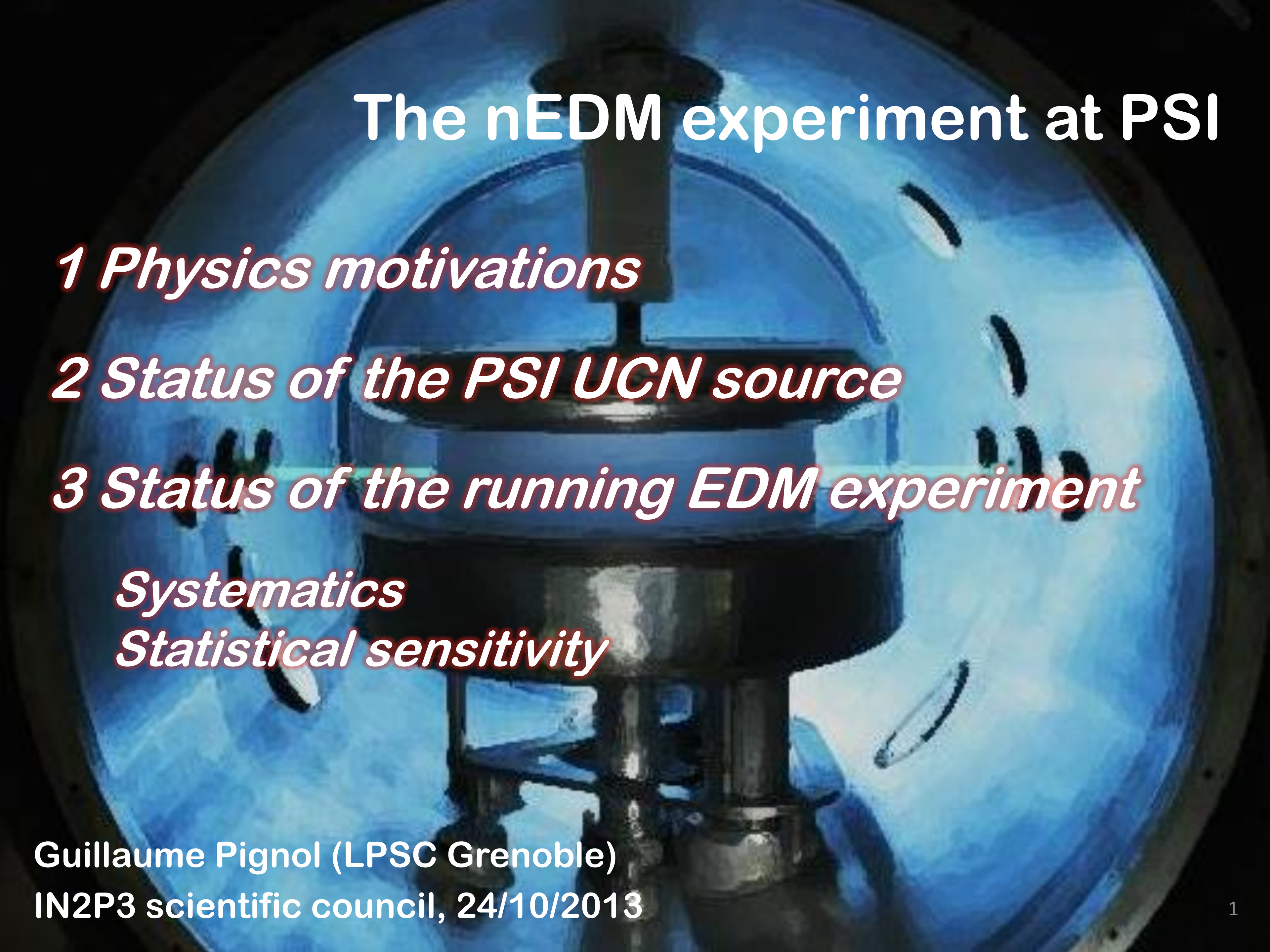


The nEDM experiment at PSI

1 Physics motivations

2 Status of the PSI UCN source

3 Status of the running EDM experiment

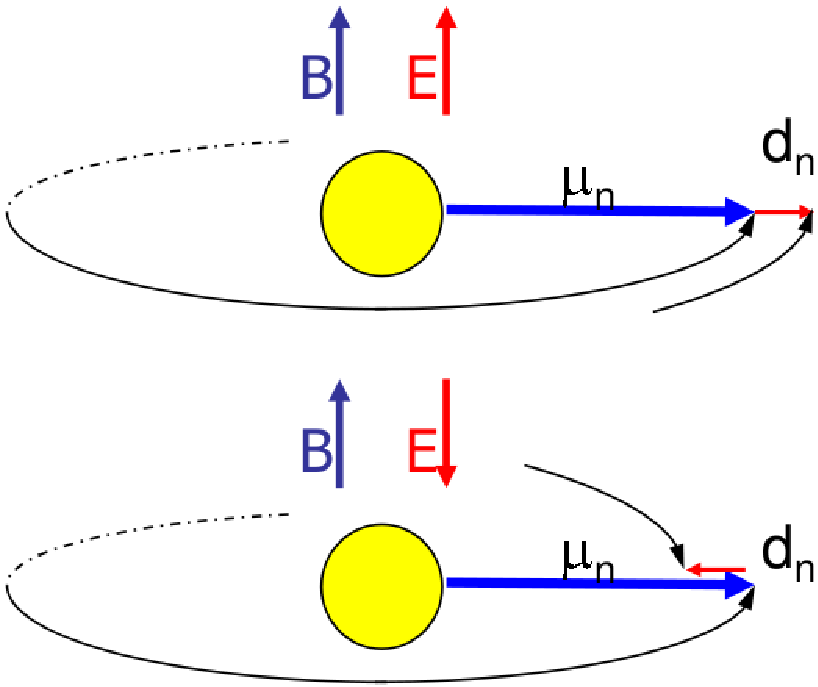
Systematics
Statistical sensitivity

Guillaume Pignol (LPSC Grenoble)

IN2P3 scientific council, 24/10/2013

The nEDM

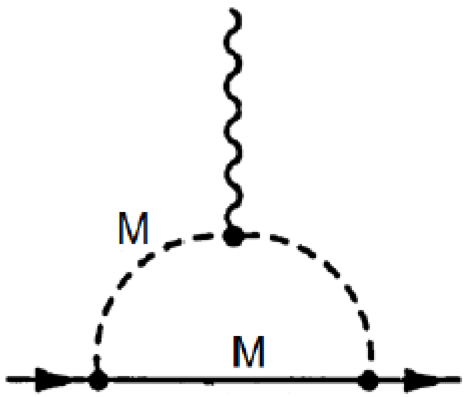
$$H = -\vec{\mu_n} \cdot \vec{B} - \vec{d_n} \cdot \vec{E} = h\nu_L/2$$



$$\nu_L(\uparrow\uparrow) - \nu_L(\uparrow\downarrow) = -\frac{4d_n}{h}E$$

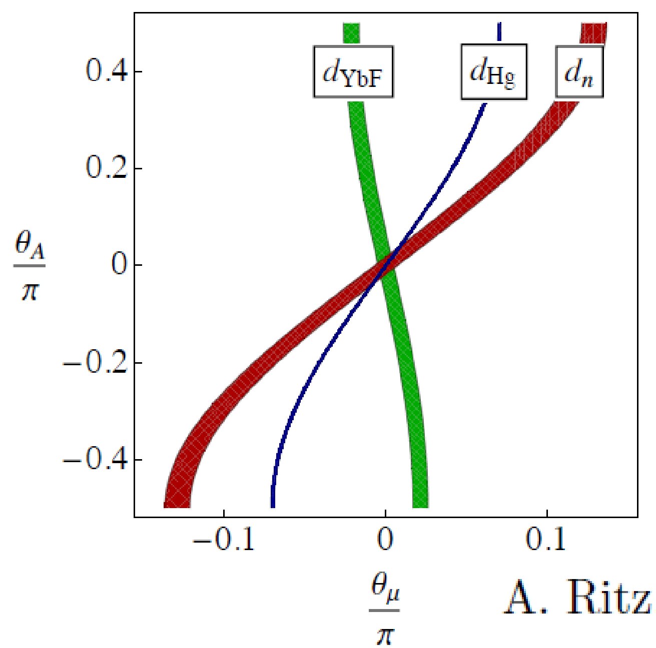
If nonzero, EDM violates T, thus CP

nEDM to probe generic BSM CP violation



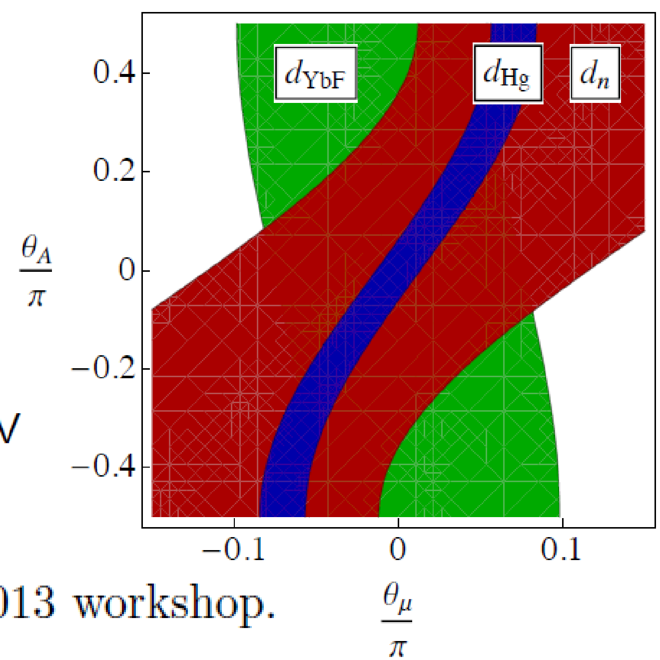
$$d_n \approx \left(\frac{1\,\mathrm{TeV}}{M}\right)^2 \times \sin(\phi) \times 10^{-25}\, e\,\mathrm{cm}$$

M_{susy} = 500 GeV



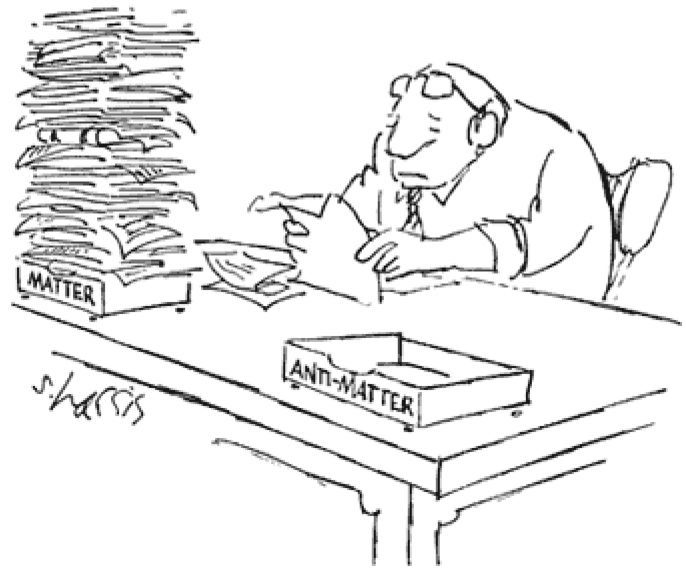
1st gen squarks excluded by direct searches at ~1 TeV

M_{susy} = 2 TeV



A. Ritz, talk at the PSI2013 workshop.

nEDM to probe electroweak baryogenesis



Sakharov conditions
at electroweak phase transition

1 Departure from thermal equilibrium
requires BSM scalar sector
to get a strong first order transition.
May or may not be accessible at the LHC

2 CP violation
requires BSM physics,
accessible by the next generation of EDM experiments

3 Violation of B conservation
SM sphaleron transitions in the symmetric phase

Minimal electroweak baryogenesis

S. J. Huber, M. Pospelov and A. Ritz, Phys. Rev. D **75**, 036006 (2007)

$$\mathcal{L}_{\rm dim-6} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda^2}(H^\dagger H)t^c H Q_3,$$

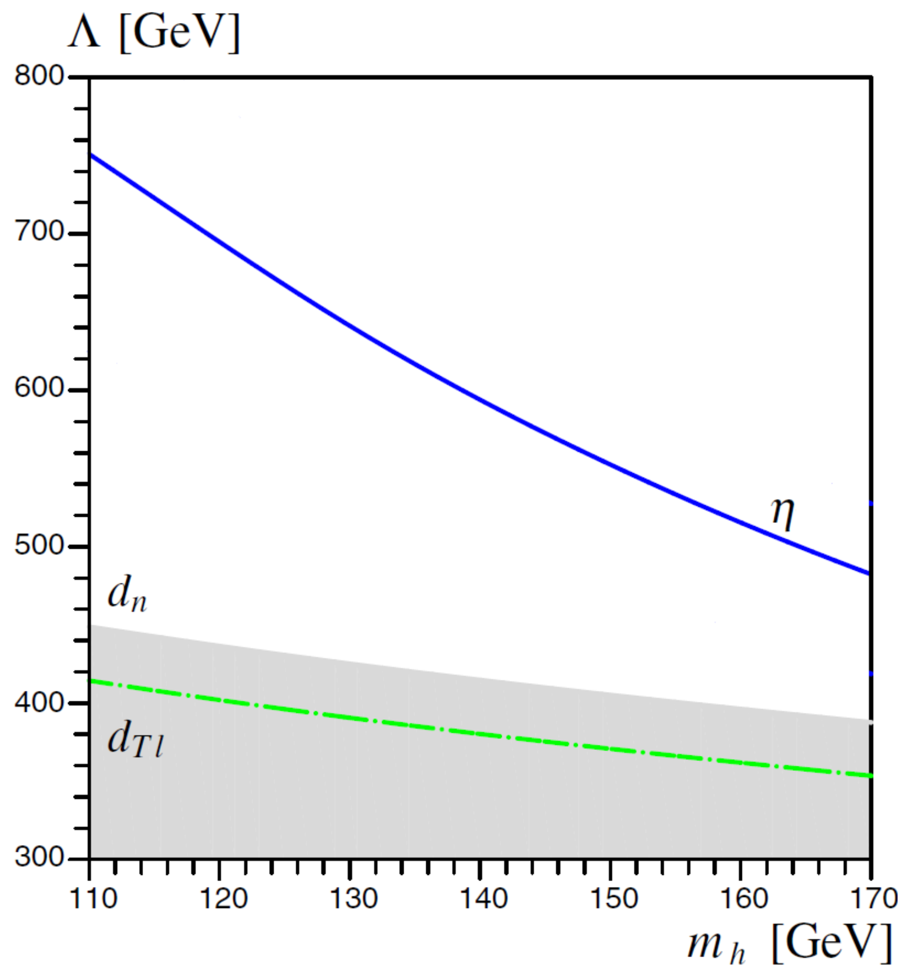
Makes the phase transition strongly first order

CP violation

Prediction for 126 GeV Higgs

nEDM = 1.3 x 10^{-26} e cm

(Current limit at 3 x 10^{-26} e cm)



The quest for EDMs

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

~200

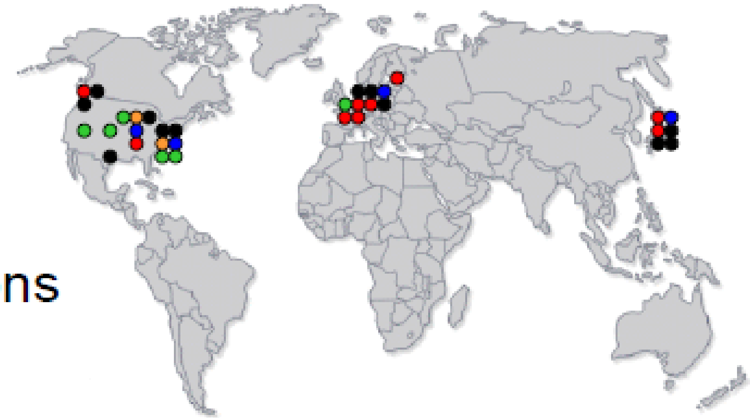
- Neutrons
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

~50

- Molecules
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

~100

- Atoms
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



~200

- Ions-Muons
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

~10

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale

The PSI EDM collaboration

M. Burghoff, S. Knappe-Grüneberg, A. Schnabel, J. Vogt	*Physikalisch Technische Bundesanstalt, **Berlin***
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W. Heil	*Inst. für Kernchemie, Johannes-Gutenberg-Universität, **Mainz***
S. Roccia,	*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Paris*
G. Bison , Z. Chowdhuri, M. Fertl, B. Lauss, S. komposch D. Ries, P. Schmidt-Wellenburg, G. Zsigmond	*Paul Scherrer Institut, **Villigen***
B. Franke, K. Kirch, J. Krempel, F. Piegsa, D. Zhu	*Eidgenössische Technische Hochschule,* **Zürich**

RED: PhD students, GREEN: spokespersons

The nEDM experiment at PSI

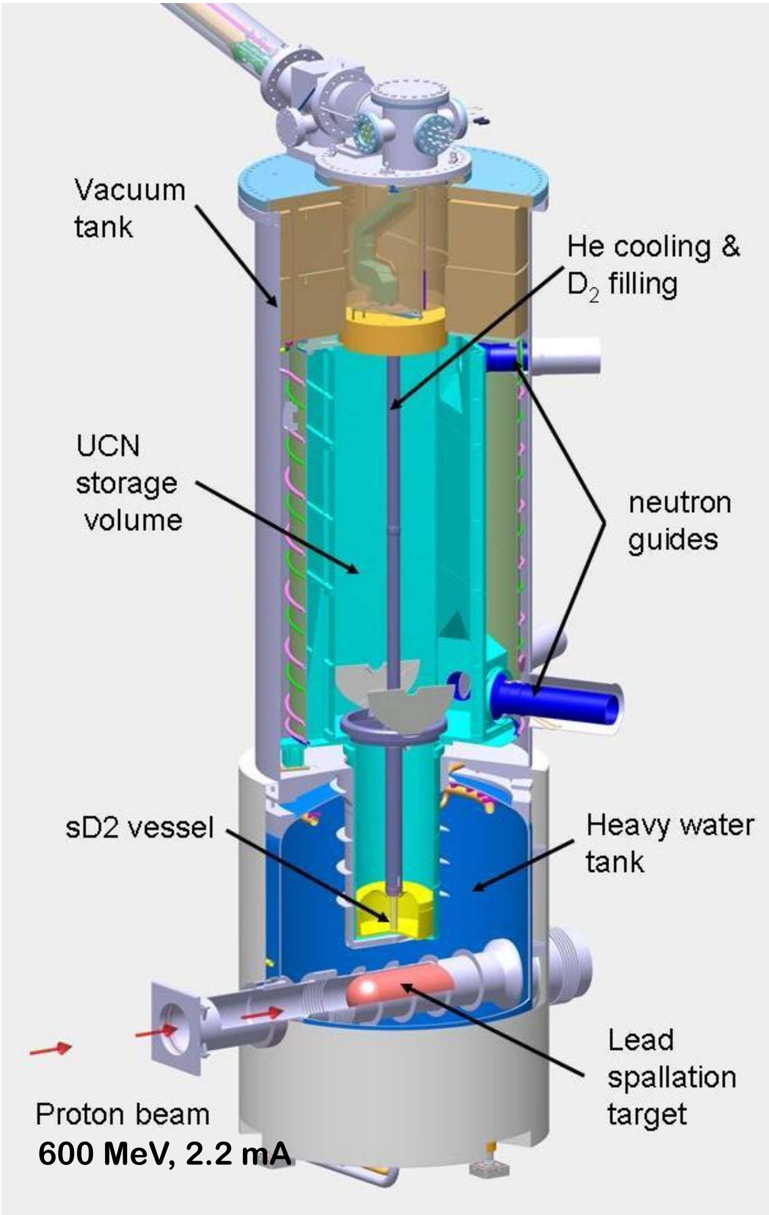
1 Physics motivations

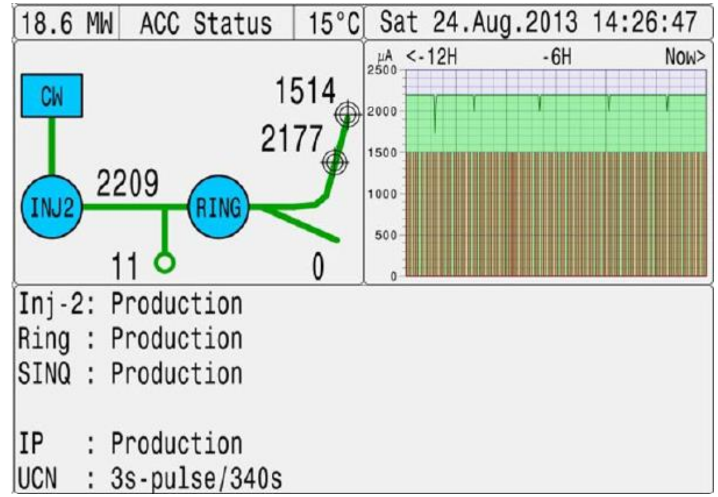
2 Status of the PSI UCN source

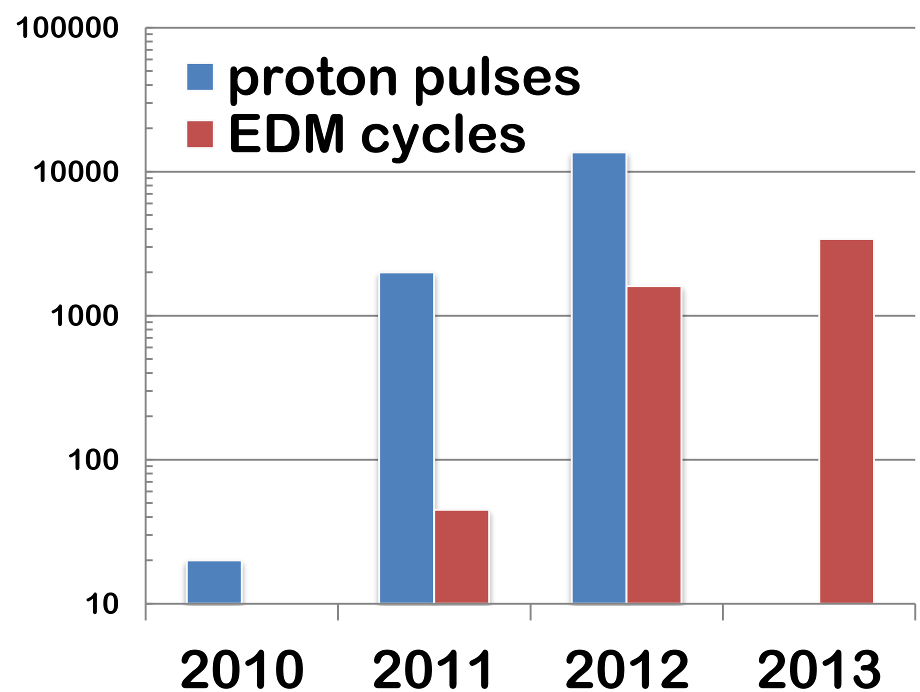
3 Status of the running EDM experiment

- Systematics
- Statistical sensitivity

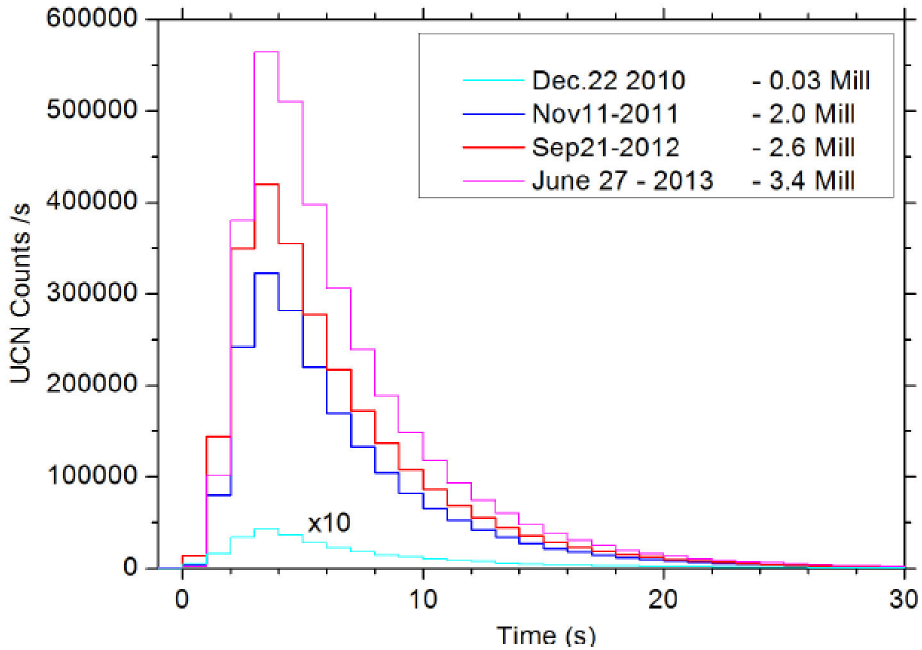
The PSI UCN source, availability

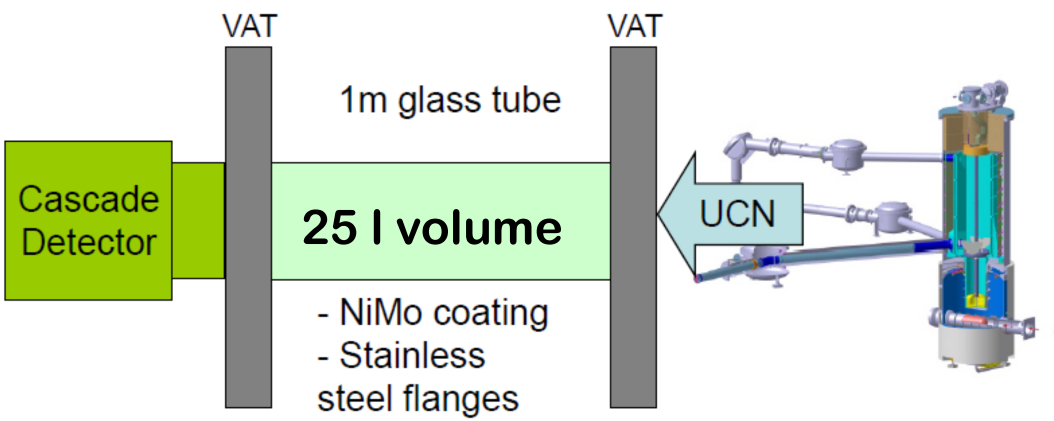






The PSI UCN source, intensity





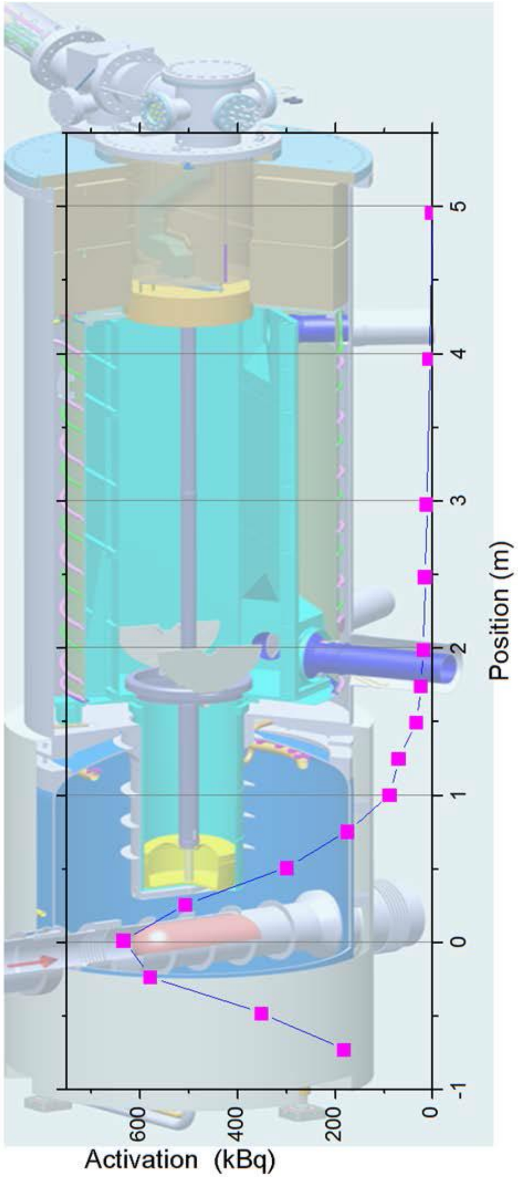
UCN density measured at West1

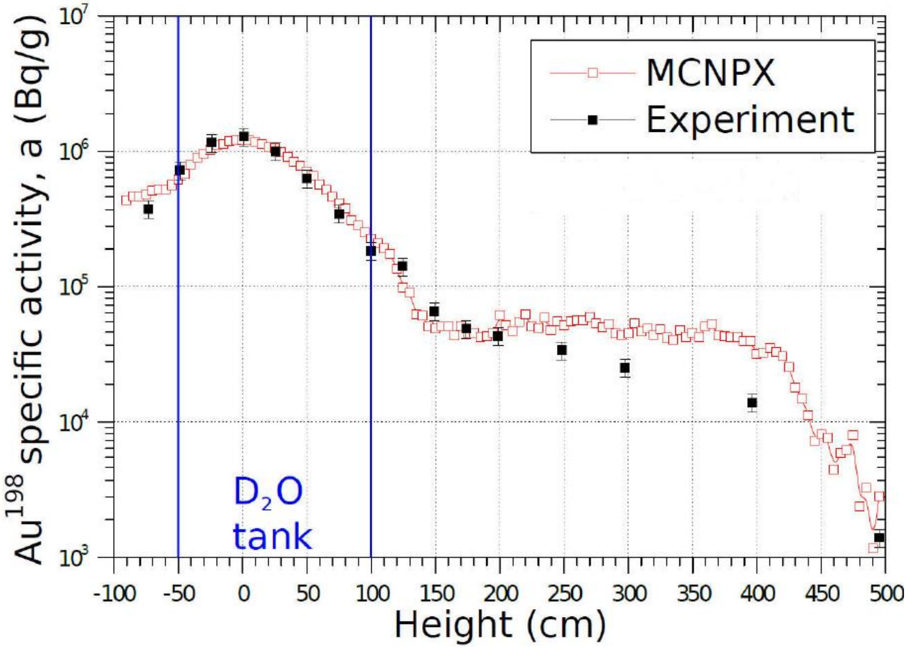
23 UCN/cm³

Same vessel used at ILL PF2

4.7 UCN/cm³

The PSI UCN source, recent progress





Recently measured thermal neutron flux agrees with calculations.

Improvement by factor of ~15 in UCN output can still be gained, a goal actively pursued by the PSI group.

The nEDM experiment at PSI

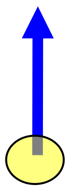
1 Physics motivations

2 Status of the PSI UCN source

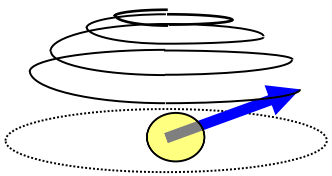
3 Status of the running EDM experiment

- *Systematics*
- *Statistical sensitivity*

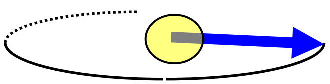
The Ramsey method



"Spin up" neutron...

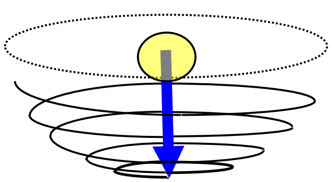


Apply $\pi/2$ spin-flip pulse...

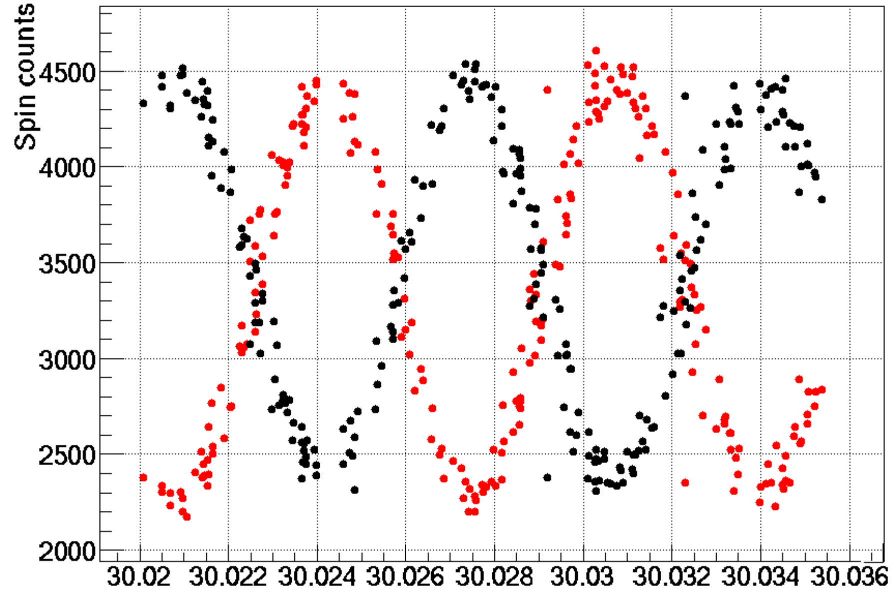


Free precession...

T ~ 200 s



Second $\pi/2$ spin-flip pulse



Applied pulse frequency [Hz]

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

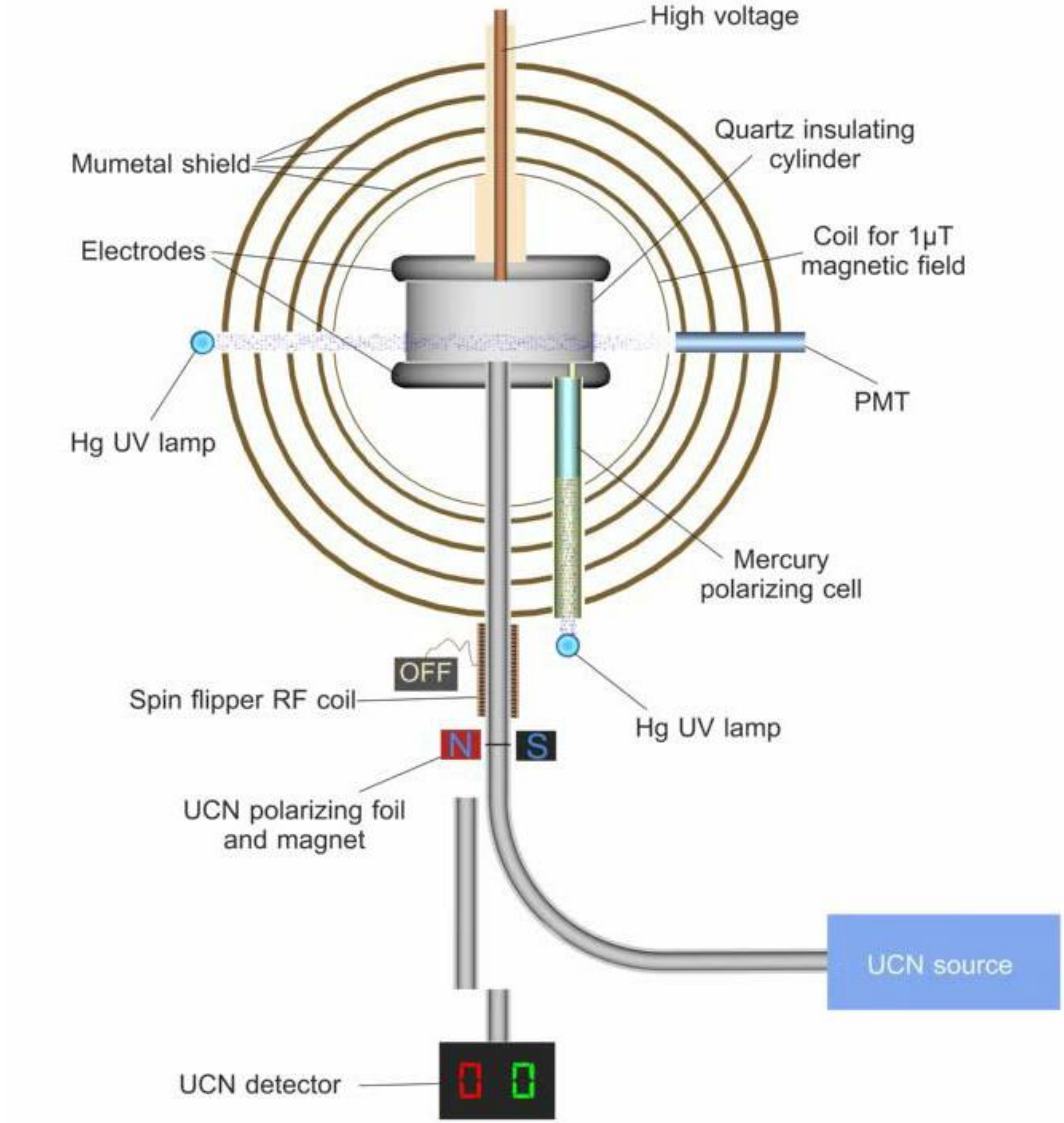
polarization (α)

electric field (E)

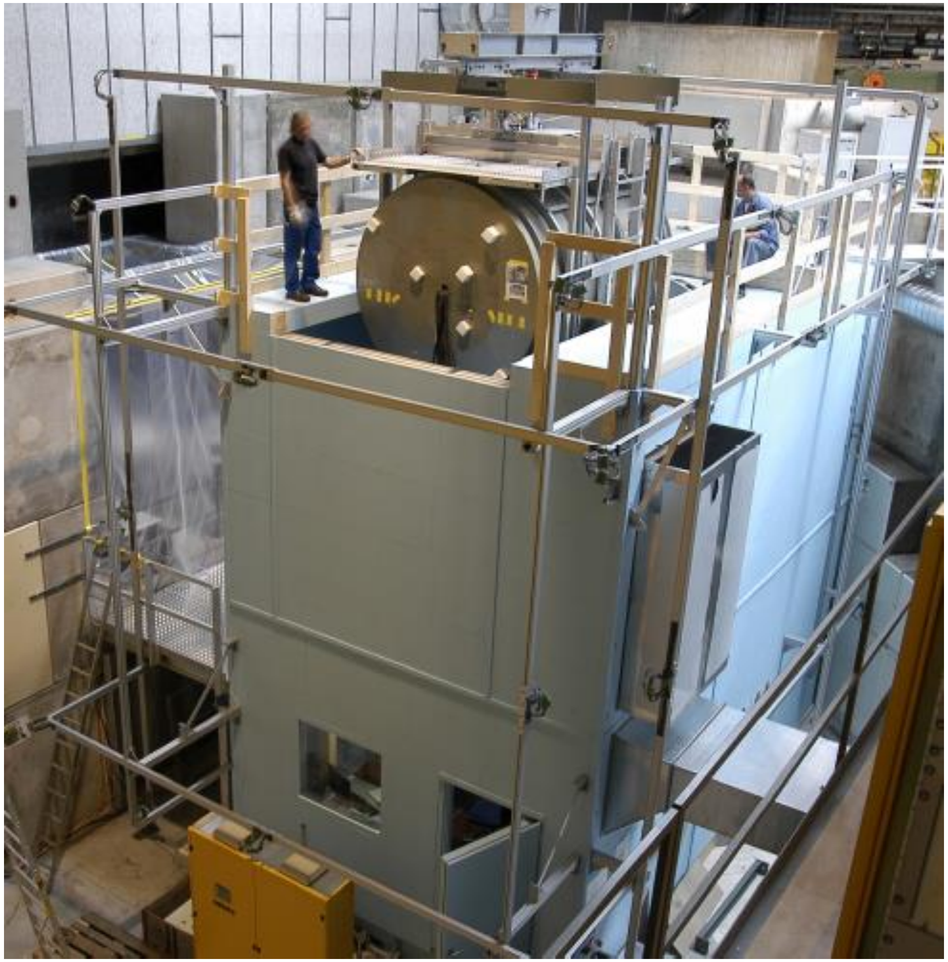
precession time (T)

counts (N)

OILL spectrometer



Current nEDM apparatus at PSI



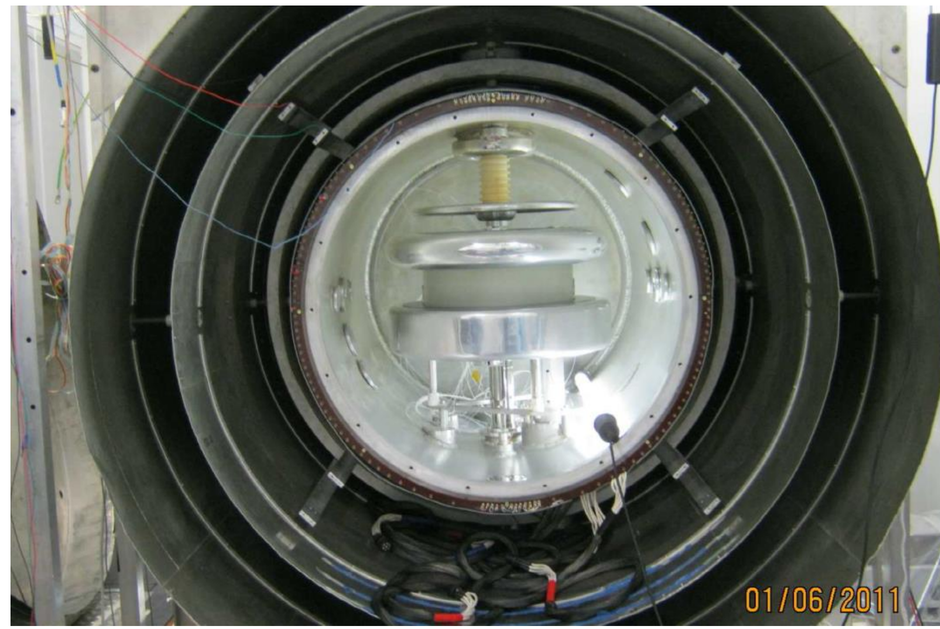
OILL apparatus moved from ILL to PSI in 2009

Shielded magnetic environment

$B_0 = 1\ \mu T$

Homogeneity < 10^{-3}

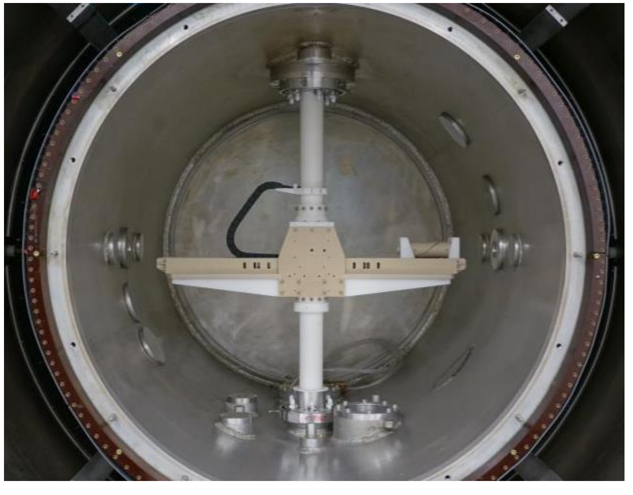
Time stability < 10^{-6}



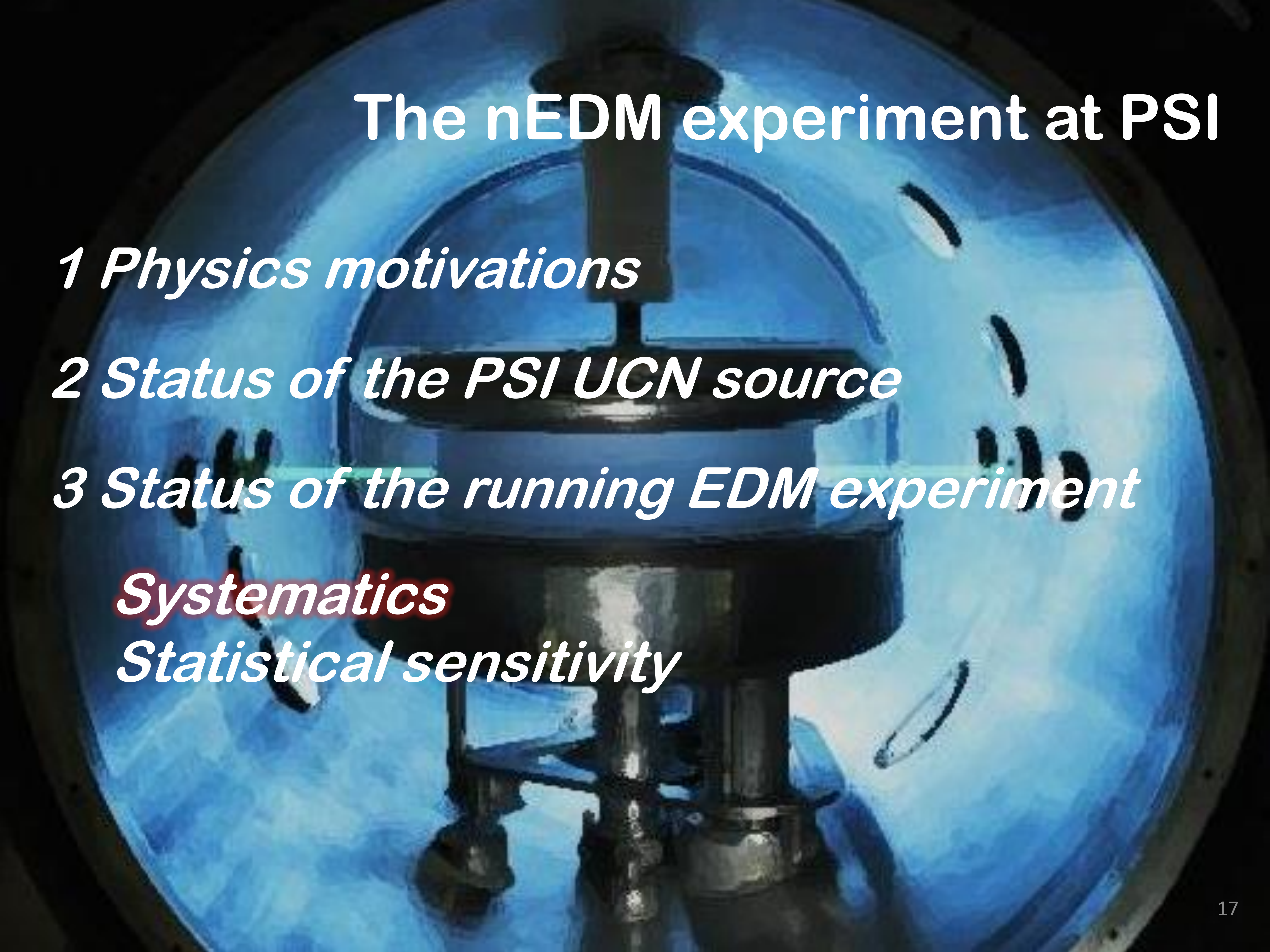
Electric field 150 kV / 12 cm

IN2P3 contribution

- UCN detectors (Nanosc) and electronics (FASTER)
- Spin analysis system (USSA)
- Magnetic field mapper



- Central DAQ module hardware+software
- B_0 stable current source
- Hg comagnetometer: optics
- Parts of precession chamber electrode, shutter



The nEDM experiment at PSI

1 Physics motivations

2 Status of the PSI UCN source

3 Status of the running EDM experiment

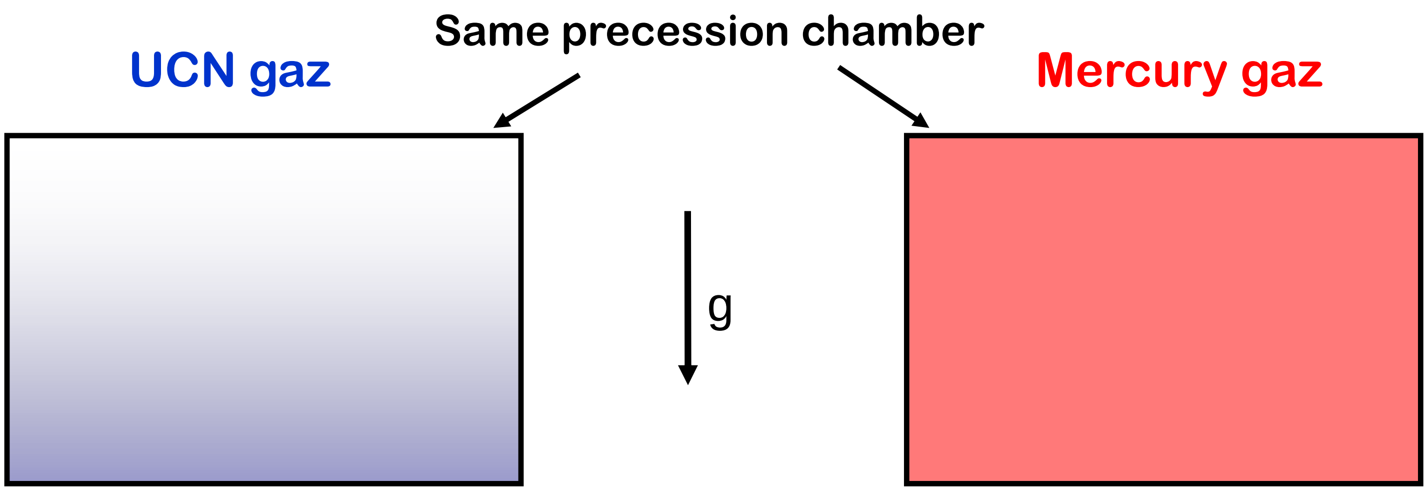
- Systematics
- Statistical sensitivity

Systematic effects

Effects	Status	RAL/Sussex/ILL (2006)
Direct Effects		
Uncompensated B-Drifts	0.5 ± 1.2	0 ± 2.4
Leakage Current	0.00 ± 0.05	0 ± 0.1
$V \times E$ UCN	0 ± 0.1	0 ± 1
Electric Forces	0 ± 0.4	0 ± 0.4
Hg EDM	0.02 ± 0.06	-0.4 ± 0.3
Hg Direct Light Shift	0 ± 0.008	0 ± 0.2
Indirect Effects		
Hg Light Shift	0 ± 0.05	3.5 ± 0.8
Quadrupole Difference	1.3 ± 2.4	-1.3 ± 2
Dipoles		-5.6 ± 6.3
At the surface	0 ± 0.4	
Other Dipoles	0 ± 3	
Total	1.8 ± 4.1	-3.8 ± 7.2

Table 2: Status of the constrain on systematic effects in units of $10^{-27} e \cdot \text{cm}$.

Example: gravitational effect

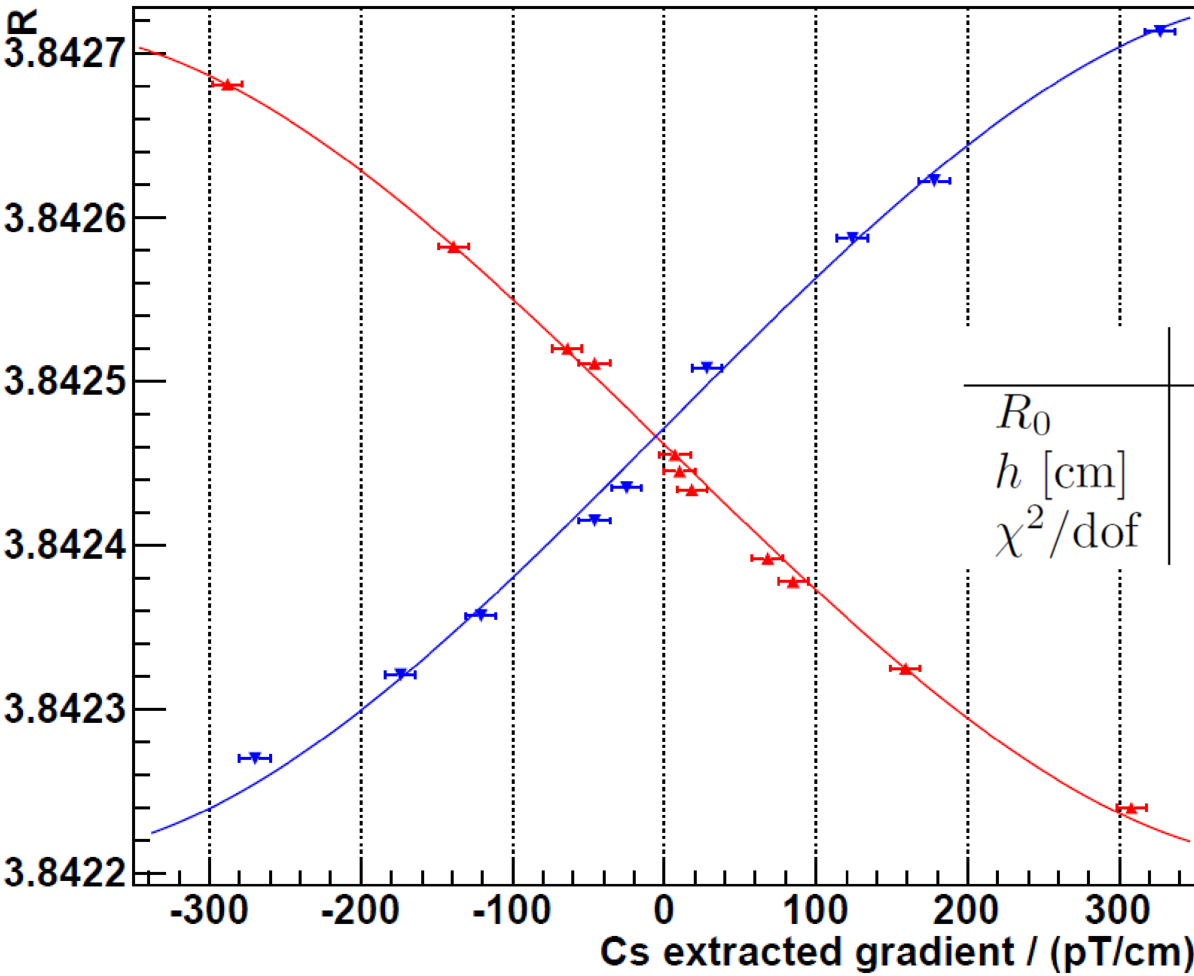


Center of gravity height difference is $h \approx 2\ \mathrm{mm}$

R = fn / fHg depends on vertical gradients

$$R = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} \left(1 - \frac{(\partial B / \partial z) h}{B} \right)$$

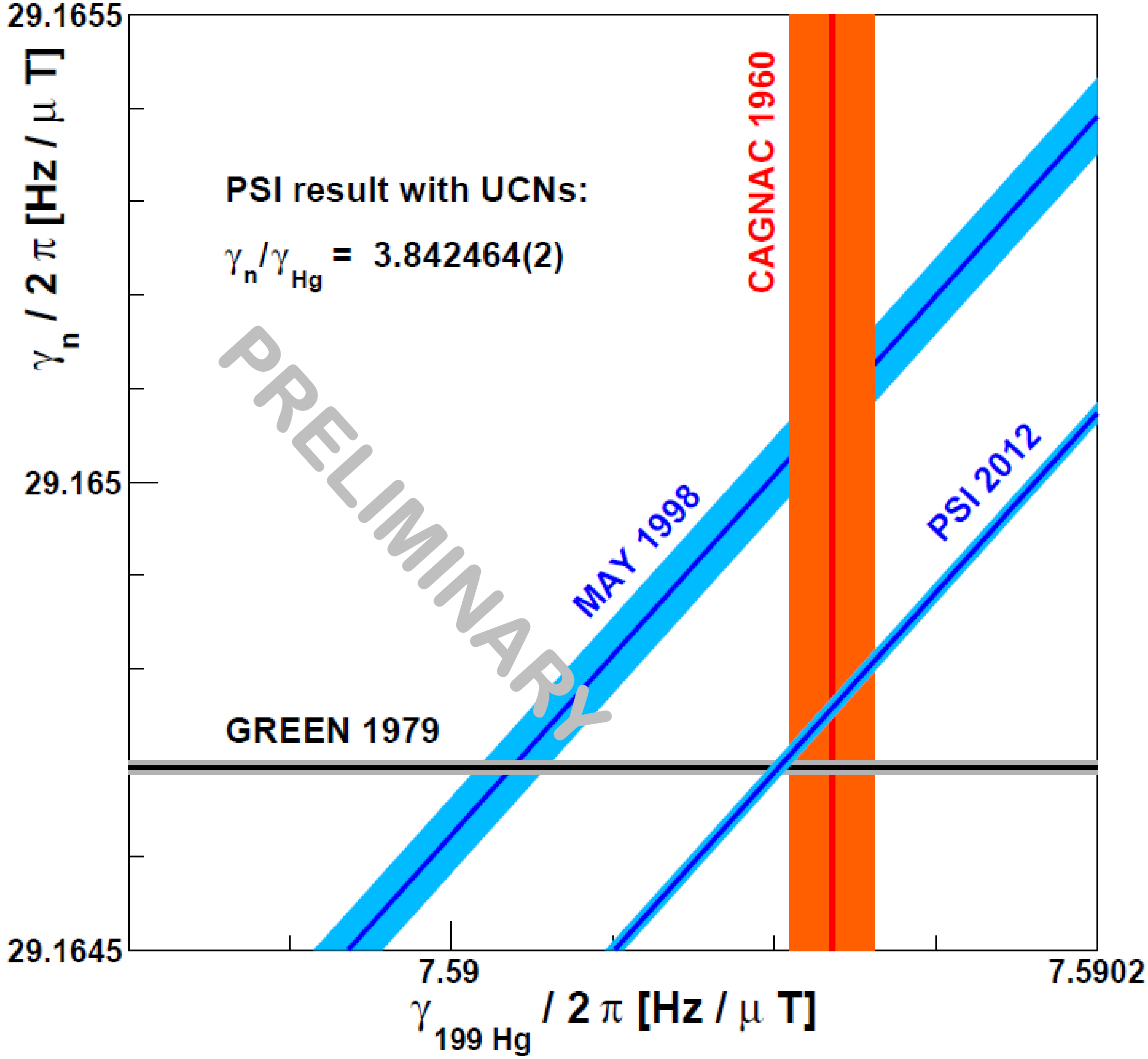
Gravitational effect



$$R = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\left(1 - \frac{(\partial B/\partial z)h}{B}\right)$$

	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

Interpretation: measurement of the neutron magnetic moment



Publications, R&D and byproducts

Experimental study of 199Hg spin anti-relaxation coatings
Z. Chowdhuri et al, **Applied Physics B (2013)** 1.

Development of a multifunction module for the neutron electric dipole moment experiment at PSI
O. Bourrion, G. Pignol, D. Rebreyend, C. Vescovi, **NIM A (2013)** 278.

Electric dipole moment searches: reexamination of frequency shifts for particles in traps
G. Pignol, S. Roccia, **Physical Review A 85 (2012)** 042105.

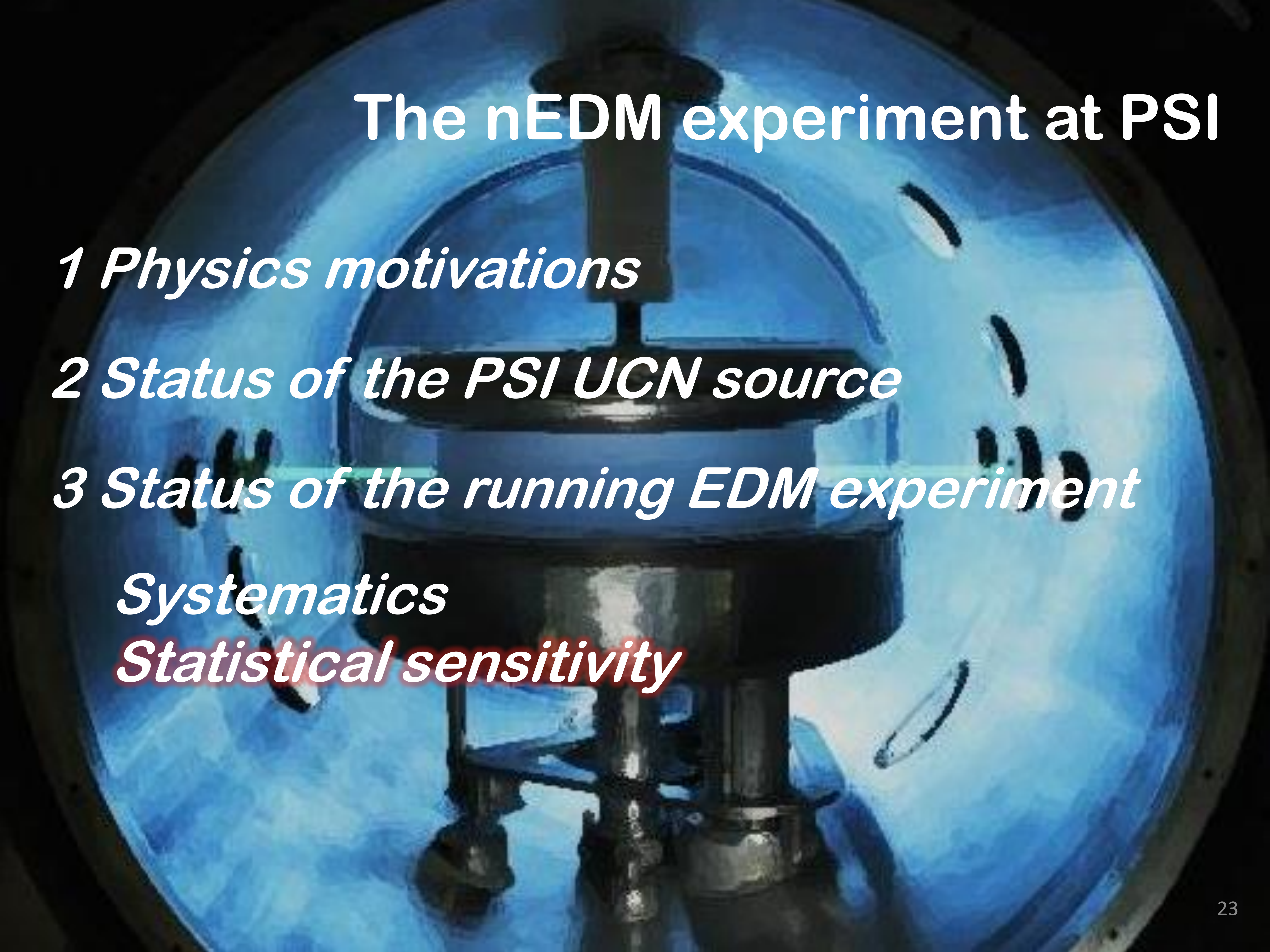
First observation of trapped high-field seeking ultracold neutron spin states
M. Daum et al, **Physics Letters B 704 (2011)** 456.

New constraints on Lorentz invariance violation from the neutron electric dipole moment
I. Altarev et al, **Europhysics Letters 92 (2010)** 51001.

Test of Lorentz invariance with spin precession of ultracold neutrons
I. Altarev et al, **Physical Review Letters 103 (2009)** 081602.

Neutron to mirror-neutron oscillations in the presence of mirror magnetic fields
I. Altarev et al, **Physical Review D 80 (2009)** 032003.

Direct Experimental Limit on Neutron–Mirror-Neutron Oscillations
G. Ban et al, **Physical Review Letters 99 (2007)** 161603.



The nEDM experiment at PSI

1 Physics motivations

2 Status of the PSI UCN source

3 Status of the running EDM experiment

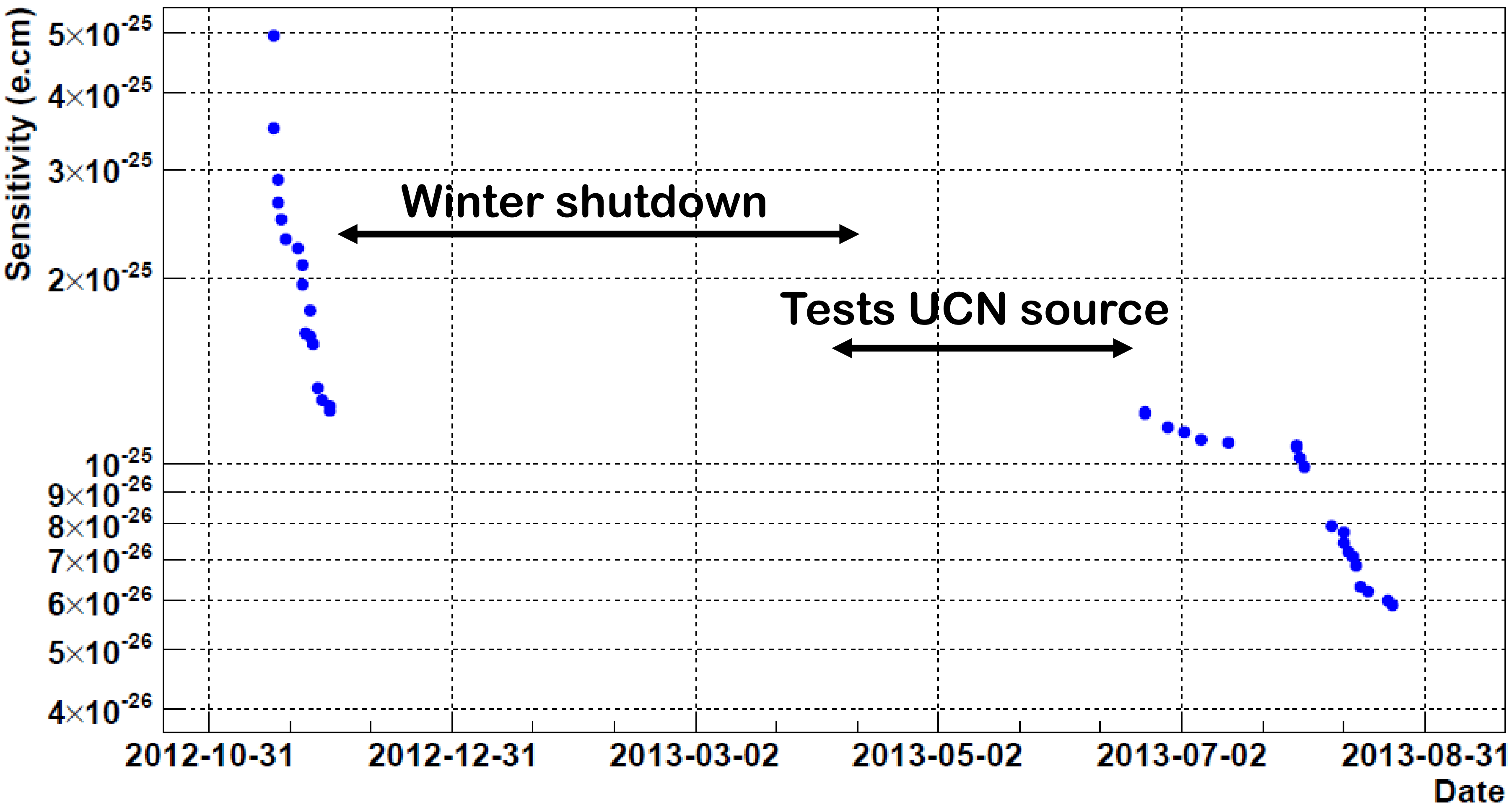
Systematics
Statistical sensitivity

Statistical sensitivity

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

	RAL-Sussex-ILL		PSI 2012		PSI 2013	
	Best	Mean	Best	Mean	Best	Mean
E (KV/cm)	8.8	8.3	8.3	7.9	12	10.3
Nb UCN	14 000	14 000	9 000	5 400	8 400	6 300
T precession (s)	130	130	200	200	180	180
α	0.6	0.45	0.65	0.57	0.62	0.56
Sensitivity per cycle ($\times 10^{-25}$ e.cm)	43	57	32	50	27	39
Nb cycle per day	360	360	150	150	200	200
Sensitivity per day ($\times 10^{-25}$ e.cm)	**2.3**	**3.0**	**2.6**	**4.0**	**1.9**	**2.8**

Statistical sensitivity



Conclusions

5000 EDM cycles recorded with OILL@PSI in 2012-2013

Statistical power at 6 x 10^{-26} e cm

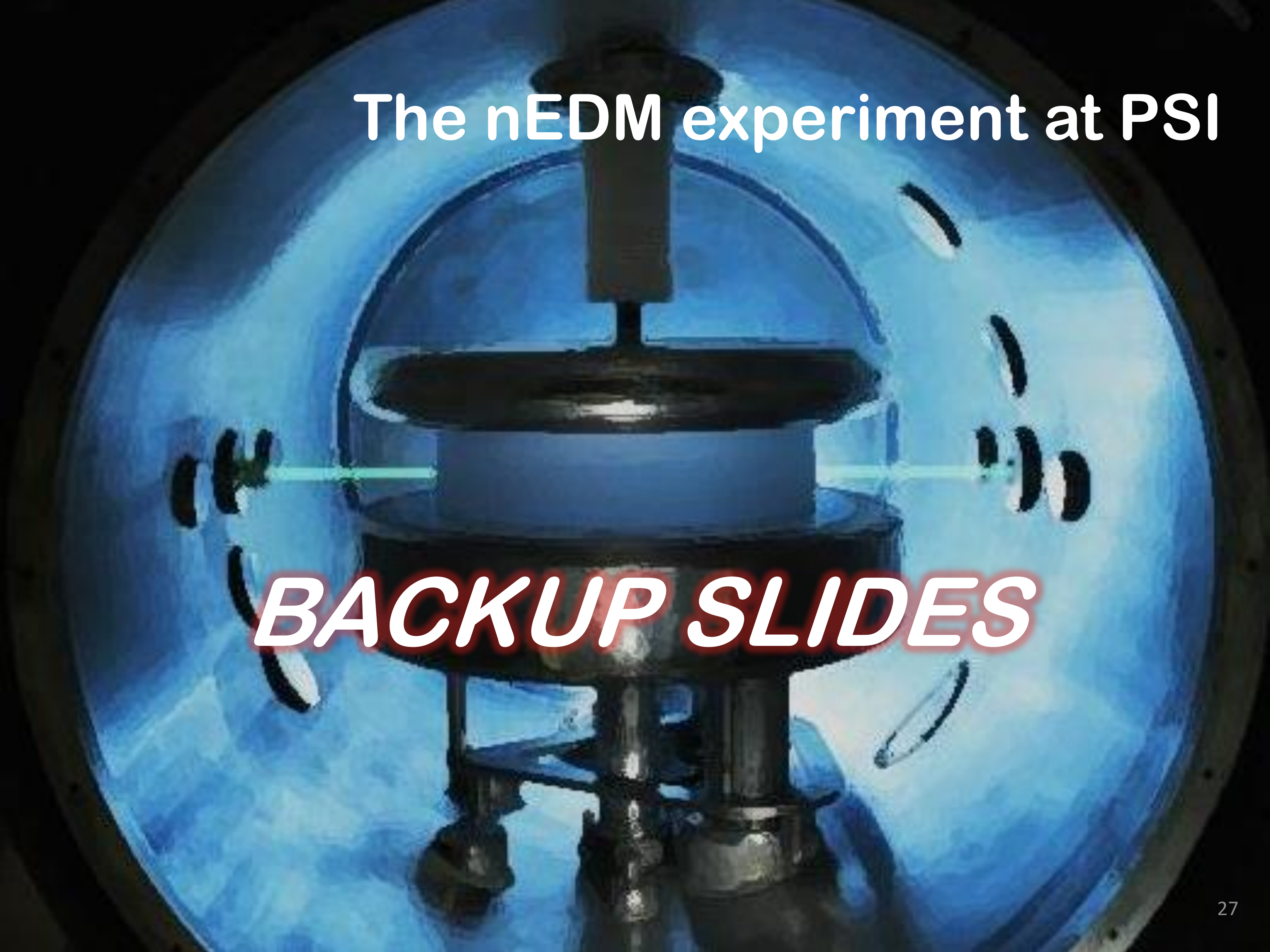
Systematics controlled at 0.4 x 10^{-26} e cm

-> a great laboratory to study n2EDM systematics

Improving the previous limit with OILL is possible provided

- **3 more years of data taking**
- **Increased availability of the source for EDM**
- **Improved statistics (better UCN source and/or UCN transport)**

The nEDM experiment at PSI



BACKUP SLIDES

Collaboration list

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K. Kirch[2,6], F. Piegsa, J. Krempel
ETHZ: *ETH Zürich, Switzerland*

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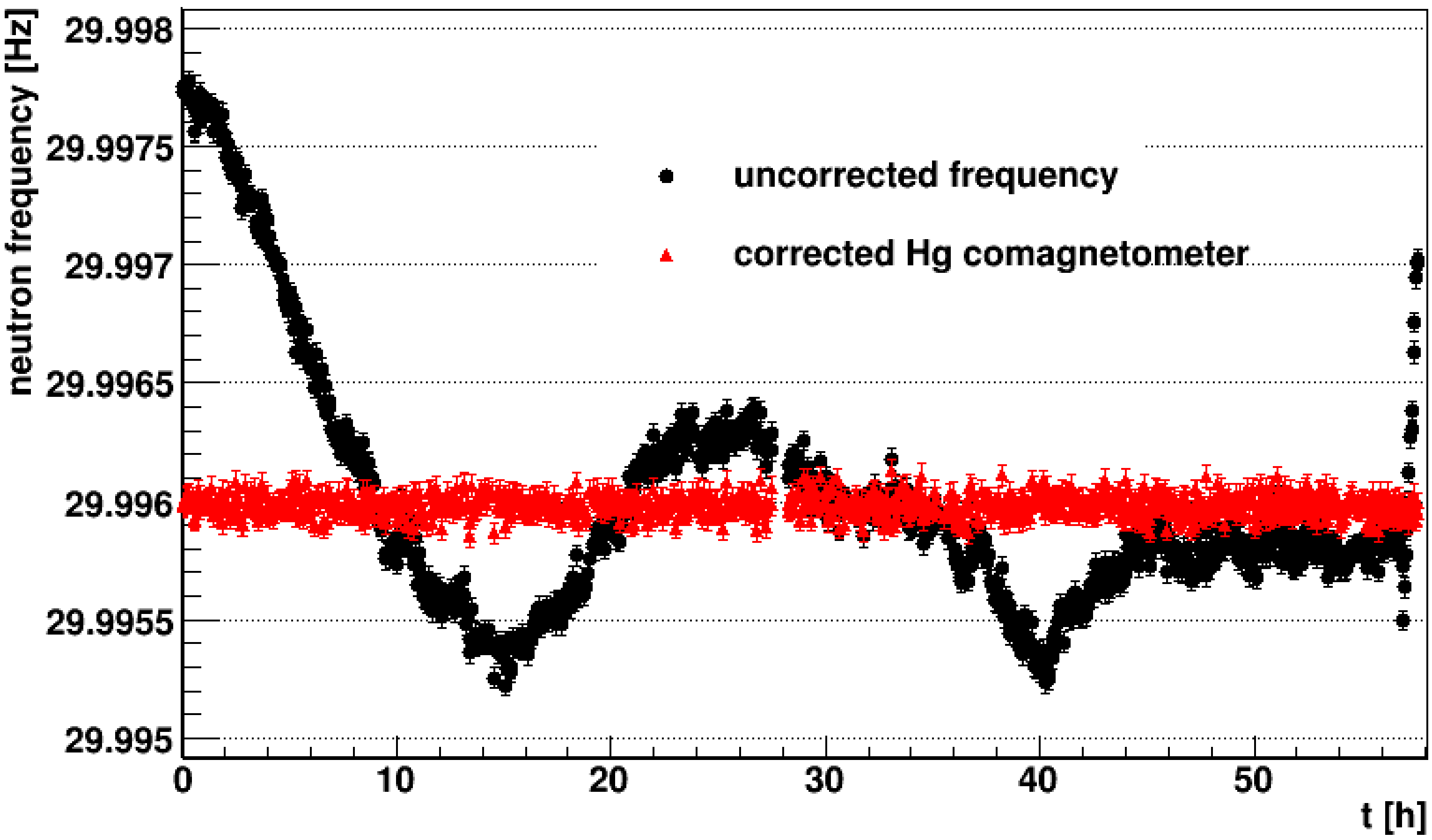
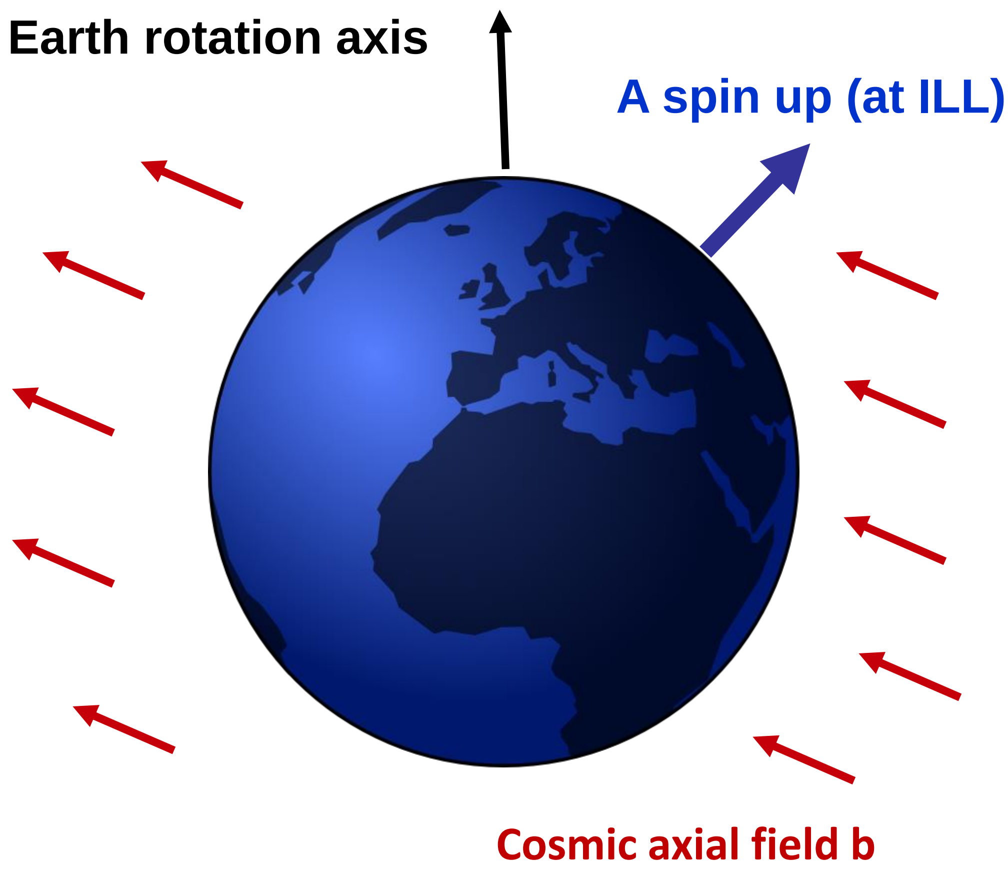
G. Ban	Professor	LPCC
V. Hélaine	PhD student	LPCC / PSI
T. Lefort	MdC	LPCC
Y. Lemière	MdC	LPCC
G. Quémńer	CR	LPCC
B. Clément	MdC	LPSC
G. Pignol	MdC	LPSC
Y. Kermaïdic	PhD student	LPSC
D. Rebreyend	DR	LPSC

Le magnétomètre mercure

Le Comagnétomètre corrige les fluctuations du champ magnétique



Test de l'invariance de Lorentz



Interaction potential

$$V = \frac{\hbar}{2}\gamma_n \, \sigma \cdot \mathbf{B} + \sigma \cdot \tilde{\mathbf{b}}$$

Neutron spin precession

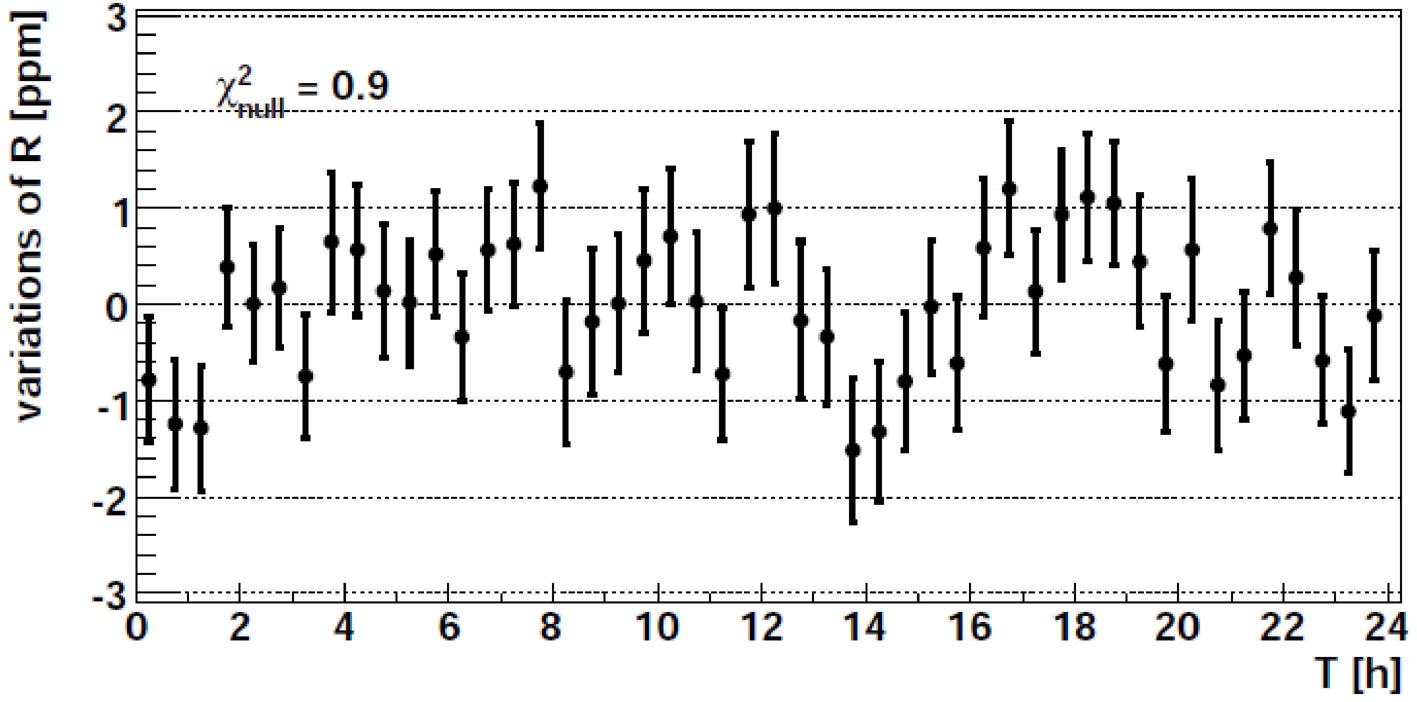
$$f_n = \frac{1}{2\pi}\left|\gamma_n \mathbf{B} + \frac{2}{\hbar}\tilde{\mathbf{b}}\right|$$

Daily modulation

$$f_n(t) = \frac{\gamma_n}{2\pi}B + \frac{1}{\pi\hbar}b_\perp \cos(\lambda)\sin(\frac{2\pi t}{24\mathrm{h}} + \phi)$$

Limite sur la modulation a 24h

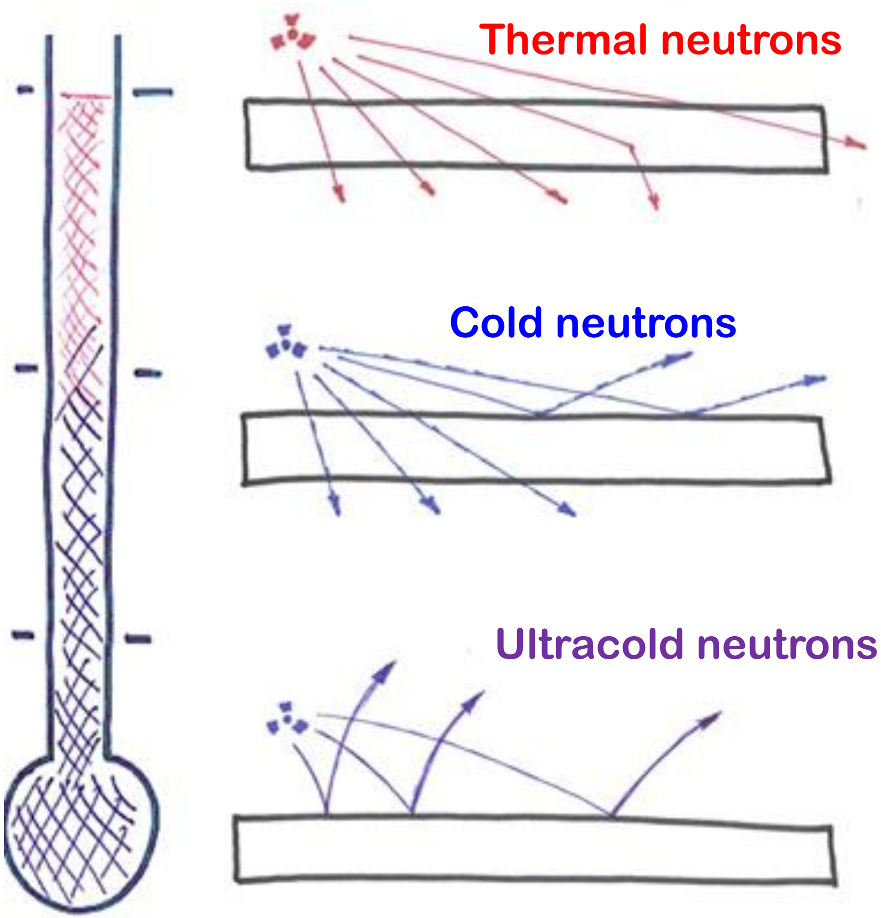
April 2008, 5 days of data.
December 2008, 6 days of data.



$$b_\perp < 1 \times 10^{-20}\,\mathrm{eV} \quad 95\%\,\mathrm{C.L.}$$

Altarev *et al*, Phys. Rev. Lett **103** (2009)

Ultracold neutrons (UCN)



Neutrons with energy < 100 neV,
or velocity < 5 m/s

are reflected by material walls

UCNs feel gravity

$$mg \times (1\,\mathrm{m}) = 100\ \mathrm{neV}$$

GRANIT to measure the bouncing quantum states

UCNs can be stored in bottles for very long times (1000 s)

precision measurement of the neutron electric dipole moment (nEDM)

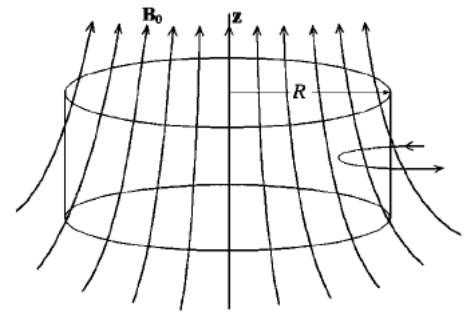
Geometric phase of mercury

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)

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

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

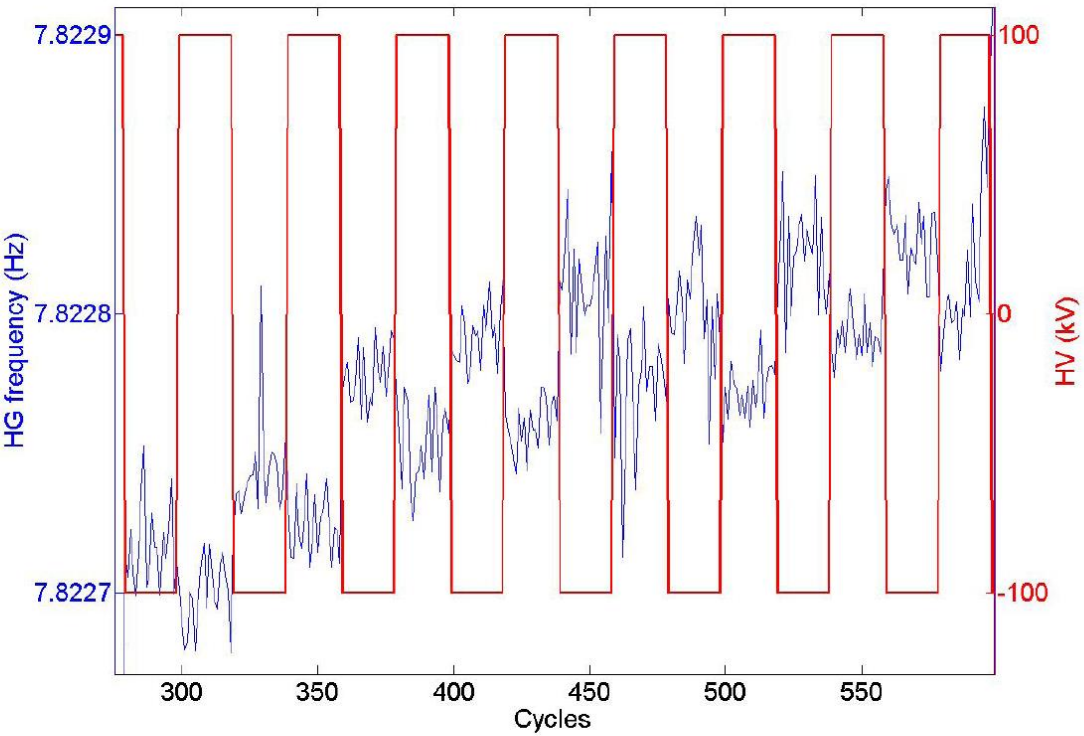
→ **False neutron EDM when using Hg comagnetometer**

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

Indirect **systematic effect**

Dedicated measurement with Hg magnetometer

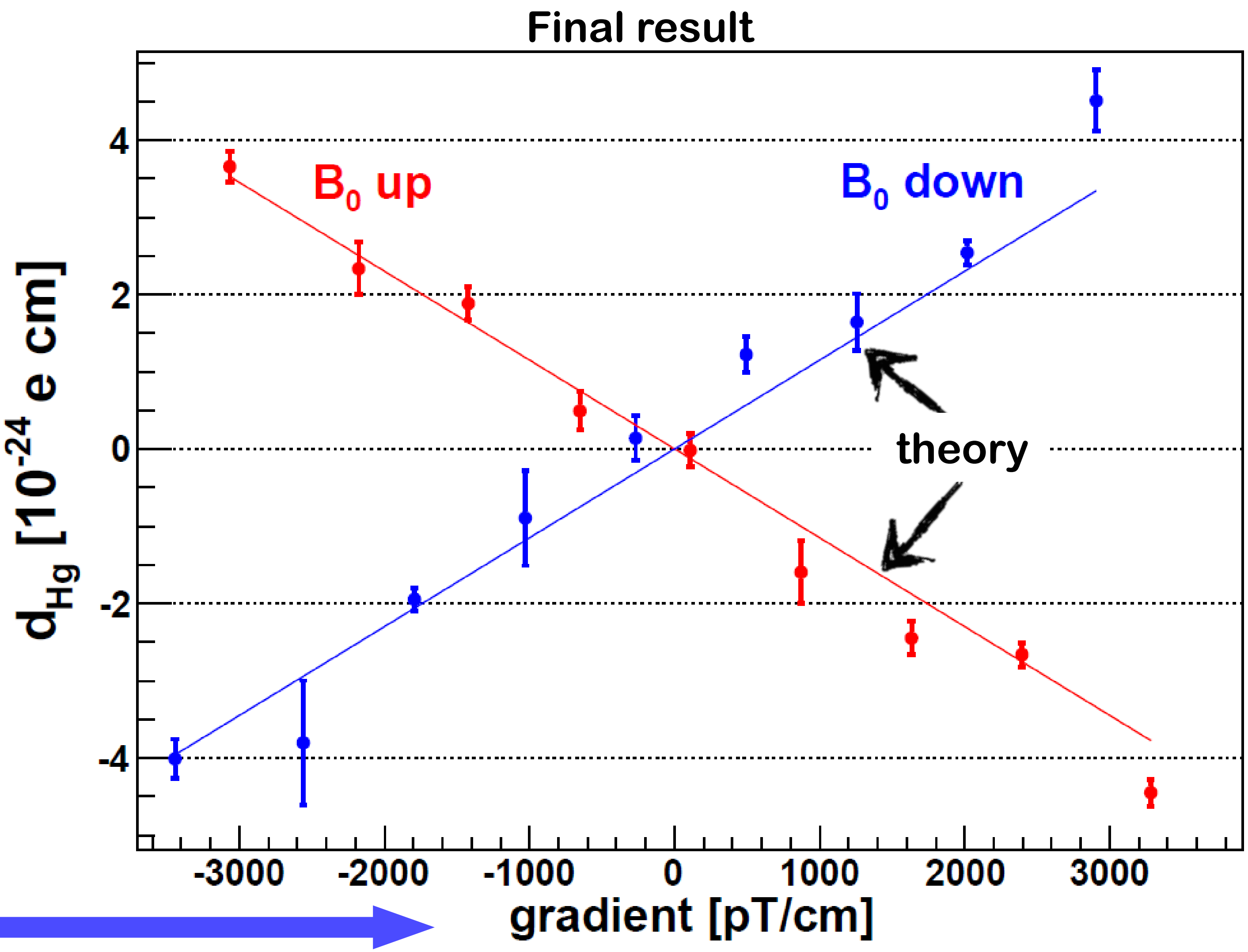
1) Apply a large magnetic gradient with trimcoils
2) Apply an electric field of 100 kV/12 cm, with polarity reversed every 20 cycles
3) Take data for 20 days with different gradient configurations



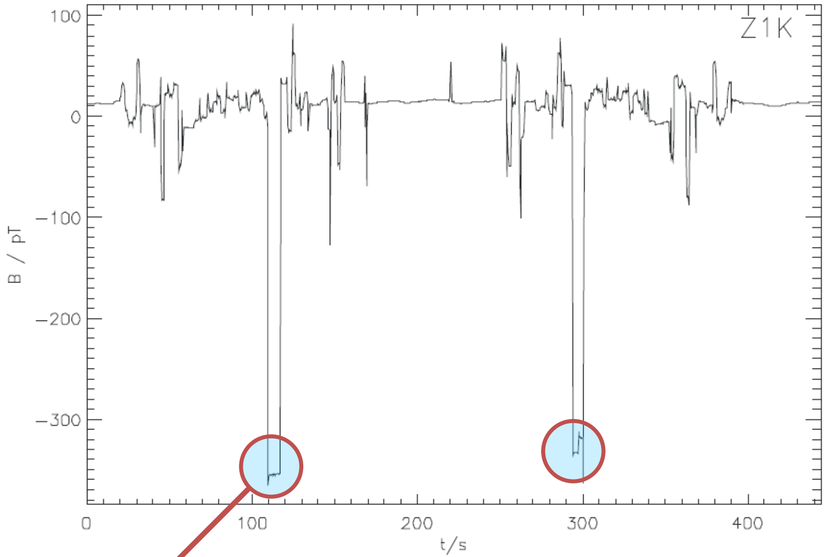
A clear correlation between Hg frequency and the electric field in the presence of a magnetic gradient.

Dedicated measurement with Hg magnetometer

Magnetic gradient extracted from fluxgates maps

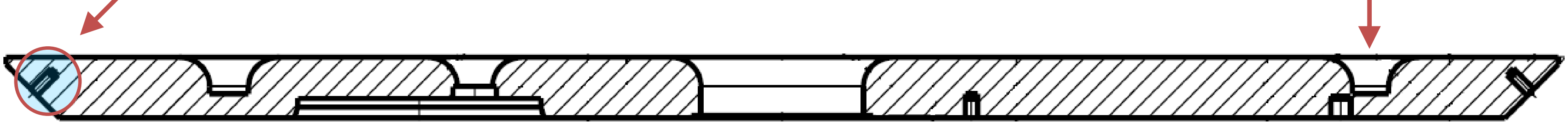


Impurities on the electrode



Scan of the Sussex bottom electrode
At PTB in Nov. 2011

Groove insulating ring



Approximate dipole position

$$x = 31 \text{ cm}, \;\; z = -0.6 \text{ cm}$$

Approximate dipole strength

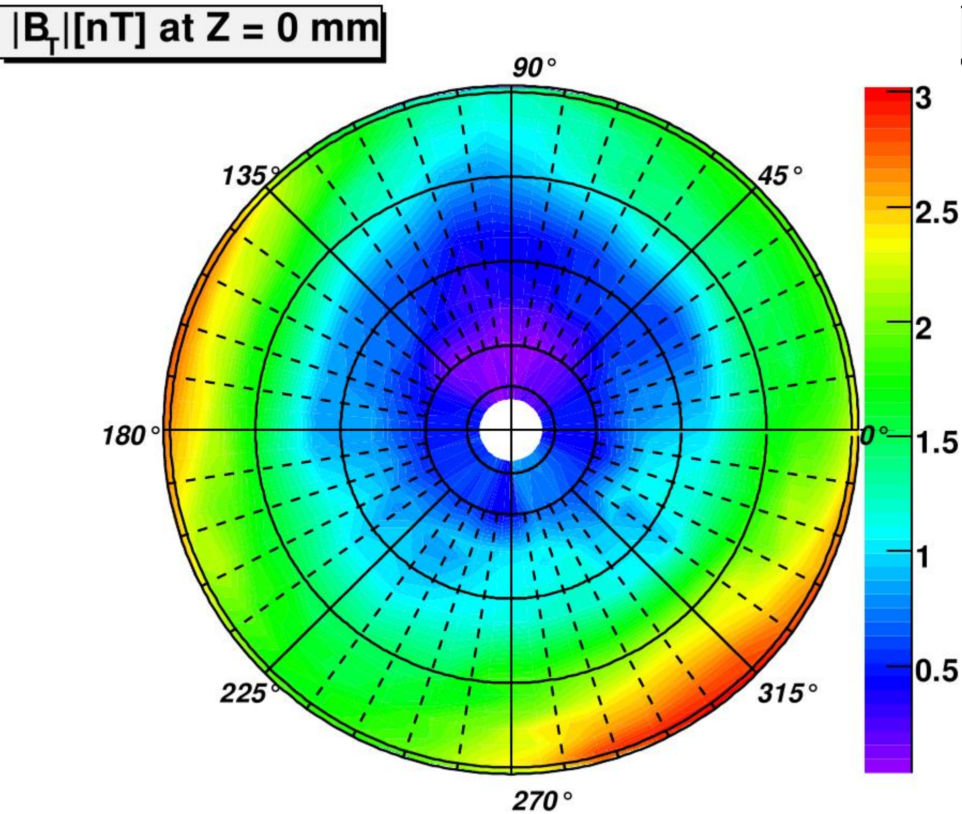
$$p = \frac{\mu_0}{4\pi} m = 26.5 \text{ nT cm}^3$$

We would then quote a systematic effect

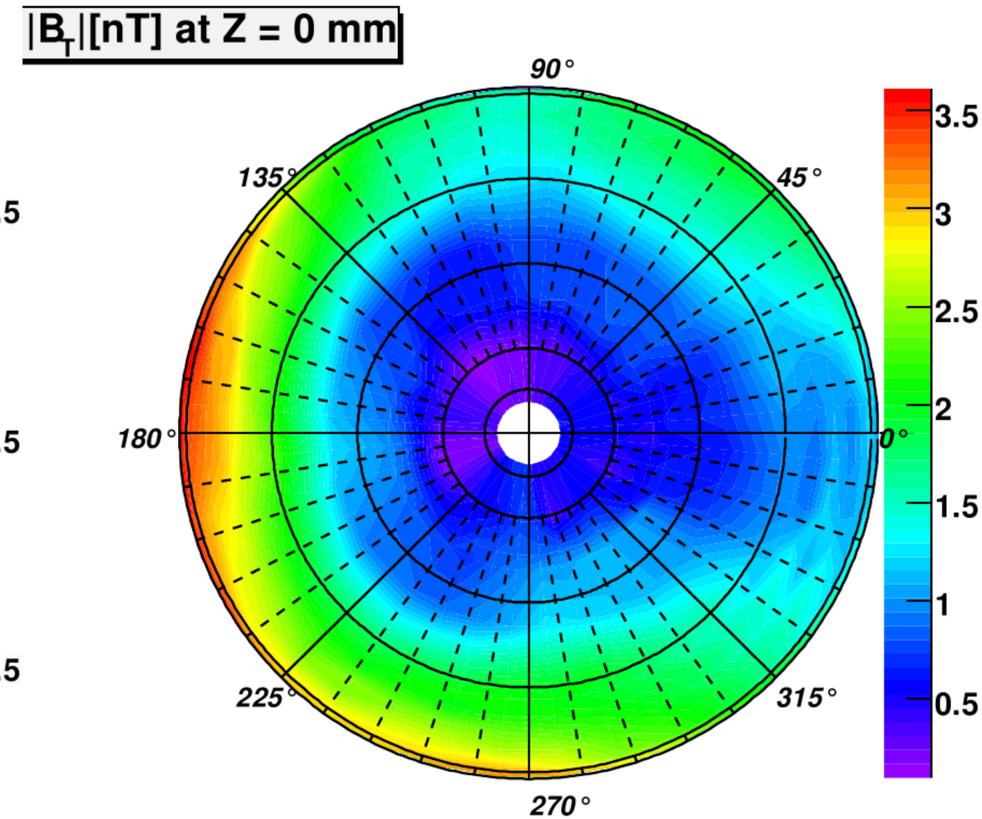
$$\Delta d_n = 0.4 \times 10^{-27} \;\; e \text{ cm}$$

Transverse field measured with fluxgate maps

$B_o \downarrow$ (Map27062010_234313)



$B_o \uparrow$ (Map27062010_180234)



$$d_{\mathrm{False}} = \frac{\hbar \gamma_n \gamma_{\mathrm{Hg}} D^2}{128 c^2 B_0 \Delta h} \left(\langle B_\perp^2 \rangle_\downarrow - \langle B_\perp^2 \rangle_\uparrow \right)$$