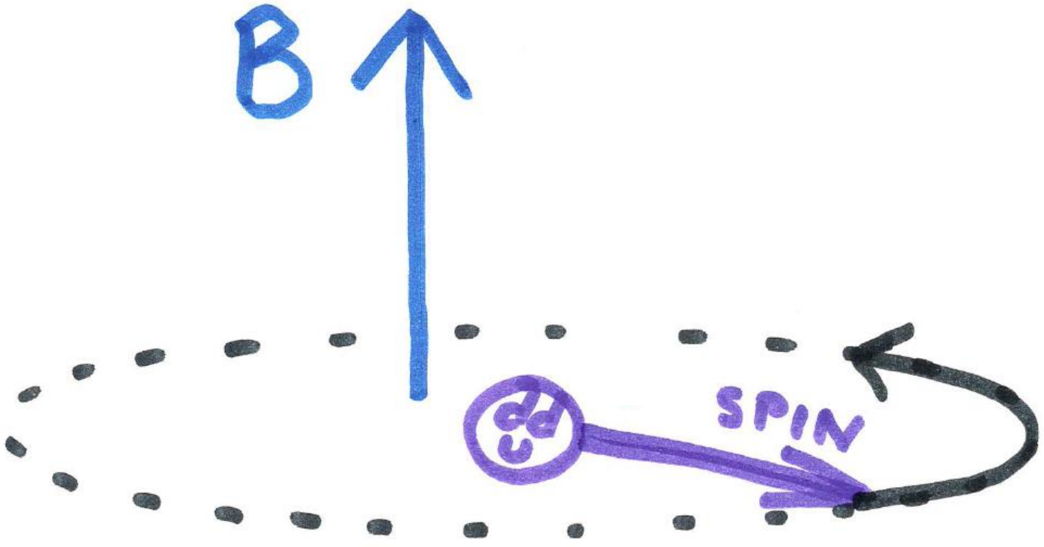
Une pensée pour Cécile

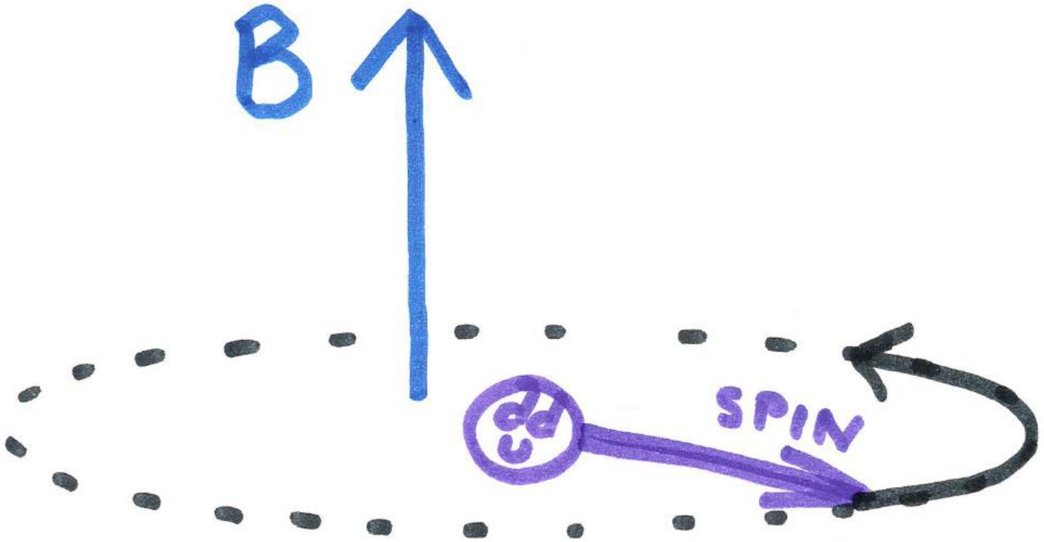
Guillaume Pignol
Séminaire LPSC, 29 Avril 2021

# Searching for the neutron Electric Dipole Moment

- Subatomic particles such as the neutron have a spin ½.




- Subatomic particles such as the neutron have a spin ½.
- One can change the orientation with a magnetic field **B**.
- This phenomenon –spin precession– is at the basis of NMR and MRI.

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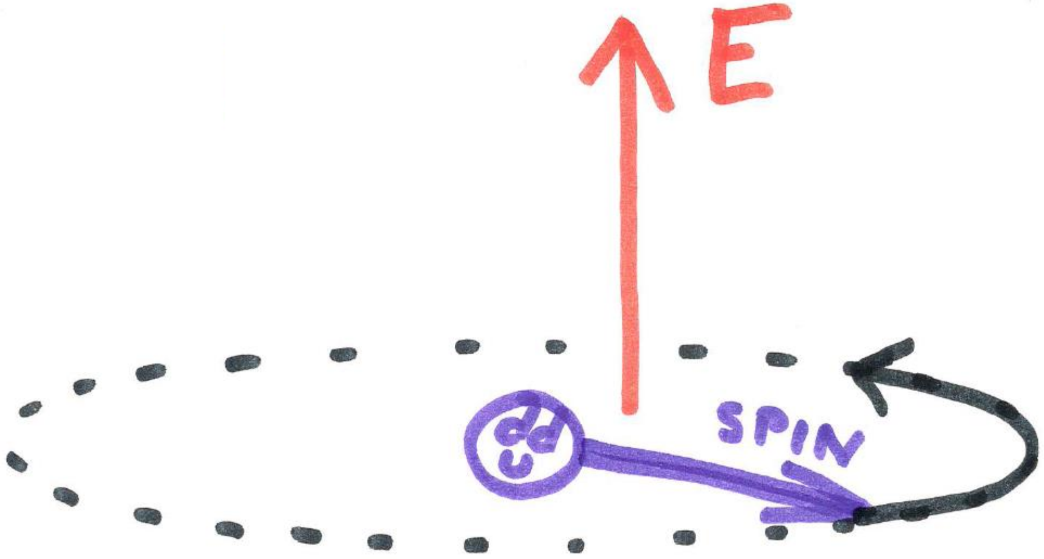
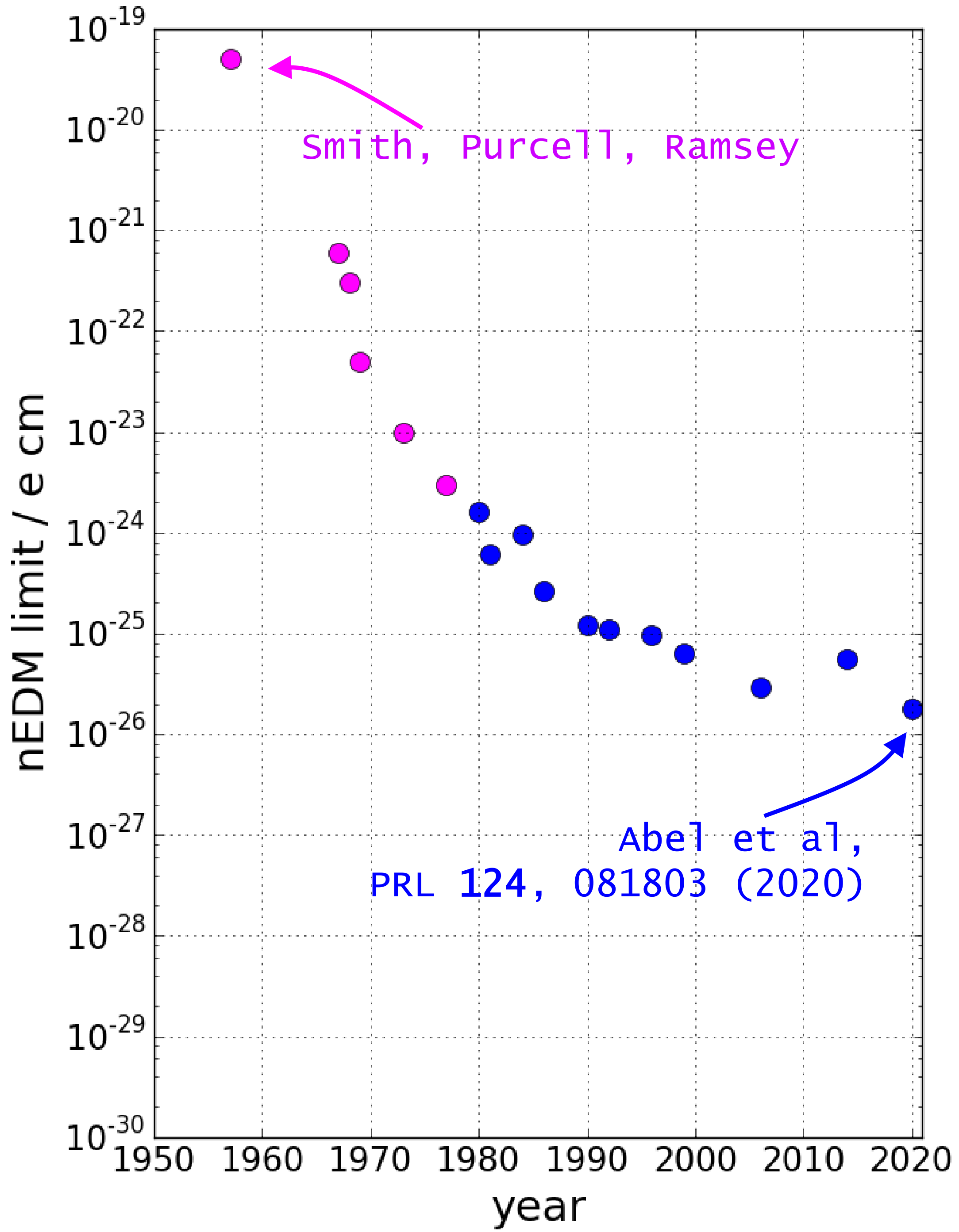



?

Question: Can we change the spin orientation with an electric field **E** instead?




# Short answer: no.

The electric dipole moment $\boldsymbol{d}$ quantifies the relation between the electric field $\boldsymbol{E}$ and the angular spin-precession frequency $\omega$.

$$\hbar\omega = 2dE$$

For $d = 10^{-26}\,e\,\mathrm{cm}$ and $E = 130\,000\,\mathrm{V}\,/\,12\,\mathrm{cm}$

A full spin turn takes a time

$$\frac{\pi\hbar}{dE} = \mathbf{200\ days}$$

# Outline of the seminar

1. Intro: What is the question.
2. **Why do we care?**
   - The matter-antimatter puzzle
   - Links between CP symmetry and nEDM
3. **How do we measure the neutron EDM with such a precision?**
   - Ultracold neutrons, atomic magnetometry, super-uniform magnetic fields

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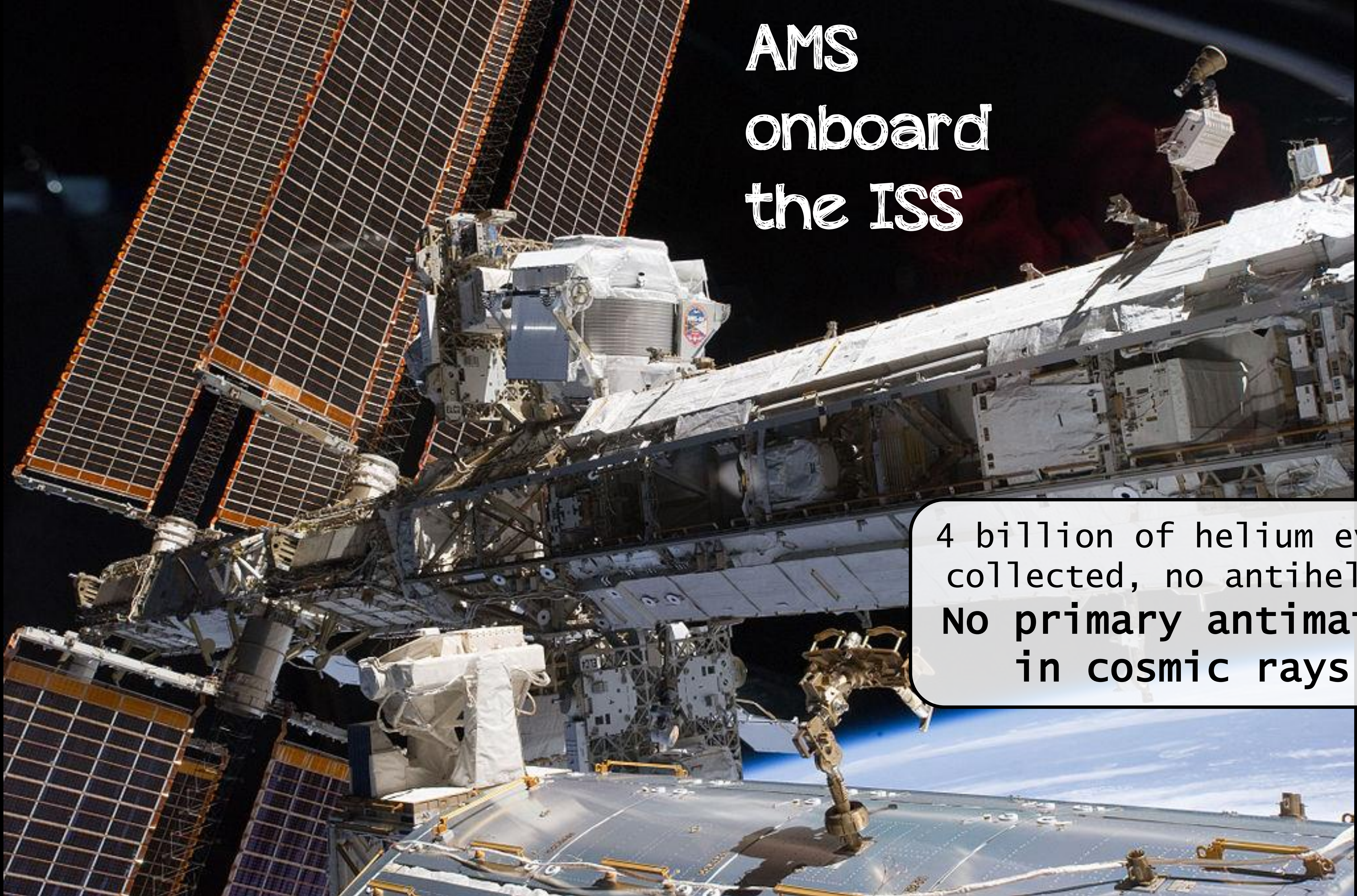
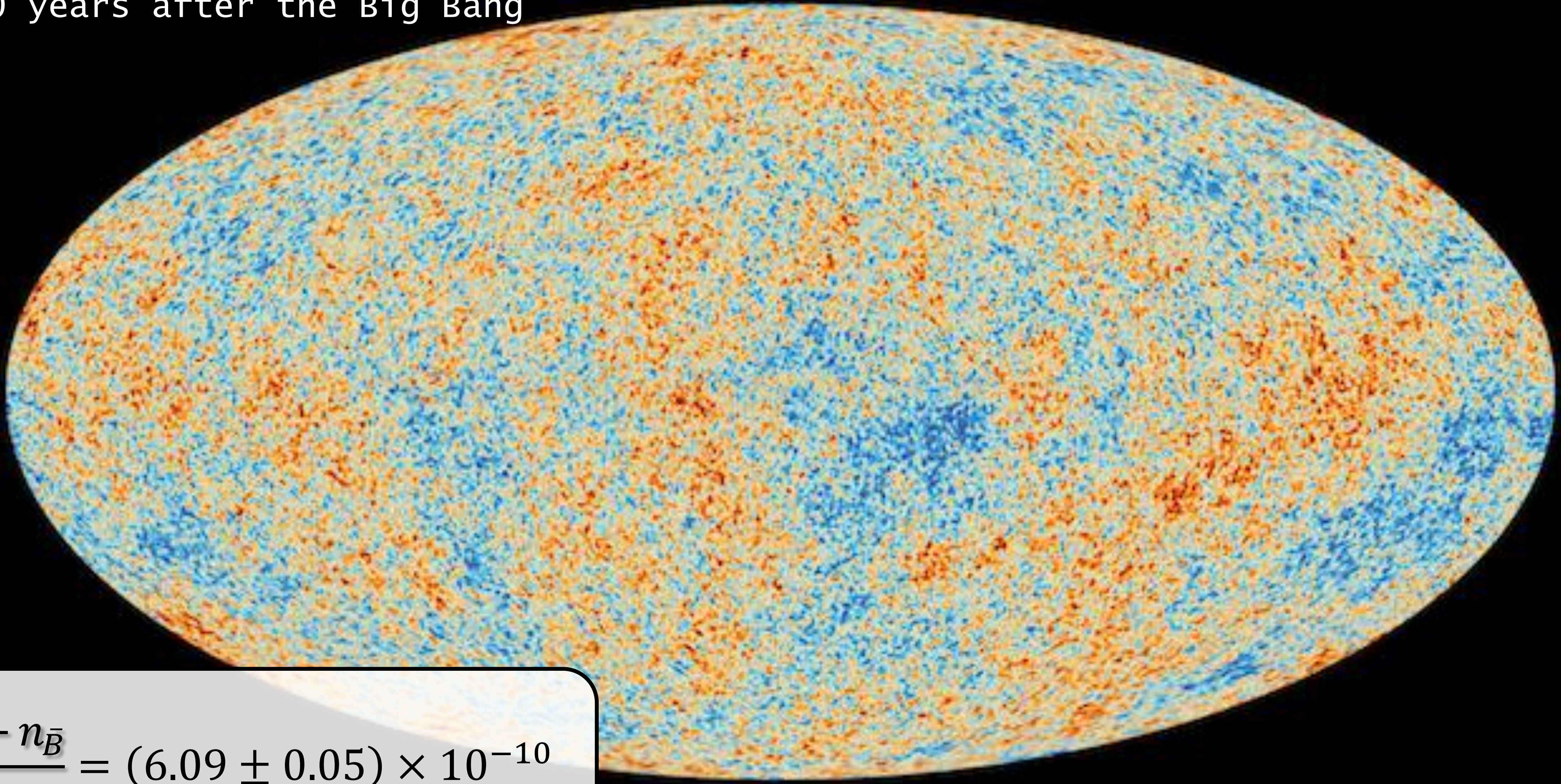
# AMS onboard the ISS



4 billion of helium events collected, no antihelium.
**No primary antimatter in cosmic rays.**

# Release of the CMB

t = 370,000 years after the Big Bang
T = 0.3 eV

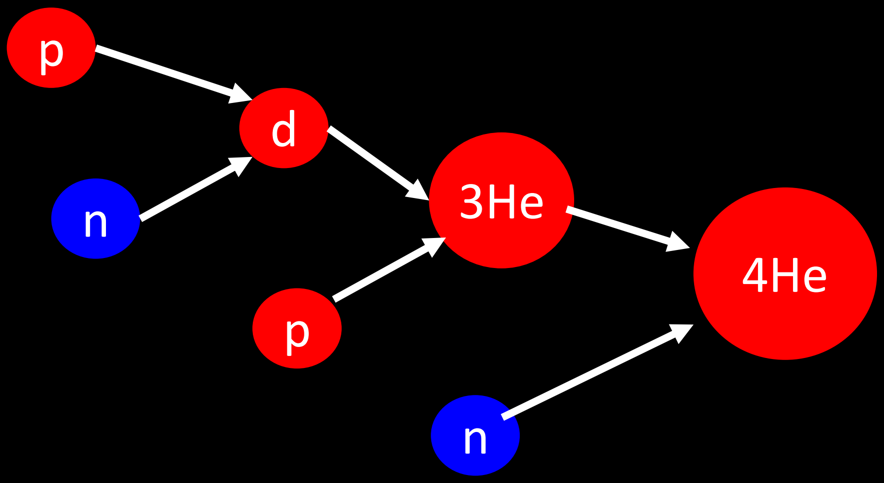


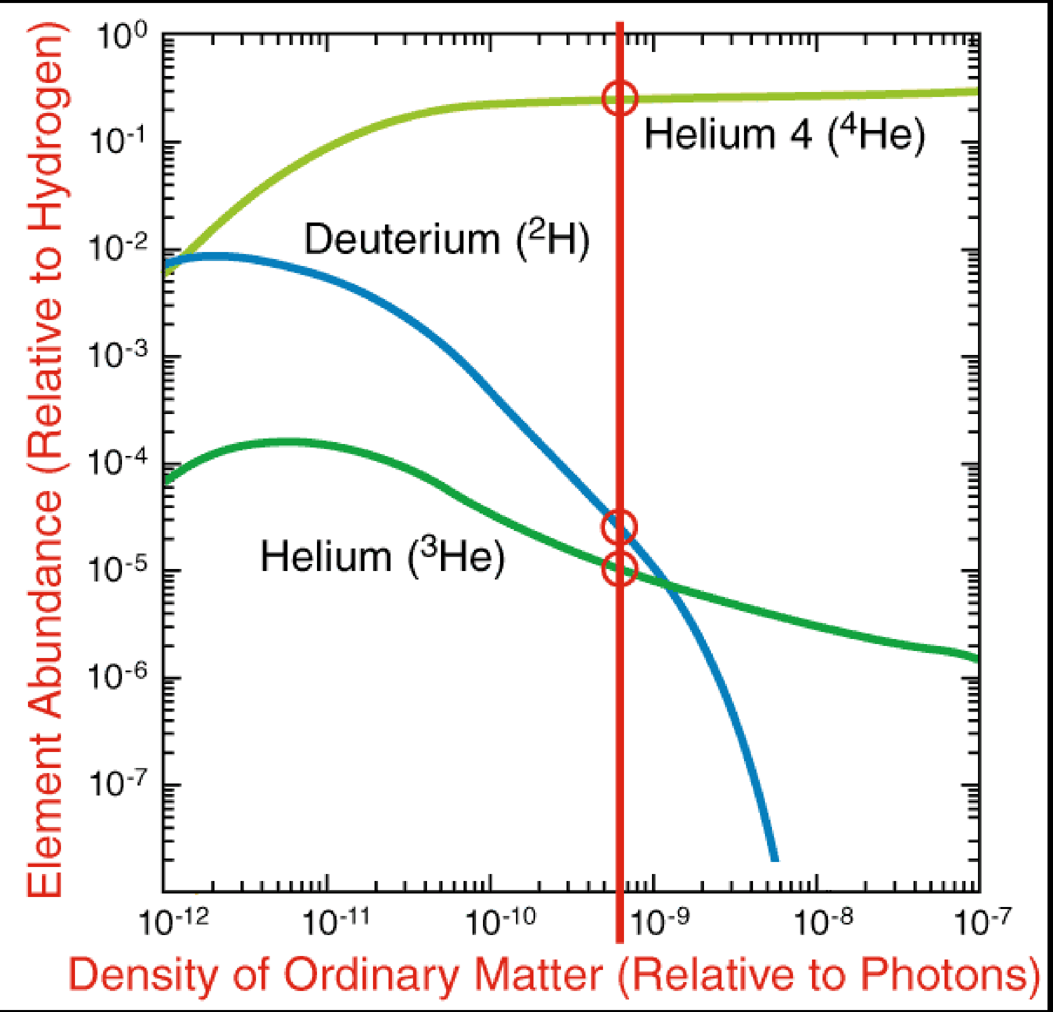
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.09 \pm 0.05) \times 10^{-10}$$

[Planck (2016)]

# Big Bang Nucleosynthesis

t = 3 minutes after the Big Bang
T = 100 keV

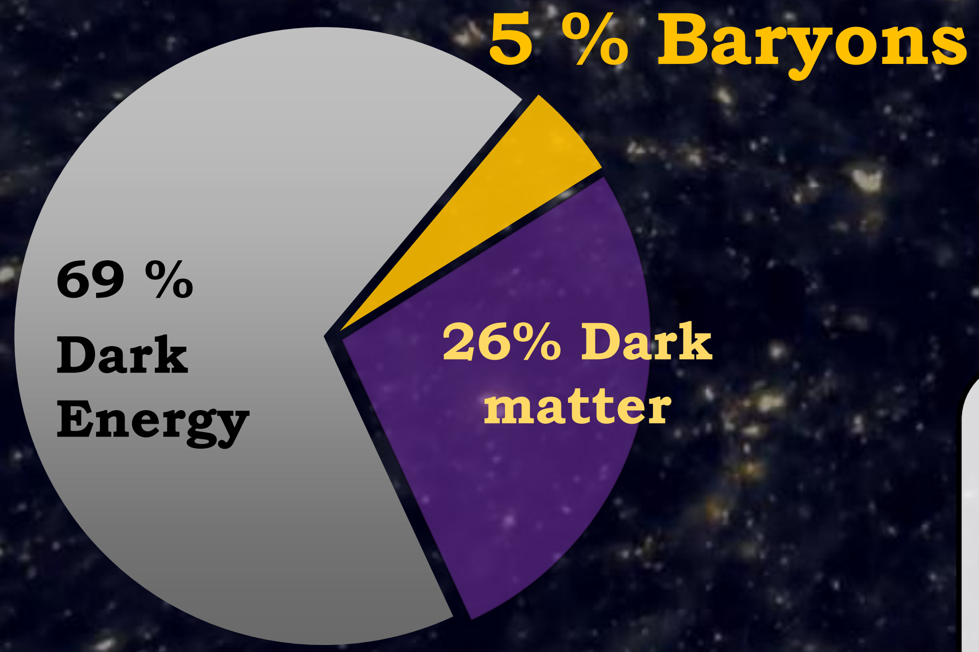



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.0 \pm 0.1) \times 10^{-10}$$

[Deuterium abundance from Lyα, Cooke *et al* (2014)]

# Content of the Universe Today




The baryons result from an imbalance of

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-9}$$

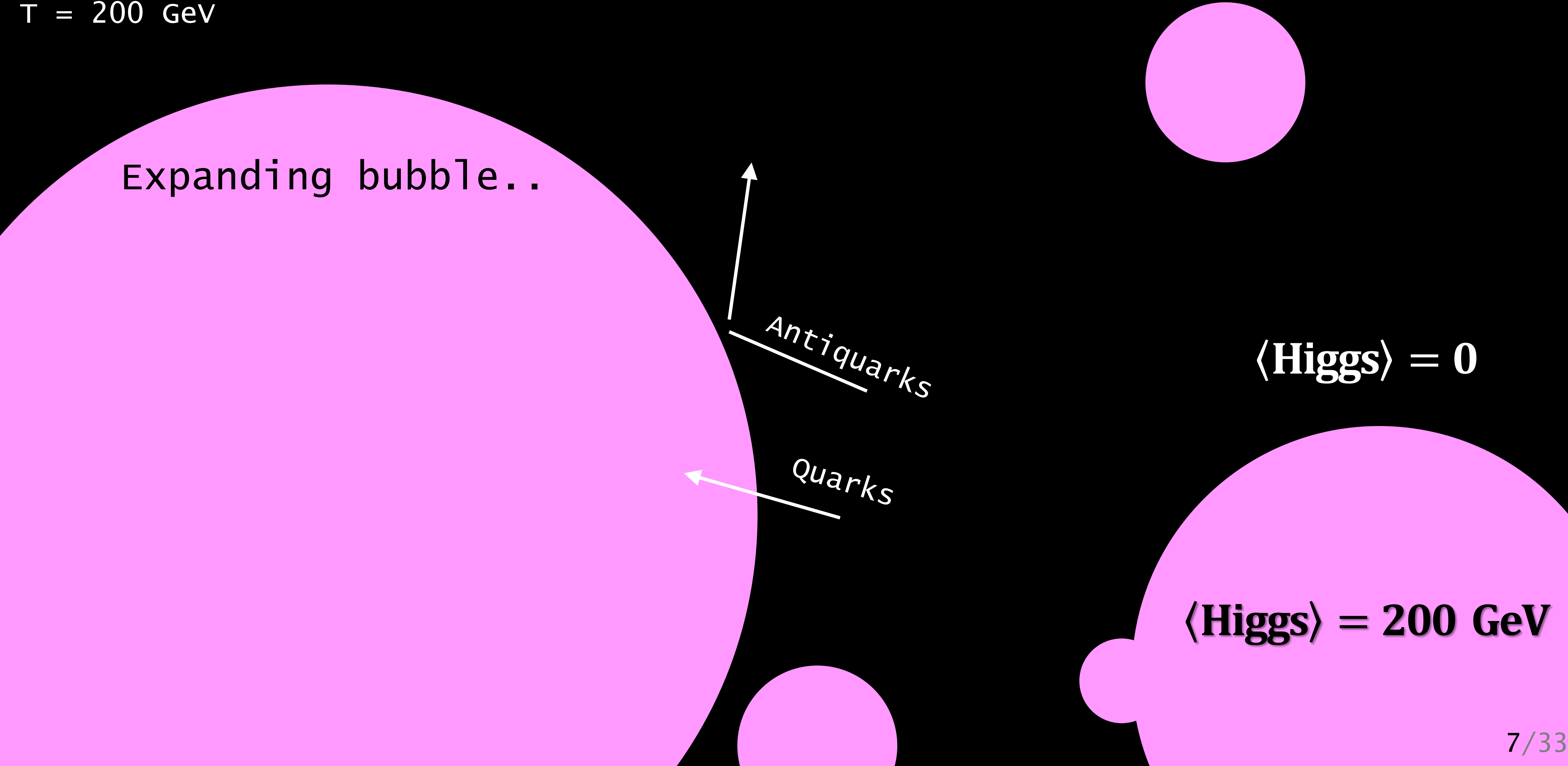
generated by an totally unknown process before t = 1 ns

Sakharov's baryogenesis recipe (1967)

- Universe out of equilibrium
- Baryon number not conserved
- Violation of C and CP symmetries

# Electroweak Phase Transition

t = 10 ps after the Big Bang
T = 200 GeV



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# Violation of time reversal


» PLAY »

« REWIND «

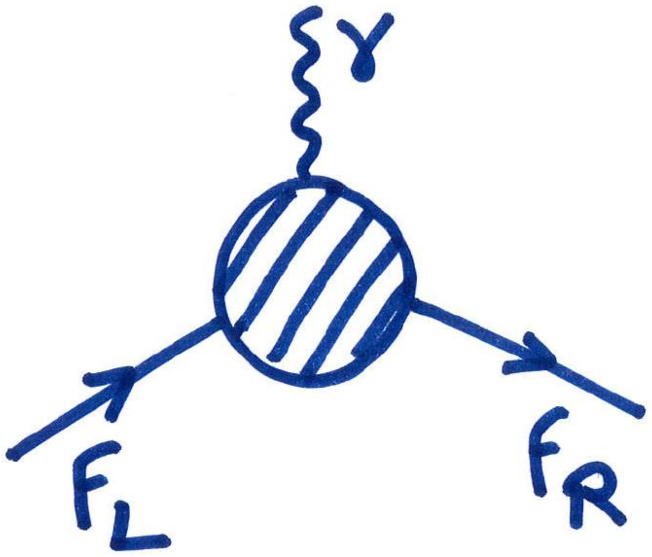
If $d \neq 0$ the process and its time reversed version are different.

Violation of T

CPT

Violation of CP

# Electric dipoles & CP symmetry

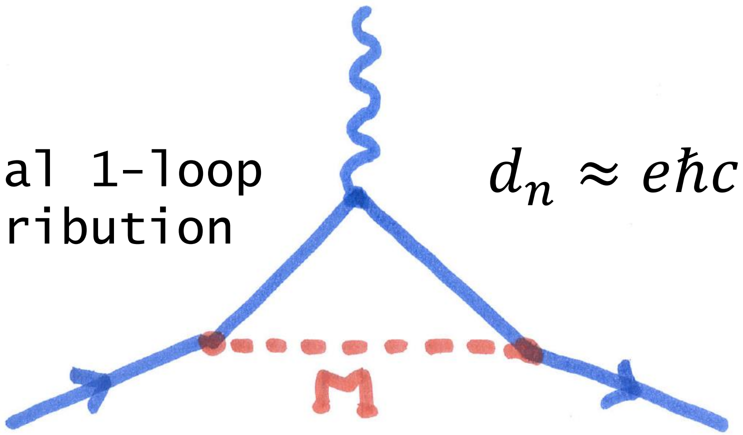



EDM = CP-violating fermion-photon coupling
-imaginary part of the diagram-
generated by radiative corrections

$$\mathcal{L} = -\frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\, F^{\mu\nu}$$

$$\rightarrow \hat{H} = -d\,\hat{\boldsymbol{\sigma}}\boldsymbol{E}$$

Typical 1-loop contribution



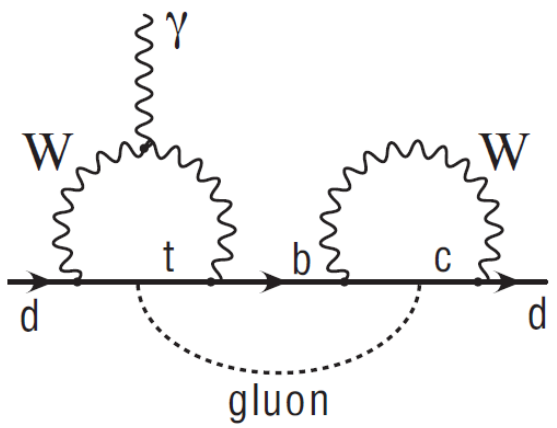

$$d_n \approx e\hbar c\,\frac{\mathrm{Im}(g^2)}{4\pi}\frac{m_q}{M^2} \approx \frac{\mathrm{Im}(g^2)}{4\pi}\left(\frac{10\ \mathrm{TeV}}{M}\right)^2 \times 10^{-25} e\ \mathrm{cm}$$

# Sources of EDMs in the Standard Model

**The QCD contribution** $\frac{\alpha}{8\pi}\bar{\theta}\, G^{\mu\nu}\widetilde{G_{\mu\nu}}$

Generates a potentially enormous neutron EDM

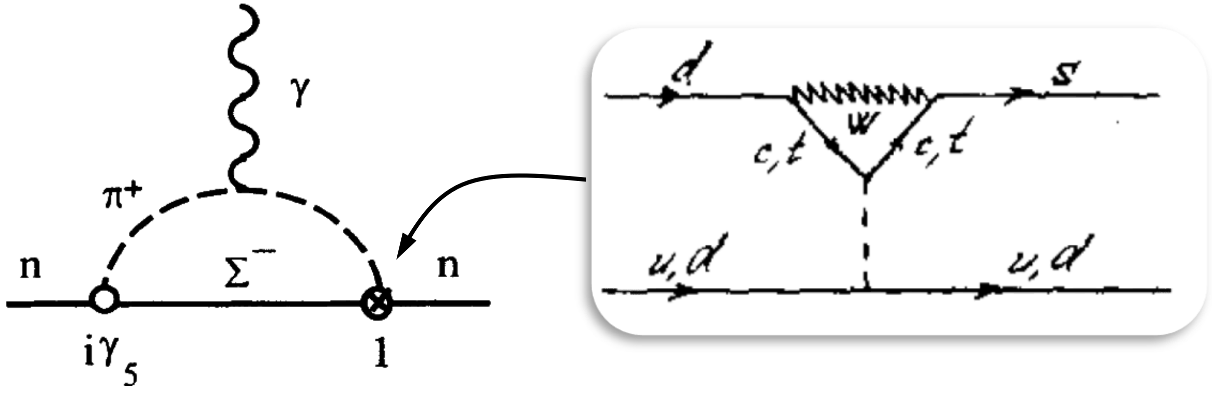
$d_n \approx \bar{\theta} \times 10^{-16}\, e\,\mathrm{cm}$
$\rightarrow \bar{\theta} < 10^{-10}$
« Strong CP problem »




**CKM contribution to the quark EDMs:** Leading order starts at 3 loops!

Negligible contribution

**CKM "long distance" contribution to nEDM**



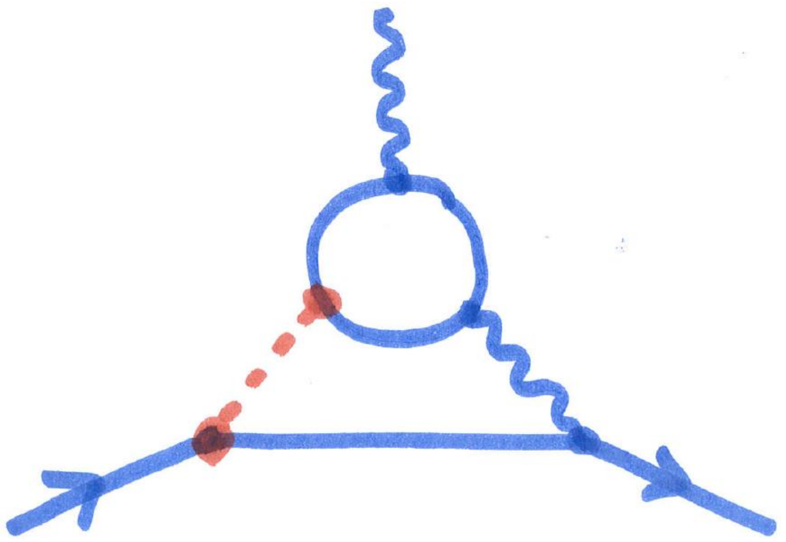

CKM prediction:
$1 \times 10^{-32}\, e\,\mathrm{cm} < |d_n| < 6 \times 10^{-32}\, e\,\mathrm{cm}$
Kobayashi-Maskawa background negligible

# EDMs beyond the SM: modified Higgs couplings

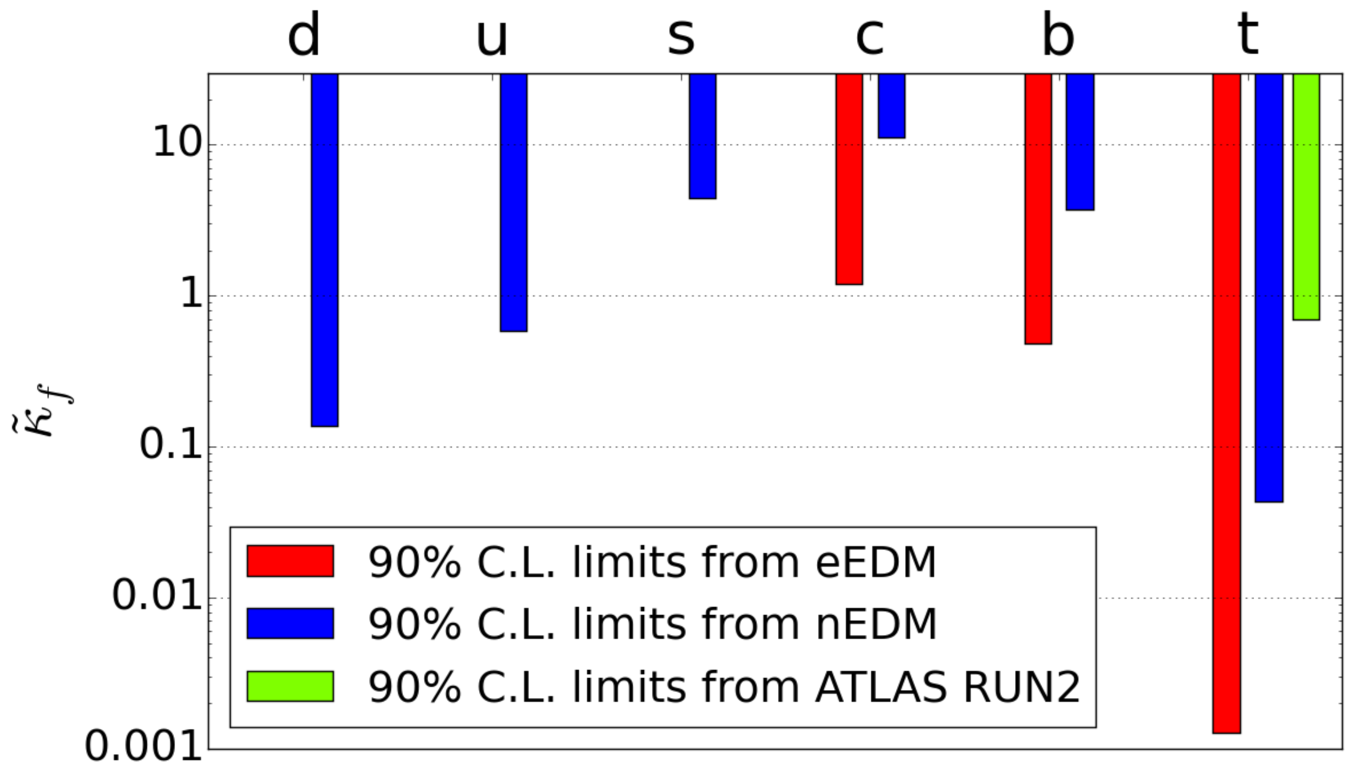
CP violating

Modified Higgs-fermion Yukawa coupling $\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h\right)$

Generates EDM at 2 loops



Barr, Zee, PRL 65 (1990)




Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480
ATLAS, PRL 125, 061802 (2020)

# Take home messages

1. **Great puzzle**: Baryogenesis still unexplained. CP-violation in the standard electroweak theory fails to explain the observed baryon asymmetry of the Universe.

2. **Great sensitivity**: EDMs are very sensitive probes of CP violation beyond the SM because
   (i) New physics at the TeV scale (and beyond) predicts generically sizable EDMs
   (ii) CKM contribution to EDMs undetectably small

3. **Complementarity**: Importance of measuring the EDMs in different systems (neutron, atoms, muons…) to cover the many different possible fundamental sources of CP violation

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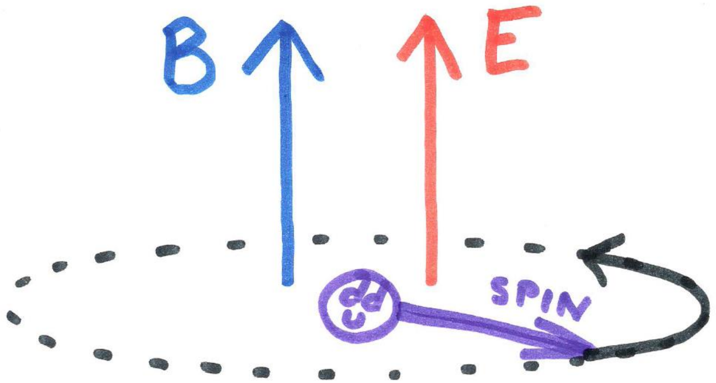
# Basics of EDM measurement



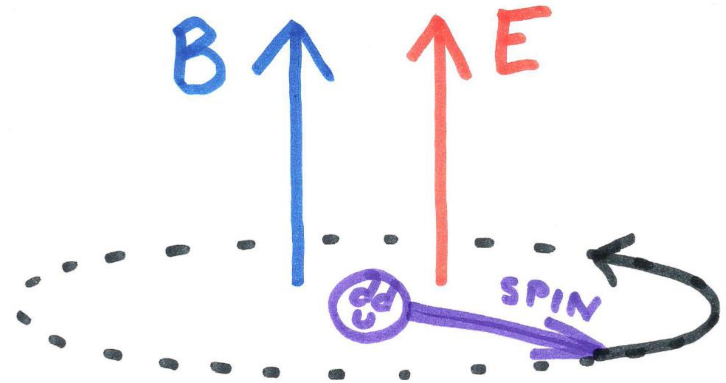

$$2\pi f = \frac{2\mu}{\hbar}B \pm \frac{2d}{\hbar}|E|$$

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}d\,E$$ **Easy!**

***The trick: measure frequencies****

** Only if you can't, try something else*

# Basics of EDM measurement




$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{2}{\pi\hbar} d\, E$$

~~Easy!~~

Larmor frequency

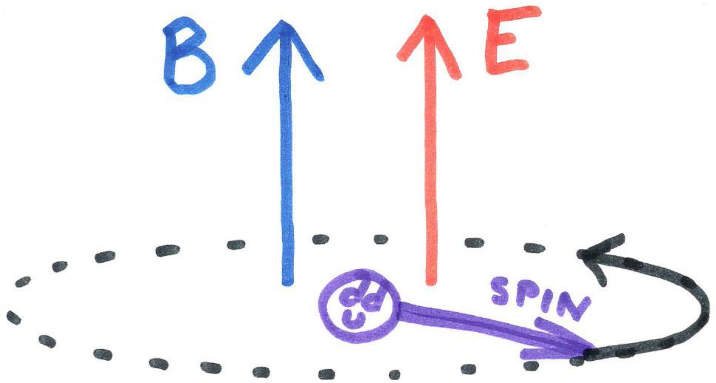
$f = 30\ \mathrm{Hz}\ @\ B = 1\ \mu\mathrm{T}$

If $d = 10^{-26}\ e\,\mathrm{cm}$ and $E = 11\ \mathrm{kV/cm}$

The spin will make **one full turn** in a time

$\frac{\pi\hbar}{dE}$ = **200 days**

# Basics of EDM measurement




$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

If $d = 10^{-26}\, e\,\text{cm}$ and $E = 11\,\text{kV/cm}$
**one full turn** in a time

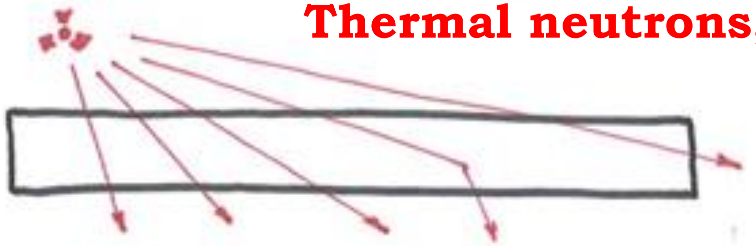
$\frac{\pi\hbar}{dE} = \mathbf{200\ days}$

**To detect such a minuscule coupling:**

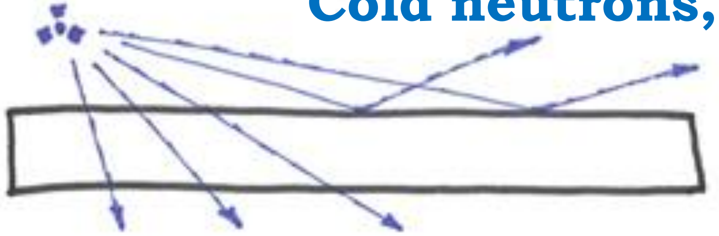
- Long interaction time
- High intensity/statistics
- Control the magnetic field

# Neutron optics, cold and ultracold neutrons

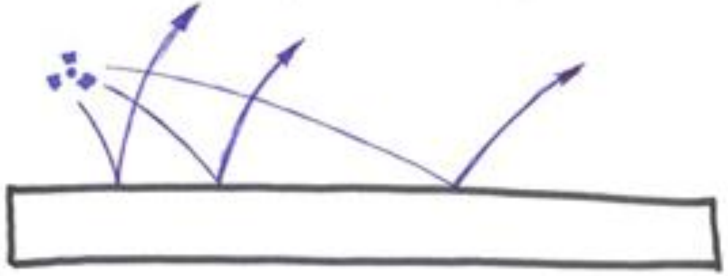
**Thermal neutrons, E=25 meV**

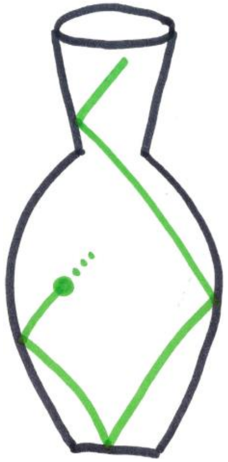


**Cold neutrons, E<25 meV**



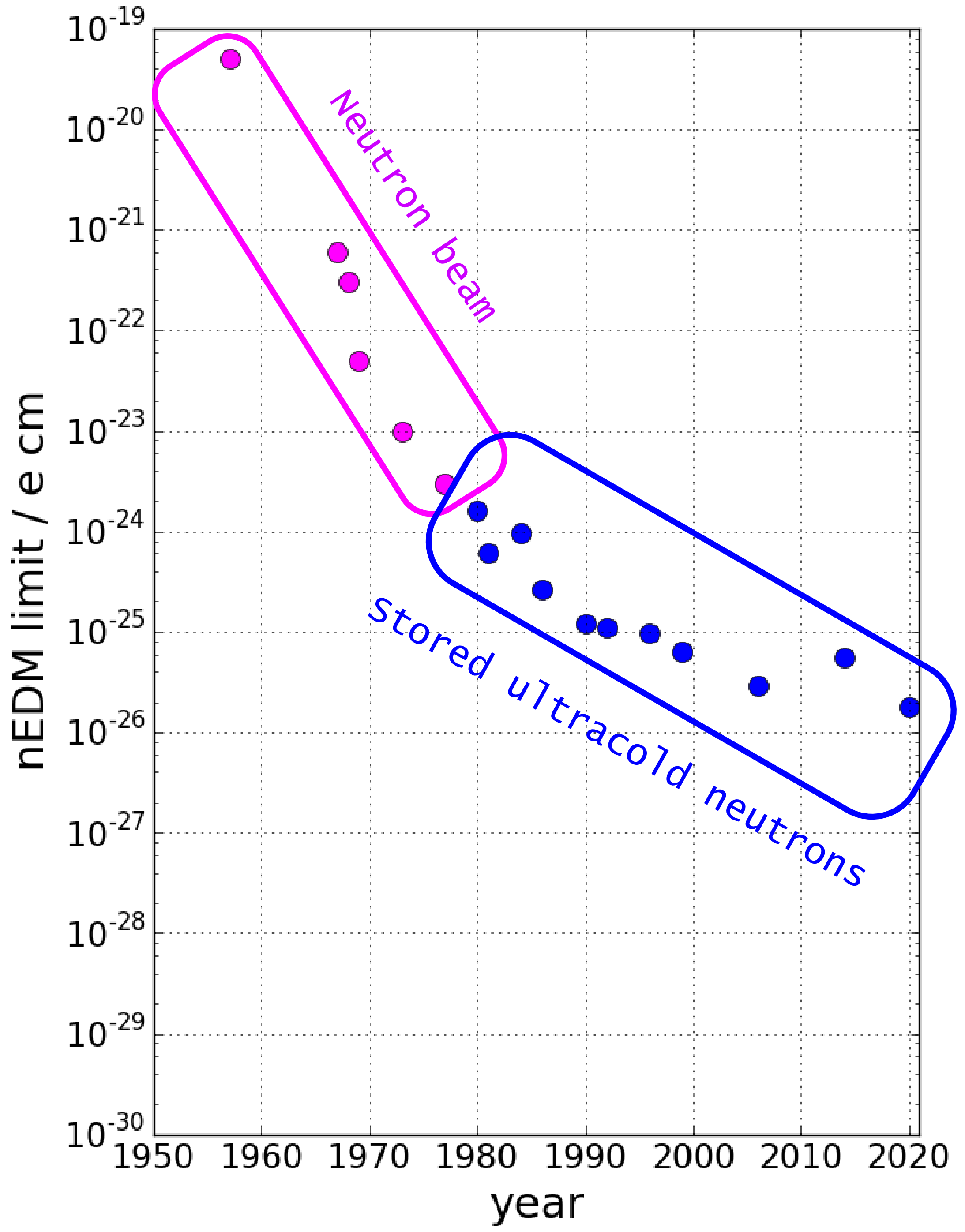
**Ultracold neutrons E< 200 neV**



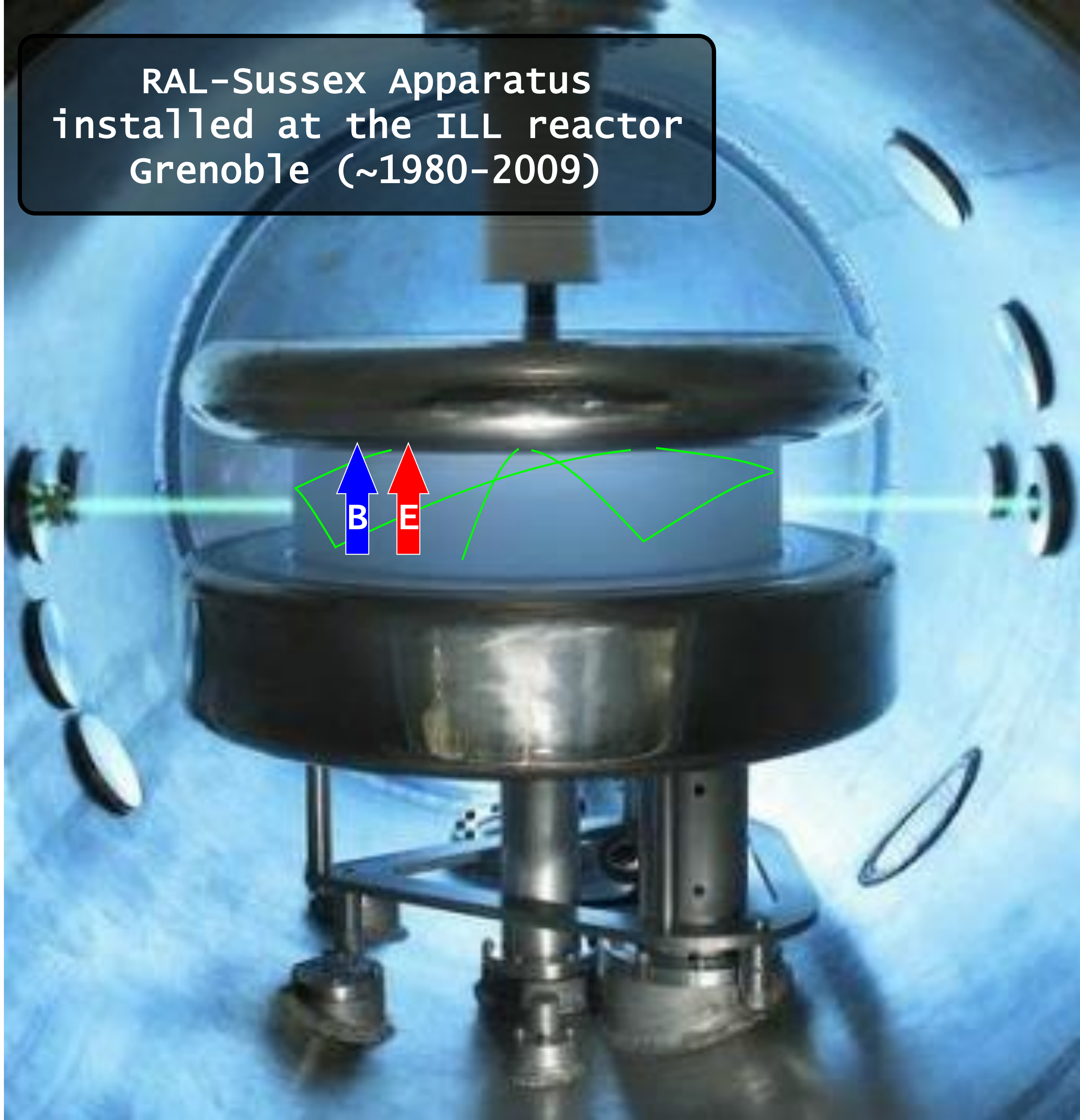


Neutrons with energy < 200 neV, are totally reflected by material walls.

They can be stored in material bottles for long times, up to 15 minutes.



nEDM limit / e cm
year
Neutron beam
Stored ultracold neutrons
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-27}$
$10^{-28}$
$10^{-29}$
$10^{-30}$
1950
1960
1970
1980
1990
2000
2010
2020

RAL-Sussex Apparatus
installed at the ILL reactor
Grenoble (~1980-2009)
B
E

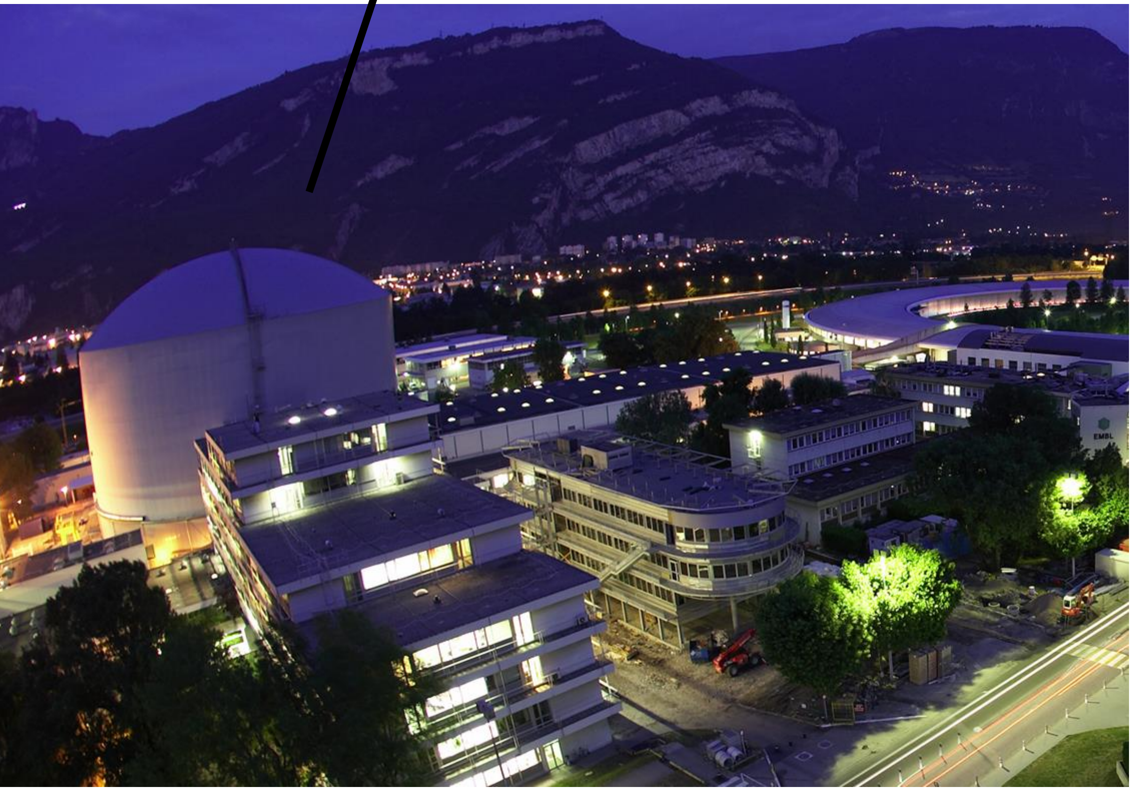
# Recent history of the single-chamber apparatus

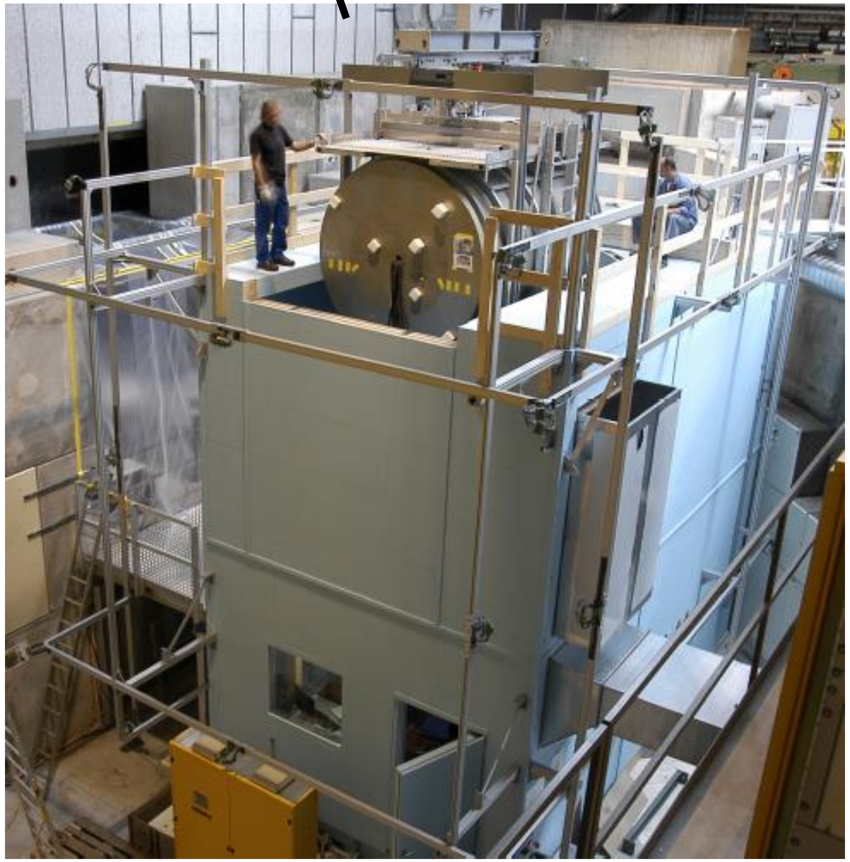
1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

**ILL data production**

UCN source startup
& nEDM upgrade

**PSI data**

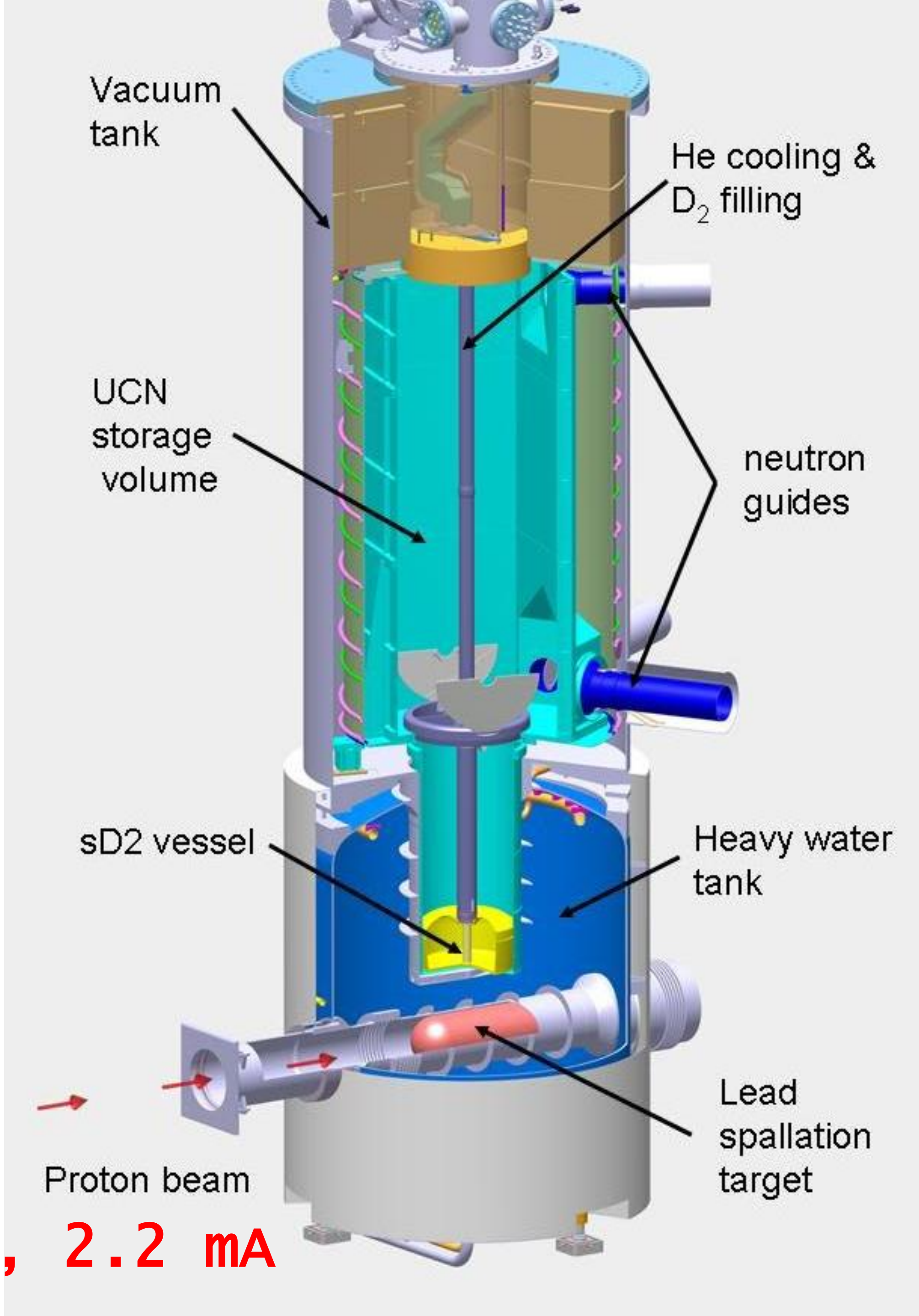




Move of the apparatus at the
Paul Scherrer Institute

Dismantling nEDM
Installing n2EDM

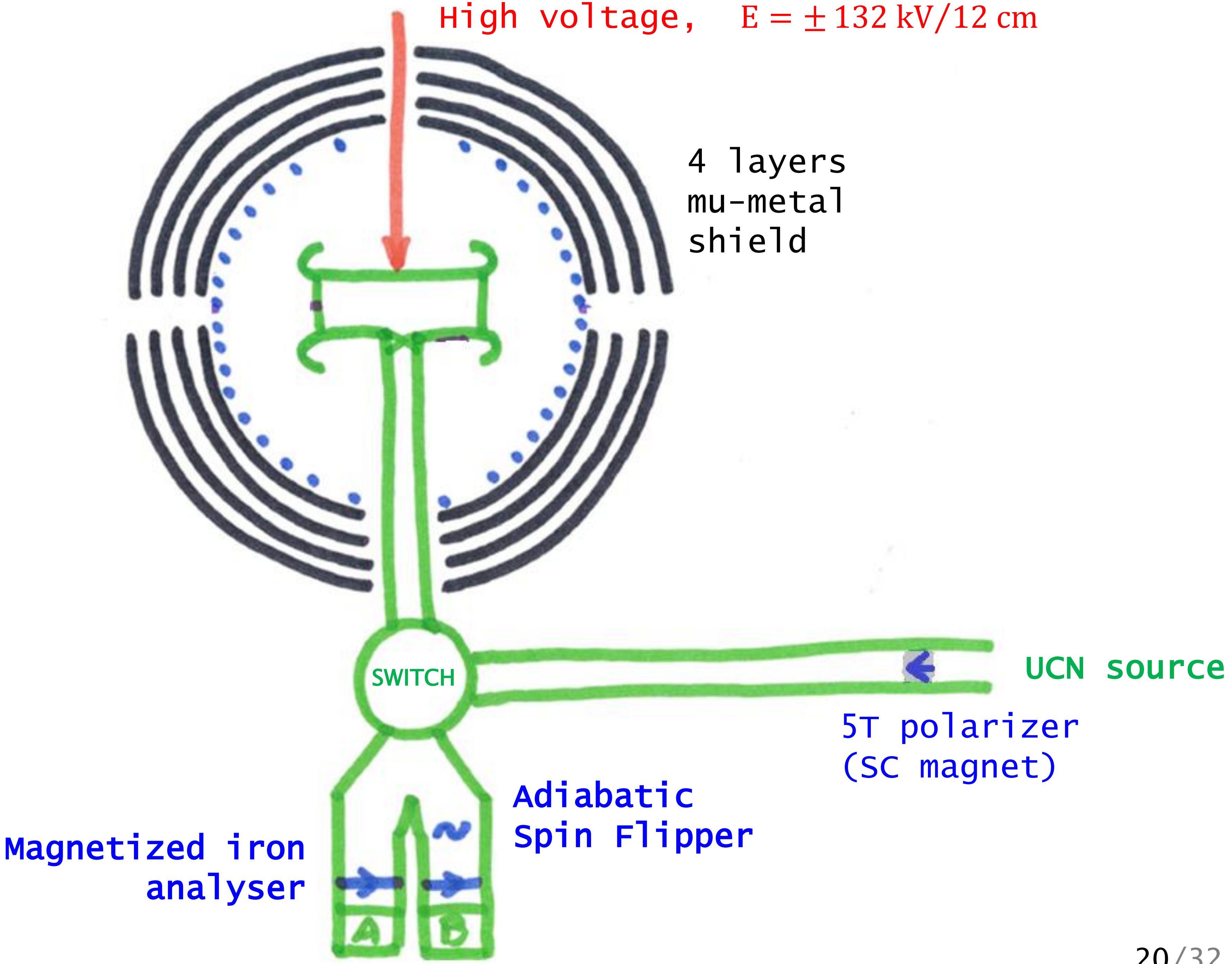
# UCN source at the Paul Scherrer Institute



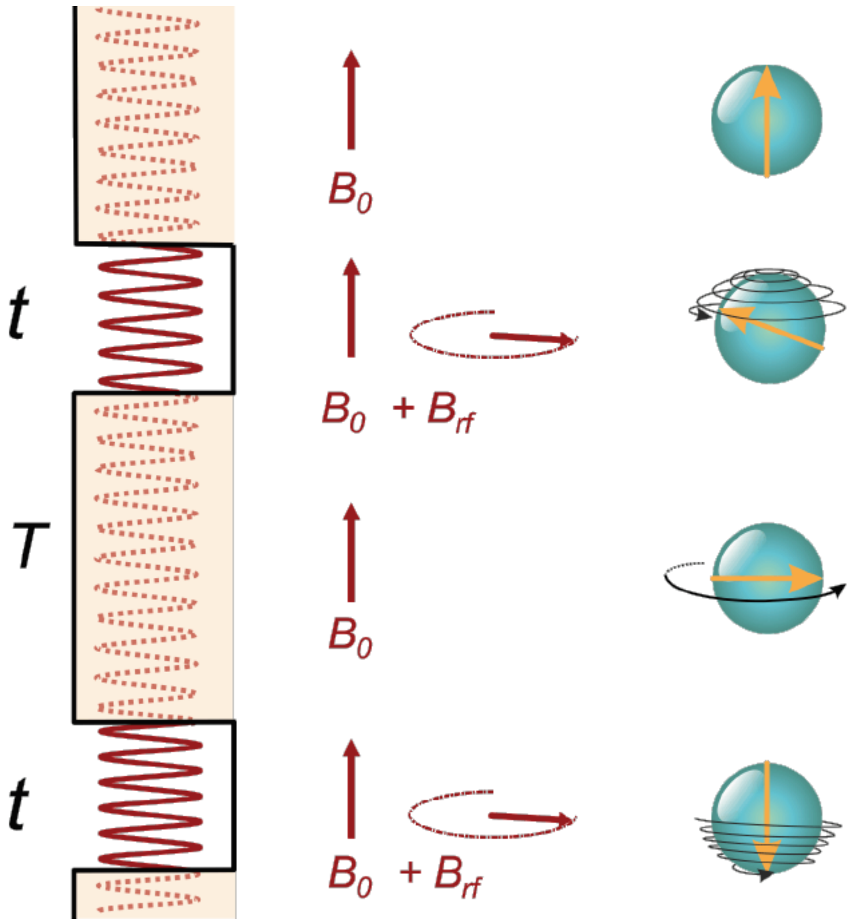

pulsed UCN source
One kick per 5 min
online since 2011

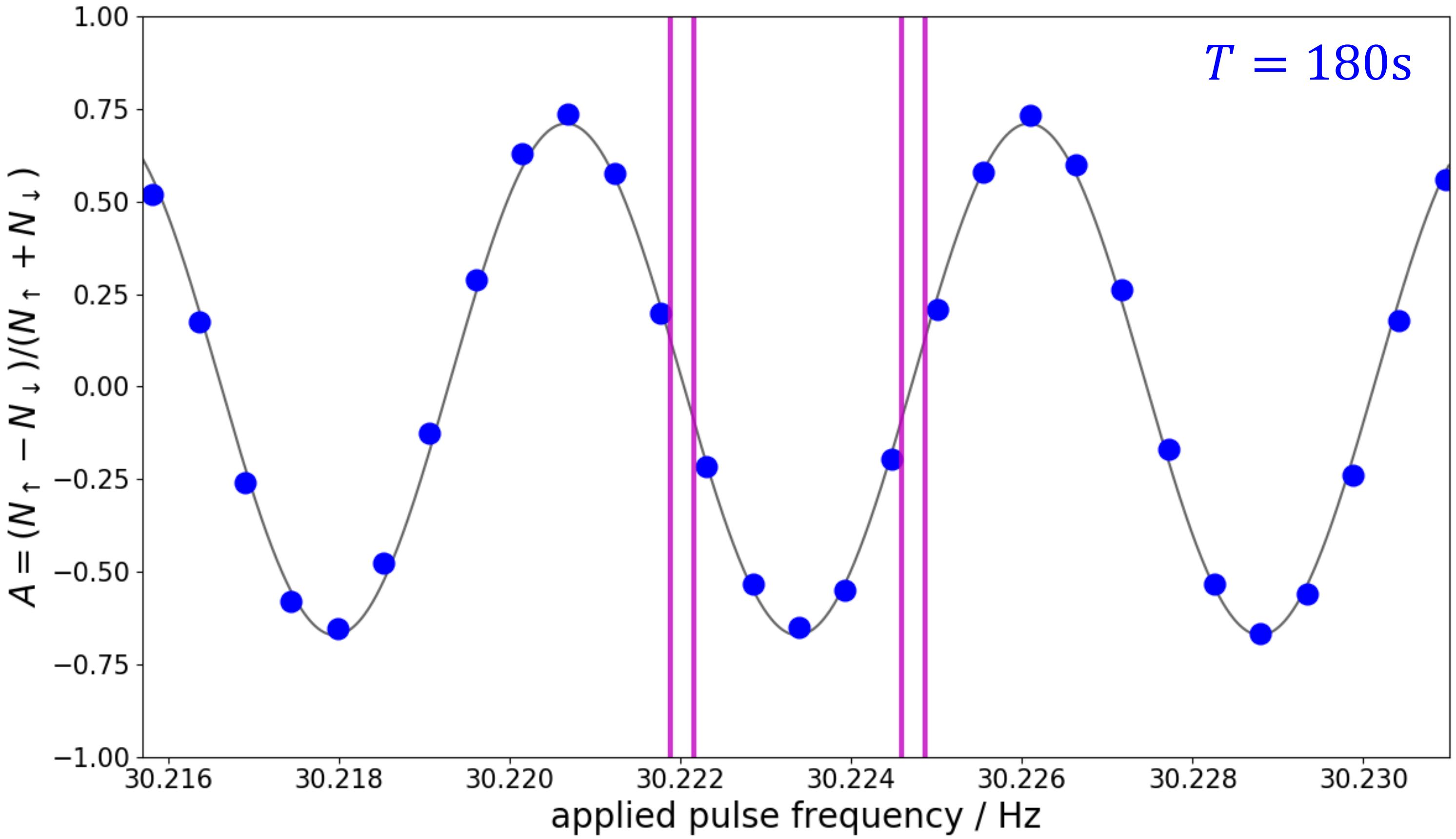
600 MeV, 2.2 mA

# Scheme of the apparatus at PSI during EDM data-taking 2015-2016



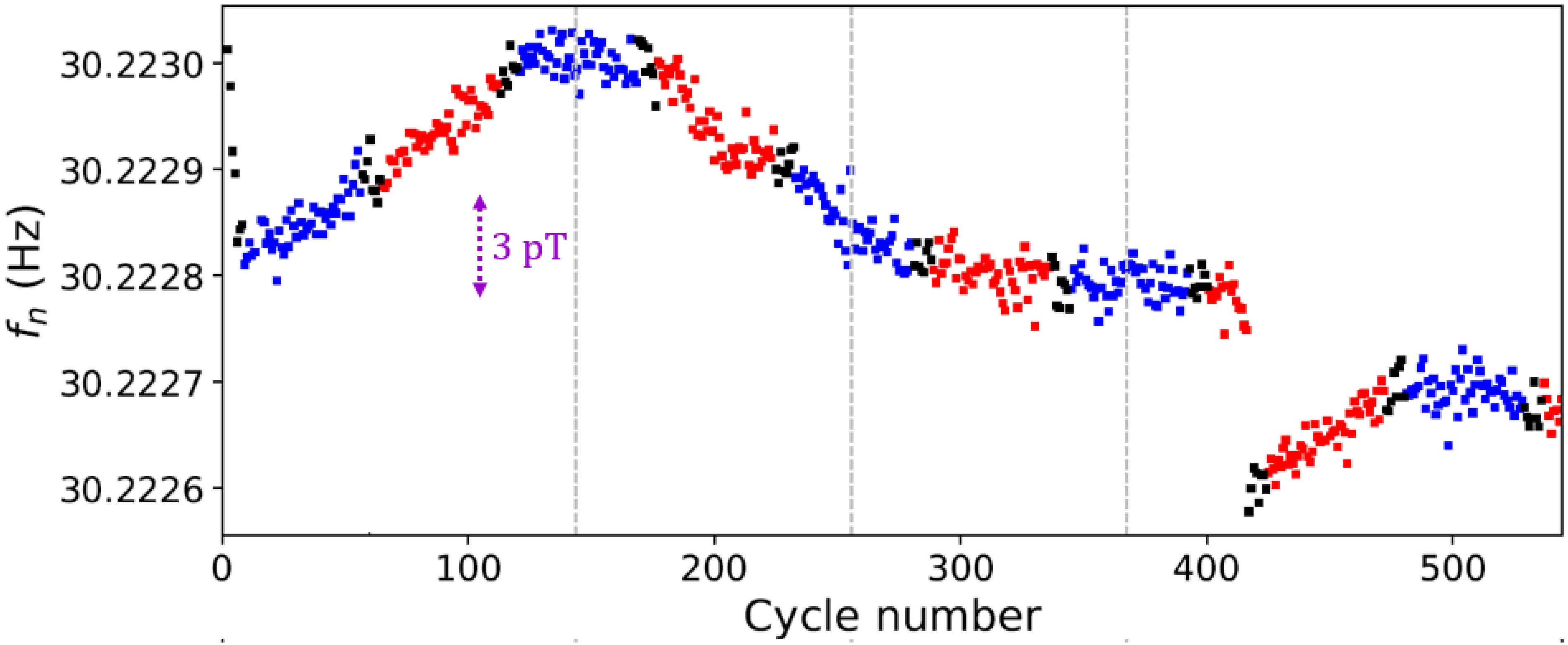
# Ramsey's method



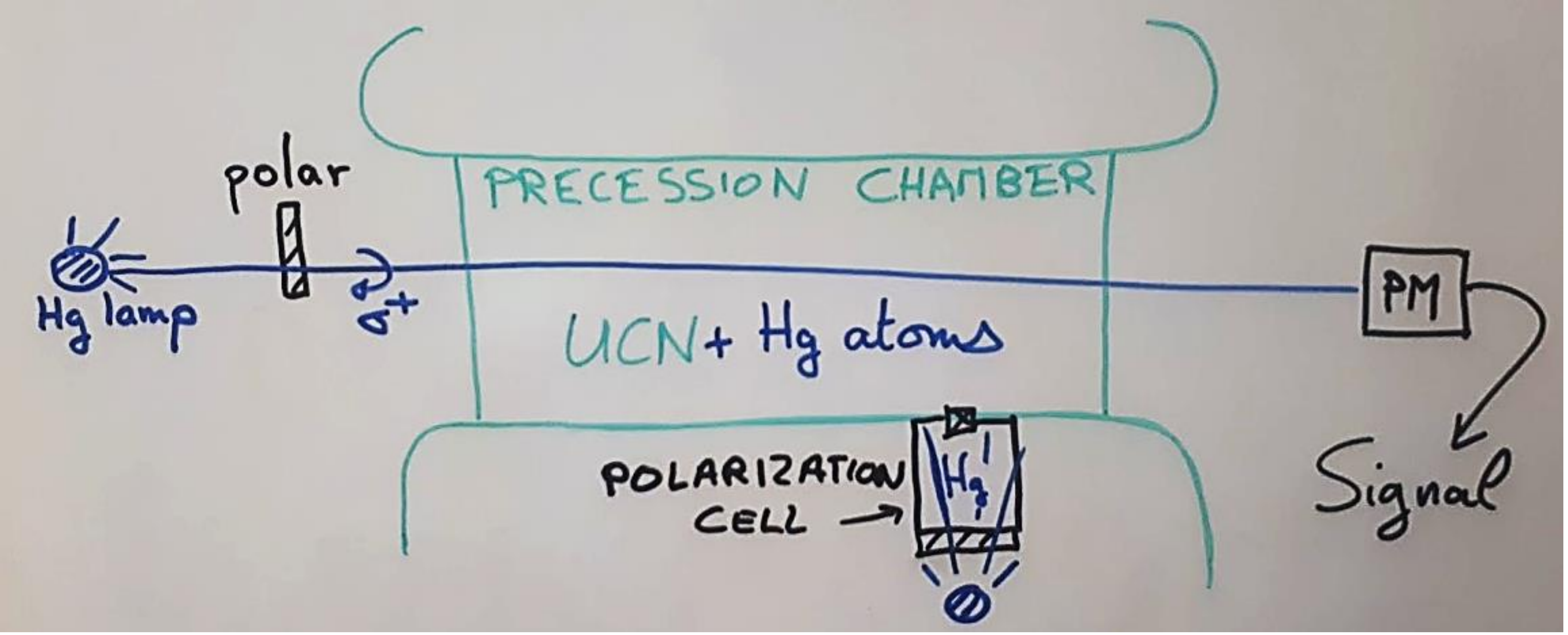




Statistical sensitivity: $\sigma d_n = \frac{\hbar}{2\,\alpha\,E\,T\,\sqrt{N}}$

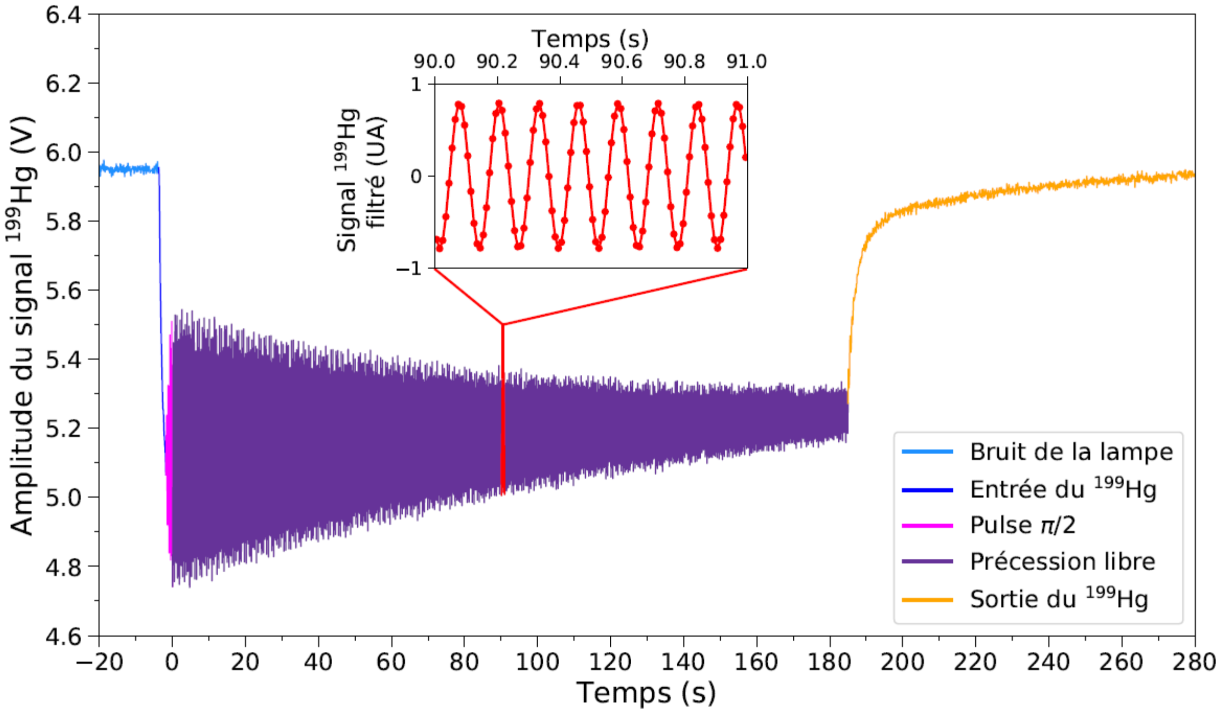
# nEDM data collected in 2015-2016




54,068 cycles recorded,
grouped in 99 sequences,
alternating E field polarity every 48 cycles
11,400 neutrons counted per cycle.




# Atomic comagnetometry with $^{199}$Hg




The magnetic field is extracted from the precession frequency of mercury-199 atoms:

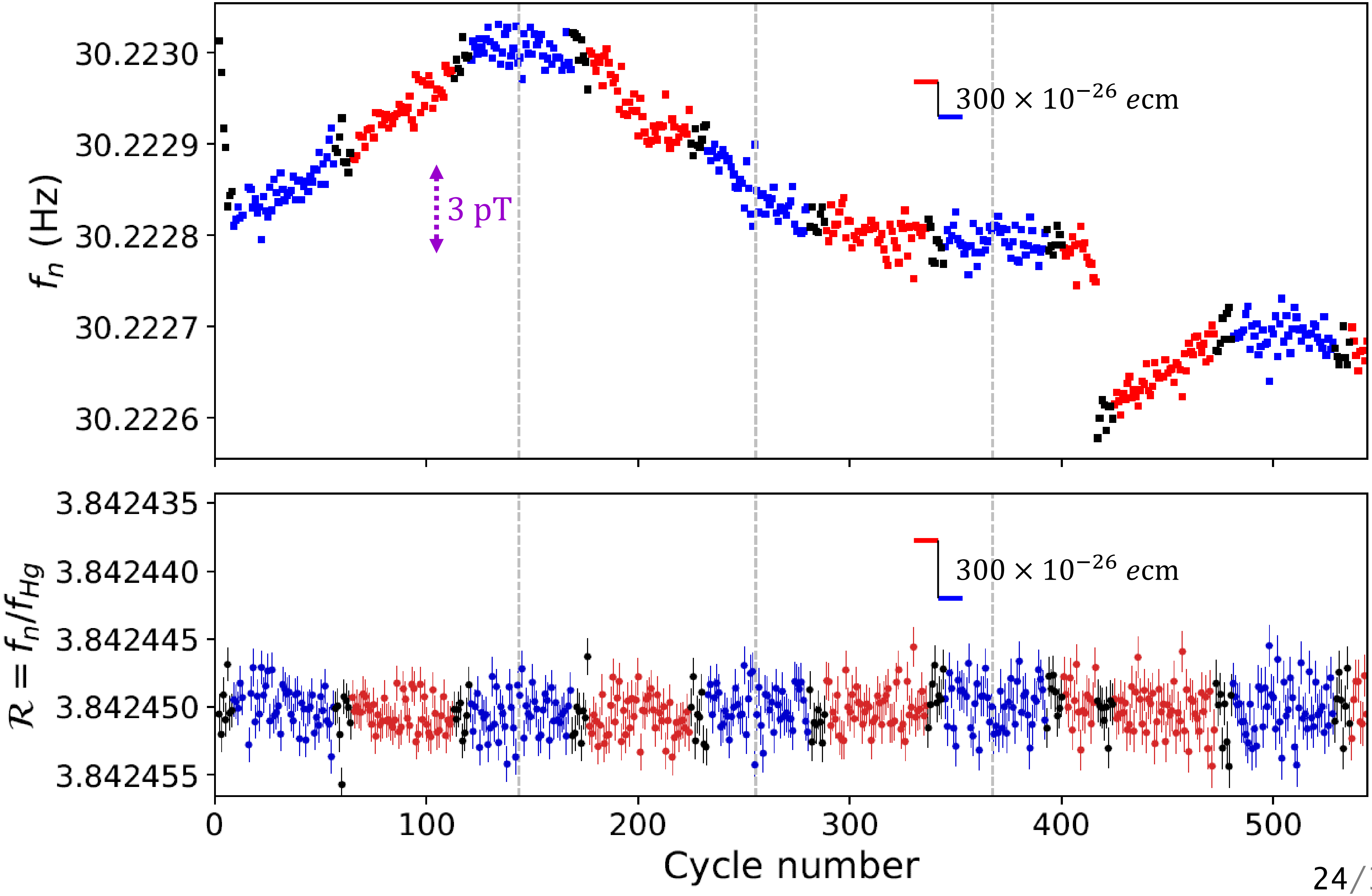
$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$

PhD thesis Yoann Kermaidic (2013-2016)

# A sequence of cycles (nEDM data)

Magnetic fluctuations (random and correlated with E) are corrected for at each cycle with the Hg magnetometer by measuring

$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$



| $d_\times$ ($10^{-26}$ $e$cm) | THE WEST | THE EAST |
| --- | --- | --- |
| DOUBLE BLIND | 15.4 ± 1.1 | 3.8 ± 1.1 |
| SINGLE BLIND |  |  |
| UNBLIND |  |  |

# Budget of systematic errors

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 |
| Higher-order gradients $\hat{G}$ | 69 | 10 |
| Transverse field correction $\langle B_T^2 \rangle$ | 0 | 5 |
| Hg EDM [8] | –0.1 | 0.1 |
| Local dipole fields | ... | 4 |
| $v \times E$ 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 |

Largest effect, associated with B-field uniformity

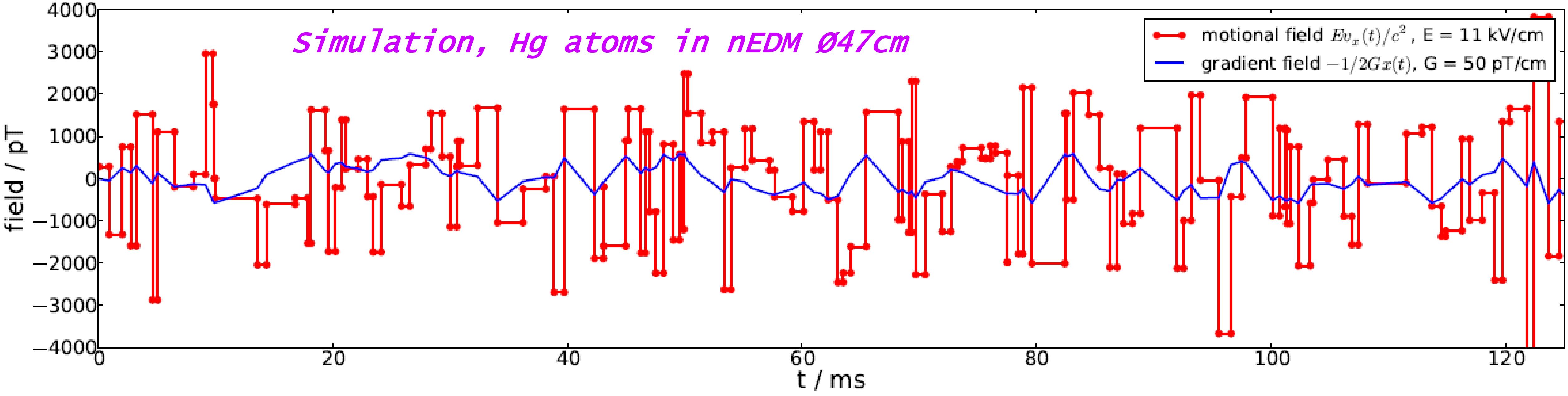
# The co-magnetometer problem: vxE/c$^2$

Transverse “noise”
on a mercury atom
in random motion

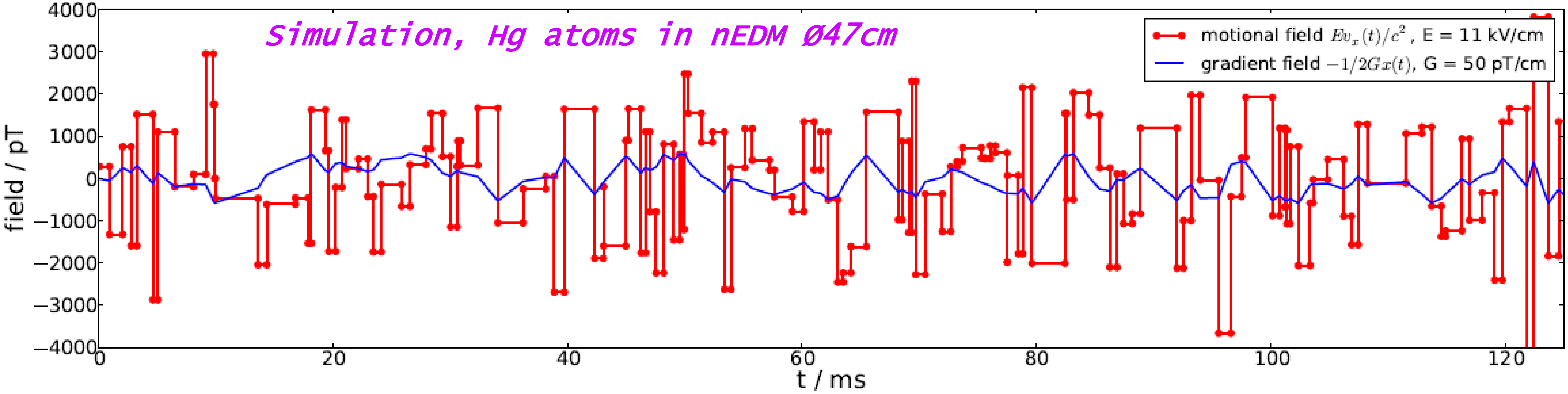
Nonuniform field

relativistic motional field

$$b(t) = \left( \vec{B}(t) + \frac{1}{c^2} \vec{E} \times \vec{v}(t) \right) \cdot \left( \overrightarrow{e_x} + i \overrightarrow{e_y} \right)$$



# The co-magnetometer problem: $v \times E/c^2$




Frequency shift from a transverse magnetic noise $\underline{b}$ (Redfield theory)

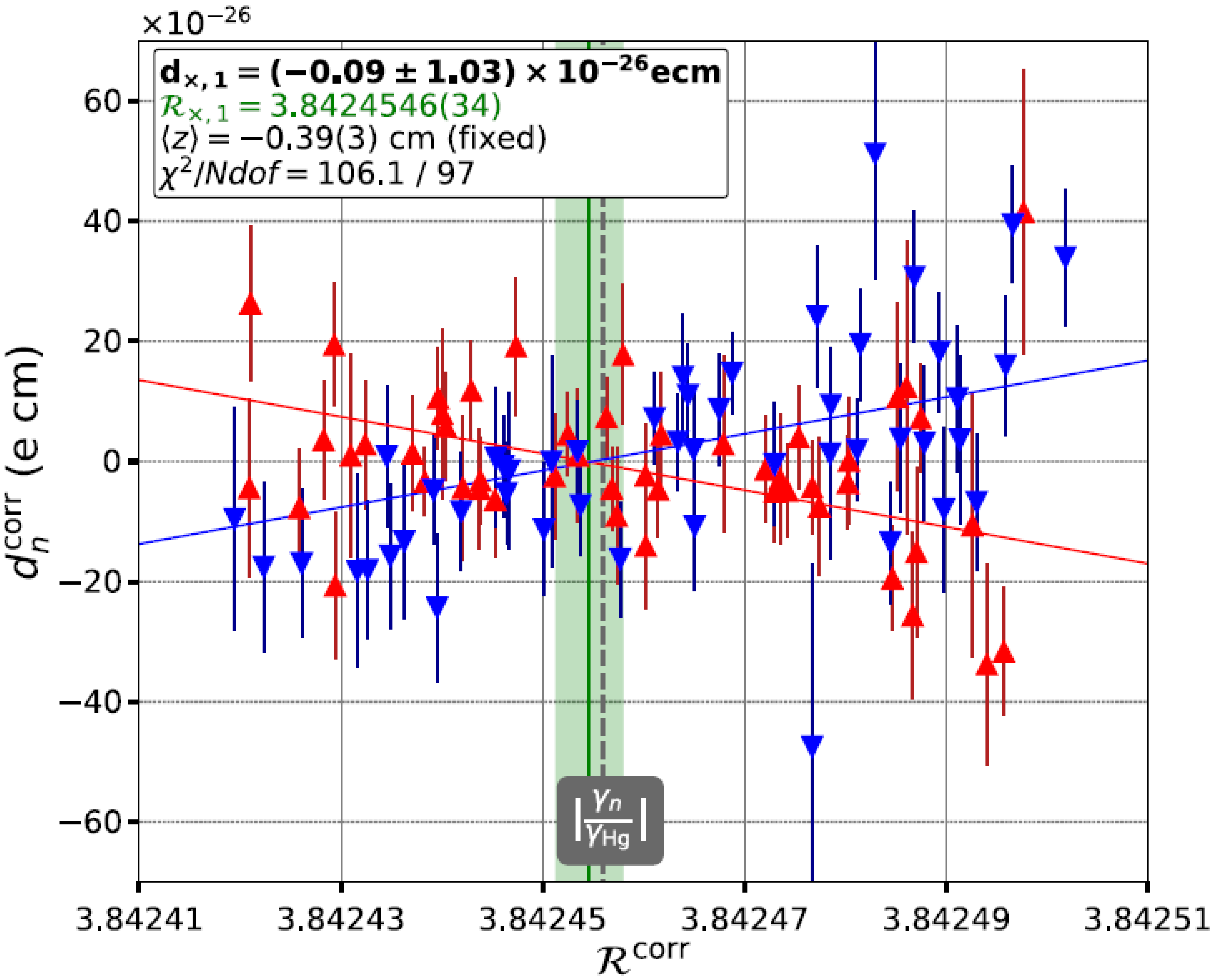
$$\delta f = \frac{\gamma^2}{4\pi} \int_0^\infty d\tau \, \mathrm{Im}\, e^{-i\omega\tau} \langle \underline{b}(0) \underline{b}^*(\tau) \rangle$$

False EDM

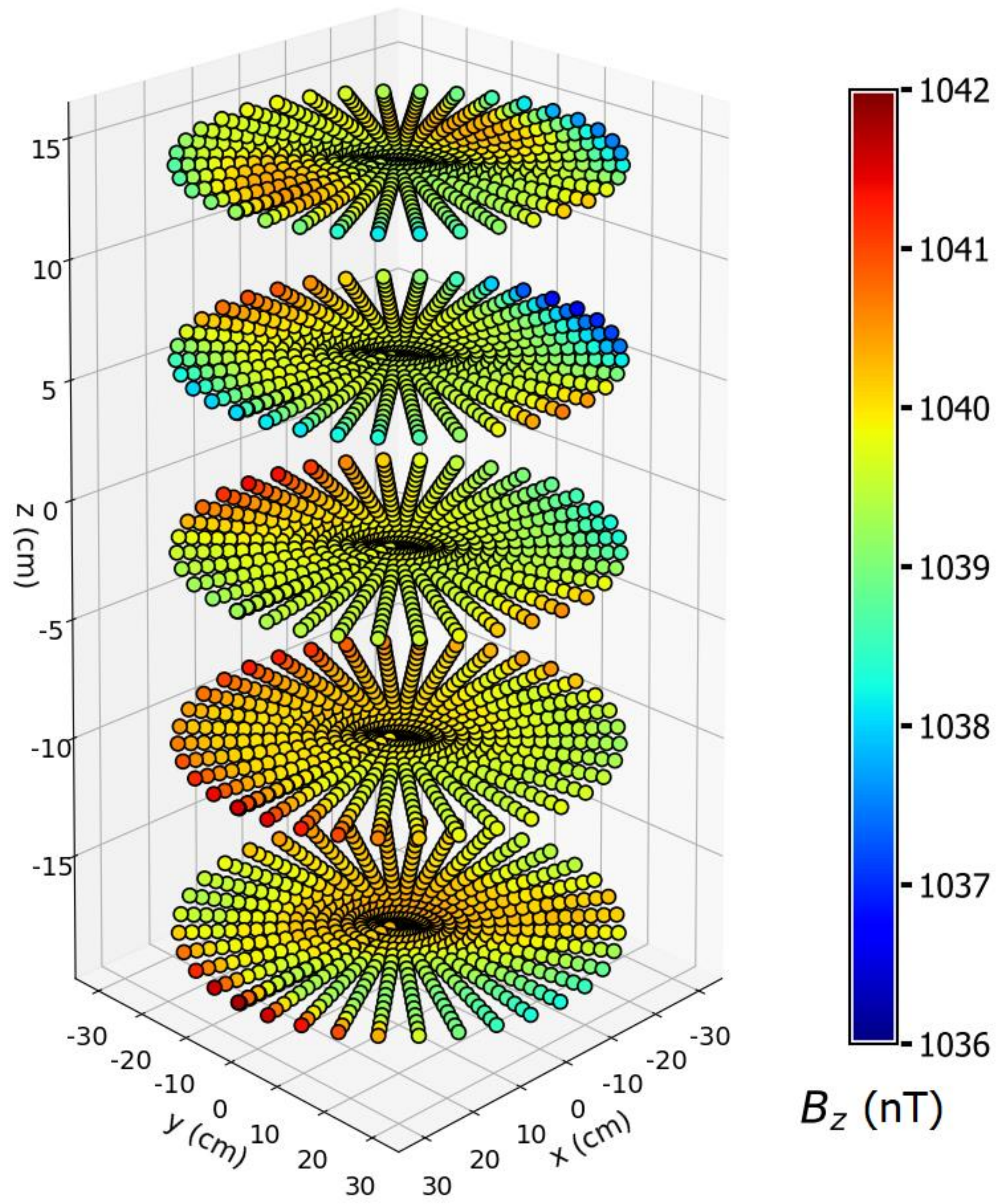
$$d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = -\frac{\hbar |\gamma_n \gamma_{\mathrm{Hg}}|}{2c^2} \langle \boldsymbol{x B_x} + \boldsymbol{y B_y} \rangle$$

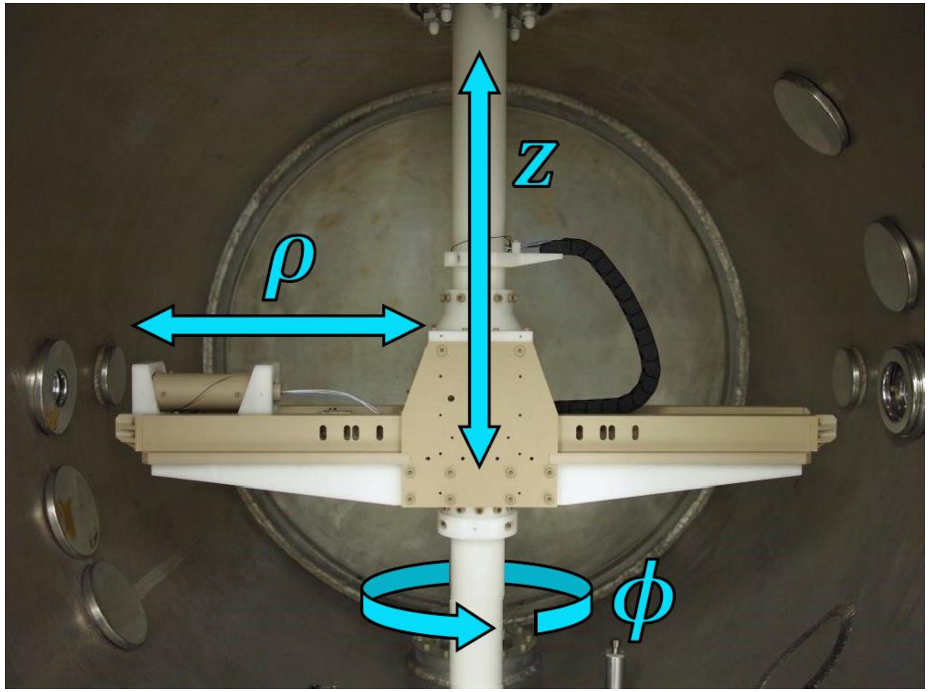
Pignol and Roccia, PRA 85, 042105 (2012)

# Crossing point analysis



# Magnetic field mapping




The « phantom mode » of the magnetic field is extracted from a global analysis of magnetic field maps.

PhD thesis Laura Ferraris-Bouchez (2017-2020)


PHYSICAL REVIEW LETTERS **124,** 081803 (2020)

**Editors' Suggestion** **Featured in Physics**

## Measurement of the Permanent Electric Dipole Moment of the Neutron

We present the result of an experiment to measure the electric dipole moment (EDM) of the neutron at the Paul Scherrer Institute using Ramsey's method of separated oscillating magnetic fields with ultracold neutrons. Our measurement stands in the long history of EDM experiments probing physics violating time-reversal invariance. The salient features of this experiment were the use of a $^{199}$Hg comagnetometer and an array of optically pumped cesium vapor magnetometers to cancel and correct for magnetic-field changes. The statistical analysis was performed on blinded datasets by two separate groups, while the estimation of systematic effects profited from an unprecedented knowledge of the magnetic field. The measured value of the neutron EDM is

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

Formidable investissement collectif du LPSC sur les projets nEDM/n2EDM depuis 15 ans !

# Le futur

Special credits to

Elec : Olivier Bourrion, Eric Lagorio, JP Scordilis, Christophe Vescovi et l'équipe du routage

Meca : Christian Fourel, Denis Grondin, Johann Menu, et l'équipe de l'atelier

Informatique : Guillaume Dargaud, Jérome Fulachier, Jérome Odier

SDI : Rémi Faure, Marc Marton, JF Muraz, Myriam Migliore, Clément Thomassé

Admin : Colette Deslorieux, Isabelle Dos-Santos, Cécile Martin, Cécile Vannier