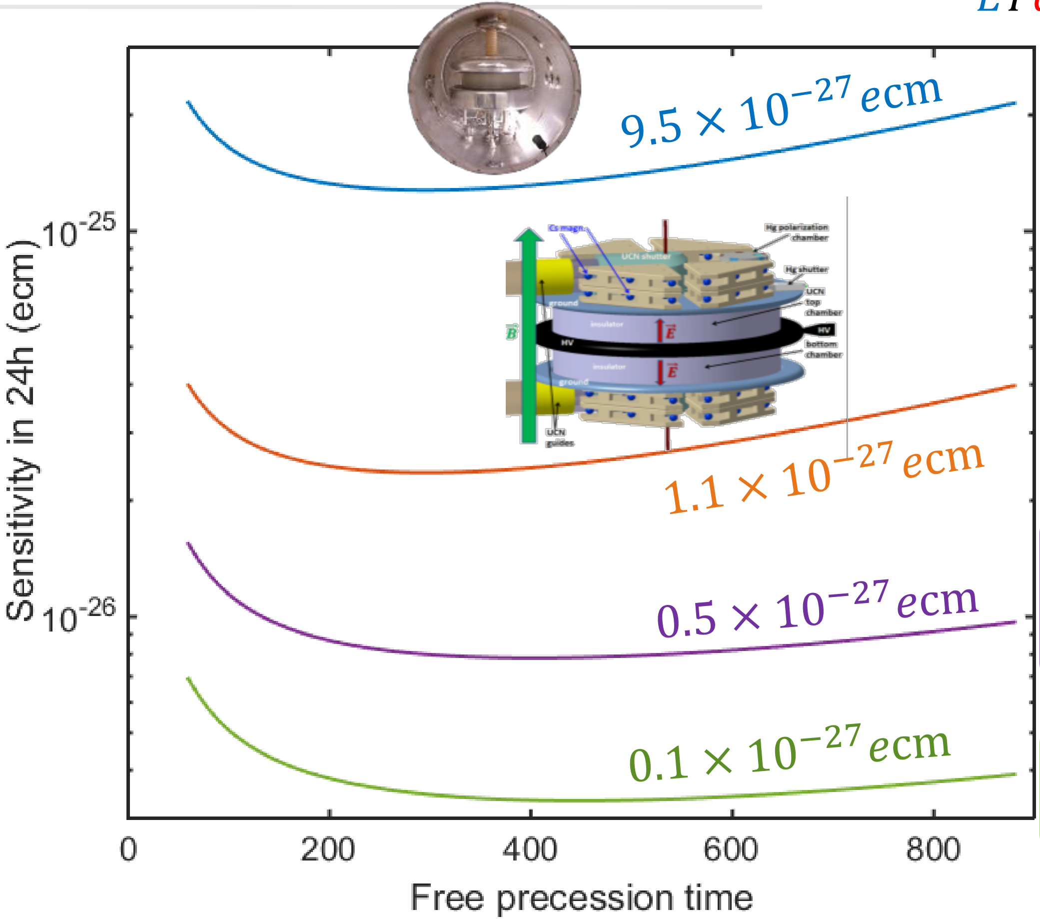
- Baseline scenario: UCN chamber with materials and coatings as present chamber, but larger diameter of storage volume - upgrades in development

- Surrounded by calibrated Cs arrays on ground potential (~ 100 sensors)

- large NiMo (^{58}NiMo) coated UCN guides

Sensitivity:

$$\sigma(d_n) = \frac{\hbar}{E T \alpha_0 e^{-T/T_2} \sqrt{2 N_0 \left(e^{-T/\tau_s} + e^{-T/\tau_f}\right)}}$$



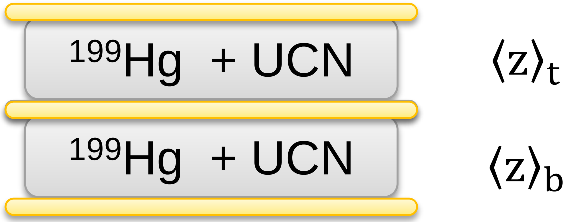
Performance in 2015/2016

Prospect TDR (start 2021)
$E = 15\,\mathrm{kV/cm},\ N = 8 \times N_{2016}$

Possible final performance at PSI
$E = 18\,\mathrm{kV/cm}$, improved UCN source, optimal magnetic field tuning

New source? At ESS?
$E = 20\mathrm{kV/cm},\ N = 128 \times N_{2016}$

Analysis: Frequency ratio $R = f_{\mathrm{n}}/f_{\mathrm{Hg}}$

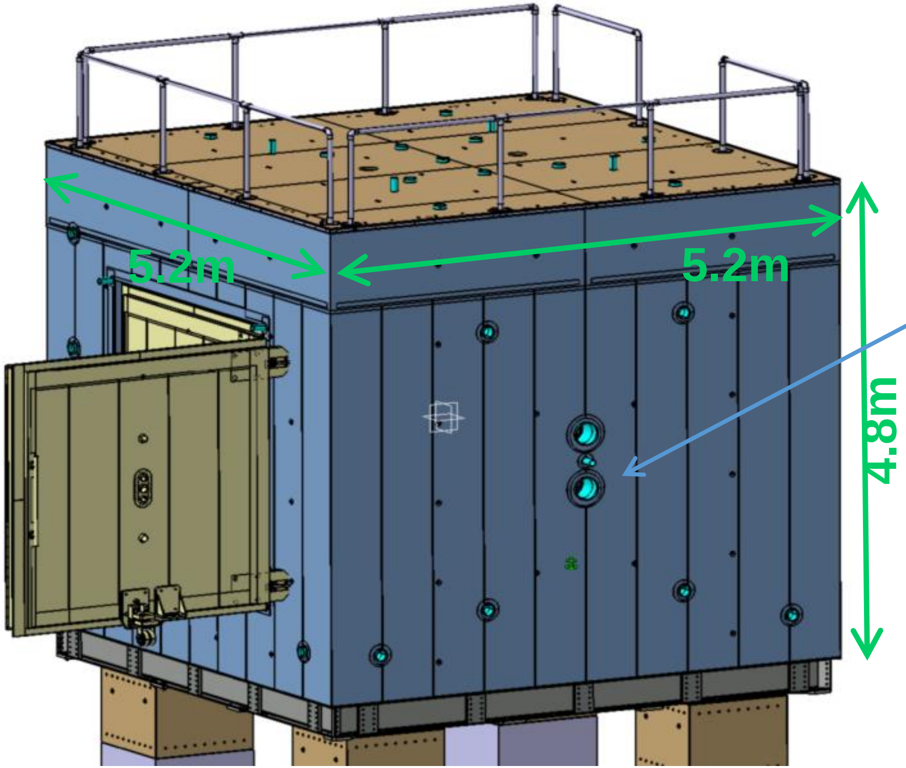


double chamber - linear $\partial B/\partial z$ is almost perfectly compensated
but due to different h_t and h_b gradient fluctuations still cause an error on a lower level though

$$R^{\mathrm{T}} - R^{\mathrm{B}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(2\delta_{\mathrm{EDM}} \quad + \left(\langle z\rangle_{\mathrm{T}} - \langle z\rangle_{\mathrm{B}}\right)\frac{g}{B_0} + \cdots\right)$$

Analysis: based on (R^{T} - R^{B}) as function of dB/dz extrapolate to 0

Magnetically Shielded Room



setup features:
- (2 + 4) layers mu-metal
- Al eddy current shield
- 78 openings for experiment use
- largest openings ID=220mm for 2 UCN guides for 2 main pumping ports

expected performance:
- quasi-static shielding factor guaranteed >70'000 (expected >100'000)
- central B-field < 0.5nT
- central gradient < 0.3 nT/m

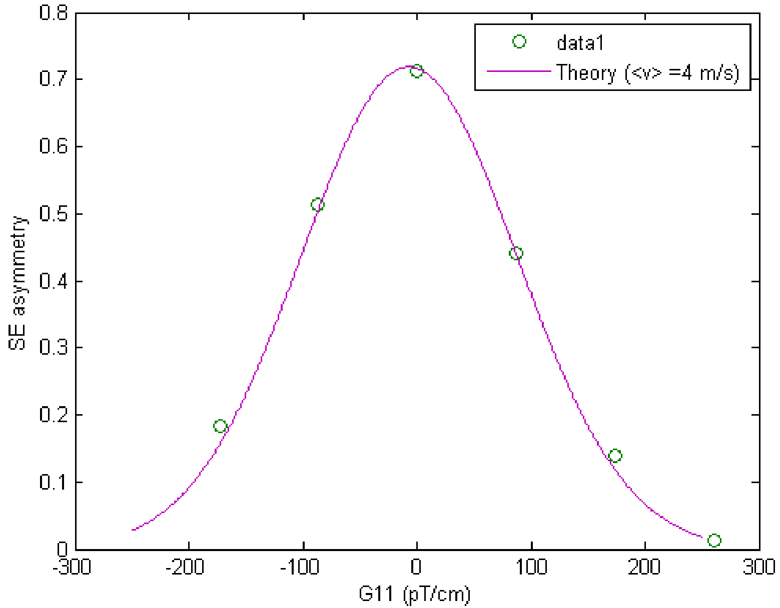
Depolarization

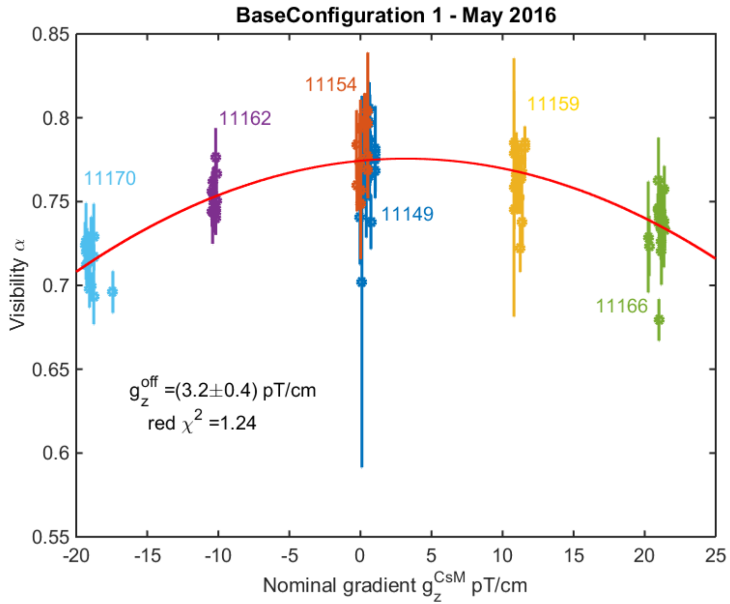
$$\Gamma_2(\epsilon) = a\frac{\gamma_n^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

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

Intrinsic depolarization

Gravitational depolarization



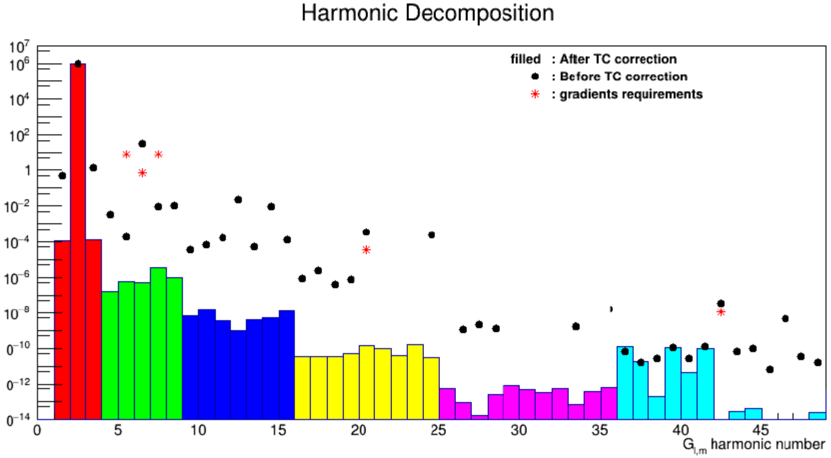


Afach et al.,PRD92(2015)052008
Afach et al.,PRL115(2015)162502

Excellent B-field uniformity

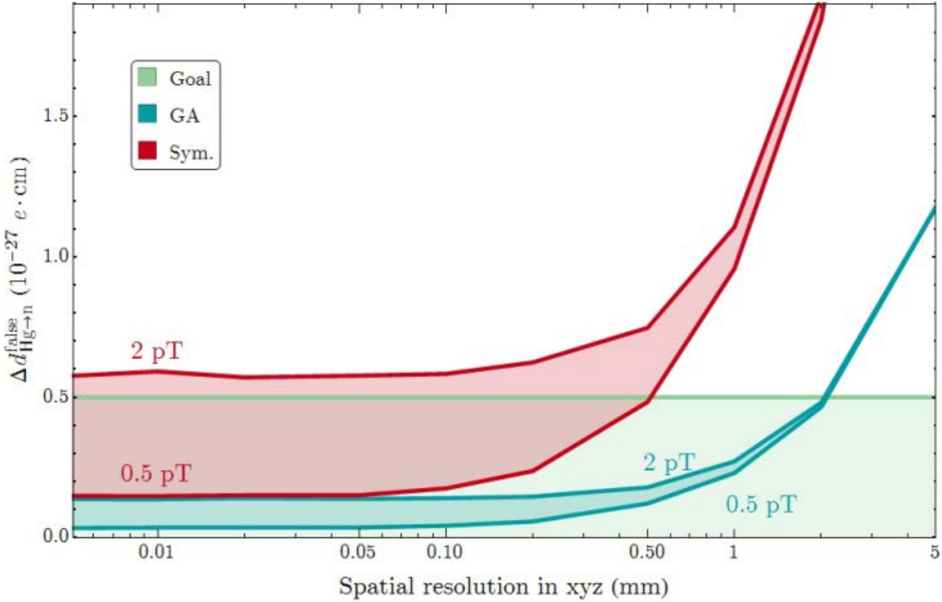
Magnetic-field generation

- Optimized main magnetic field coil
- 64 correction coils



Magnetic-field measurement

- Order 100 CsM sensors
- Optimal placement



Today's status of n2EDM

Status of setup:

- MSR installed and commissioning has started
- Installation of coil system, vacuum tank and precession chambers next
- Area and environmental setup ongoing