

Neutron EDM and its implications for HEP

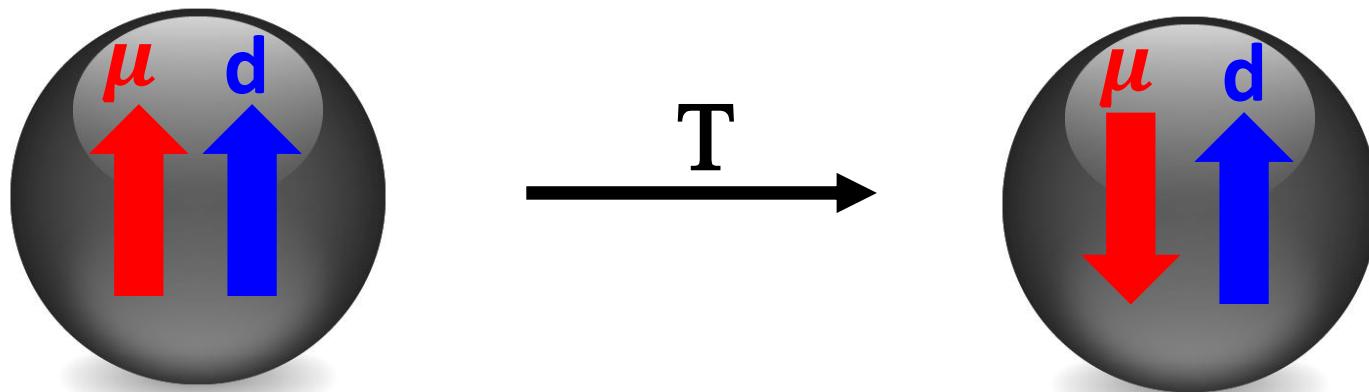
Yoann KERMAÏDIC
UCN group

GDR Terascale
BSM session

Grenoble, FR
23 – 25 nov 2015

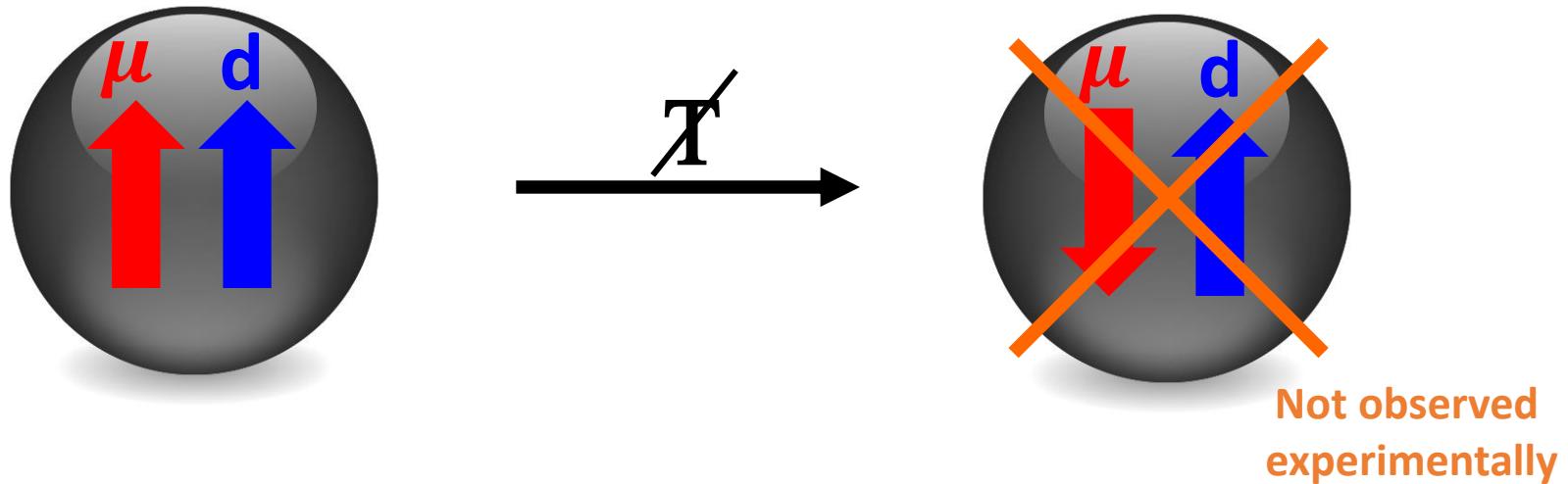
CP violation

Spin $\frac{1}{2}$ particle
with non zero Electric Dipole Moment



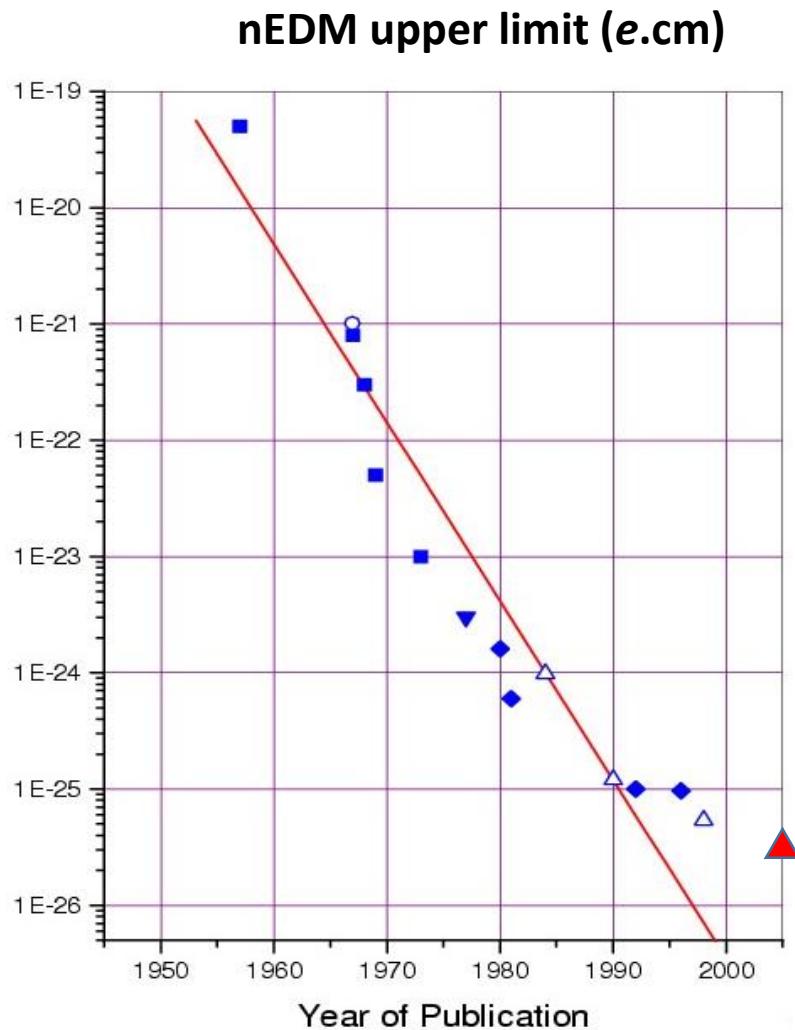
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By virtue of the CPT theorem
T violation \rightarrow CP violation

Where do we stand?



$$|d_n| \leq 3 \times 10^{-26} \text{ } e.\text{cm} \text{ (90\% CL)}$$

RAL/Sussex/ILL

[Baker, 2006]

[Pendlebury, 2015]

Standard models

Very low weak SM sector background!

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

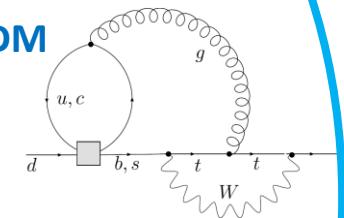
SM weak sector:

K – B mesons decay

K_S & K_L
[Christenson, 1964]

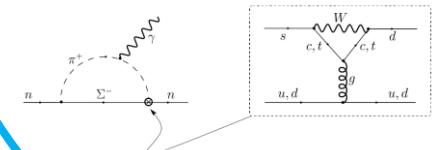
3 loops quark EDM

$d_n \approx 10^{-34} \text{ e.cm}$
[Khriplovitch, 1986]

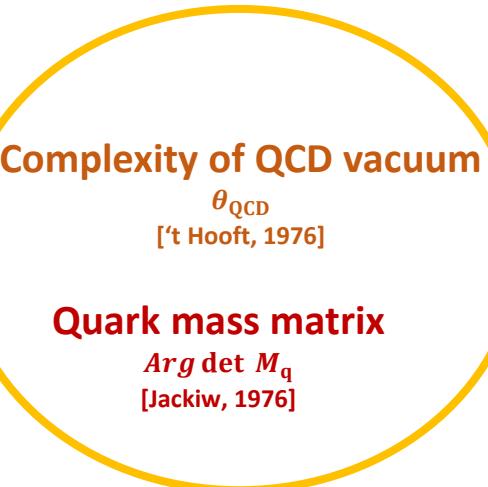


Strong penguin diagram

$d_n \approx 10^{-32} \text{ e.cm}$
[Khriplovitch, 1981]



Standard models



SM strong sector:

GDR Terascale - nEDM implications for HEP

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Strong SM sector predictions unknown

$$\bar{\theta}_{QCD} < 10^{-10}$$

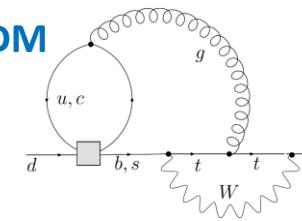
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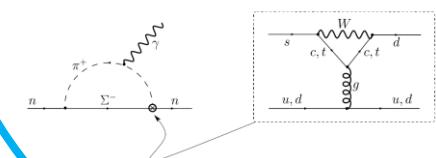
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Standard models

SCM:

[Sakharov, 1967]

Baryonic number violation

Sphaleron mechanism
[Klinkhamer, 1984]

Departure from
Thermal Equilibrium

CP violation

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Baryon Asymmetry of the Universe

$$\eta_{\text{CMB}} = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-10}$$

Complexity of QCD vacuum

θ_{QCD}
['t Hooft, 1976]

Quark mass matrix

$\text{Arg det } M_q$
[Jackiw, 1976]

SM strong sector:

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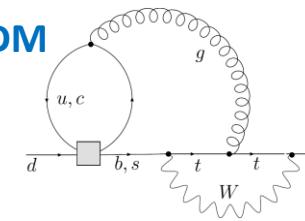
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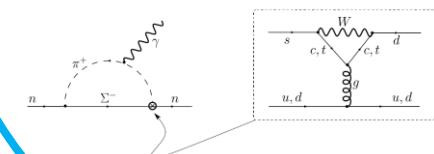
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CP violation

Some challenges addressed by EDM searches:

- Which **baryogenesis** scenario?
- What is the new physics **energy scale**?
- Axions solving **strong CP problem** as **dark matter** candidate?

Complexity of QCD vacuum

θ_{QCD}
['t Hooft, 1976]

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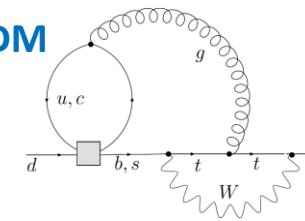
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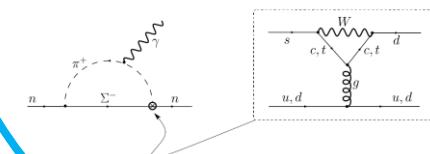
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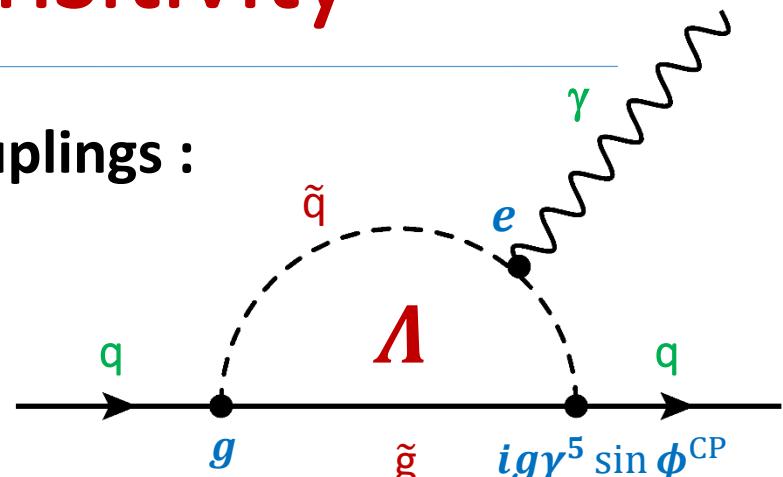


High energy scale sensitivity

1. EDMs arise at 1 loop with BSM couplings :

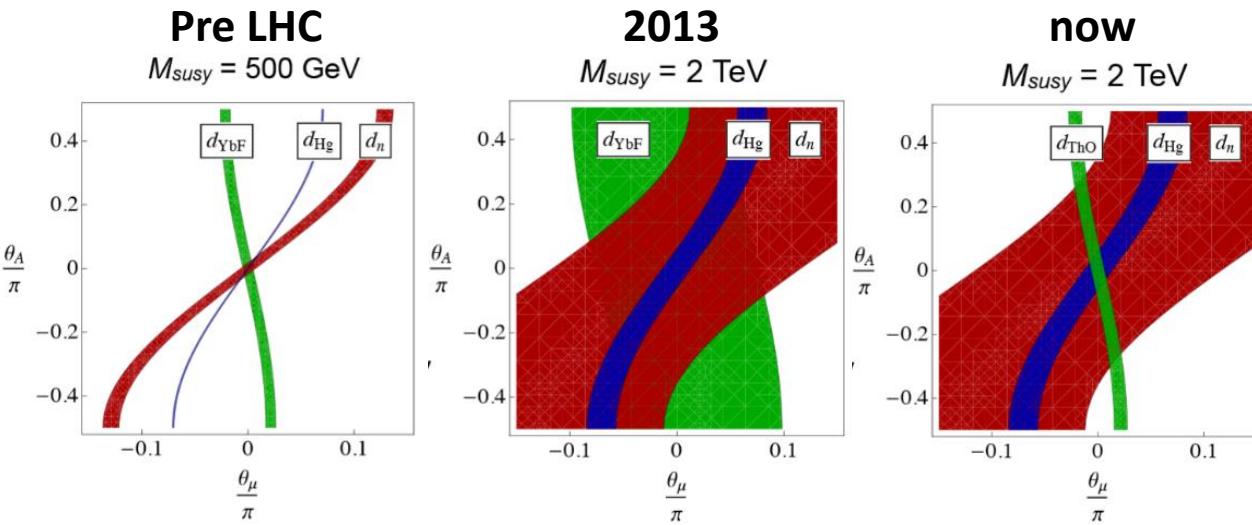
$$d_n \approx 10^{-25} e.\text{cm} \times \sin(\phi^{\text{CP}}) \times \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2$$

- Balance between : $\phi^{\text{CP}} / \Lambda$
- $\sin(\phi^{\text{CP}}) \sim 1$ implies $\Lambda > 10 \text{ TeV}$



[Pospelov & Ritz, 2005]

2. LHC / EDMs complementarity :



[Ritz, 2015]

- Various EDM experiments needed
- Why BSM CP violating phases would be small?

BSM Electroweak Baryogenesis

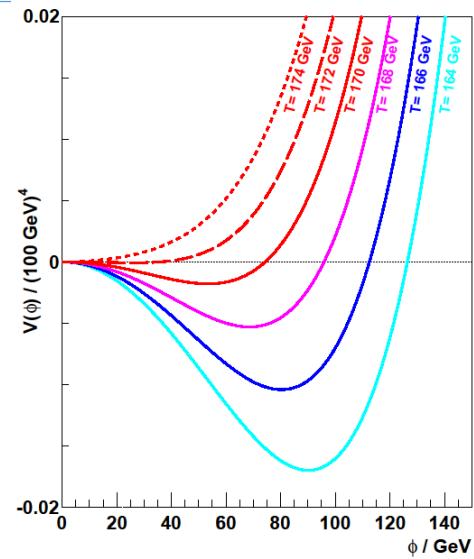
- **SM EWBG** is already **excluded** :

m_H too high

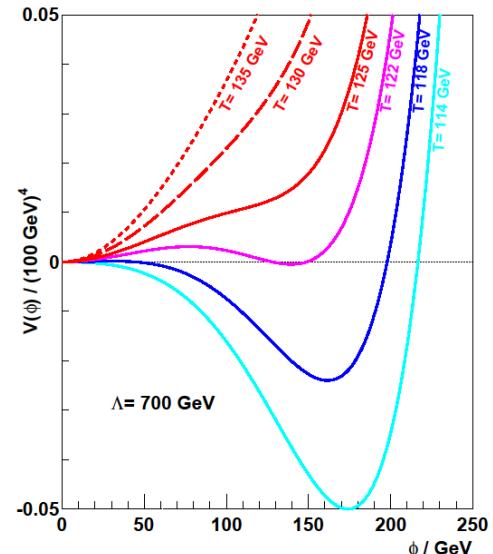
δ_{CKM} not large enough

- Adding $\mathcal{O}(6)$ operator $\sim \frac{1}{8\Lambda} \varphi^6$ allows strong 1st order EW phase transition
-> **falsifiable theory**

SM only

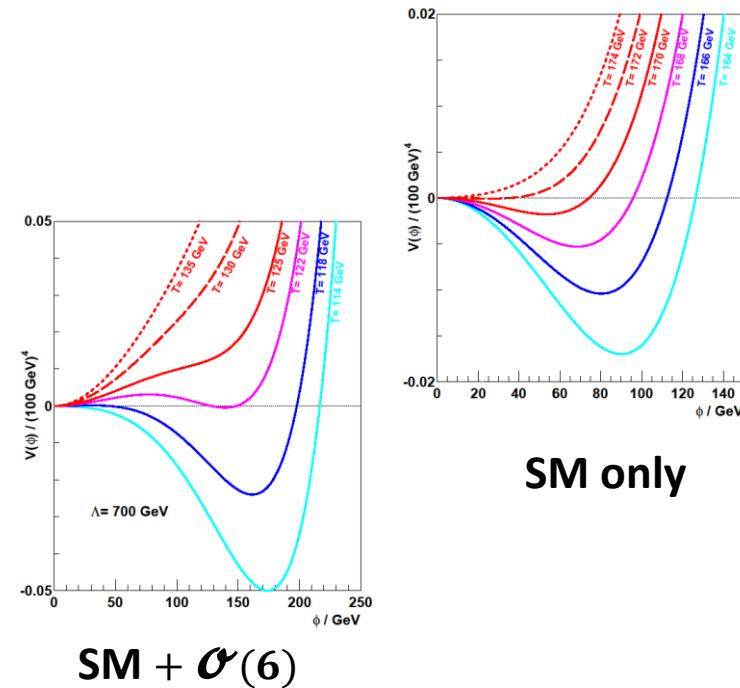


SM + $\mathcal{O}(6)$



BSM Electroweak Baryogenesis

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-> falsifiable theory



- HOW? :
EWBG requires CP violation at EW scale from BSM physics
BSM CP violation phases $\delta_{BSM} > \delta_{CKM}$
-> new sources of CP violation best probed by EDM experiments

[Bernreuther, 2002]

[Huet, 1994]

EDM projects worldwide

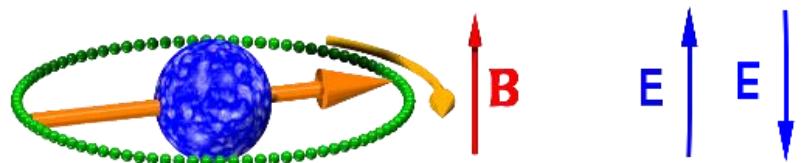
- **PSI** nEDM experiment Paul Scherrer Institute (CH)
8 countries (Switzerland, Germany, France, UK, Poland, Belgium, USA, Russia)
48 members / 11 PhD students
- **SNS** nEDM experiment Oak Ridge (USA)
- **JEDI** pEDM experiment Julich (GE)
- **Seattle** Hg EDM experiment Seattle (USA)
- **ACME** e^- EDM experiment Yale/Harvard (USA)
- ...

nEDM measurement principle

- Hamiltonian of the problem :

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

- Goal : Measure a neutron spin precession frequency shift proportional to an applied electric field

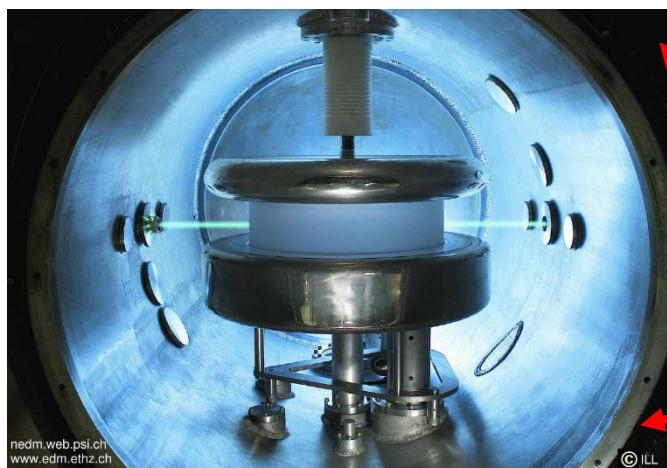
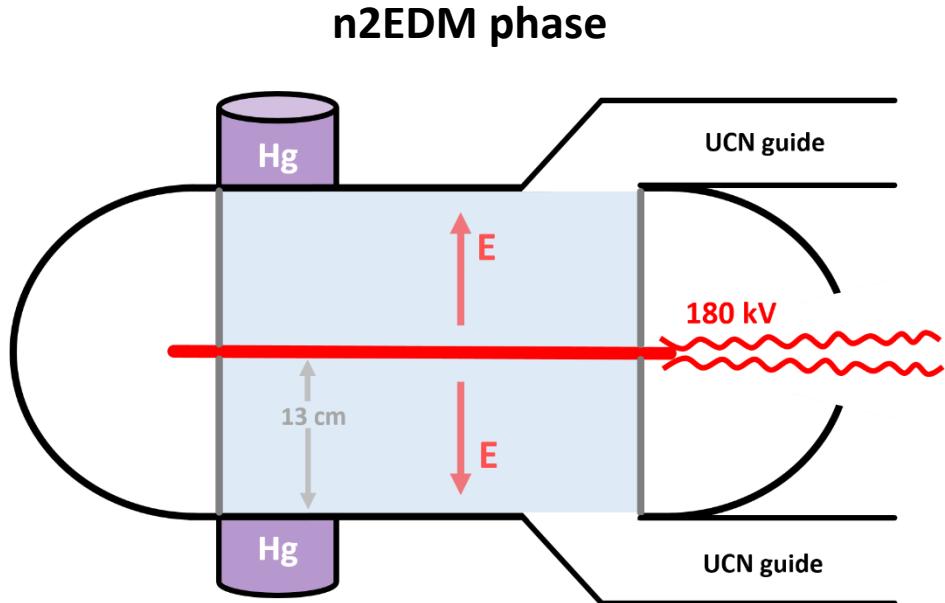
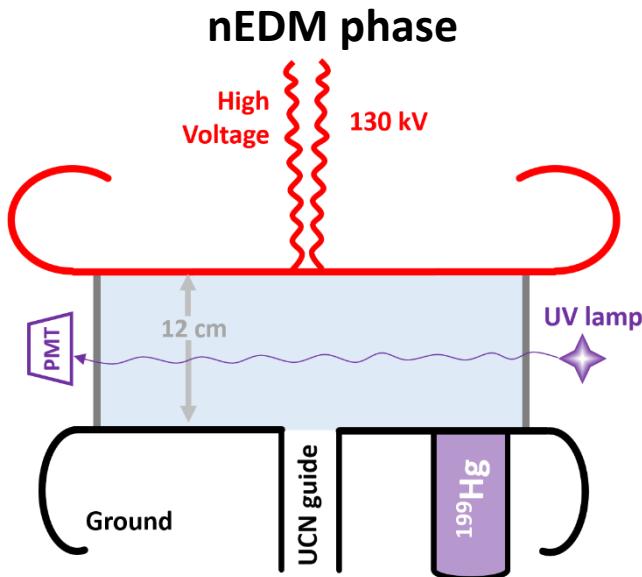


$$\left. \begin{aligned} \frac{h\nu^{\uparrow\uparrow}}{2} &= -\mu B^\uparrow - d E^\uparrow \\ \frac{h\nu^{\uparrow\downarrow}}{2} &= -\mu B^\uparrow + d E^\downarrow \end{aligned} \right\} |d| = \left| \frac{h(\nu^{\uparrow\uparrow} - \nu^{\uparrow\downarrow})}{4E} \right|$$

True only if
 $B^\uparrow = B^\downarrow$!

Experimental setup

Use of ultracold neutrons (UCN) with $E \approx 100$ neV!



external
4 layers mu-metal shield

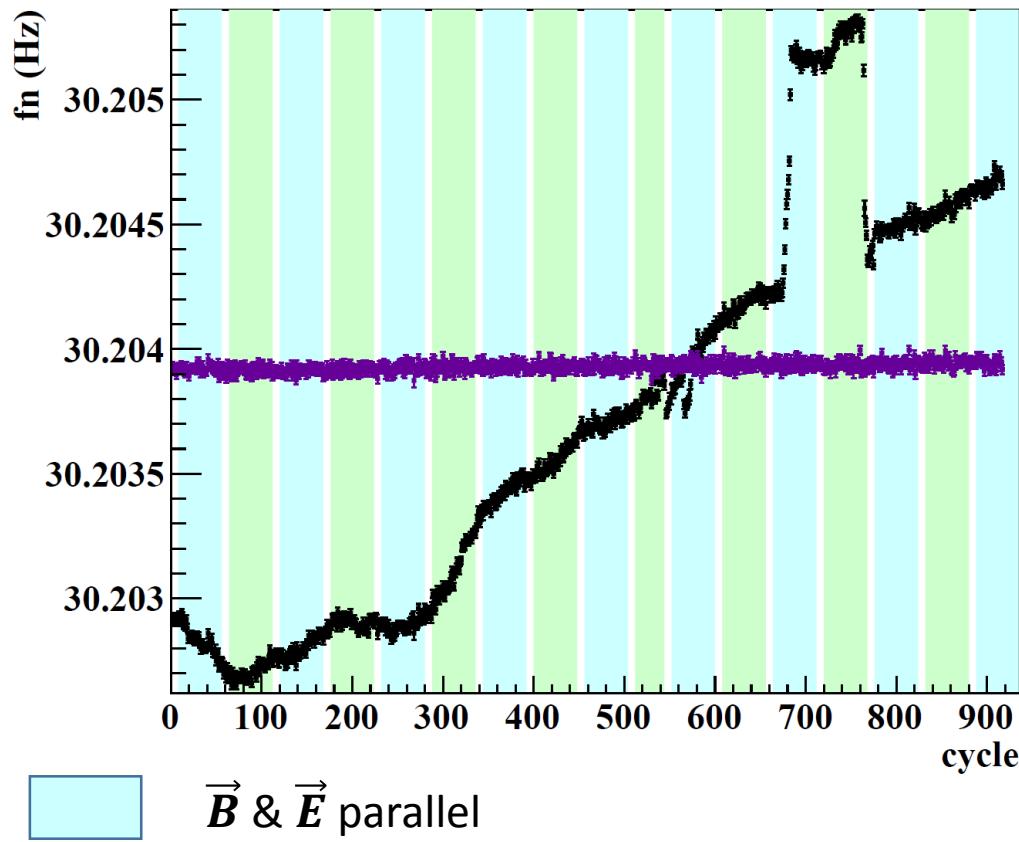
$\cos \theta$ coil
 $B_z \sim 1 \mu\text{T}$

R&D phase

NB: Upgraded RAL-Sussex spectrometer

Challenge

- **10^{-7} stability level** over 200 s
- **10^{-4} homogeneity** over a 20ℓ volume



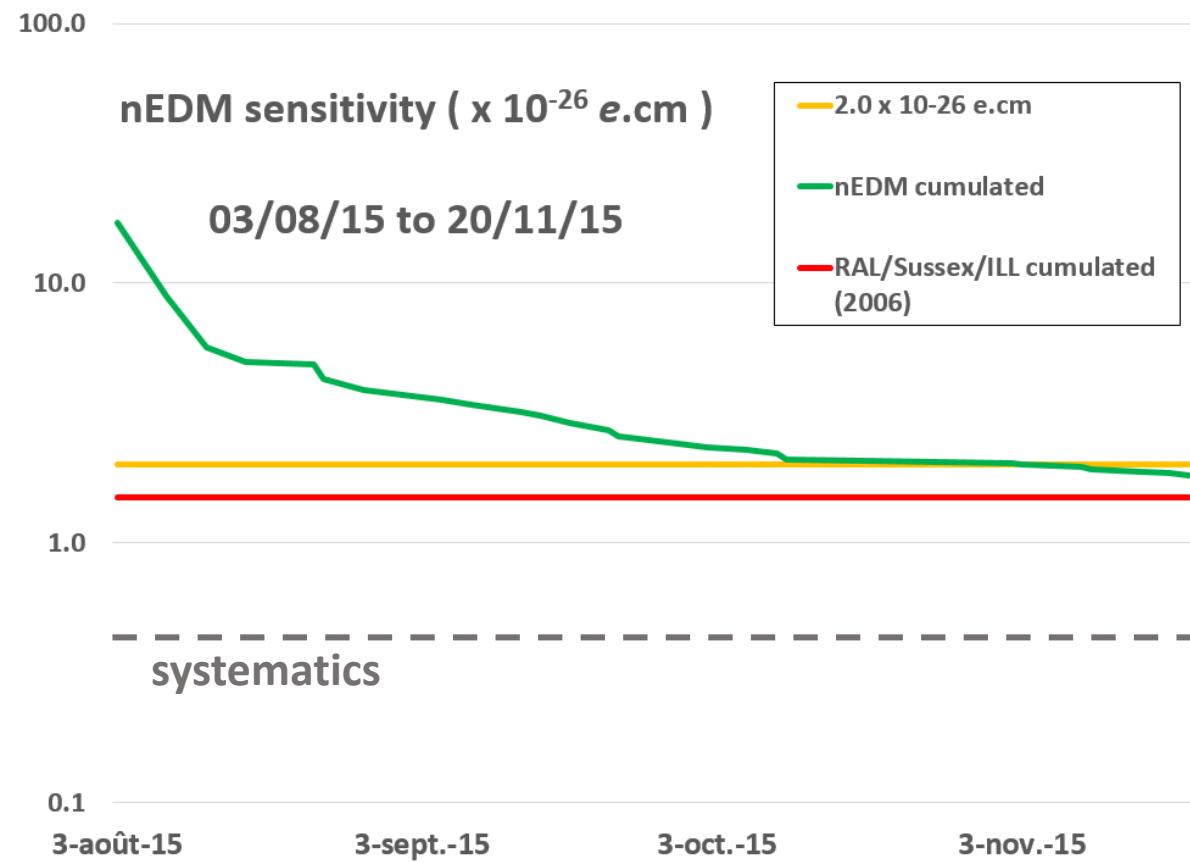
Co-magnetometry allows to be only statistically by UCN

$$\sigma_d/\text{cycle} = 1.10^{-24} \text{ e.cm}$$

Need to repeat thousands time the measurement to reach

$$\sigma_d = 1.10^{-26} \text{ e.cm}$$

Statistical sensitivity



1. The nEDM spectrometer installed at the PSI takes data with the best daily sensitivity. Cumulated :
 $\sigma_d \approx 1.8 \times 10^{-26} \text{ e.cm}$
2. nEDM phase goal:
 $\sigma_d \approx 1 \times 10^{-26} \text{ e.cm}$ within **two years**
3. n2EDM phase goal:
 $\sigma_d \approx 1 \times 10^{-27} \text{ e.cm}$ within the **next decade**

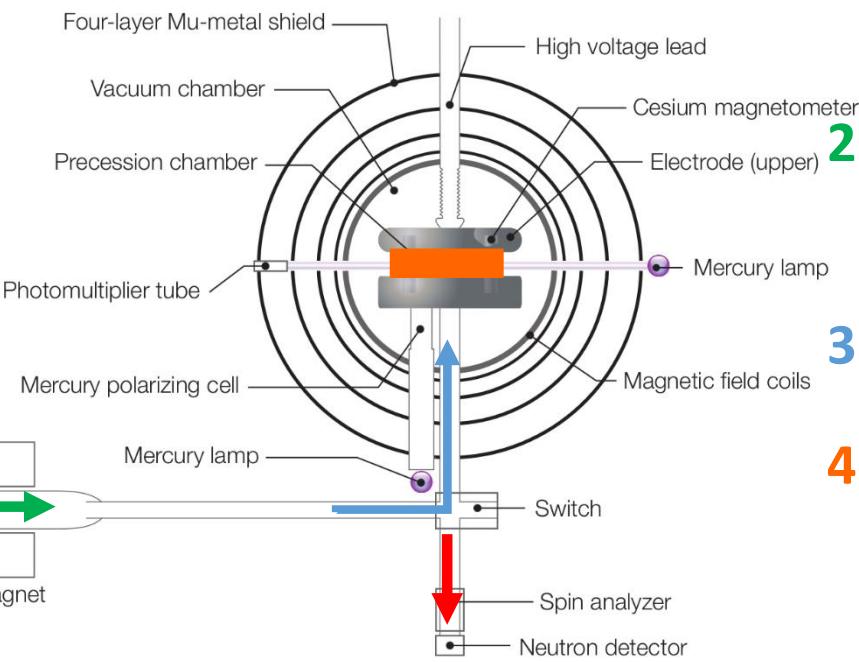
Conclusion

- Lowering the nEDM upper bound implies larger constraints in the **HEP parameter space**
- Probing a non-zero nEDM would reveal either **new CP violation** sources or θ_{QCD}
- Many experiments running worldwide with **different probes** (h , Hg , e^- ...)
- **Data taking ongoing** at PSI to lower the current nEDM sensitivity

Thank you for your
attention

Experimental setup

Cycle length : 5 min



$$P(\uparrow \rightarrow \downarrow) \propto \cos\left(\frac{f_{\text{RF}} - f_L}{\Delta\nu}\right)$$

1. Production of Ultra Cold Neutrons (UCN) in the new PSI UCN source

$$E_{\text{UCN}} \sim 100 \text{ neV}$$

2. UCN are spin-polarized \uparrow with a 5T magnetic field

3. Fill the precession chamber

4. Store UCN for 200 s with (E, B) parallel or antiparallel

1. Apply $\frac{\pi}{2}$ pulse (2s)
2. Spin freely precess (200s)
3. Apply $\frac{\pi}{2}$ pulse (2s)

5. Measure spin Up & Down neutron

Strong CP problem

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} + \frac{\bar{\theta} g_s^2}{32\pi^2} G \cdot \tilde{G}$$

Dimension 4 operator authorized by TQC
Can exist at 1 loop correction diagrams
Violates CP symmetry

[Peccei, 2006]

- $G \cdot \tilde{G}$ not a global gauge transformation invariant $\rightarrow U(1)_A$ problem (Weinberg 1975)
- $\bar{\theta}$ -term arising from QCD vacuum complexity and quark mass matrix imaginary part ($\bar{\theta} = \theta + \text{Arg det } M$)
- $\bar{\theta}$ -term constrains from nEDM upper bound:

$$d_n \sim e^{\frac{\bar{\theta} m_q}{M_n^2}} \quad \rightarrow \quad \bar{\theta} < 10^{-10}$$

- SM needs non-explained fine tuning or an additional scalar field: the Axion

MSSM parametrization

1. R-parity symmetry conserved
 - $\sim 20 \phi^{\text{CP}}$
2. Tri-linear couplings proportional to Yukawa : $A_i = A_i Y_i$
Flavor universality : $M_S^2 = m_S^2 \mathbf{1}$
 - $\sim 4 \phi^{\text{CP}}$
3. Common gaugino mass phase = 0
 - $\text{Arg}(A_i) = \theta_A$
 - $\text{Arg}(\mu) = \theta_\mu$

Oscillating EDMs

- Axion seen as a dynamical field $a(t)$
- Look for axion to gluon couplings (not EM)
nucleon axial-vector current
- Expected frequency shift in atomic systems

$$d(t) \propto \frac{a_0}{f_a} \sin(m_a t + \phi) \text{ e.cm}$$

Axion field
Axion decay constant

[Graham, 2011]

- Order of magnitude : $m_a \sim 10^{-20}$ eV
-> Translate to monthly EDM oscillations