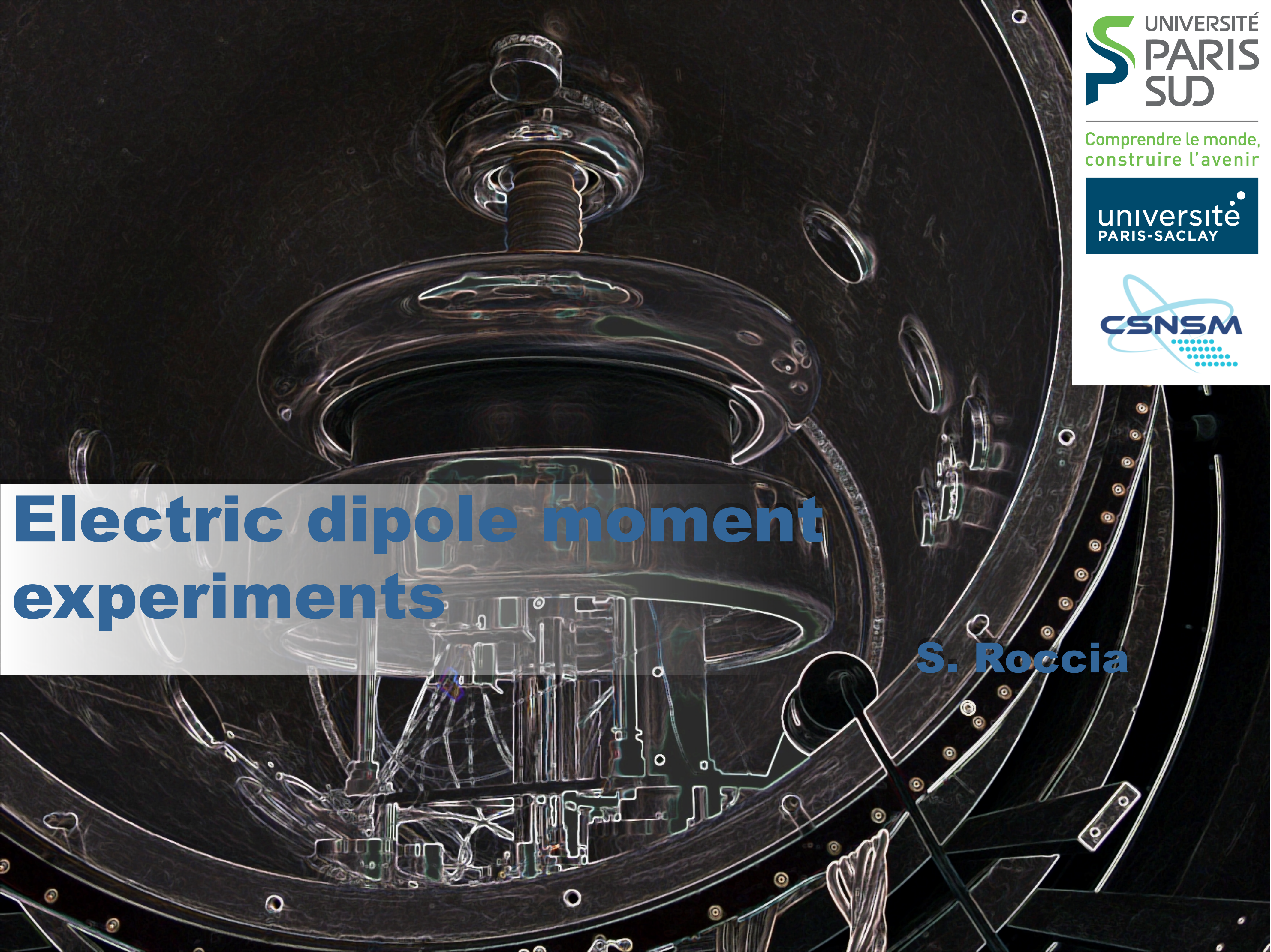
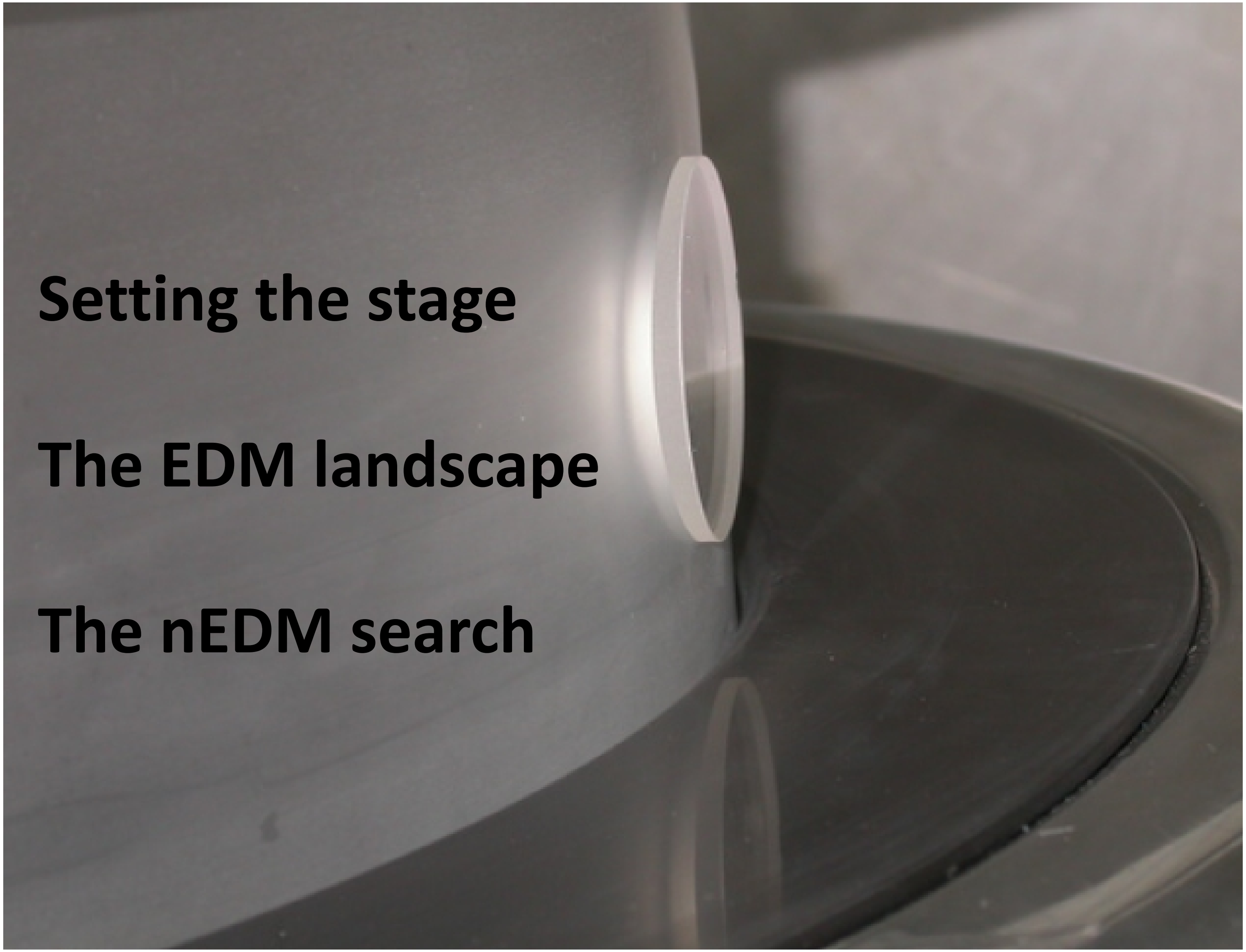


Electric dipole moment experiments

S. Roccia

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

Outlines



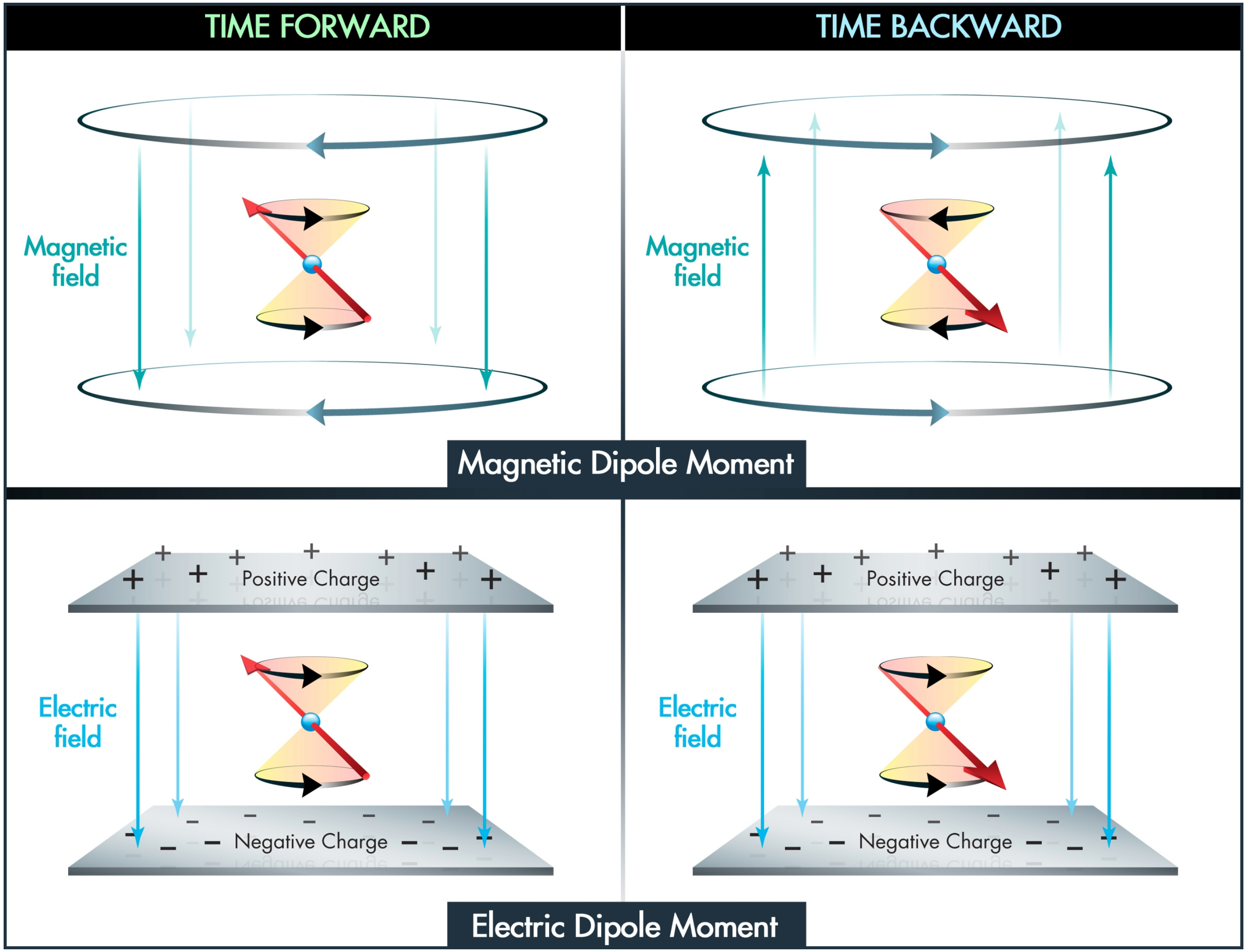
Setting the stage

The EDM landscape

The nEDM search

Setting the stage

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



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 → “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 $d = 0$?

Setting the stage

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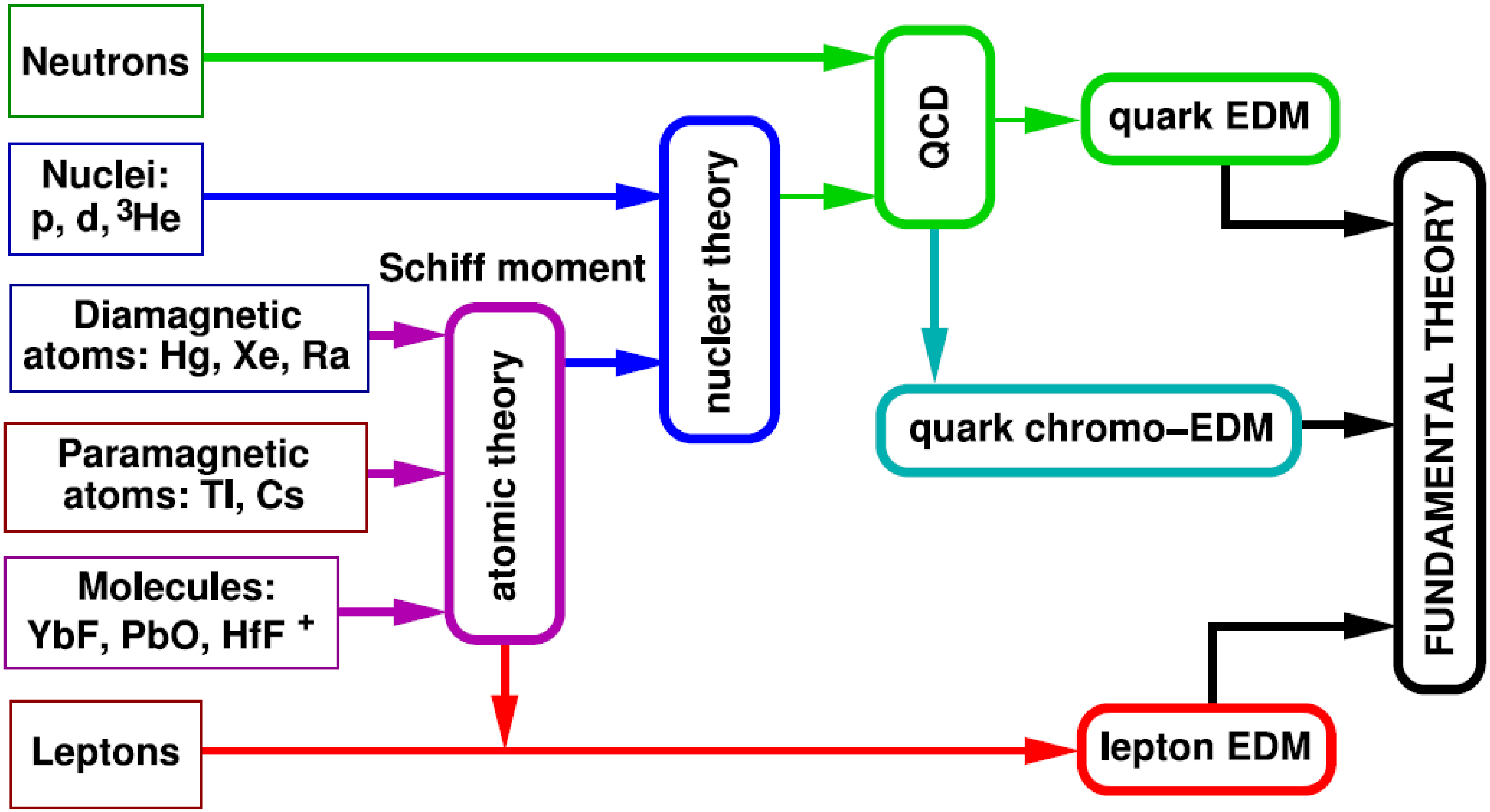
    - dark matter
    - strong CP problem
    - hierarchy problem
    - gravity, dark energy
- which of these are related to $d = 0$?
    - need CP violation
    - CP violation within the SM:
        - weak CP violation δ_{CKM}
        - strong CP violation $\theta_{QCD} < 10^{-10}$
    - CP violation outside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

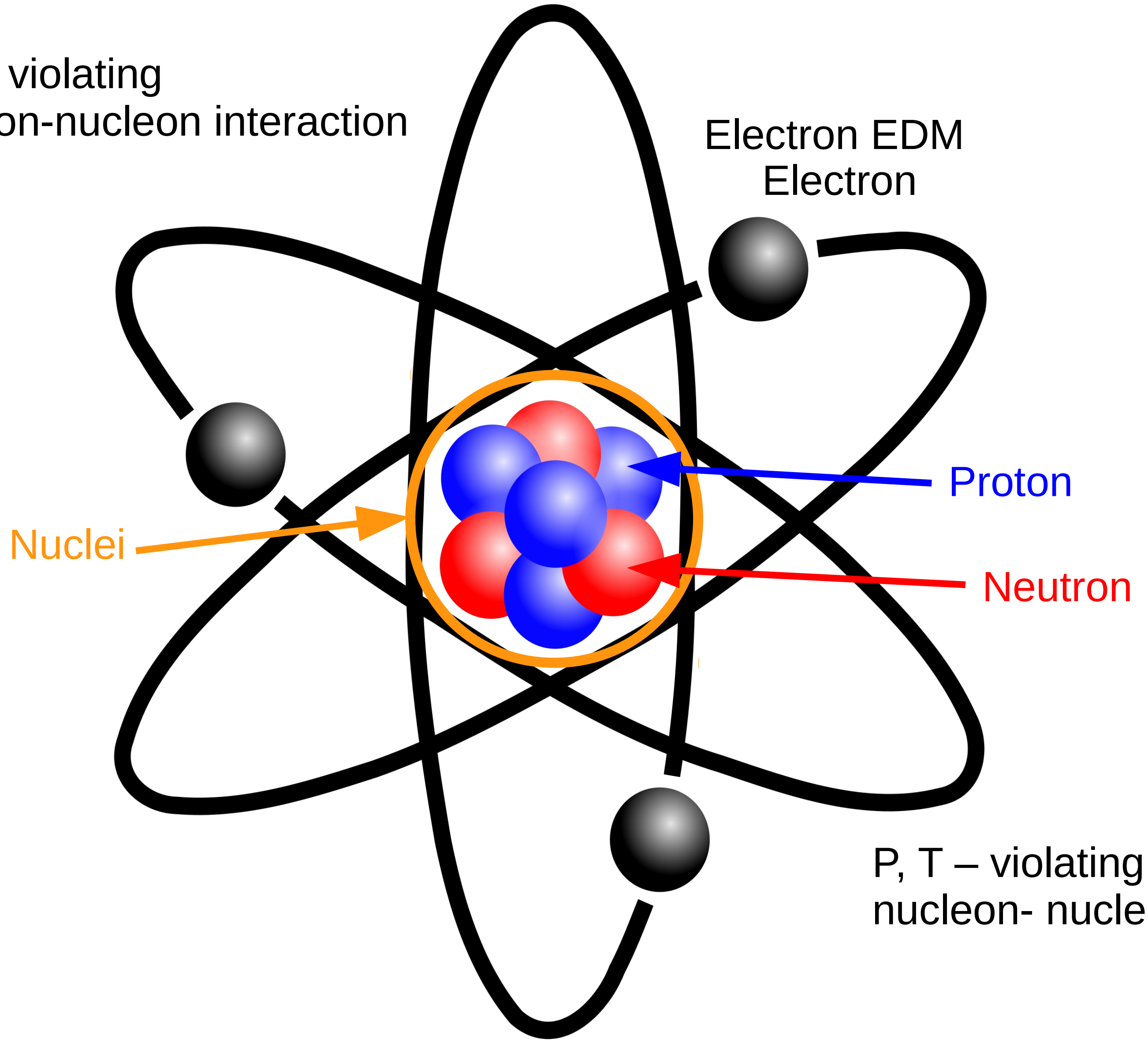
The EDM landscape



C. R. Physique 13 168 (2012)

EDM of charged particles by Themis Bowcock
Today at 11:40

EDM of atoms and molecules



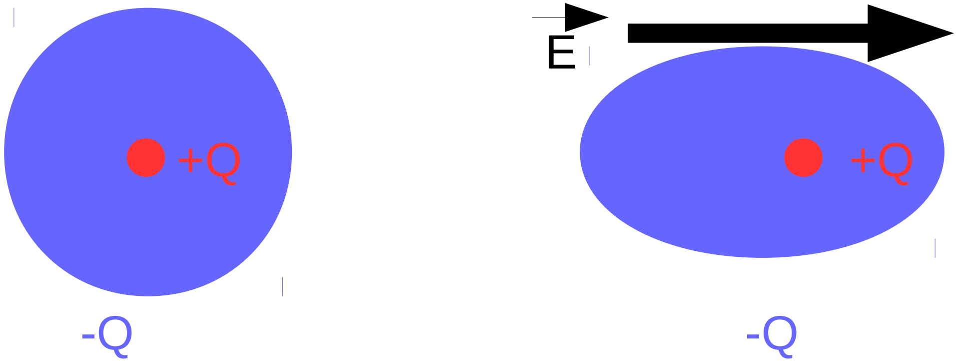
P, T – violating
electron-nucleon interaction

Electron EDM
Electron

Nucleon EDM

P, T – violating
nucleon- nucleon interaction

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

Deformed nuclei

–Enhanced signal

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

GOING PEAR-SHAPED

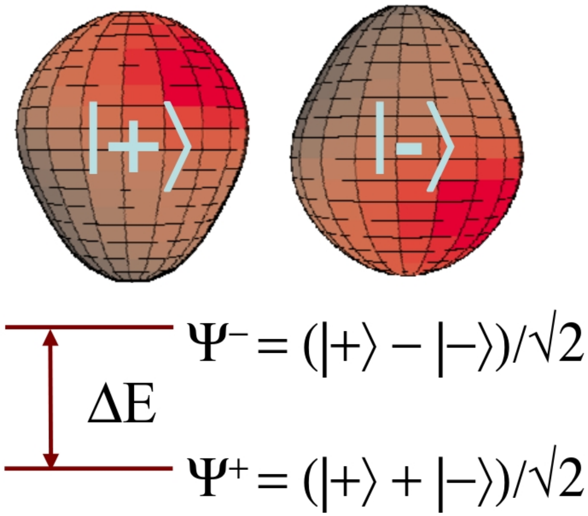
Exotic radium-224 atomic nuclei seen at CERN

PAGES 196 & 199

STAYING IN TOUCH

HEATED ARGUMENT

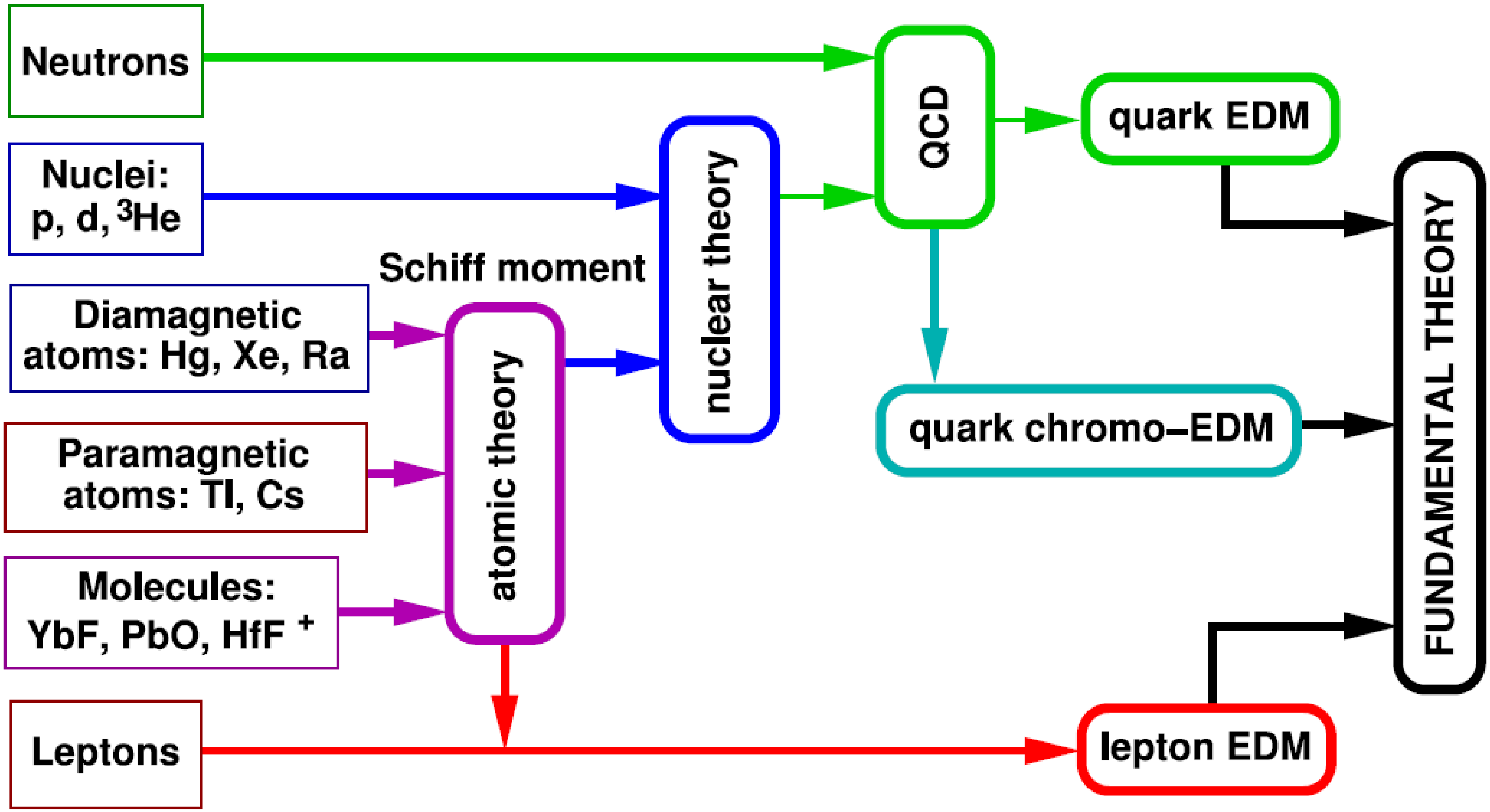
THE AGE OF THE BRAIN



$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

The EDM landscape



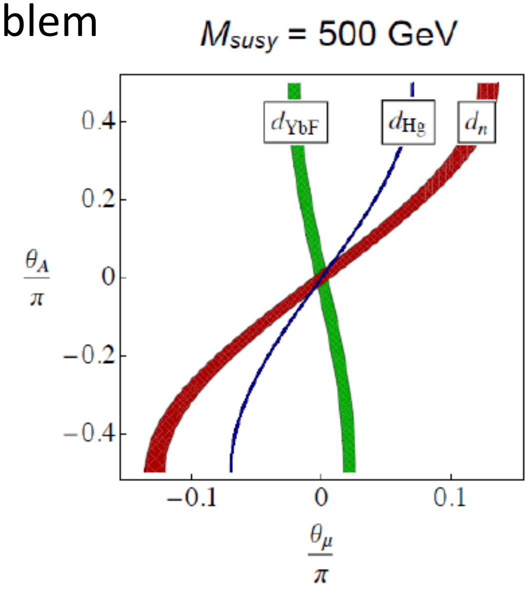
C. R. Physique 13 168 (2012)

Probing a theory

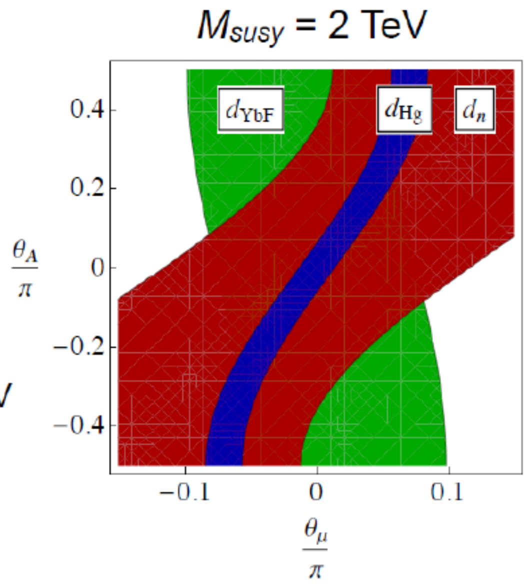
The EDM landscape

SUSY, EDMs and the LHC

SUSY CP problem



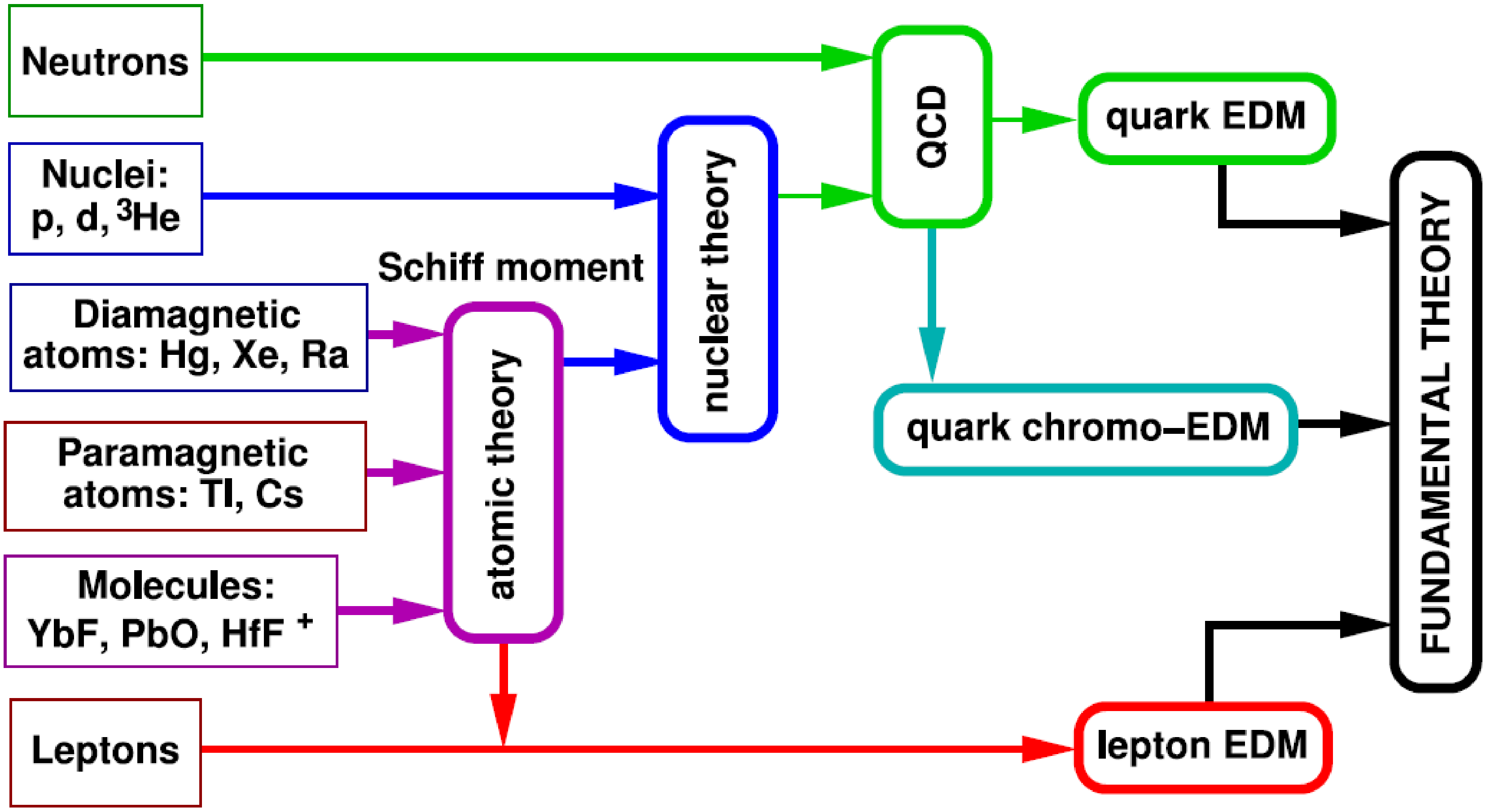
1st gen squarks excluded by direct searches at ~1 TeV



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



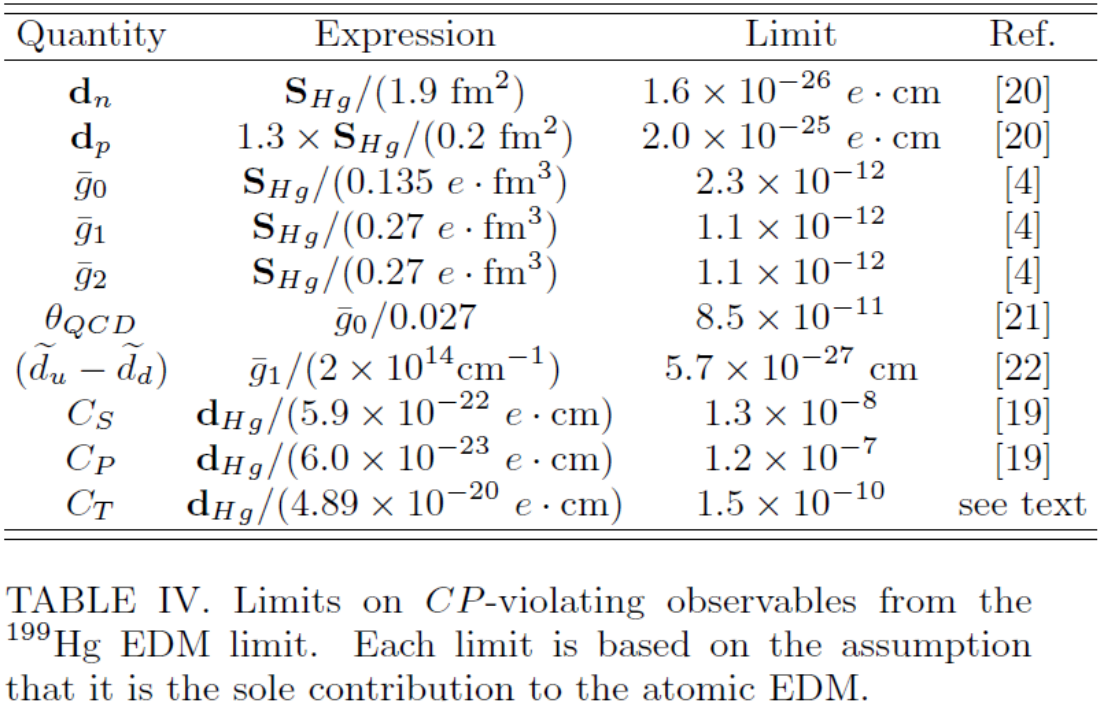
C. R. Physique 13 168 (2012)

The EDM landscape

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

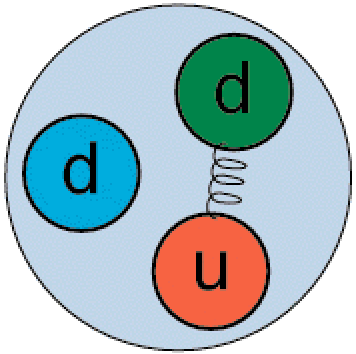
TABLE IV. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM.

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

- Without “single-source” restriction

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

The nEDM search



Adrian SIGNER

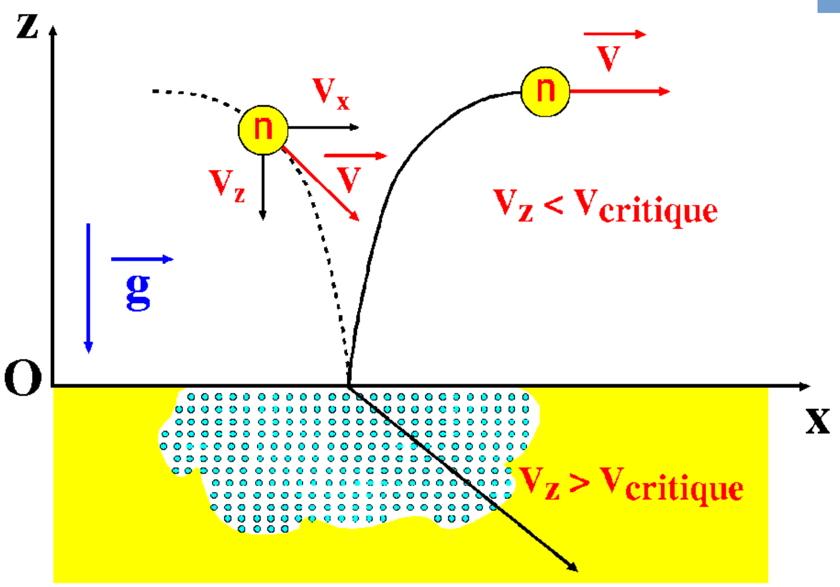
I will discuss why we theorists always knew that you wouldn't find a non-vanishing nEDM. Just in case you will measure one, it will also be discussed, why we theorists always knew that you would eventually find a non-vanishing nEDM.

The nEDM search

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;

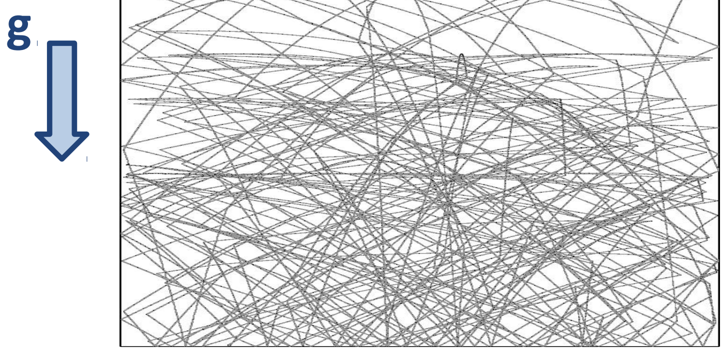
$T_n \approx 2$ mK ;

$E_n \approx 130$ neV

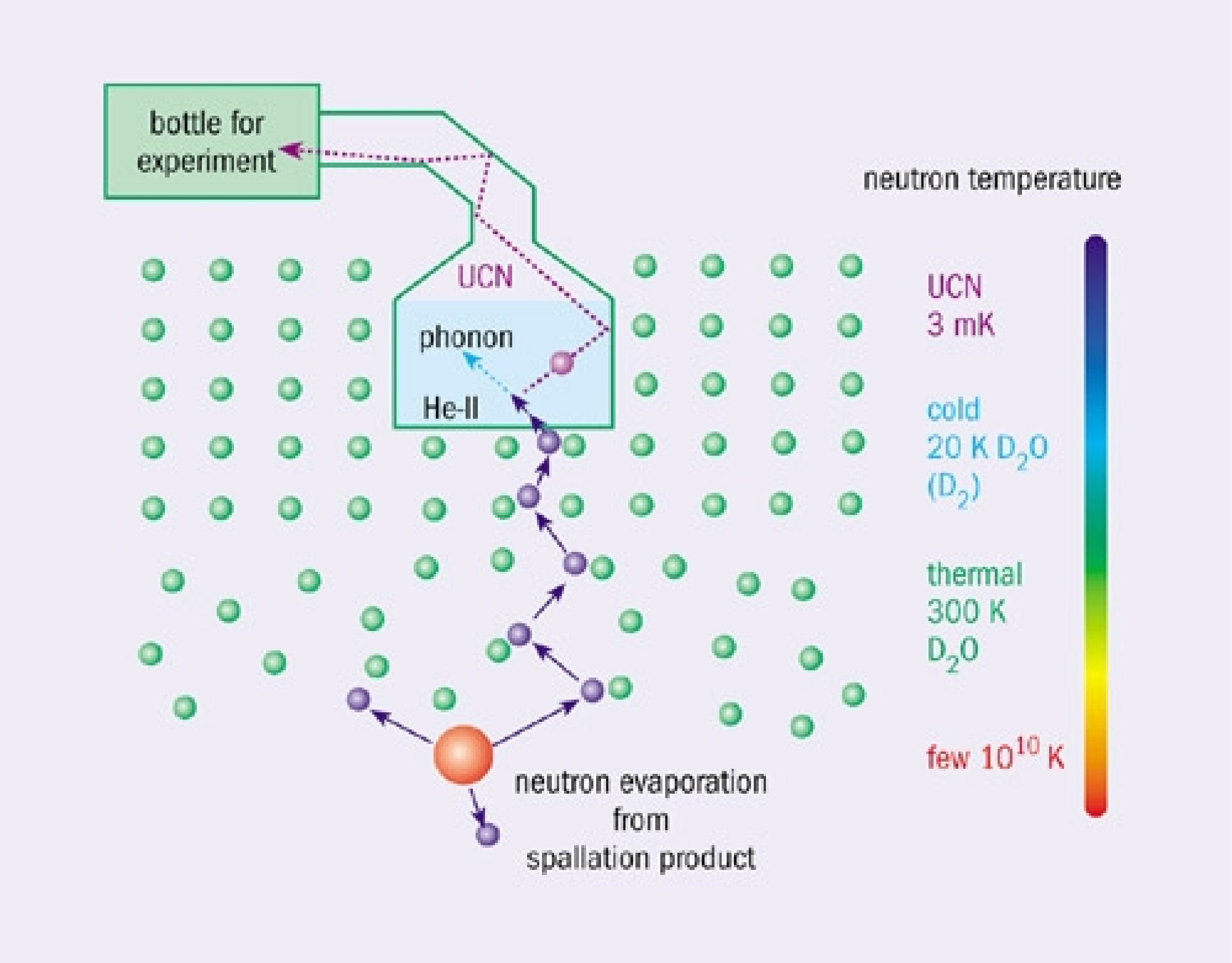
λ_n>>2 Å :

Neutrons see the Fermi potential

Can be stored !



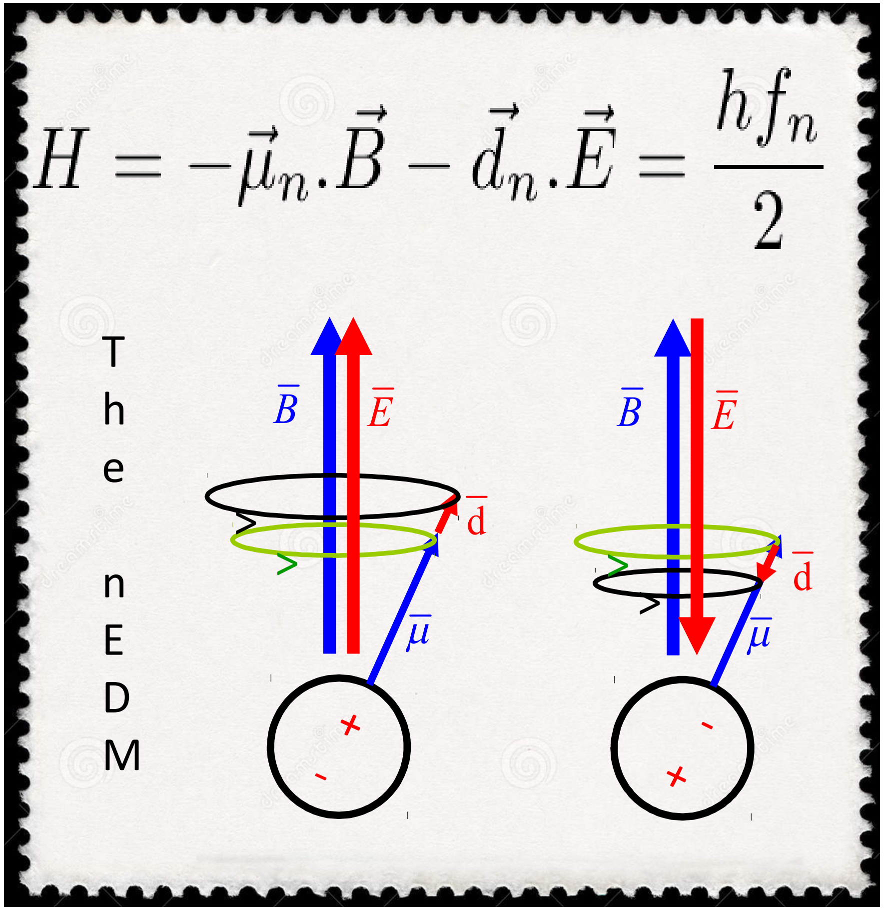
The nEDM search



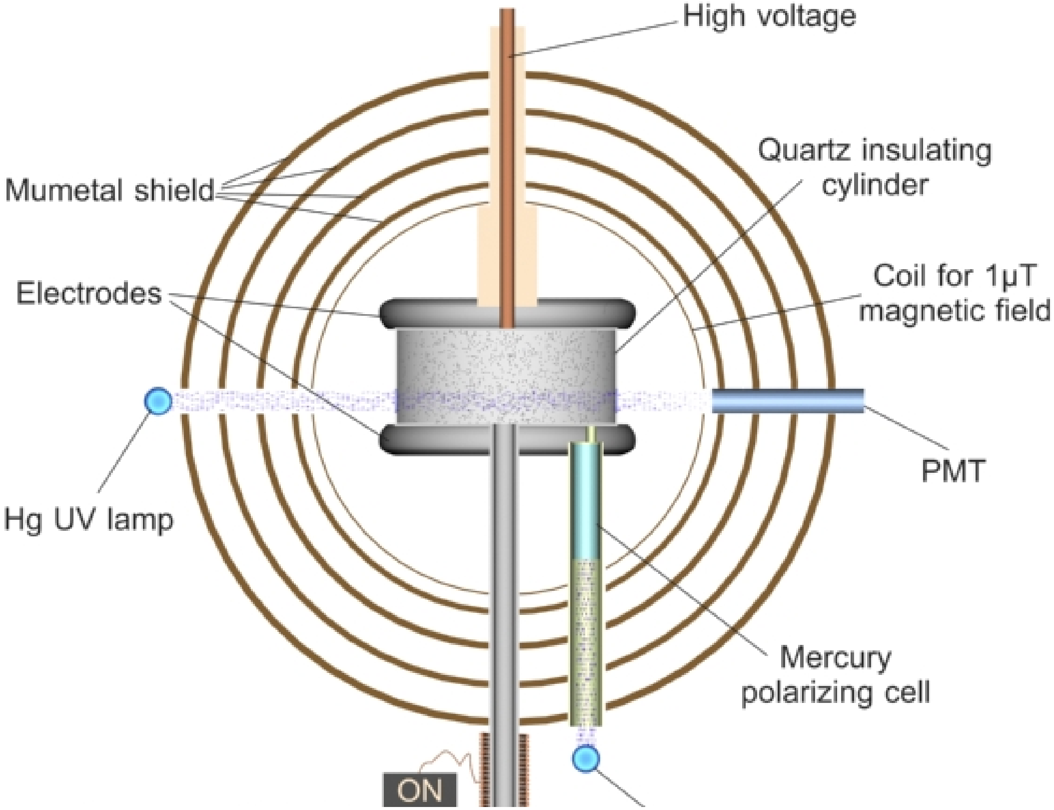
In vacuum ?
In He ?

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

A nEDM apparatus



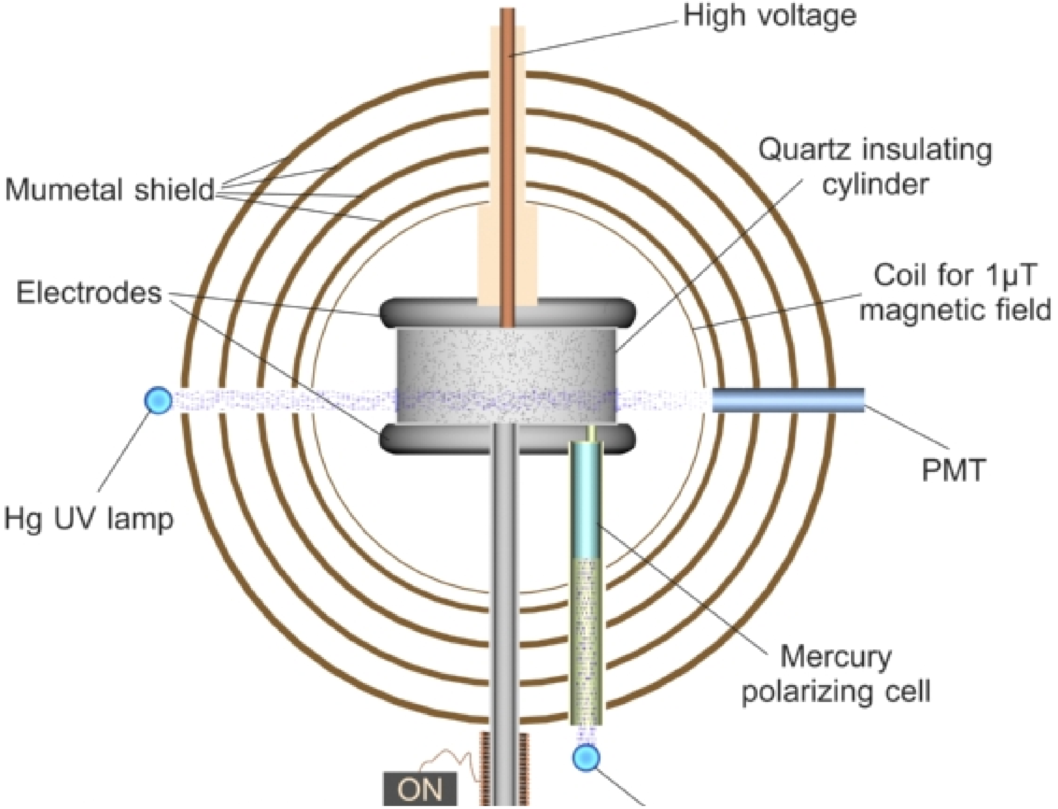
$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$



First limitation ….. Magnetic field fluctuations

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

A nEDM apparatus



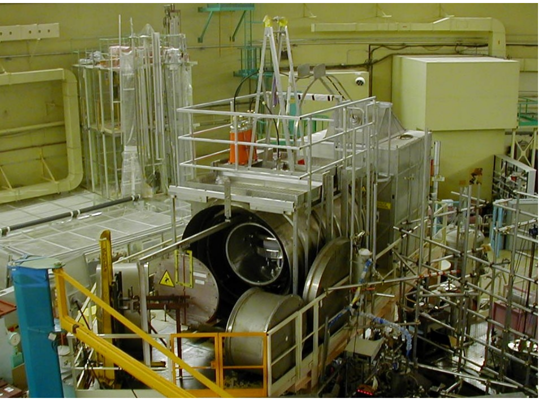
Mercury co-magnetometer (1998)

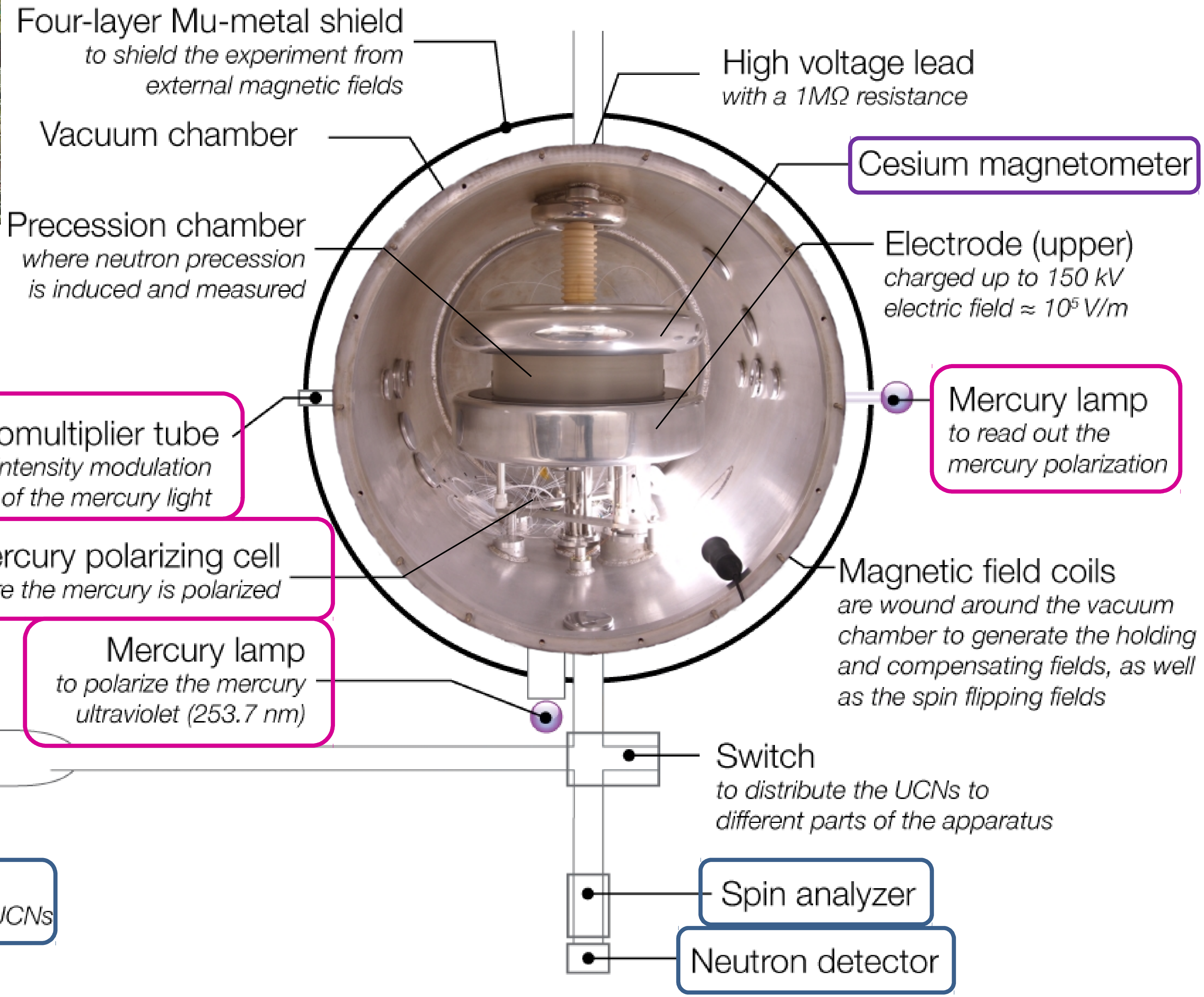
$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

First limitation ….. Magnetic field fluctuations

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

A nEDM apparatus





Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber
where neutron precession is induced and measured

High voltage lead
with a 1MΩ resistance

Cesium magnetometer

Electrode (upper)
charged up to 150 kV
electric field ≈ 10^5 V/m

Photomultiplier tube
to detect the intensity modulation of the mercury light

Mercury lamp
to read out the mercury polarization

Mercury polarizing cell
where the mercury is polarized

Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)

Switch
to distribute the UCNs to different parts of the apparatus

5 tesla magnet
to spin polarize the UCNs

Spin analyzer

Neutron detector

A completely new experiment or an old one?

A nEDM apparatus

Geometrical phase shift

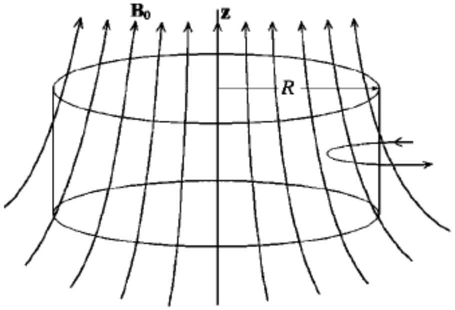
Hg comagnetometer

Motional (transverse) field

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

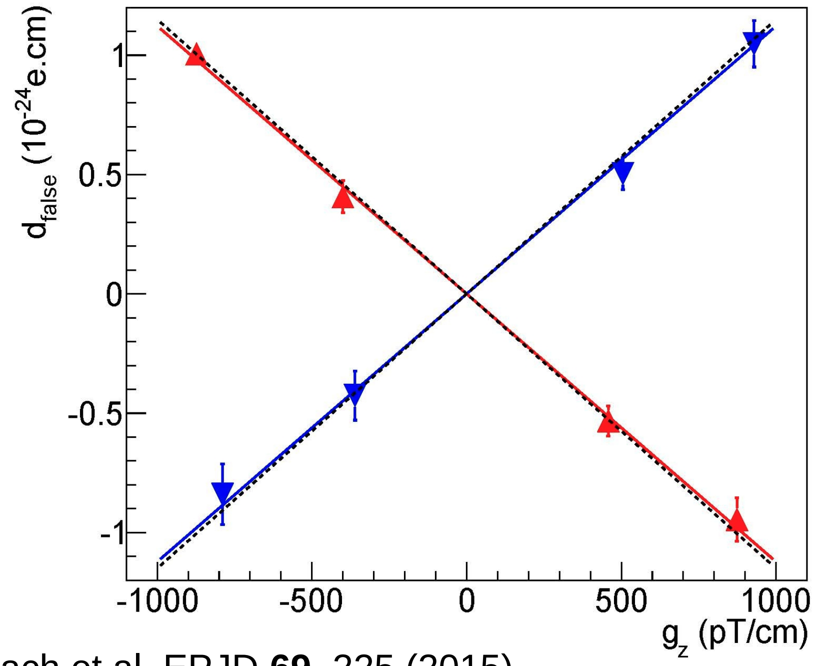
+

Magnetic transverse field



→ Frequency shift correlated with electric field

False EDM for Mercury (fast regime of GPE)



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

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

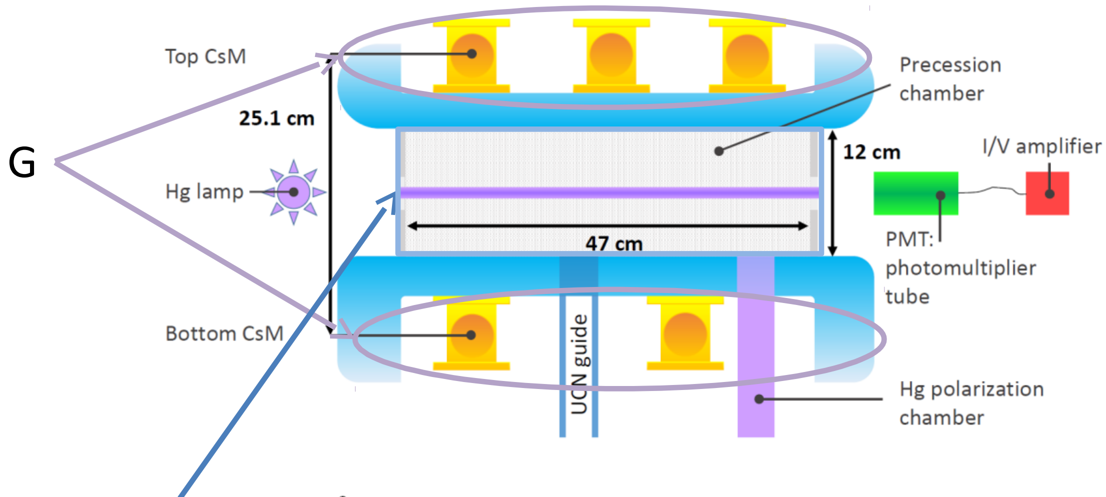
$$\longrightarrow d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

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

A nEDM apparatus

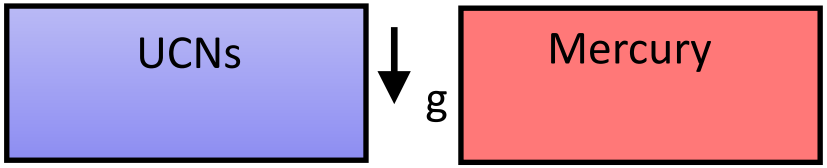
A non perfect Co-magnetometer

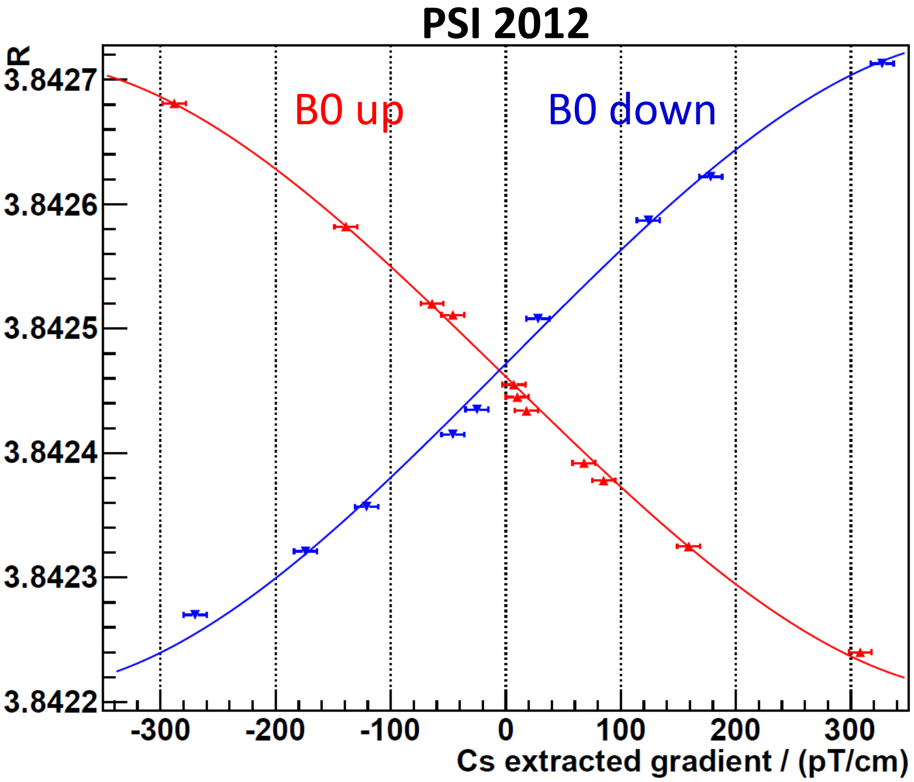
- Gravitational shift



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

In the precession chamber





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

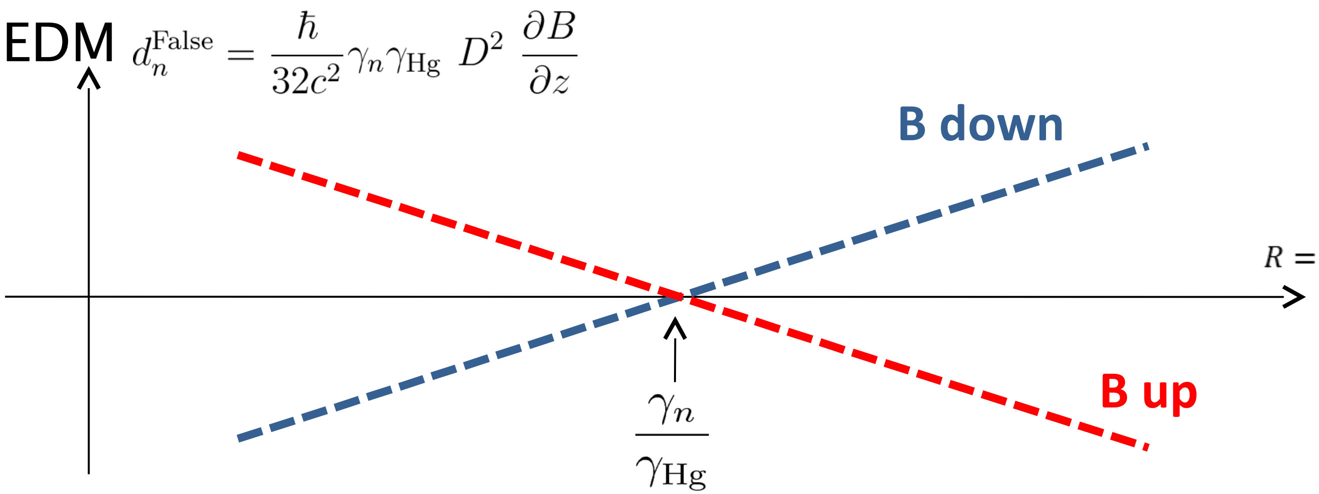
Δh=2.7 mm

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

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)



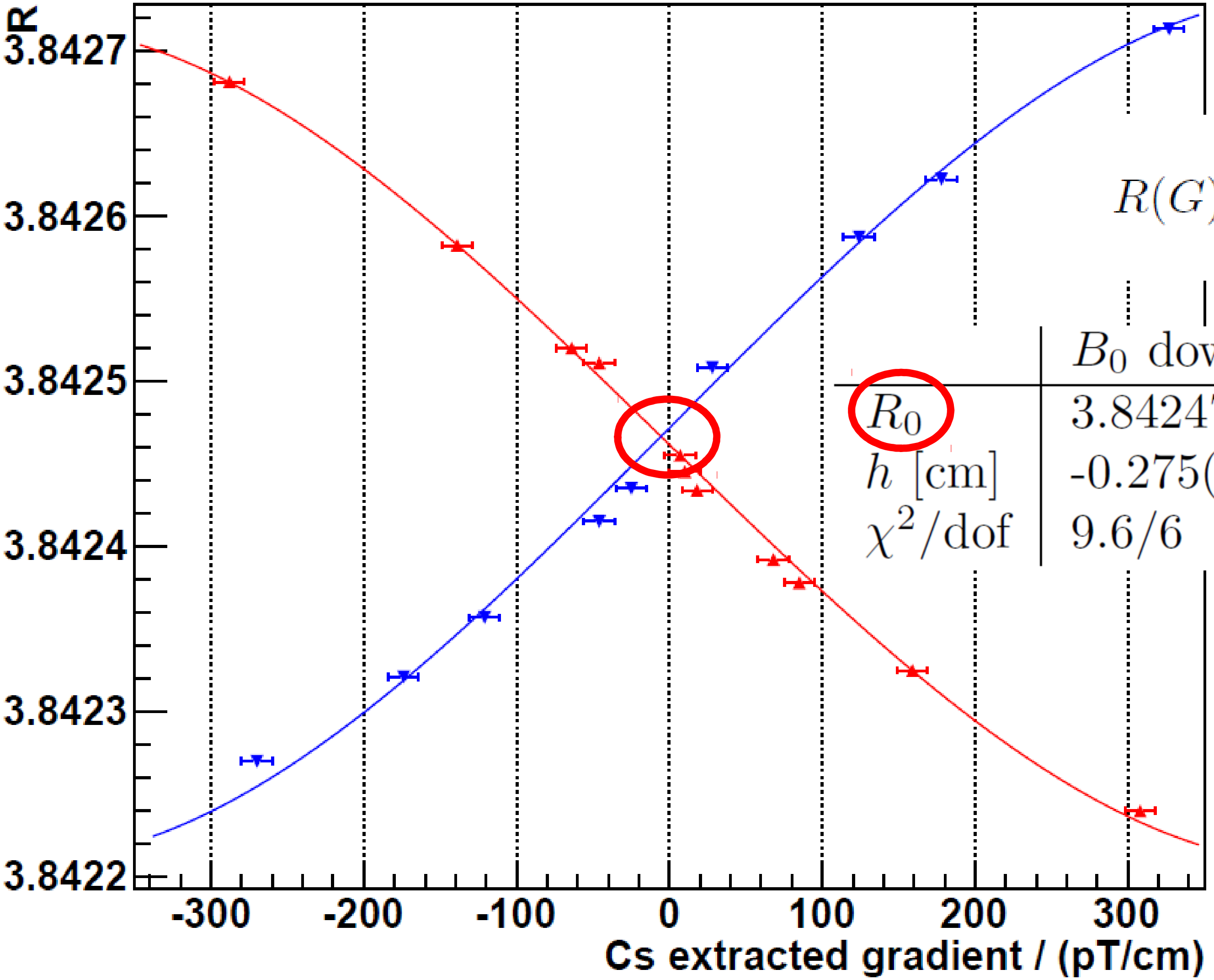
$$d_n^{\mathrm{False}} = \frac{\hbar}{32c^2}\gamma_n\gamma_{\mathrm{Hg}}\ D^2\ \frac{\partial B}{\partial z}$$

$$\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}$$

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

Some results

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



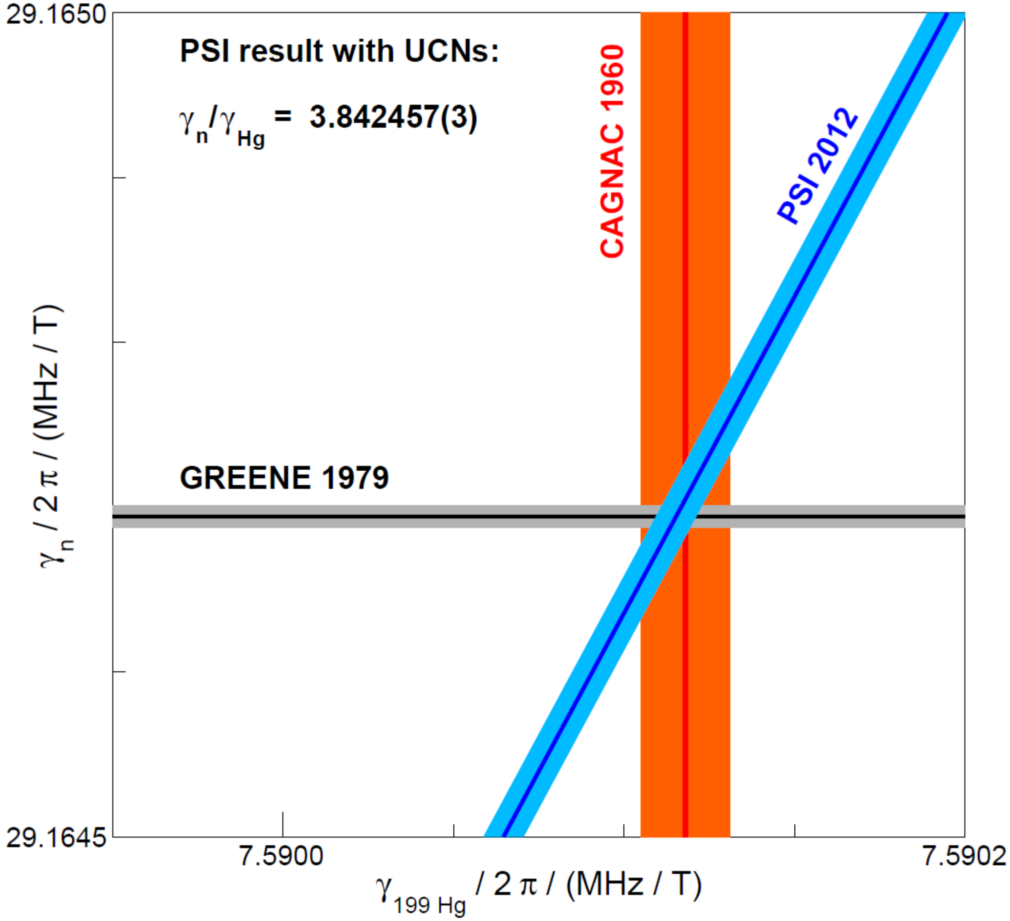
$$R(G) = R_0 \left(1 \pm \frac{Gh}{B_0} + cG^3 \right)$$

	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

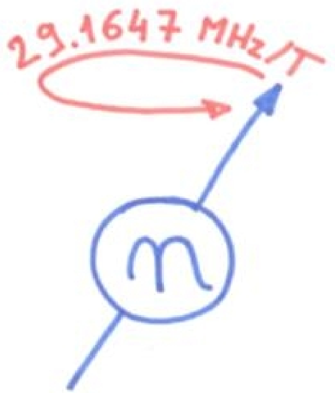
$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy} xy + g_{xz} xz + g_{yz} yz$$

Some results

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



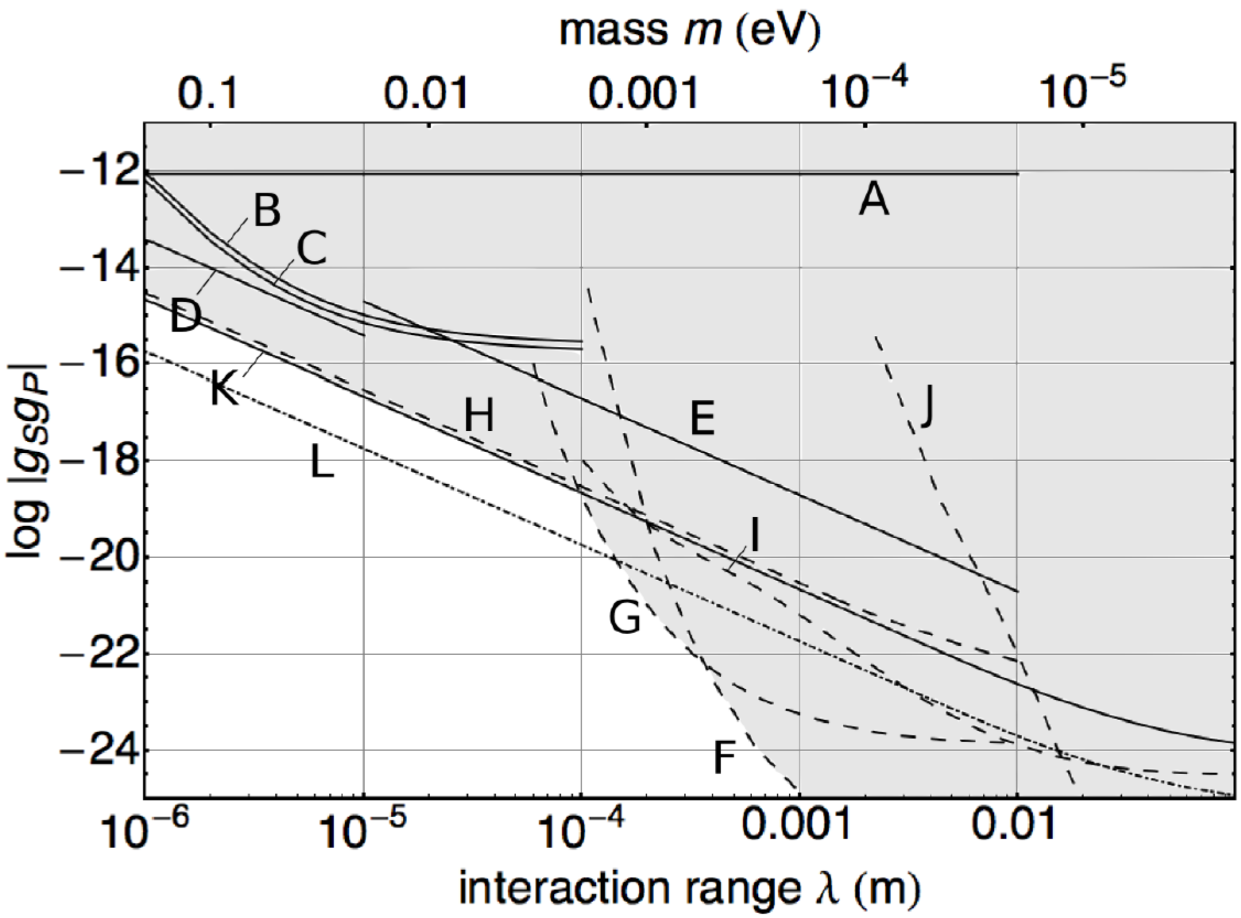
Effect	$B_0 \uparrow$	$B_0 \downarrow$
Counting statistics	$\pm 0.5 \times 10^{-6}$	$\pm 0.5 \times 10^{-6}$
Gravitational shift $(3.84 \times \delta_{\mathrm{Grav}})$	$(-8.9 \pm 2.3) \times 10^{-6}$	$(-1.8 \pm 2.7) \times 10^{-6}$
Intermediate R_0	3.8424580(23)	3.8424653(27)
Transverse shift $(3.84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

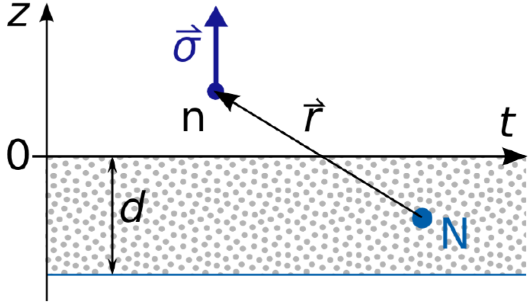


*S. Afach et al., PLB **739**, 128 (2014)*

Some results

Searching for axion-like particles with ultracold neutrons





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

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

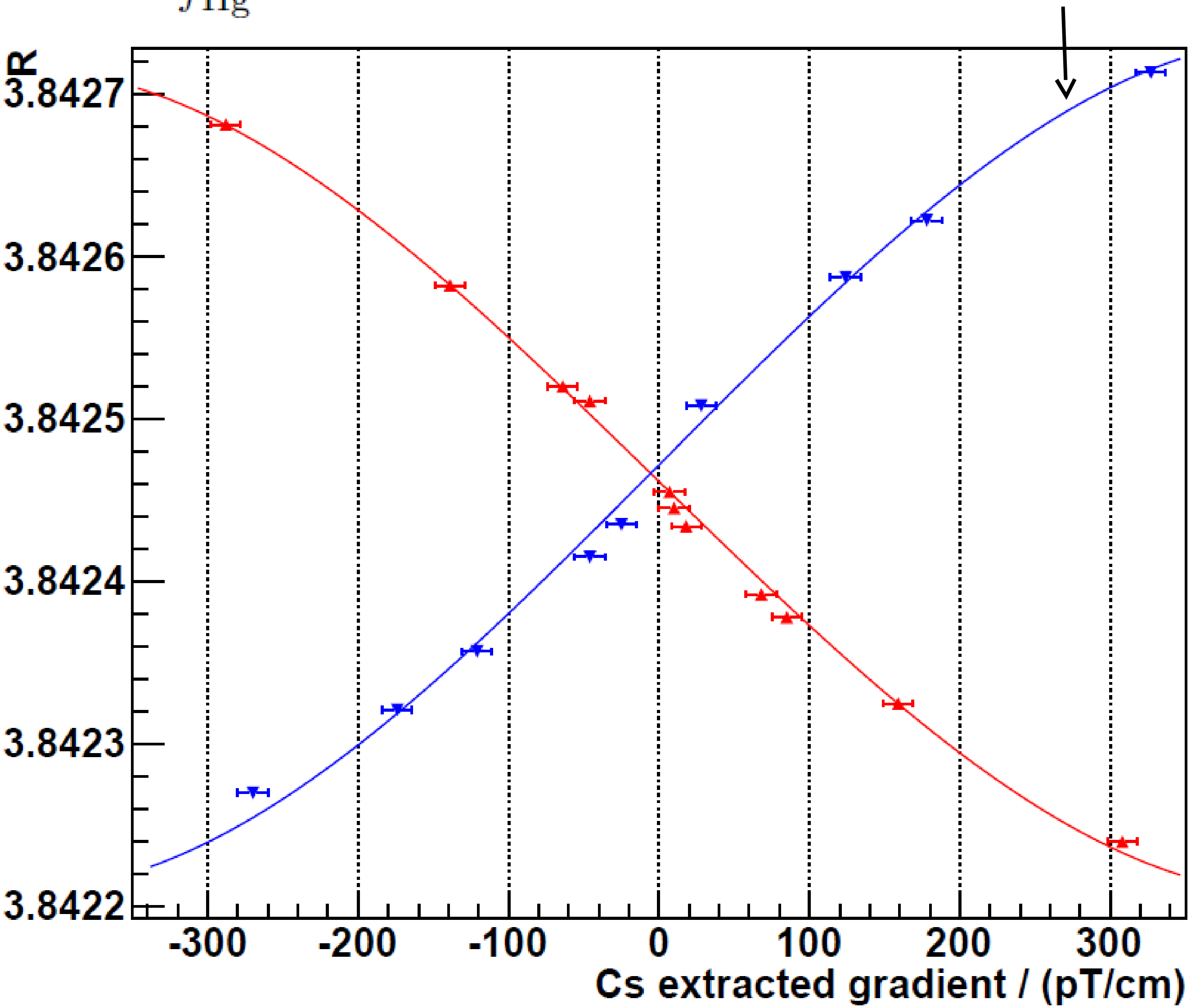
*S. Afach et al., PLB **745**, 58 (2015)*

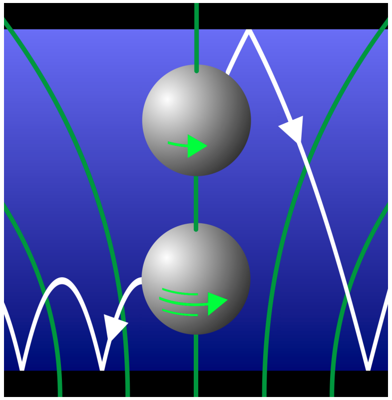
Towards the neutron EDM

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

Gravitational enhanced depolarization and associated frequency shift

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



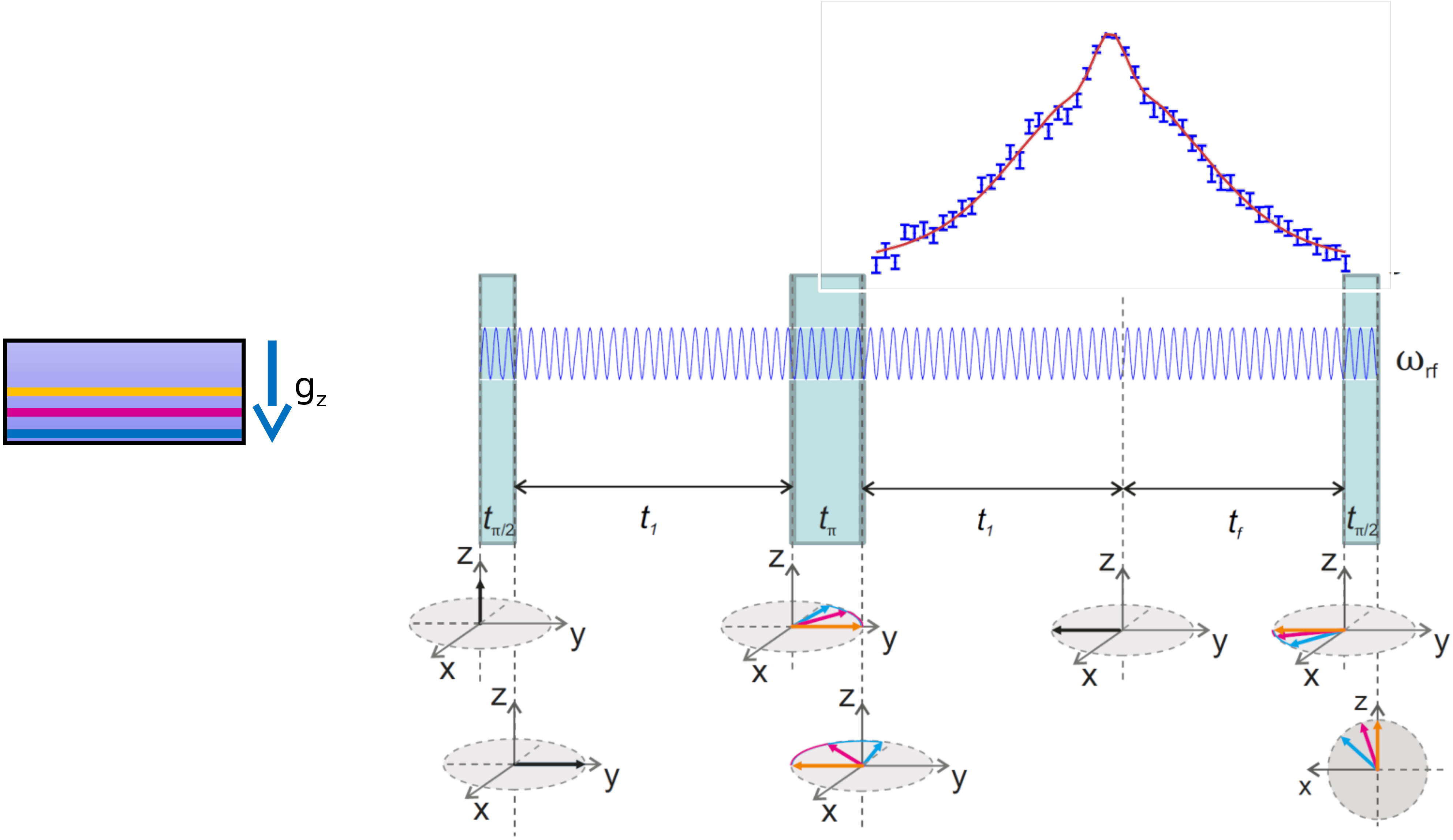


Also slower UCNs depolarize faster and contribute less to the measured frequency

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

Towards the neutron EDM

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



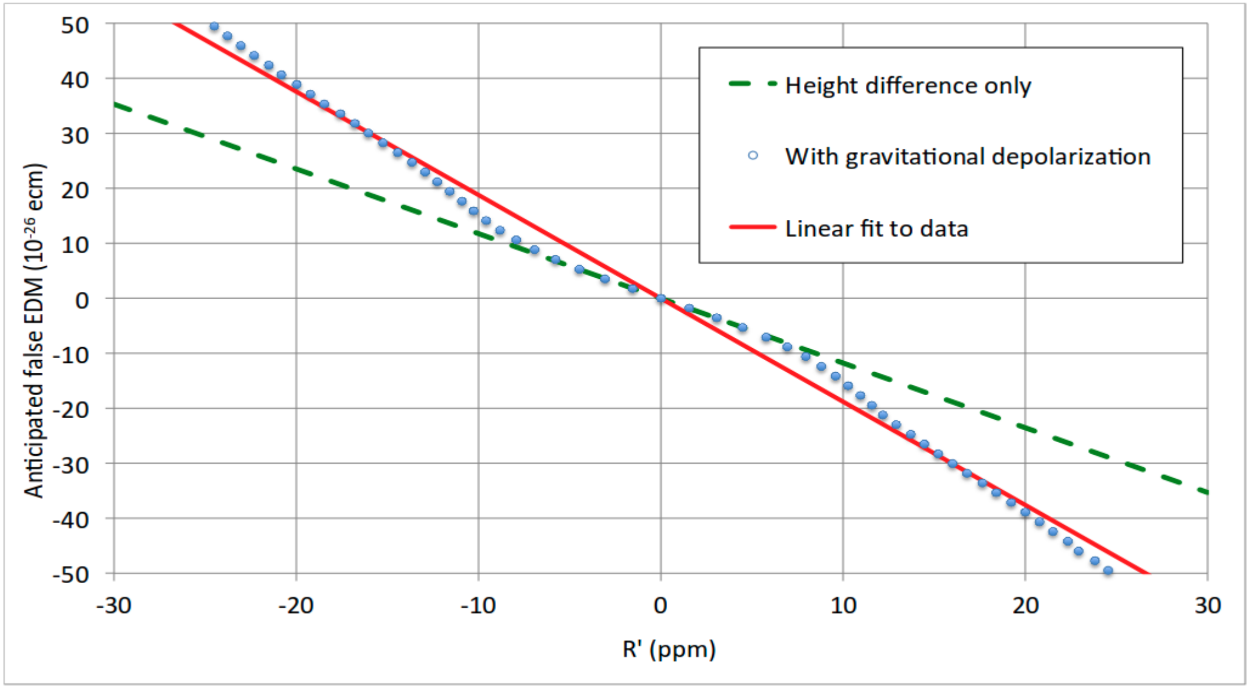
PRL 115, 162502 (2015)

RAL-Sussex-ILL limit revised

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

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

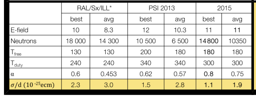
Analysis stage	**EDM**	σ
Crossing point $d_\times$	-0.59	1.53
Gradient-corrected d_0	-0.92	1.68
Dipole-corrected d_{fec}	-0.21	1.79
Final result d_n	**-0.21**	**1.82**



The strategy is validated

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

Towards the neutron EDM

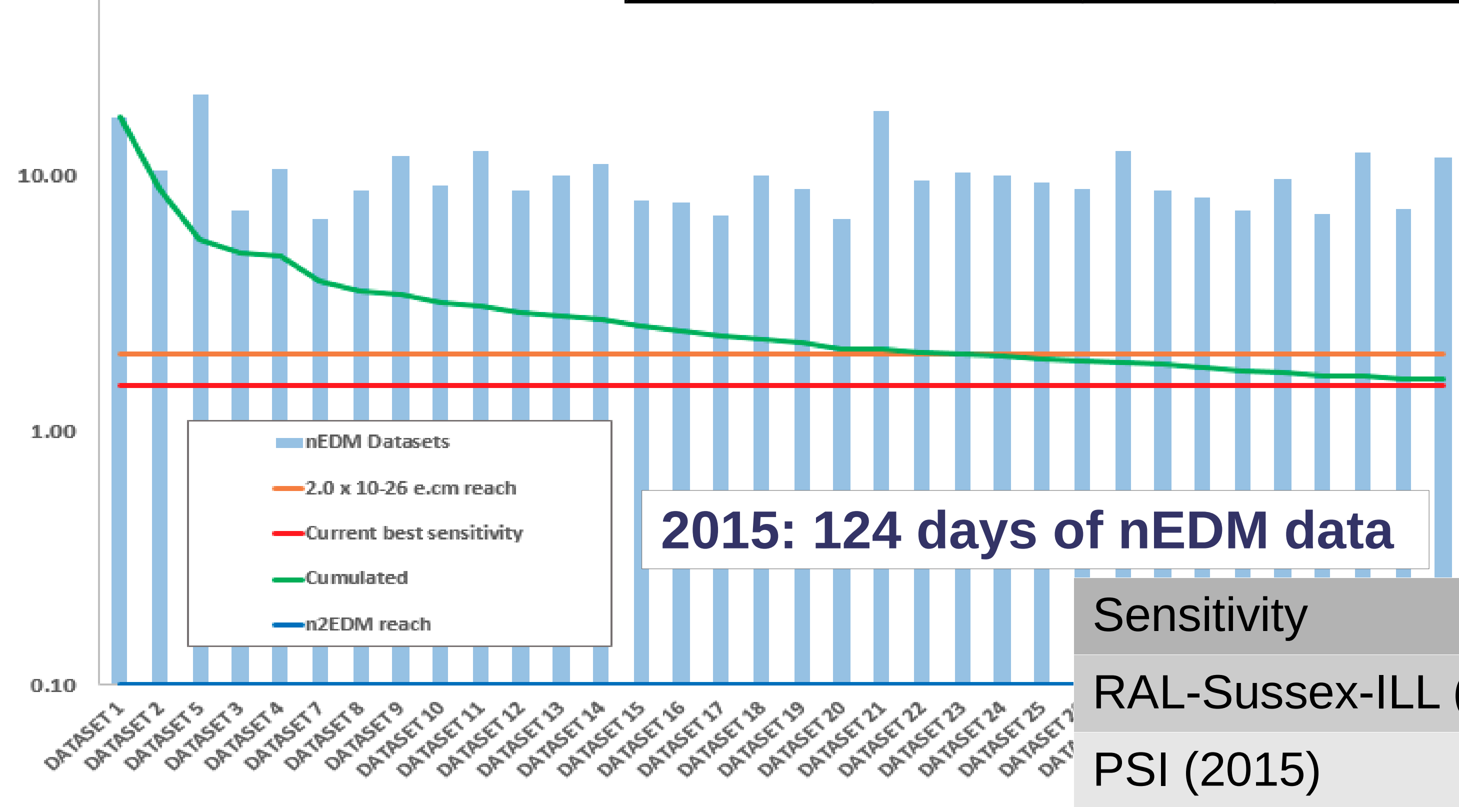
	RAL/Sx/ILL*		PSI 2013		2015	
	best	avg	best	avg	best	avg
E-field	10	8.3	**12**	10.3	11	11
Neutrons	18 000	14 300	10 500	6 500	**14 800**	10350
T_{free}	130	130	**200**	180	180	180
T_{duty}	240	240	340	340	**300**	300
α	0.6	0.453	0.62	0.57	**0.8**	0.75
	2.3	3.0	1.5	2.8	**1.1**	**1.9**

	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	14800	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
σ/d (10^{-25}ecm)	2.3	3.0	1.5	2.8	1.1	1.9

(10^{-25}ecm)

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

(10^{-26}ecm)

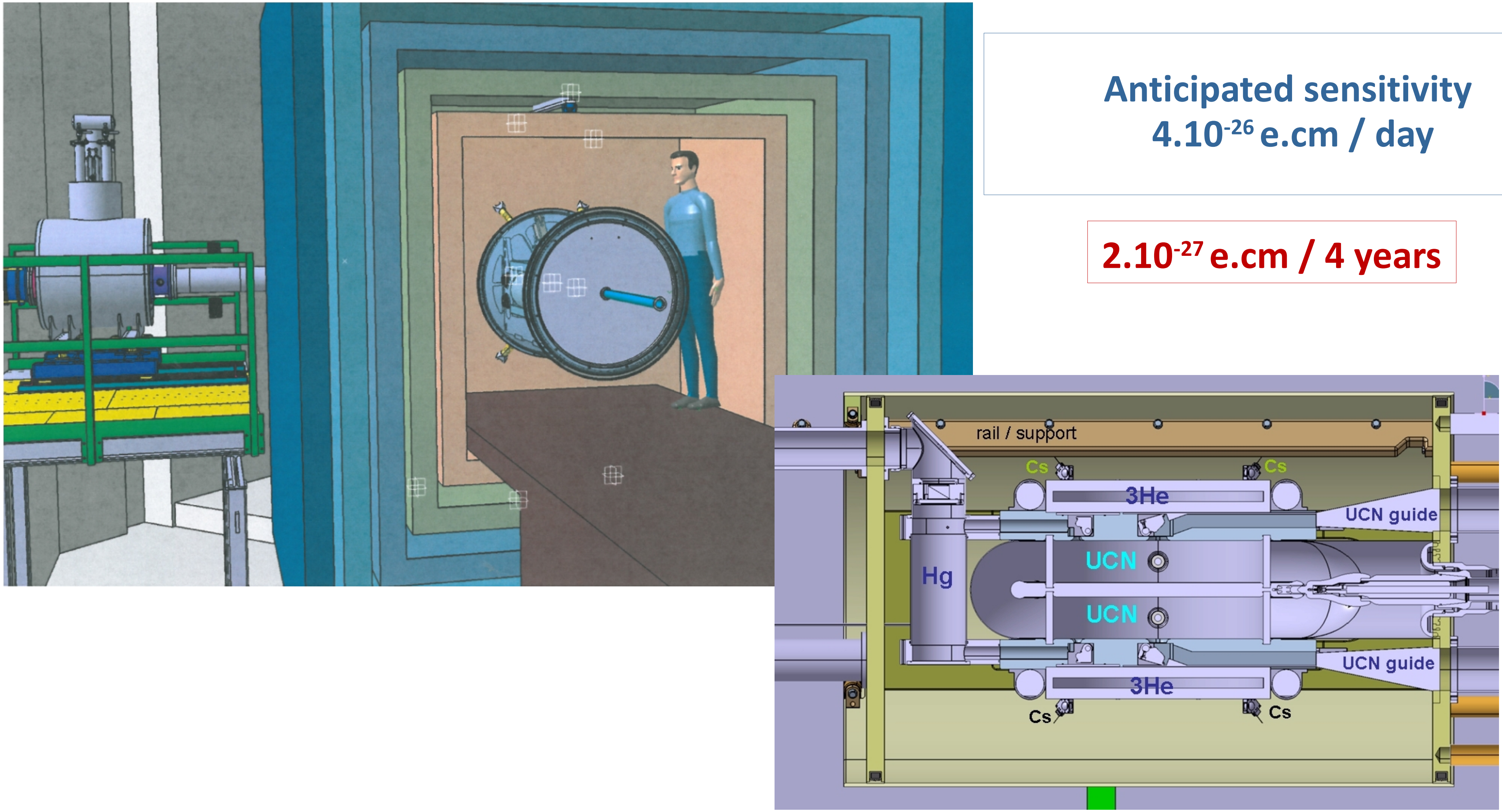


2015: 124 days of nEDM data

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

Towards n2EDM



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

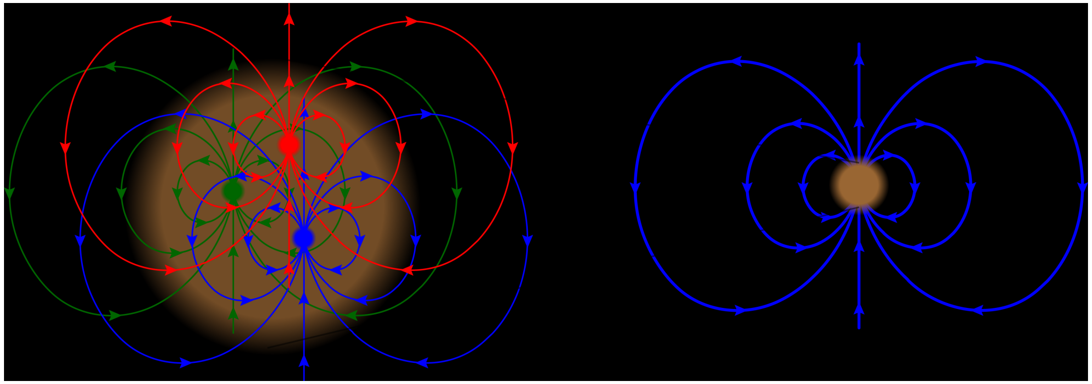
2.10^{-27} e.cm / 4 years

- **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

EDM landscape

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

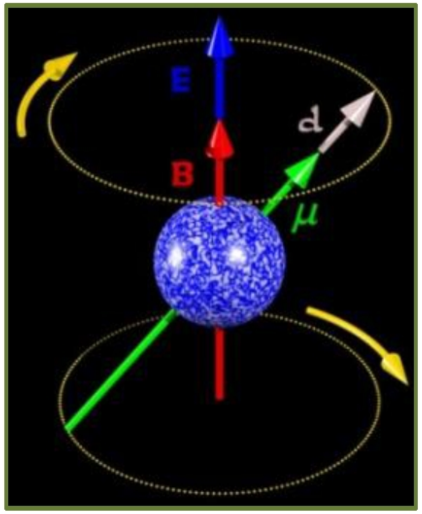


nEDM

- We are taking data with the highest sensitivity ever
- We expect with 300 data-days until 2016 :

statistical sensitivity of $\sigma\sim10^{-26}$ *e*.cm

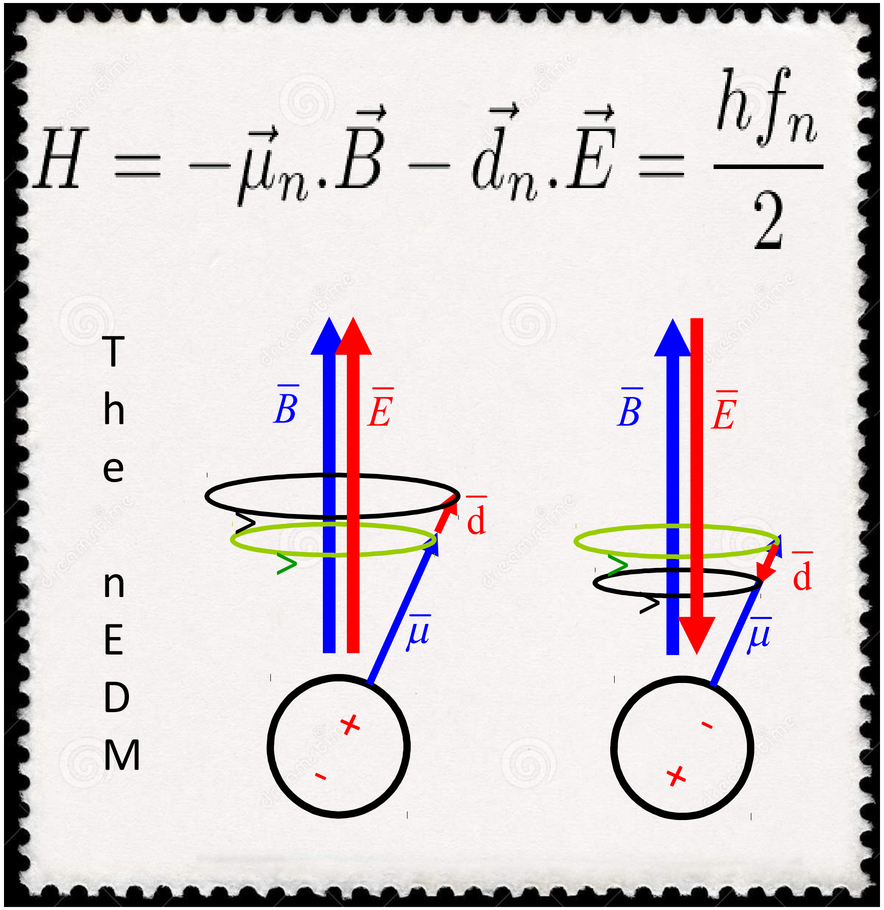
- n2EDM in active phase too but strong competition
- Cryogenic technique



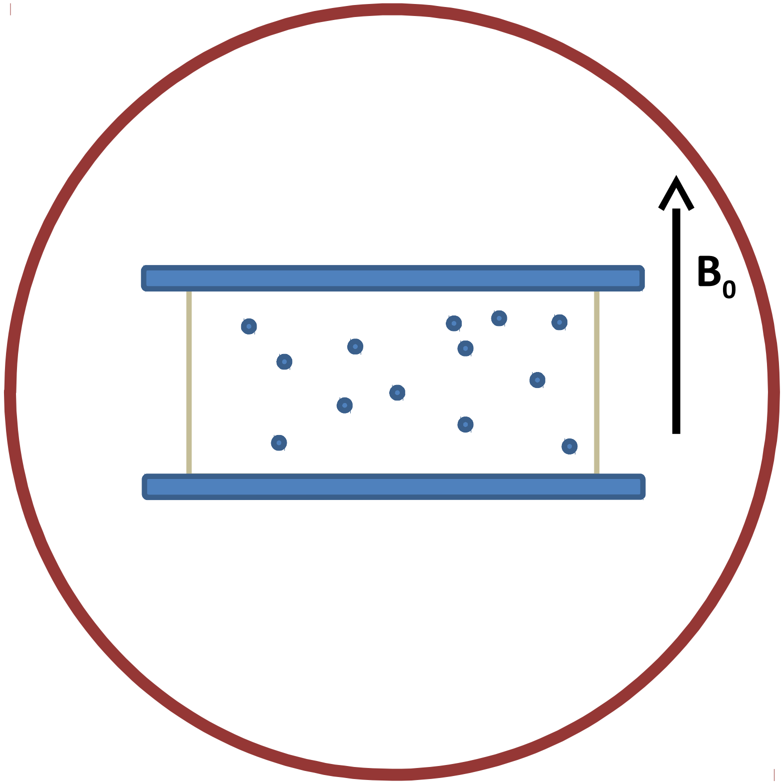
Thanks

Merci

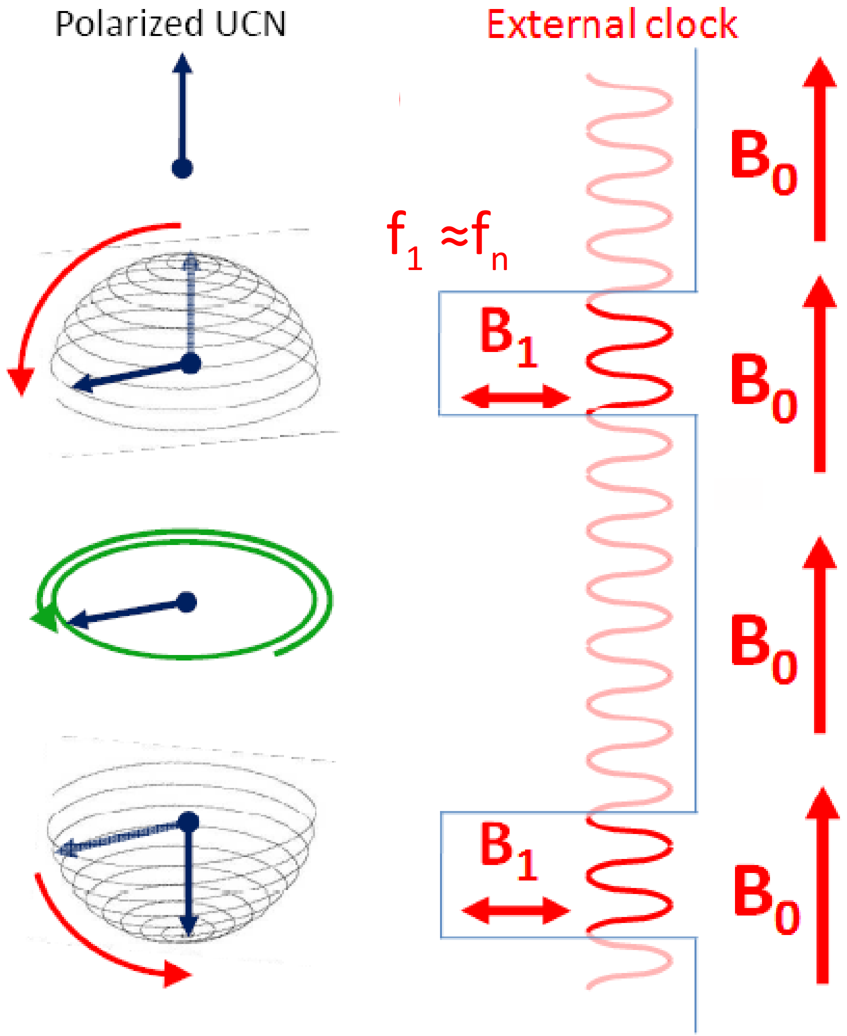
The nEDM search

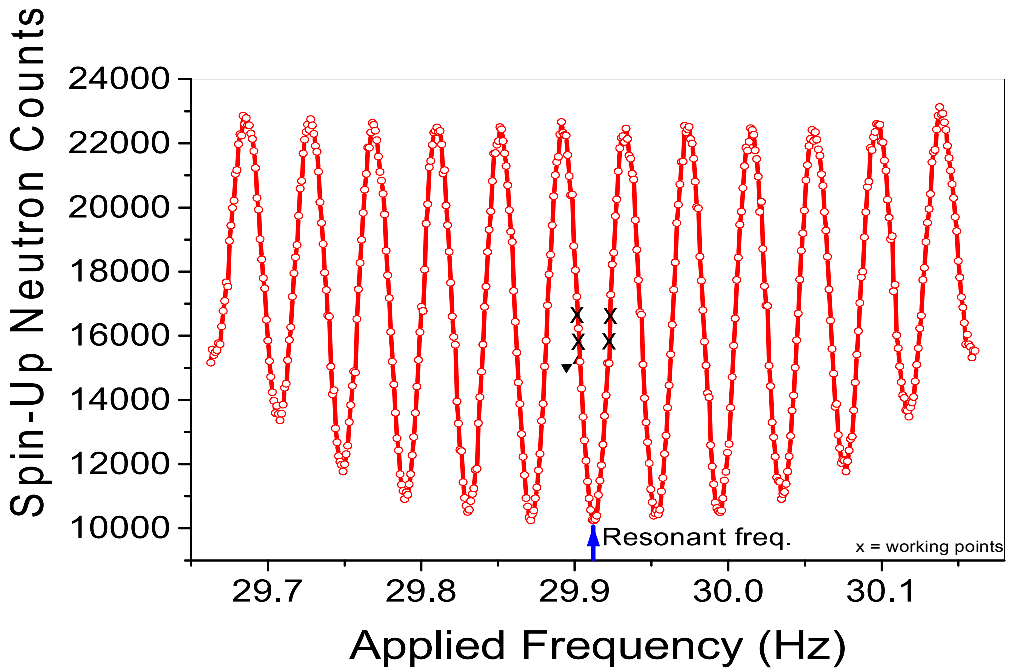


$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$



The Ramsey's method of separated oscillating fields

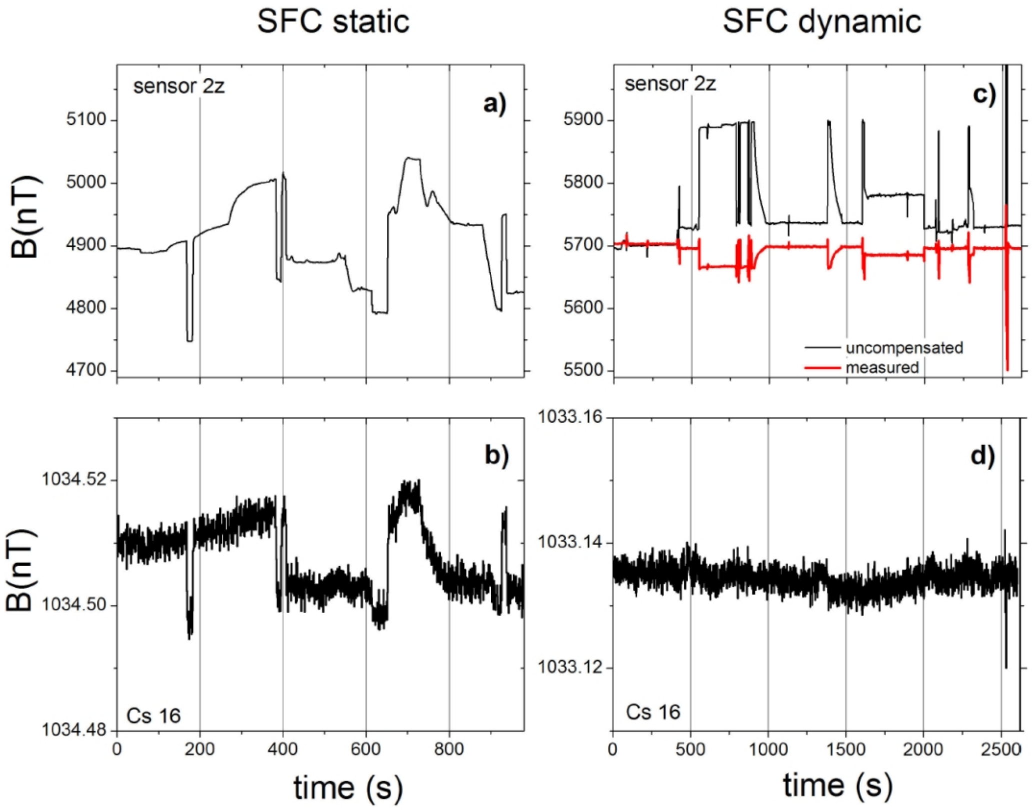




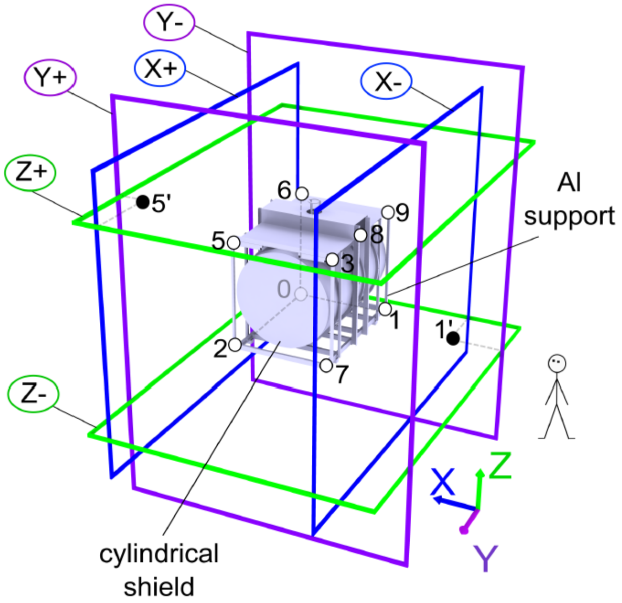
$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

A nEDM apparatus

Magnetic stability



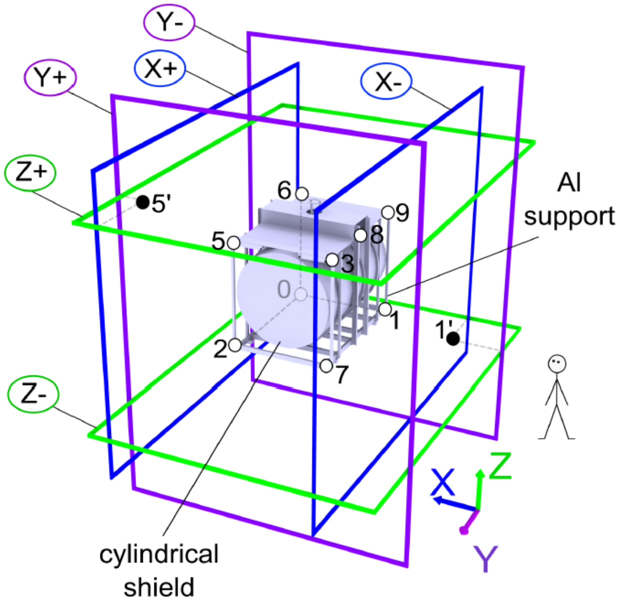
Afach et al., J. Appl. Phys. ***116****, 084510 (2014)*

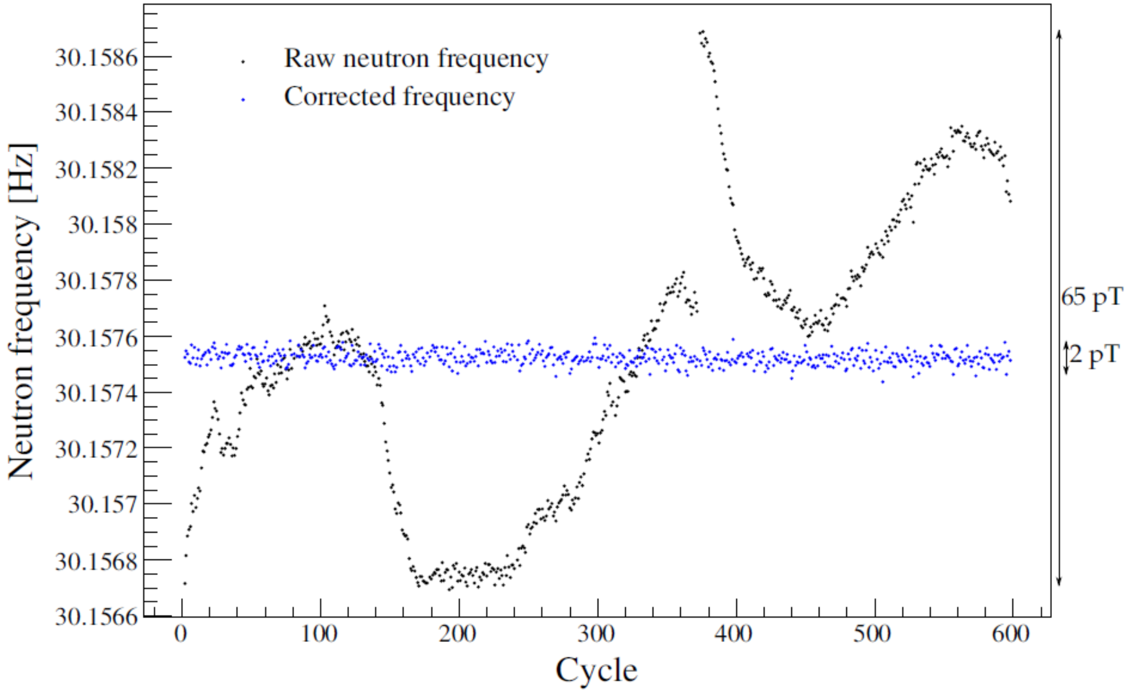


- Active compensation
- Improved degaussing procedure
- Temperature stabilization
- New current source
- …

A nEDM apparatus

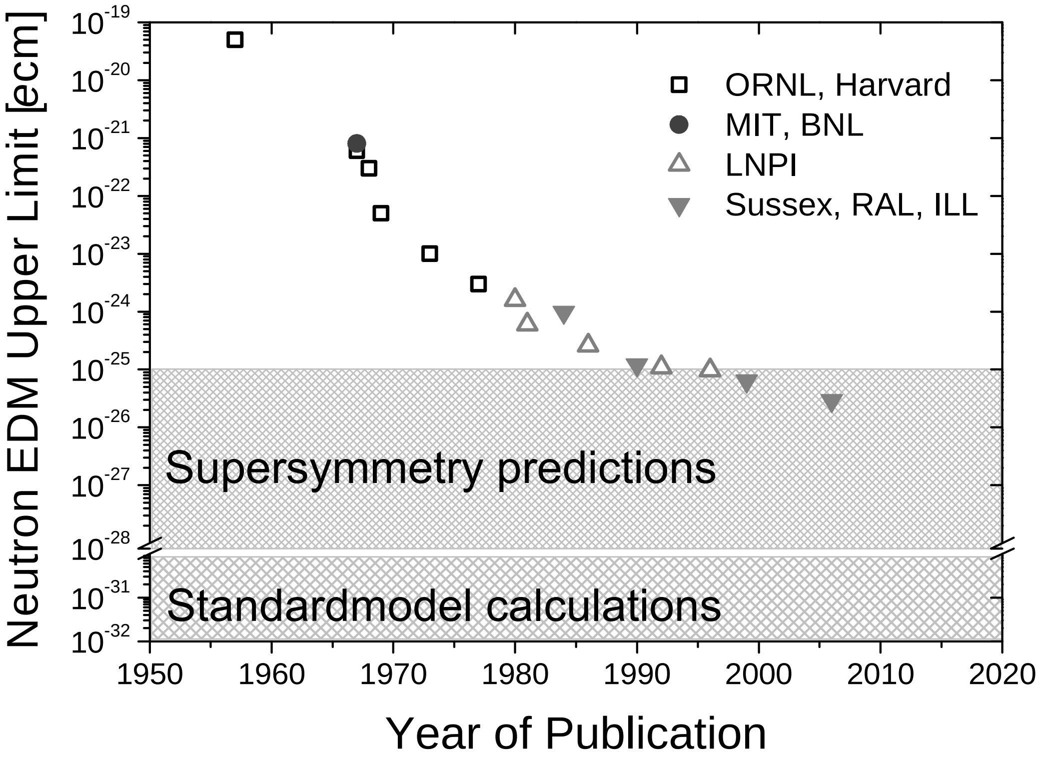
Magnetic stability



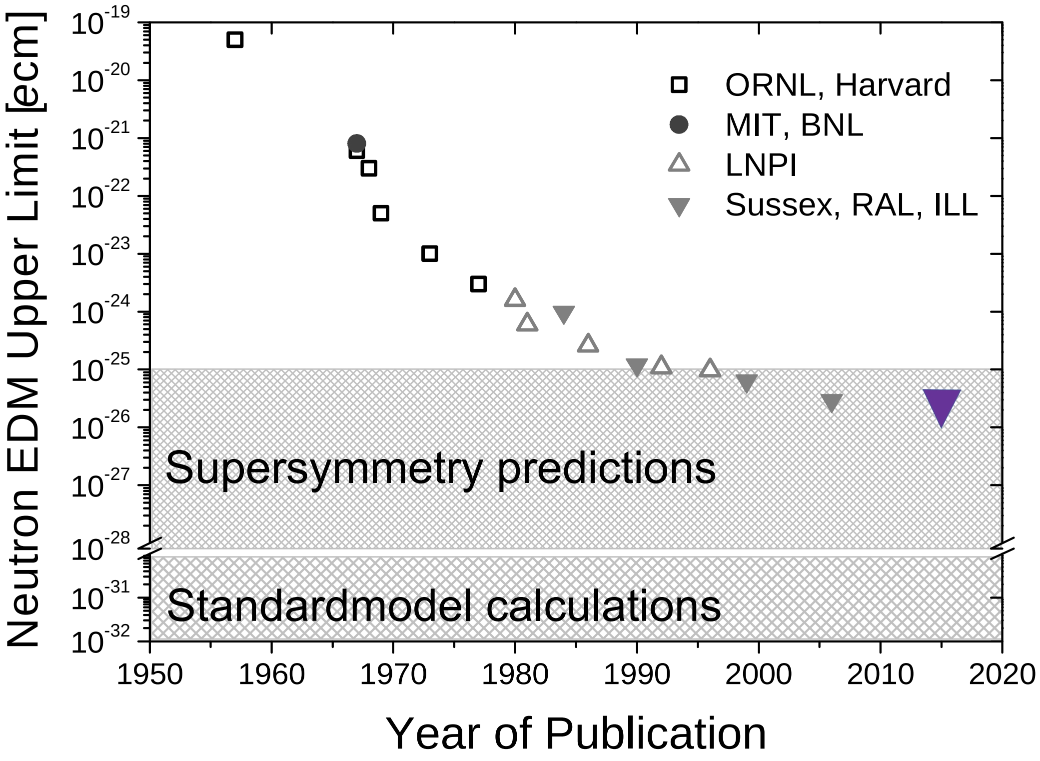


- Active compensation
- Improved degaussing procedure
- Temperature stabilization
- New current source
- …

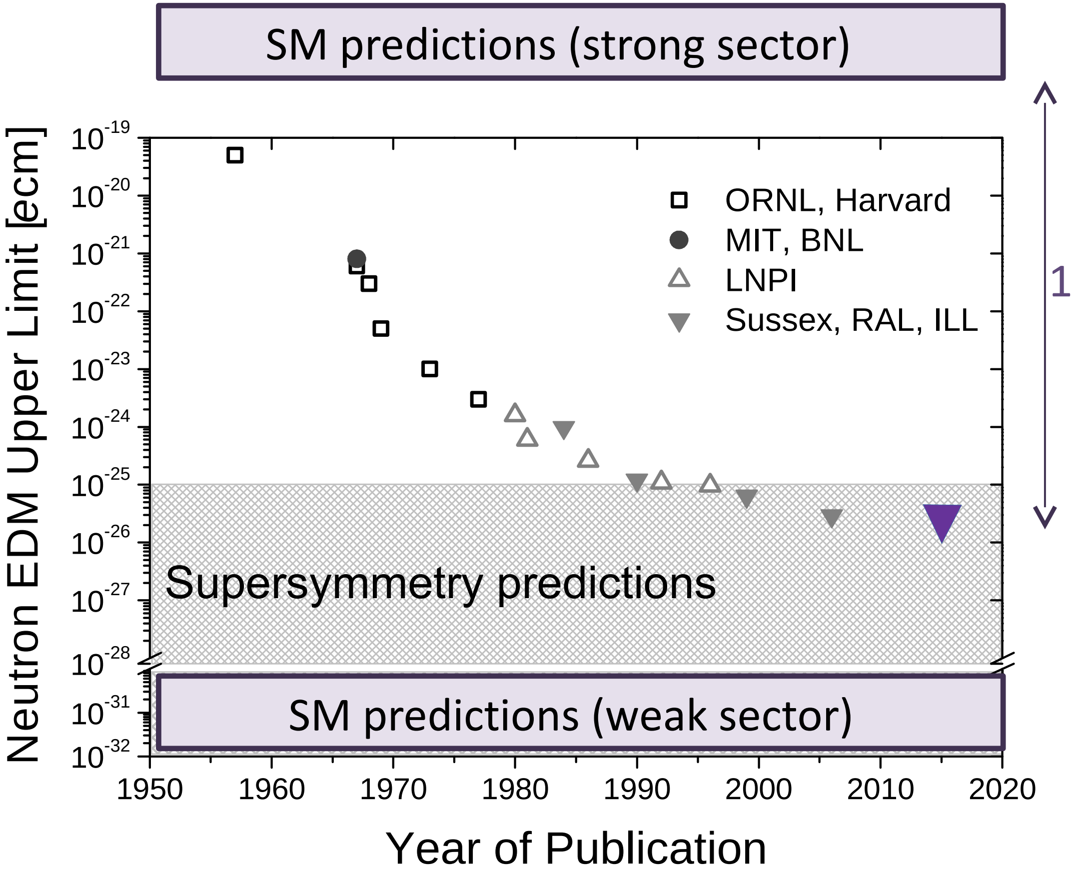
The nEDM landscape



The nEDM landscape



The nEDM landscape



10 orders of magnitude

Strong CP problem

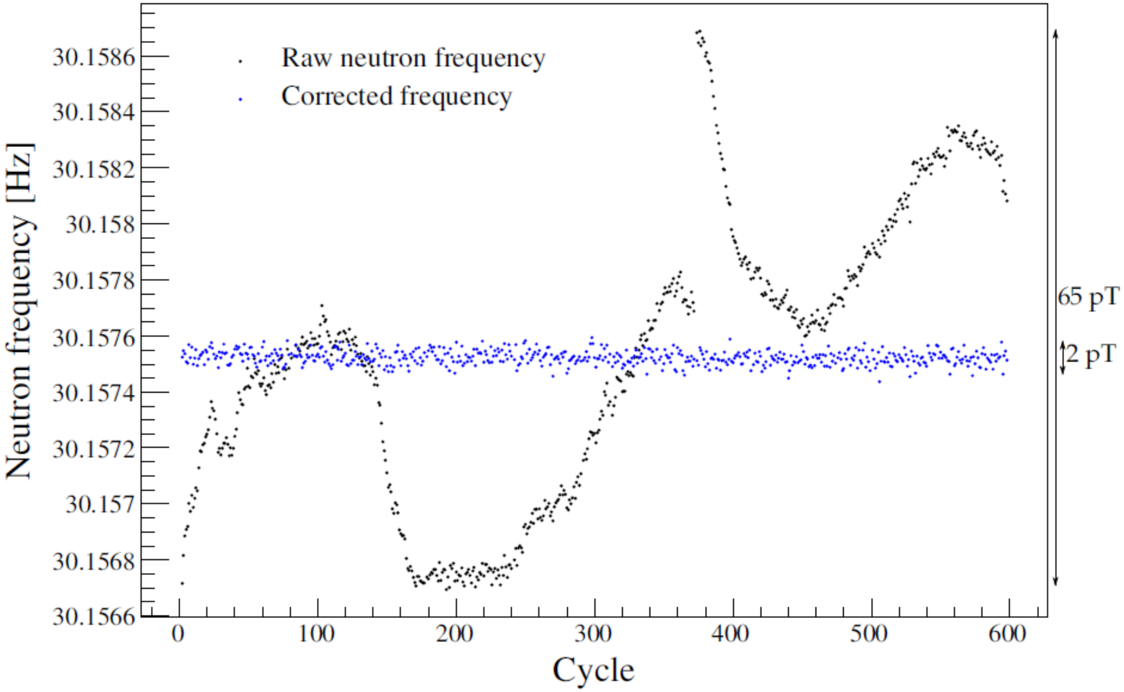
$\theta_{QCD} < 10^{-10}$

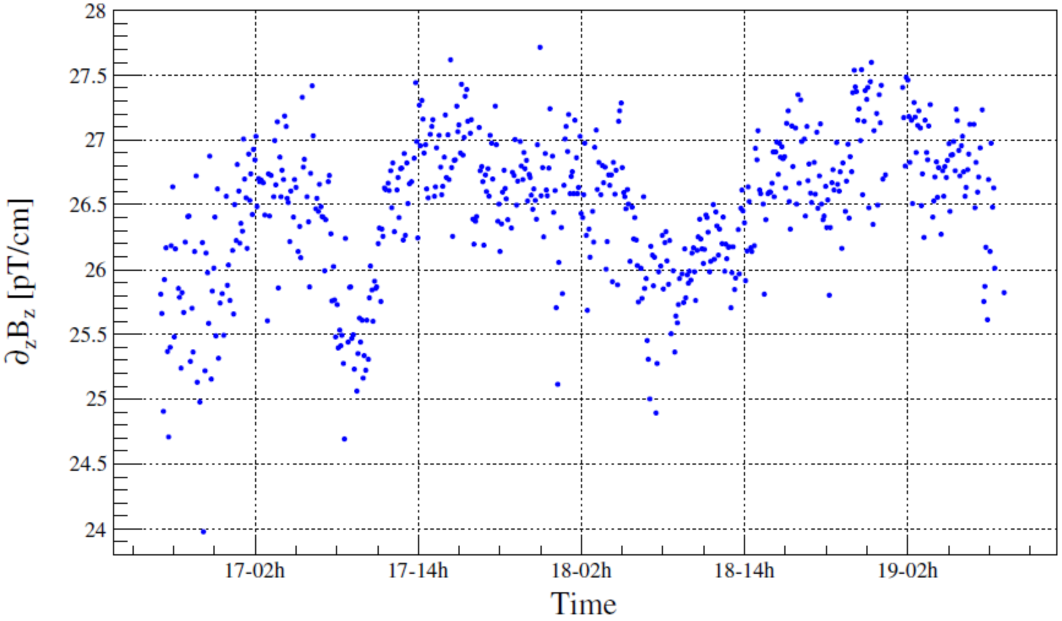
Phase in the CKM matrix

δ_{CKM}

A nEDM apparatus

Magnetic stability





Vertical gradient
~ 2 pT/cm daily variation

The EDM landscape

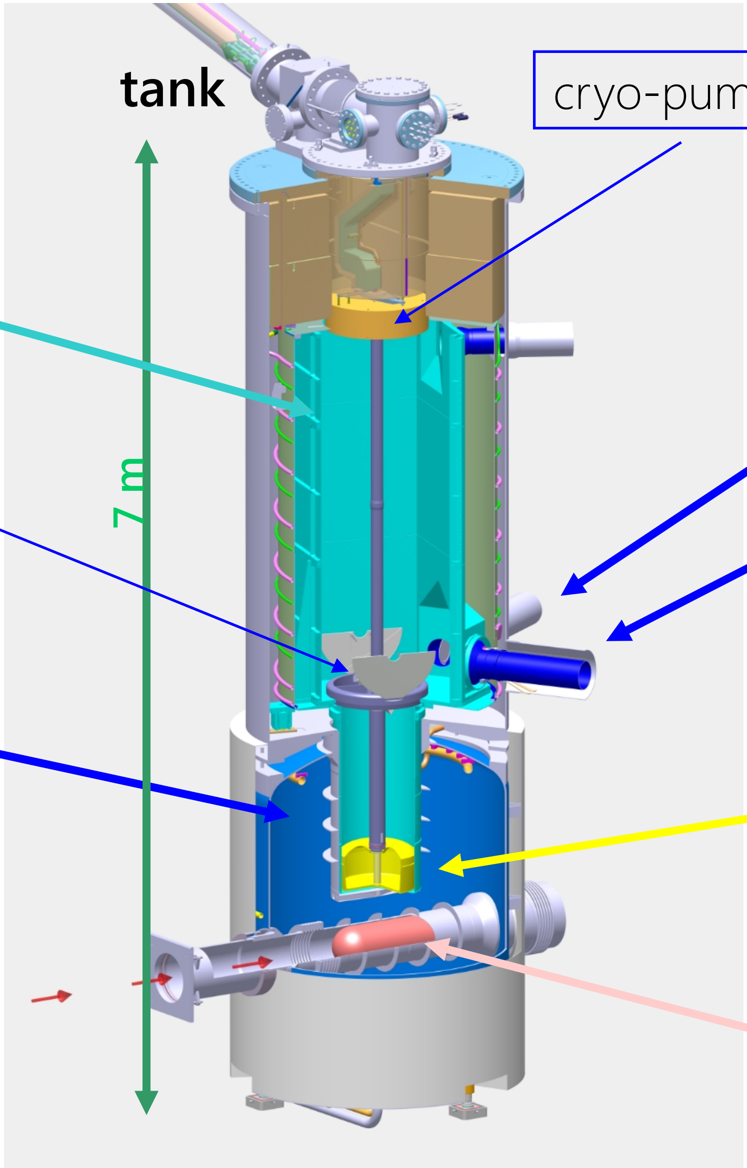
Adrian SIGNER

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 → “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 nEDM search



cryo-pump

DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

SV-shutter

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

cold UCN-converter
~30 dm^3 solid D_2 at 5 K

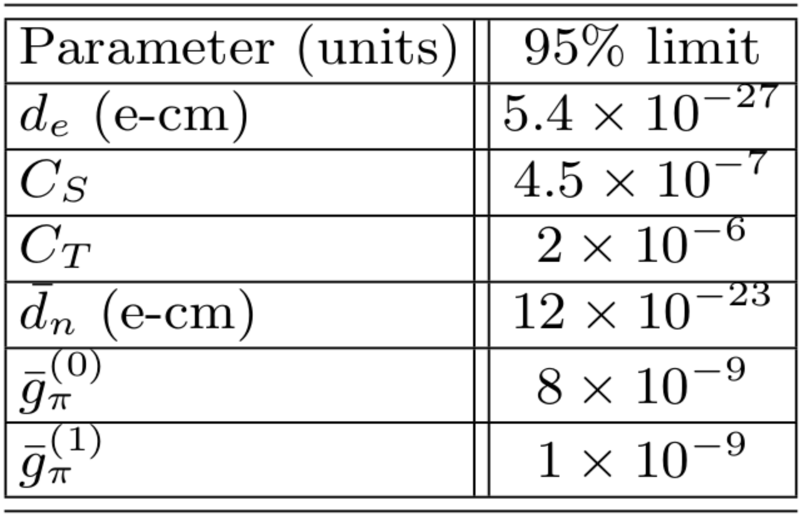
pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
1% duty cycle

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

The EDM landscape

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

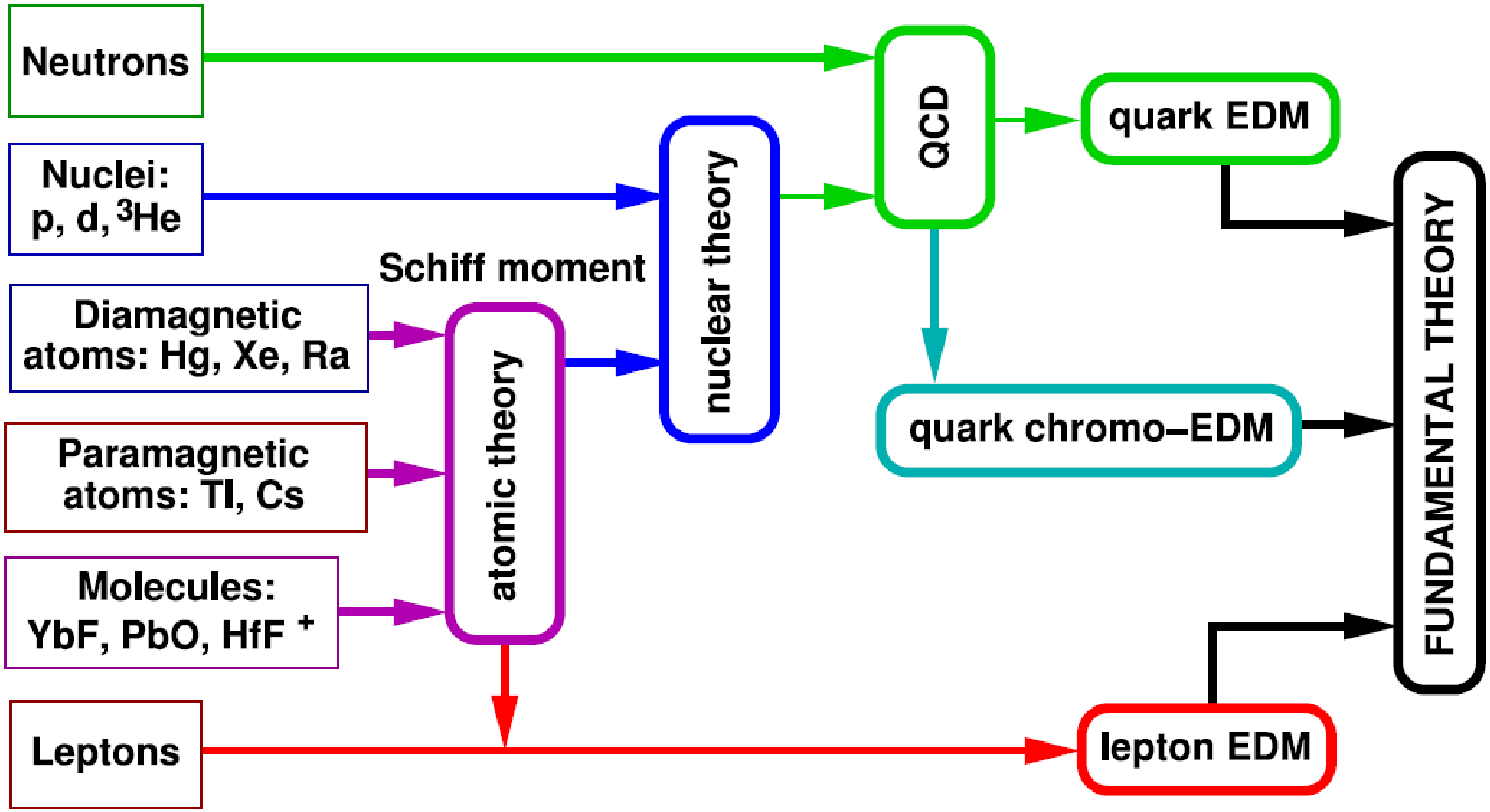


Parameter (units)	95% limit
d_e (e-cm)	5.4×10^{-27}
C_S	4.5×10^{-7}
C_T	2×10^{-6}
$\bar{d}_n$ (e-cm)	12×10^{-23}
$\bar{g}_\pi^{(0)}$	8×10^{-9}
$\bar{g}_\pi^{(1)}$	1×10^{-9}

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 theore
Including the TlF and 129 Xe in the global fit
(0)

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

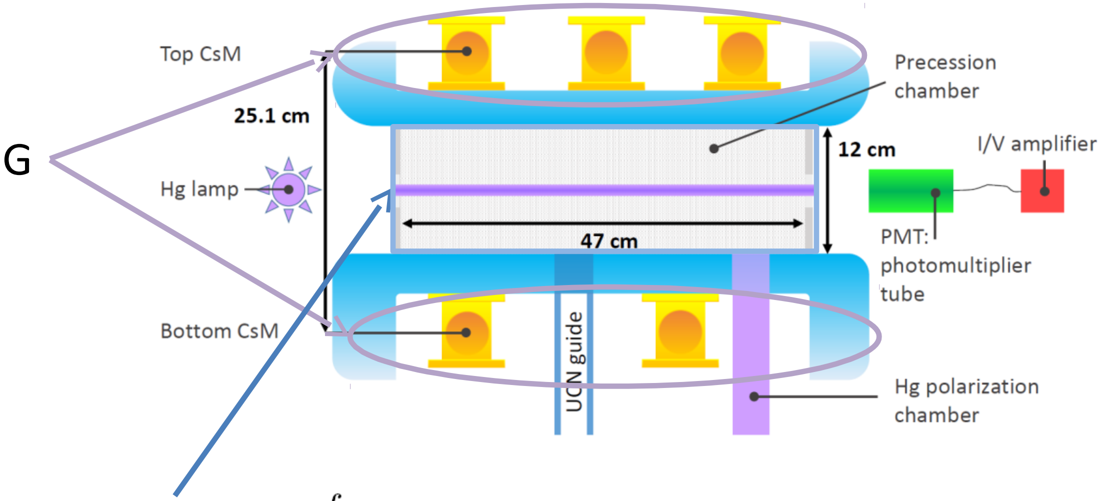
if $d_n > 10^{-30}$ e cm is found it is not clear whether this is BSM or strong CPV ($\bar{\theta} \neq 0$)

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

A nEDM apparatus

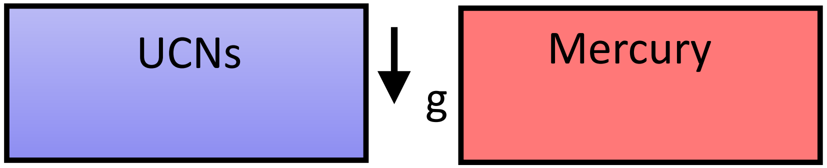
A non perfect Co-magnetometer

- Gravitational shift



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

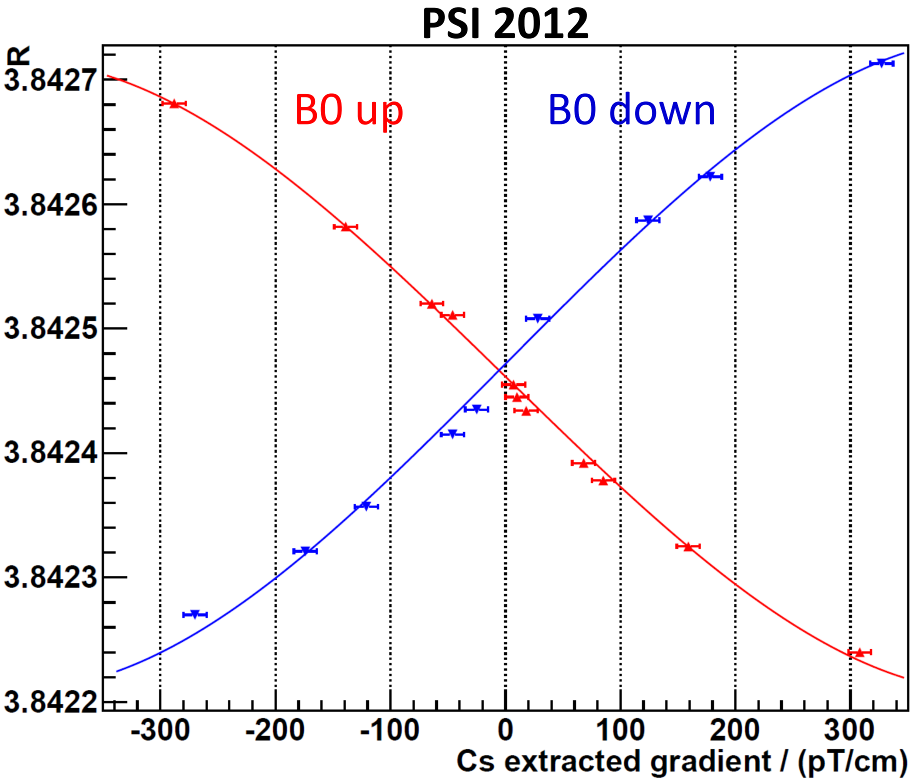
In the precession chamber



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

$\Delta h = 2,7$ mm

=2,7 mm



A nEDM apparatus

A non perfect Co-magnetometer

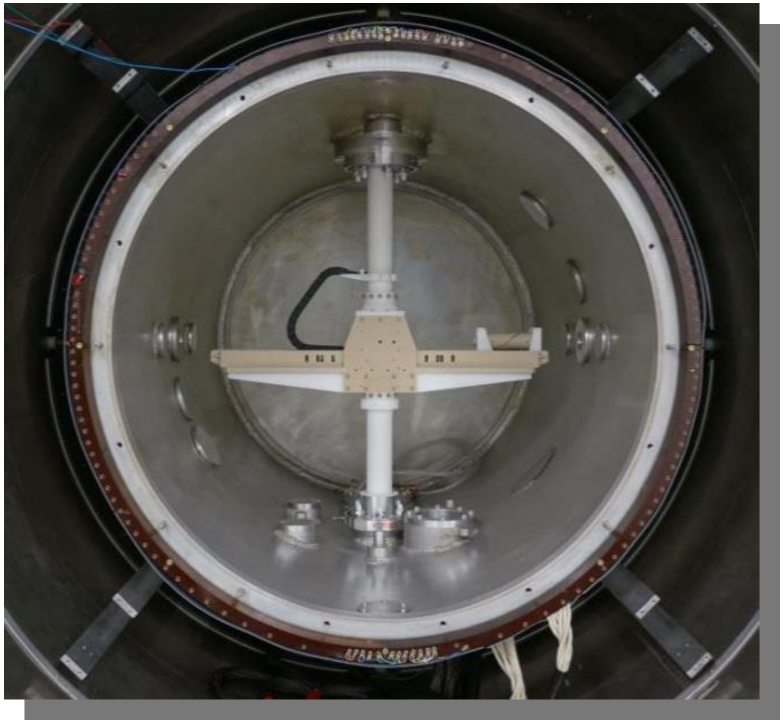
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling

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

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

$\Delta h = 2{,}7$ mm

A nEDM apparatus

A non perfect Co-magnetometer

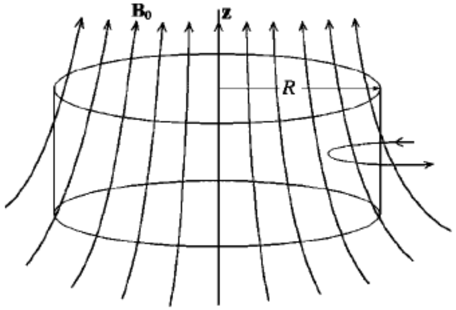
- Gravitational shift
- Adiabatic vs Non-adiabatic field sampling
- Geometrical phase shift

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)

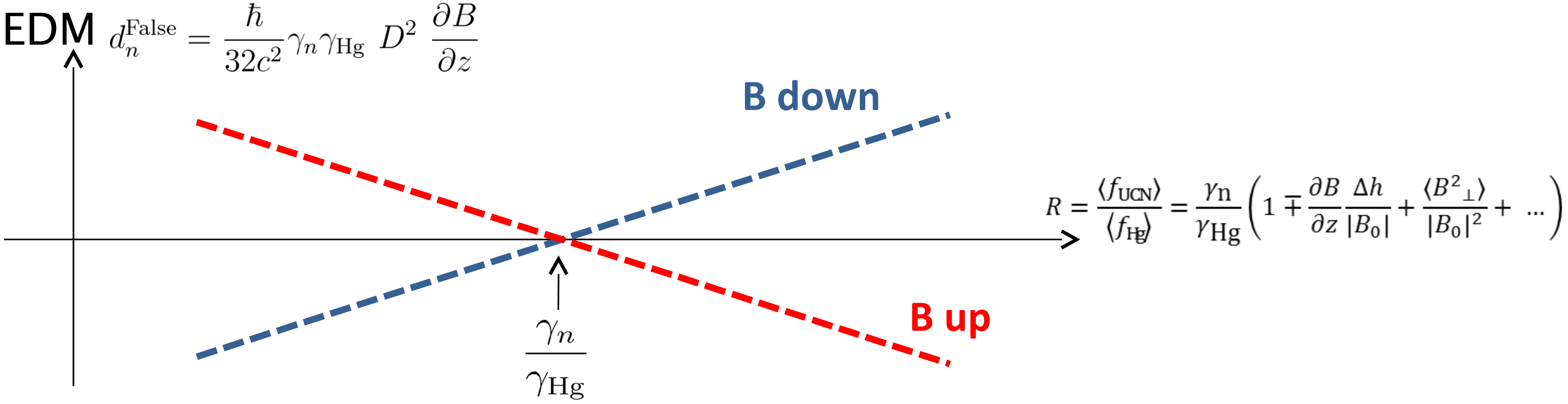
$$d_{\mathrm{Hg}}^{\mathrm{False}} = \frac{\hbar \gamma_{\mathrm{Hg}}^2}{32c^2} D^2 \frac{\partial B}{\partial z} \longrightarrow d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

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

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)



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

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

$$\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}$$

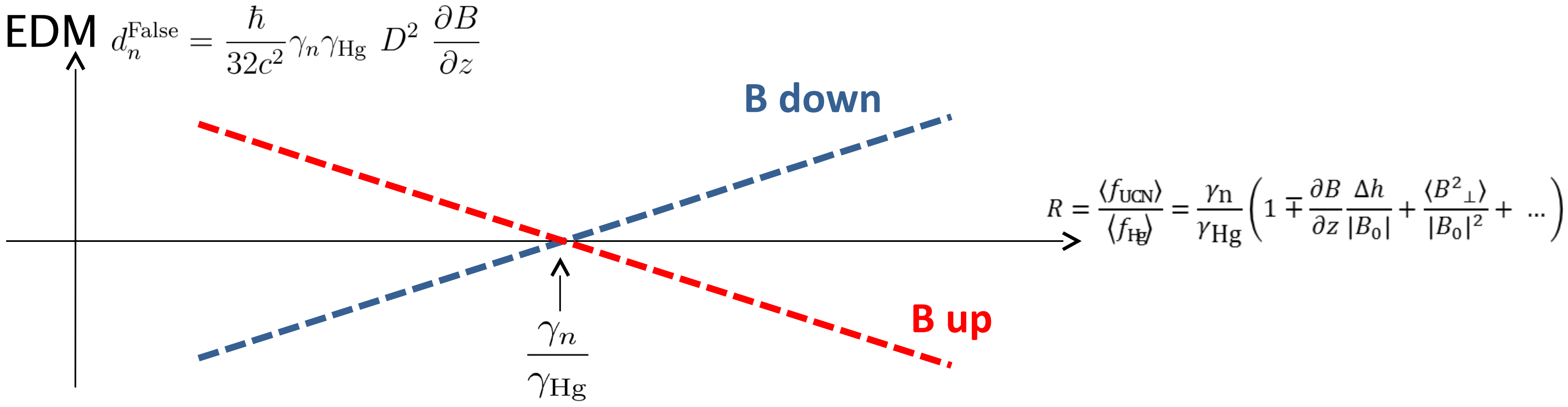
And any shift of the neutron and/or Hg precession frequency linear with the E-field

→ **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)



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

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

$$\frac{\gamma_n}{\gamma_{\text{Hg}}}$$

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)*

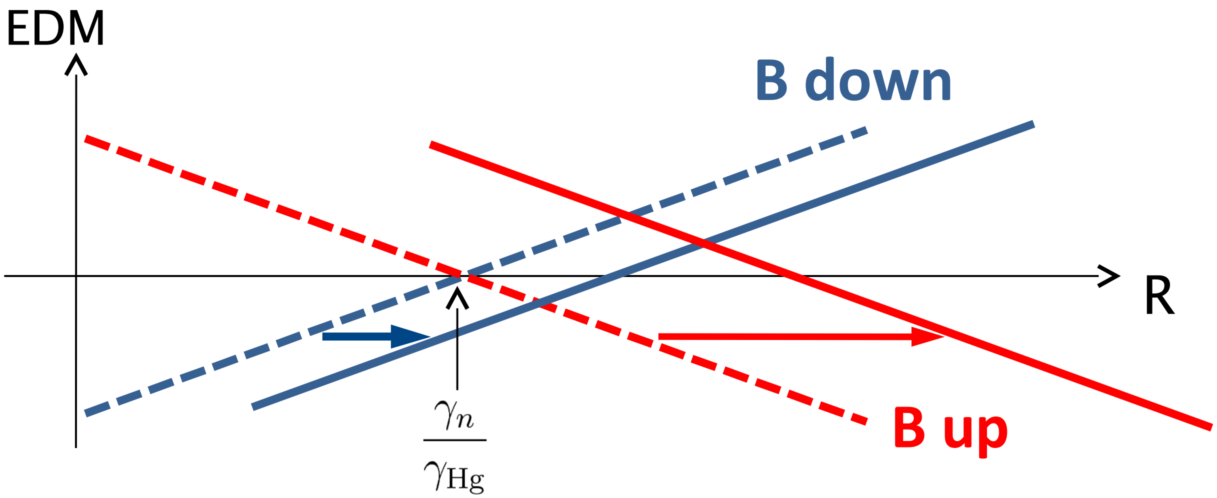
A nEDM apparatus

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)

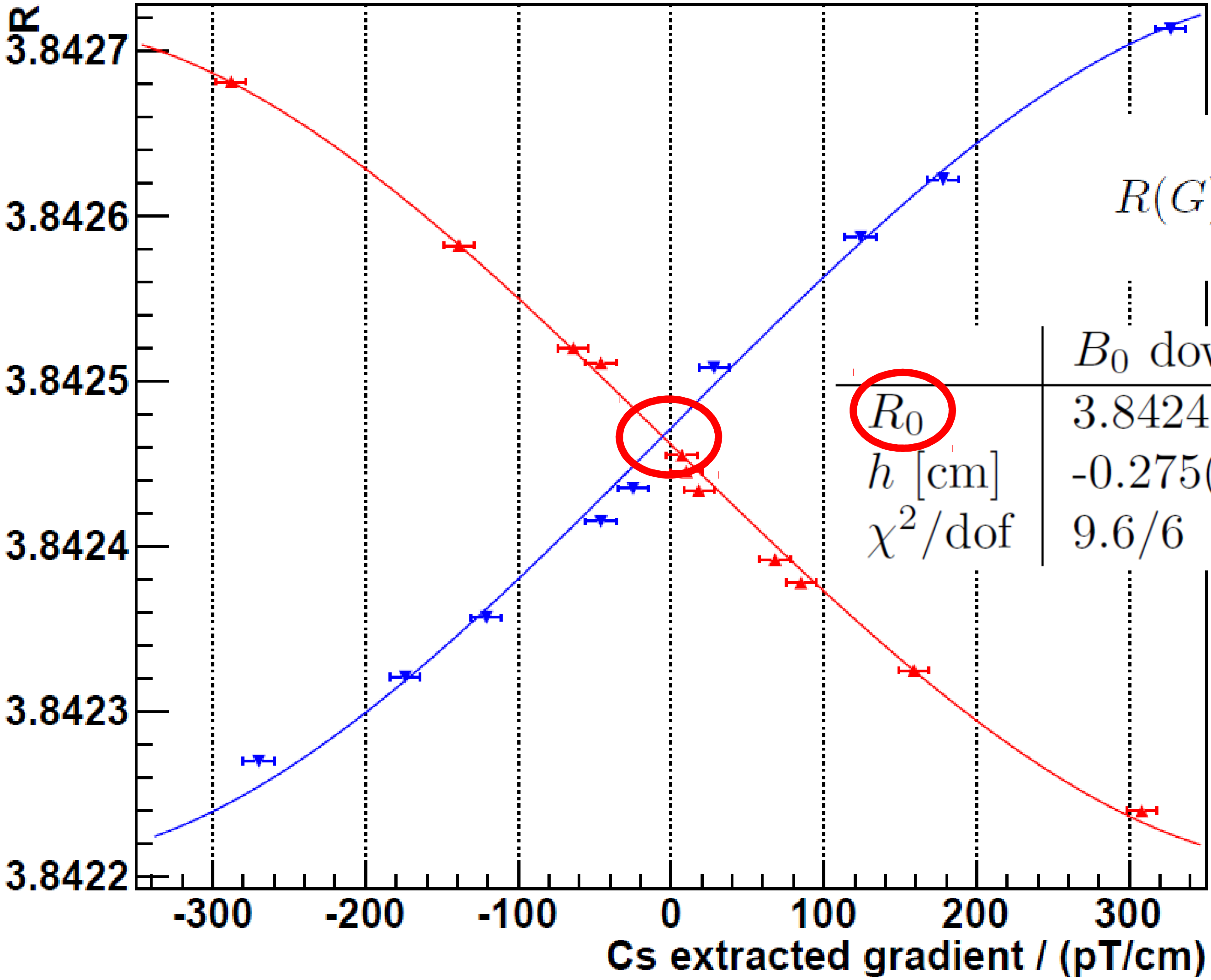
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \boxed{\frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2}} + \ \dots \right)$$

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



Some results

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

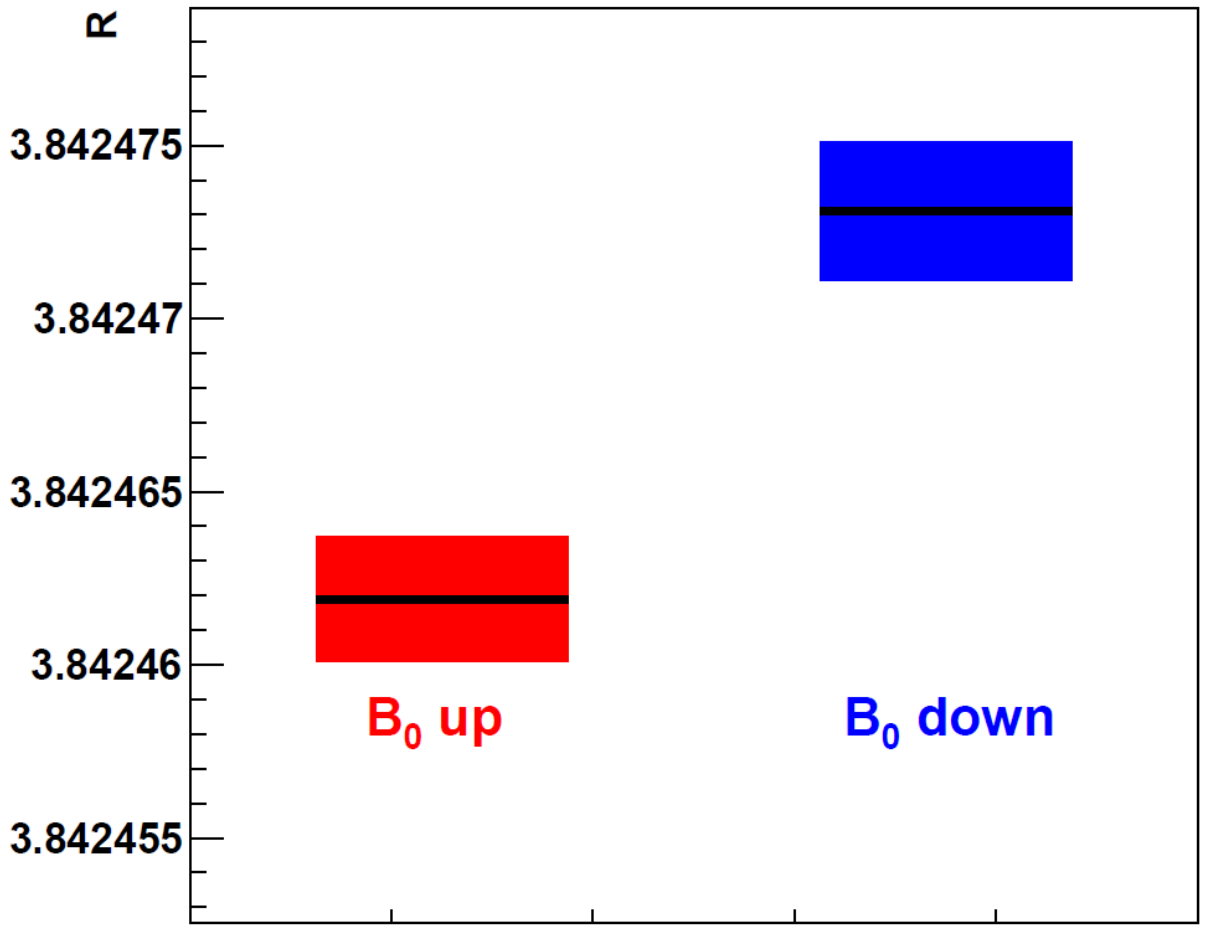


$$R(G) = R_0 \left(1 \pm \frac{Gh}{B_0} + cG^3 \right)$$

	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

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

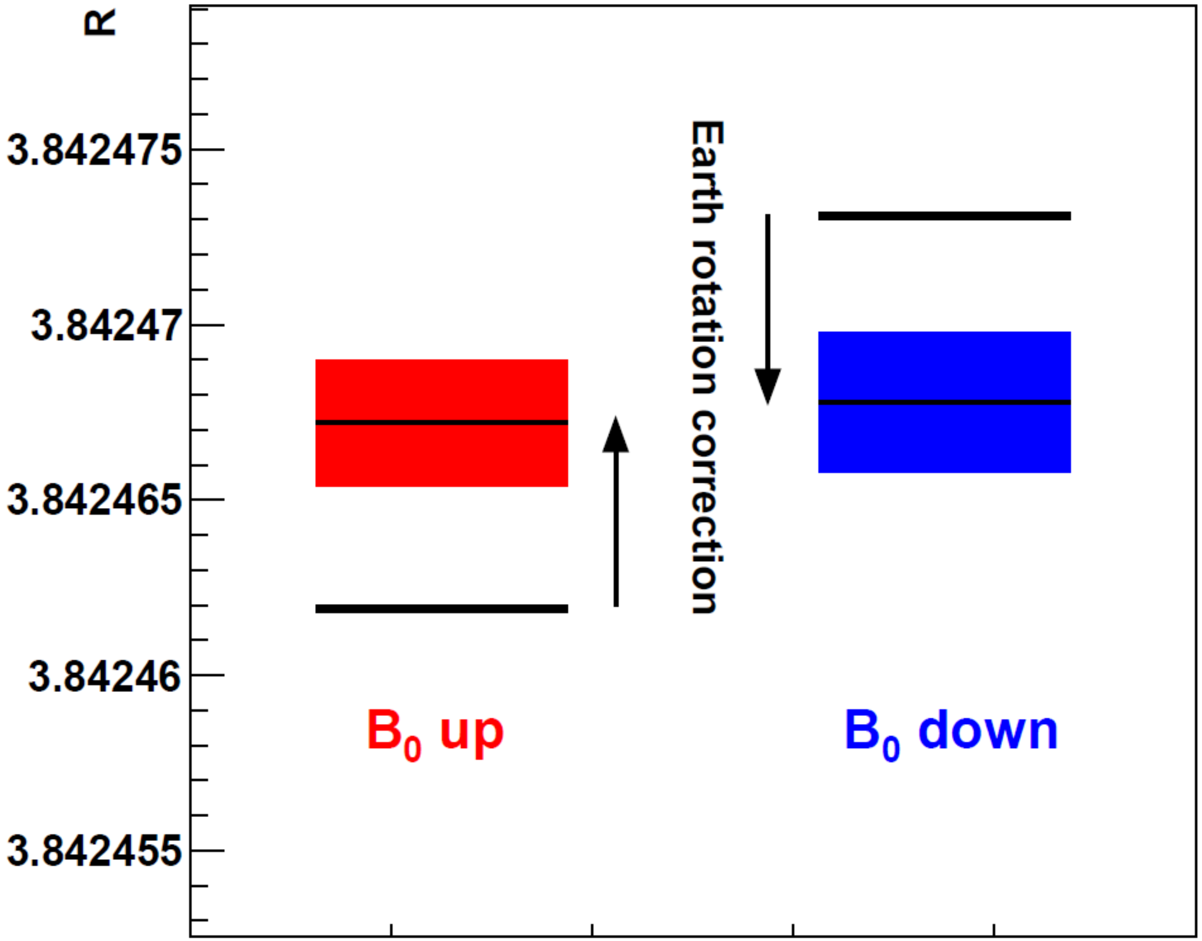
Some results



Some results

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

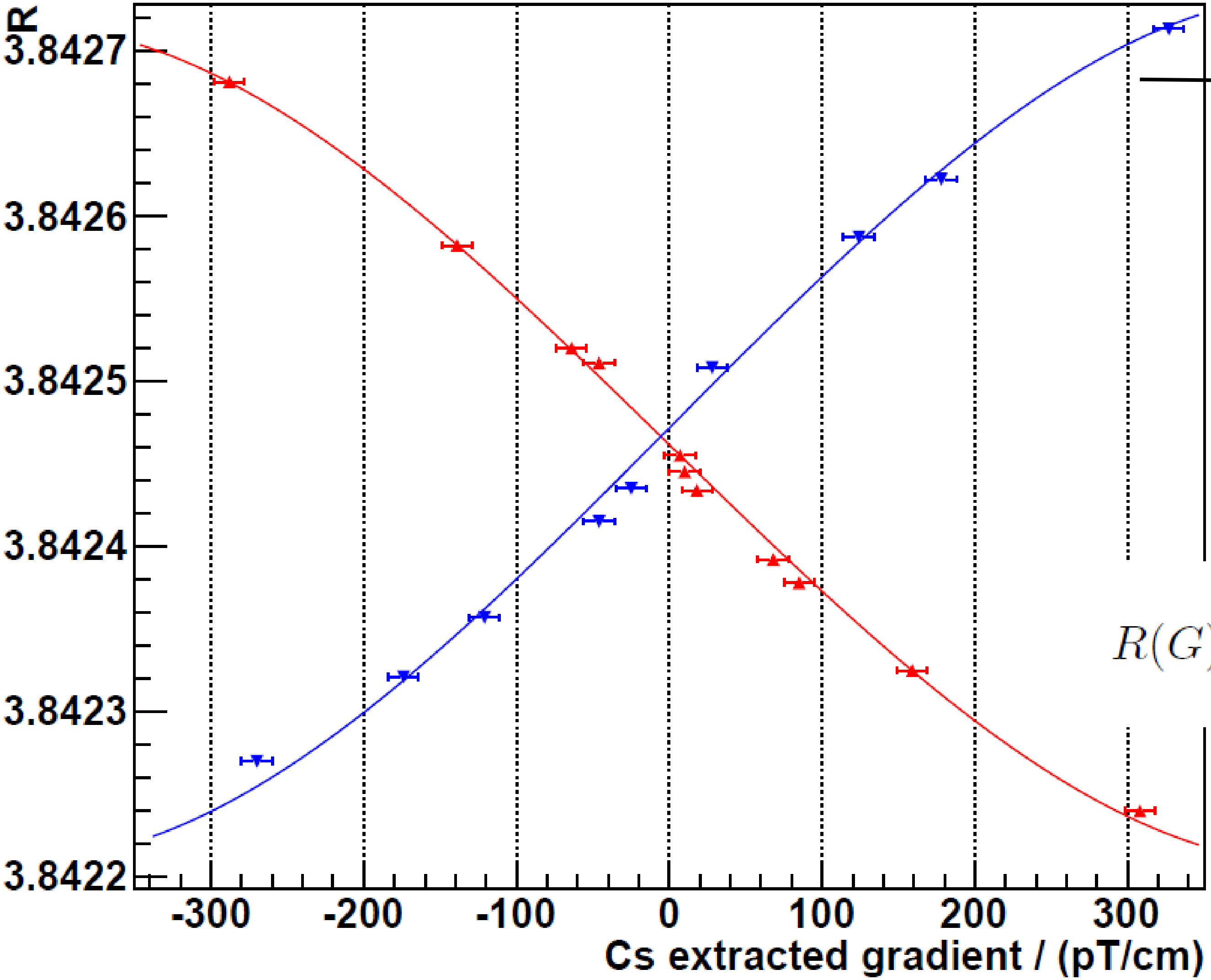
$$f_{\text{Hg}} = \left| \frac{\gamma_{\text{Hg}}}{2\pi} B_0 \pm f_{\text{Earth}} \sin(\lambda) \right|$$



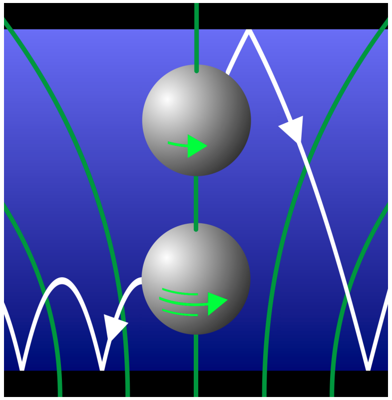
$$\begin{aligned} \delta R_{\text{Earth}} &= \mp \frac{\gamma_n}{\gamma_{\text{Hg}}} \left(\frac{f_{\text{Earth}}}{f_n} + \frac{f_{\text{Earth}}}{f_{\text{Hg}}} \right) \sin(\lambda) \\ &= \mp 5.3 \times 10^{-6} \end{aligned}$$

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 ?



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

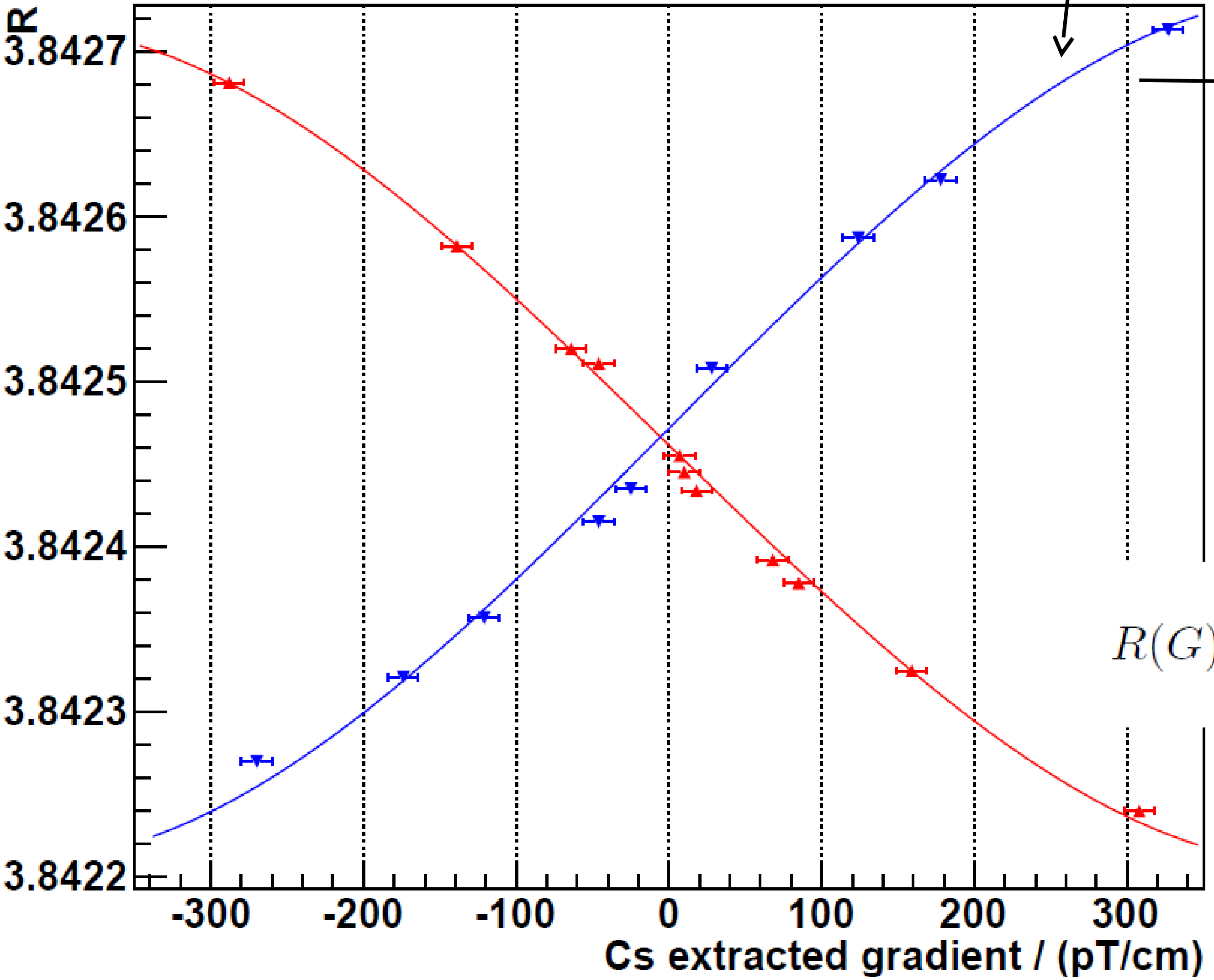
$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy} xy + g_{xz} xz + g_{yz} yz$$

Some results

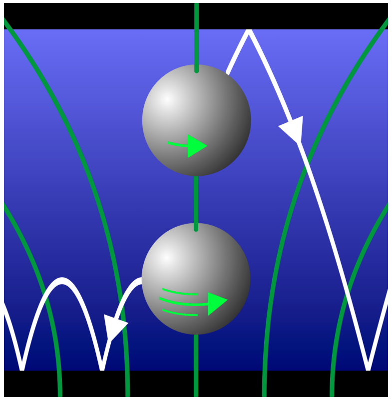
$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}}$$

Gravitational enhanced depolarization and associated frequency shift

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



Transverse component ?
Gravitational ?



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

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

Some results

Featured in Physics

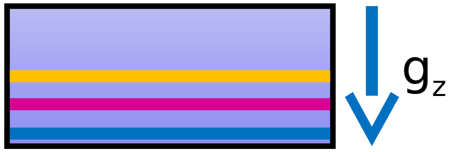
Editors' Suggestion

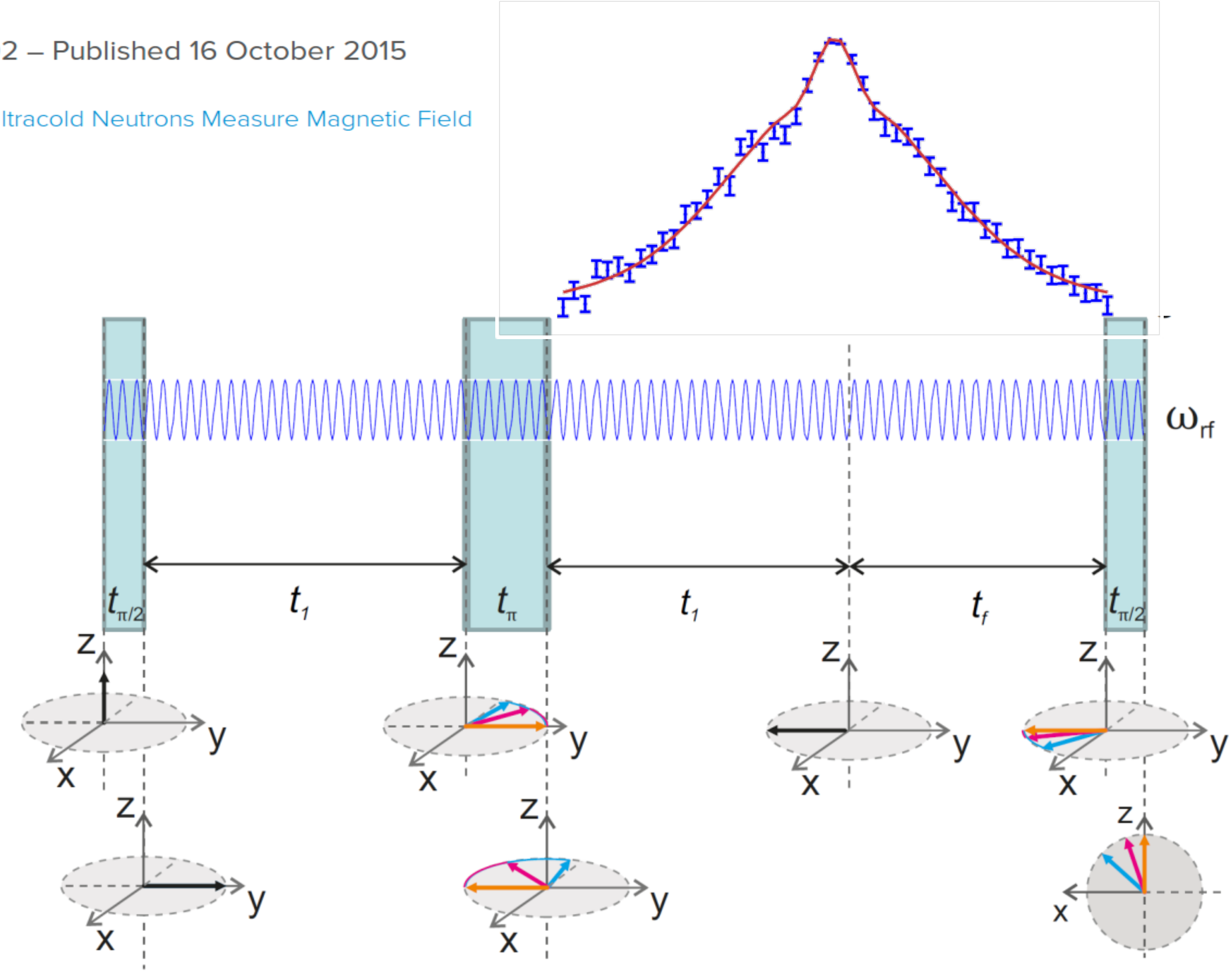
Observation of Gravitationally Induced Vertical Striation of Polarized Ultracold Neutrons by Spin-Echo Spectroscopy

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

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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]
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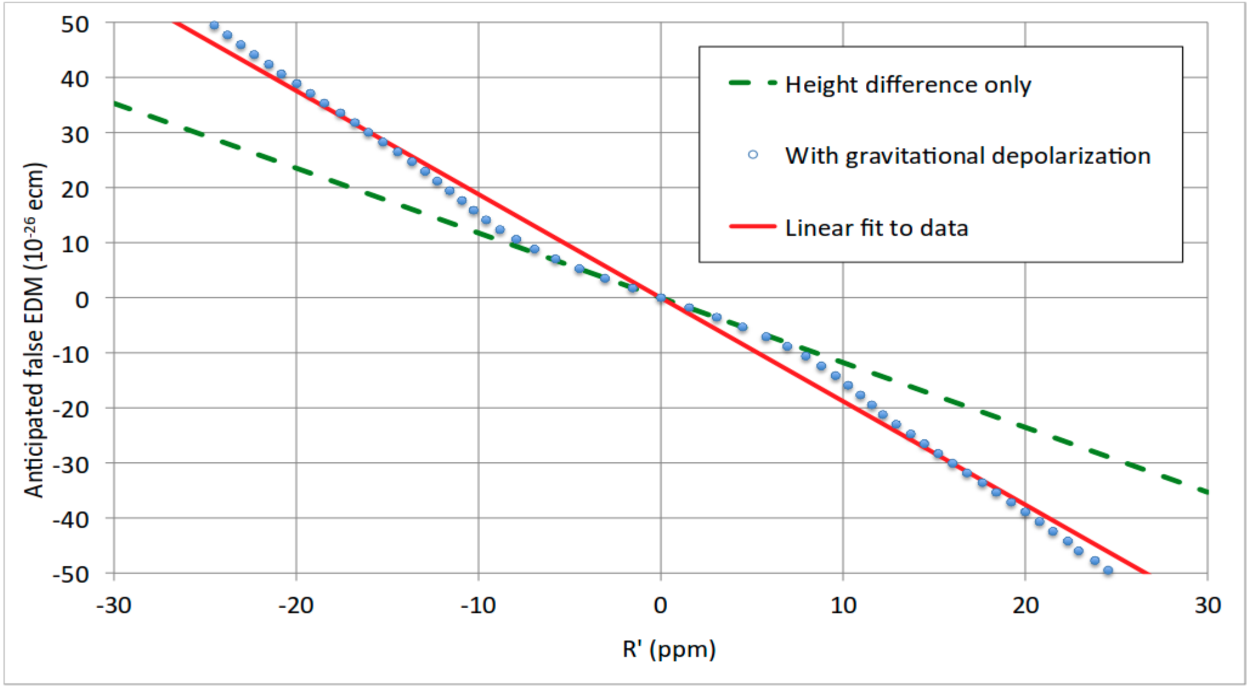
J.D. Richardson,[1] D. Ries,[2,3] S. Roccia,[15] D. Rozpedzik,[7] A. Schnabel,[8] P. Schmidt-Wellenburg,[2] N. Severijns,[11]
D. Shiers,[1] J.A. Thorne,[1] A. Weis,[10] O.J. Winston,[1] E. Wursten,[11] J. Zejma,[7] and G. Zsigmond[2]

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

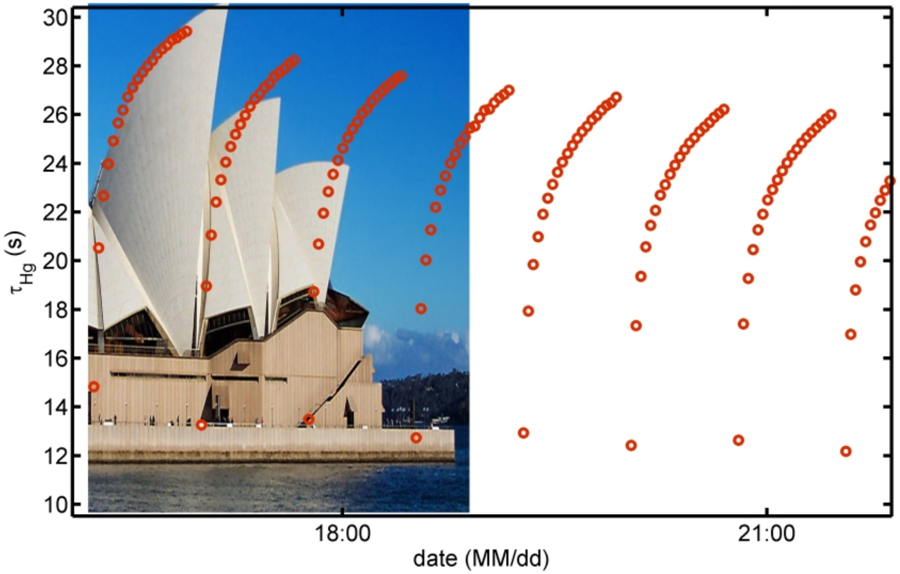
Analysis stage	**EDM**	σ
Crossing point $d_\times$	-0.59	1.53
Gradient-corrected d_0	-0.92	1.68
Dipole-corrected d_fec	-0.21	1.79
Final result d_n	**-0.21**	**1.82**

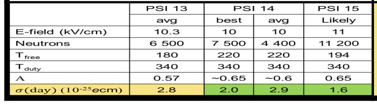


Final result to appear in Phys. Rev. D

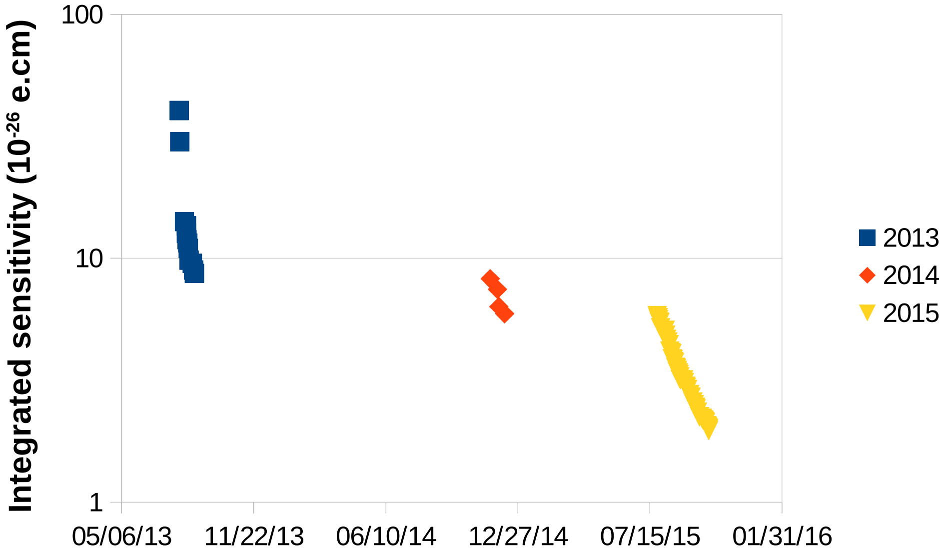
Some results

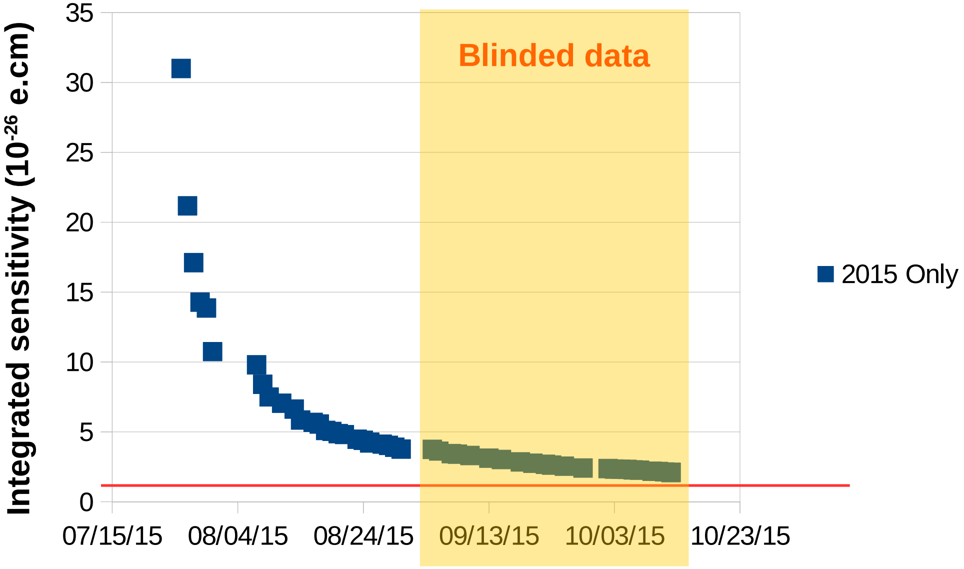
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$



	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

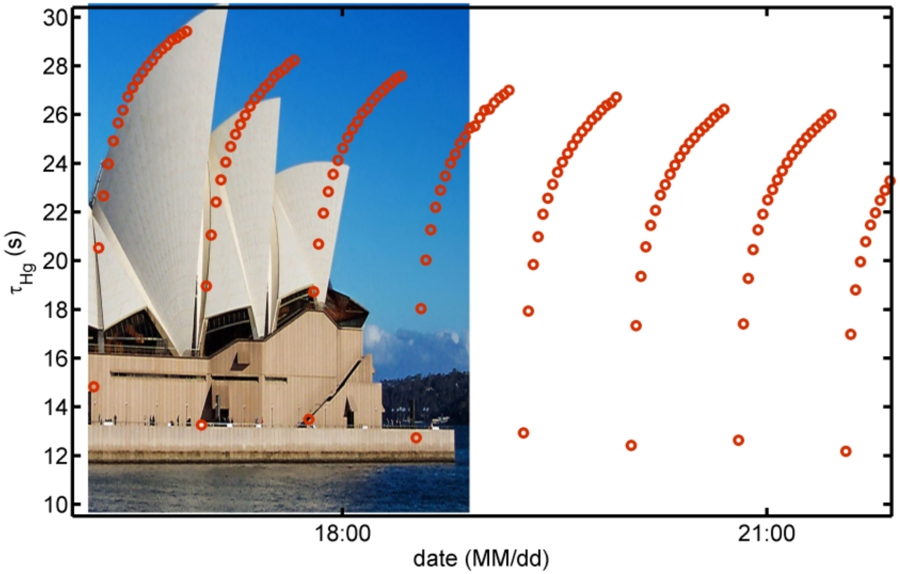
	PSI 13	PSI 14		PSI 15
	avg	best	avg	Likely
E-field (kV/cm)	10.3	10	10	11
Neutrons	6 500	7 500	4 400	11 200
T_{free}	180	220	220	194
T_{duty}	340	340	340	340
A	0.57	~0.65	~0.6	0.65
σ(day) (10^{-25}ecm)	2.8	2.0	2.9	1.6



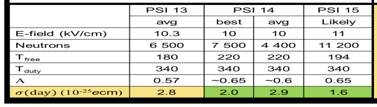


Some results

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



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
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
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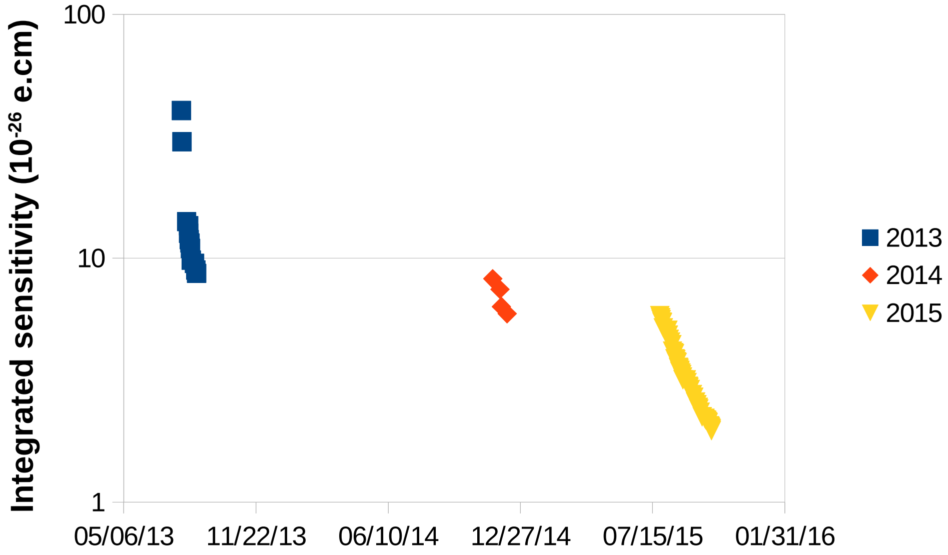
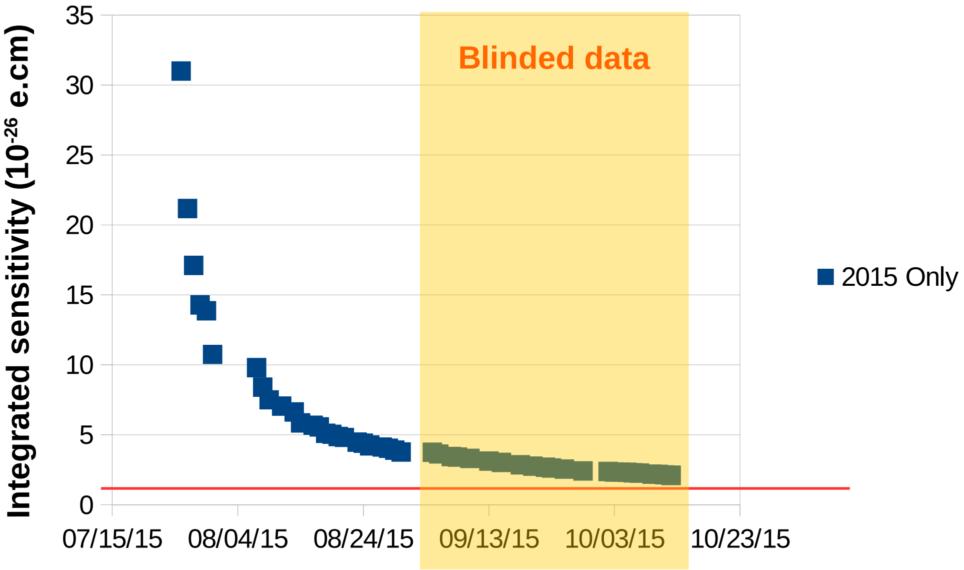
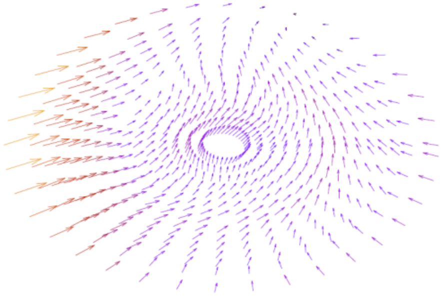




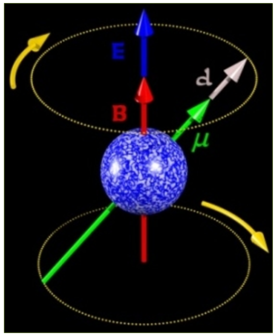
Summary

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

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

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