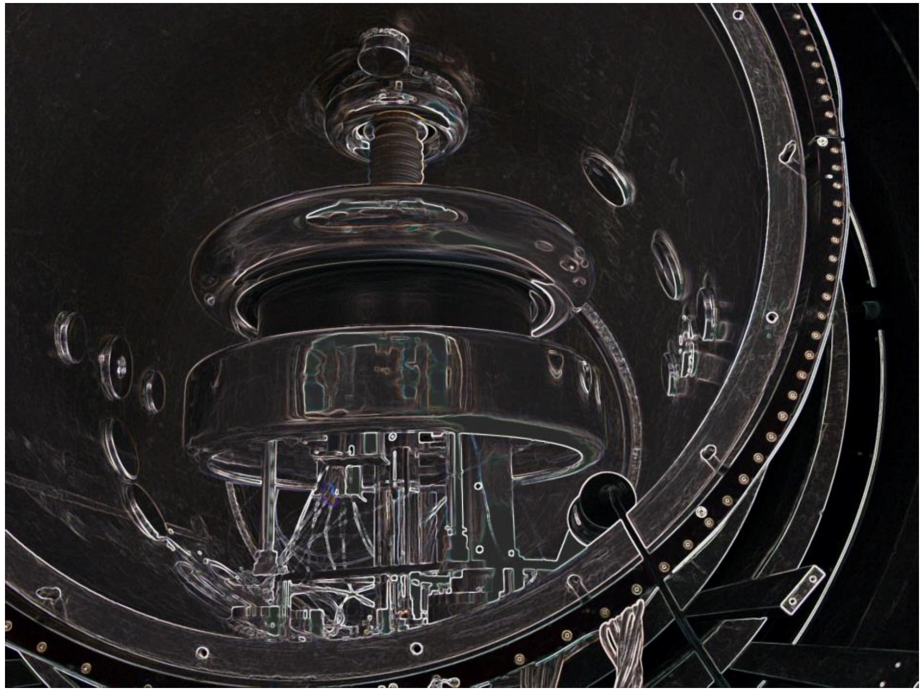
Probing fundamental symmetries with ultra-cold neutrons: the measurement of the neutron electric dipole moment at PSI



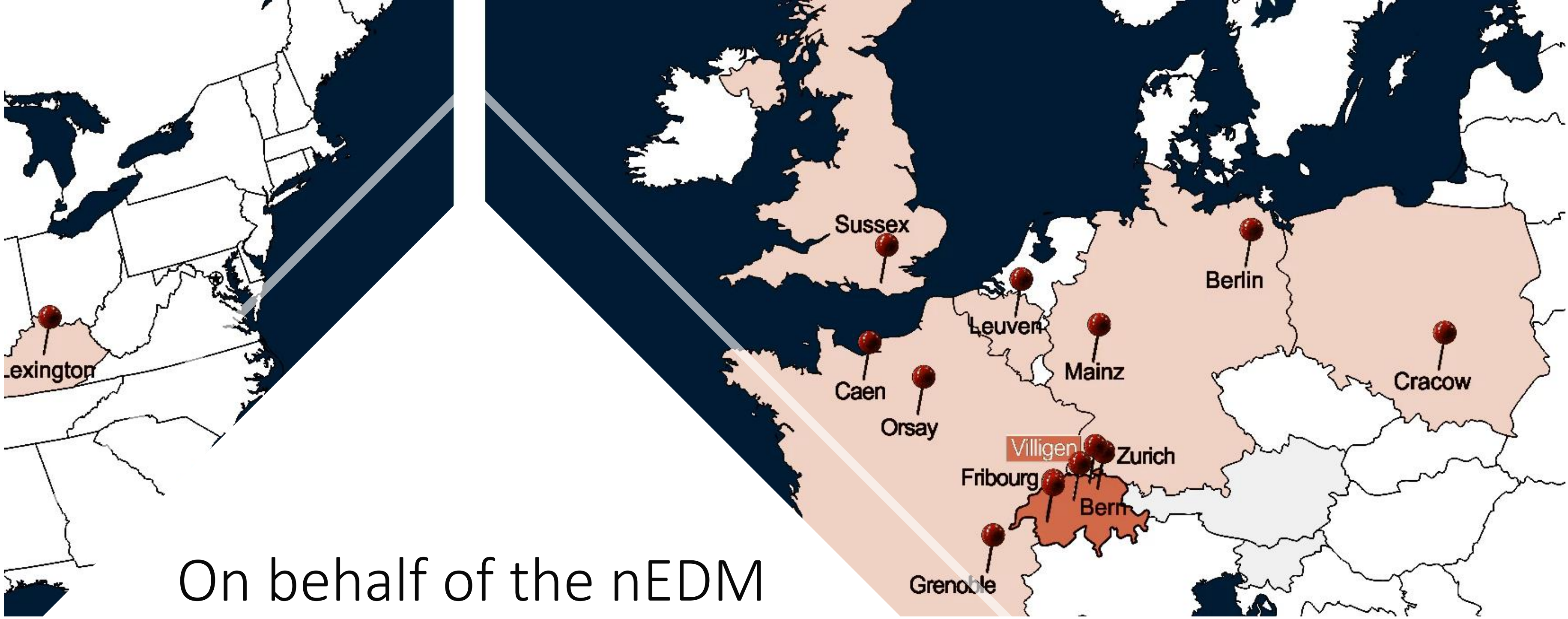
Université Grenoble Alpes

LPSC GRENOBLE | MODANE

NEUTRONS FOR SOCIETY

S. Roccia

22/02/2021



On behalf of the nEDM collaboration

Outlook

What is an EDM?
The neutron EDM in the standard model
The strong CP problem and the axion
Beyond the standard model
Cosmology, dark matter, baryogenesis

.... And how we searched for it at PSI!

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst})\ 10^{-26} e.\text{cm}$ → 10 years, 34 PhD thesis, 55 persons at a given time

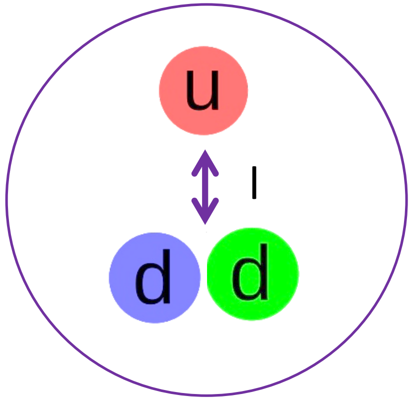
RAL/SUSSEX/ILL result, Phys. Rev. D 92 092003 (2015) based on data taken 1998-2002
$d_n = (-0.2 \pm 1.5_{stat} \pm 1.0_{syst})\ 10^{-26} e.\text{cm}$

What is an EDM?

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

30 Hz in 1µT

58 nHz in 12 KV/cm



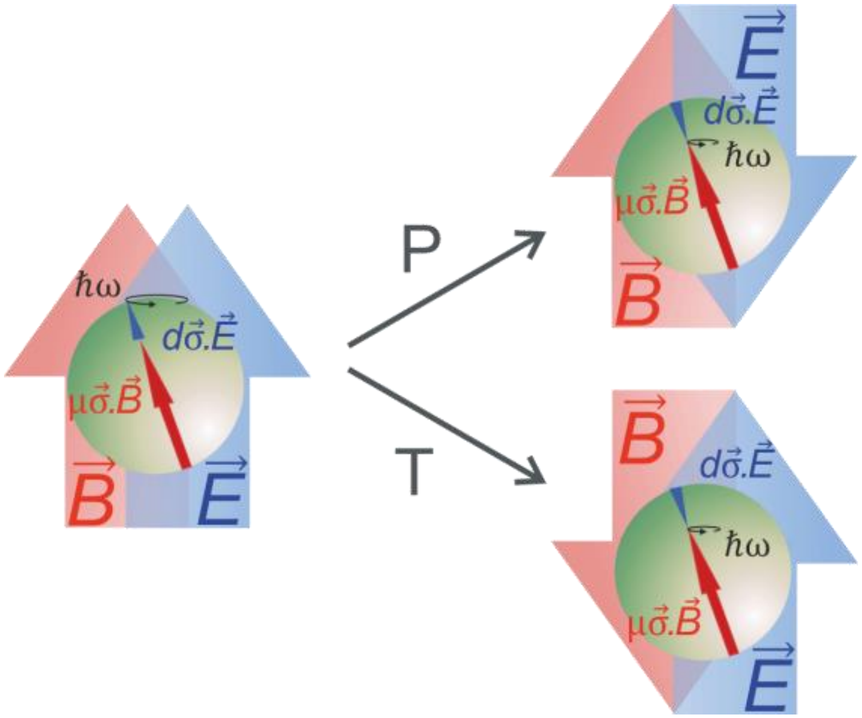
d_n=2/3 e*l

$l=0.1 r_n \rightarrow d_n=4.10^{-14}$ e.cm

But $d_n<1.8\ 10^{-26}$ e.cm (90% C.L.)

Symmetry

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



We have this quantity, that is breaking P, T and CP symmetries.

What is it interesting for?

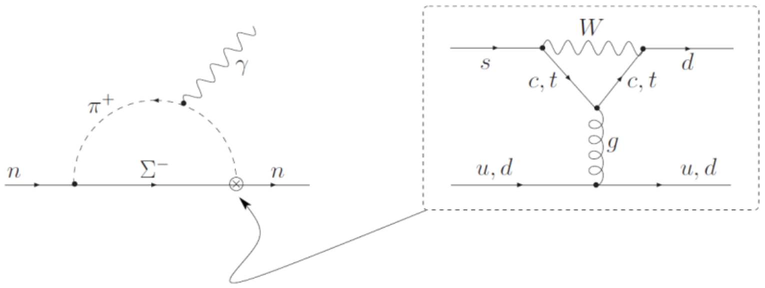
CP violation in the standard model: the weak sector

The neutron EDM (from quarks' EDM)

Naive (valence) approach: $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u \leq 10^{-34}\ e.cm$

The neutron EDM (from "long" distance effect)

The largest Standard Model contribution to d_n comes not from quark EDMs, but from a four-quark operator generated by a so-called "strong penguin" diagram. This is enhanced by long distance effects, namely the pion loop, and it has been estimated that this mechanism



$$d_n \approx 10^{-32}\ e.cm$$

The neutron EDM is essentially free of SM background!

Annals of Physics 318 (2005) 119–169

* PRL(2015)062001

The strong CP problem and the axion

$$L_{eff} = L_{QCD} + \theta \frac{\alpha_S}{8\,\pi}\, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.0039(2)(9)\theta\ e.fm$*

Experimental upper limit: $|d_n| \leq\ 2.10^{-13}\ \ e.fm$

$\theta \lesssim 10^{-10}$

The strong CP problem
* One mass quark is exactly zero but PDG: $m_u\ = 2.2^{+0.6}_{-0.4}\ MeV$
* Introducing a global chiral U(1) symmetry

This symmetry is necessarily spontaneously broken, and its introduction into the theory effectively replaces the static CP-violating angle θ with a dynamical CP- conserving field- the axion. The axion is the Nambu-Goldstone boson of the broken U(1) symmetry.

Axion detour

The axion is a well motivated dark matter candidate

Axion density relative to the critical density of the universe

$$\Omega_a \approx \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{\frac{7}{6}} \approx \Omega_m = 0.23\ (m_a \approx 20\ \mu eV)$$

Entire dark matter density

The theory is quite predictive

Essentially all of the physics of the axion depends on a large unknown energy scale

f_a, at which Peccei-Quinn symmetry is broken.

The axion has a two photons coupling,

and g_γ is model dependant.

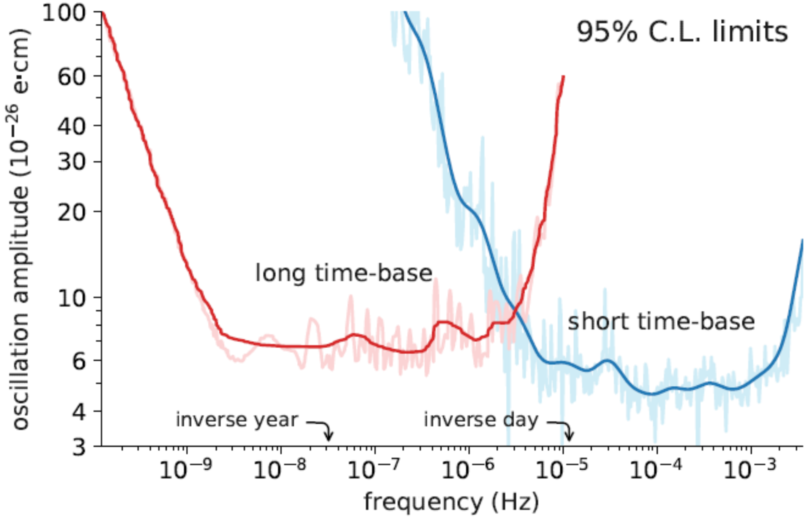
$$m_a \approx 6\,\text{eV}\left(\frac{10^6\ \text{GeV}}{f_a}\right)$$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Annual Review of Nuclear and Particle Science Vol. 65:485-514 (2015)

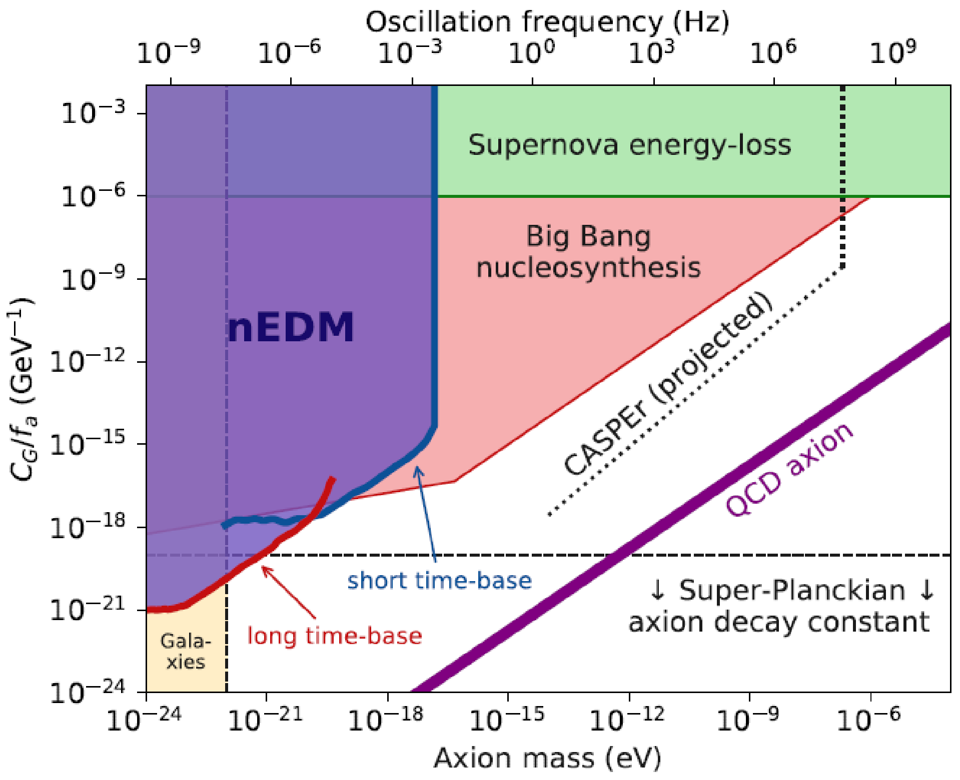
Search for Axion-like dark matter

$$d_\mathrm{n}(t) \approx +2.4 \times 10^{-16} \, \frac{C_G a_0}{f_a} \cos(m_a t) \; e \cdot \mathrm{cm} \, .$$



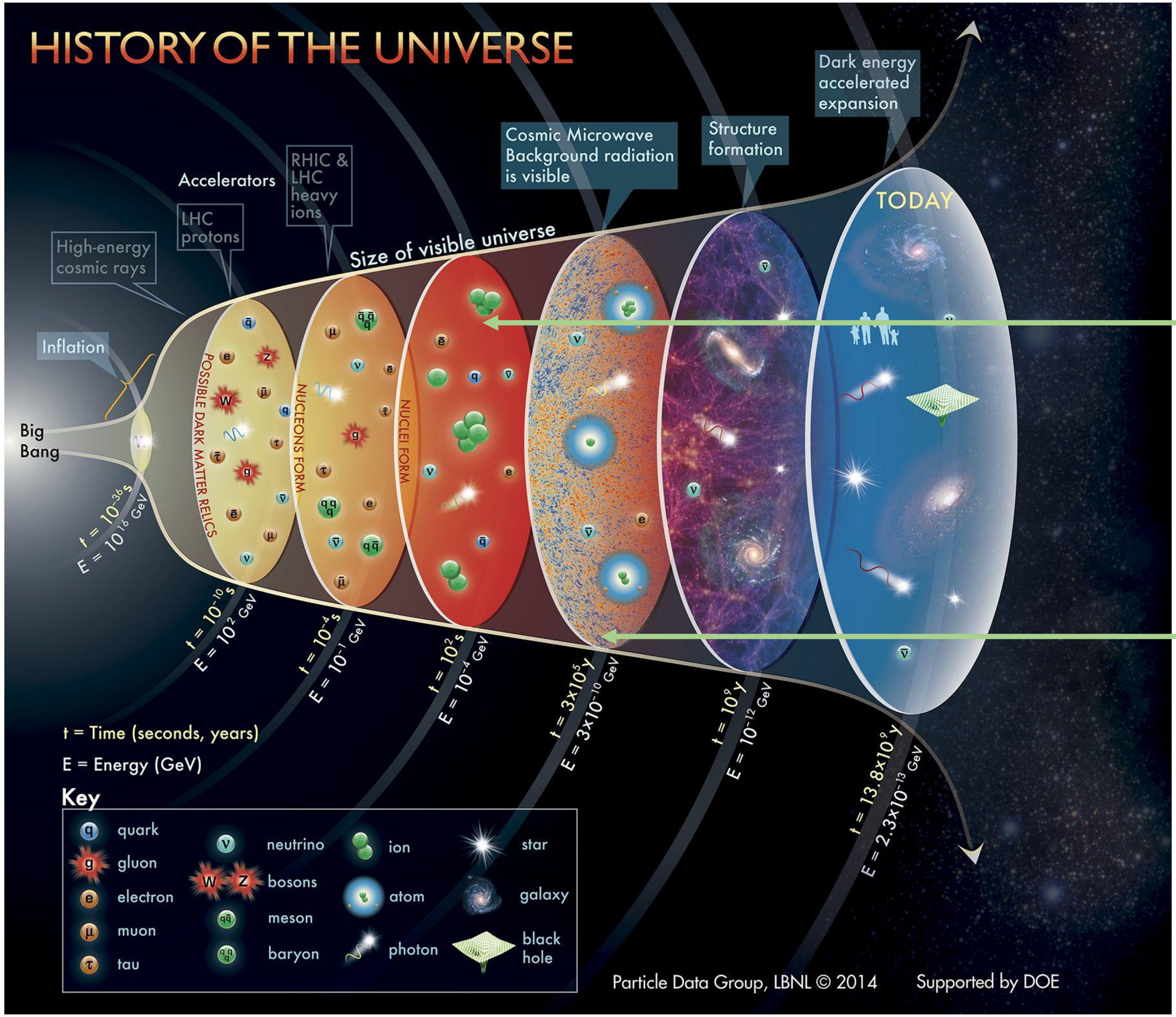
ILL data: long data taking

PSI data: high sensitivity
Still blinded



C. Abel et al., Phys. Rev. X 7, 041034 (2017)

Matter/Antimatter Asymmetry of the Universe



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The abundances of the light elements depend almost solely on the baryon-to-photon ratio

D/H measurements* + nucleosynthesis models

$$5.8\ 10^{-10} < \eta < 6.6\ 10^{-10}$$

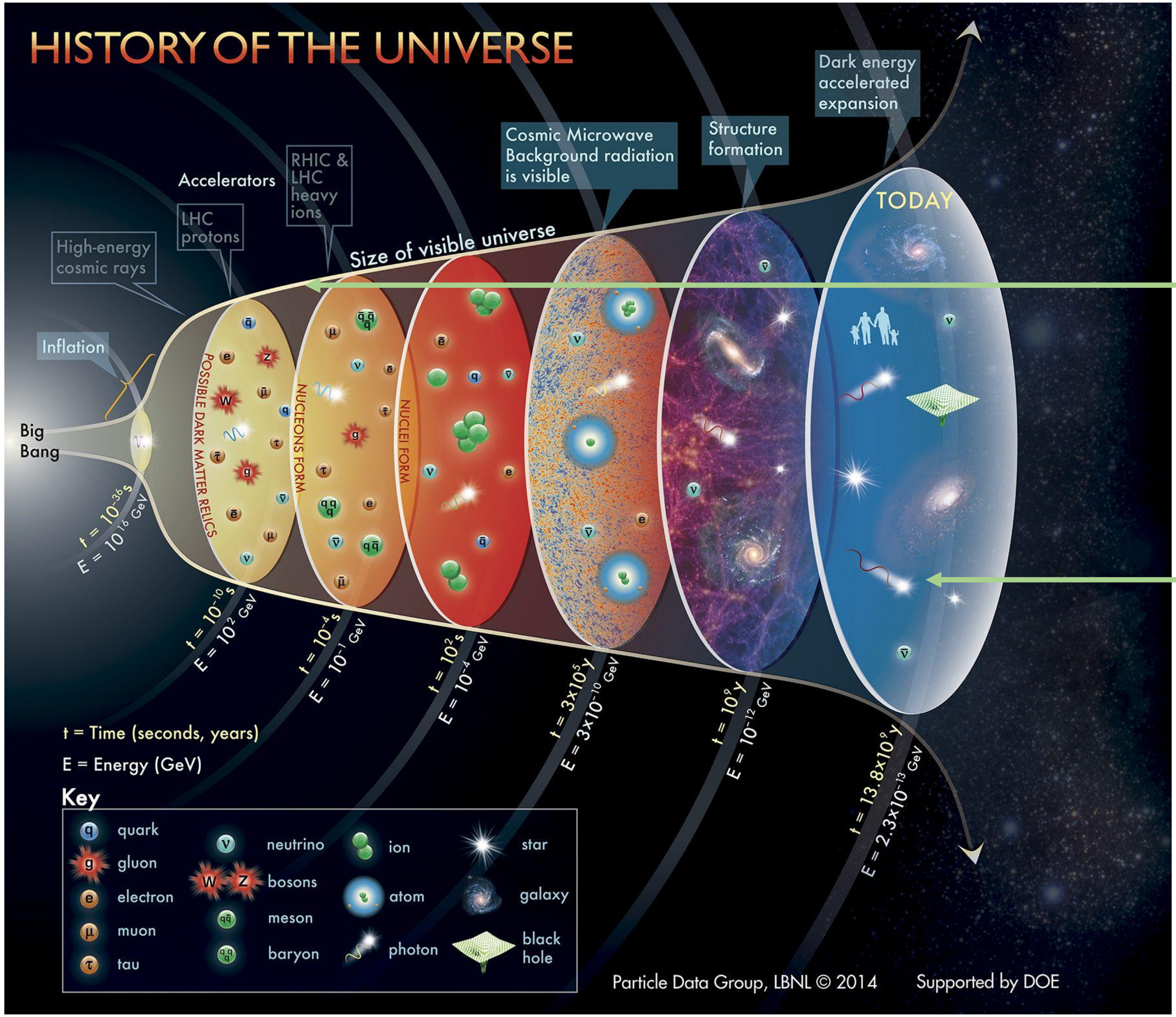
The Planck result**: fraction of cosmological density contained in baryons:

$$\eta = 6.09\ (6)\ 10^{-10}$$

*Universe 3, 44 (2017)

**Astron. & Astrophys. 594, A13 (2016)

Matter/Antimatter Asymmetry of the Universe



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

(1) You prepare the system in thermal equilibrium with

$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 0$$

(2) Baryogenesis happens.

(3) You find the system in thermal with

$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 1, \eta \approx 0$$

Can we say anything general about what happens in Step 2?

Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?
→ **Sakharov criteria for baryogenesis**

1) There must exist an interaction that violates B-number.

2) The B-violating interaction must go out of thermal equilibrium.

3) There must be an interaction that violates C & CP.

Standard Model

1) OK (Sphalerons)

2) ~OK (Requires low Higgs mass)

3) Not OK (CKM)

Electroweak baryogenesis

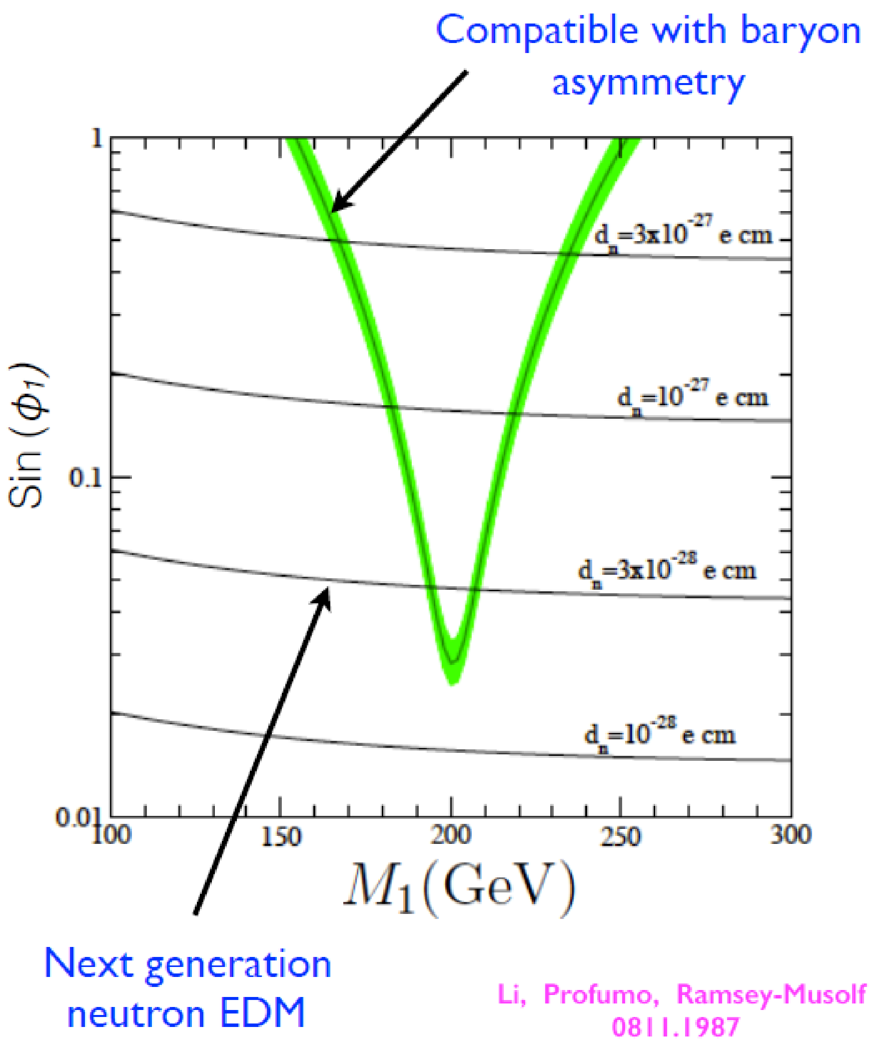
New CP violating phases
contributes to

* baryonic asymmetry of the universe
* neutron EDM

$$d_n = d_n^{CKM} + 10^{-16}\, e.cm\, (\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

The nEDM is the most stringent test of
electroweak baryogenesis

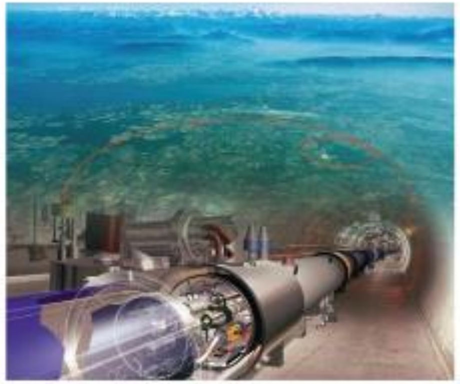
Another possibility is the leptogenesis

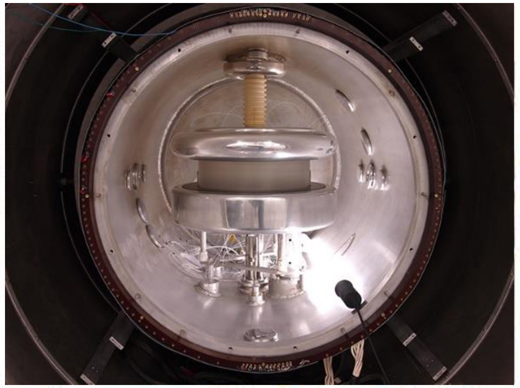


Picture by V. Cirigliano

Search for new physics

$$d_n = d_n^{CKM} + 10^{-16}\, e.cm\, (\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$





Search for new physics

$$d_n = d_n^{CKM} + 10^{-16}\, e.cm\, (\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

At D=4

$$d_n = -\,0.003(7)(20)\ e\ \text{fm}\left[\theta + \arg\det M_q\right]$$

Bhattacharya et al. 2101.07230

At D=6

$$\mathcal{O}^{ij\,lm}_{1\,LR} = \bar{d}^m \gamma^\mu P_L u^l\, \bar{u}^i \gamma_\mu P_R d^j\,, \qquad \mathcal{O}^{ij\,lm}_{2\,LR} = \bar{d}^m_\alpha \gamma^\mu P_L u^l_\beta\, \bar{u}^i_\beta \gamma_\mu P_R d^j_\alpha$$

Nuclear dipoles pick up many contributions from many CP violating operators; even more when RG running is taken into account

$$\begin{aligned} d_n = & \Big((43 \pm 27)\tilde{C}^{us\,us}_{1\,LR} + (210 \pm 130)\,\tilde{C}^{us\,us}_{2\,LR} + (22 \pm 14)\,\tilde{C}^{ud\,ud}_{1\,LR} + (110 \pm 70)\,\tilde{C}^{ud\,ud}_{2\,LR} \\ & -(0.93 \pm 0.05)\,\tilde{c}^{uu}_{\gamma u} - (4.0 \pm 0.2)\,\tilde{c}^{dd}_{\gamma d} - (0.8 \pm 0.9)\,\tilde{c}^{ss}_{\gamma d} \\ & -(3.9 \pm 2.0)\,\tilde{c}^{uu}_{gu} - (16.8 \pm 8.4)\,\tilde{c}^{dd}_{gd} \pm (320 \pm 260) v^2 C_{\tilde{G}}\Big) \times 10^{-9}\ e\,\text{fm}\,, \end{aligned}$$

$$-\frac{eQ_d}{2} \sum_{ij\in\{d,s,b\}} m_{d_j} C^{ij}_{\gamma d} \bar{d}^i_L \sigma^{\mu\nu} F_{\mu\nu} d^j_R$$

$$-\frac{eQ_u}{2} \sum_{ij\in\{u,c\}} m_{u_j} C^{ij}_{\gamma u} \bar{u}^i_L \sigma^{\mu\nu} F_{\mu\nu} u^j_R$$

$$-\frac{g_s}{2} \sum_{ij\in\{u,c\}} m_{u_j} C^{ij}_{gu} \bar{u}^i_L \sigma^{\mu\nu} G^a_{\mu\nu} t^a u^j_R - \frac{g_s}{2} \sum_{ij\in\{d,s,b\}} m_{d_j} C^{ij}_{gd} \bar{d}^i_L \sigma^{\mu\nu} G^a_{\mu\nu} t^a d^j_R$$

$$C_{\tilde{G}} \frac{g_s}{3} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} \widetilde{G}^c_{\rho\mu}$$

Alioli et al. 1703.04751

Adam Falkowski, lecture at the Houches (nEDM2021)

Milano detour

Eur. Phys. J. C (2017) 77:828
https://doi.org/10.1140/epjc/s10052-017-5400-x

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Electromagnetic dipole moments of charged baryons with bent crystals at the LHC

E. Bagli[1], L. Bandiera[1], G. Cavoto[2], V. Guidi[1], L. Henry[3], D. Marangotto[4], F. Martinez Vidal[3], A. Mazzolari[1], A. Merli[4,5], N. Neri[4,5,a], J. Ruiz Vidal[3]

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[3] IFIC, Universitat de València-CSIC, Valencia, Spain
[4] INFN Sezione di Milano and Università di Milano, Milan, Italy
[5] CERN, Geneva, Switzerland

The search for the neutron EDM

ILL 1986-2009

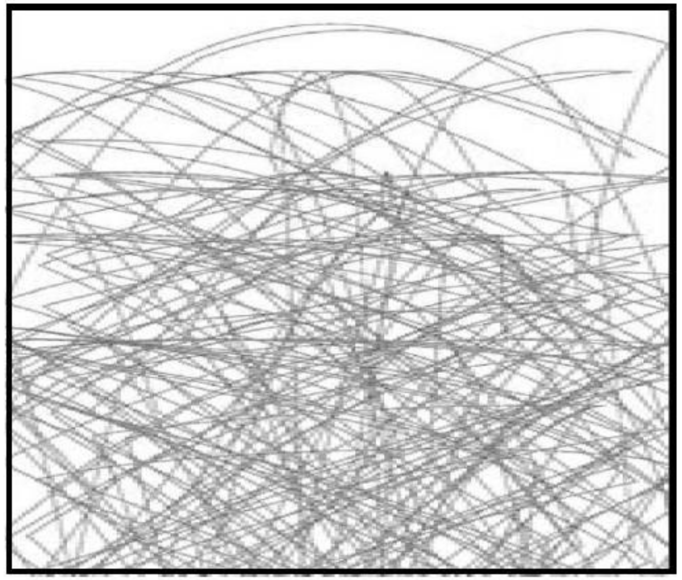
EDM, ALP, mirror neutrons

PSI 2009-2017

RAL/Sussex/ILL collab.
dn<3.10-26 e.cm (2006, 2015)

The search for the neutron EDM

Neutrons reflected for all incidence angles: UCNs

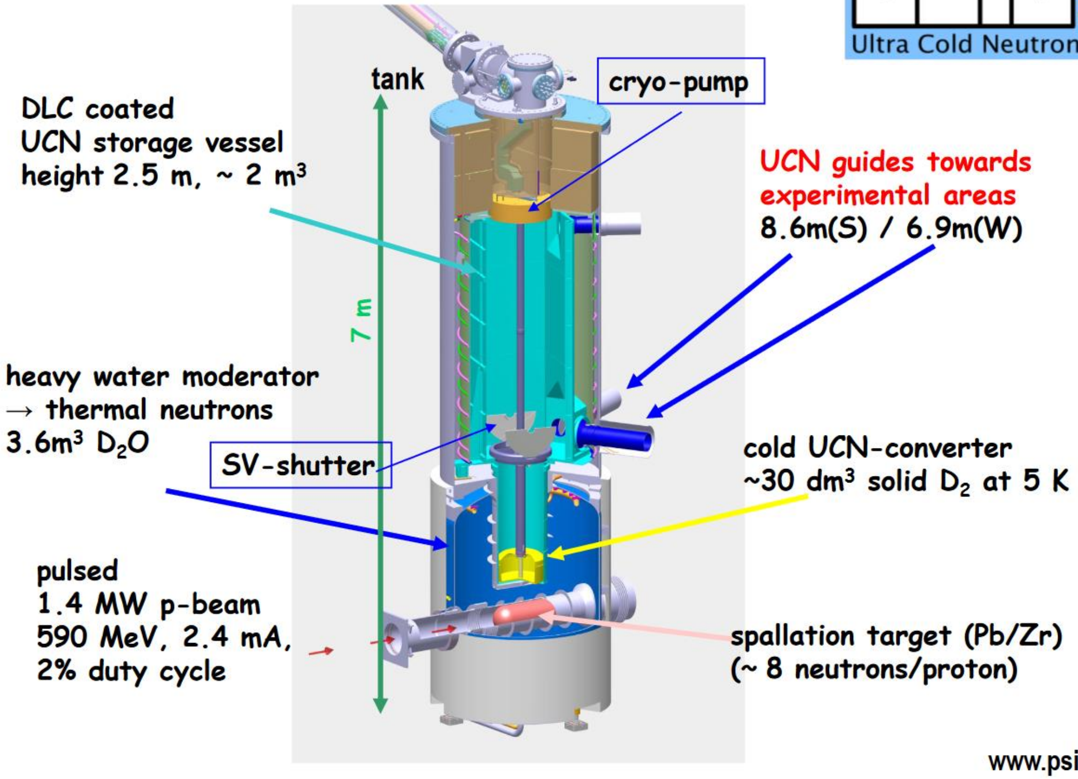


$\lambda_n \approx 800$ Å;

$v_n \approx 5$ m/s;

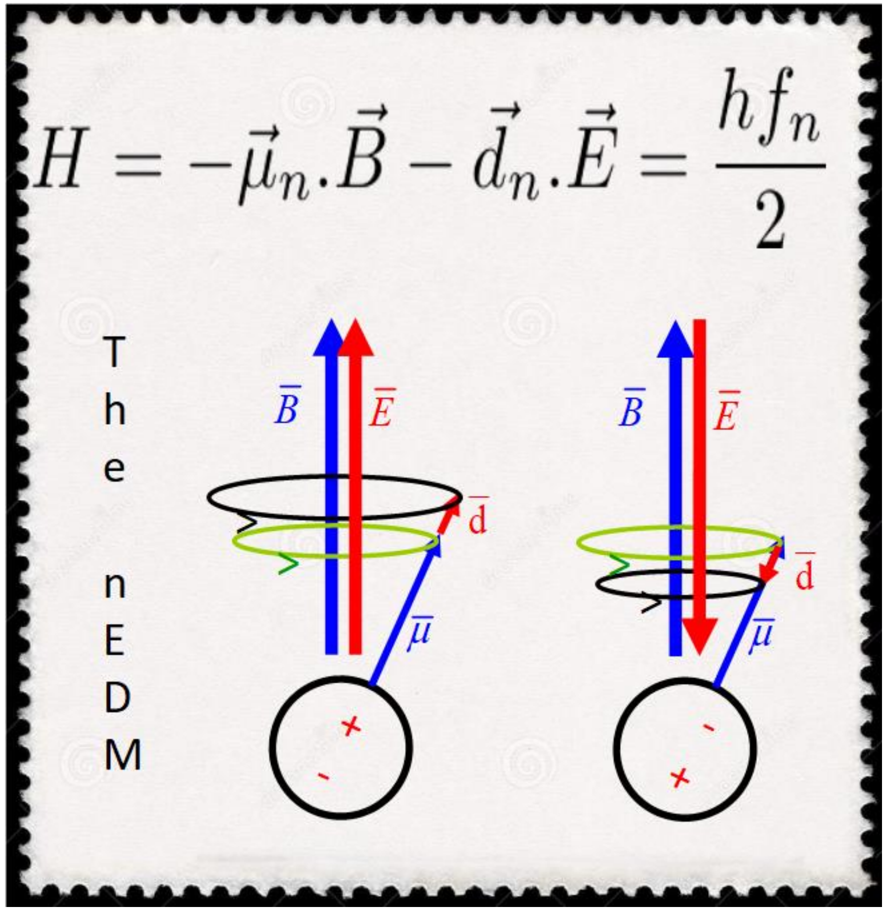
$T_n \approx 2$ mK ;

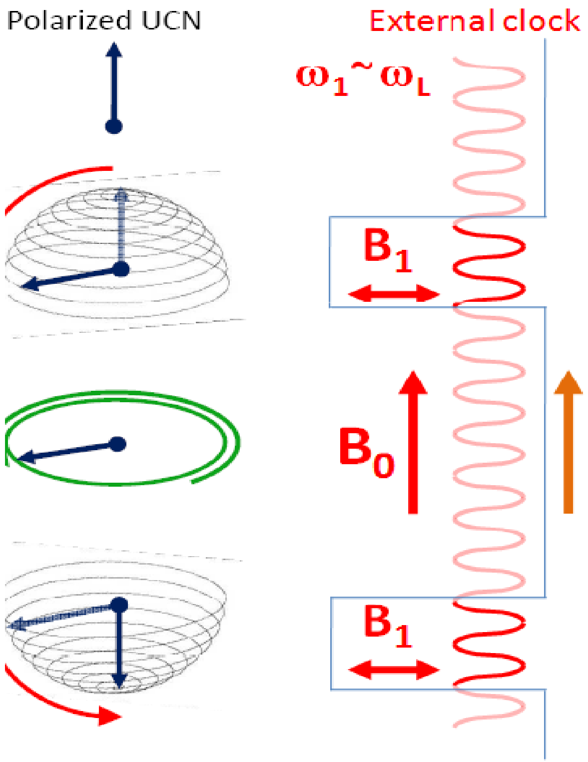
$E_n \approx 130$ neV

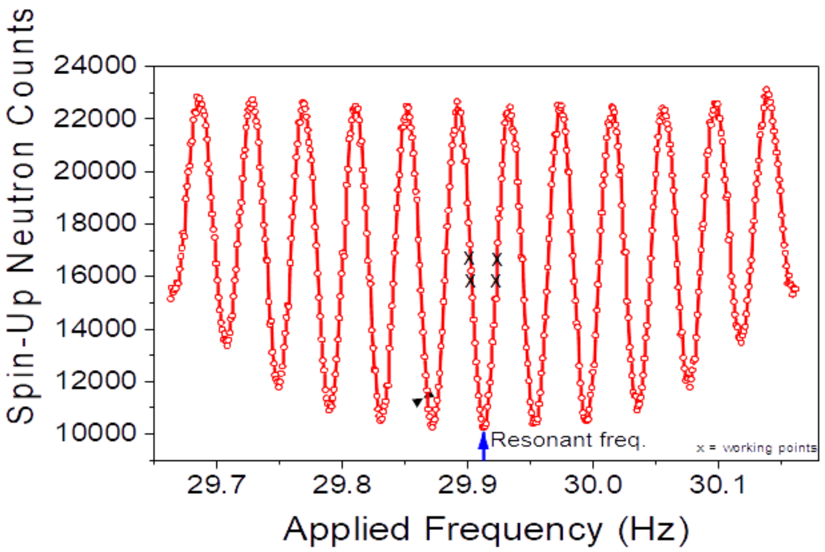


www.psi.ch/ucn/

The search for the neutron EDM



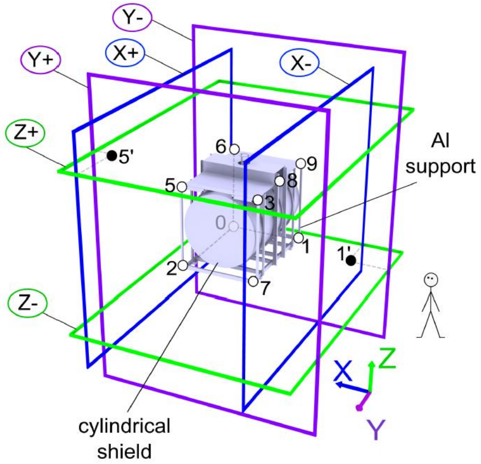


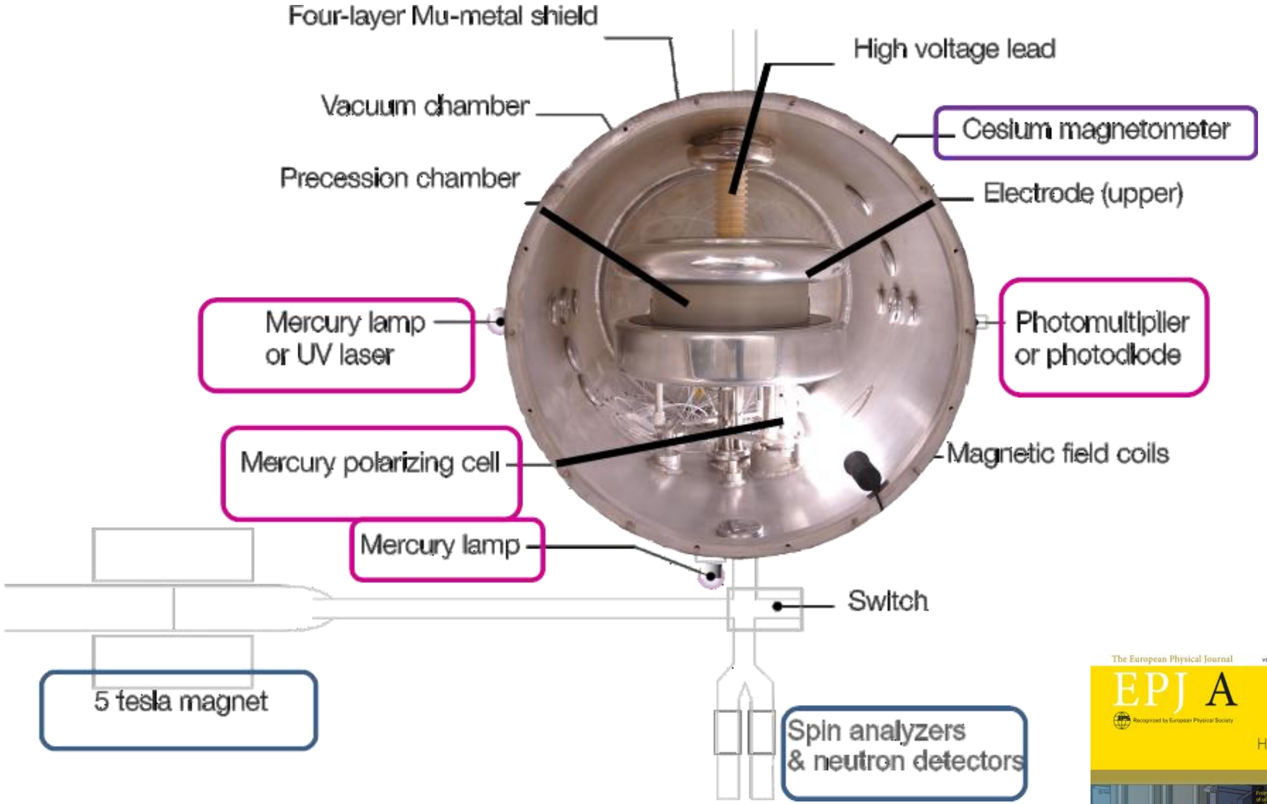


$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

The Ramsey's method of separated oscillating fields

The search for the neutron EDM

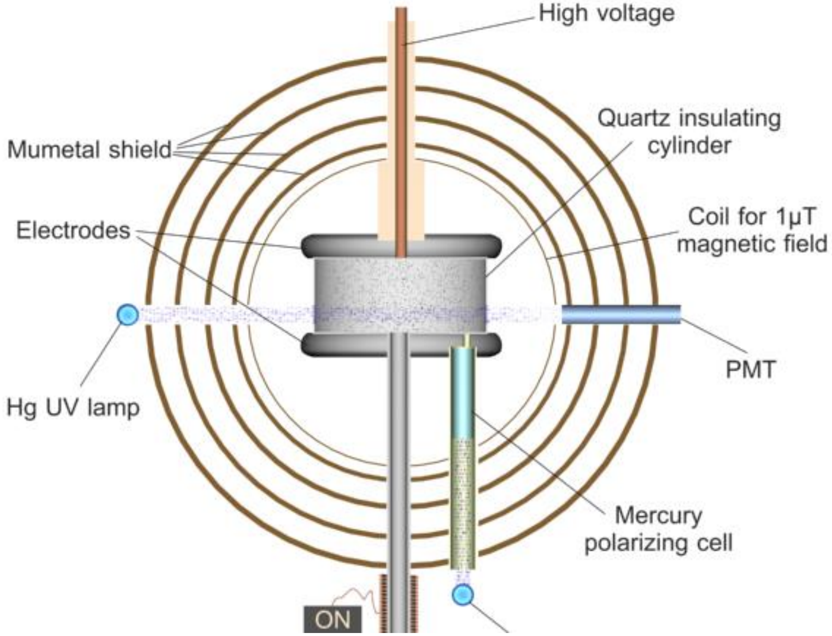




The search for the neutron EDM

First limitation ….. Magnetic field fluctuations

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



Mercury co-magnetometer (1998)

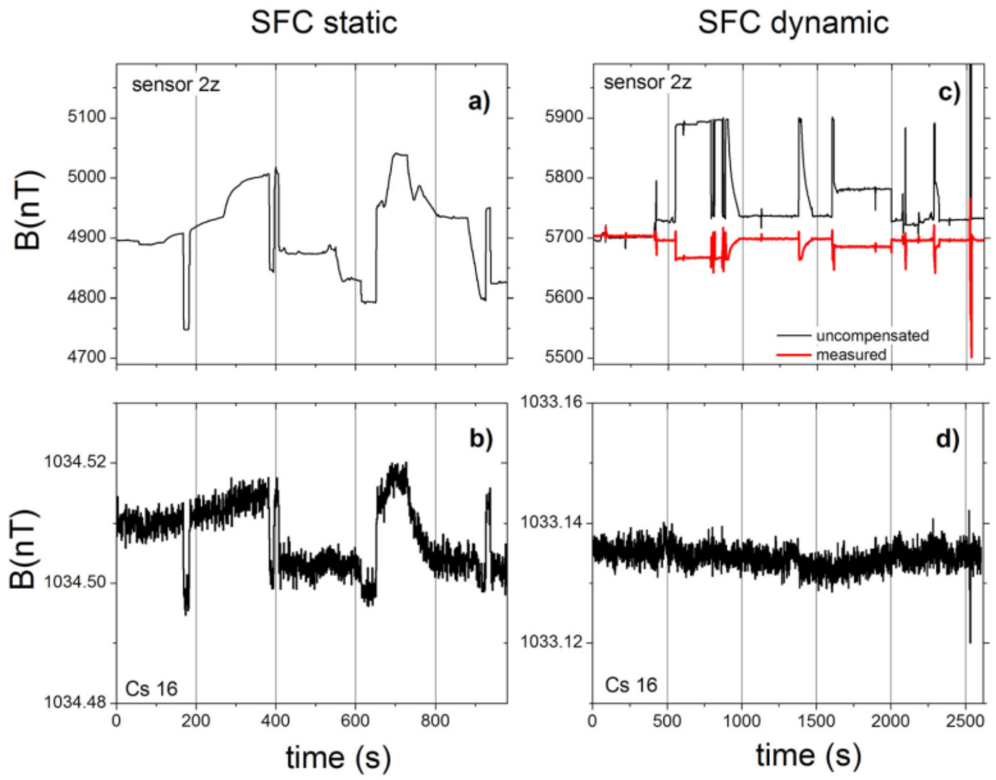
$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

Cesium magnetometer array (2009)

The search for the neutron EDM

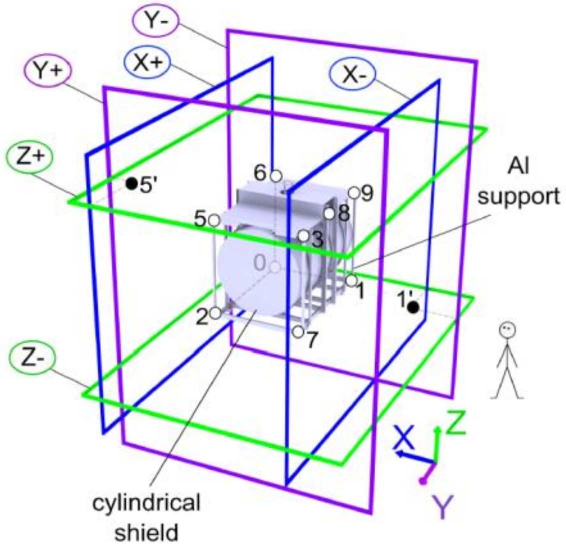
Dynamic shielding

Static shielding



Stabilisation of the ambient field ~ 100 nT

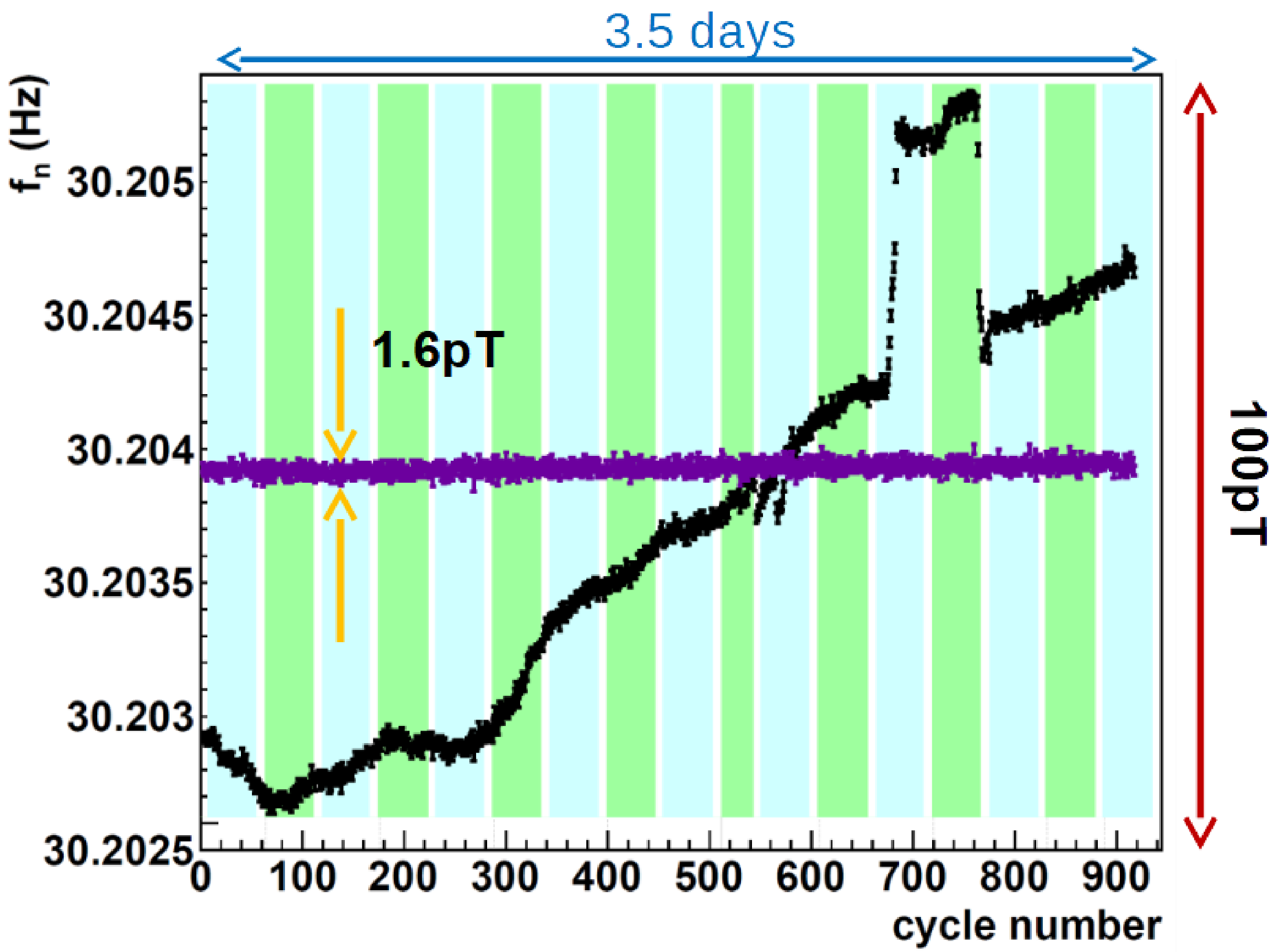
Stabilisation of the inner field ~ 100 pT



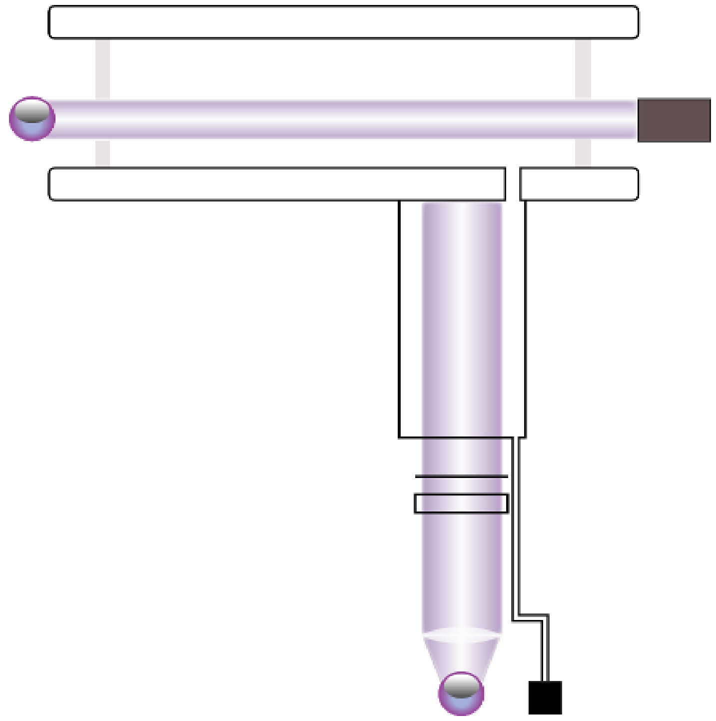
Excellent stability
(dynamic SFC & 4 layer magnetic shield)
Stability (AD) @400s: ~<400fT

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

The search for the neutron EDM

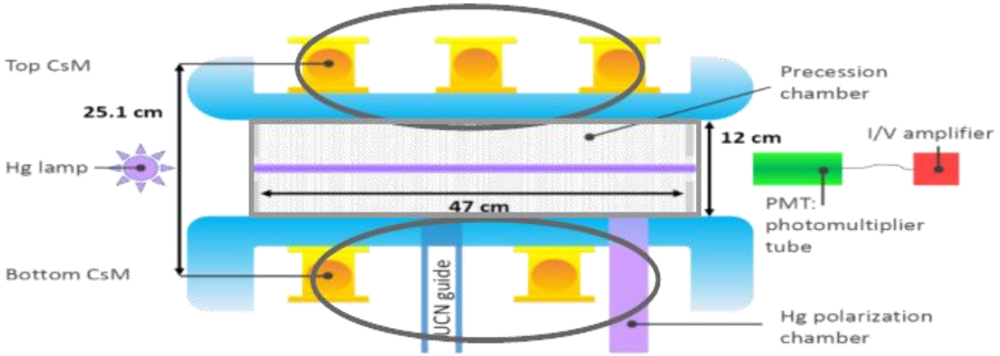


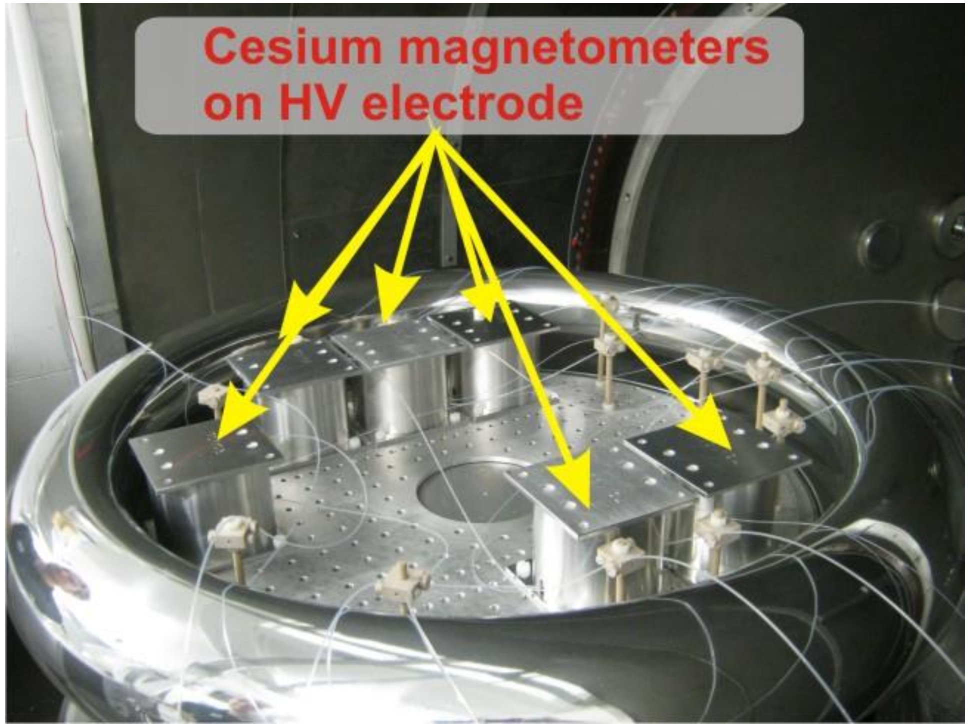
The Hg co-magnetometer



The search for the neutron EDM

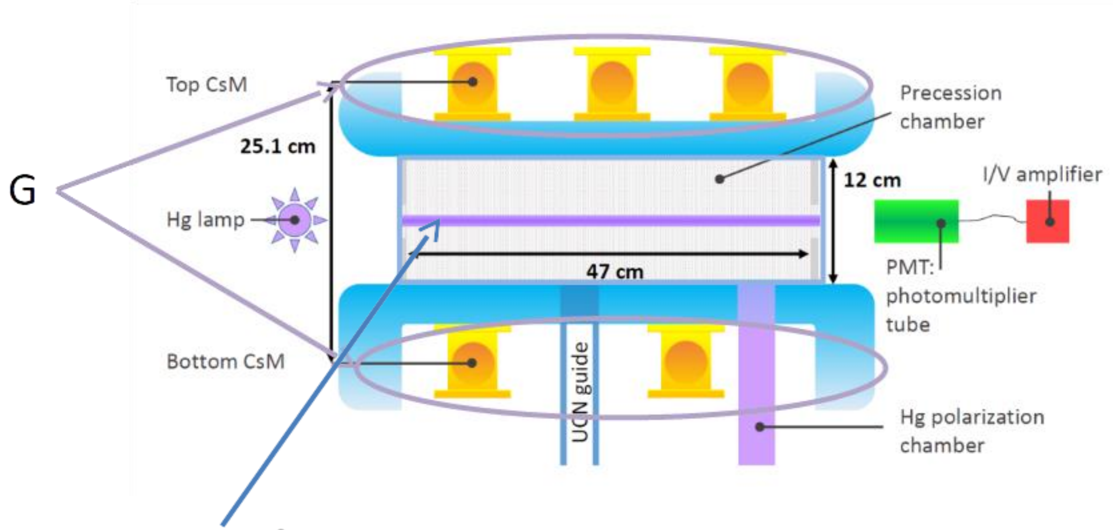
- Monitoring of the vertical gradient
- Homogenisation of the magnetic field



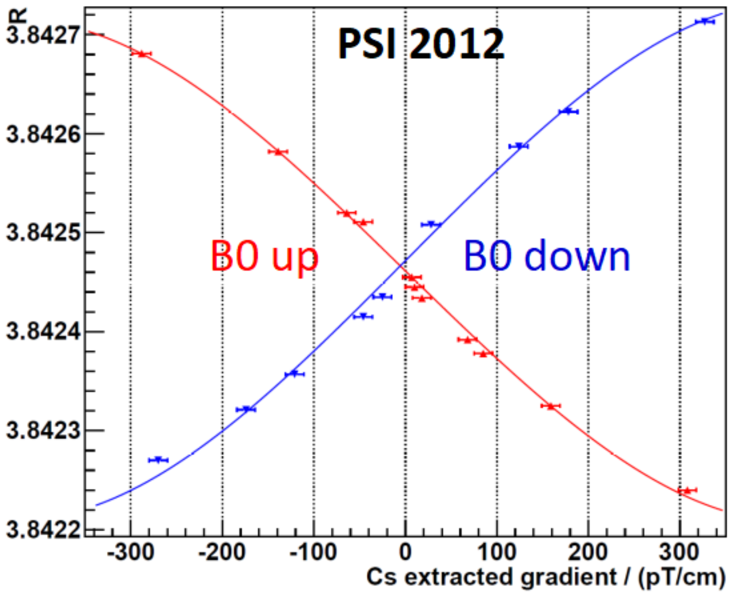


A non perfect Co-magnetometer

- Gravitational shift

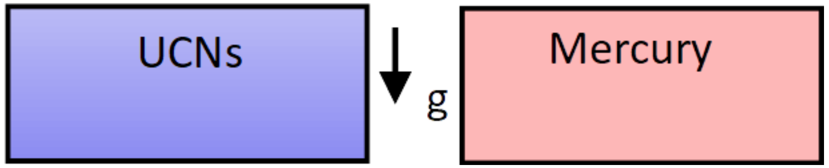


$$R = \frac{f_{\rm n}}{f_{\rm Hg}}$$

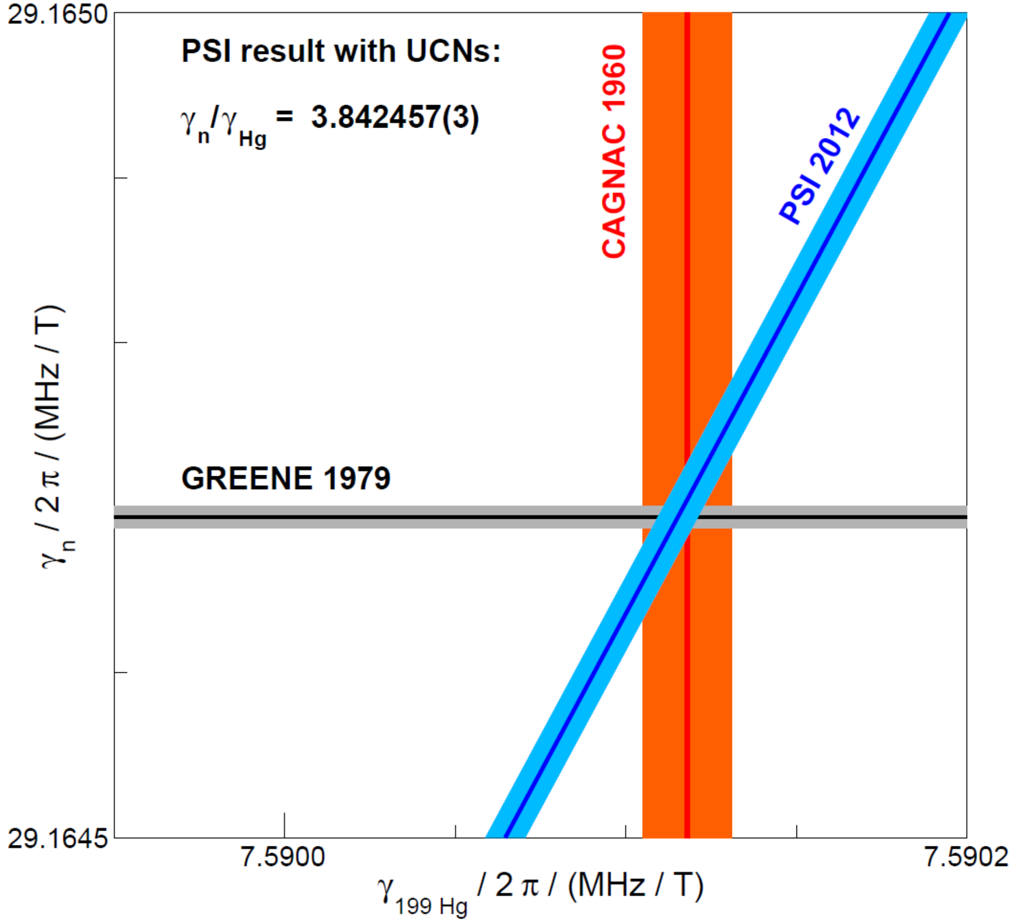


$$R = \frac{\langle f_{\rm UCN}\rangle}{\langle f_{\rm Hg}\rangle} = \frac{\gamma_{\rm n}}{\gamma_{\rm Hg}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \ ...\right)$$

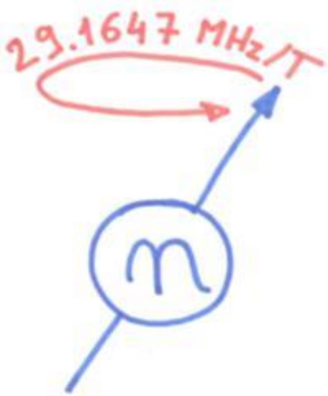
In the precession chamber



The search for the neutron EDM



Effect	$B_0 \uparrow$	$B_0 \downarrow$
Counting statistics	$\pm 0.5 \times 10^{-6}$	$\pm 0.5 \times 10^{-6}$
Gravitational shift ($3.84 \times \delta_{Grav}$)	$(-8.9 \pm 2.3) \times 10^{-6}$	$(-1.8 \pm 2.7) \times 10^{-6}$
Intermediate R_0	3.8424580(23)	3.8424653(27)
Transverse shift ($3.84 \times \delta_T$)	$(3.7 \pm 0.8) \times 10^{-6}$	$(3.0 \pm 1.2) \times 10^{-6}$
Light shift ($3.84 \times \delta_{Light}$)	$(1.3 \pm 0.7) \times 10^{-6}$	$(0.8 \pm 0.6) \times 10^{-6}$
Earth rotation ($3.84 \times \delta_{Earth}$)	-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)

The search for the neutron EDM

A non perfect Co-magnetometer

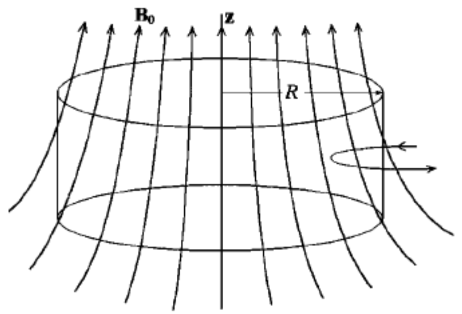
- Gravitational shift
- Geometrical phase shift

Motional (transverse) field

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

+

Magnetic transverse field

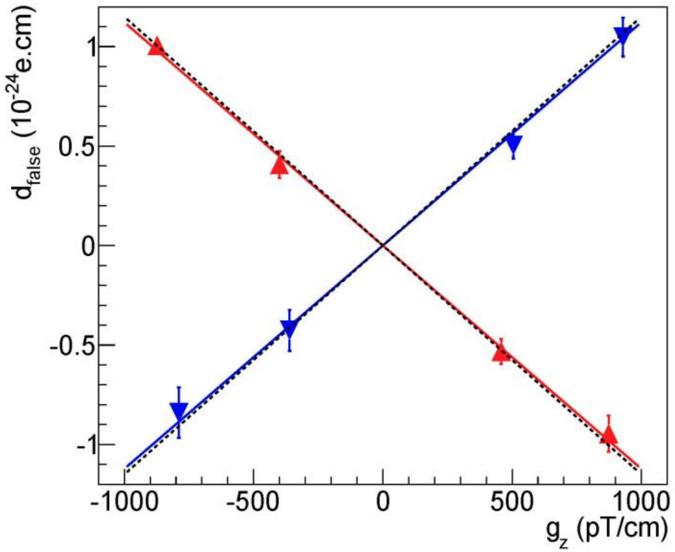


→ Frequency shift correlated with electric field

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

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

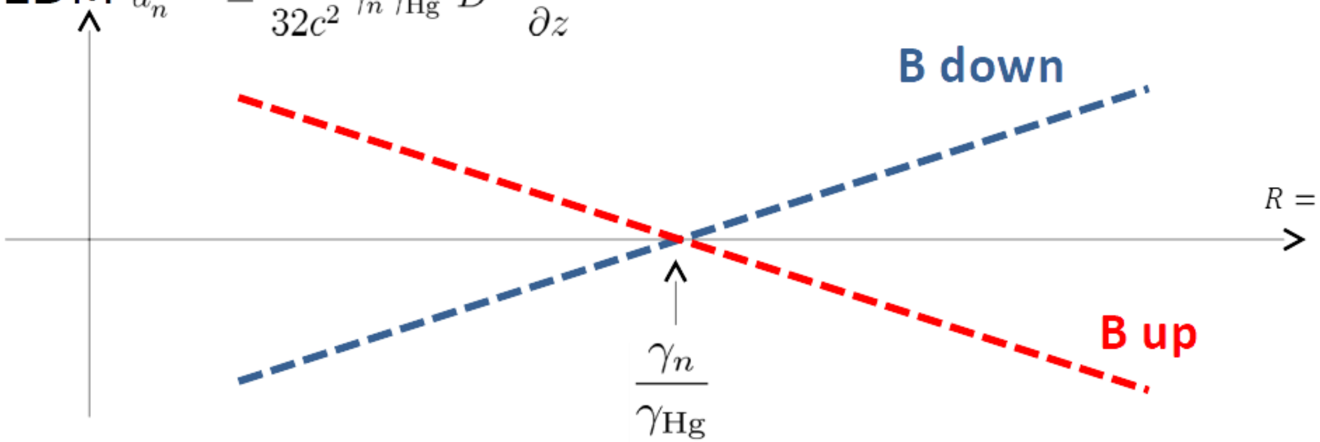
At 1st order in gradients



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

The search for the neutron EDM

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



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

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

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

In the case of an inhomogeneous B-field

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

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

Indirect systematic effect due to local dipoles

At 1st order in gradients

Pignol et al, PRA 85 042105 (2012)

The search for the neutron EDM

	nEDM@ILL 2006	nEDM@PSI 2016
Chamber	1	1
Diameter (cm)	47	47
Neutron/cycle	14 000	15 000
E(kV/cm)	8.3	11 (15)
T(s)	130	180
α	0.45 (0.6)	0.75 (0.80)
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$
Sens (500 days)	$1.3*10^{-26}$	$5.0*10^{-27}$

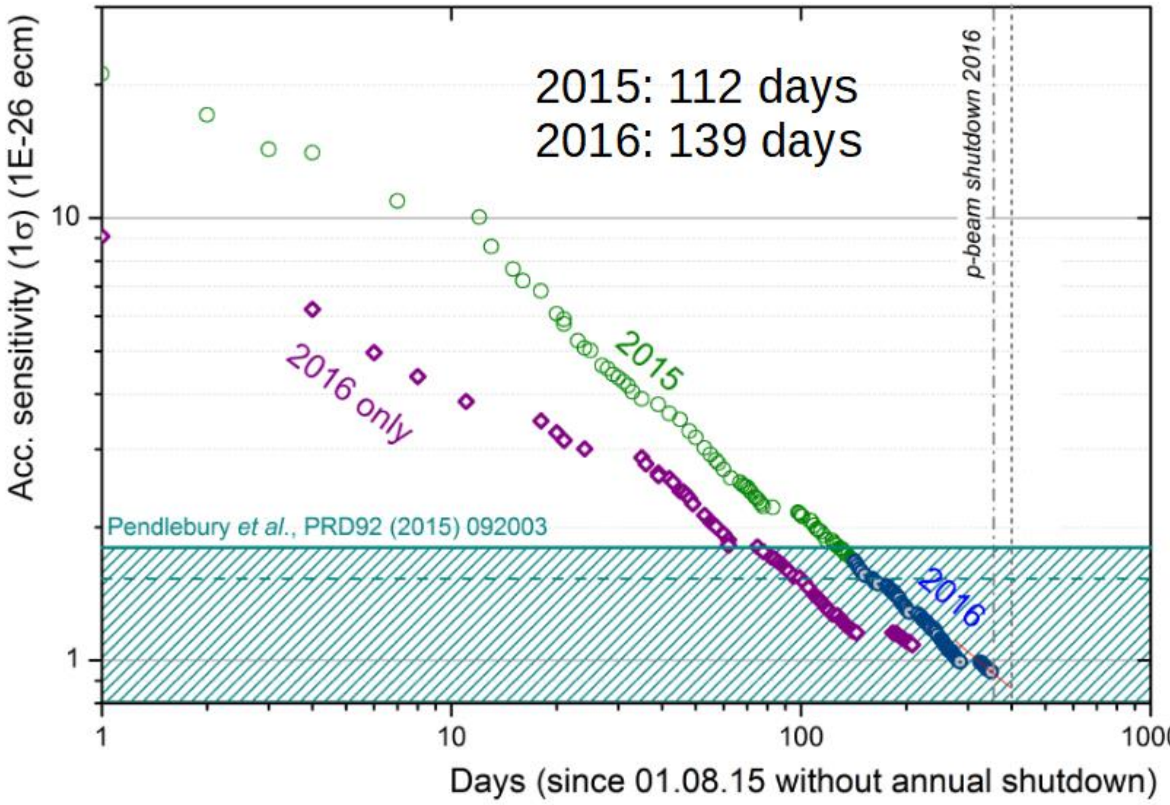
Statistical sensitivity

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

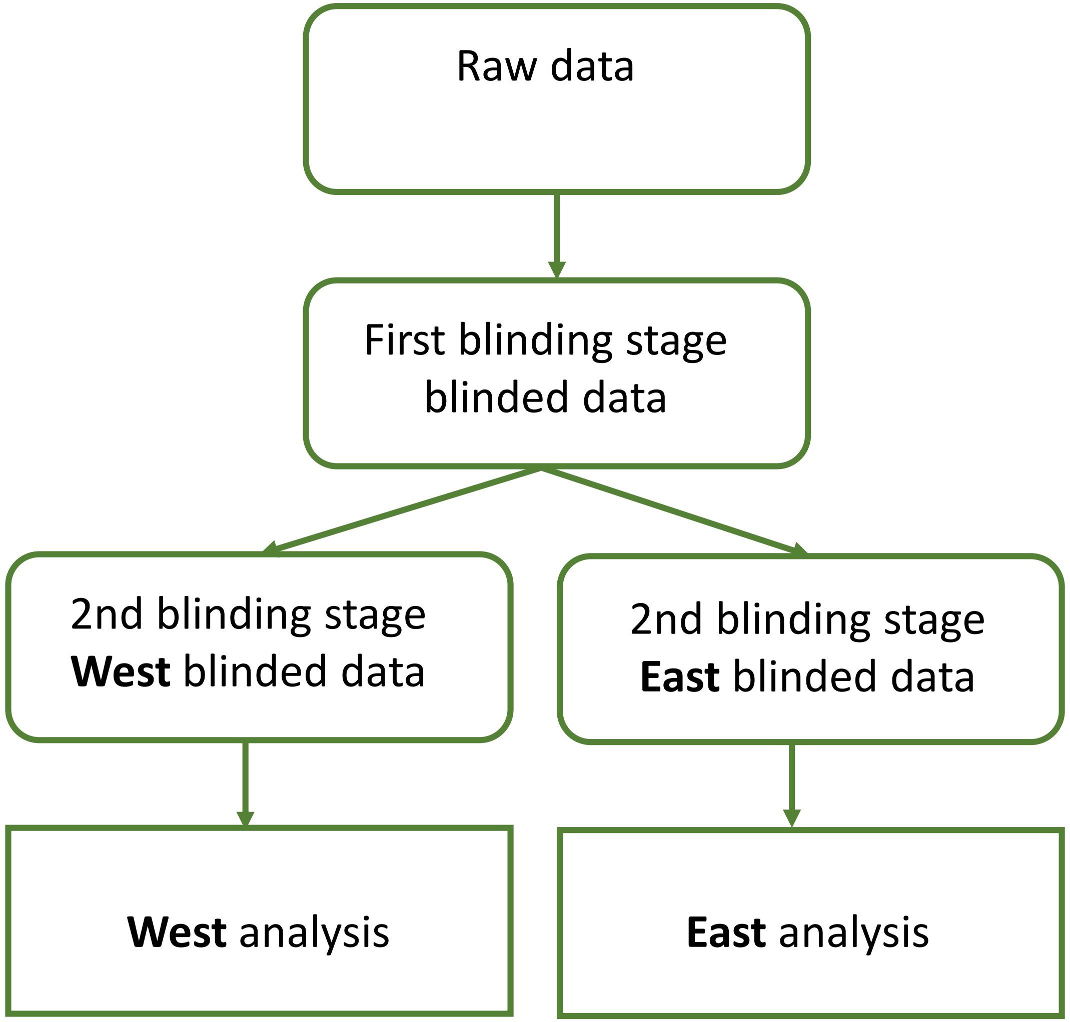
2015: $1.7\ 10^{-26}$ e.cm
2016: $1.1\ 10^{-26}$ e.cm
Total: $0.94\ 10^{-26}$ e.cm

Pushing the limit of the technique at room temperature

World record for sensitivity

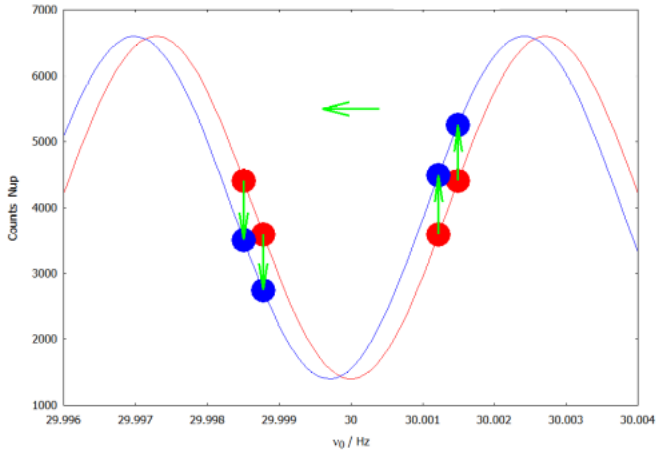


The search for the neutron EDM

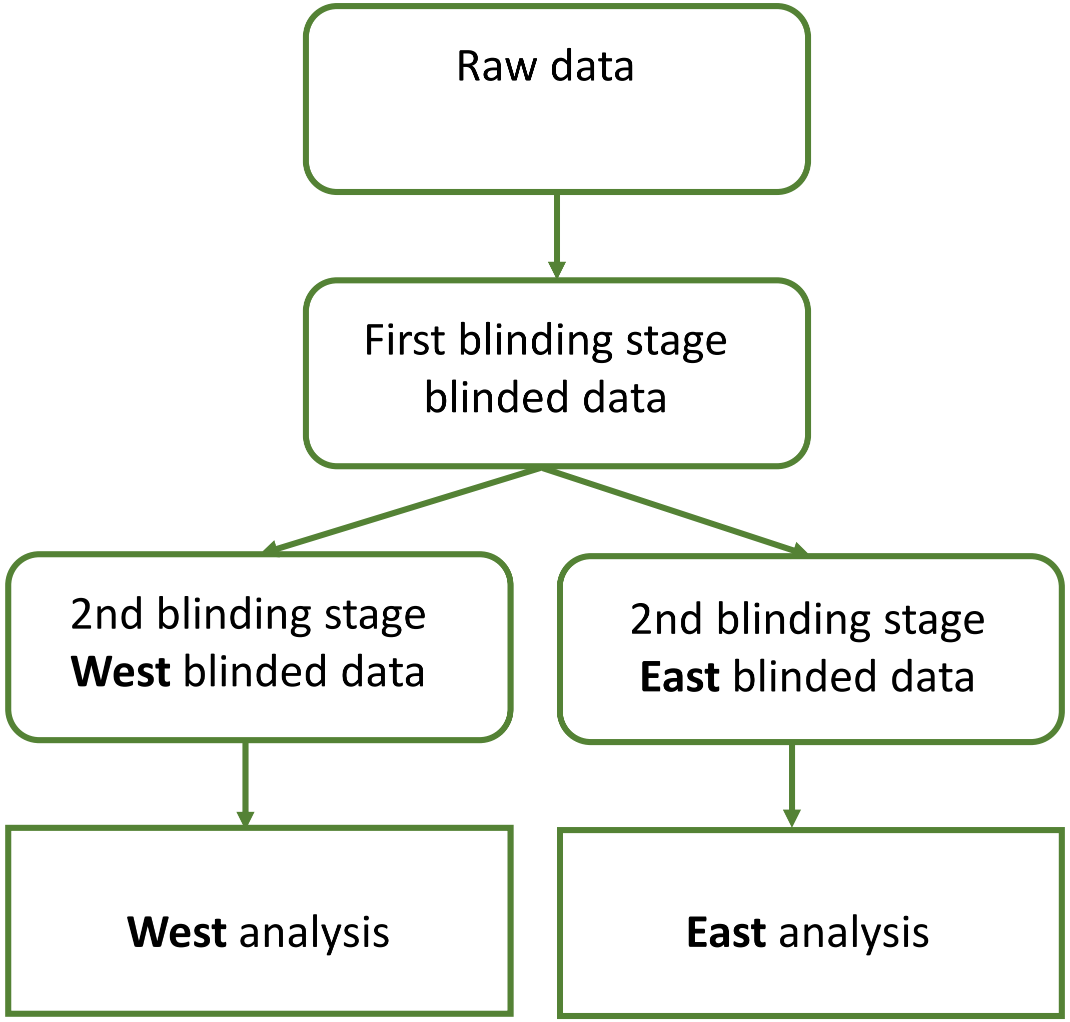


2 independent analysis teams and 2 blinding stages

Add a shift to the value of the neutron EDM without impacting any other observable



The search for the neutron EDM



2 independent analysis teams and 2 blinding stages

Paper submitted Dec. the 18th 2019
Analysis on raw data + full unblinding
Nov. the 28th 2019

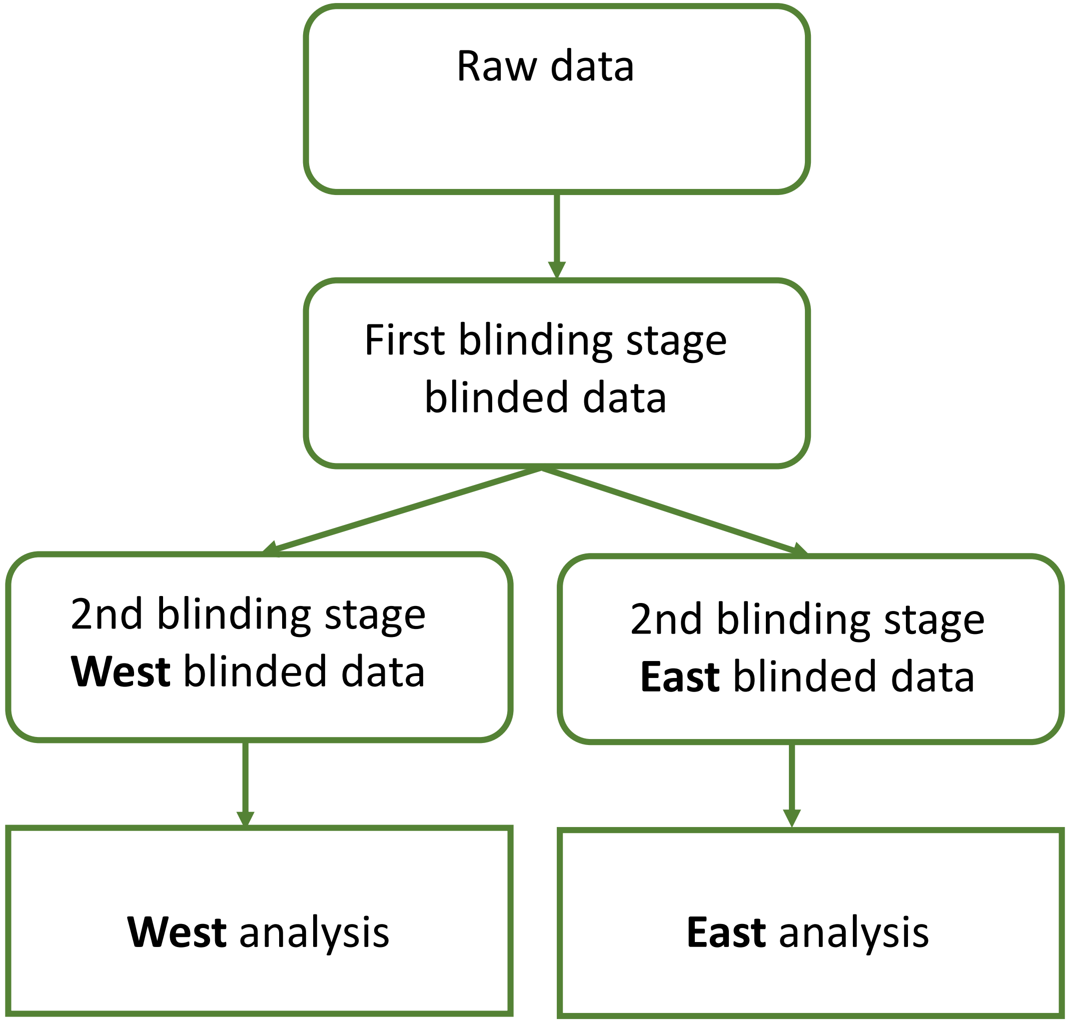
Frozen analysis + final systematic error budget
Analysis on single blinded data + first unblinding
+ direct comparison
Oct. the 23rd 2019

Analysis comparison
Late 2018

d_n = (u ± d_{at} ± d_{yst}) 10^{-26} e.cm

Analysis task
Ongoing since 2011

The search for the neutron EDM



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$$d_n = (u \pm 1.1_{stat} \pm d_{syst})\ 10^{-26} e.cm$$

Analysis task
Ongoing since 2011

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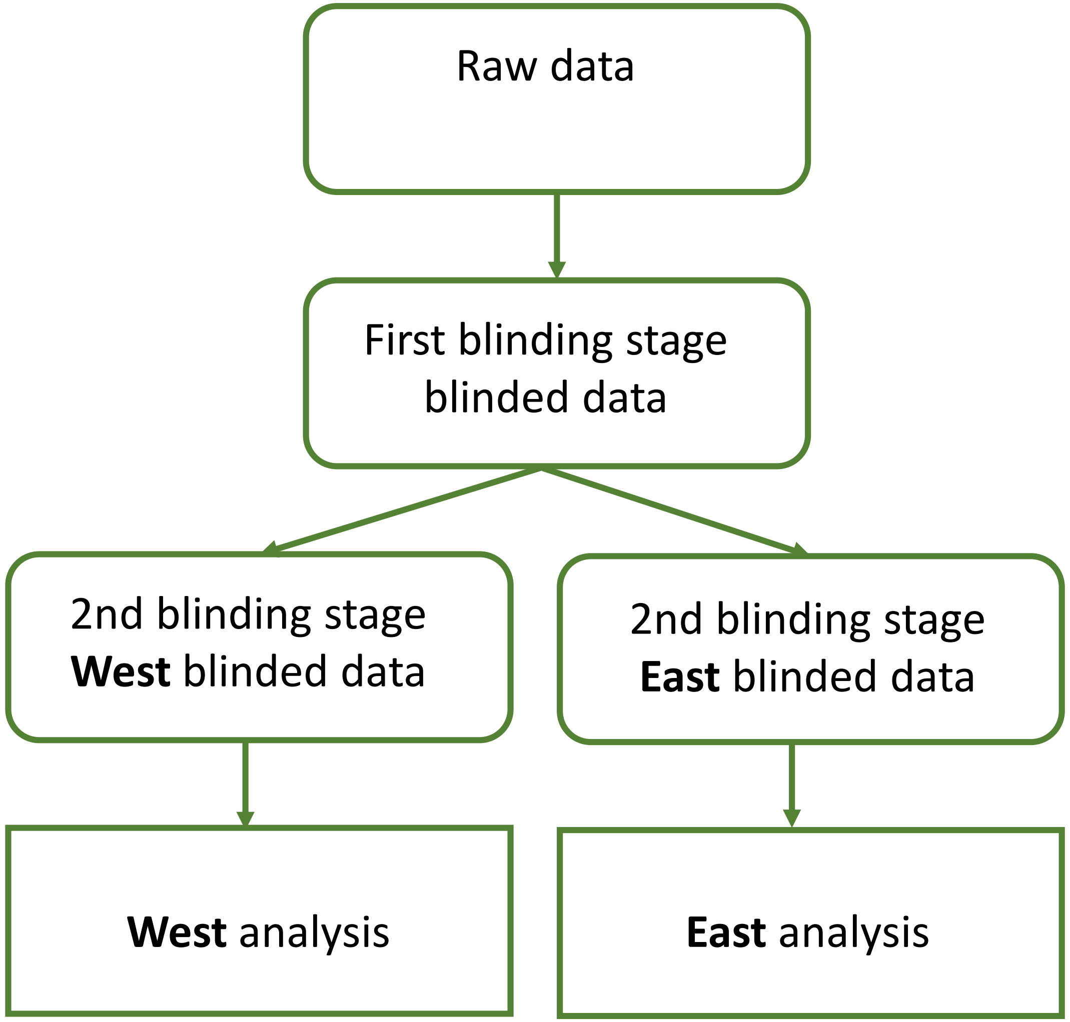

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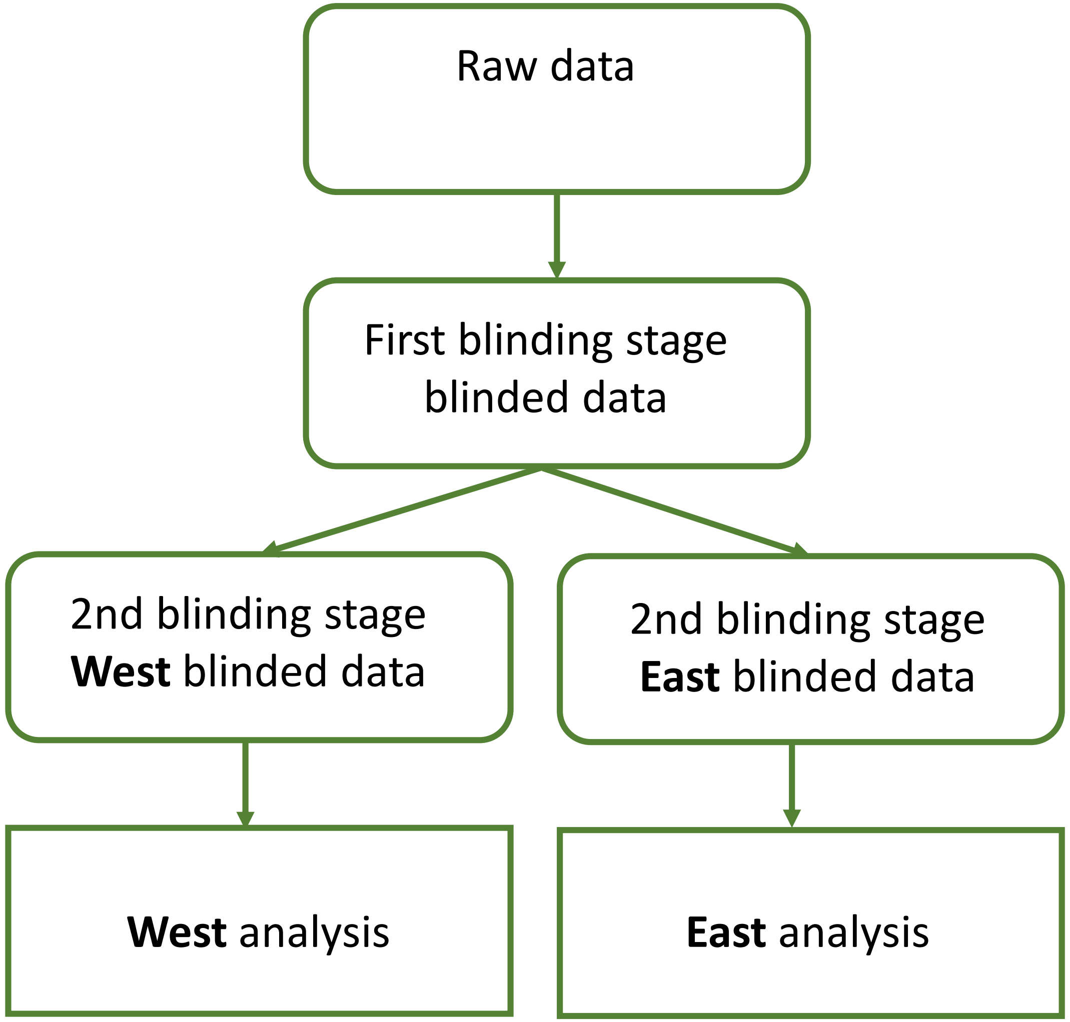
$$d_n = (u \pm 1.1_{stat} \pm 0.2_{syst})\, 10^{-26} e.\mathrm{cm}$$

Analysis task
Ongoing since 2011

The search for the neutron EDM



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$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst})\, 10^{-26} e.\mathrm{cm}$$

Analysis task
Ongoing since 2011

The search for the neutron EDM

TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error	
Error on $\langle z \rangle$	...	7	(0 ± 68)
Higher-order gradients $\hat{G}$	69	10	
Transverse field correction $\langle B_T^2 \rangle$	0	5	(33 ± 14)
Hg EDM [8]	−0.1	0.1	
Local dipole fields	...	4	(-71 ± 81)
$v \times E$ UCN net motion	...	2	
Quadratic $v \times E$	...	0.1	
Uncompensated G drift	...	7.5	
Mercury light shift	...	0.4	
Inc. scattering ^{199}Hg	...	7	
TOTAL	69	18	(-38 ± 99)

Systematic error budget:

- Divided by a factor of 5
- Dominated by “new” effects
- Opens the door to a new generation of experiments

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \; e.\text{cm}.$$

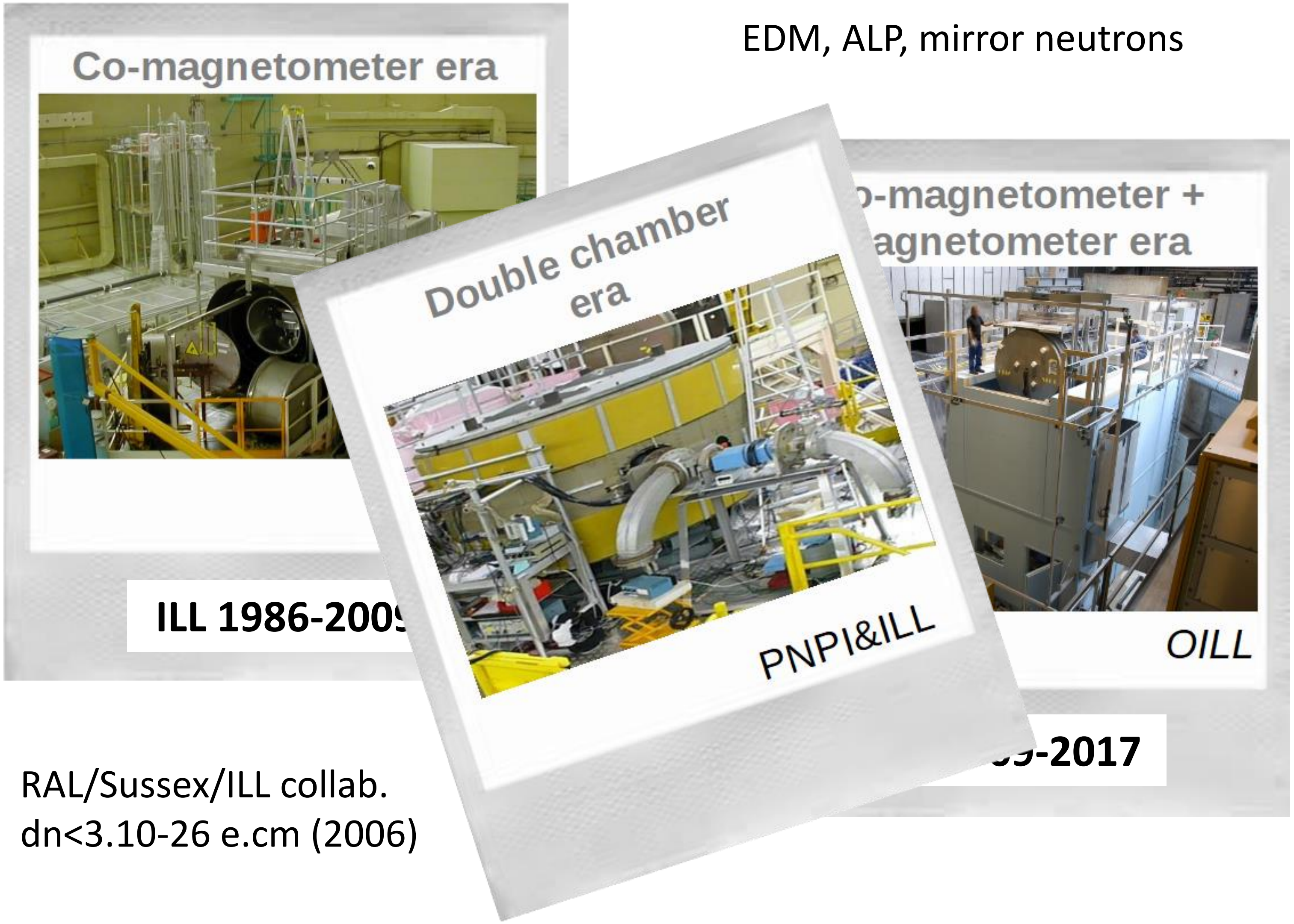
Outlooks

RAL/Sussex/ILL collab.
dn<3.10-26 e.cm (2006)

EDM, ALP, mirror neutrons

Outlooks

EDM, ALP, mirror neutrons



RAL/Sussex/ILL collab.
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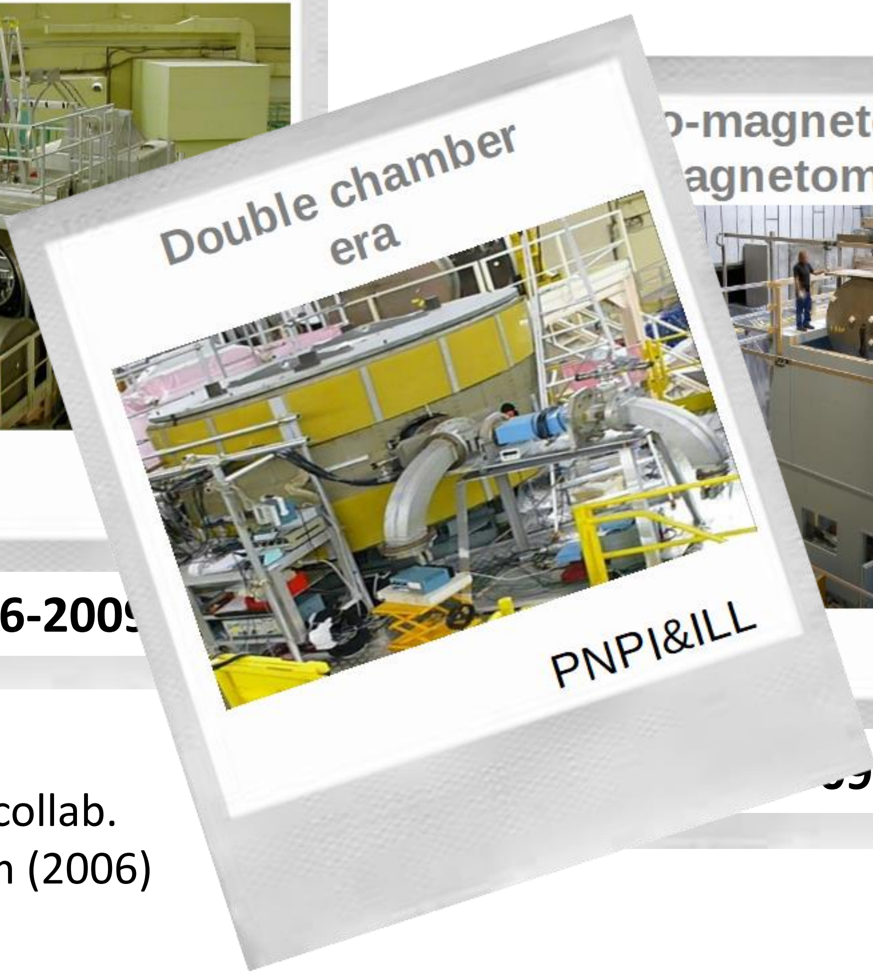
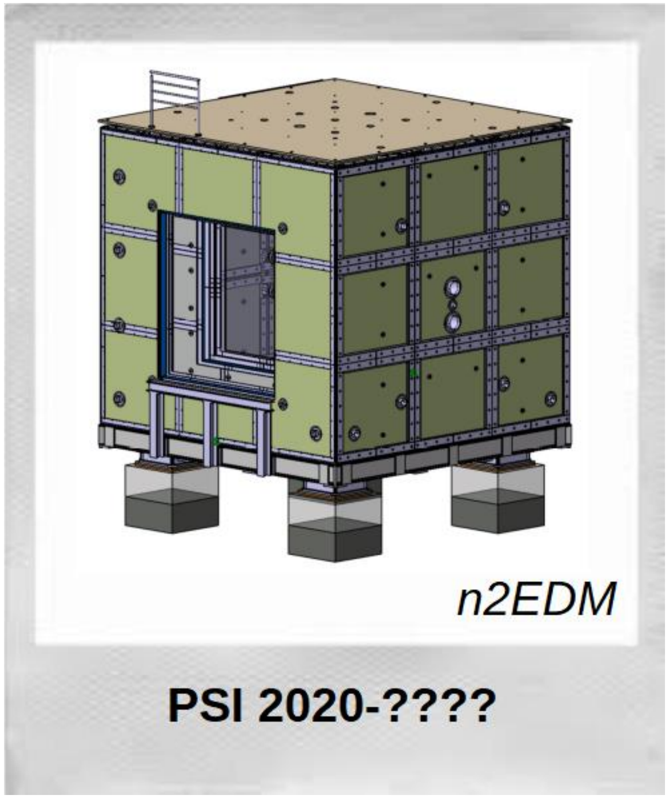
Outlooks

EDM, ALP, mirror neutrons





RAL/Sussex/ILL collab.
dn<3.10-26 e.cm (2006)

Merci

* Probe the Electroweak baryogenesis
* Probe physics beyond the standard model at the multi-TeV scale

* Different EDMs will probe the source of CP violation

One might stop measuring zero!

* A first measurement at PSI
* A new era is beginning

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}\ e.\text{cm}.$$

Merci

Come and join us in Grenoble!