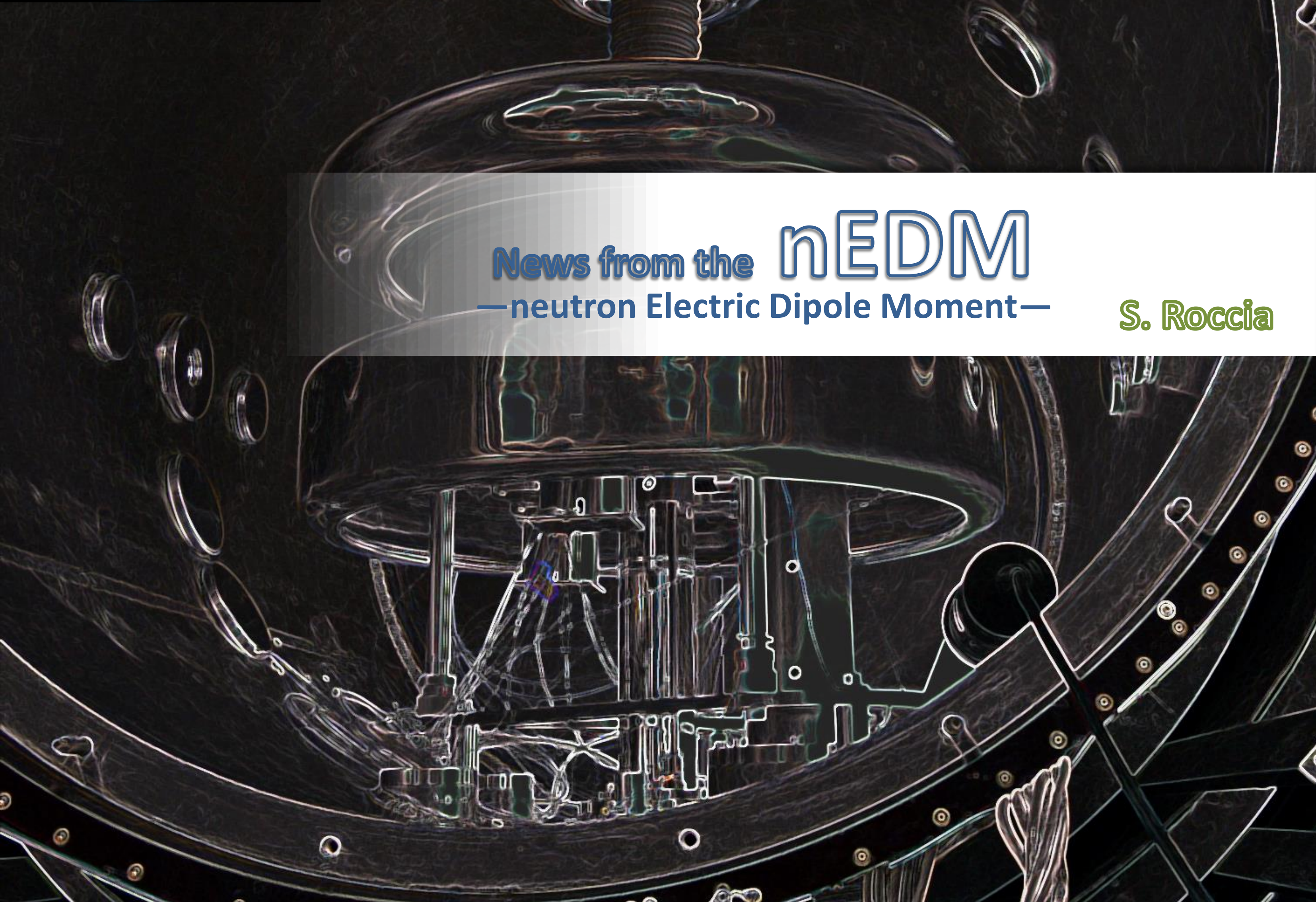
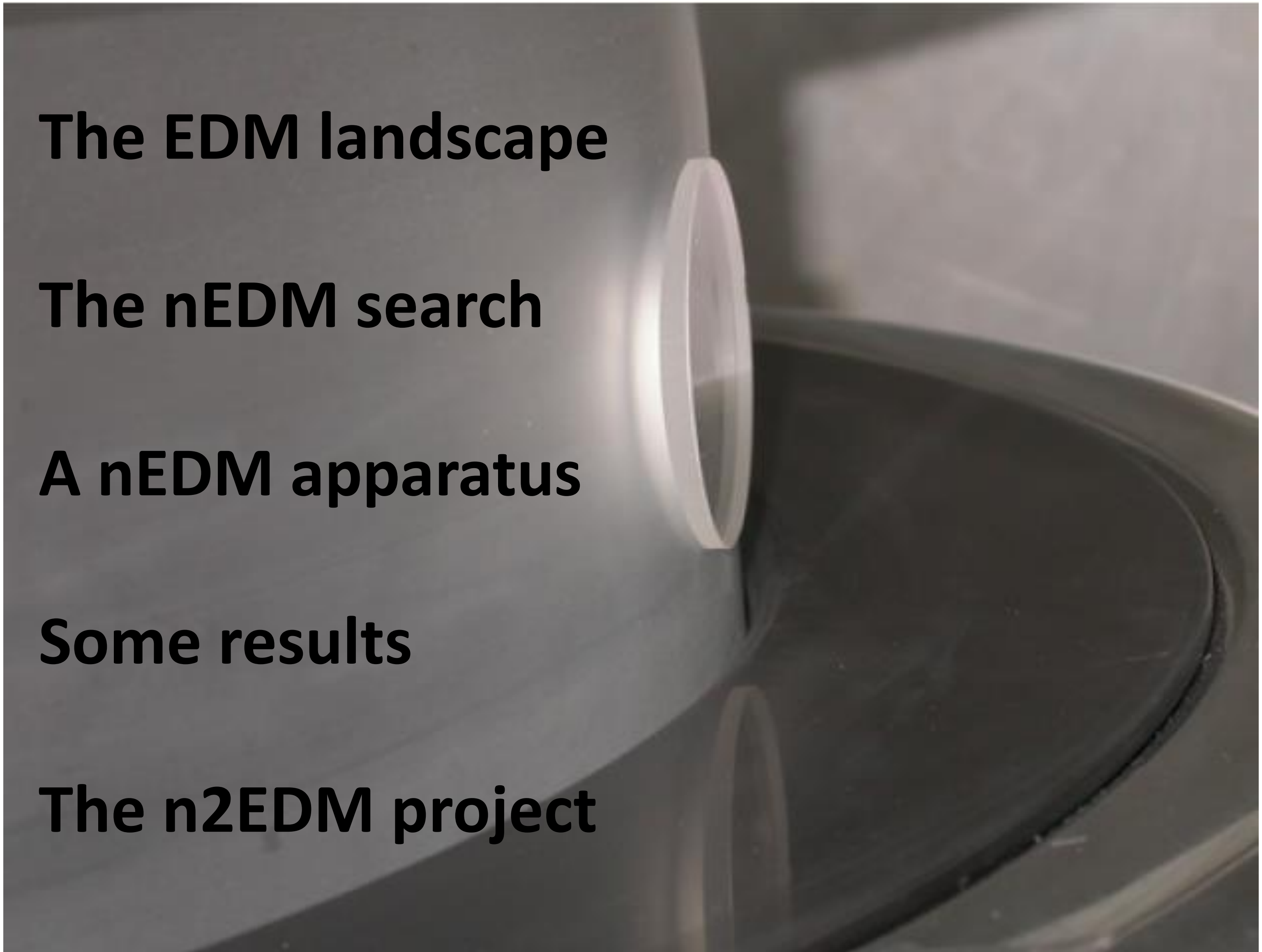
News from the nEDM

—neutron Electric Dipole Moment—

S. Roccia



Outlines



The EDM landscape

The nEDM search

A nEDM apparatus

Some results

The n2EDM project

The EDM landscape

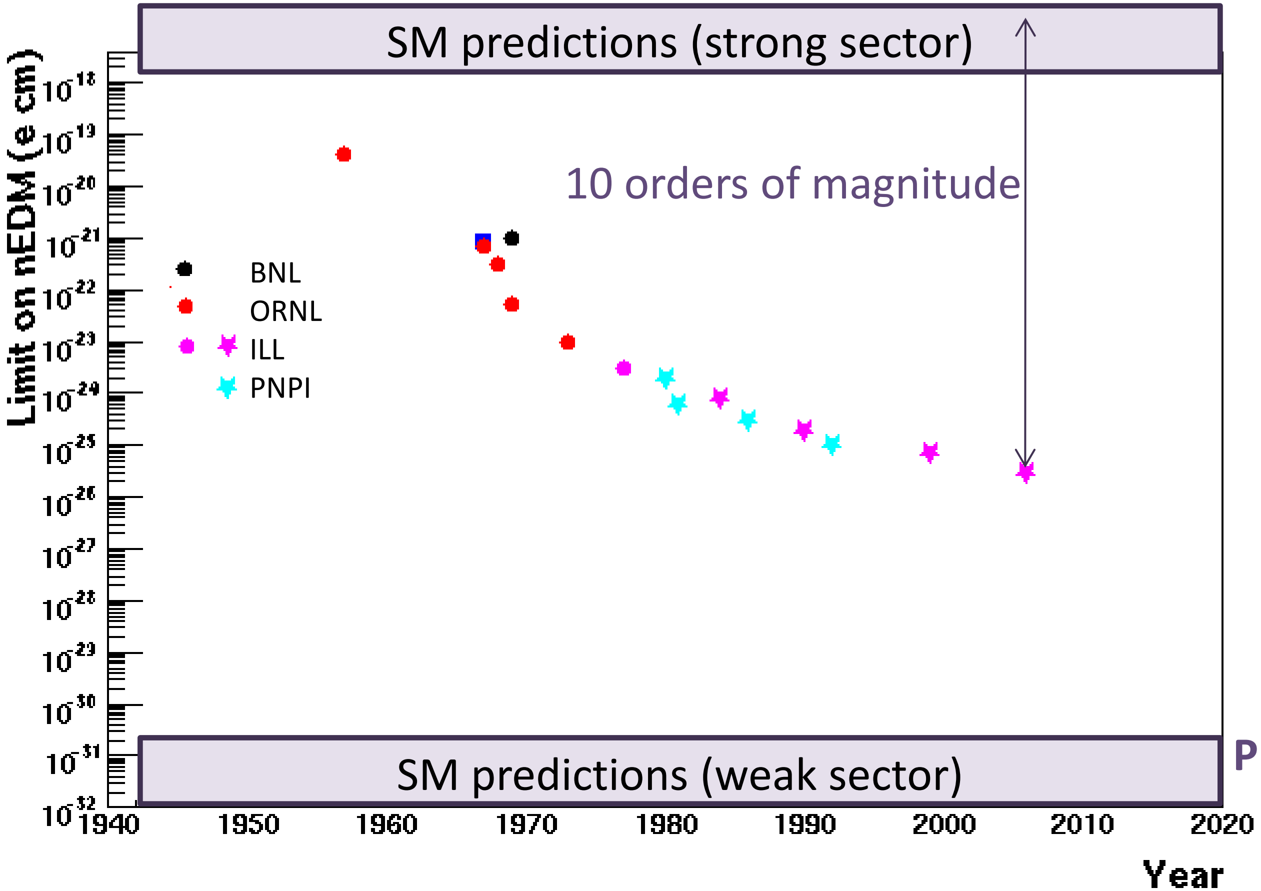
Adrian SIGNER

I will discuss why we theorists always knew that you wouldn't find a non-vanishing nEDM. Just in case you will measure one, it will also be discussed, why we theorists always knew that you would eventually find a non-vanishing nEDM.

SM $\longrightarrow$ "only" an effective theory valid up to some scale Λ_{UV}

- in case you won't find one:
  of course not, $\Lambda_{\mathrm{UV}} \gg 1\ \mathrm{TeV}$ (complete absence of 'new' physics) and $\bar{\theta} = 0$
- in case you will find one:
  of course, CP violation in BSM is unaviodable, and it has to show up in nEDM

The EDM landscape



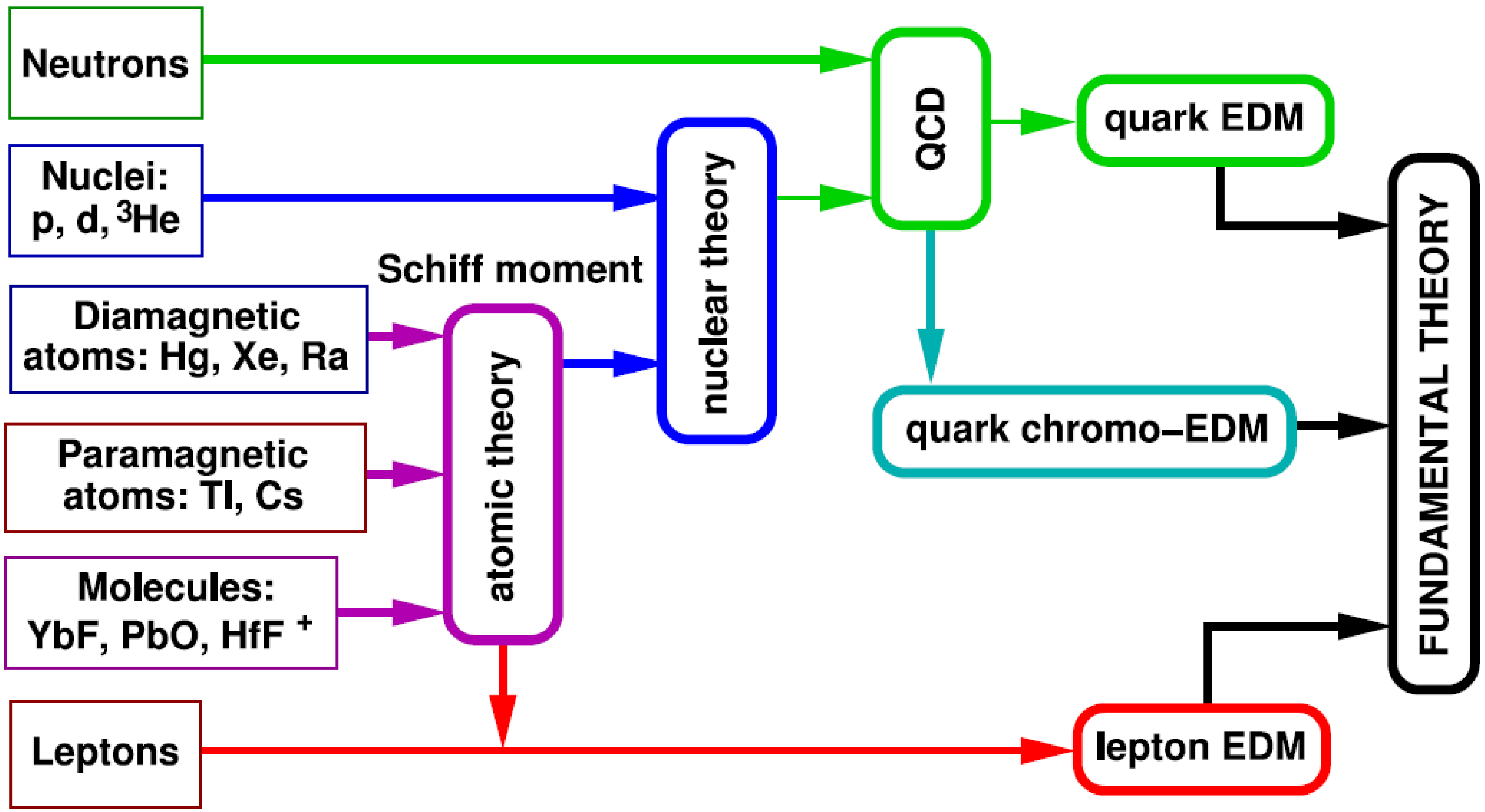
Strong CP problem

$$\theta_{QCD} < 10^{-10}$$

Phase in the CKM matrix

$$\delta_{CKM}$$

The EDM landscape



C. R. Physique 13 168 (2012)

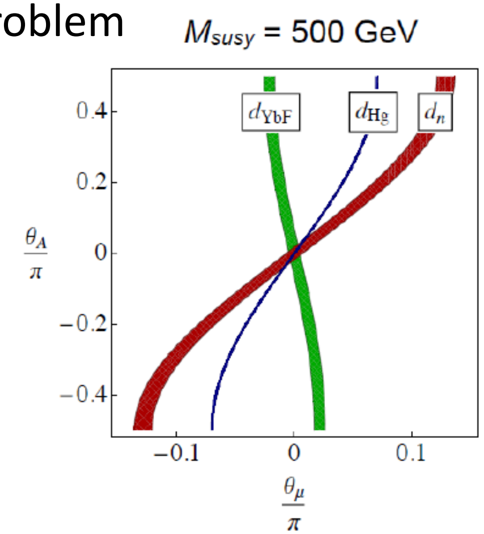
in $\bar{\theta} = 0$ SM: $d_n \sim 10^{-32}$ e cm with considerable uncertainties
playing devils advocate $d_n \lesssim 10^{-30}$ e cm

if $d_n > 10^{-30}$ e cm is found it is not clear whether this is BSM or strong CPV ($\bar{\theta} \neq 0$)

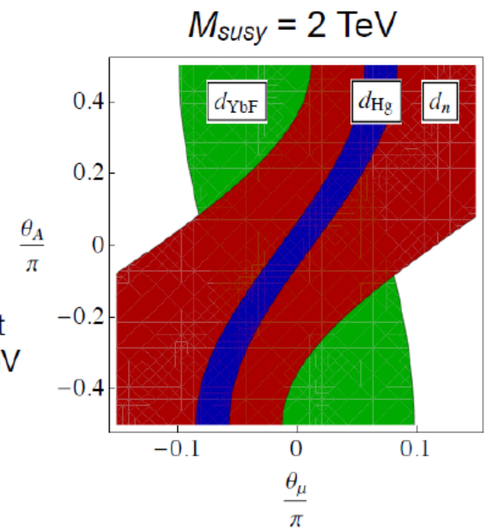
but it would be the beginning of a new era
$\Longrightarrow$ need further EDM's to disentangle origin of d_n

SUSY, the nEDM and the LHC

SUSY CP problem



1st gen squarks excluded by direct searches at ~1 TeV



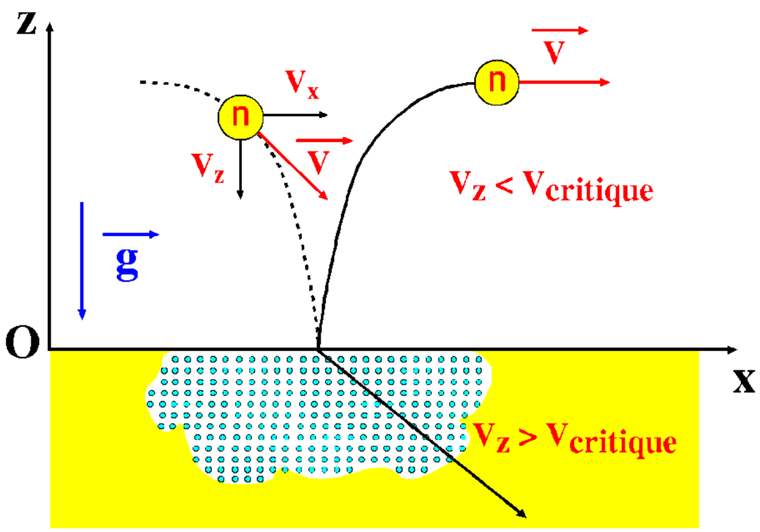
A. Ritz, talk at the PSI 2013 workshop.

The recent LHC results have shown that no superpartner exists below 1 TeV pushing the SUSY scale to higher energy. This relaxed the constraints brought by the EDM bounds on SUSY CP violating phases as shown in the right panel of

Neutrons reflected for all incidence angles: UCNs

Interactions

Kinetic energy	**Energy 1 T**	**Energy 1 m**	**Fermi potential**	**β decay**
100 neV	100 neV	100 neV	100 neV	886 s



$\lambda_n \approx 800$ Å;

$v_n \approx 5$ m/s;

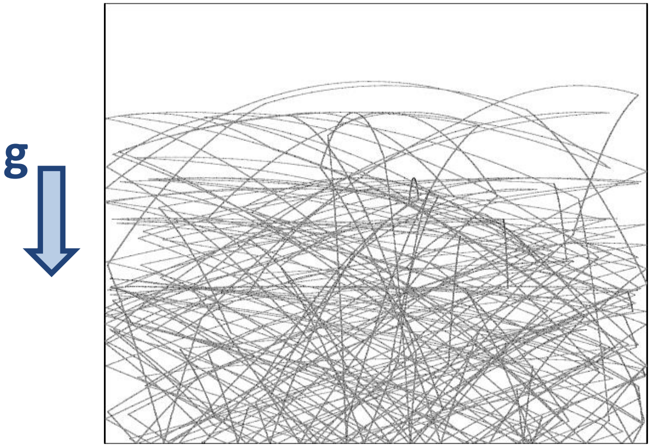
$T_n \approx 2$ mK ;

$E_n \approx 130$ neV

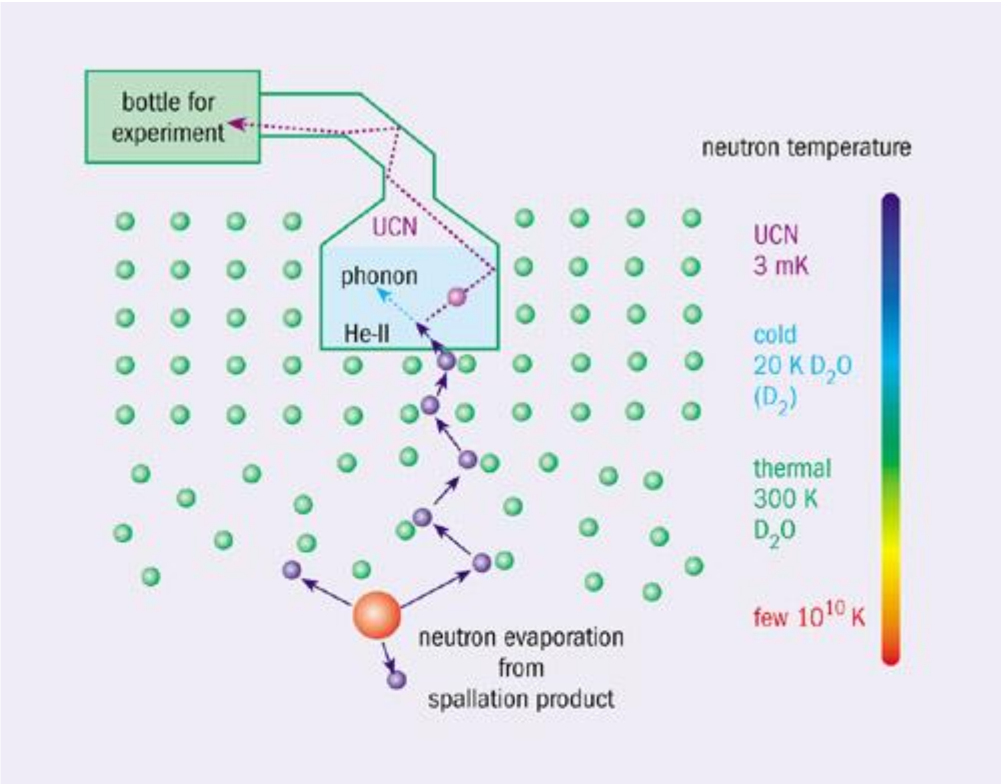
λ_n>>2 Å :

Neutrons see the Fermi potential

Can be stored !

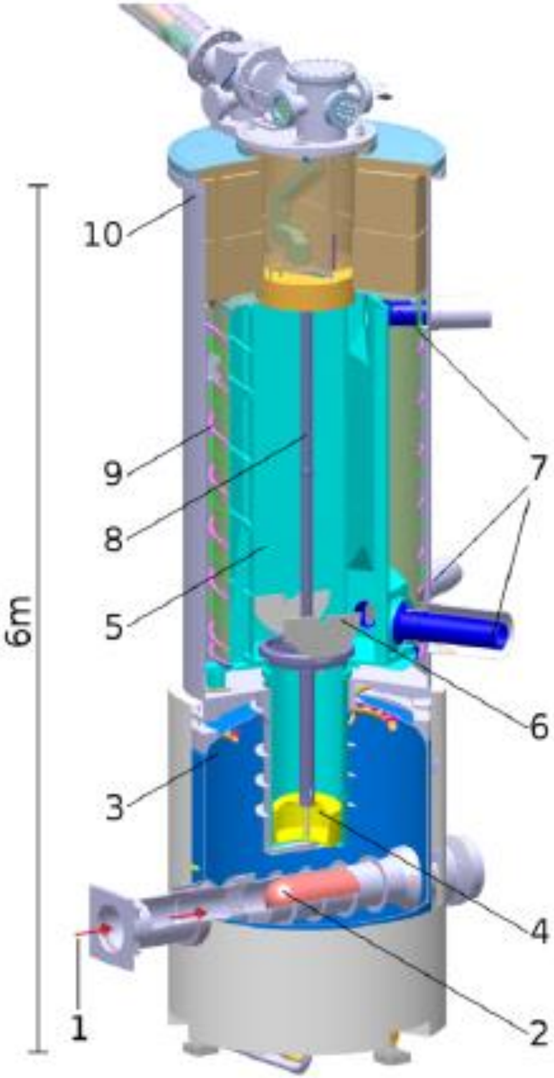


UCN source



Inelastic down scattering of cold neutrons (CN) into the UCN regime by one excitation of phonons and suppression of the up scattering by cooling the converter

The PSI-UCN source



1. PSI proton beam, up to 8 s pulses
2. spallation target (Pb)
3. D_2O vessel
4. 30 dm^3 solid D_2 moderator
5. ~2 m^3 source UCN storage vessel, coating: diamond-like carbon (DLC)
6. source UCN storage vessel shutter
7. UCN guides towards experiments
   - ~ 8 m long
   - coated with NiMo (85/15)
8. He and D_2 supply lines
9. thermal shield
10. vacuum tank

Original design goal: 1000 UCN/cm^3 in a typical external storage volume.

Two concepts

VS

Room temperature

- Proven technics
- Known systematic effects
- High sensitivity magnetometers

nEDM@PSI
n2EDM@PSI
nEDM@FRM2
nEDN@KEK-RCNP-Osaka
nEDM@TRIUMF
nEDM@ILL
nEDM@Gatchina

In helium

- Production of UCNs within the apparatus
- Use of 3He co-magnetometer
- Liquid He as insulator
- Supraconducting shield

nEDM@SNS
cryoEDM

The nEDM search

Two concepts

VS

Room temperature

- Proven technics
- Known systematic effects
- High sensitivity magnetometers

nEDM@LANL
nEDM@PSI
n2EDM@PSI
nEDM@FRM2
nEDN@KEK-RCNP-Osaka
nEDM@TRIUMF
nEDM@ILL
nEDM@Gatchina

In helium

- Production of UCNs within the apparatus
- Use of 3He co-magnetometer
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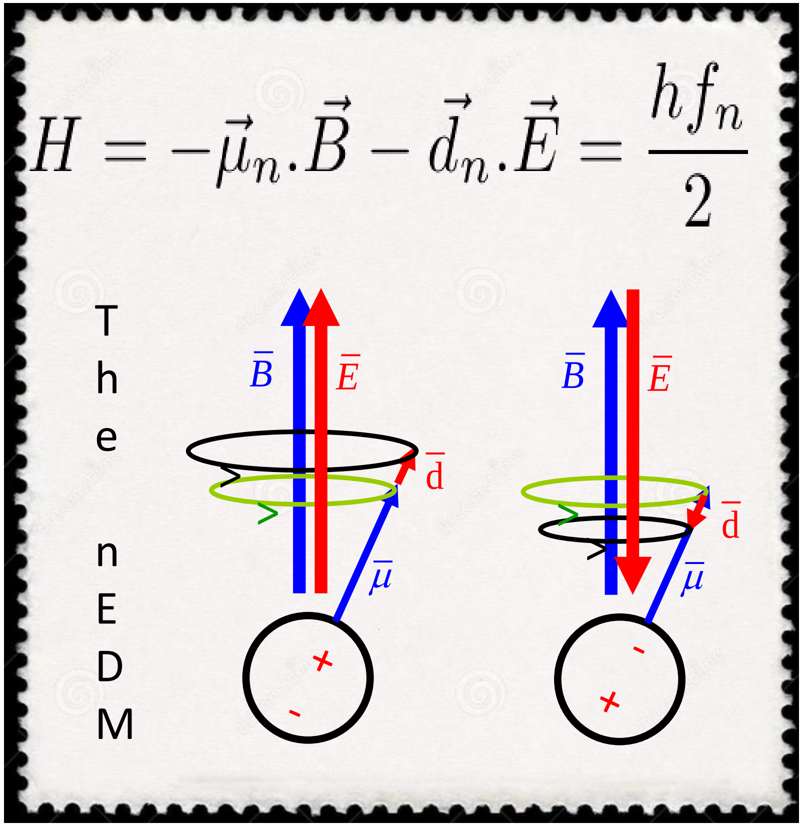
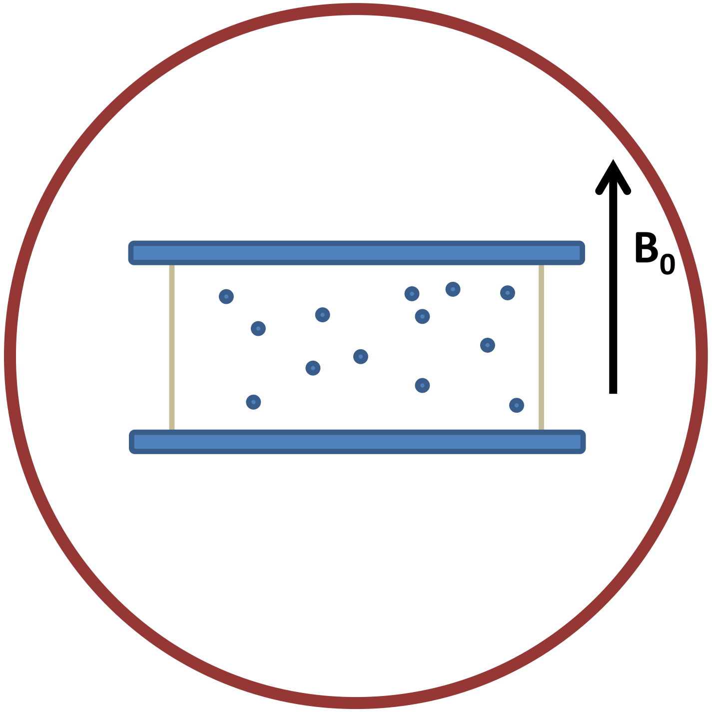
- Supraconducting shield

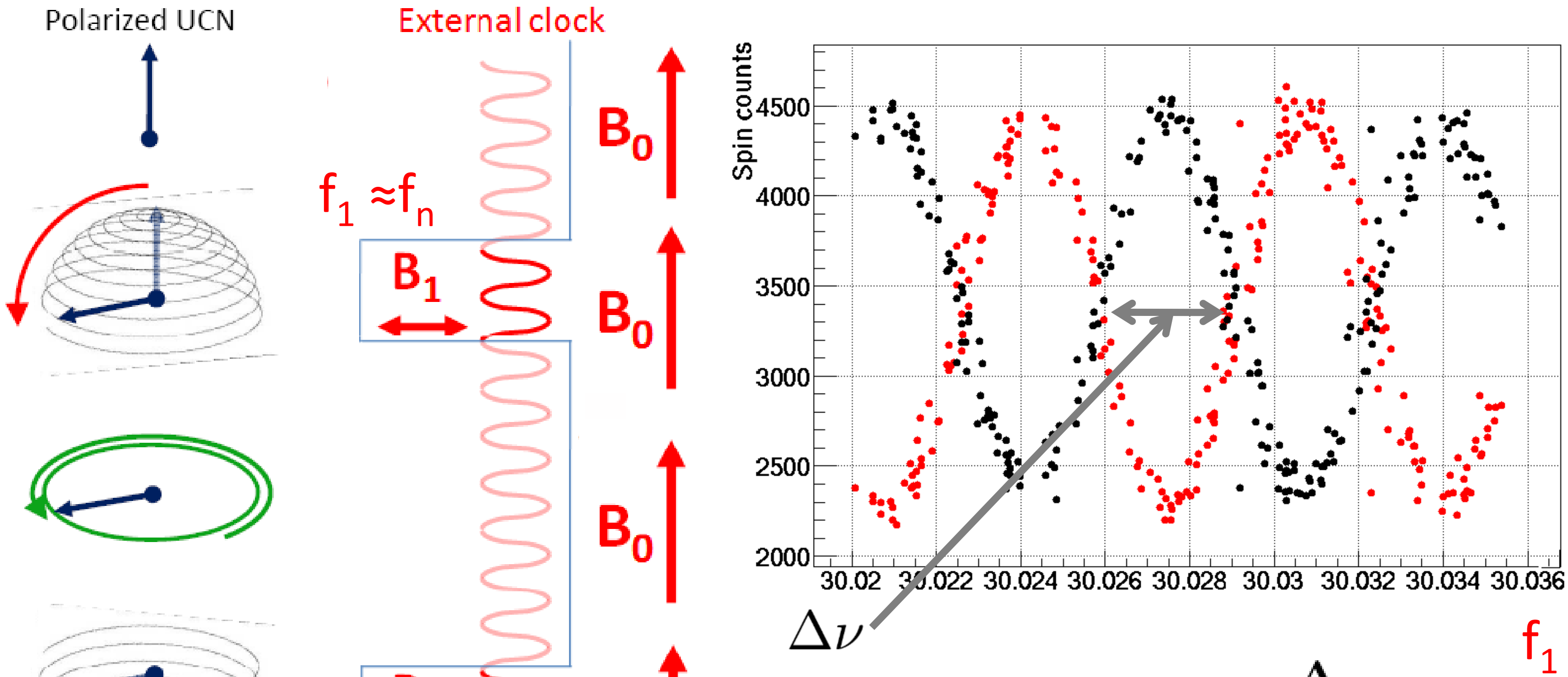
nEDM@SNS
cryoEDM

A nEDM apparatus





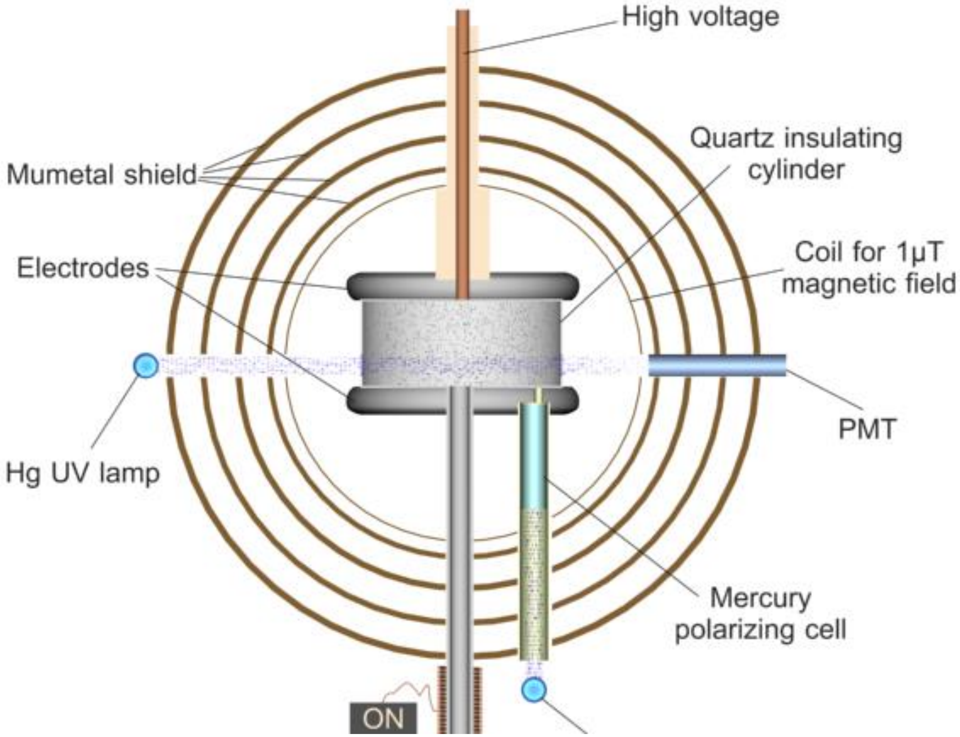
The Ramsey's method of separated oscillating fields



$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

First limitation ….. Magnetic field fluctuations

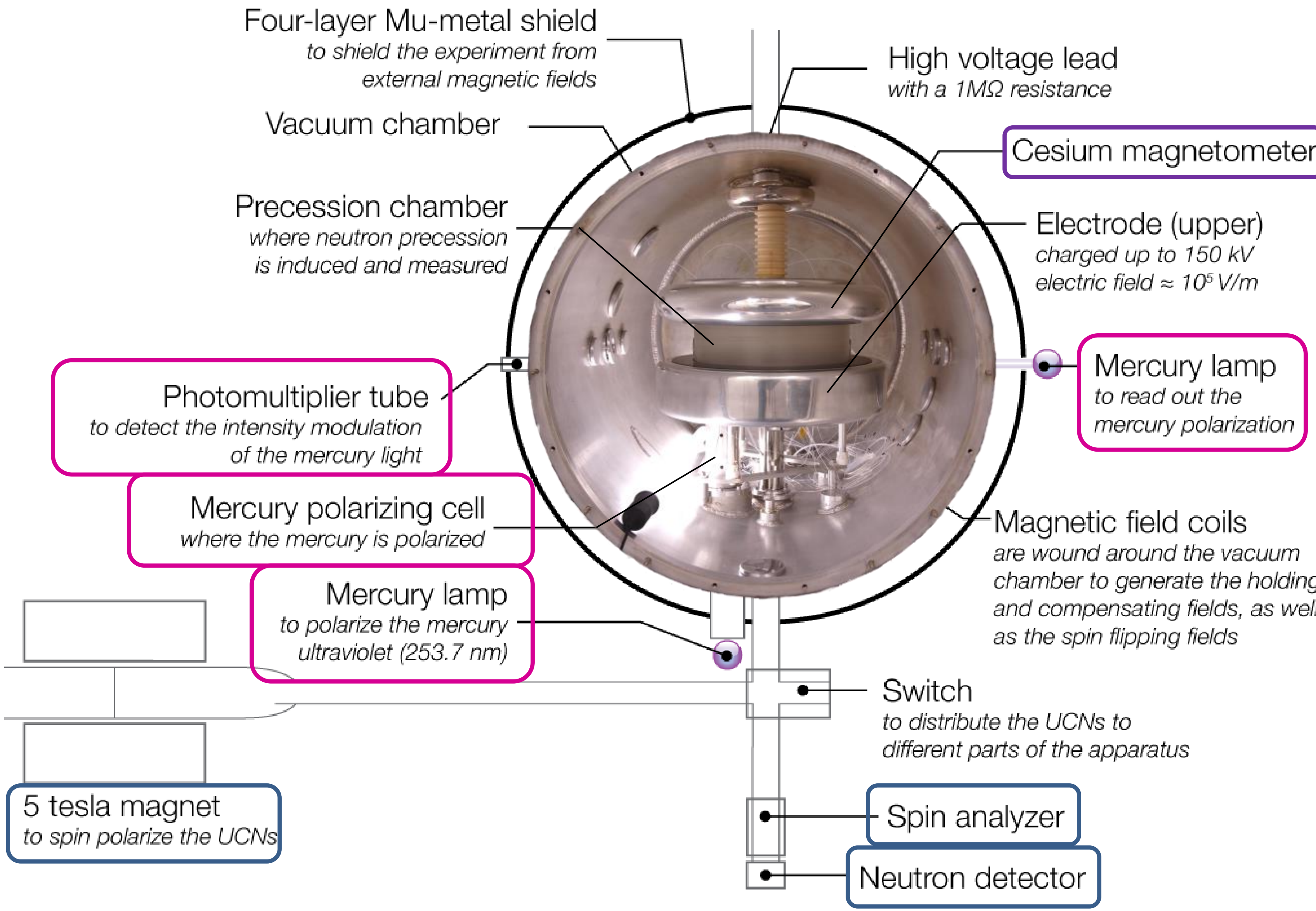
$$\begin{array}{llll} \mathrm{h}\ f_n\ (\uparrow\uparrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) & + & 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\ \mathrm{h}\ f_n\ (\uparrow\downarrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) & - & 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\ \hline \mathrm{h}(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) & = & 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) & - & 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow)) \end{array}$$



Mercury co-magnetometer (1998)

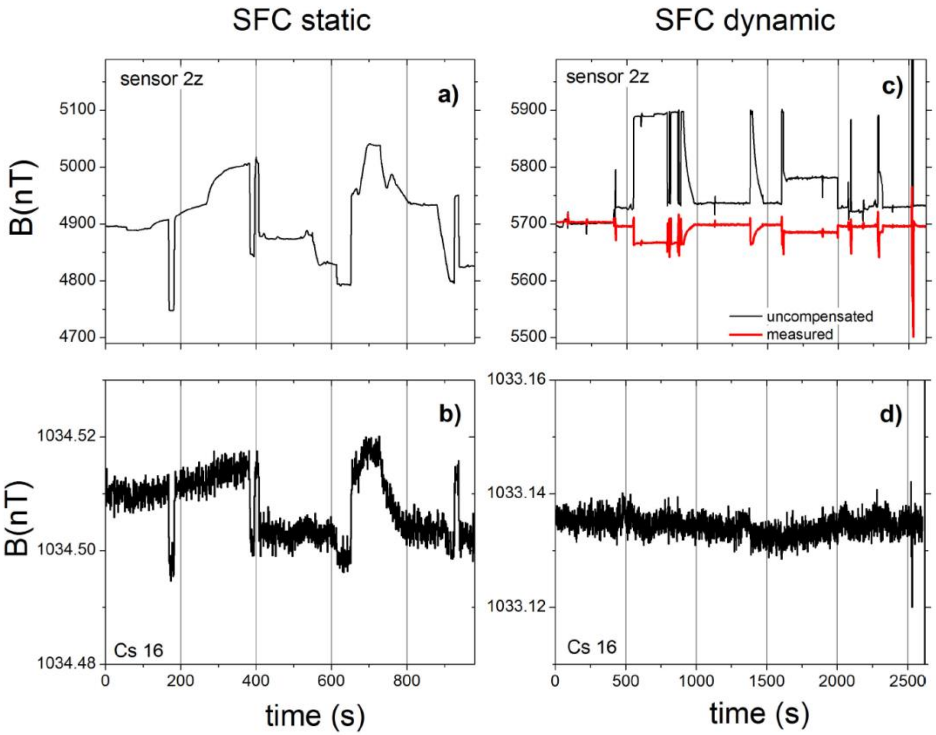
$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

A nEDM apparatus

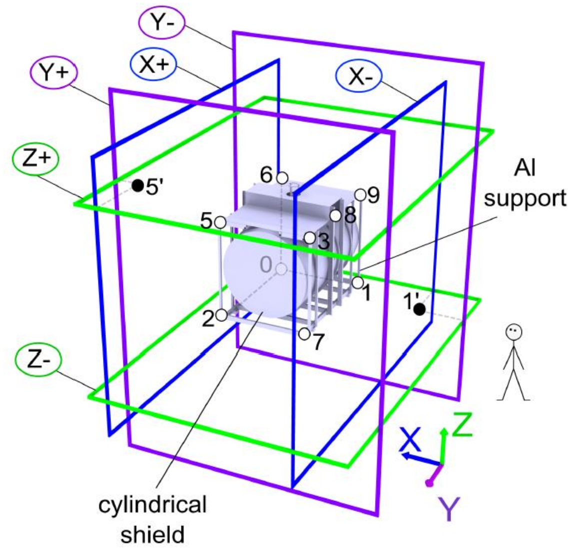


A nEDM apparatus

Magnetic stability



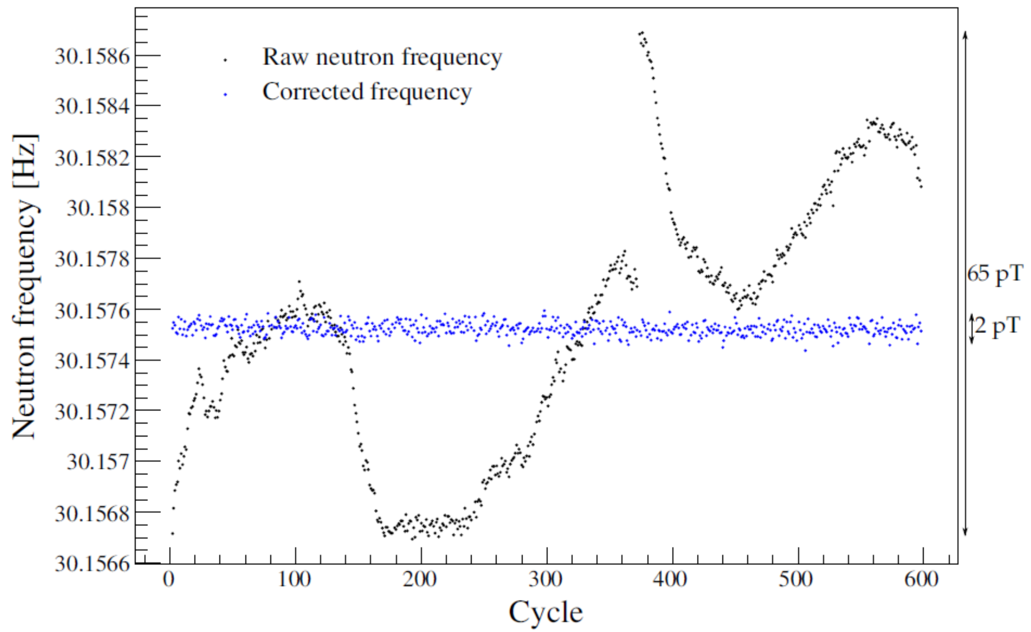
Afach et al., J. Appl. Phys. ***116****, 084510 (2014)*

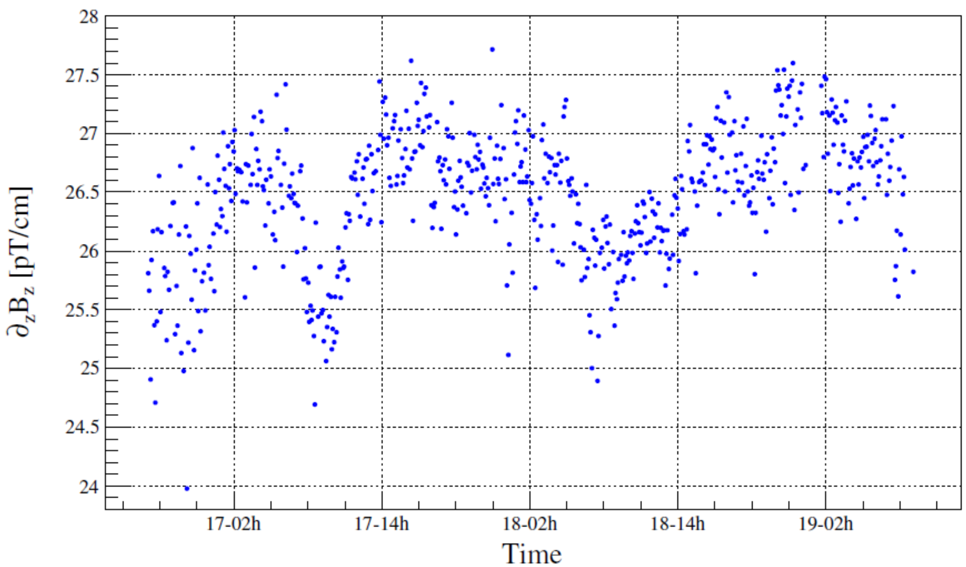


- Active compensation
- Improved degaussing procedure
- Temperature stabilization
- New current source
- ...

A nEDM apparatus

Magnetic stability



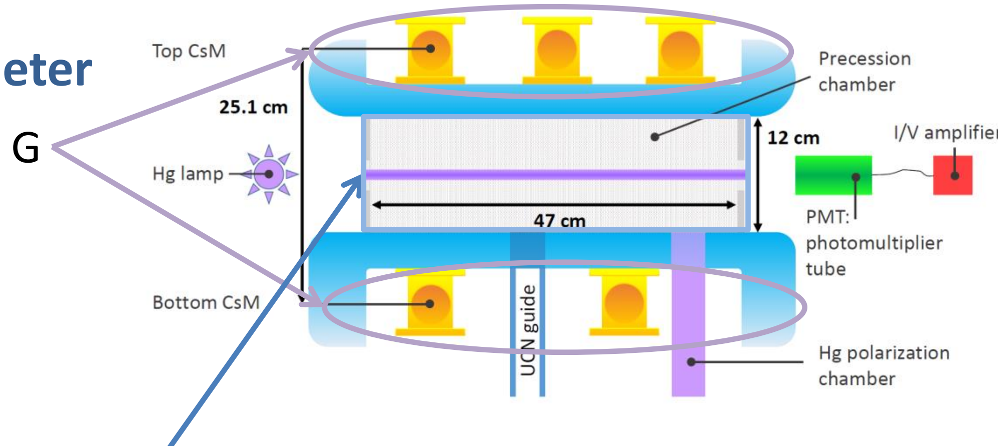


Vertical gradient

~ 2 pT/cm daily variation

A non perfect Co-magnetometer

- Gravitational shift

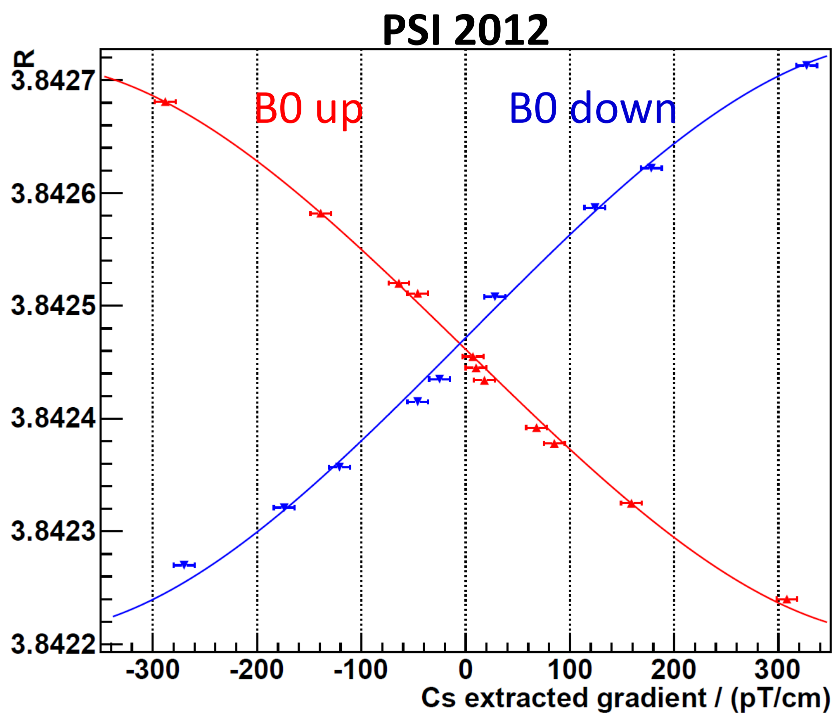


$$R = \frac{f_n}{f_{Hg}}$$

In the precession chamber

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \ \ldots \right)$$

Δh =2,7 mm



A non perfect Co-magnetometer

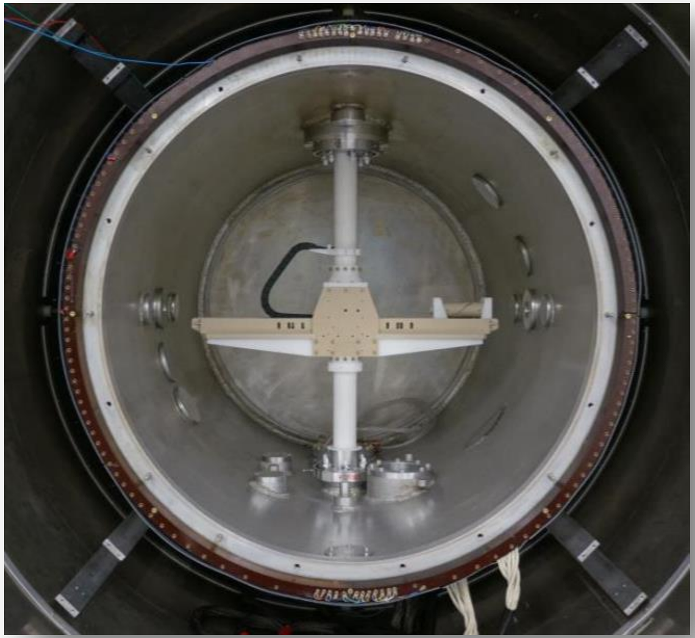
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling

UCNs: Adiabatic regime

$$f_n \propto \langle |\vec{B}| \rangle = B_0 + \frac{\langle B_T^2 \rangle}{2B_0}$$

^{199}Hg: Non-adiabatic regime

$$f_{\mathrm{Hg}} \propto | \langle \vec{B} \rangle | = B_0$$



Field map using fluxgate

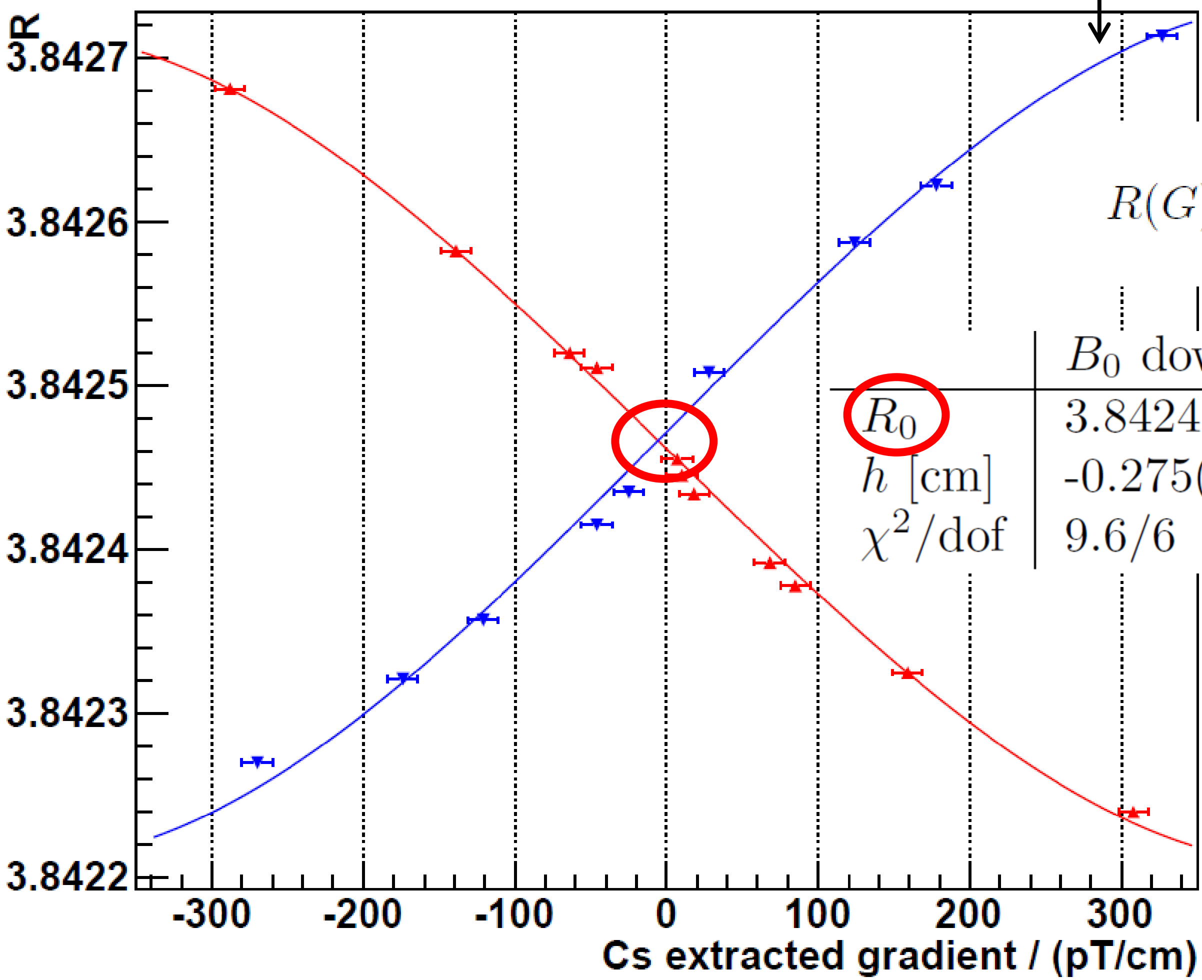
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_\perp \rangle}{|B_0|^2} + \ \ldots \right)$$

Δh =2,7 mm

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

Gravitational enhanced depolarization and associated frequency shift

P. G. Harris et al., Phys. Rev. D 89, 016011, (2014)

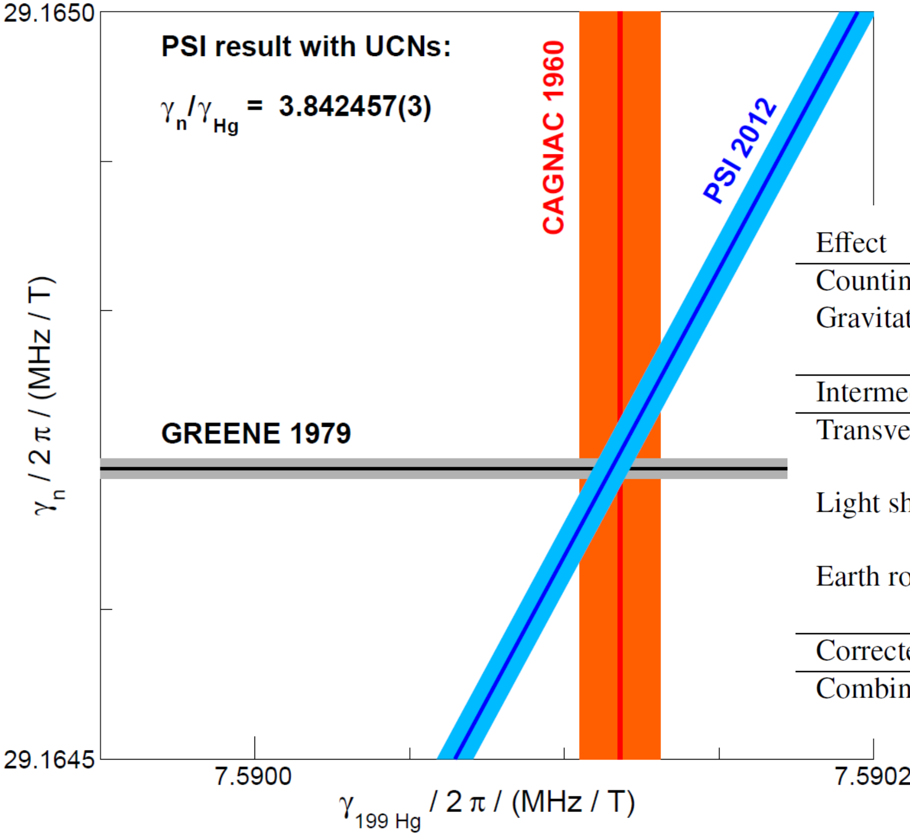


$$R(G) = R_0\left(1 \pm \frac{Gh}{B_0} + cG^3\right)$$

	B_0 down	B_0 up
R_0	3.8424731(20)	3.8424619(18)
h [cm]	-0.275(13)	0.268(13)
χ^2/dof	9.6/6	5.7/8

$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy}xy + g_{xz}xz + g_{yz}yz$$

Some results



Effect	$B_0 \uparrow$	$B_0 \downarrow$
Counting statistics	$\pm 0.5 \times 10^{-6}$	$\pm 0.5 \times 10^{-6}$
Gravitational shift ($3.84 \times \delta_{\mathrm{Grav}}$)	$(-8.9 \pm 2.3) \times 10^{-6}$	$(-1.8 \pm 2.7) \times 10^{-6}$
Intermediate R_0	3.8424580(23)	3.8424653(27)
Transverse shift ($3.84 \times \delta_{\mathrm{T}}$)	$(3.7 \pm 0.8) \times 10^{-6}$	$(3.0 \pm 1.2) \times 10^{-6}$
Light shift ($3.84 \times \delta_{\mathrm{Light}}$)	$(1.3 \pm 0.7) \times 10^{-6}$	$(0.8 \pm 0.6) \times 10^{-6}$
Earth rotation ($3.84 \times \delta_{\mathrm{Earth}}$)	-5.3×10^{-6}	$+5.3 \times 10^{-6}$
Corrected value	3.8424583(26)	3.8424562(30)
Combined final $\gamma_n/\gamma_{\mathrm{Hg}}$	3.8424574(30)	

A measurement of the neutron to ^{199}Hg magnetic moment ratio

S. Afach[a,b], C. A. Baker[c], G. Ban[d], G. Bison[b], K. Bodek[e], M. Burghoff[f], Z. Chowdhuri[b], M. Daum[b], M. Fertl[a,b,1], B. Franke[a,b,2], P. Geltenbort[g], K. Green[c,h], M. G. D. van der Grinten[c,h], P. G. Harris[h], V. Hélaine[b,d], W. Heil[i], R. Henneck[b], M. Horras[a,b], P. Iaydjiev[c,3], S. N. Ivanov[c,4], M. Kasprzak[j], Y. Kermaidic[k], K. Kirch[a,b], A. Knecht[b], J. Krempel[a], M. Kuźniak[b,e,5], B. Lauss[b], T. Lefort[d], Y. Lemière[d], A. Mtchedlishvili[b], O. Naviliat-Cuncic[d,6], J. M. Pendlebury[h], M. Perkowski[e], F. M. Piegsa[a], G. Pignol[k], P. N. Prashanth[l], G. Quéméner[d], D. Rebreyend[k], D. Ries[b], S. Roccia[m], P. Schmidt-Wellenburg[b], A. Schnabel[f], N. Severijns[l], D. Shiers[h], K. F. Smith[h,7], J. Voigt[f], A. Weis[j], G. Wyszynski[a,e], J. Zejma[e], J. Zenner[a,b,n], G. Zsigmond[b]

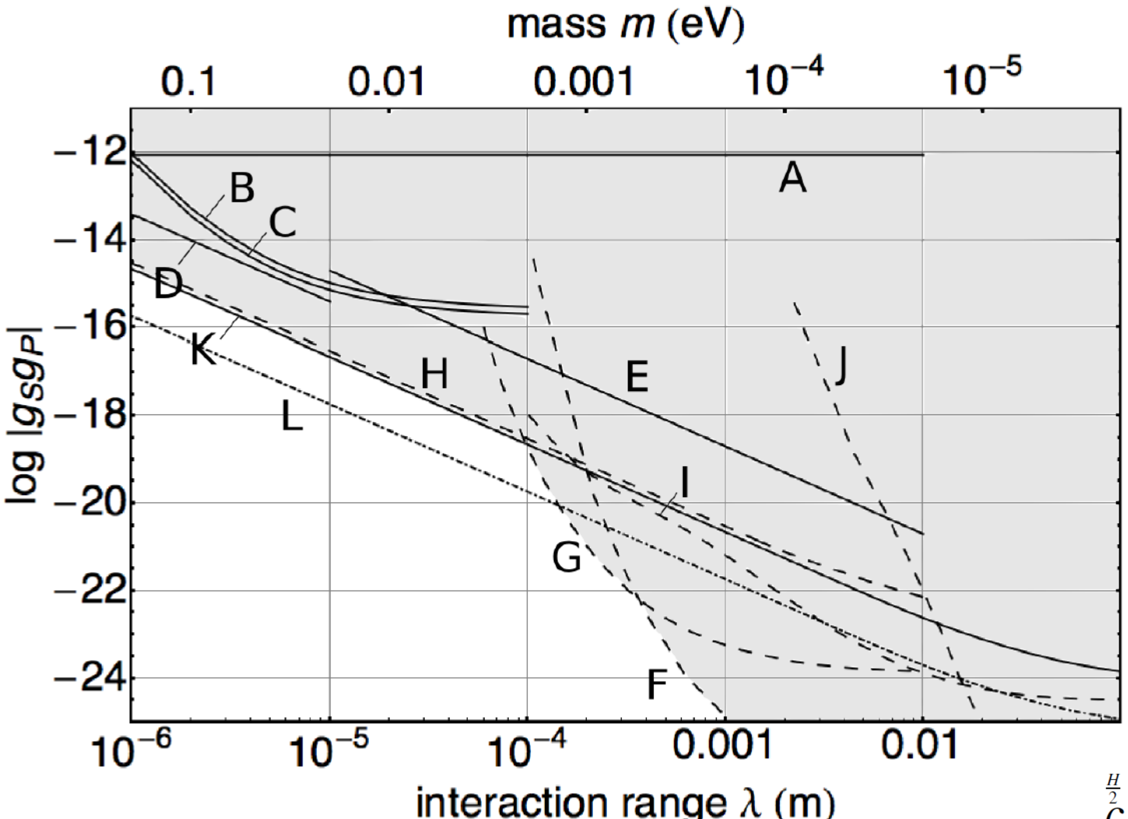
*S. Afach et al., PLB **739**, 128 (2014)*

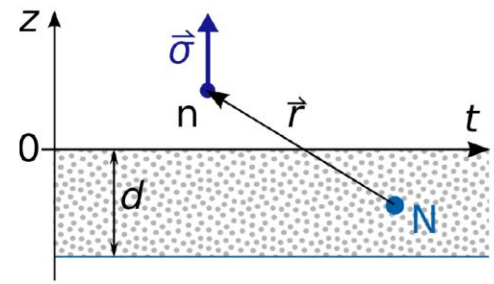
Some results

Submitted version available on arxiv

Searching for axion-like particles with ultracold neutrons

S. Afach[a,b,c], G. Ban[d], G. Bison[b], K. Bodek[e], M. Daum[b], M. Fertl[a,b,1], B. Franke[a,b,2], V. Hélaine[b,d], Y. Kermaïdic[f], K. Kirch[a,b], P. Knowles[g,3], H.-C. Koch[g,h], S. Komposch[a,b], A. Kozela[i], J. Krempel[a], B. Lauss[b], T. Lefort[d], Y. Lemière[d], O. Naviliat-Cuncic[d,4], F. M. Piegsa[a], G. Pignol[f], P. N. Prashanth[j], G. Quéméner[d], D. Rebreyend[f], D. Ries[b], S. Roccia[k], P. Schmidt-Wellenburg[b], N. Severijns[j], A. Weis[g], G. Wyszynski[a,e], J. Zejma[e], J. Zenner[a], G. Zsigmond[b]

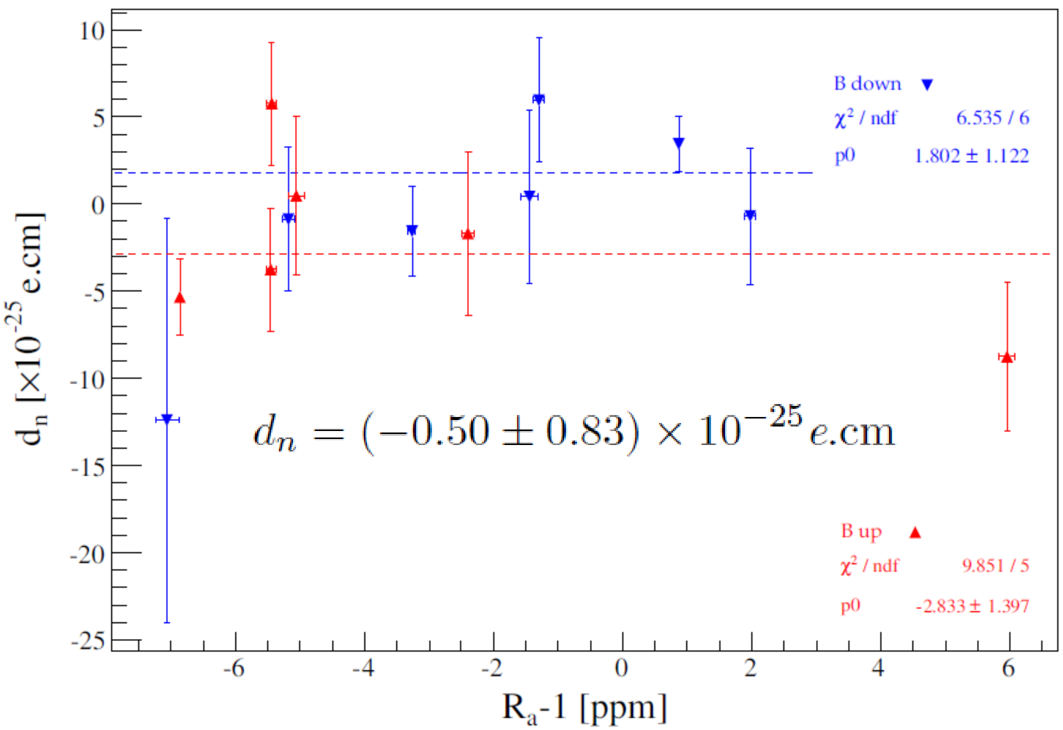




$$R^{\uparrow\downarrow} = \frac{\gamma_n}{\gamma_{Hg}}\left(1 \pm \frac{b}{B_0}\right)$$

$$b_{UCN} \approx \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\rho_{bottom}\, b_{bottom}\, e^{-\frac{z+H/2}{\lambda}} - \rho_{top}\, b_{top}\, e^{-\frac{-z+H/2}{\lambda}}\right) dz$$

Some results



2013 data

4 % above the expected sensitivity

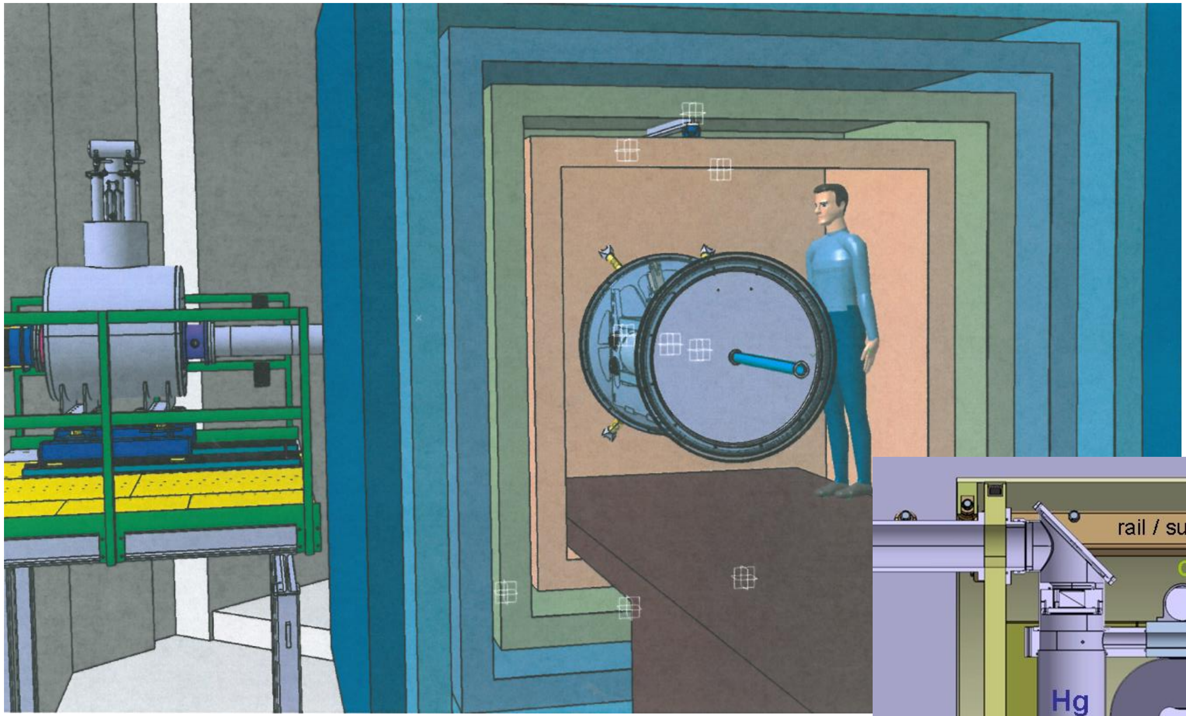
2013 data taking: 2867 cycles
25 days
2013 accumulated sensitivity $8.0 * 10^{-26}$ e.cm

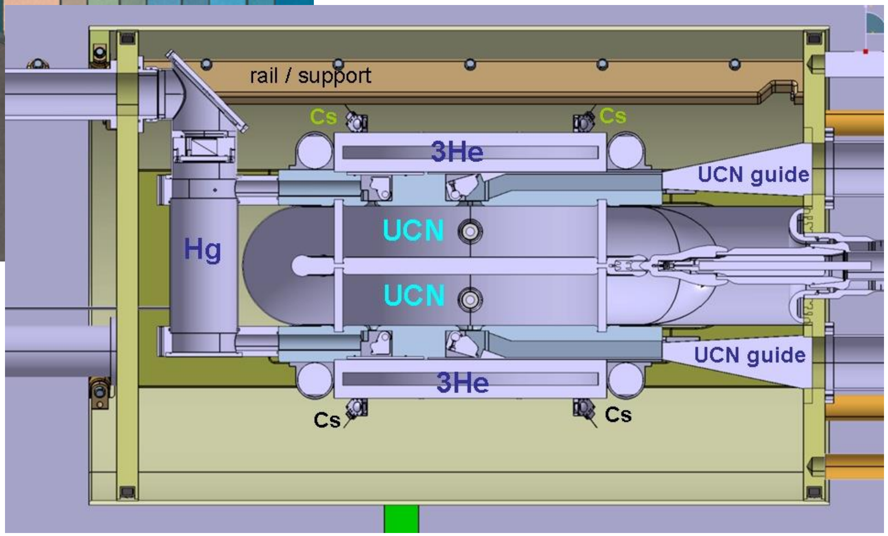
Some results

Statistical sensitivity

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

	RAL-Sussex-ILL		PSI 2012		PSI 2013	
	Best	Mean	Best	Mean	Best	Mean
E (kV/cm)	8.8	8.3	8.3	7.9	12	10.3
UCNs per cycle	14 000	14 000	9 000	5 400	10 500	6 500
T precession (s)	130	130	200	200	200	180
Visibility α	0.6	0.45	0.65	0.57	0.62	0.57
Sensitivity per cycle (10^{-25} e·cm)	43	57	32	50	22	39
Cycles per day	360	360	200	200	200	200
Sensitivity per day (10^{-25} e·cm)	2.3	3.0	2.3	3.5	1.5	2.8





- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetometry Hg – laser read out of Hg-FID to avoid light shift**
  Cs – vectorial
  3He – free from geometrical phase shift

Towards n2EDM

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

→ work on improving (α,E,T,N) parameters

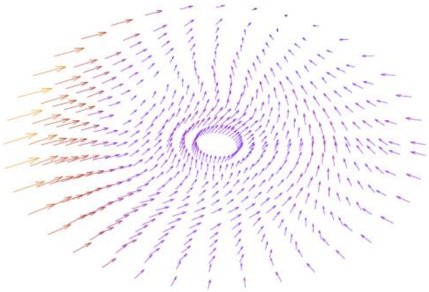
Parameter	Improvement factor	Comment
Neutrons number N	5	Better adaptation to the source (x 3) Two precession chambers (x 1.5)
Electric field E	1.3	New electrodes geometry
Visibility α	1.25	Larger T2 (field homogeneity)
Precession time T	?	Coating investigation (Diamond)
Statistical sensitivity	8	Based on the current source performances

Anticipated sensitivity
4.10^{-26} e.cm / day

→

2.10^{-27} e.cm / 4 years

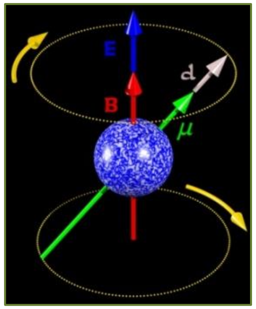
Magnetic field



- Cs and Hg magnetometers are complementary
- Coherent picture for the magnetic field
- Improved control on systematics effects
- By-product: measurement of Hg and neutron gyromagnetic ratios

nEDM

- We are taking data with a high sensitivity
- We expect with 300 data-days until 2016 :
  statistical sensitivity of $\sigma \lesssim 10^{-26}\, e{\cdot}\mathrm{cm}$
- n2EDM in R&D phase towards 2.10^{-27} e.cm



Thanks
Merci

The nEDM@PSI collaboration

2007

2014

A growing team … getting oversea

The dual magnetometry concept

A non perfect Co-magnetometer

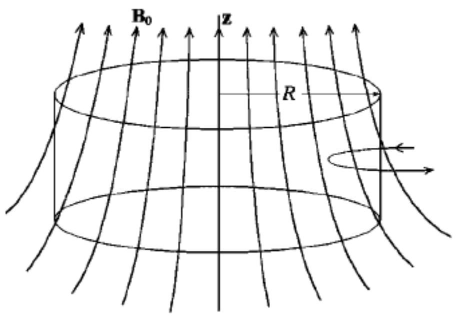
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling
- Geometrical phase shift

Motional (transverse) field

$$B_v = \frac{1}{c^2} E \times v$$

+

Magnetic transverse field



→ Frequency shift correlated with electric field

False EDM for Mercury (fast regime of GPE)

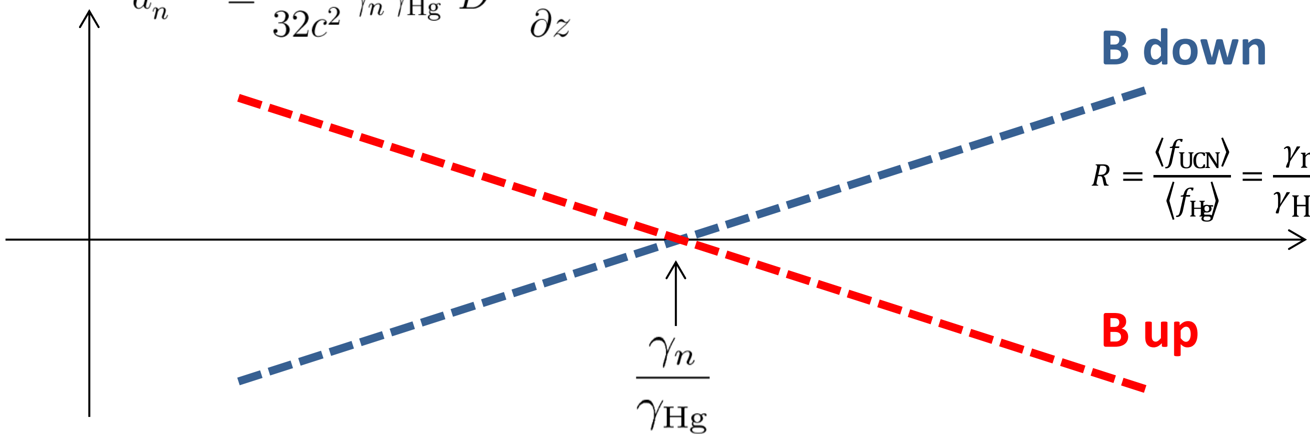
$$d_{\mathrm{Hg}}^{\mathrm{False}} = \frac{\hbar \gamma_{\mathrm{Hg}}^2}{32 c^2} D^2 \frac{\partial B}{\partial z} \longrightarrow d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

*Pendlebury et al, PRA **70** 032102 (2004)*

The analysis strategy (RAL/Sussex/ILL like) and associated systematic errors

Geometrical phase shift: frequency shift for particles in traps (large for the Hg atoms)

EDM $d_n^{\mathrm{False}} = \frac{\hbar}{32c^2}\gamma_n\gamma_{\mathrm{Hg}}\ D^2\ \frac{\partial B}{\partial z}$



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

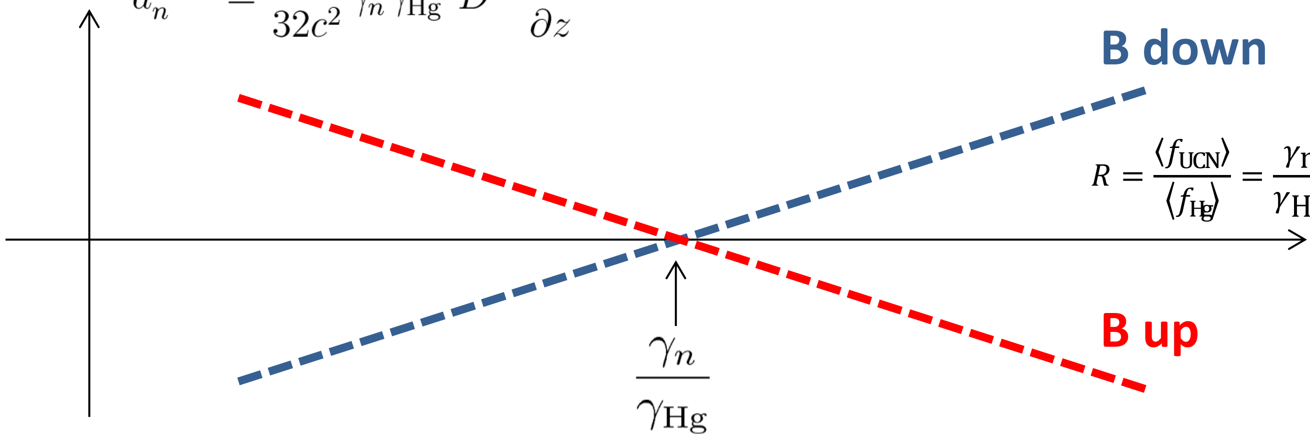
And any shift of the neutron and/or Hg precession frequency linear with the E-field
→ **Direct systematic effect**

The measurement strategy

The analysis strategy (RAL/Sussex/ILL like) and associated systematic errors

Geometrical phase shift: frequency shift for particles in traps (large for the Hg atoms)

EDM $d_n^{\mathrm{False}} = \frac{\hbar}{32c^2}\gamma_n\gamma_{\mathrm{Hg}}\ D^2\ \frac{\partial B}{\partial z}$



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

In the case of an inhomogeneous B-field

$$d_n^{\mathrm{False}} = -\frac{\hbar}{2c^2}\gamma_n\gamma_{\mathrm{Hg}}\ \langle xB_x + yB_y\rangle$$

$$d_n^{\mathrm{False}} = \frac{\hbar}{32c^2}\gamma_n\gamma_{\mathrm{Hg}}\ D^2\ \frac{\partial B}{\partial z}$$ At 1st order in gradients

} Indirect systematic effect due to local dipoles

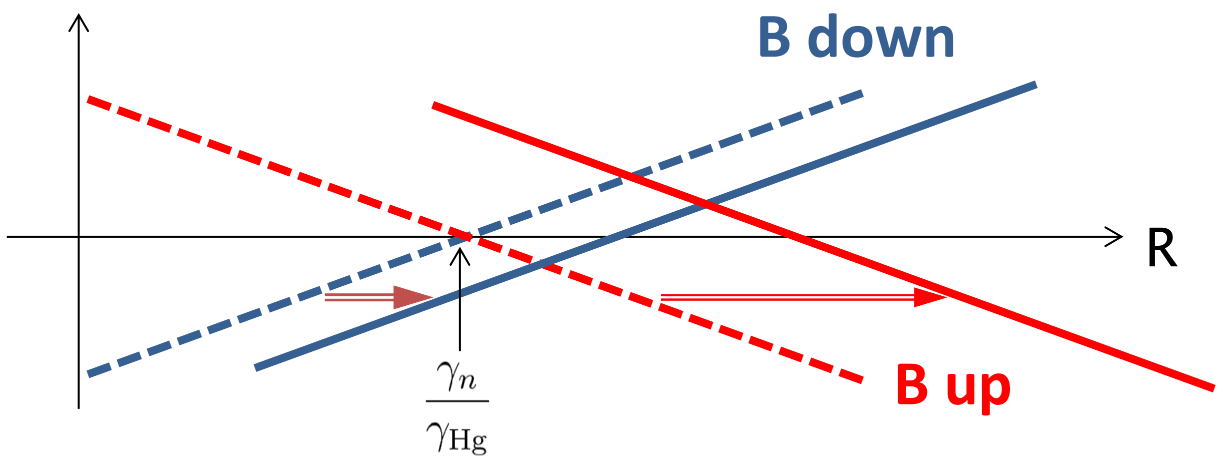
*Pignol et al, PRA **85** 042105 (2012)*

The analysis strategy (RAL/Sussex/ILL like) and associated systematic errors

Geometrical phase shift: frequency shift for particles in traps (large for the Hg atoms)

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

Residual systematic effect
if different for B up and down → **Indirect systematic effect**



The analysis strategy (RAL/Sussex/ILL like) and associated systematic errors

Effects	Goal	Status (Dec. 2012)	Status (Nov. 2014)
Direct Effects			
Uncompensated B-Drifts	0 ± 0.9	2.9 ± 8.6	-0.2 ± 0.4
Leakage Current	0 ± 0.1	0.00 ± 0.05	0.00 ± 0.05
$V \times E$ UCN	0 ± 0.1	0 ± 0.1	0 ± 0.1
Electric Forces	0 ± 0.4	0 ± 0.4	0 ± 0.0
Hg EDM		0.02 ± 0.06	0.02 ± 0.06
Hg Direct Light Shift	0 ± 0.4	0 ± 0.008	0 ± 0.008
Indirect Effects			
Hg Light Shift		0 ± 0.05	0 ± 0.05
Quadrupole Difference	0 ± 0.6	1.3 ± 2.4	1.3 ± 2.4
Dipoles	0 ± 0.5		
At the surface		0 ± 0.4	0 ± 0.4
Other Dipoles		0 ± 3	0 ± 3
Total	0 ± 1.3	4.2 ± 9.4	0.2 ± 4.0

Status of the constrain on systematic effects in units of $10^{-27} e \cdot \mathrm{cm}$.

Y. Kermaidic poster

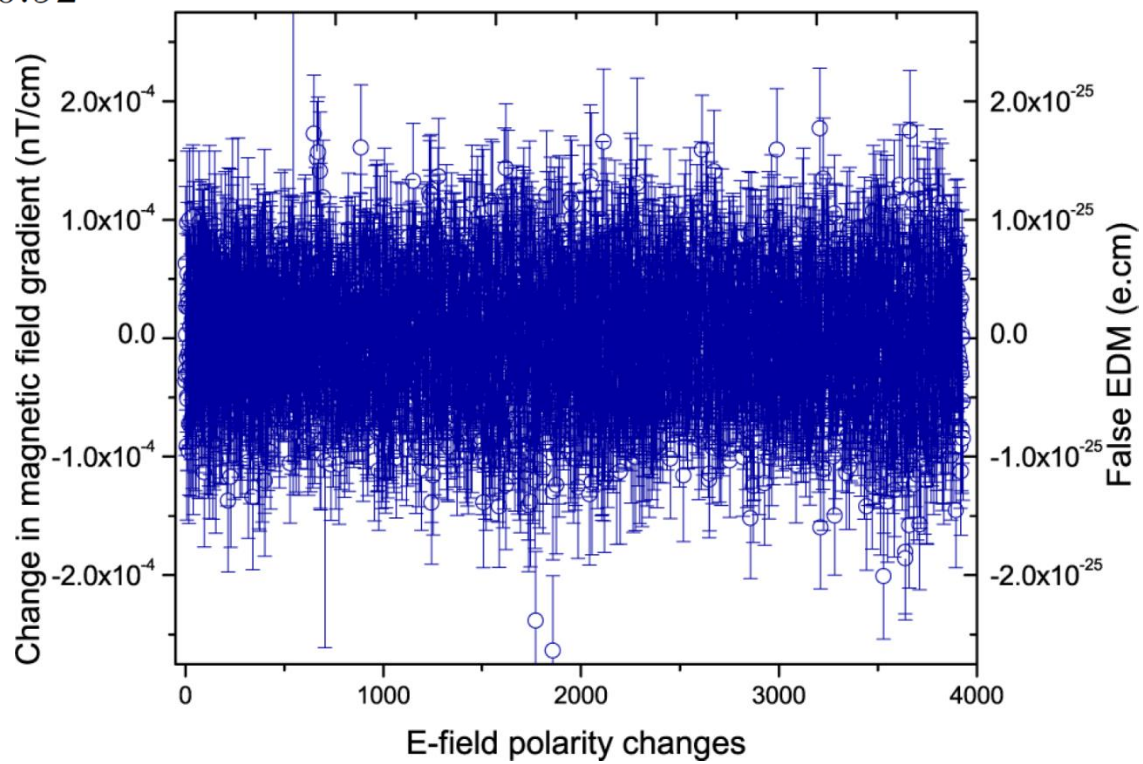
The error budget

Period	Result (10^{-27} e·cm)
2010	2.9 ± 8.6
Sept. 2011	-1.8 ± 3.9
Dec. 2011 B0 ↑	-7.5 ± 3.7
Dec. 2011 B0 ↓	-0.7 ± 1.0
Dec. 2012 B0 ↑	0.2 ± 0.6
Dec. 2012 B0 ↓	-0.7 ± 1.1
Sept. 2013	-0.1 ± 0.7
Weighted avg.	-0.2 ± 0.4
Chi$^2/\nu$	0.92

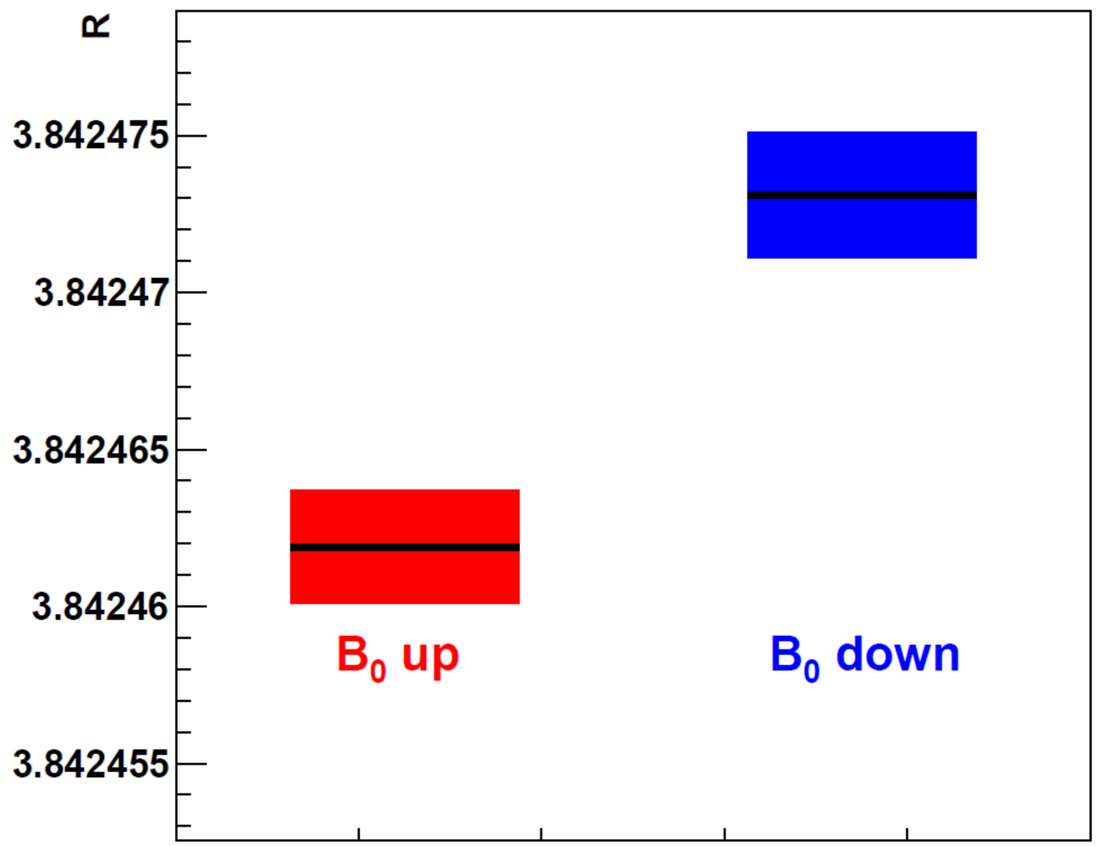
The uncompensated B-Drift

Search for Uncompensated B-drift due to charging current

Search for Uncompensated B-drift due to sparks



The R-curve … and the nEDM indirect systematic effects

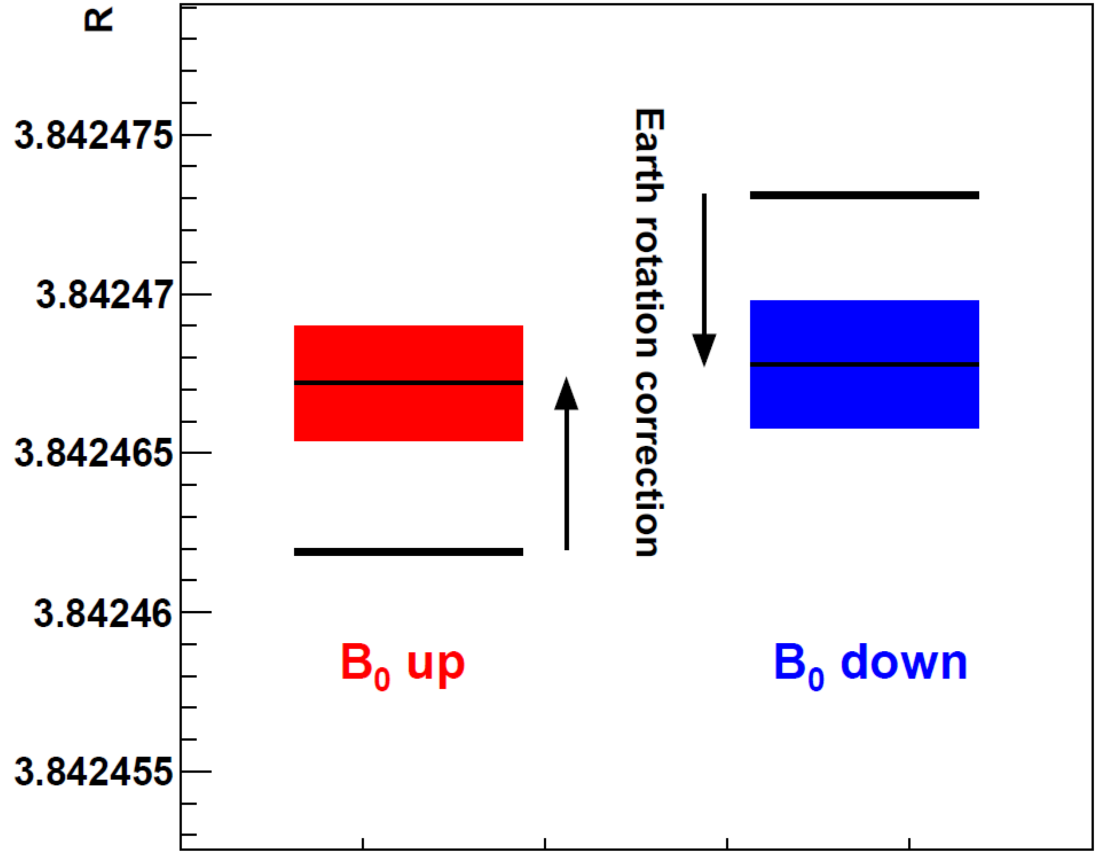


The R-curve … and the nEDM indirect systematic effects

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

$$f_n = \left| -\frac{\gamma_n}{2\pi} B_0 \pm f_{\mathrm{Earth}} \sin(\lambda) \right|$$

$$f_{\mathrm{Hg}} = \left| \frac{\gamma_{\mathrm{Hg}}}{2\pi} B_0 \pm f_{\mathrm{Earth}} \sin(\lambda) \right|$$



$$\begin{aligned} \delta R_{\mathrm{Earth}} &= \mp \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} \left(\frac{f_{\mathrm{Earth}}}{f_n} + \frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}} \right) \sin(\lambda) \\ &= \mp 5.3 \times 10^{-6} \end{aligned}$$

False EDM in the crossing point analysis

$$d_{\mathrm{False}} = \frac{\hbar \gamma_n \gamma_{\mathrm{Hg}} D^2}{128 c^2 B_0 \Delta h} \left(\langle B_\perp^2 \rangle_\downarrow - \langle B_\perp^2 \rangle_\uparrow \right)$$

Using the 2010 fluxgate maps

$$\langle B_T^2 \rangle_\downarrow - \langle B_T^2 \rangle_\uparrow = (0.3 \pm 0.5)\ \mathrm{nT}^2$$

$$d_{\mathrm{False}} = (1.3 \pm 2.4) \times 10^{-27}\, e\,\mathrm{cm}$$

Using the 2012 R curves alone

$$\langle B_T^2 \rangle_\downarrow - \langle B_T^2 \rangle_\uparrow = (0.3 \pm 2.8)\ \mathrm{nT}^2$$

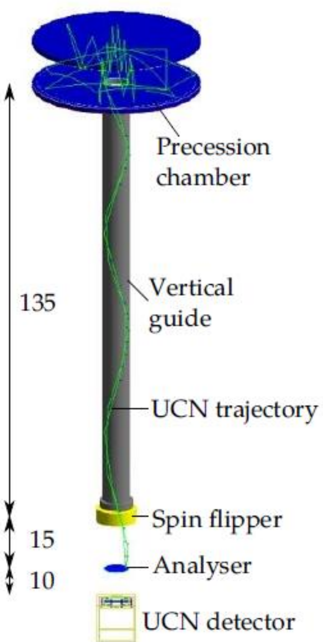
$$d_{\mathrm{False}} = (1.3 \pm 7.2) \times 10^{-27}\, e\,\mathrm{cm}$$

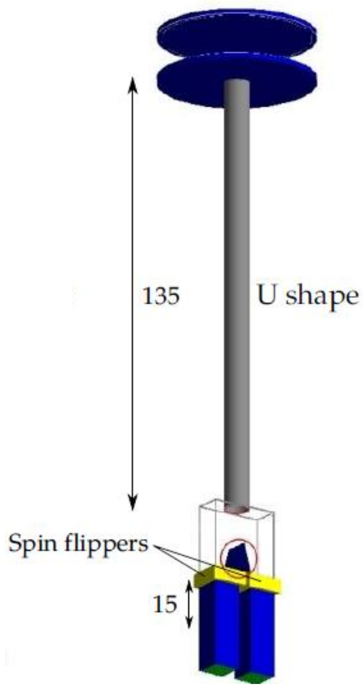
E. Wursten poster

A unique consistency check and demonstration of the quality of the magnetic field control

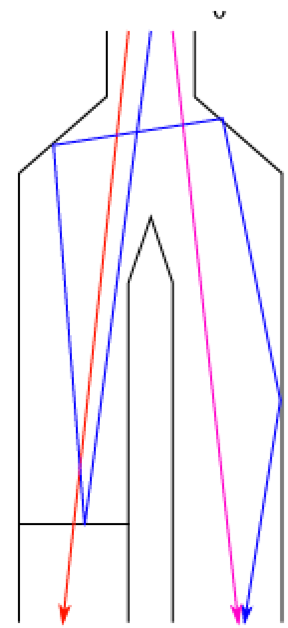
The statistical sensitivity

2014 preview





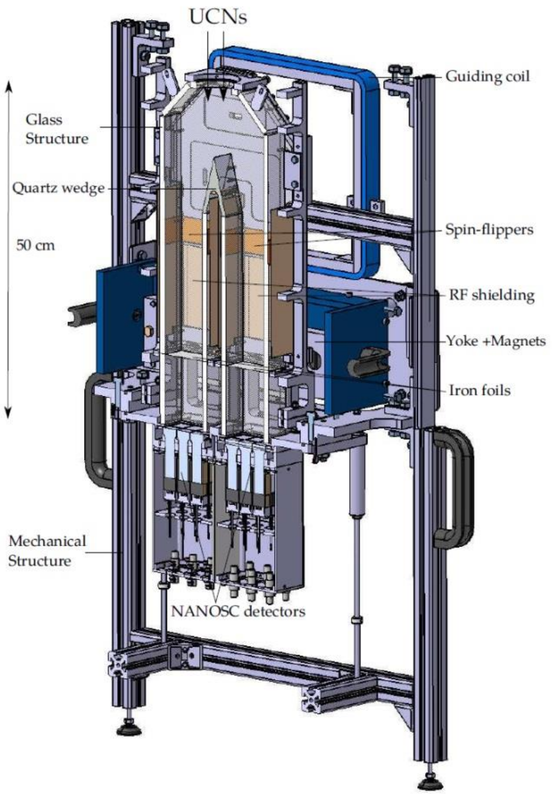
USSA

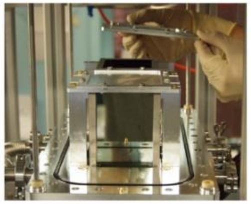


	α [%]	N_{tot}	$N_{\text{West-1}}$
USSA	63.4(18)	3791(14)	1.878(5) $\times 10^6$
Sequential	59.7(22)	2692(15)	1.651(16) $\times 10^6$
Ratio	1.062(49)	1.239(10)	

The statistical sensitivity

2014 preview





Simultaneous spin analysis:
Increase in sensitivity on the nEDM

$$18.2 \pm 6.1\%$$

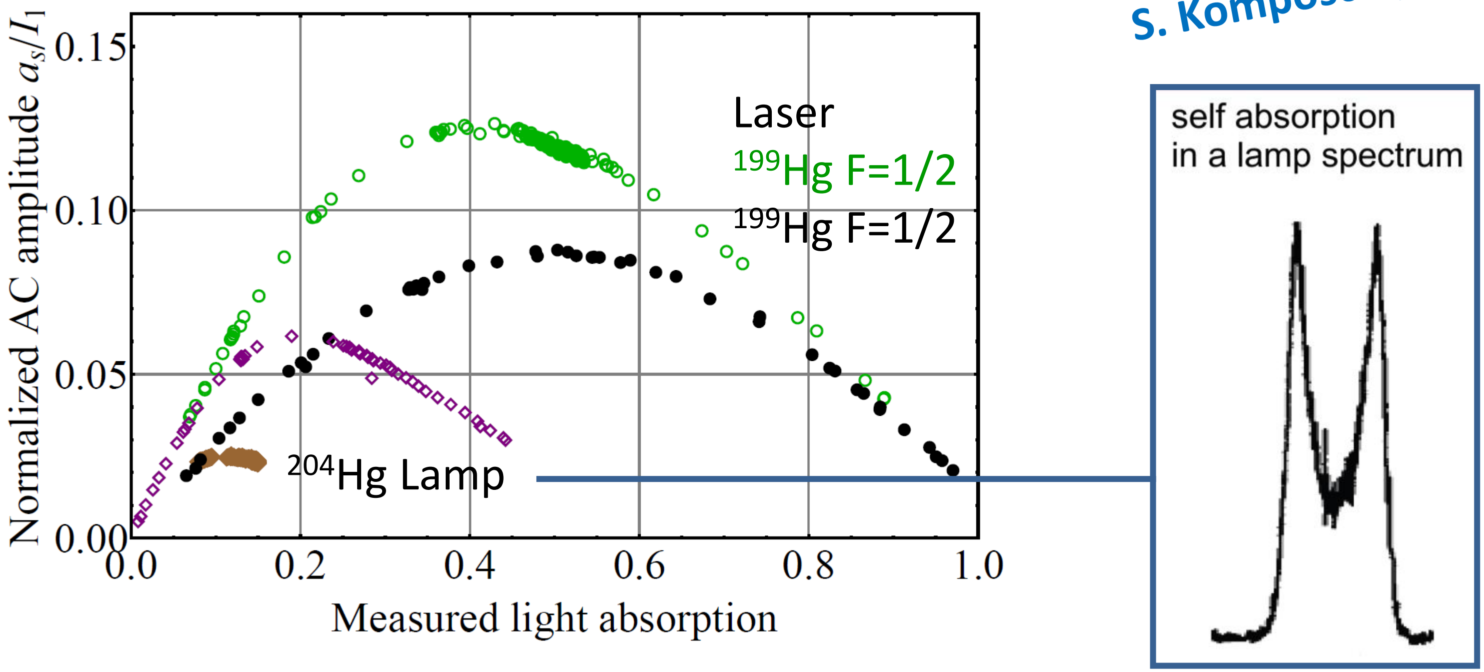
	α [%]	N_{tot}	$N_{\text{West-1}}$
USSA	63.4(18)	3791(14)	$1.878(5) \times 10^6$
Sequential	59.7(22)	2692(15)	$1.651(16) \times 10^6$
Ratio	1.062(49)	1.239(10)	

T. Lefort talk
Tuesday 16:45

Laser based Hg co-magnetometer

Sensitivity improvement from ~400fT → <100fT

S. Komposch poster



- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetometry Hg – laser read out of Hg-FID to avoid light shift**
  Cs – vectorial
  3He – free from geometrical phase shift

S. Afach poster
H.-C. Koch poster

Thanks for your attention