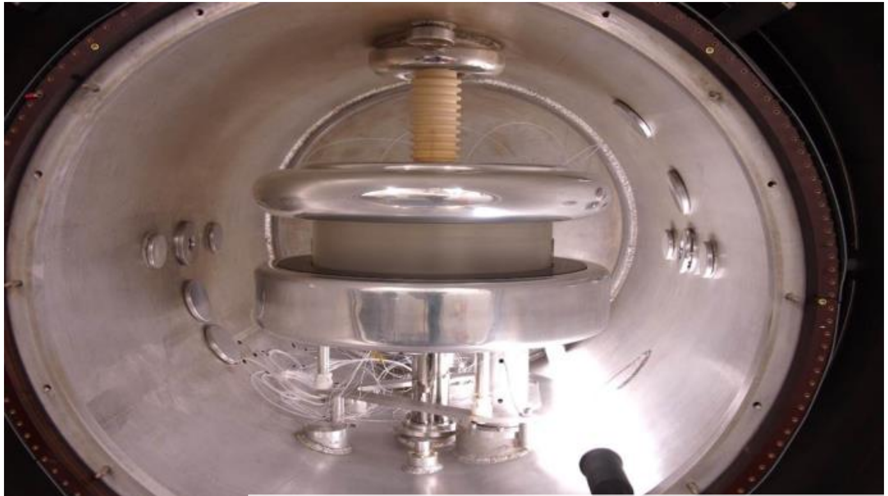
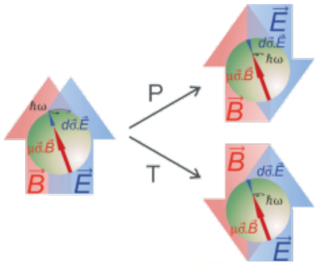

nEDM spectrometer at PSI

PAUL SCHERRER INSTITUT PSI

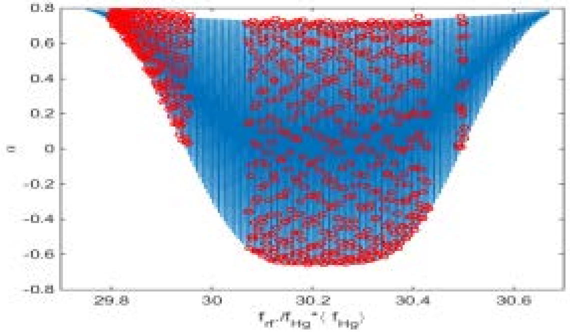
P. Schmidt-Wellenburg, Paul Scherrer Institute

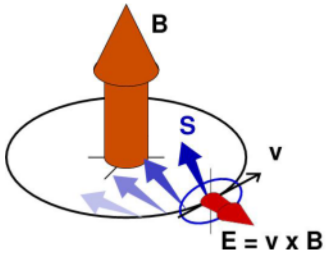
Electric dipole moments: a window to physics beyond the Standard Model

Outline



- What is an electric dipole moment, and why search for it?
- The neutron EDM search
  - Techniques and methods
  - Search for an oscillating EDM
- A future project: Search for a muon EDM
- Conclusion





CP violation & edm

$$H = -(\mu\, \vec{s} \cdot \vec{B} \;+\; d\, \vec{s} \cdot \vec{E}\,)$$

⇩ Time reversal

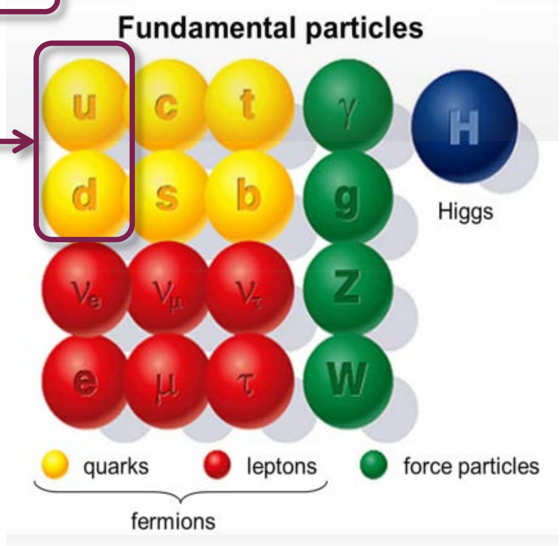
$$H = -(\mu(-)\vec{s} \cdot (-)\vec{B} \;+\; d(-)\vec{s} \cdot \vec{E}\,)$$
$$= -(\mu\vec{s} \cdot \vec{B} \;-\; d\vec{s} \cdot \vec{E}\,)$$

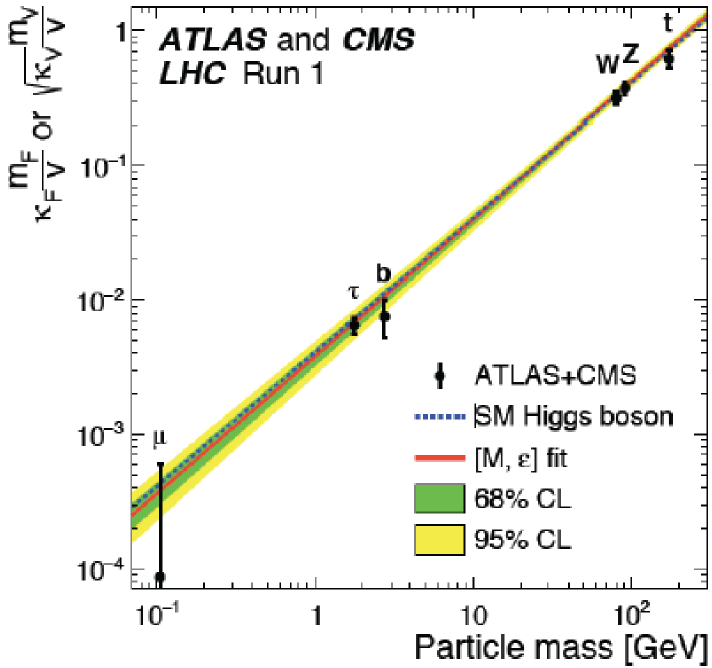
A non-zero particle EDM violates *P, T* and, assuming *CPT* conservation, also ***CP***.

EDM ⟺ CPV

The standard model

- Higgs at 125 GeV
- Higgs coupling to heavy particles consistent with SM
- **But**: no gravity, no dark matter, no **baryon creation, strong CP problem**, …





Footprints not explained by Standard Model

- ***Gravity***
- ***Dark matter /Dark energy***

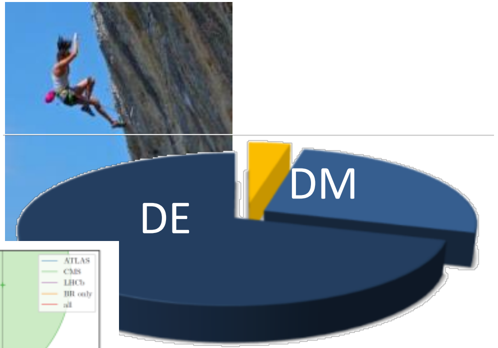
  Only about 4% of the Universe's energy content are explained by the SM.
- ***Tension in B-decays***

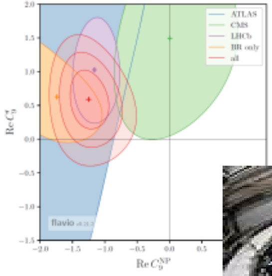
  Several ~3σ
- ***g-2 of the muon***

  The g-2 value for muon disagrees by $\sim 3.6\ \sigma$
- ***Matter/Anti-matter asymmetry***

  SM cannot expectation observed baryon asymmetry
- ***Strong CP problem***

  Hadron EDM gives access to QCD vacuum term





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)

The strong CP -problem

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

$$d_{\text{n}} = \frac{e g_A \bar{\theta} M^*}{(4\pi F_\pi)^2} \log \frac{m_{\text{n}}}{m_\pi} + \cdots$$

Lattice calculations

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

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

Solutions to strong CP problem

- One quark mass exactly zero
- Peccei-Quin scheme

  Axions and oscillating EDMs

Need to measure more than one EDM to identify source

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Why the neutron EDM is not sufficient

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

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

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

↓

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

What is generating the EDM of the neutron?

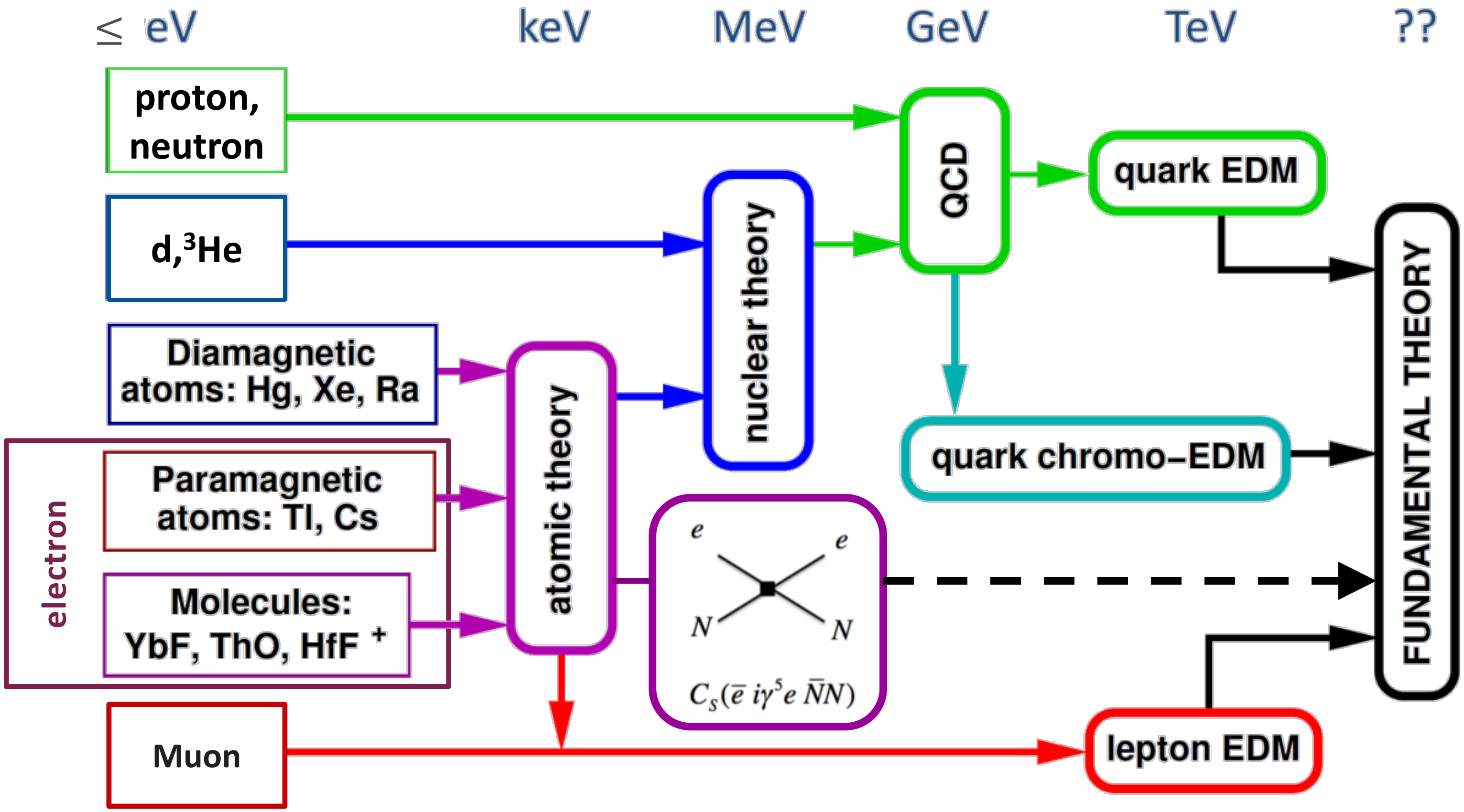
↓

Need to search for lepton EDMs and hadron EDMs

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

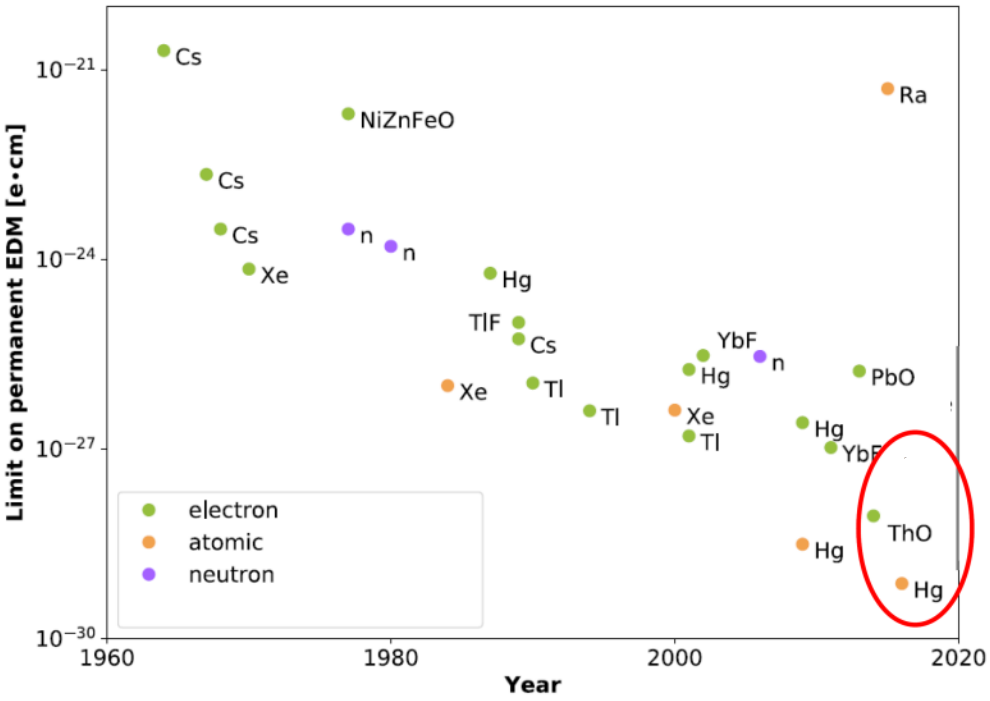
Guo et al., **PRL(2015)062001

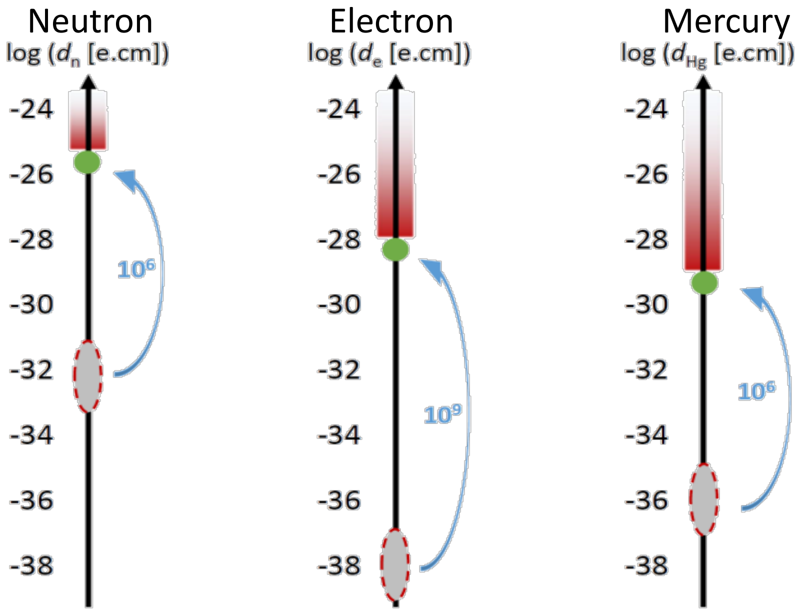
Complementarity of EDM searches



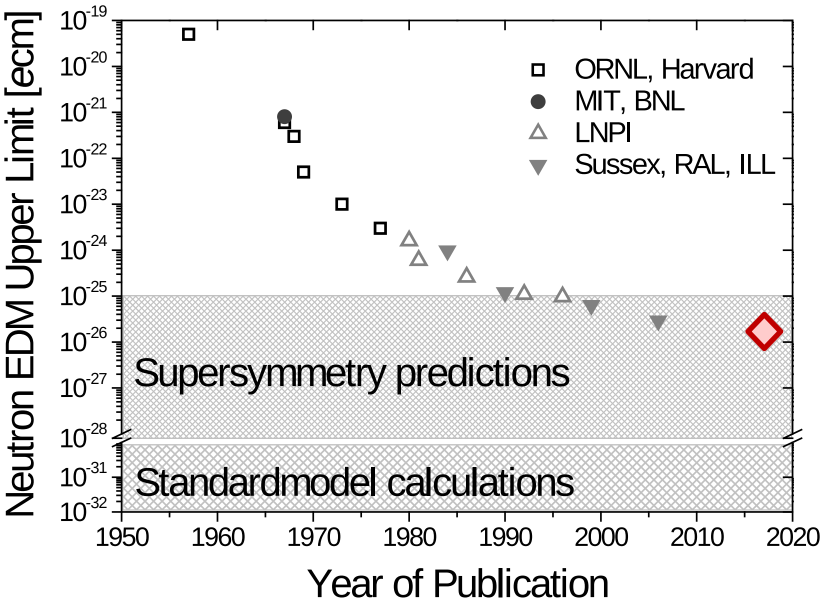
Scheme: courtesy Rob G. E. Timmermans

Overview of EDM limits





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

60 years

Last

RAL-Sussex-ILL

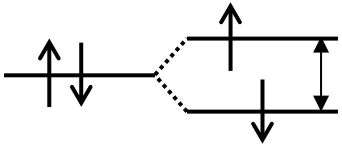
$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

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

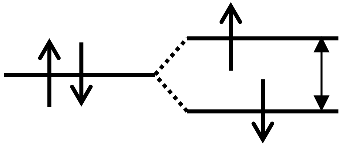
Modified Larmor Frequency

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



$\Delta E_{\mathrm{B}} = \hbar\omega_L = 2\mu_n B$ with: $\mu_n = \frac{1}{2}\hbar\gamma_n$

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



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

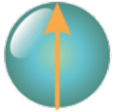
For parallel electric and magnetic fields the precession frequencies add up and for anti-parallel fields the frequencies have to be subtracted. The precession frequency difference of the two cases can be measured:

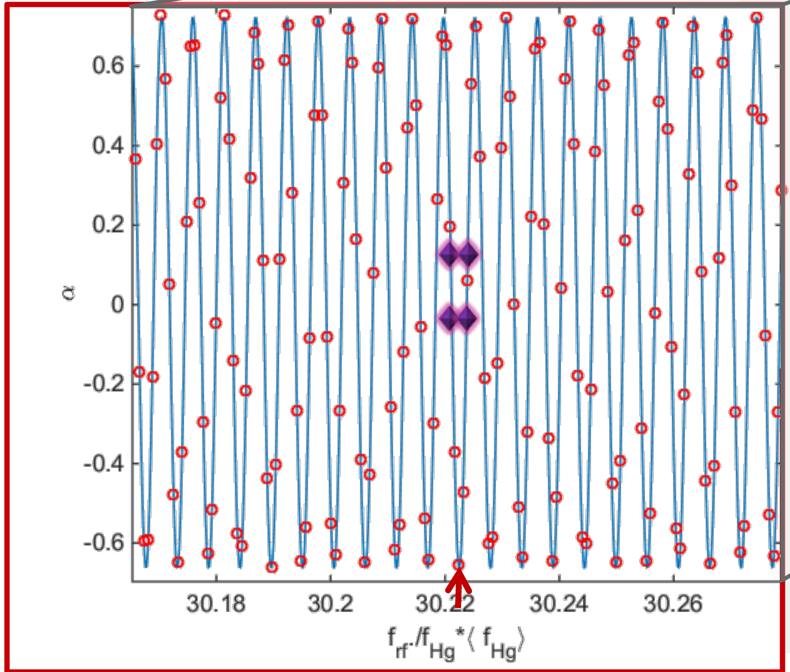
$$\hbar\omega_{\uparrow\uparrow} = \hbar(\omega_L + \omega_{edm}) = 2(\mu_n B + d_n E)$$
$$\hbar\omega_{\uparrow\downarrow} = \hbar(\omega_L - \omega_{edm}) = 2(\mu_n B - d_n E)$$

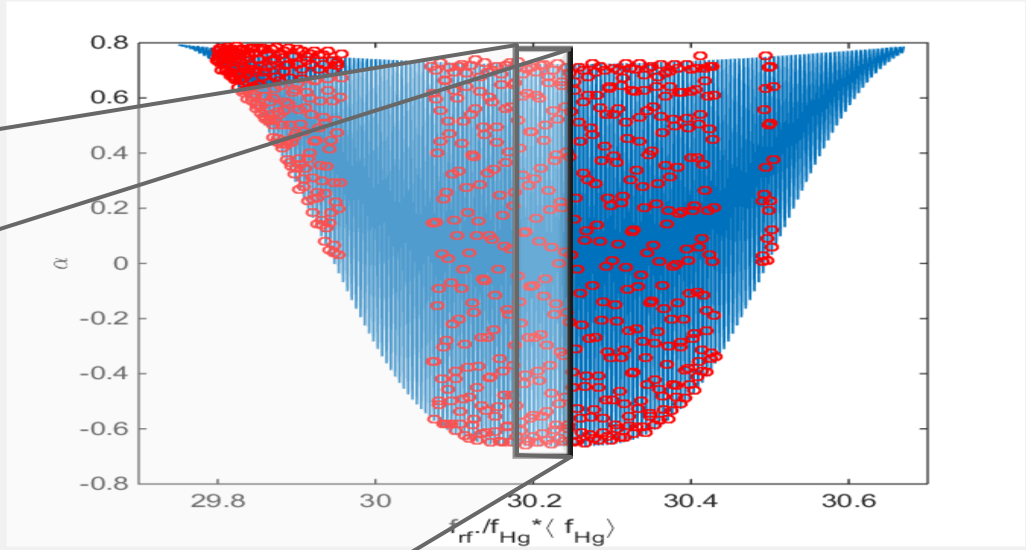
$$\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) = 4\, d_n E$$

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

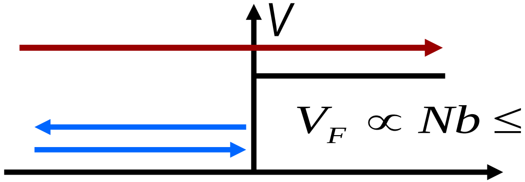
N Number of neutrons

E Electric field strength

Ultracold neutrons (UCN)

$$\sigma(d_n) \propto \frac{1}{T\sqrt{N}}$$

Storable neutrons (UCN)

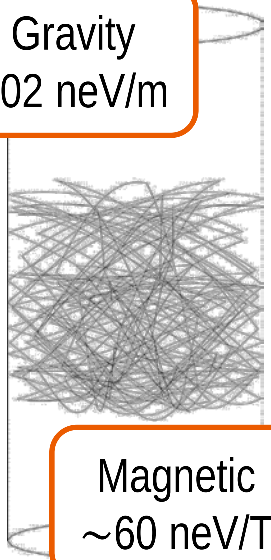


$V_F \propto Nb \leq 350\,\mathrm{neV}$

Storage properties are material dependent

Strong V_F

Gravity 102 neV/m

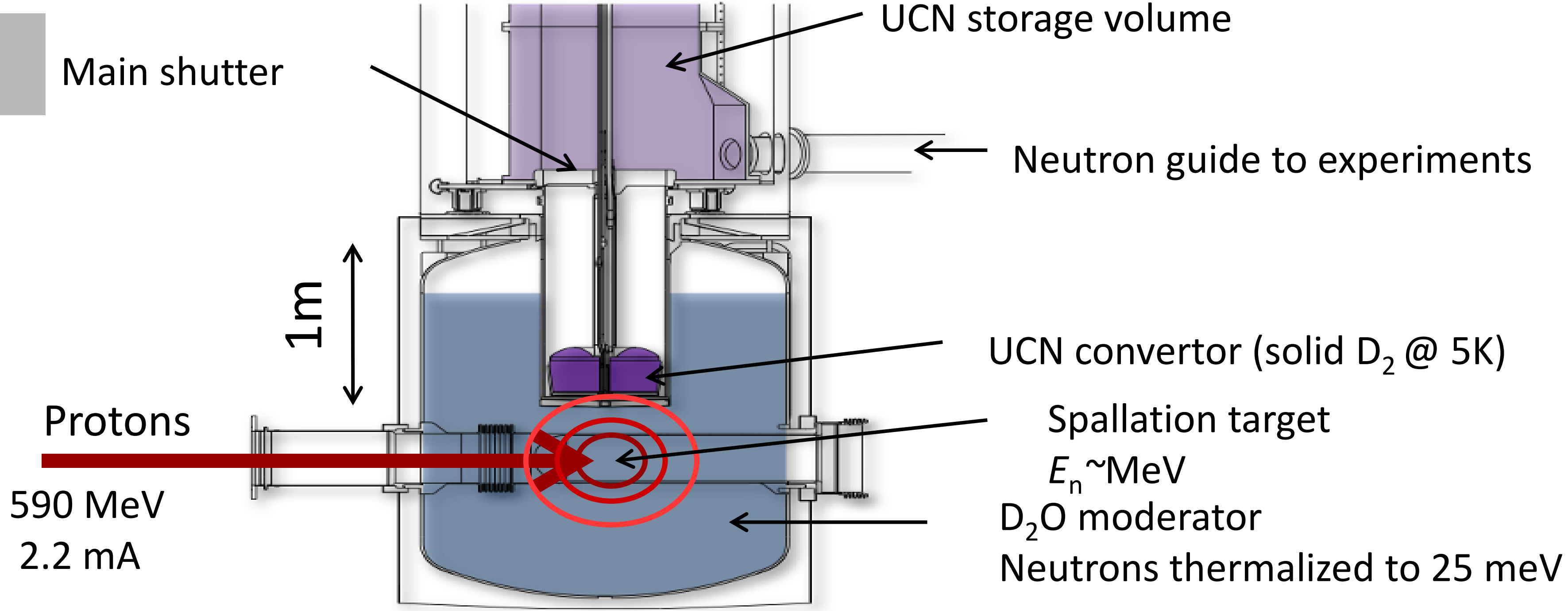


Magnetic ~60 neV/T

350 neV ↔ 8 m/s ↔ 500 Å ↔ 3 mK

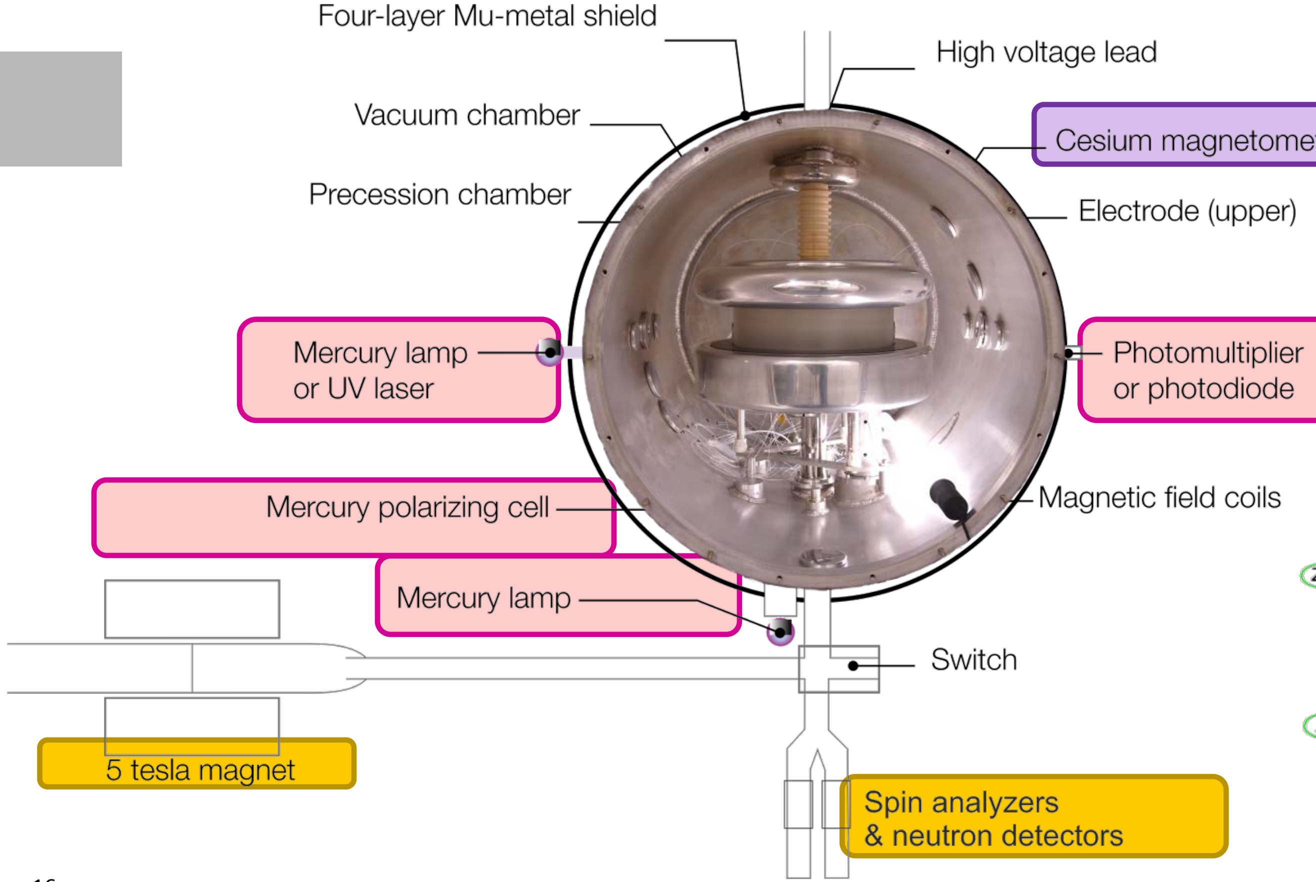
E. Fermi & W.H. Zinn (1946) unpublished,
Y. B. Zeldovich, Sov. Phys. JETP (1959) 389

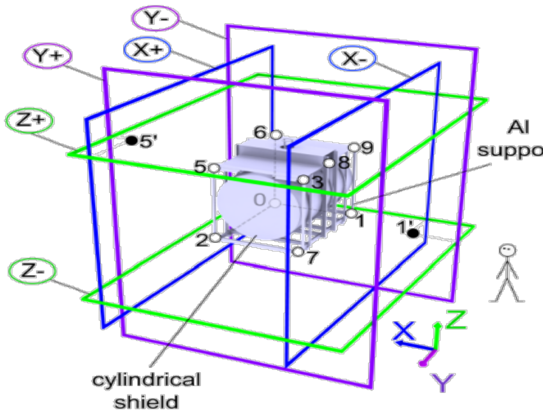
PSI UCN source



Golub, R. & Pendlebury, J. M, *PLA* (**1975**)133
Anghel, *et. al NIMA* **(2009)** 272
Lauss B., Phys. Proc. **(2013)**

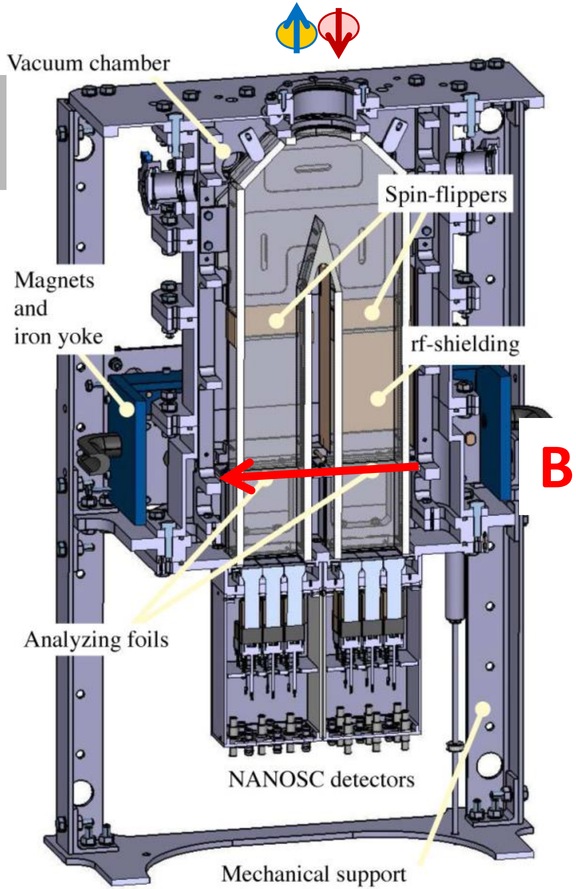
The nEDM spectrometer



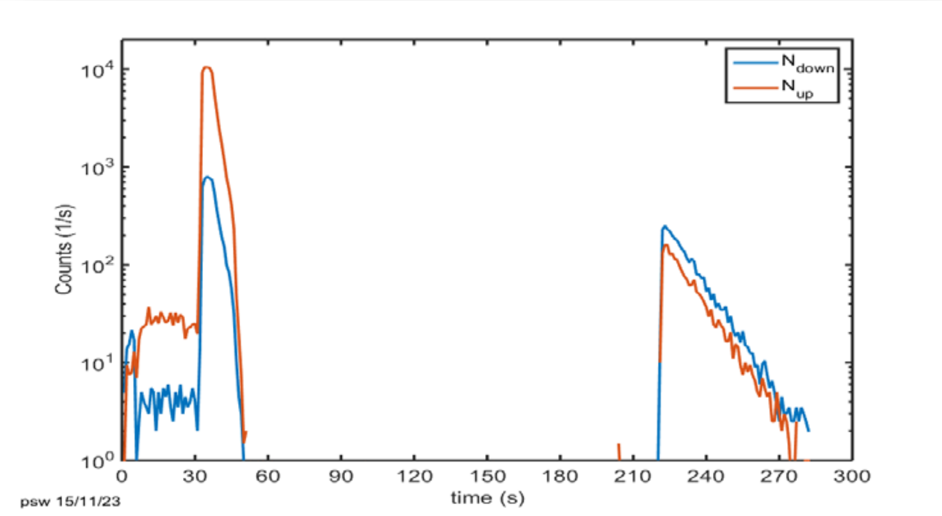


Simultaneous spin detection

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



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



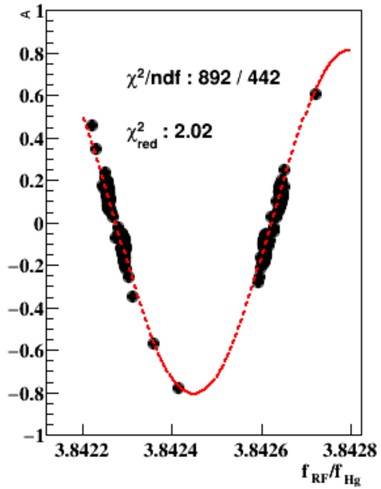
S. Afach *et al.*, EPJA (2015)51

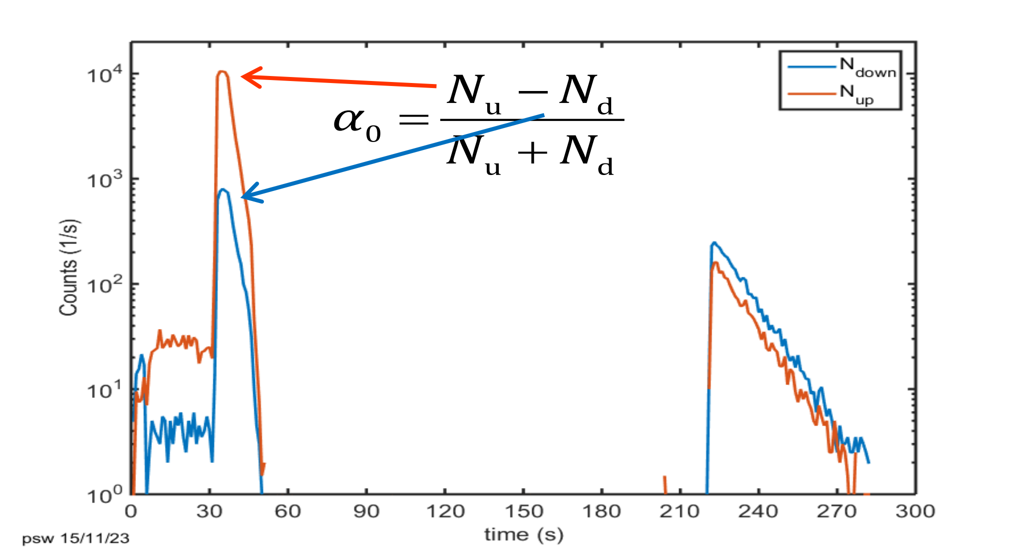
Transverse polarization time

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

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

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





Philipp Schmidt-Wellenburg | FZ Jülich - Seminar | 29.01.2018

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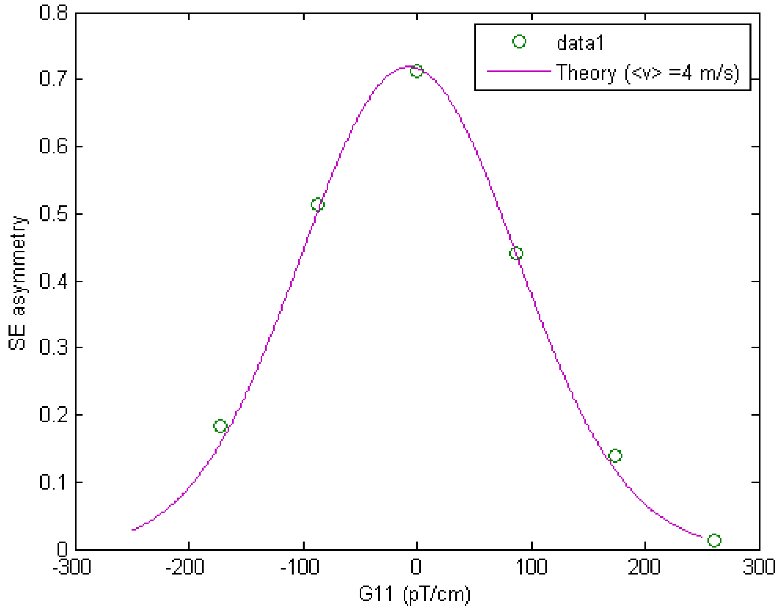
$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

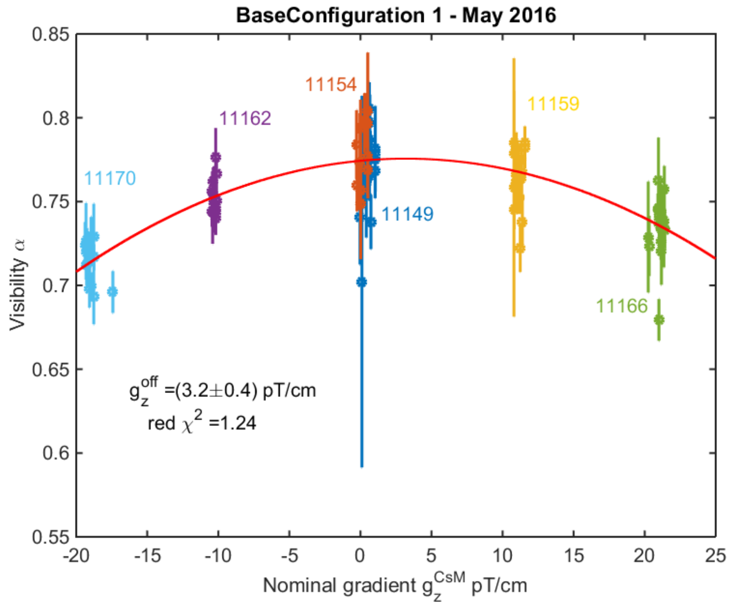
$$\Gamma_2(\epsilon) = a\frac{\gamma_n^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

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

Intrinsic depolarization

Gravitational depolarization



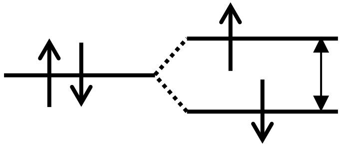


Afach *et al.*, PRD92(2015)052008

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

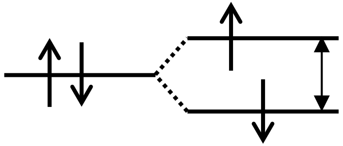
Modified Larmor Frequency

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



$$\Delta E_{\mathrm{B}} = \hbar\omega_L = 2\mu_n B \qquad \text{with: } \mu_n = \tfrac{1}{2}\hbar\gamma_n$$

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



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

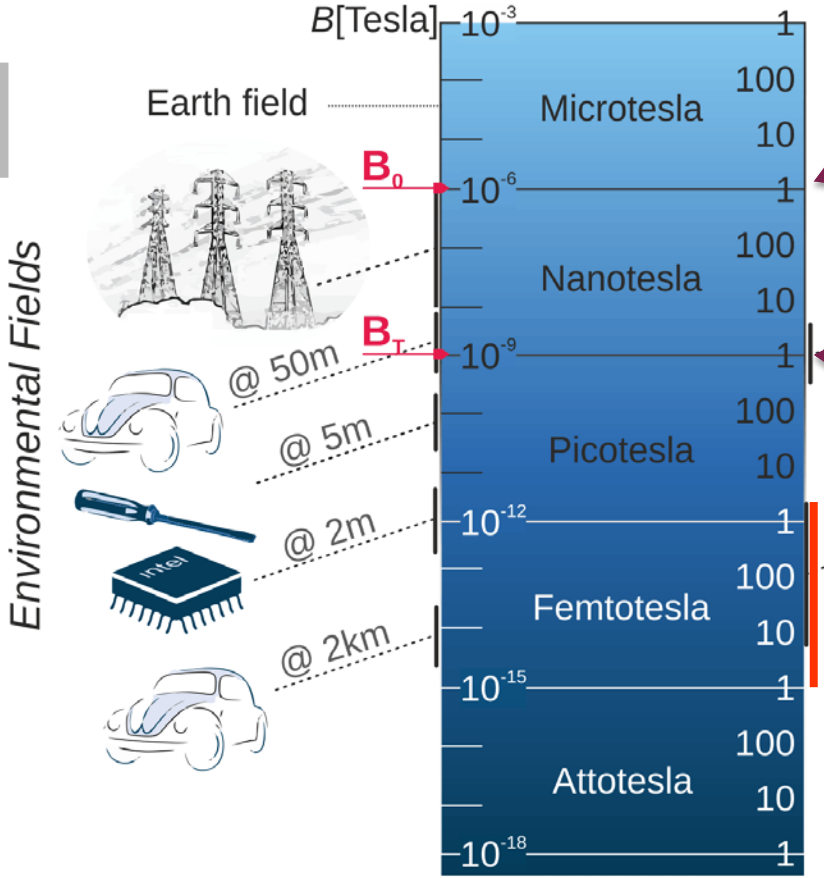
For parallel electric and magnetic fields the precession frequencies add up and for anti-parallel fields the frequencies have to be subtracted. The precession frequency difference of the two cases can be measured:

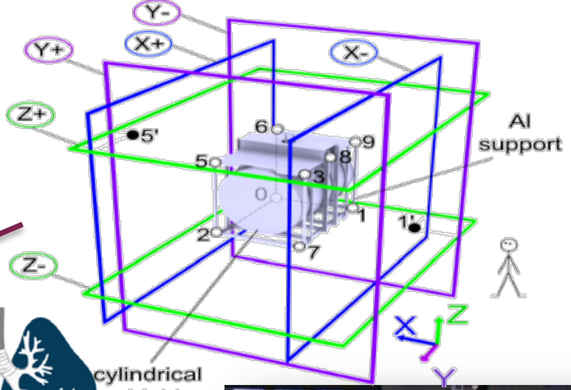
Have to cancel “perfectly”

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

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

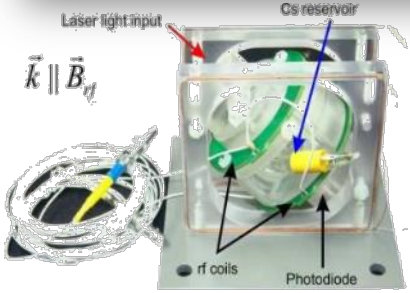
Magnetic fields



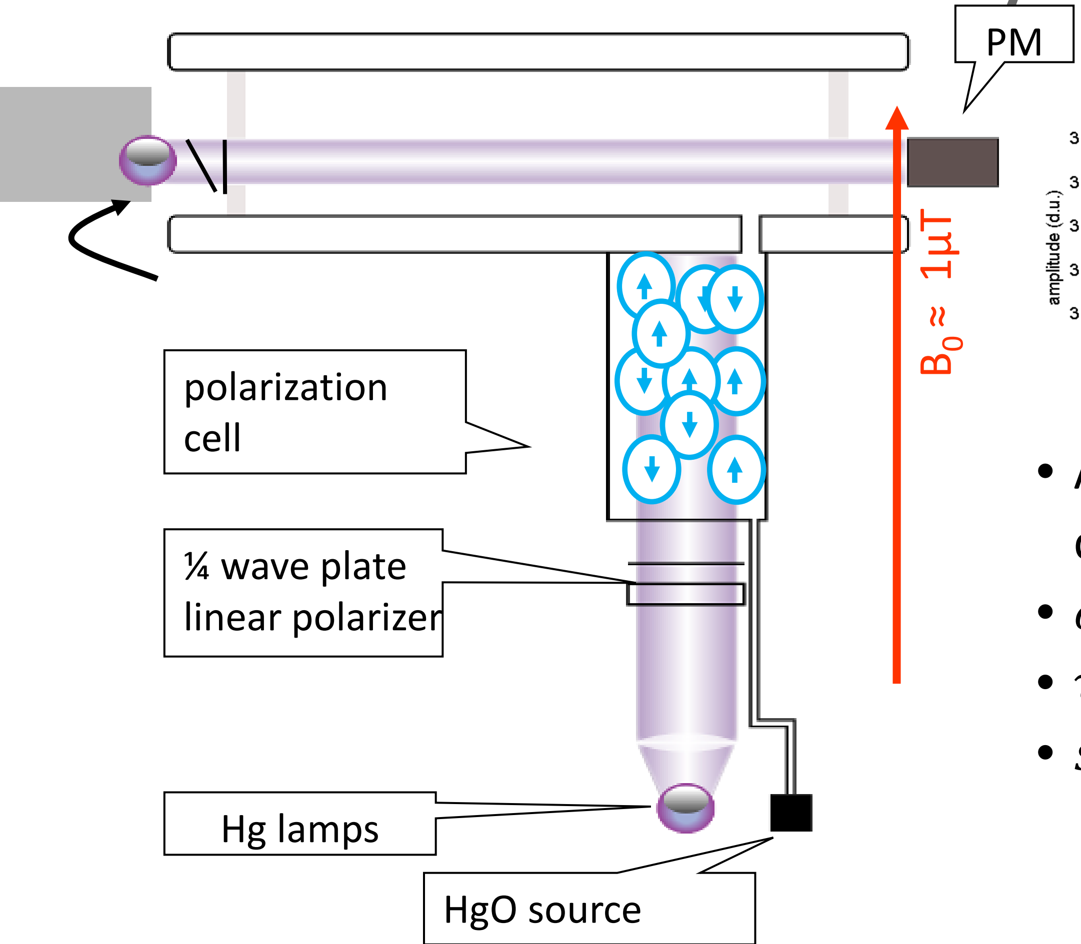


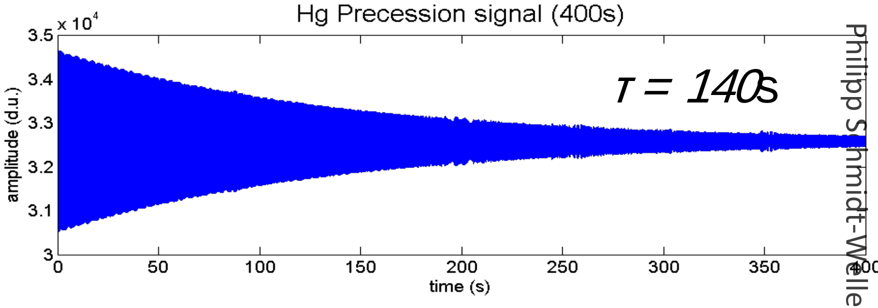
$\delta B < 100\text{fT}$

optical pumped magnetometers (CsM/HgM/XeM…)



Mercury co-magnetometer

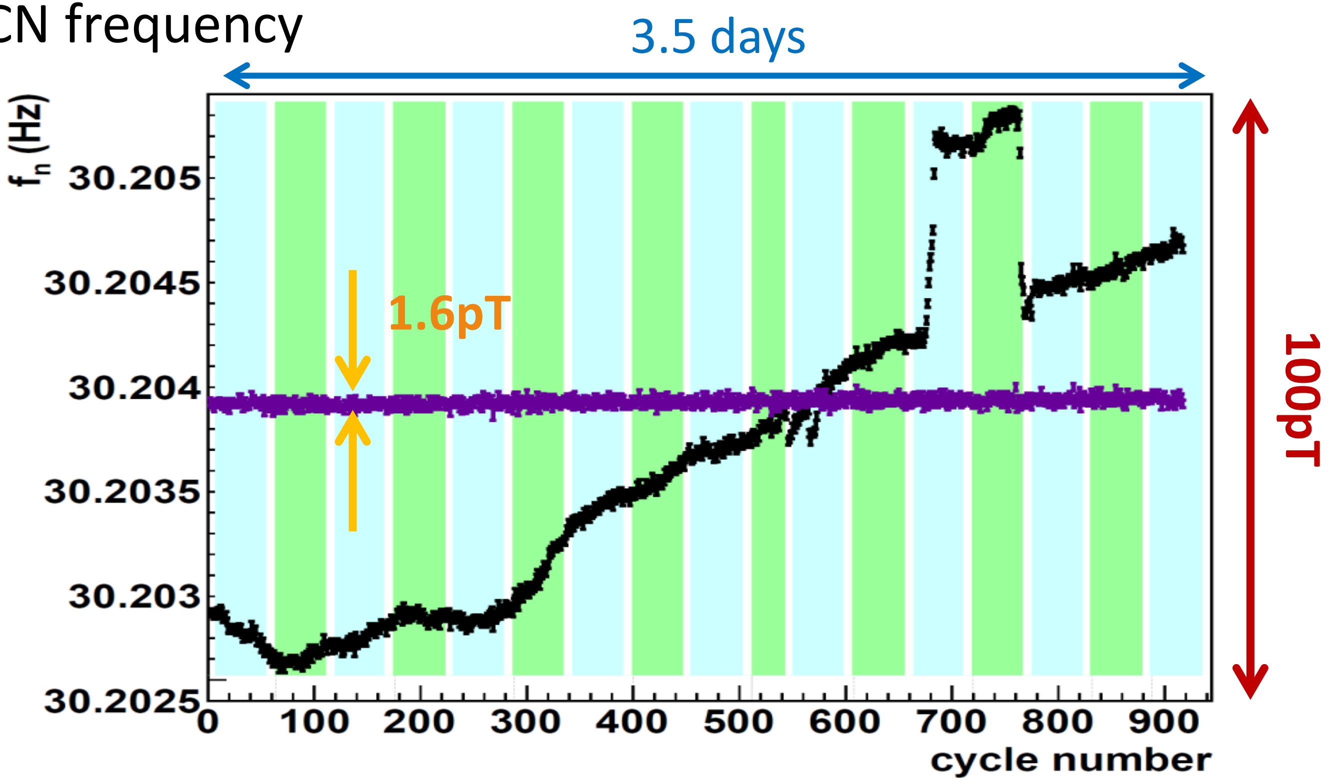




- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with 90s)
- $s/n > 1000$

Hg co-magnetometer

Extract B-field from Larmor frequency
and correct UCN frequency



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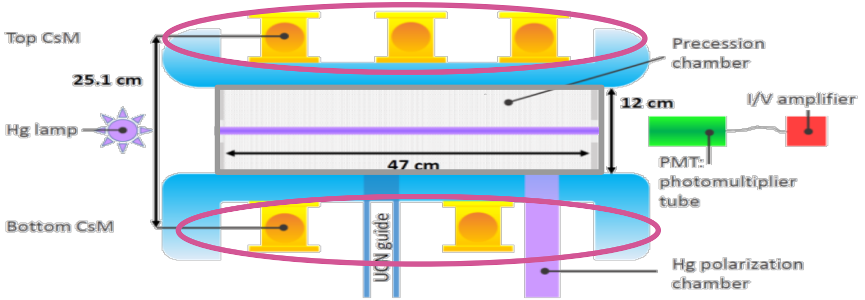
Frequency ratio $R = f_n/f_{Hg}$

- Center of mass offset
- Non-adiabaticity



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

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

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

+ further sys.

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

Dominant systematic

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

$$|B| = B_0 + \dots$$
$$+ \left\langle \frac{\theta v_x}{c^2} E \right\rangle$$
$$+ \left\langle \frac{(x v_y + y v_x + \theta y v_z)}{2 B_0 c^4} \frac{\partial B_z}{\partial z} E \right\rangle$$
$$+ \left\langle \frac{v_y{}^2 + \left(v_x - \theta v_z\right)}{2 B_0 c^4} E^2 \right\rangle$$

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: transferred from mercury to neutron by correction for drifts

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

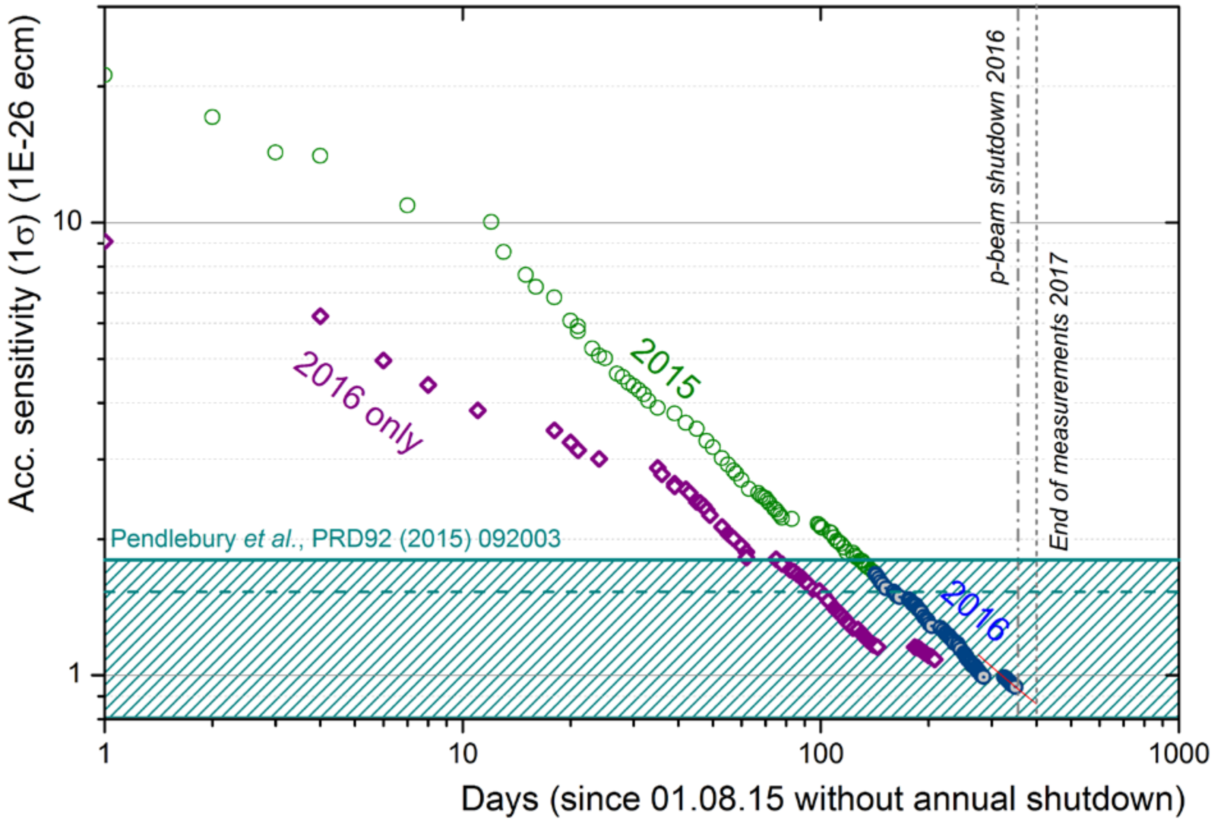
$$d_{\rm Hg}^{\rm false} = \frac{\partial B_z}{\partial z} \cdot 1.15 \times 10^{-27}\, e\cdot{\rm cm} \frac{\rm cm}{\rm pT}$$

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

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

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

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



54362 cycles
(exclude runs with issues)

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

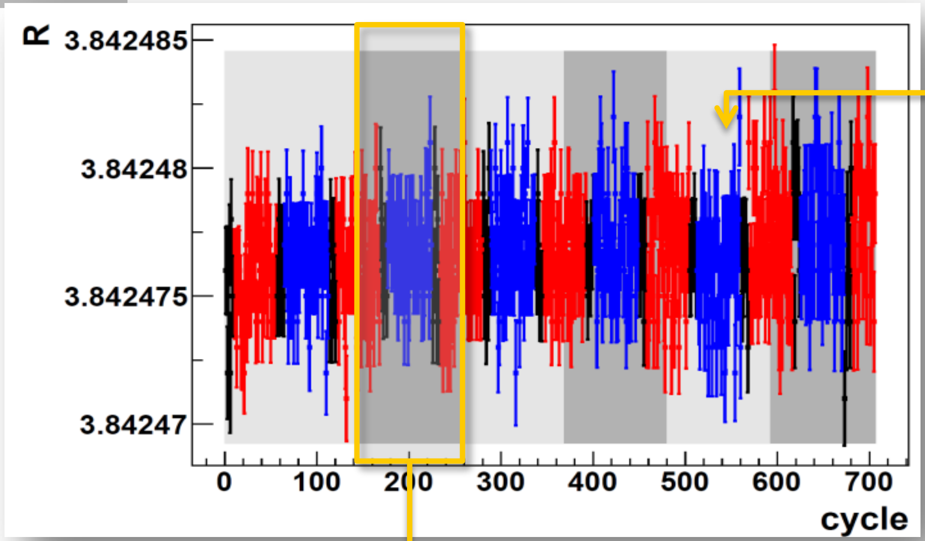
Analysis ongoing:

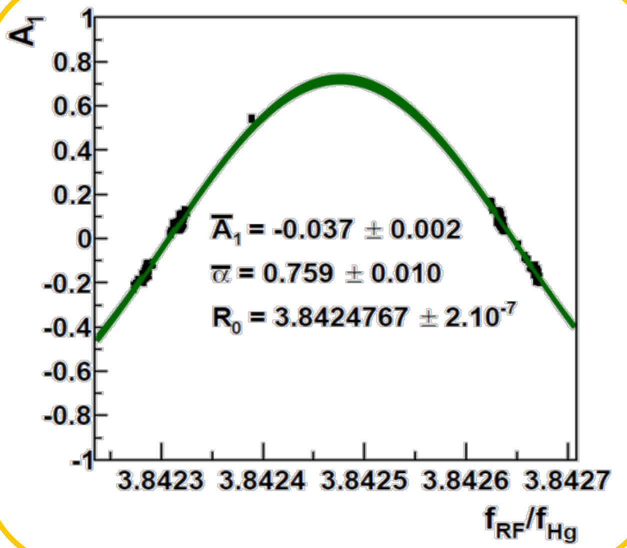
- Blinded data
- Two groups
- Result: 2018

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.

Fit central Ramsey fringe for each state





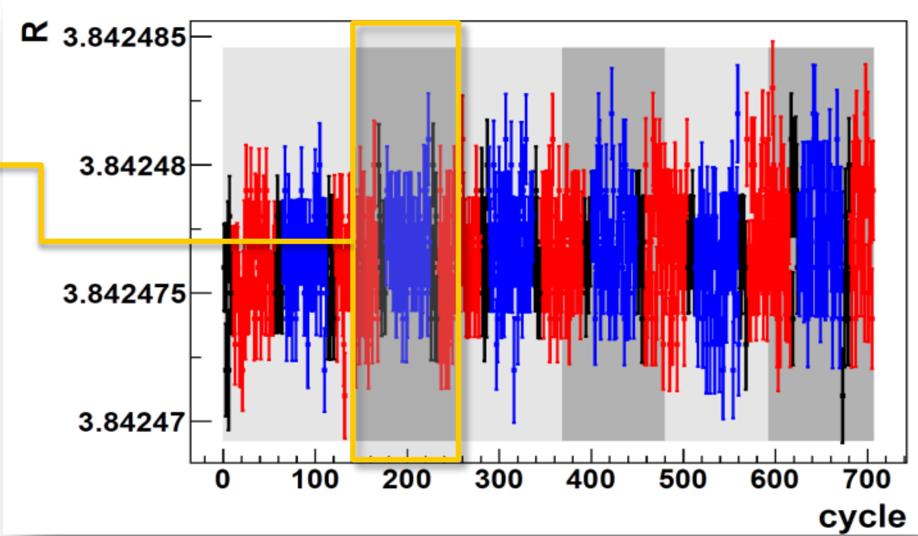
$$d_n = \frac{h\left(f_{\mathrm{n}}^{+} - f_{\mathrm{n}}^{-}\right)}{2E}$$

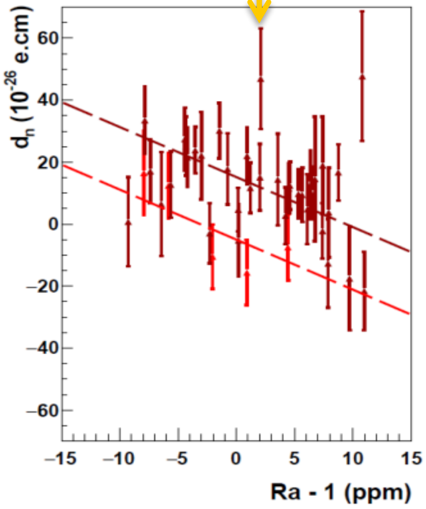
$$R = \frac{f_{\mathrm{n}}^{i}}{f_{\mathrm{Hg}}^{i}}$$

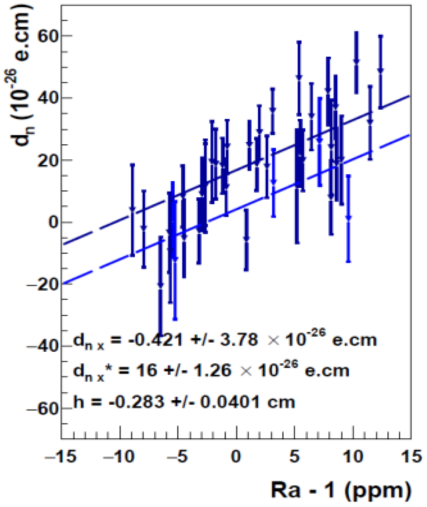
Crossing point analysis

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

$$R^i = \frac{f_n^i}{f_{Hg}^i} = \frac{\gamma_n}{\gamma_{Hg}}\left(1 - \frac{\partial B}{\partial z}\frac{\Delta h}{B} + \ldots\right)$$







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

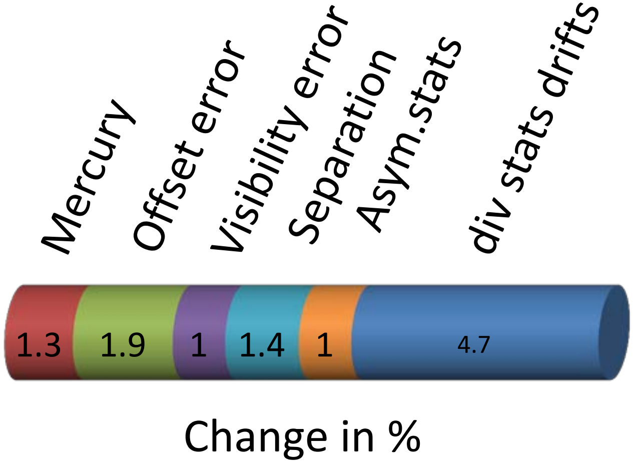
$$R_a - 1 = \frac{\gamma_{Hg}}{\gamma_n} R - 1 = -\frac{\partial B}{\partial z}\frac{\Delta h}{B} + \cdots$$

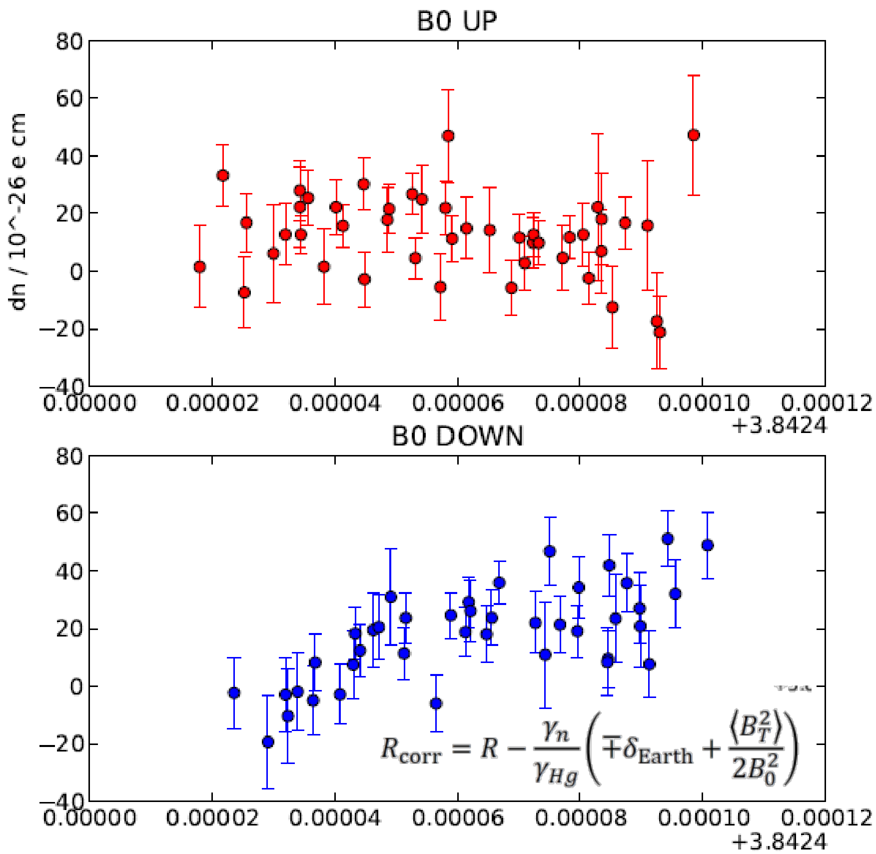
Crossing point analysis

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

$$R_0 = 3.8424521(28)$$

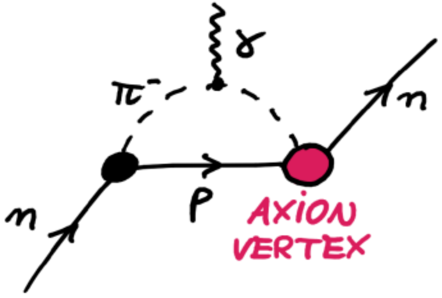
$$\chi^2/NDF = 109/86$$





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

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

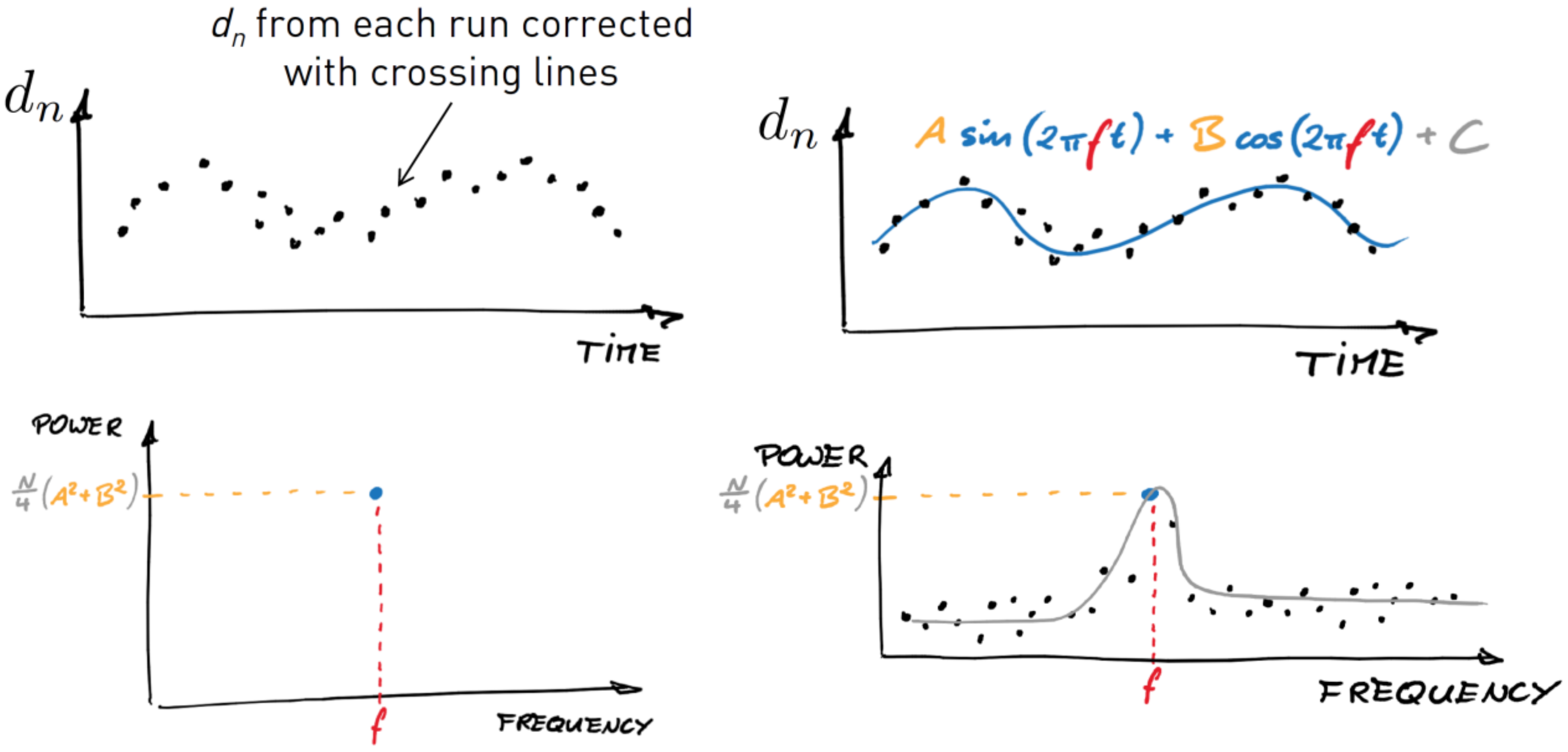
Produces oscillating EDM through same diagrams as θ_{QCD}

Produces oscillations in precession frequency "Axion Wind"

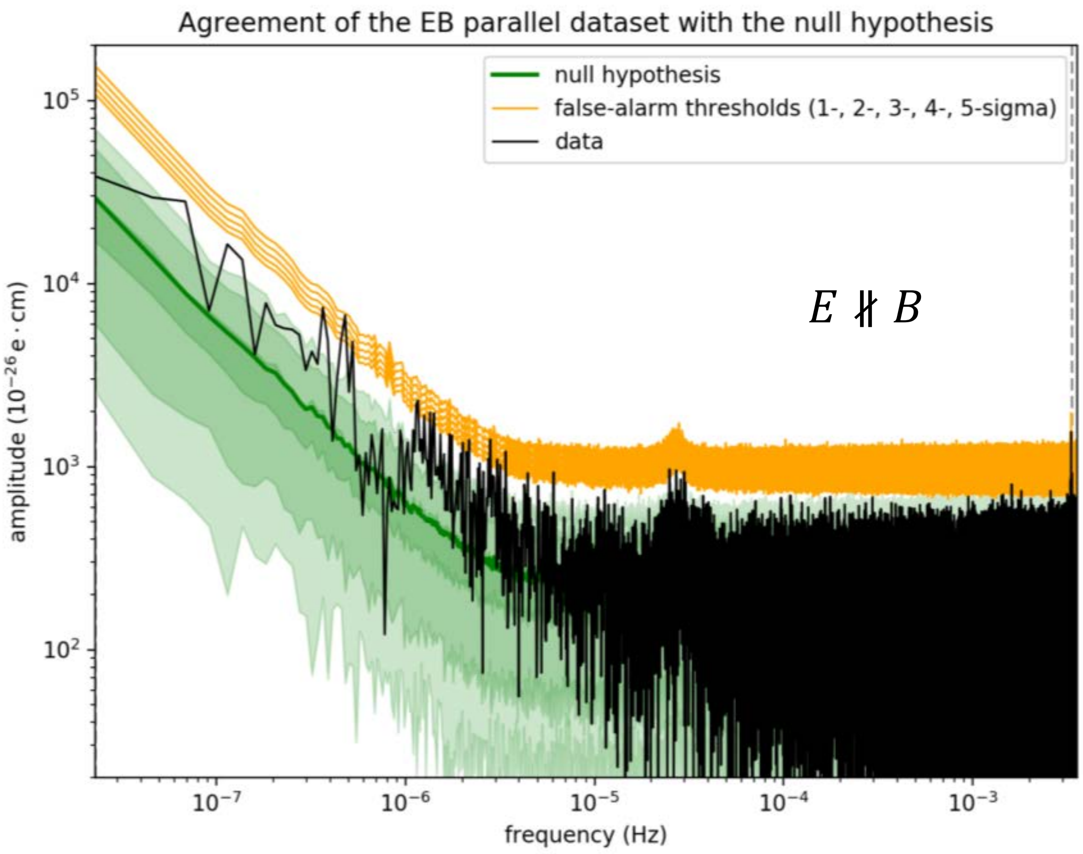
Nick Ayres

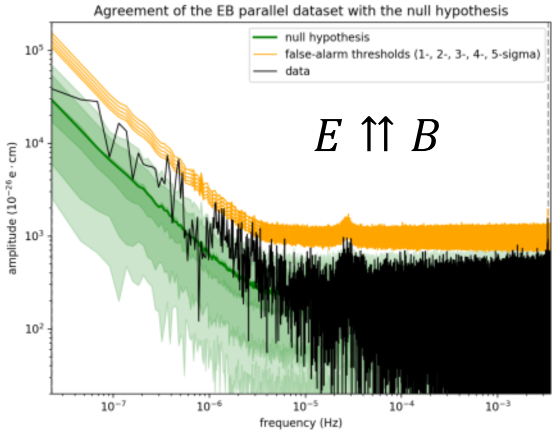
Michal Rawlik

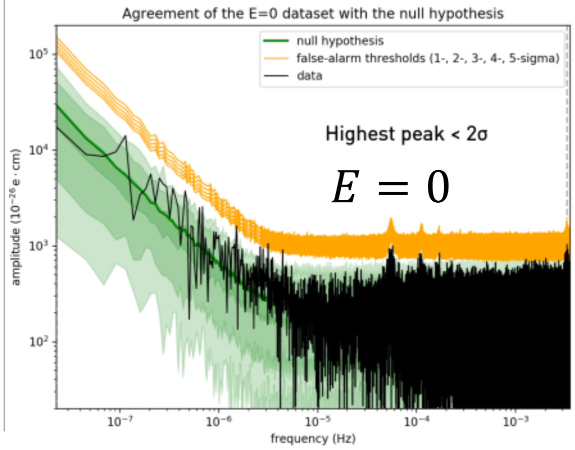
Least square spectral analysis



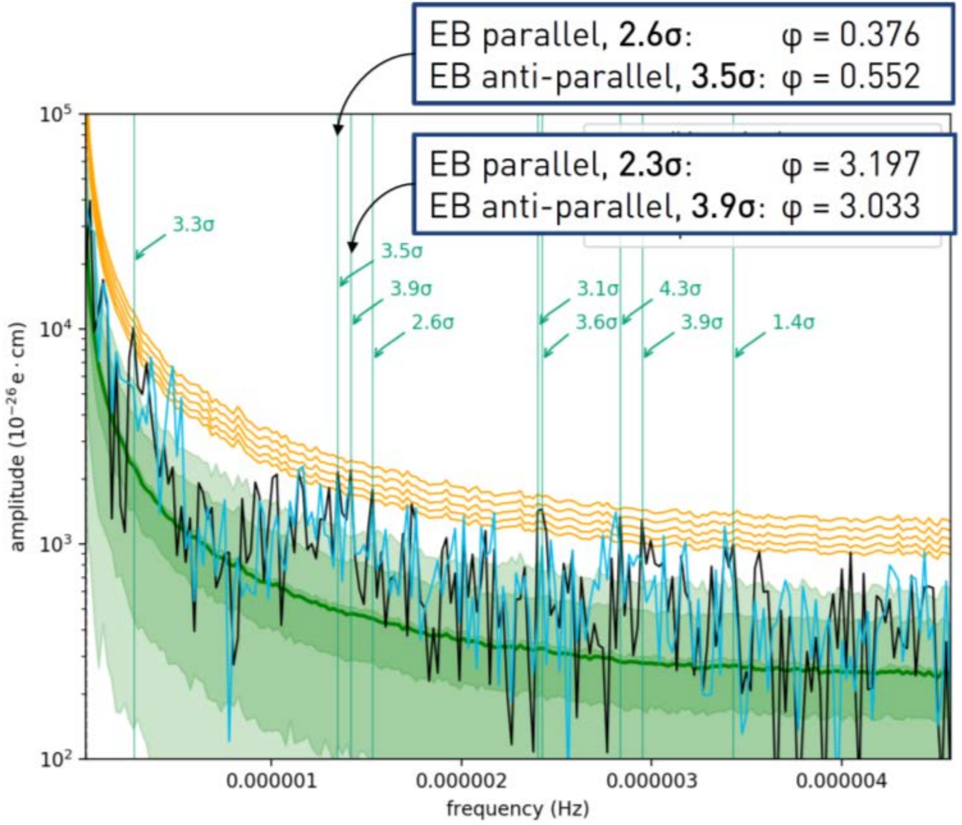
Three Periodograms







Highest peaks



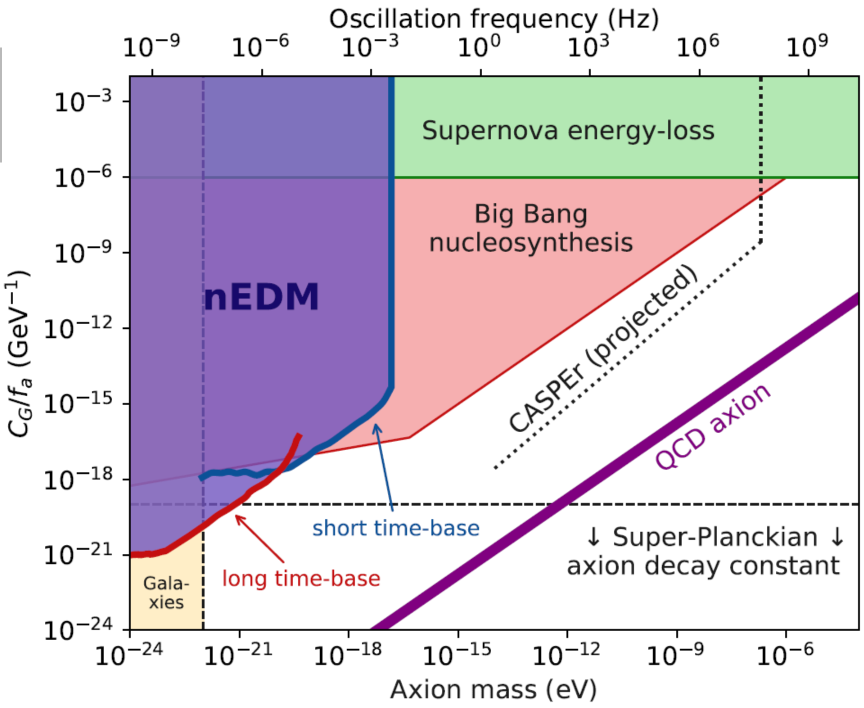
Three "data sets":

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

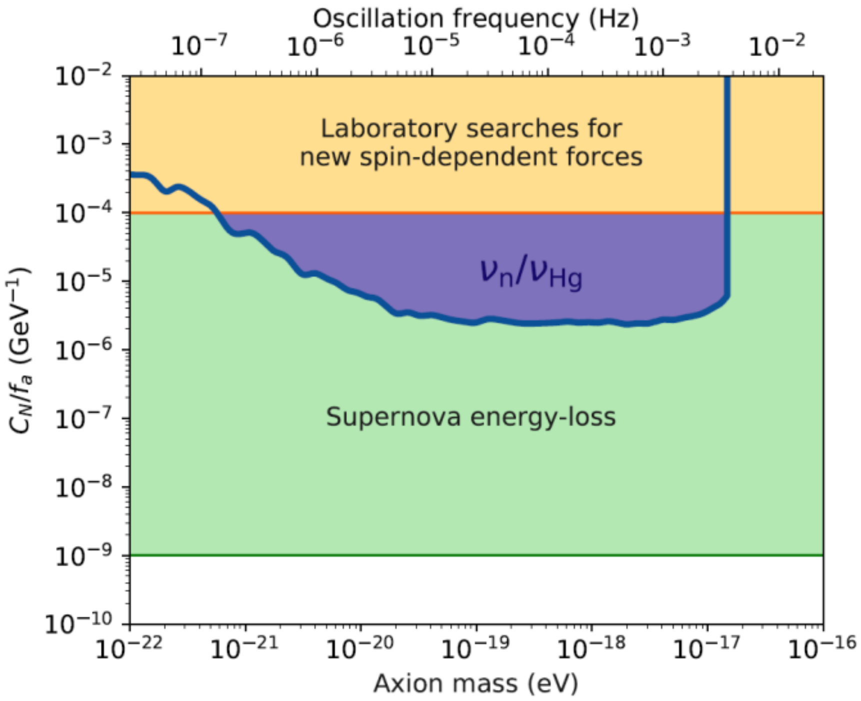
Requirements for signal:

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

Exclusion limits



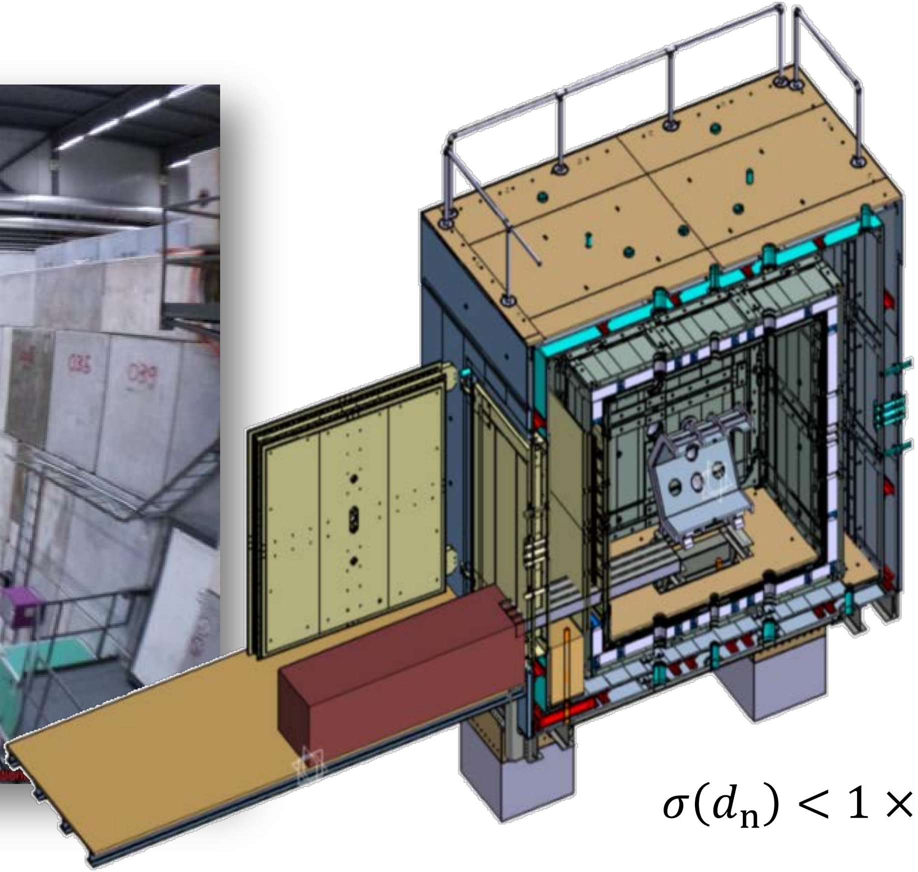
First experimental limits on gluonic coupling



40 times better limit on fermionic coupling

C. Abel *et al.*, PRX7(20017)041034

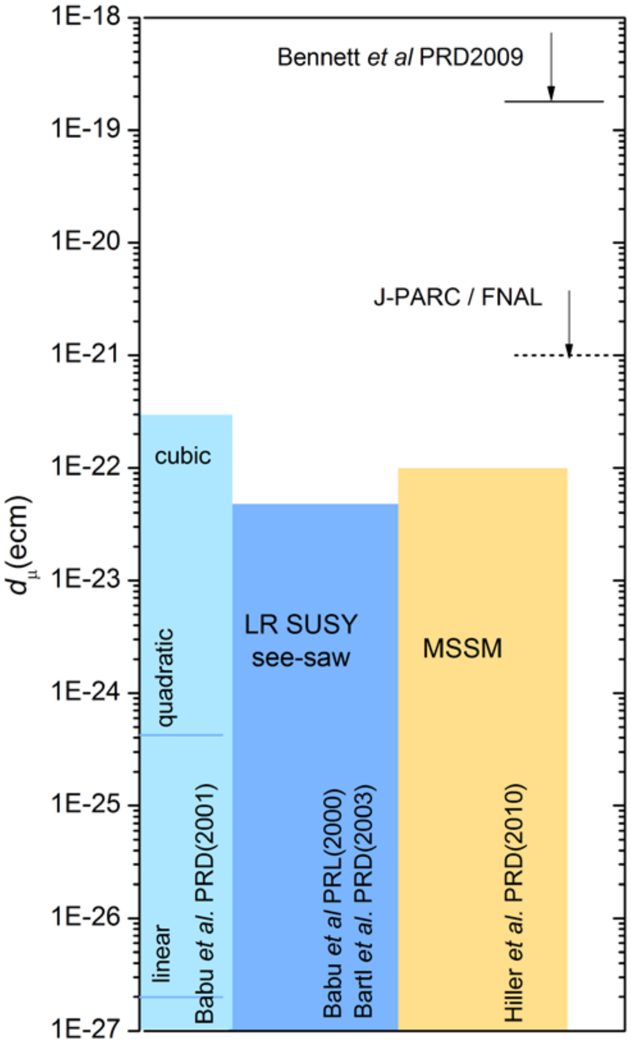
A new nEDM spectrometer with 6-layer mu-metal



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

The collaboration

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



The muon EDM

SM expectation:

$$d_\mu \approx 10^{-36} ecm$$

BSM: *Possible up to*

$$d_\mu \approx 10^{-22} ecm$$

And: Signs for lepton universality violation:

- *B*-meson decays (up to 4.4 σ)*
- g-2 of muon (3.6 σ)**

First dedicated experiment to search for EDM of second generation

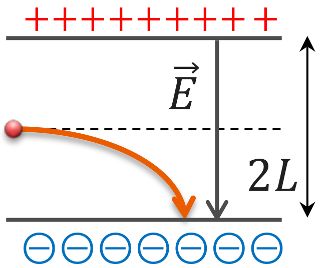
*Altmannshofer *et al*. EPJC(2017)

**Hertzog DW, EPJ Conf 118(2016)

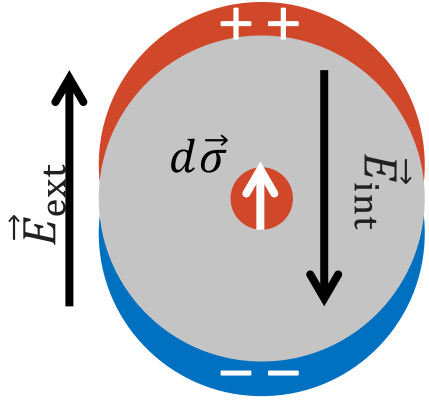
How to measure an EDM of a charged particle?

- Measurement in an electric field?
  $\rightarrow$ Observation time too short. ☹

$$dt \sim \sqrt{\frac{2mL}{q|\vec{E}|}} \sim O(\text{ns})$$

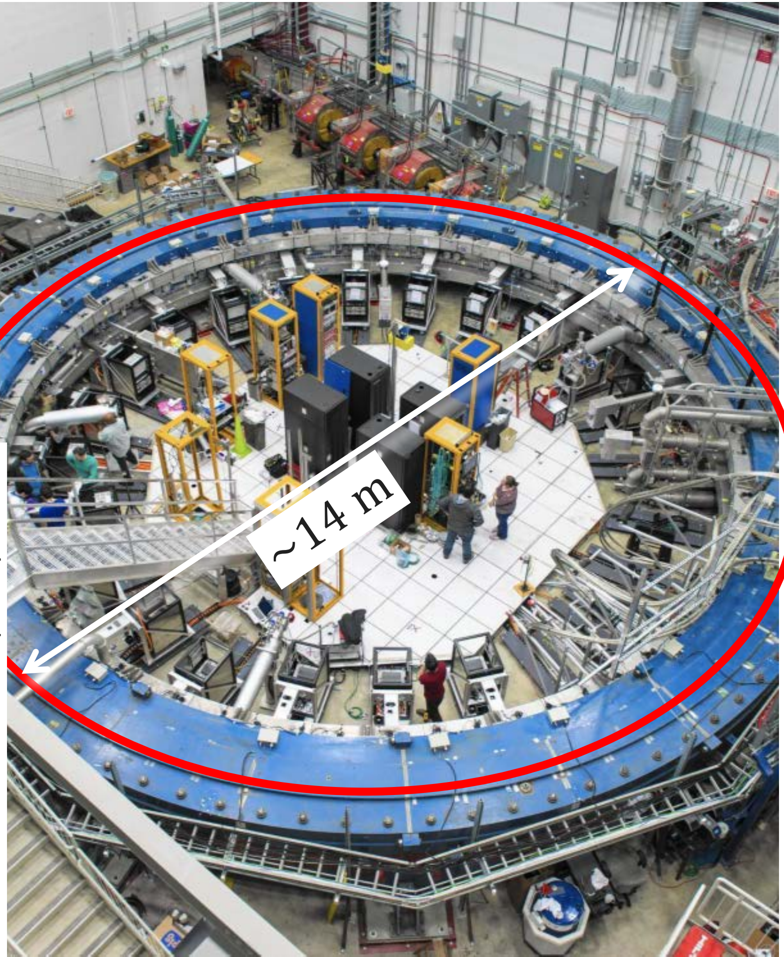


- Measurement in an atom (p,d)?
  $\rightarrow$ nearly perfect Schiff screening. ☹



- Observation of a relativistic particle in a magnetic field: $\vec{\boldsymbol{E}} = \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}}$ ☺

Results from BNL and prospects an FNAL



E821@Brookhaven*:

$$a_\mu^{\mathrm{exp}} = 0.001\,165\,920\,80\,(63) \quad \text{0.54 ppm}$$

$$a_\mu^{\mathrm{th}} = 0.001\,165\,918\,04\,(51) \quad \text{0.44 ppm}$$

$\sim 3.6\ \sigma$ discrepancy

$$d_\mu < 1.8 \times 10^{-19} e\mathrm{cm}\ (95\%\ \mathrm{C.L})^{**}$$

FNAL E969: (start 2018)

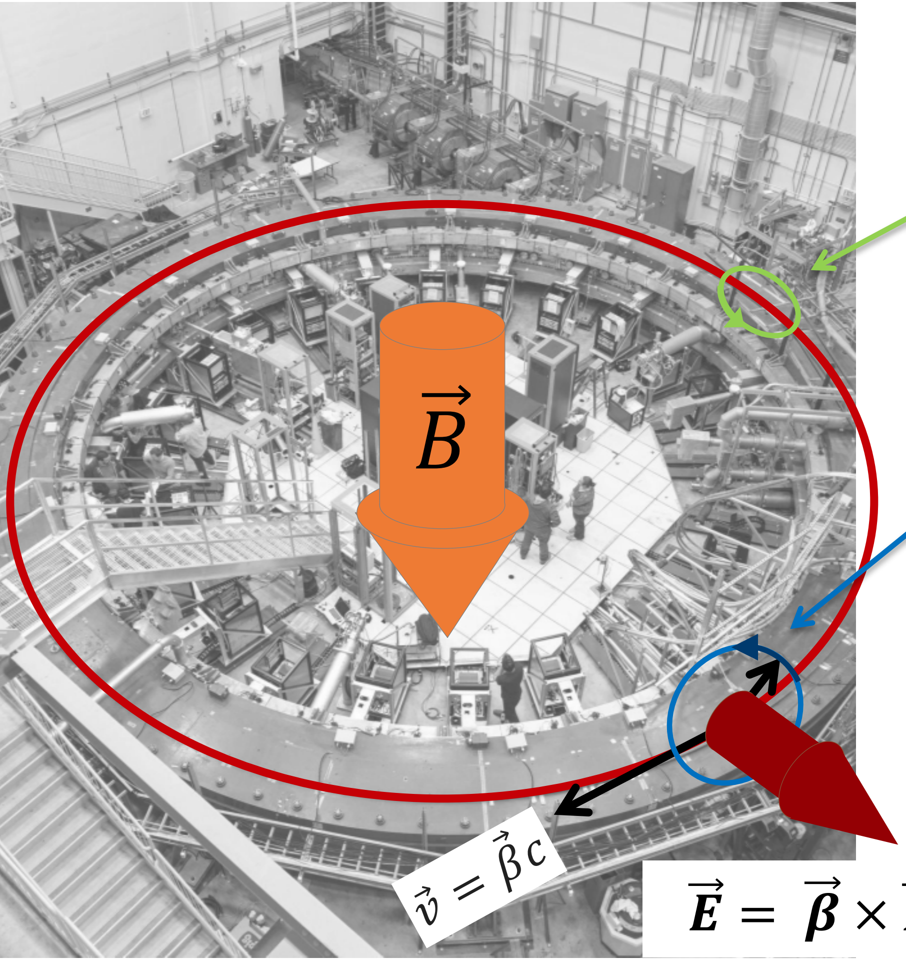
$$\sigma(a_\mu)/a_\mu \leq 0.14\ \mathrm{ppm}$$

$$\sigma(d_\mu) \approx 1 \times 10^{-21} e\mathrm{cm}$$

*Bennett *et al.*, *PRD73(2006)072003*

**Bennett *et al.* *PRD80(2009)052008*

Spin precession in $\vec{B}$ and $\vec{E}$ fields of a storage rings:



$$\vec{\omega}_a = \frac{e}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Spin precession in orbital plane

$$\left(a = \frac{g-2}{2}\right)$$

$$\vec{\omega}_d = \frac{e}{m}\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

Spin precession out of orbital plane:
"EDM signal"

$$\left(\eta = \frac{4mcd}{q\hbar}\right)$$

Sum $\vec{\omega} = \vec{\omega}_a + \vec{\omega}_d$ dilutes the EDM signal and increases systematic effects

$$\vec{E} = \vec{\beta}\times\vec{B} \approx O(100\mathrm{MV/m})$$

PAUL SCHERRER INSTITUT

Frozen spin technique for the muon EDM

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta_d}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

- Cancel anomalous precession with matched E-field:

$$E \cong aBc\beta\gamma^2$$

- Spin remains parallel on orbit
- No contamination from anomalous spin precession

- An EDM signal is visible as growing vertical polarization

$$s_y(t) \propto \eta\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)t$$

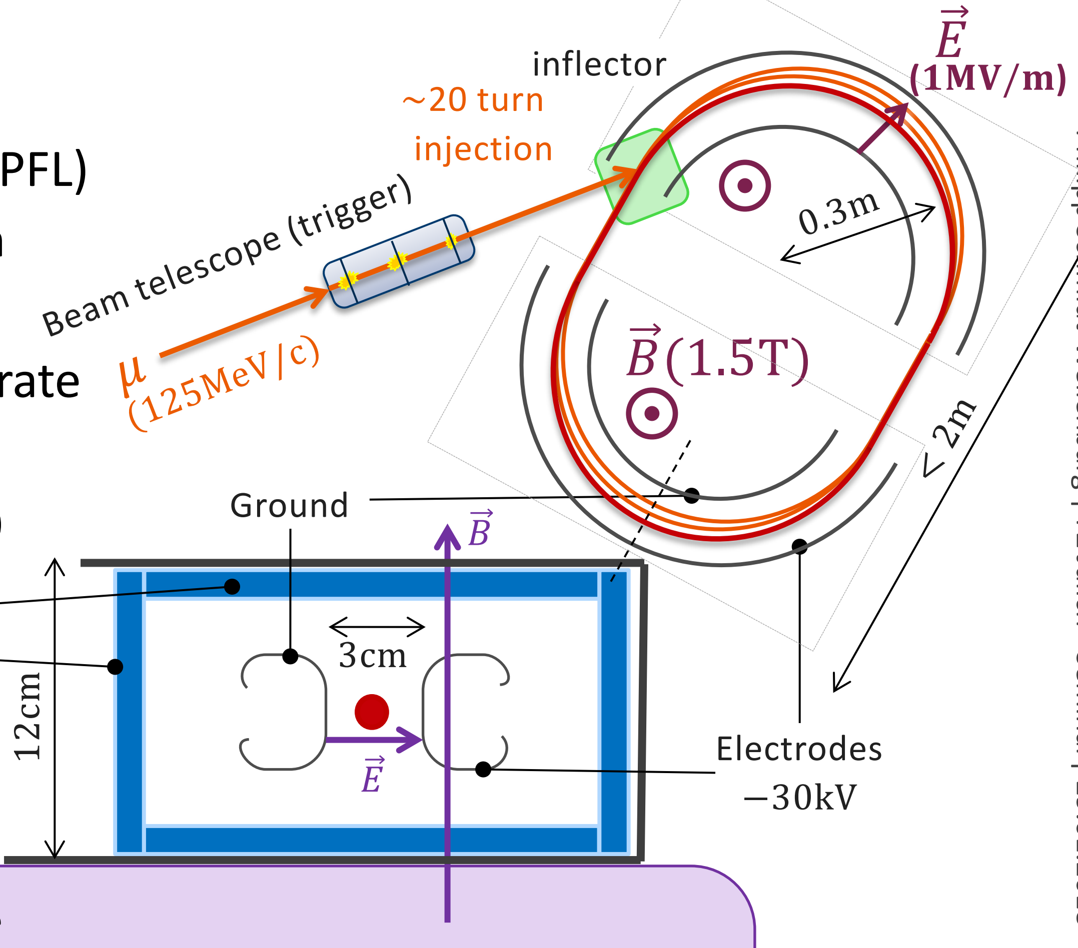
- Detected as decay asymmetry of the muon

Farley *et al.*, PRL93(2004)
Adelmann *et al.*, JPG37(2010)

Proposal for a dedicated compact μ-EDM at PSI

- Polarized μ −beam (PSI)
- Trigger from beam telescope (EPFL) for start of inflector ramp down (resonance injection*)
- One muon at a time ~200kHz rate
- Tracking detector for positrons (resolution $\sim 0.25 \times 0.25\text{mm}^2$)

Detector (EPFL):
3-layer scintillating fibers with SiPM readout and stereo angle

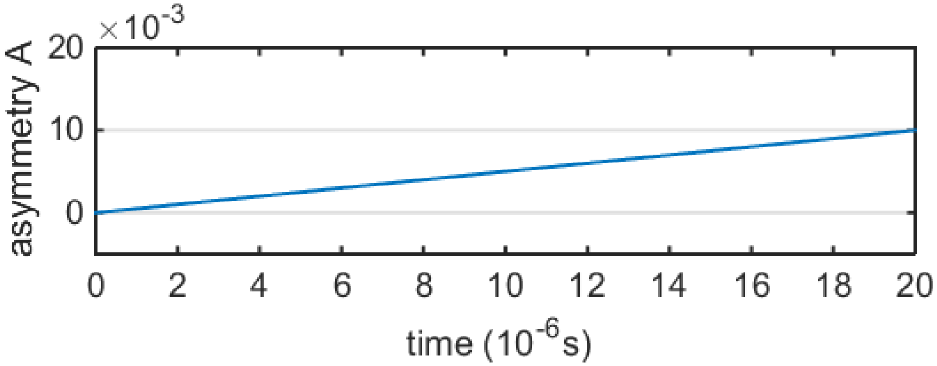


A. Adelmann *et al.* JPG 37(2010)085001

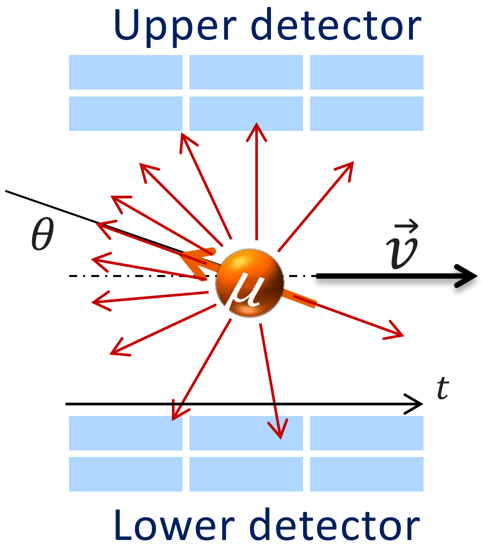
* H. Yamada et al. NIMA467/368(2001)

Signal: asymmetry of upper to lower detector

- Up / down detector measure decay positrons ($\tau_\mu = 2.2\mu s$)
- Side detectors (not shown) measure a_μ-precession to tune $E \cong aBc\beta\gamma^2$



$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)}$$

A. Adelmann *et al.* JPG 37(2010)085001

Prospects for compact μ-EDM at PSI

Apply **frozen spin technique**

- PSI μE1: $2 \times 10^8 \mu^+/s$ $\gamma = 1.57$
- Polarization from pion decay: $P = 0.9$
- Mean asymmetry of muon decay: $\alpha = 0.3$
- Compact conventional magnet:

$$B = 1.5\,T \Rightarrow R = 0.28\text{m}, E = 10\text{kV/cm}$$

- Detection rate: 200 kHz

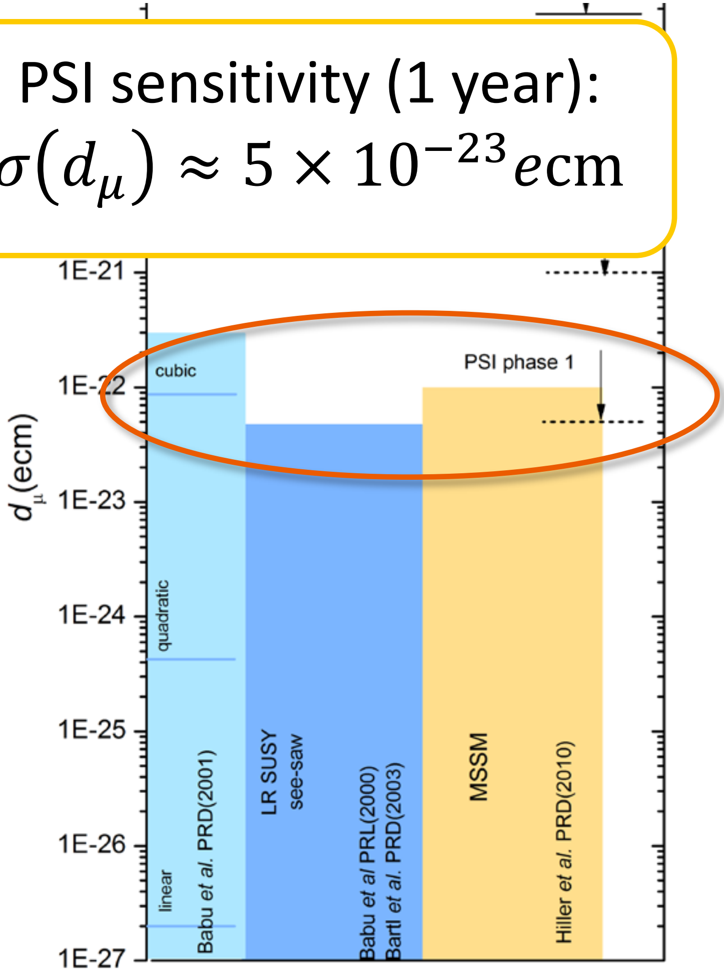
$$\sigma(d_\mu) = \frac{\hbar \gamma a}{2E\tau_\mu \alpha P \sqrt{N}} = 1 \times 10^{-16} \frac{ecm}{\sqrt{N}}$$

- Run time of 2×10^7 s

$\Rightarrow N = 4 \times 10^{12}$ positrons per year.

PSI sensitivity (1 year):

$$\sigma(d_\mu) \approx 5 \times 10^{-23} ecm$$

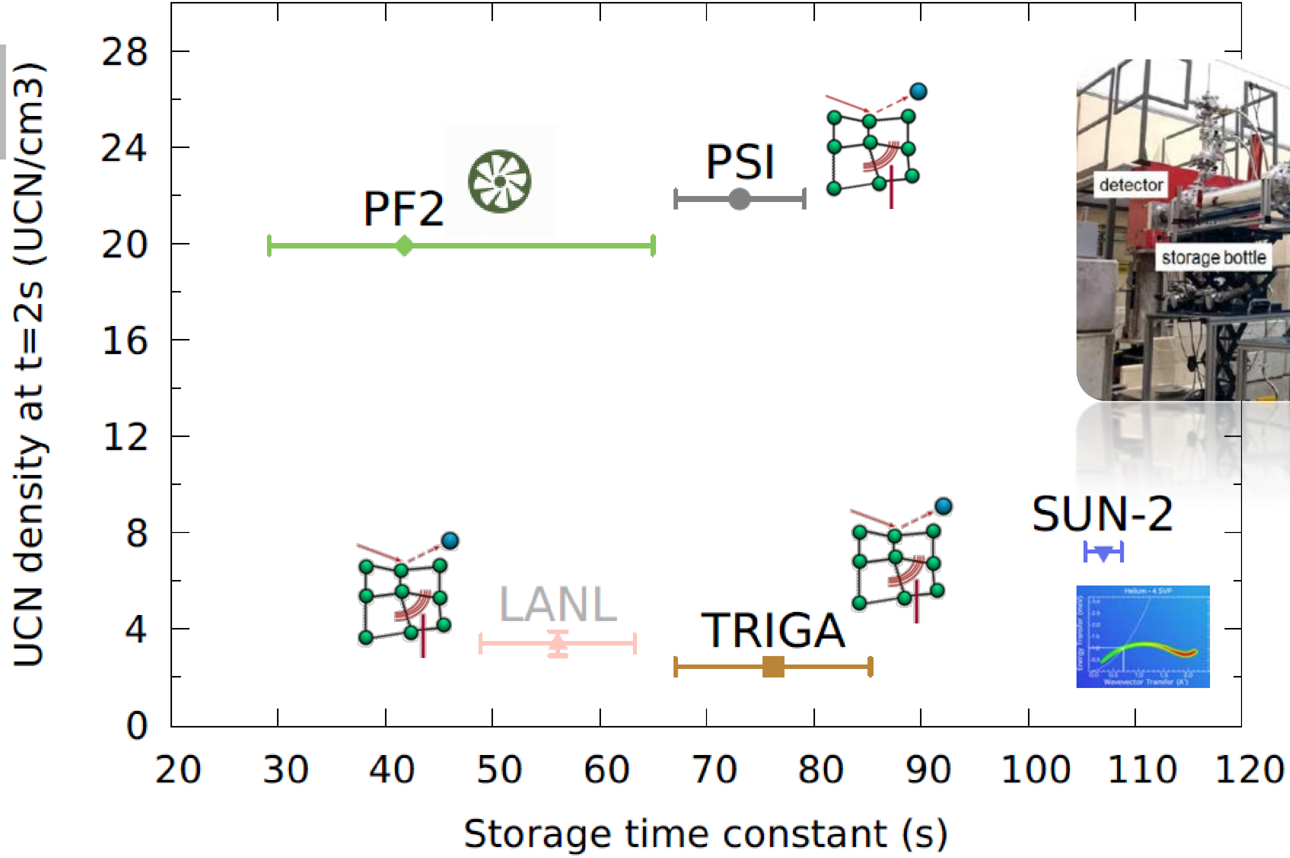


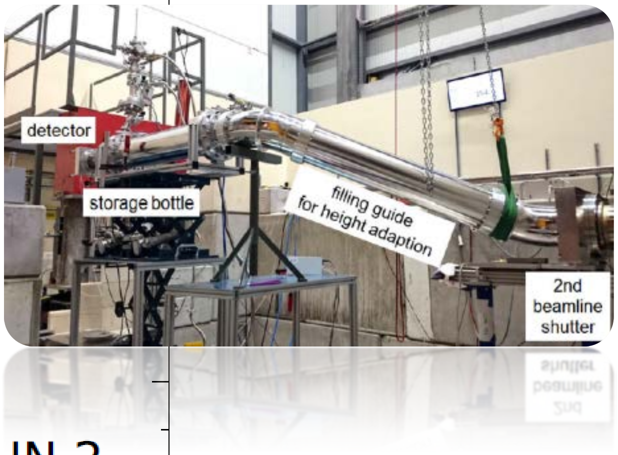
Conclusions

- EDM are unique probes for CP-violation and open a window to physics beyond the standard model
- The nEDM@PSI collaboration has taken the world most sensitive data set and prepares a new result in 2018
- The same data-set was used to set the first laboratory limit on an gluonic axion
- A search for an EDM of the muon using a compact storage ring at PSI is a unique science opportunity, and complements the electron EDM searches.

Backup

Worldwide comparison of UCN sources





Bison *et al.*, PRC 95(2017)045503