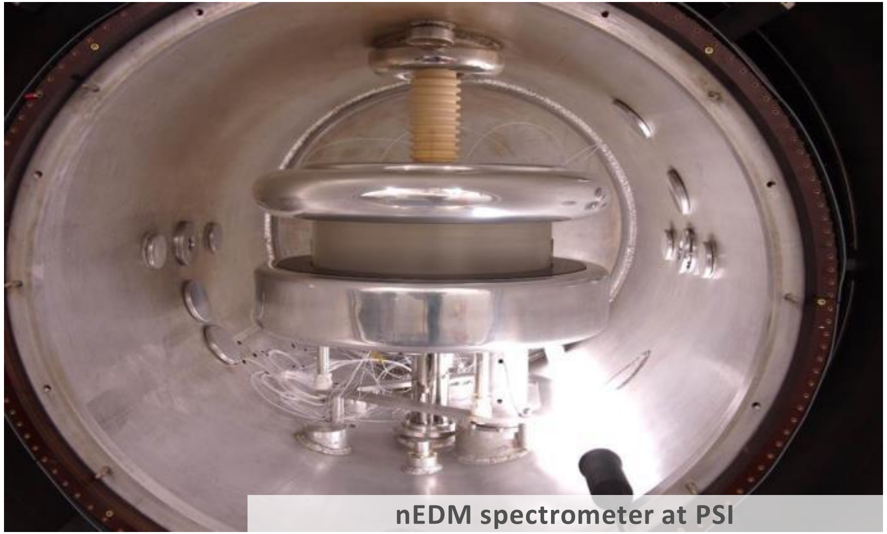
PAUL SCHERRER INSTITUT

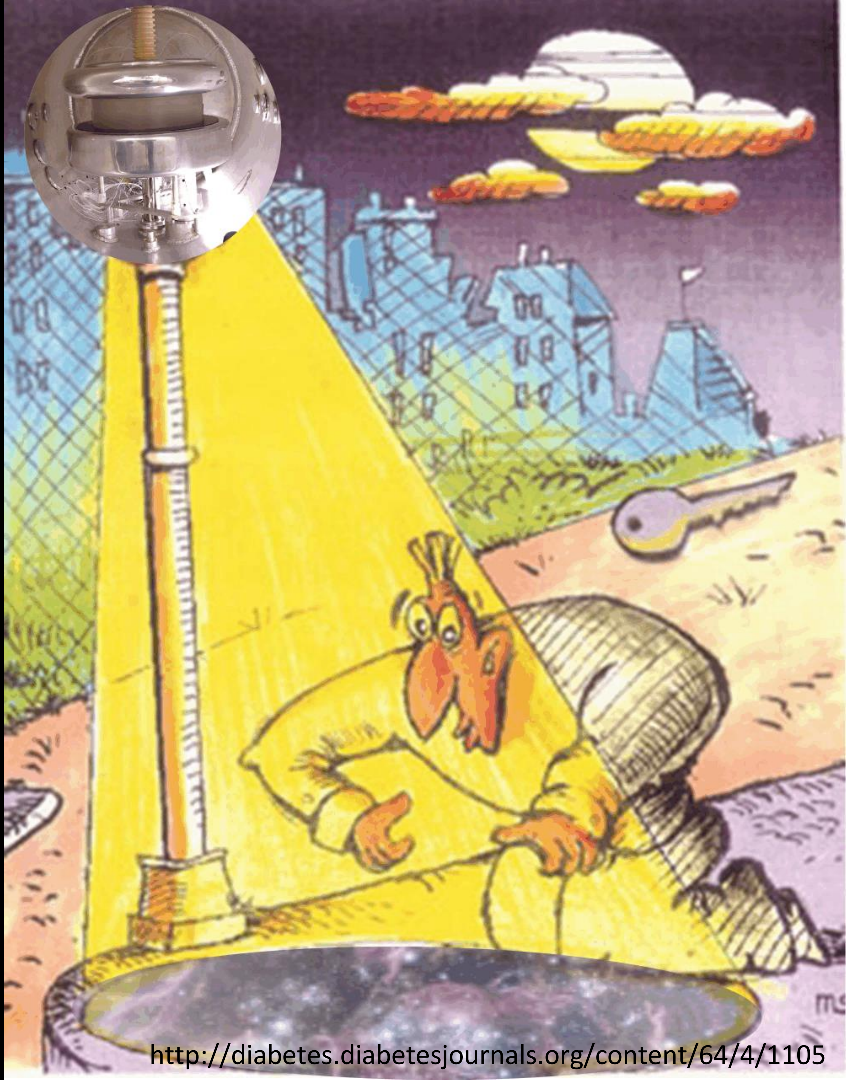


nEDM spectrometer at PSI

XIIth International Workshop on the Interconnection between Particle Physics and Cosmology

Searching for dark matter using ultracold neutrons

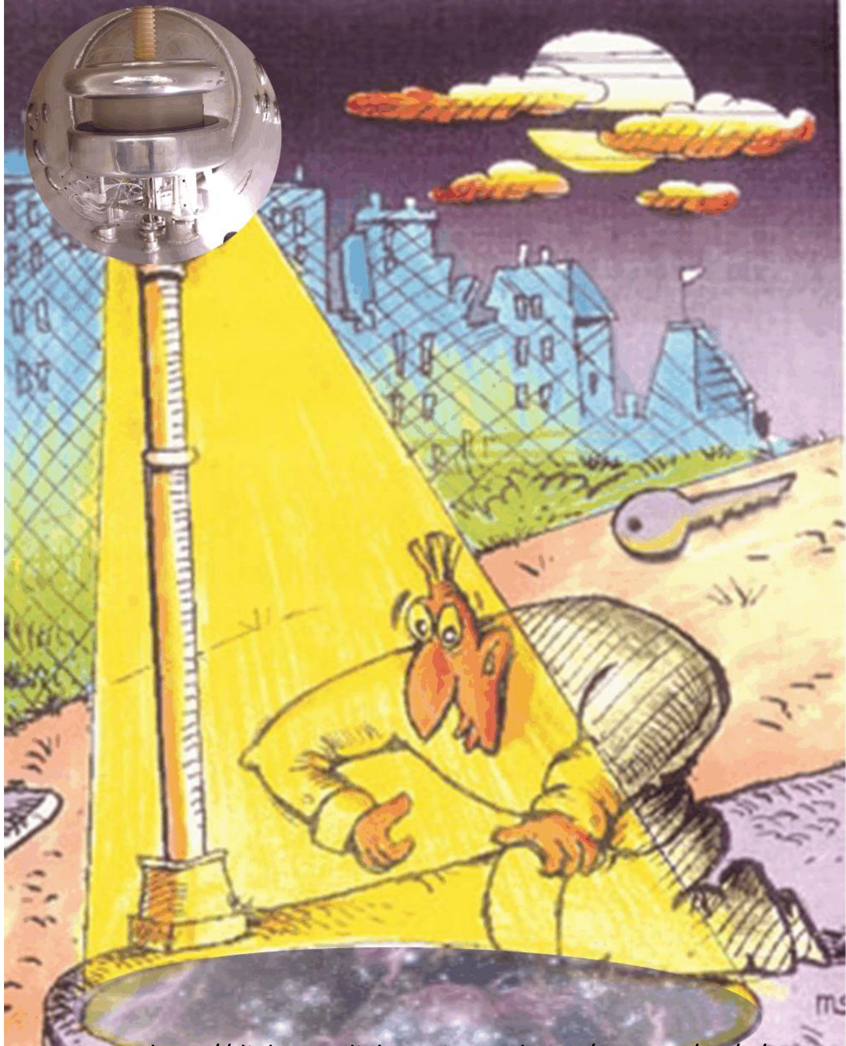
Philipp Schmidt-Wellenburg | Paul Scherrer Institute | 20.-24.08.18



http://diabetes.diabetesjournals.org/content/64/4/1105

Outline

- Measuring frequencies with neutrons (UCN)
- The neutron electric dipole moment and the Axion
- Results from dark matter searches with UCN
- Summary and conclusion



http://diabetes.diabetesjournals.org/content/64/4/1105

Spin precession and magnetic moment

a neutron (fermion) with spin 1/2

suddenly, turn on magnetic field B

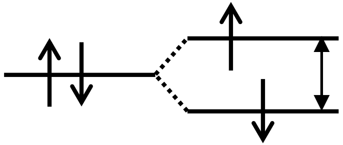
spin starts to precess about B with frequency $\vec{\omega}$

Larmor precession: $\vec{\omega} = -\gamma\vec{B}$

Magnetic moment: $\vec{\mu} = \gamma\vec{s}$

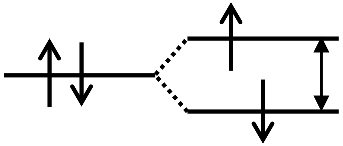
Modified Larmor Frequency in the case of EDM

$V_{\mathrm{mag}} = -\gamma_{\mathrm{n}} \vec{s} \cdot \vec{B}$



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

$V_{\mathrm{mod}} = -d_{\mathrm{n}} \vec{s} \cdot \vec{E}$



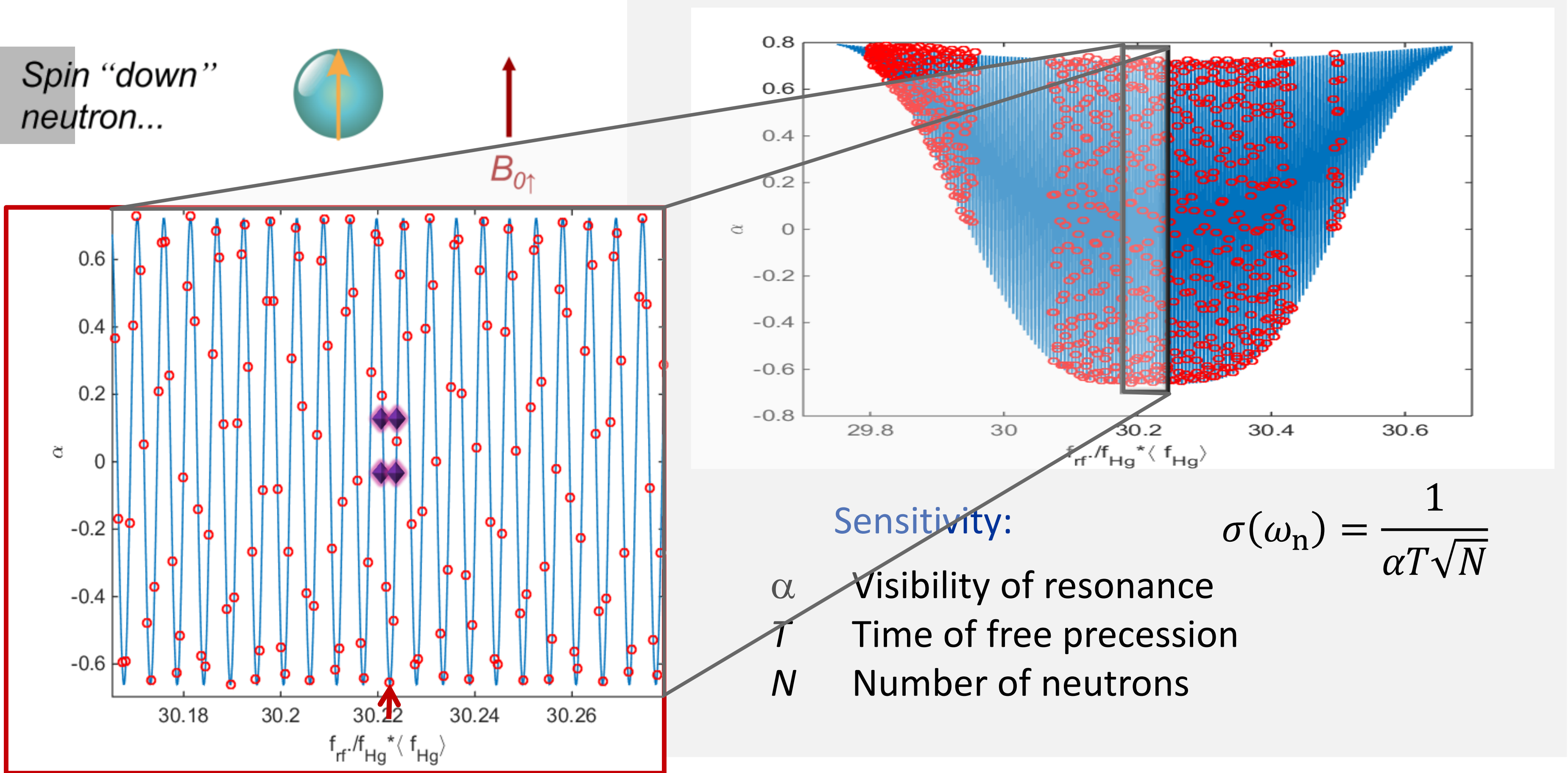
$\Delta E_{\mathrm{mod}} = \hbar\omega_{\mathrm{mod}} = 2d_n E$

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



Sensitivity:

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

α Visibility of resonance

T Time of free precession

N Number of neutrons

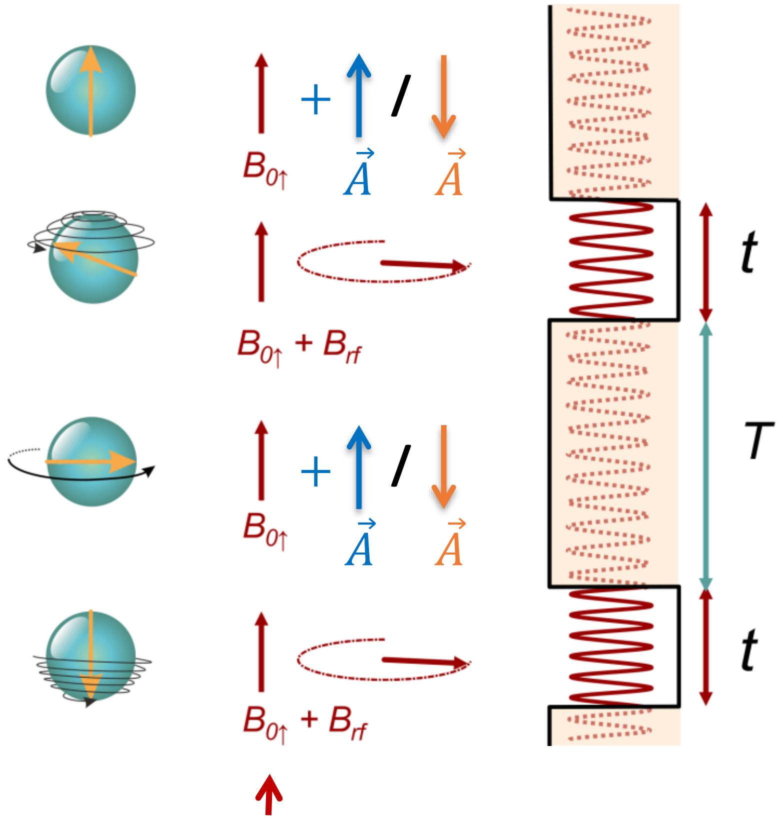
Searching for an additional coupling to the spin

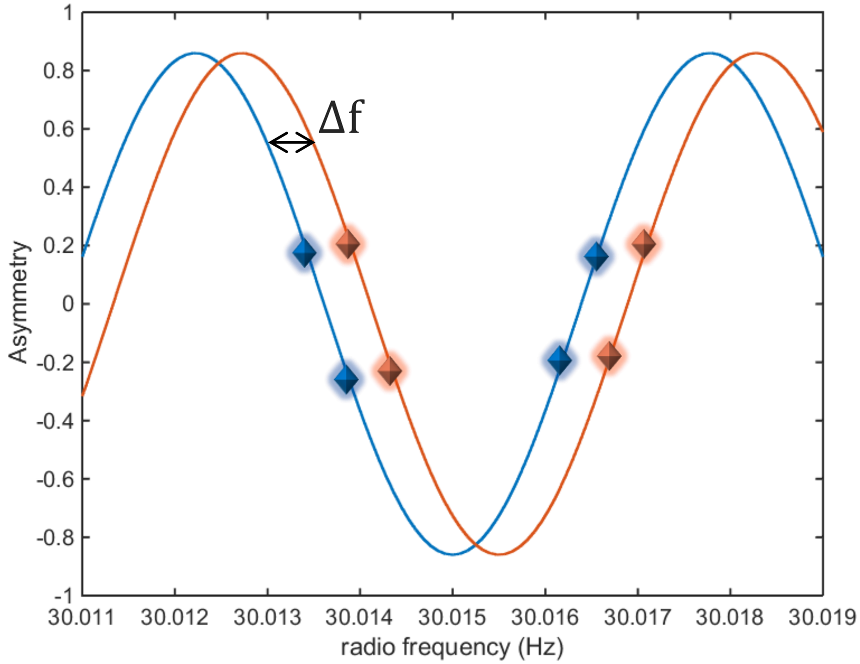
Spin "down" neutron...

Apply π/2 spin flip pulse...

Free precession at ω_L

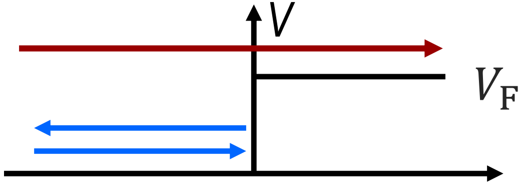
Second π/2 spin flip pulse.





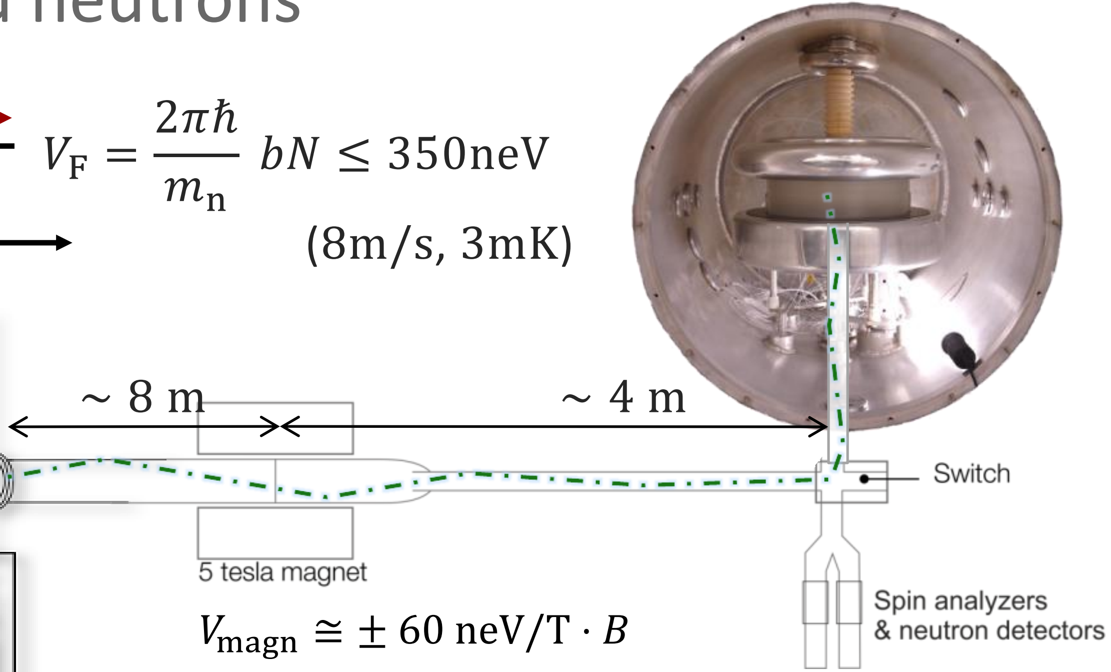
for d_n and $\vec{A} = \vec{E}$ $\quad \sigma(d_n) = \dfrac{\hbar}{2\alpha T E\sqrt{N}}$

Ultracold neutrons

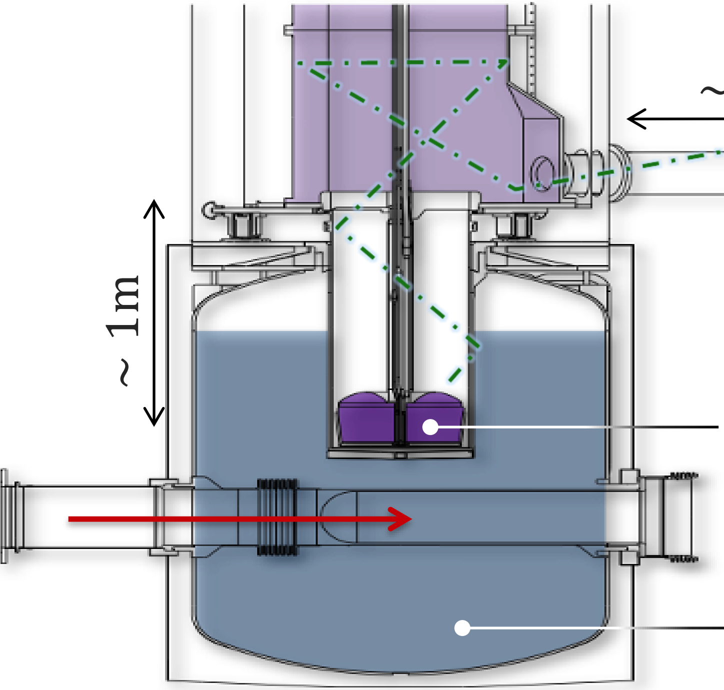


$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m_{\mathrm{n}}} bN \leq 350\mathrm{neV}$$

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



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



solid deuterium
(phonon excitation → UCN conversion)

D_2O thermal moderator

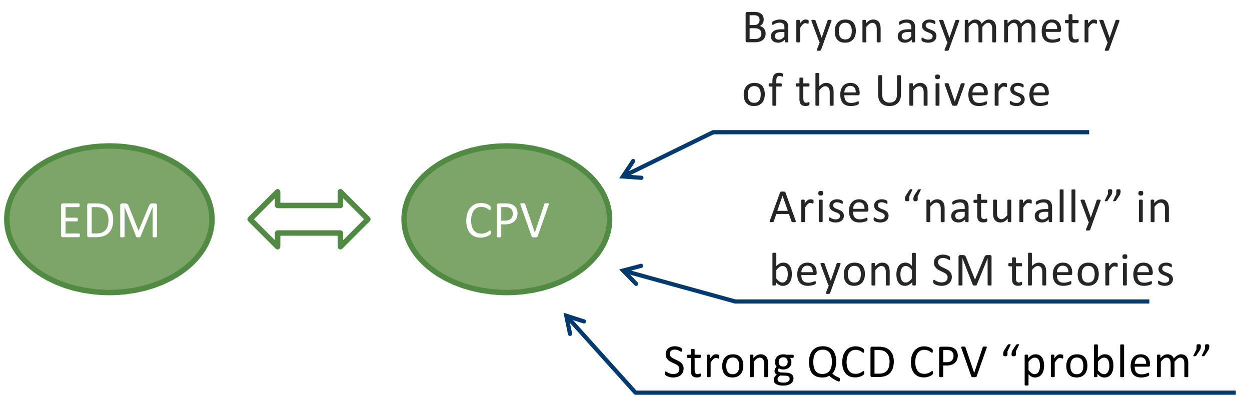
CP violation & edm

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

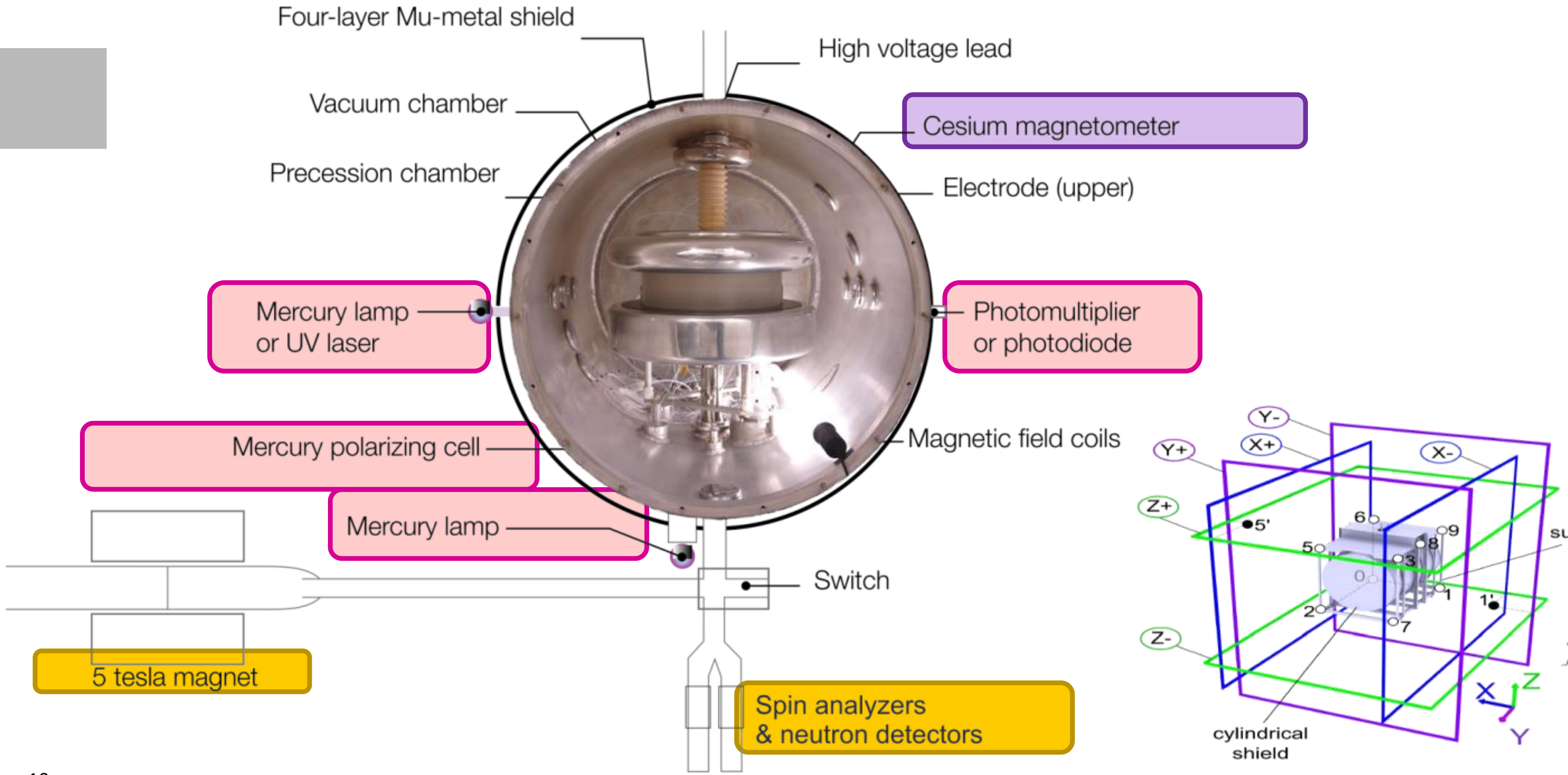
Time reversal

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

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

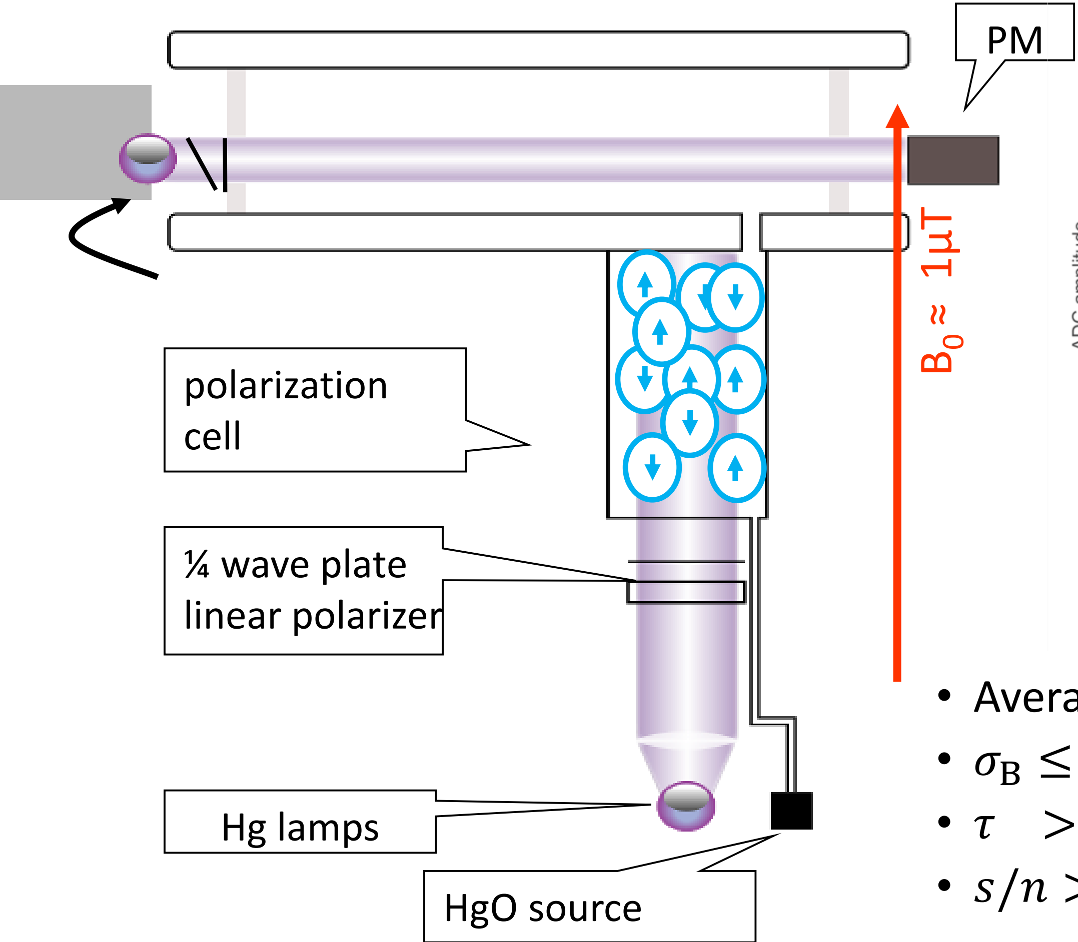


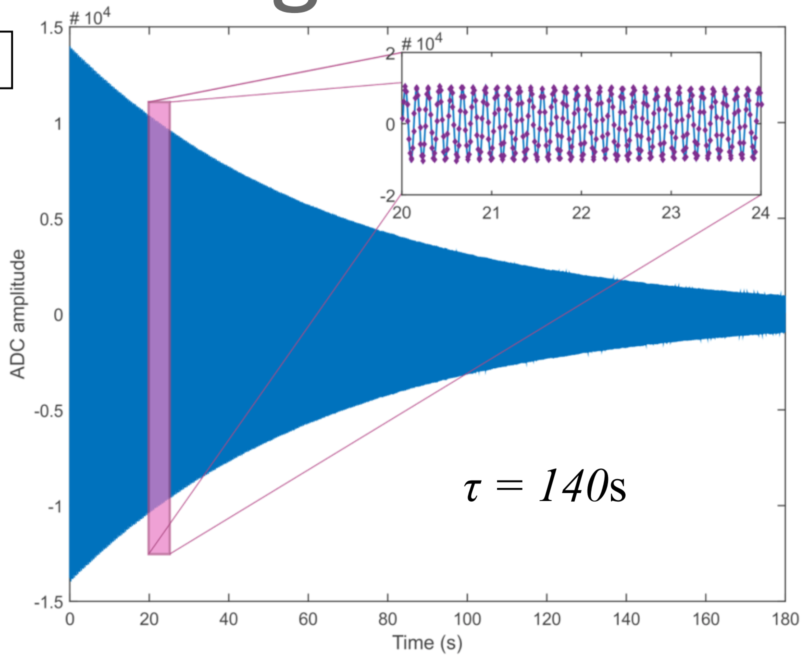
The nEDM spectrometer



Philipp Schmidt-Wellenburg | PPC – 2018 | 20.08-24.08.18

Mercury co-magnetometer

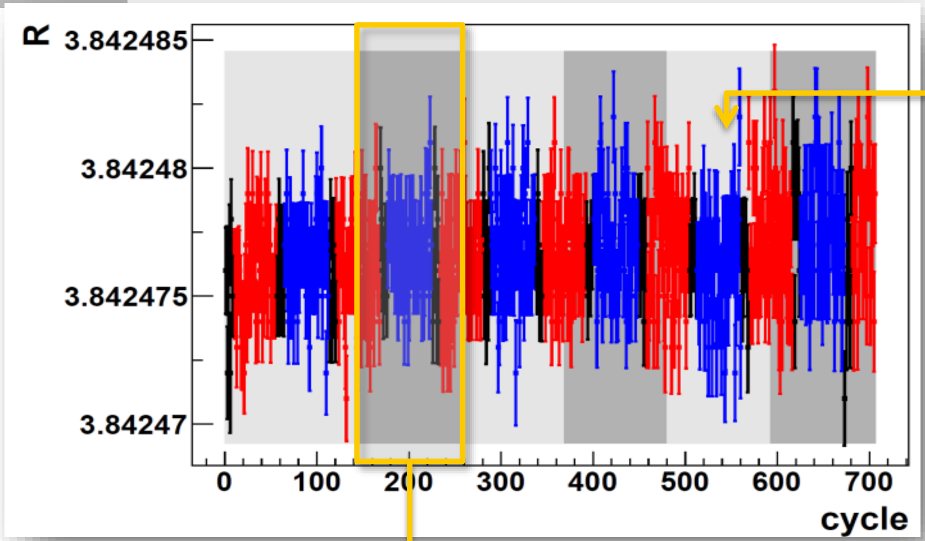


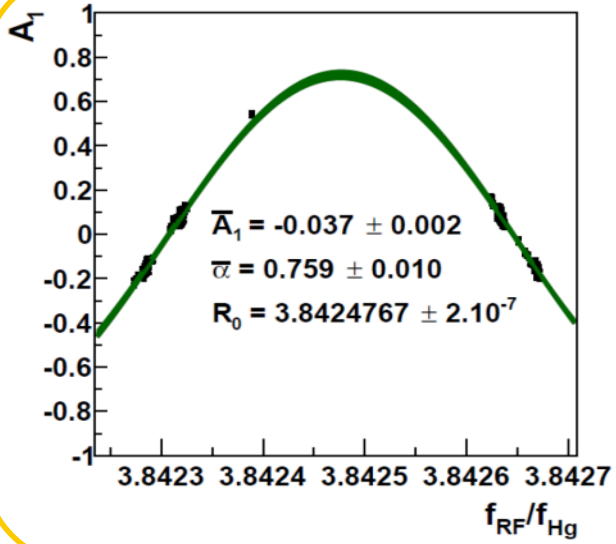


- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with ~ 90 s)
- $s/n > 1000$

Analysis

Fit central Ramsey fringe for each state

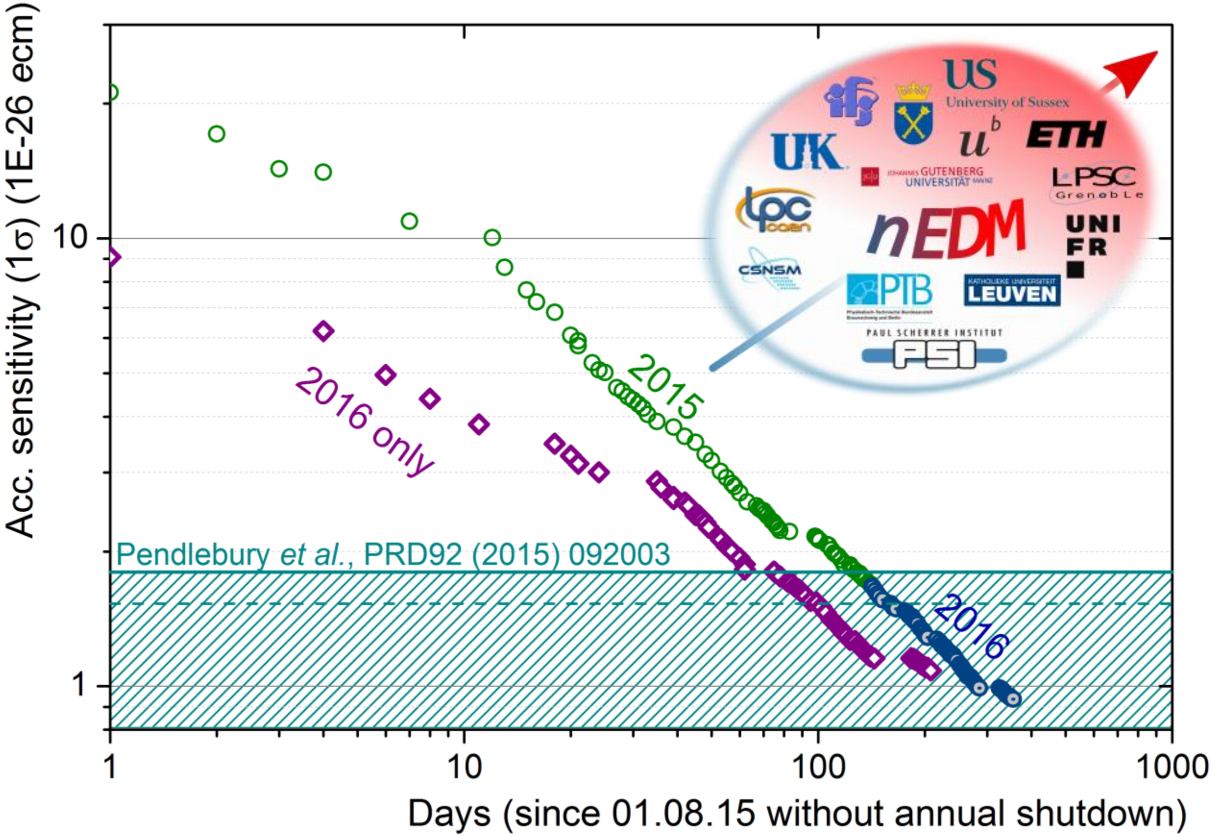




$$d_n = \frac{h\left(f_n^+ - f_n^-\right)}{2E}$$

$$R = \frac{f_n^i}{f_{Hg}^i}$$

Status of the nEDM search at PSI



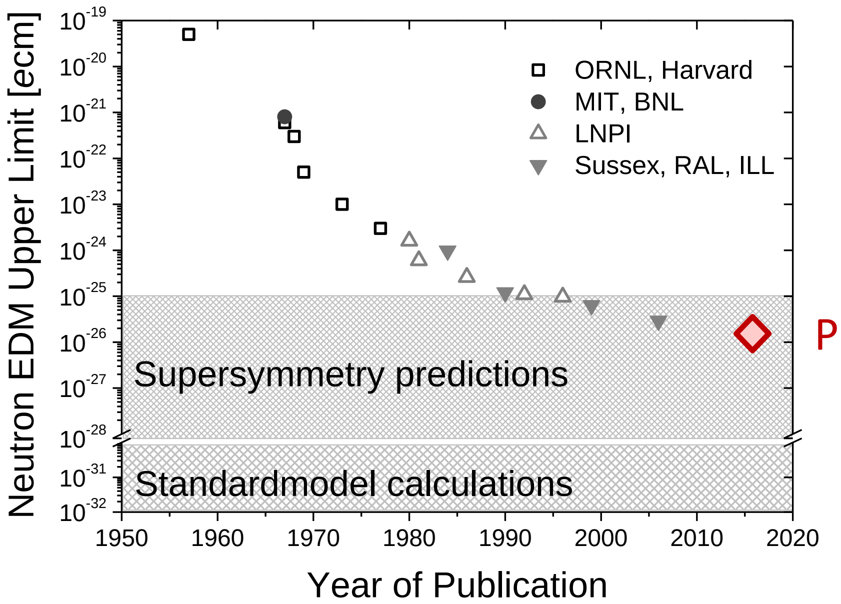
624’364’314 neutrons

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

Analysis ongoing:

- Blinded data
- Two groups
- Result planned for 2018

A brief history of nEDM searches



PSI sensitivity 2015/16

“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

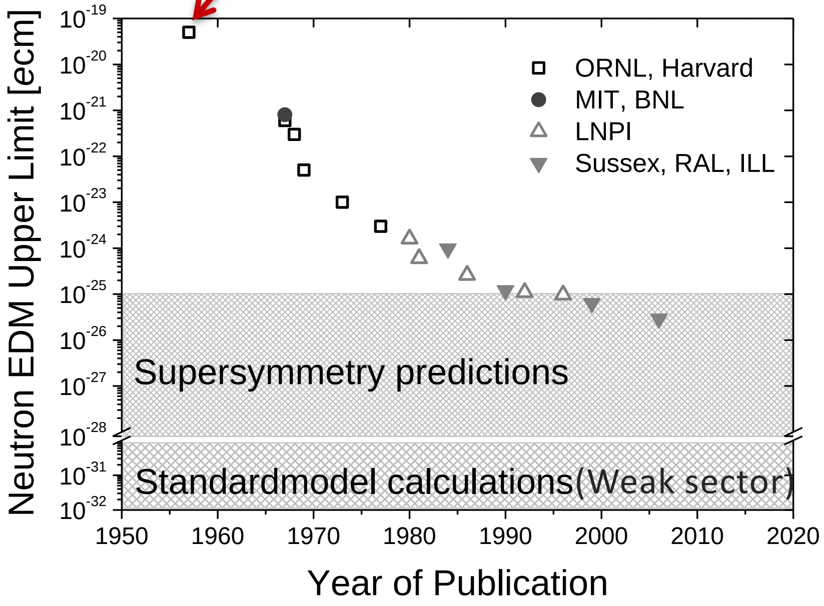
$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

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

The strong CP -problem

already a surprise



$$L_{\text{total}} = L_{\text{SM}} + \theta \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

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

$$\frac{d_n}{\theta} = -3.8(2)(9) \times 10^{-16} ecm^{**}$$

but

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

$$\theta < 1 \times 10^{-10}\ ecm$$

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

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

Axion solution to the strong CP-problem

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the CP conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

Add an additional global $U(1)$ chiral symmetry*,** to the Standard Model:

$$L_{\text{total}} = L_{\text{SM}} + \frac{\theta g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a + L_{\text{int}}\left[\frac{\partial^\mu a}{f_a}, \psi\right] + \xi \frac{a}{f_a} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

Axion dynamics   Axion interactions   chiral anomaly

Axion solution to the strong CP-problem

The chiral term also represents an effective potential for the axion field with a minimum at $\langle a \rangle = -\theta\, f_a/\xi$

Hence the CPV term of the QCD is effectively canceled out at the minimum of the Axion potential.

$$L_{\text{total}} = L_{\text{SM}} + \frac{\theta g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a + L_{\text{int}}\left[\frac{\partial^\mu a}{f_a}, \psi\right] + \xi \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

Axion dynamics   Axion interaction   chiral anomaly

Searching for an oscillating EDM or Axion wind

Graham Rajendran
PRD88, 035023 (2013)

- 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

gluonic | fermionic

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

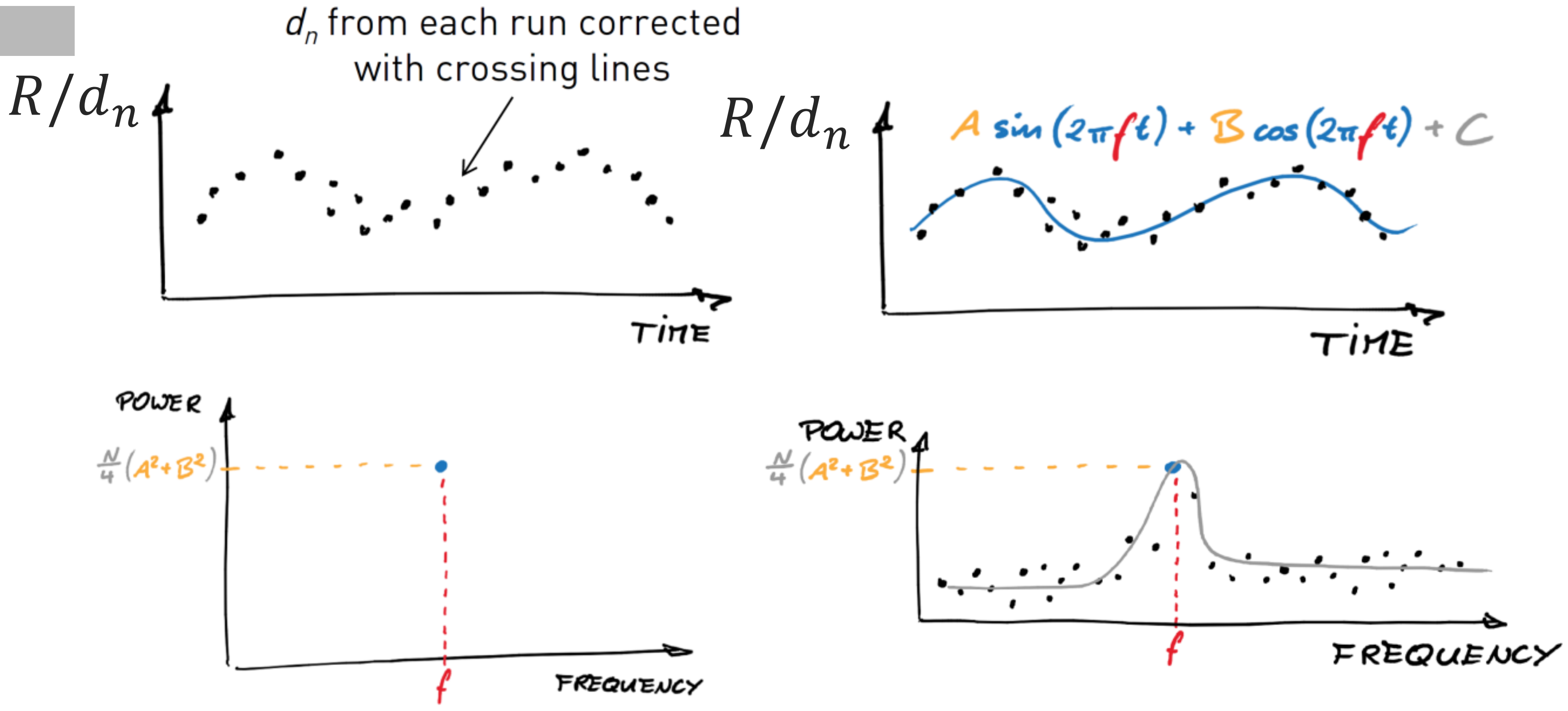
Produces oscillating EDM through same diagrams as θ_{QCD}

Produces oscillations in precession frequency "Axion Wind"

Nick Ayres

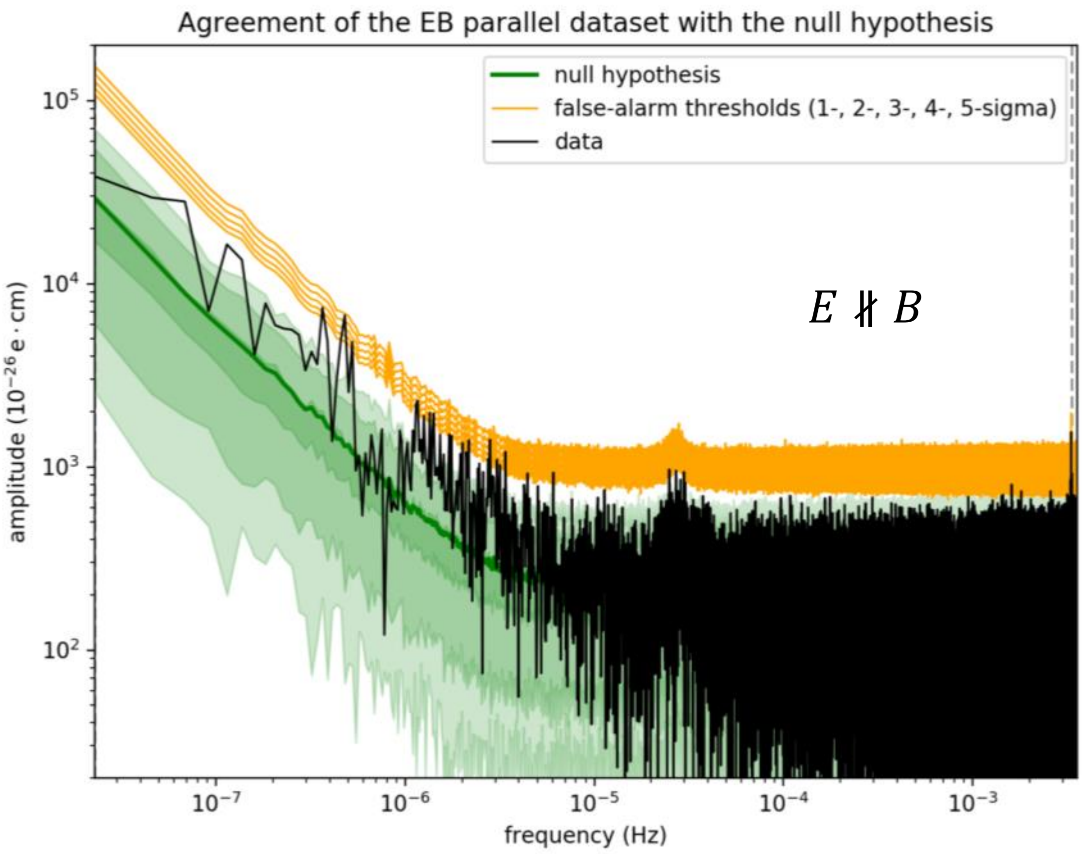
Michal Rawlik

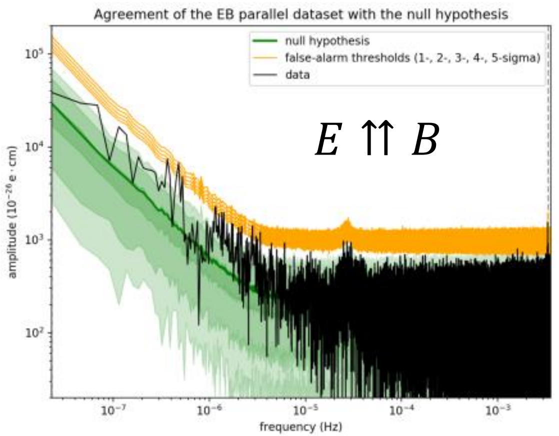
Least square spectral analysis

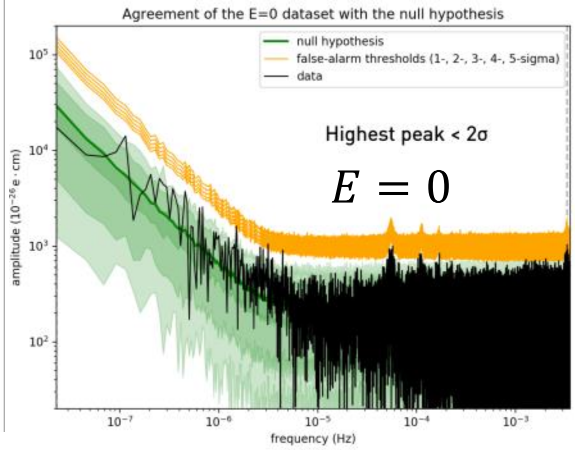


courtesy: M. Rawlik

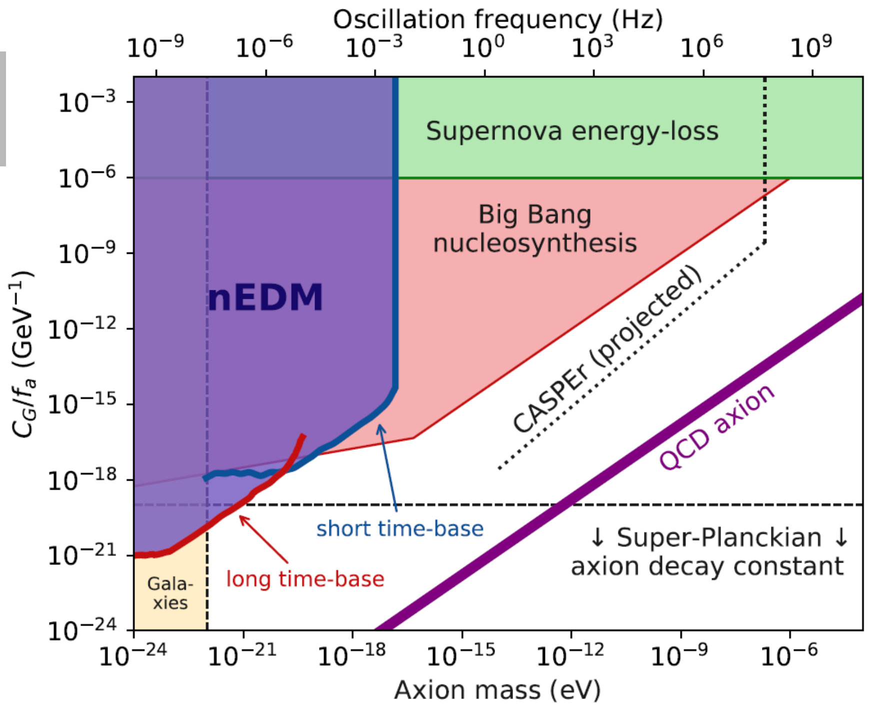
Three periodograms

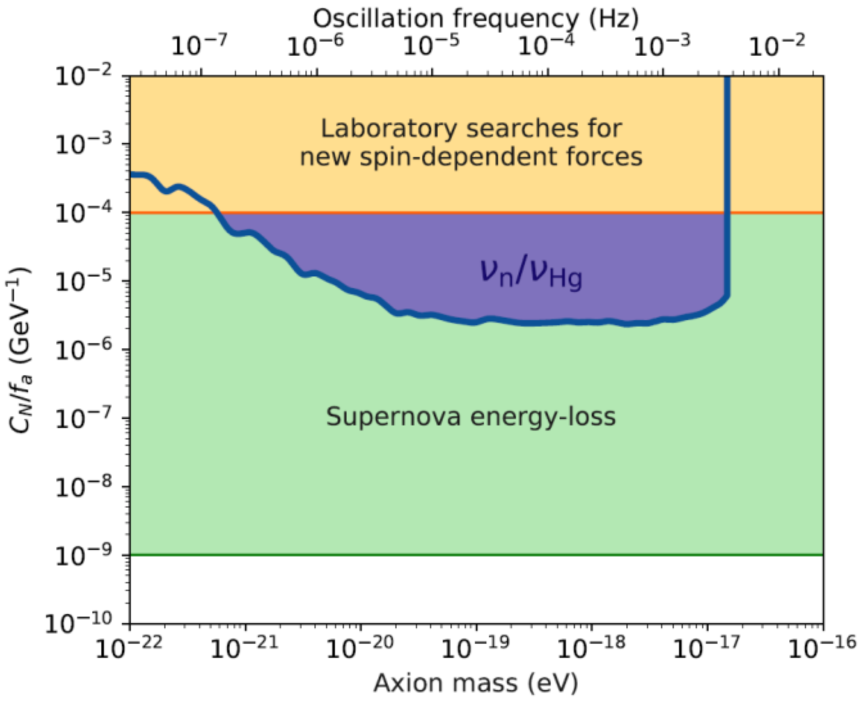






Exclusion limits



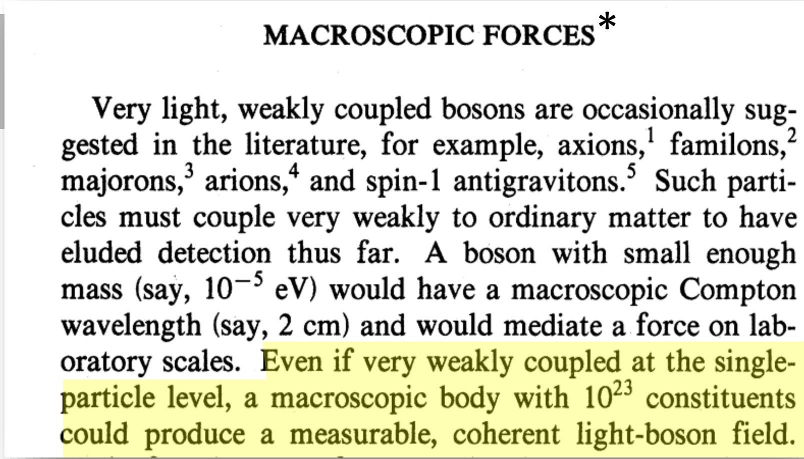


C. Abel *et al.*, PRX7(2017)041034

First experimental limits on gluonic coupling

40 times better limit on fermionic coupling

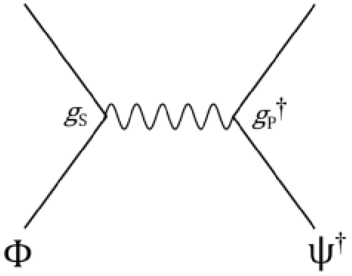
ALPS: Spin dependent forces



MACROSCOPIC FORCES*

Very light, weakly coupled bosons are occasionally suggested in the literature, for example, axions,[1] familons,[2] majorons,[3] arions,[4] and spin-1 antigravitons.[5] Such particles must couple very weakly to ordinary matter to have eluded detection thus far. A boson with small enough mass (say, 10^{-5} eV) would have a macroscopic Compton wavelength (say, 2 cm) and would mediate a force on laboratory scales. Even if very weakly coupled at the single-particle level, a macroscopic body with 10^{23} constituents could produce a measurable, coherent light-boson field.

Nucleons in electrode



polarized UCN

$$V(\vec{r}) = g_s g_p \frac{\hbar^2}{8\pi \mathrm{m}} (\vec{s}\cdot\vec{r}) \left(\frac{1}{r\lambda} + \frac{1}{r^2}\right) \mathrm{e}^{-\frac{r}{\lambda}}$$

* Moody&Wilzek, PRD**30**(1984)1

ALPS: Spin dependent forces

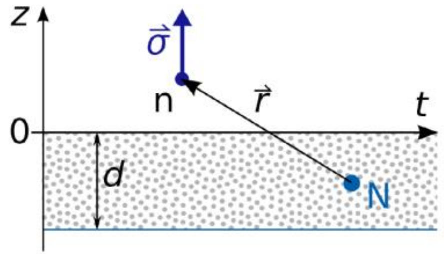
$$V(\vec{r}) = g_s g_p \frac{\hbar^2}{8\pi m}(\vec{s}\cdot\vec{r})\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}$$

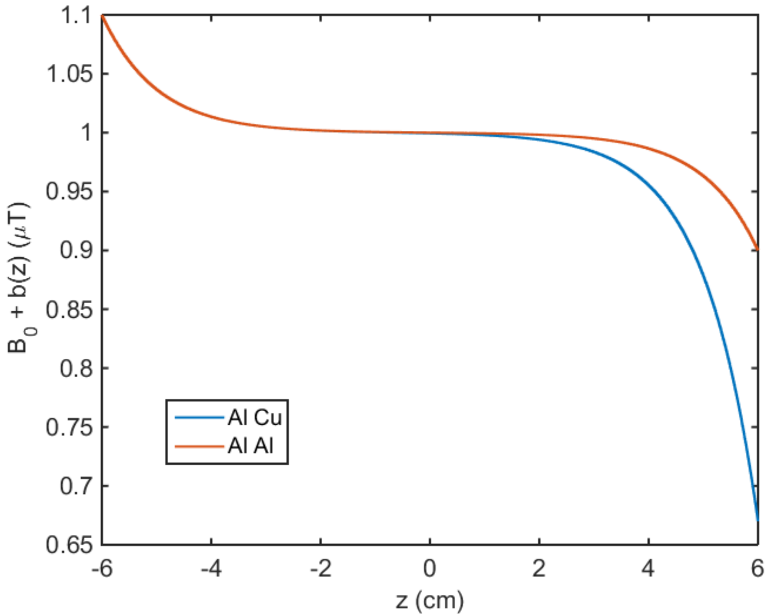
integrate over bulk

$$b(z) = g_s g_p \frac{\hbar\lambda N}{2\gamma m}\left(1-e^{-d/\lambda}\right)e^{-z/\lambda}$$

for two electrodes (top and bottom)

$$b(z) = b_{\mathrm{bot}}e^{-\frac{z+H/2}{\lambda}} - b_{\mathrm{top}}e^{\frac{z-H/2}{\lambda}}$$





PAUL SCHERRER INSTITUT

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

- Center-of-mass offset
- Non-adiabaticity

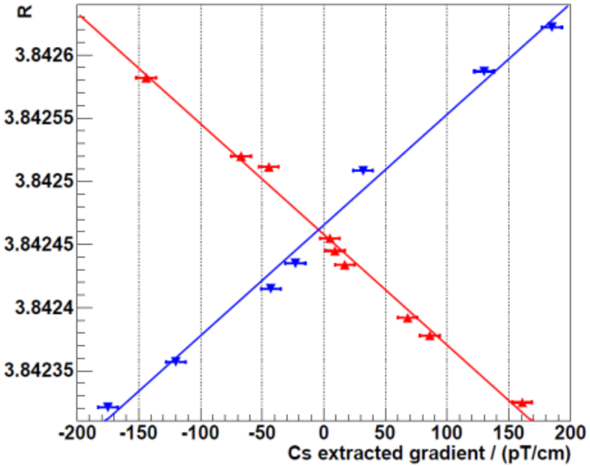
$\frac{\gamma_{Hg}}{2\pi} \approx 8$ Hz/μT

$\frac{\gamma_n}{2\pi} \approx 30$ Hz/μT

$\bar{v}_{Hg} \approx 160$m/s vs. $\bar{v}_{ucn} \approx 3$ m/s

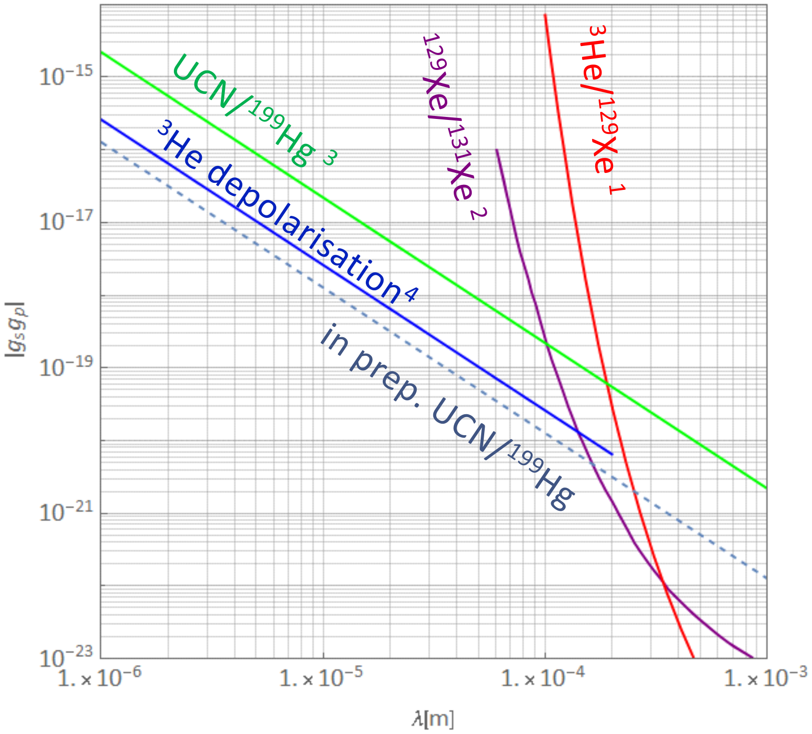
$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_\perp \rangle}{|B_0|^2} \mp \delta_{Earth} + \delta_{Hg-lightshift} + \frac{\bar{b}}{B_0} \right)$$

Limit on CP violating light scalar boson



Effect	$B_0{\uparrow}$	$B_0{\downarrow}$
Statistics	$\pm 0.5 \cdot 10^{-6}$	$\pm 0.5 \cdot 10^{-6}$
Gravitational shift	$(-8.9 \pm 2.3) \cdot 10^{-6}$	$(-1.8 \pm 2.7) \cdot 10^{-6}$
Transverse shift	$(3.7 \pm 0.8) \cdot 10^{-6}$	$(3.0 \pm 1.2) \cdot 10^{-6}$
Light shift	$(1.3 \pm 0.7) \cdot 10^{-6}$	$(0.8 \pm 0.6) \cdot 10^{-6}$
Earth rotation shift	$-5.3 \cdot 10^{-6}$	$+5.3 \cdot 10^{-6}$
R	3.8424583(26)	3.8424562(30)

$$g_s g_p \lambda^2 \propto \bar{b} = B_0 \frac{(R^{\uparrow} - R^{\downarrow})}{(R^{\uparrow} + R^{\downarrow})} = 0.28(0.53)\mathrm{pT}$$



[1]Bulatowicz *et al.*PRL111(2013)102001
[2]Tullney *et al.*, PRL111(2013)100801
[3]Afach *et al.*, PLB745(2015)58
[4]Guigue *et al.*,PRD92(2015)114001

Conclusions

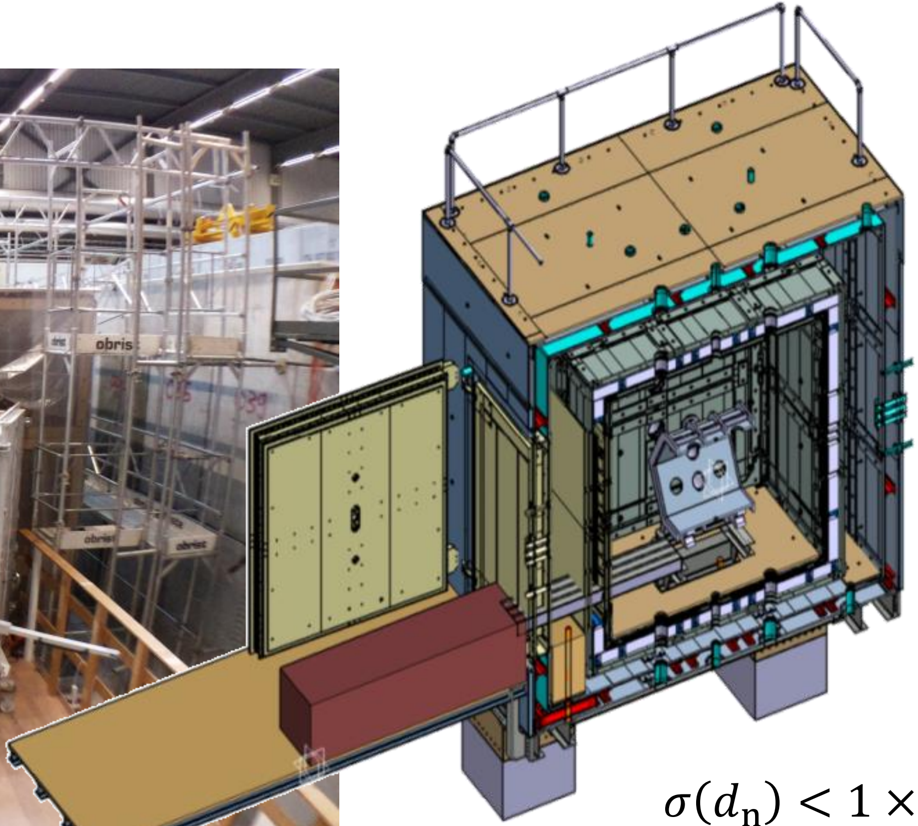
In recent years the nEDM spectrometer at the Paul Scherrer Institute delivered data for:

- The first laboratory limit on gluonic coupling of a coherent oscillating axion background field
- The best limit on a fermionic coupling (axion-wind) with a coherent oscillating axion background field
- An update for a spin dependent coupling to bulk nucleons (analysis in progress)
- An improved limit of the neutron EDM (analysis in progress)

The collaboration

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

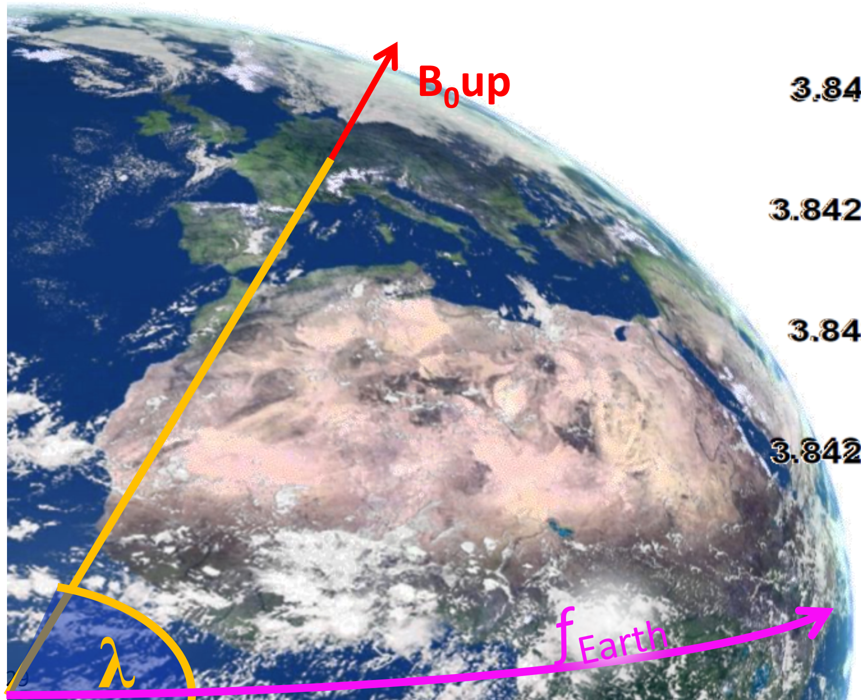
A new lamp: with 6-layer mu-metal

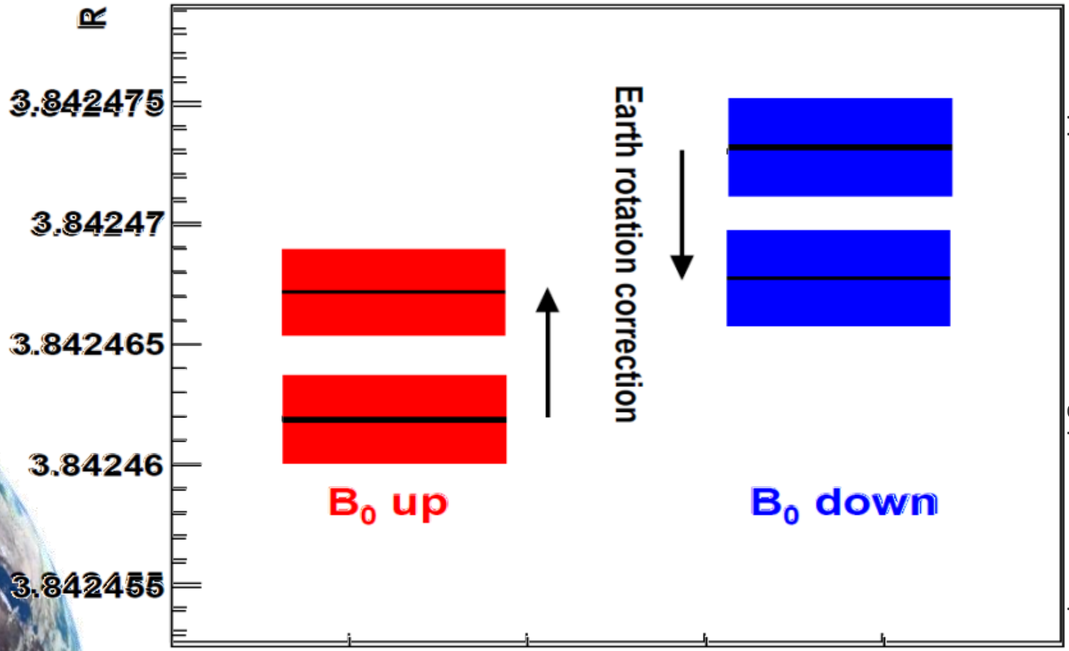


$$\sigma(d_{\mathrm{n}}) < 1 \times 10^{-27}$$

Earth rotation correction

$$\delta_{\mathrm{Earth}} = \mp\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(\frac{f_{\mathrm{Earth}}}{f_{\mathrm{n}}}+\frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}}\right)\sin(\lambda)$$
$$= \mp 5.3\times10^{-6}$$

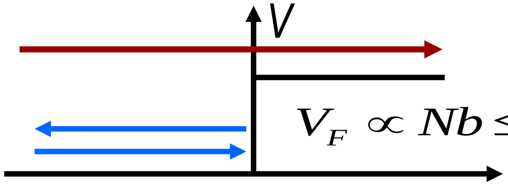




Ultracold neutrons (UCN)

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

Storable neutrons (UCN)

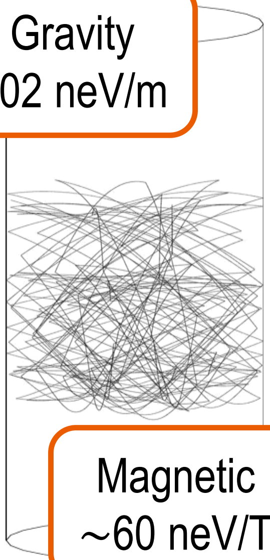


$$V_F \propto Nb \leq 350\,\text{neV}$$

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