Photo by Reidar Hahn, Fermilab with Sandbox Studio, Chicago

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir
université PARIS-SACLAY
CSNSM

Electric dipole moment experiments

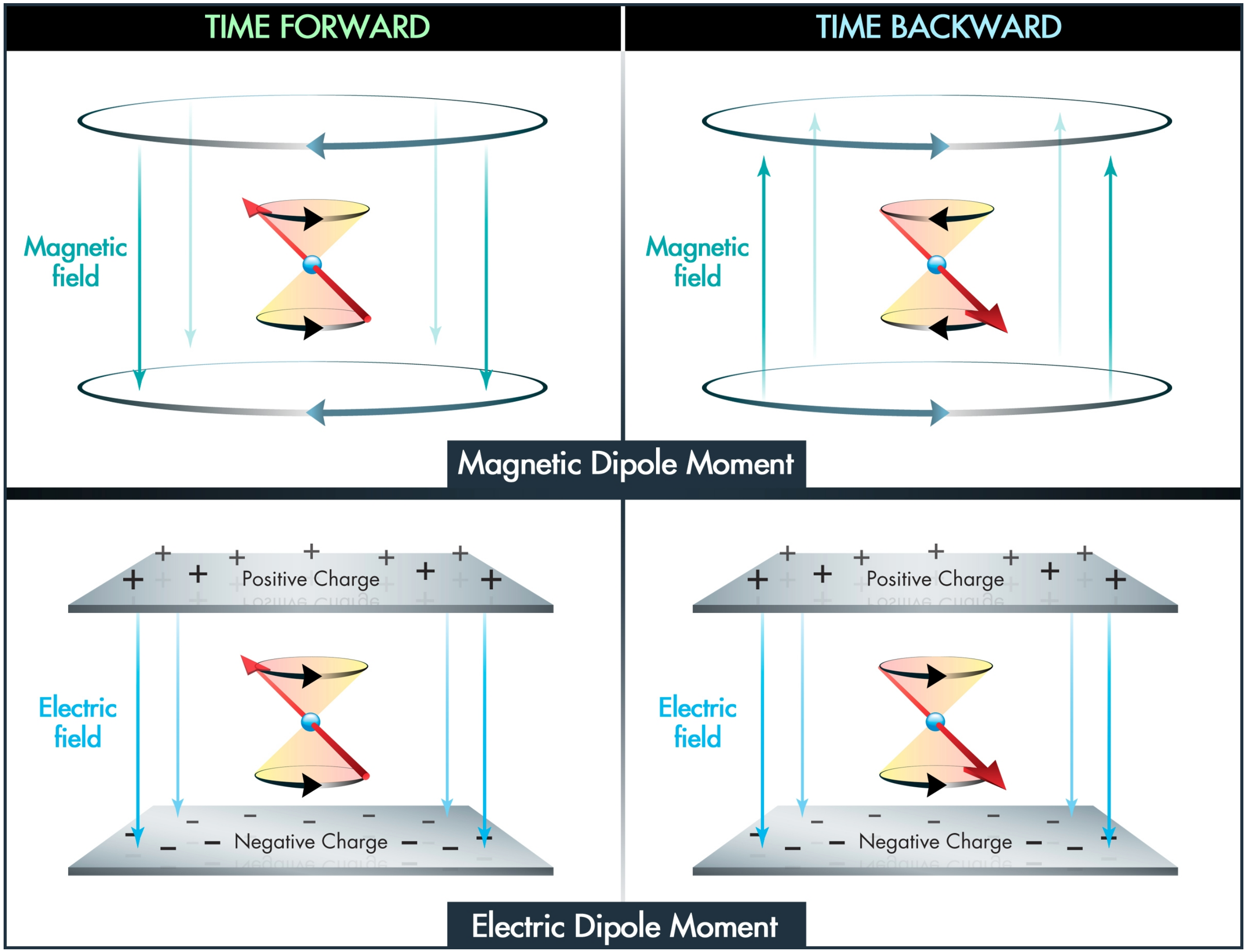
S. Roccia

Setting the stage

The EDM landscape

EDM of radioactive nuclei

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



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 $\rightarrow$ "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
    - gravity, dark energy
- which of these are related to $d = 0$?

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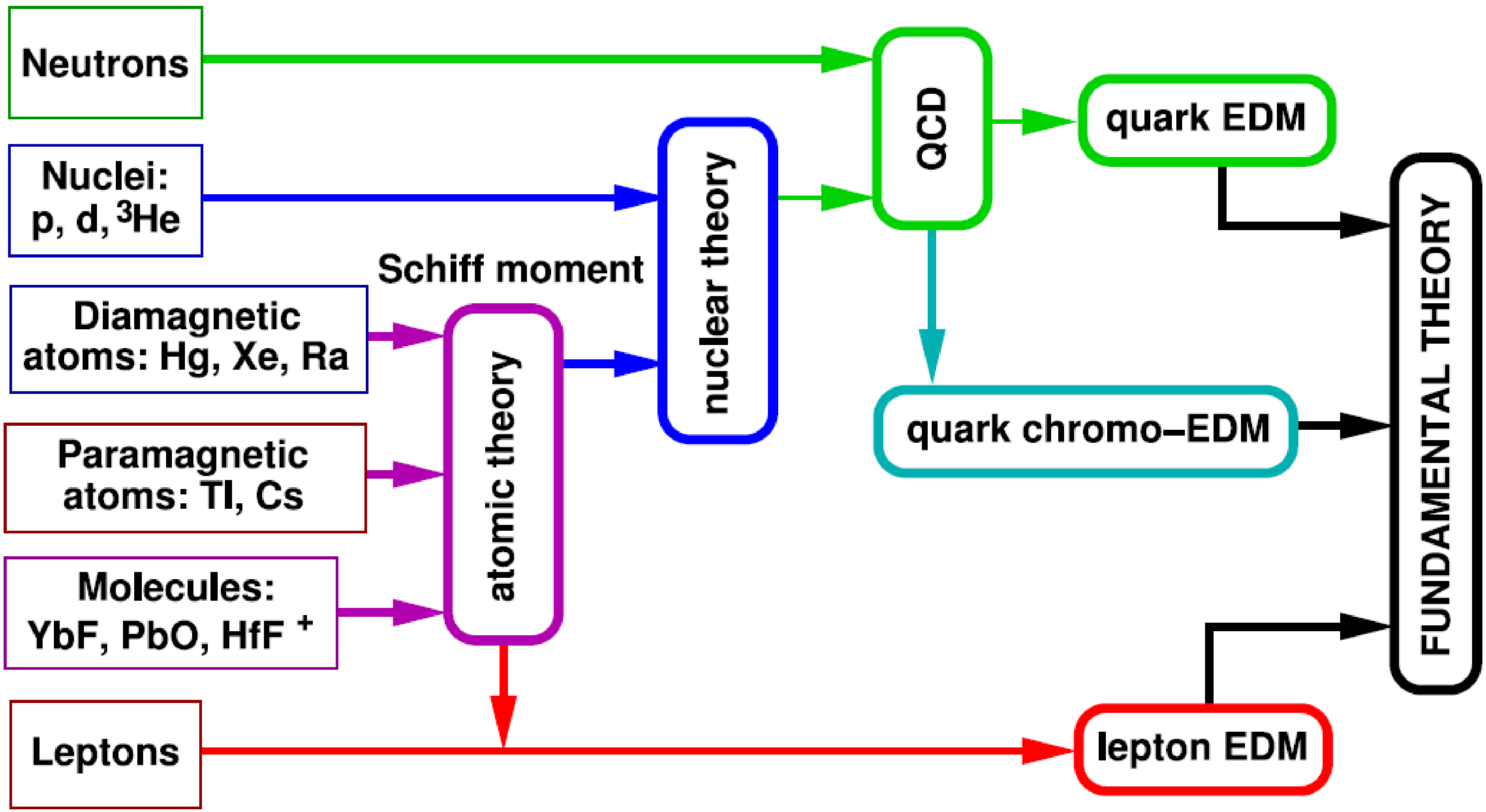
    - dark matter
    - strong CP problem
    - hierarchy problem
    - gravity, dark energy
- which of these are related to $d = 0$?
    - need CP violation
    - CP violation within the SM:
        - weak CP violation δ_{CKM}
        - strong CP violation $\theta_{QCD} < 10^{-10}$
    - CP violation outside SM

The EDM landscape

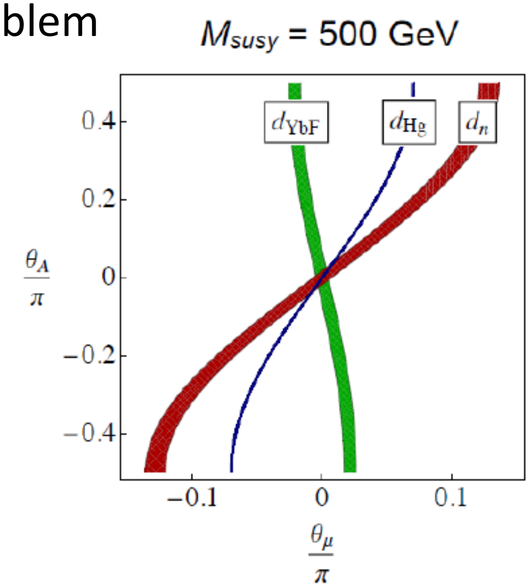


C. R. Physique 13 168 (2012)

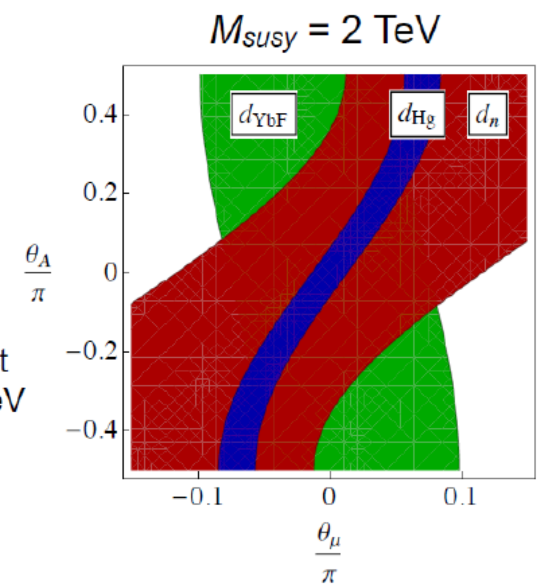
Probing a theory

SUSY, EDMs and the LHC

SUSY CP problem



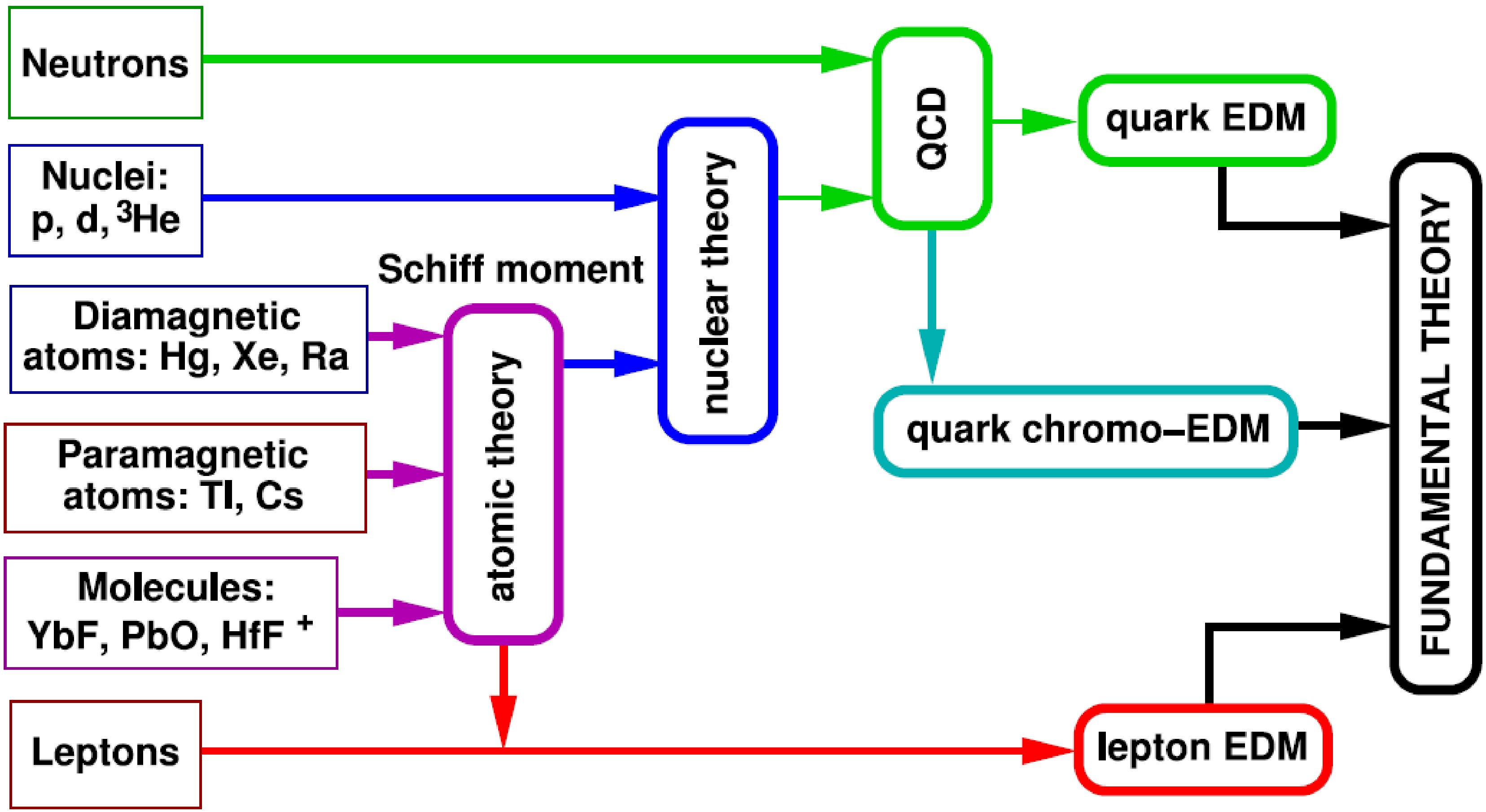
1st gen squarks excluded by direct searches at ~1 TeV



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

The EDM landscape



C. R. Physique 13 168 (2012)

Single source hypothesis

EDMs from a model-independent perspective

- With "single-source" restriction

$$|d_{Hg}| < 7.4 \times 10^{-30} e \cdot \mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e \cdot \mathrm{cm}$	[20]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{Hg}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e \cdot \mathrm{cm}$	[20]
$\bar{g}_0$	$\mathbf{S}_{Hg}/(0.135\ e \cdot \mathrm{fm}^3)$	2.3×10^{-12}	[4]
$\bar{g}_1$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[4]
$\bar{g}_2$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[4]
θ_{QCD}	$\bar{g}_0/0.027$	8.5×10^{-11}	[21]
$(\widetilde{d}_u - \widetilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[22]
C_S	$\mathbf{d}_{Hg}/(5.9 \times 10^{-22}\ e \cdot \mathrm{cm})$	1.3×10^{-8}	[19]
C_P	$\mathbf{d}_{Hg}/(6.0 \times 10^{-23}\ e \cdot \mathrm{cm})$	1.2×10^{-7}	[19]
C_T	$\mathbf{d}_{Hg}/(4.89 \times 10^{-20}\ e \cdot \mathrm{cm})$	1.5×10^{-10}	see text

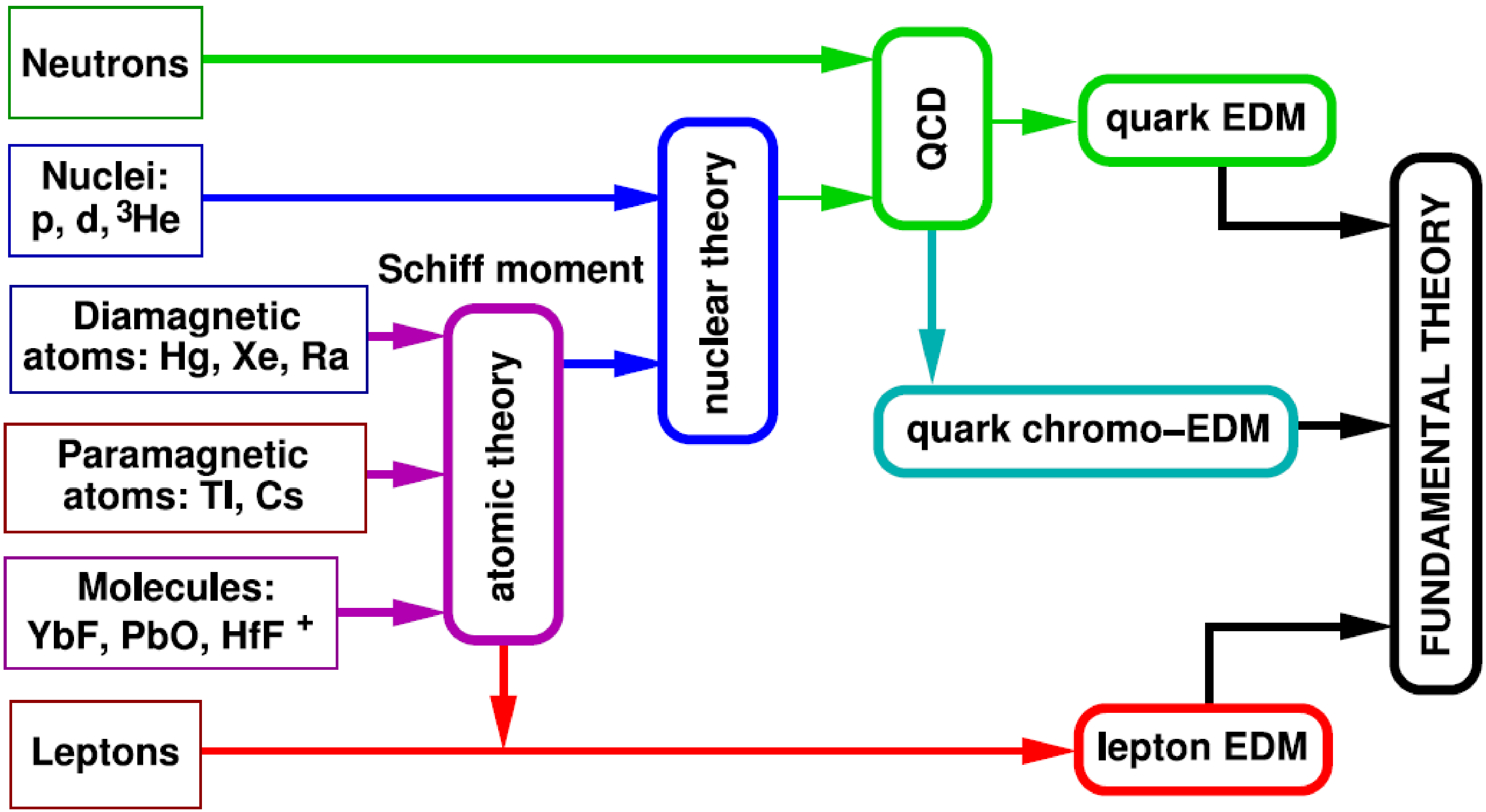
TABLE IV. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM.

Reduced Limit on the Permanent Electric Dipole Moment of 199Hg
B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel
Arxiv

- Without "single-source" restriction

Electric Dipole Moments: A Global Analysis
By Timothy Chupp and Michael Ramsey-Musolf

The EDM landscape



C. R. Physique 13 168 (2012)

A global analysis ?

Electric Dipole Moments: A Global Analysis
By Timothy Chupp and Michael Ramsey-Musolf

EDMs from a model-independent perspective that does not impose the “single-source” restriction

Parameter (units)	95% limit	
d_e (e-cm)	5.4×10^{-27}	e EDM
C_S	4.5×10^{-7}	T&P-odd Pseudoscalar electron-nucleon interaction
C_T	2×10^{-6}	T&P-odd Tensor electron-nucleon interaction
$\bar{d}_n$ (e-cm)	12×10^{-23}	“short distance” contribution to the neutron EDM
$\bar{g}_\pi^{(0)}$	8×10^{-9}	T-odd & P-odd Isoscalar pion-nucleon coupling
$\bar{g}_\pi^{(1)}$	1×10^{-9}	T-odd & P-odd Isovector pion-nucleon coupling

95 % confidence level bounds on the six parameters characterizing the EDMs of the neutron, neutral atoms, and molecules

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EDMs from a model-independent perspective that does not impose the “single-source” restriction

Parameter (units)	95% limit	
d_e (e-cm)	5.4×10^{-27}	Paramagnetic atoms
C_S	4.5×10^{-7}	Paramagnetic atoms
C_T	2×10^{-6}	Diamagnetic atoms
$\bar{d}_n$ (e-cm)	12×10^{-23}	Neutron
$\bar{g}_\pi^{(0)}$	8×10^{-9}	Neutron and Diamagnetic atoms
$\bar{g}_\pi^{(1)}$	1×10^{-9}	Diamagnetic atoms

95 % confidence level bounds on the six parameters characterizing the EDMs of the neutron, neutral atoms, and molecules

Limited by nuclear theory uncertainty (from 199Hg)

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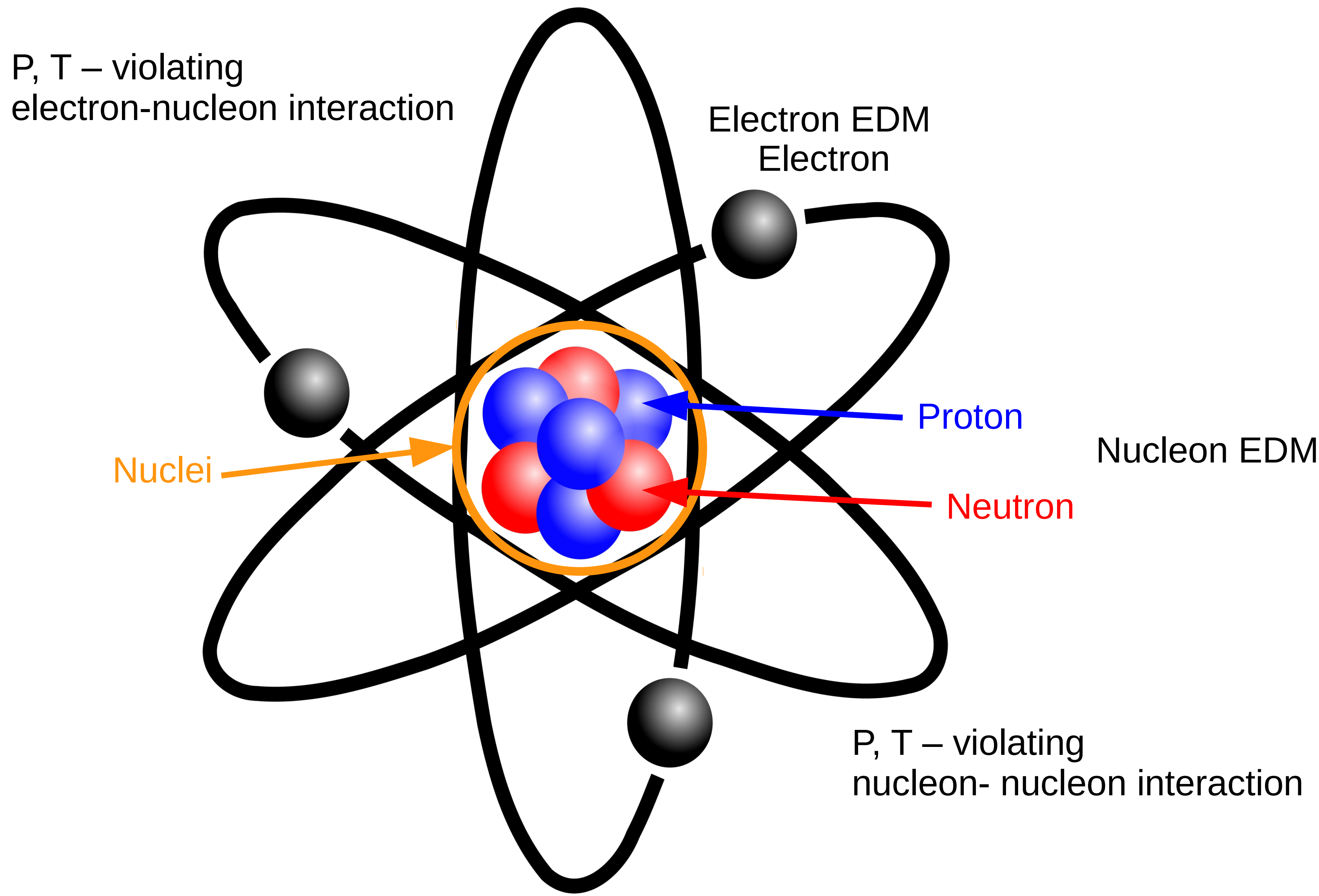
EDMs from a model-independent perspective that does not impose the "single-source" restriction

Parameter (units)	95% limit	
d_e (e-cm)	5.4×10^{-27}	Francium (10^{-28} e.cm)
C_S	4.5×10^{-7}	Francium
C_T	2×10^{-6}	
$\bar{d}_n$ (e-cm)	12×10^{-23}	
$\bar{g}_\pi^{(0)}$	8×10^{-9}	Neutron, Xenon, Radium
$\bar{g}_\pi^{(1)}$	1×10^{-9}	Neutron, Xenon, Radium

95 % confidence level bounds on the six parameters characterizing the EDMs of the neutron, neutral atoms, and molecules

Limited by nuclear theory uncertainty (from 199Hg)

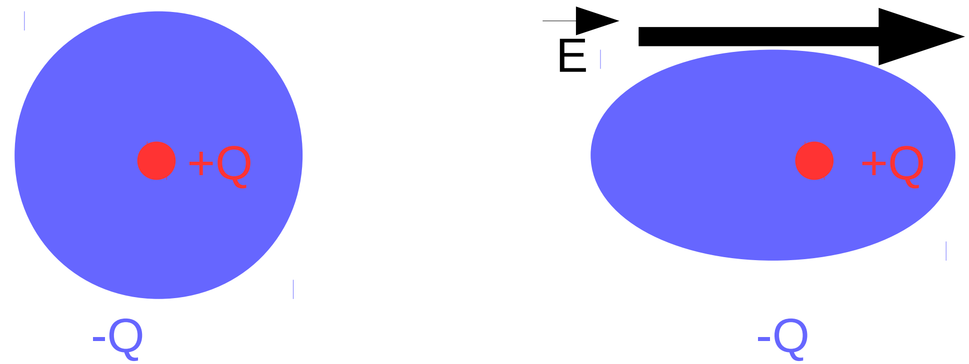
EDM of atoms and molecules



EDM of atoms and molecules

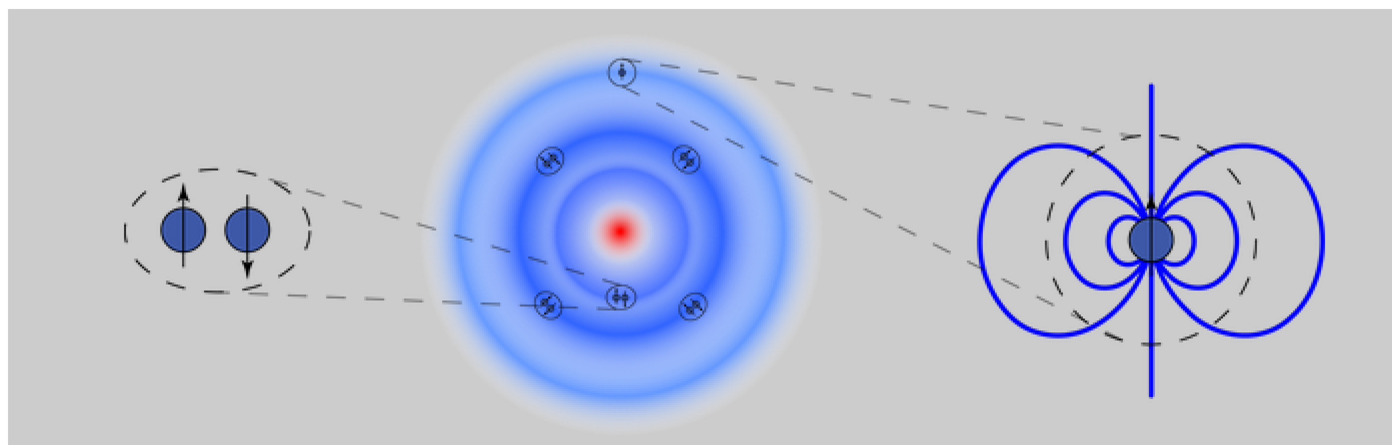
Schiff Theorem

– Neutral atomic system of point particles in Electric field readjusts itself to give zero E field at all charges



BUT relativistic effects and finite size of nucleus can break the symmetry

Atom	*Z*	*R*
Li	3	0.004
Na	11	0.439
K	19	3.588
Rb	37	33.732
Cs	55	154.657
Fr	87	1066.891
Tl	81	-792.665



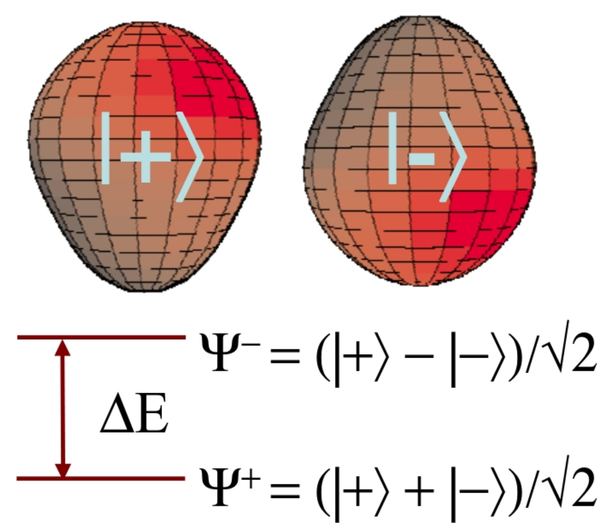
S. Blundell, J. Griffith, J. Sapirstein, Phys. Rev. D (86) 025023 (2012).

Deformed nuclei

–Enhanced signal

Intrinsic Schiff moment

$$S \approx eZR_0 \frac{9}{20\pi\sqrt{35}} \beta_2 \beta_3$$

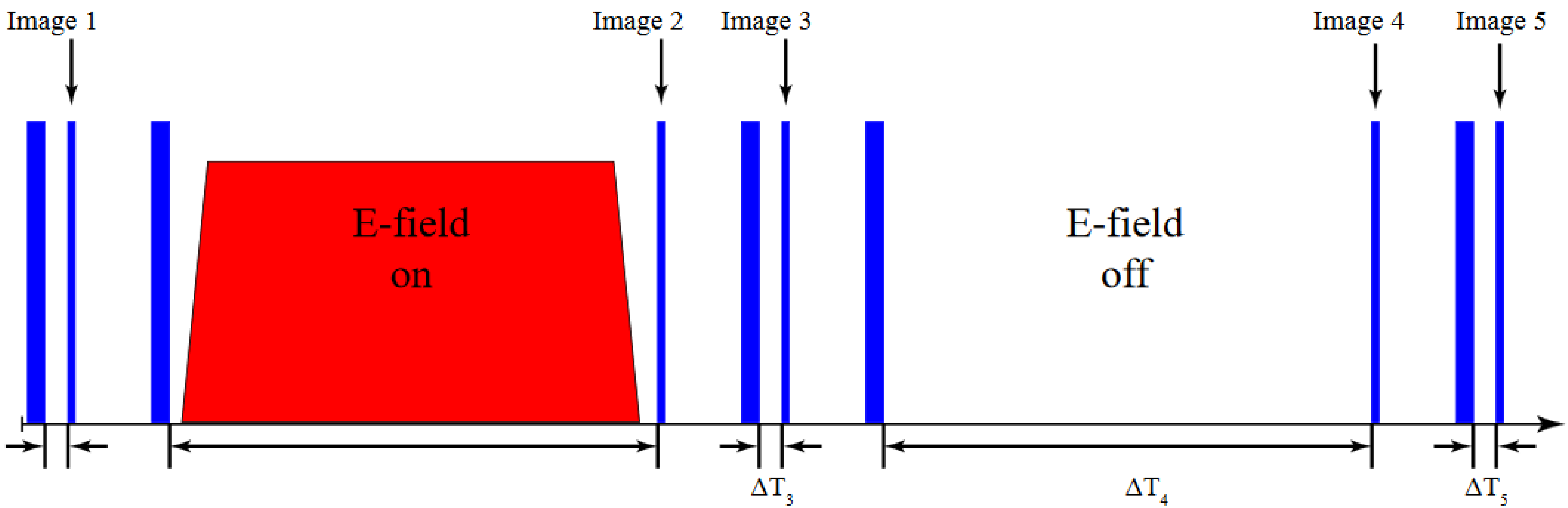


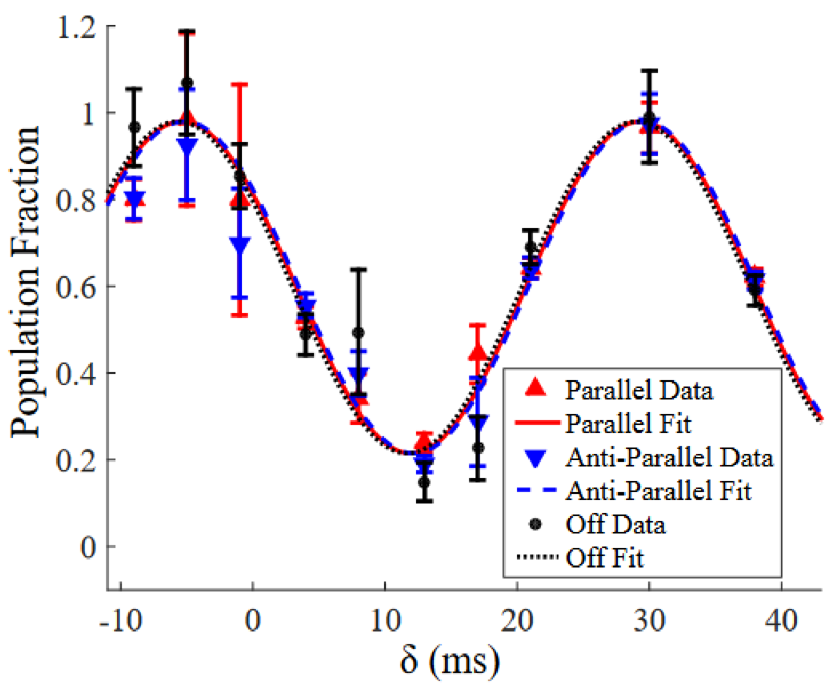
T-P odd interaction → coupling of the 2 states of opposite parity

$$|\alpha| \sim 2\beta_3 A^{-1/3} \eta \, \mathrm{eV}/|E^+ - E^-|$$

V. Spevak et al., Phys. Rev. C, 56, 3, (1997)

Radium





$$\sigma_{EDM} = \frac{\hbar}{2E\sqrt{\tau N T}}$$

E= 65 KV/cm
N=500
Ʈ=20 s

$$\left|d(^{225}\mathrm{Ra})\right| \leq 1.4\times10^{-23}\ e\ \mathrm{cm}$$

Protactinium

	^{223}Ra	^{225}Ra	^{223}Rn	^{221}Fr	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe	^{133}Cs
$\alpha(WS)(10^7\eta)$	1	2	4	0.7	2	3	34			
$\Delta E(WS)$ (keV)	170	47	37	216	75	49	5			
π_p(WS)	0.81	-0.02	0.17	-0.55	-0.34	-0.35	0.01			
$\alpha(Nl)(10^7\eta)$	2	5	2							
$\Delta E(Nl)$ (keV)	171	55	137							
$\Delta E_{\rm expt}$ (keV)	50.2	55.2		234	160.5	40.1	0.22			
$S_{\rm intr}(e\ {\rm fm}^3)$	24	24	15	21	20	28	25			
$S(10^8\eta e\ {\rm fm}^3)$	400	300	1000	43	500	900	1.2×10^4	-1.4	1.75	3
d(at) $(10^{25}\eta e$ cm)	2700	2100	2000	240	2800		**-11000**	5.6	0.47	2.2

$$|\alpha| \sim 2\beta_3 A^{-1/3}\eta\ {\rm eV}/|E^+ - E^-|$$

V. Flambaum, Phys. Rev. A, 77, 2, (2008)

$$S \approx eZR_0 \frac{9}{20\pi\sqrt{35}}\beta_2\beta_3$$

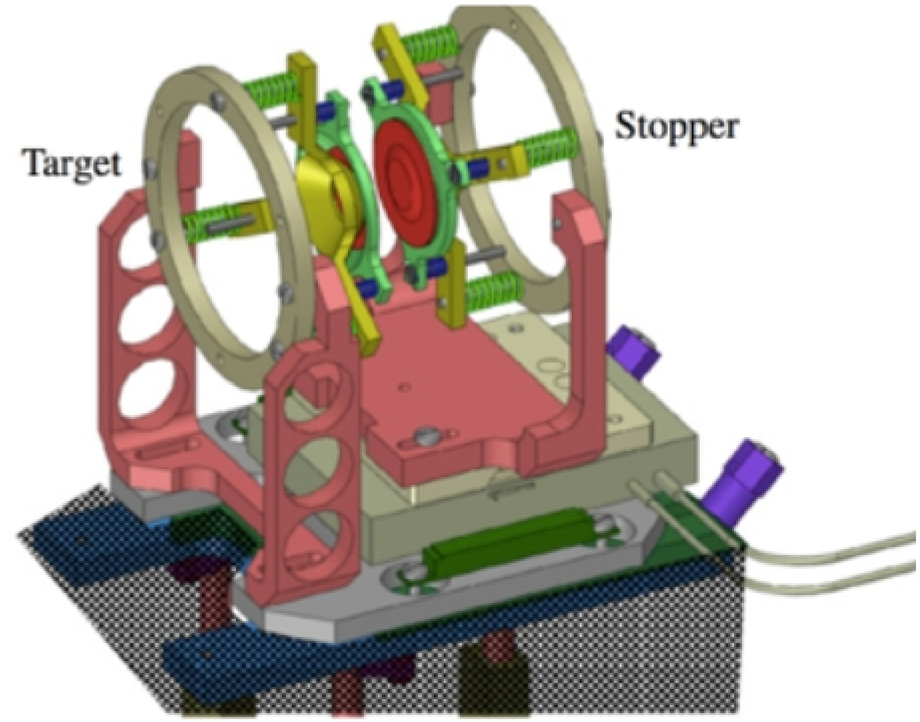
BUT: large uncertainty
on those numbers!

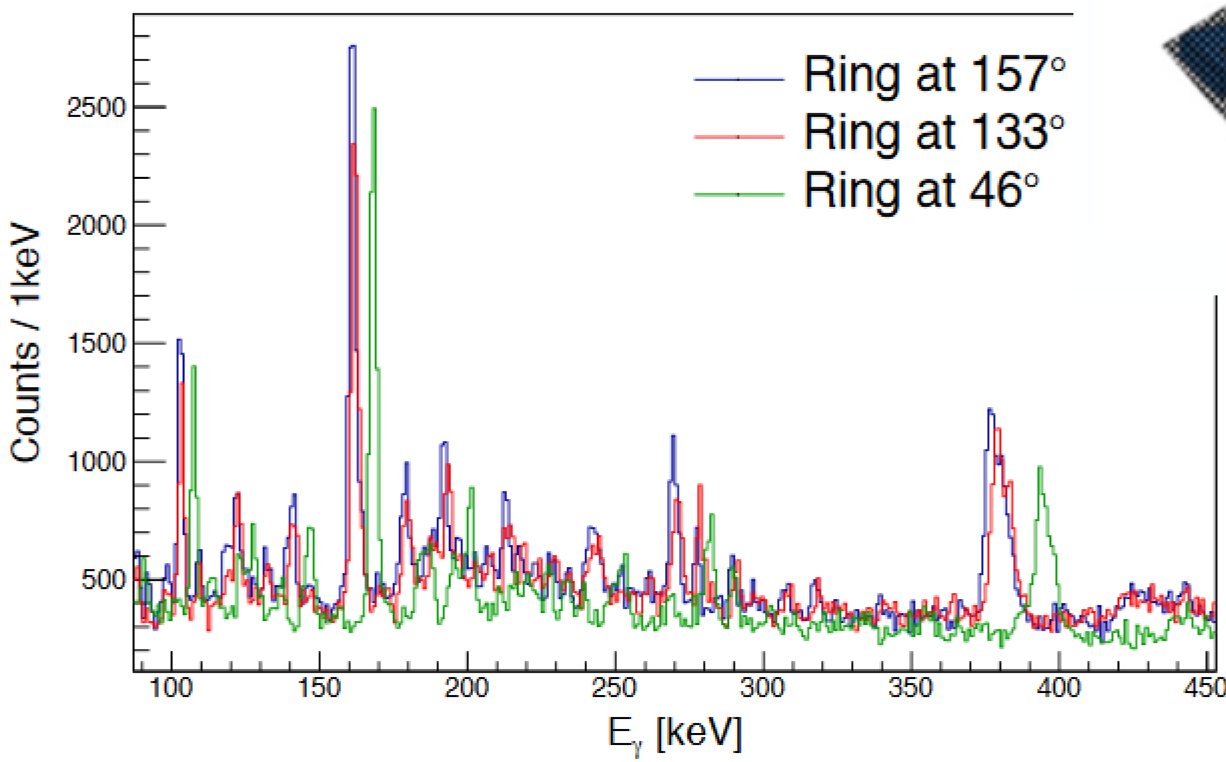
V. Spevak et al., Phys. Rev. C, 56, 3, (1997)

Protactinium

Study of the octupolar deformation in 229Pa

The Orsay Universal Plunger System (**OUPS)** for AGATA campaign at GANIL



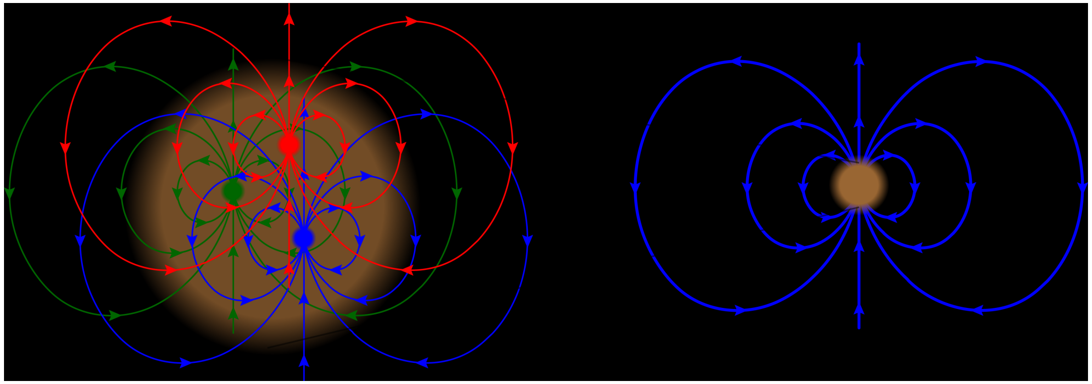


Ratio of Doppler shifted gamma
→ lifetimes of excited states
→ strength of the transition
→ deformation

Summary

☆ EDM landscape

- EDMs are P, T, CP violating probes
- Complementary to accelerator-based results



☆ EDM of radioactive nuclei

- High sensitivity
- Limited by nuclear structure knowledge
- Lot of on-going programs to be supported by associated nuclear structure studies

Thanks

Merci

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EDMs from a model-independent perspective that does not impose the "single-source" restriction

Parameter (units)	95% limit
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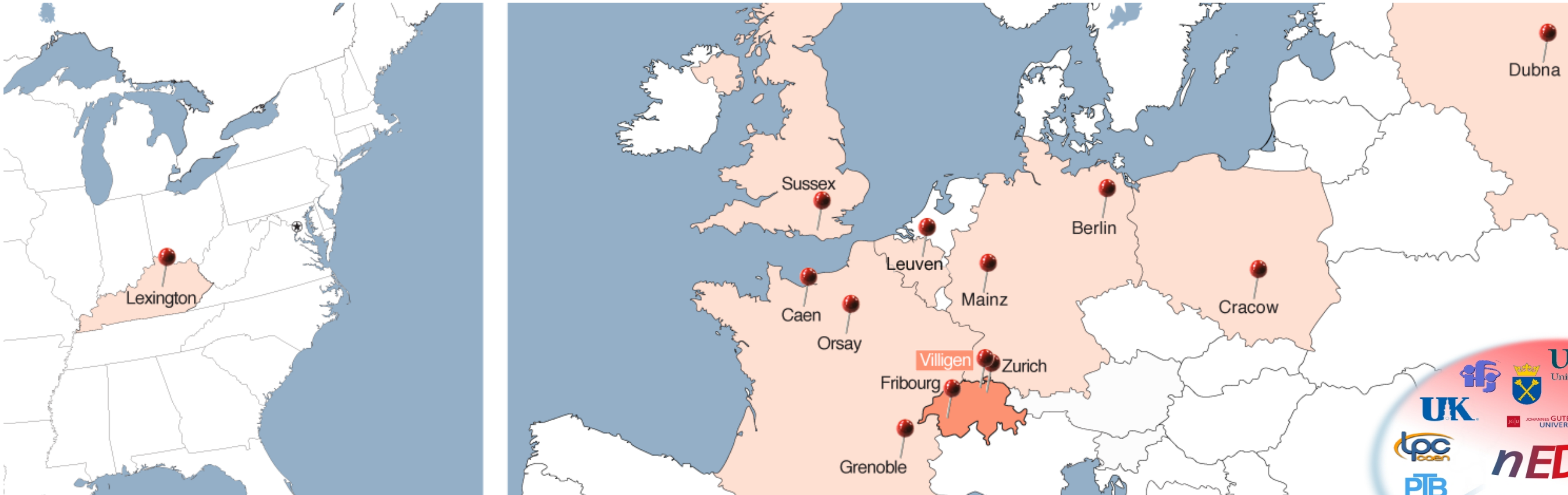
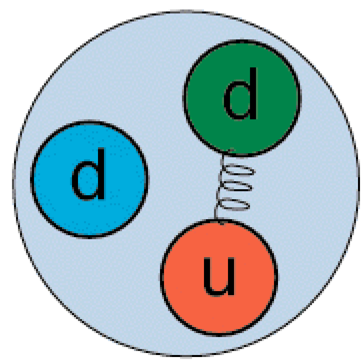
$\bar{g}_\pi^{(0)}$	8×10^{-9}
$\bar{g}_\pi^{(1)}$	1×10^{-9}

95 % confidence level bounds on the six parameters characterizing the EDMs of the neutron, neutral atoms, and molecules

(i) The EDMs of paramagnetic systems are prima
the d e and C S . 2
(0,1)
(ii) Diamagnetic atom EDMs carry the strongest s
and the g ¯π , whereas the neutron EDM depend
(0)
most strongly on d ¯n and g ¯π providing four eff
parameters that are constrained by results from f
experimental systems.
(iii) Inclusion of both d e and C S in the global fit y
bound on each parameter that is an order of
magnitude less stringent than would be obtained
source" assumption.
(1)
(iv) Uncertainties in the nuclear theory preclude e
significant limit on g ¯π from d A (199 Hg), where
(0)
the situation regarding g ¯π is under better theor
Including the TlF and 129 Xe in the global fit
(0)

The nEDM search

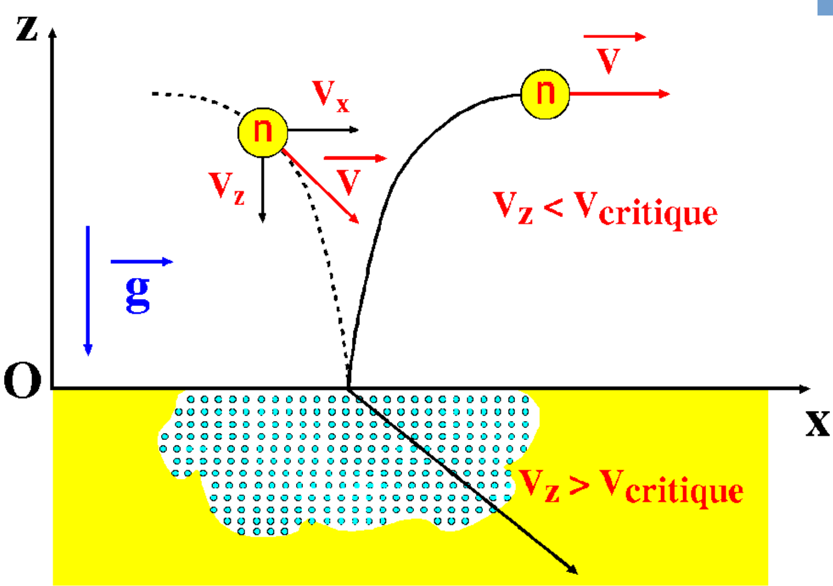




Adrian SIGNER

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.

Neutrons reflected for all incidence angles: UCNs



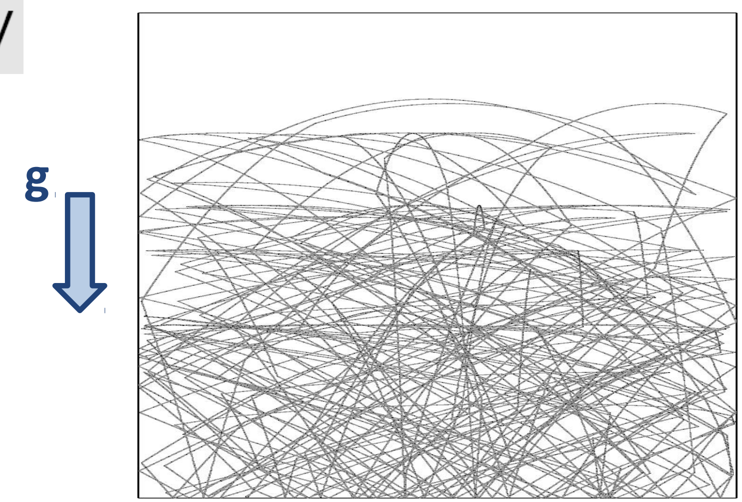
λ_n>>2 Å :
Neutrons see the Fermi potential

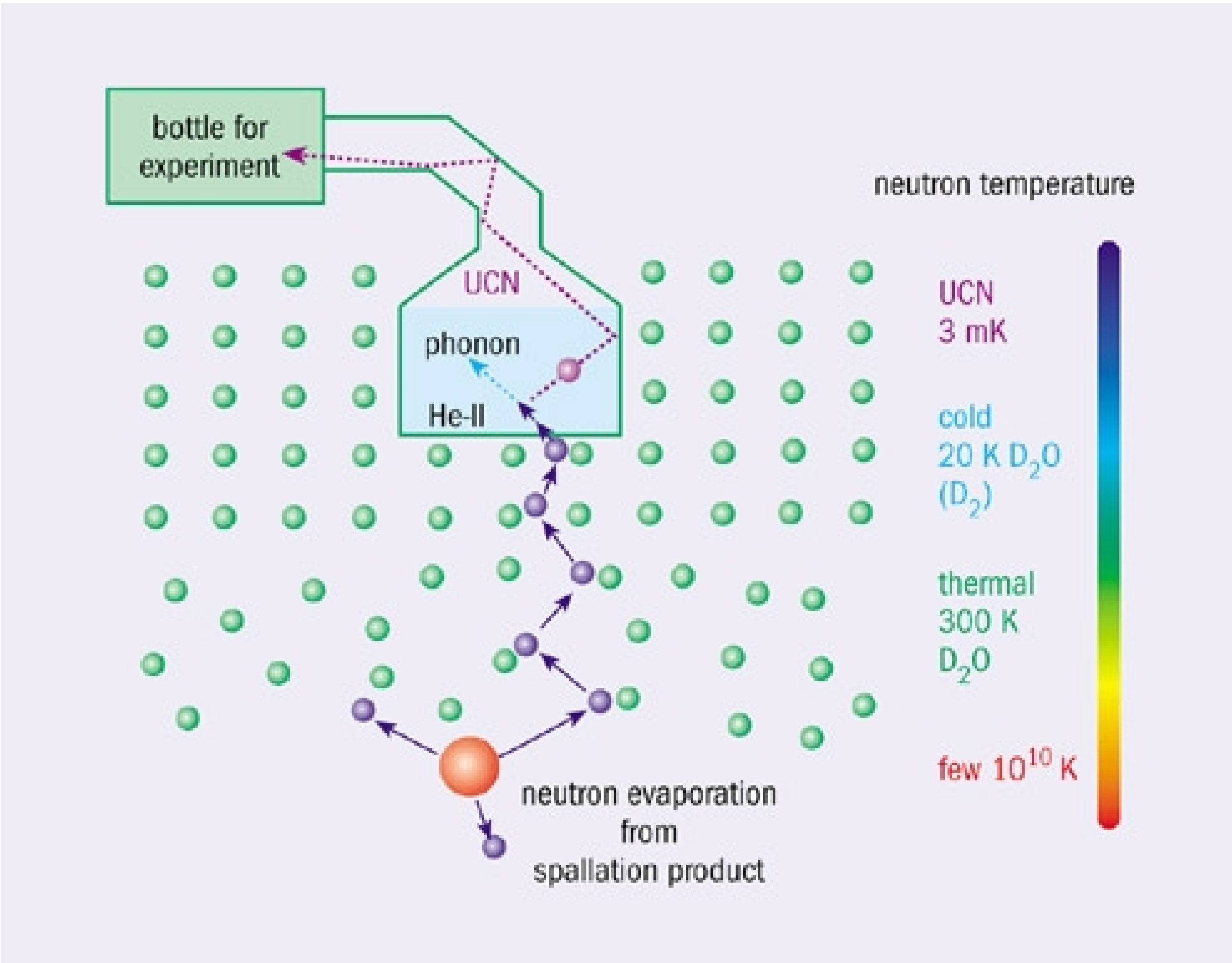
Interactions

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

Can be stored !

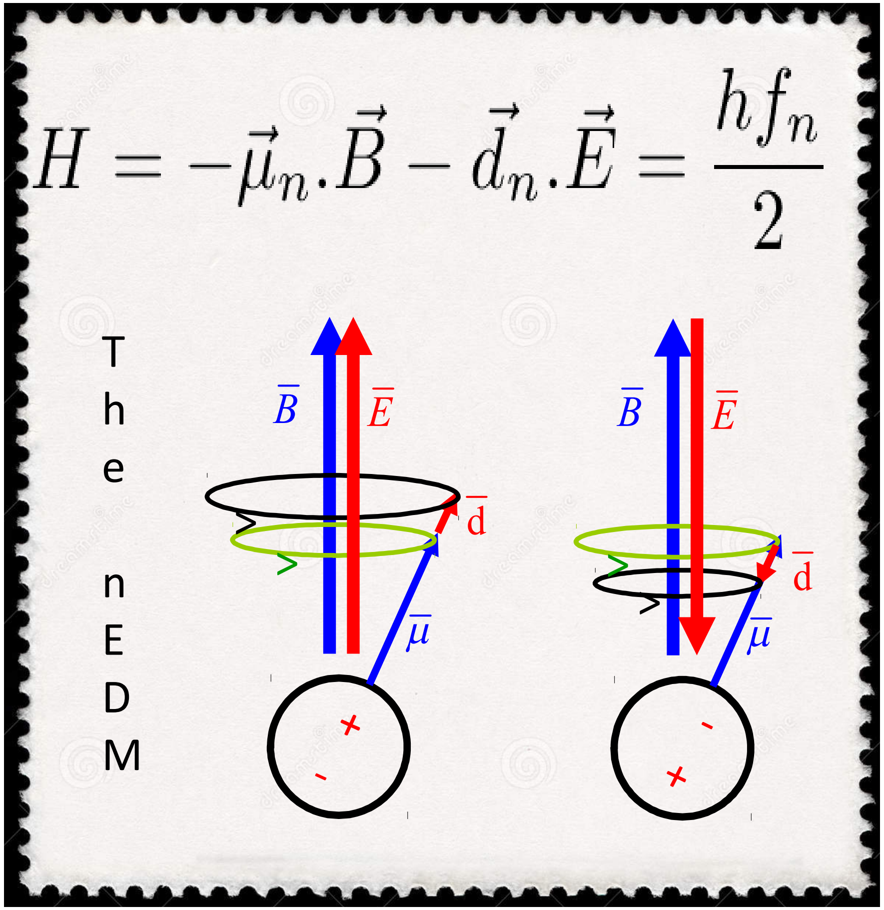


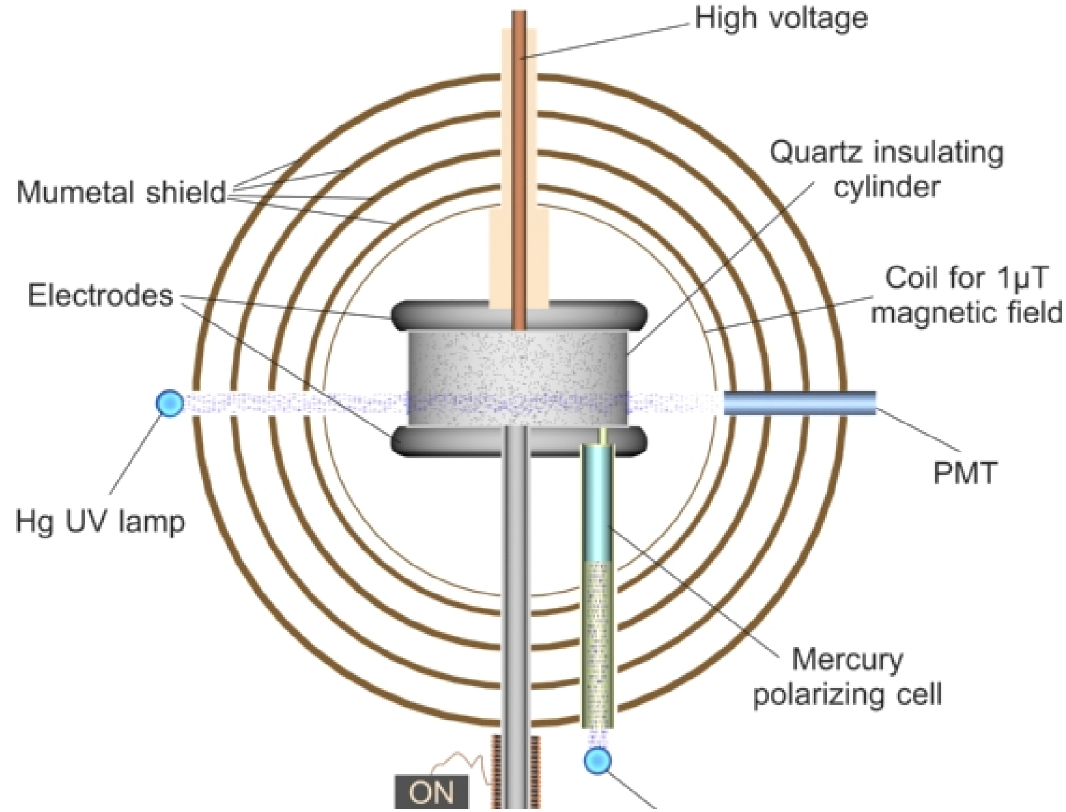


In vacuum ?
In He ?

R. Golub and J. M. Pendlebury, Phys. Lett. 62A (1977) 337.

A nEDM apparatus





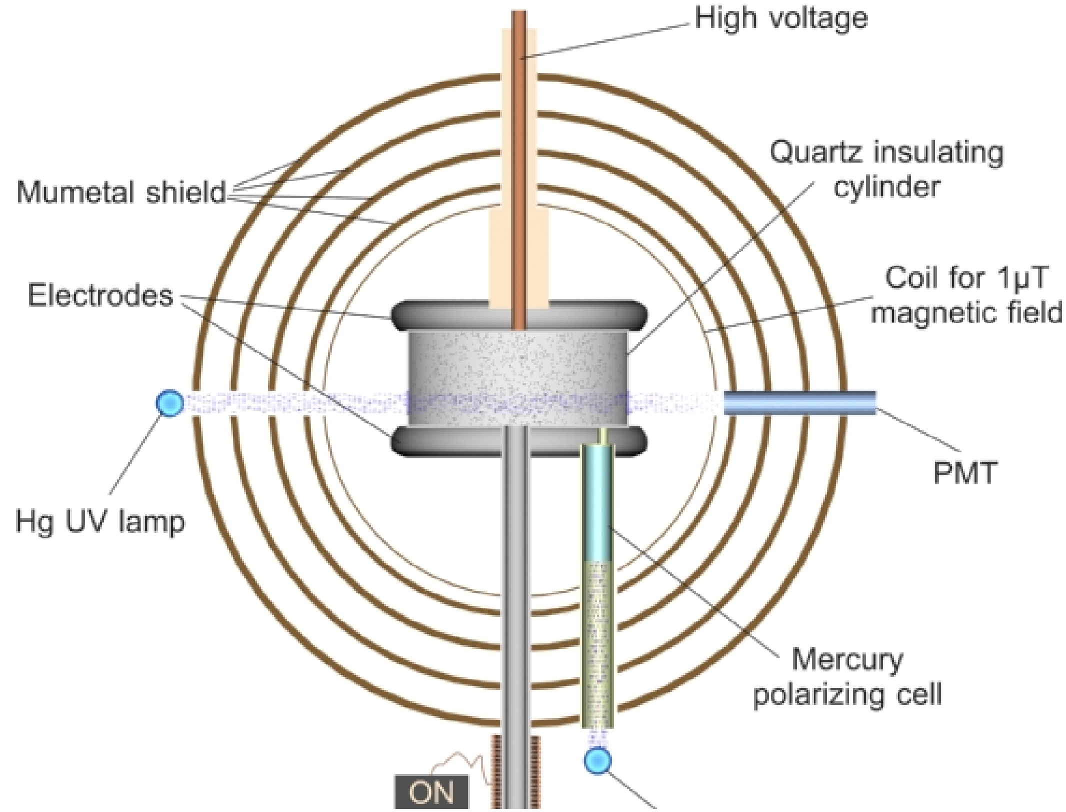
First limitation ….. Magnetic field fluctuations

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

A nEDM apparatus

Mercury co-magnetometer (1998)

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



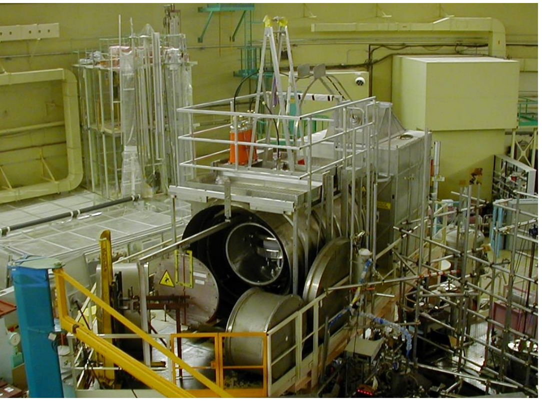
First limitation ….. Magnetic field fluctuations

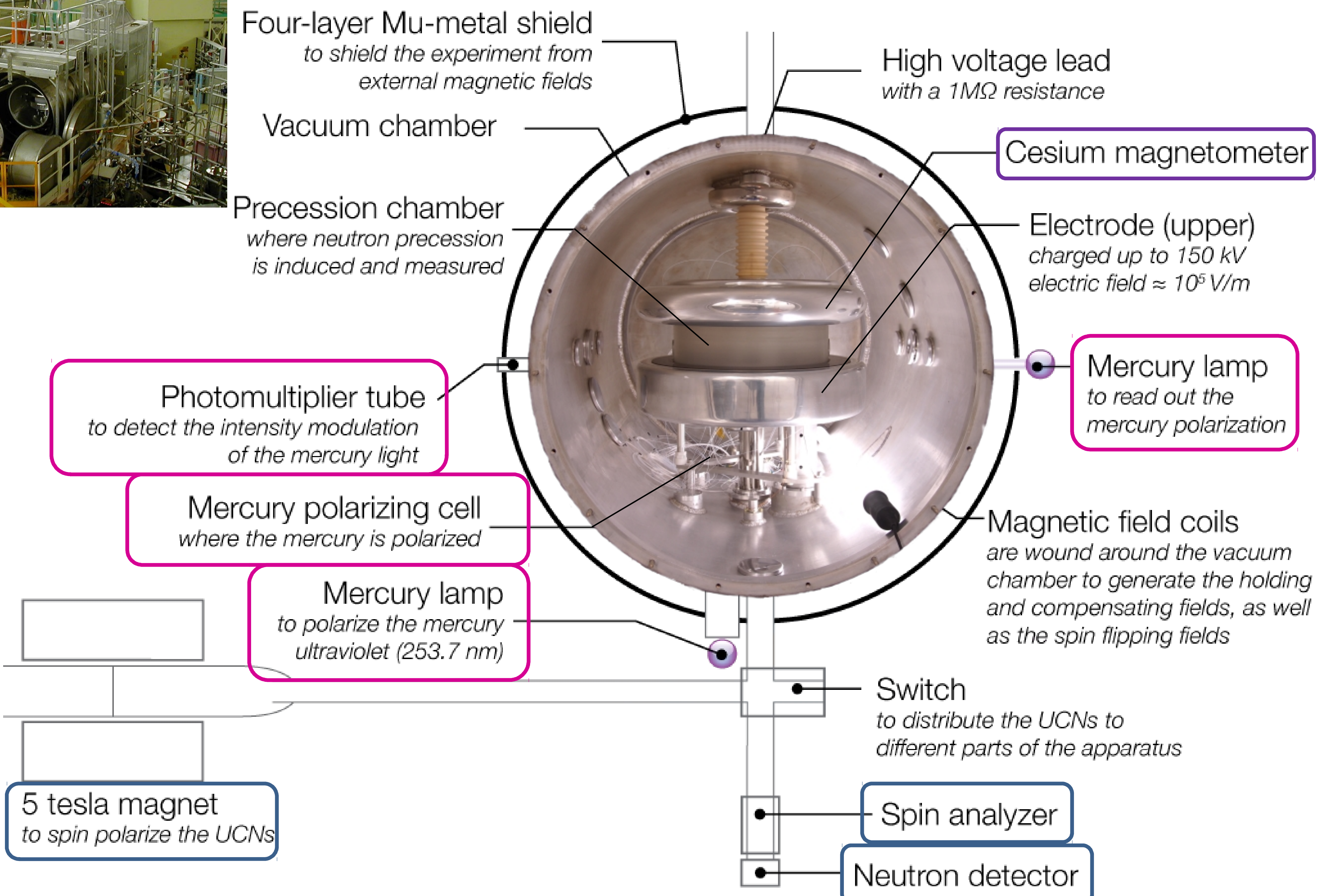
$$\mathrm{h}\ f_n\ (\uparrow\uparrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow)$$

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

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

A nEDM apparatus





A completely new experiment or an old one?

A nEDM apparatus

Geometrical phase shift

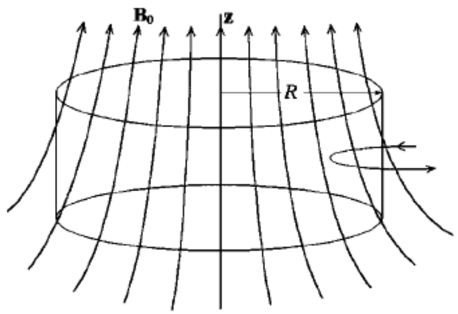
Hg comagnetometer

Motional (transverse) field

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

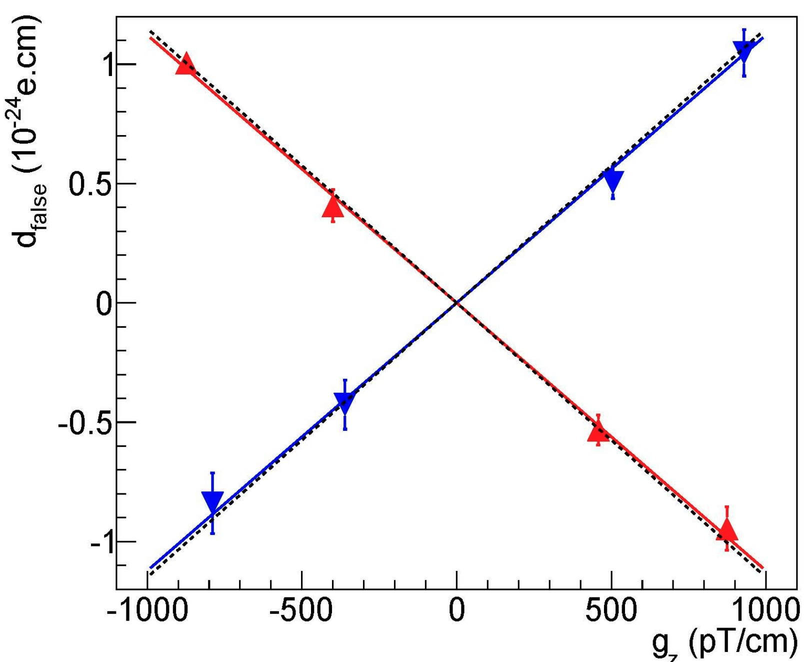
+

Magnetic transverse field



→ Frequency shift correlated with electric field

False EDM for Mercury (fast regime of GPE)



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

$$\longrightarrow d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

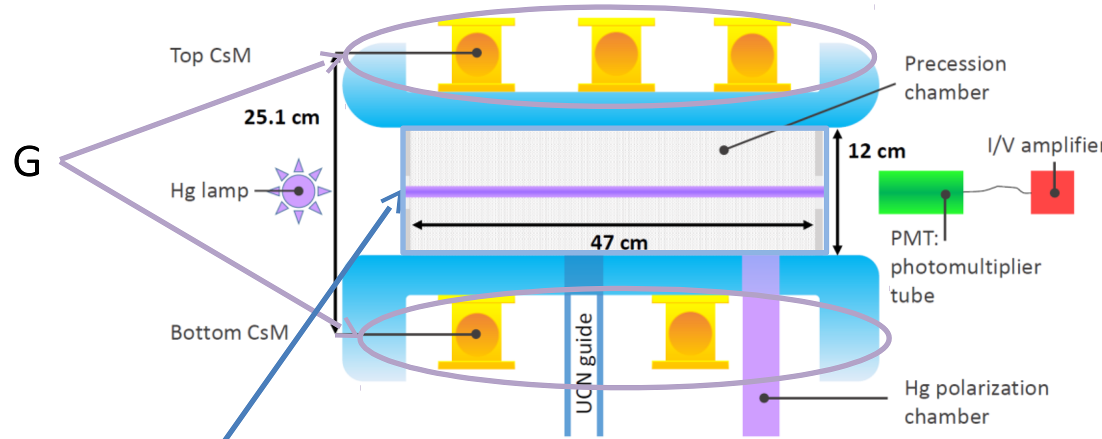
*Pendlebury et al, PRA **70** 032102 (2004)*

S. Afach et al, EPJD **69**, 225 (2015)

Measurement of a false electric dipole moment signal from 199Hg atoms exposed to an inhomogeneous magnetic field

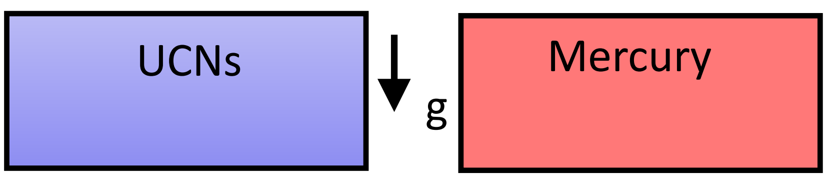
A non perfect Co-magnetometer

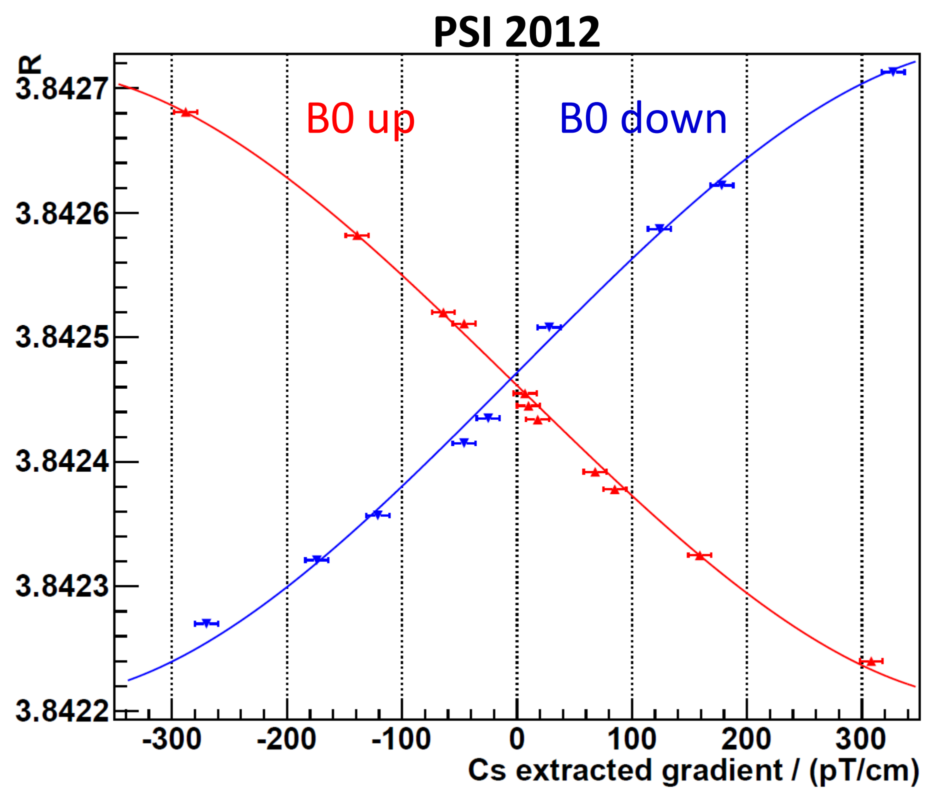
- Gravitational shift



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

In the precession chamber





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

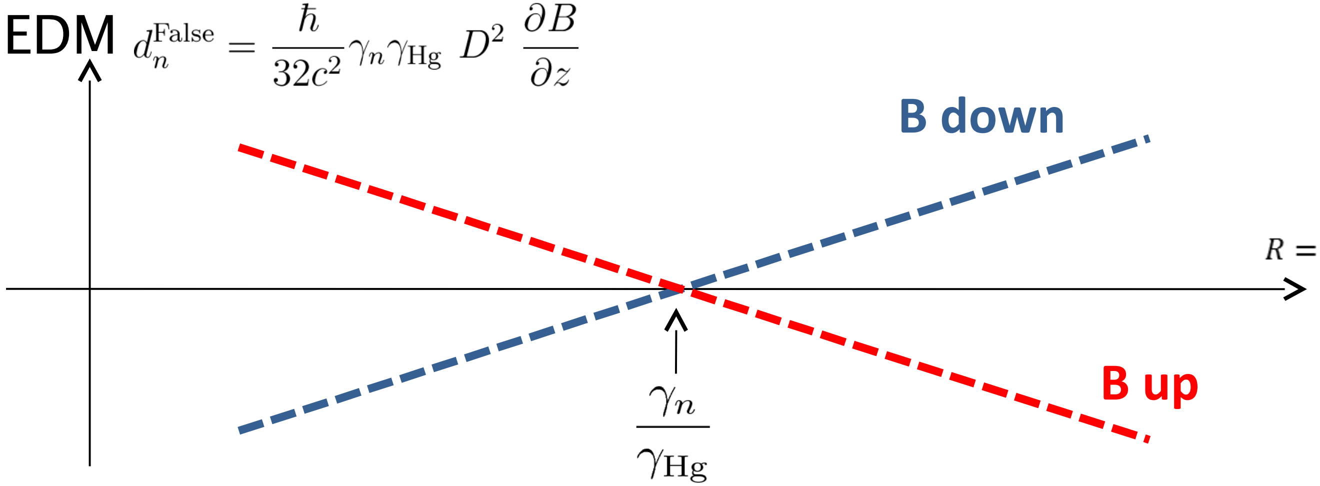
Δh=2.7 mm

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

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)

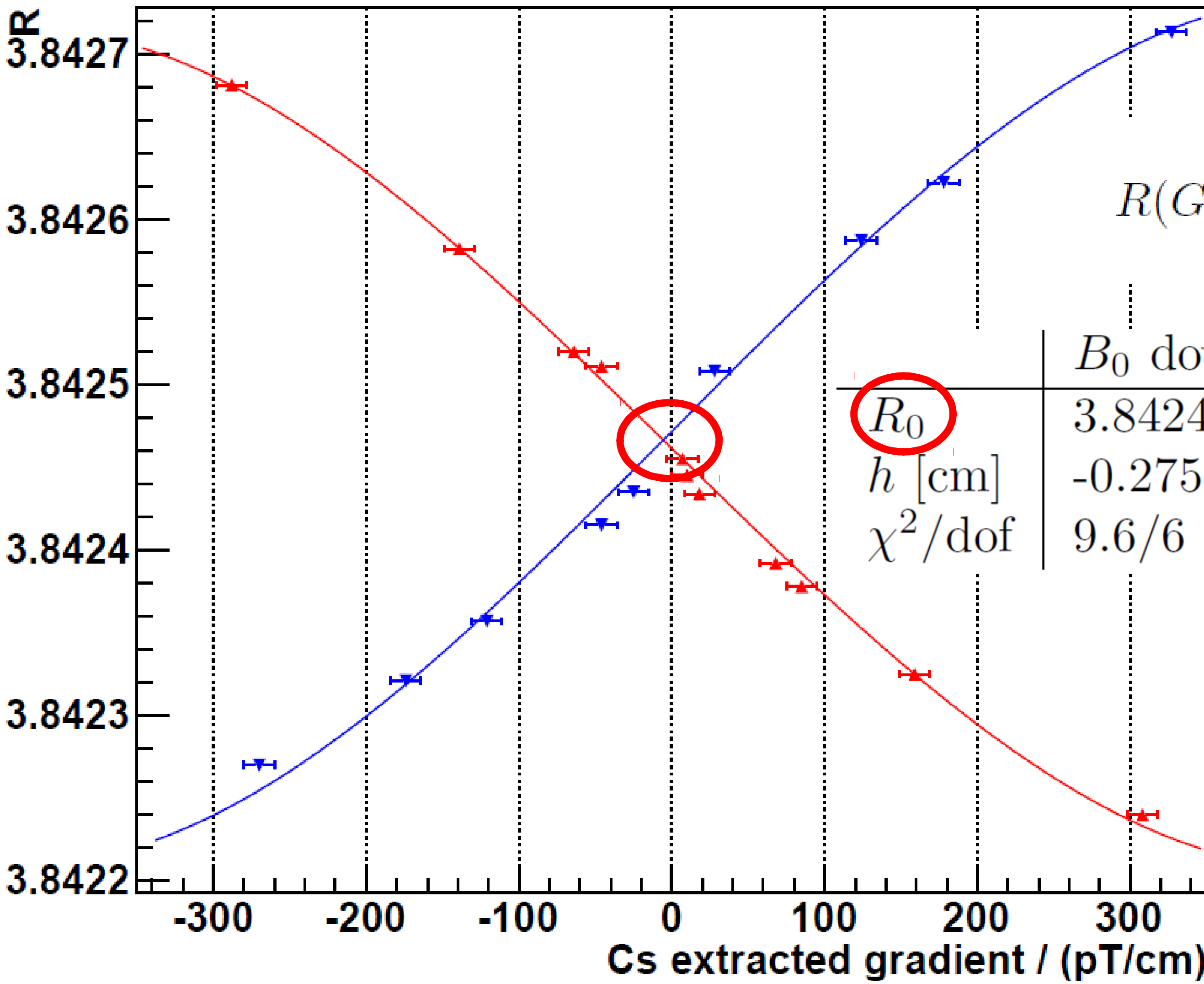
$$d_n^{\text{False}} = \frac{\hbar}{32c^2}\gamma_n\gamma_{\text{Hg}}\ D^2\ \frac{\partial B}{\partial z}$$



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

Some results

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



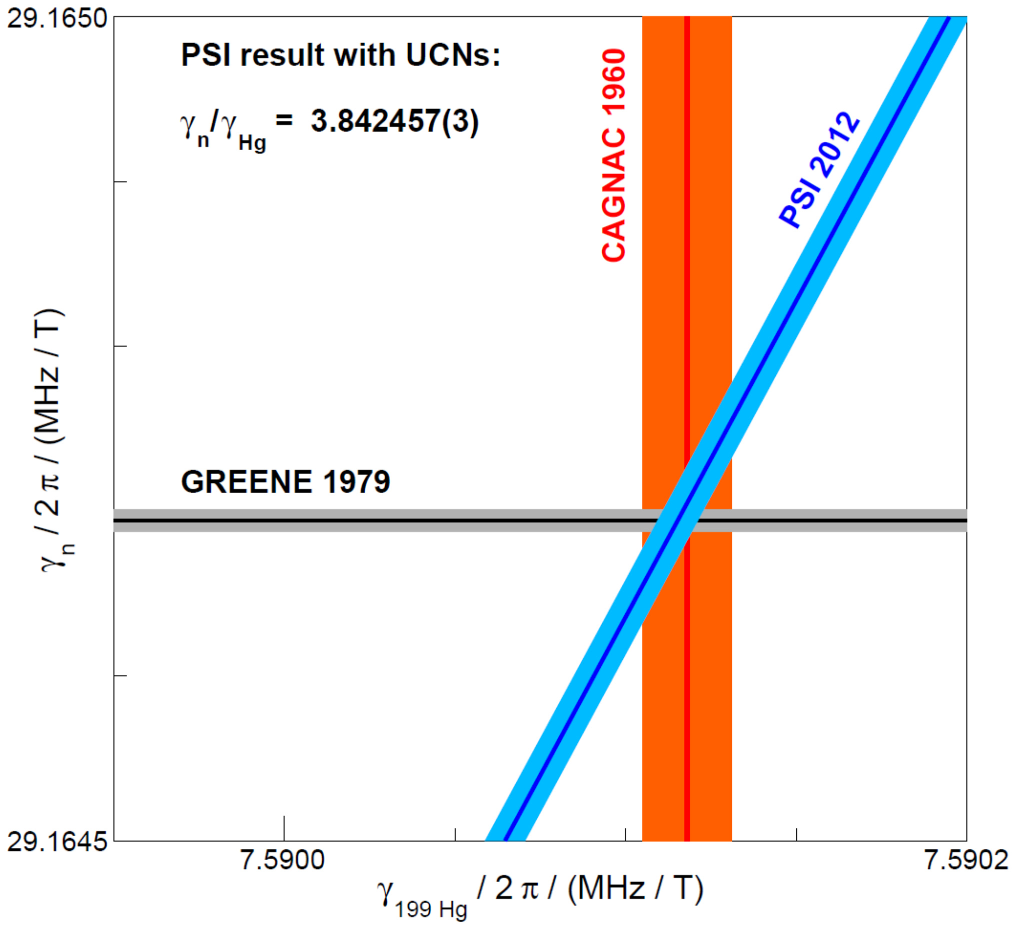
$$R(G) = R_0\left(1 \pm \frac{Gh}{B_0} + cG^3\right)$$

	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

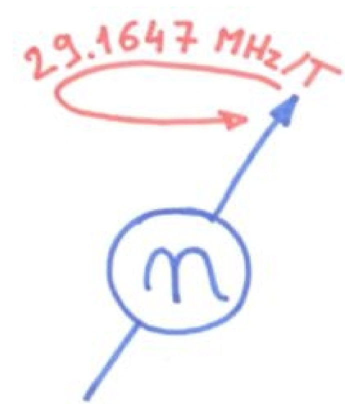
$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy}xy + g_{xz}xz + g_{yz}yz$$

Some results

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

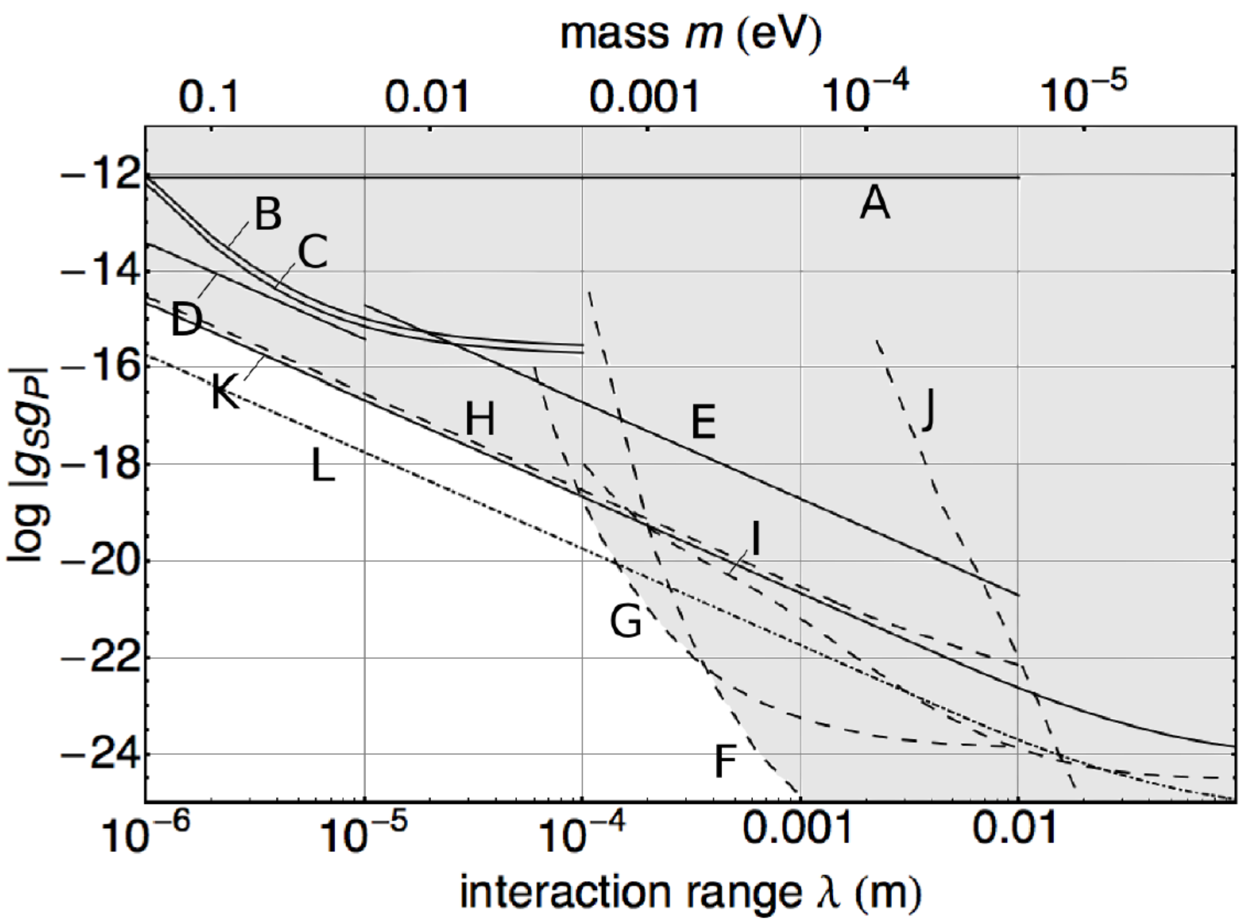


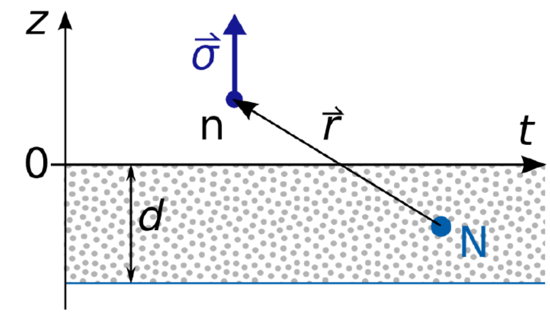
Effect	$B_0 \uparrow$	$B_0 \downarrow$
Counting statistics	$\pm 0.5 \times 10^{-6}$	$\pm 0.5 \times 10^{-6}$
Gravitational shift ($3.84 \times \delta_{\mathrm{Grav}}$)	$(-8.9 \pm 2.3) \times 10^{-6}$	$(-1.8 \pm 2.7) \times 10^{-6}$
Intermediate R_0	3.8424580(23)	3.8424653(27)
Transverse shift ($3.84 \times \delta_{\mathrm{T}}$)	$(3.7 \pm 0.8) \times 10^{-6}$	$(3.0 \pm 1.2) \times 10^{-6}$
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 $\gamma_{\mathrm{n}}/\gamma_{\mathrm{Hg}}$	3.8424574(30)	



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

Searching for axion-like particles with ultracold neutrons





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

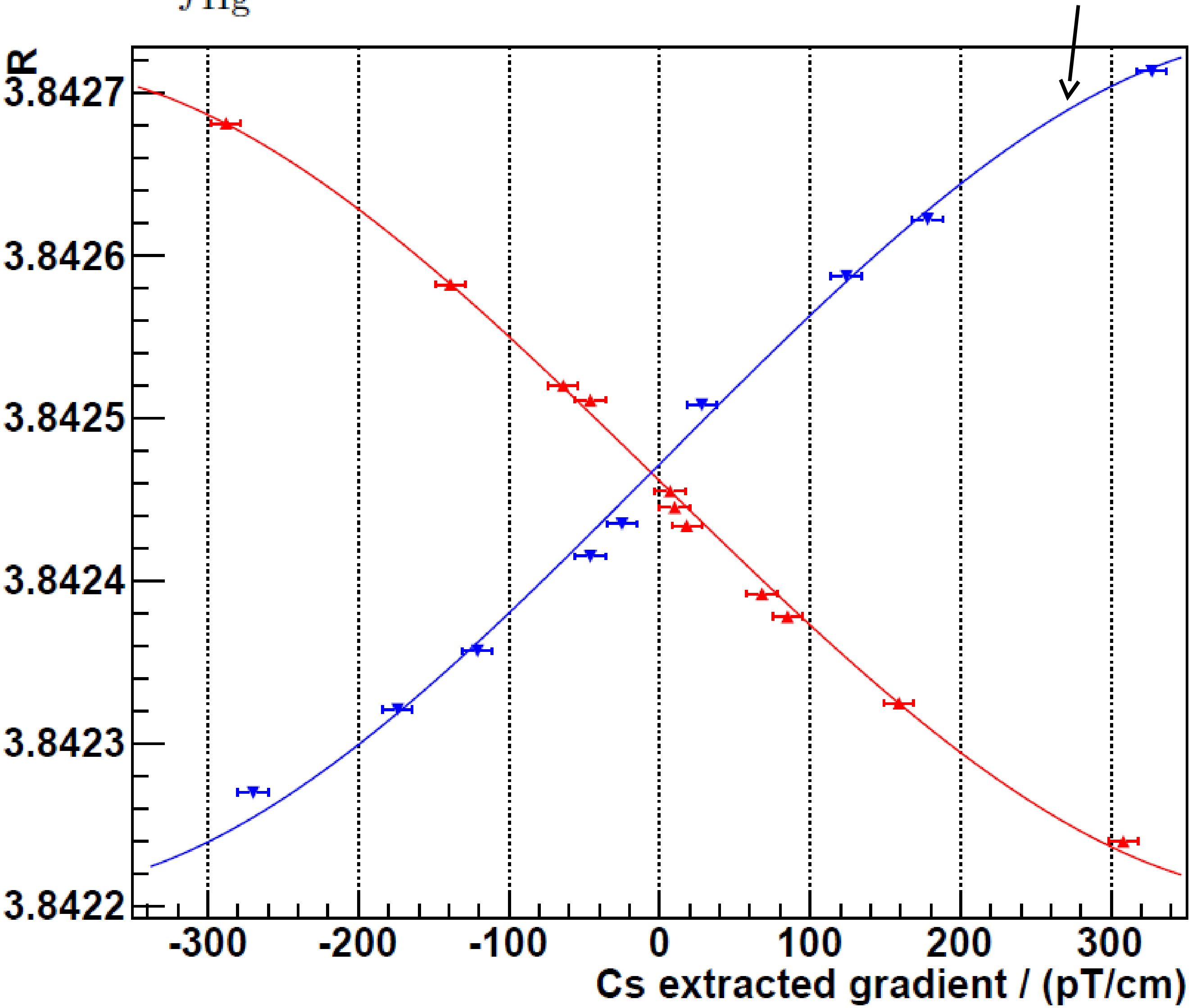
$$b_{UCN} \approx \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\rho_{bottom}\, b_{bottom}\, e^{-\frac{z+H/2}{\lambda}} - \rho_{top}\, b_{top}\, e^{-\frac{-z+H/2}{\lambda}}\right) dz$$

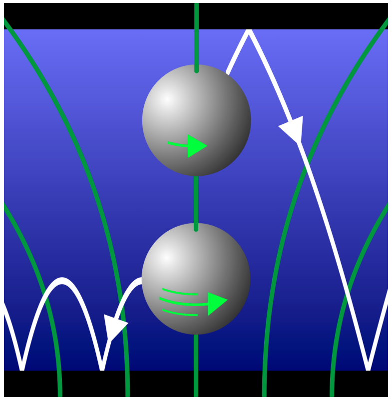
*S. Afach et al., PLB **745**, 58 (2015)*

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

Gravitational enhanced depolarization and associated frequency shift

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

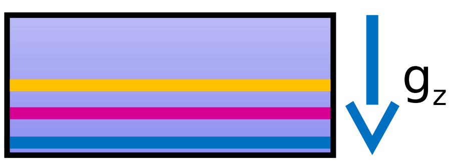


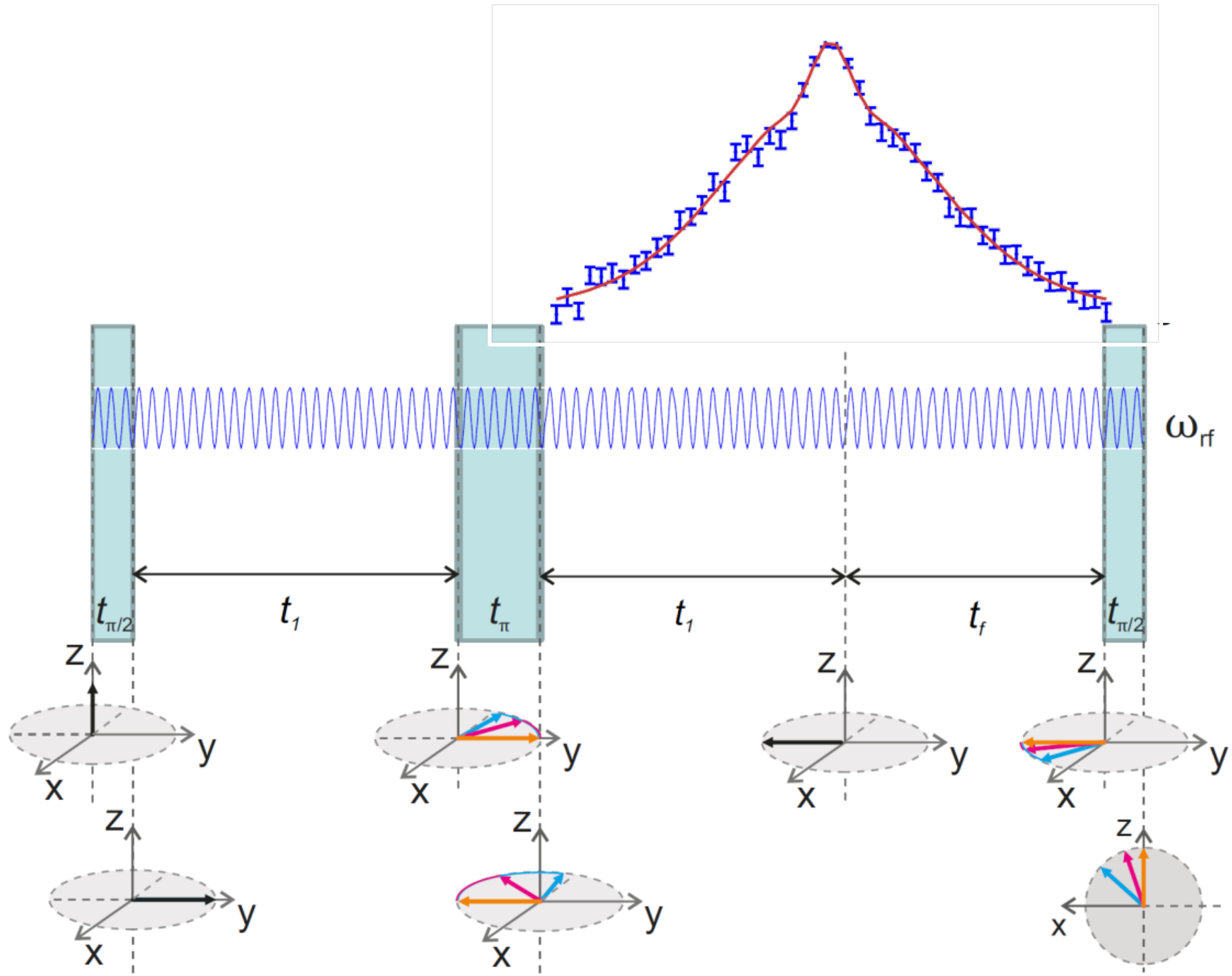


Also slower UCNs depolarize faster and contribute less to the measured frequency

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

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





PRL 115, 162502 (2015)

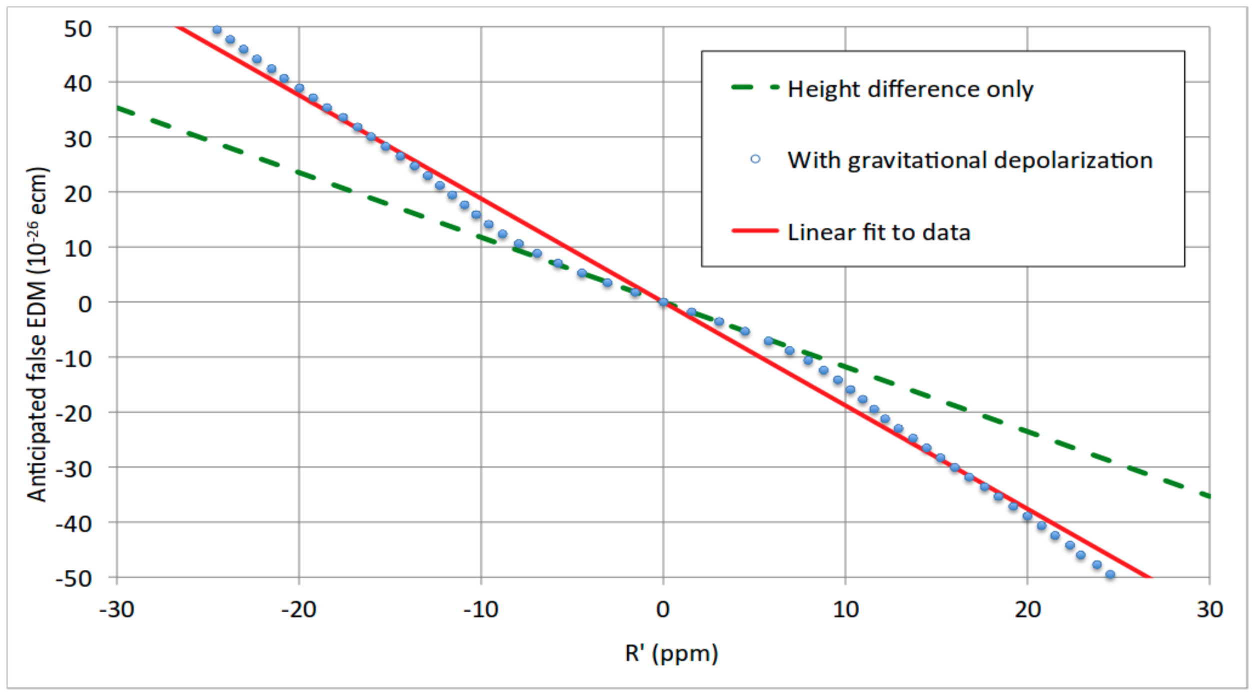
RAL-Sussex-ILL limit revised

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

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

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**

The strategy is validated

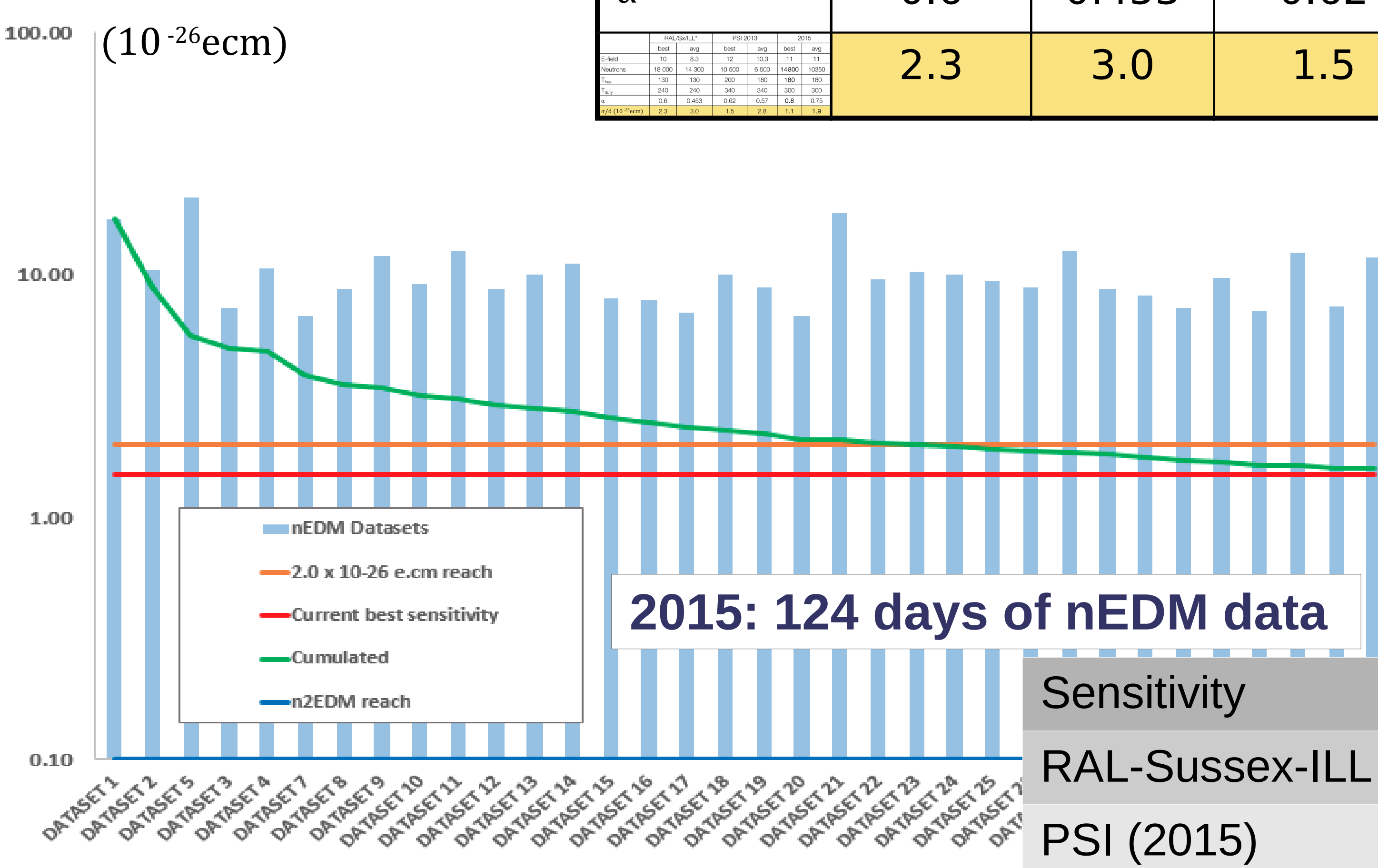


J. M. Pendlebury et al.
Phys. Rev. D 92, 092003 – Published 4 November 2015

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

	RAL/Sx/ILL*		PSI 2013		2015	
	best	avg	best	avg	best	avg
E-field	10	8.3	**12**	10.3	11	11
Neutrons	18 000	14 300	10 500	6 500	**14 800**	10350
T_{free}	130	130	**200**	180	180	180
T_{duty}	240	240	340	340	**300**	300
α	0.6	0.453	0.62	0.57	**0.8**	0.75
	2.3	3.0	1.5	2.8	**1.1**	**1.9**

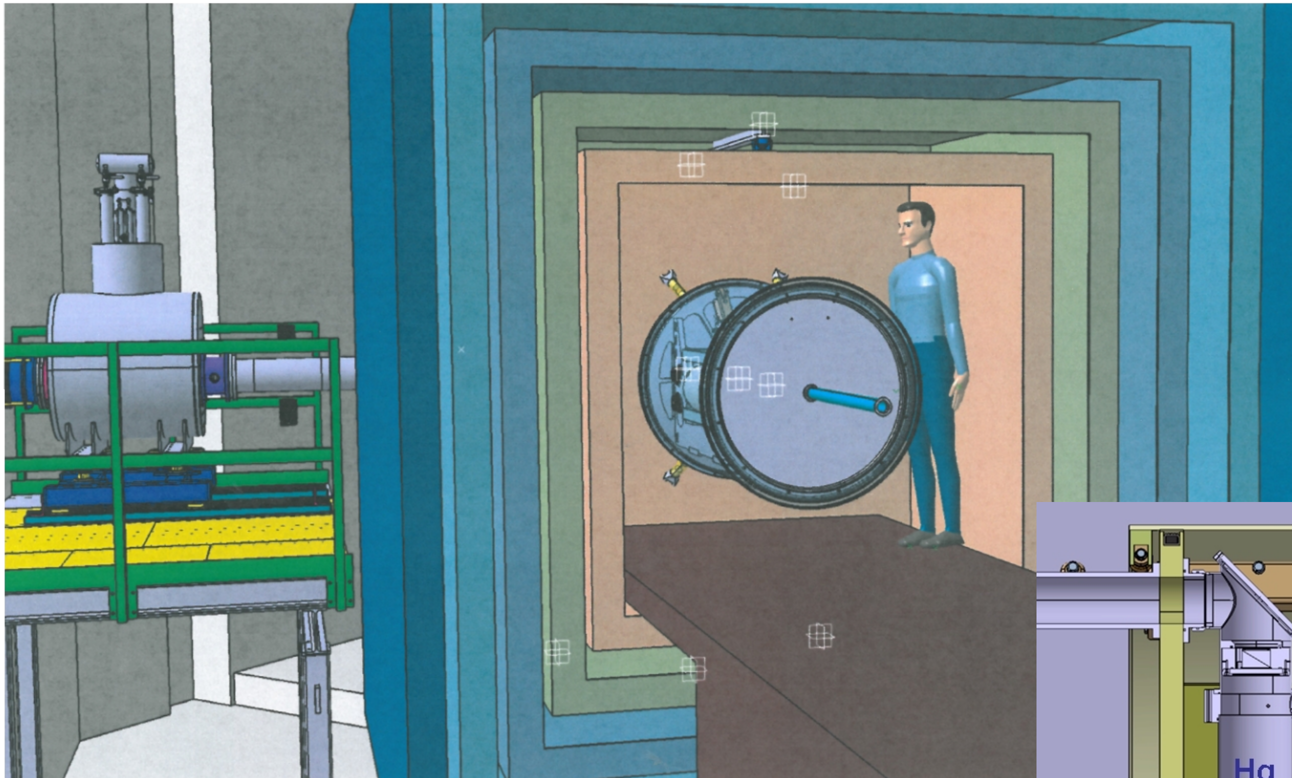
$(10^{-25}$ecm)



2015: 124 days of nEDM data

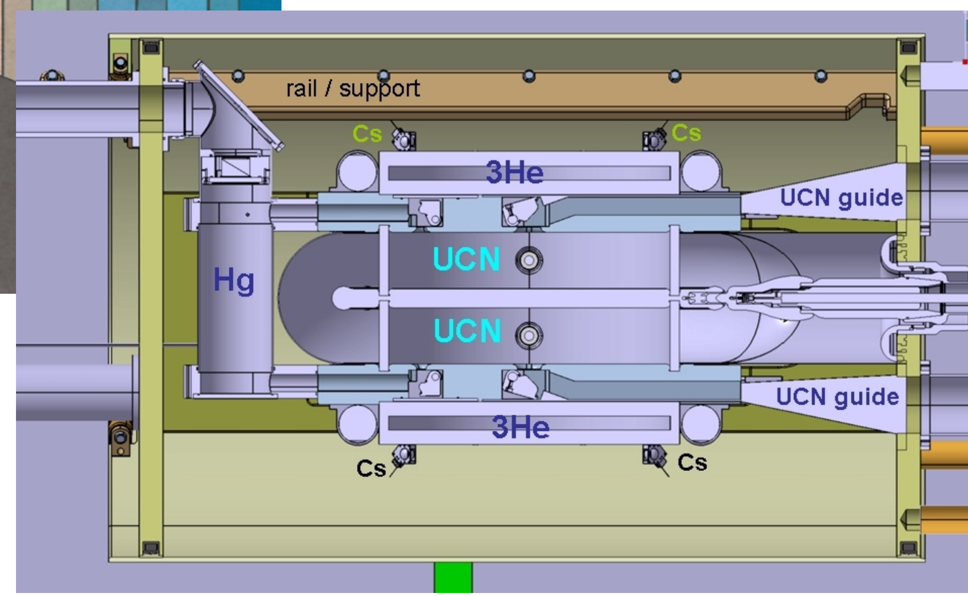
Cumulated sensitivity
1.7×10^{-26} e.cm

Sensitivity	Stat	Syst	Tot
RAL-Sussex-ILL (2015)	1.53	0.99	1.82
PSI (2015)	1.65	0.36	1.69

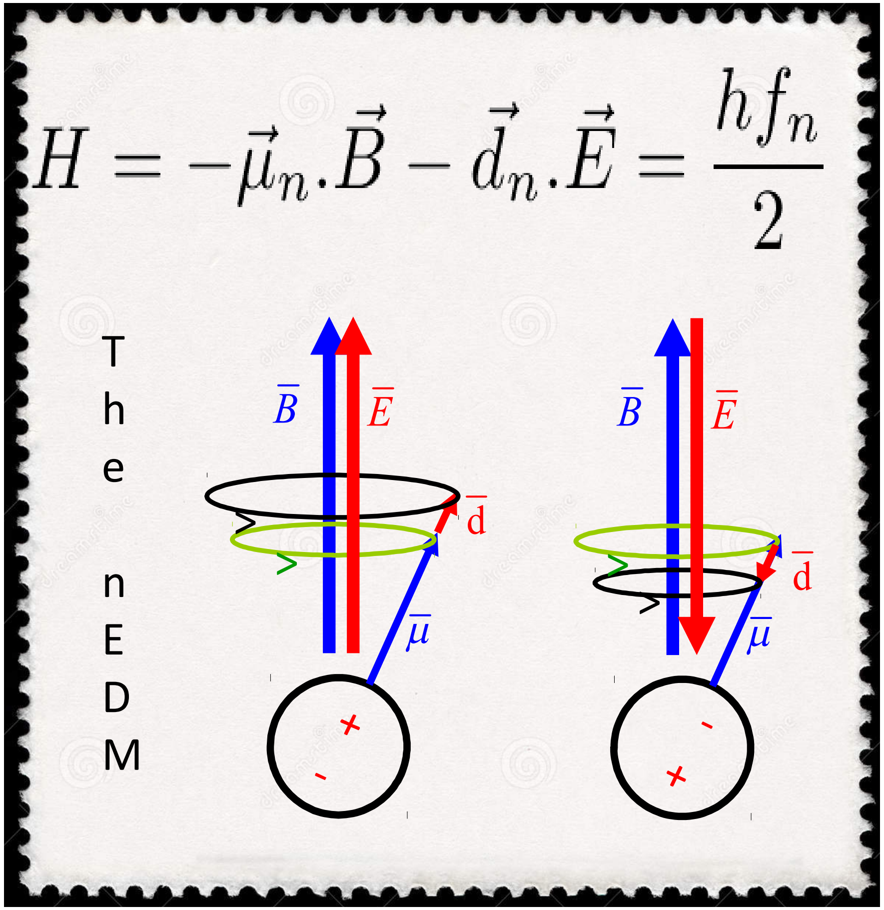


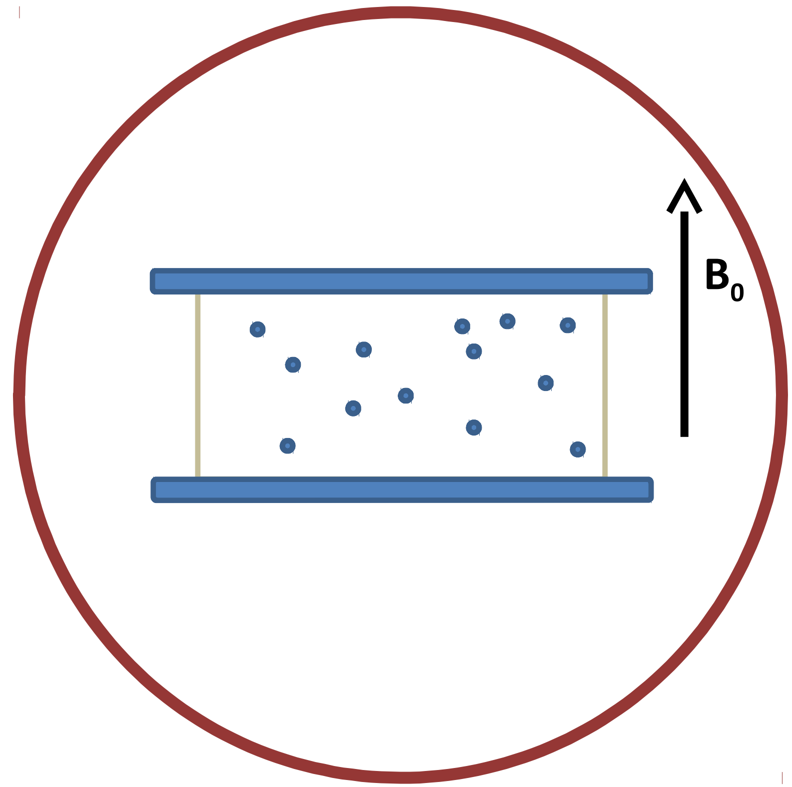
Anticipated sensitivity
4.10^{-26} e.cm / day

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

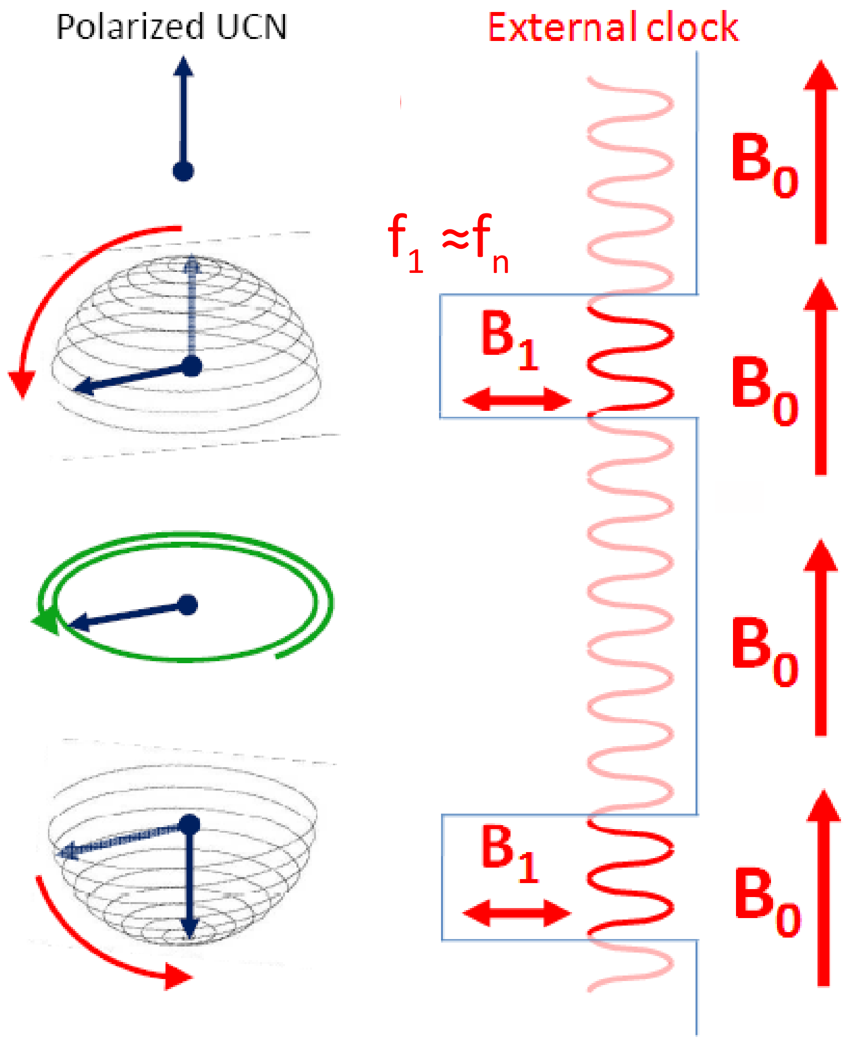


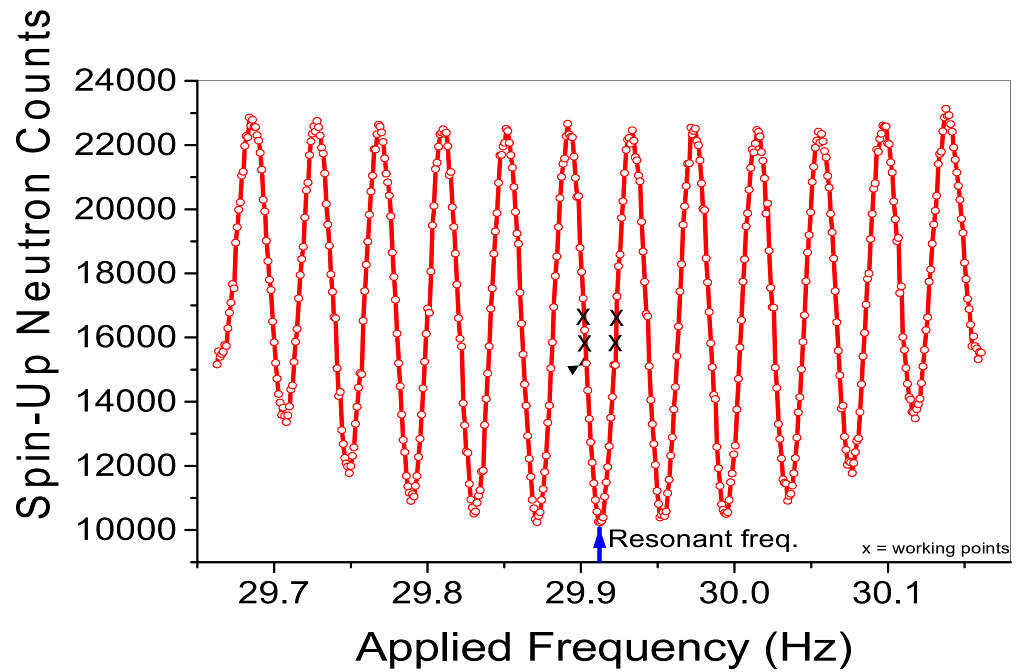
- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetometry Hg – laser read out of Hg-FID to avoid light shift**
  Cs – vectorial
  3He – free from geometrical phase shift


$H = -\vec{\mu}_n . \vec{B} - \vec{d}_n . \vec{E} = \frac{h f_n}{2}$
T
h
e
n
E
D
M
$\overline{B}$
$\overline{E}$
$\overline{d}$
$\overline{\mu}$
+
-
$\overline{B}$
$\overline{E}$
$\overline{d}$
$\overline{\mu}$
-
+


B_0

The Ramsey's method of separated oscillating fields

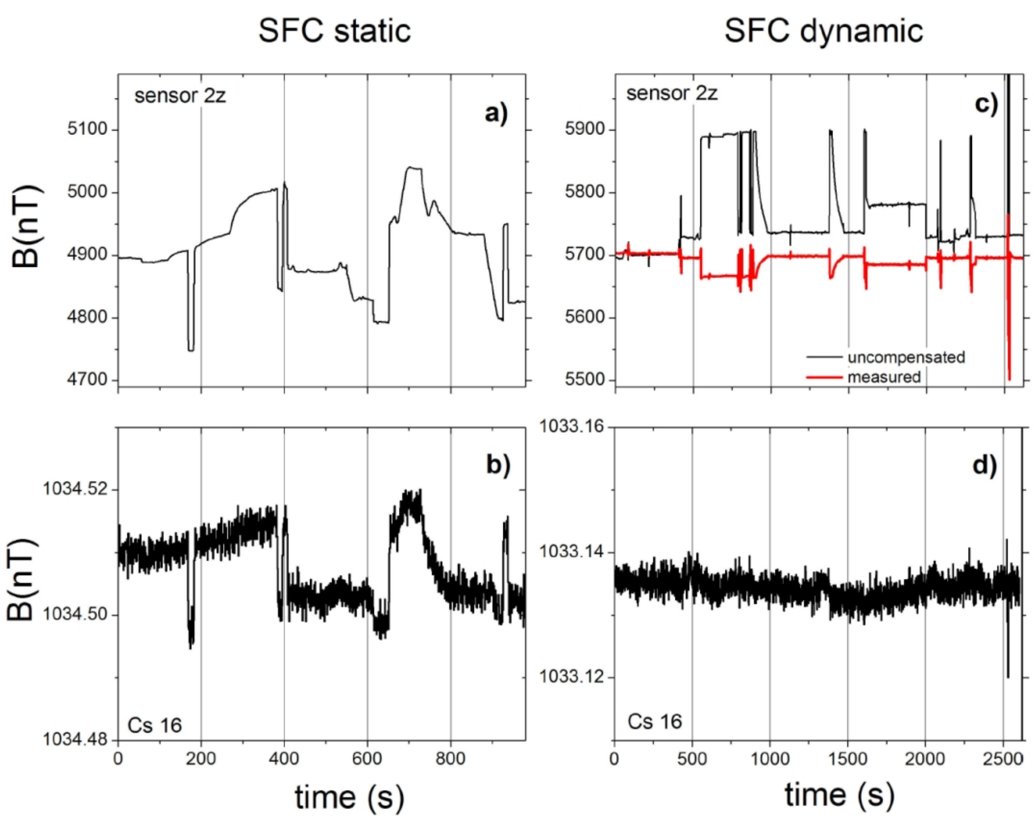


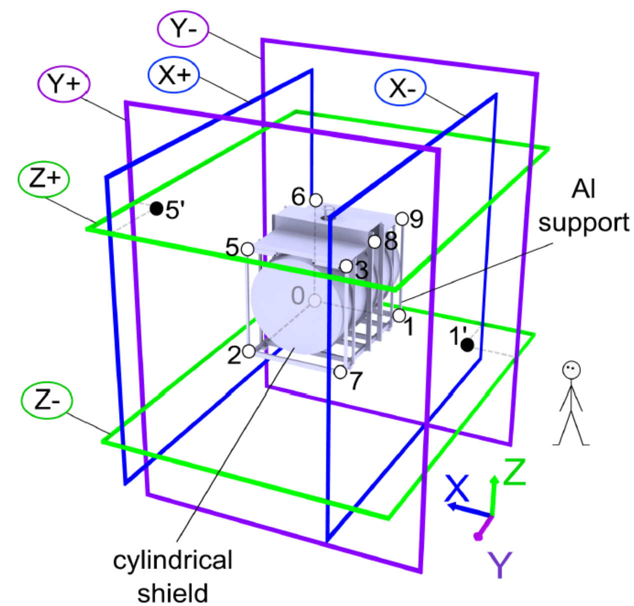


$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

A nEDM apparatus

Magnetic stability

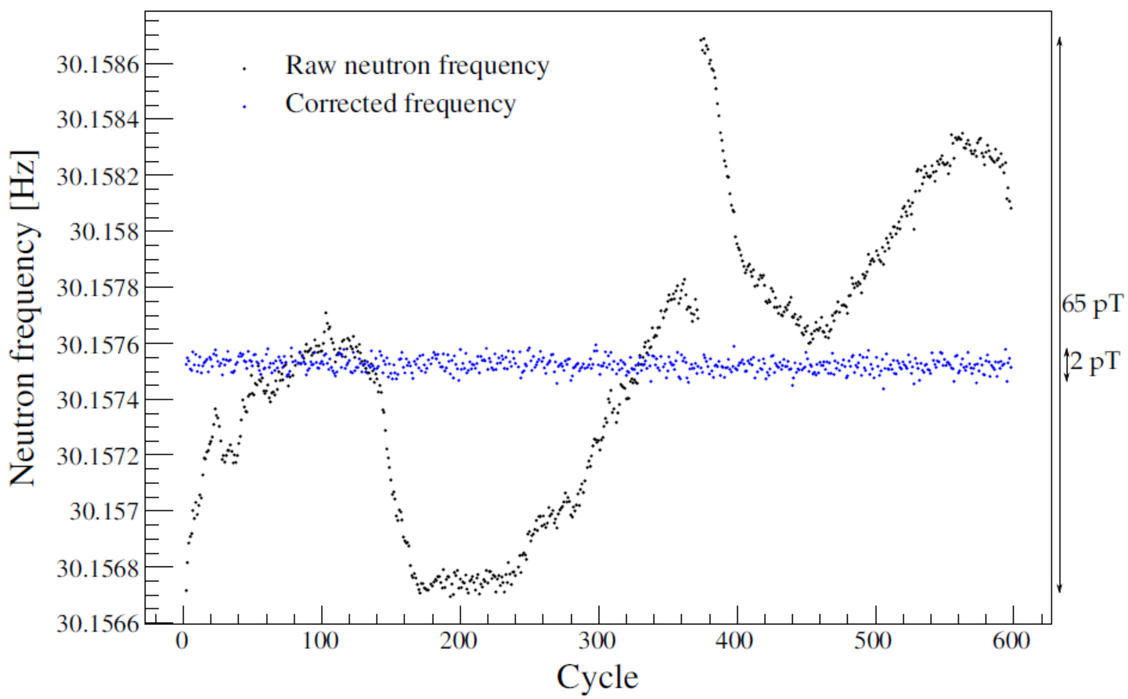


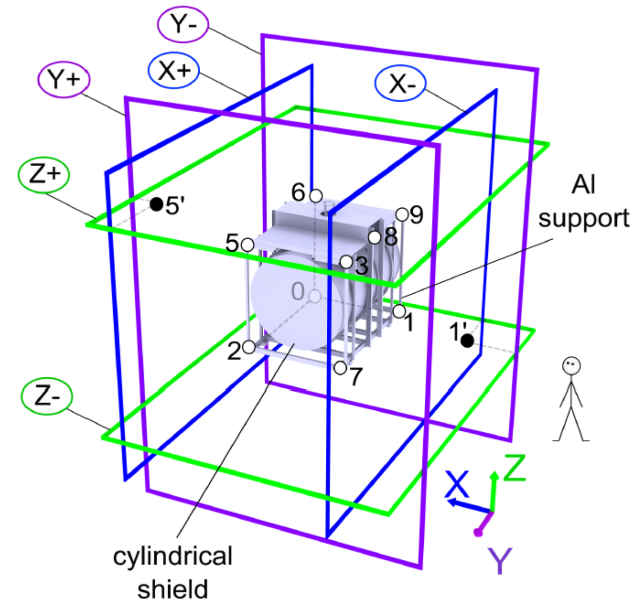


Afach et al., J. Appl. Phys. ***116****, 084510 (2014)*

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

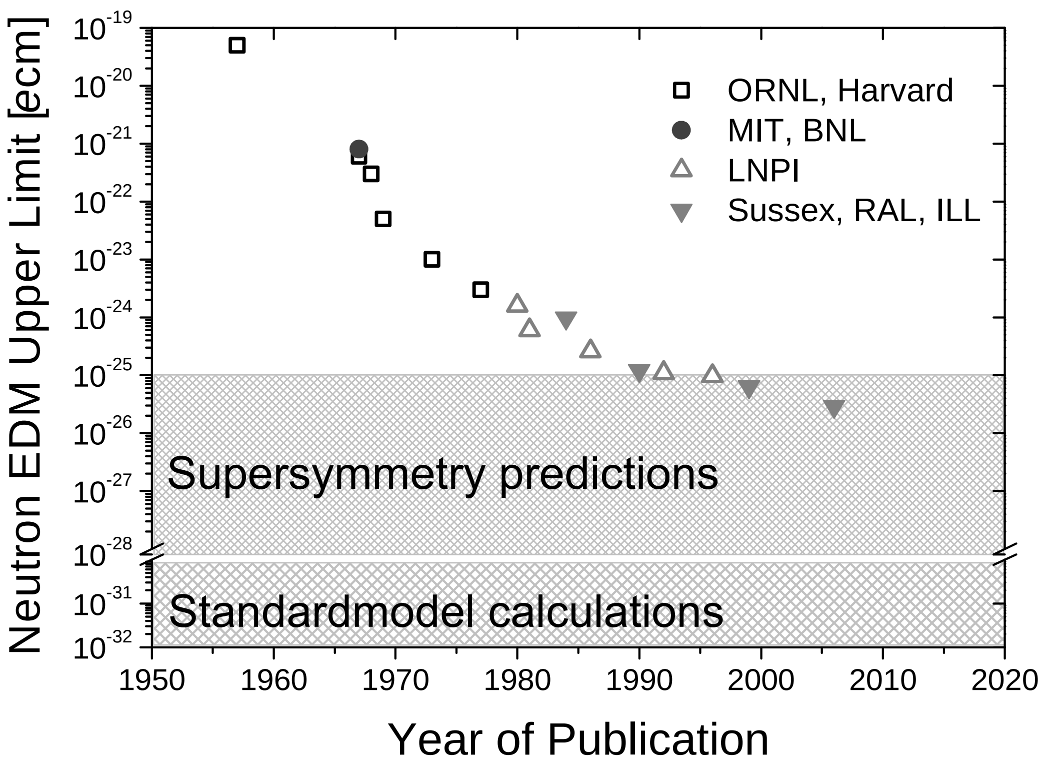
Magnetic stability



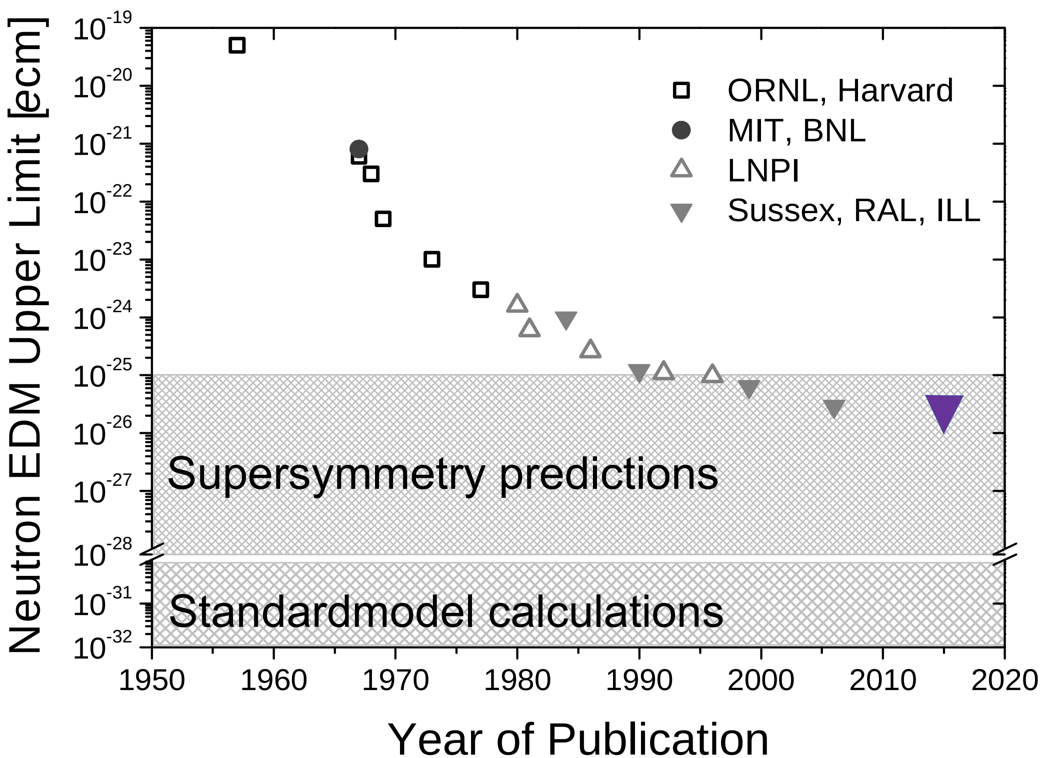


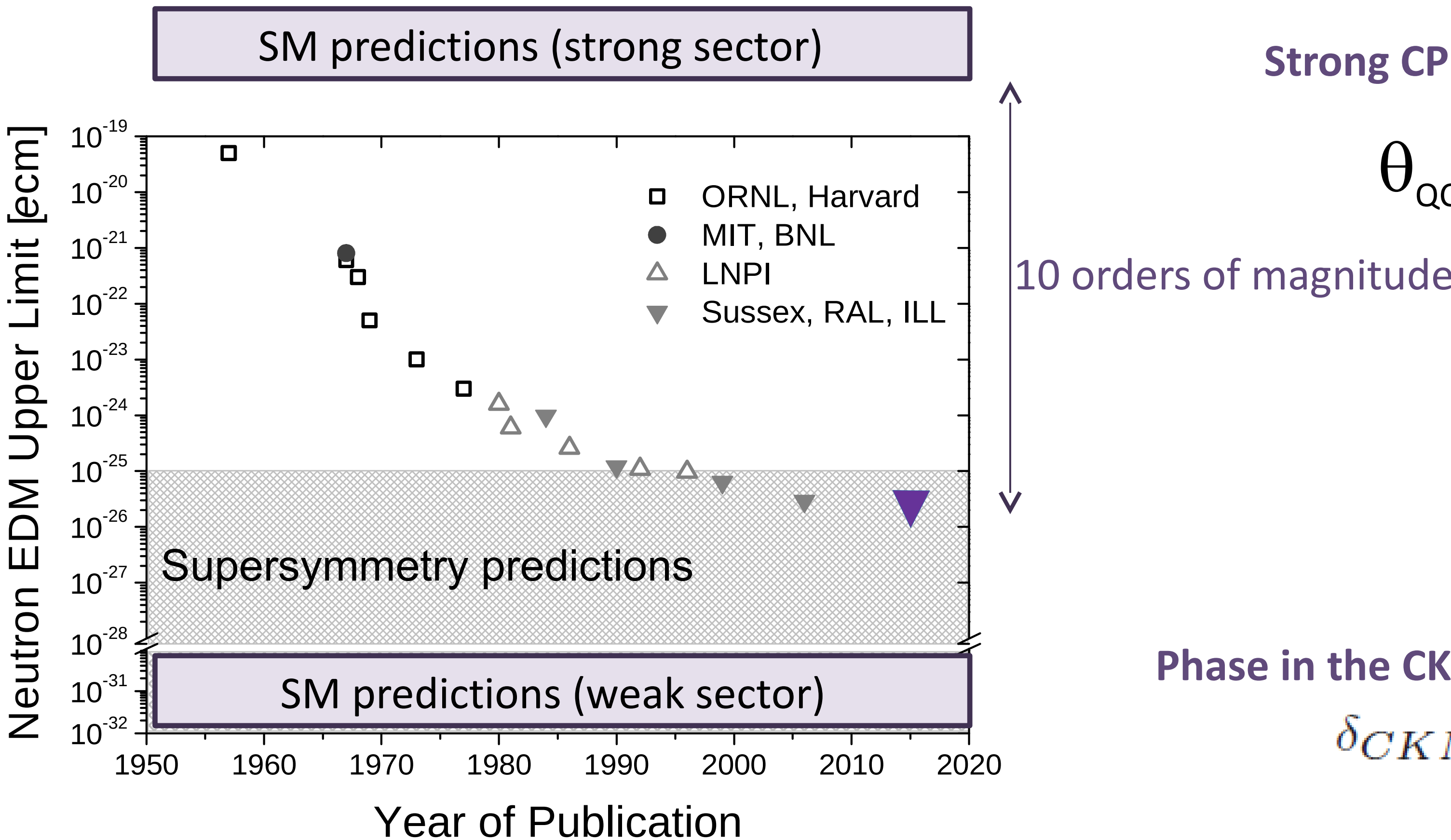
- Active compensation
- Improved degaussing procedure
- Temperature stabilization
- New current source
- …

The nEDM landscape



The nEDM landscape





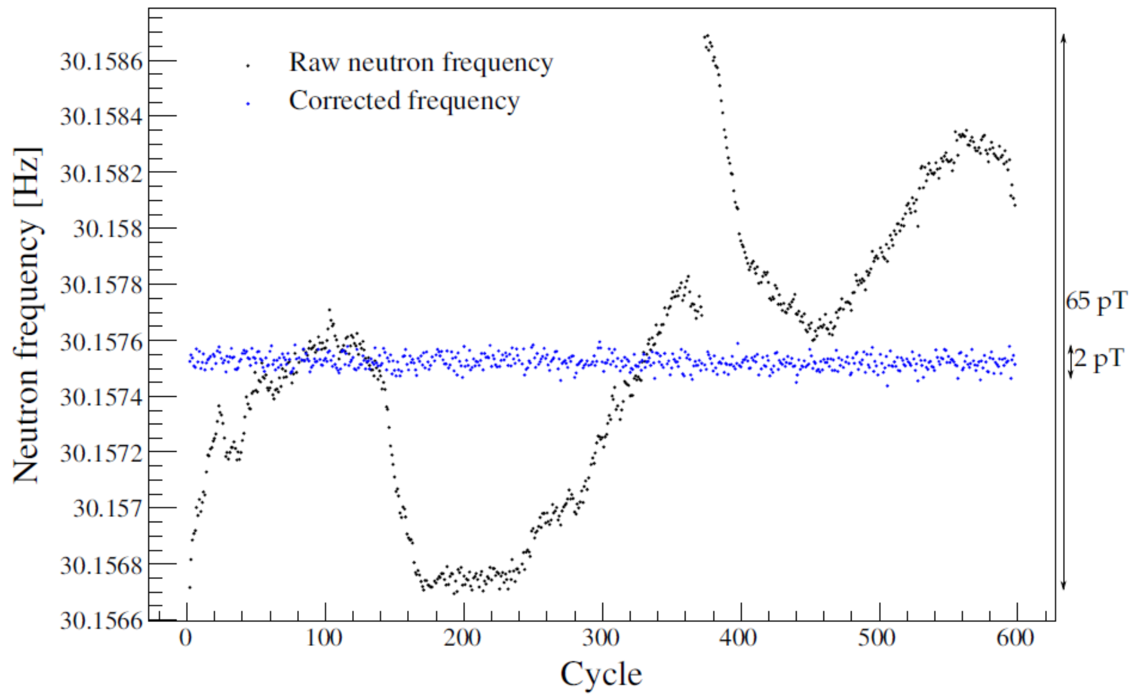
Strong CP problem

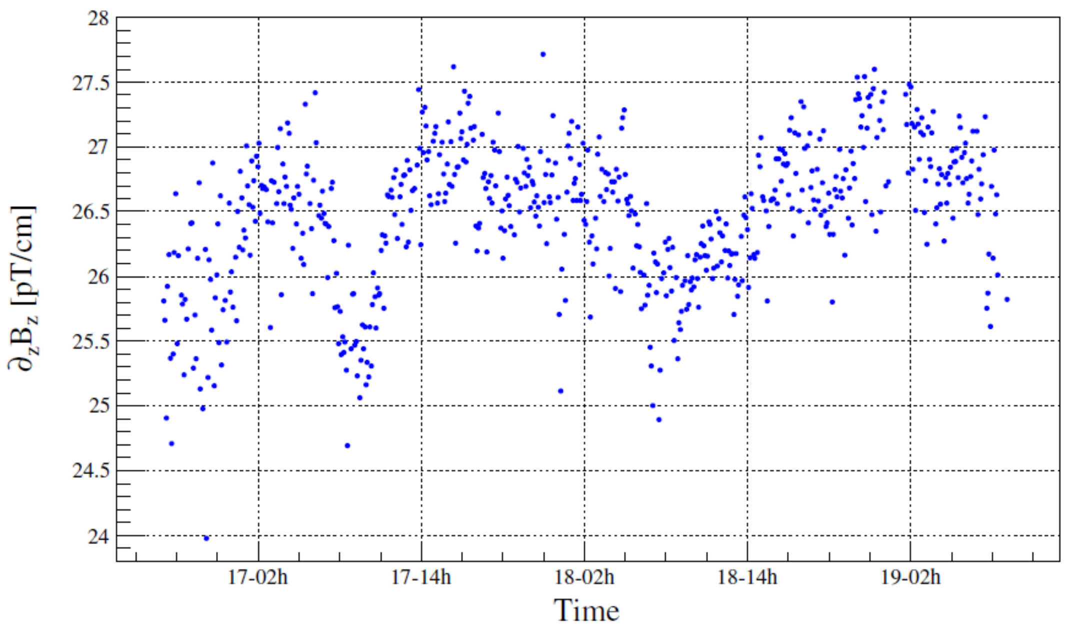
$\theta_{QCD} < 10^{-10}$

Phase in the CKM matrix

δ_{CKM}

Magnetic stability





Vertical gradient
~ 2 pT/cm daily variation

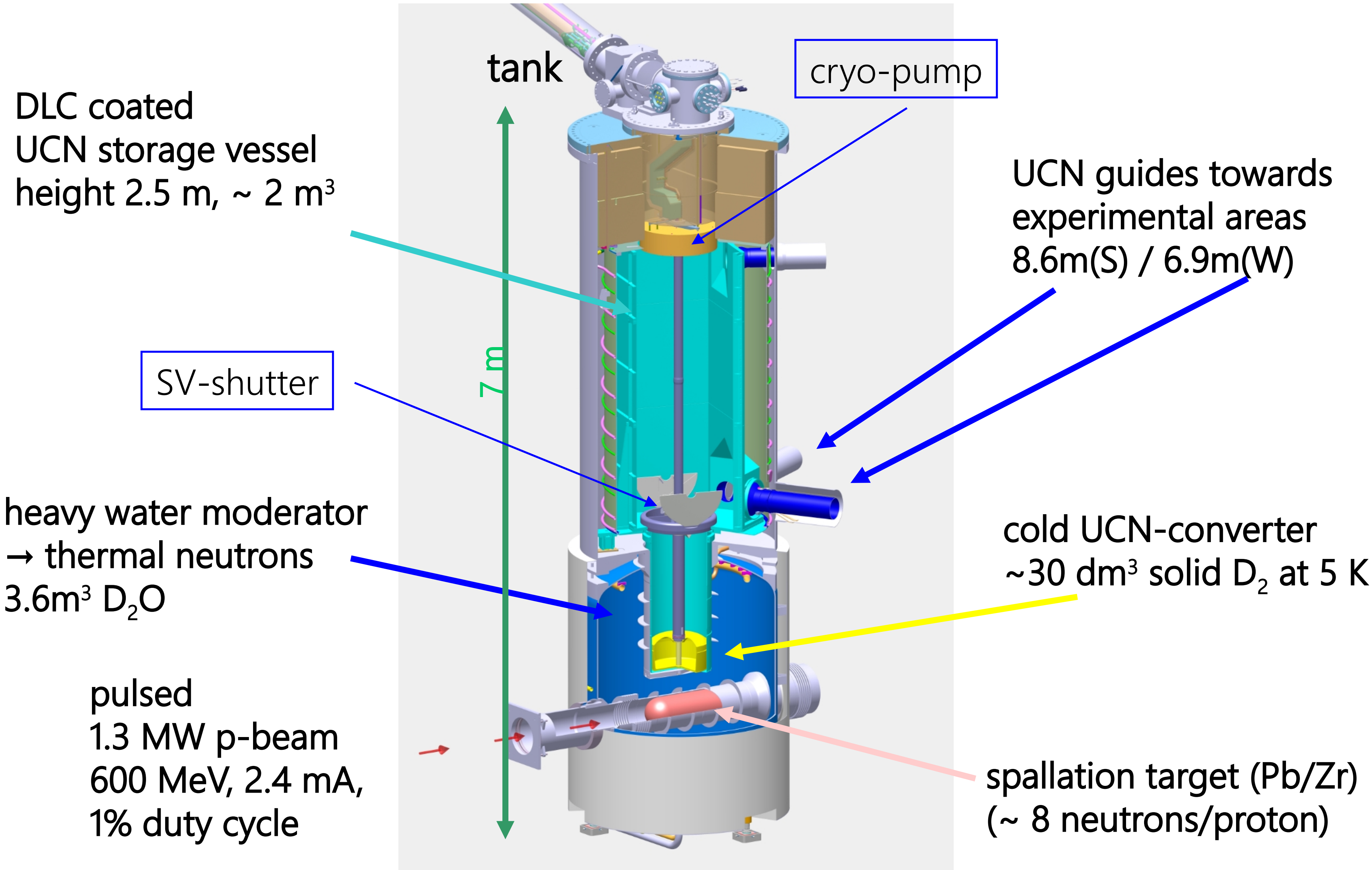
The EDM landscape

Adrian SIGNER

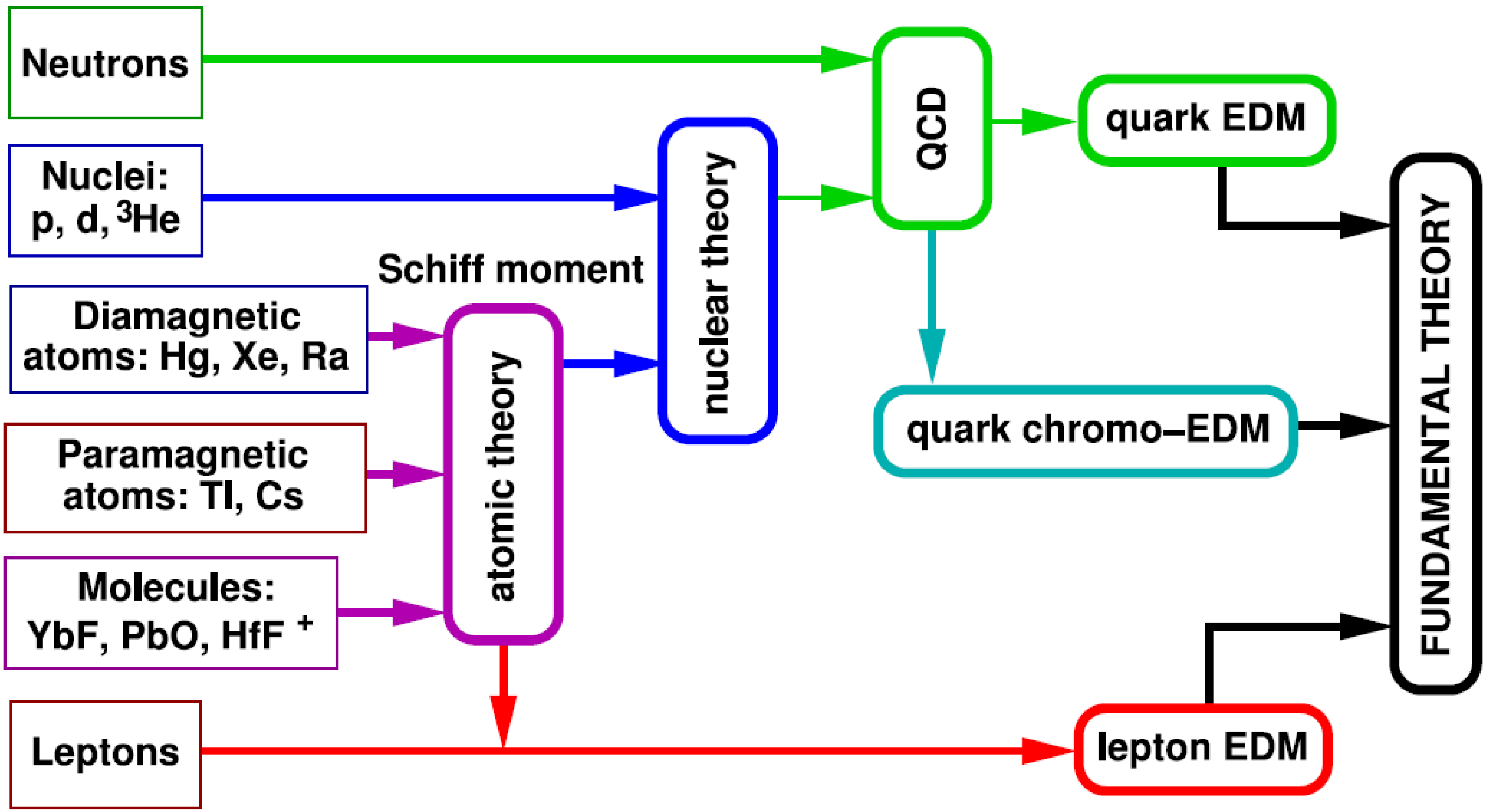
I will discuss why we theorists always knew that you wouldn't find a non-vanishing nEDM. Just in case you will measure one, it will also be discussed, why we theorists always knew that you would eventually find a non-vanishing nEDM.

SM $\rightarrow$ “only” an effective theory valid up to some scale $\Lambda_{\rm UV}$

- in case you won’t find one:
  of course not, $\Lambda_{\rm UV} \gg 1\ {\rm TeV}$ (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


tank
cryo-pump
DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m³
UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)
SV-shutter
7 m
heavy water moderator
→ thermal neutrons
3.6m³ D₂O
cold UCN-converter
~30 dm³ solid D₂ at 5 K
pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
1% duty cycle
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

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

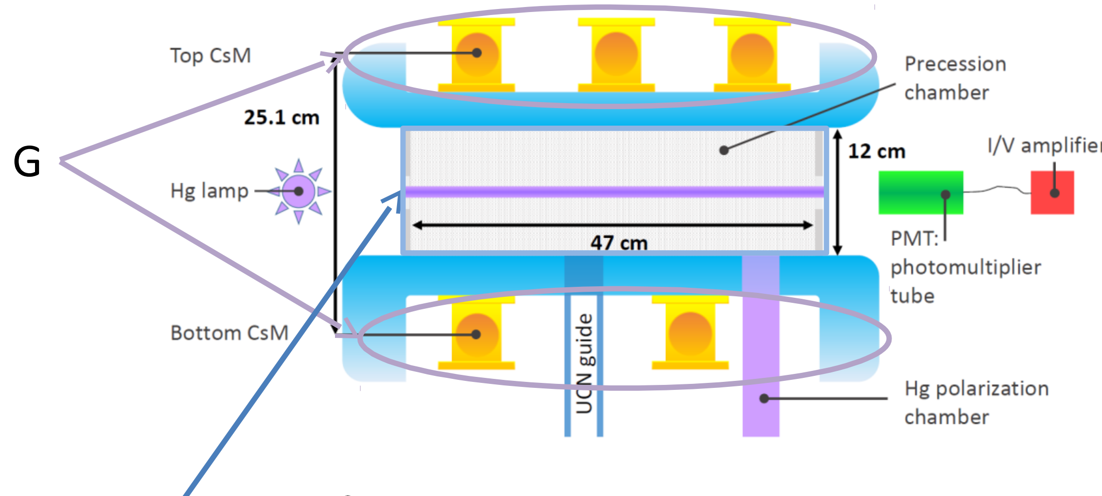
if $d_n > 10^{-30}$ e cm is found it is not clear whether this is BSM or strong CPV ($\bar{\theta} \neq 0$)

but it would be the beginning of a new era

$\Longrightarrow$ need further EDM's to disentangle origin of d_n

A non perfect Co-magnetometer

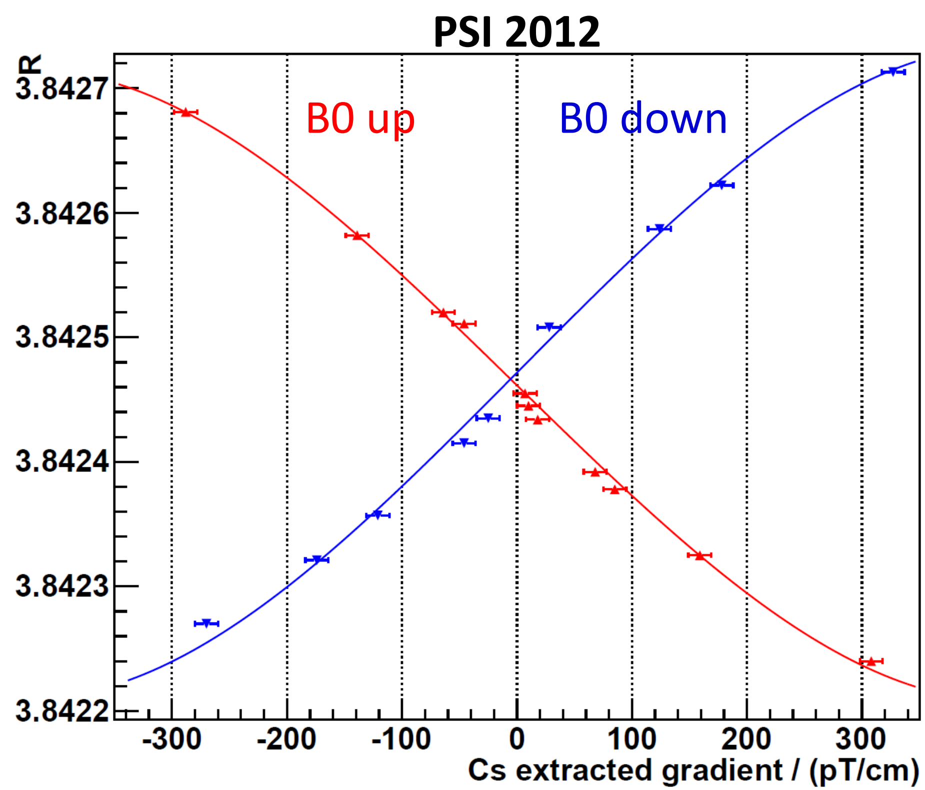
- Gravitational shift



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

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

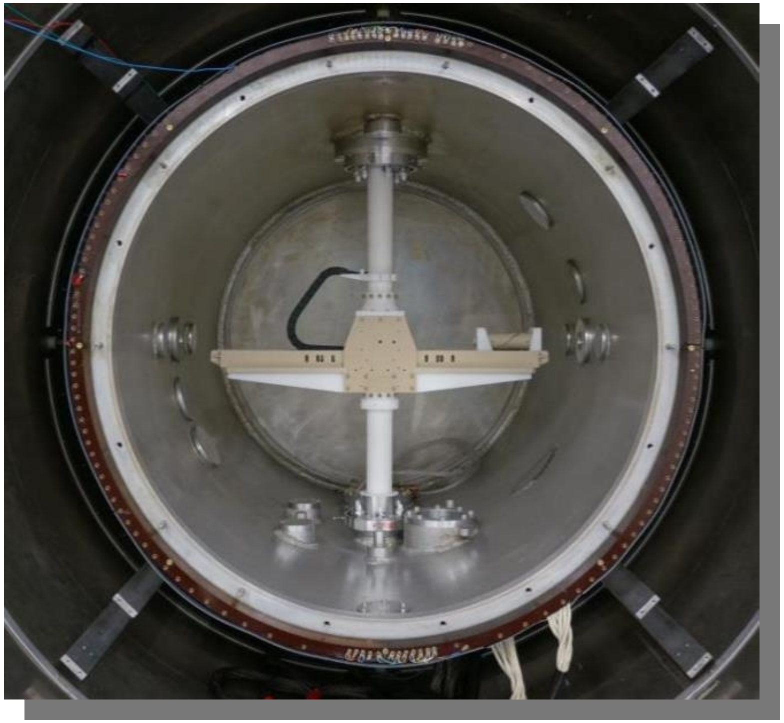
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling

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 non perfect Co-magnetometer

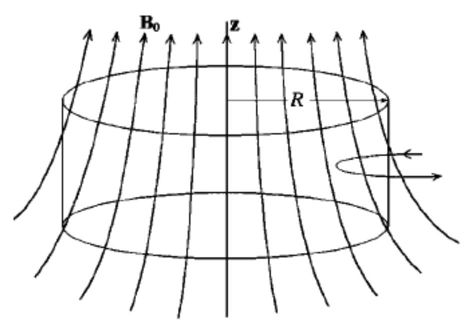
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling
- Geometrical phase shift

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)

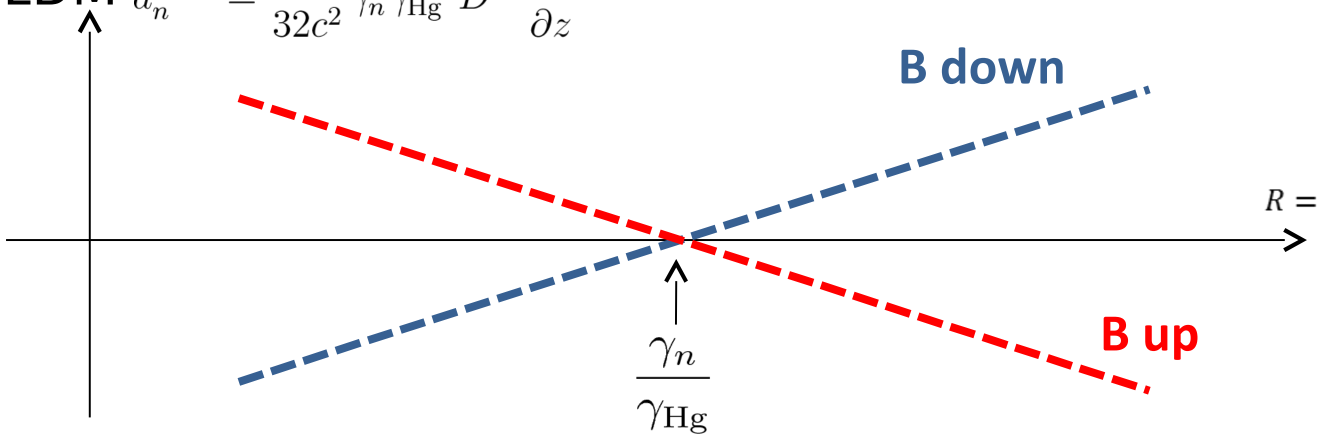
$$d_{\mathrm{Hg}}^{\mathrm{False}} = \frac{\hbar \gamma_{\mathrm{Hg}}^2}{32c^2} D^2 \frac{\partial B}{\partial z} \longrightarrow d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

*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)

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



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

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

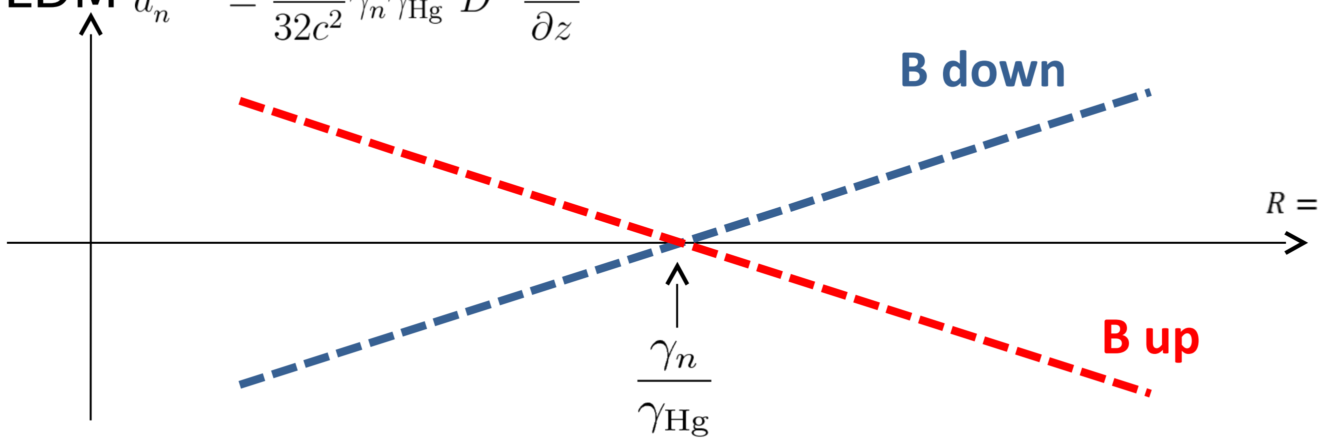
→ **Direct systematic effect**

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)

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



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

In the case of an inhomogeneous B-field

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

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

} Indirect systematic effect due to local dipoles

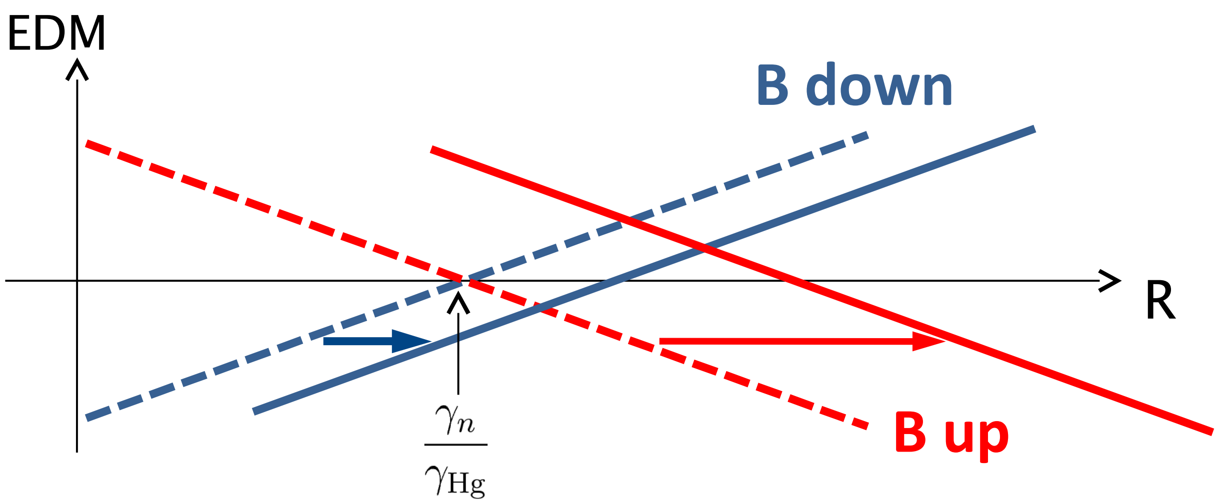
*Pignol et al, PRA **85** 042105 (2012)*

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)

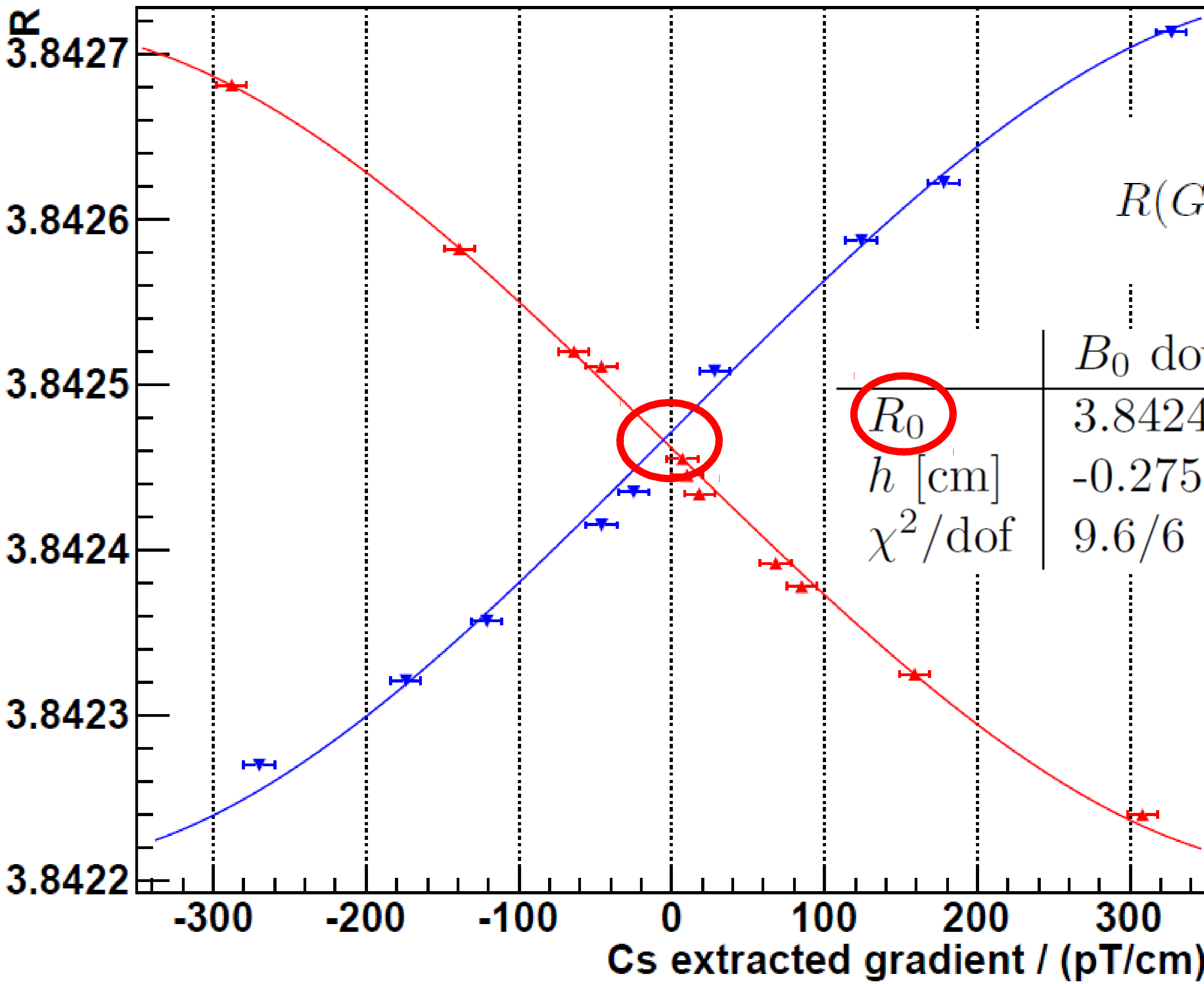
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} + \ \dots \right)$$

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



Some results

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

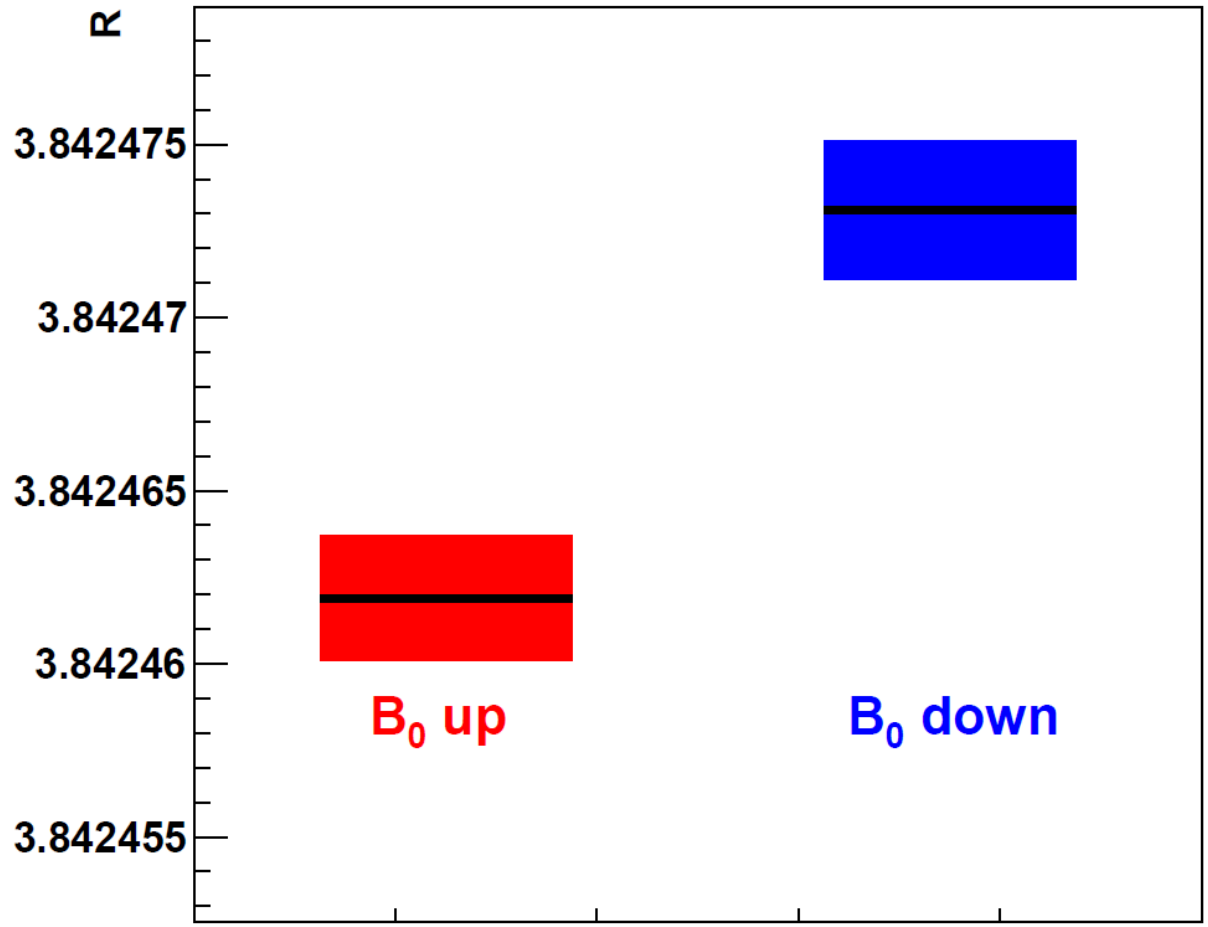


$$R(G) = R_0 \left(1 \pm \frac{Gh}{B_0} + cG^3 \right)$$

	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

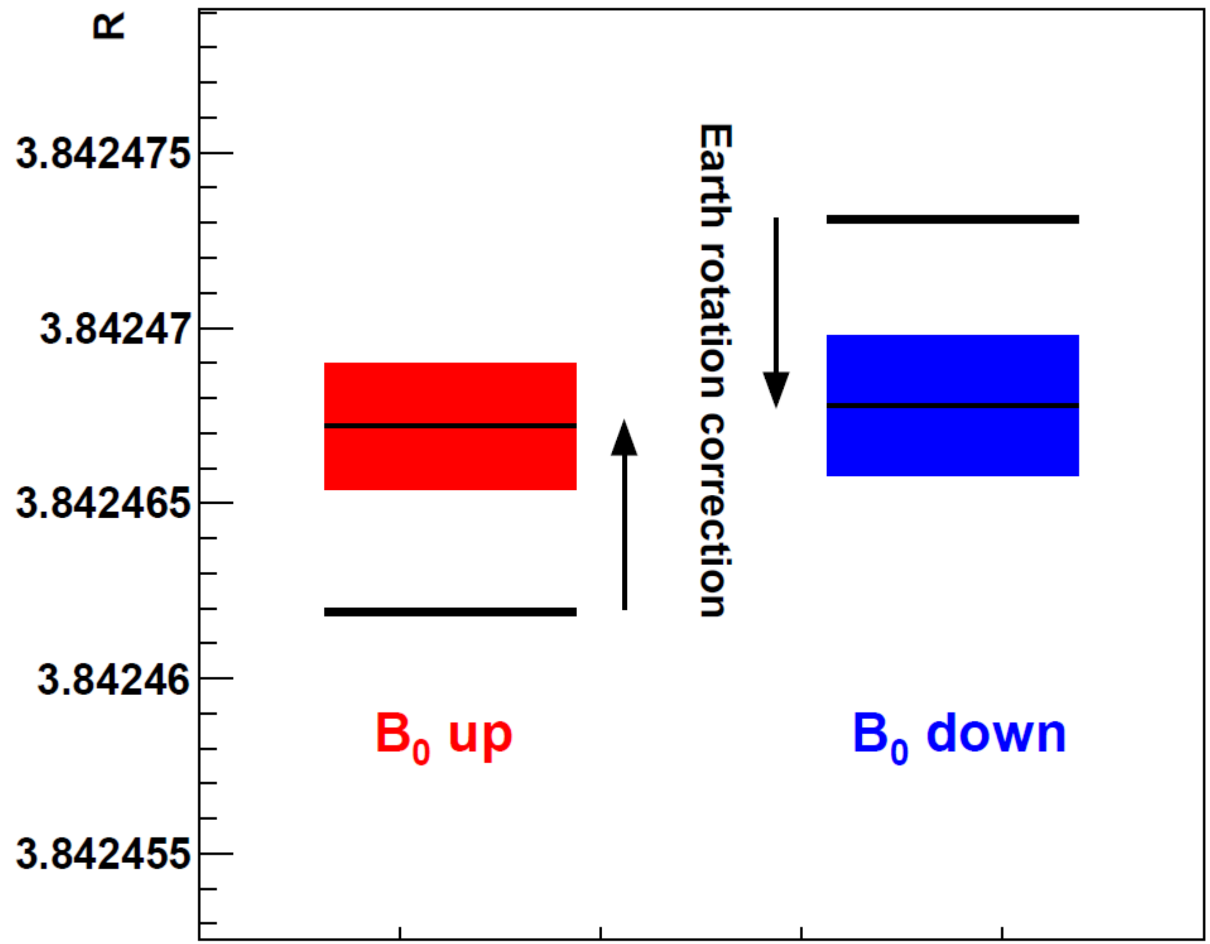
$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy} xy + g_{xz} xz + g_{yz} yz$$

Some results



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

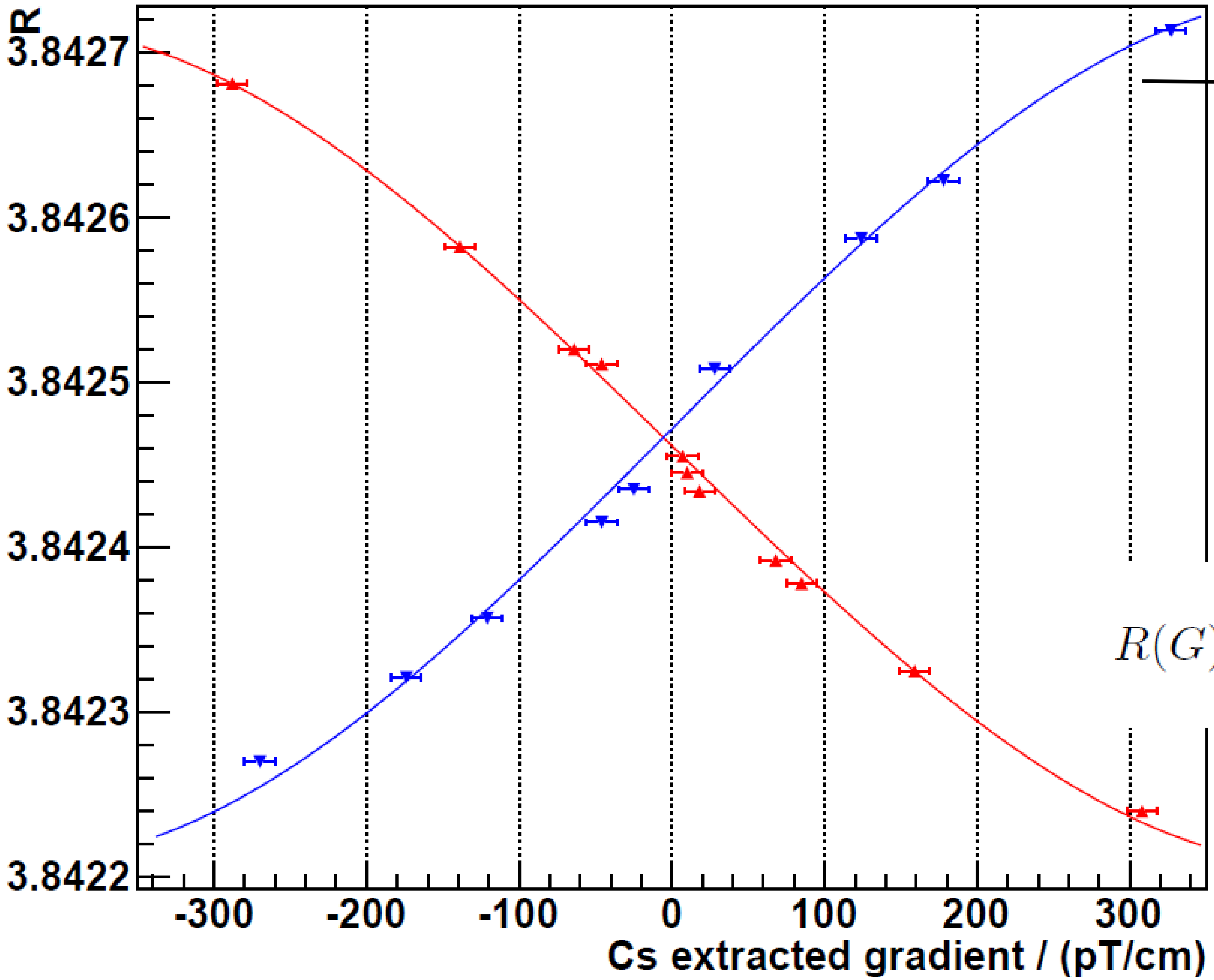
$$f_{\mathrm{Hg}} = \left| \frac{\gamma_{\mathrm{Hg}}}{2\pi} B_0 \pm f_{\mathrm{Earth}} \sin(\lambda) \right|$$



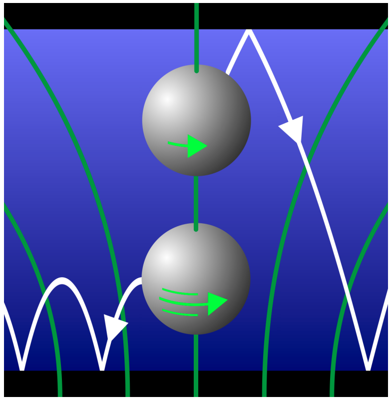
$$\delta R_{\mathrm{Earth}} = \mp \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} \left(\frac{f_{\mathrm{Earth}}}{f_n} + \frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}} \right) \sin(\lambda) = \mp 5.3 \times 10^{-6}$$

Some results

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



Transverse component ?
Gravitational ?



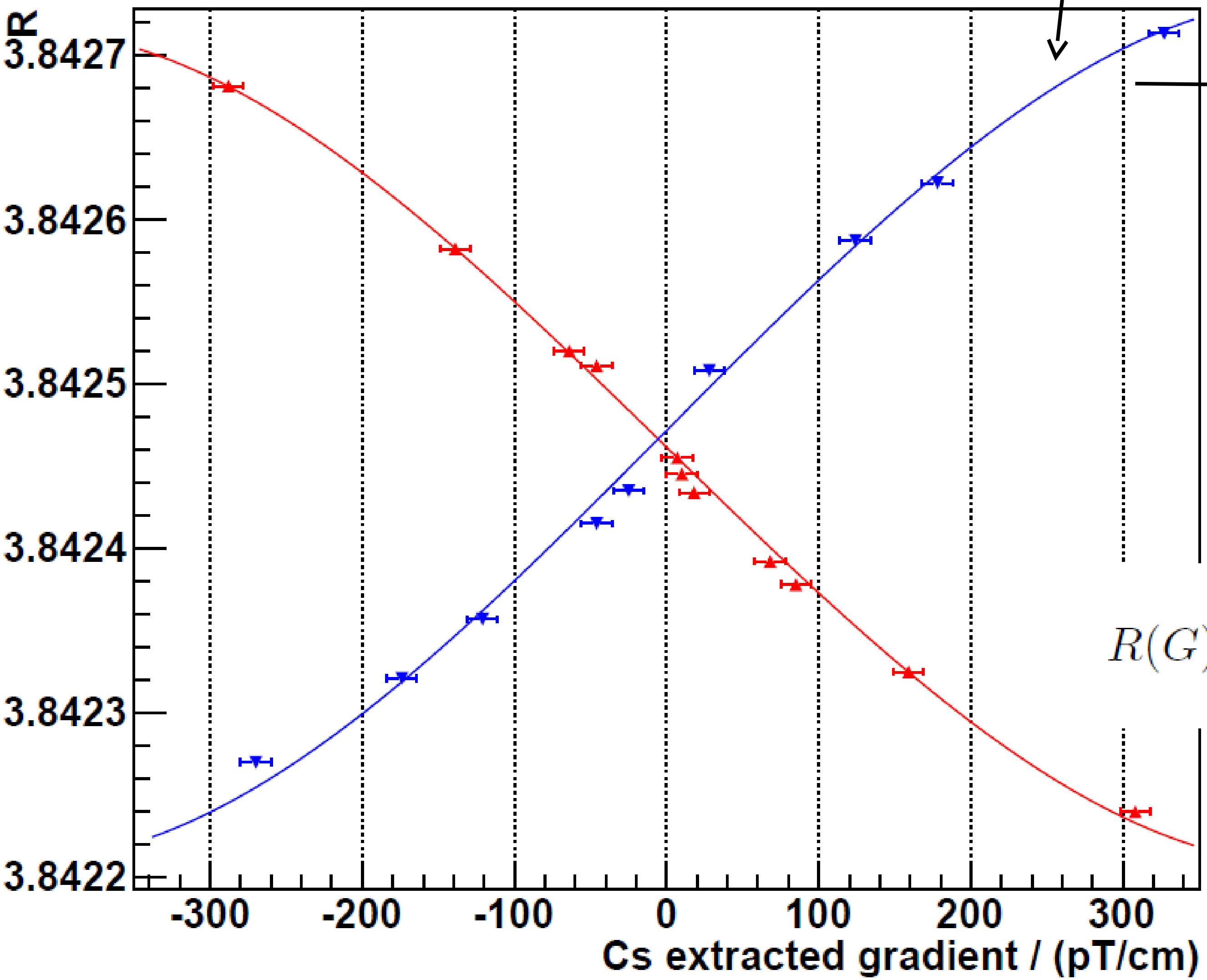
$$R(G) = R_0 \left(1 \pm \frac{Gh}{B_0} + cG^3 \right)$$

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

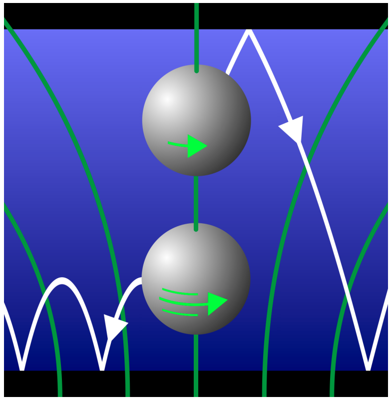
$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}}$$

Gravitational enhanced depolarization and associated frequency shift

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



Transverse component ?
Gravitational ?



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

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Some results

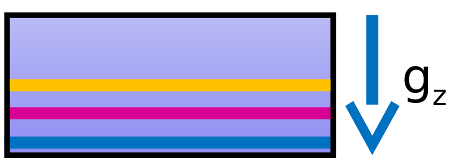
Featured in Physics   Editors' Suggestion

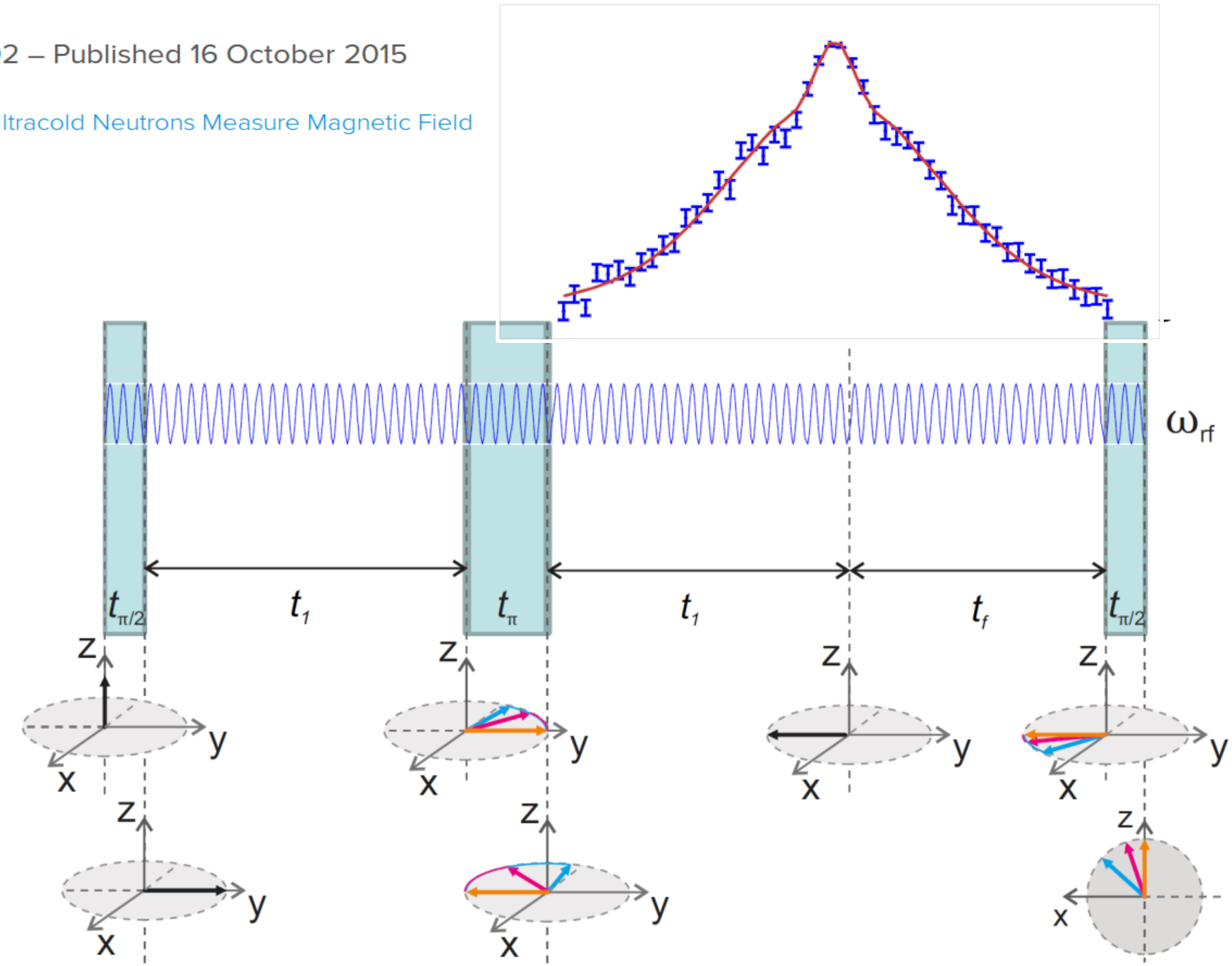
Observation of Gravitationally Induced Vertical Striation of Polarized Ultracold Neutrons by Spin-Echo Spectroscopy

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

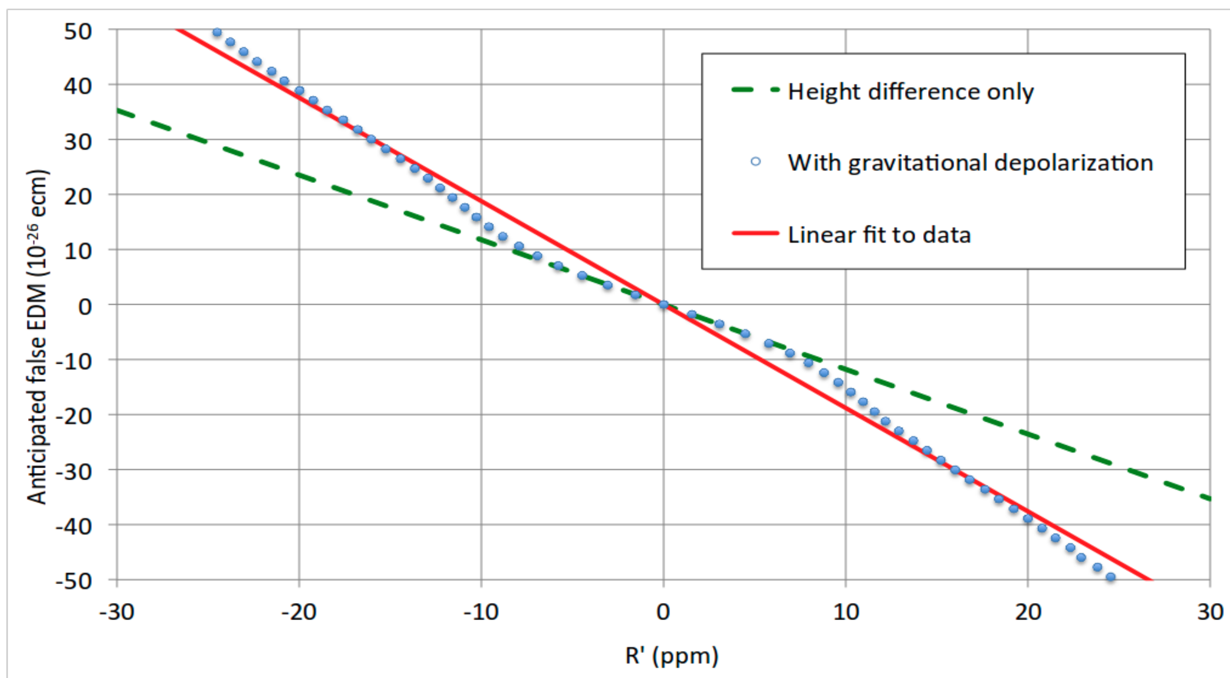
Some results

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]

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

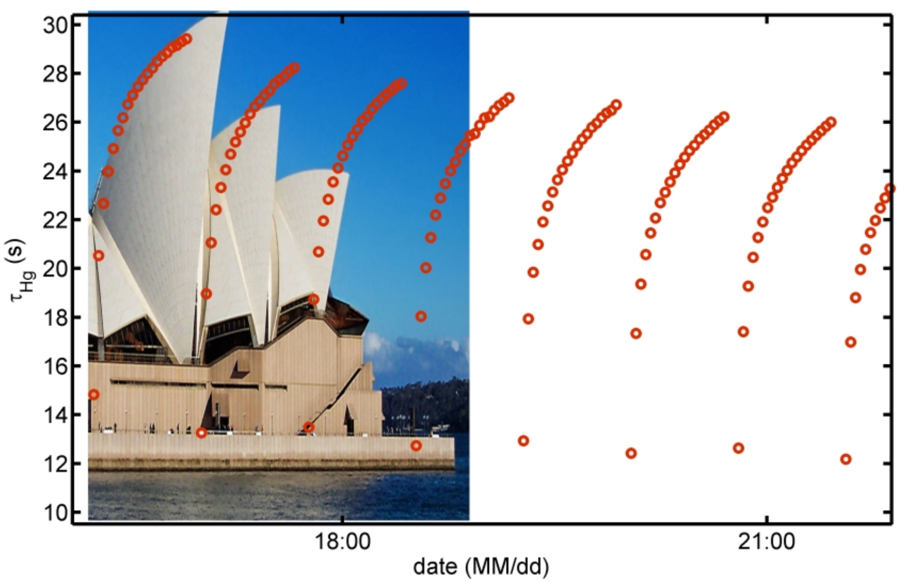
Analysis stage	**EDM**	σ
Crossing point $d_\times$	-0.59	1.53
Gradient-corrected d_0	-0.92	1.68
Dipole-corrected d_{fec}	-0.21	1.79
Final result d_n	**-0.21**	**1.82**



Final result to appear in Phys. Rev. D

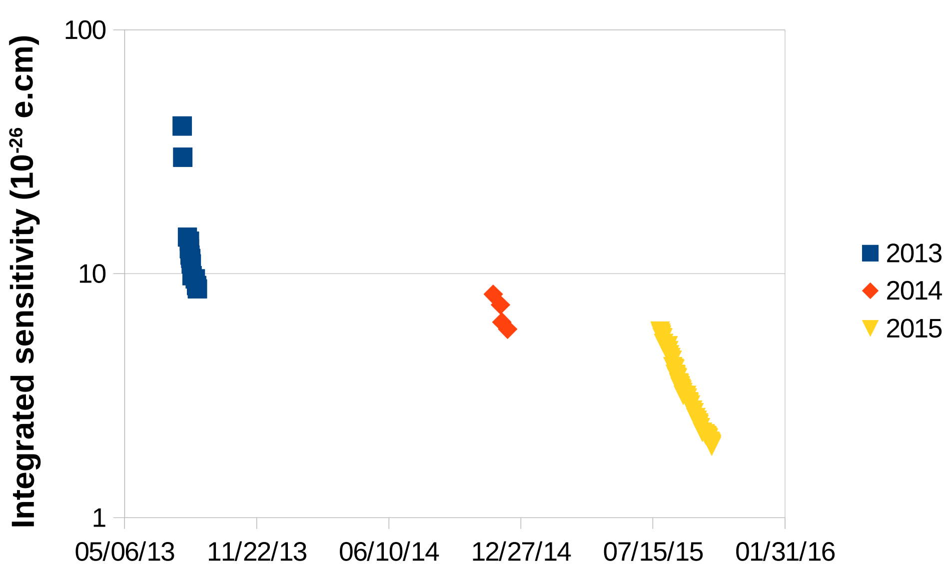
Some results

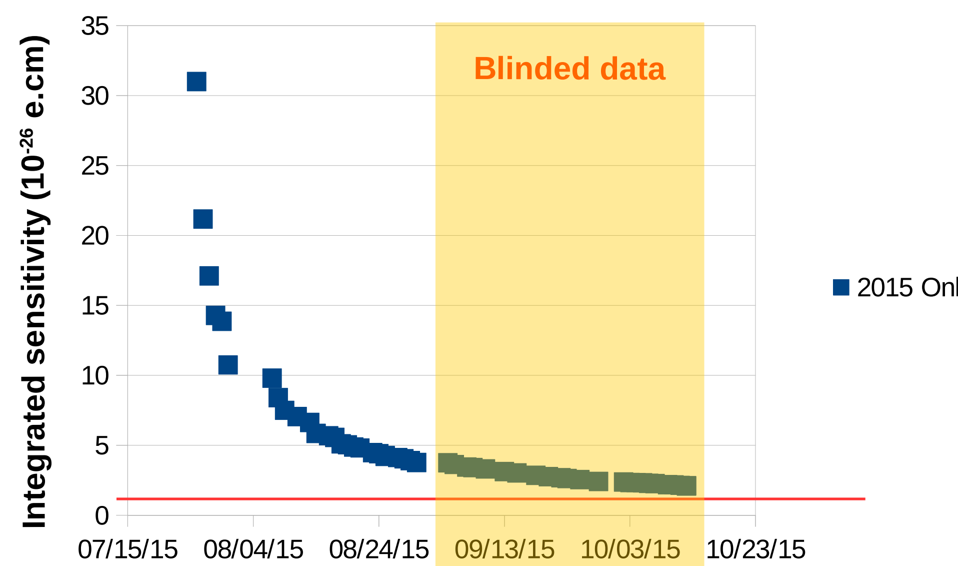
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$



	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
	2.8	2.0	2.9	1.3

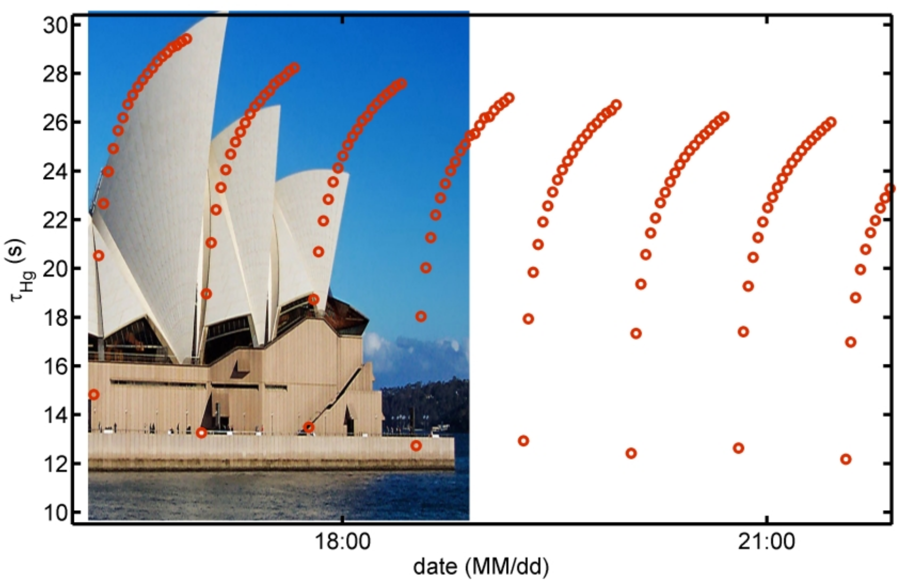
	PSI 13	PSI 14		PSI 15
	avg	best	avg	Likely
E-field (kV/cm)	10.3	10	10	11
Neutrons	6 500	7 500	4 400	11 200
T_{free}	180	220	220	194
T_{duty}	340	340	340	340
A	0.57	~0.65	~0.6	0.65
σ(day) (10^{-25}ecm)	2.8	2.0	2.9	1.6





Some results

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



New limit in 2016 ?

	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
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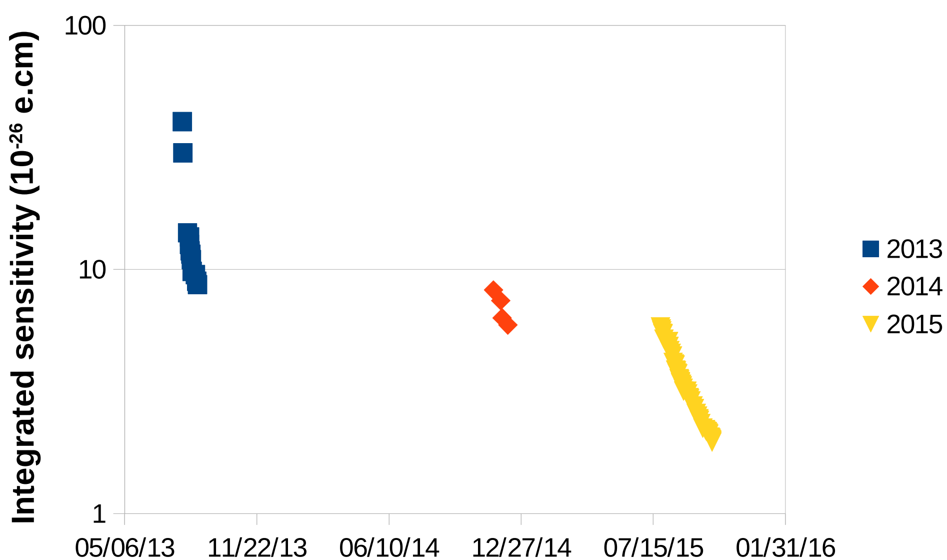
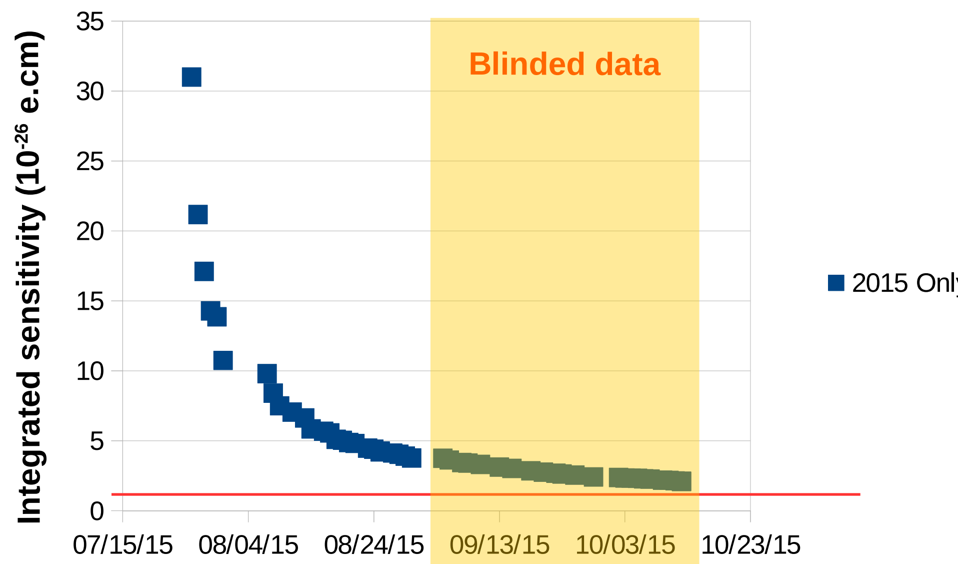
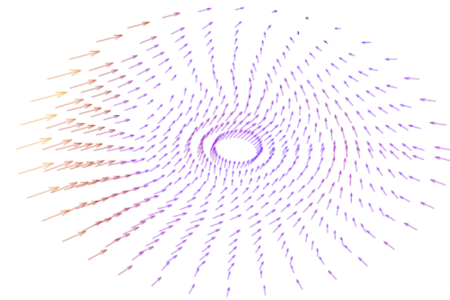


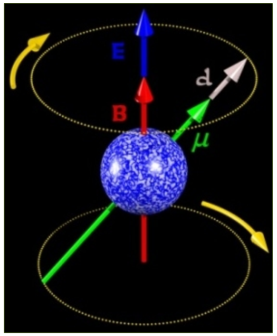


Magnetic field



- 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* cm
- n2EDM in R&D phase towards 2.10^{-27} e.cm

Thanks
Merci

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 nEDM@PSI collaboration

2007

2014

A growing team … getting oversea