Probing oscillating cosmic fields with neutrons

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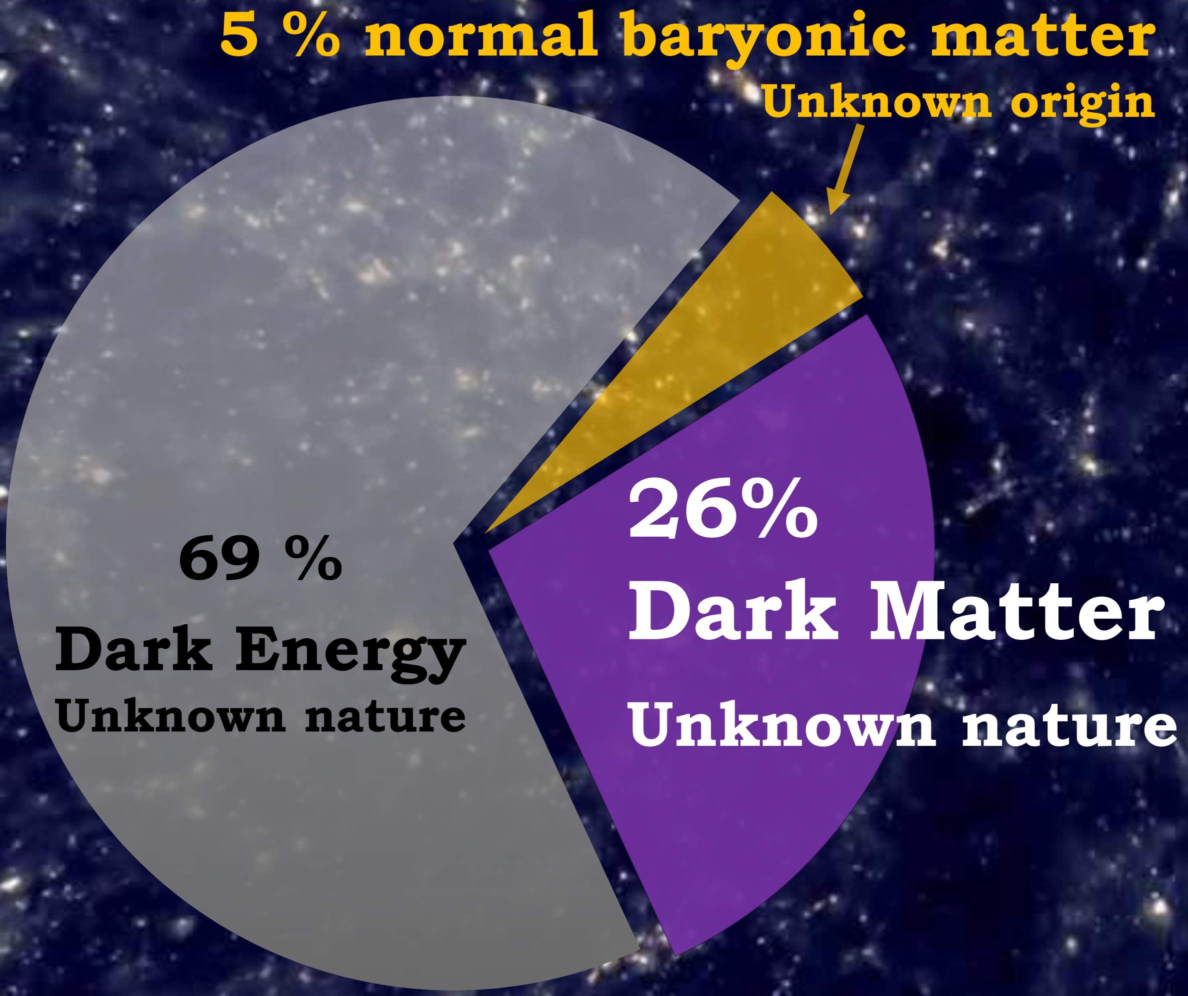
UNIVERSITÉ Grenoble Alpes
erc European Research Council

Energy budget of the Universe in ΛCDM



Dark matter is a pressure-less fluid

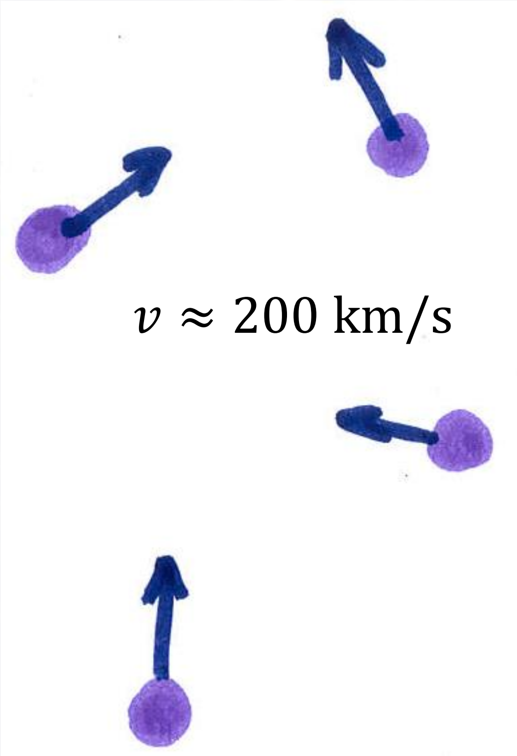
Cosmological density
$10^{-6}\ \mathrm{GeV/cm^3}$

Local density
$0.4\ \mathrm{GeV/cm^3}$

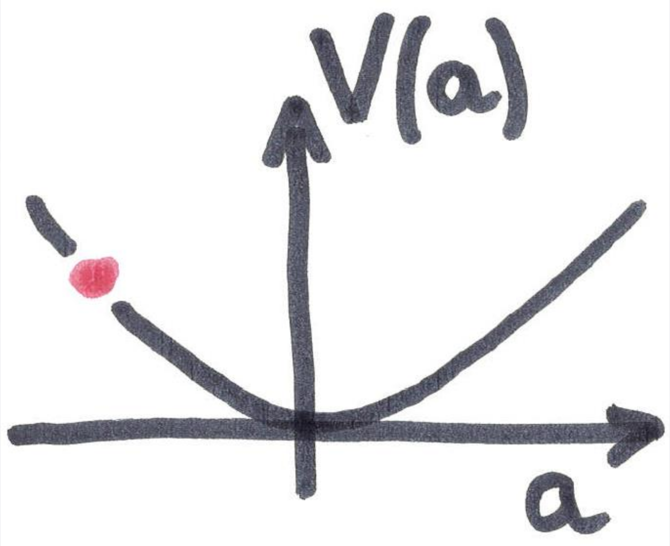
Nature of pressure-less Dark matter?

Weakly Interacting Massive Particles

$\mathbf{M > 2\ GeV}$



Coherent oscillation of a light scalar field

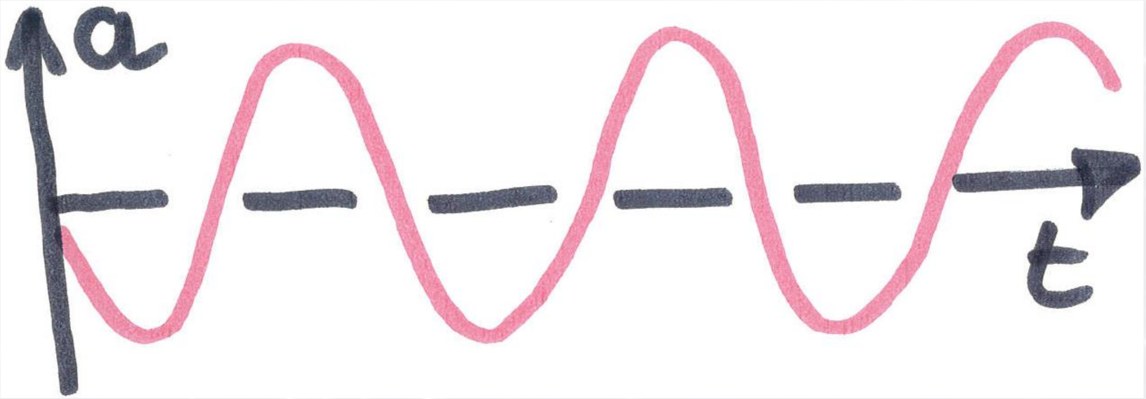


$\mathbf{10^{-22}\,eV < m_a < 0.1\ eV}$

$$\mathrm{V}(a) = \frac{1}{2} m_a a^2$$

$$a(t) = a_0 \cos m_a t$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2$$



How to detect the oscillation?

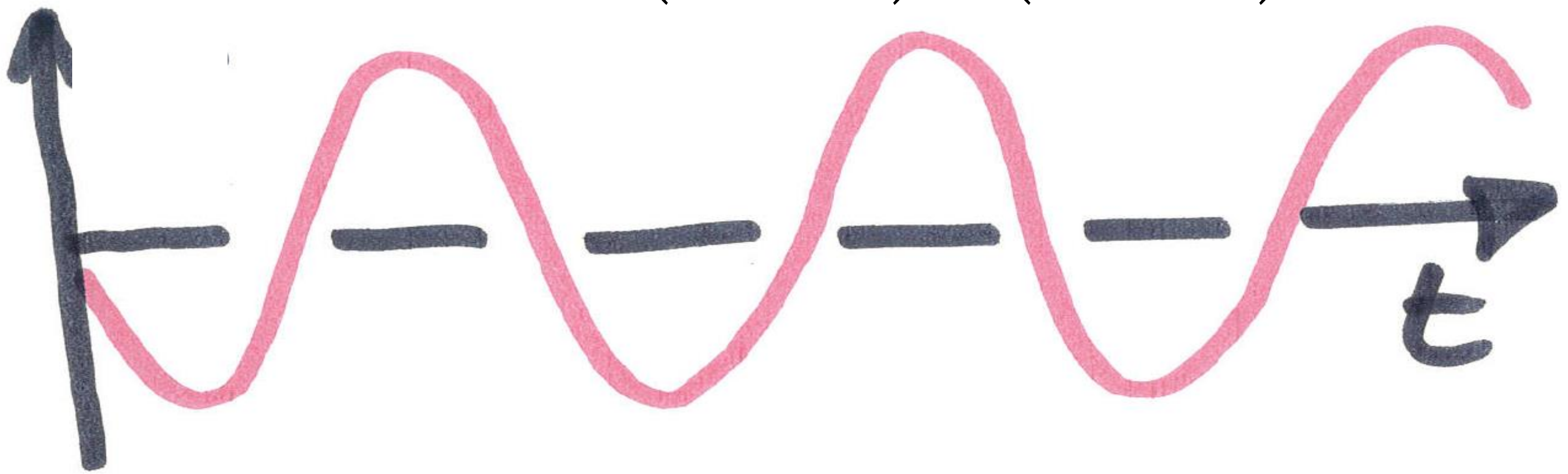
$$\mathcal{L} = \boxed{g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}} + \boxed{\frac{C_G}{f_a}\frac{g^2}{32\pi^2}\, a\, G_{\mu\nu}\tilde{G}^{\mu\nu}}$$

+ other possible terms
(see talk Aurélien Hees)

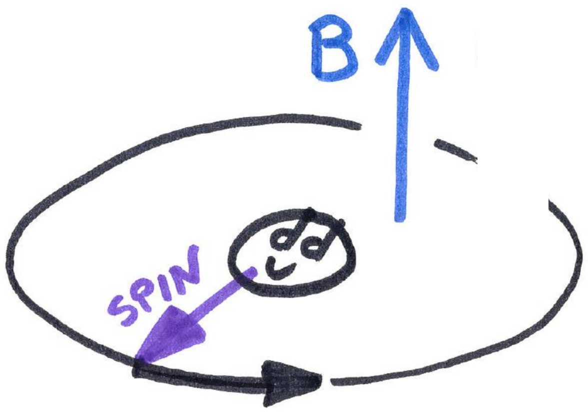
Coupling to photons
Induce axion-photon conversion

Coupling to gluons
Induce a neutron electric dipole moment

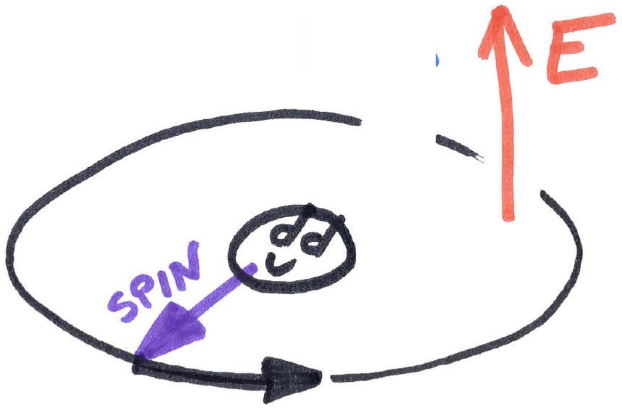
$$d_n(t) = 6 \times 10^{-22}\, e\,\text{cm} \times \left(\frac{10^{-22}\text{eV}}{m_a}\right) \times \left(\frac{10^{16}\text{GeV}}{f_a}\right) \times \cos m_a t$$



Electric and Magnetic Dipoles



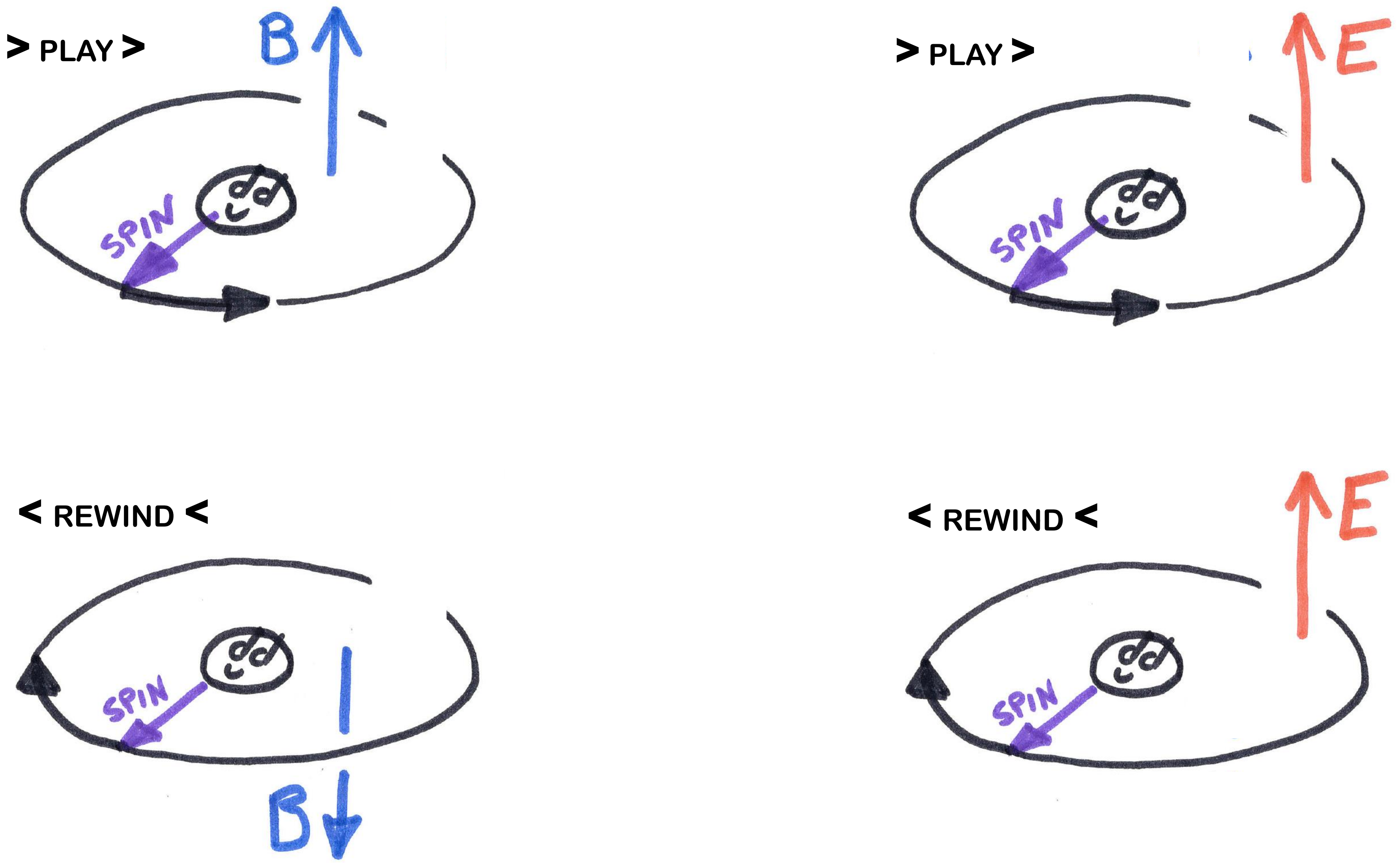
Spin precession due to the magnetic dipole μ_n



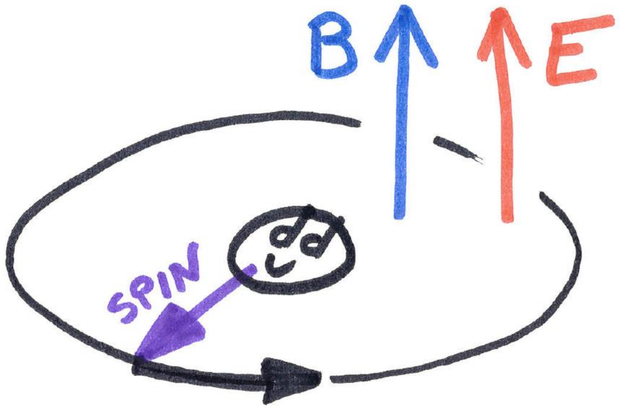
Spin precession due to the electric dipole d_n?

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

Electric dipole violates time reversal invariance!



Hunting the neutron Electric Dipole Moment

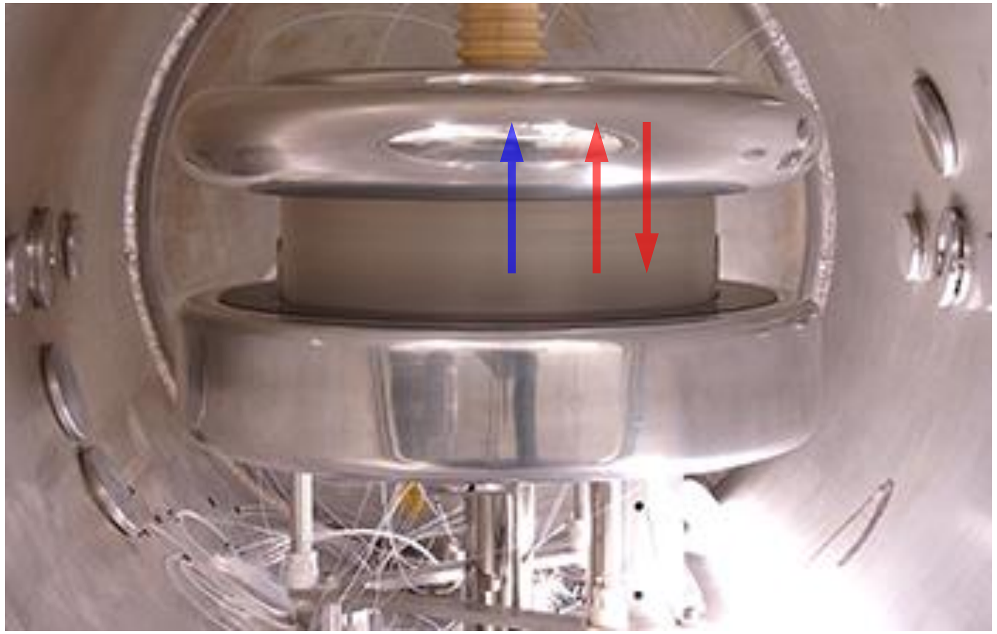


One measures the neutron Larmor precession frequency f_L in weak Bagdetic and strong Electric fields

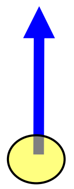
$$f_L(\uparrow\uparrow) - f_L(\uparrow\downarrow) = -\frac{2}{\pi\hbar} \boxed{d_n} E$$

Neutron EDM

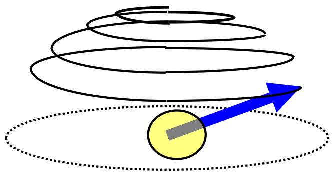
The most sensitive experiments use Ramsey's method with polarized ultracold neutrons stored in a "precession" chamber
Here a cylinder, Ø50 cm, H12 cm.



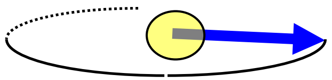
Ramsey's method



"Spin up" neutron...

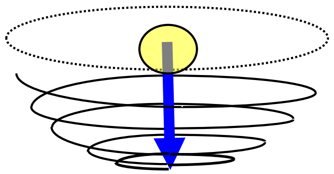


Apply π/2 spin-flip pulse...

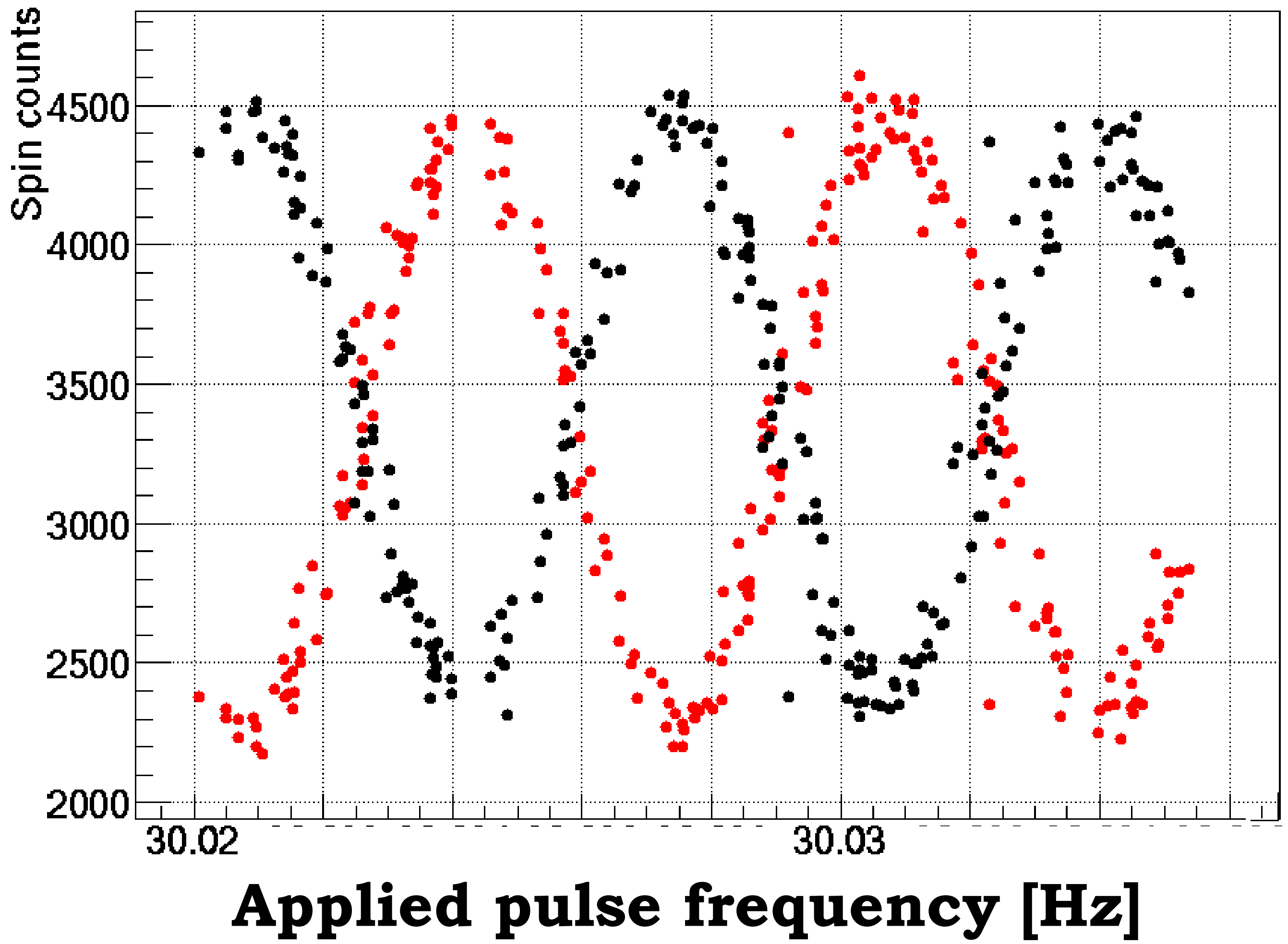


Free precession...

duration T



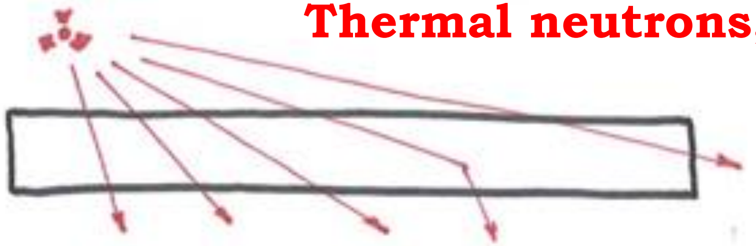
Second π/2 spin-flip pulse



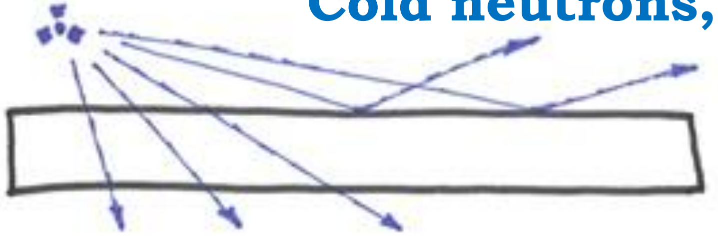
Statistical sensitivity: $\sigma d_n = \frac{\hbar}{2\,\alpha\,E\,T\,\sqrt{N}}$

Neutron optics, cold and ultracold neutrons

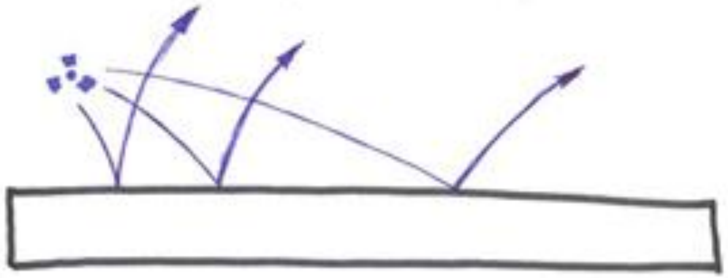
Thermal neutrons, E=25 meV

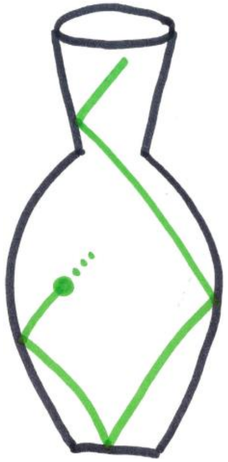


Cold neutrons, E<25 meV



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.

History of the venerable UCN nEDM apparatus

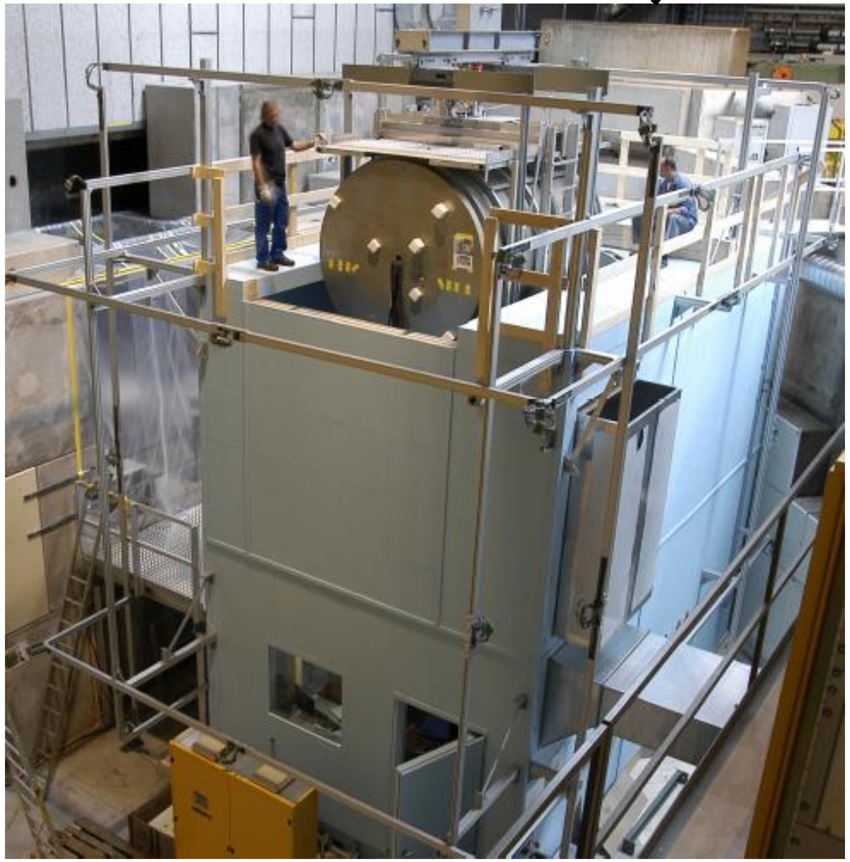
1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

ILL data production

UCN source startup
& nEDM upgrade

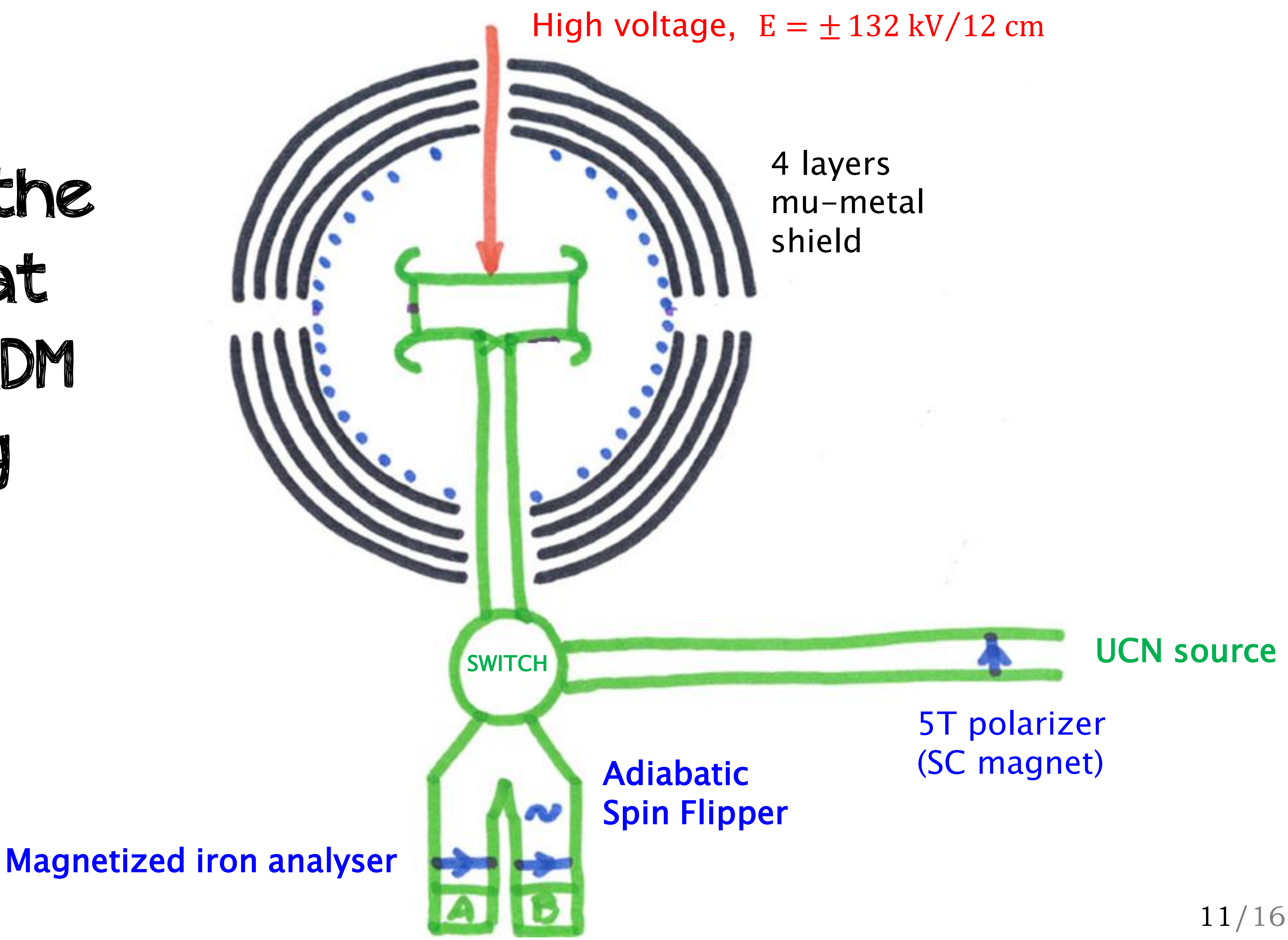
PSI data

Dismantling nEDM
n2EDM construction starts

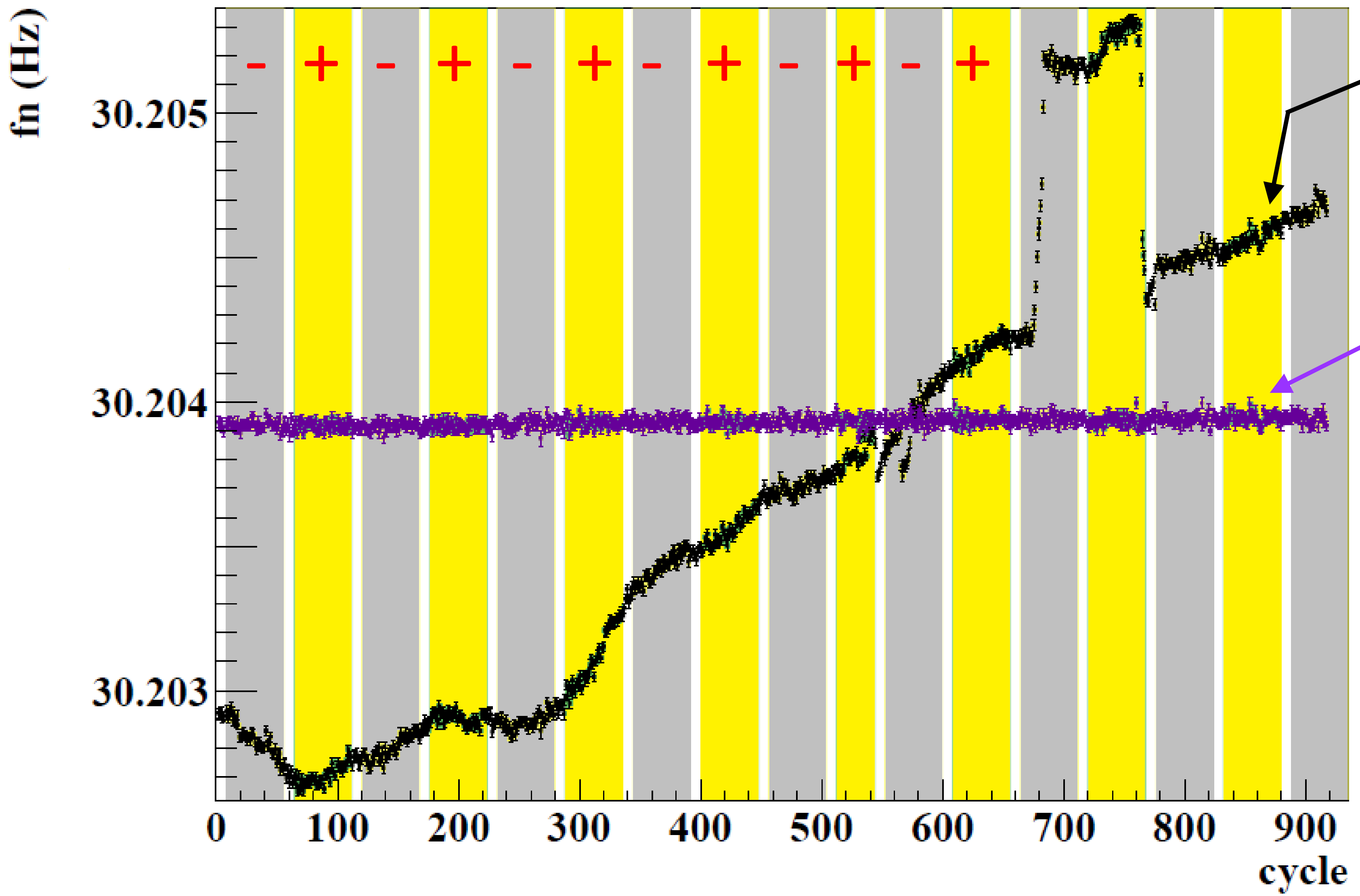


Move of the apparatus at Paul Scherrer Institute (PSI)

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



Typical measurement sequence at PSI, 1 cycle every 5 minutes



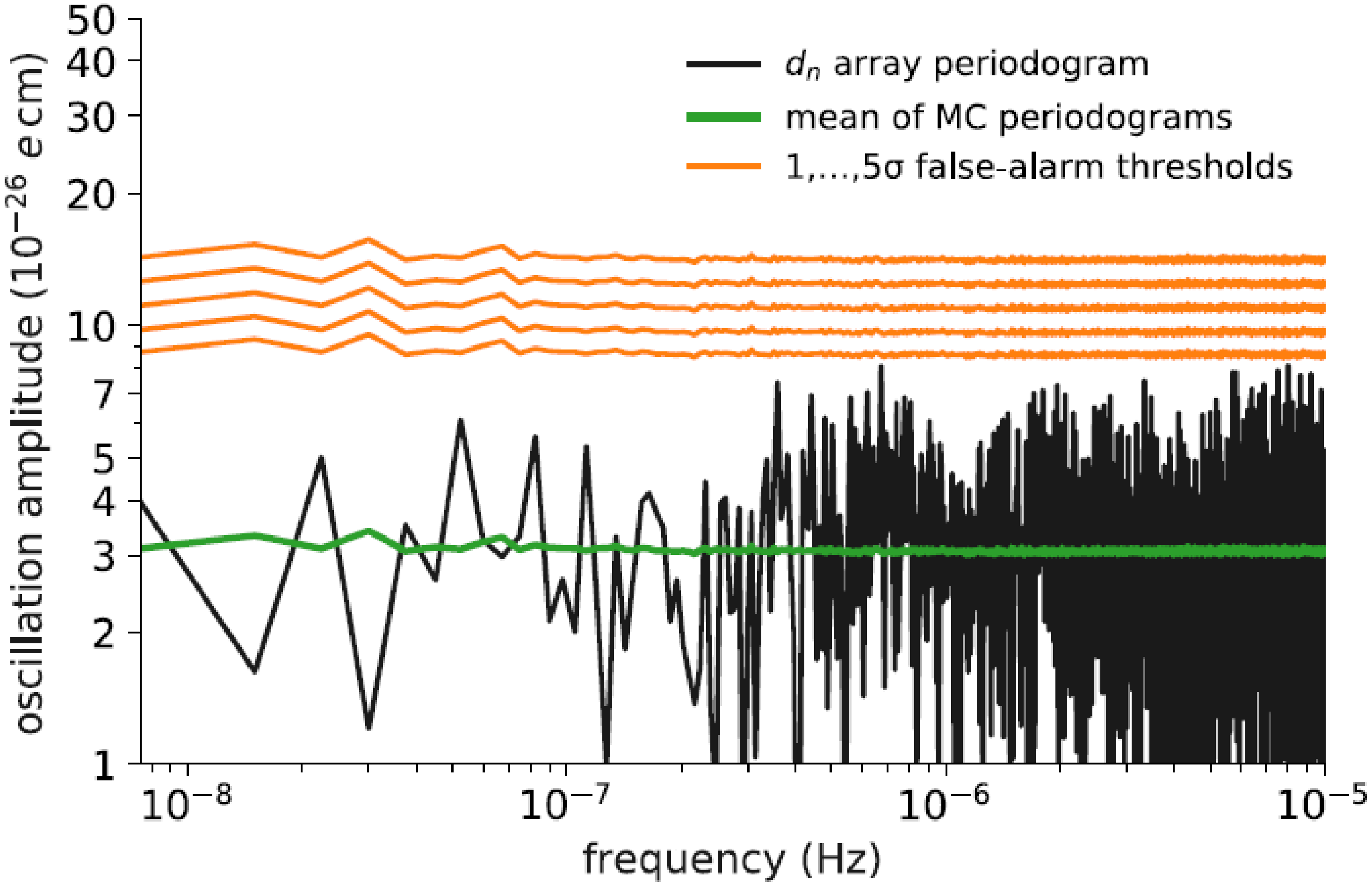
Uncorrected neutron frequency

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

Mercury-corrected neutron frequency

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

Long-time-base analysis of the ILL data



We performed a **Least Square Spectral Analysis** of the d_n timeseries.

For each of the 1334 trial frequencies we fit

$$d_n(t) = A \cos \omega t + B \sin \omega t$$

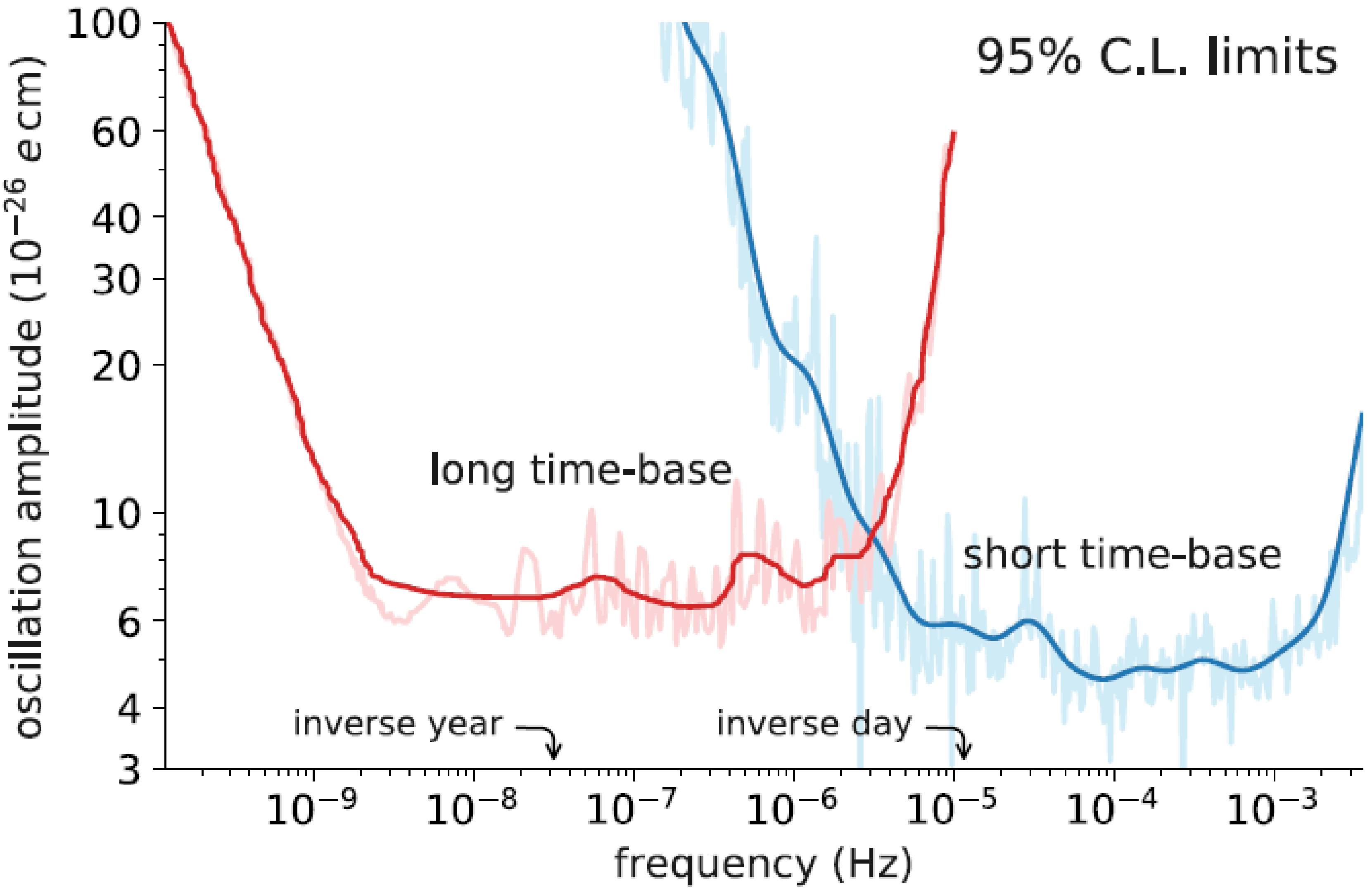
The set of fitted amplitudes $\sqrt{A^2 + B^2}$ is an estimator of the **periodogram**

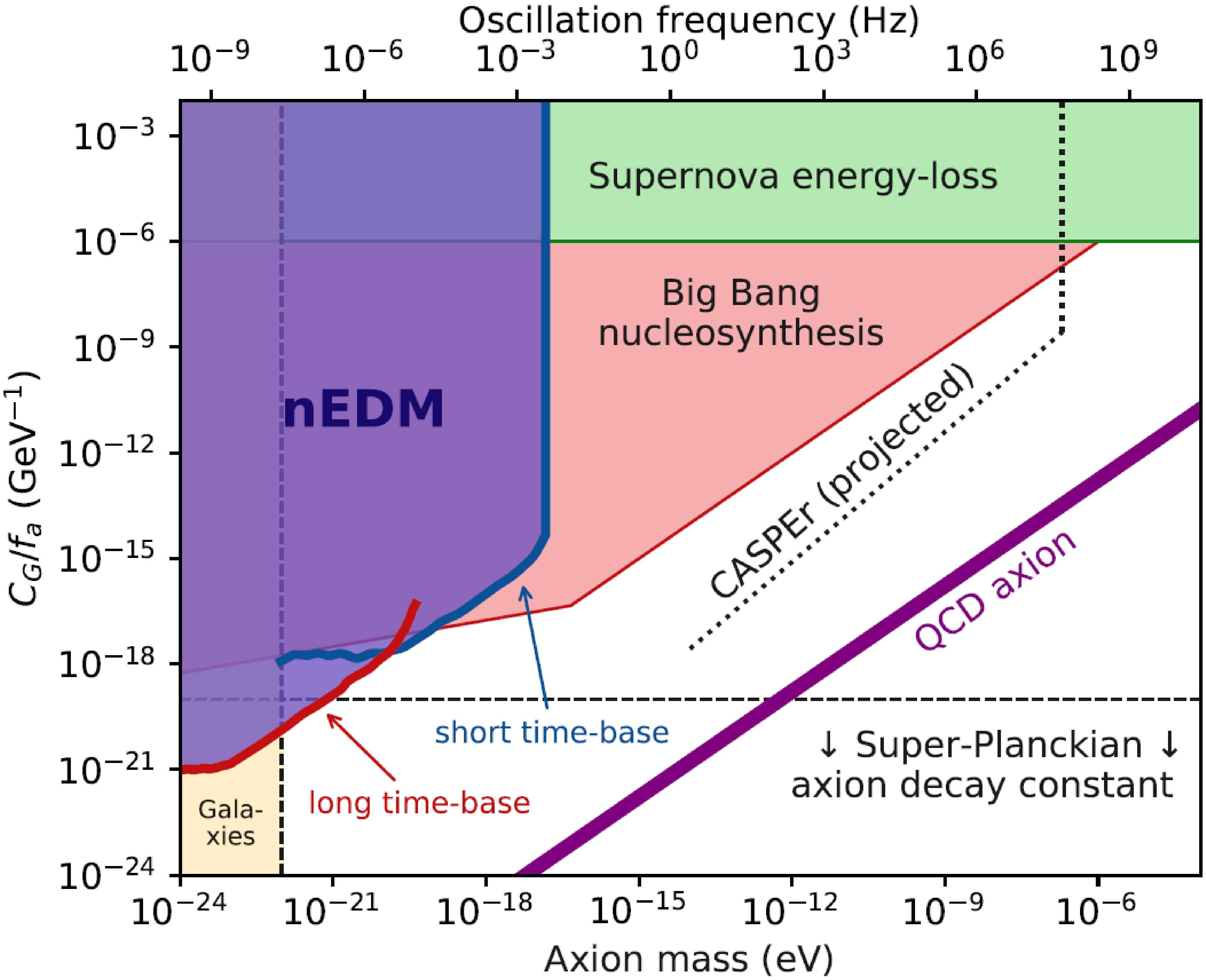
False alarm thresholds are estimated by Monte-Carlo.
(look elsewhere effect is taken into account)

PHYSICAL REVIEW X 7, 041034 (2017)

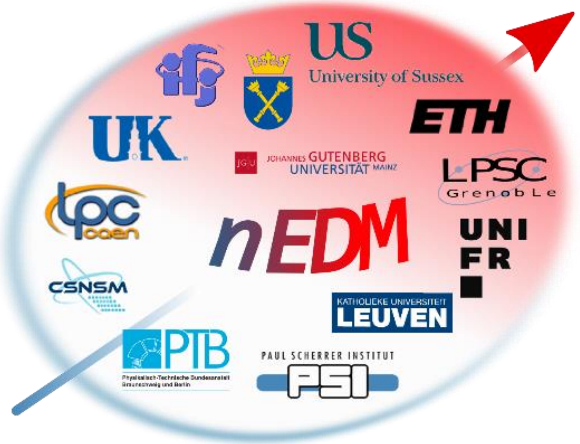
Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

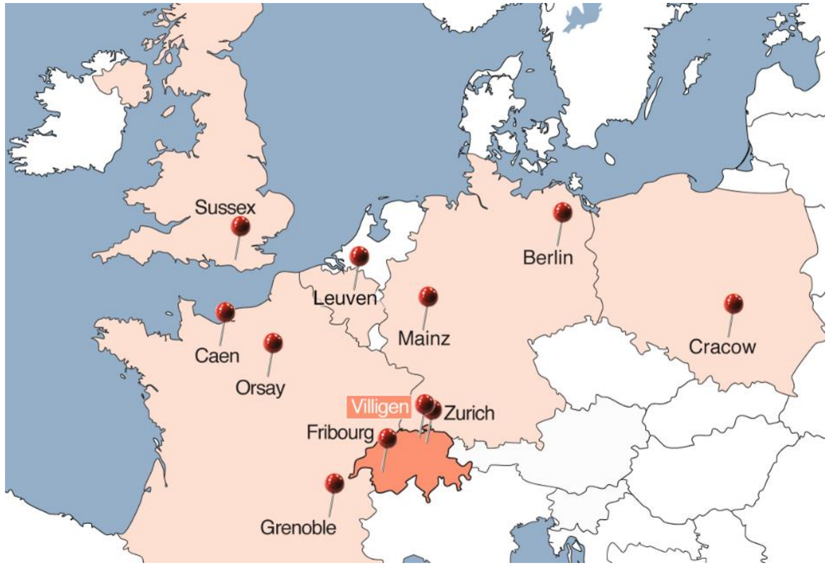
No oscillation in both datasets




Oscillation frequency (Hz)
10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9}
10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24}
C_G/f_a (GeV^{-1})
Supernova energy-loss
Big Bang
nucleosynthesis
nEDM
CASPEr (projected)
QCD axion
short time-base
long time-base
↓ Super-Planckian ↓
axion decay constant
Gala-
xies
10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6}
Axion mass (eV)

Credits





Credits

- The nEDM collaboration, particularly

N. Ayres (analysis ILL data)
M. Rawlik (analysis PSI data)

- The theory team

M. Fairbairn, D.J.E. Marsh, Kings College London
V.V. Flambaum, University of New South Wales
Y.V. Stadnik, Johannes Gutenberg Universität Mainz