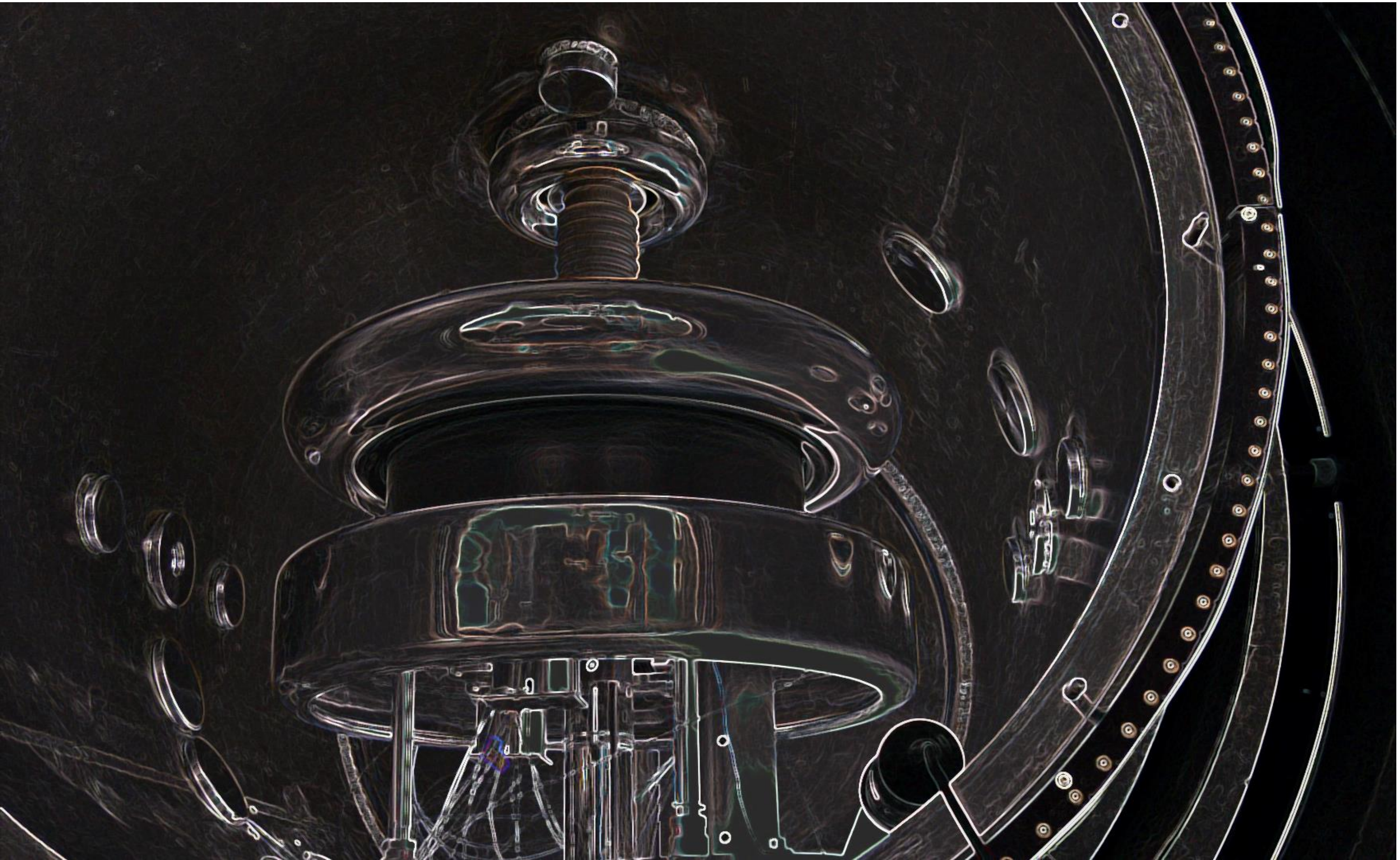
Towards a new measurement of the neutron electric dipole moment at the Paul Scherrer Institute



Stéphanie Roccia
CSNSM – Orsay (Paris)

On behalf of ....

The nEDM collaboration at PSI

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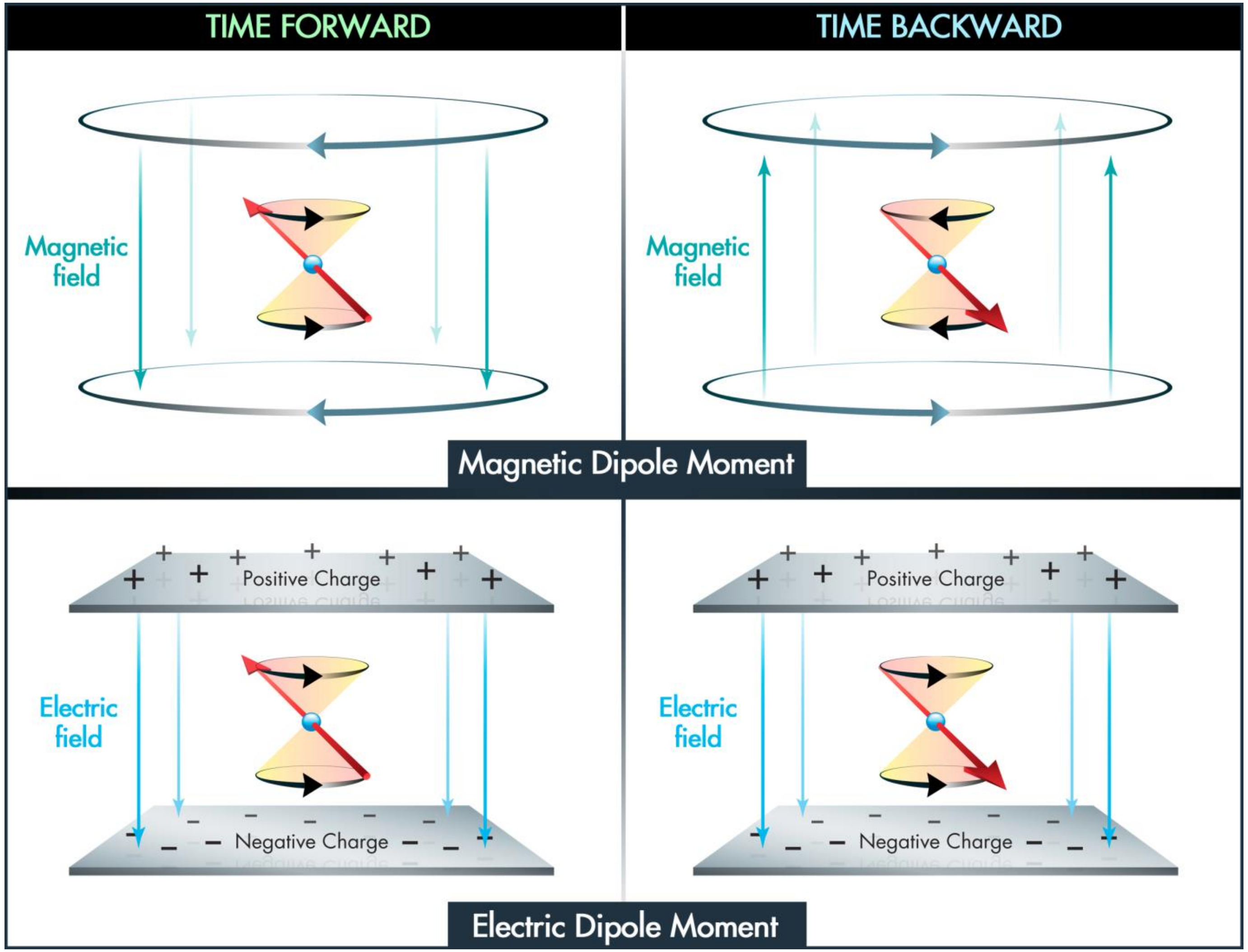
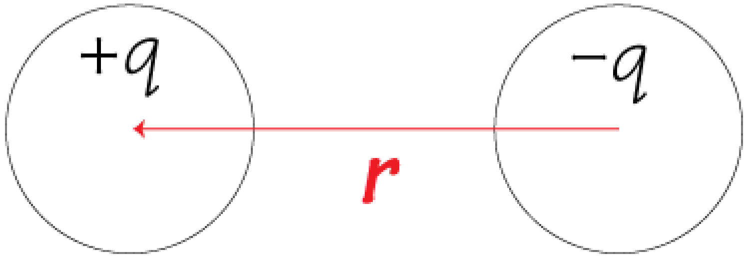
Setting the stage





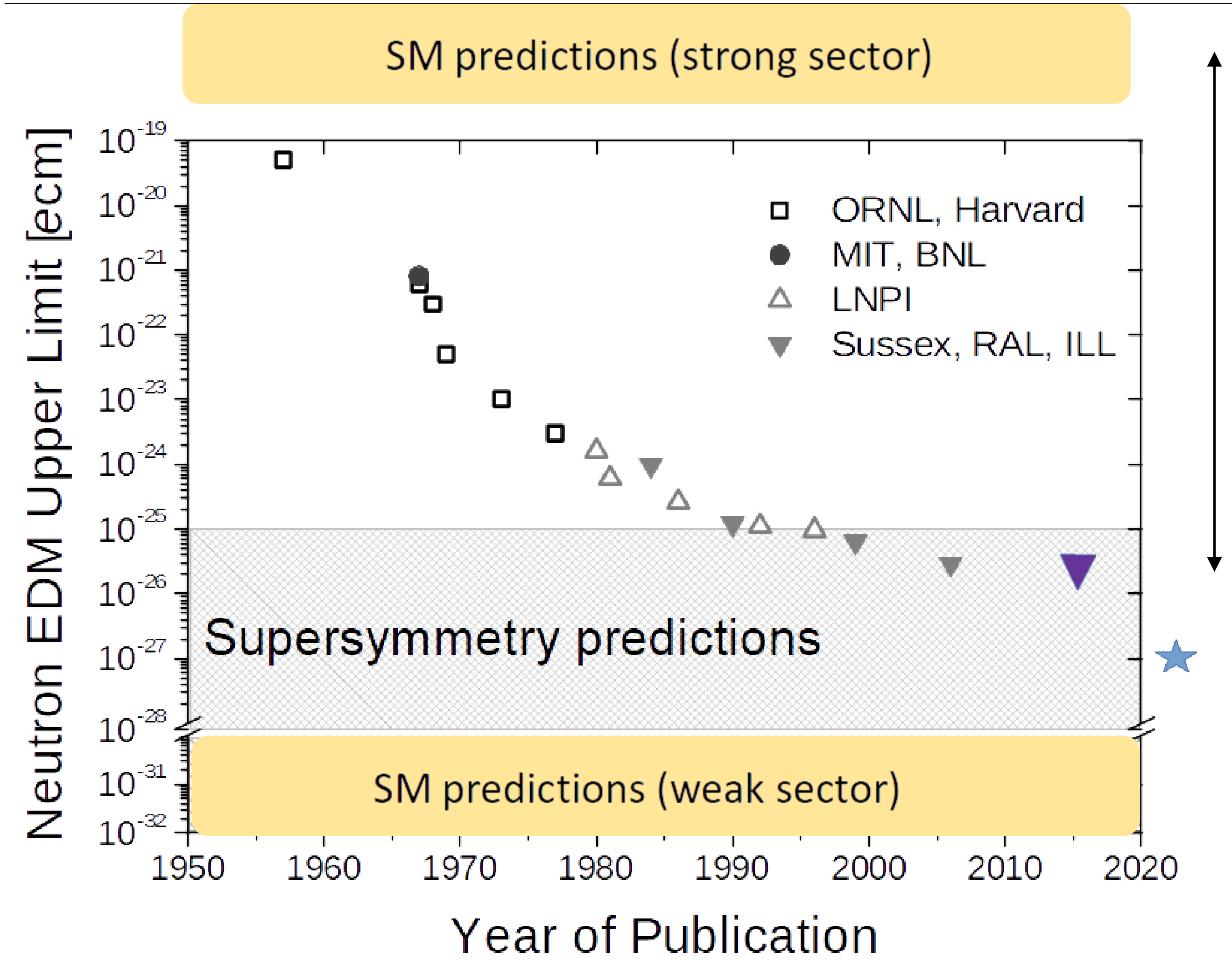
$$\overrightarrow{d_E} = q\vec{r}$$

$$\overrightarrow{d_E} = \int \vec{x}\,\rho(\vec{x})\,d\vec{x}$$

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

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

The nEDM landscape



10 orders of magnitude

$\theta_{QCD} < 10^{-10}$ Strong CP problem

δ_{CKM} Phase in the CKM matrix

Beyond the standard model

SM→"only" an effective theory valid up to some scale Λ

Annals of Physics 318, 119 (2005)

E

L_{BSM}

Λ

First CP violating operators @ DIM6

Information about the underlying physics

1 GeV

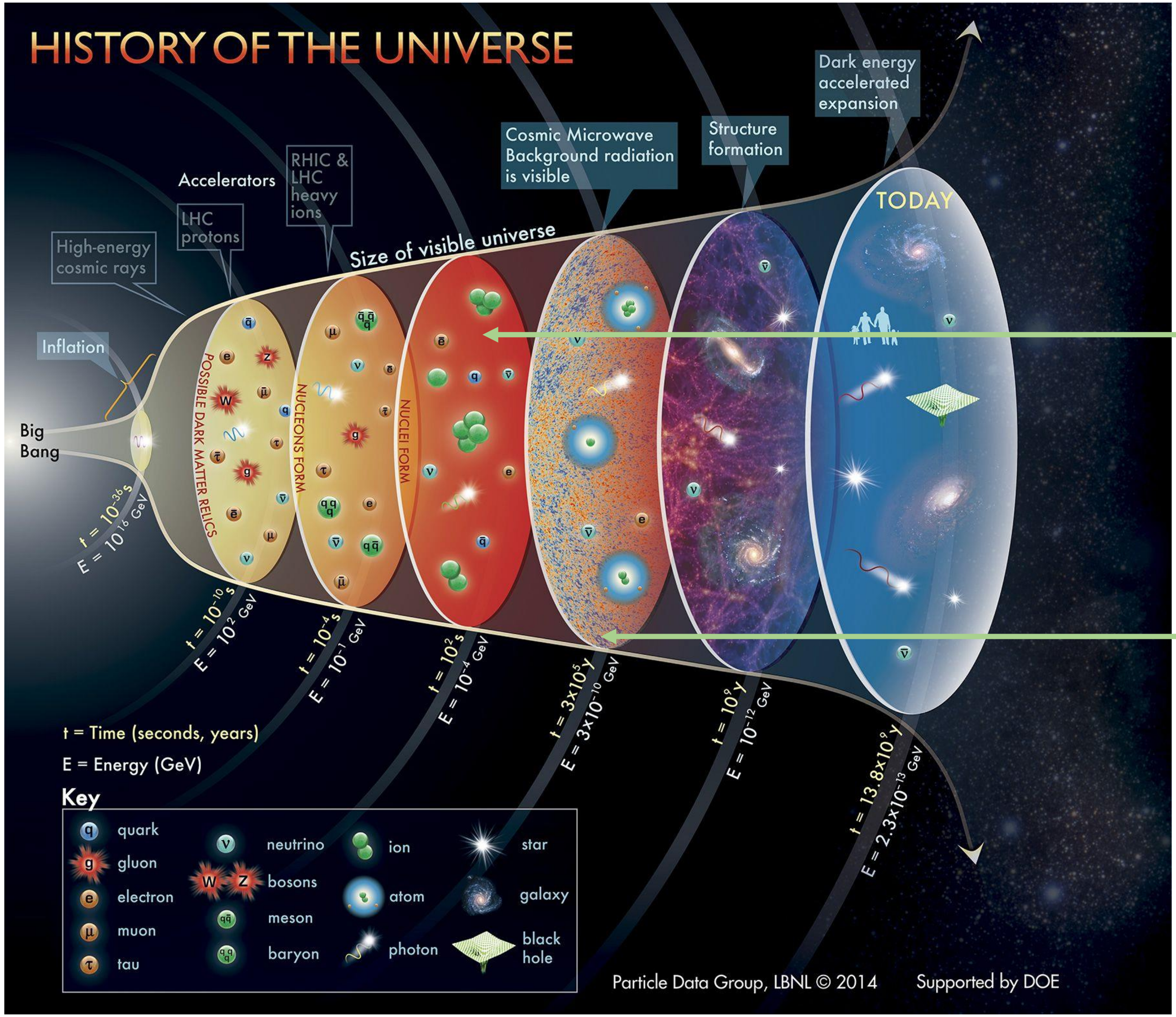
$$L_{eff} = L_{SM} + \frac{C^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}$$

Λ_{had}

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

nEDM is sensitive to new physics at the multi-TeV scale.

Matter/Antimatter Asymmetry of the Universe



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

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)

Electroweak baryogenesis

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.

1) OK (Sphalerons)

2) Baryogenesis at the weak scale (accessible to EDMs and LHC)

3) New source of CP violation

	Before Electroweak phase transition	After Electroweak phase transition	Today
$\frac{N_B - N_{\overline{B}}}{N_B + N_{\overline{B}}}$	0	10^{-10}	1
$\frac{N_B}{N_\gamma}$	$1/2$	$1/2$	10^{-10}

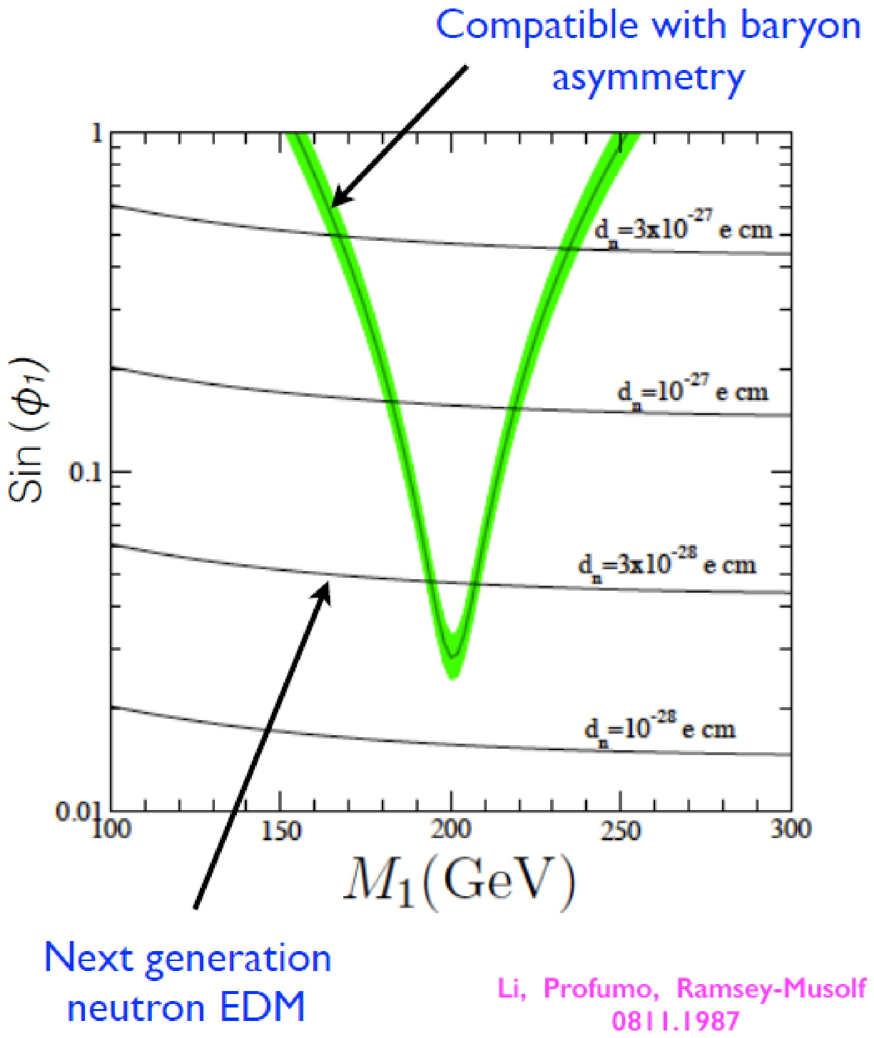
Electroweak baryogenesis

Exemple in SUSY

New CP violating phases
contributes to
* baryonic asymmetry of the universe
* neutron EDM

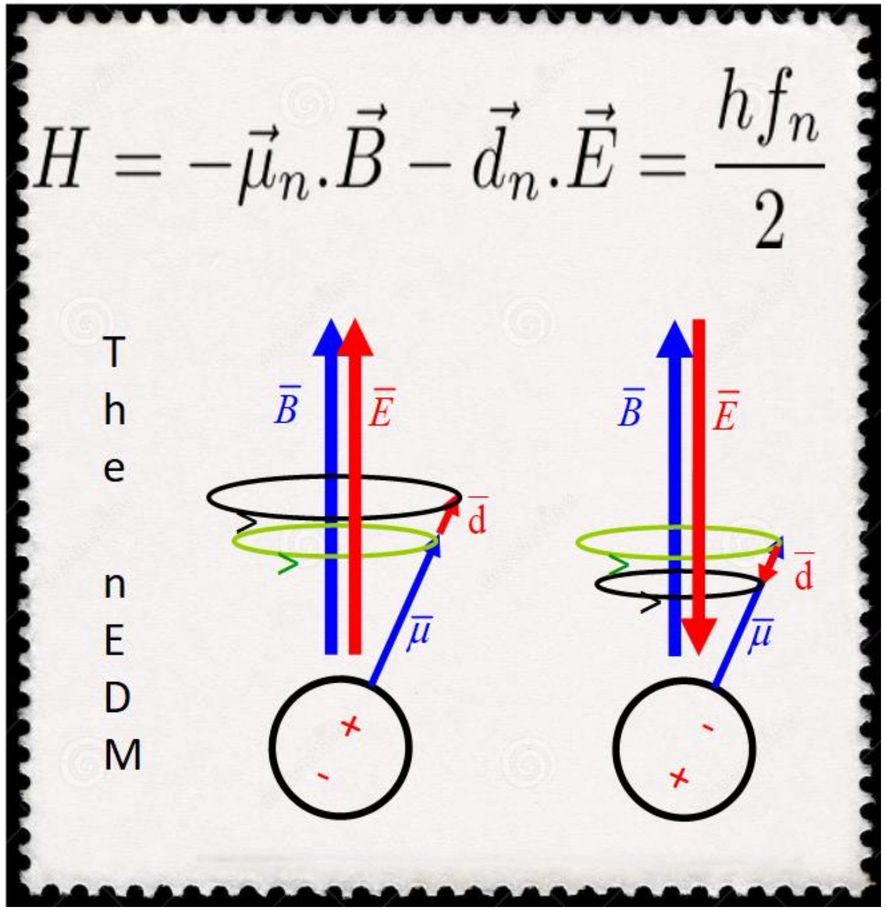
The nEDM is the most stringent test of electroweak baryogenesis

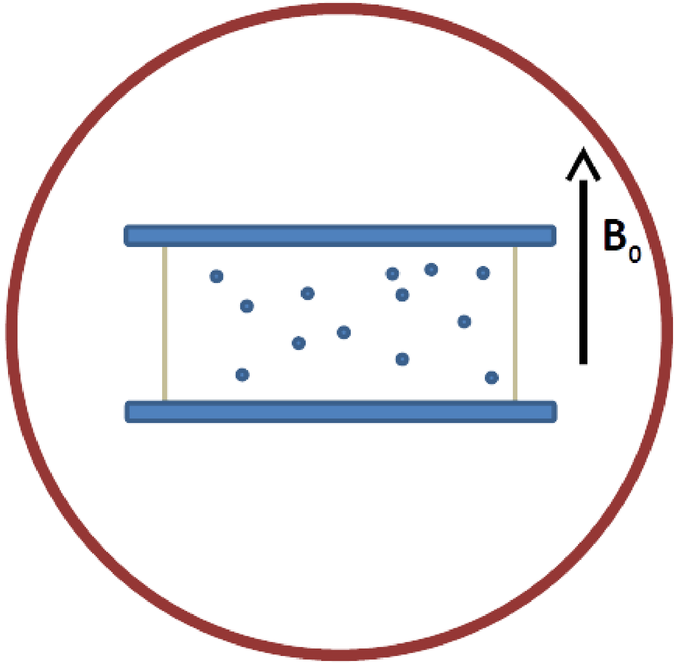
Another possibility is the leptogenesis where the new source of CP violation is in the lepton sector



Picture by V. Cirigliano

The search for the nEDM





Neutrons reflected for all incidence angles: UCNs

Ultra Cold Neutron Source

$\lambda_n \approx 800$ Å;

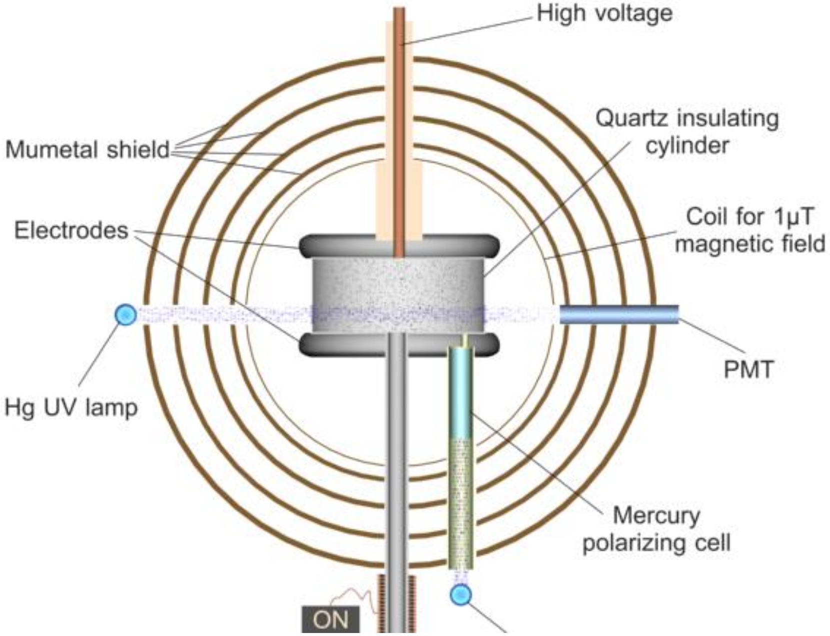
$v_n \approx 5$ m/s;

$T_n \approx 2$ mK ;

$E_n \approx 130$ neV

The search for the nEDM

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



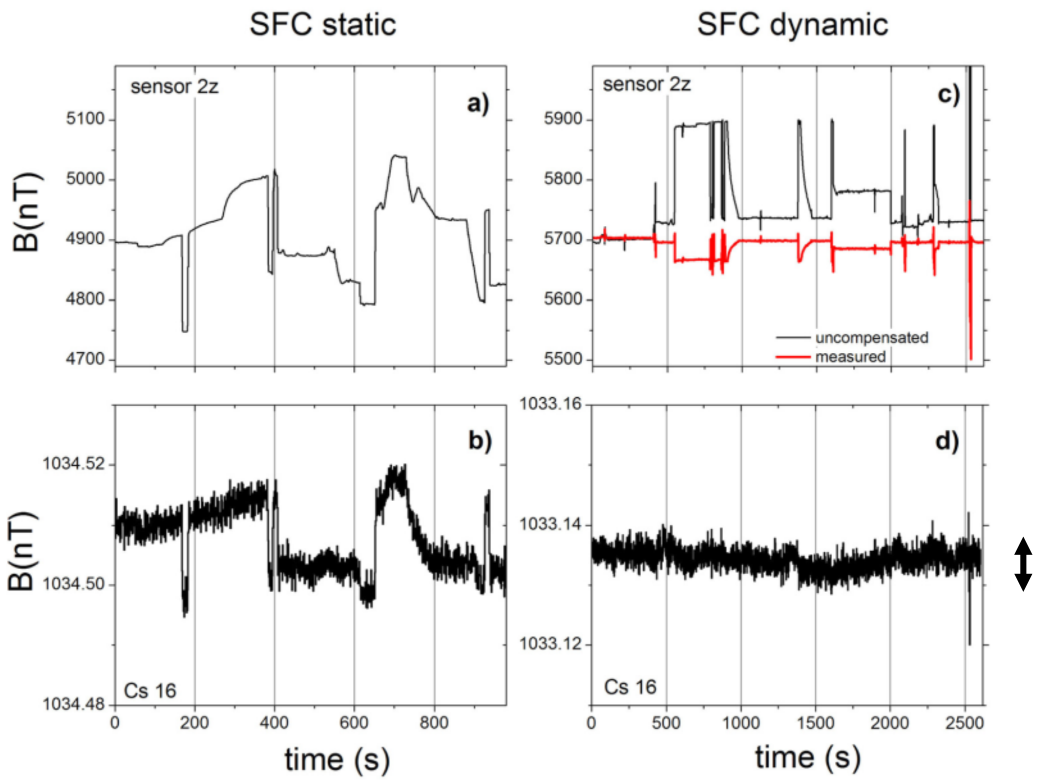
1998: the mercury co-magnetometer

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

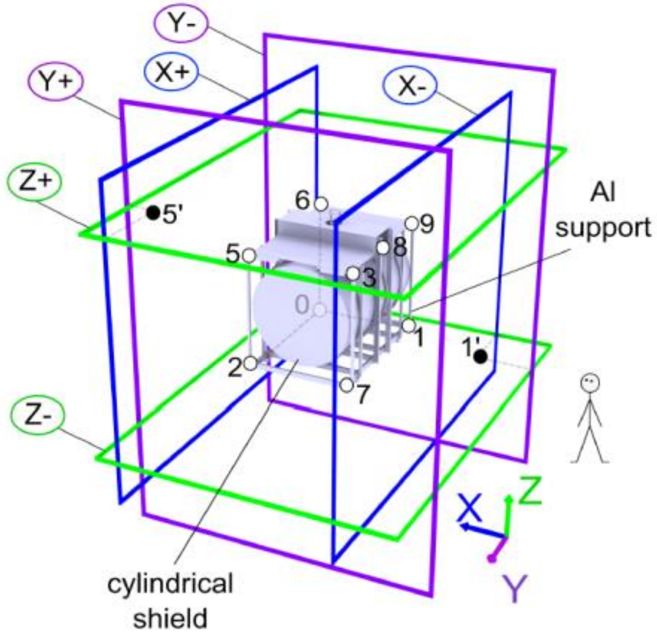
2009: the Cs magnetometer array

The search for the nEDM

1 four layer mu-metal shield + 1 dynamic shield

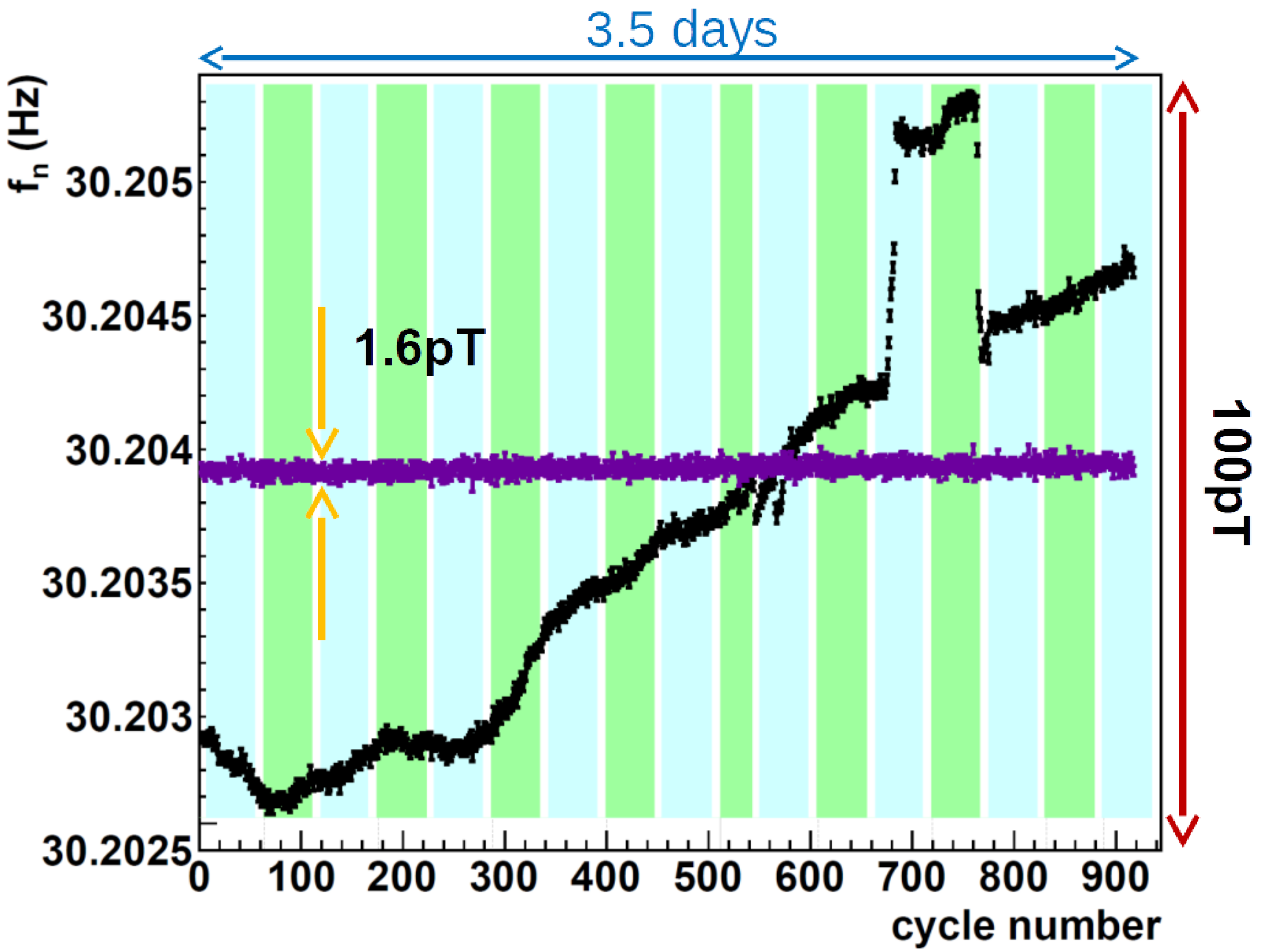


100 pT over few hours

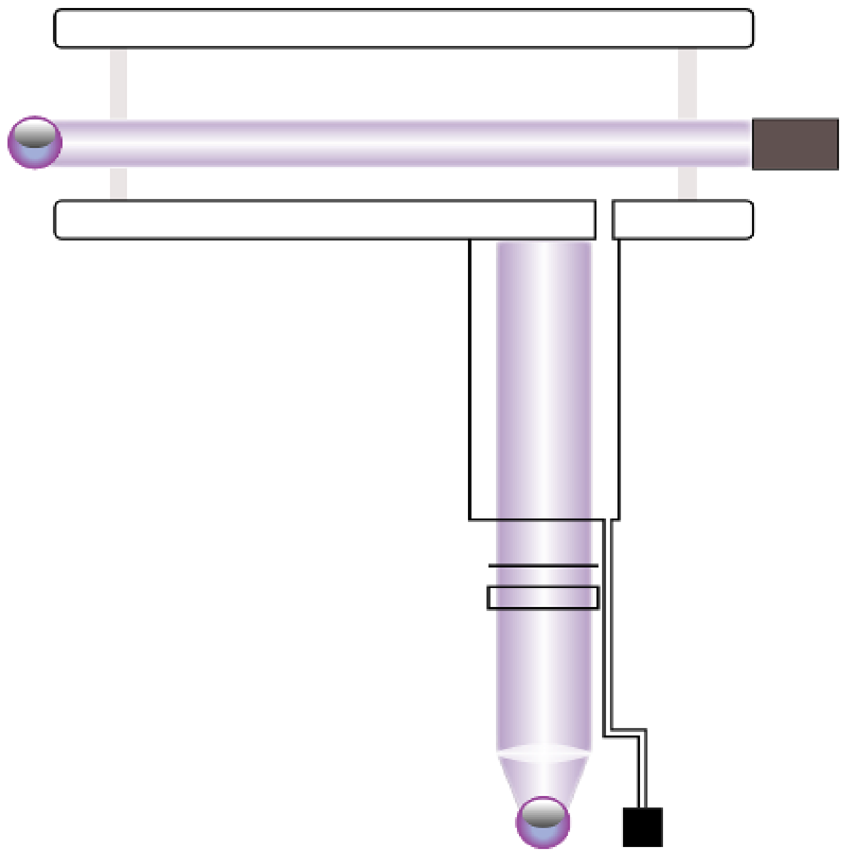


Afach et al., J. Appl. Phys. 116, 084510 (2014)

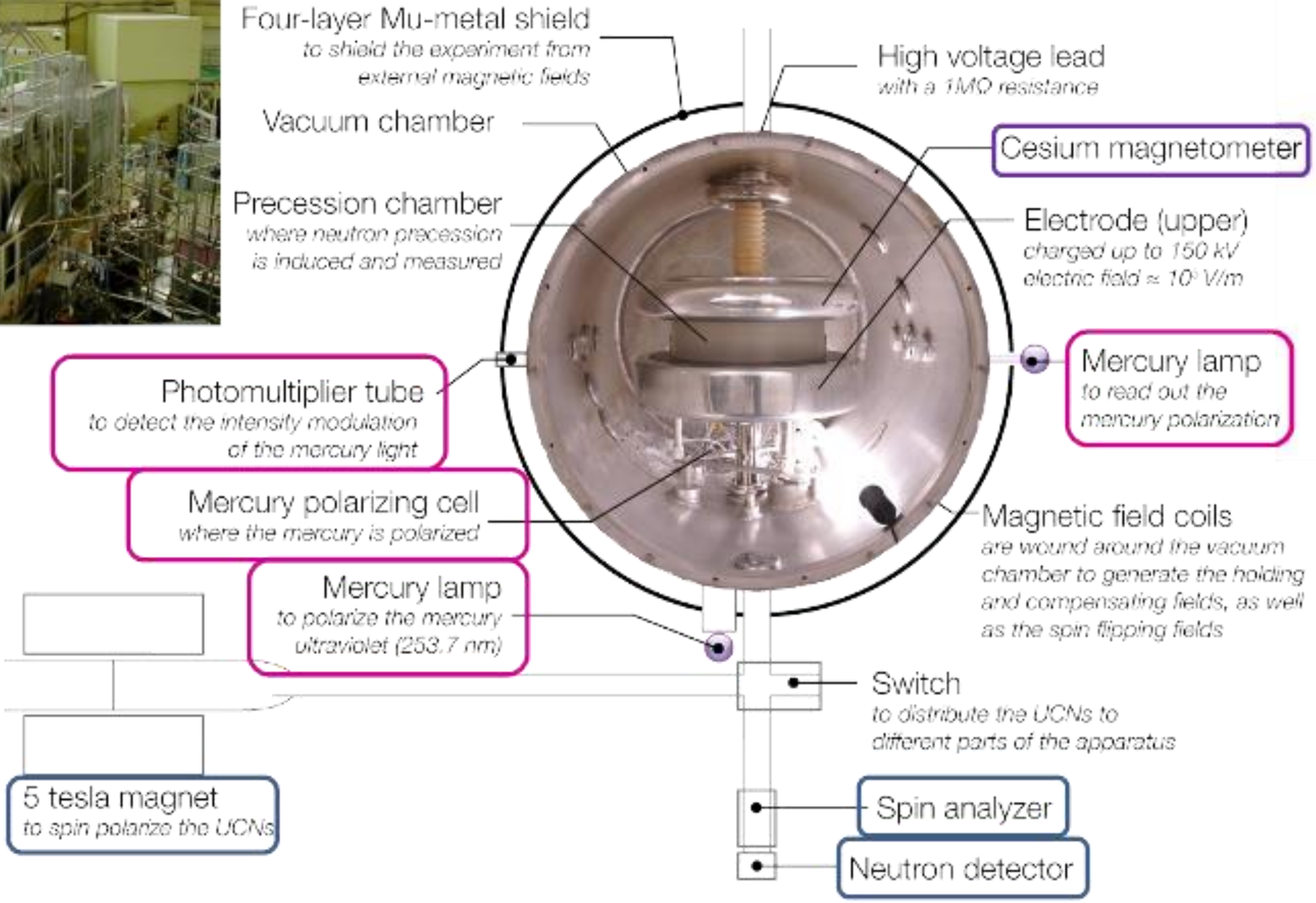
The search for the nEDM

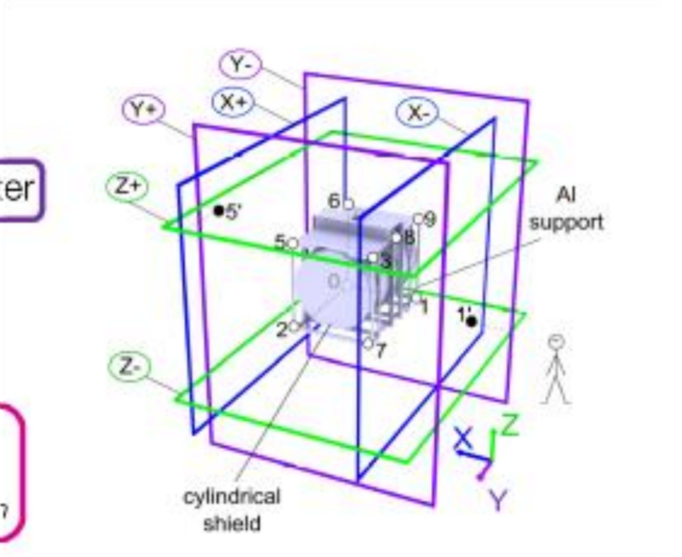


The Hg co-magnetometer

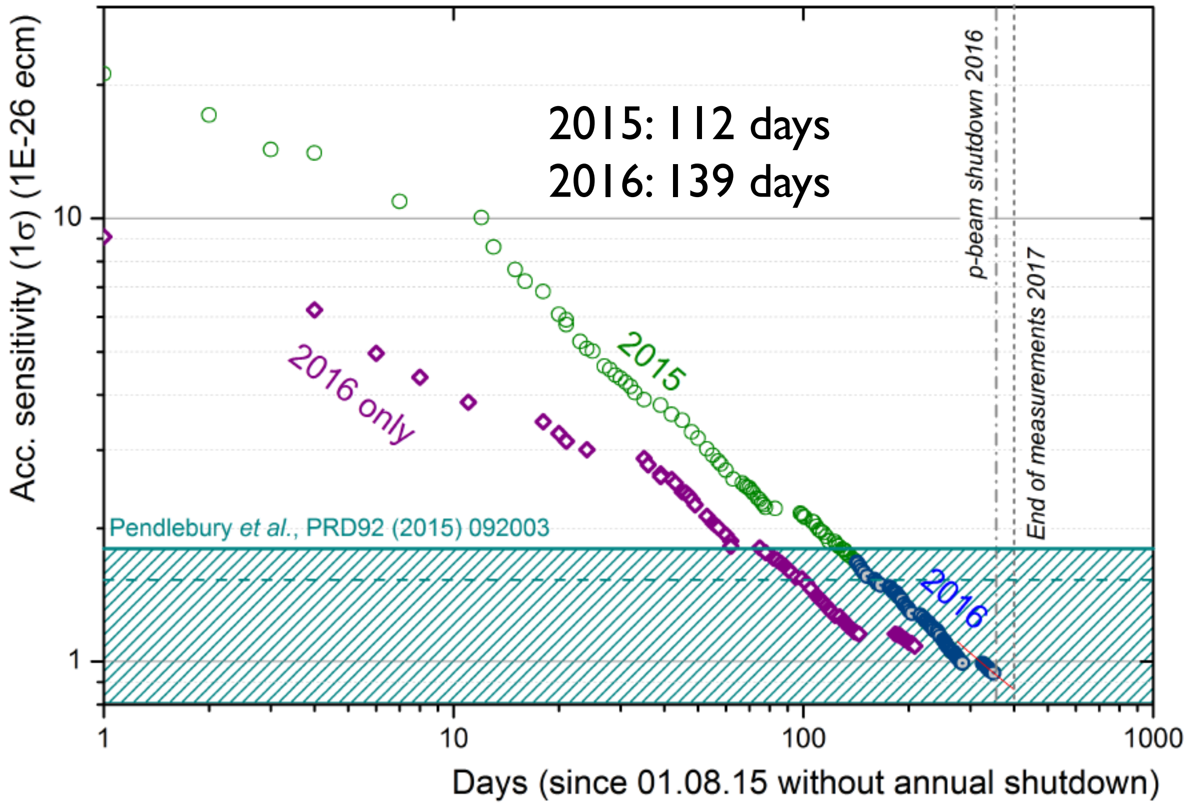


The search for the nEDM





Sensitivity



Accumulated raw sensitivity

2015: 1.7×10^{-26} ecm

2016: 1.1×10^{-26} ecm

Total: 0.94×10^{-26} ecm

(values from simple fit)

After taxes:
$1.06\ 10^{-26}\ e.cm$

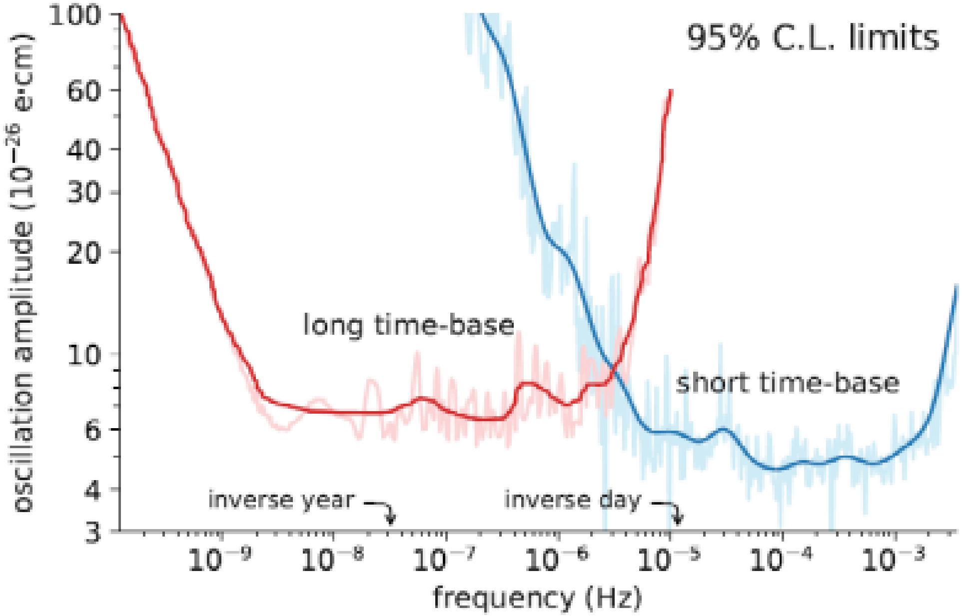
Analysis still on-going, data still blinded

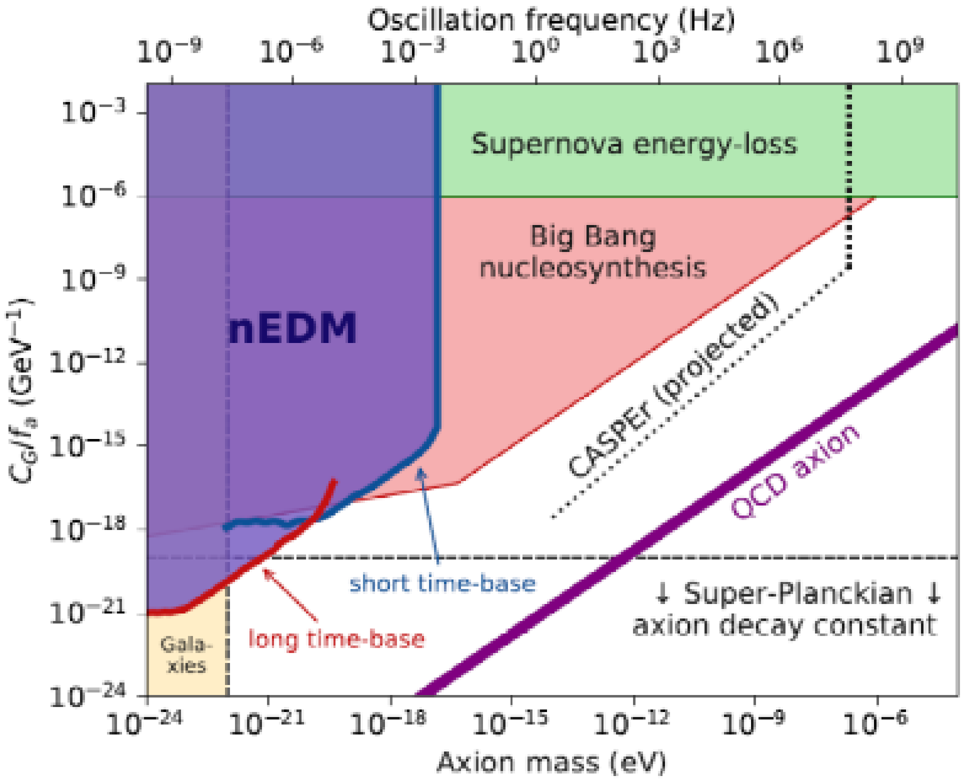
Beyond the nEDM

Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields

C. Abel et al. (RAL-Sussex_ILL collab. + PSI collab + King's College London)
Physical Review X 7, 041034 (2017)

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





PSI data: high sensitivity
Still blinded

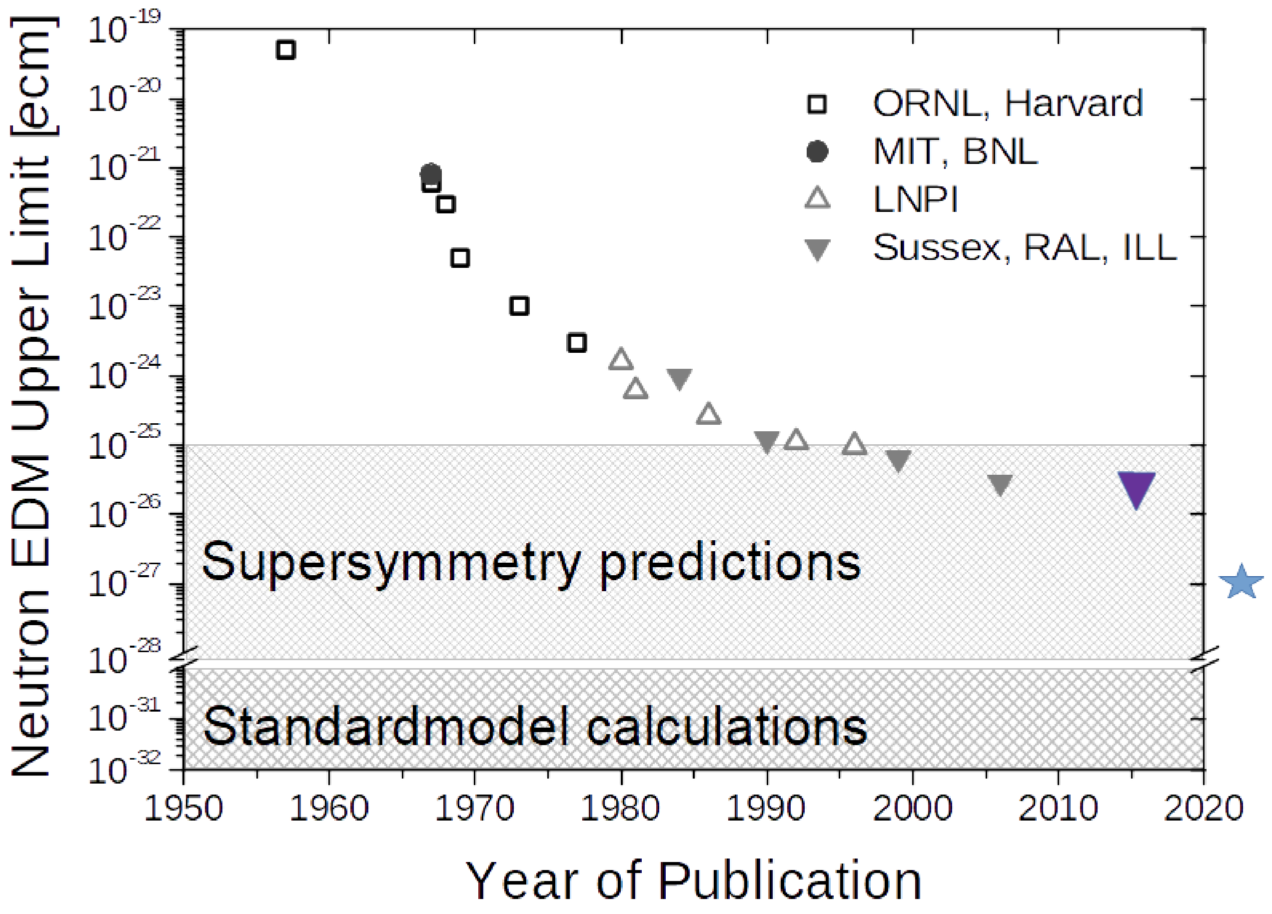
The neutron EDM

* Probe the Electroweak baryogenesis
* Probe physics beyond the standard model at the multi-TeV scale
* A new result is to be expected
* A new setup is being built

EAT
SLEEP
EDM
REPEAT

MERCI

The nEDM landscape



NEUTRONS FOR SCIENCE

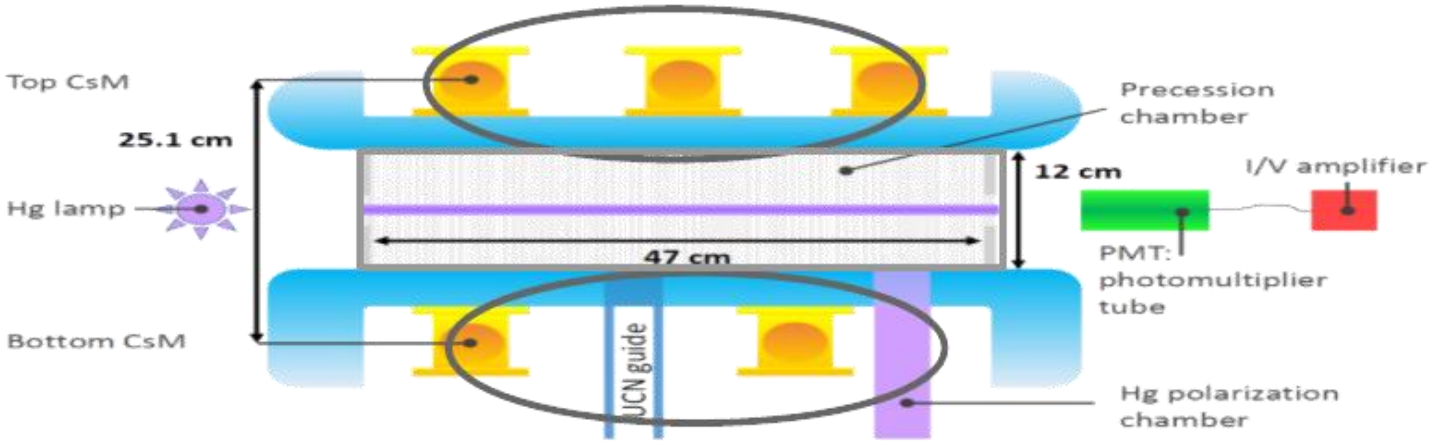
PAUL SCHERRER INSTITUT

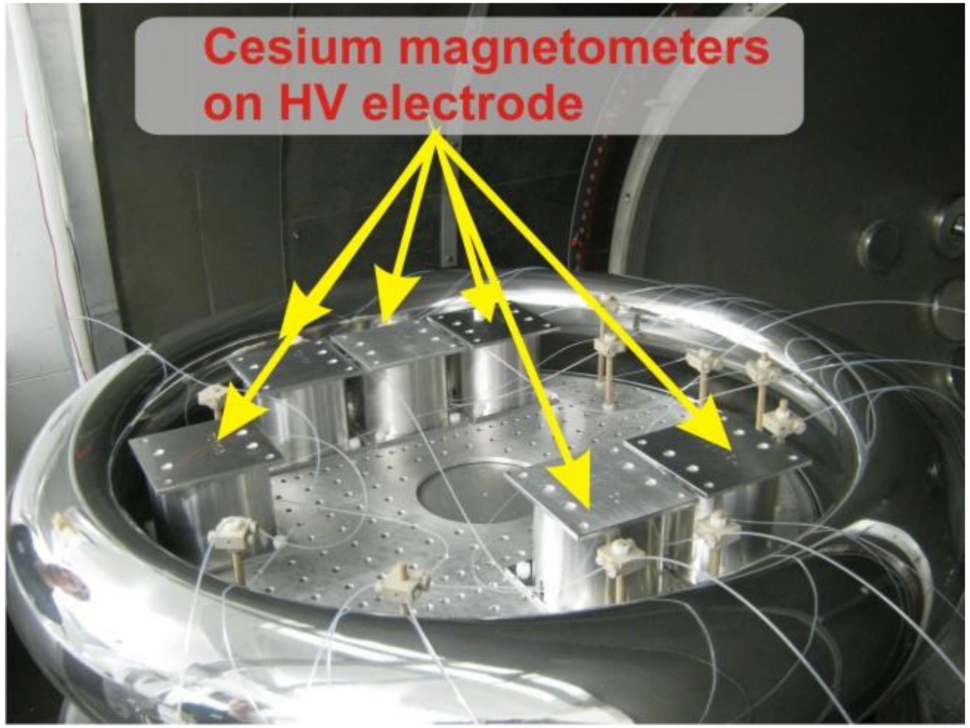
PSI

The search for the nEDM

Cs magnetometer array:

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





Sensitivity

	nEDM@ILL 2006	nEDM@PSI 2016	n2EDM@PSI 2020
Chamber	1	1	2
Diameter (cm)	47	47	100
Neutron/cycle	14 000	15 000	400 000
E(kV/cm)	8.3	11 (15)	15
T(s)	130	180	180
α	0.45 (0.6)	0.75 (0.80)	0.8
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$	$1.4*10^{-26}$

Statistical sensitivity

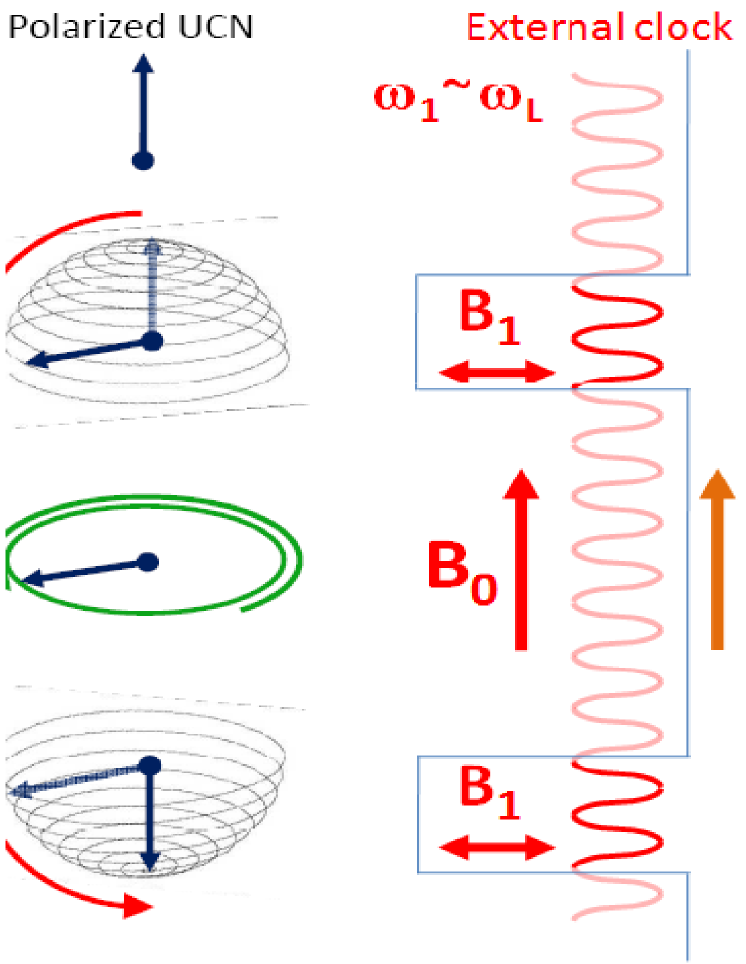
$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

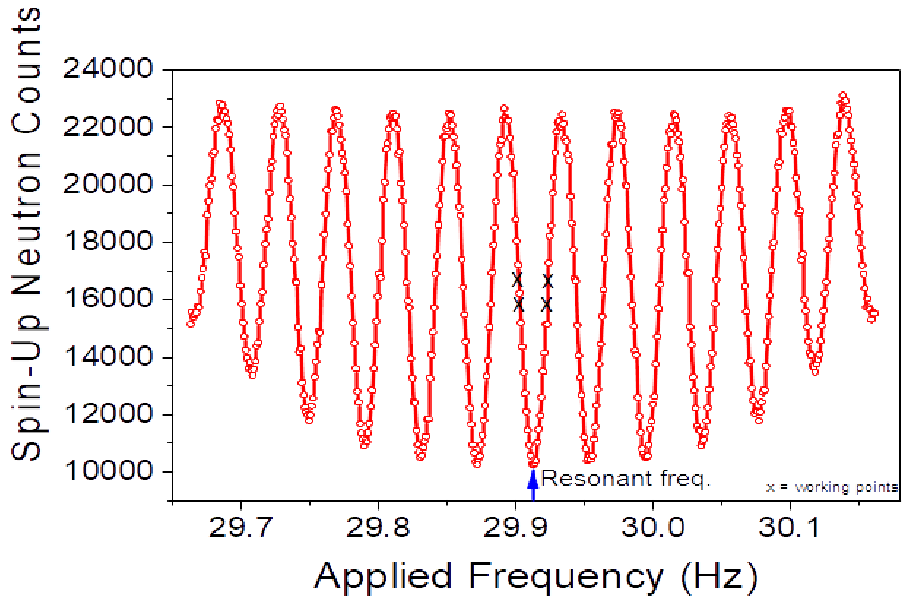
Pushing the limit of the technique at room temperature

World record for sensitivity

The search for the nEDM

The Ramsey's method of separated oscillating fields



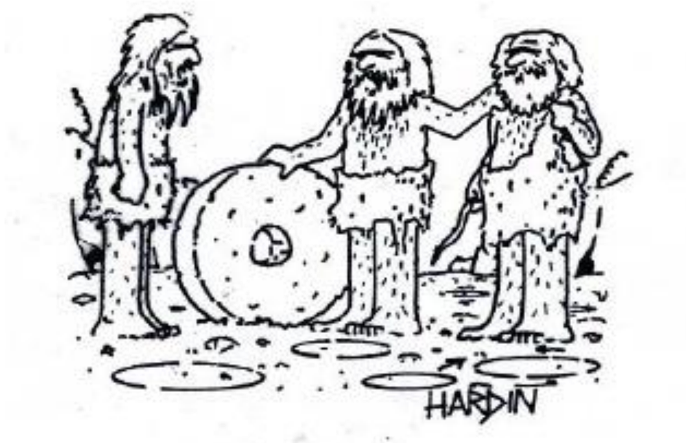


$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

The neutron EDM in the standard model and beyond

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.



"To be honest, I never would have invented the wheel if not for Urg's groundbreaking theoretical work with the circle."

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: $|d_n| \leq\ 3.10^{-13}\ \ e.fm$

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

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.

* PRL(2015)062001

Axion detour

The axion is a well motivated dark matter candidate

Axion density relative to the critical density of the universe

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

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.

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

The axion has a two photons coupling, and g_γ is model dependant.

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

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

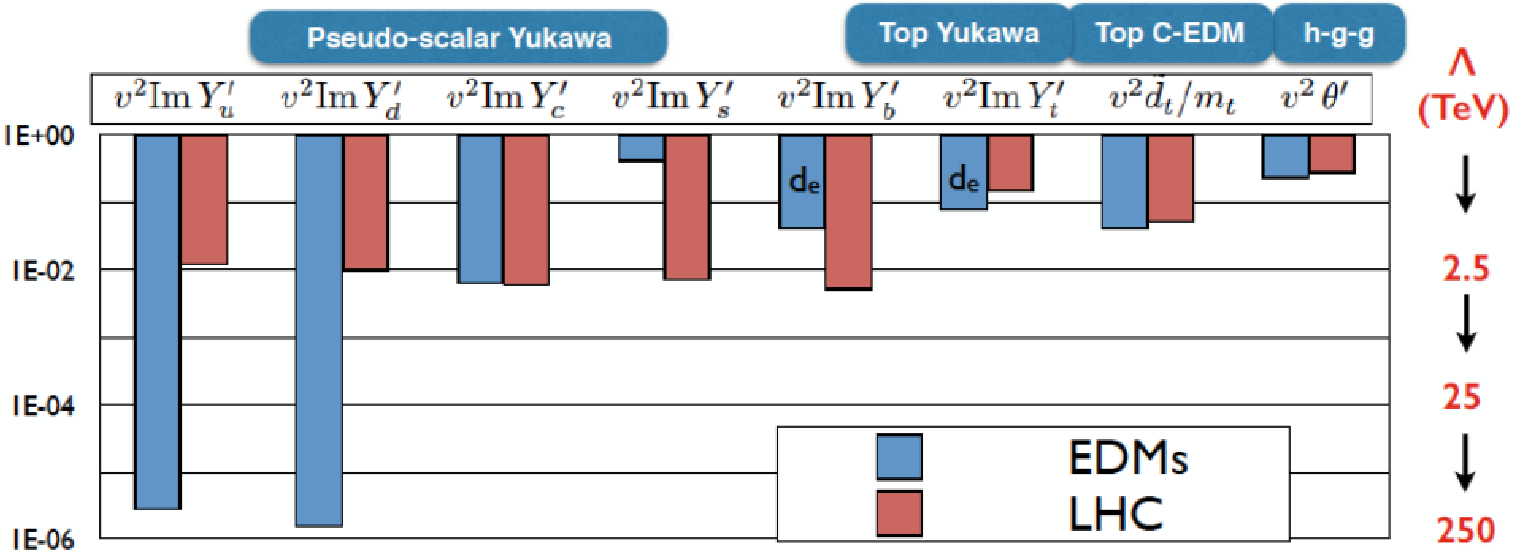
Beyond the standard model

Constraint on non-standard CPV Higgs couplings

Higgs production at LHC

VS

EDMs



Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Picture by V. Cirigliano (PPNS2018)