

# *Precision tests of symmetries with Ultracold neutrons*

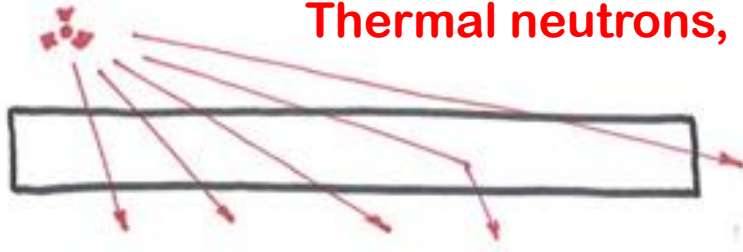
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Romain Viot  
Yinghao Xi

Guillaume Pignol, 07/12/2017  
ENIGMASS meeting, Grenoble

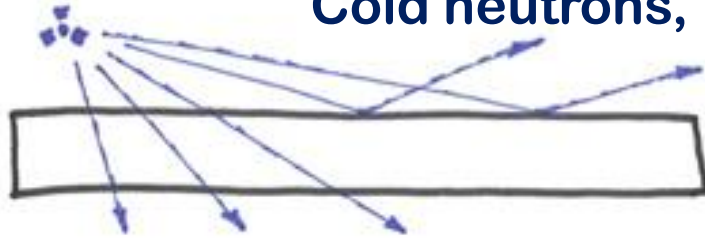
# Neutron optics, cold and ultracold neutrons



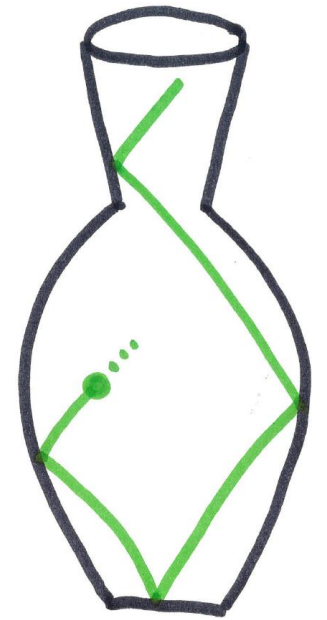
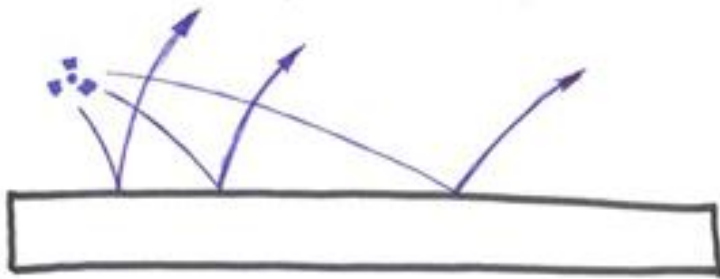
Thermal neutrons,  $E=25 \text{ meV}$



Cold neutrons,  $E < 25 \text{ meV}$



Ultracold neutrons  $E < 200 \text{ neV}$

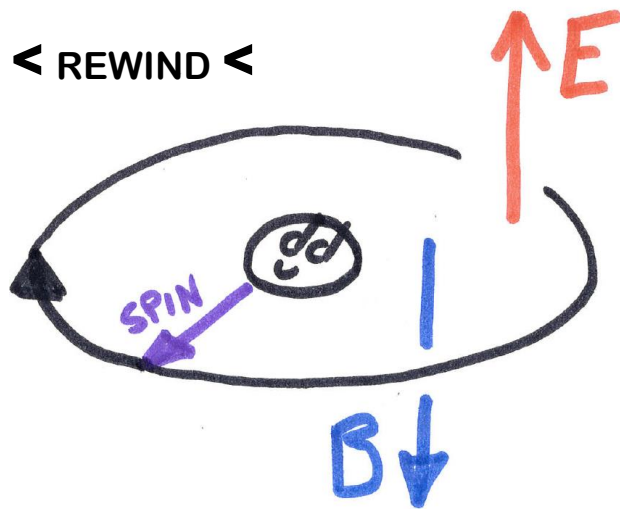
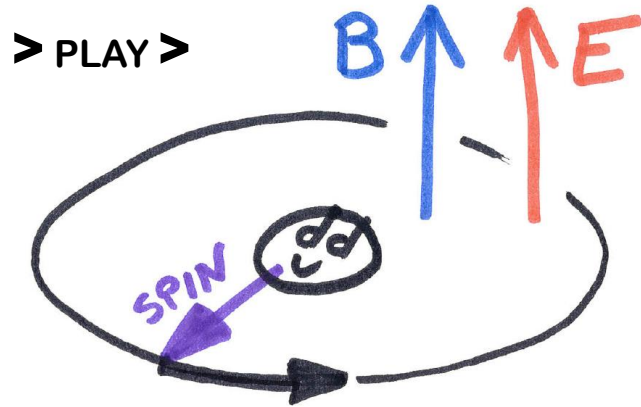


Neutrons with energy  $< 200 \text{ neV}$ , are totally reflected by material walls.

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

They are significantly affected by gravity.

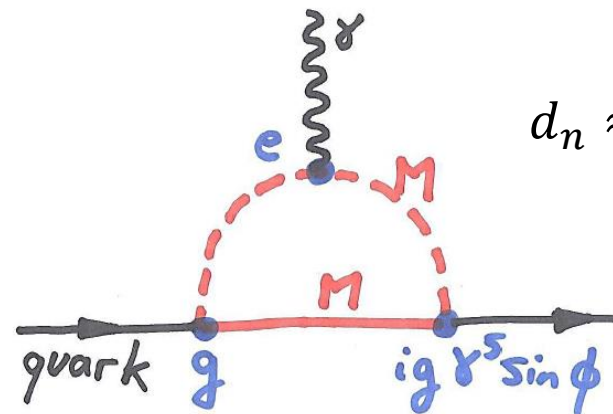
# Electric Dipole Moments and T symmetry



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

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

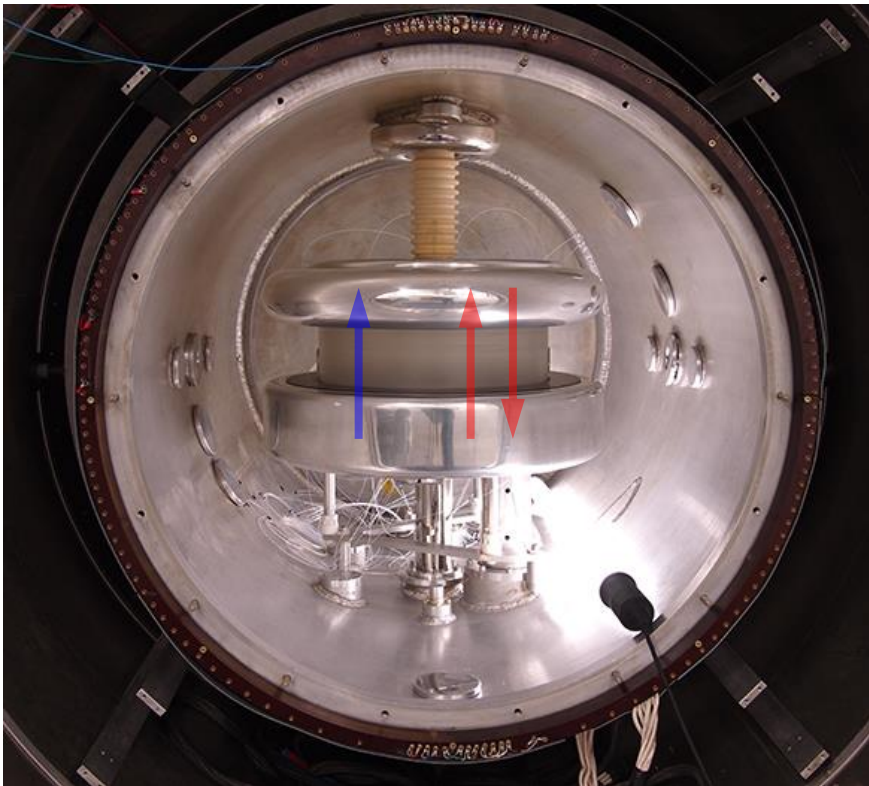
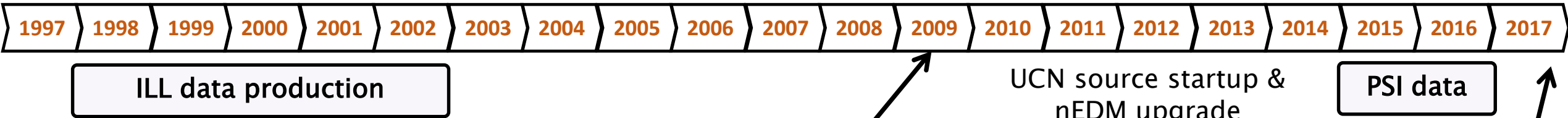
The existence of an electric dipole violates the T symmetry and therefore the CP symmetry



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



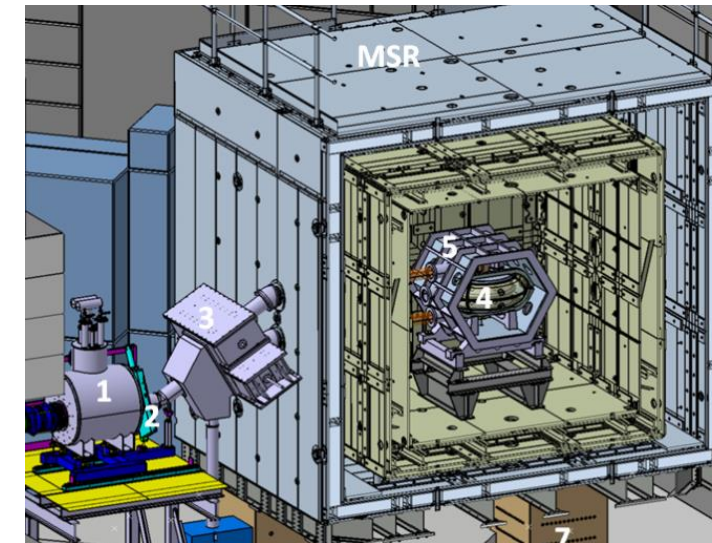
# History of the UCN nEDM apparatus



Best limit:  $d_n < 3 \times 10^{-26} e \text{ cm}$   
 [Baker *et al*, PRL (2006)  
 Pendlebury *et al*, PRD (2015)]

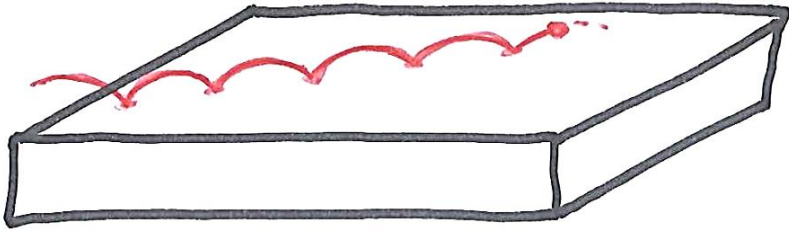


*Move of the apparatus at Paul Scherrer Institute (PSI)*



Goal:  $\sigma d_n < 1 \times 10^{-27} e \text{ cm}$

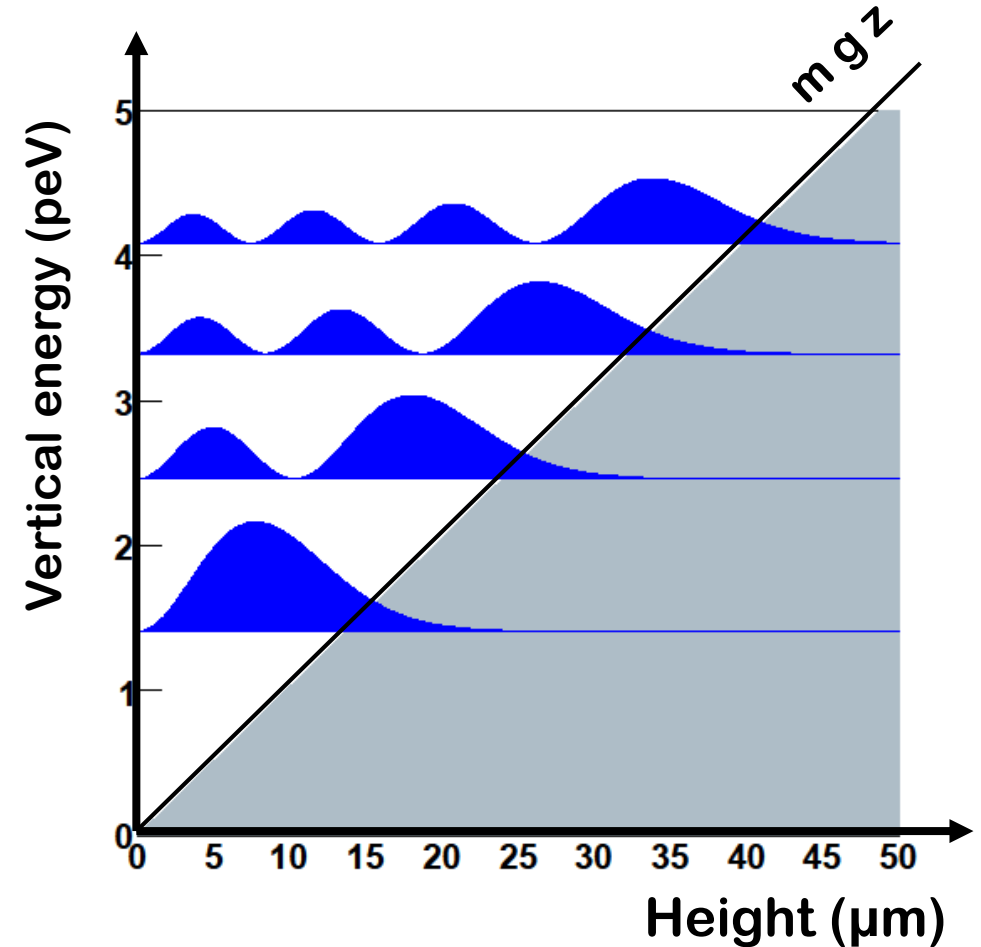
# Bouncing neutrons: quantum states



The vertical motion is a simple quantum well problem

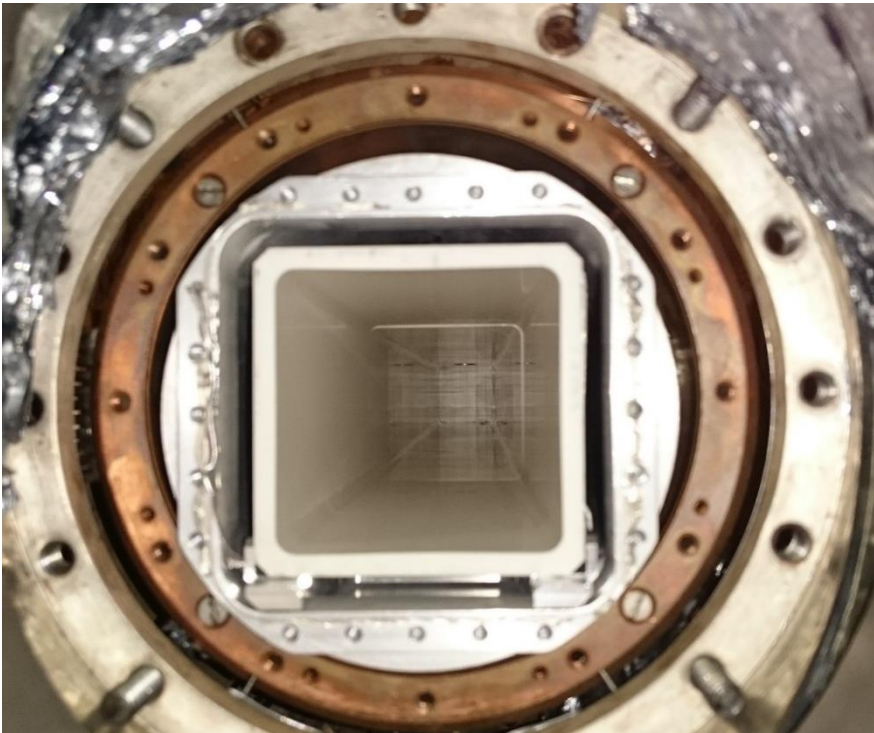
$$-\frac{\hbar^2}{2m_i} \frac{d^2\psi}{dz^2} + m_g g z \psi = E \psi$$

We want to test Einstein's equivalence principle for a quantum particle in a classical gravity field.

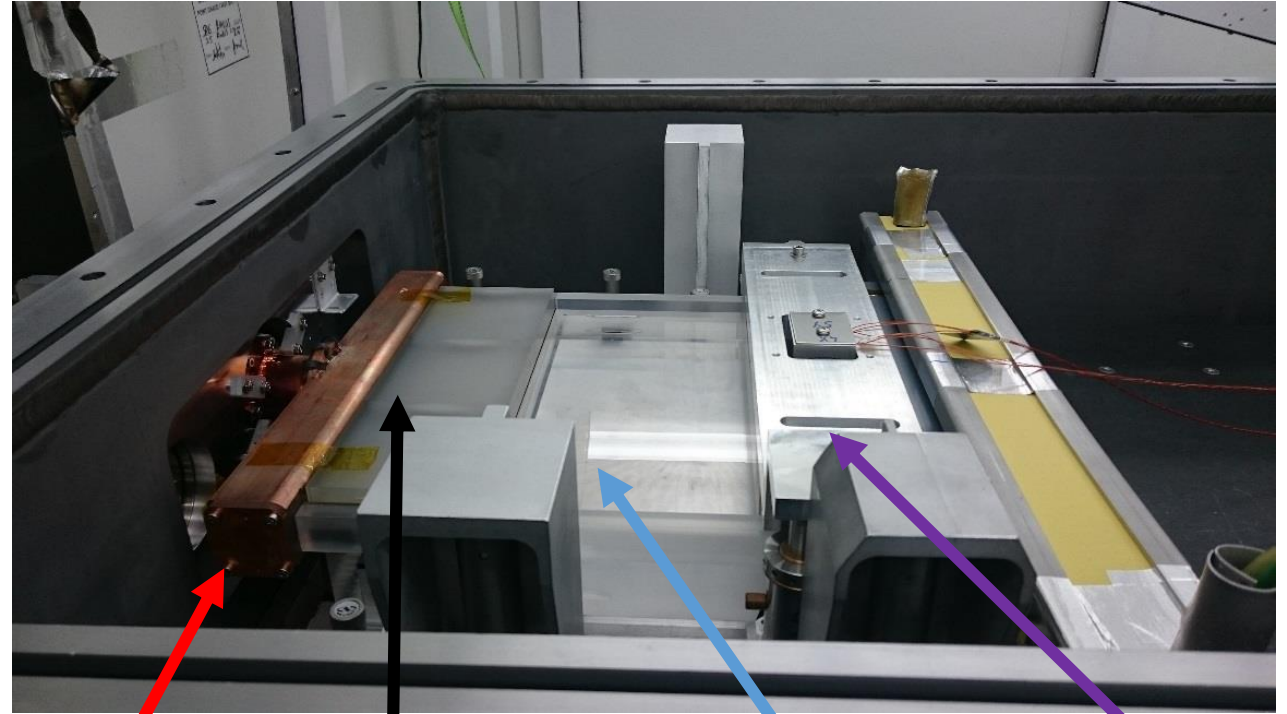




# The GRANIT instrument at ILL: UCN source + spectrometer



New generation source  
production of UCNs in superfluid He  
Cooled down to 0.7 K



Copper  
volume

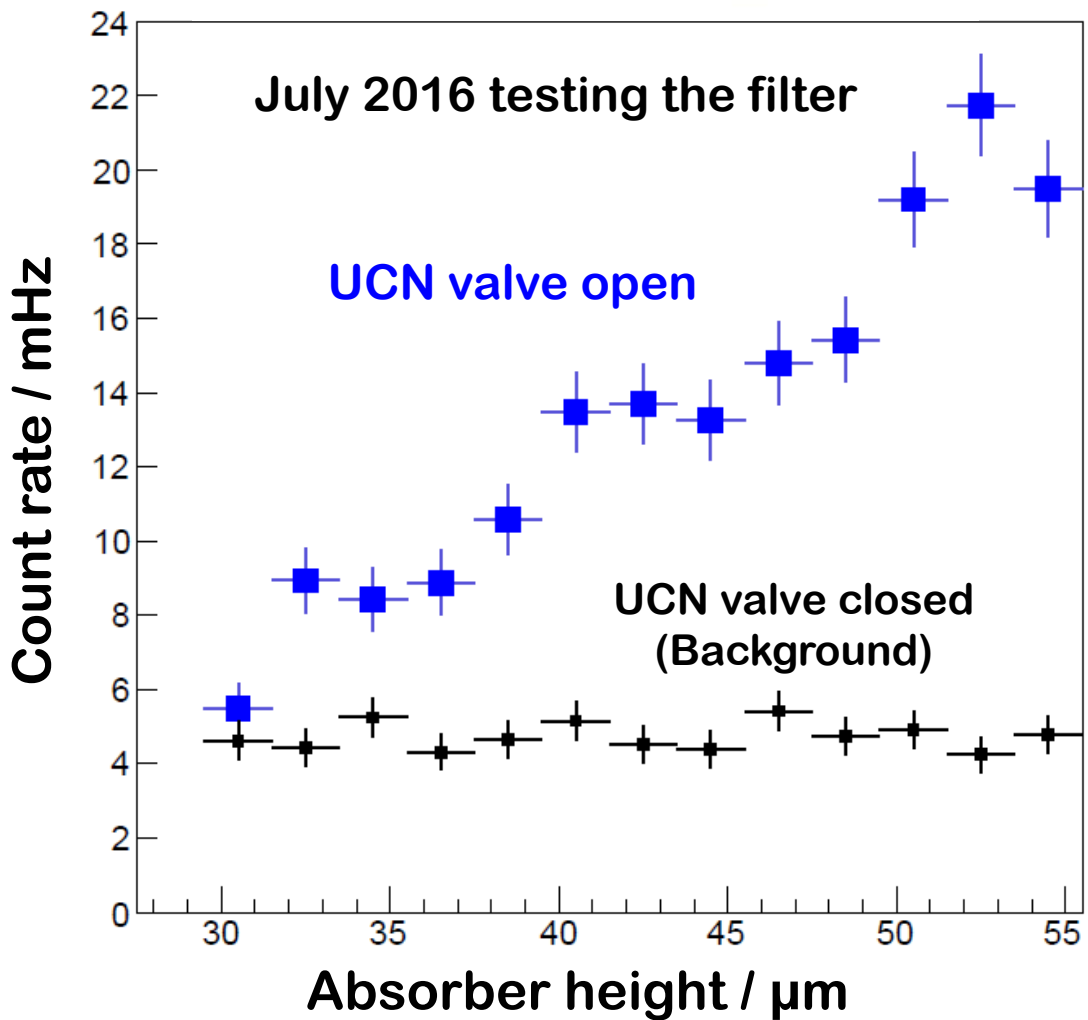
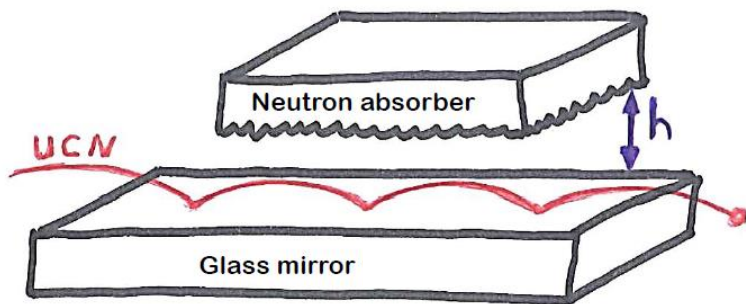
Semi diffusive slit

127microns

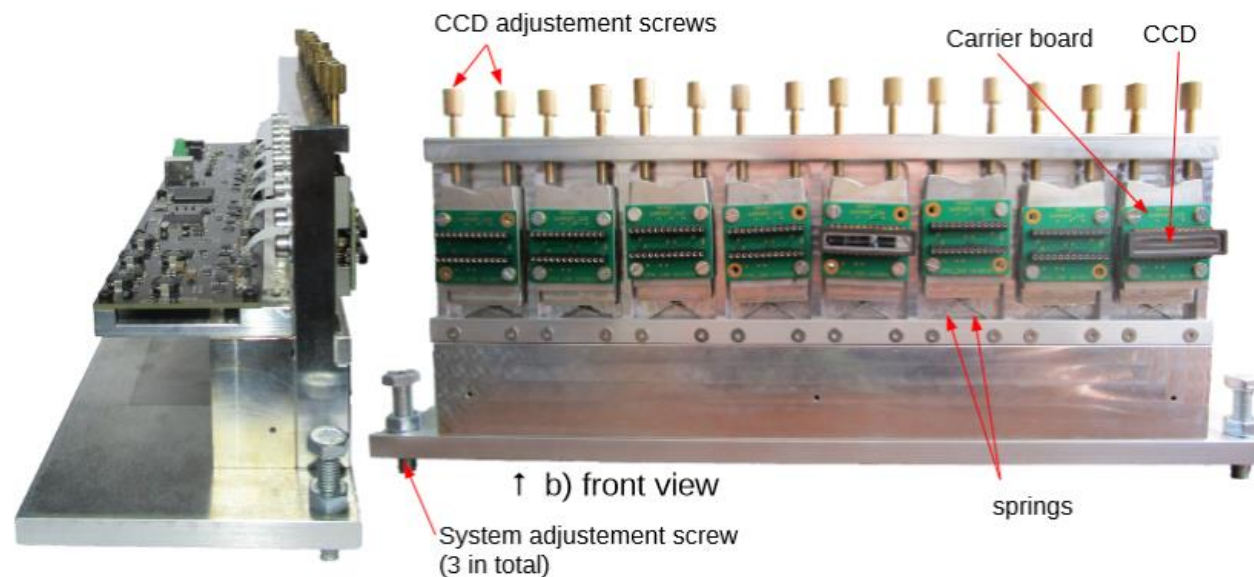
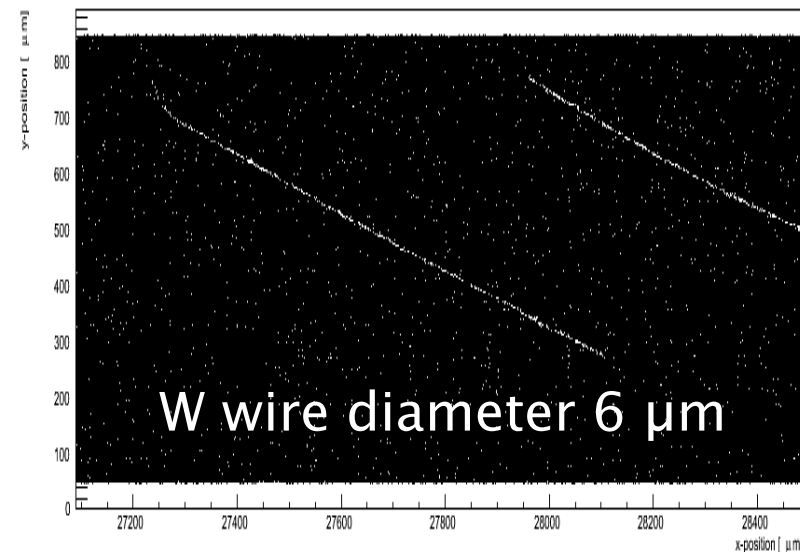
Main bottom mirror, 25 cm long

absorber

Considerable involvement of LPSC technical departments



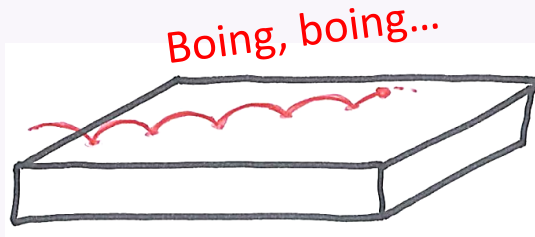
## Developments of position sensitive UCN detectors with LPSC plasma group



# Perspectives 2020 – 2030

Precision experiments involve relatively **small teams**, but develop over **long periods of time** and require **interdisciplinary research**.

## GRANIT

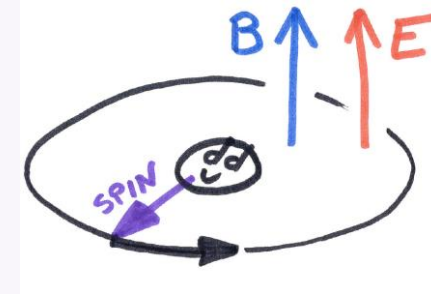


A team of ~5 physicists and ~2 IT

Started in 2006.  
First UCNs in 2013

Scientific exploitation starting 2018

## nEDM



A collaboration of ~50 physicists and ~20 IT

nEDM started in ~1980 at ILL, 2009 at PSI.

n2EDM construction starts 2017

First EDM runs foreseen in 2020

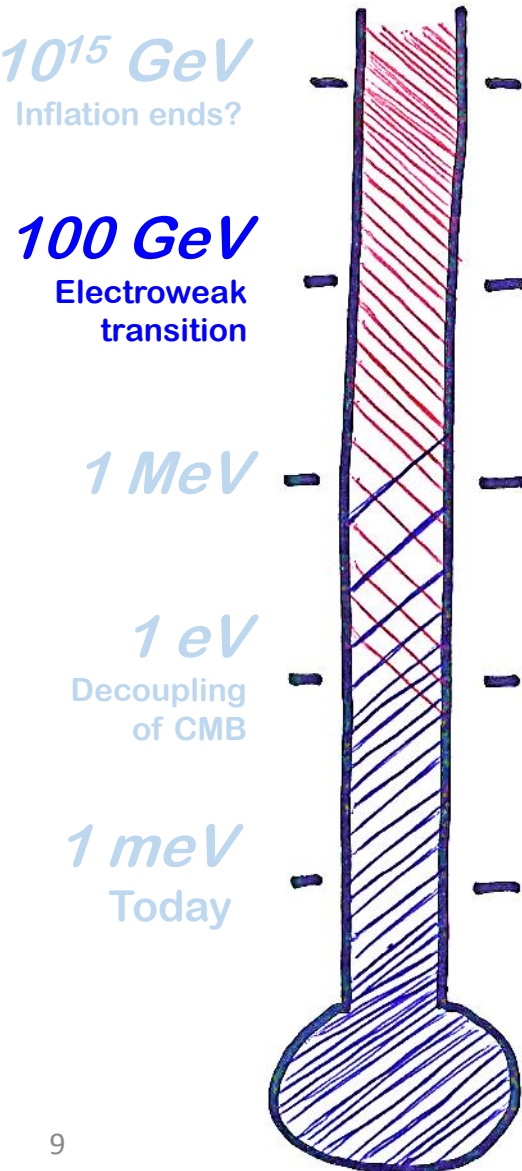
Exploitation : 2020 – 2030

Possibility for even longer term: measure the proton EDM in storage rings. Scientific connection with the LPSC accelerator group.

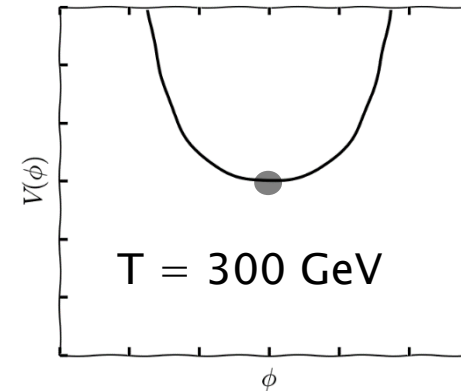


# Scientific vision within ENIGMASS+10

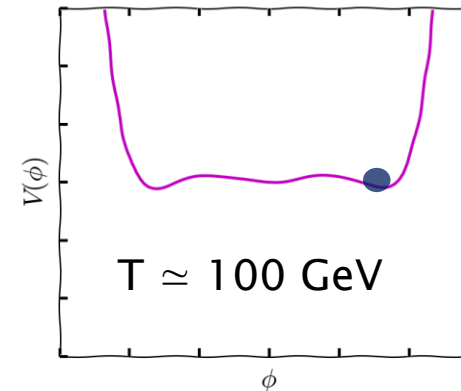
## CP violation and baryogenesis



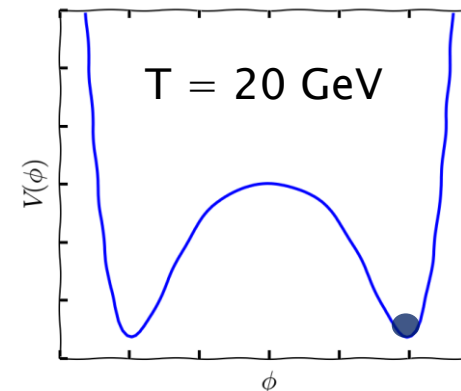
symmetric phase  
 $\phi = 0$



boiling



broken phase  
 $\phi \neq 0$

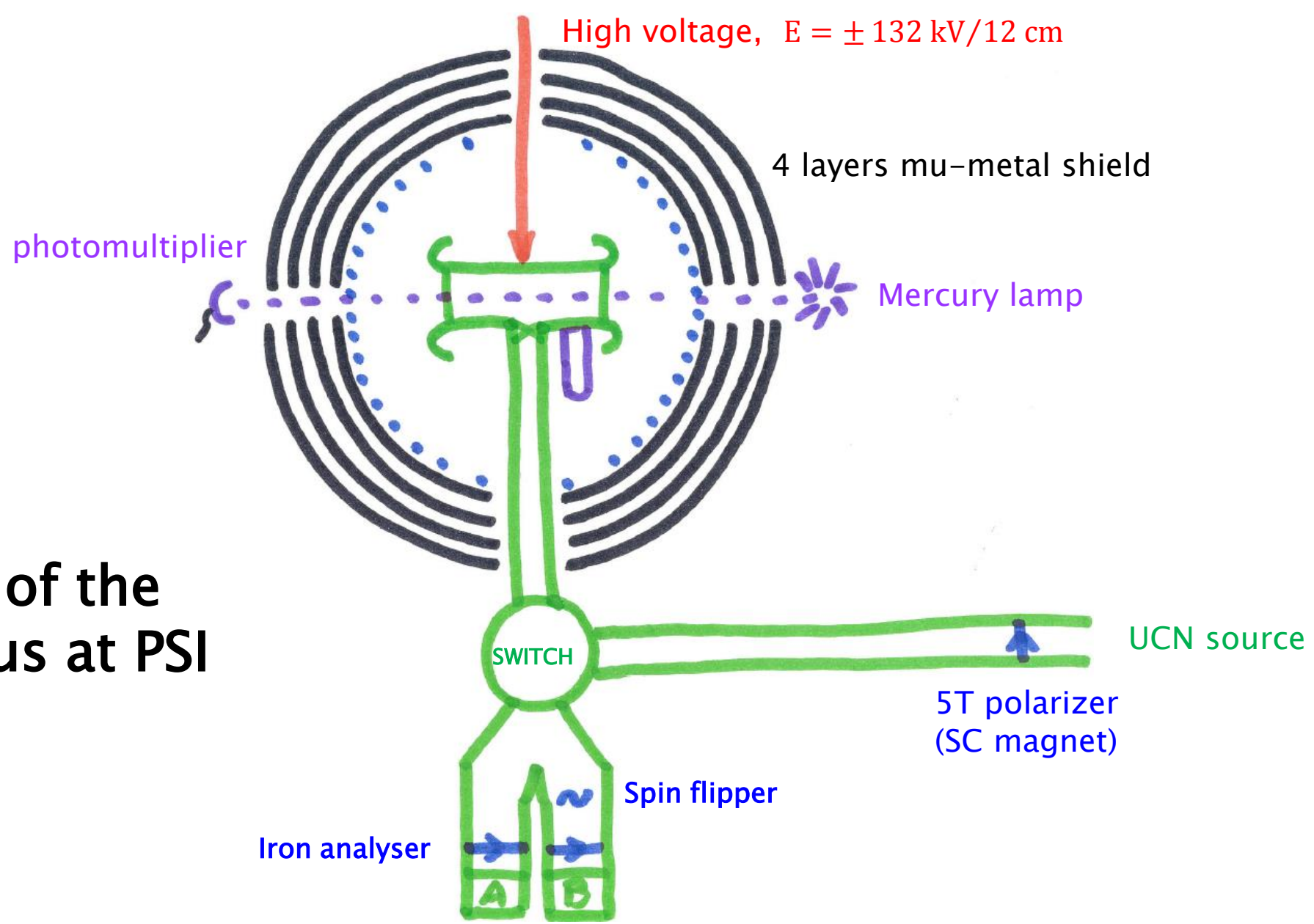


Sakharov's Baryogenesis recipe (1967)

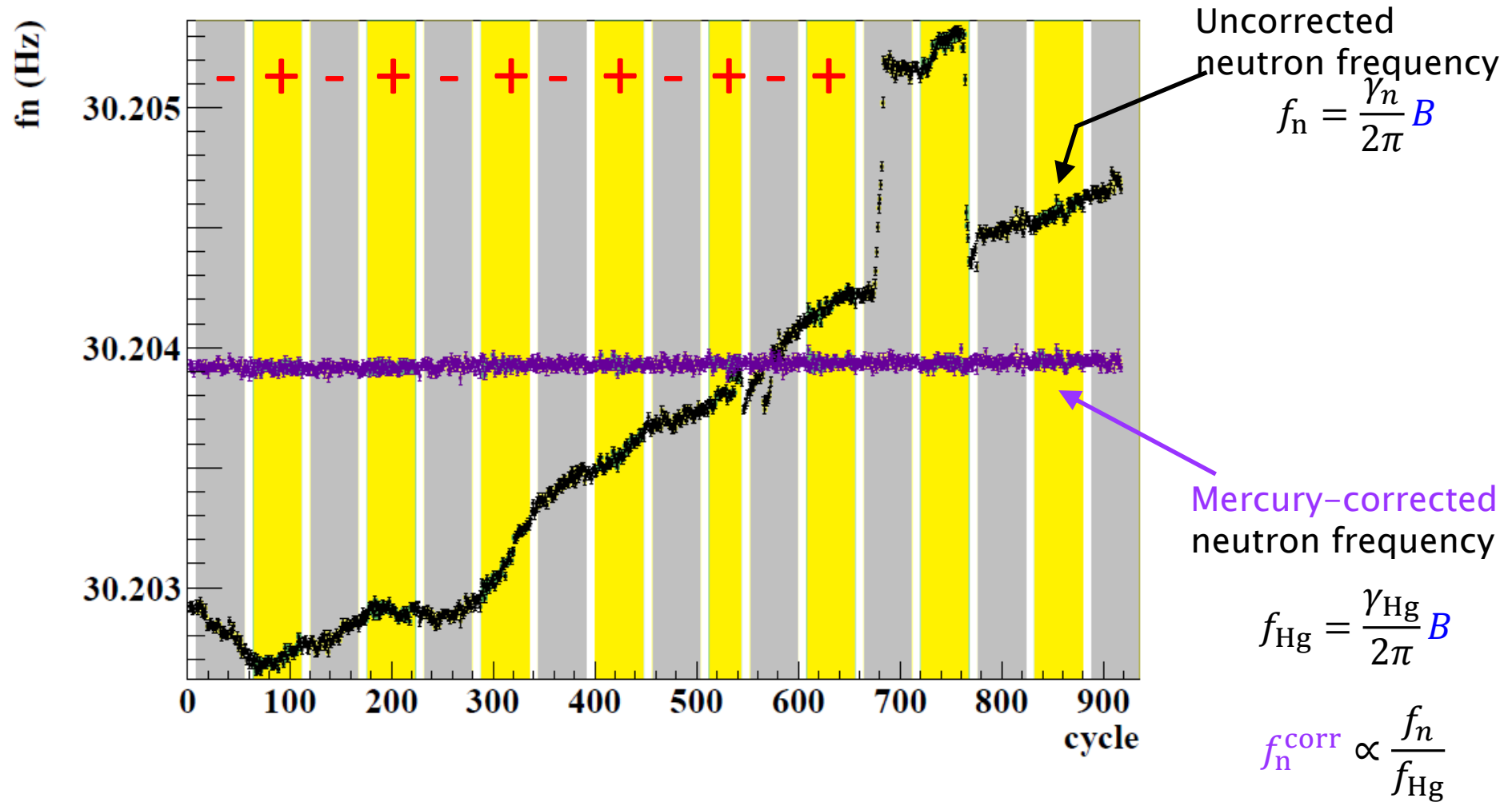
- Baryon number not conserved
- Universe out of equilibrium
  - > Higgs self coupling
- Violation of CP symmetry
  - > nEDM, pEDM

Other possibility:  
leptogenesis  
Probed by CP violation in  
neutrinos

## Scheme of the apparatus at PSI



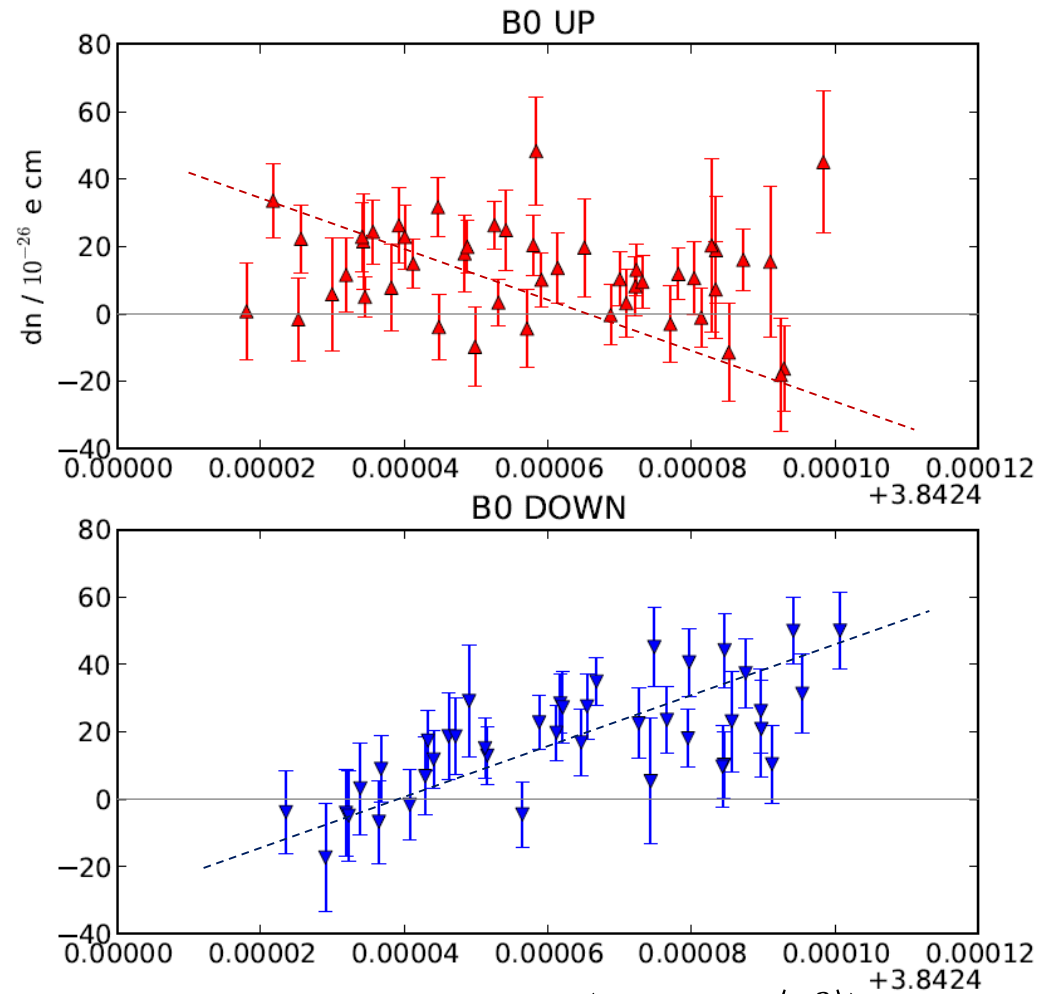
# Typical measurement sequence at PSI, 1 cycle every 5 minutes



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



# Analysis of the 2015/2016 PSI data is still congoing



Relativistic Hg false EDM

$$d_{\text{False}} \propto \langle xB_x + yB_y \rangle$$

Gravitational shift

$$\delta R \propto \frac{dB_z}{dz}$$

*Preliminary blind result*

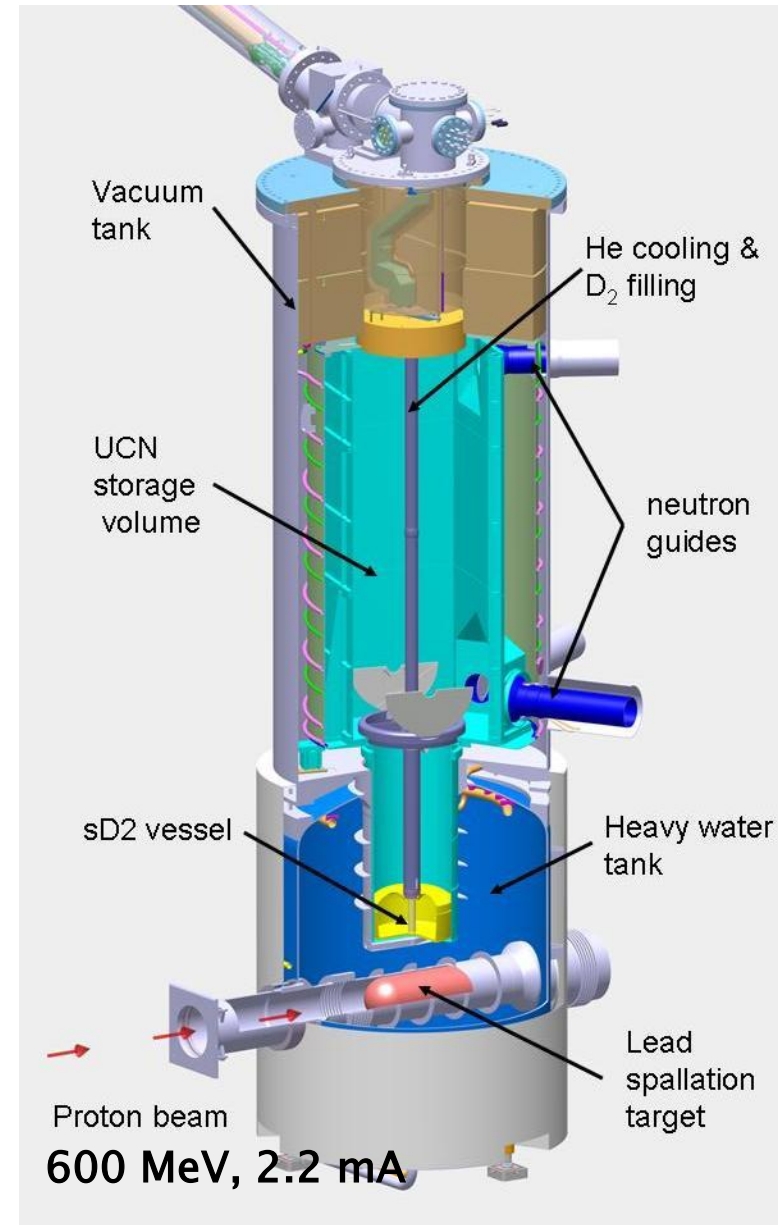
$$d_{\times} = (14.6 \pm 1.1) \times 10^{-26} \text{ e cm}$$

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

# UCN source at the Paul Scherrer Institute



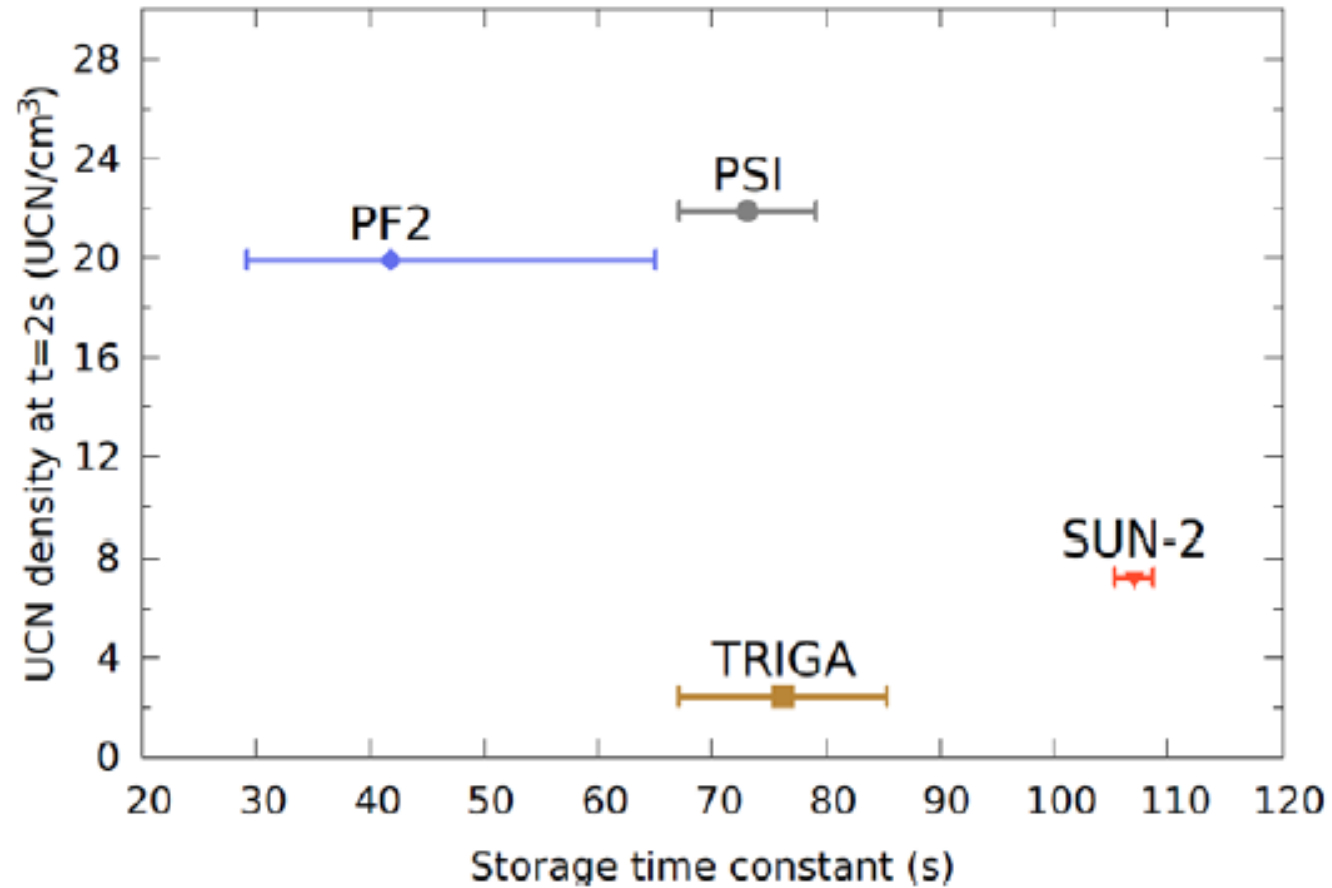
pulsed UCN source  
One kick per 5 min  
online since 2011



# Finally a worldwide comparison of UCN sources

PHYSICAL REVIEW C **95**, 045503 (2017)

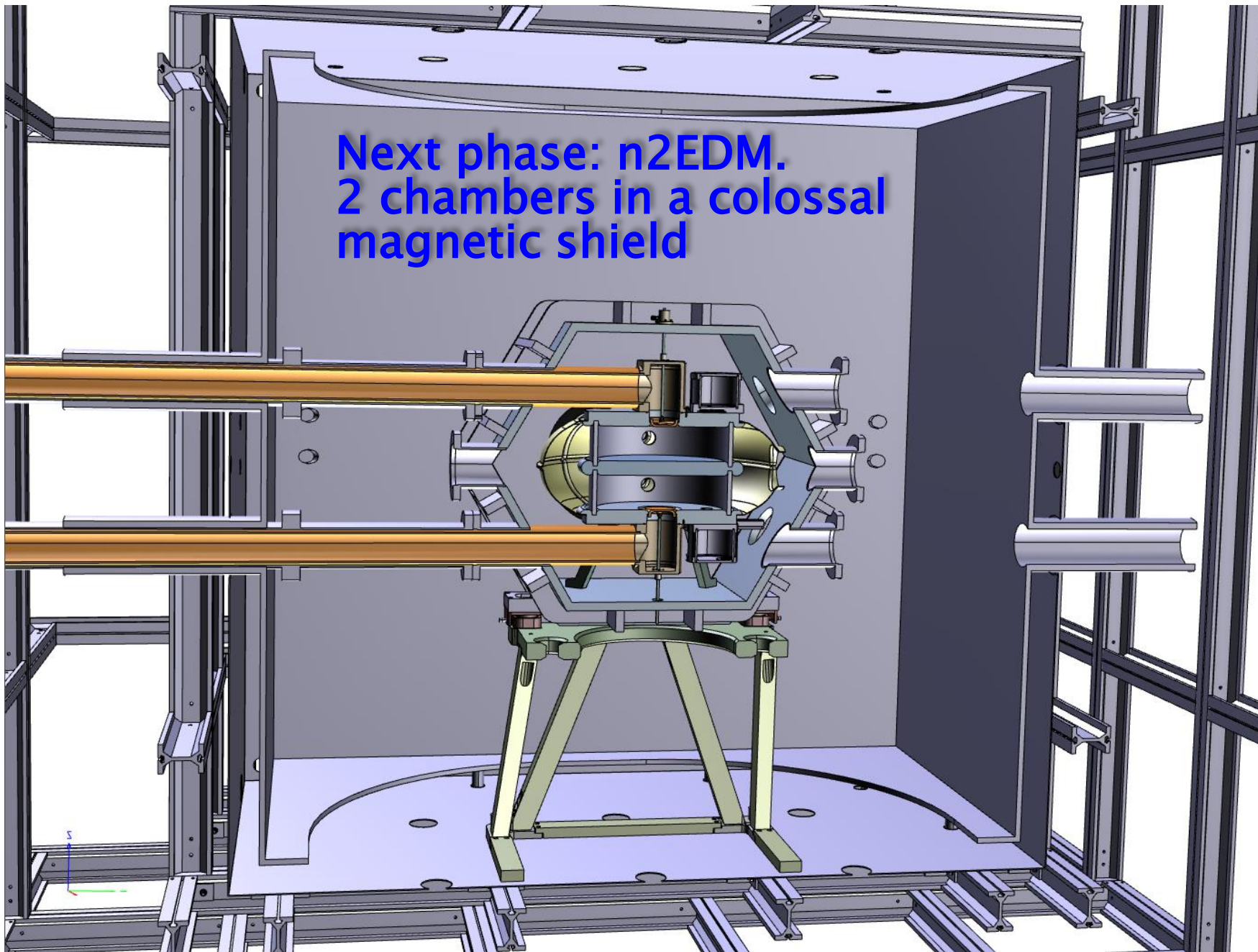
Comparison of ultracold neutron sources for fundamental physics measureme



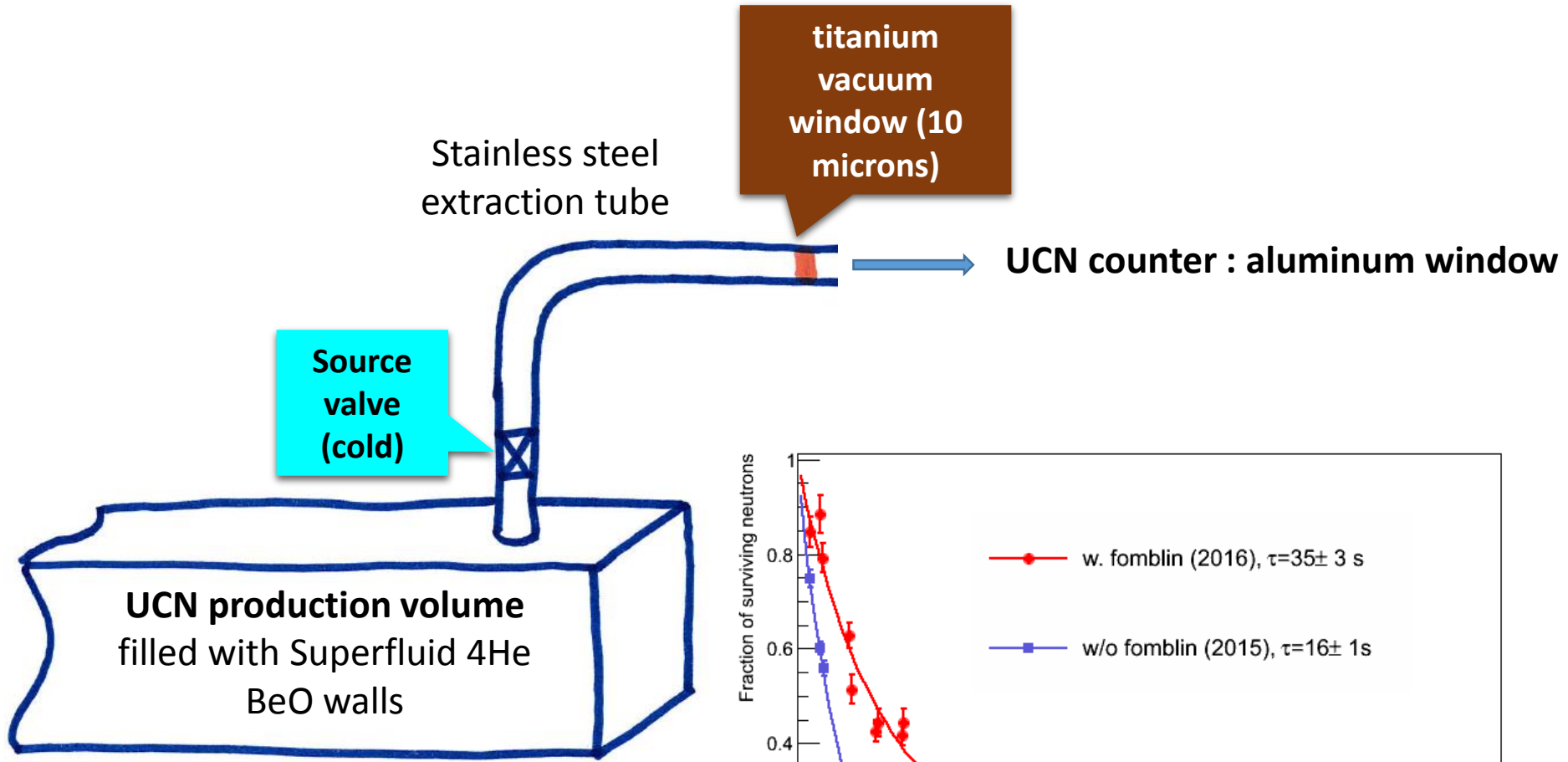
Diter Ries standard stainless steel bottle



Next phase: n2EDM.  
2 chambers in a colossal  
magnetic shield



# Performance de la source



Storage time inside the source

