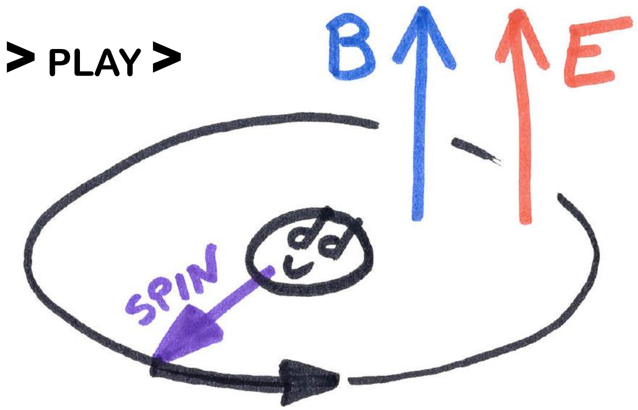
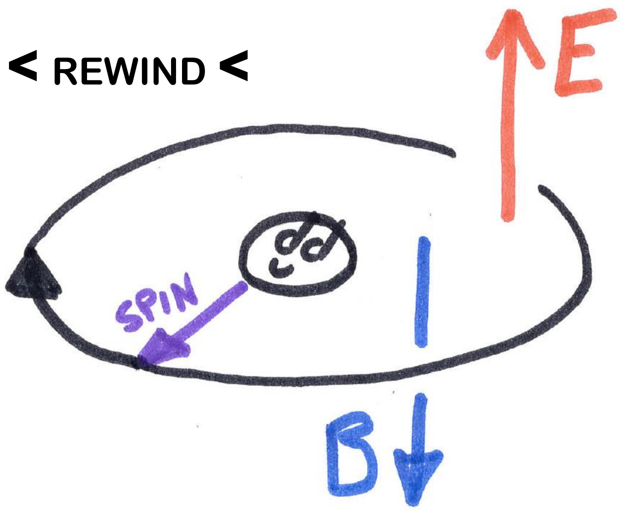
Measuring the neutron electric dipole moment

Guillaume Pignol, Feb 03 2018
Workshop Intensity Frontier CERN

UNIVERSITÉ Grenoble Alpes
erc European Research Council

Electric Dipole Moments and T symmetry





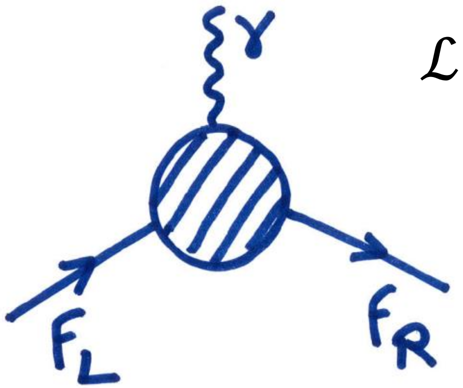
$$\hat{H} = -\mu_n \, B \, \hat{\sigma}_z - d_n \, E \, \hat{\sigma}_z$$

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

The existence of an electric dipole violates the T symmetry and therefore the CP symmetry

Electric dipoles & CP symmetry

EDMs: fermion-photon coupling
-imaginary part of the diagram-
generated by radiative corrections



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

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

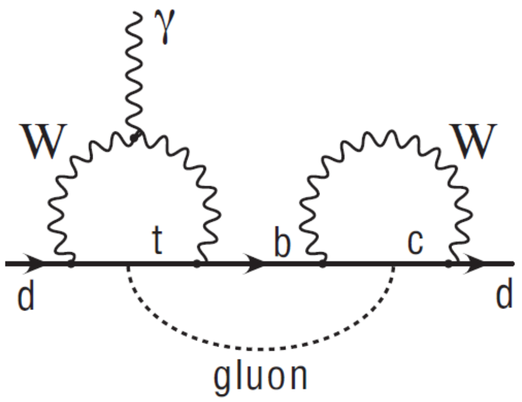
$$d_n < 300 \times 10^{-28}\; e\;\text{cm}\;\; (\text{Grenoble}, 2006)$$

$$d_p < 2000 \times 10^{-28}\; e\;\text{cm}\;\; (\text{Seattle}, 2016)$$

$$d_e < 0.9 \times 10^{-28}\; e\;\text{cm}\;\; (\text{Harvard}, 2014)$$

EDMs: indirect probe of physics at distance 10^{-26} cm
LHC: direct probe at large distance 10^{-17} cm

Sources of EDMs in the SM and BSM



CKM contribution to the quark EDM vanishes at two loops…

Prediction: $d_n \approx d_p \approx 10^{-33} e$ cm

Kobayashi-Maskawa background negligible

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

Generates a potentially enormous EDM

$d_n = -d_p \approx \theta \times 10^{-16}\, e$ cm

$\rightarrow \theta < 10^{-10}$

« Strong CP problem »

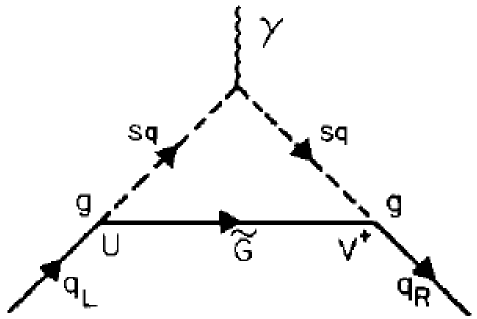


Fig. 2. One-loop diagram which may contribute to d_n in a softly broken susy model.

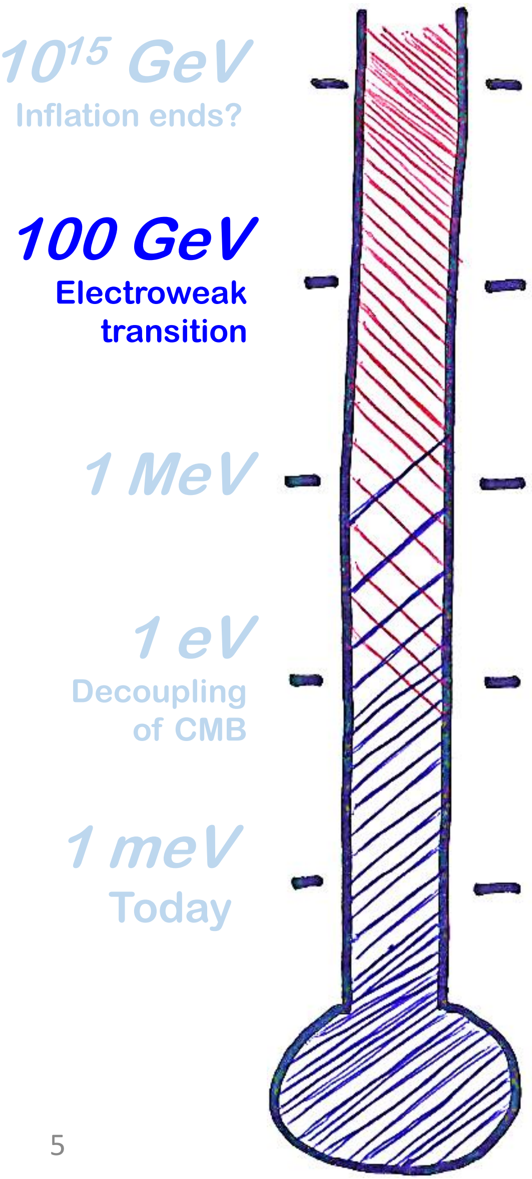
Ellis, Ferrara, Nanopoulos, PLB 114 (1982). EDM induced by soft mass terms for squarks and gluinos

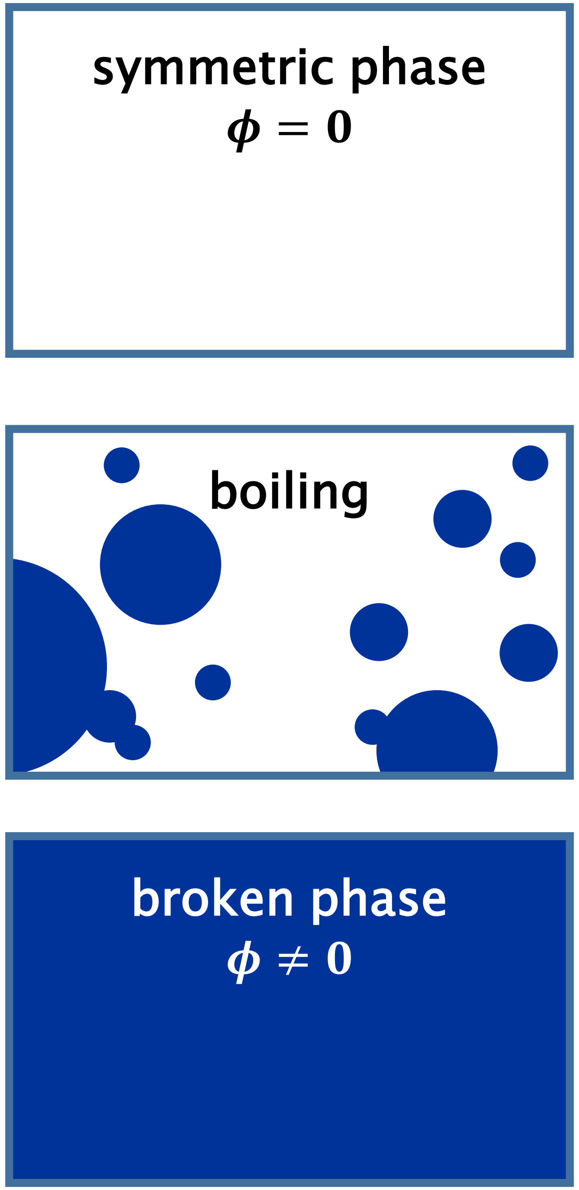
MSSM contains ~40 CP violating imaginary parameters…

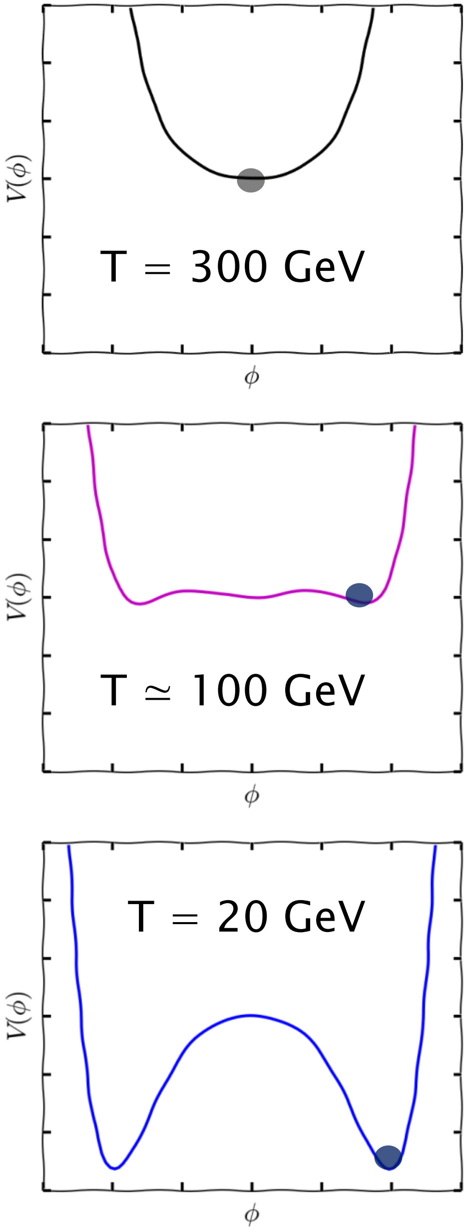
$$d_n \approx e\frac{\alpha}{4\pi}\frac{m_q}{M_{CPV}^2} \approx \left(\frac{1\ \mathrm{TeV}}{M_{CPV}}\right)^2 \times 10^{-25}\, e\ \mathrm{cm}$$

« SUSY CP problem »

CP violation and baryogenesis



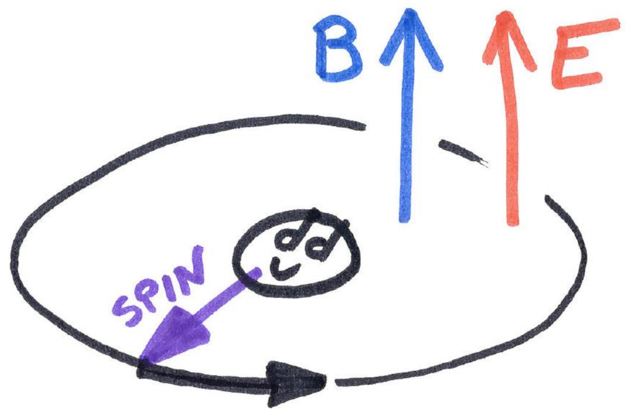


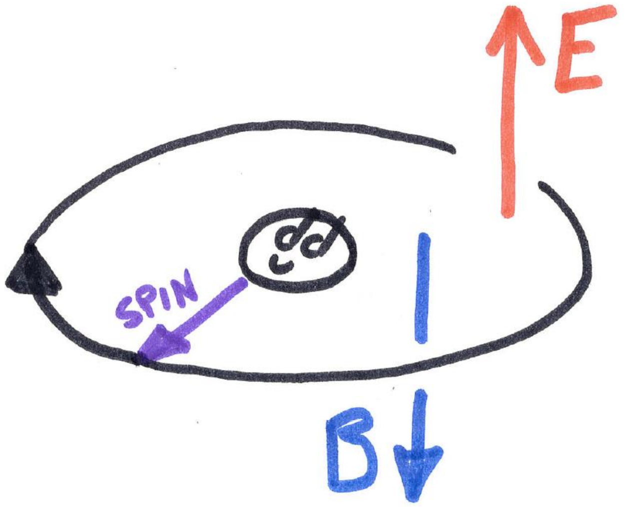


Sakharov's Baryogenesis recipe (1967)

- Baryon number not conserved -> sphalerons
- Universe out of equilibrium
  > Higgs self coupling
- **Violation of CP symmetry**
  > nEDM, pEDM

Current nEDM bound constrains many scenarios of BSM electroweak baryogenesis





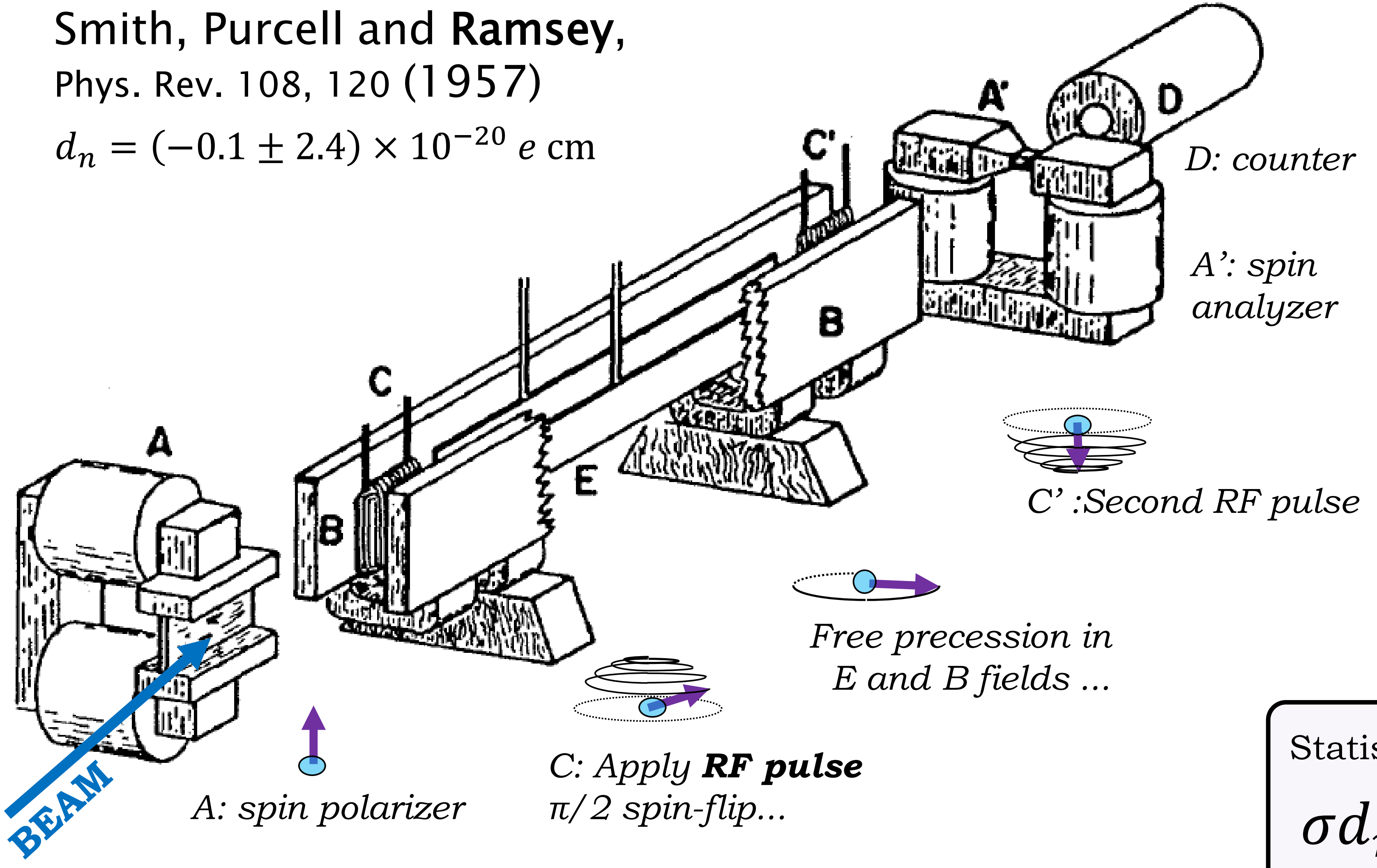
Back to the experiment

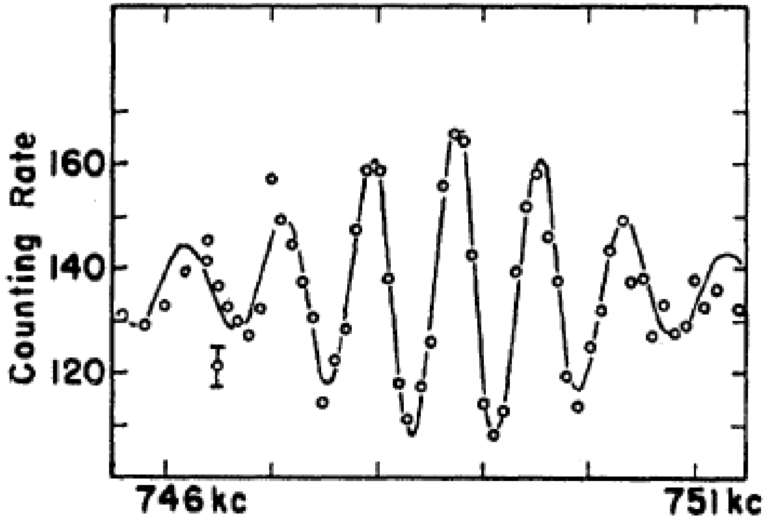
How to measure a frequency, precisely?

First EDM experiment with a neutron beam

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

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



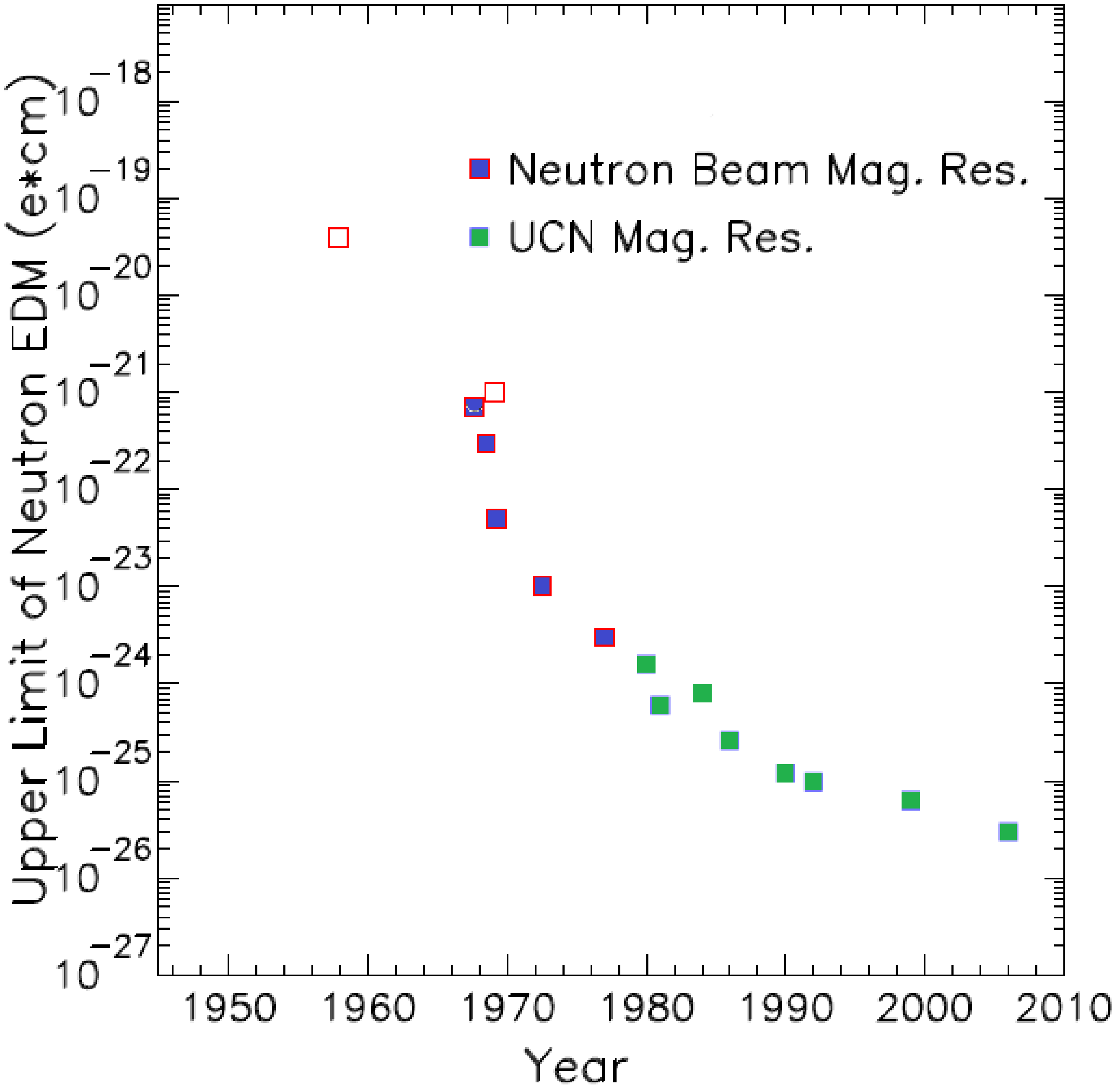


Vary the RF frequency and measure the resonance curve to extract f_L. Do it for parallel and antiparallel E and B fields.

Statistical sensitivity:

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

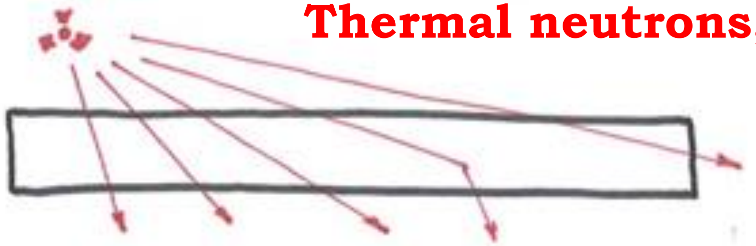
$T \approx 1\ \text{ms}$



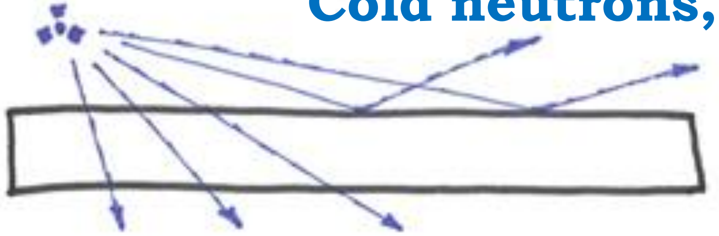
The slower,
the better...

Neutron optics, cold and ultracold neutrons

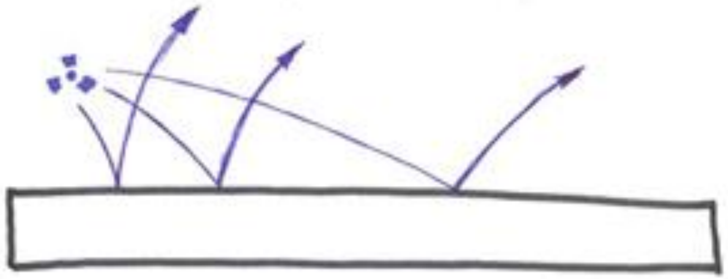
Thermal neutrons, E=25 meV

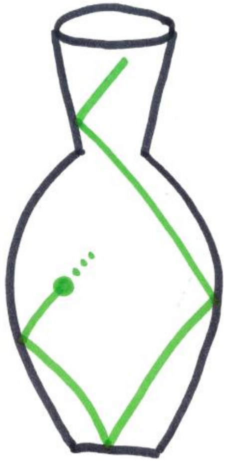


Cold neutrons, E<25 meV



Ultracold neutrons E< 200 neV



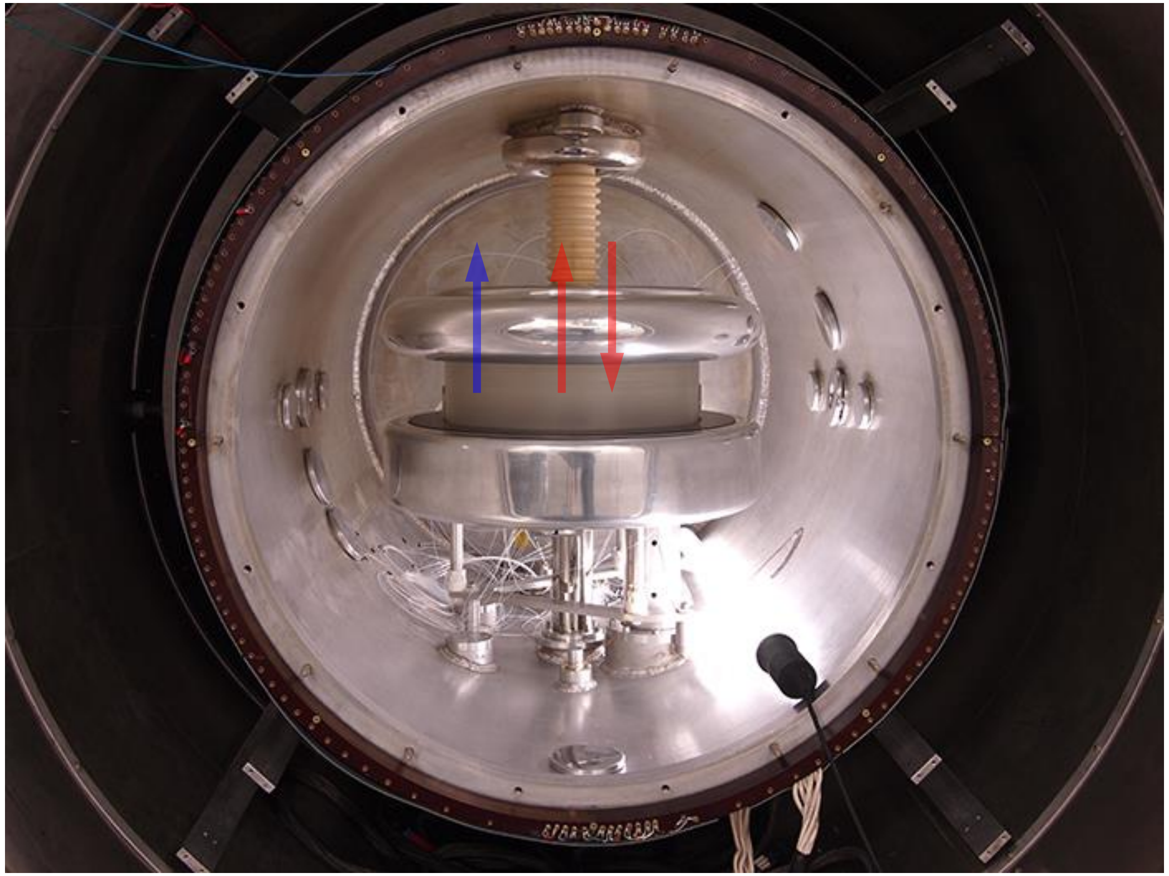


Neutrons with energy < 200 neV, are totally reflected by material walls.

They can be stored in material bottles for long times (minutes).

They are significantly affected by gravity.

The Sussex/RAL/ILL apparatus

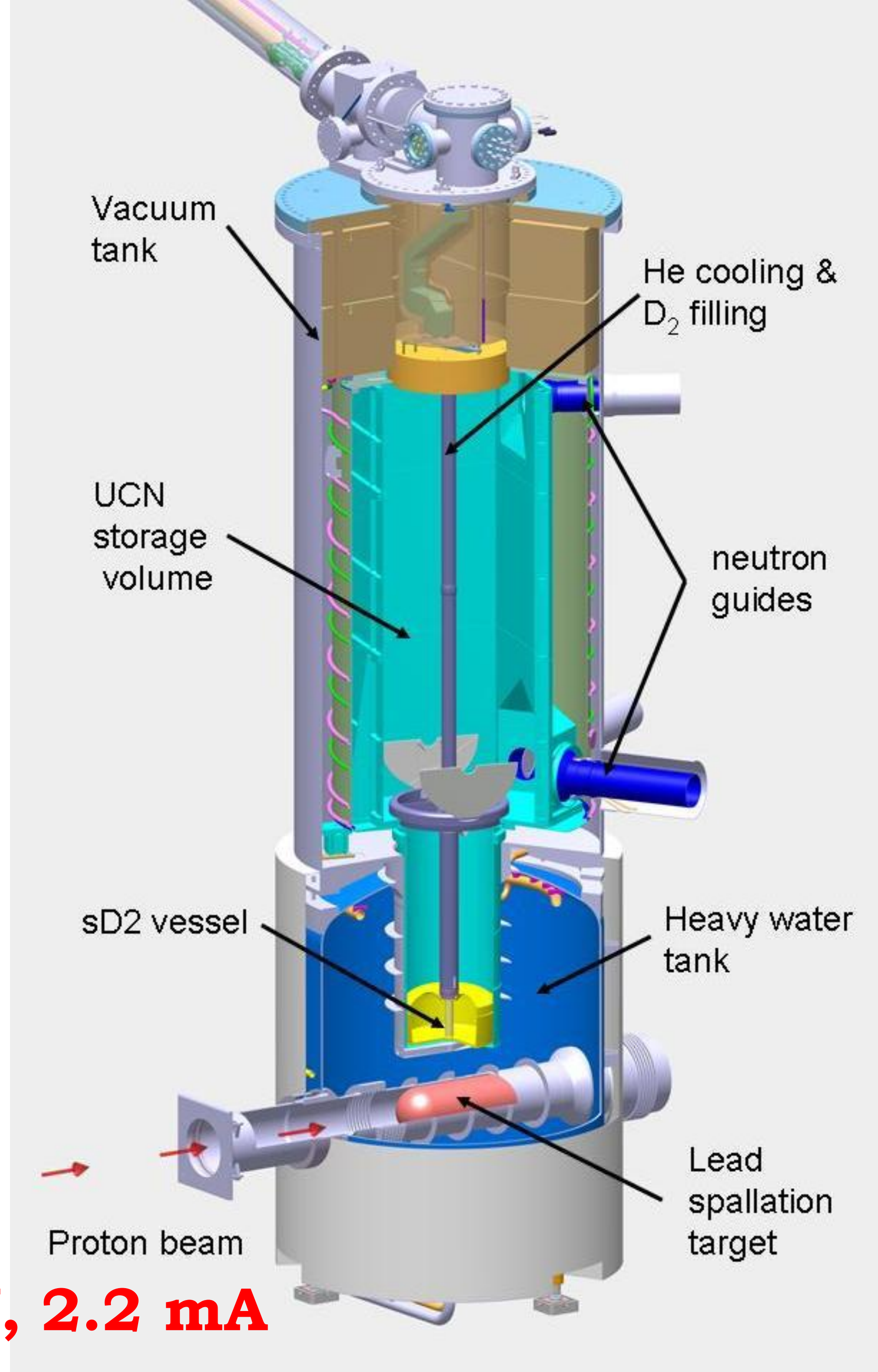


Apparatus installed at the ILL reactor Grenoble (1986-2009)

Best limit: $d_n < 3 \times 10^{-26}\ e$ cm
obtained with 1998 – 2002 data

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

UCN source at the Paul Scherrer Institute

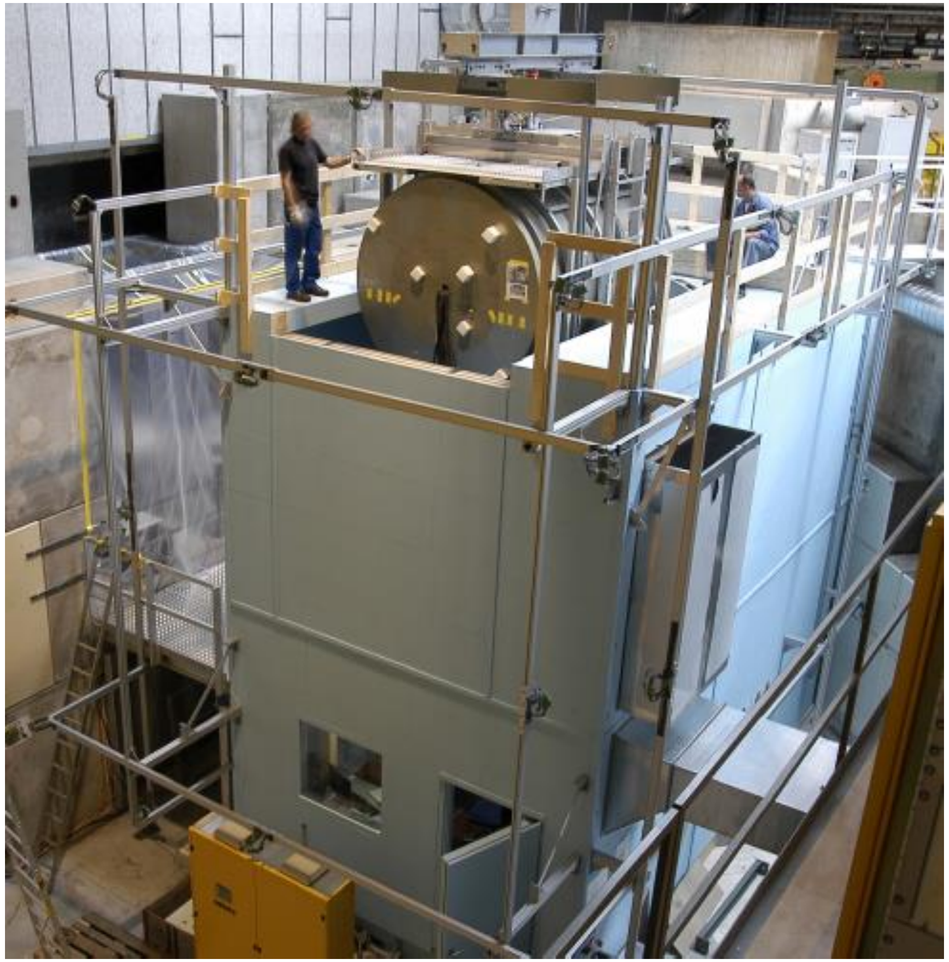


pulsed UCN source
One kick per 5 min
online since 2011

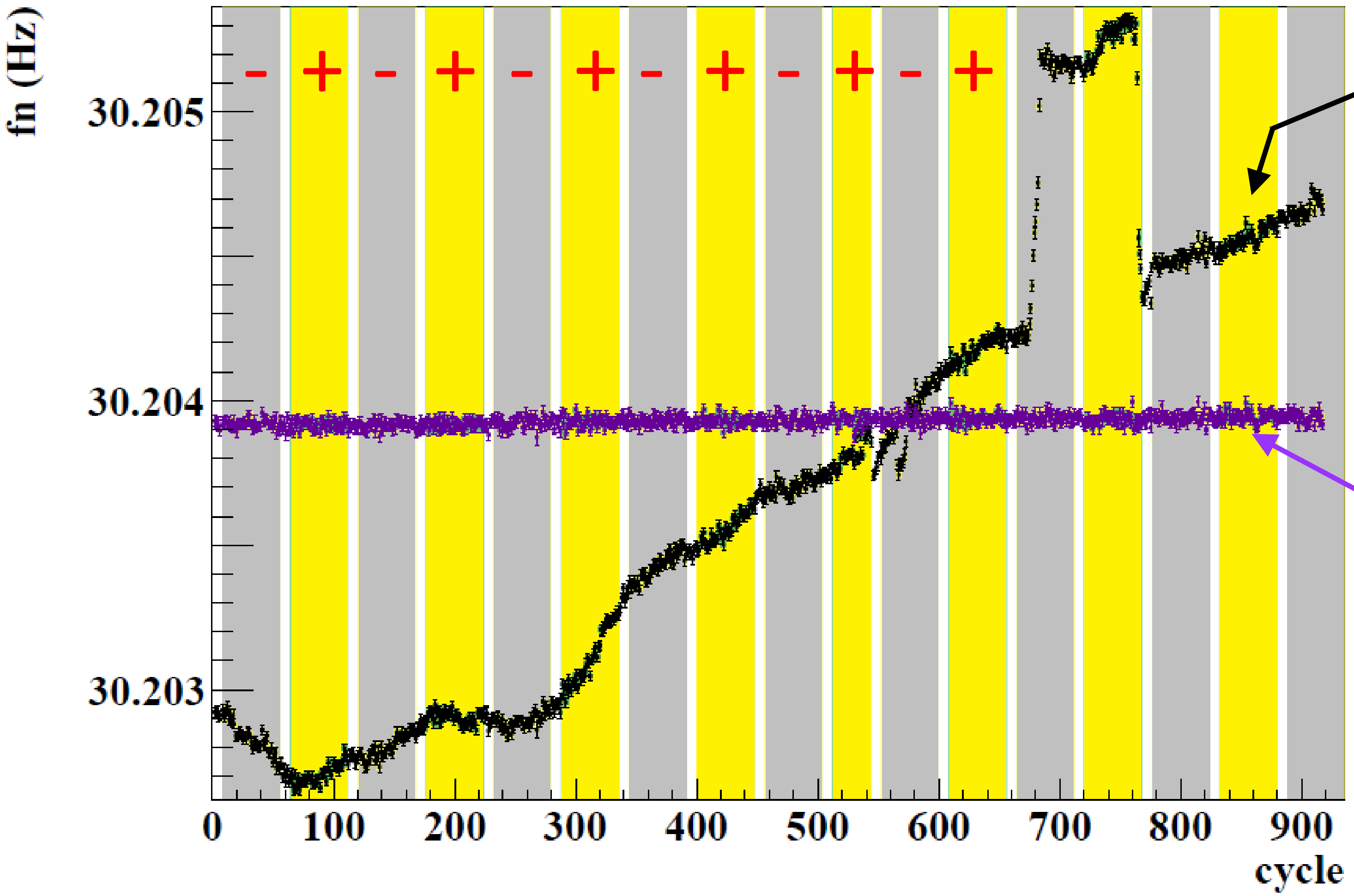
Intensity frontier!!

600 MeV, 2.2 mA

Moving the apparatus to PSI in 2009



Typical measurement sequence at PSI, 1 cycle every 5 minutes



Uncorrected neutron frequency

$$f_n = \frac{\gamma_n}{2\pi} B$$

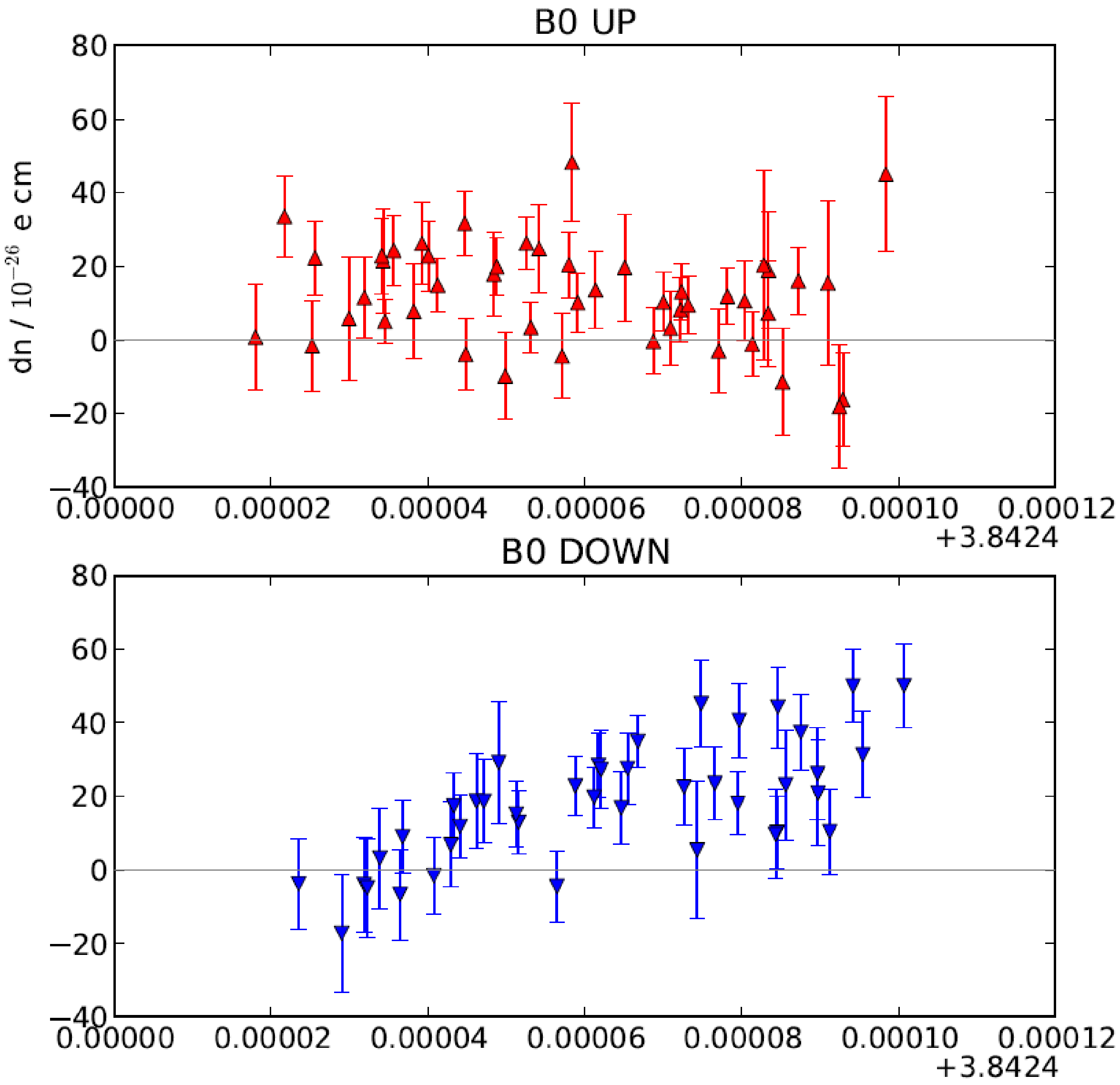
Mercury-corrected neutron frequency

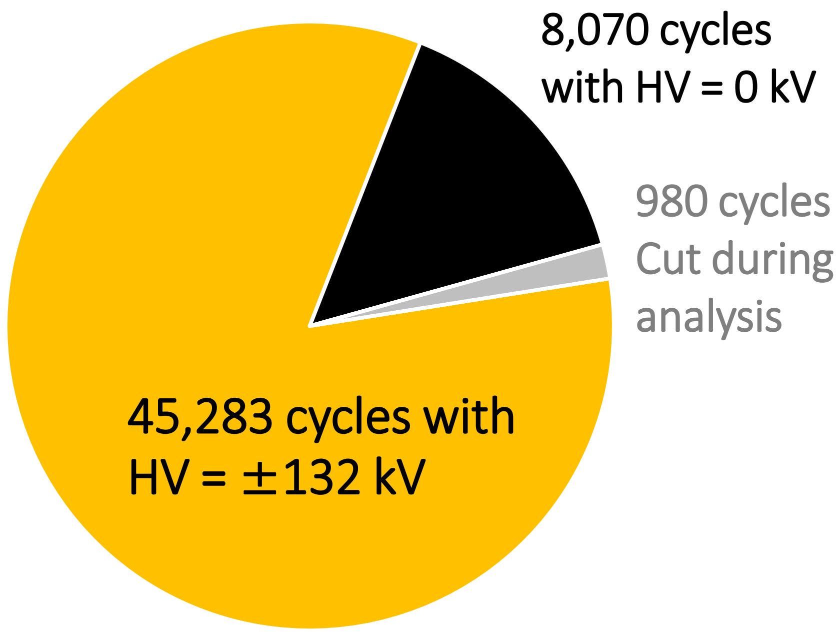
$$f_{Hg} = \frac{\gamma_{Hg}}{2\pi} B$$

$$f_n^{corr} \propto \frac{f_n}{f_{Hg}}$$

The **mercury co-magnetometer** compensates for the residual magnetic field fluctuations

Analysis of the 2015/2016 PSI data, still congoing



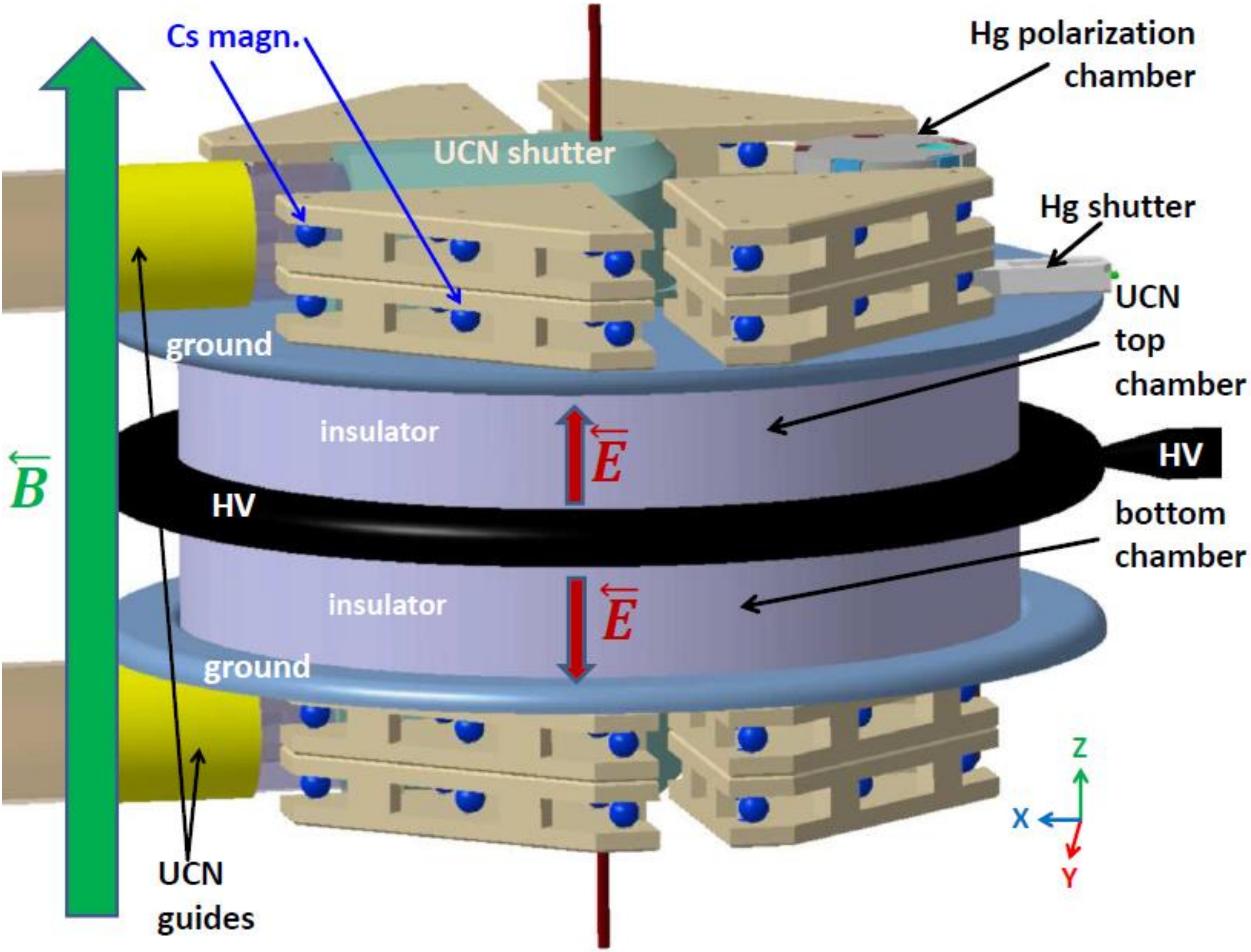


$$R_{\text{corr}} = \frac{f_n}{f_{\text{Hg}}} - \frac{\gamma_n}{\gamma_{\text{Hg}}}\left(\mp\delta_{\text{Earth}} + \frac{\langle B_T^2\rangle}{2B_0^2}\right)$$

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

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

Next generation: n2EDM experiment at PSI



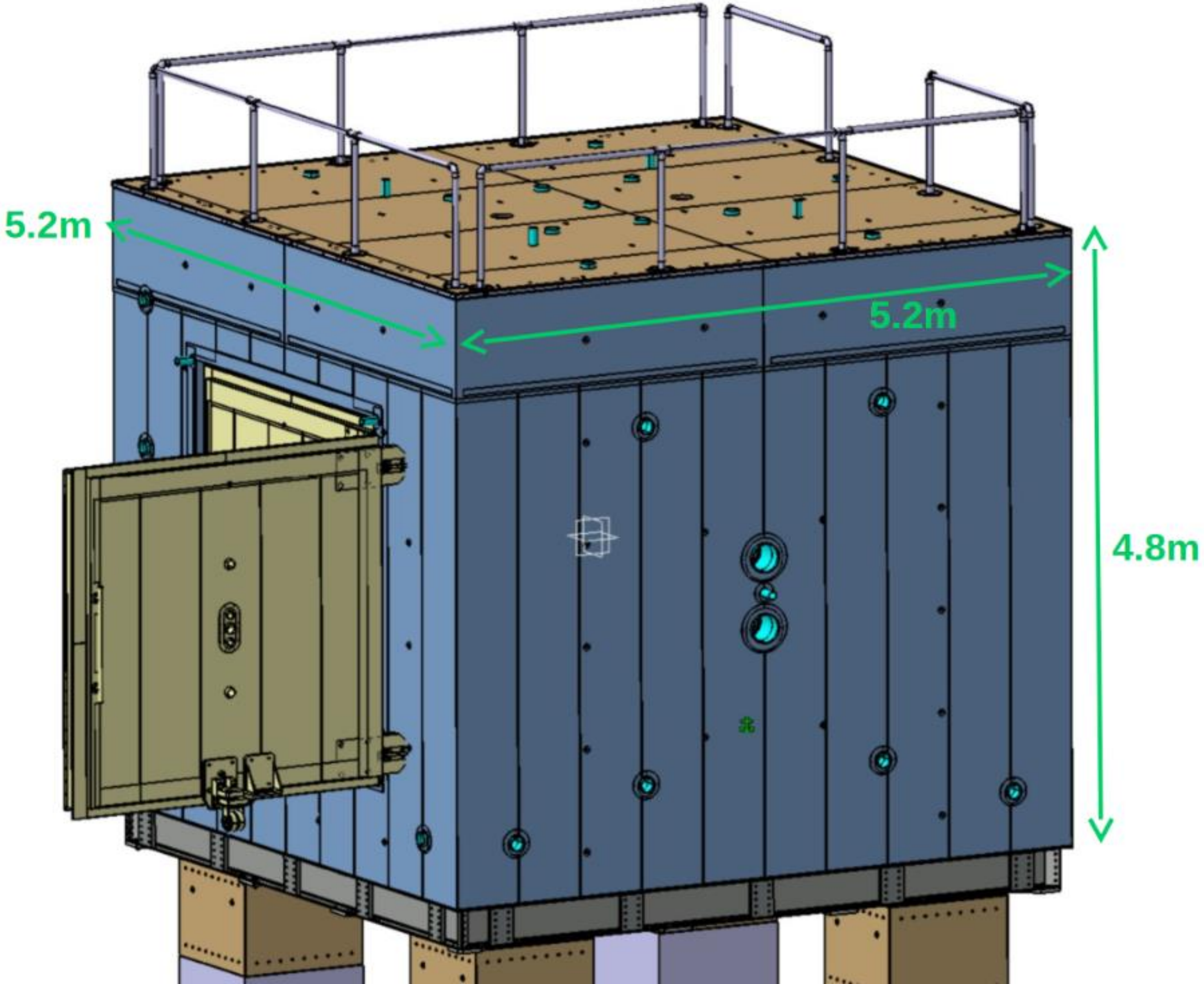
$$f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow} = \frac{2E}{\pi\hbar} d_n$$

neutron EDM

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
   - $B_0 = 1\ \mu T$

A colossal magnetic shield



6 mumetal layers

Inner cabin 3x3x3 m^3

Construction starts spring 2018

n2EDM science reach

Error due to UCN counting statistics

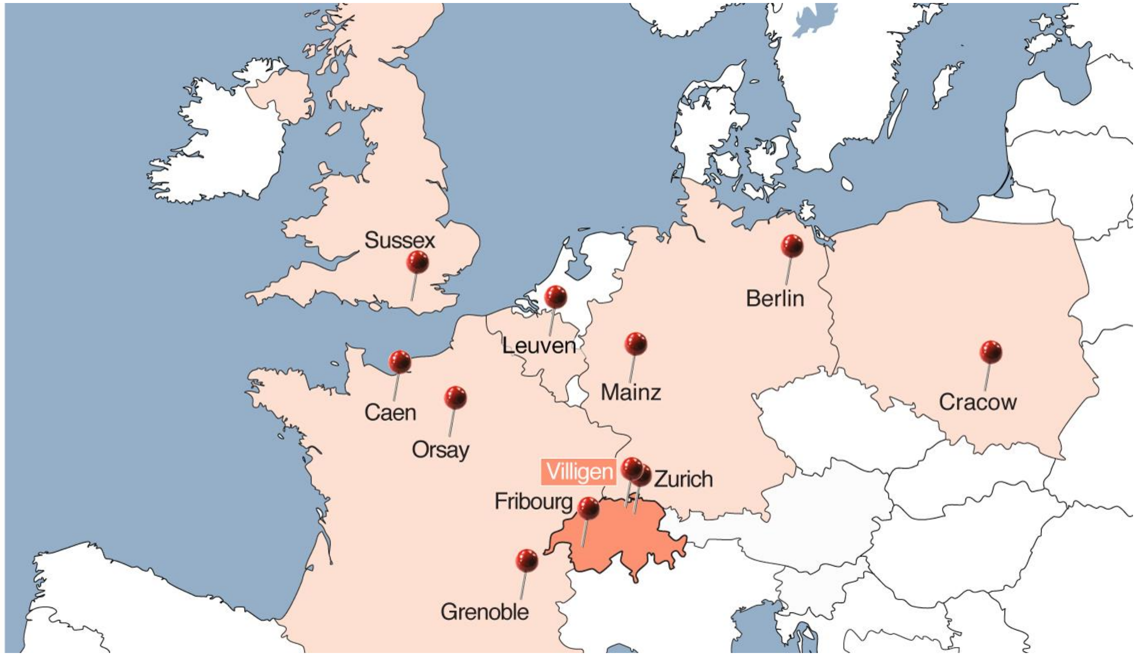
$$\sigma(d_n) = \frac{\hbar}{2\alpha E\, T\sqrt{N}}$$

	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·cm	2.6×10^{-26} e·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. TDR under way.
- Start of data production in 2020
- We have ideas to go beyond that with future upgrades

Credits to the n2EDM collaboration

48 members
10 PhD students
7 countries
13 laboratories
(LPSC, LPCC, CSNSM in France)



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)

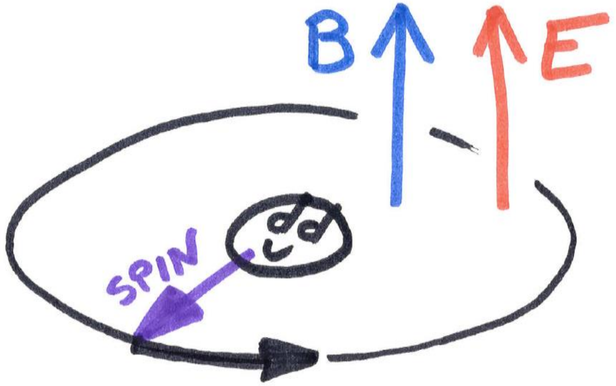
@TRIUMF Canada room temperature experiment (design phase) at a He UCN source (in construction)

@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)

Remarks about the future



- Precision experiments involve relatively **small teams**, but develop over **long periods of time** and require **interdisciplinary research,** in this case: accelerators, neutron detection, atomic physics, electric and magnetic fields

- The previous UCN nEDM apparatus was operated 32 years.

- **For n2EDM the future is starting now**. Construction of the magnetic shield is happening now, in parallel of detailed design of the inner parts. The scientific exploitation of this instrument will be at least 2020 – 2030.

Announcement 1/2

We are pleased to announce the workshop
"**The strong CP puzzle and axions**",
to be held on May 15- 16, 2018 at the LPSC, Grenoble, France.
This workshop will be preceded, on May 14, by a one day mini-school, with basic lectures on anomalies, strong CP violation, EDM searches, and axion physics from low-energy to cosmology.
This event is sponsirized by the GDR Intensity Frontier and ERC NEDM

Registration will open shortly. Prospective speakers are invited to contact the organizers directly:
Experiment: guillaume.pignol@lpsc.in2p3.fr , stephanie.roccia@csnsm.in2p3.fr
Theory: diego.guadagnoli@lapth.cnrs.fr , jeremie.quevillon@lpsc.in2p3.fr , christopher.smith@lpsc.in2p3.fr

Announcement 2/2

The n2EDM collaboration is open to new collaborators

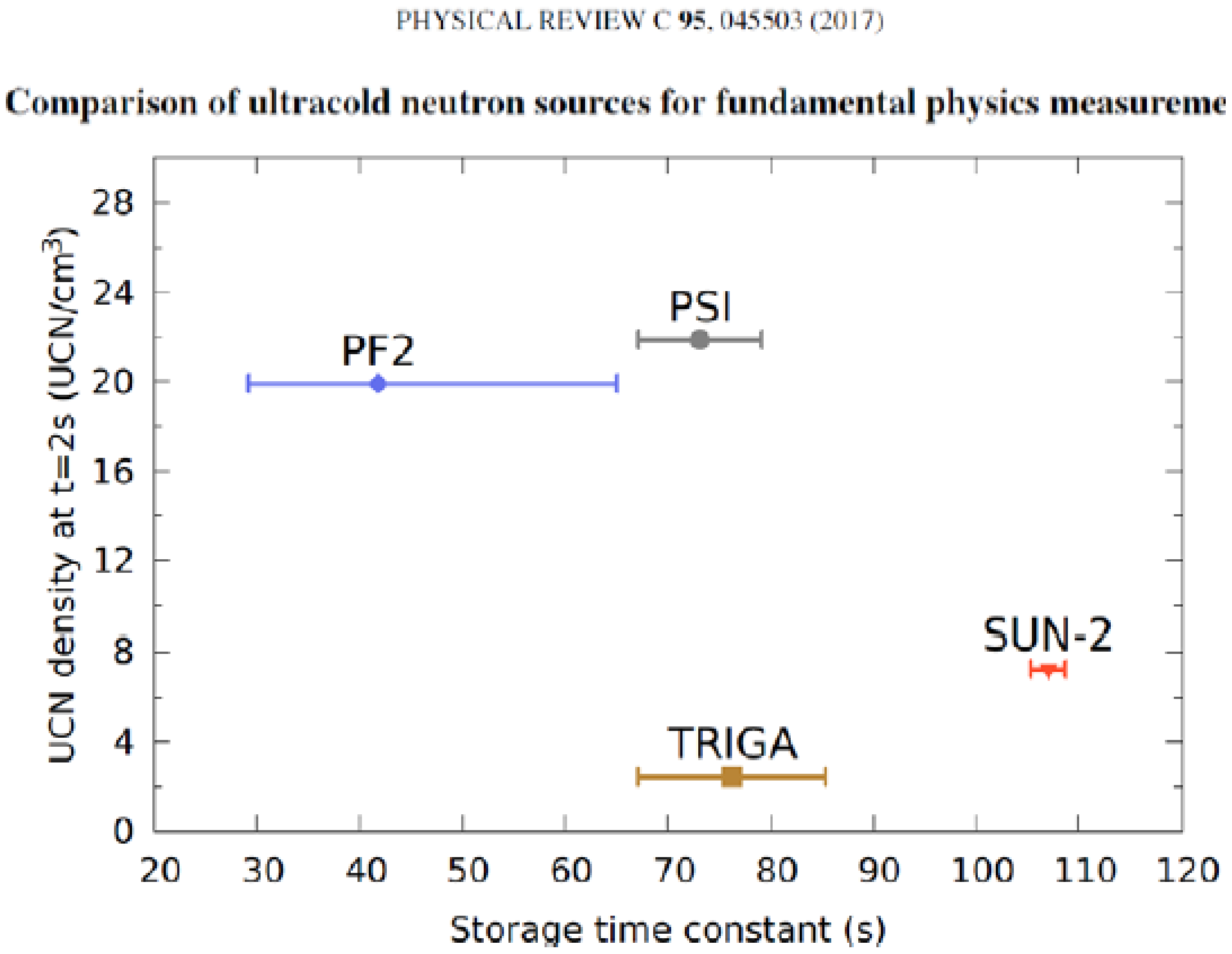
We could get help in hardware and software, e.g.

- Higher electric field, please.
- Better neutron storage time in the chamber, please.
- A professional data quality monitoring software, please
- Organize data legacy
- …

thank you for listening,

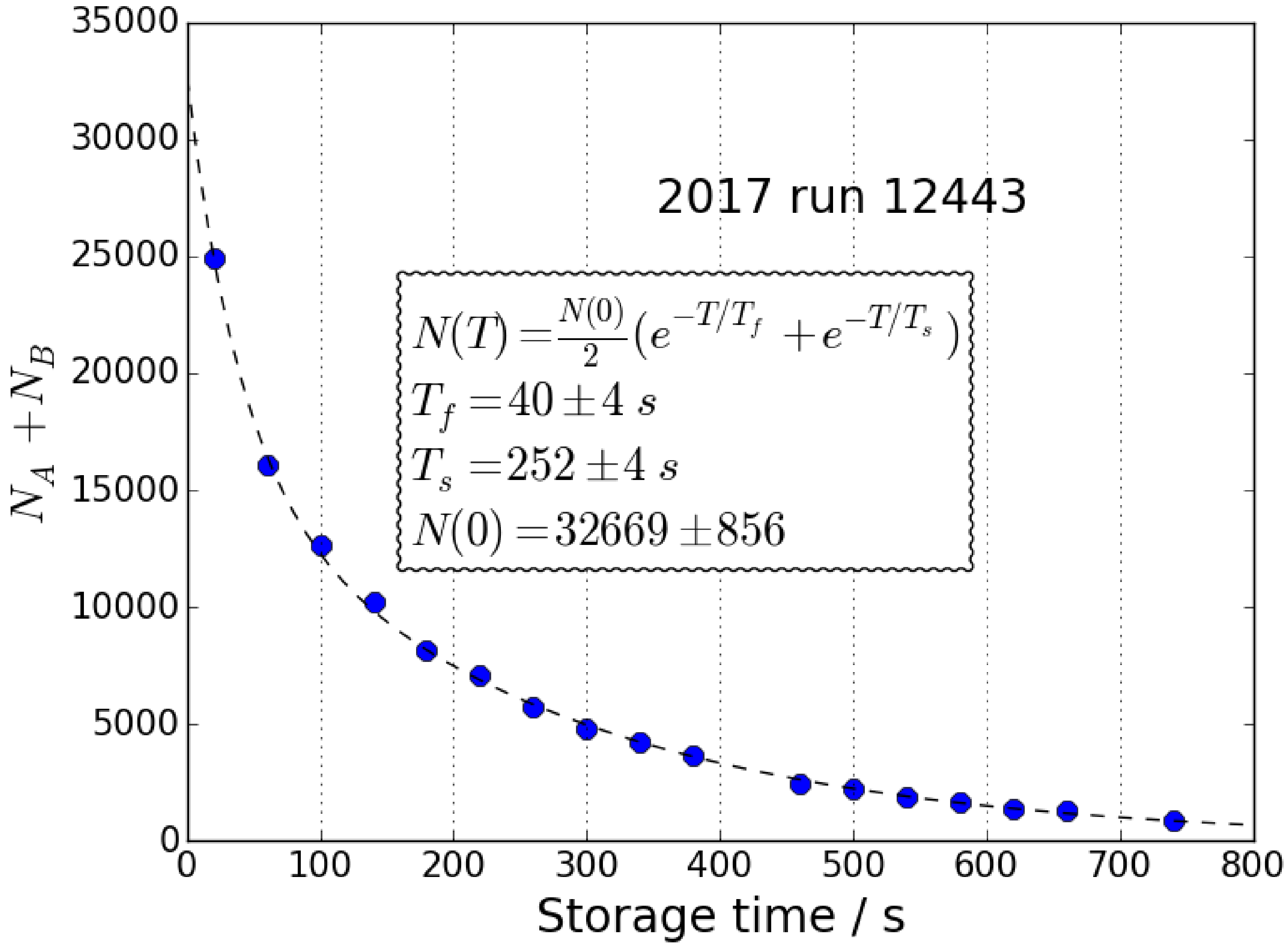
the rest are backup slides

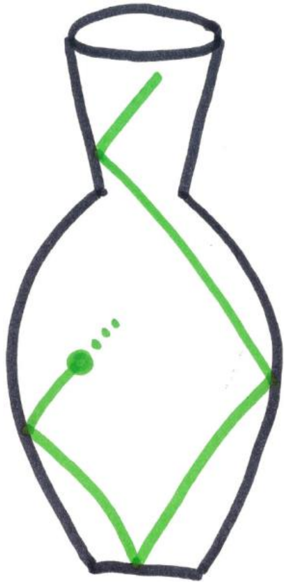
Finally a worldwide comparison of UCN sources



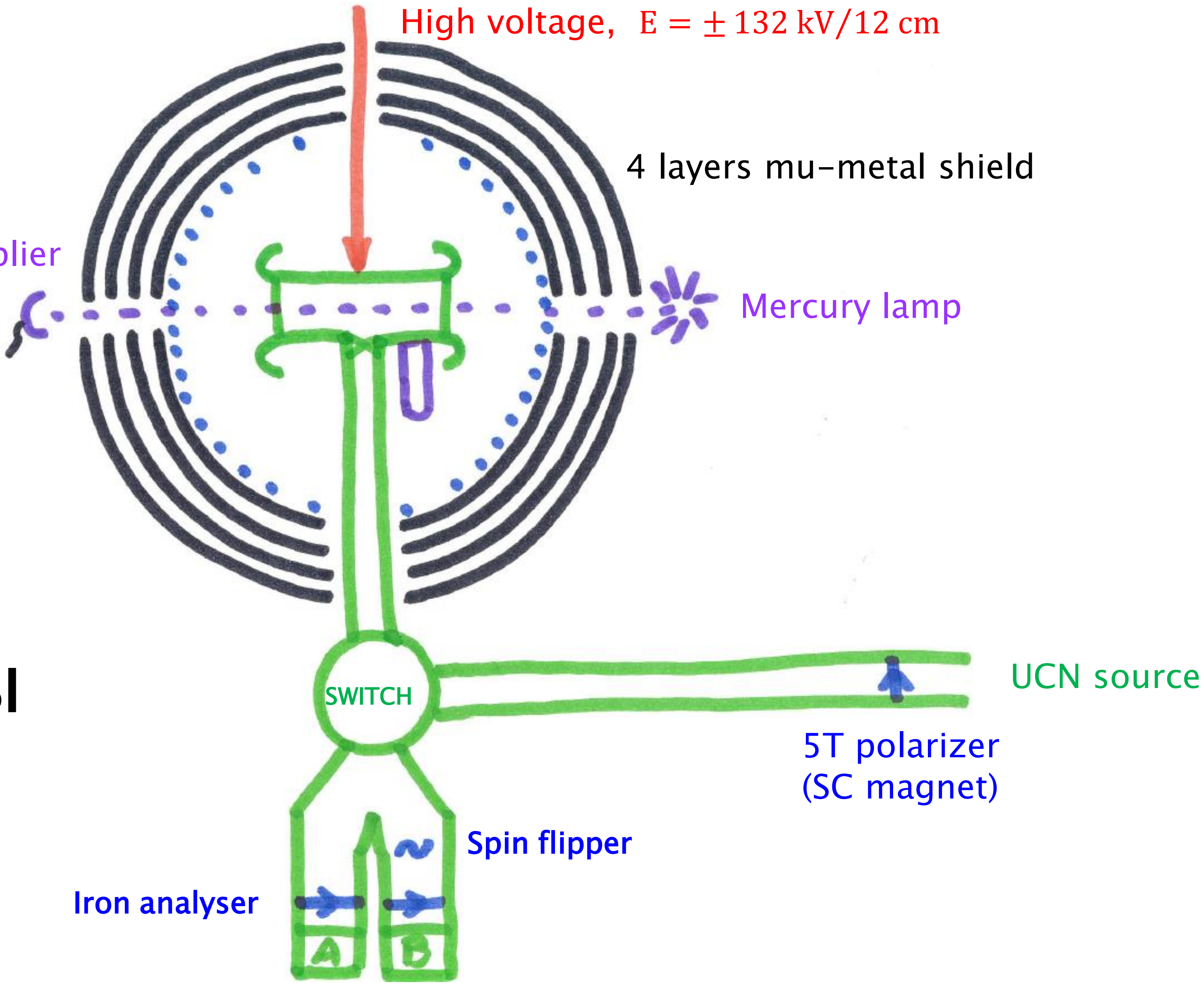
Diter Ries standard stainless steel bottle

Storing Ultracold neutrons in the nEDM apparatus

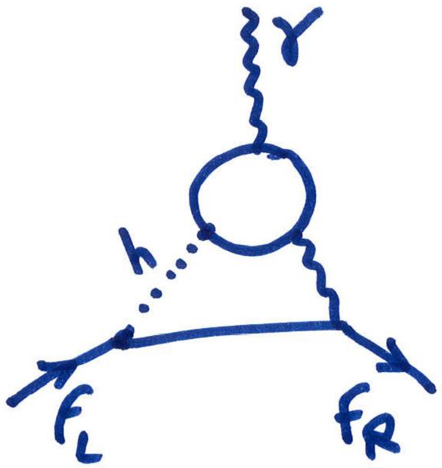




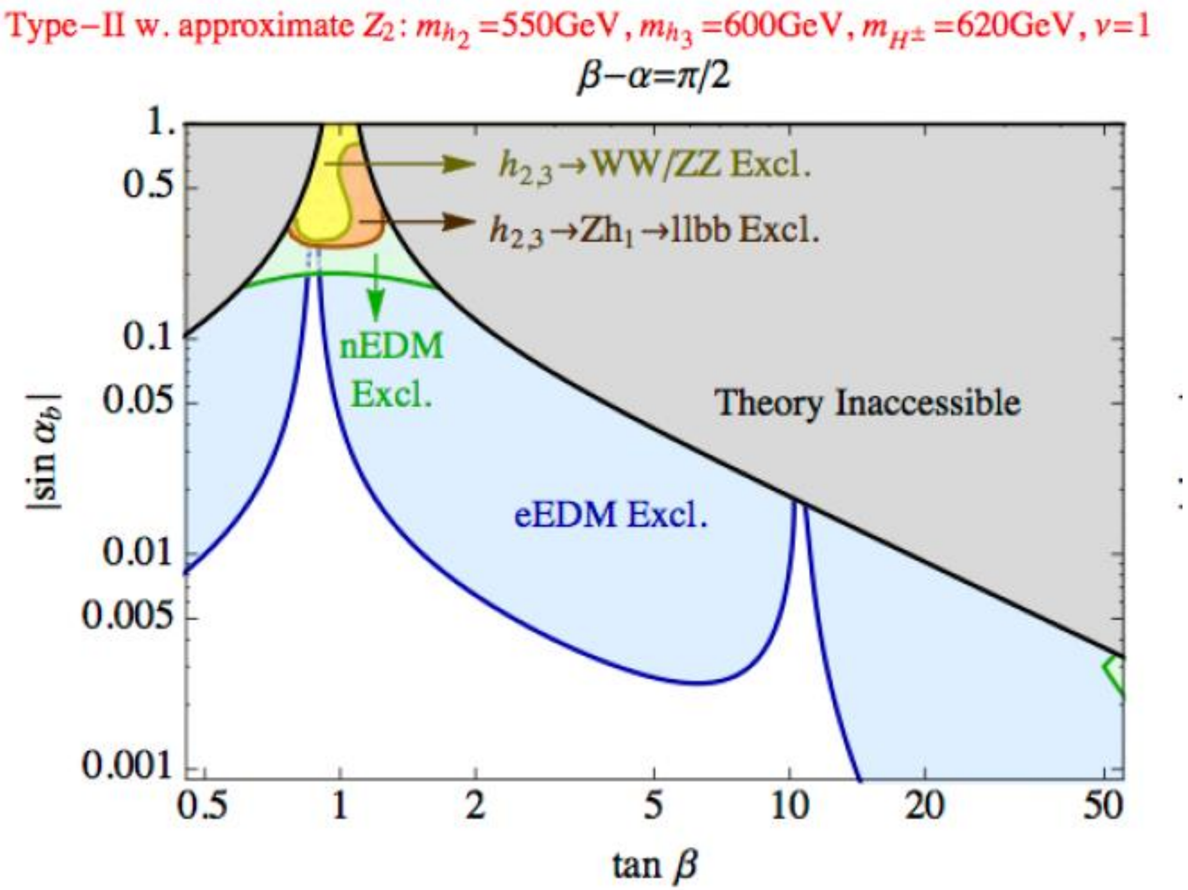
Scheme of the apparatus at PSI



EDMs et les couplages du Higgs



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



Chen, Dawson, Zhang JHEP (2015)

EDMs sensibles au couplage du Higgs violant CP.