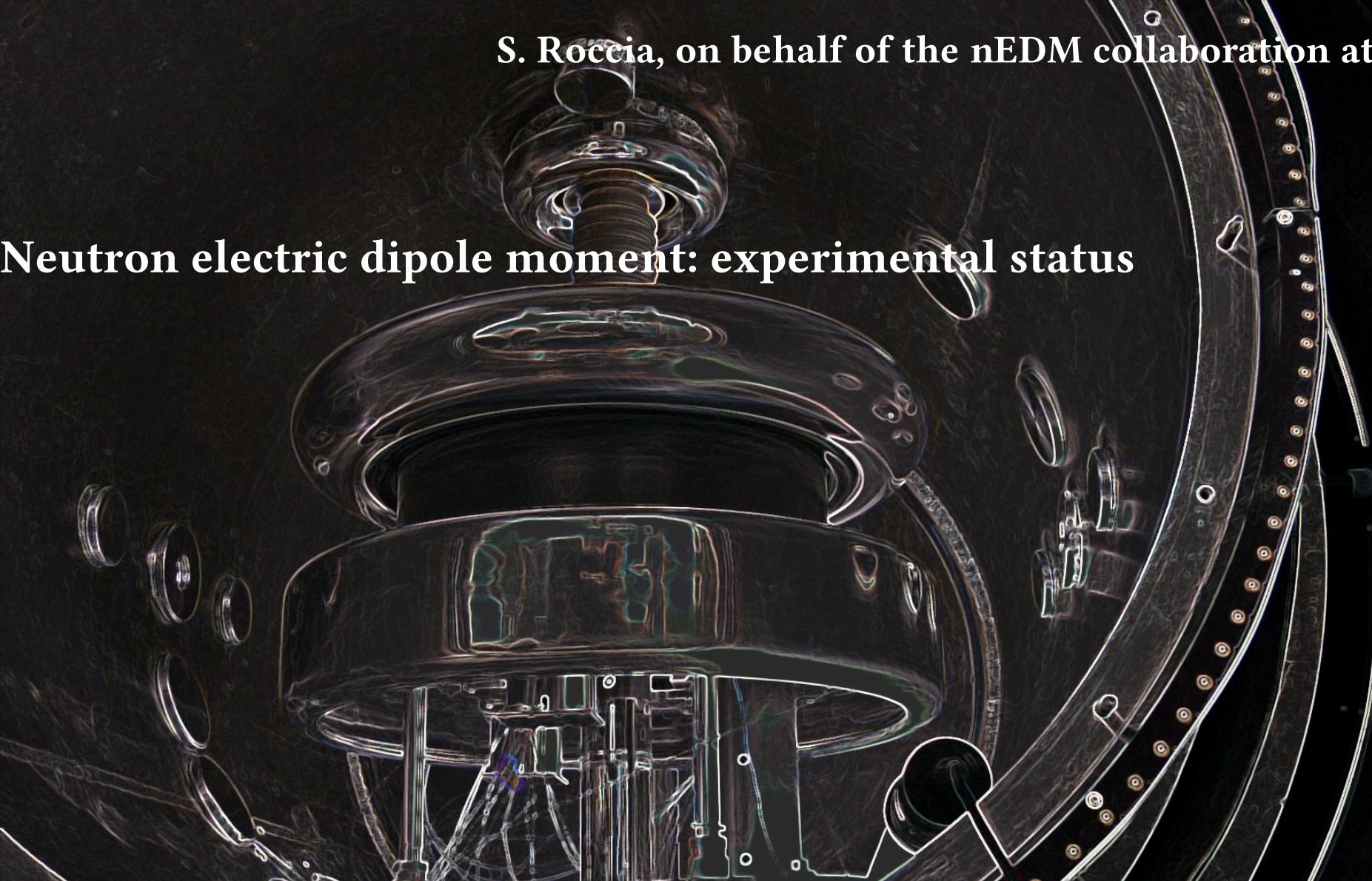


S. Roccia, on behalf of the nEDM collaboration at PSI



## Neutron electric dipole moment: experimental status



Comprendre le monde,  
construire l'avenir®

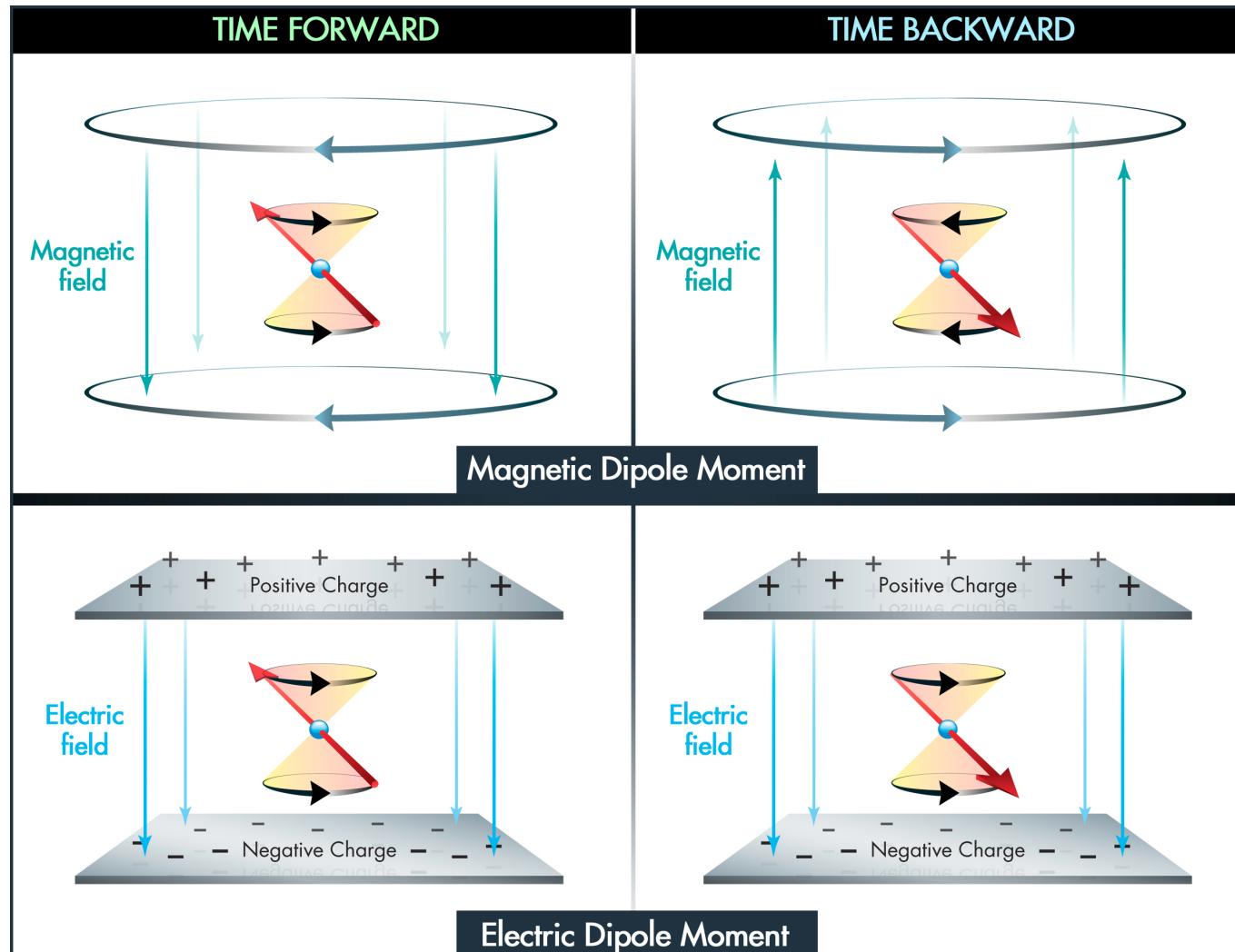
- nEDM
- n2EDM
- 2016: highlights

$u^b$

Welcome University of Bern

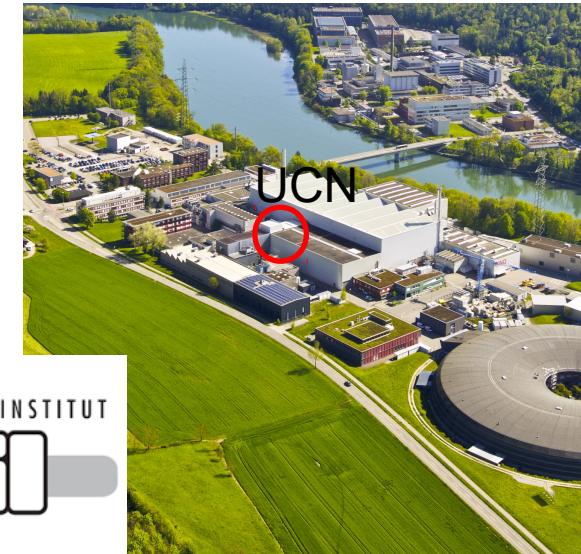
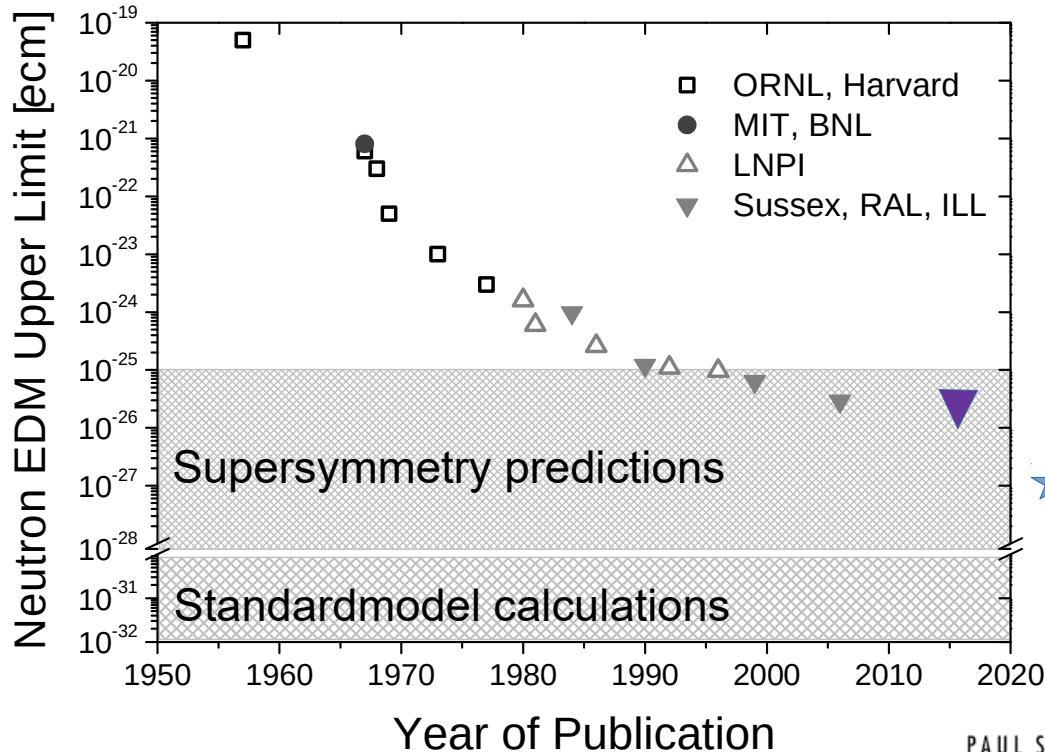


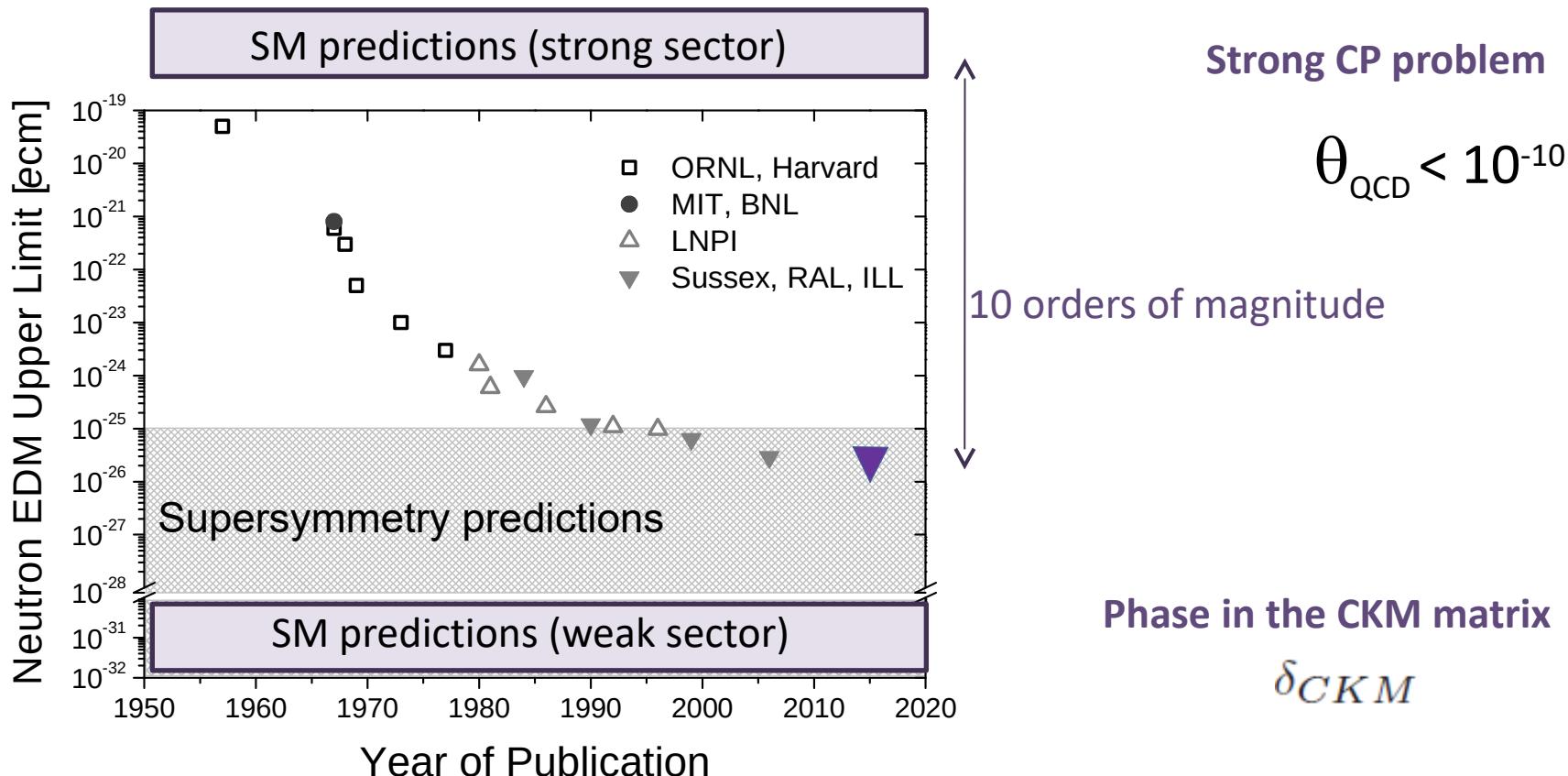
The nEDM collaboration

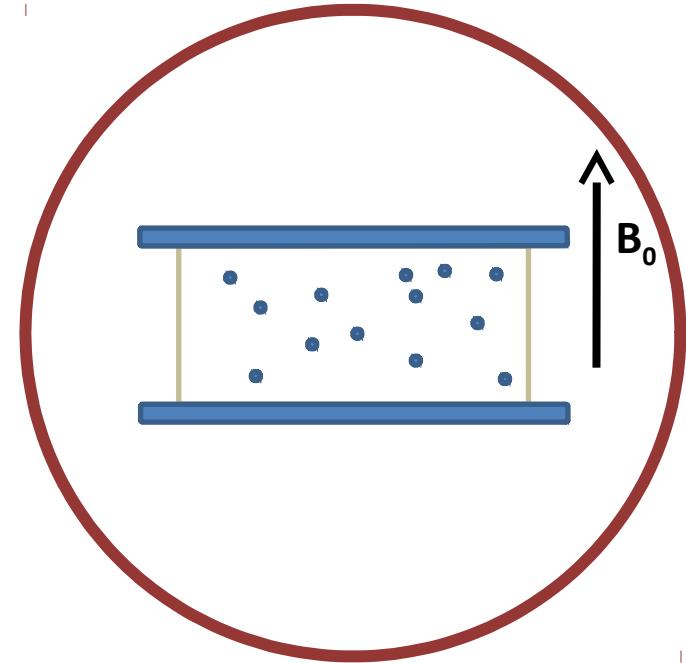
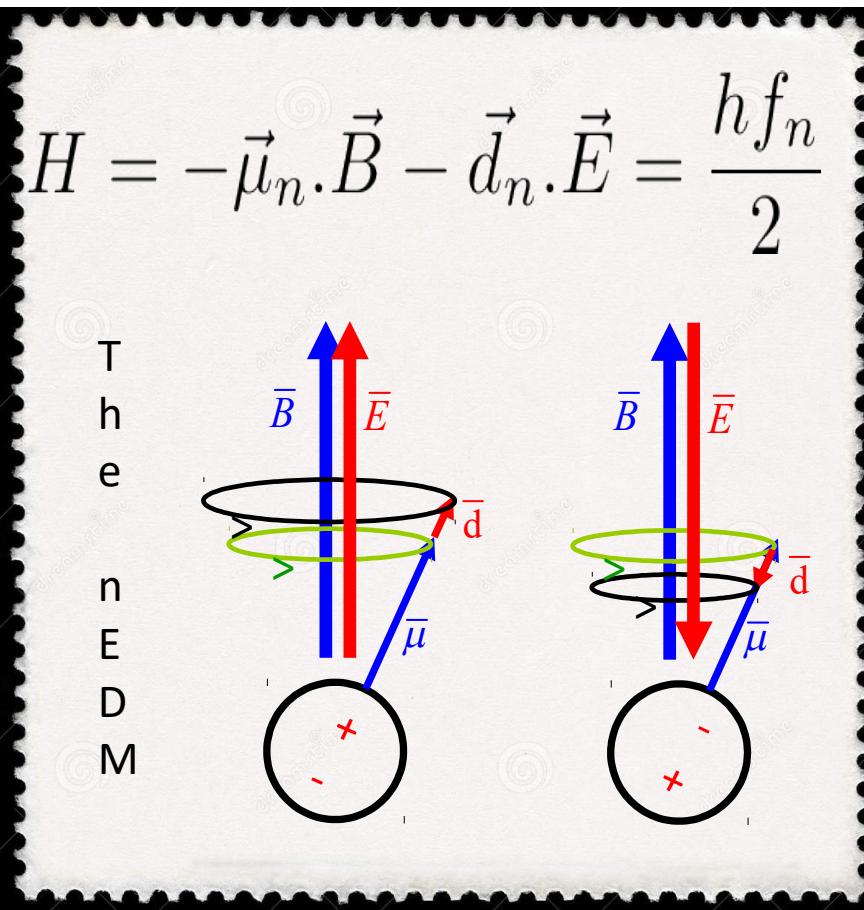


$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

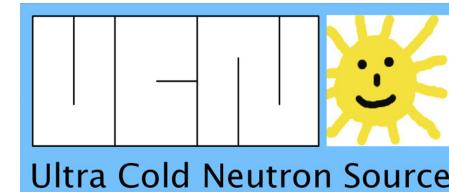
A nonzero particle EDM violates **T**, **P** and, assuming **CPT** conservation, also **CP**.







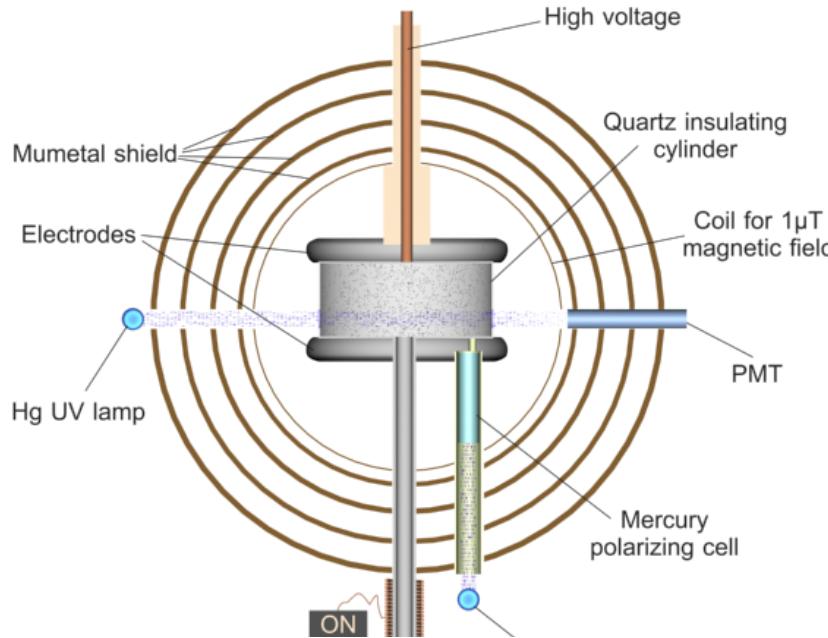
Neutrons reflected for all incidence angles: UCNs



$\lambda_n \approx 800 \text{ \AA};$   
 $v_n \approx 5 \text{ m/s};$   
 $T_n \approx 2 \text{ mK};$   
 $E_n \approx 130 \text{ neV}$

## First limitation ..... Magnetic field fluctuations

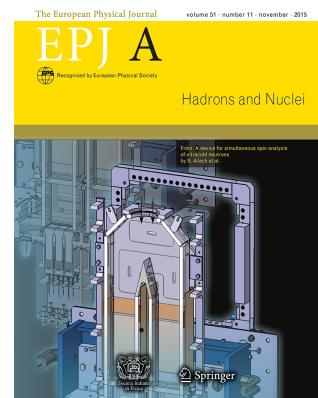
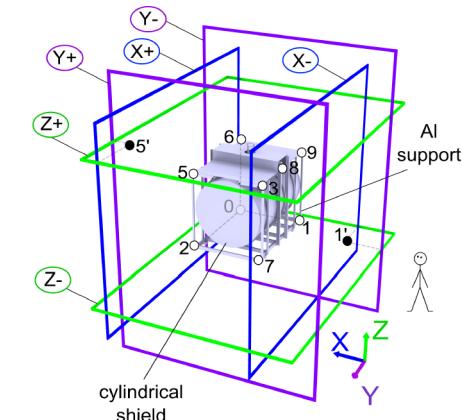
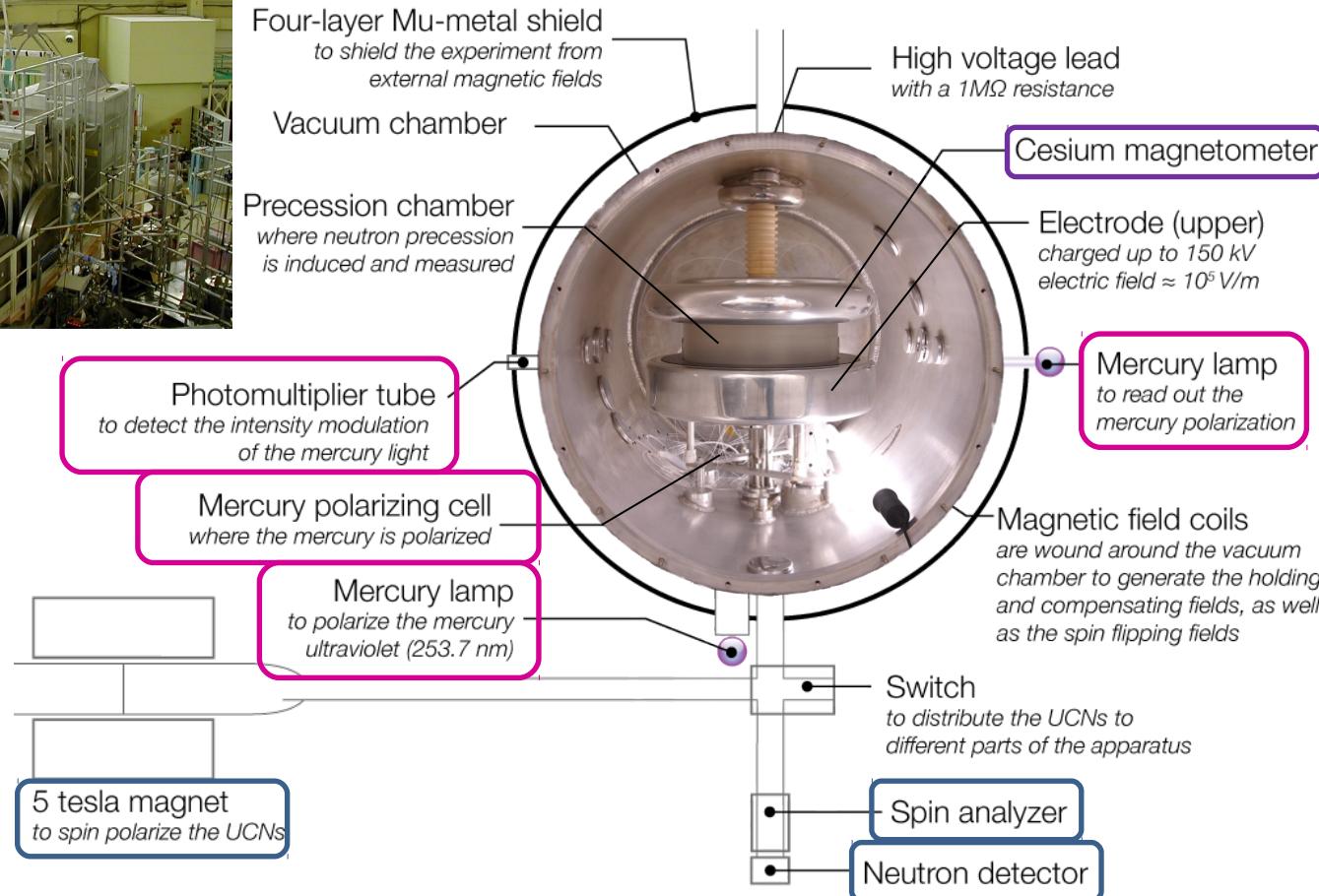
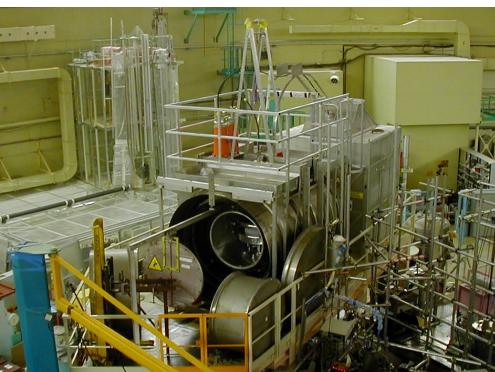
$$\begin{aligned}
 h f_n (\uparrow\uparrow) &= 2 \vec{\mu}_n \cdot \vec{B}(\uparrow\uparrow) \\
 h f_n (\uparrow\downarrow) &= 2 \vec{\mu}_n \cdot \vec{B}(\uparrow\downarrow) \\
 \hline
 h(f_n (\uparrow\uparrow) - f_n (\uparrow\downarrow)) &= 2 \vec{\mu}_n \cdot (\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow))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



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)



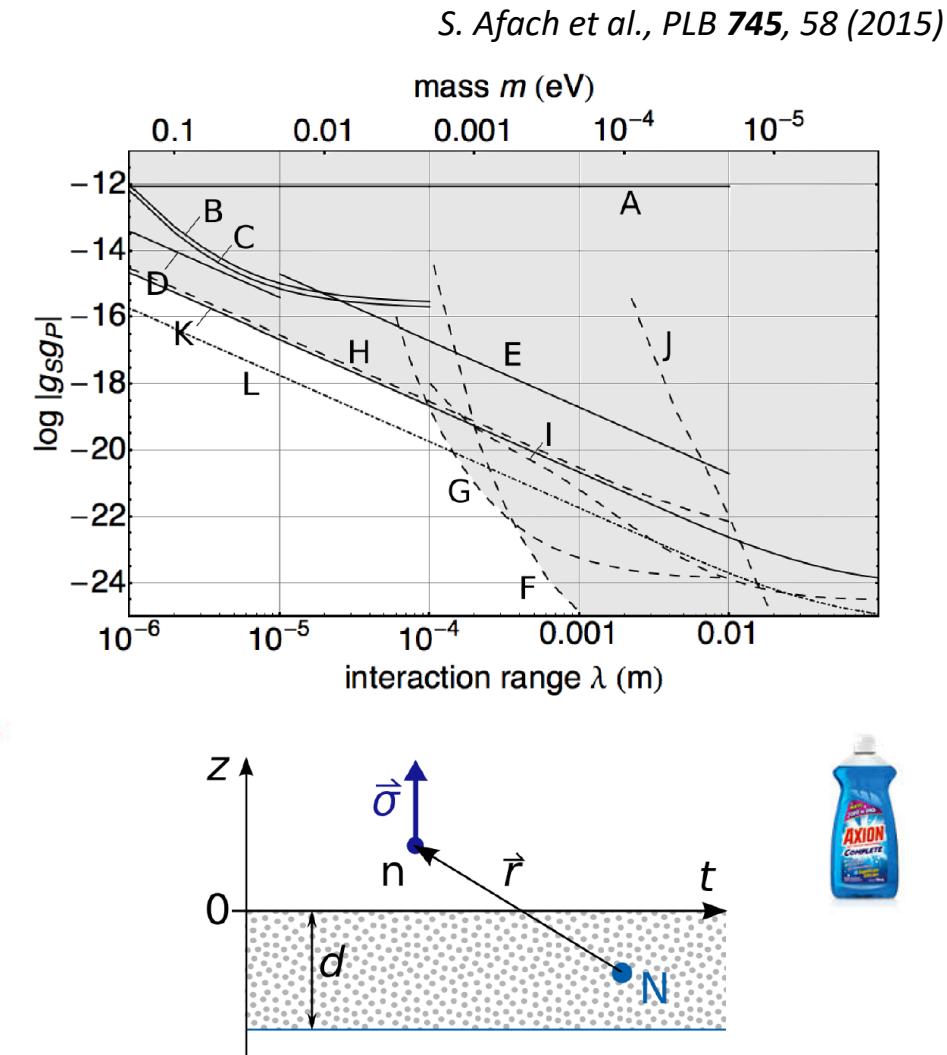
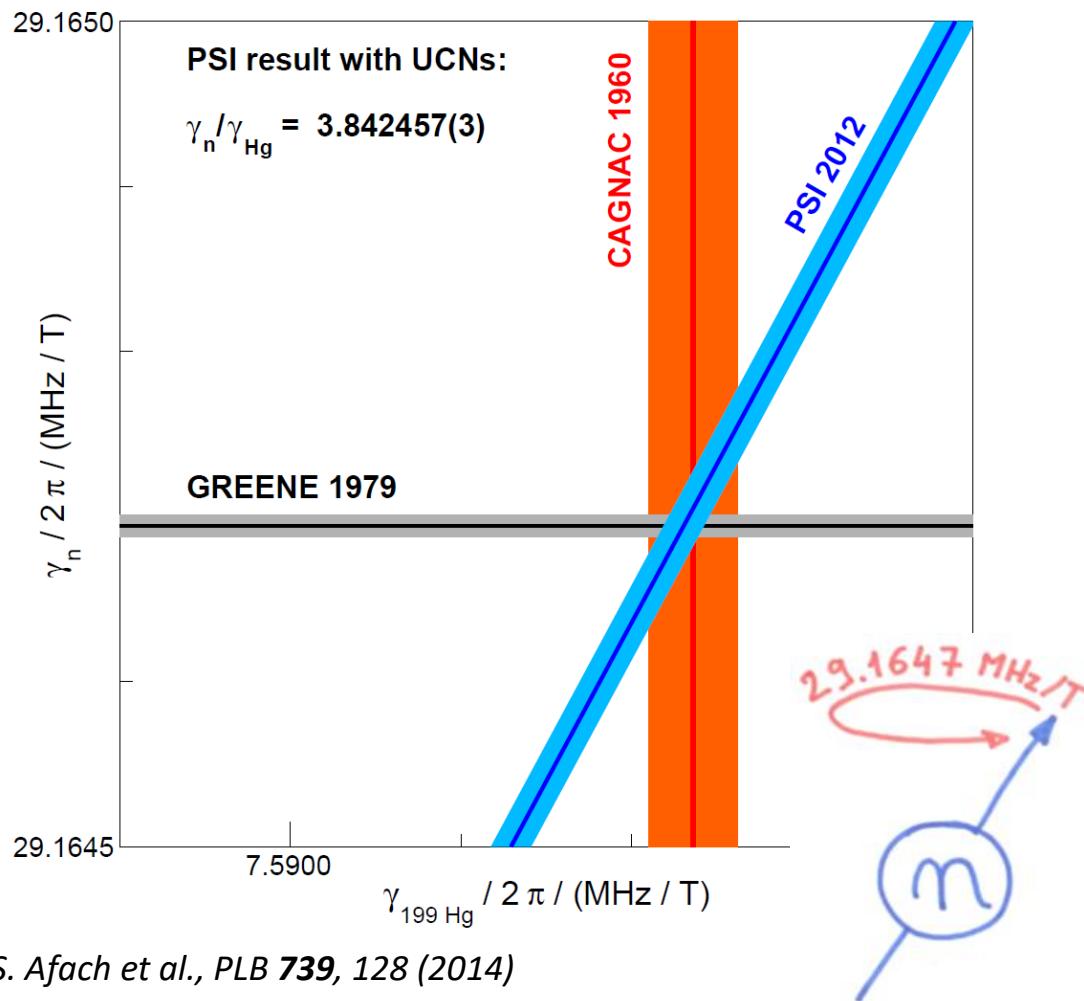
	nEDM@ILL 2006	nEDM@PSI 2016
Chamber	1	1
Diameter (cm)	47	47
Neutron/cycle	14 000	15 000
E(kV/cm)	8.3	11 (15)
T(s)	130	180
$\alpha$	0.45 (0.6)	0.75 (0.80)
Sens/day(e.cm)	$30 \times 10^{-26}$	$11 \times 10^{-26}$

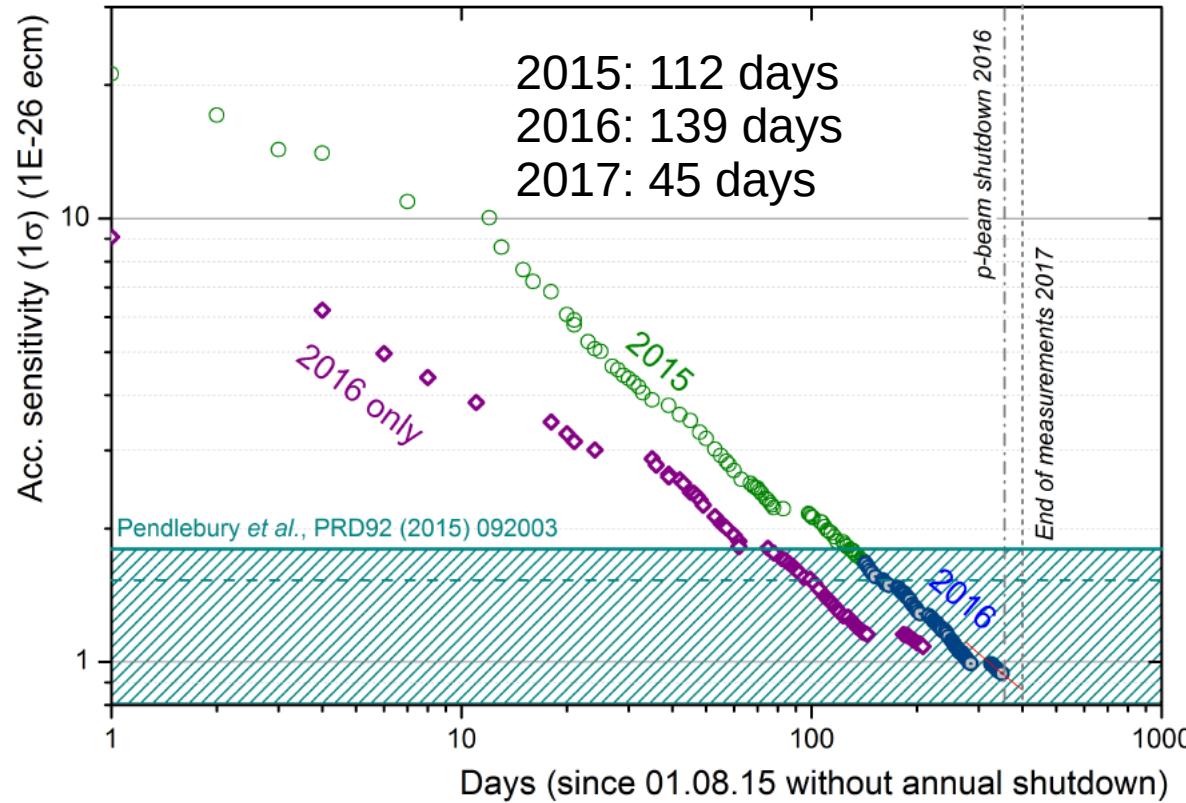
Statistical sensitivity

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

Pushing the limit of the technique  
at room temperature

World record for sensitivity





Accumulated raw sensitivity

2015:  $1.7 \times 10^{-26}$  ecm

2016:  $1.1 \times 10^{-26}$  ecm

Total:  $0.94 \times 10^{-26}$  ecm

(values from simple fit)

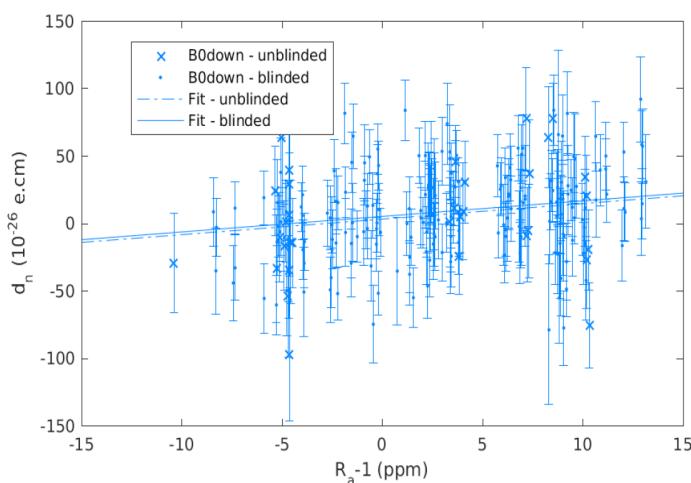
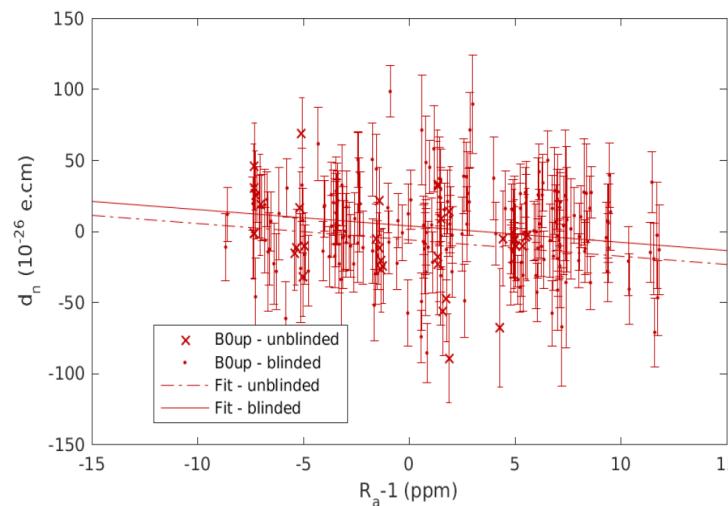
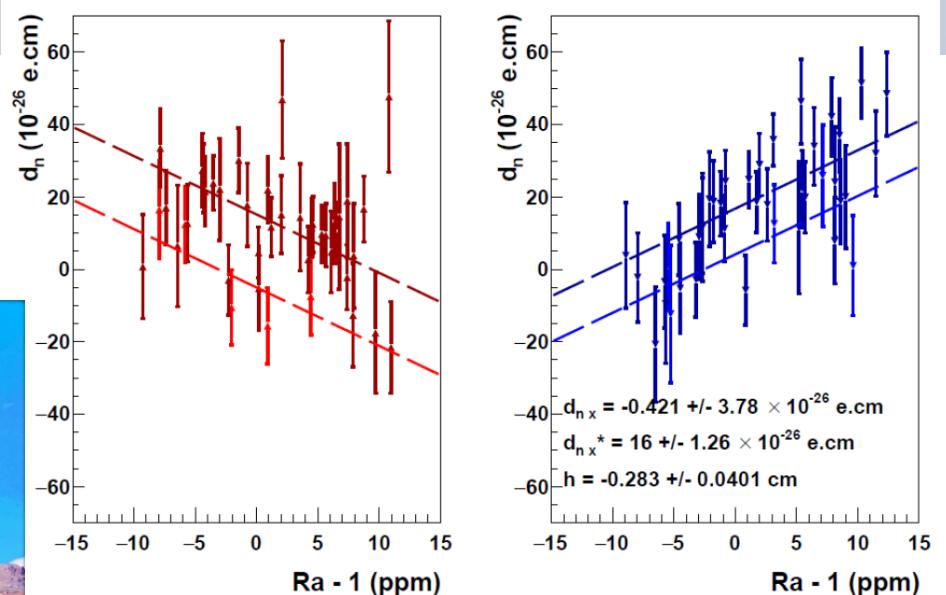
2016 : 1.5 % of available pulses missed

On-going analysis (preliminary)

- Blinded data
- 2 analysis teams (East/West)

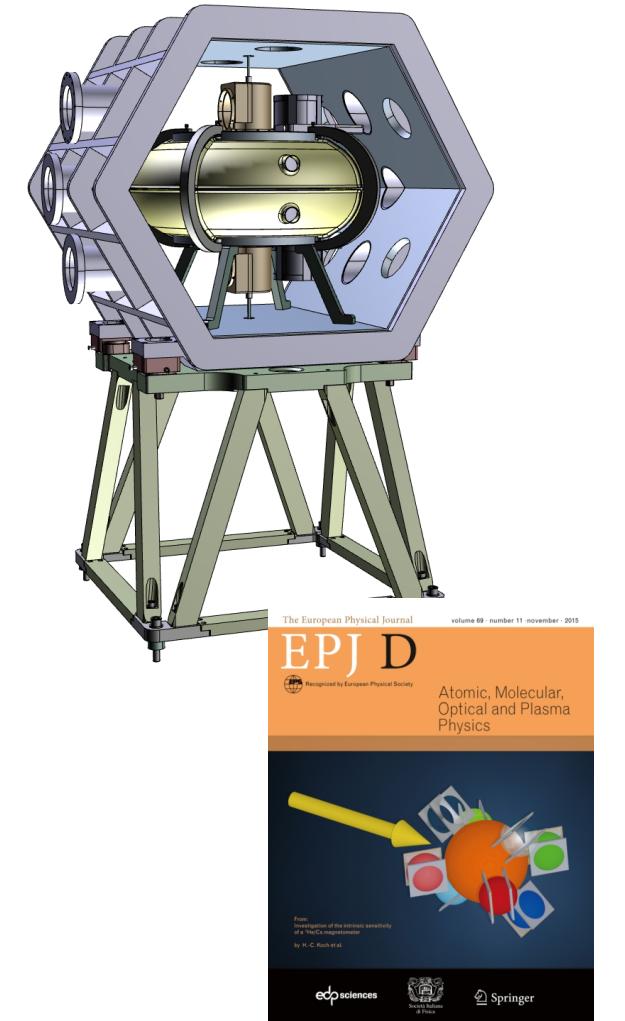
Demonstrated sensitivity  
after analysis (2015-2016)

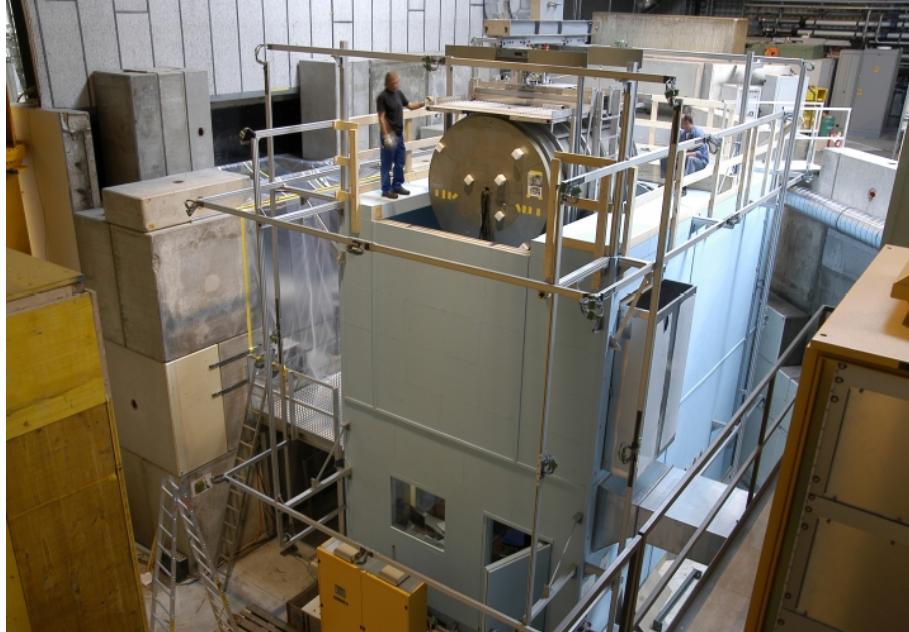
$$1.15 \times 10^{-26} e \cdot \text{cm}$$



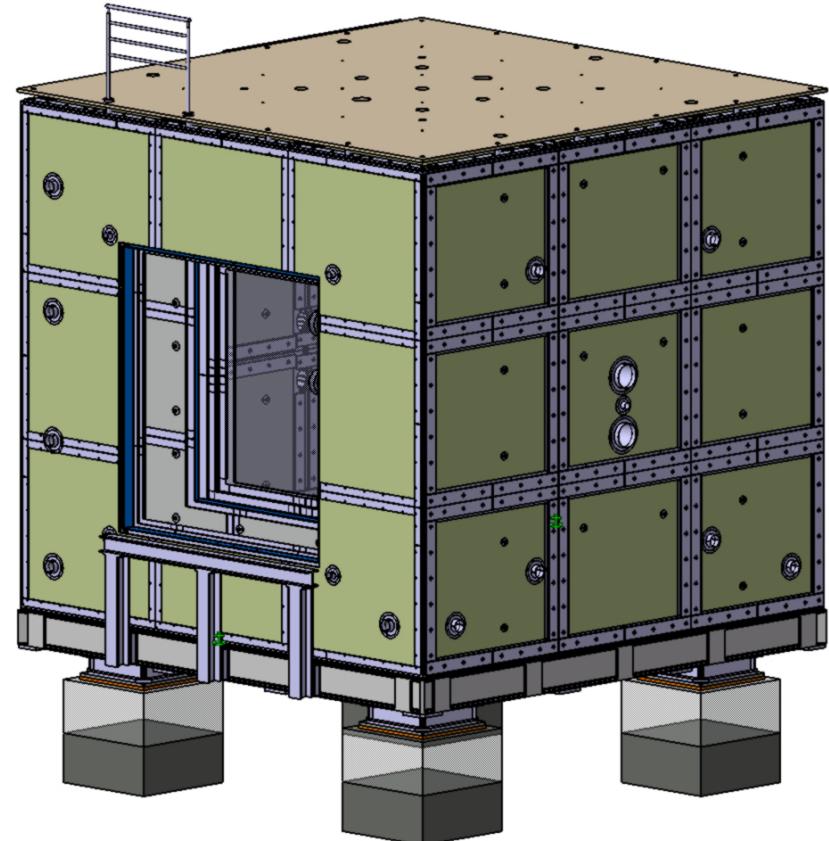
Unblinded  $d_n : -1.28 \pm 3.85 \times 10^{-26} e \cdot \text{cm}$   
 Blinded  $d_n : 4.63 \pm 1.22 \times 10^{-26} e \cdot \text{cm}$   
 $h : 0.40 \pm 0.07 \text{ cm}$   
 $\chi^2/\text{DoF} : 708/464, \quad p\text{-value: } 2.02e-12$

	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
$\alpha$	0.45 (0.6)	0.75 (0.80)	0.8
Sens/day(e.cm)	$30 \times 10^{-26}$	$11 \times 10^{-26}$	$1.4 \times 10^{-26}$
Sens (500 days)	$1.3 \times 10^{-26}$	$5.0 \times 10^{-27}$	$6.4 \times 10^{-28}$



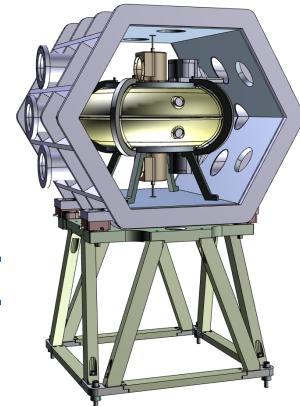


July 2009 & August 2017 ??



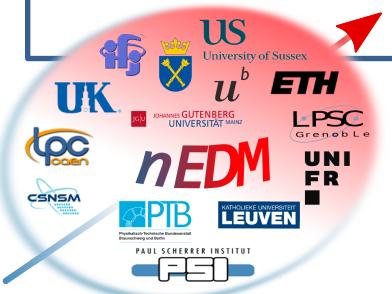
December 2017 installation of the  
shielded room

- n2EDM R&D efforts merged into one concept design
- Highly based on demonstrated techniques
- Shielded room expected in 2017



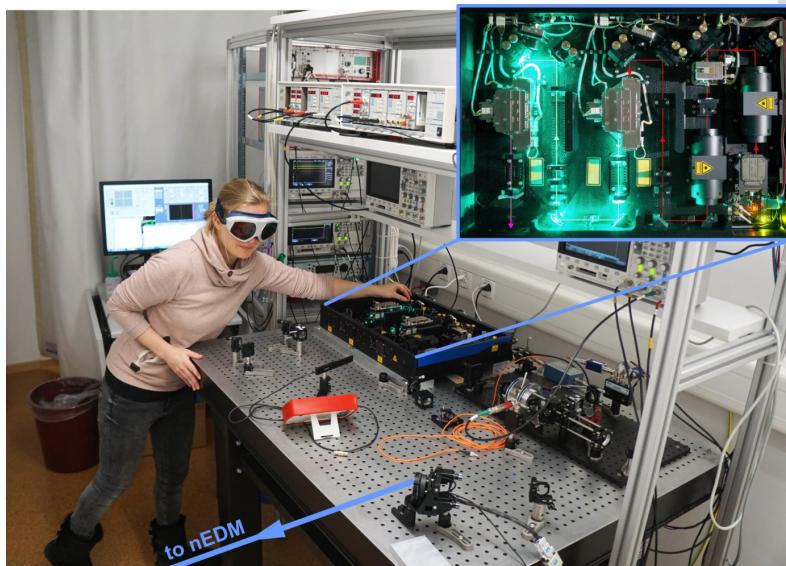
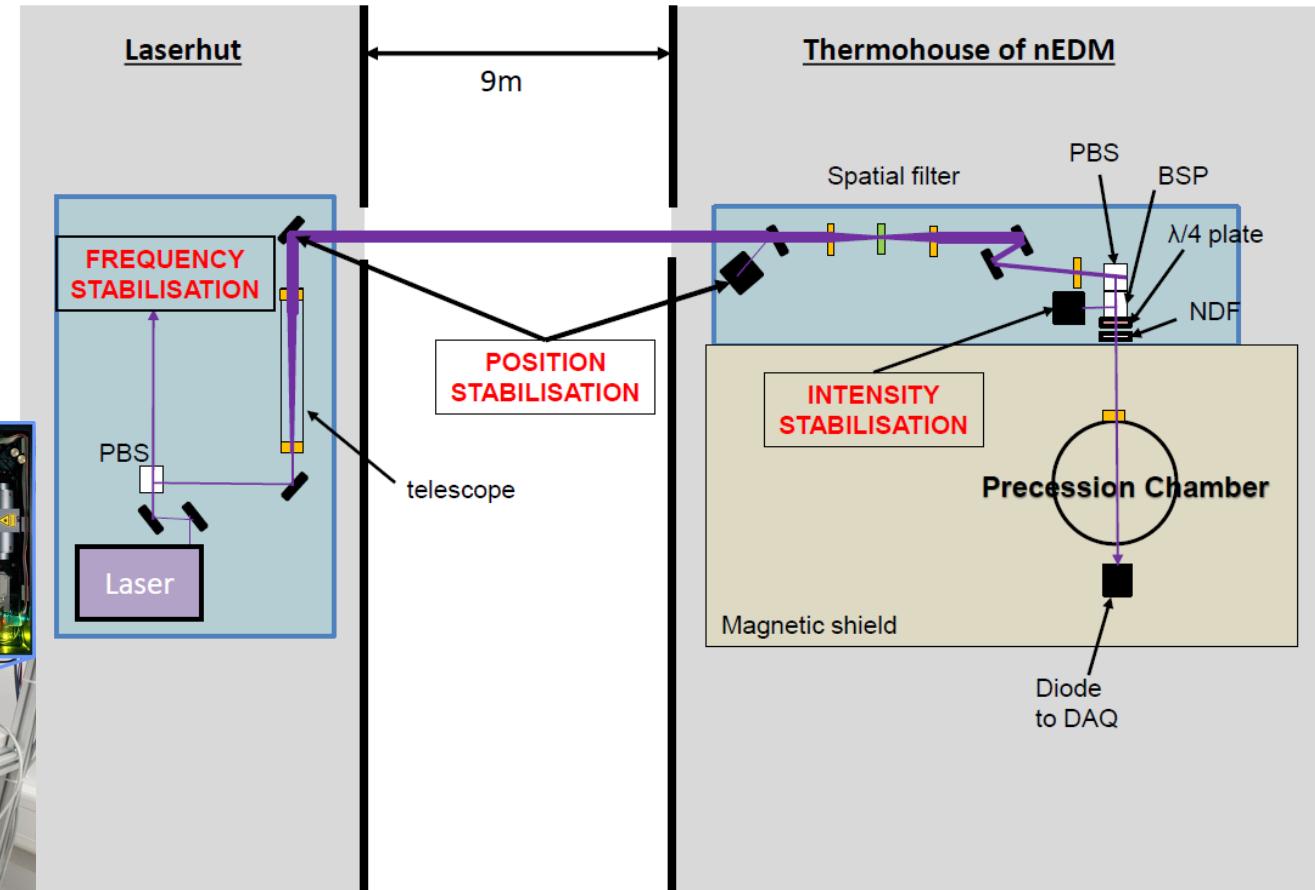
- nEDM operated with high efficiency and world-record sensitivity
- Systematic effect studies reanalysis of 2006 data
- More data in 2017

Sensitivity	Stat	Syst	Tot
RAL-Sussex-ILL (2015)	1.53	0.99	1.82
PSI (2016)	1.15	0.50	1.25



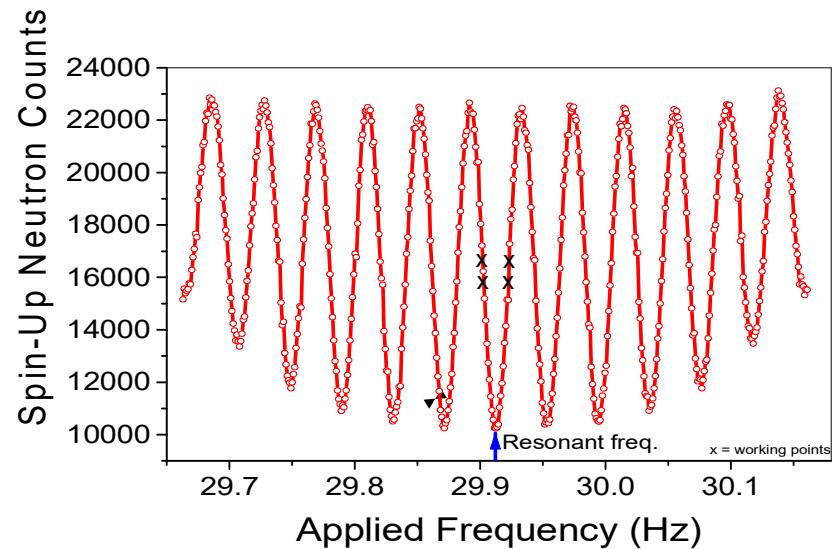
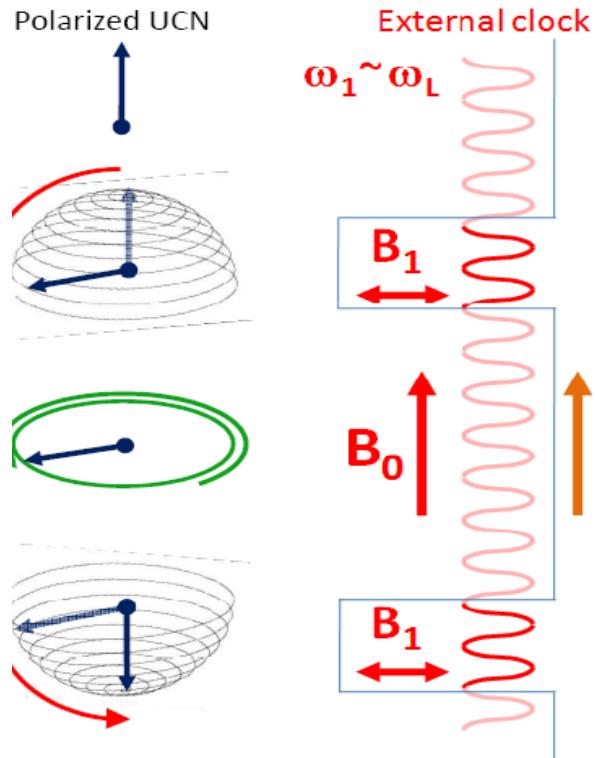
Thanks  
Merci

Hg co-magnetometer  
nEDM sensitivity: 50-70 fT (35 fT)  
n2EDM requirements: 26 fT



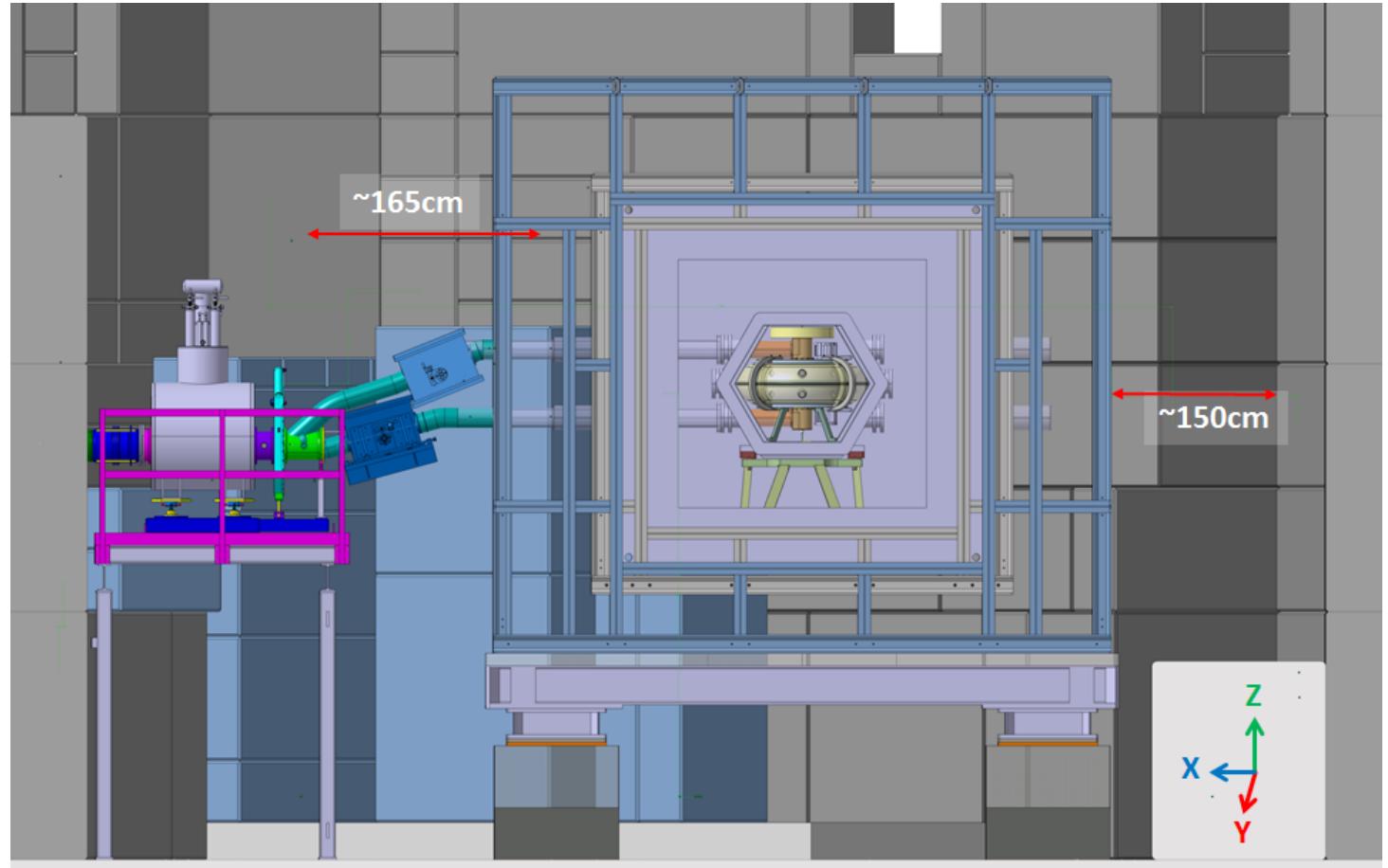
Demonstrated sensitivity: 8 fT

## The Ramsey's method of separated oscillating fields



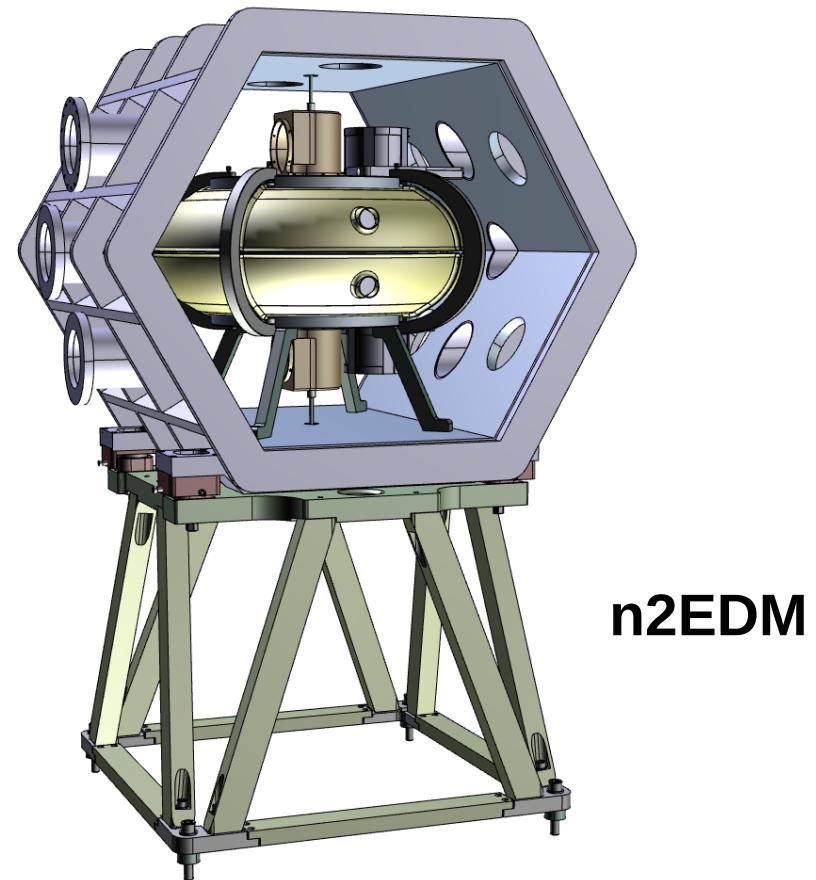
$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

n2EDM

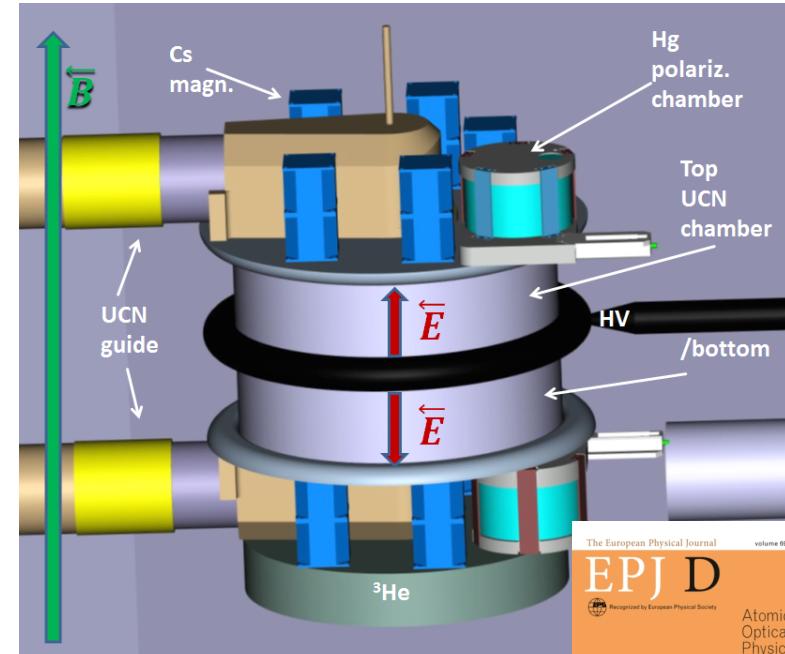


	nEDM@ILL 2006	nEDM@PSI 2016
Chamber	1	1
Diameter (cm)	47	47
Neutron/cycle	14 000	15 000
E(kV/cm)	8.3	11 (15)
T(s)	130	180
$\alpha$	0.45 (0.6)	0.75 (0.80)
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$
Sens (500 days)	$1.3*10^{-26}$	$5.0*10^{-27}$

Larger volume + Higher voltage

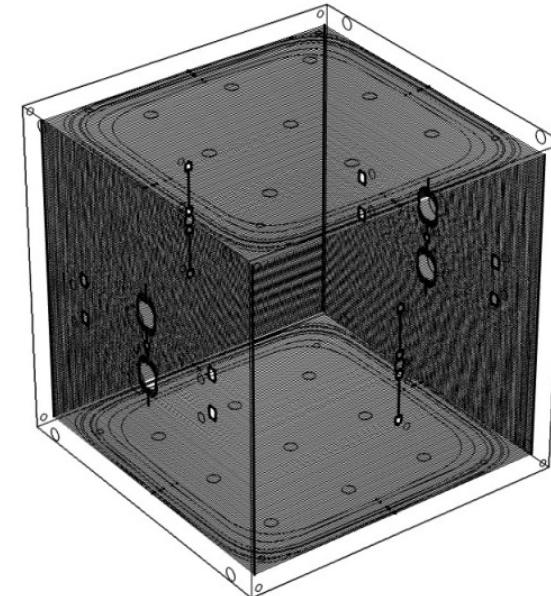


	nEDM@ILL 2006	nEDM@PSI 2016
Chamber	1	1
Diameter (cm)	47	47
Neutron/cycle	14 000	15 000
E(kV/cm)	8.3	11 (15)
T(s)	130	180
$\alpha$	0.45 (0.6)	0.75 (0.80)
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$
Sens (500 days)	$1.3*10^{-26}$	$5.0*10^{-27}$

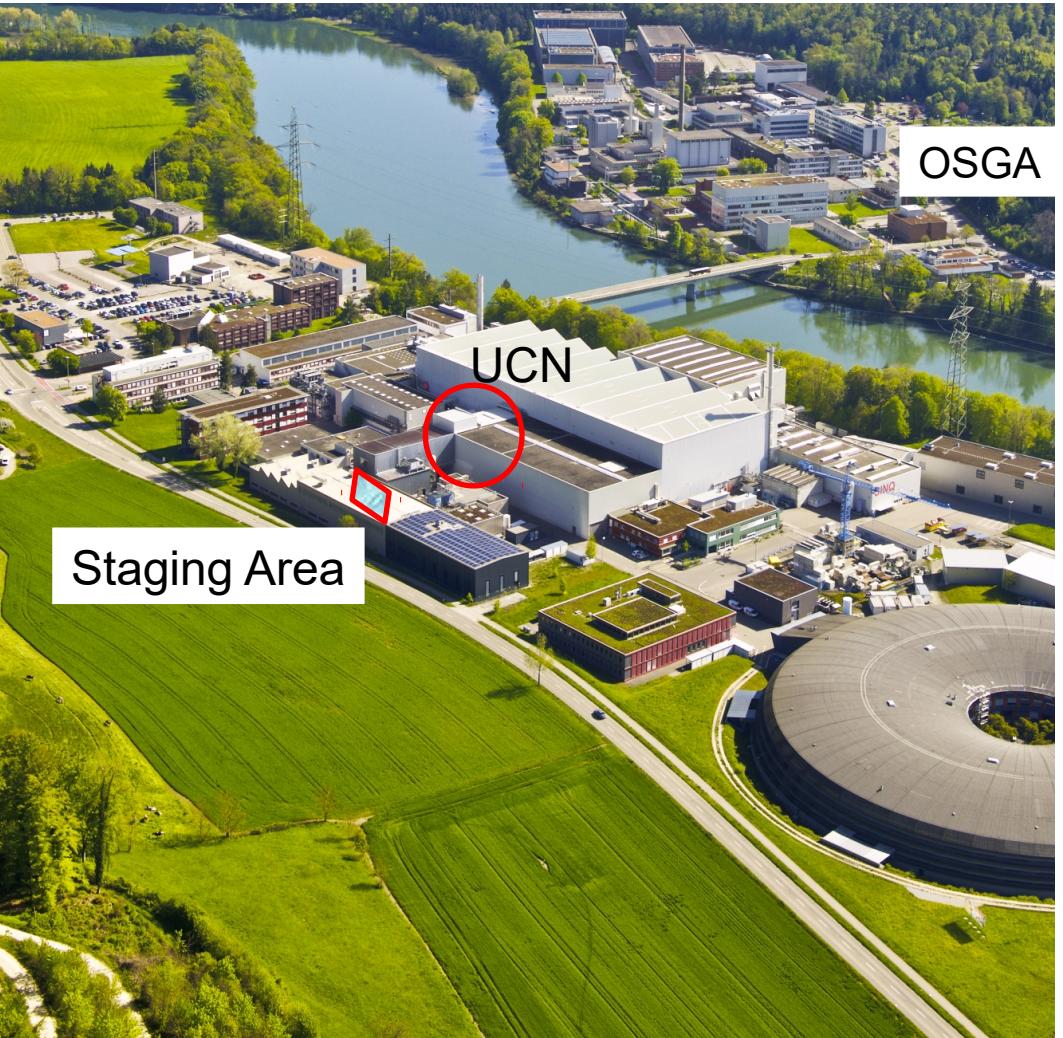
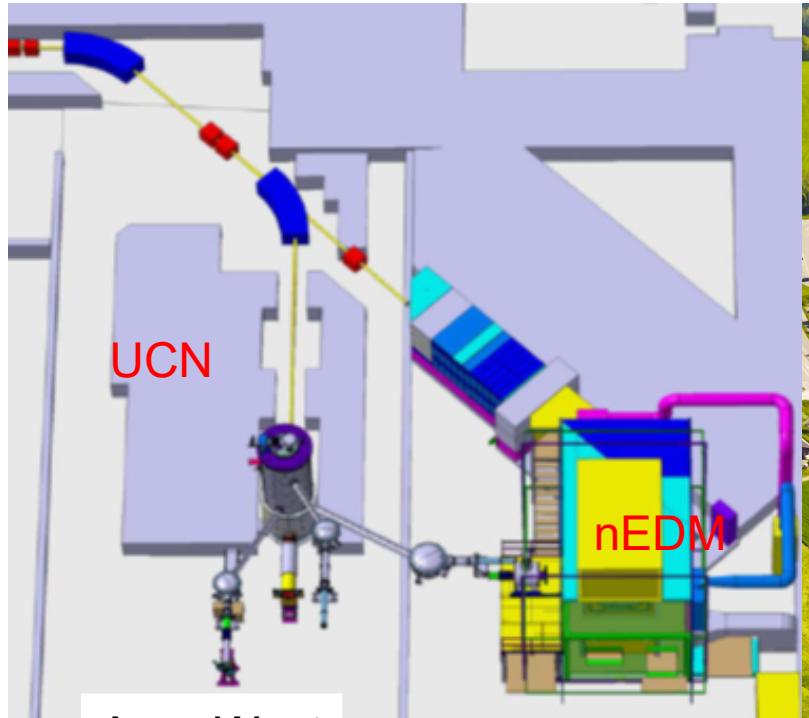


Better control on fluctuations + improved magnetometry

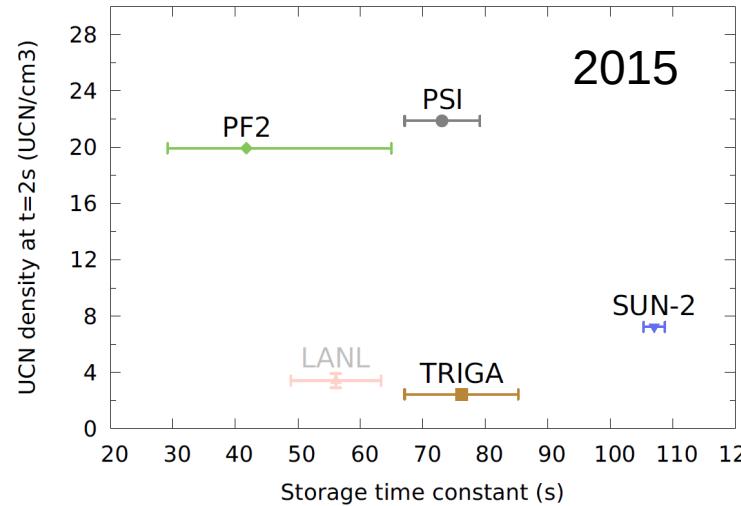
	nEDM@ILL 2006	nEDM@PSI 2016
Chamber	1	1
Diameter (cm)	47	47
Neutron/cycle	14 000	15 000
E(kV/cm)	8.3	11 (15)
T(s)	130	180
$\alpha$	0.45 (0.6)	0.75 (0.80)
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$
Sens (500 days)	$1.3*10^{-26}$	$5.0*10^{-27}$



Highly homogeneous magnetic field



Area South

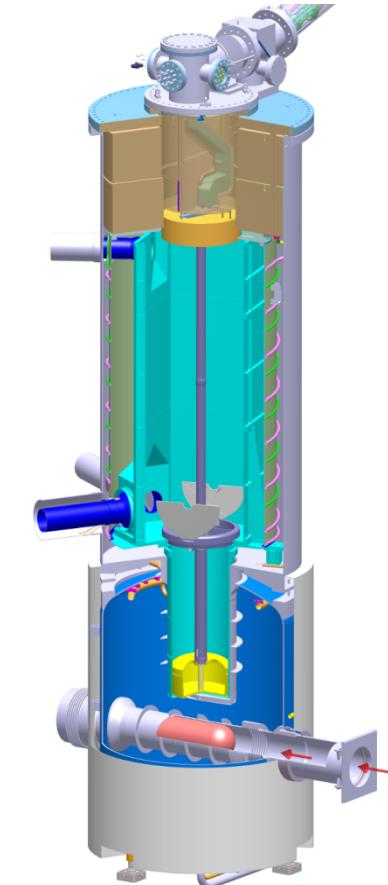
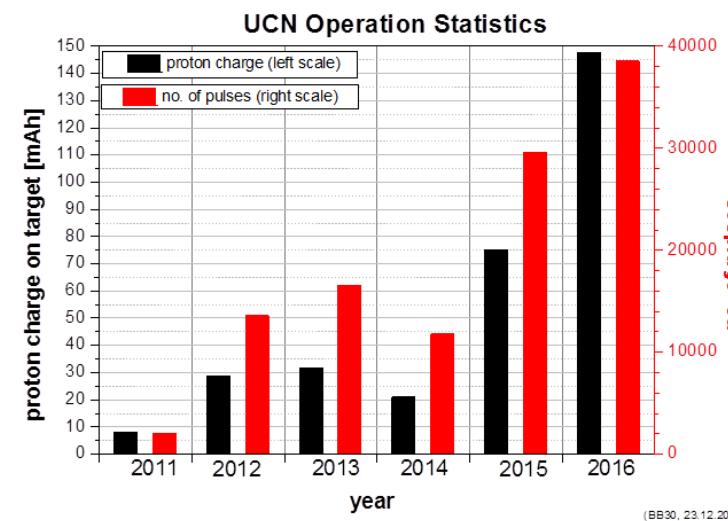


submitted to  
Phys. Rev. C

Many thanks go to the operating team: Alexander Anghel, Bertrand Blau, Pascal Erisman and the BSQ Group

## UCNs per benchmark pulses

Year	Month	UCN counts
2010	Dec.	30 000
2011	Nov.	2 020 000
2012	Sep.	2 400 000
2013	June	3 450 000
2014	Nov.	2 400 000
2015	Dec.	3 030 000
<b>2016</b>	<b>Sept.</b>	<b>4 800 000</b>



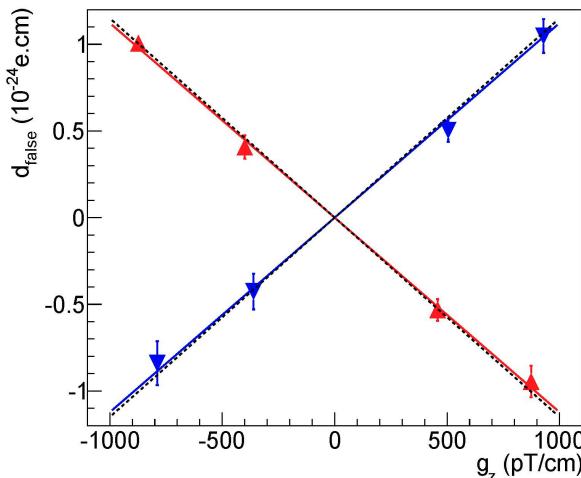
# The nEDM apparatus

Geometrical phase shift

Motional (transverse) field

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

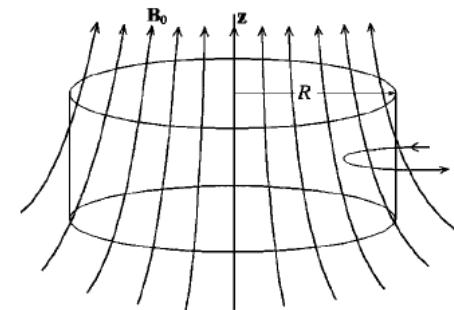
→ Frequency shift correlated with electric field  
False EDM for Mercury (fast regime of GPE)



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

## Hg comagnetometer

Magnetic transverse field



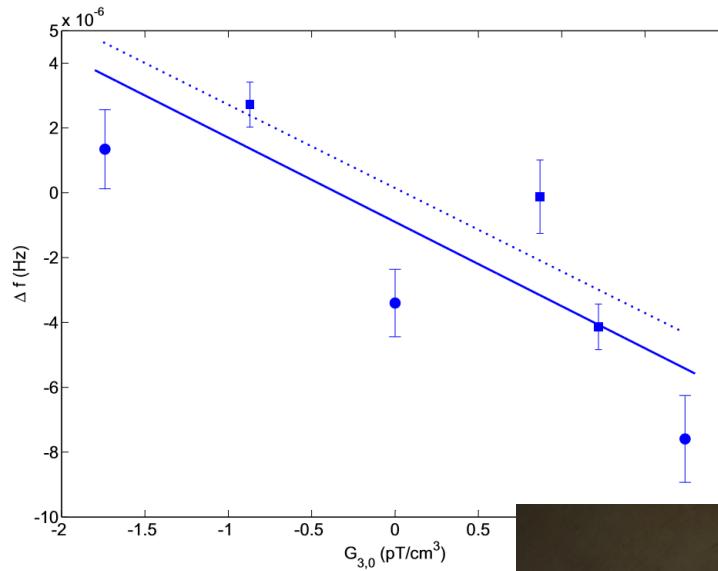
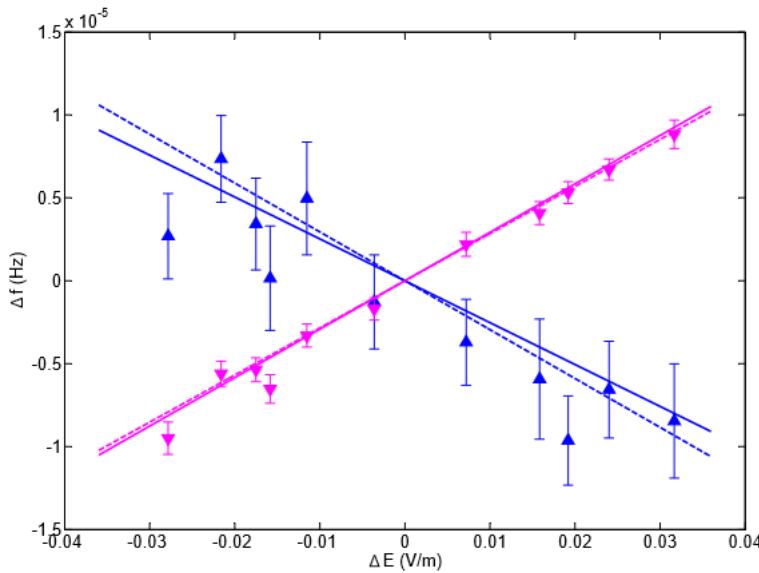
$$d_{\text{Hg}}^{\text{False}} = \frac{\hbar \gamma_{\text{Hg}}^2}{32c^2} D^2 \frac{\partial B}{\partial z}$$

$$\rightarrow d_n^{\text{False}} = \frac{\gamma_n}{\gamma_{\text{Hg}}} d_{\text{Hg}}^{\text{False}}$$

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

# The nEDM apparatus

## Measuring the enlarged systematic effect



Test our ability to predict the systematic effect from field map  
 Test the linearity of the effect

Last field map campaign is on-going

### 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)

