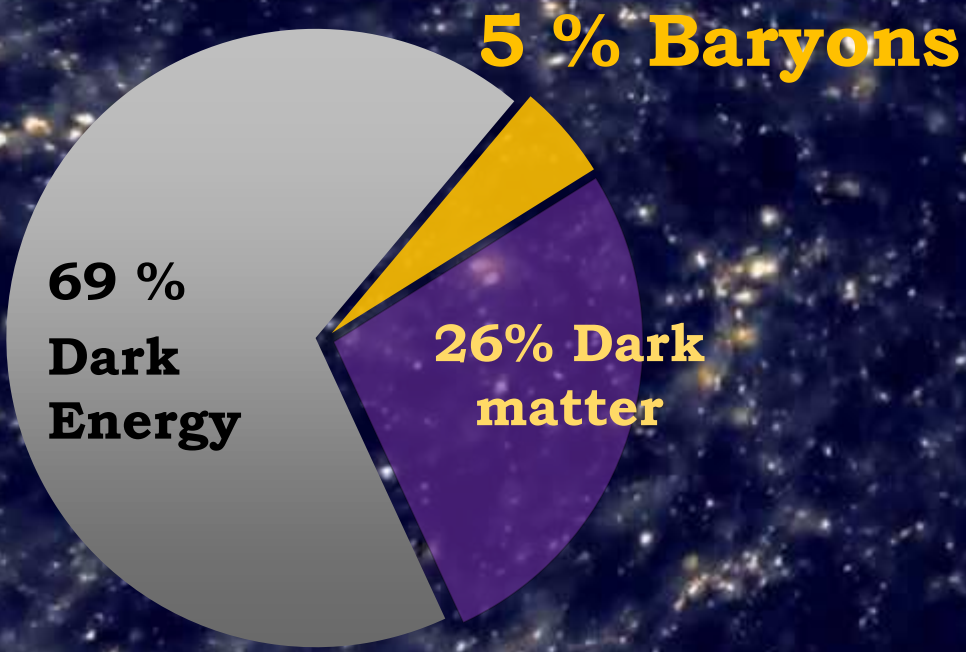
Search for the electric dipole of the neutron

Guillaume Pignol, 29 Avril 2019
Séminaire LPNHE Paris

Why is there more matter than antimatter in the Universe?

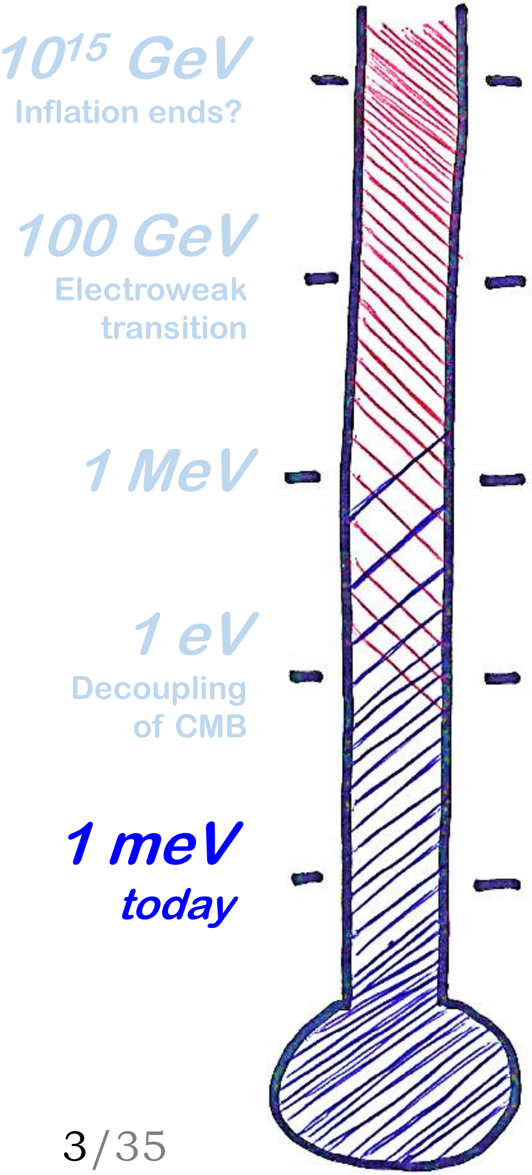
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 1 \text{ per billion}$$

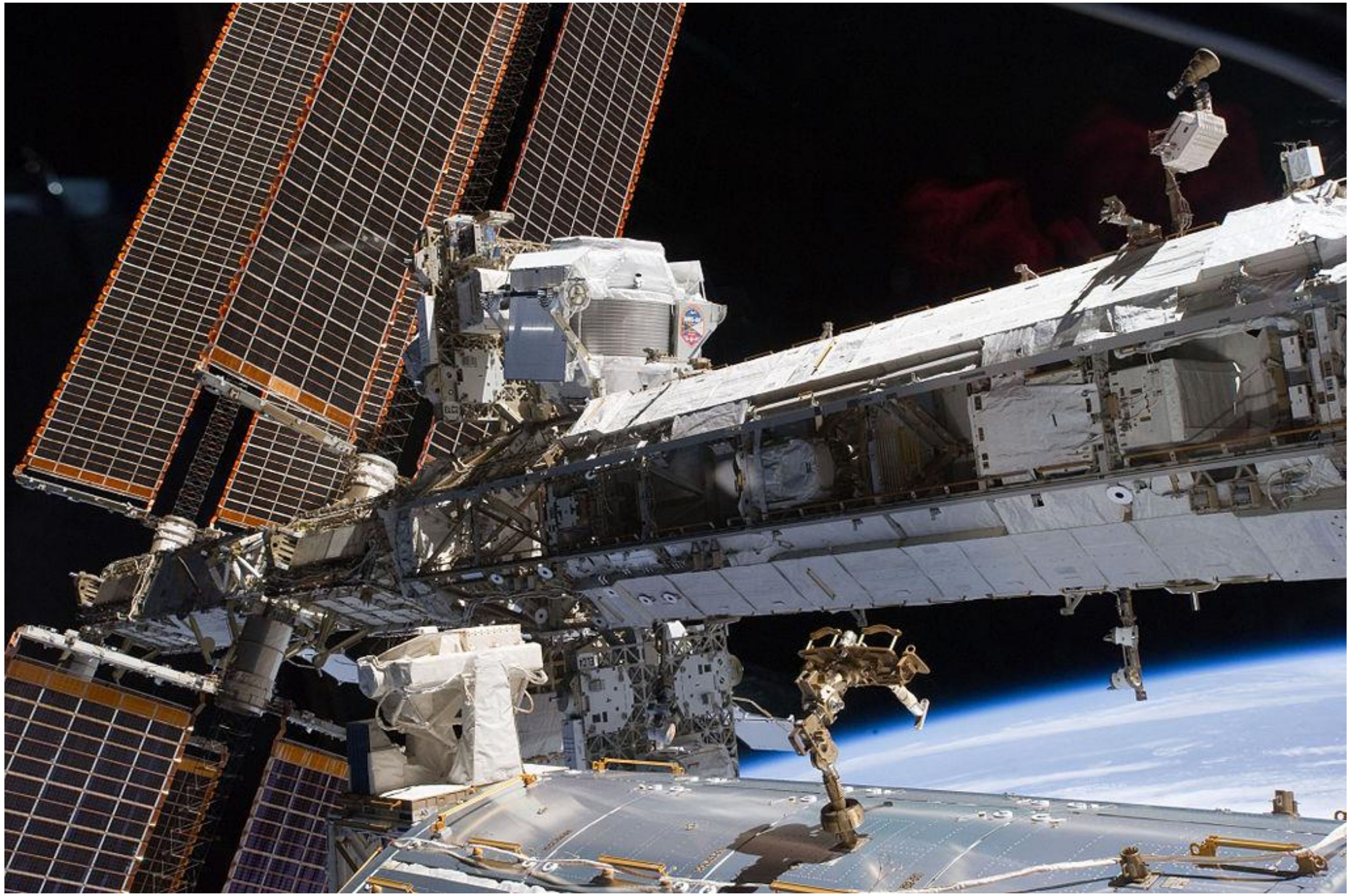


Sakharov's baryogenesis recipe (1967)

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

Antibaryons in the Universe

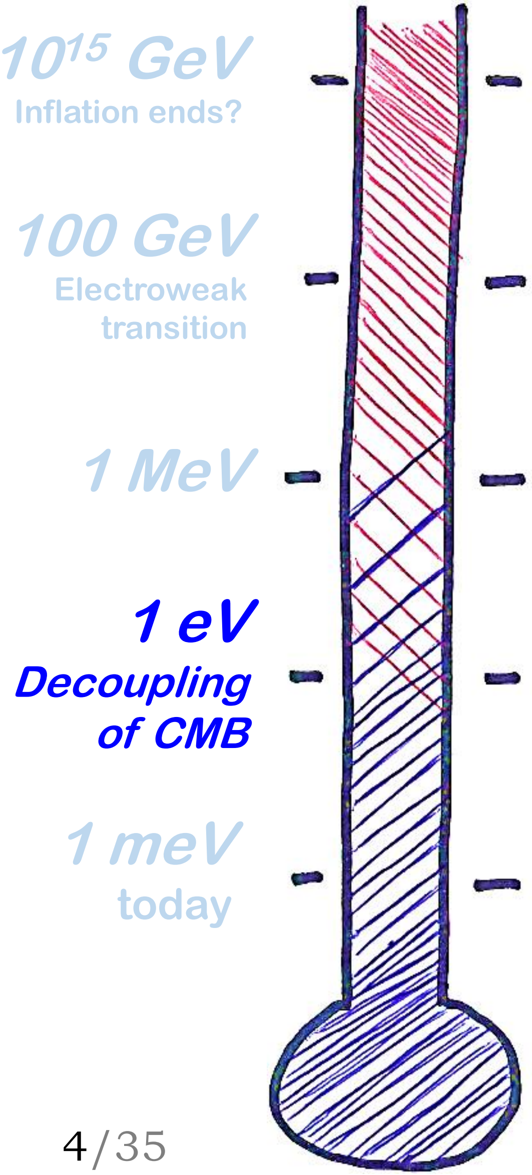


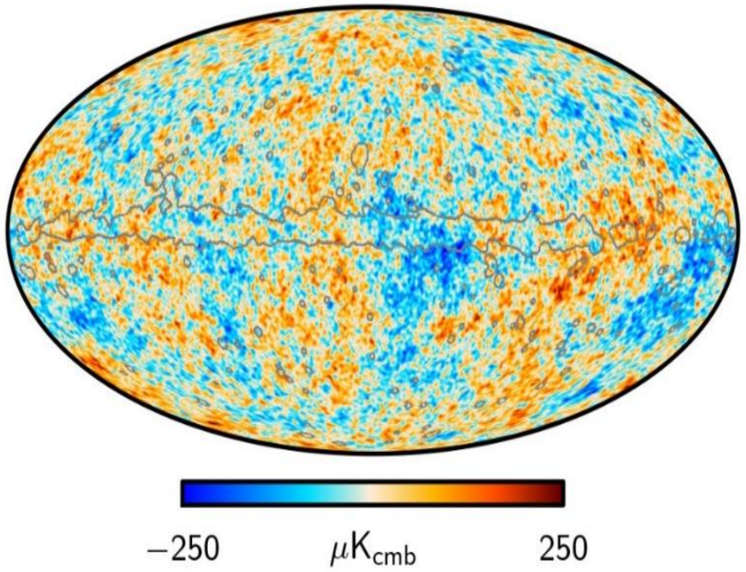


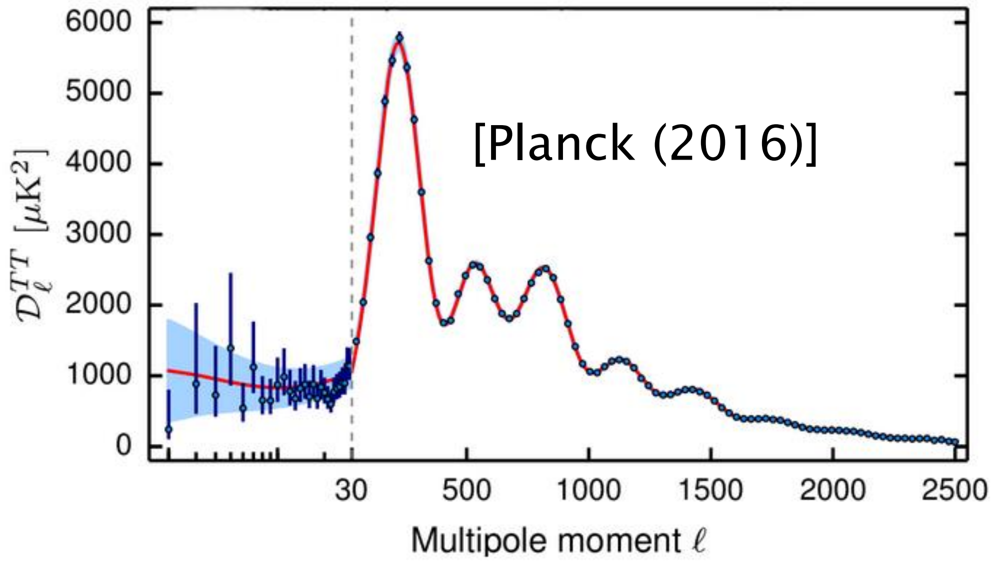
AMS onboard the International Space Station

4 billion of helium events collected, no antihelium

Cosmic microwave background

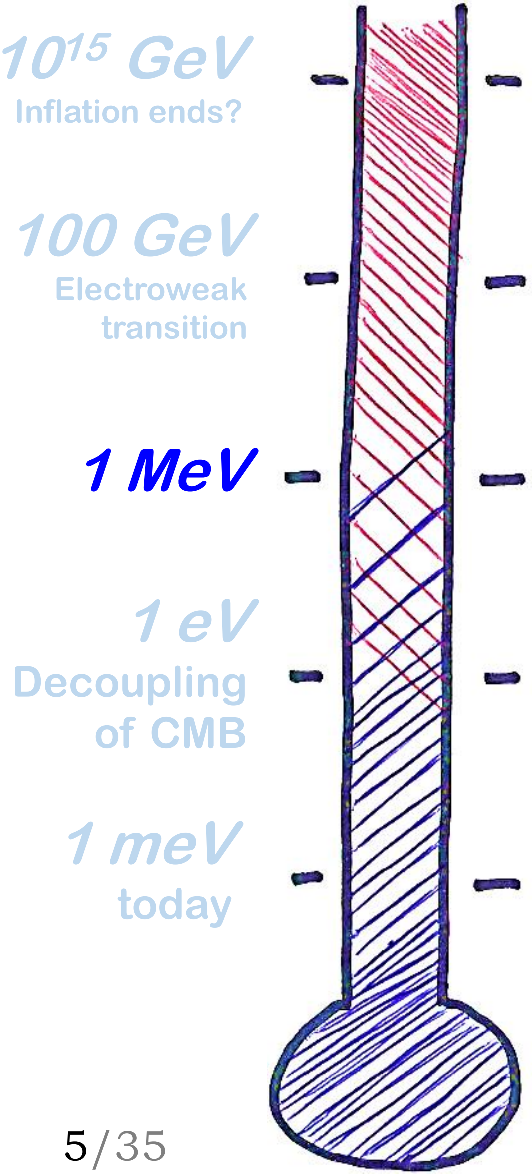


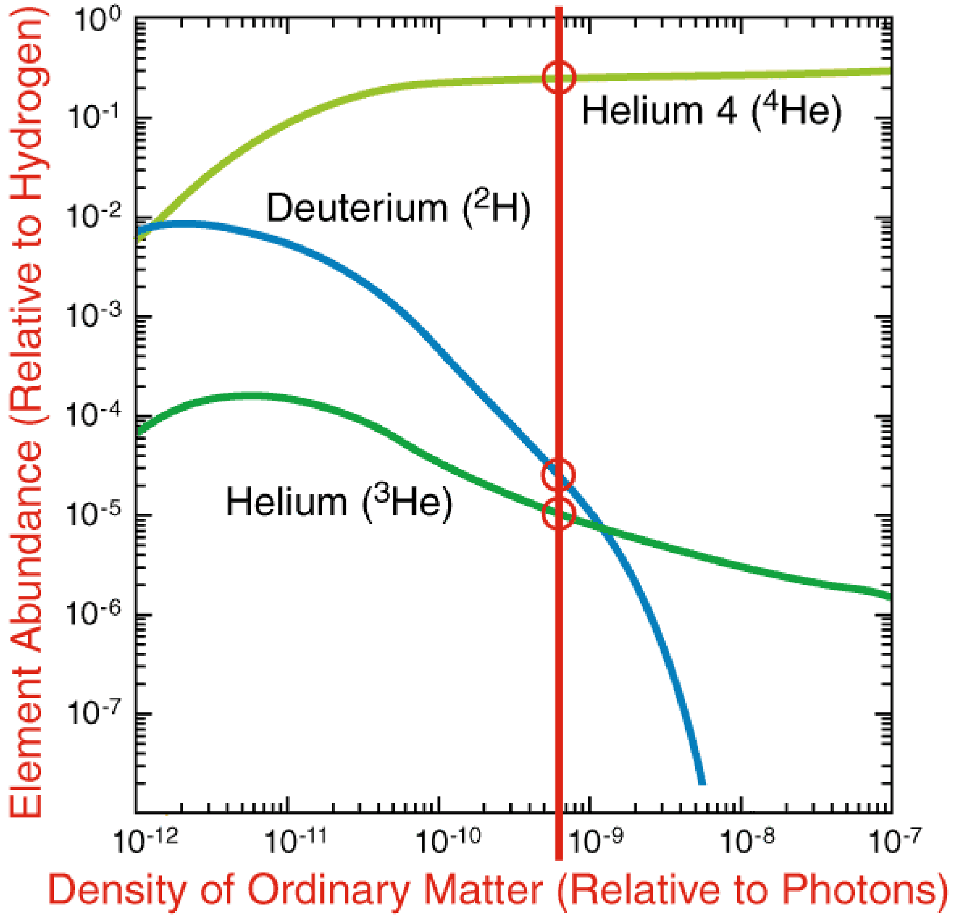




$$\eta_{\rm CMB} = (6.09 \pm 0.05) \times 10^{-10}$$

Big Bang nucleosynthesis

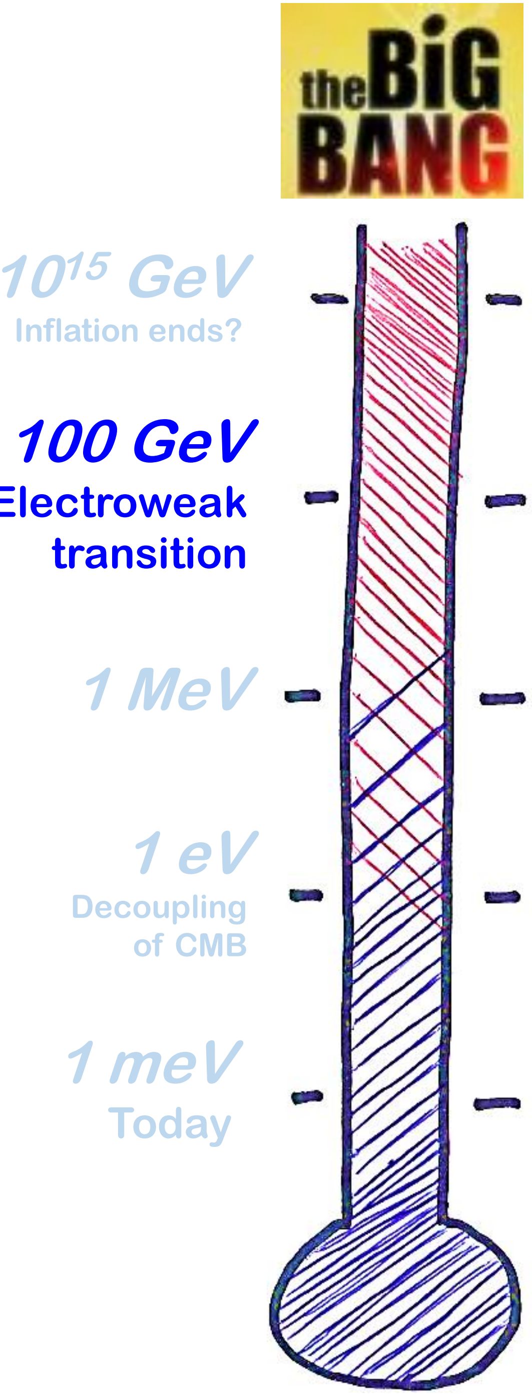


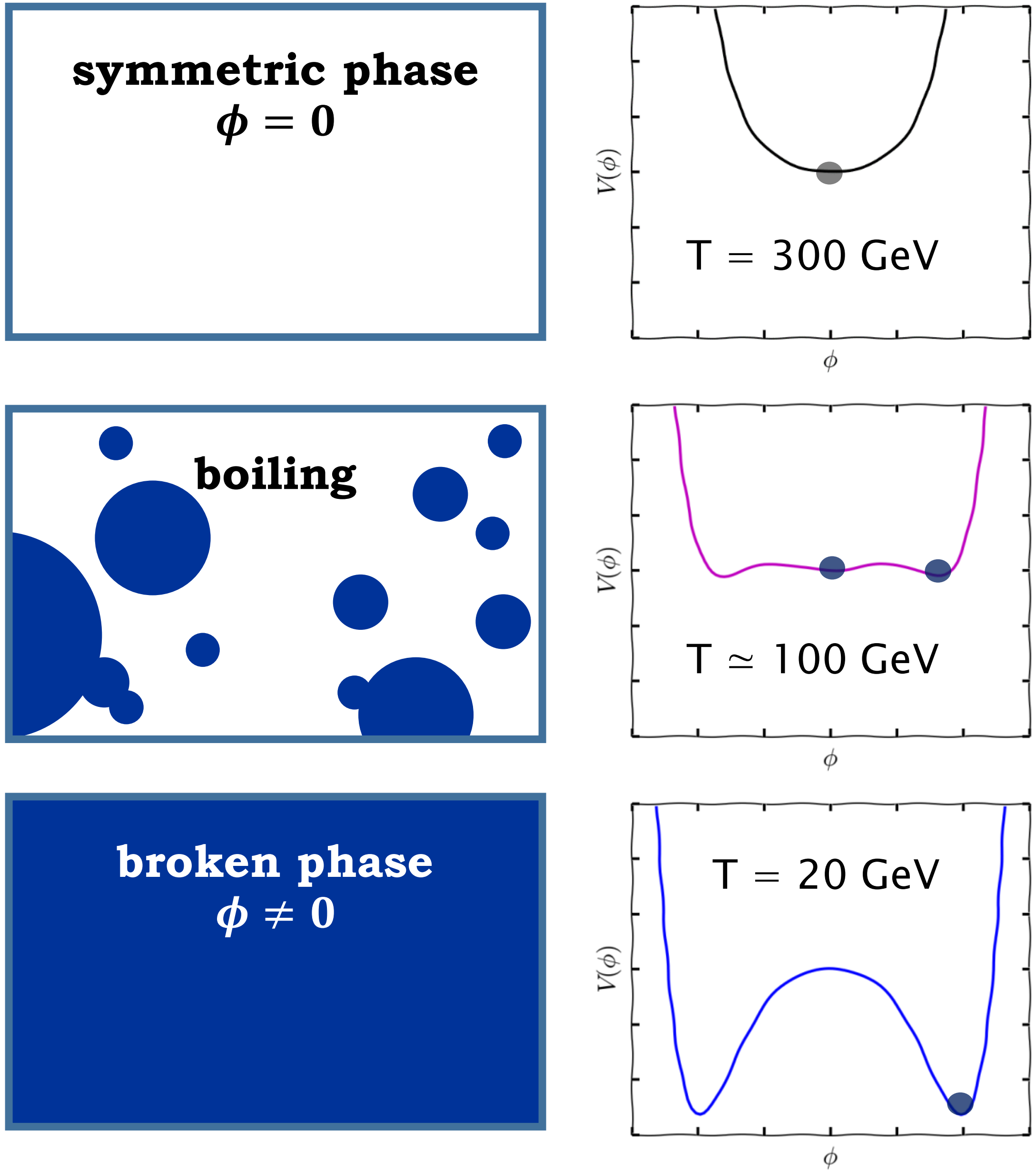


[Deuterium abundance from Lyα, Cooke *et al* (2014)]

$$\eta_{\rm BBN} = (6.0 \pm 0.1) \times 10^{-10}$$

Electroweak baryogenesis?





Sakharov's conditions

- Baryon number not conserved
- **Universe out of equilibrium**
- Violation of CP symmetry

CP violation in weak interactions

- Tiny ($\sim 10^{-3}$) CP asymmetry discovered by Cronin and Fitch (1964)

  looking at $K^0 \to \pi^+\pi^-$ $\quad u\bar{d} \leftarrow d\bar{s} \rightarrow u\bar{d}$

- Explained by the Kobayashi-Maskawa mechanism (1973)

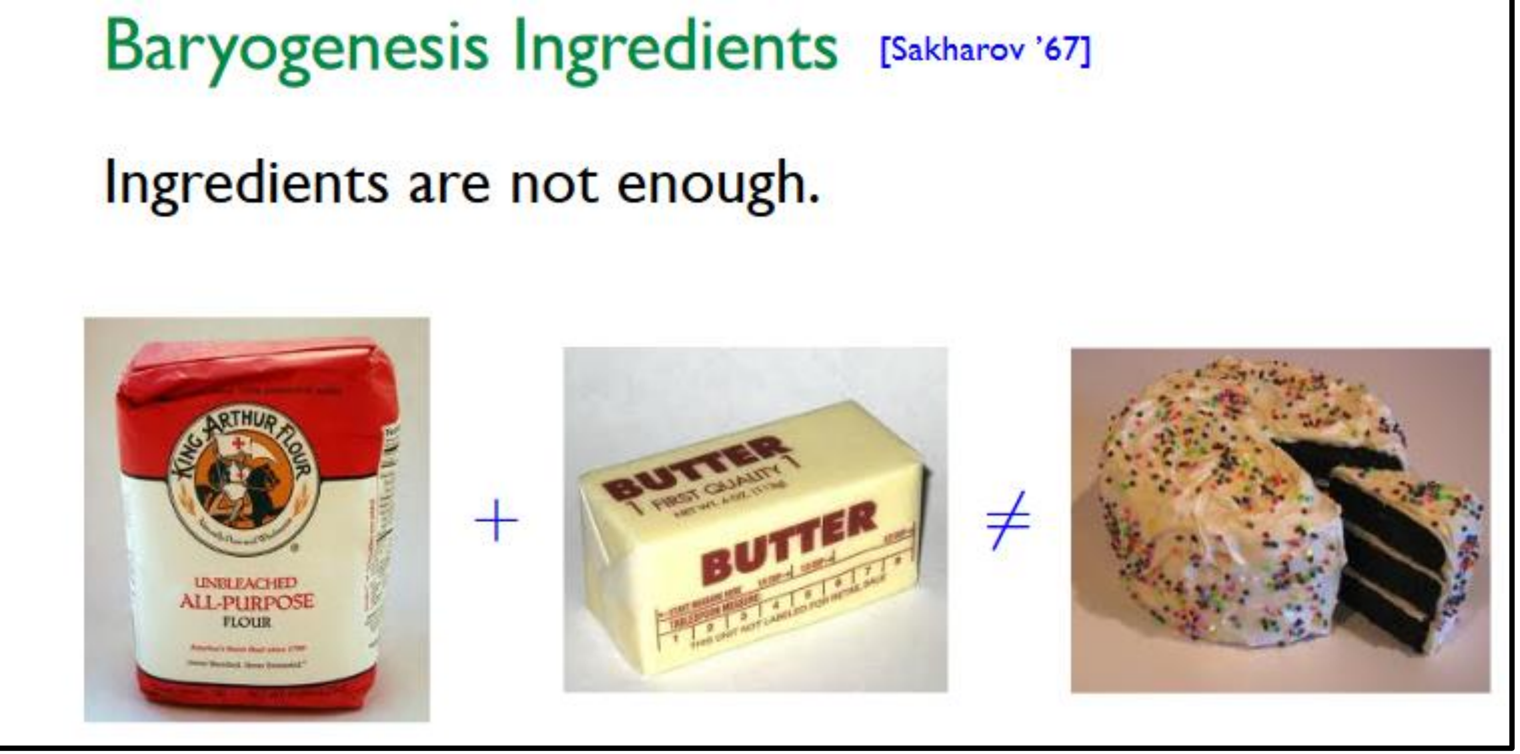
$$\text{Flavour eigenstates} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \text{Mass eigenstates}$$

Complex CKM matrix

- Confirmed with "B factories" in 2000's with many observables, e.g.

$$\Gamma(B^0 \to \pi^+\pi^-) \neq \Gamma(\overline{B^0} \to \pi^-\pi^+) \quad u\bar{d} \leftarrow d\bar{b} \rightarrow u\bar{d}$$

Asymmetry $\approx 30\,\%$!



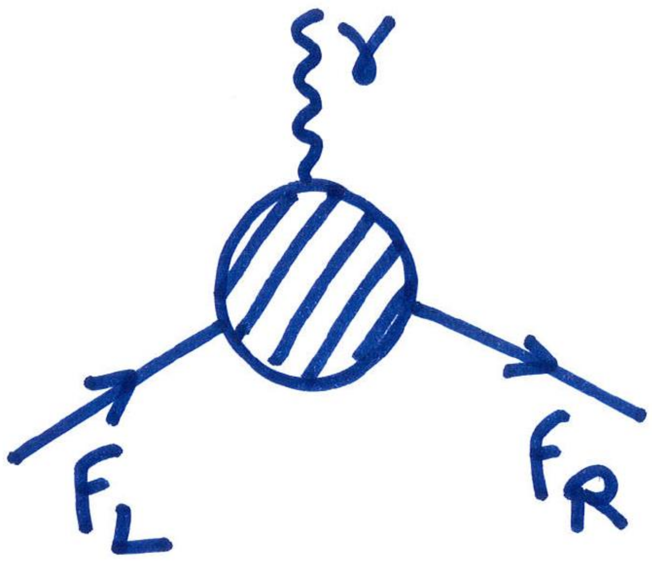
Failure of SM electroweak baryogenesis: needs new physics

Departure from thermal equilibrium: the EW phase transition is 2d order in SM. New physics is required in the scalar sector.

Non-conservation of B: ok in the SM with sphalerons transitions!

CP violation: SM not good enough. **Requires CP violation beyond the Standard Model at the ~TeV scale**

Electric dipoles & CP symmetry



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

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

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

$d_n < 3 \times 10^{-26}\ e$ cm (Grenoble, 2006)

$d_e < 1 \times 10^{-29}\ e$ cm (Harvard, 2018)

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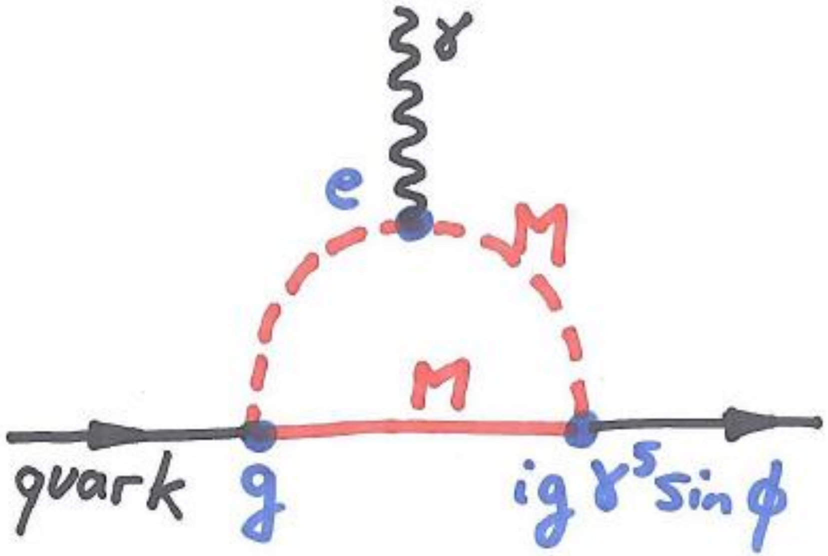
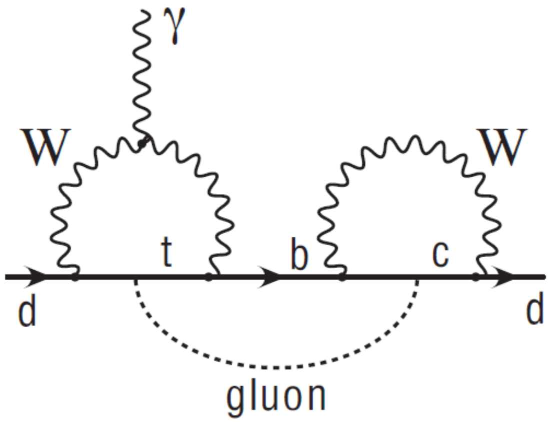


$$d_n \approx e\frac{g^2}{16\pi^2}\sin\phi\,\frac{m_q}{M_{\rm CPV}^2}$$

$$\approx \left(\frac{1\ \text{TeV}}{M_{\rm CPV}}\right)^2 \sin\phi \times 10^{-25}\ e\ \text{cm}$$

Two sources of EDMs in the SM



CKM contribution to the quark EDM vanishes at two loops…

Prediction: $d_n \approx 10^{-33} e$ cm
Kobayashi-Maskawa background negligible

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

Generates an enormous EDM

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

EDMs beyond the SM: SUSY

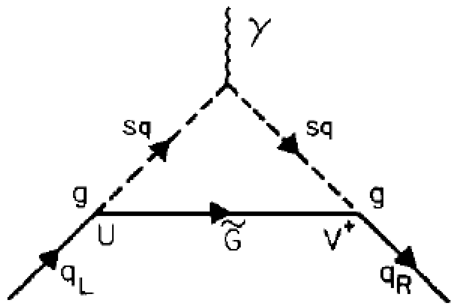


Fig. 2. One-loop diagram which may contribute to d_n in a softly broken susy model.

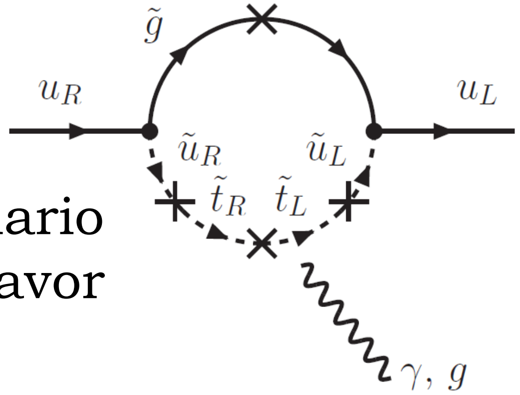
Ellis, Ferrara, Nanopoulos, PLB 114 (1982).
EDM induced by soft mass terms for squarks and gluinos

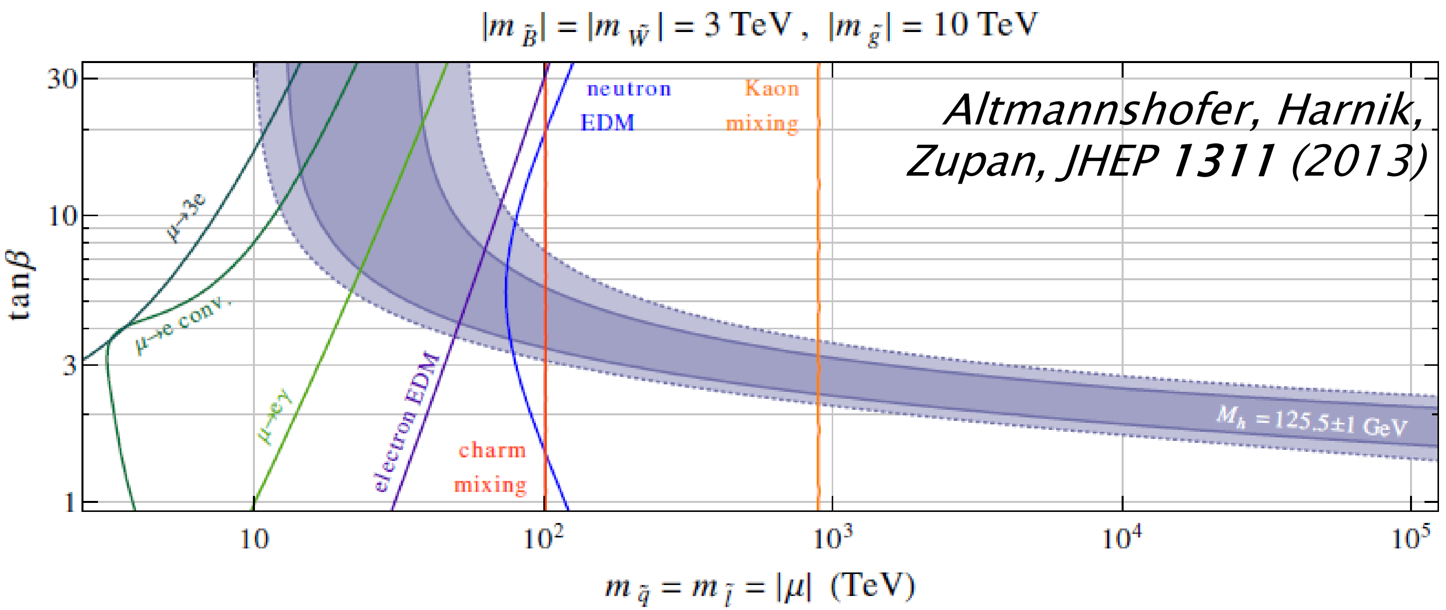
MSSM contains ~40 CP violating imaginary parameters…

$$d_n \approx e\,\frac{\alpha}{4\pi}\,\frac{m_q}{M_{CPV}^2} \approx \left(\frac{1\ \mathrm{TeV}}{M_{CPV}}\right)^2 \times 10^{-25}\ e\ \mathrm{cm}$$

« SUSY CP problem »

Split SUSY scenario with anarchic flavor mass matrix





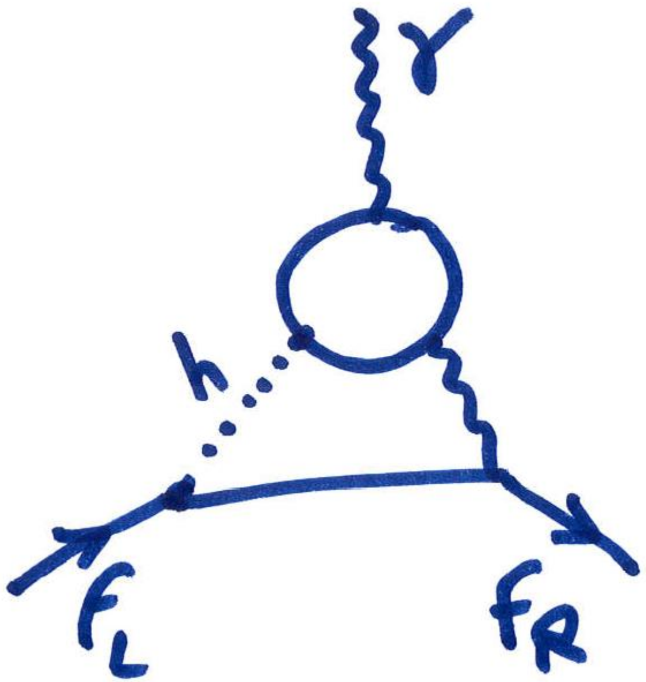
Altmannshofer, Harnik, Zupan, JHEP 1311 (2013)

EDMs beyond the SM: modified Higgs couplings

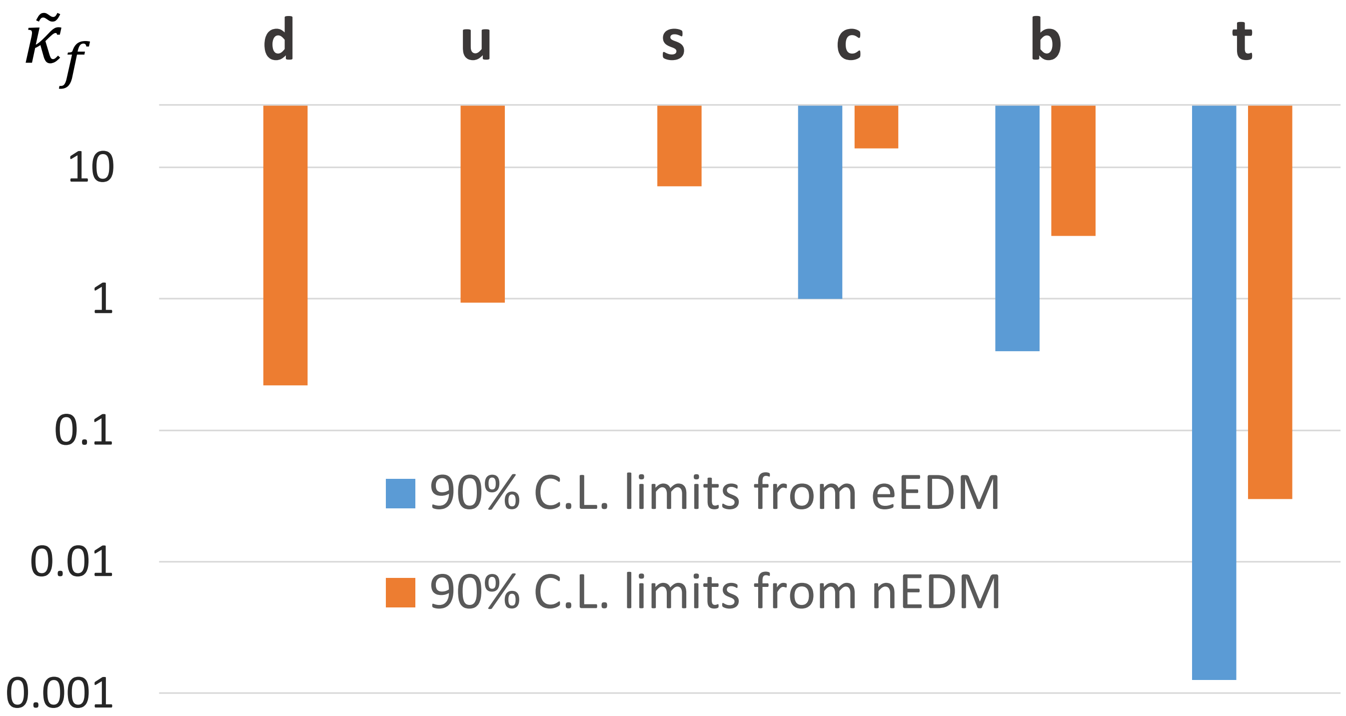
Modified Higgs-fermion Yukawa coupling: $\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h\right)$

CP violating

Generates EDM at 2 loops



Barr, Zee, PRL ***65*** *(1990)*

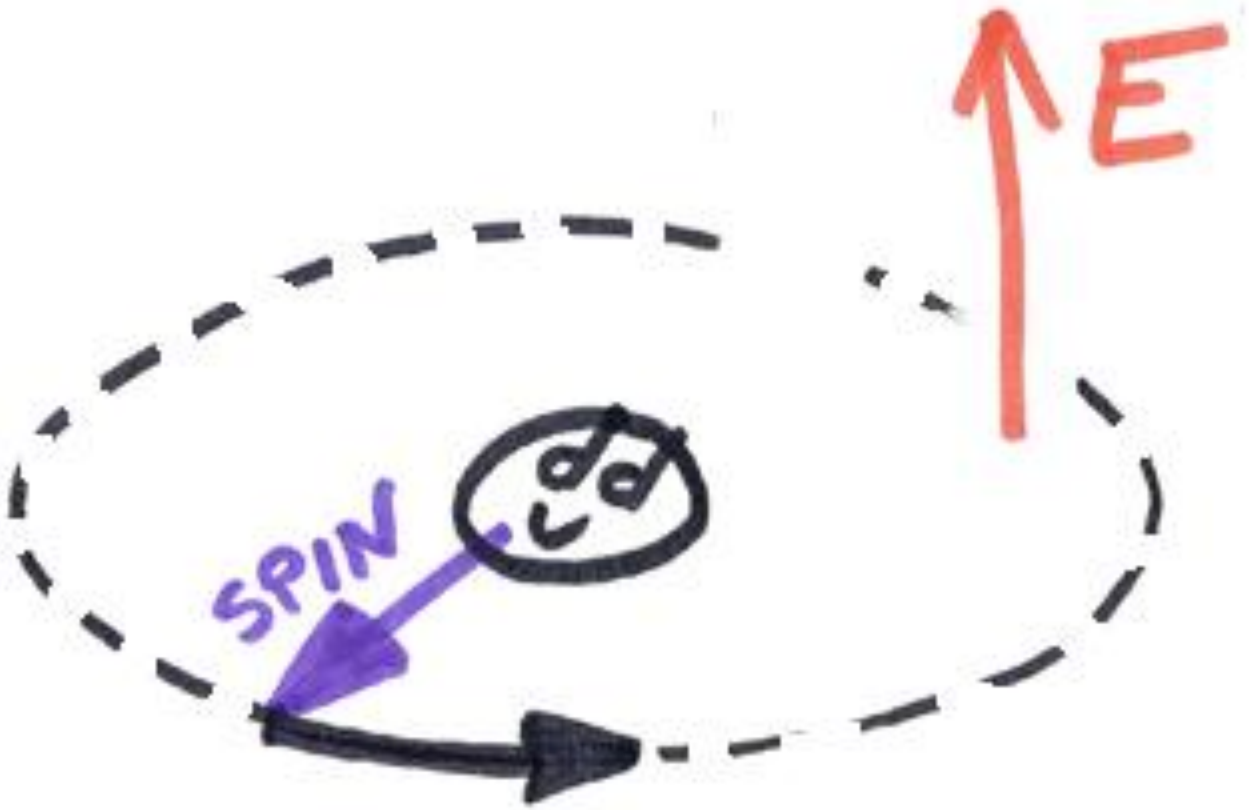


Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480

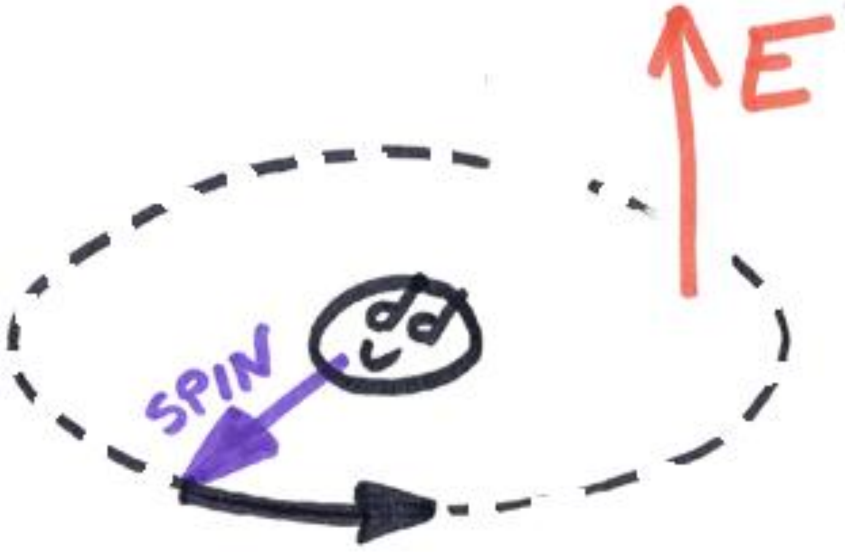
How to measure the neutron EDM?

Rotation of the spin in an external E field

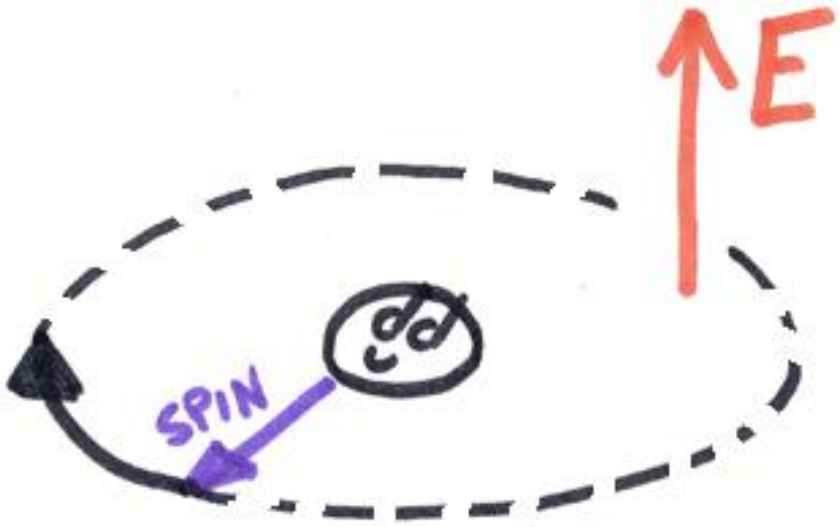
$$\hat{H} = -d_n \, \vec{E} \cdot \hat{\vec{\sigma}}$$



Violation of time reversal



>> PLAY >>



<< REWIND <<

If $d_n \neq 0$ the process and its time reversed version are different. $\Rightarrow$ Violation of T $\xRightarrow{CPT}$ Violation of CP

Detecting the neutron electric dipole

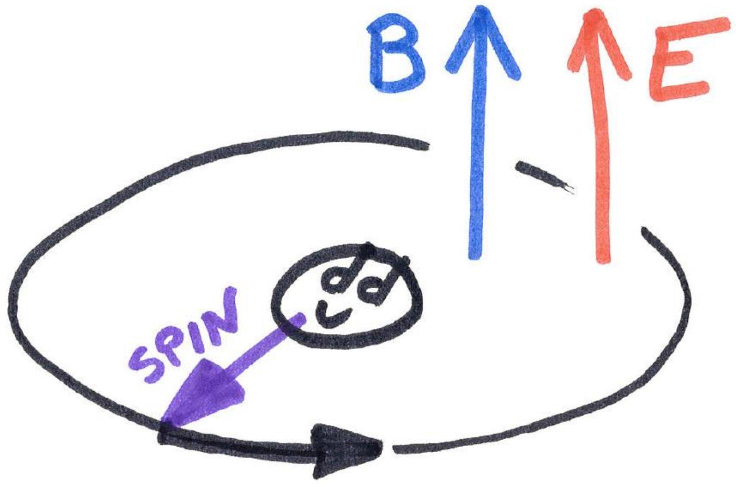
$$\hat{H} = -d_n\, \vec{E} \cdot \vec{\sigma}$$

If the neutron EDM is $d_n = 10^{-27}\, e$ cm
And the electric field is $E = 15$ kV/cm
The neutron spin will make **one full turn** in a time
$\frac{\pi\hbar}{d_n E} = 1.4 \times 10^6$ s = **4 years**

In order to detect such a minuscule coupling we need:

- The slowest possible neutrons
  to maximize the interaction time in the electric field
- An intense source of such neutrons
  to maximize the statistical sensitivity

Importance of the magnetic field



$$f_n = \left|\frac{\mu_n}{\pi\hbar} B\right| \mp \frac{d_n}{\pi\hbar} |E|$$

30 Hz @ 1 μT

7×10^{-7} Hz @ 15 kV/cm

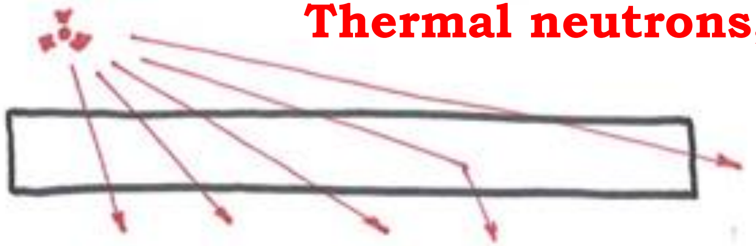
for $d_n = 1 \times 10^{-27} e\mathrm{cm}$

Basic measurement strategy

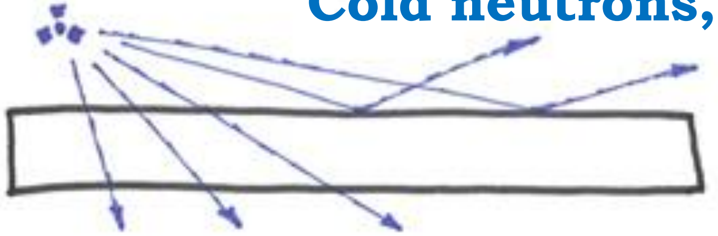
$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d_n E$$

Neutron optics, cold and ultracold neutrons

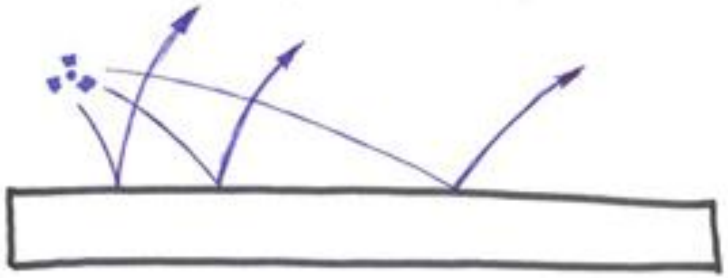
Thermal neutrons, E=25 meV

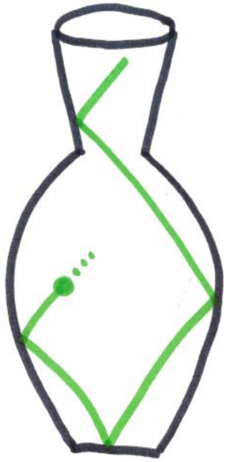


Cold neutrons, E<25 meV



Ultracold neutrons E< 200 neV

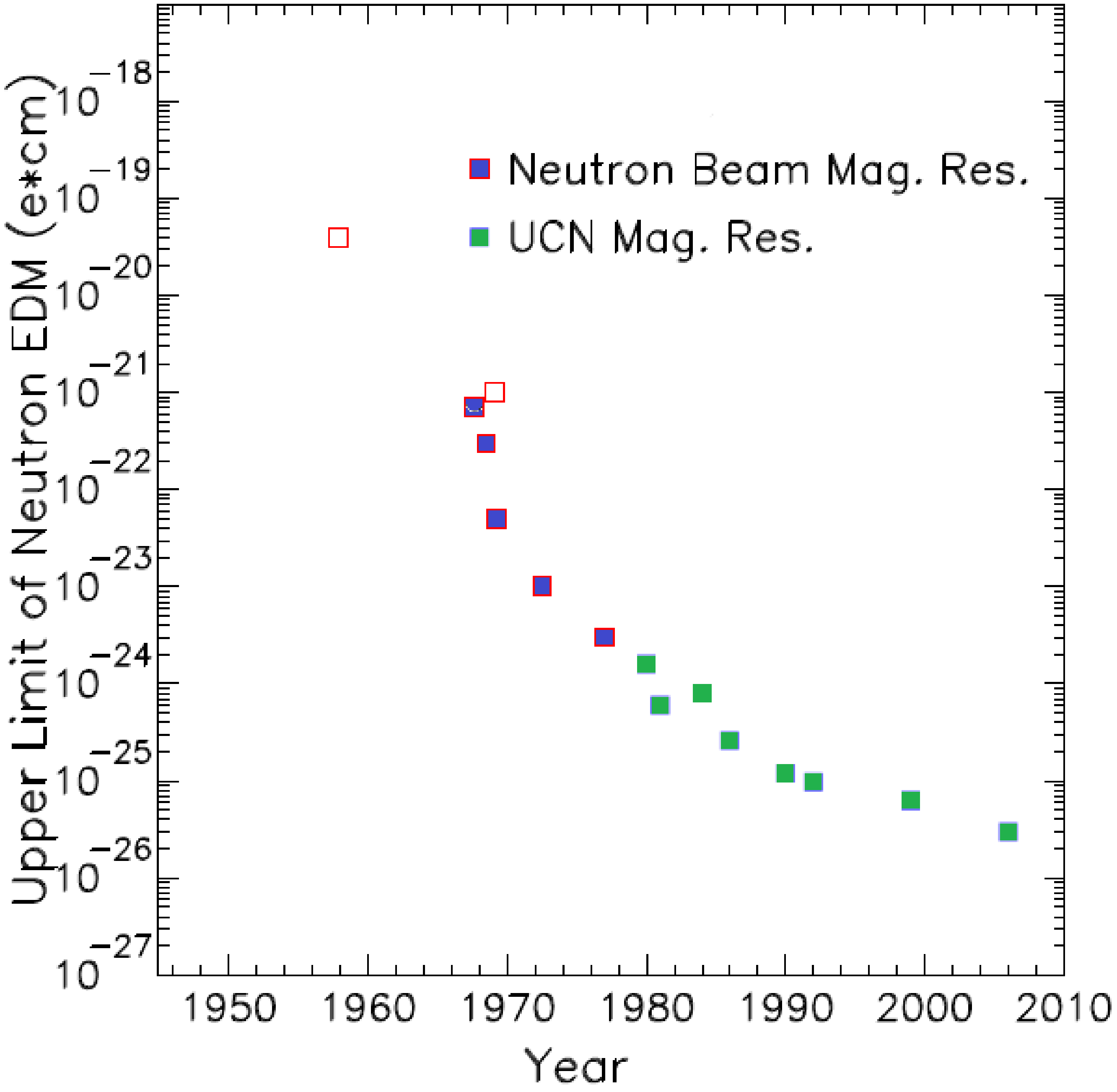




Neutrons with energy < 200 neV, are totally reflected by material walls.

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

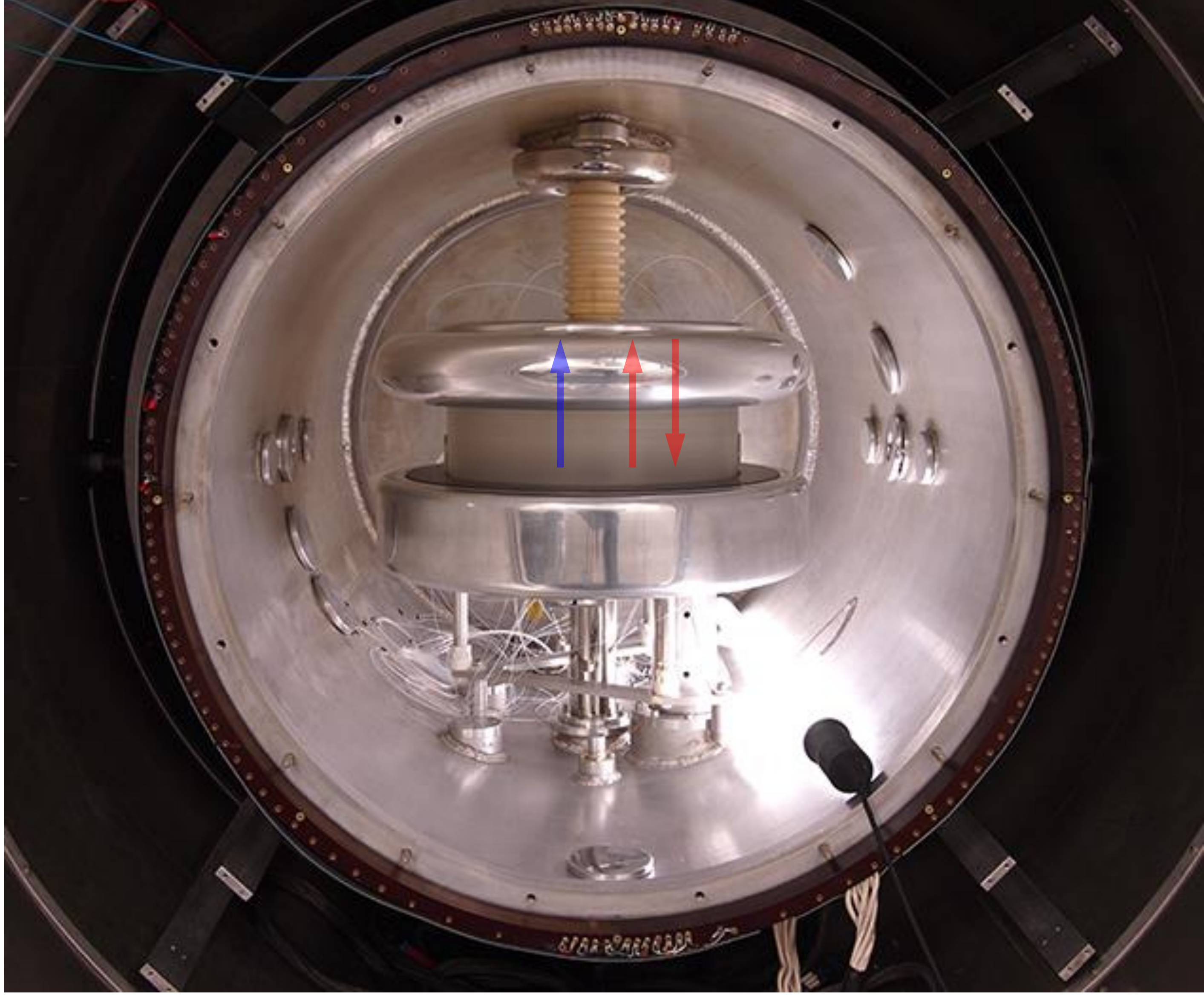
They are significantly affected by gravity.



The slower, the better...

The Sussex/RAL/ILL apparatus

Apparatus installed at the ILL reactor Grenoble (~1980-2009)



Best limit: $d_n < 3 \times 10^{-26}\ e\ \mathrm{cm}$

Baker et al, PRL (2006); Pendlebury et al, PRD (2015)

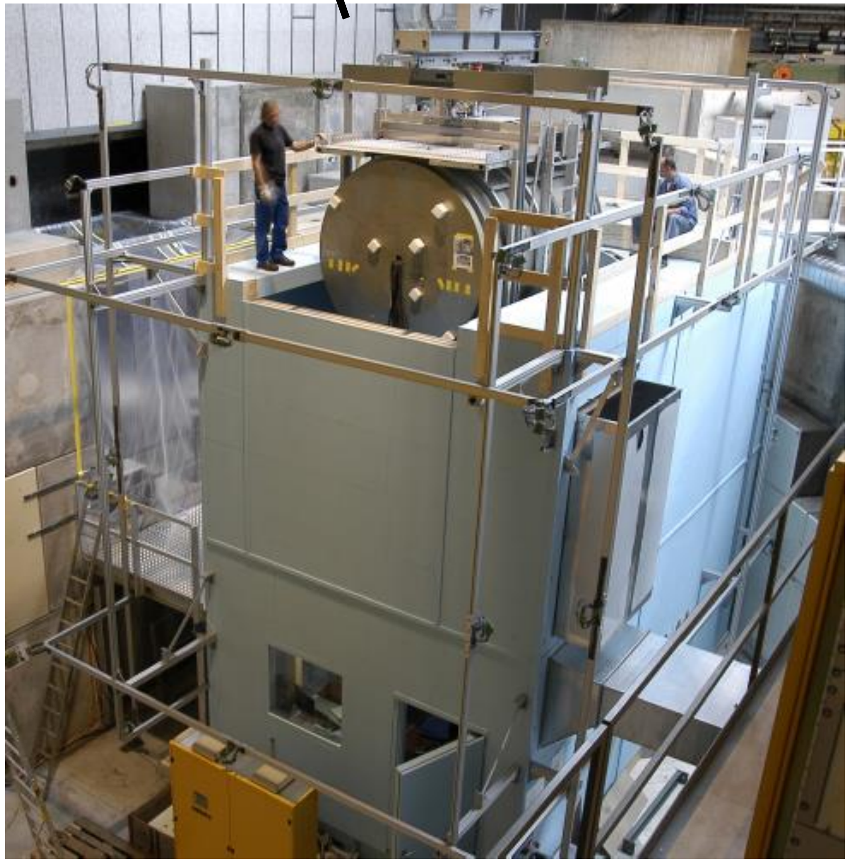
History of the venerable UCN nEDM apparatus

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



Dismantling nEDM
Installing n2EDM

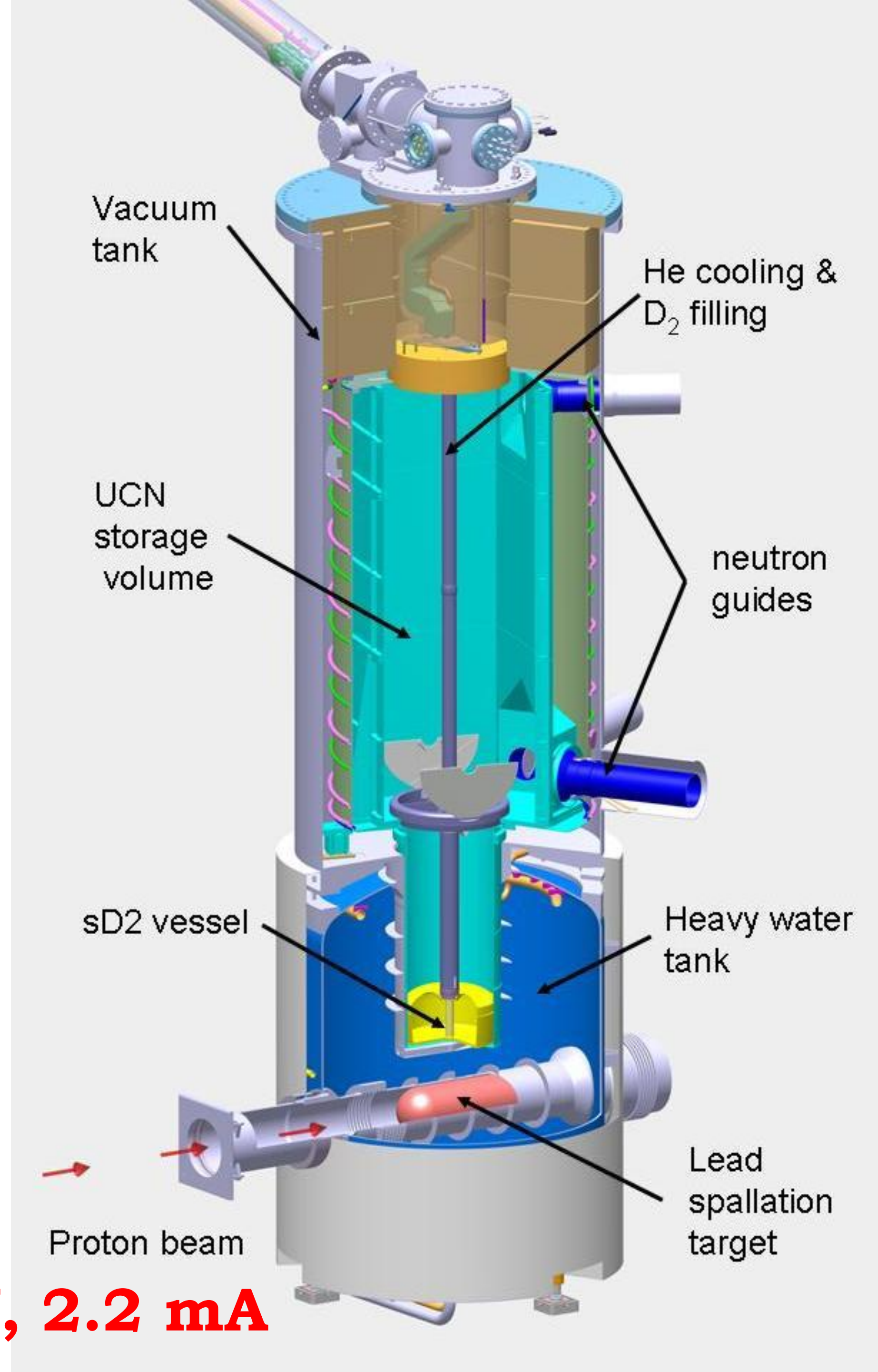
Move of the apparatus at
Paul Scherrer Institute (PSI)

UCN source at the Paul Scherrer Institute

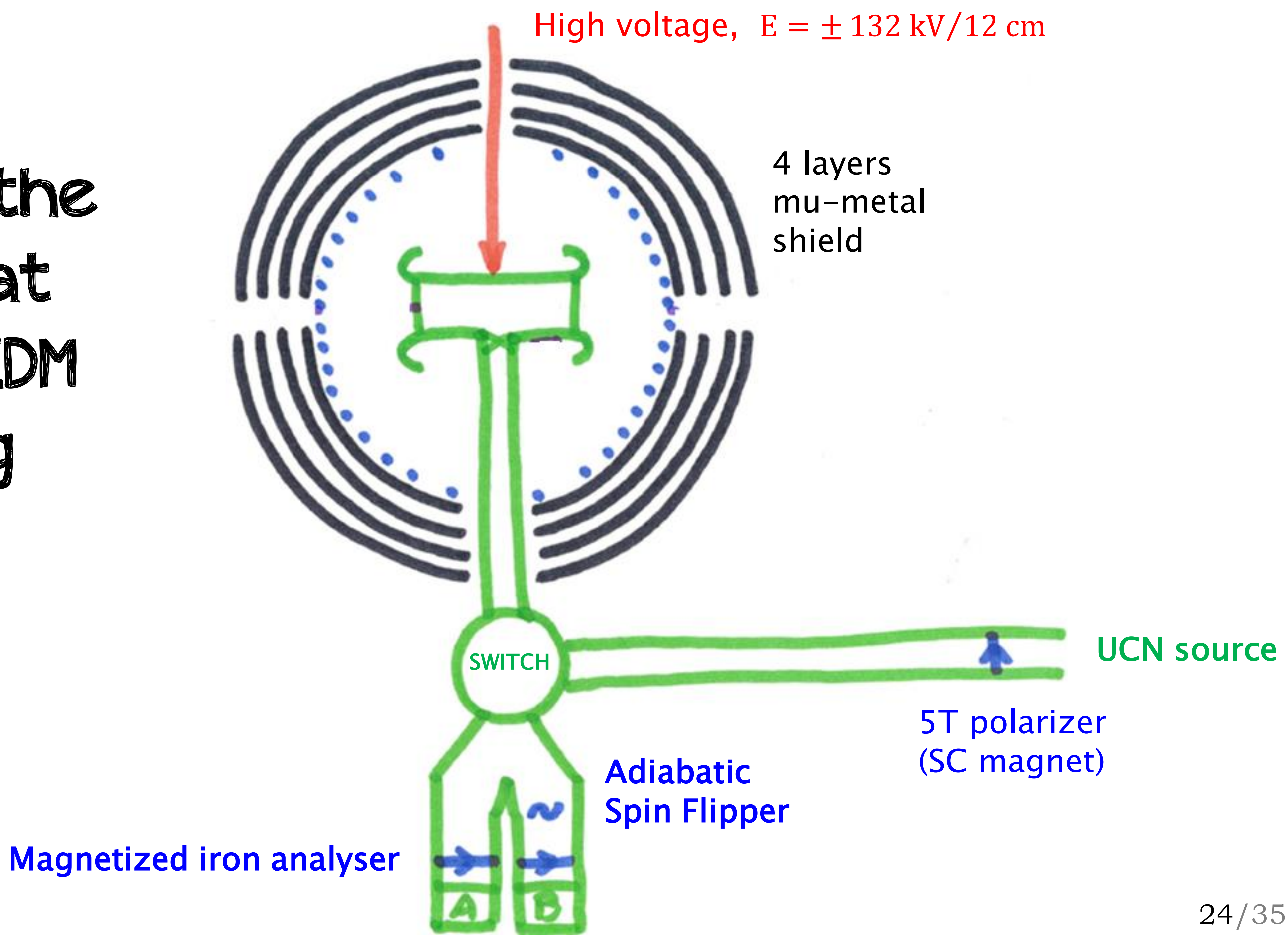
pulsed UCN source
One kick per 5 min
online since 2011

Intensity frontier!!

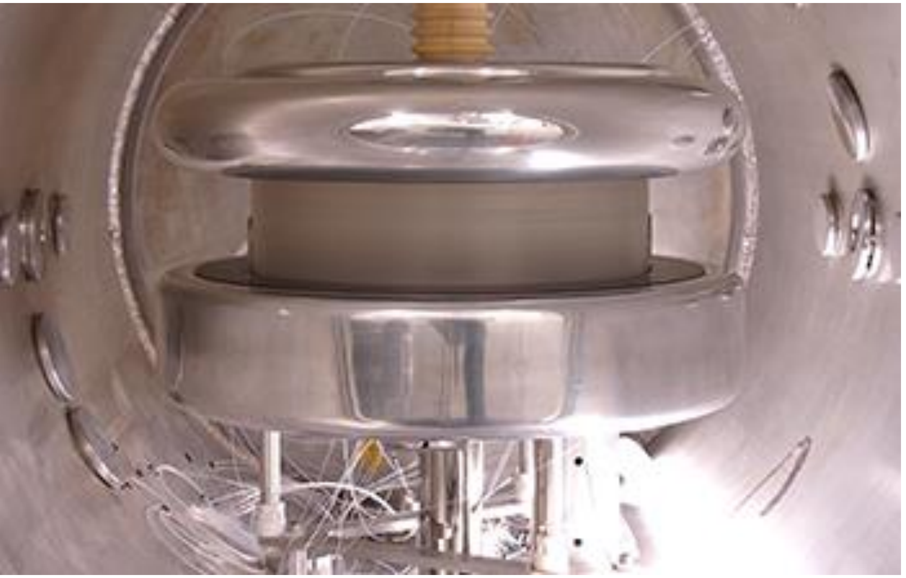
600 MeV, 2.2 mA

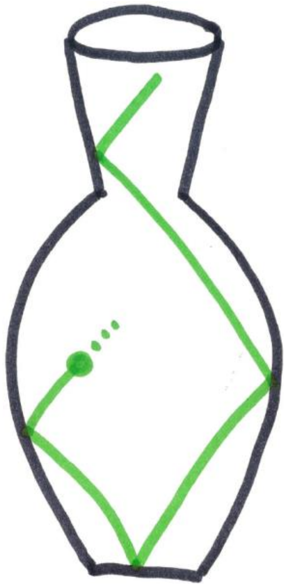


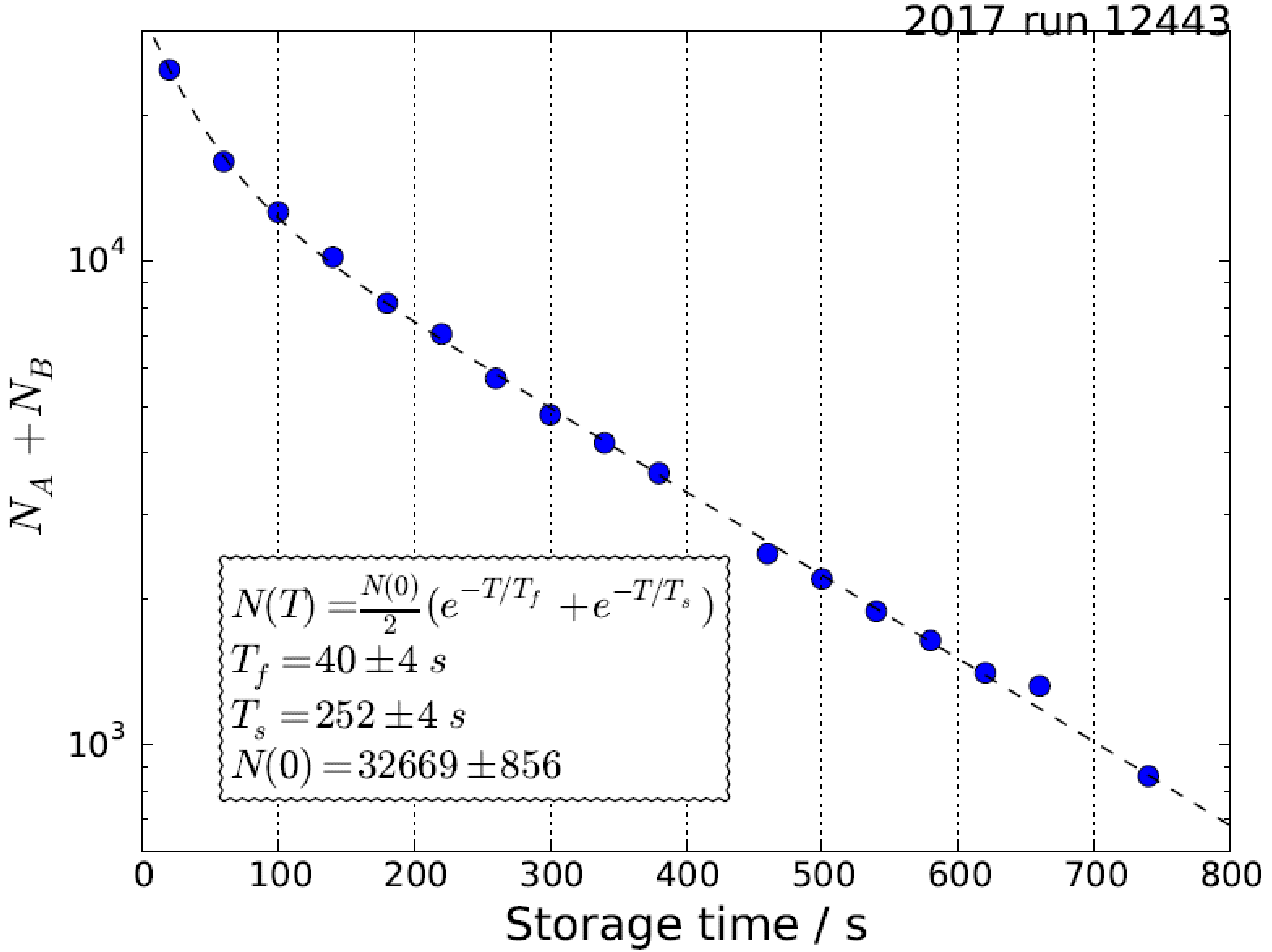
Scheme of the apparatus at PSI during EDM data-taking 2015-2016



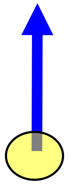
Storing Ultracold neutrons in the nEDM apparatus



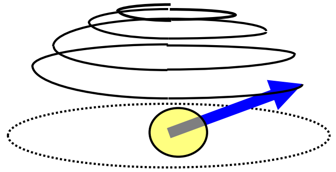




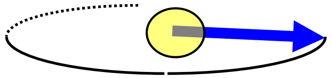
Ramsey's method



"Spin up" neutron...

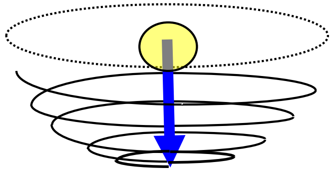


Apply π / 2 spin-flip pulse...

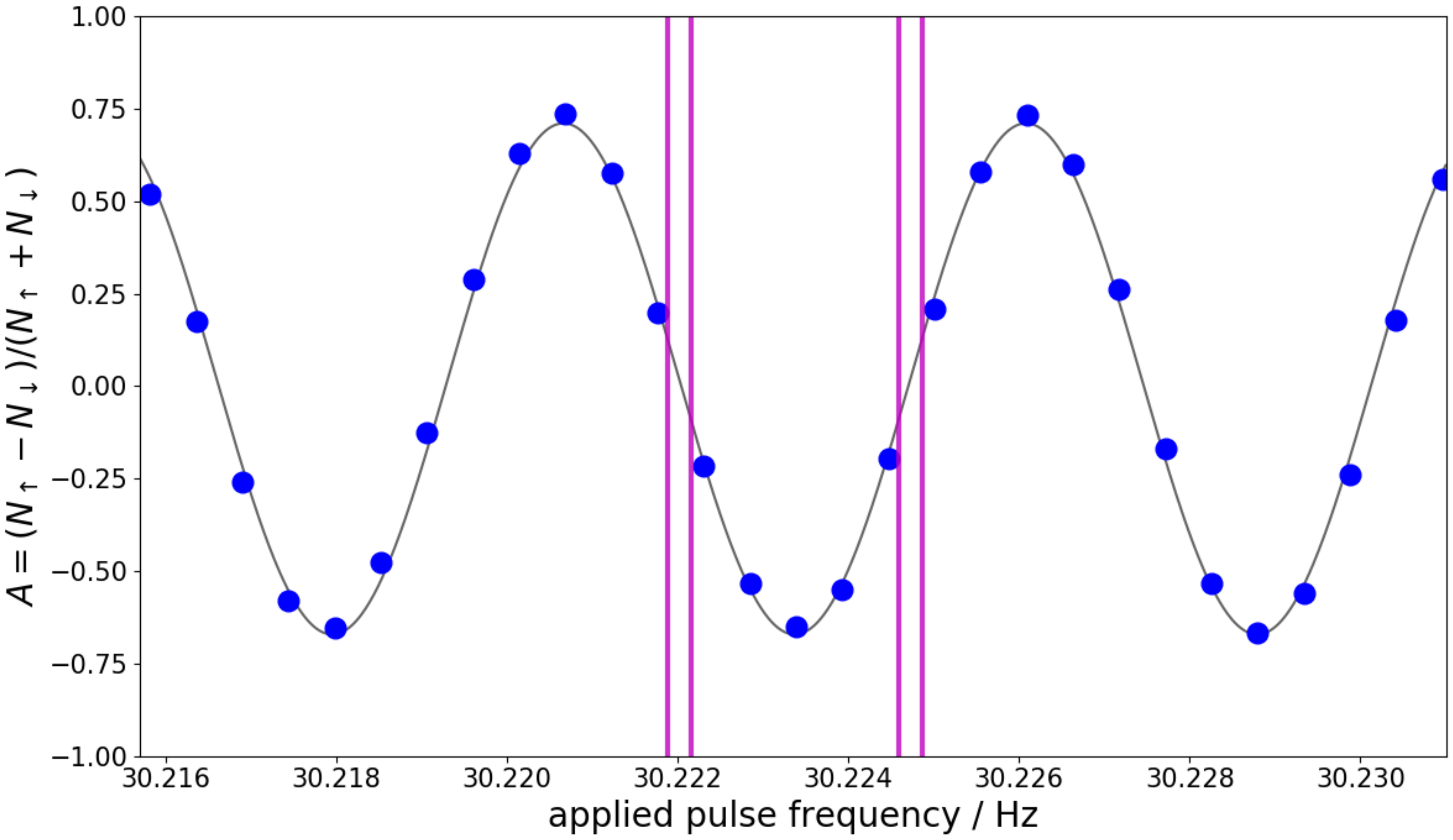


Free precession...

duration T

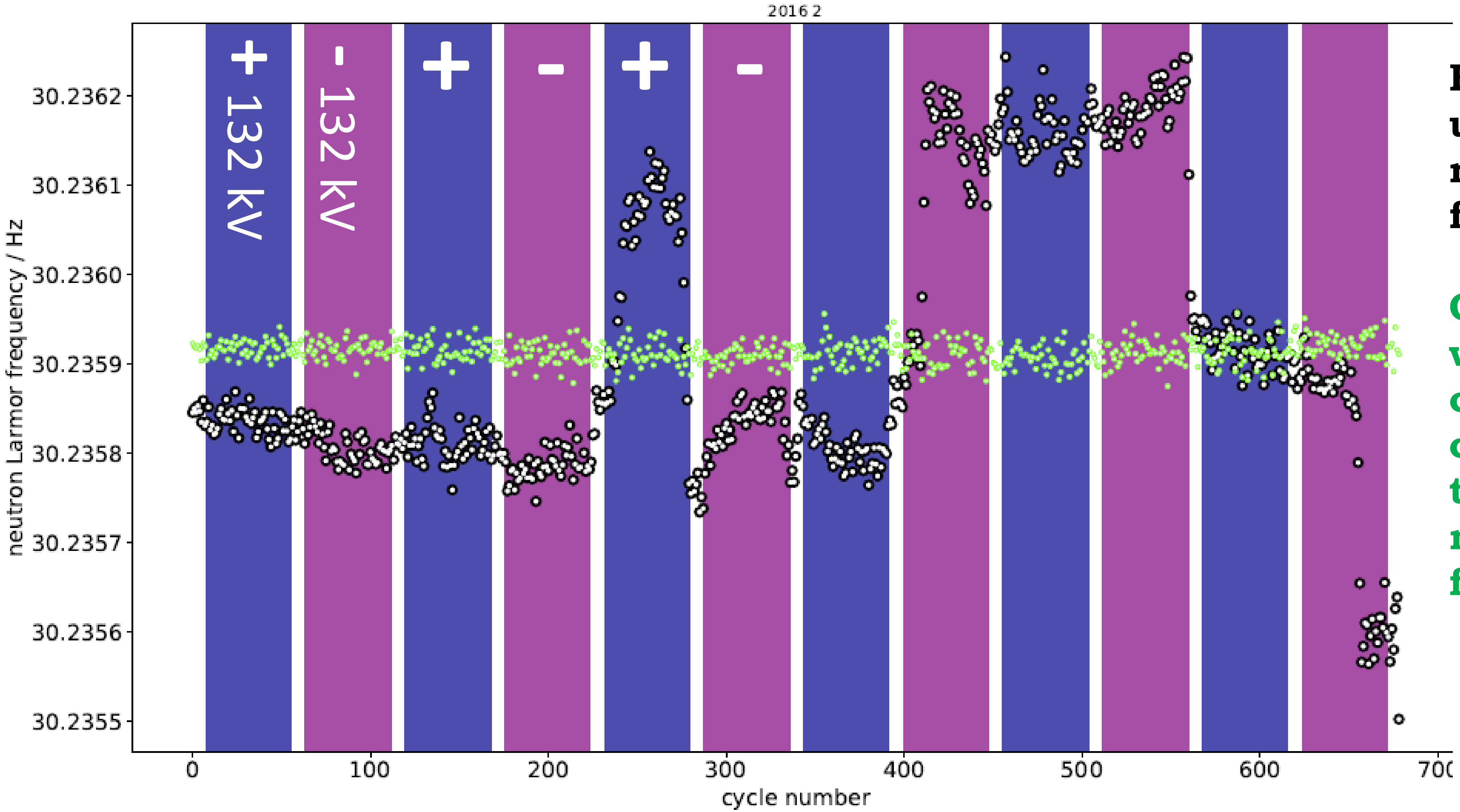


Second π / 2 spin-flip pulse



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

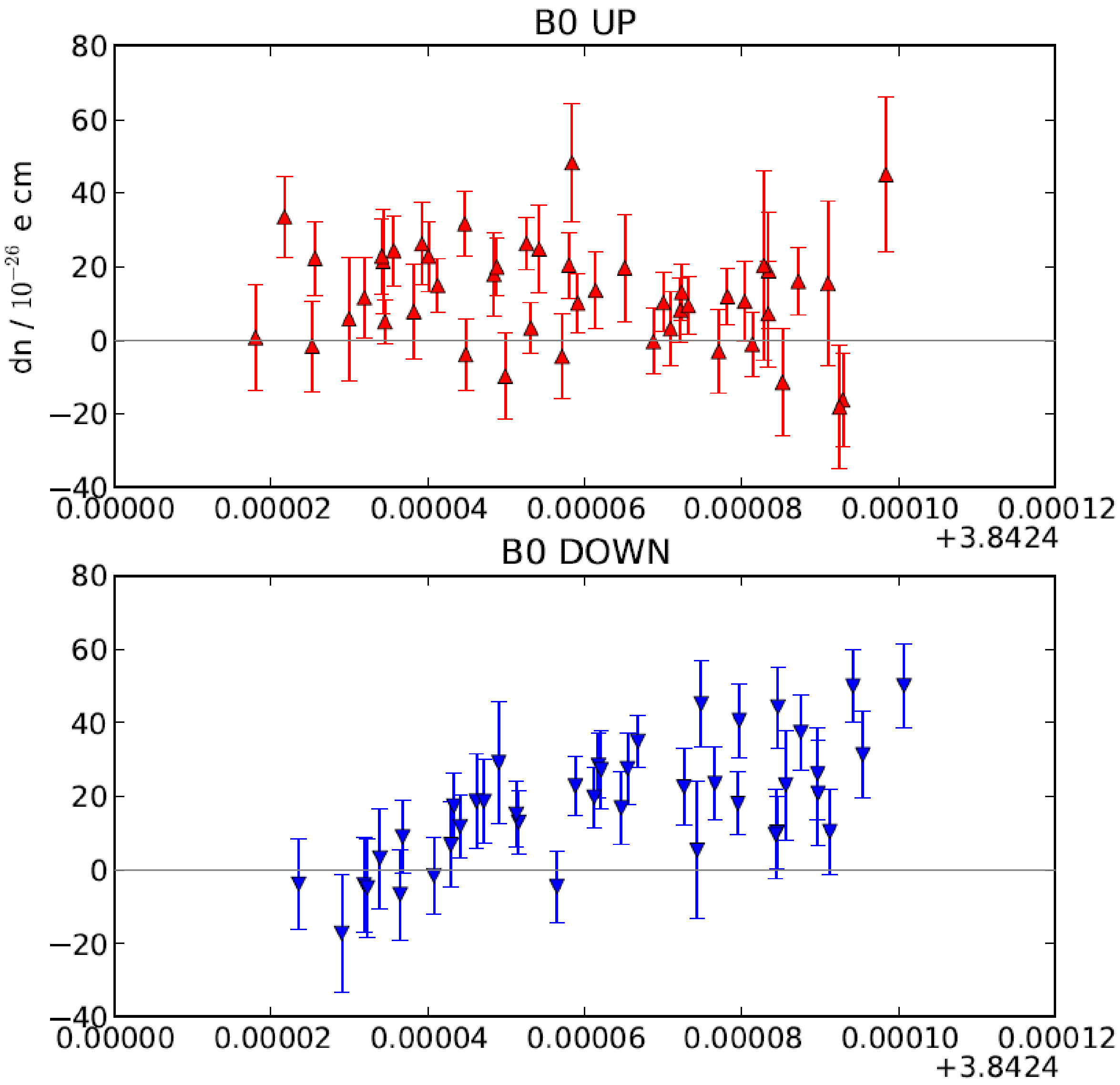
Typical measurement sequence at PSI, 1 cycle every 5 minutes



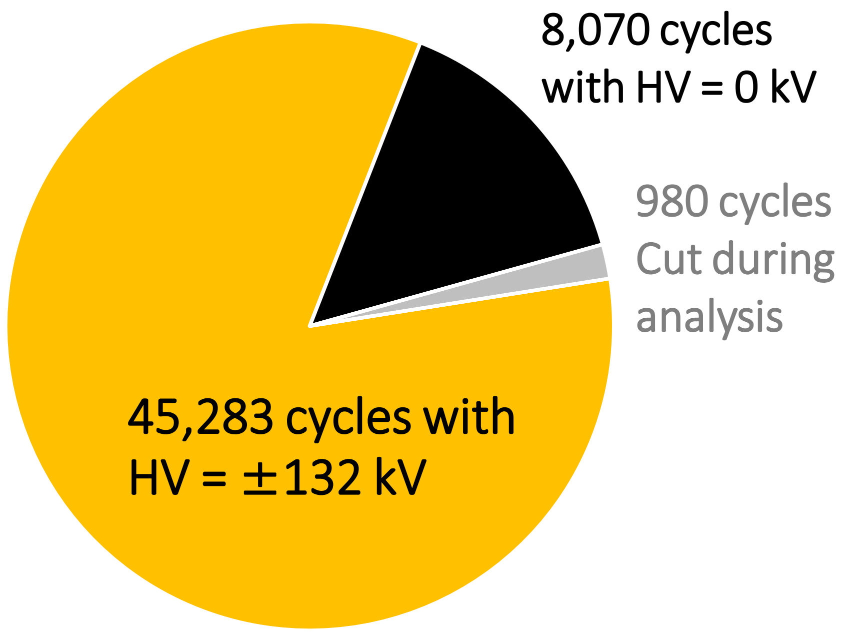
Black: uncorrected neutron frequency

Green: corrected with the mercury co-magnetometer, compensates for the residual magnetic field fluctuations

Analysis of the 2015/2016 PSI data, still ongoing



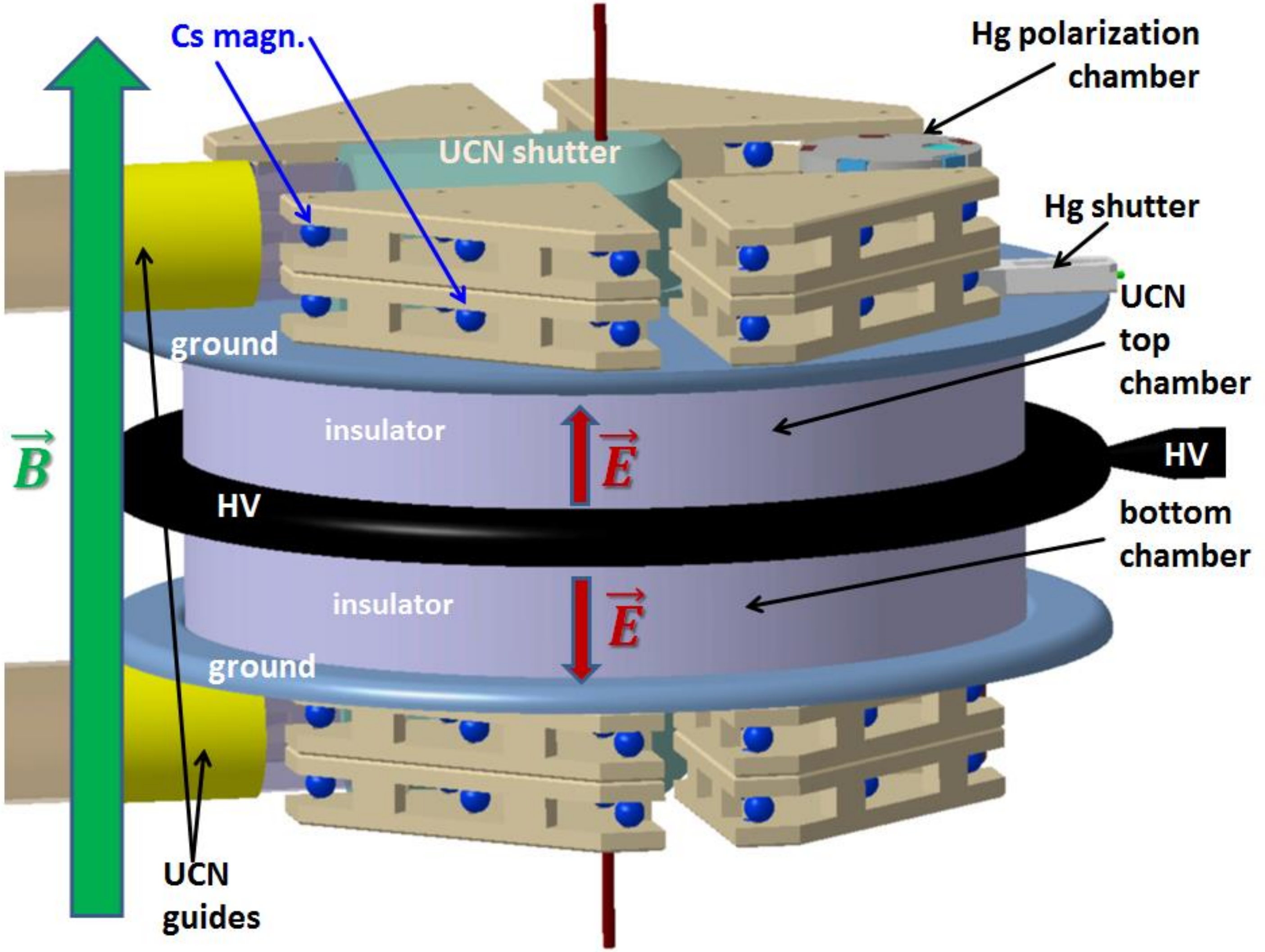
$$R_{\mathrm{corr}} = \frac{f_n}{f_{\mathrm{Hg}}} - \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\left(\mp\delta_{\mathrm{Earth}} + \frac{\langle B_T^2\rangle}{2B_0^2}\right)$$



*Preliminary **blind** result, west analysis*

$$d_\times = (14.6 \pm 1.1) \times 10^{-26} e\ \mathrm{cm}$$

n2EDM concept & baseline design

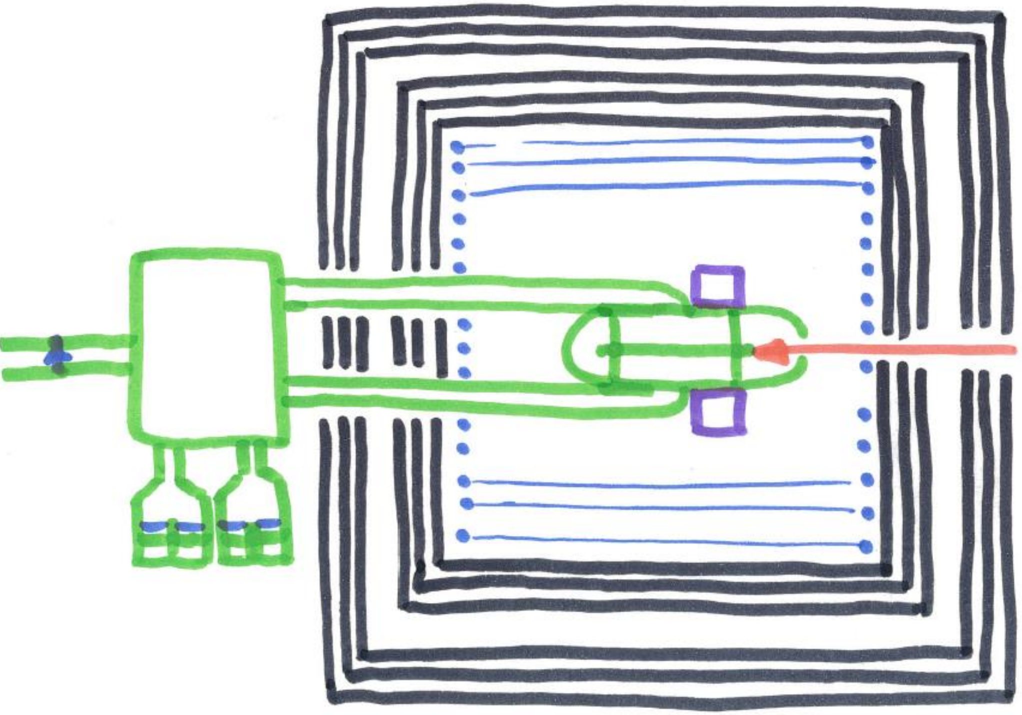


$$f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow} = \frac{2E}{\pi\hbar} d_n$$

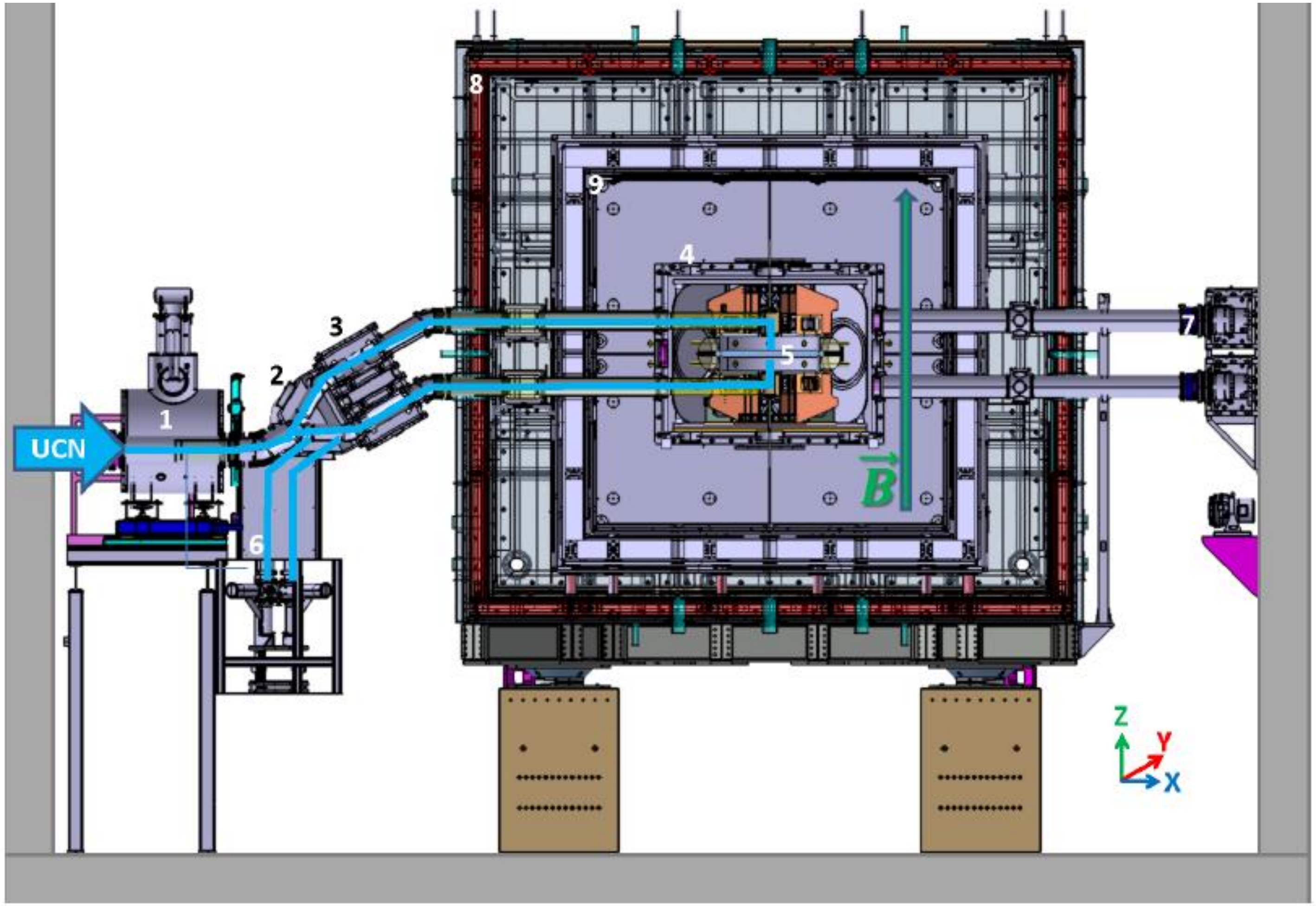
1. **Large double UCN chamber**
   - Vertically stacked
   - Height H = 12 cm each
   - Diameter D = 80 cm

2. **Magnetometry**
   - Hg co-magnetometers
   - Array of Cs magnetometers
   - B_0 = 1 μT

concept



Technical Design Report



Colossal magnetic shield
5m x 5m x 5m

n2EDM science reach

Error due to UCN counting statistics

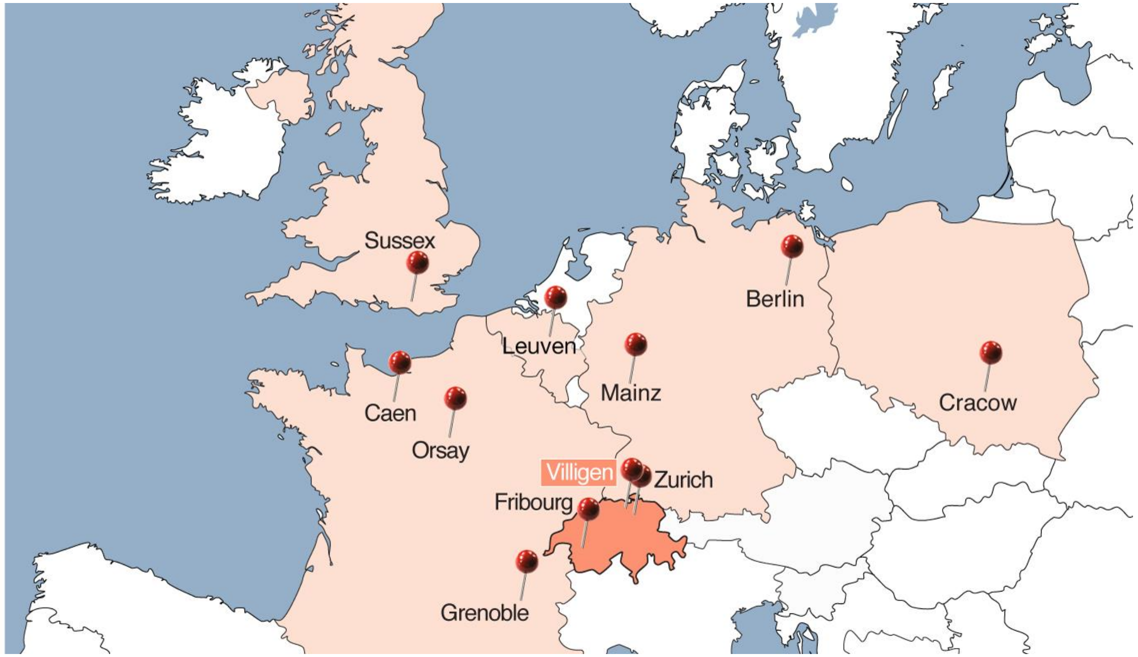
$$\sigma(d_n) = \frac{\hbar}{2\alpha E\, T\sqrt{N}}$$

	nEDM 2016	n2EDM baseline
diameter (cm)	47	80
α	0.75	0.8
E (kV/cm)	11	15
T (s)	180	180
N (per cycle)	15'000	121'000
$\sigma(d_n)$ (per day)	11×10^{-26} $e{\cdot}$cm	2.6×10^{-26} $e{\cdot}$cm

- We have a precise plan (baseline design) for an improved measurement by a factor of 10 (i.e. $\sqrt{10}$ for the BSM mass reach) with 500 live days of data described in the 2019 TDR.
- Start of data production in 2022
- We have ideas to go beyond that with future upgrades

Credits to the nEDM collaboration

49 members
10 PhD students
8 countries
16 laboratories
(LPSC, LPCC, CSNSM in France)

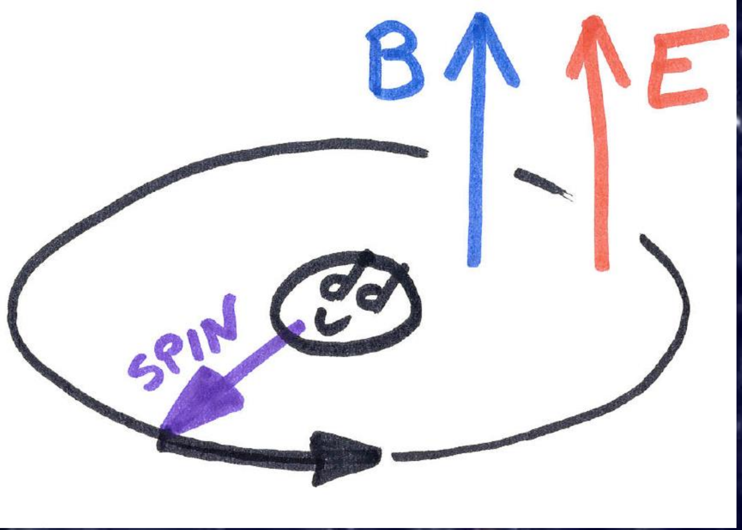


Announcements

1 The LPSC group is recruiting 1 postdoc

2 the nEDM collaboration is open to new collaborators

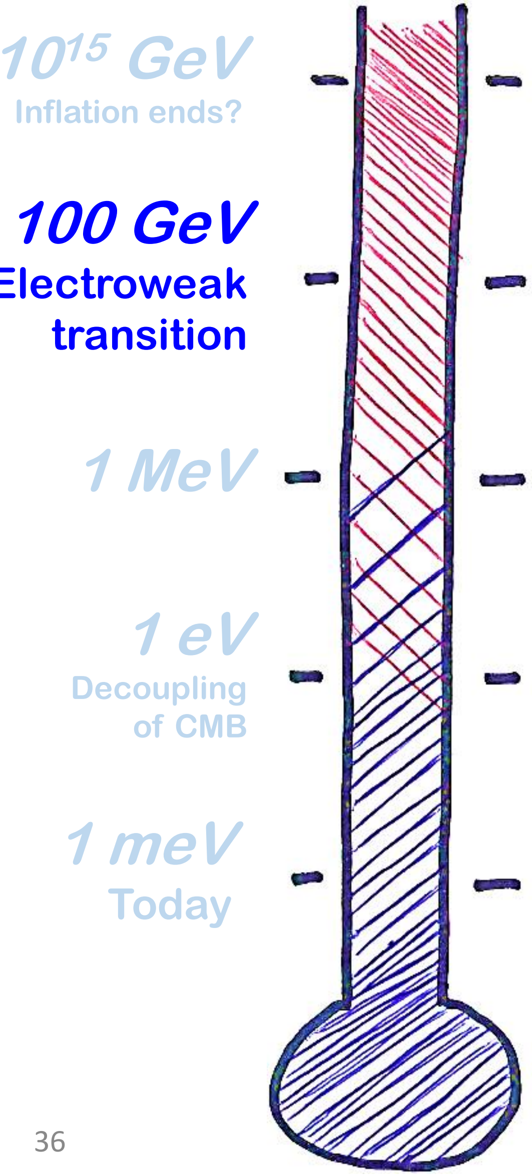
- Software: data quality monitoring, automatic detection of system failures with machine learning, online and offline analysis, data blinding, data storage and legacy
- Hardware for upgrades: new UCN chambers with storage properties and higher electric fields

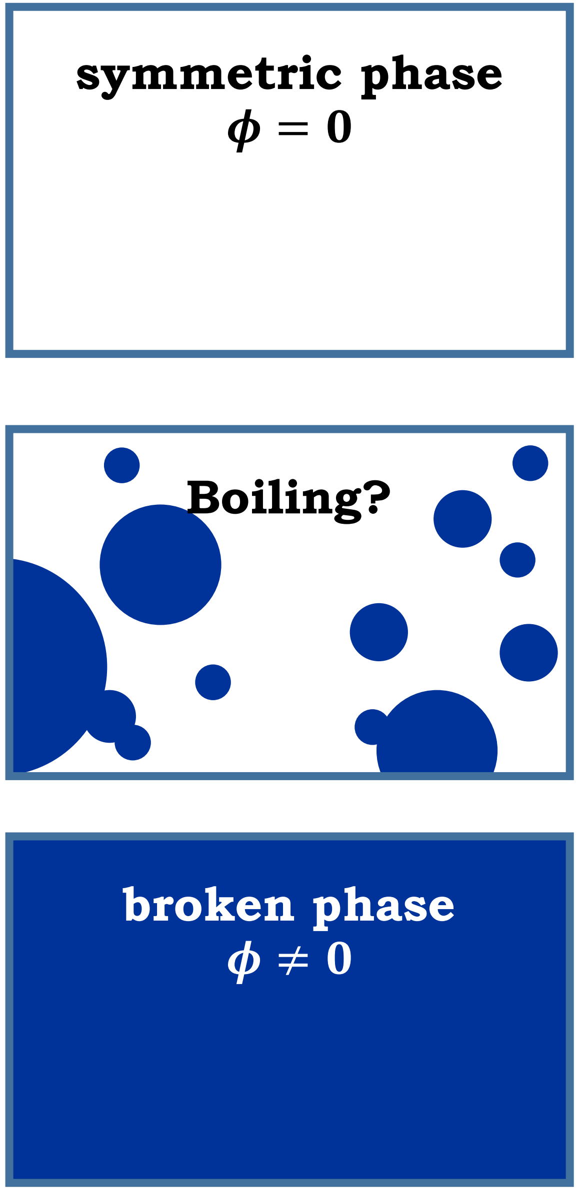


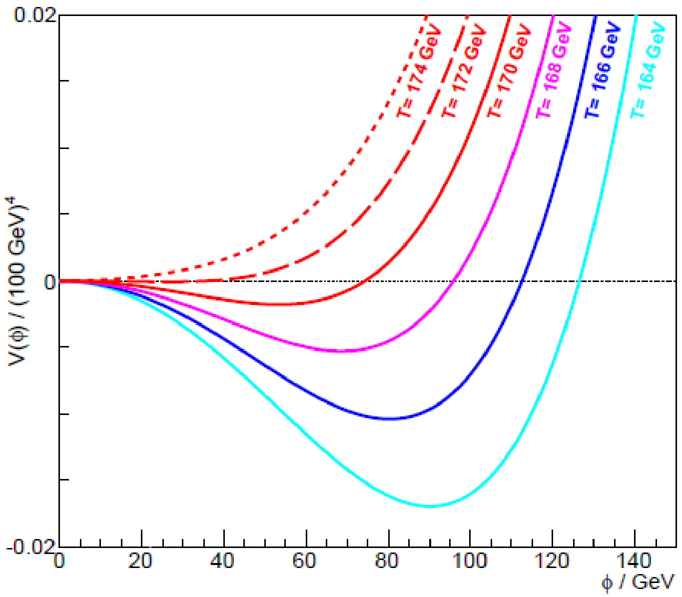
thank you,

the rest are backup slides

Electroweak phase transition

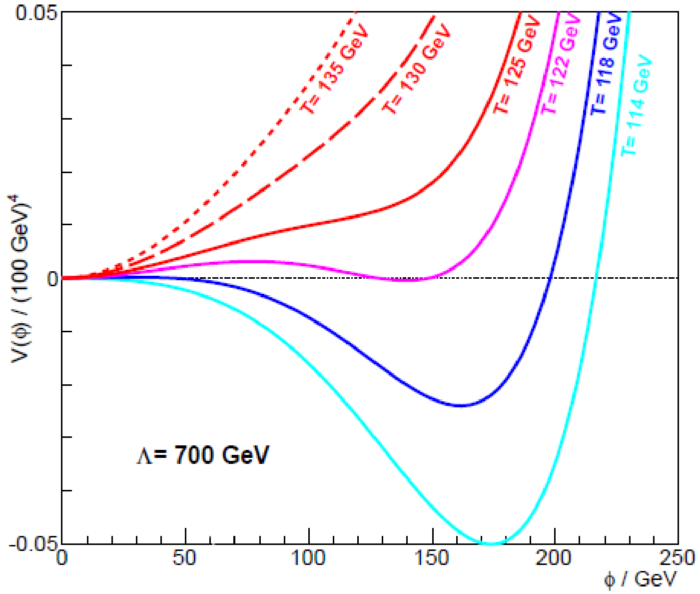






Standard Model:

2d order
Phase transition



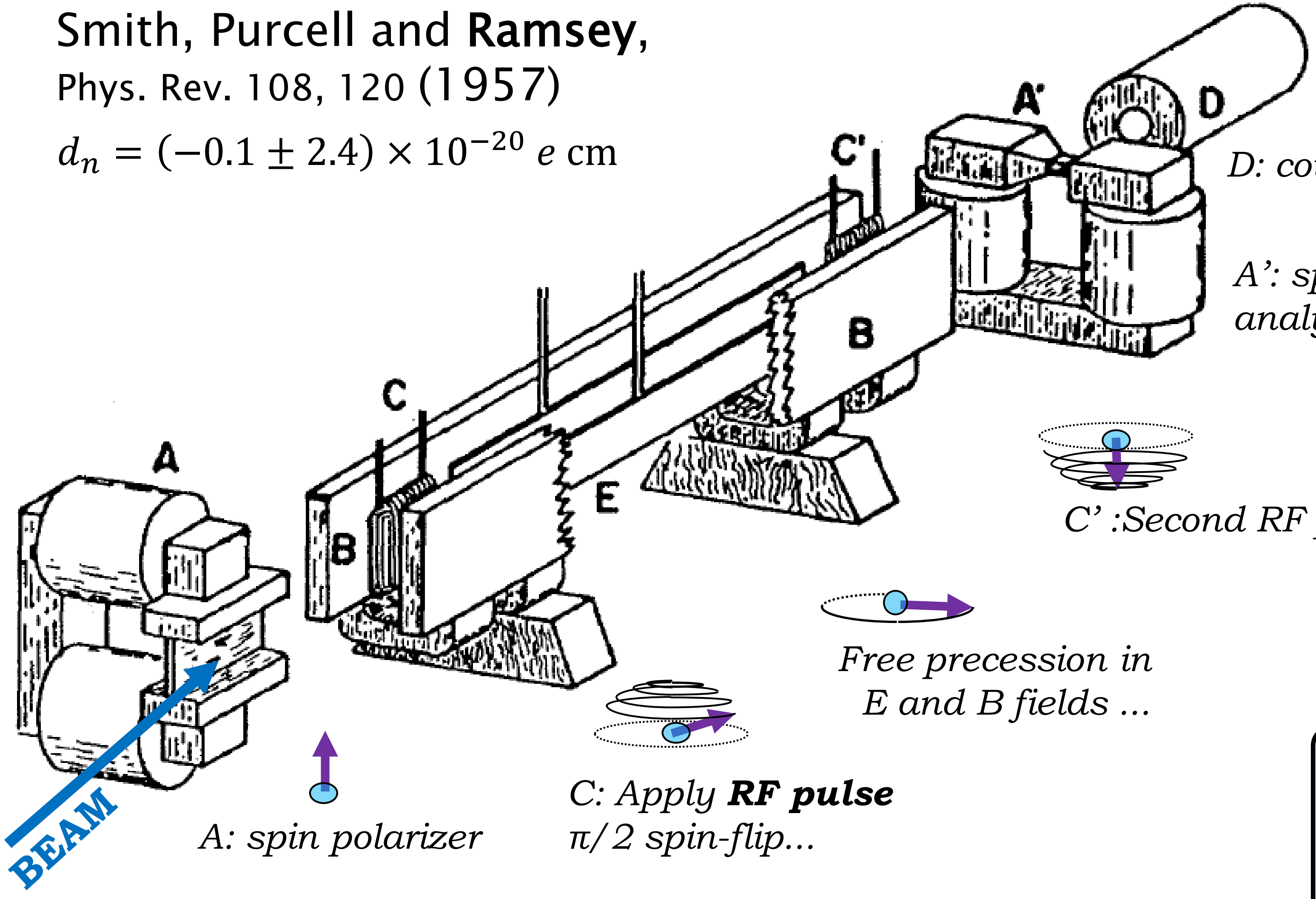
Beyond
Standard Model:

1st order
Phase transition?

First EDM experiment with a neutron beam

Smith, Purcell and **Ramsey**,
Phys. Rev. 108, 120 (1957)

$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ e\ \mathrm{cm}$



A: spin polarizer

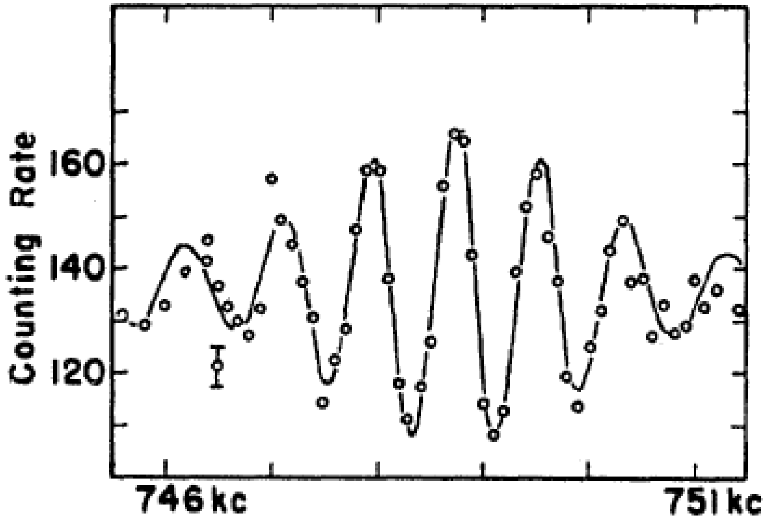
*C: Apply **RF pulse***
π/2 spin-flip…

Free precession in
E and B fields …

C' :Second RF pulse

D: counter

A': spin analyzer



Vary the RF frequency and measure the resonance curve to extract f_L. Do it for parallel and antiparallel E and B fields.

Statistical sensitivity:

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

$T \approx 1\ \mathrm{ms}$

International competition

@SNS US novel cryogenic concept, UCN produced in-situ (operation planned 2023)

@Los Alamos US room temperature experiment (design & funding phase) at a D2 UCN source (existing)

@TRIUMF Canada room temperature experiment (design phase) at a He UCN source (in construction)

@ILL(Munich+PNPI) room temperature experiment (in construction) at a He UCN source (in construction)

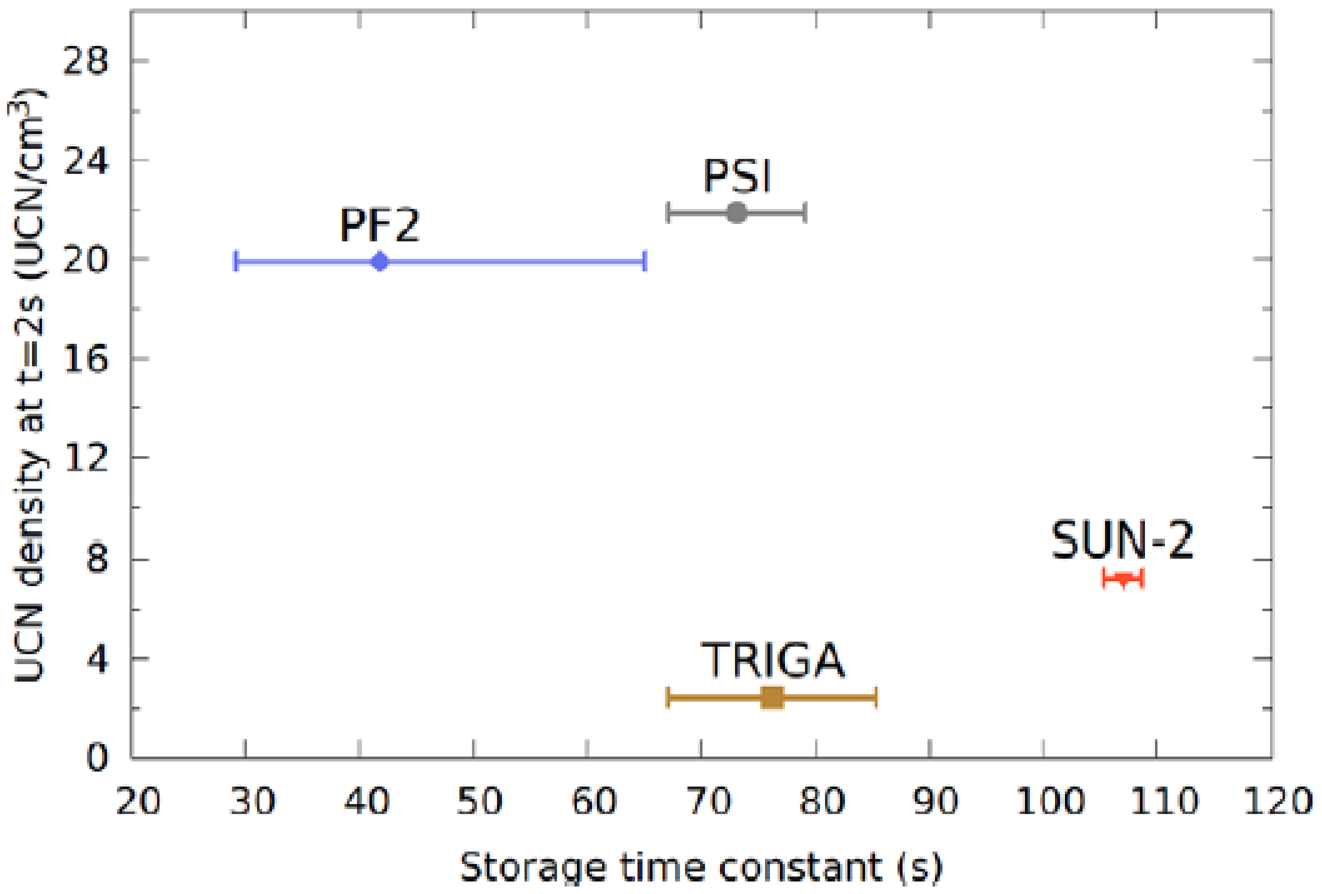
@ESS neutron beam experiment (concept phase)

@Seattle indirect access of the nEDM by measuring the EDM of the 199Hg atom (improving since decades)

Finally a worldwide comparison of UCN sources

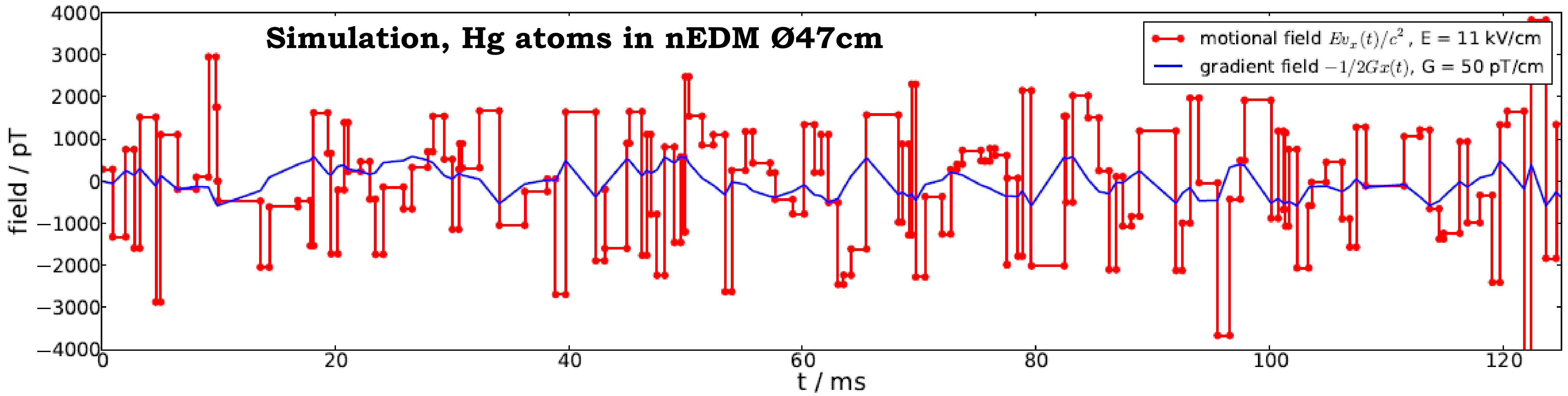
PHYSICAL REVIEW C 95, 045503 (2017)

Comparison of ultracold neutron sources for fundamental physics measureme



Diter Ries standard stainless steel bottle

The co-magnetometer problem: vxE/c²



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

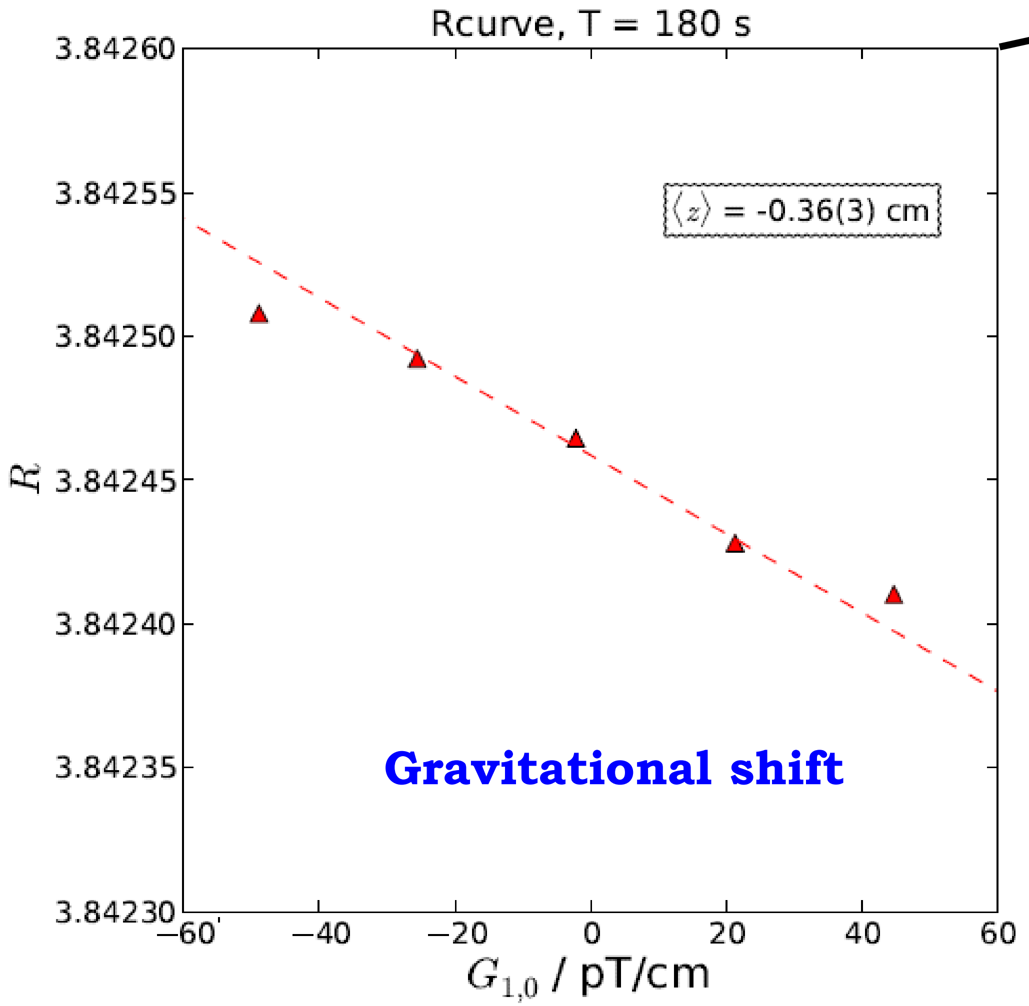
$$\delta f = \frac{\gamma^2}{4\pi}\int_0^\infty d\tau \, \mathrm{Im}\, e^{-i\omega\tau}\left\langle \underline{B}(0)\underline{B}^*(\tau)\right\rangle$$

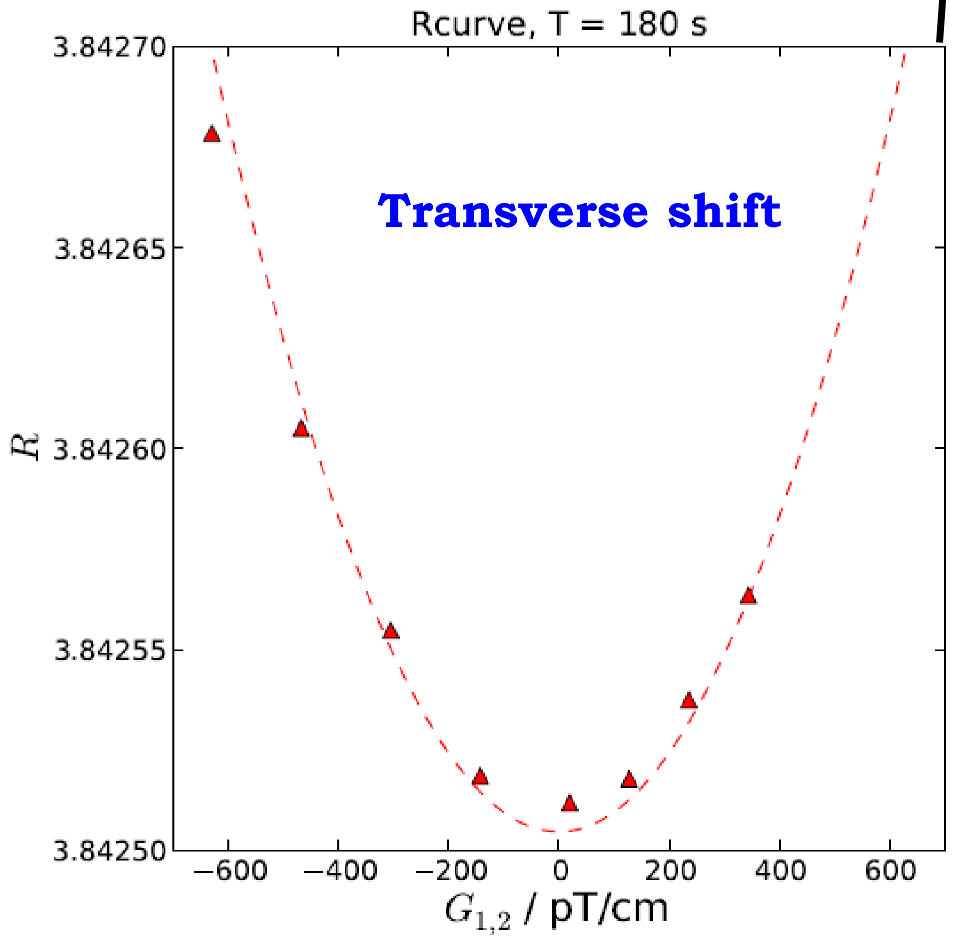
Linear in E field frequency shift:

$$d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar|\gamma_n\gamma_{\mathrm{Hg}}|}{2c^2}\int_0^\infty dt \cos\omega t \left\langle \boldsymbol{B_x(0)}\boldsymbol{\dot{x}(t)} + \boldsymbol{B_y(0)}\boldsymbol{\dot{y}(t)}\right\rangle$$

co-magnetometer equation

$$\mathcal{R} = \frac{f_n}{f_{\mathrm{Hg}}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\left(1 + \frac{2E}{\pi\hbar f_{\mathrm{Hg}}}\left(d_n^{\mathrm{true}} + d_n^{\mathrm{false}}\right) + \frac{G\langle z\rangle}{B_0} + \frac{\langle B_T^2\rangle}{2B_0^2} + \cdots\right)$$





Magic field

$$d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}}(\boldsymbol{\omega}) = \frac{\hbar|\gamma_n\gamma_{\mathrm{Hg}}|}{2c^2}\int_0^\infty dt\cos\boldsymbol{\omega}t\,\langle B_x(0)\dot{x}(t)+B_y(0)\dot{y}(t)\rangle$$