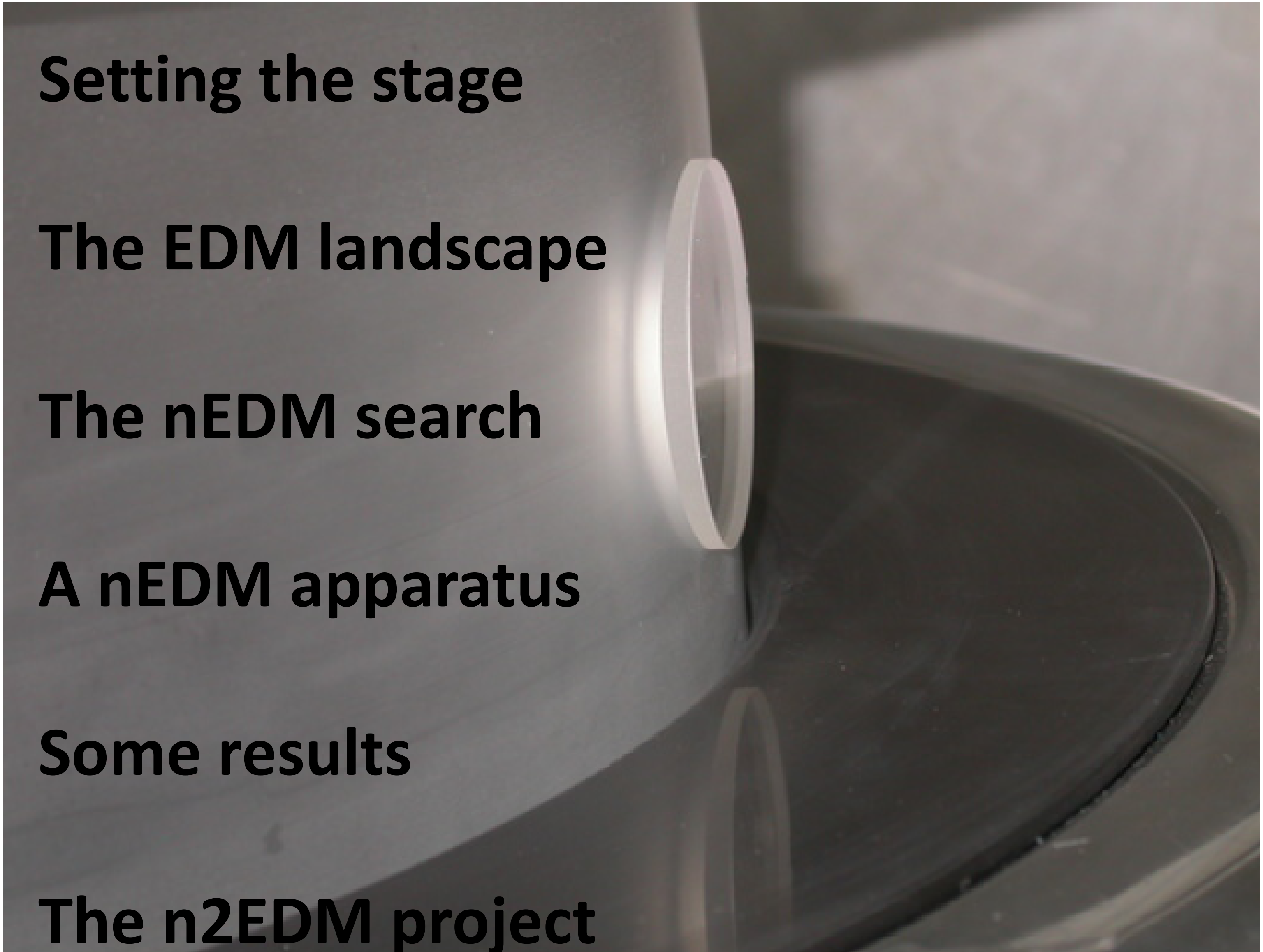
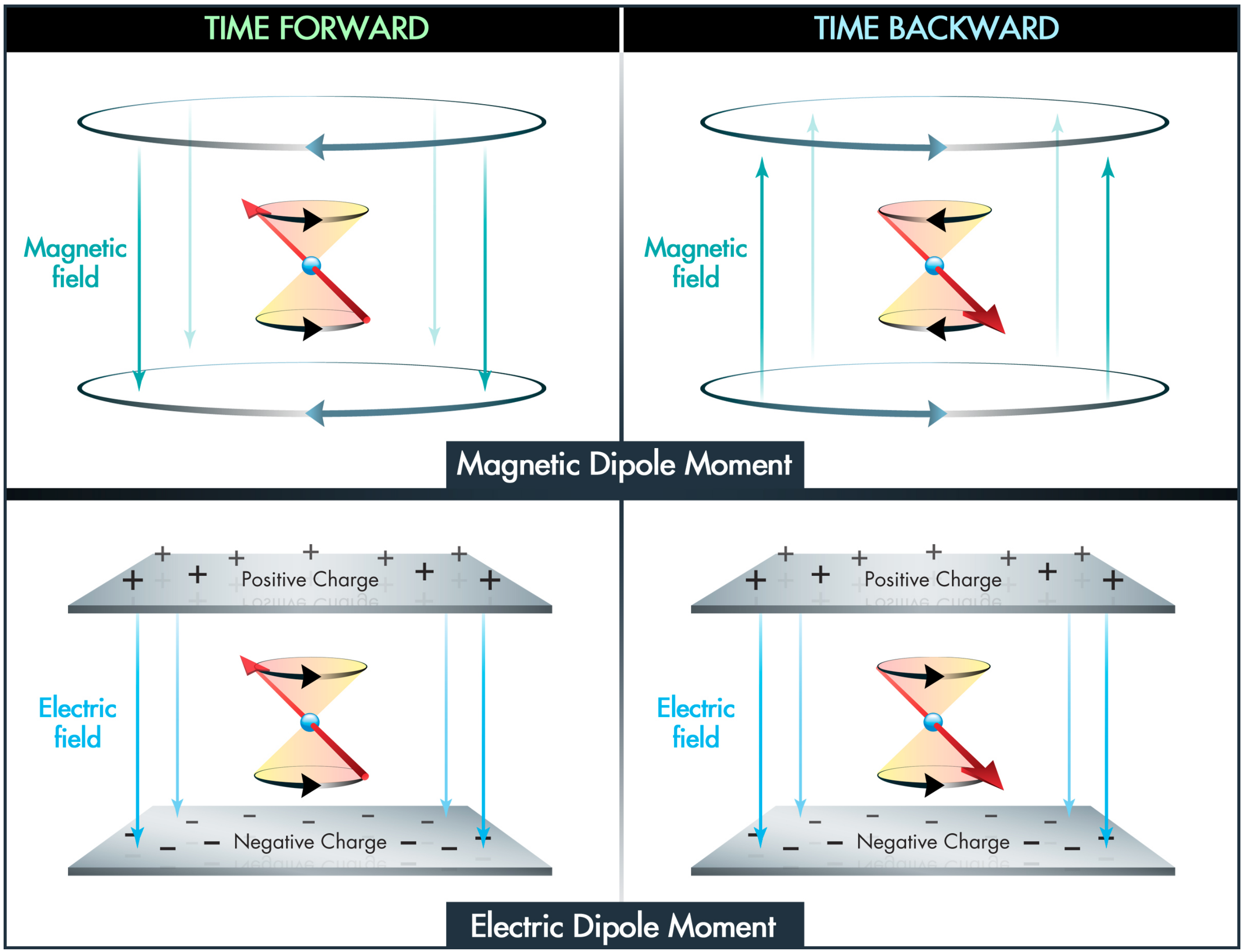
Upper limit on the neutron EDM

S. Roccia


Setting the stage
The EDM landscape
The nEDM search
A nEDM apparatus
Some results
The n2EDM project

$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E}$$



A nonzero particle EDM violates **T, P** and, assuming **CPT** conservation, also **CP**.

Setting the stage

- Despite the phenomenal success of SM, it is not the theory of everything
- SM → "only" an effective theory valid up to some scale
- Most pressing problems of SM:
    - neutrino masses (can be accommodated)
    - matter-antimatter asymmetry
    - dark matter
    - strong CP problem
    - hierarchy problem
    - dark energy
- which of these are related to $d_n = 0$?

Setting the stage

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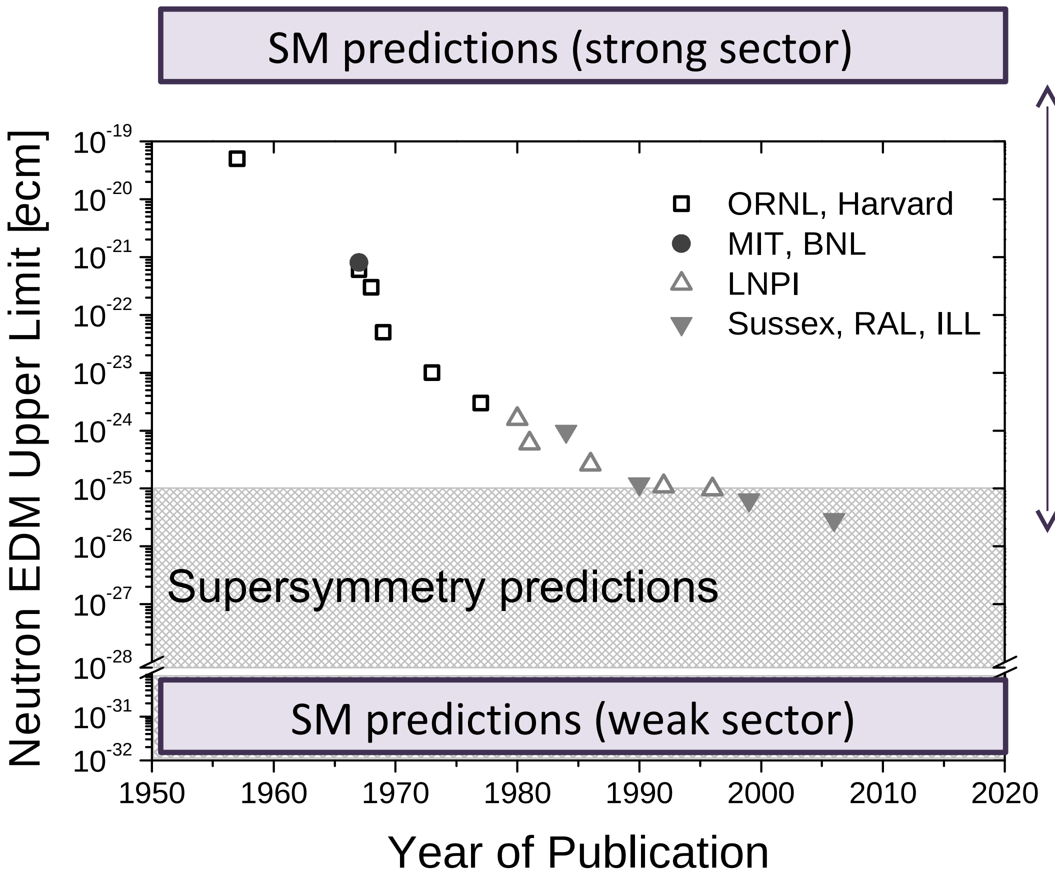
- which of these are related to $d_n = 0$?
  - need CP violation
  - CP violation within the SM:
    - weak CP violation δ_{CKM}
    - strong CP violation θ_{QCD}
  - CP violation outside SM

The EDM landscape



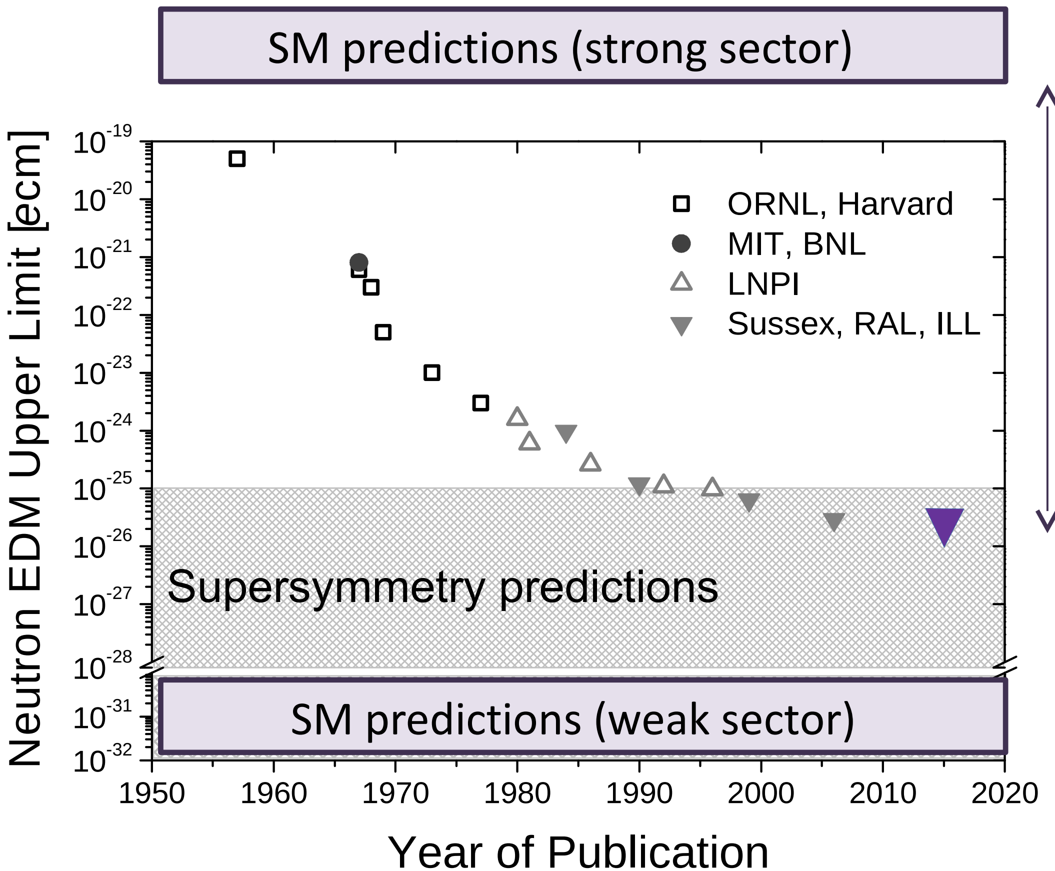
Strong CP problem

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

Phase in the CKM matrix

δ_{CKM}

The EDM landscape



10 orders of magnitude

Strong CP problem

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

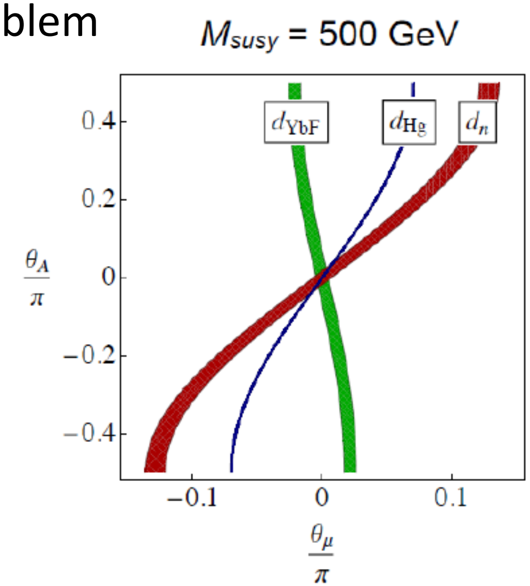
Phase in the CKM matrix

δ_{CKM}

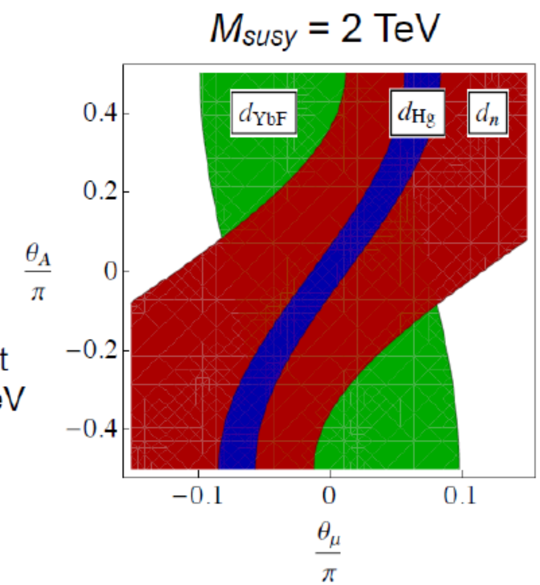
The EDM landscape

SUSY, the nEDM and the LHC

SUSY CP problem



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



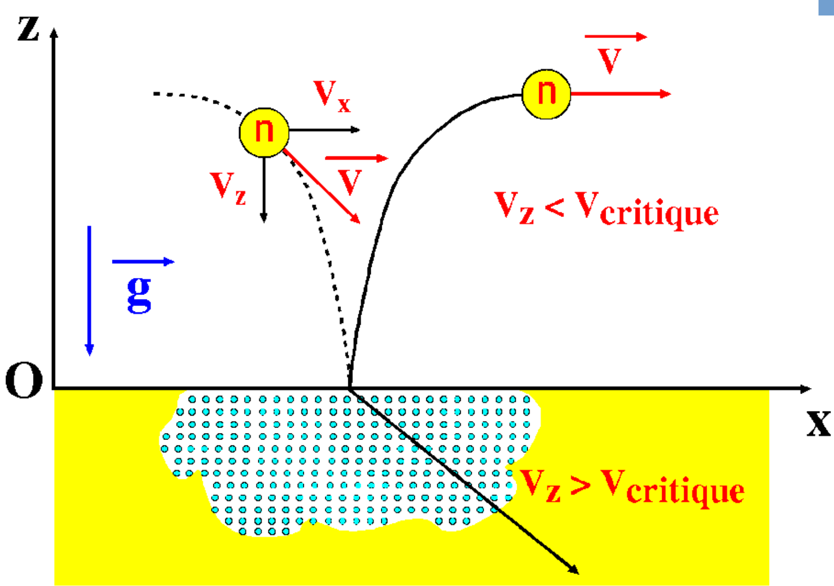
A. Ritz, talk at the PSI 2013 workshop.

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;

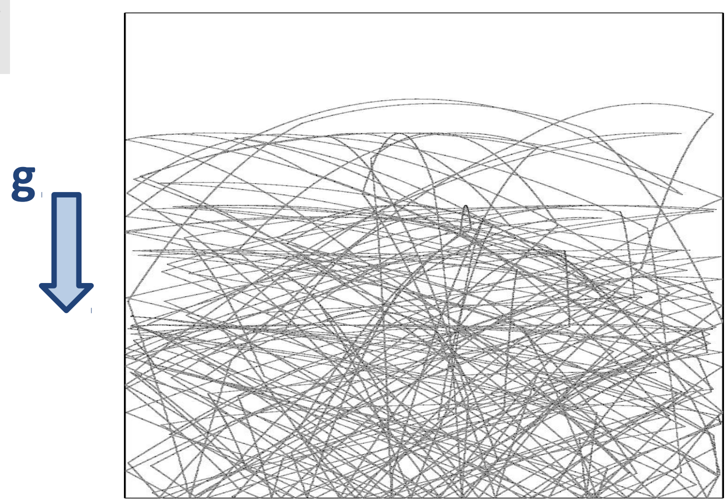
$T_n \approx 2$ mK ;

$E_n \approx 130$ neV

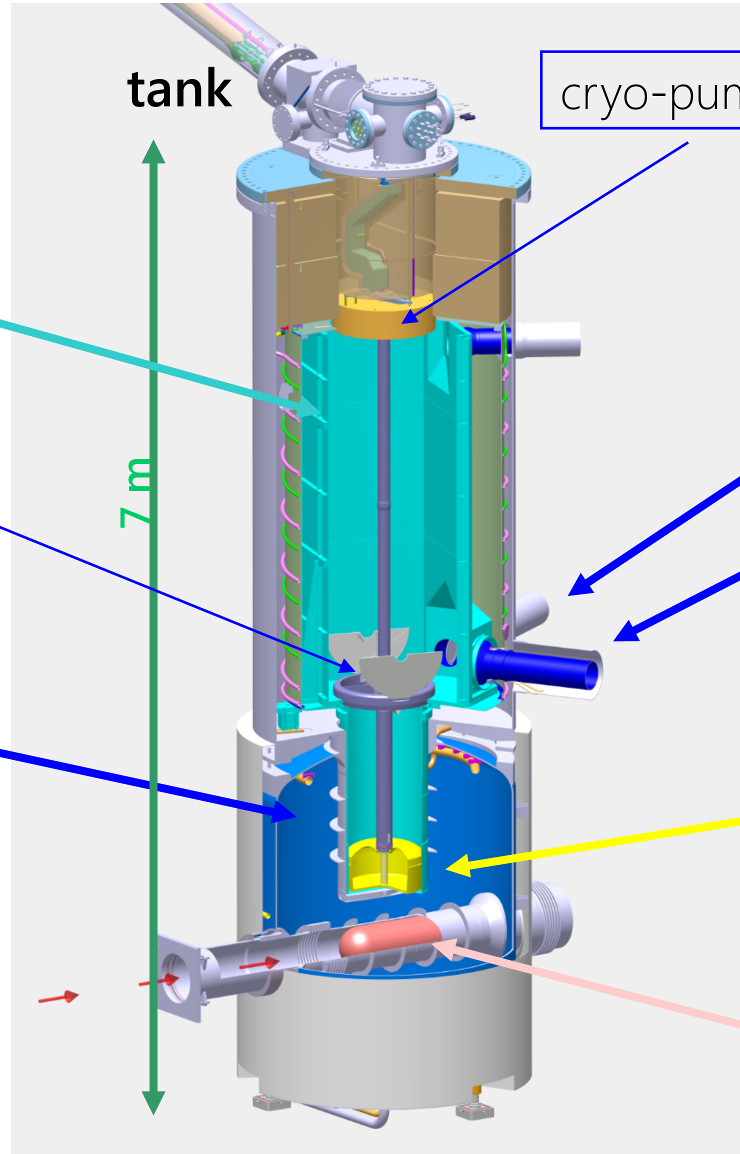
λ_n>>2 Å :

Neutrons see the Fermi potential

Can be stored !



The nEDM search



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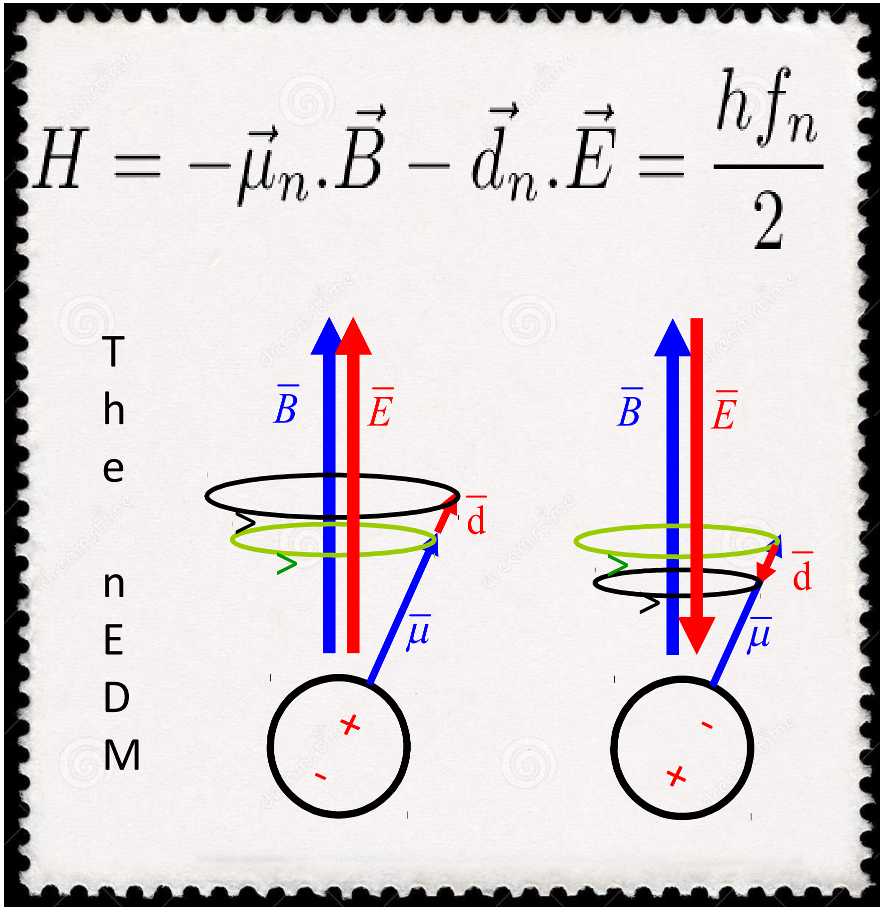
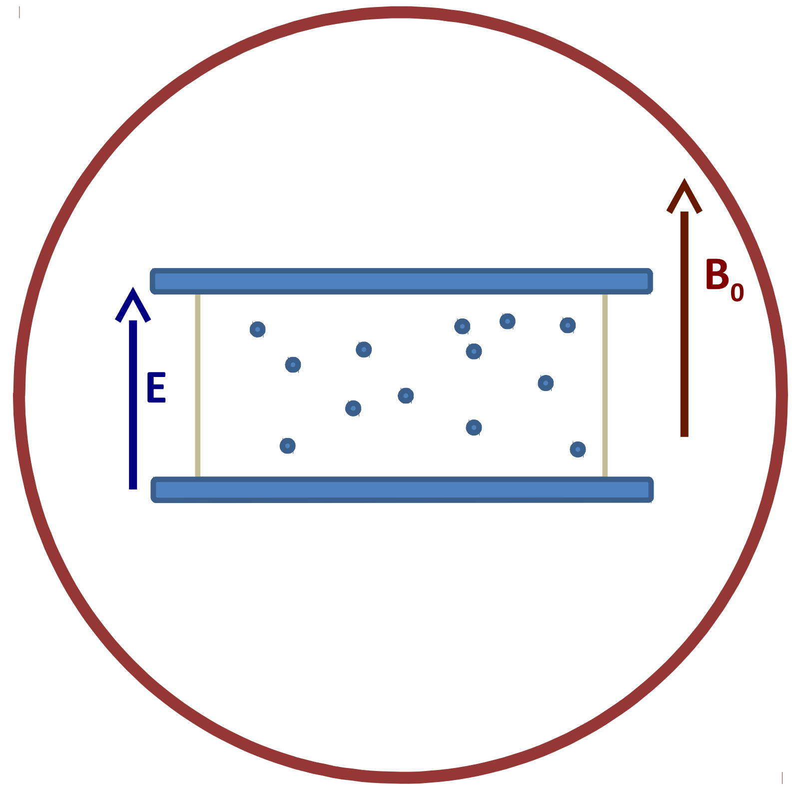
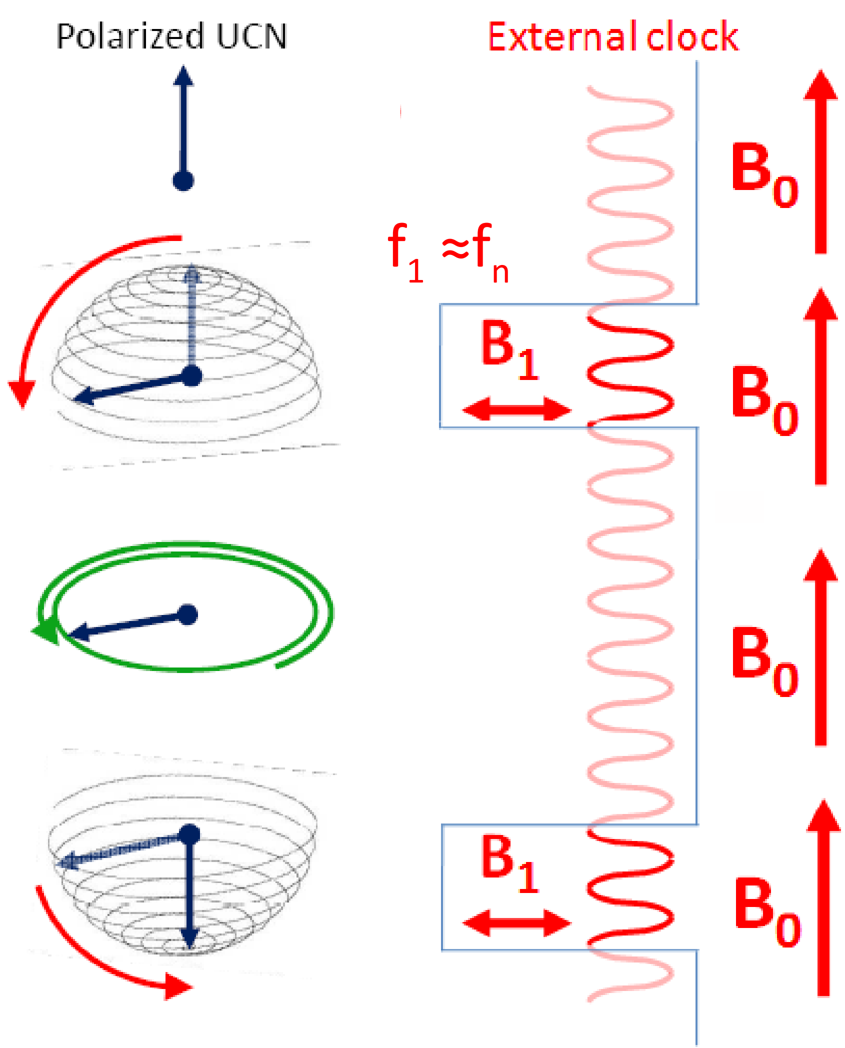
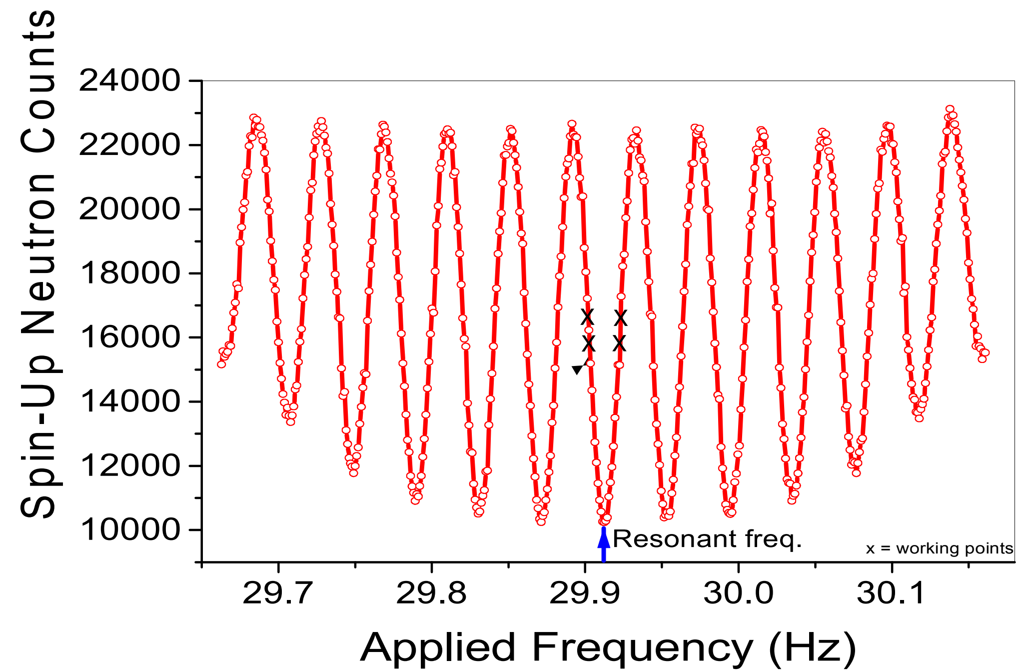




B=1 μT
E=130KV/12cm

The Ramsey's method of separated oscillating fields





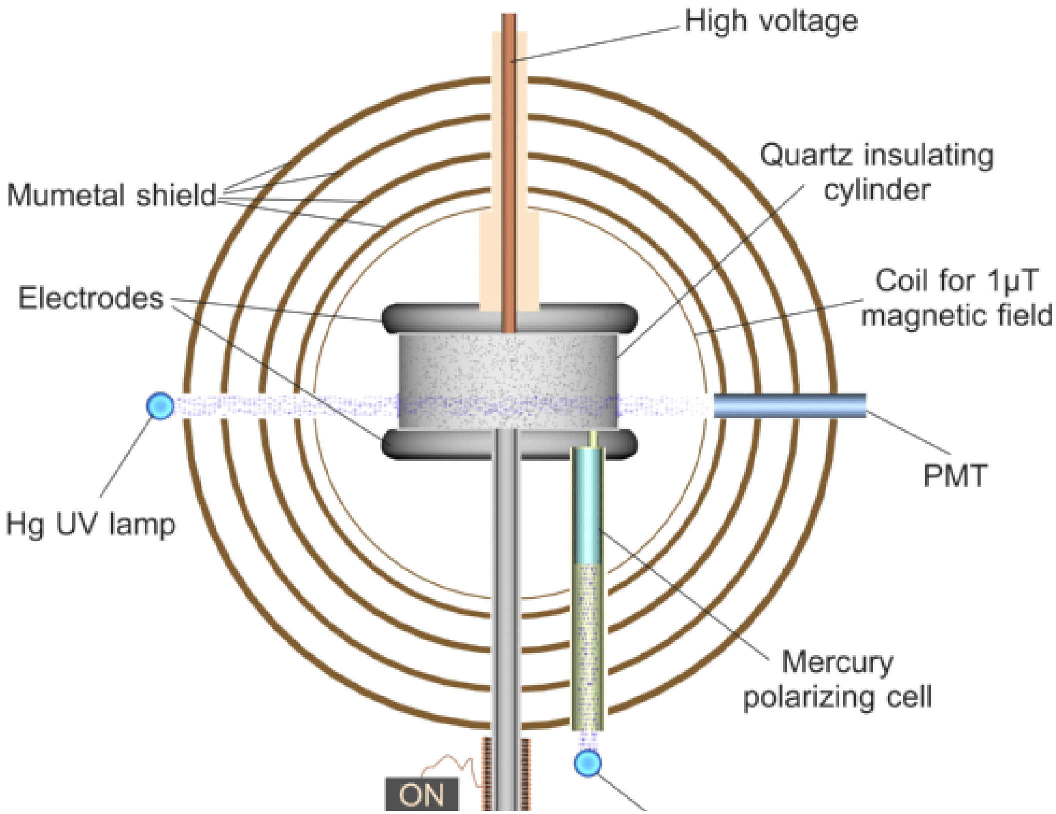
$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

First limitation ….. Magnetic field fluctuations

$$\mathrm{h}\ f_n\ (\uparrow\uparrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow)$$

$$\mathrm{h}\ f_n\ (\uparrow\downarrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) - 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow)$$

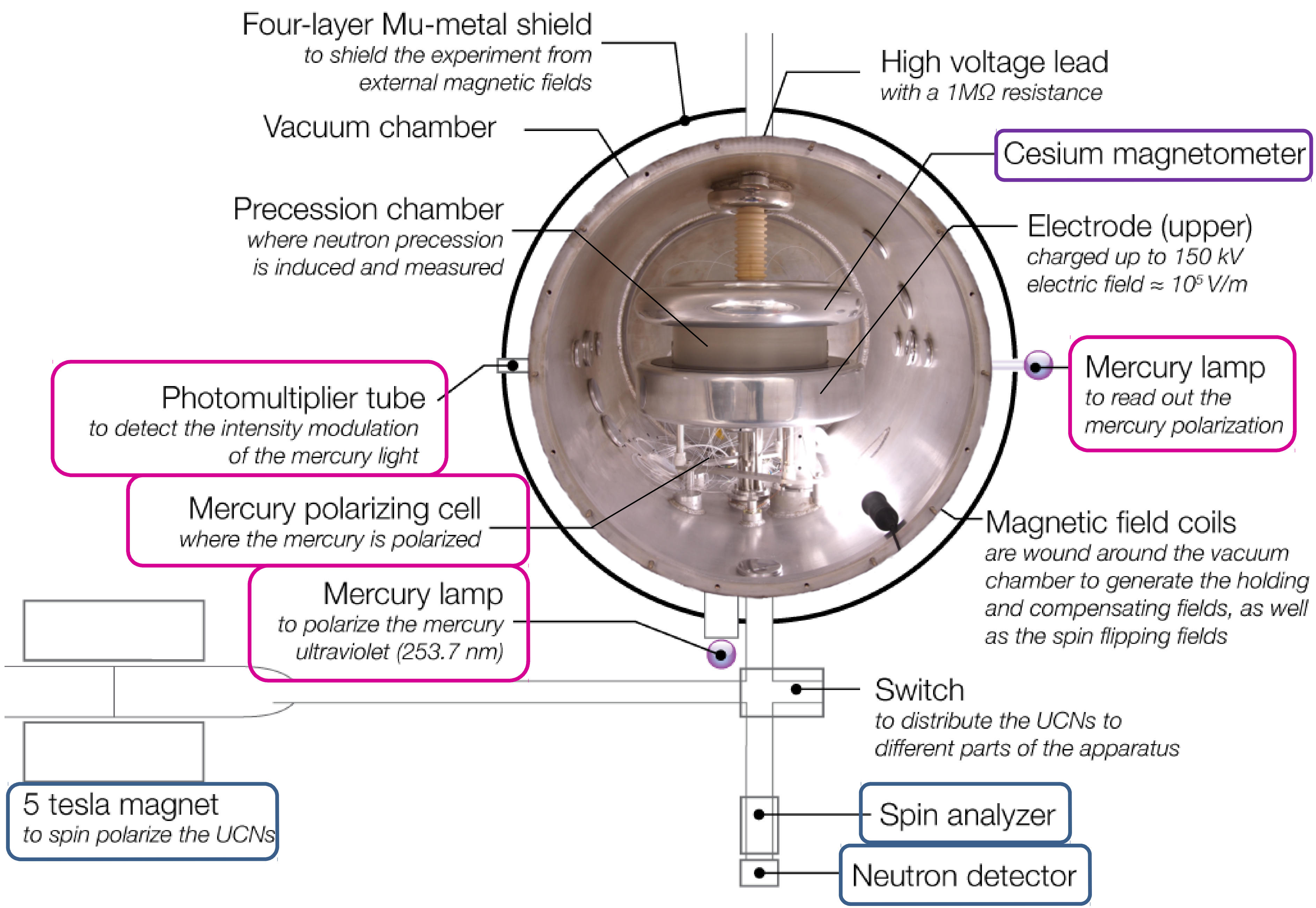
$$\mathrm{h}(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) = 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) - 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))$$



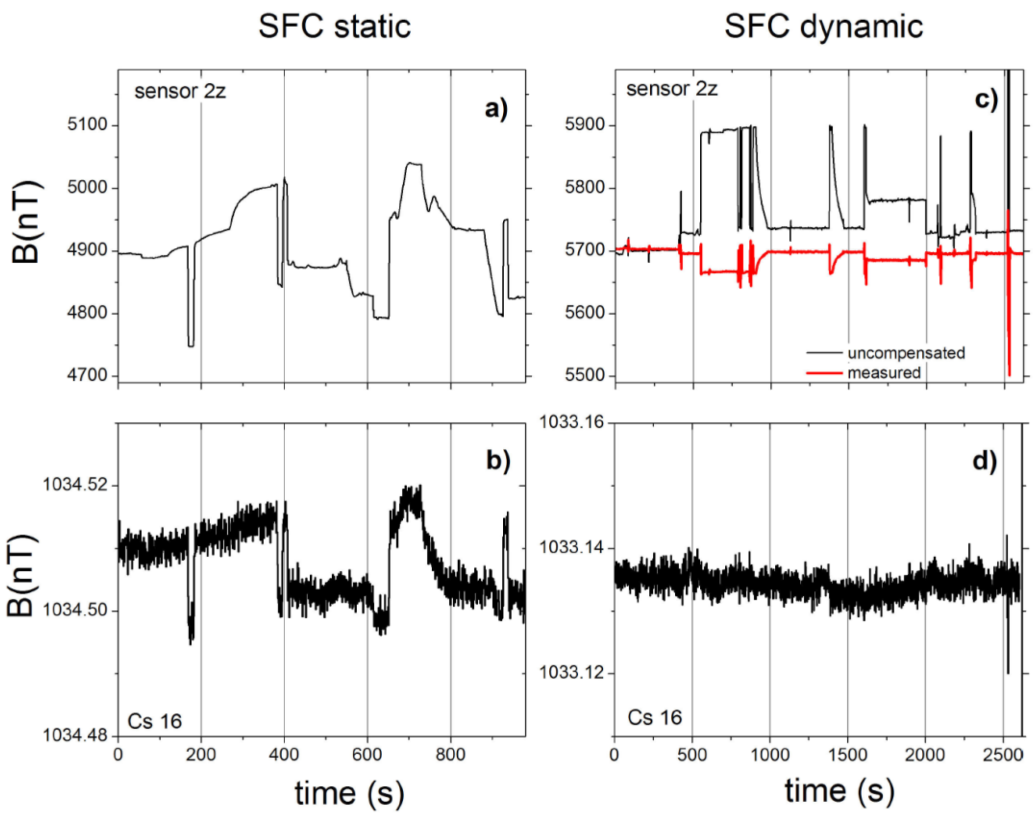
Mercury co-magnetometer (1998)

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

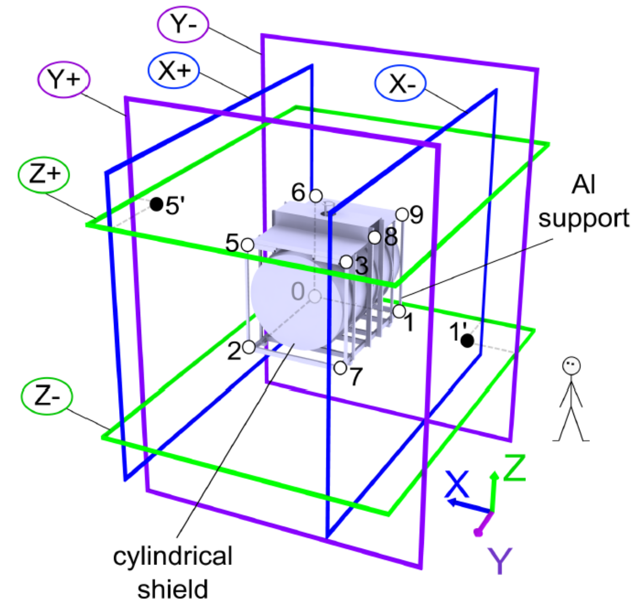
A nEDM apparatus



Magnetic stability



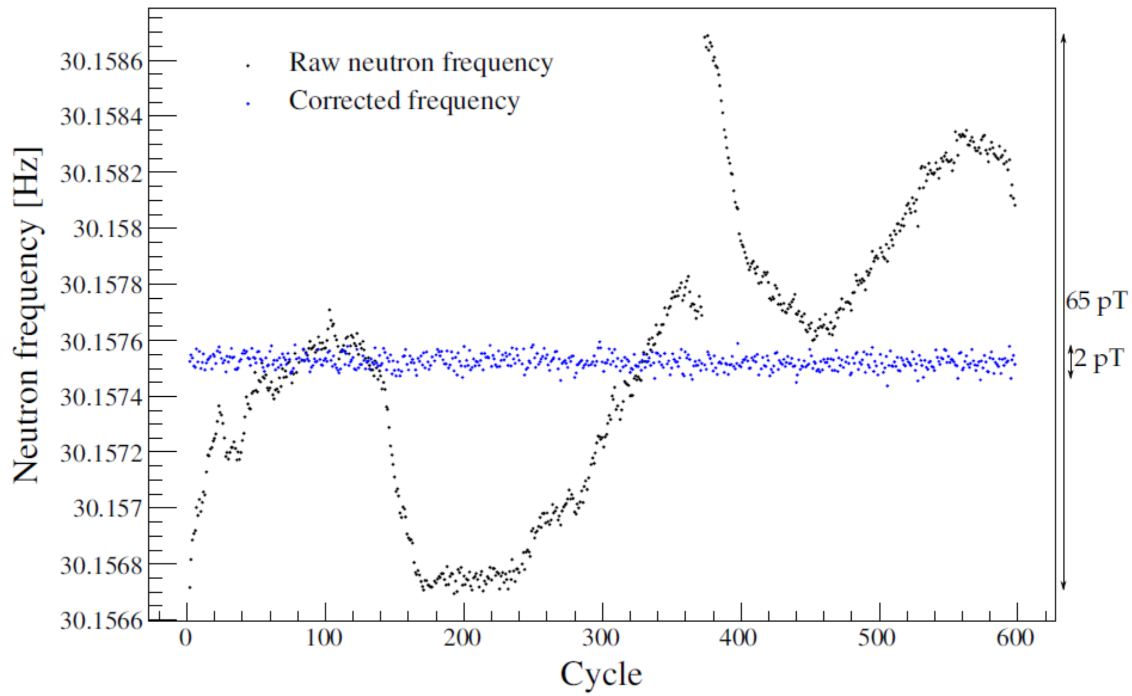
Afach et al., J. Appl. Phys. ***116****, 084510 (2014)*

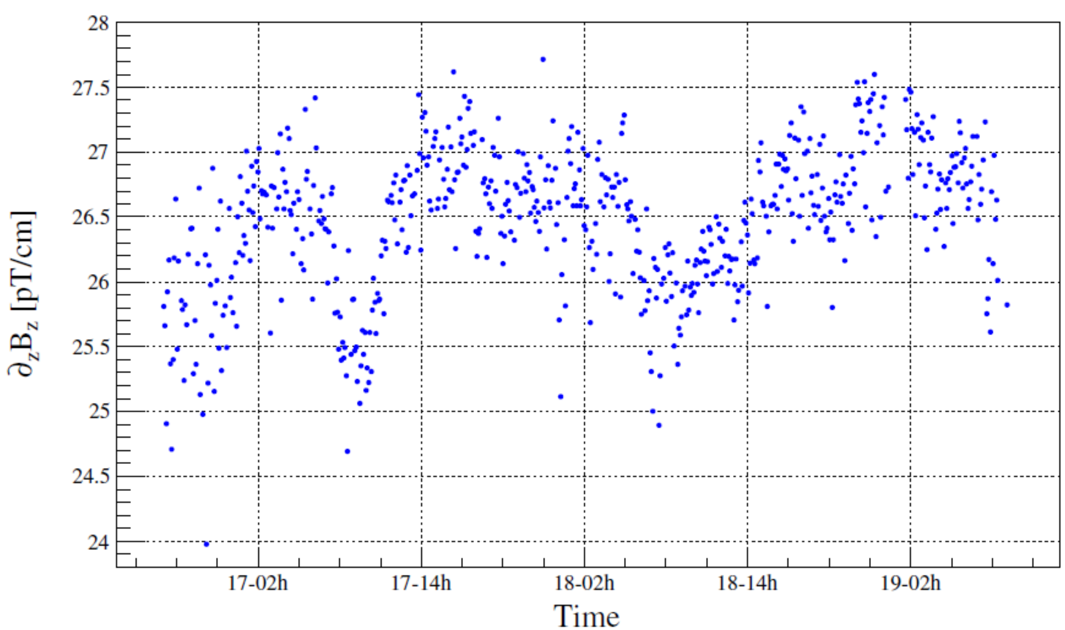


- Active compensation
- Improved degaussing procedure
- Temperature stabilization
- New current source
- …

A nEDM apparatus

Magnetic stability

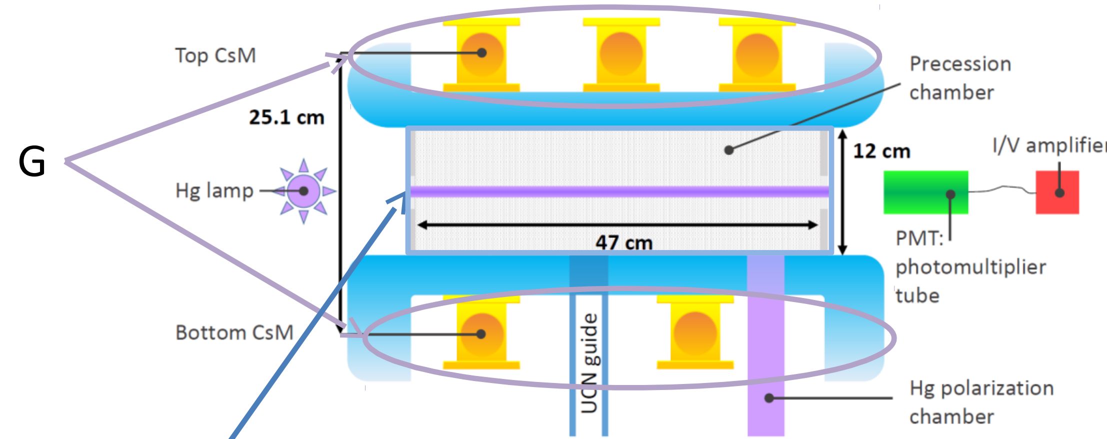




Vertical gradient
~ 2 pT/cm daily variation

A non perfect Co-magnetometer

- Gravitational shift



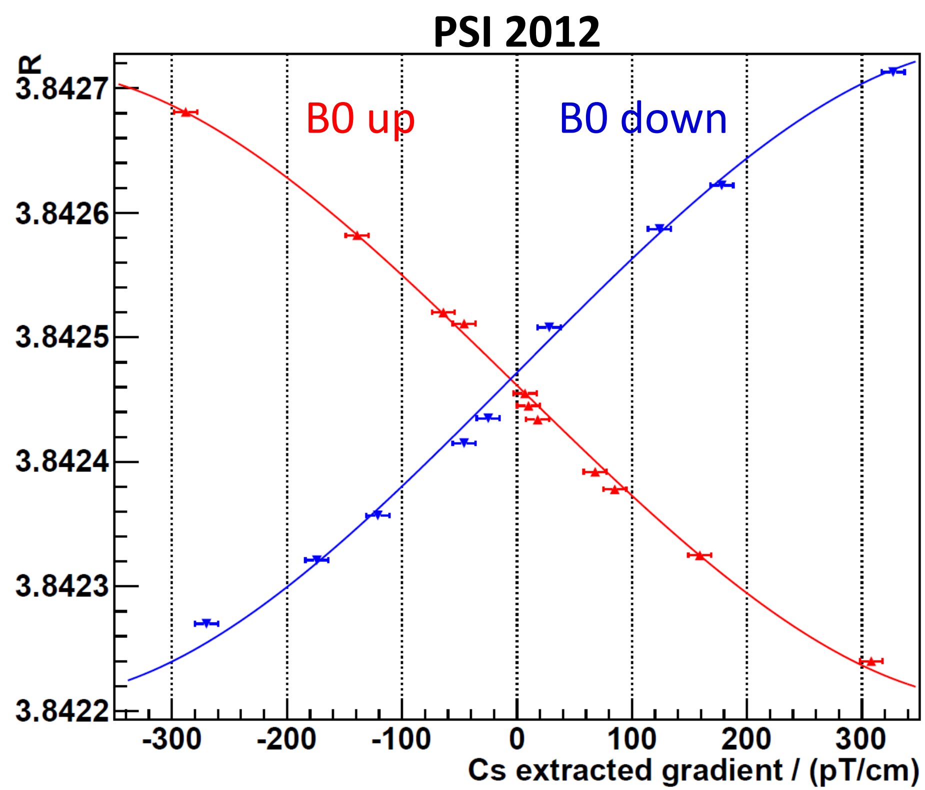
$$R = \frac{f_n}{f_{Hg}}$$

In the precession chamber

UCNs | g | Mercury

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

Δh =2,7 mm



A non perfect Co-magnetometer

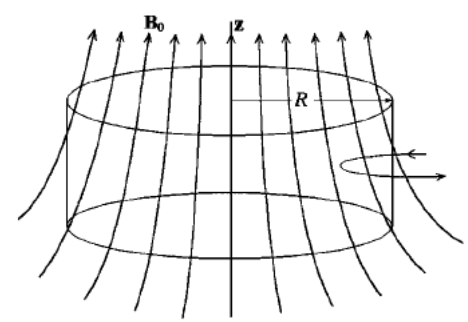
- Gravitational shift
- Geometrical phase shift

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)

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

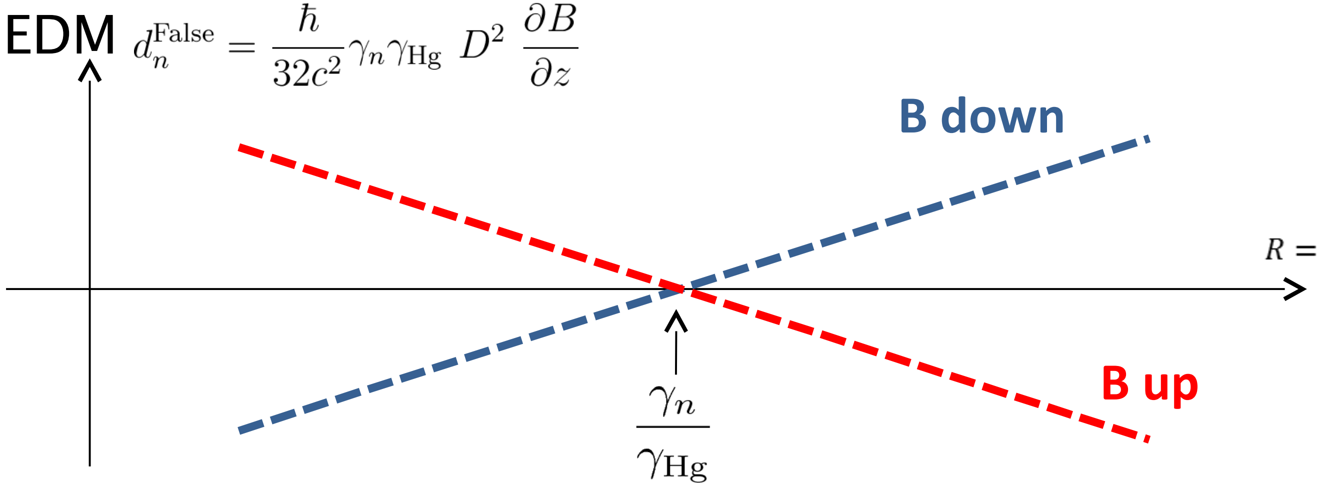
*Pendlebury et al, PRA **70** 032102 (2004)*

A nEDM apparatus

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)

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



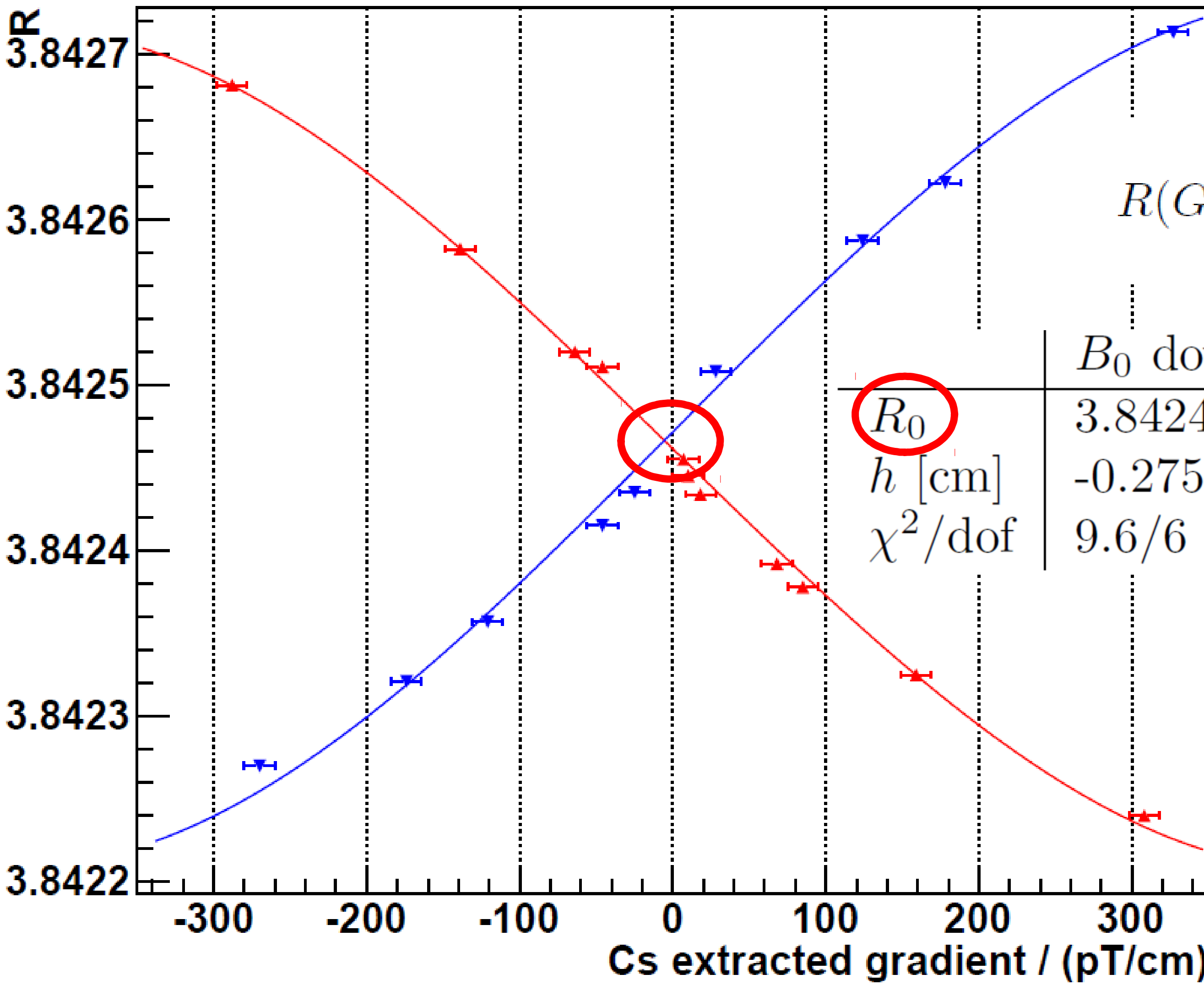
$$R = \frac{\langle f_{\mathrm{UCN}}\rangle}{\langle f_{\mathrm{Hg}}\rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp}\rangle}{|B_0|^2} + \ ...\right)$$

And any shift of the neutron and/or Hg precession frequency linear with the E-field

→ **Direct systematic effect**

Some results

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

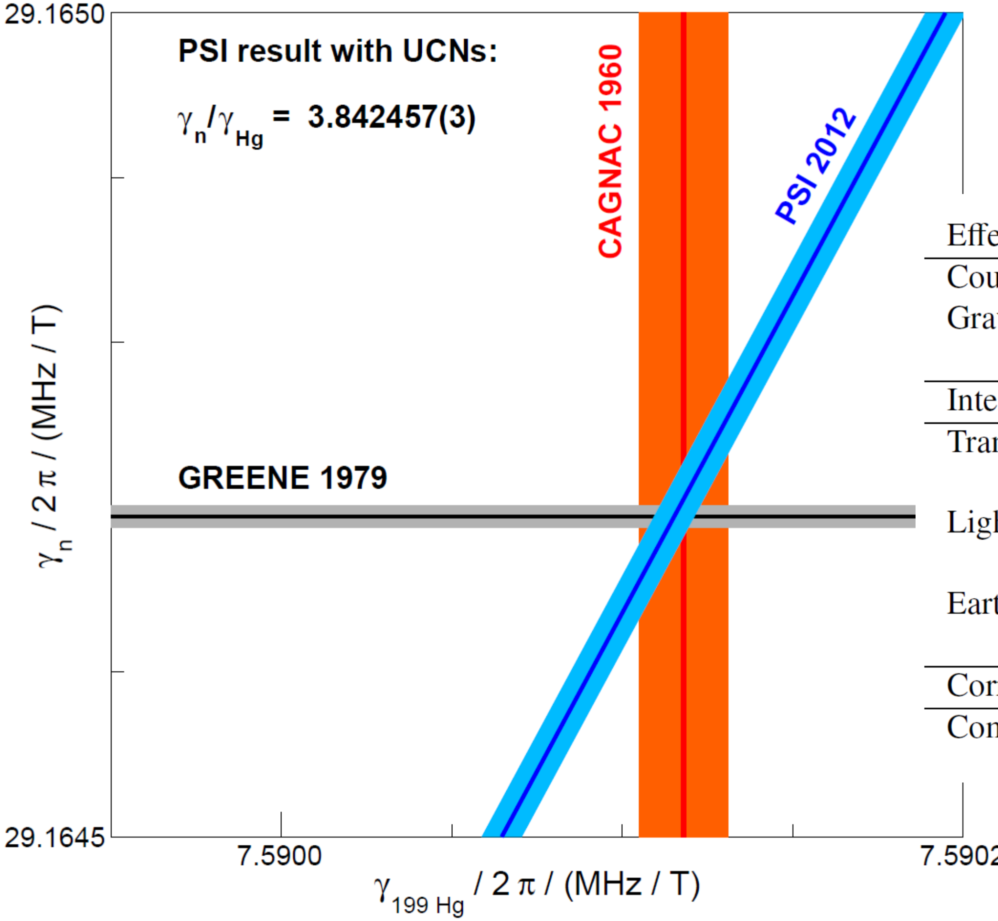


$$R(G) = R_0 \left(1 \pm \frac{Gh}{B_0} + cG^3 \right)$$

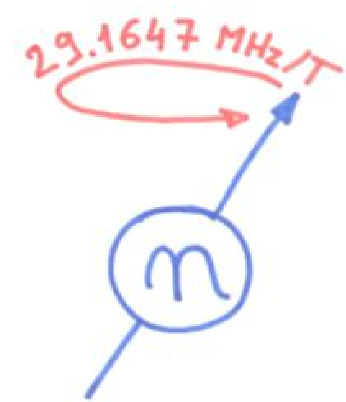
	B_0 down	B_0 up
R_0	3.8424731(20)	3.8424619(18)
h [cm]	-0.275(13)	0.268(13)
χ^2/dof	9.6/6	5.7/8

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

Some results



Effect	$B_0\uparrow$	$B_0\downarrow$
Counting statistics	$\pm 0.5\times10^{-6}$	$\pm 0.5\times10^{-6}$
Gravitational shift ($3.84\times\delta_{Grav}$)	$(-8.9\pm2.3)\times10^{-6}$	$(-1.8\pm2.7)\times10^{-6}$
Intermediate R_0	3.8424580(23)	3.8424653(27)
Transverse shift ($3.84\times\delta_T$)	$(3.7\pm0.8)\times10^{-6}$	$(3.0\pm1.2)\times10^{-6}$
Light shift ($3.84\times\delta_{Light}$)	$(1.3\pm0.7)\times10^{-6}$	$(0.8\pm0.6)\times10^{-6}$
Earth rotation ($3.84\times\delta_{Earth}$)	-5.3×10^{-6}	$+5.3\times10^{-6}$
Corrected value	3.8424583(26)	3.8424562(30)
Combined final γ_n/γ_{Hg}	3.8424574(30)	



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

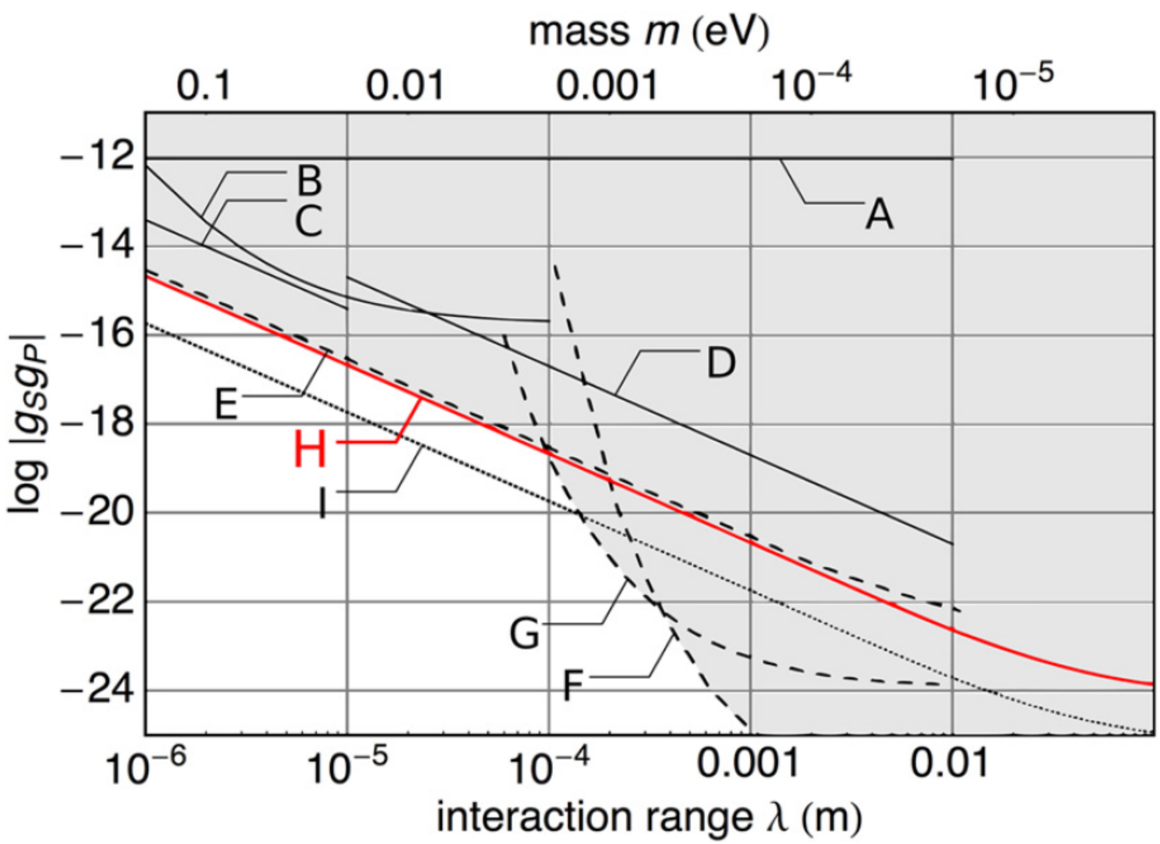
S. Afach[a,b], C. A. Baker[c], G. Ban[d], G. Bison[b], K. Bodek[e], M. Burghoff[f], Z. Chowdhuri[b], M. Daum[b], M. Fertl[a,b,1], B. Franke[a,b,2], P. Geltenbort[g], K. Green[c,h], M. G. D. van der Grinten[c,h], P. G. Harris[h], V. Hélaine[b,d], W. Heil[i], R. Henneck[b], M. Horras[a,b], P. Iaydjiev[c,3], 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]

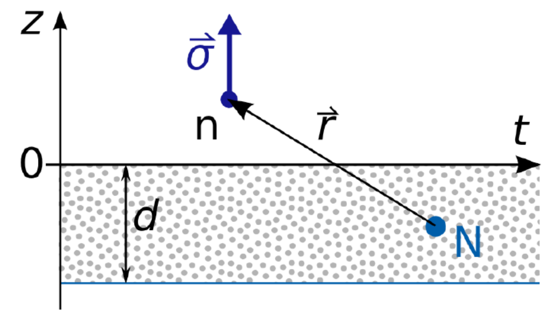
*S. Afach et al., PLB **739**, 128 (2014)*

Exotic Break

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]





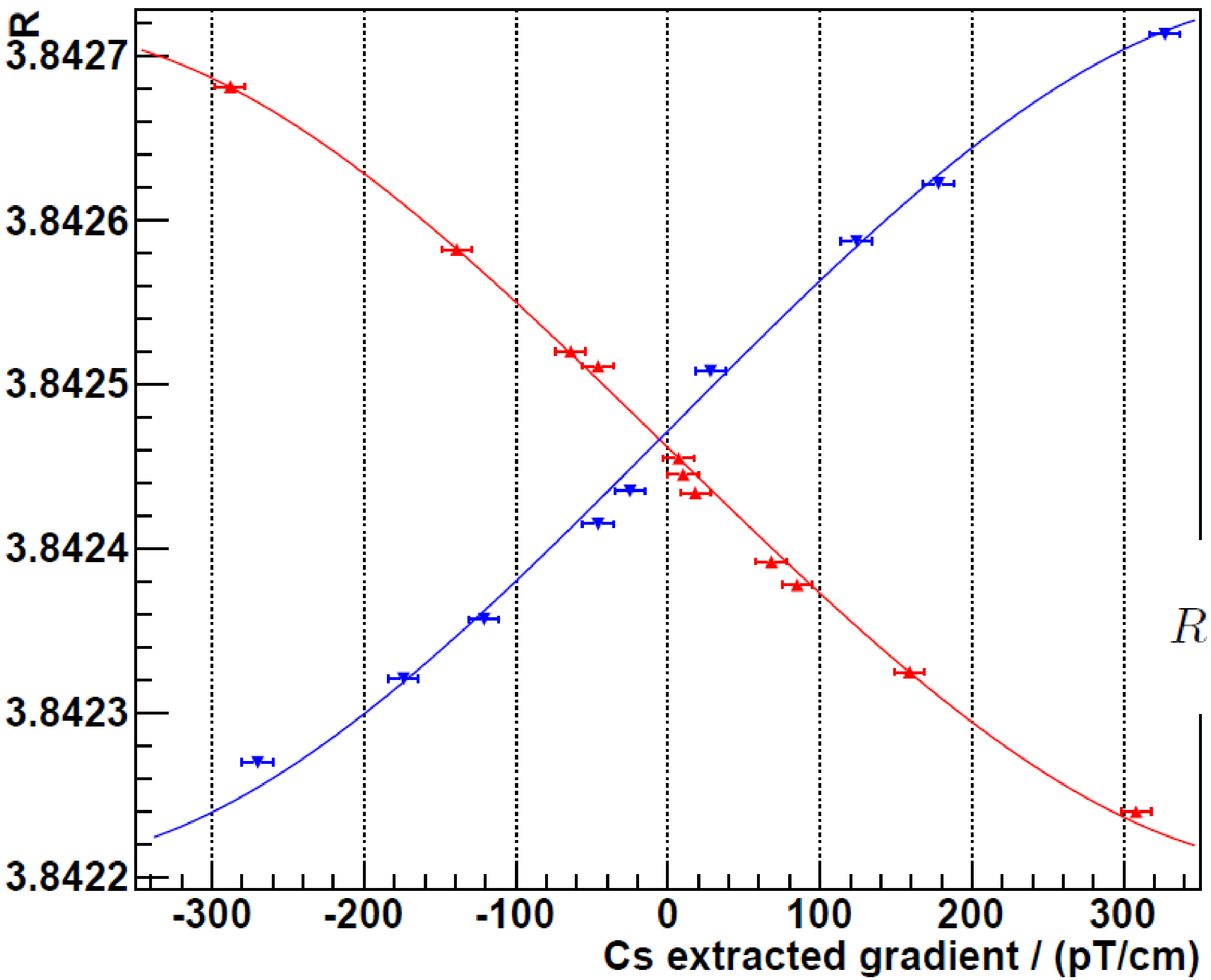
$$R^{\uparrow\downarrow} = \frac{\gamma_n}{\gamma_{Hg}}\left(1 \pm \frac{b}{B_0}\right)$$

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

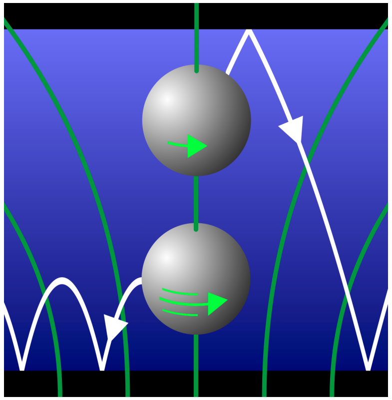
*S. Afach et al., PLB **745**, 58 (2015)*

Some results

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



Transverse component ?
Gravitational ?



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

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

Some results

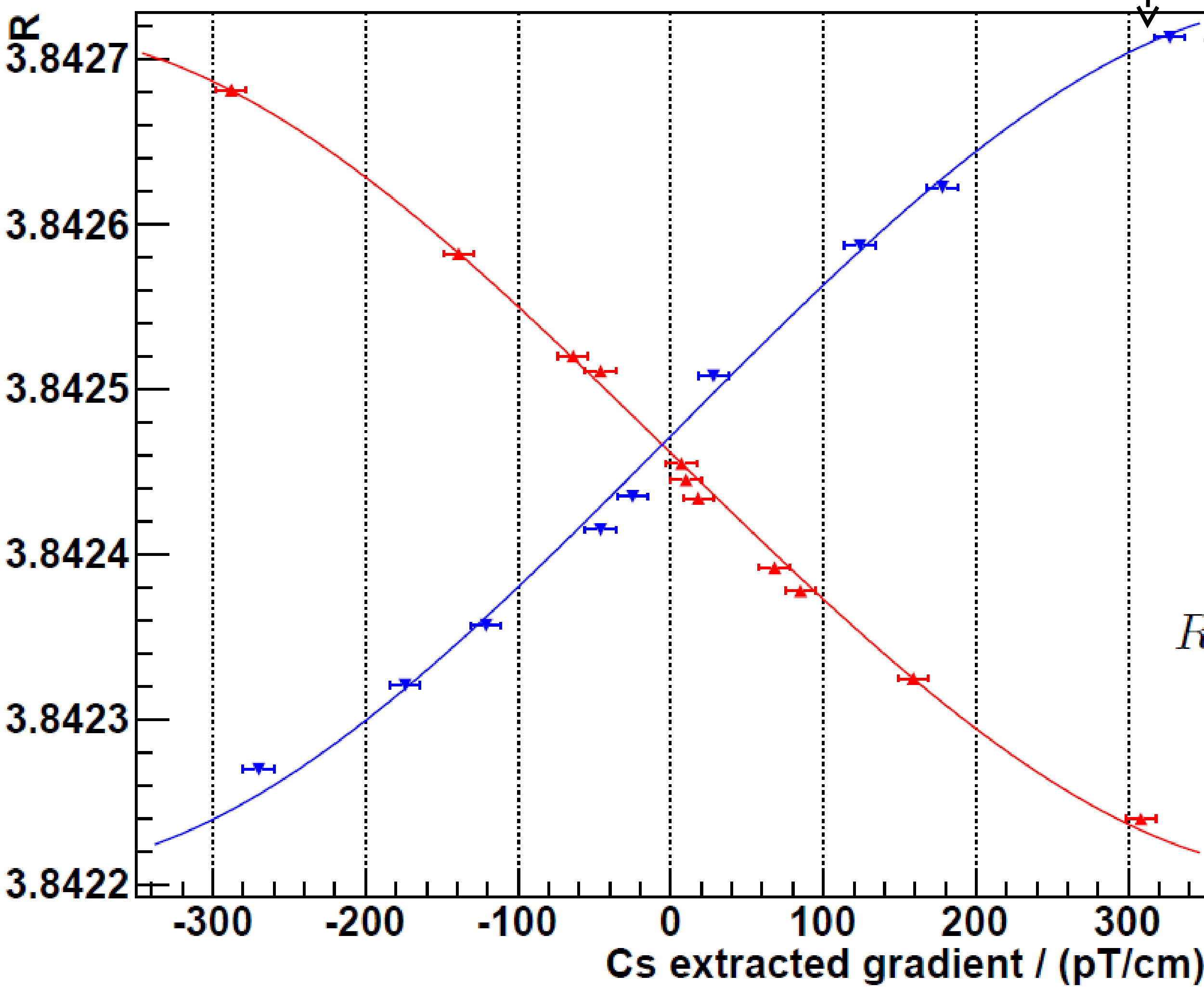
$$R = \frac{f_{\text{n}}}{f_{\text{Hg}}}$$

Gravitational enhanced depolarization and associated frequency shift

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

Gravitational Depolarization of Ultracold Neutrons: Comparison with Data

S. Afach et al., Phys. Rev. D 92, 052008 (2015)



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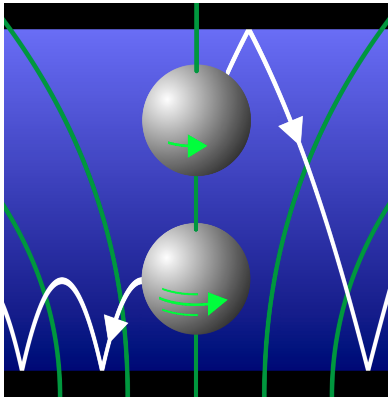

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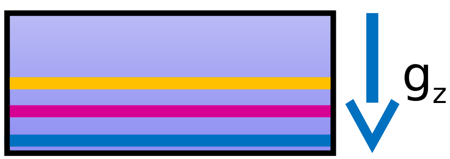
Featured in Physics | Editors' Suggestion

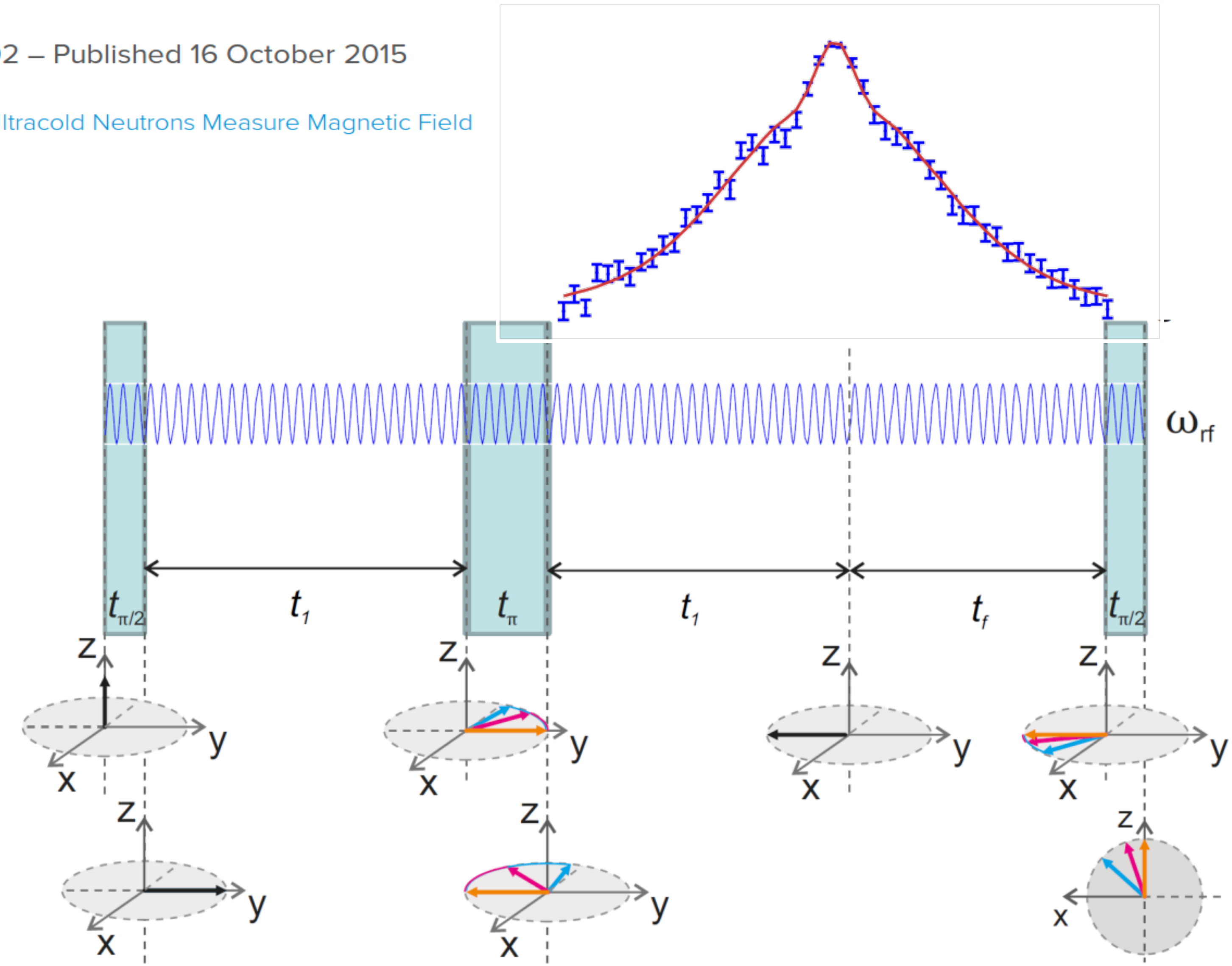
Observation of Gravitationally Induced Vertical Striation of Polarized Ultracold Neutrons by Spin-Echo Spectroscopy

S. Afach *et al.*

Phys. Rev. Lett. **115**, 162502 – Published 16 October 2015

Physics See Focus story: Ultracold Neutrons Measure Magnetic Field





- Impact for the nEDM limit
- Impact for the neutron lifetime

Some results

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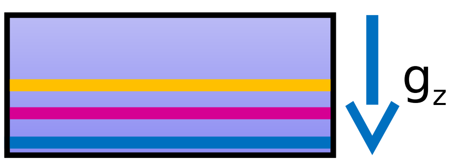
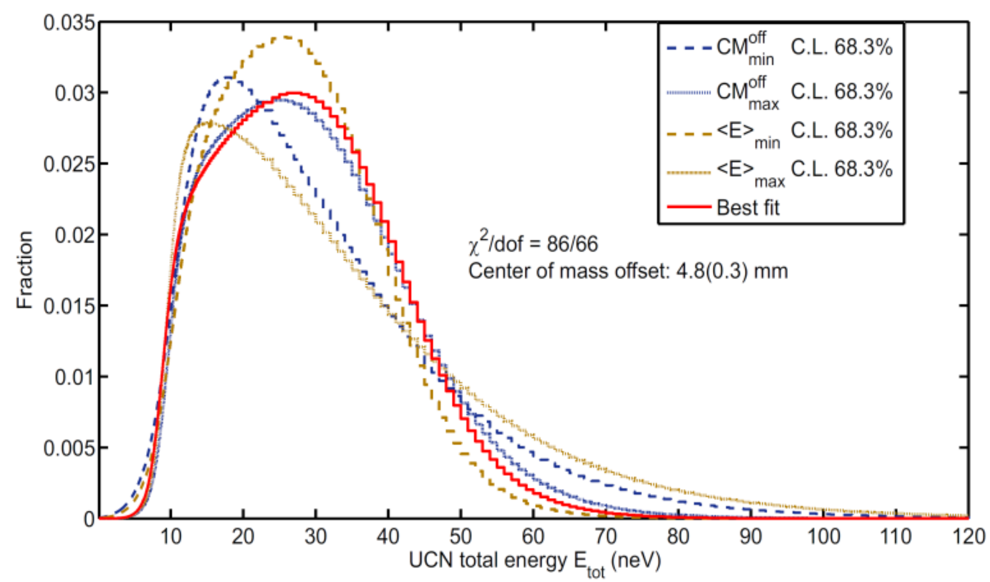




- Impact for the nEDM limit
- Impact for the neutron lifetime

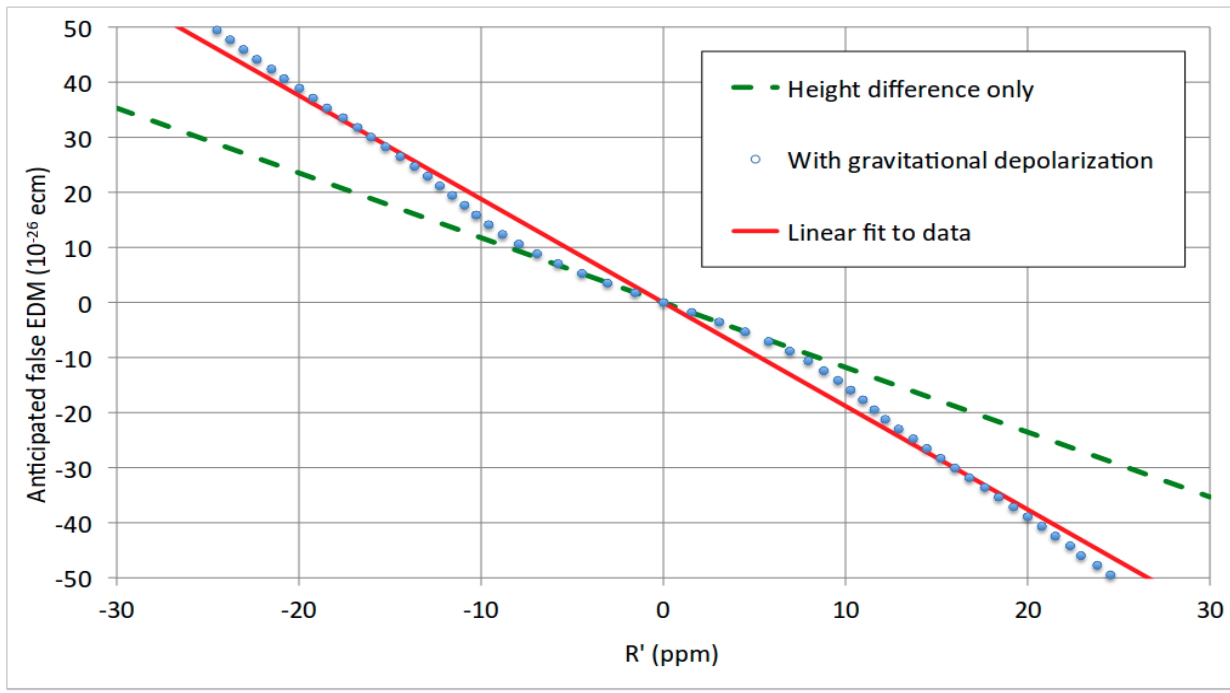
Some results

A Revised Experimental Upper Limit on the Electric Dipole Moment of the Neutron

J.M. Pendlebury[*,1] S. Afach,[2,3,4] N.J. Ayres,[1] C.A. Baker,[5] G. Ban,[6] G. Bison,[2] K. Bodek,[7] M. Burghoff,[8] P. Geltenbort,[9] K. Green,[5] W.C. Griffith,[1] M. van der Grinten,[5] Z.D. Grujić,[10] P.G. Harris [†,1] V. Hélaine [‡,6] P. Iaydjiev[§,5] S.N. Ivanov[¶,5] M. Kasprzak,[10,11] Y. Kermaidic,[12] K. Kirch,[2,3] H.-C. Koch,[10,13] S. Komposch,[2,3] A. Kozela,[14] J. Krempel,[3,2] B. Lauss,[2] T. Lefort,[6] Y. Lemière,[6] D.J.R. May,[1] M. Musgrave,[1] O. Naviliat-Cuncic,[6,**] F.M. Piegsa,[3] G. Pignol,[12] P.N. Prashanth,[11] G. Quéméner,[6] M. Rawlik,[3] D. Rebreyend,[12] J.D. Richardson,[1] D. Ries,[2,3] S. Roccia,[15] D. Rozpedzik,[7] A. Schnabel,[8] P. Schmidt-Wellenburg,[2] N. Severijns,[11] D. Shiers,[1] J.A. Thorne,[1] A. Weis,[10] O.J. Winston,[1] E. Wursten,[11] J. Zejma,[7] and G. Zsigmond[2]

$$|d_{\mathrm{n}}| < 3.0 \times 10^{-26}\ e\,\mathrm{cm}\ (90\%\ \mathrm{CL})$$

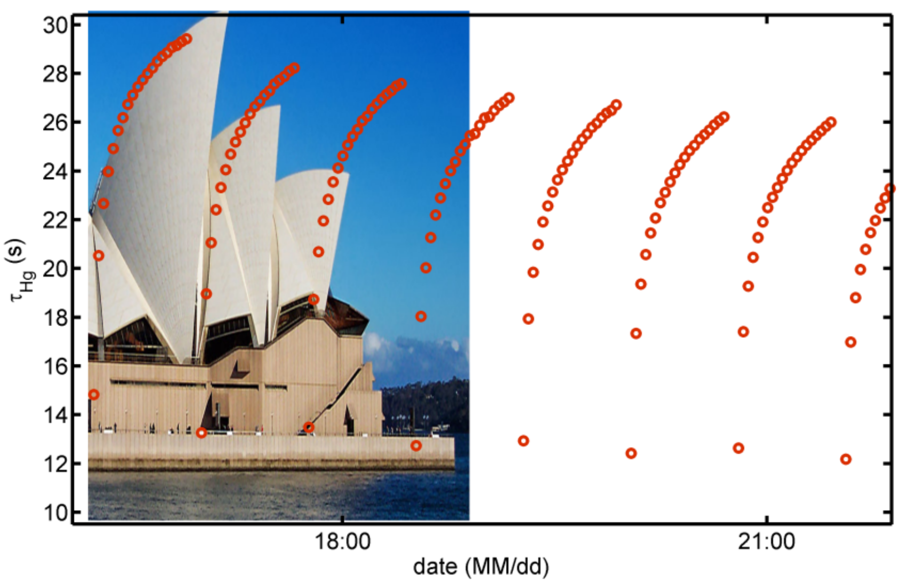
Analysis stage	**EDM**	σ
Crossing point $d_\times$	-0.59	1.53
Gradient-corrected d_0	-0.92	1.68
Dipole-corrected d_{fec}	-0.21	1.79
Final result d_n	**-0.21**	**1.82**



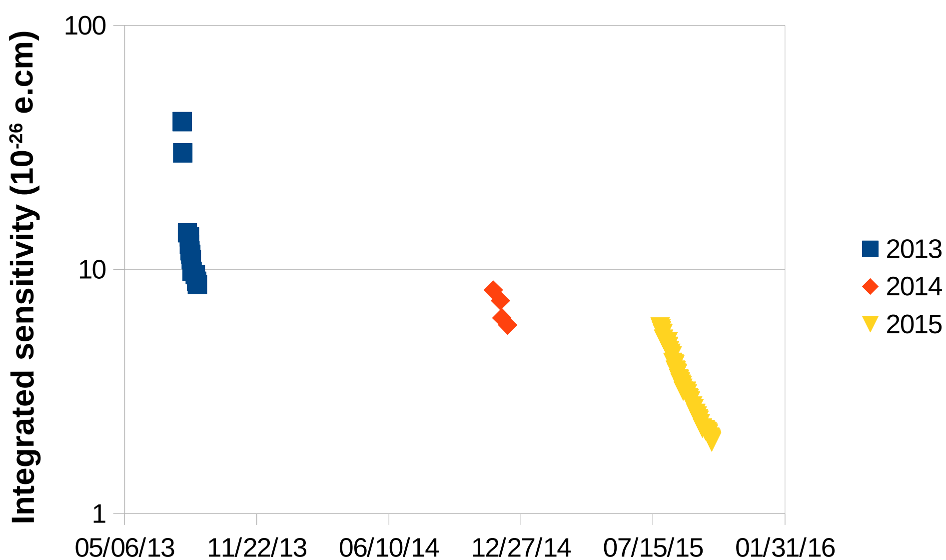
Final result to appear in Phys. Rev. D

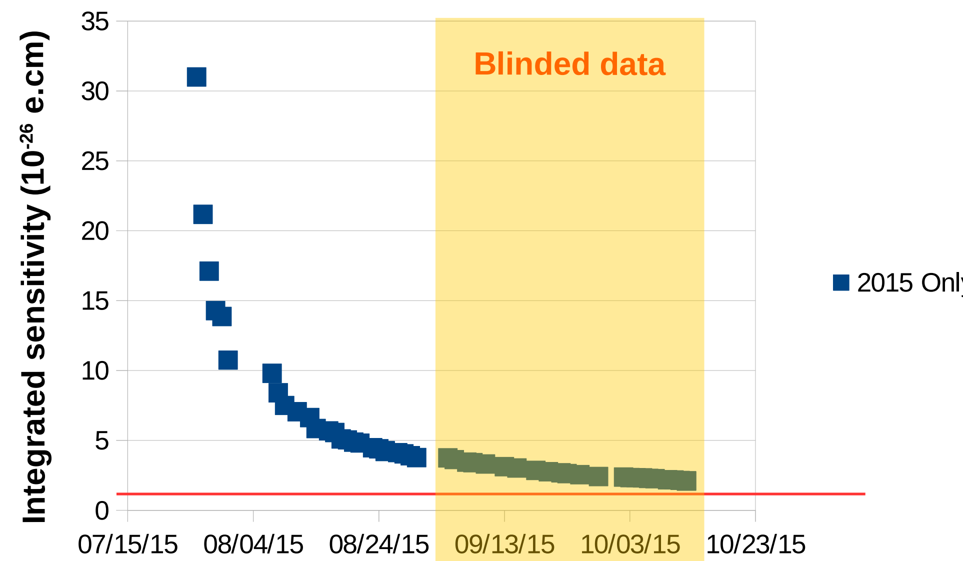
nEDM@PSI

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



	PSI 13	PSI 14		PSI 15
	avg	best	avg	good
E-field (kV/cm)	10.3	10	10	11
Neutrons	6 500	7 500	4 400	10 000
T_{free}	180	220	220	180
T_{duty}	340	340	340	340
A	0.57	0.65	0.6	0.8
Sens. (10^{-26} e.cm/day)	2.8	2.0	2.9	1.3

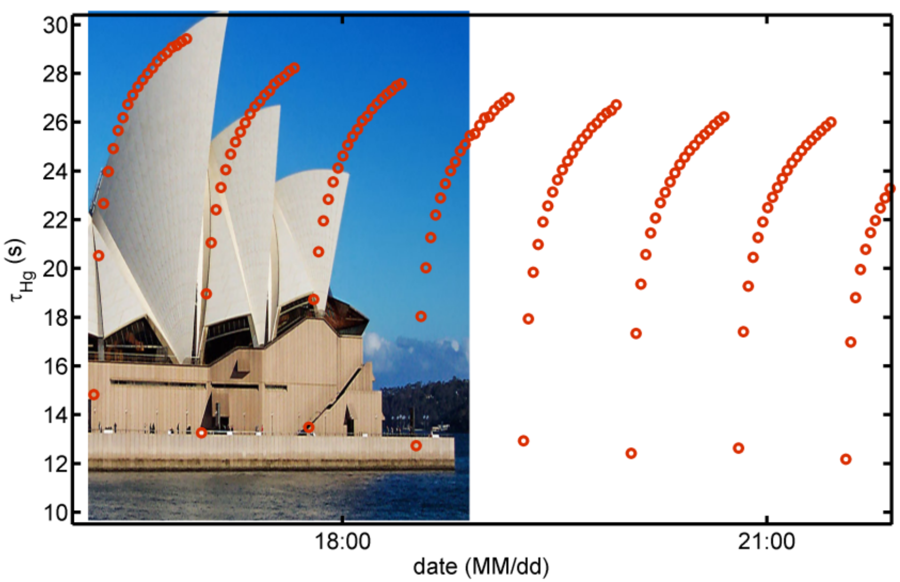




nEDM@PSI

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

New limit in 2016 ?



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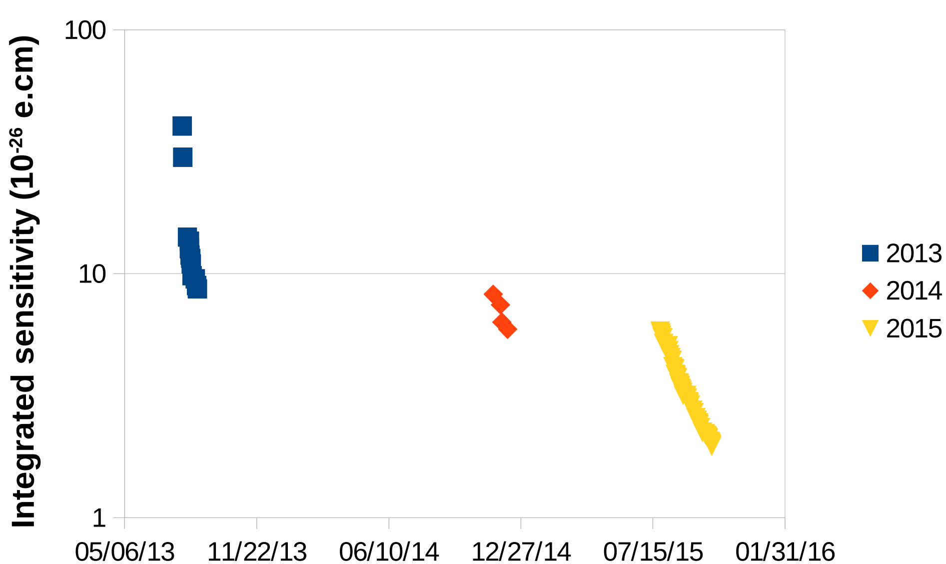
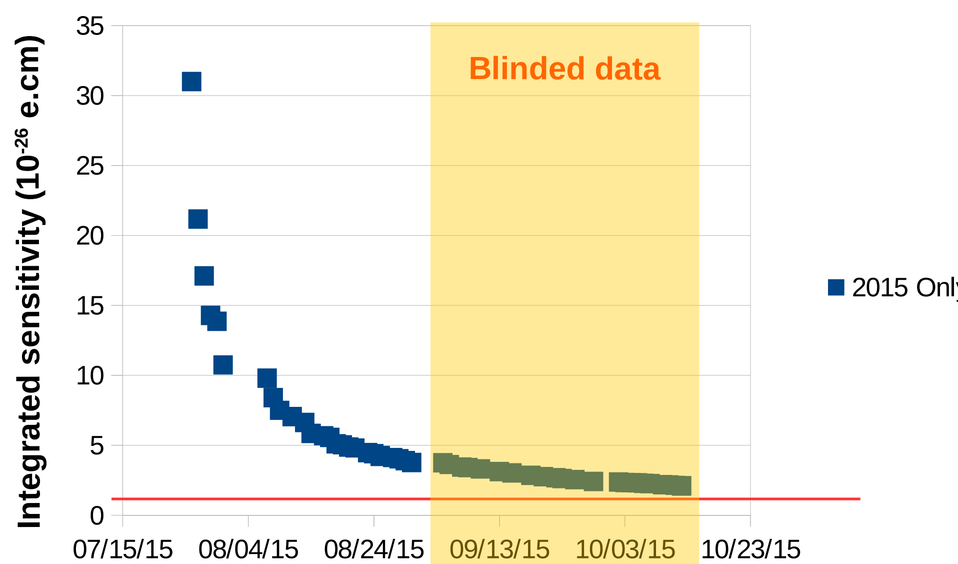
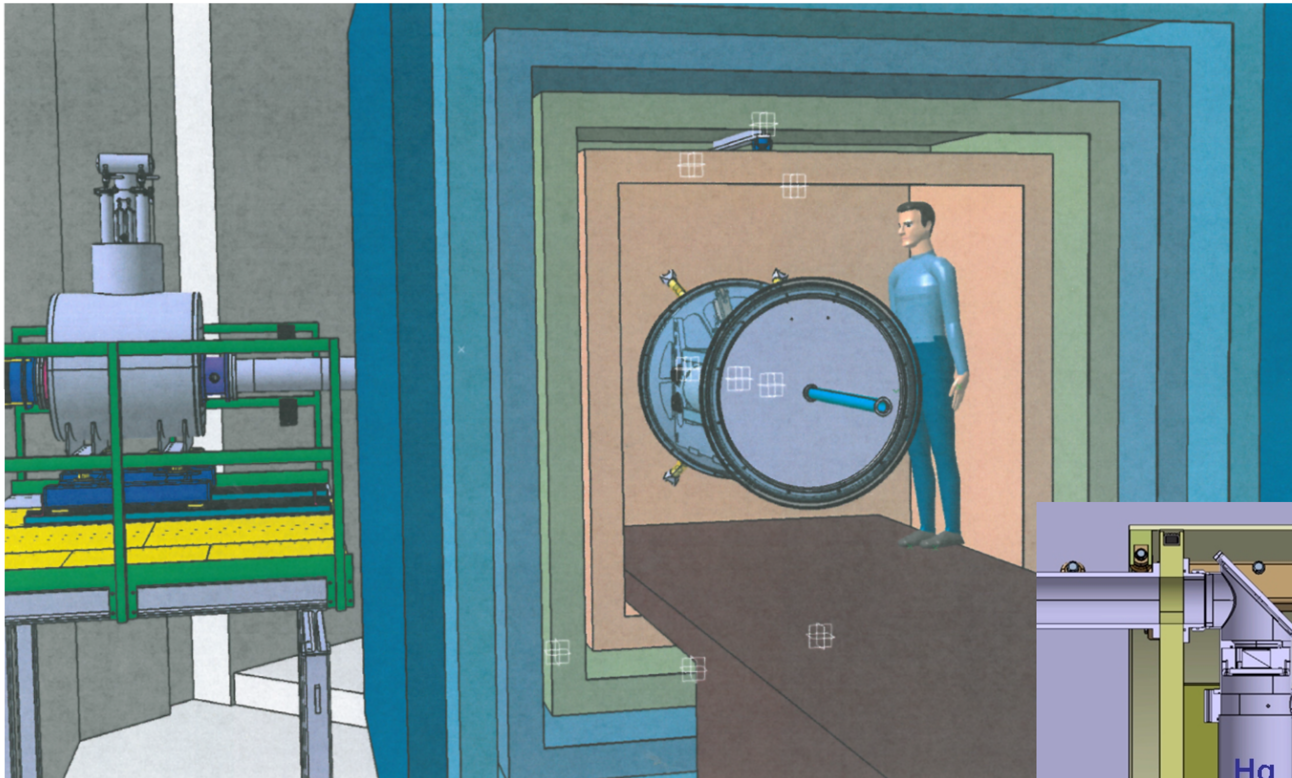


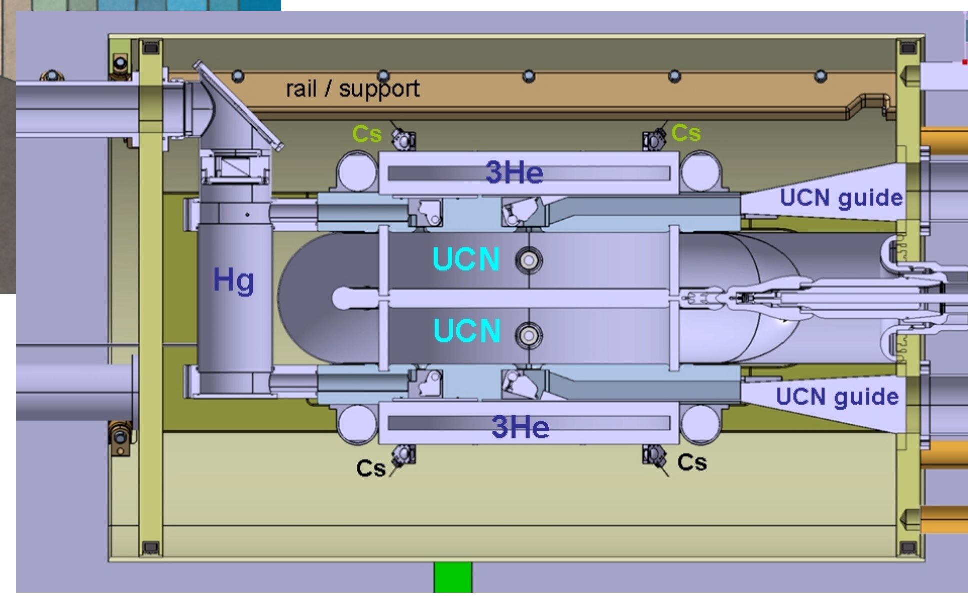


Towards n2EDM



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

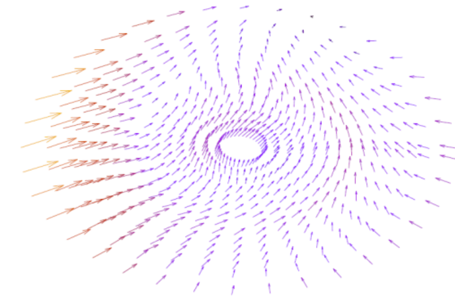
2.10^{-27} e.cm / 4 years



- **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

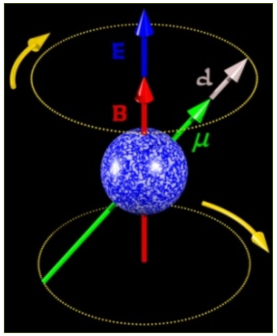
Summary

☆ 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/ALPs

☆ nEDM



- We are taking data with a high sensitivity
- We expect with 300 data-days until 2016 :

  statistical sensitivity of $\sigma * 10^{-26}$ *e*.cm
- n2EDM in R&D phase towards 2.10^{-27} e.cm

Thanks

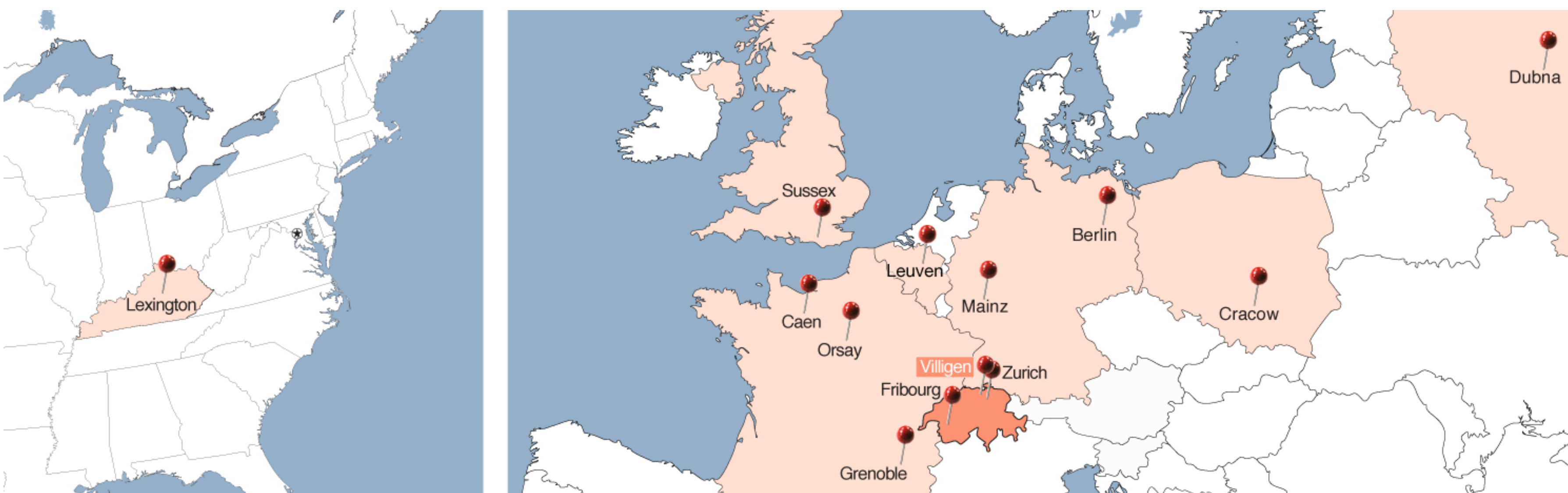
Merci

The nEDM@PSI collaboration

2007

2014

A growing team … getting oversea



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

The EDM landscape

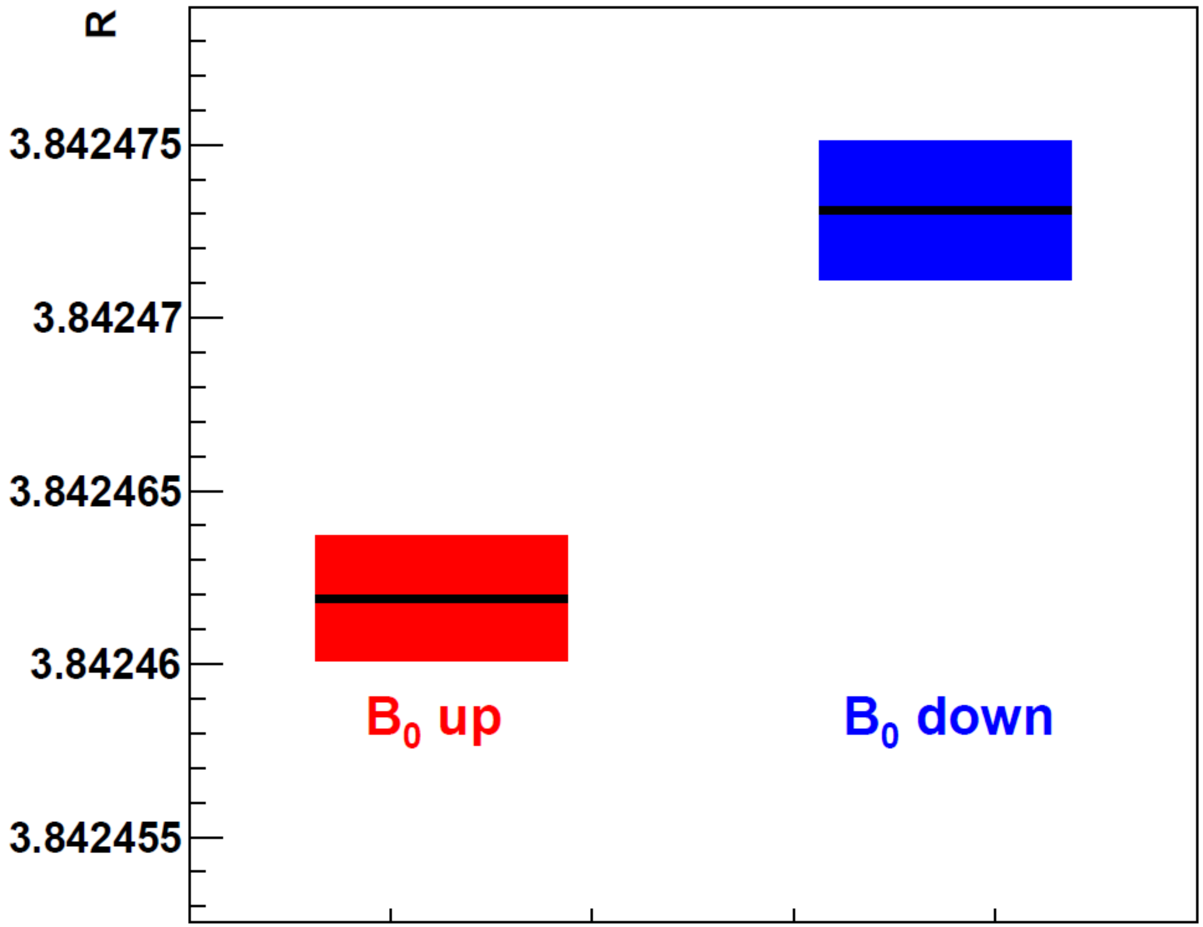
Adrian SIGNER

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

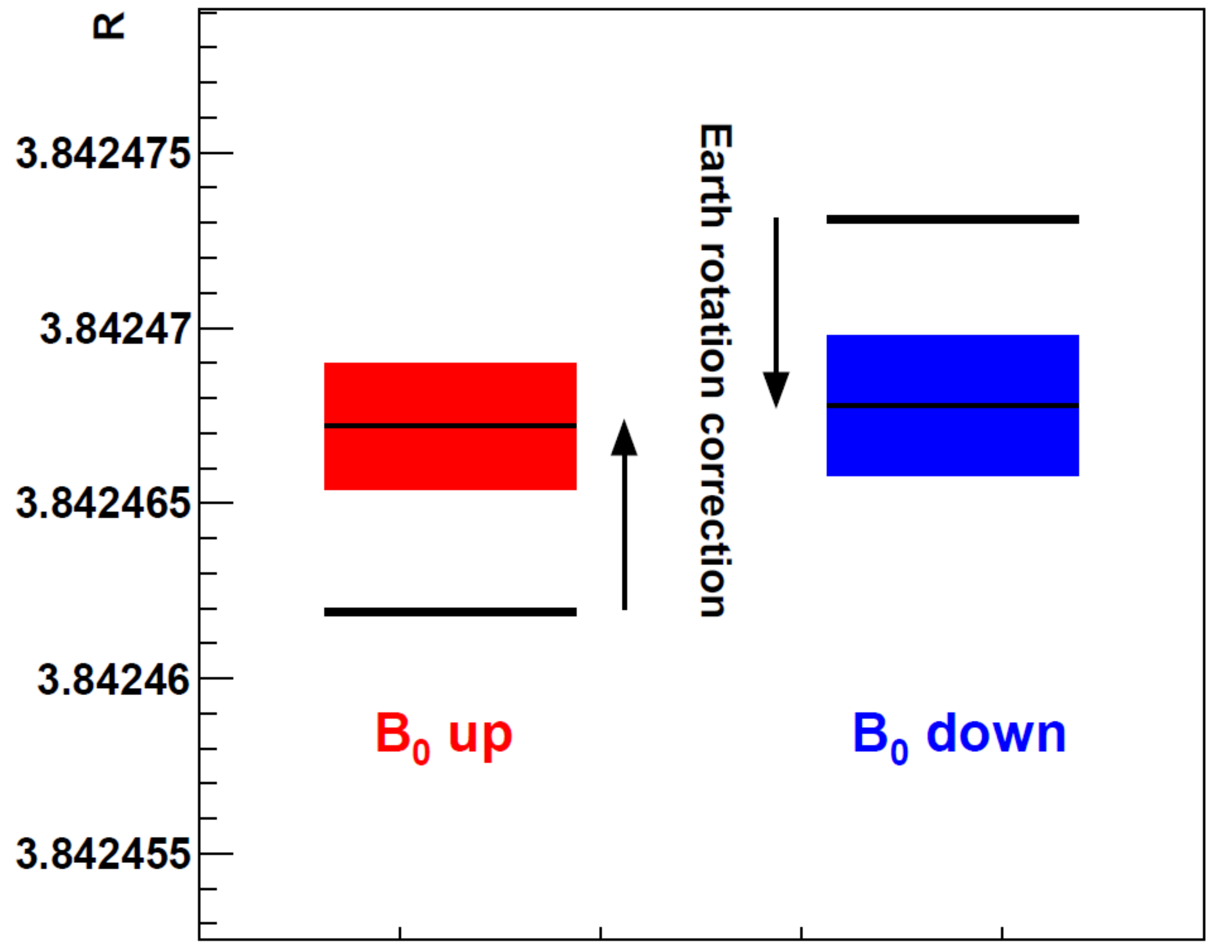
Some results



Some results

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

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



$$\delta R_{\mathrm{Earth}} = \mp \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} \left(\frac{f_{\mathrm{Earth}}}{f_n} + \frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}} \right) \sin(\lambda)$$

$$= \mp 5.3 \times 10^{-6}$$

A non perfect Co-magnetometer

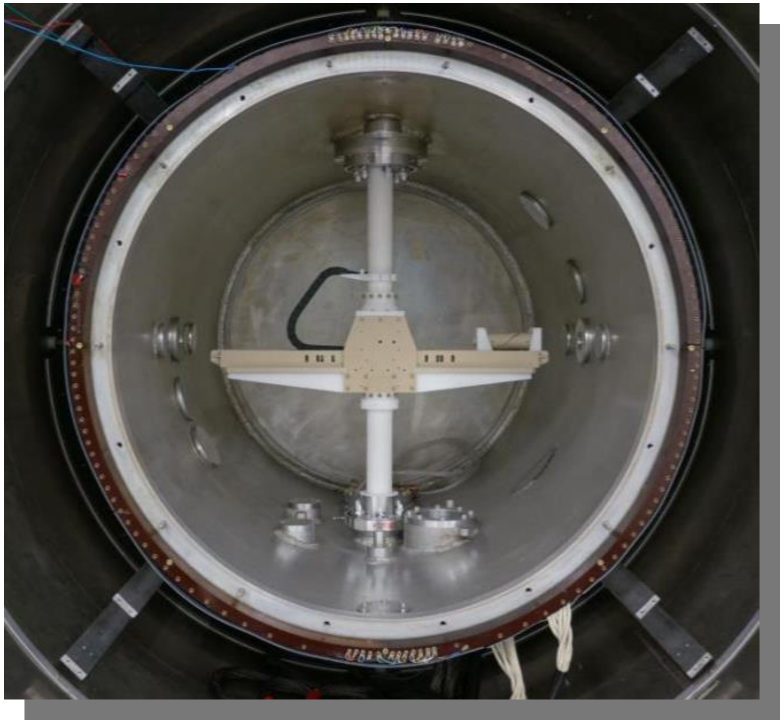
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling

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

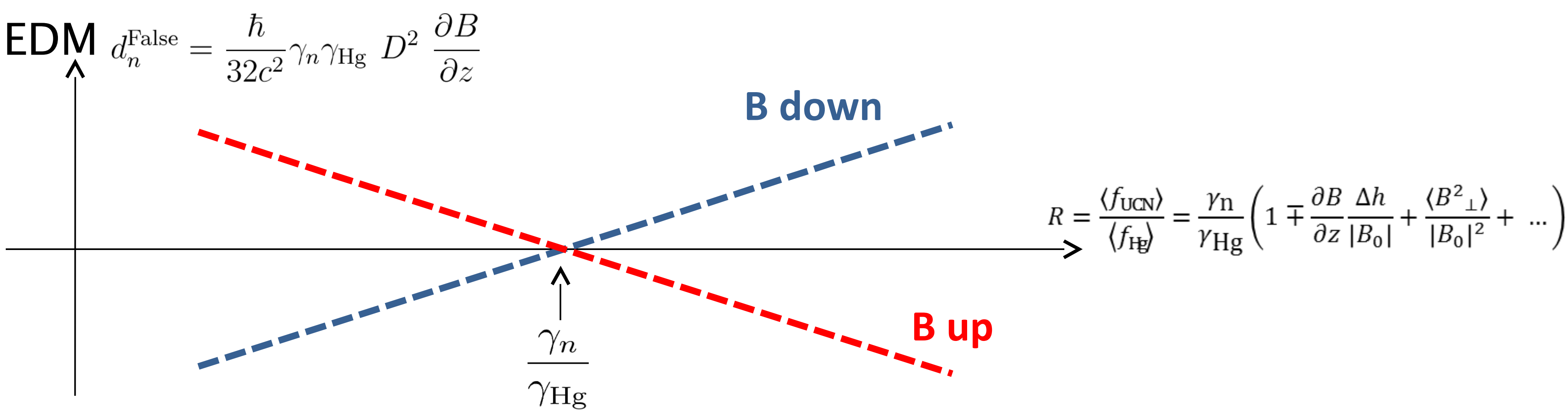
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} + \ \dots \right)$$

Δh =2,7 mm

A nEDM apparatus

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)



In the case of an inhomogeneous B-field

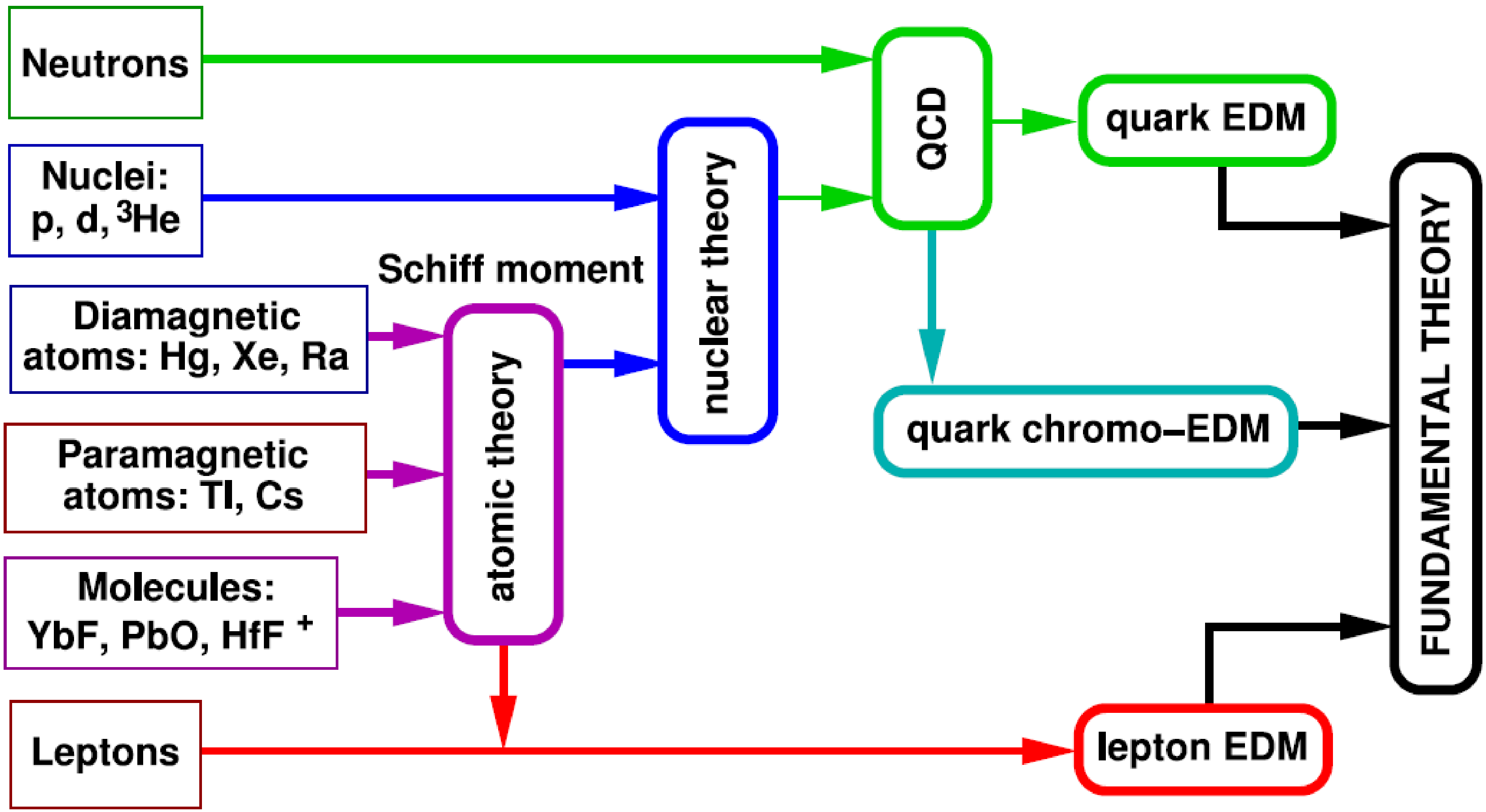
$$d_n^{\mathrm{False}} = -\frac{\hbar}{2c^2}\gamma_n\gamma_{\mathrm{Hg}}\ \langle xB_x + yB_y\rangle$$

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

Indirect systematic effect due to local dipoles

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

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

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)

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

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