Search for Axion Dark Matter with neutrons

Guillaume Pignol, December 6 2018
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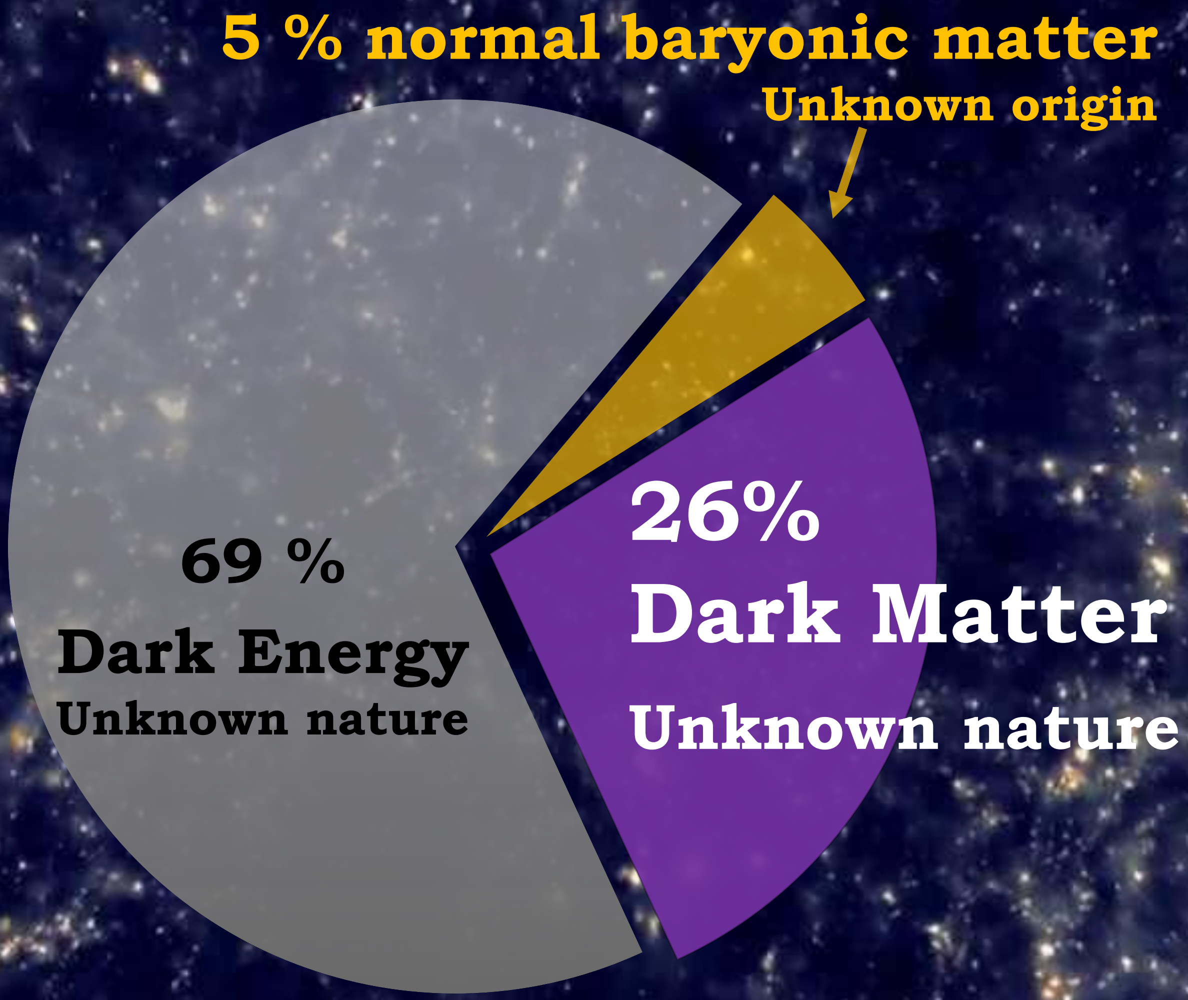
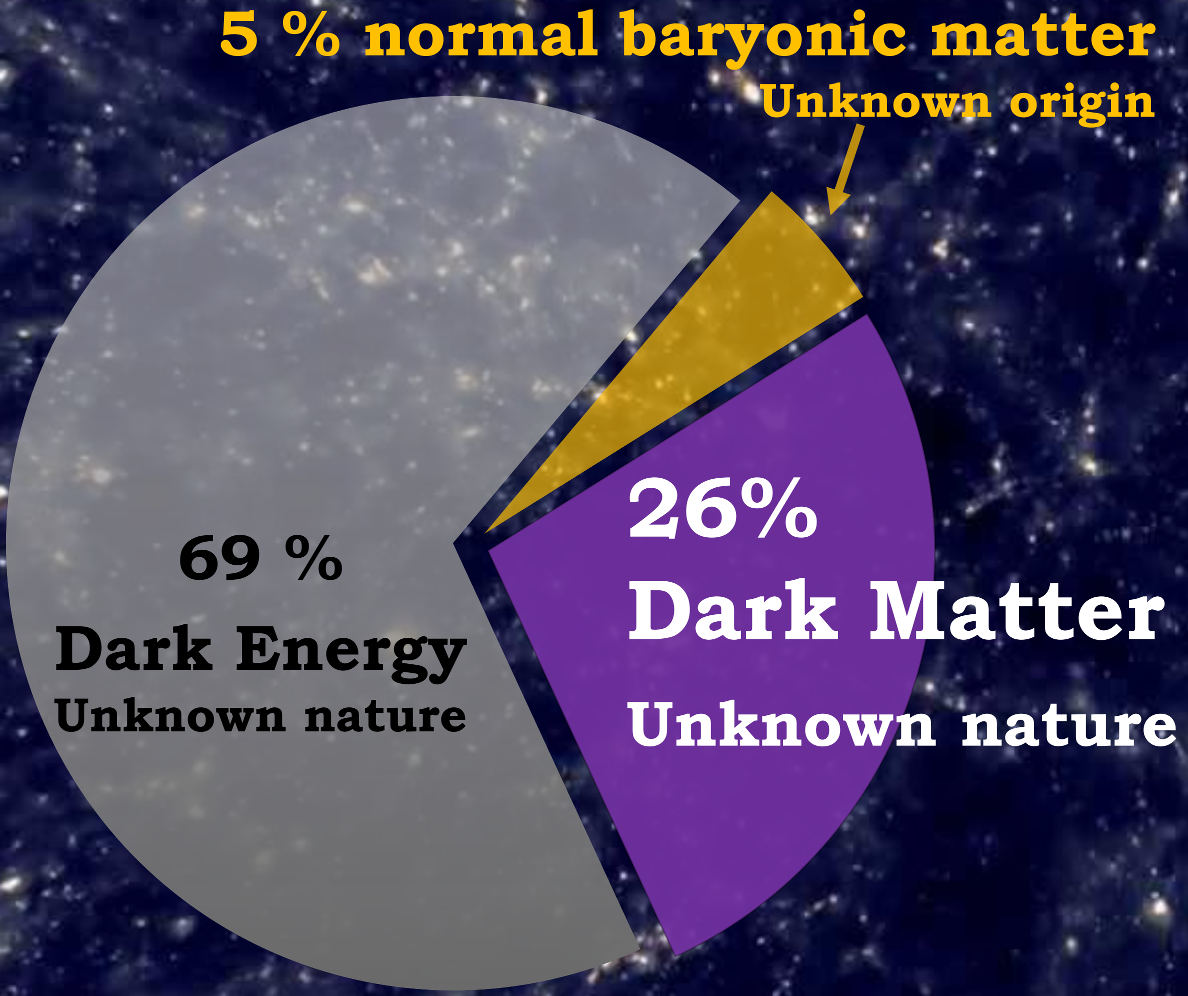
erc European Research Council

Energy budget of the Universe in ΛCDM



Energy budget of the Universe in ΛCDM



Dark matter is a pressure-less fluid

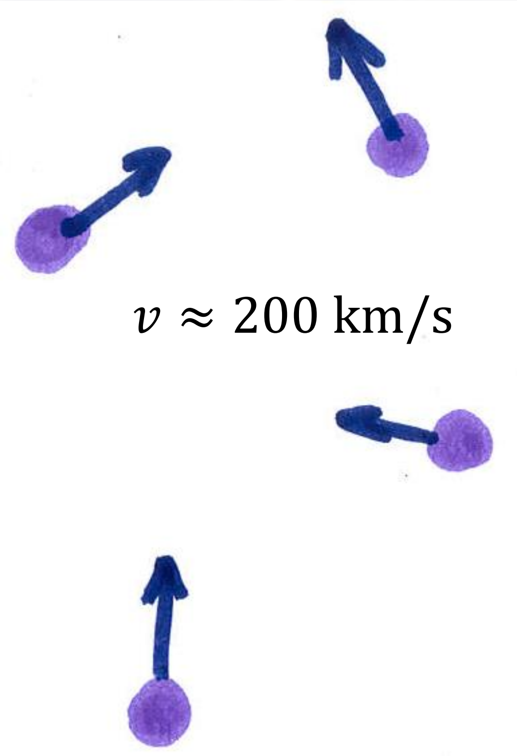
Cosmological density
10^{-6} GeV/cm^3

Local density
0.4 GeV/cm^3

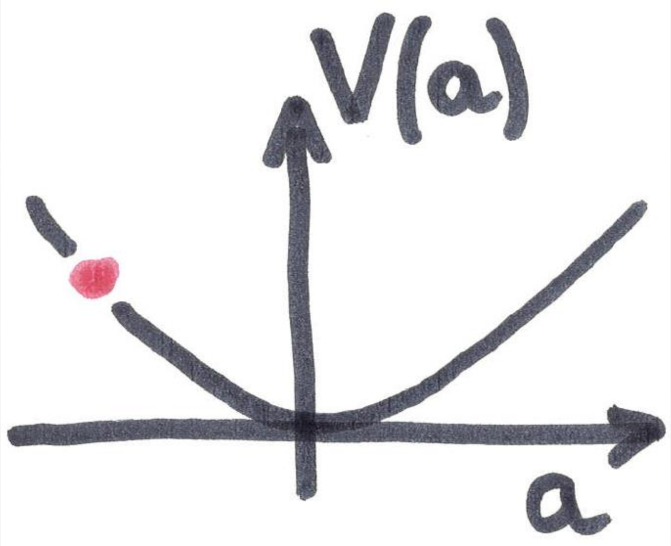
Microscopic Nature of pressure-less Dark matter?

Weakly Interacting Massive Particles

$M > 2$ GeV



Coherent oscillation of a light scalar field

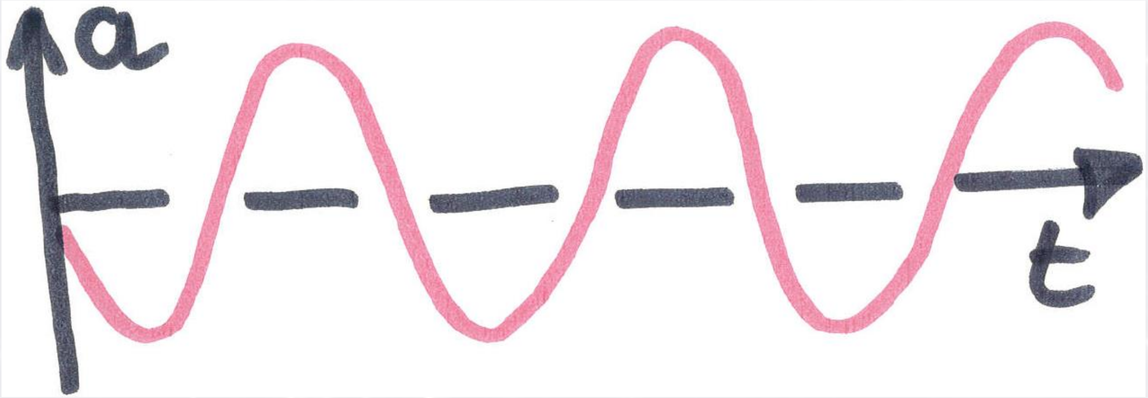


$10^{-22}\,\mathrm{eV} < m_a < 0.1\,\mathrm{eV}$

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

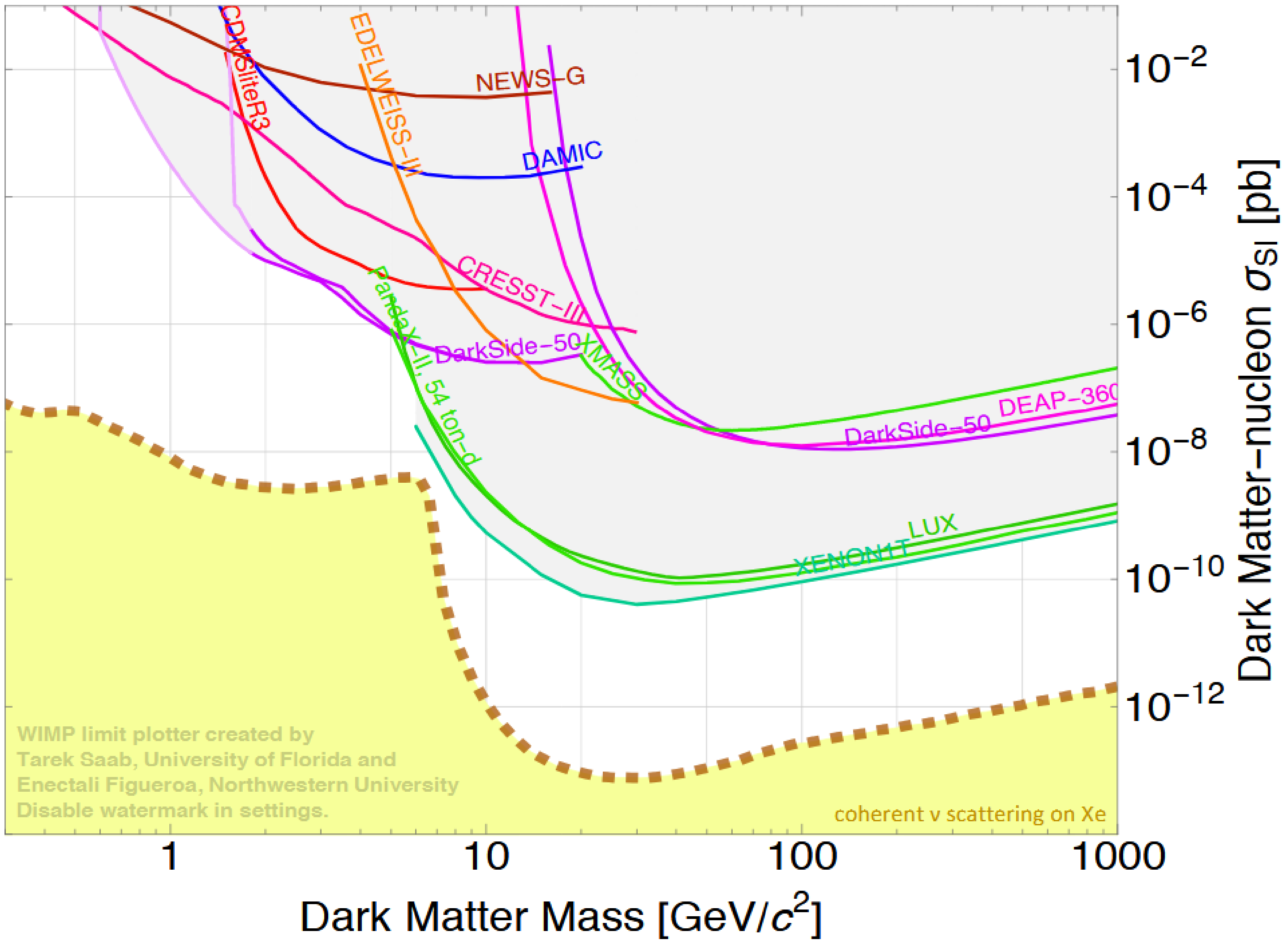
$$a(t) = a_0 \cos m_a t$$

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



Direct detection of WIMP dark matter

Search for nuclear recoils in underground labs



Microscopic Nature of pressure-less Dark matter?

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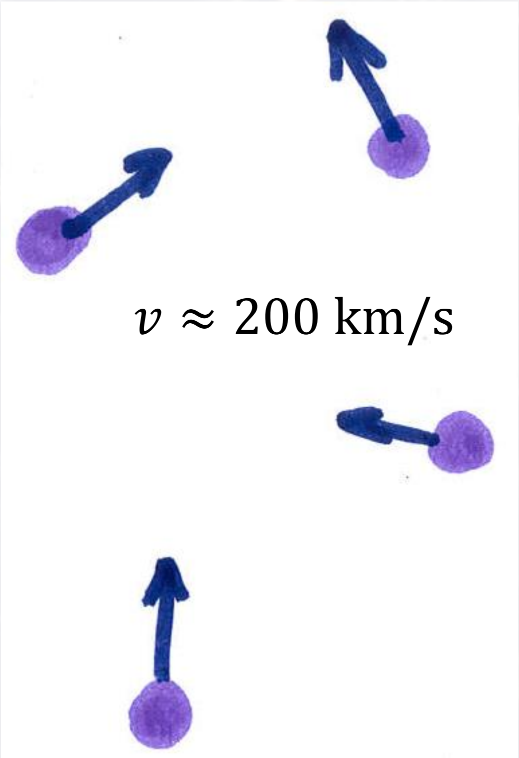

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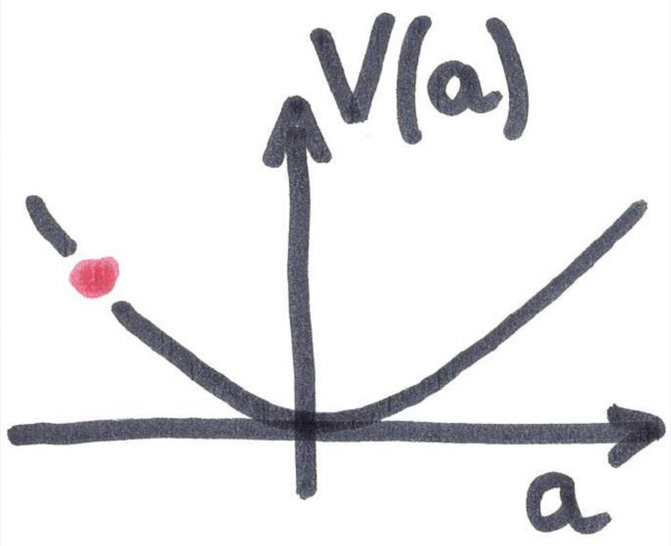

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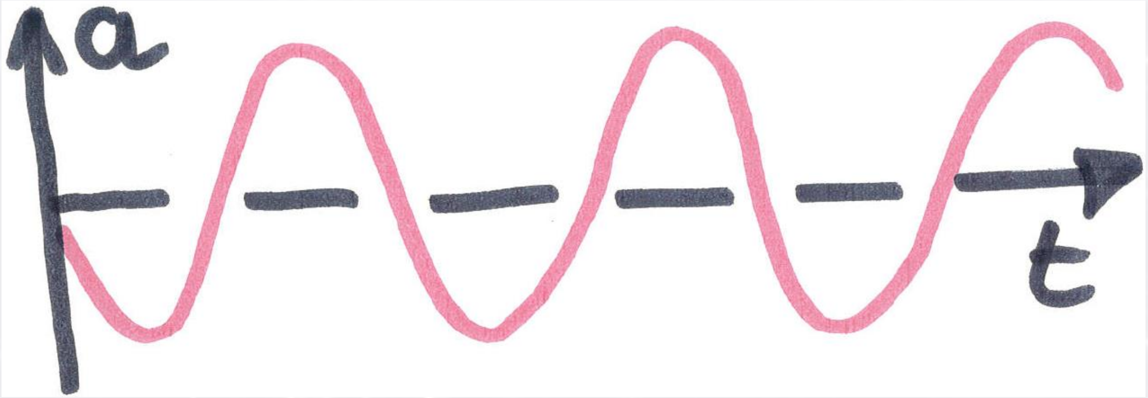


Possible range of oscillating DM

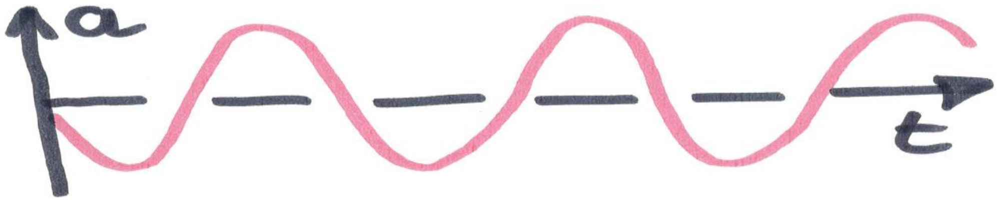
Mass [eV/c^2]

10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3}

21 decades in frequency to scan

10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

Oscillation frequency $f = m_a/h$ **[Hz]**



De Broglie wavelength must be larger than the size of Dwarf Galaxies (1 kpc)

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

Classical field limit of large number of particles inside a “De Broglie volume”:

$\mathbf{m_a < 0.1\,eV}$

For $\mathbf{m_a > 0.1\,eV}$ it behaves as independent particles and hot Dark Matter

The strong CP puzzle and the Axion

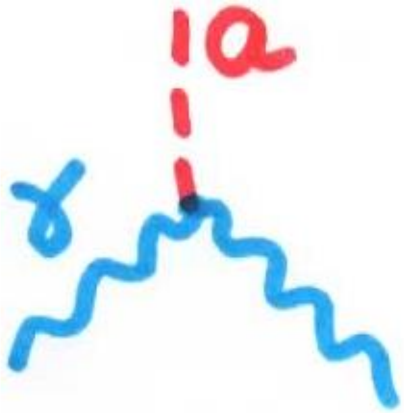
- La théorie de l'interaction forte (QCD)prédit
  - Violation de CP :
    difference matière antimatière
  - Violation de T :
    difference passé – futur

- La non-mesure du dipole électrique du neutron donne la contrainte
  $|\theta| < 10^{-10}$ *(strong CP puzzle)*

Une théorie, **l'Axion**, « nettoie » le problème et prédit l'existence d'une particule scalaire très légère.

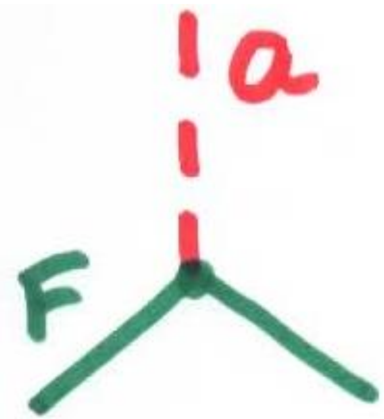
Non gravitational interactions of the Axion

$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi}\, a\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \frac{C_G}{f_a}\frac{\alpha_s}{8\pi}\, a\, \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu} - \sum_F \frac{C_F}{2f_a}\partial_\mu a \bar{F}\gamma^\mu\gamma_5 F$$



Coupling to photons
axion-photon conversion

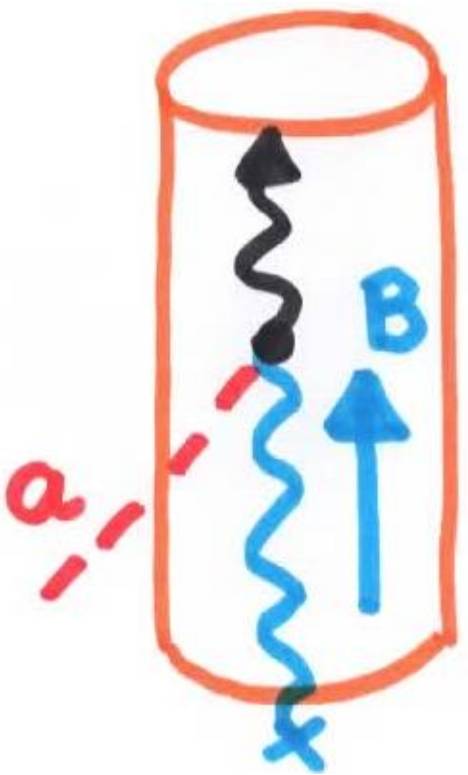
Coupling to gluons
Oscillating EDM



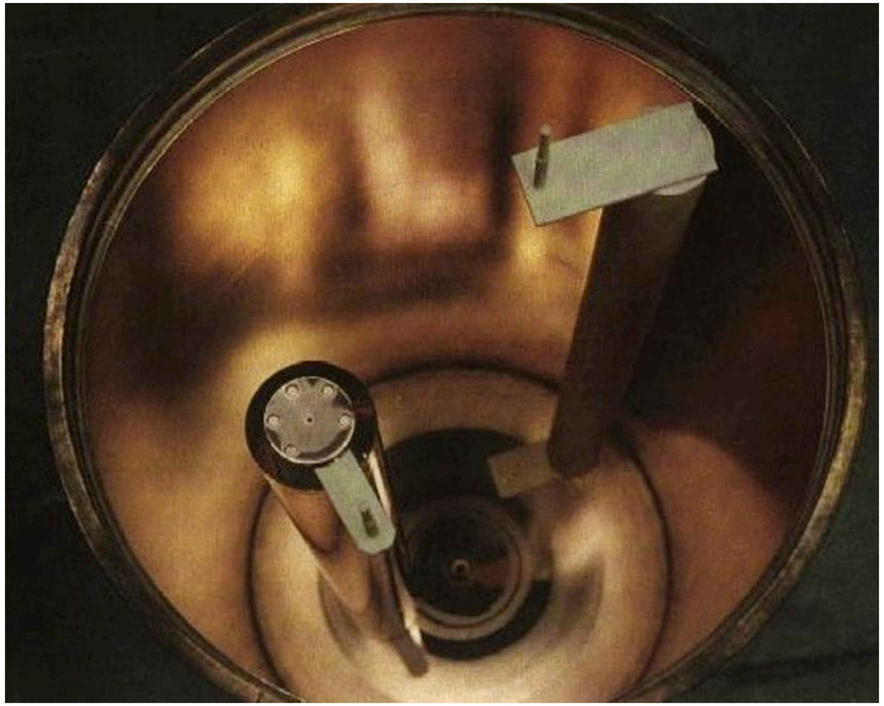
Coupling to fermions
"Axion wind"

Axion-photon coupling

Resonant cavity "haloscopes" to search for the signal at f ~ 1 GHz, λ~30cm (microwave)



ADMX @ Seattle



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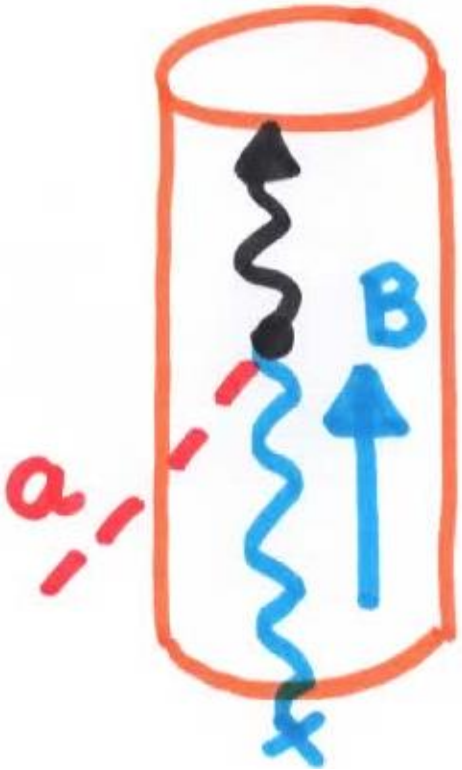
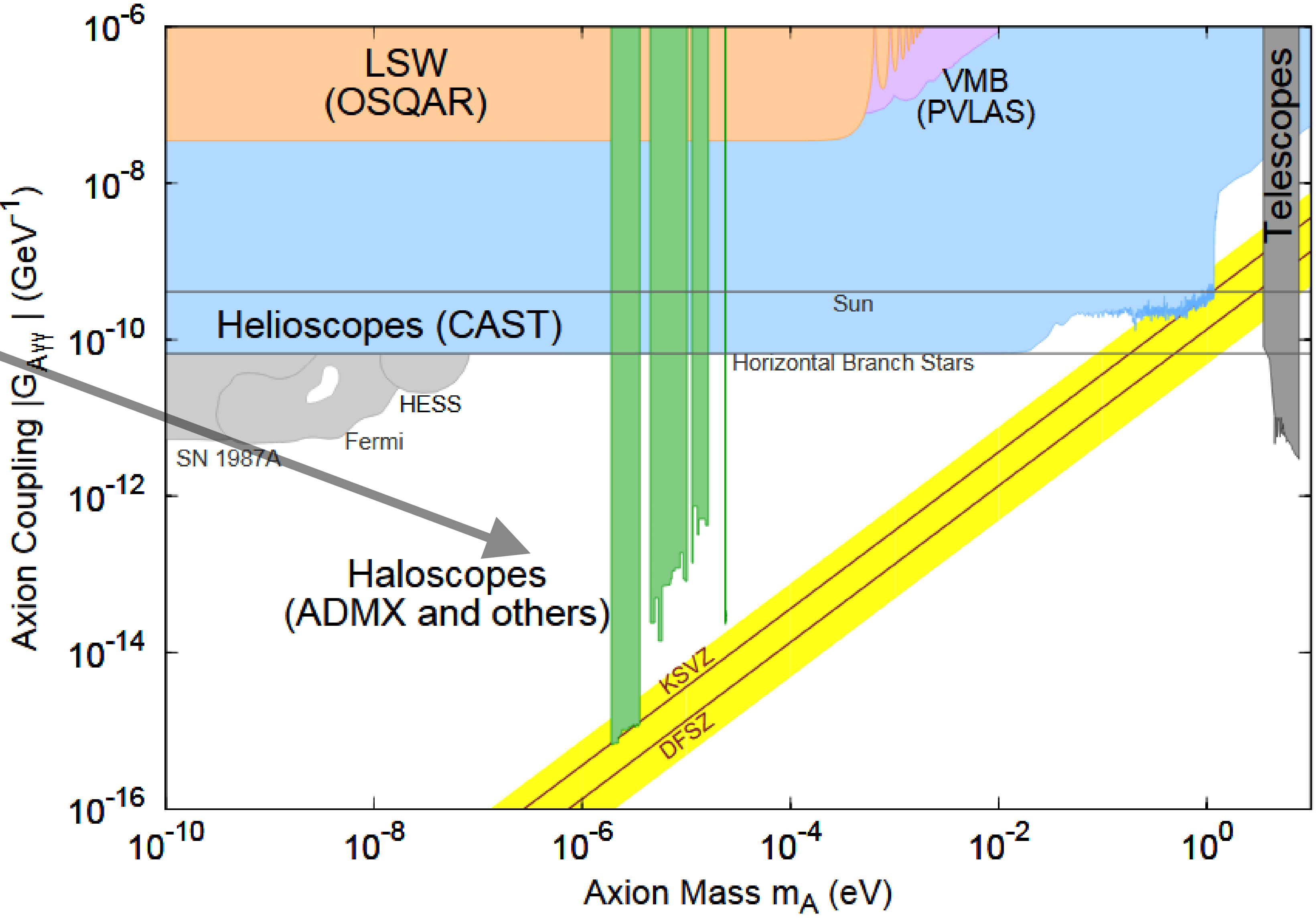


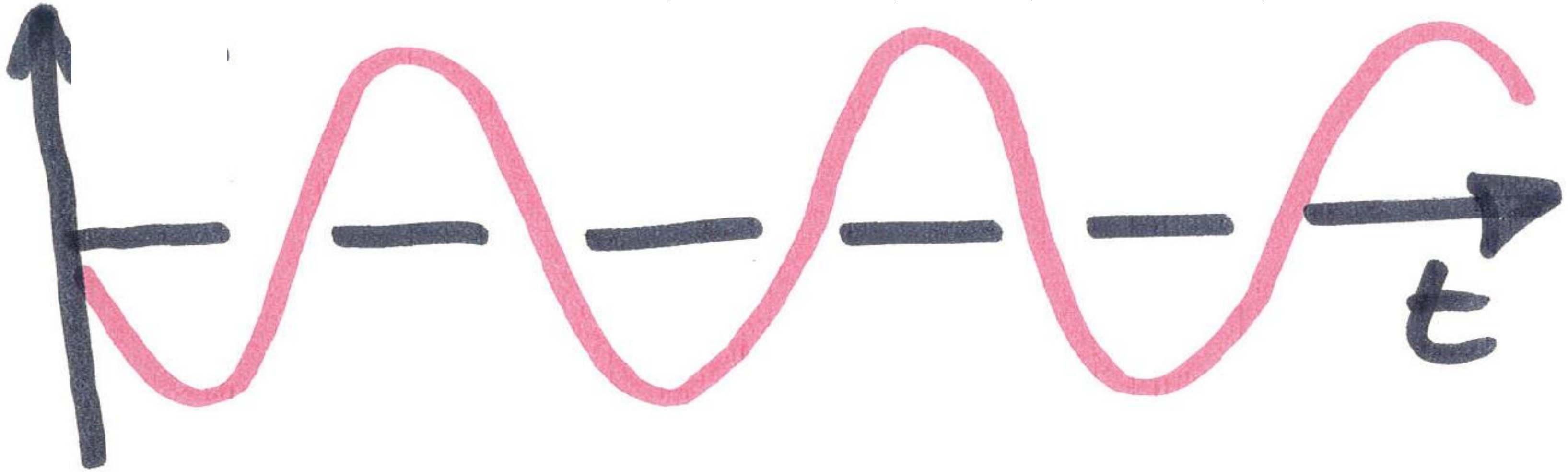


Oscillating neutron EDM

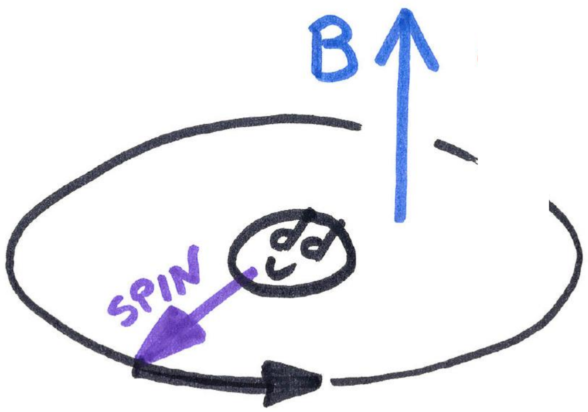
$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi}\, a\, \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \boxed{\frac{C_G}{f_a}\frac{\alpha_s}{8\pi}\, a\, \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}} - \sum_F \frac{C_F}{2f_a}\partial_\mu a \bar{F}\gamma^\mu\gamma_5 F$$

Coupling to gluons
Oscillating neutron EDM

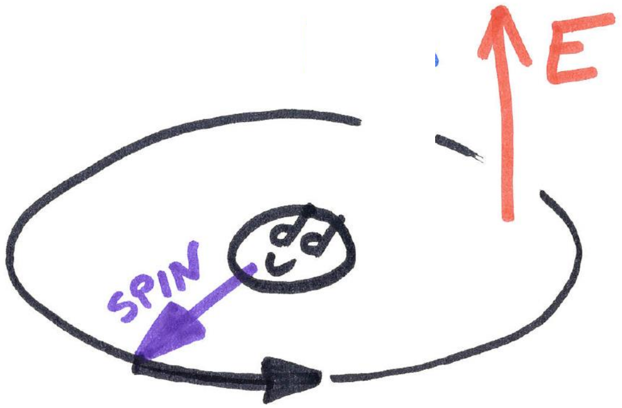
$$d_n(t) = 6\times 10^{-22}\, e\,\mathrm{cm} \times \left(\frac{10^{-22}\mathrm{eV}}{m_a}\right) \times \left(\frac{10^{16}\mathrm{GeV}}{f_a}\right) \times \cos m_a t$$



Electric and Magnetic Dipoles



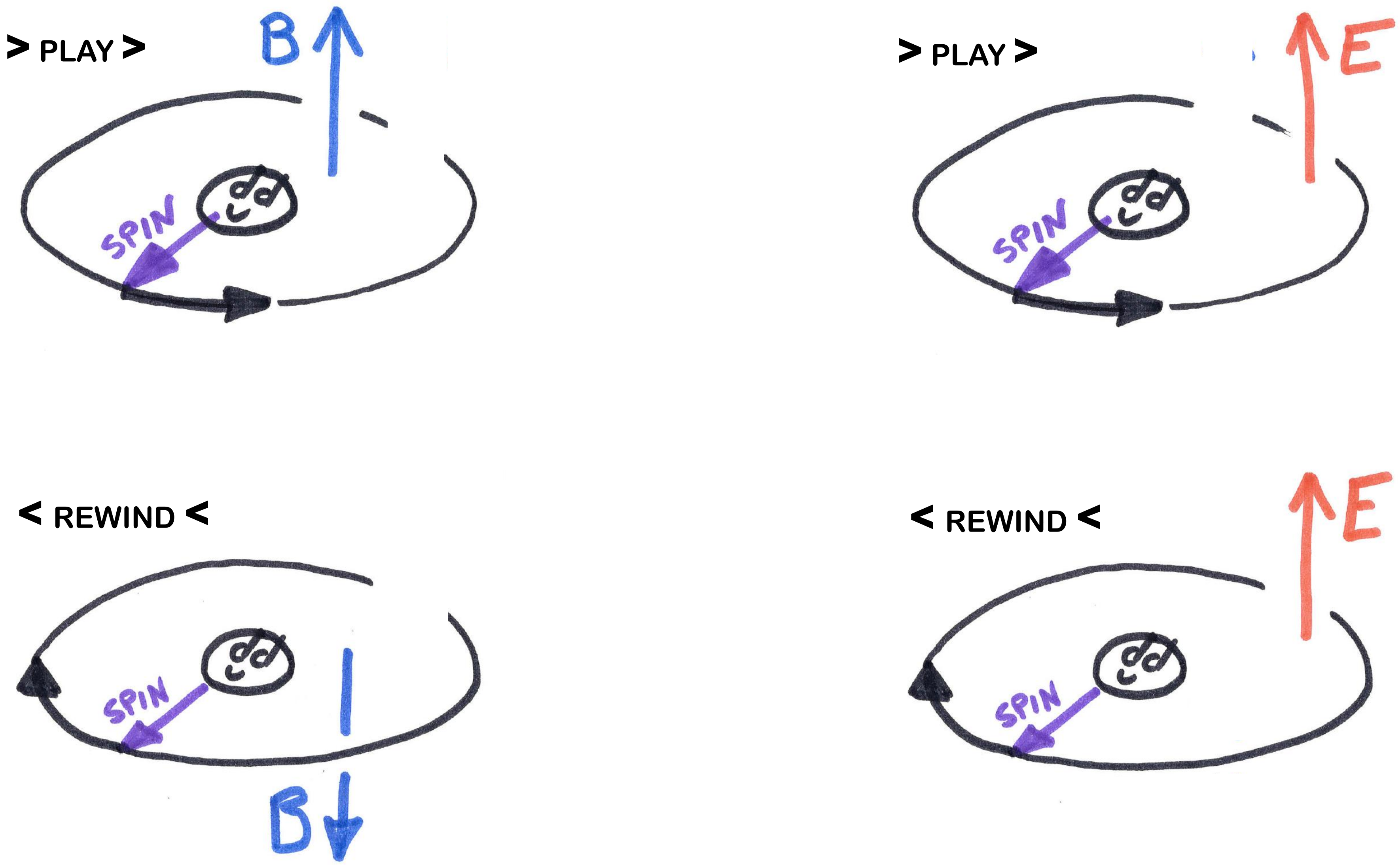
Spin precession due to the magnetic dipole μ_n



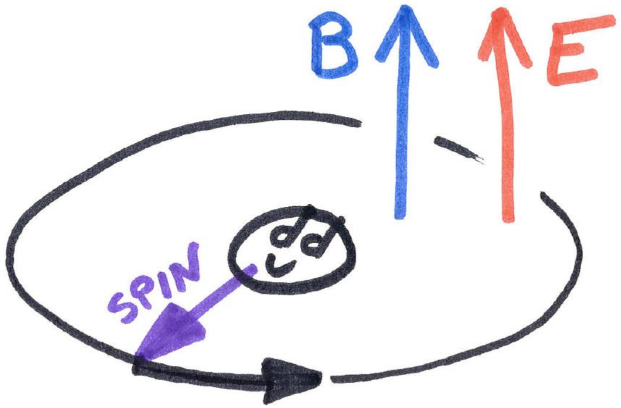
Spin precession due to the electric dipole d_n?

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

Electric dipole violates time reversal invariance!



Hunting the neutron Electric Dipole Moment

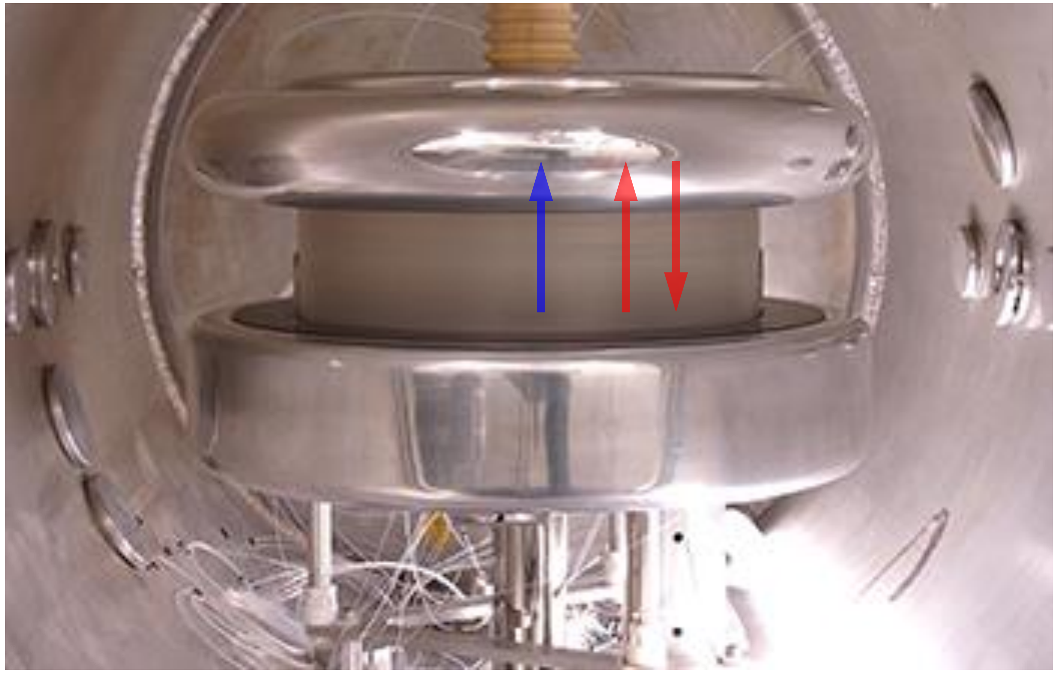


One measures the neutron Larmor precession frequency f_L in weak Bagdetic and strong Electric fields

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

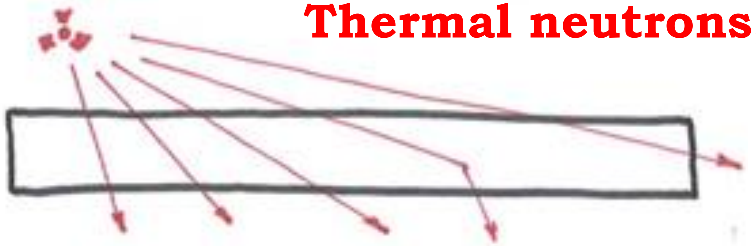
Neutron EDM

The most sensitive experiments use Ramsey’s method with polarized ultracold neutrons stored in a “precession” chamber Here a cylinder, Ø47 cm, H12 cm.

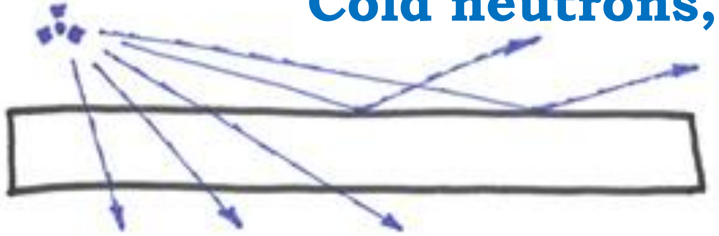


Neutron optics, cold and ultracold neutrons

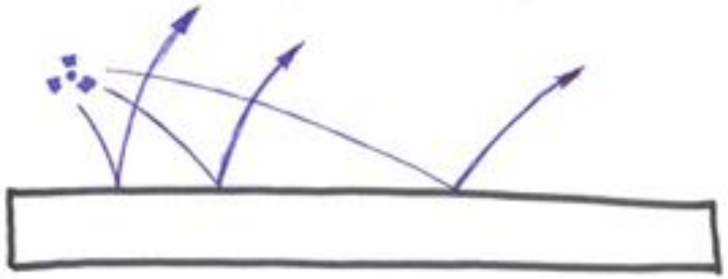
Thermal neutrons, E=25 meV

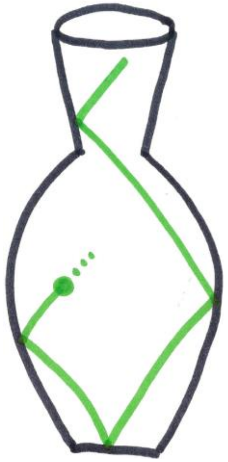


Cold neutrons, E<25 meV



Ultracold neutrons E< 200 neV



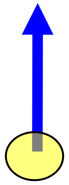


Neutrons with energy < 200 neV, are totally reflected by material walls.

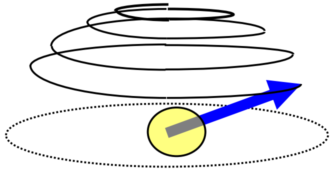
They can be stored in material bottles for long times (minutes).

They are significantly affected by gravity.

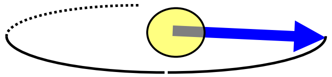
Ramsey's method



"Spin up" neutron…

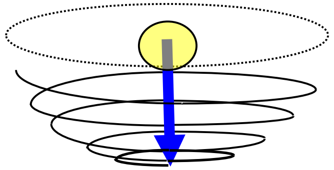


Apply π / 2 spin-flip pulse…

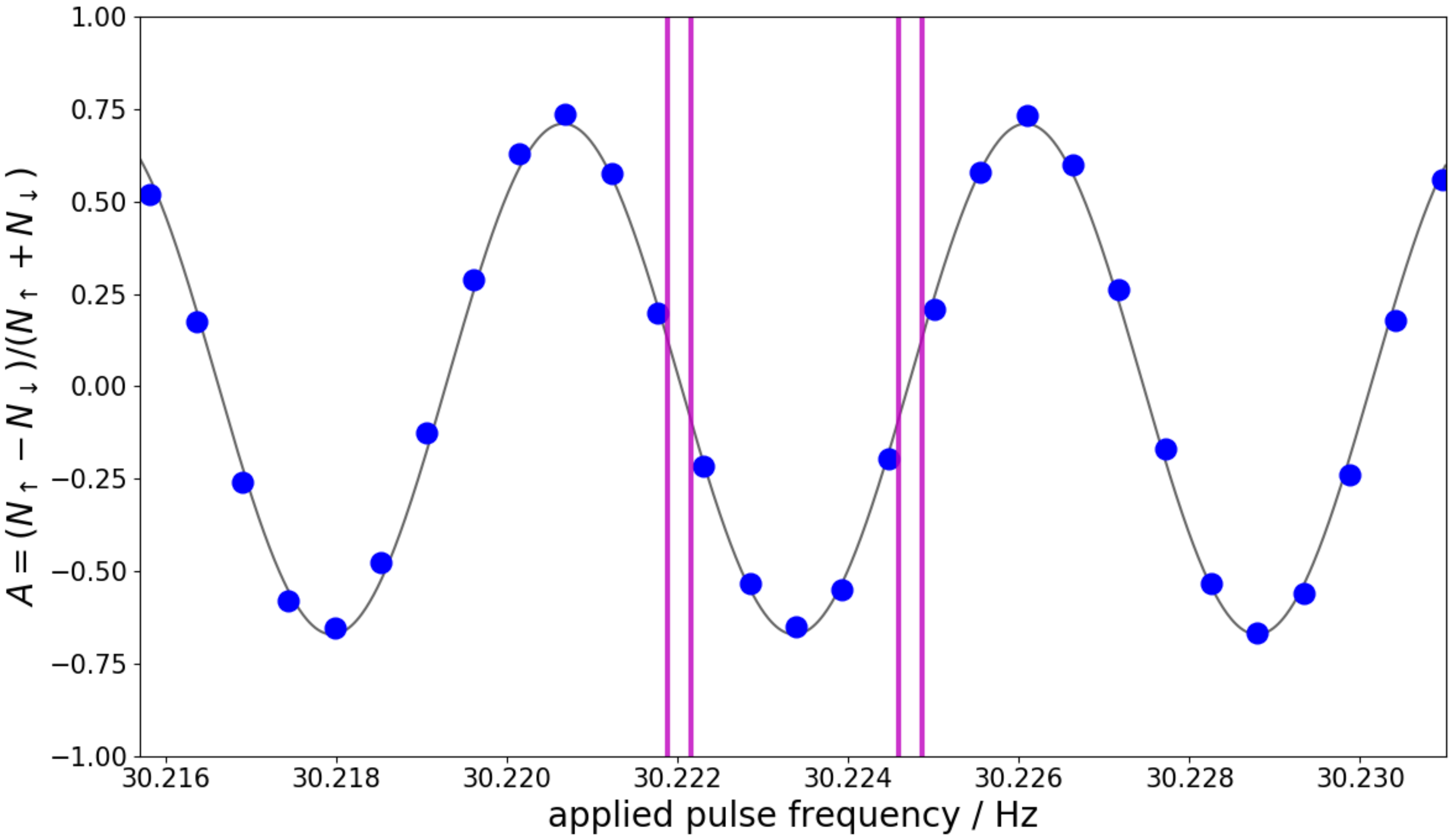


Free precession…

duration T



Second π / 2 spin-flip pulse



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

History of the venerable UCN nEDM apparatus

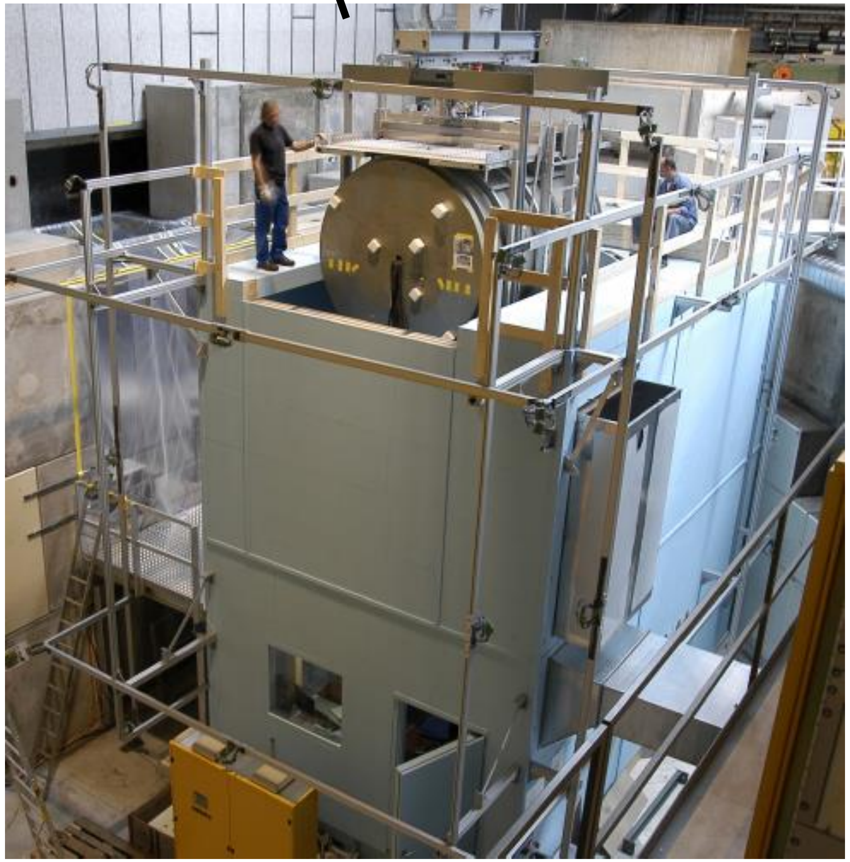
1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

ILL data production

UCN source startup
& nEDM upgrade

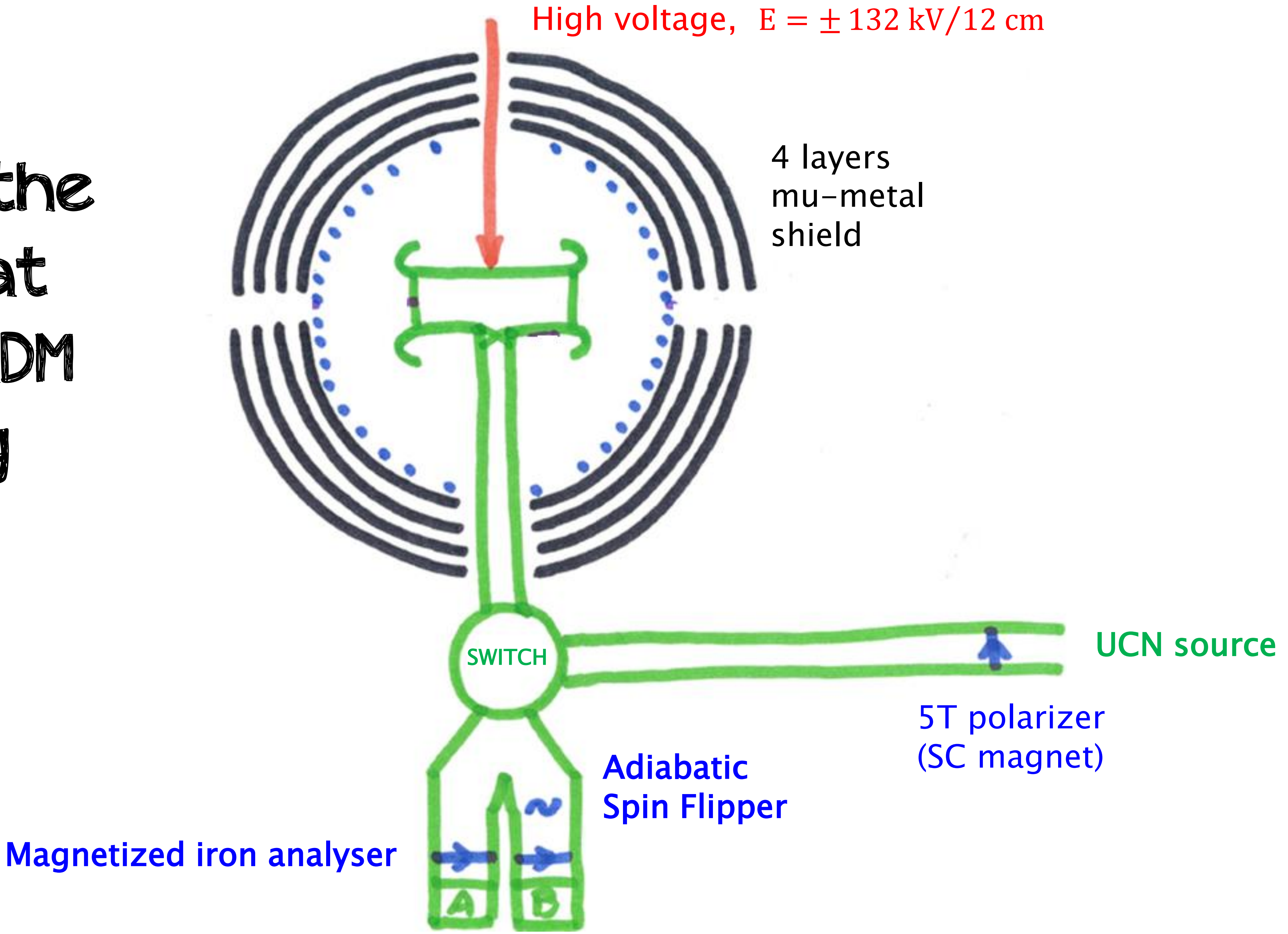
PSI data

Dismantling nEDM
Installing n2EDM

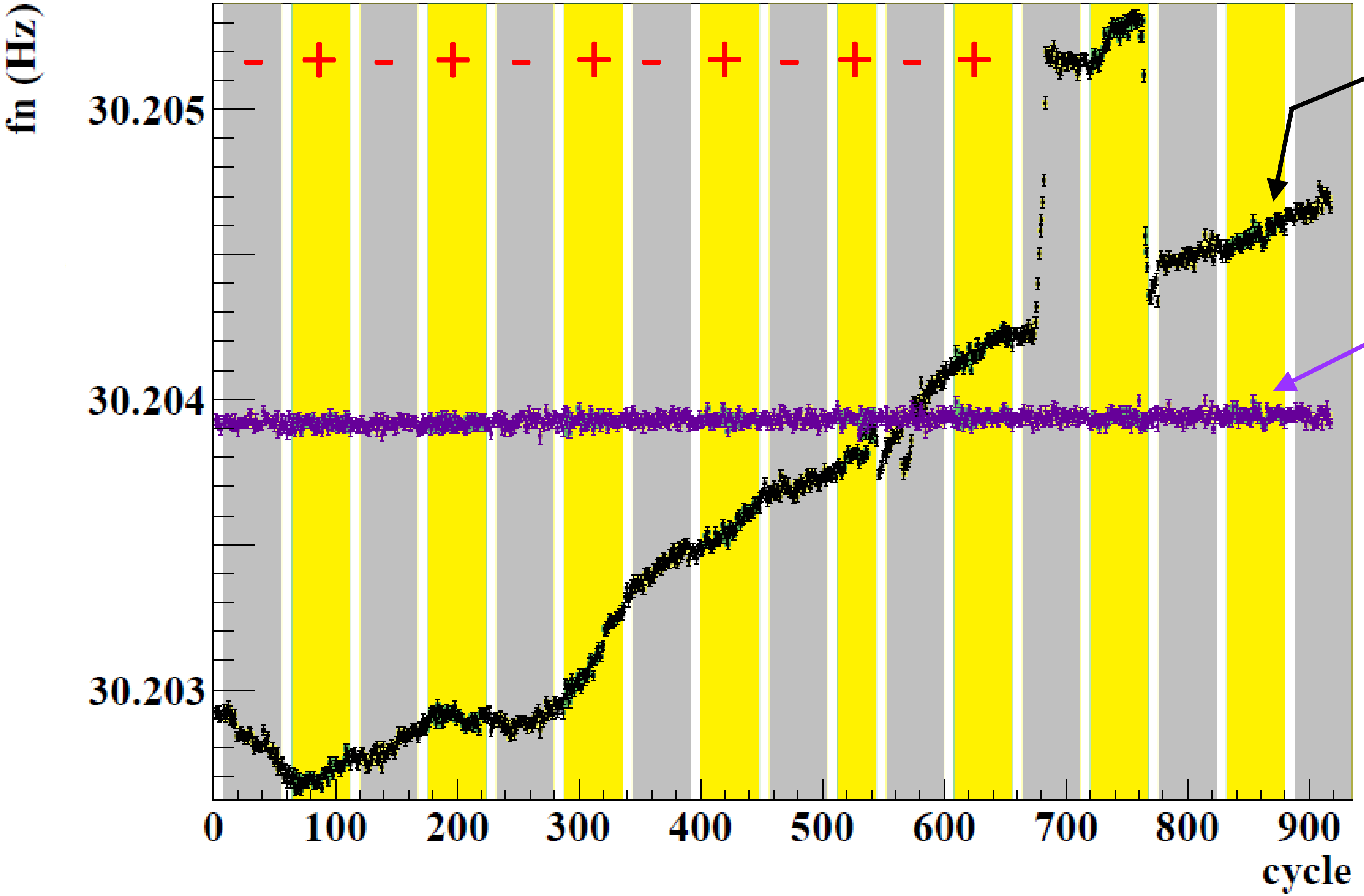


Move of the apparatus at Paul Scherrer Institute (PSI)

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



Typical measurement sequence at PSI, 1 cycle every 5 minutes



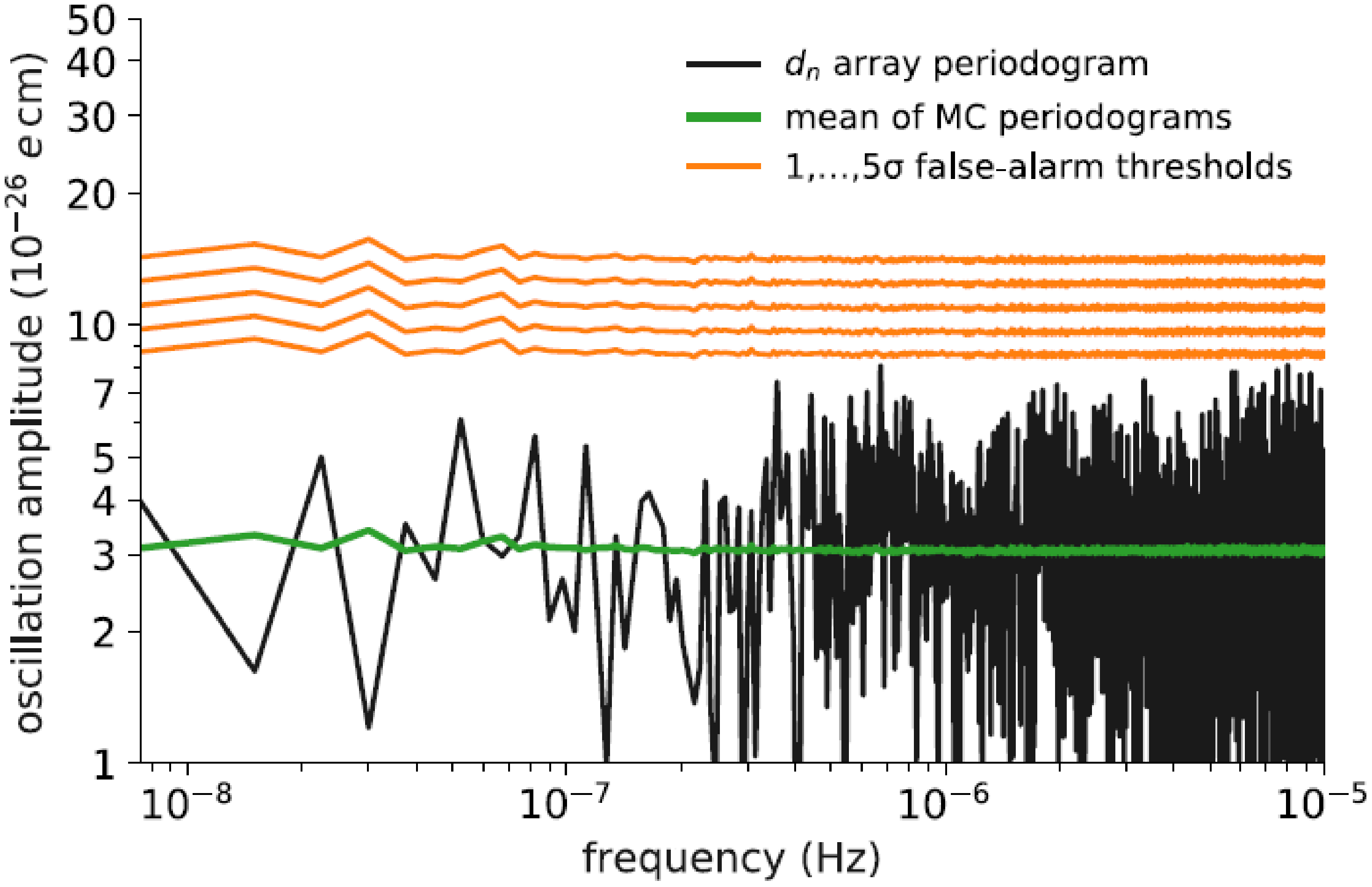
Uncorrected neutron frequency

$$f_{\mathrm{n}} = \frac{\gamma_n}{2\pi} B$$

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

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

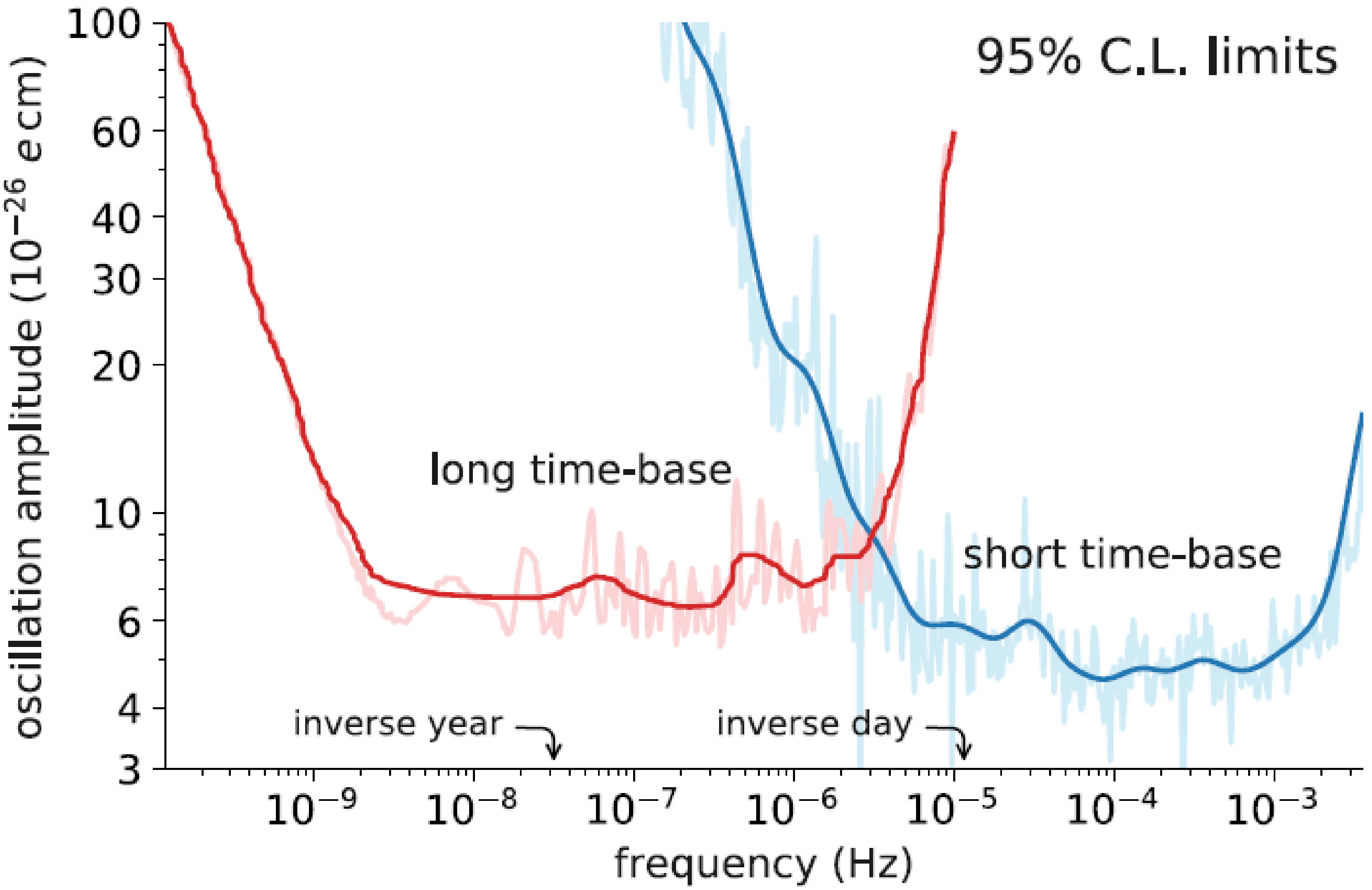
The set of fitted amplitudes $\sqrt{A^2 + B^2}$ is an estimator of the **periodogram**

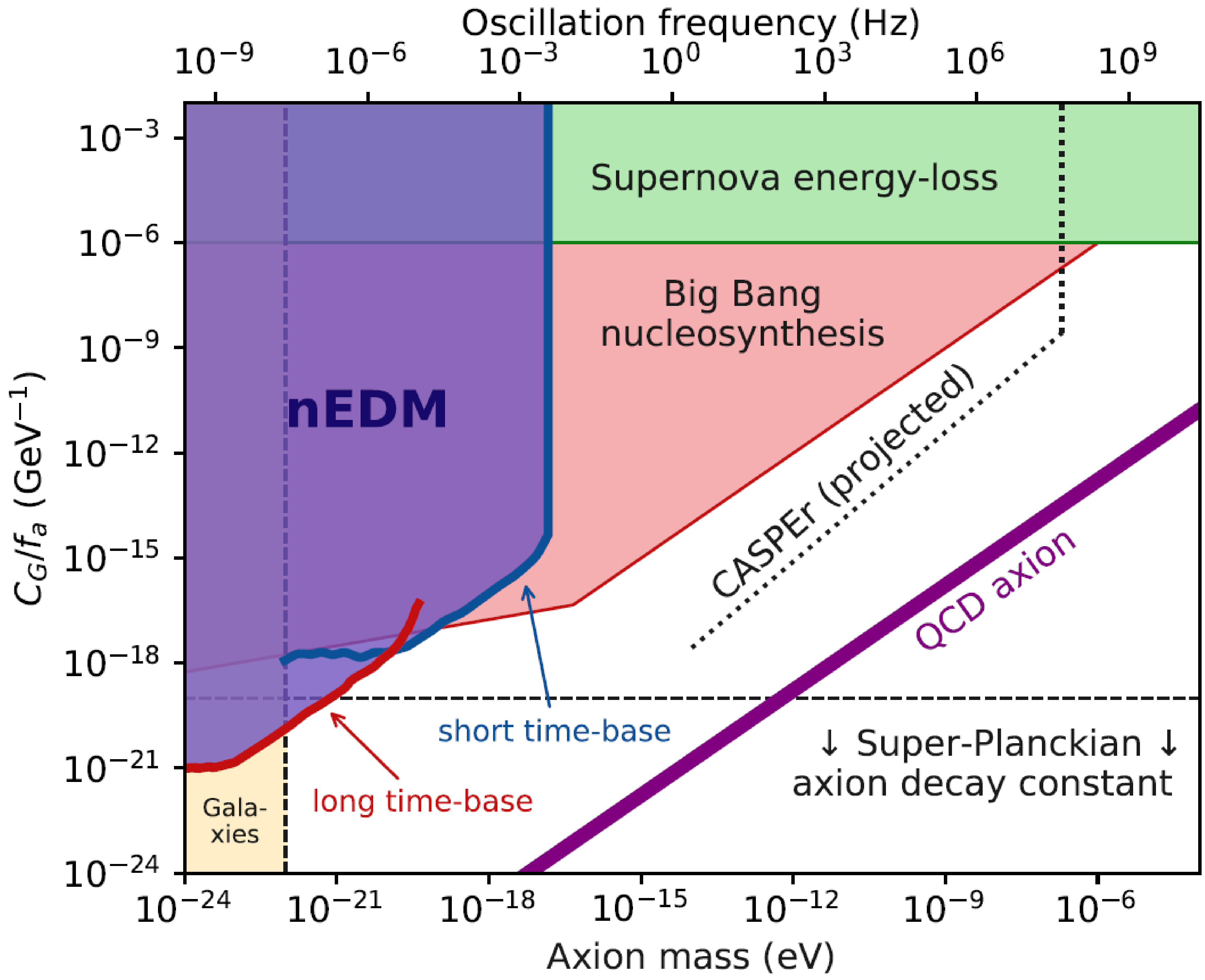
False alarm thresholds are estimated by Monte-Carlo.
(look elsewhere effect is taken into account)

PHYSICAL REVIEW X 7, 041034 (2017)

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

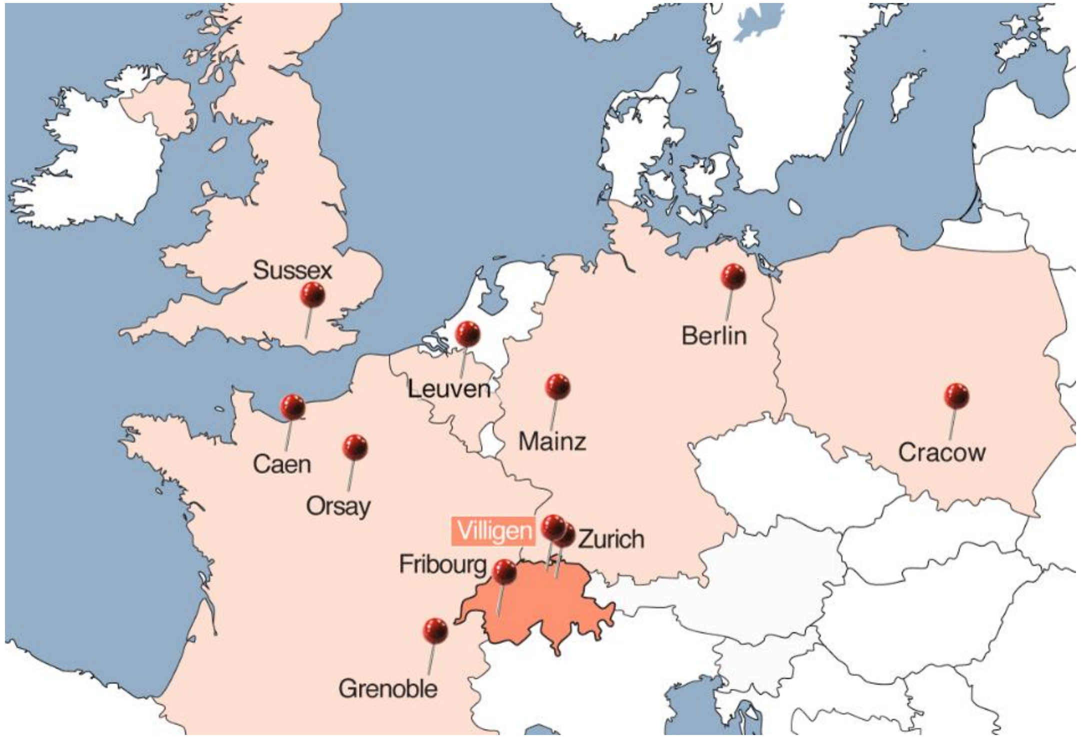
No oscillation in both datasets





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