ETH zürich

Looking for axion-like dark matter candidates with nEDM

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Big Open Question

- Matter – Antimatter asymmetry?

i) Baryon number violation
ii) C and CP violation
iii) Departure from thermal equilibrium

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (*C* asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of *C* asymmetry in the hot model of the expanding universe (see Ref. 1) by making use of effects of *CP* invariance violation (see Ref. 2). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put

for antimuons μ_+ and $\nu_\mu = \mu_0 : n_\mu = -1$, $n_\kappa = +1$.

for muons μ_- and $\nu_\mu = \mu_0 : n_\mu = +1$, $n_\kappa = -1$.

negative in the excess of μ neutrinos over μ antineutrinos).

According to our hypothesis, the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

We assume that the asymmetry has occurred in an earlier stage of the expansion, in which the particle, energy, and entropy densities, the Hubble constant, and the temperatures were of the order of unity in gravitational units (in conventional units the particle and energy densities were $n \sim 10^{98}$ cm^{-3} and $\varepsilon \sim 10^{114}$ erg/cm^3).

M. A. Markov (see Ref. 3) proposed that during the early stages there existed particles with maximum mass of the order of one gravitational unit ($M_0 = 2 \times 10^{-5}$ g in ordinary units), and called them maximons. The presence of

CP Violation

- No CP violation in strong sector → fine tuning problem
- nEDM → CP violation:

$$H = -2(\mu \boldsymbol{B} + d\boldsymbol{E})\boldsymbol{S}$$

⇩ CP-transformation

$$H = +2(\mu \boldsymbol{B} - d\boldsymbol{E})\boldsymbol{S} \neq H$$

- If CPT is conserved:
  CP = T transformation

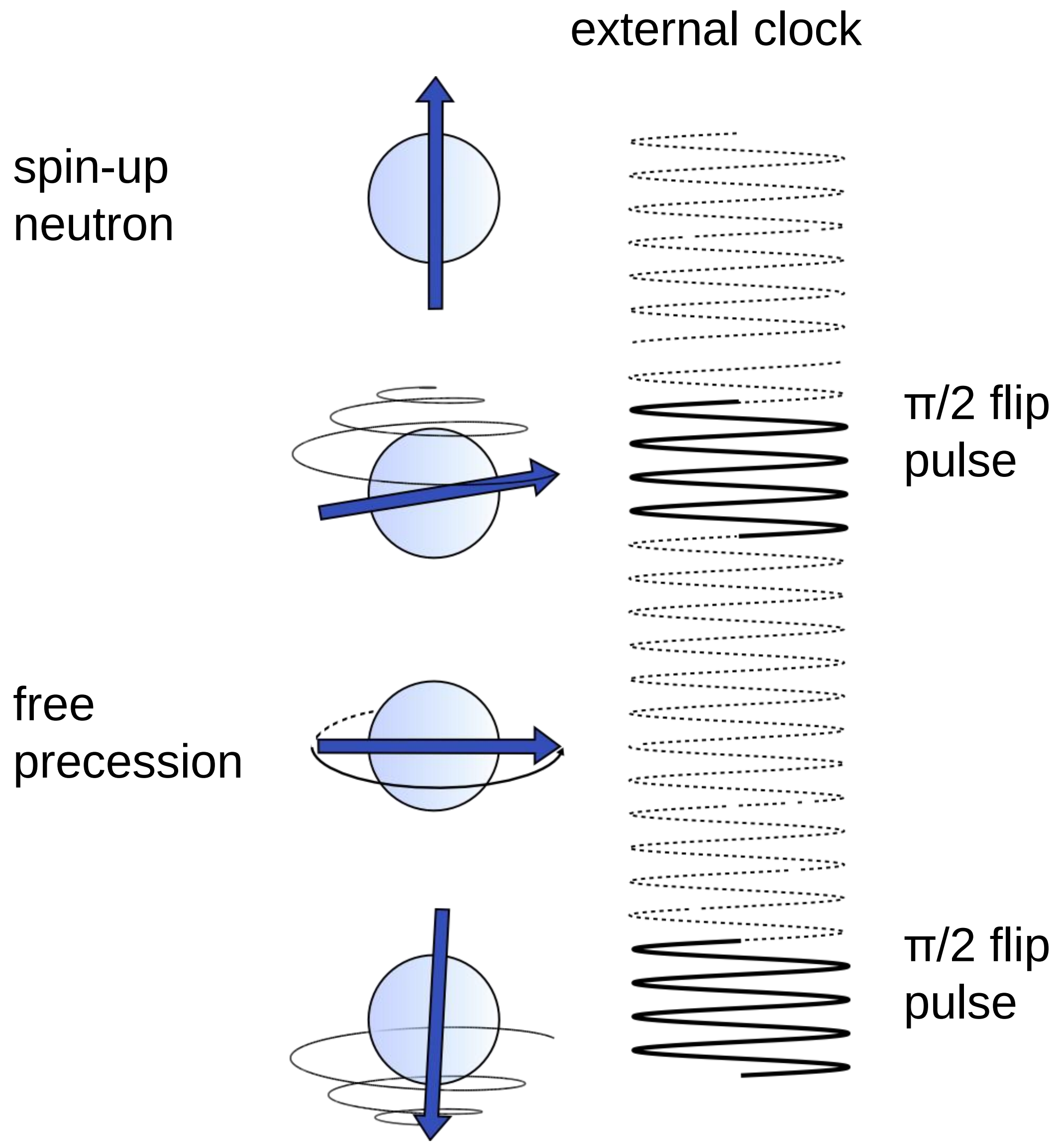
- Spin ***S*** and magnetic field ***B*** reversed under T transformation
- Electric field ***E*** is not affected.

Measurement of an nEDM (1)

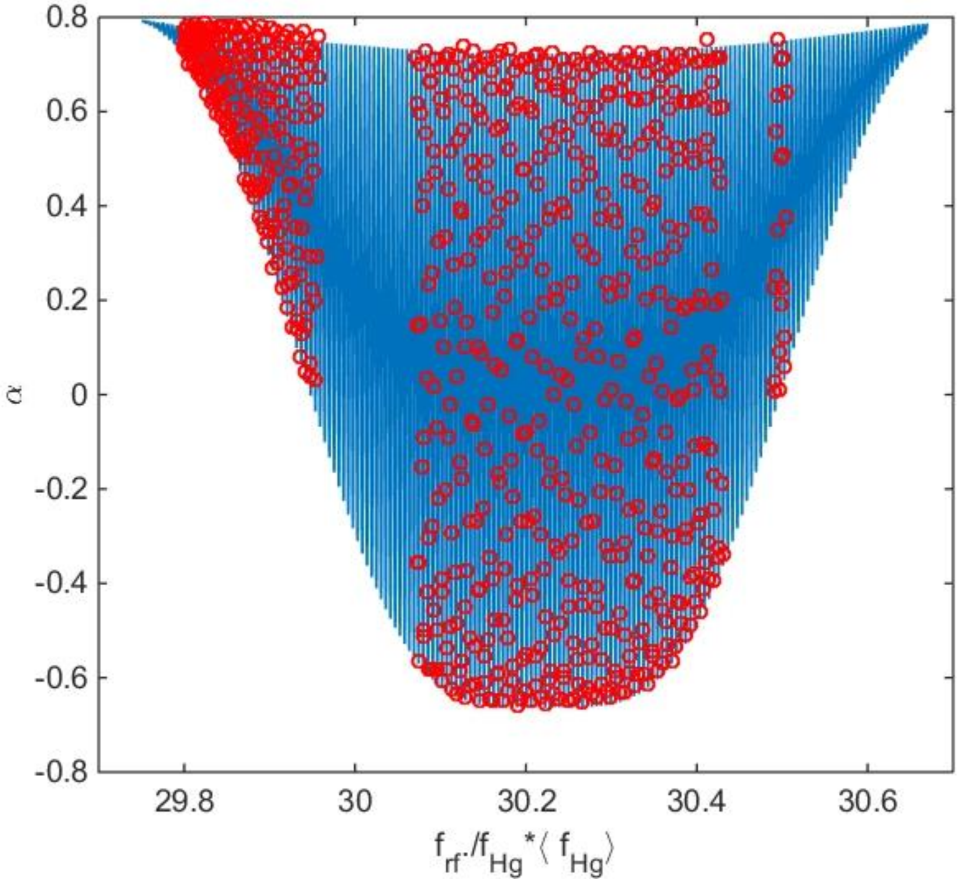
- Difference between E-field up and down:

$$\Delta E_{\uparrow\downarrow} = 4 d_n E$$

- Ultra cold neutrons (UCN) are stored in the precession chamber



Measurement of an nEDM (2)



- Measurement for different RF frequencies →Ramsey pattern
- Center of the curve = Larmor frequency of the neutrons
- α visibility

nEDM at PSI

- Apparatus at PSI
- World's best result:

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26} e \cdot \mathrm{cm}$$

Corresponds to:

$$|d_n| < 1.8 \times 10^{-26}\, e \cdot \mathrm{cm} \qquad \text{(90\% CL)}$$

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Editors' Suggestion | Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

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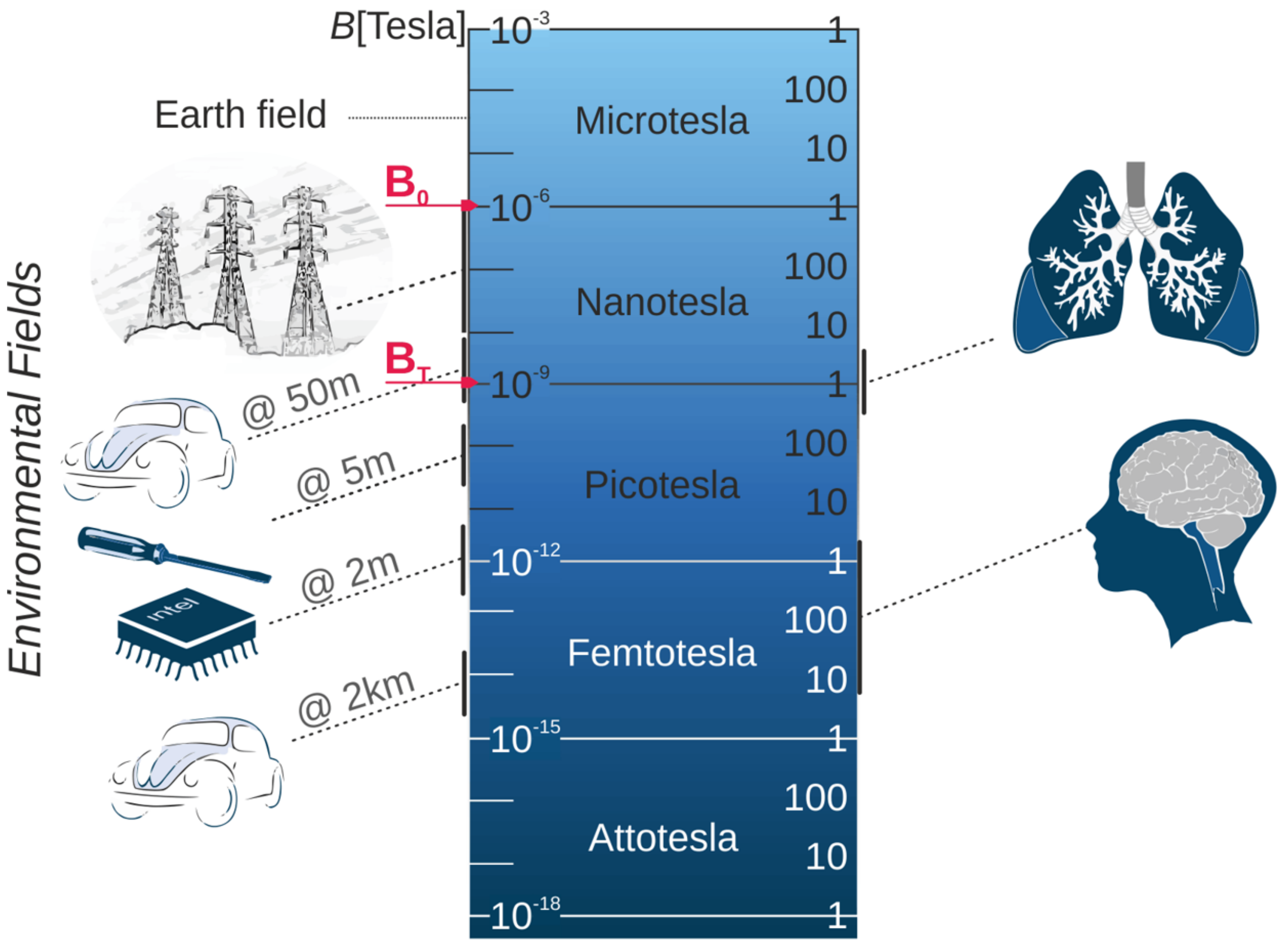
We present the result of an experiment to measure the electric dipole moment (EDM) of the neutron at the Paul Scherrer Institute using Ramsey's method of separated oscillating magnetic fields with ultracold neutrons. Our measurement stands in the long history of EDM experiments probing physics violating time-reversal invariance. The salient features of this experiment were the use of a ^{199}Hg comagnetometer and an array of optically pumped cesium vapor magnetometers to cancel and correct for magnetic-field changes. The statistical analysis was performed on blinded datasets by two separate groups, while the estimation of systematic effects profited from an unprecedented knowledge of the magnetic field. The measured value of the neutron EDM is $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e.cm.

Next Endeavour: n2EDM

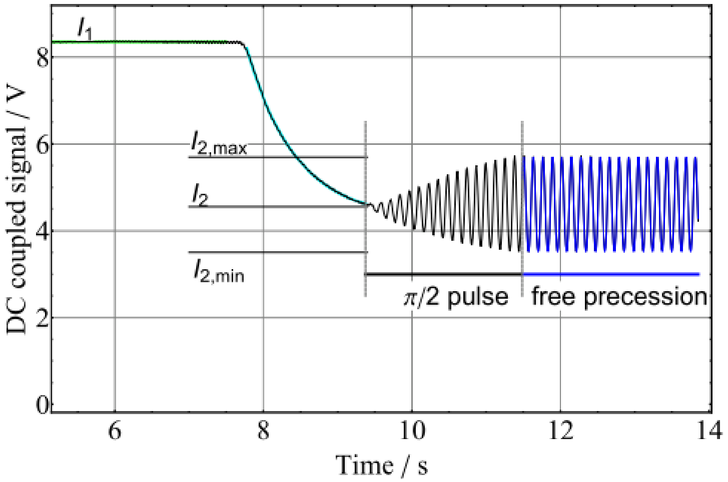
- Goal: one order of magnitude of improvement
- Challenge: Control of magnetic fields

30 fT over 180s stability



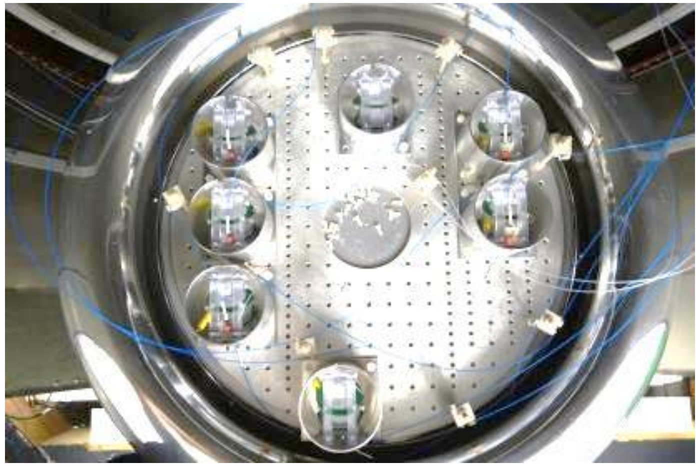
Achieving Magnetic Field Stability

Passive Shielding



Mercury
co-magnetometer

Active shielding
→ Other part
of my work



Cs Magnetometry
→ Duarte's talk

Axion-like Dark Matter

- SM Prediction:

$$\mathcal{L}_{QCD} = -\theta \left(\frac{\alpha_s}{8\pi}\right) G_G^{\mu\nu} G_{\mu\nu}^G$$

- Current limit of d_n → $\theta \lesssim 10^{-10}$

- Peccei Quinn suggest: turning θ into an dynamical field, the axion $a(x)$

→ Coherently oscillating field with amplitude depending on DM density

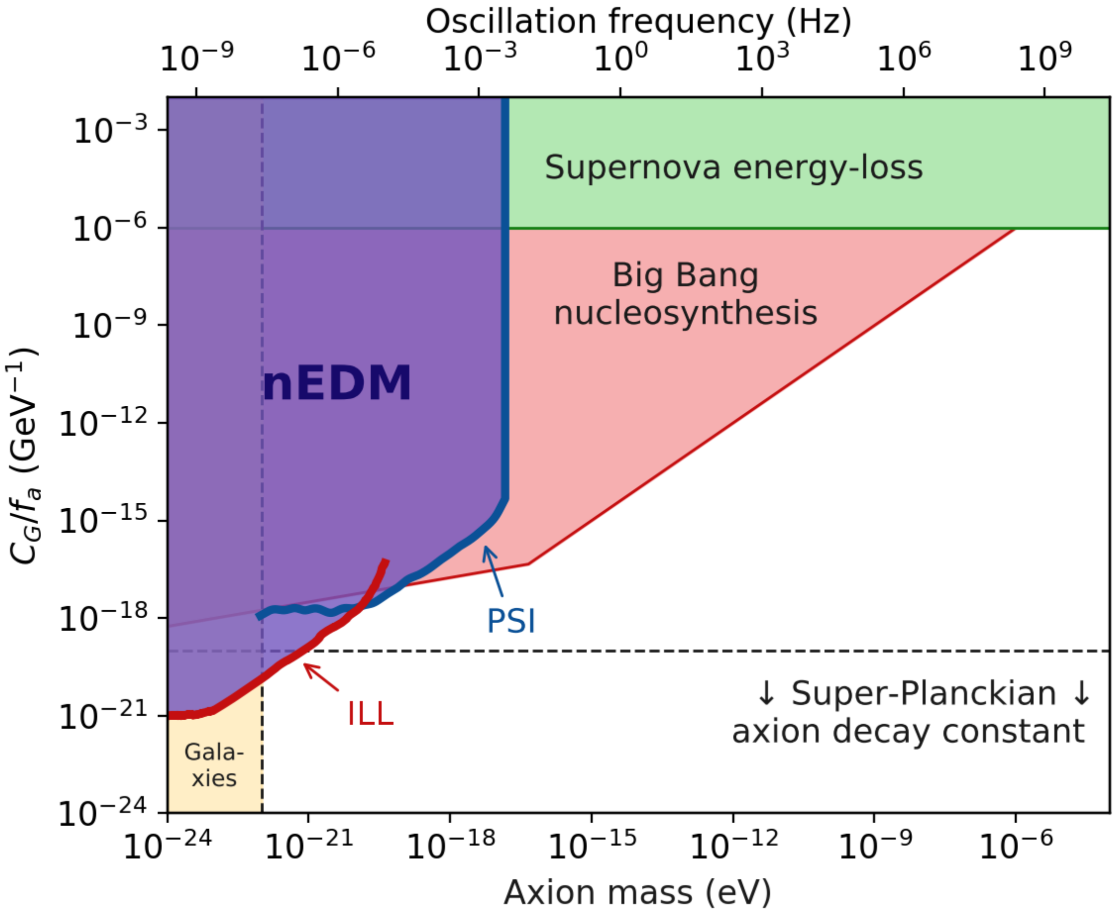
$$\theta_a = \frac{a}{f_a}$$

Axion – Gluon Coupling (1)

- Axion manifestation:

$$d_n \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\, e \cdot cm$$

- Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields
  C. Abel *et al.* Phys. Rev. X **7**, 041034 (2017)



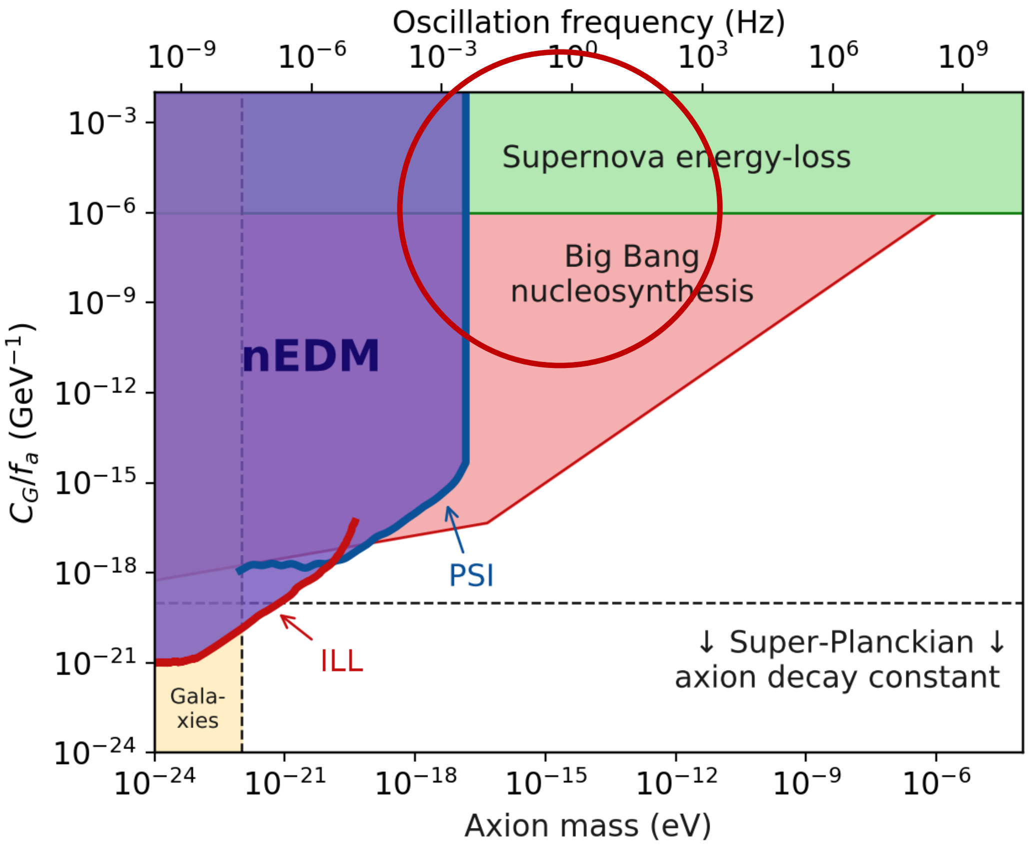
Axion – Gluon Coupling (2)

- Axion can also couple to the Hg-atoms

$$d_{Hg} \approx +1.3 \times 10^{-19} \frac{C_G a_0}{f_a} \cos(m_a t)\, e \cdot cm$$

Intrinsically smaller sensitivity

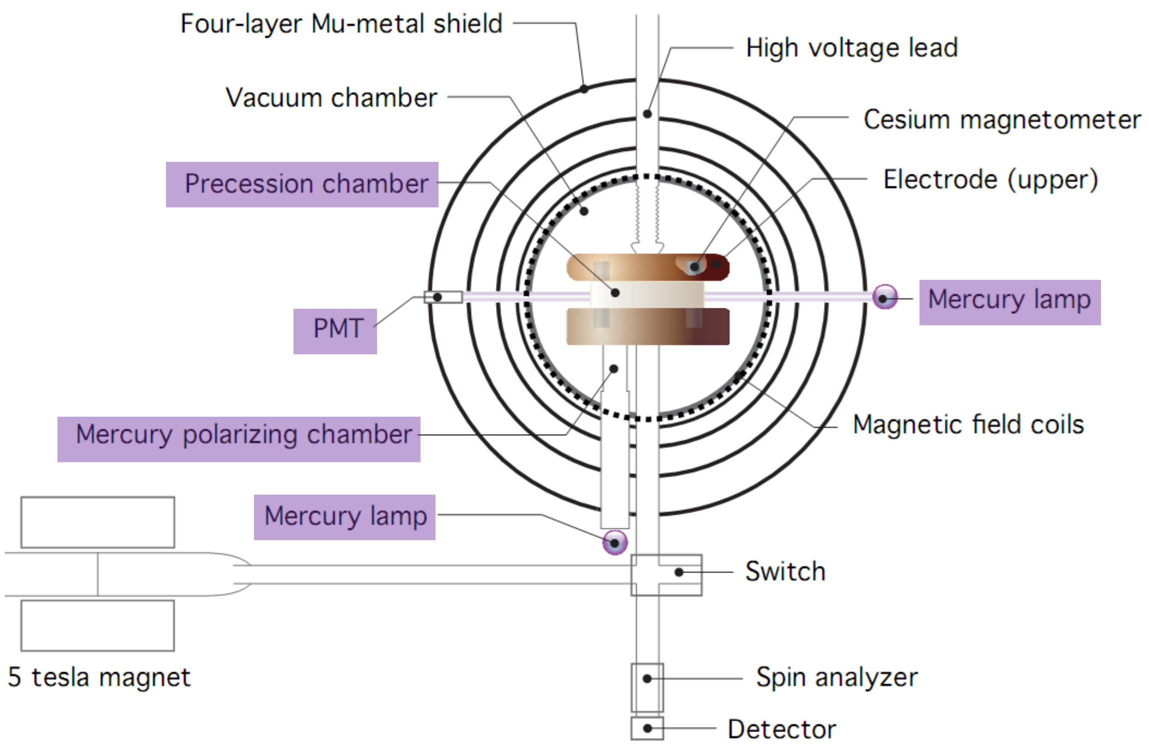
- Advantage: higher sampling rate & equidistant sampling

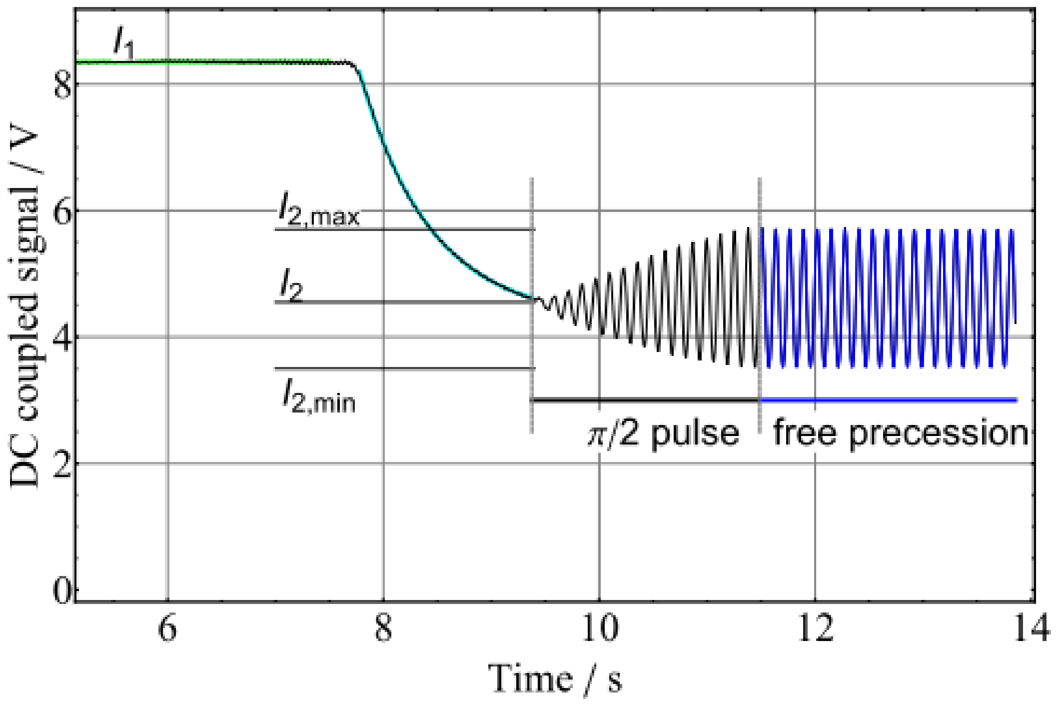


Hg Co-Magnetometer

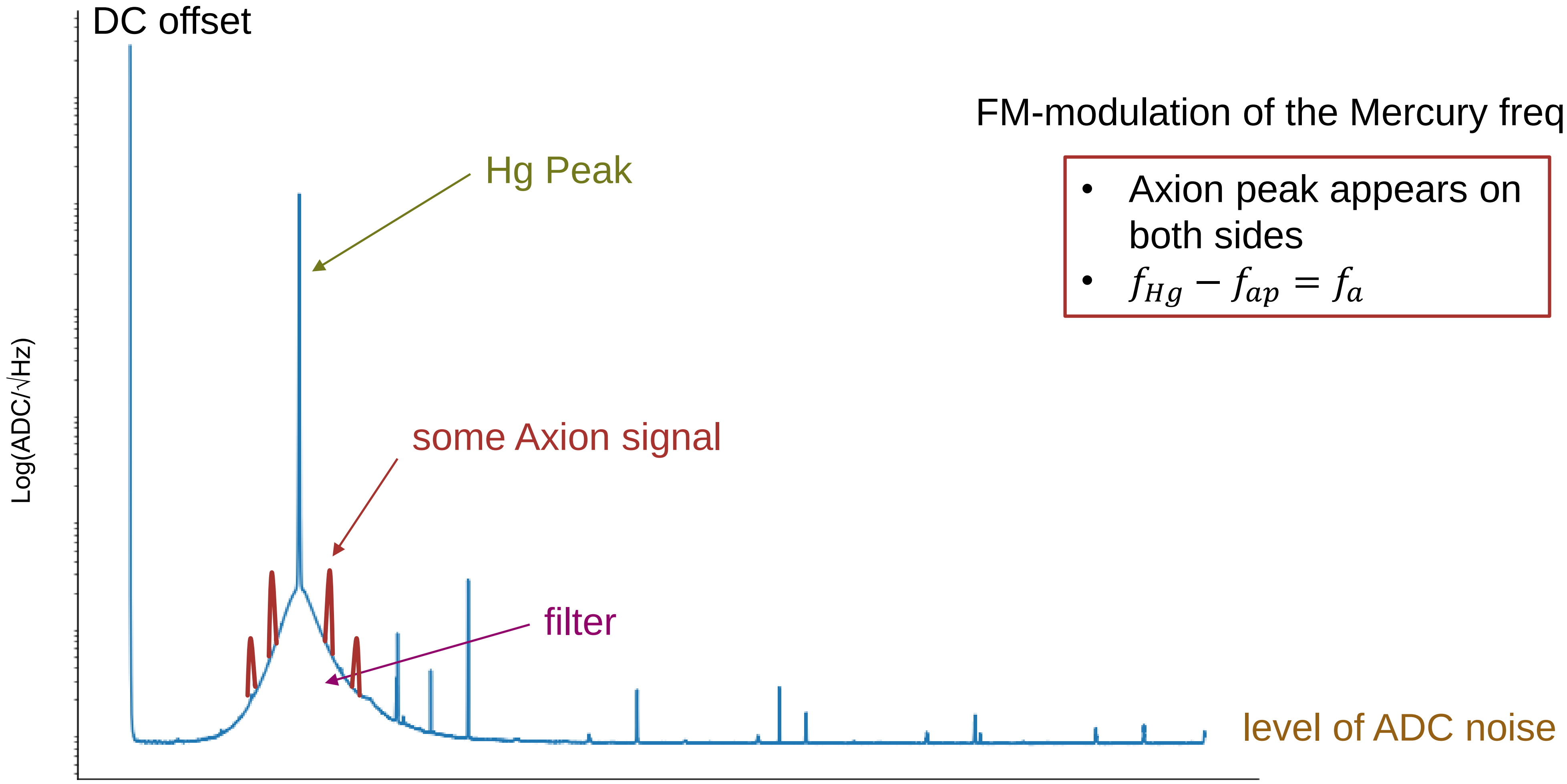
50’000 cycles x 180 s x 100 Hz

Layout of nEDM





What signal to expect?



FM-modulation of the Mercury frequency

- Axion peak appears on both sides
- $f_{Hg} - f_{ap} = f_a$

Outline of the Analysis

- RMS Average FT of the data (average over 50’000 cycles)
- Construct H_0:

  Hg signal + Gaussian noise

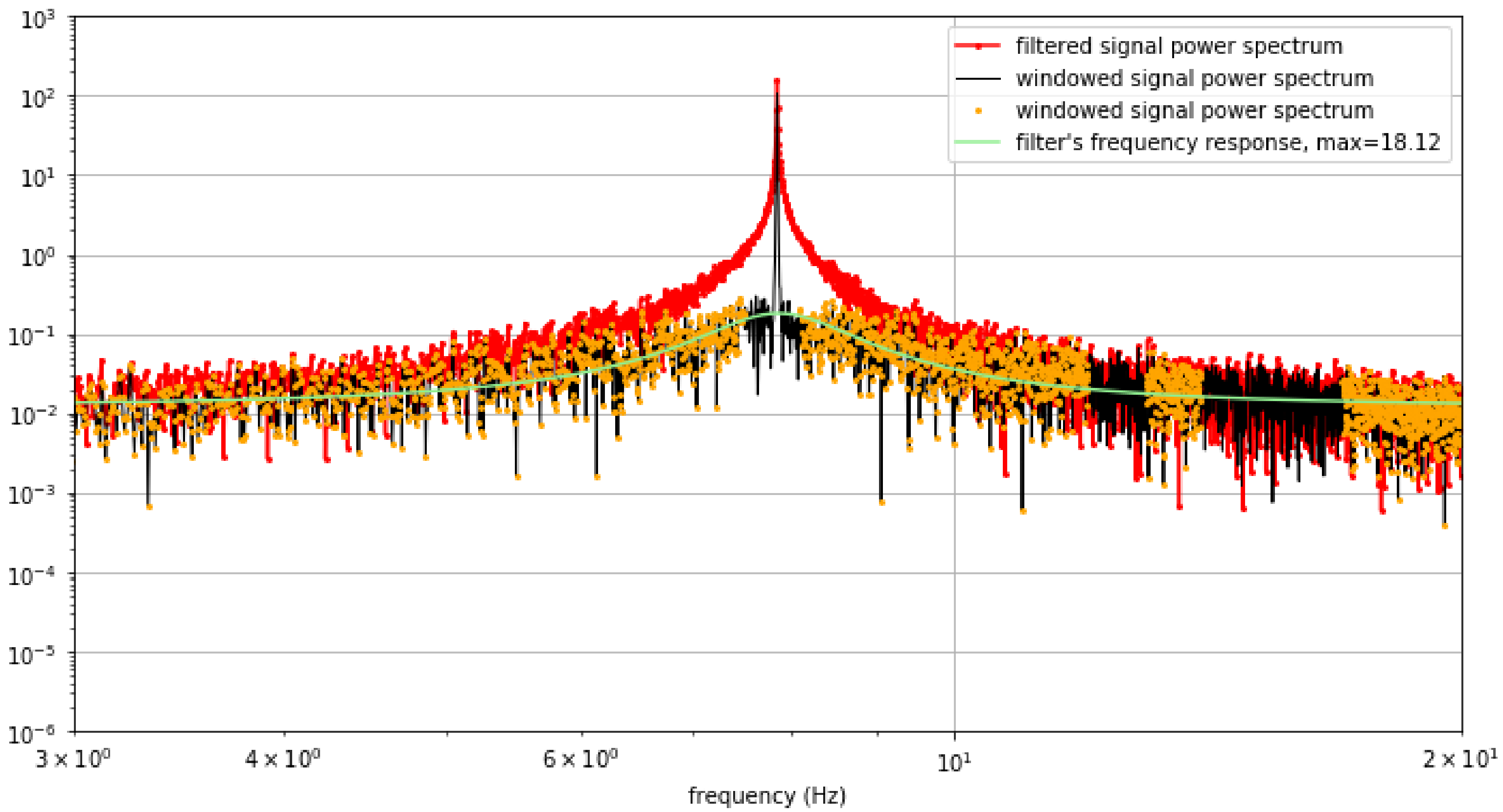
  + filter + ADC

- Construct H_1: … + axion signal

- Use CLs method

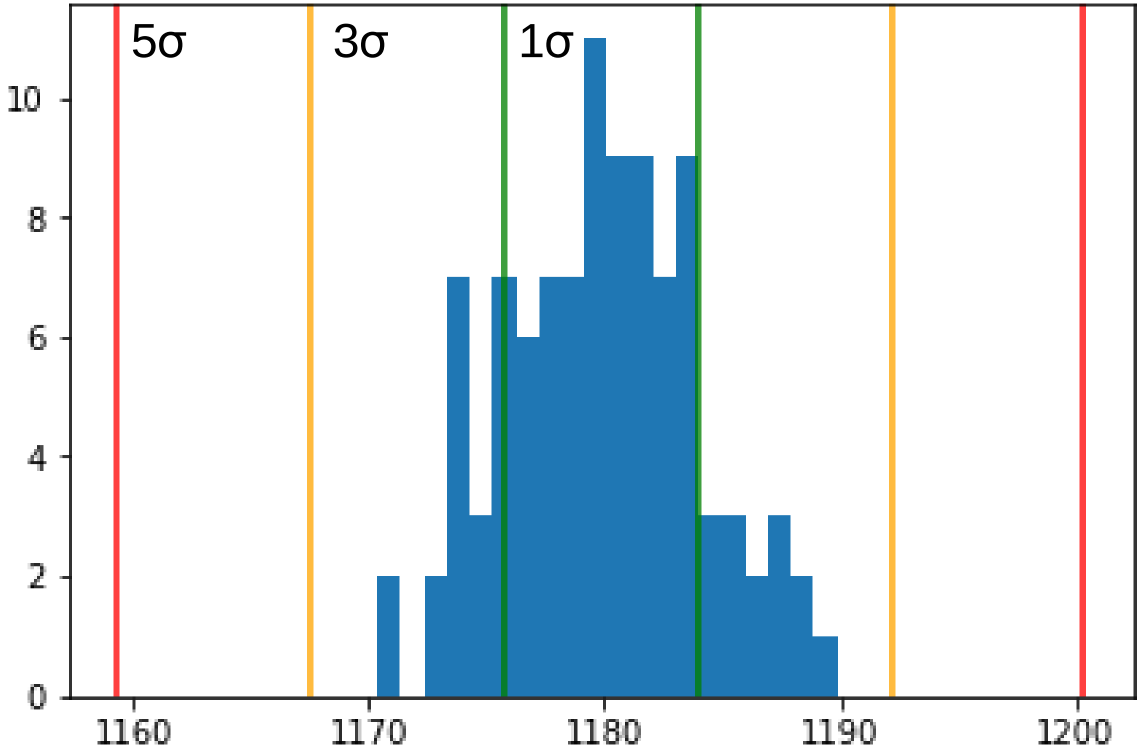
Filter, Noise & ADC Noise

- Transmission function of the filter is given
- Can extract ADC noise



Distribution of power for every frequency

100 simulations of 50’000 cycles



power

Axion Hypothesis

$$(A_1 e^{-\tau_1 * t} + A_2 e^{-\tau_2 * t}) * \sin(2\pi f (1 + A_a \sin(2\pi f_a * t + \varphi_a) * t + \varphi_{Hg})$$

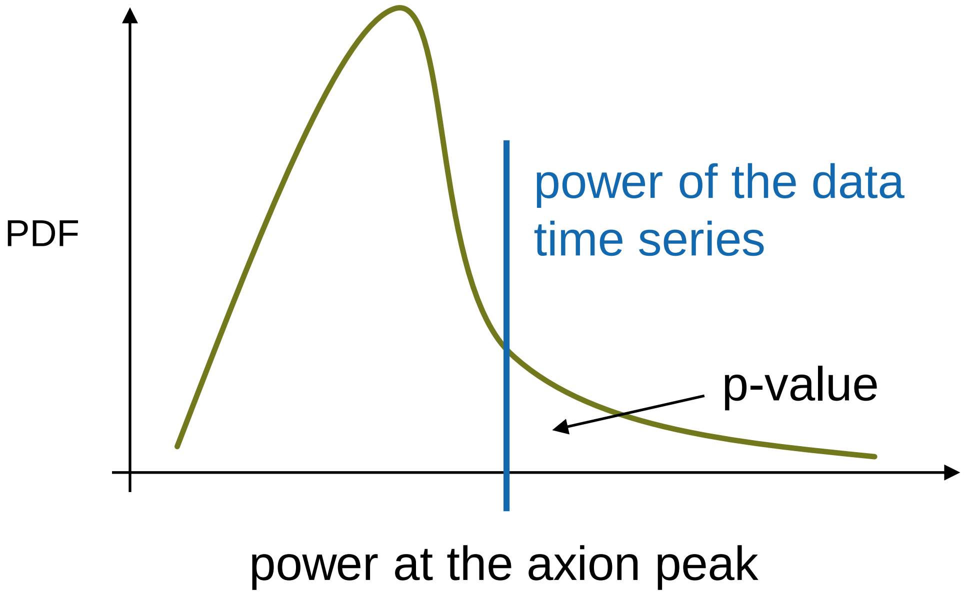
axion part

Which of those axion signals would one see ?

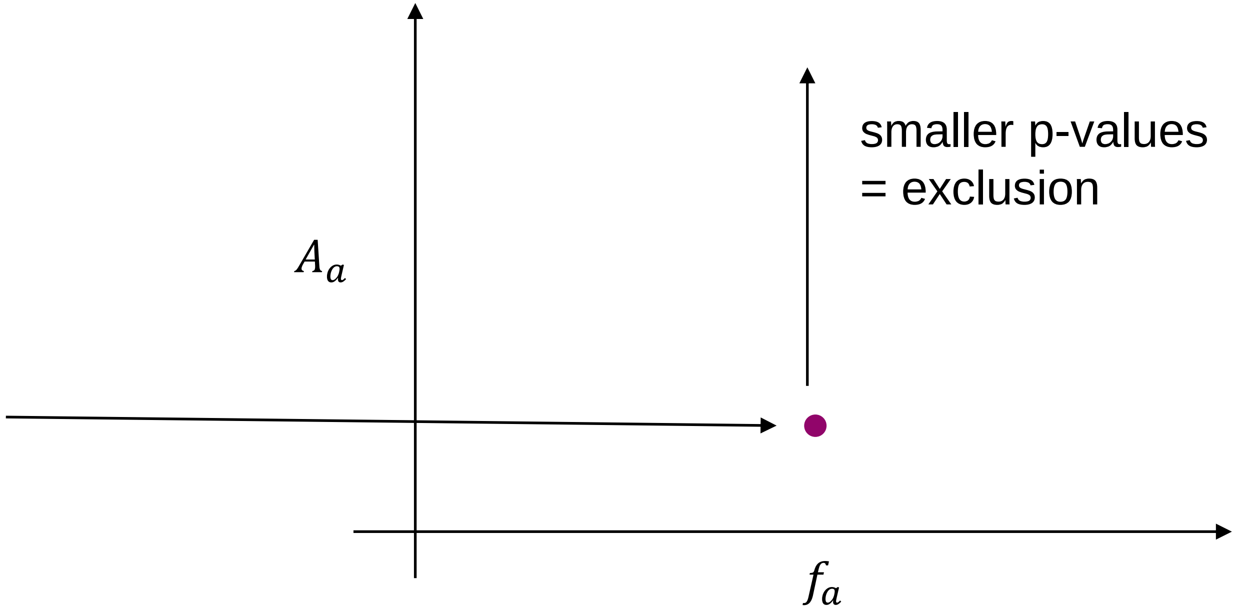
- Depends on A_a and f_a (axion amplitude and axion frequency)
- Simulate datasets with axions in this 2D parameter space

Axion Hypothesis

Simulation with f_a and A_a



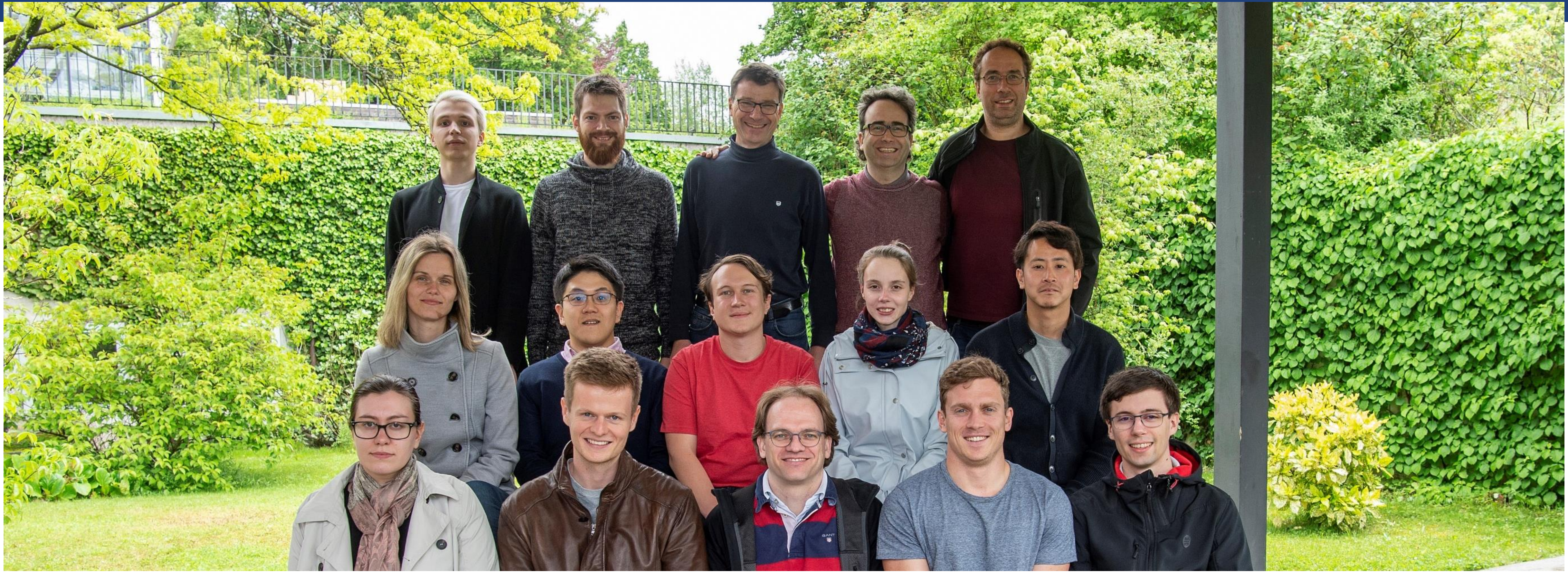
exclusion plot



→ cover the whole exclusion plot

Conclusion

- With nEDM measurement very interesting side analysis are possible
- New result on axion-gluon coupling



Thank you for the attention!