Search for Axion-Like Dark Matter and Exotic Yukawa-Like Interaction

UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

Ivo Schulthess

12. January 2023 - LTP / UCN Seminar

University of Bern | Albert Einstein Center for Fundamental Physics

Fundamental Neutron and Precision Physics

Experiments and Projects

Beam EDM

Axion-Like Dark Matter

search for an oscillating neutron electric dipole moment (EDM) in *Beam EDM* data

Proton NMR

Exotic Yukawa-Like Interaction

search for a new spin-dependent interaction beyond the Standard Model

Axion-Like Dark-Matter Search

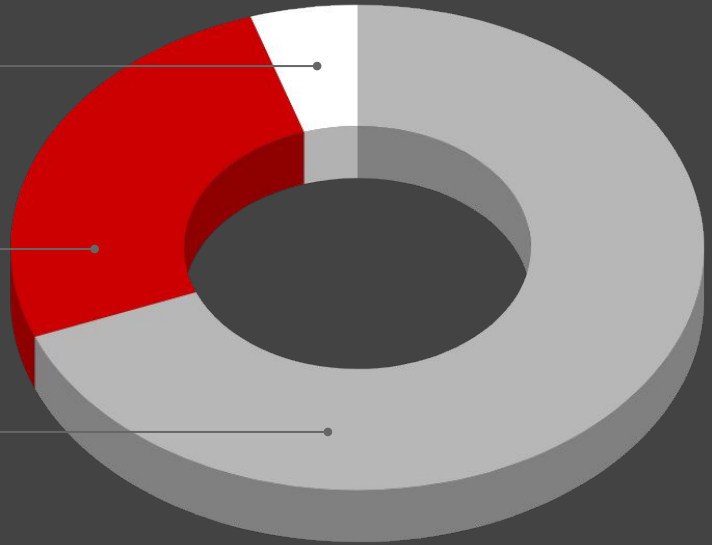
Axion-Like Dark-Matter Search

The Universe and Dark Matter

ordinary matter
5%

dark matter[1]
26%

dark energy
69%



what we know:

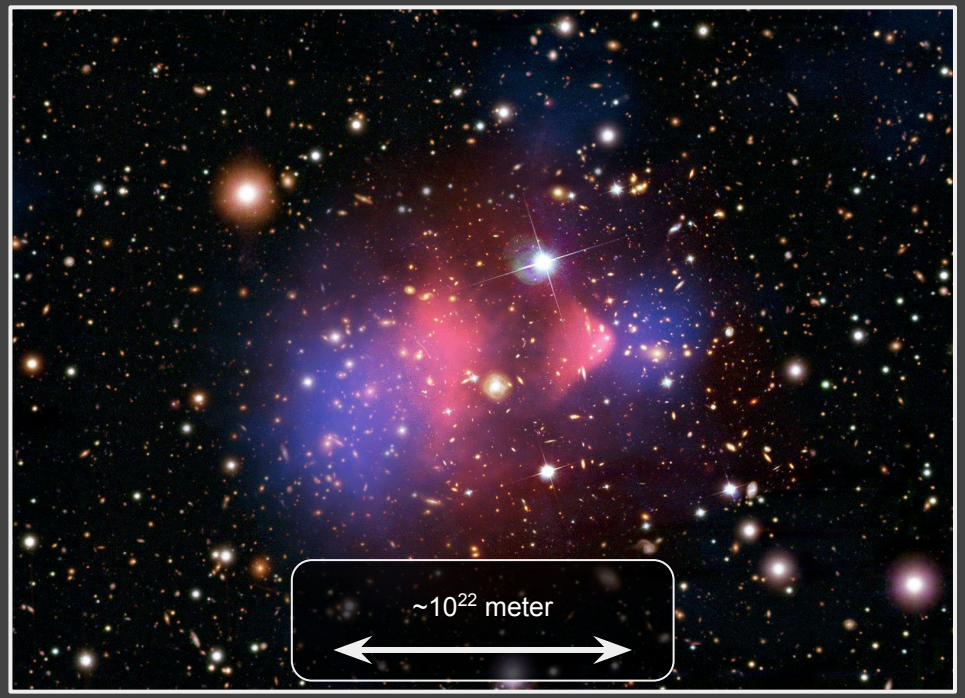
- no interaction with photons
- gravitational interaction
- (no self-interaction)

[1] doi:10.1051/0004-6361/201833880

Axion-Like Dark-Matter Search

The Universe and Dark Matter

example:
Bullet Cluster 1E 0657-56



picture courtesy of:
Chandra X-Ray Observatory: 1E 0657-56

Axion-Like Dark-Matter Search

The Axion as a Solution to the Strong *CP* Problem

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G_c^{\mu\nu} \tilde{G}_{\mu\nu}^c$$

$$d_n = 2.4 \times 10^{-16}\, e\,\mathrm{cm} \cdot \theta$$

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$$ (90% C.L.)[2]

[2] doi:10.1103/PhysRevLett.124.081803

Axion-Like Dark-Matter Search

The Axion as a Solution to the Strong *CP* Problem

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G_c^{\mu\nu} \tilde{G}^c_{\mu\nu}$$

$$d_n = 2.4 \times 10^{-16}\, e\,\mathrm{cm} \cdot \theta$$

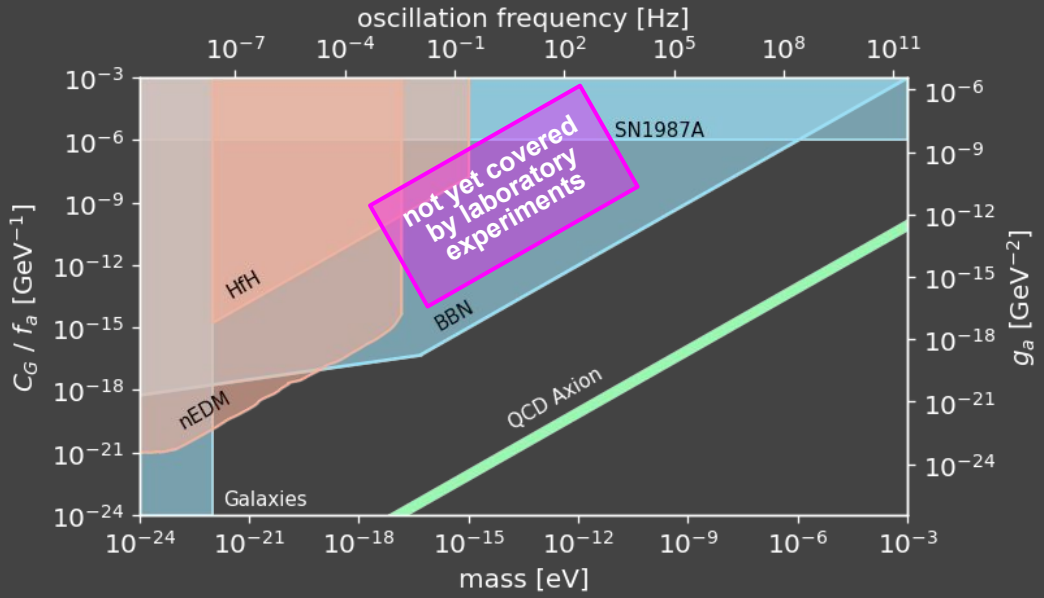
$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm} \quad \text{(90\% C.L.)}[2]$$

$$\mathcal{L}_{\mathrm{axion}} = \underbrace{-\frac{1}{2}\partial_\mu a \partial^\mu a}_{\mathcal{L}_{\mathrm{kin}}} + \underbrace{C_G \frac{a}{f_a} \frac{g^2}{32\pi^2} G_c^{\mu\nu} \tilde{G}^c_{\mu\nu}}_{-V_{\mathrm{eff}}} + \mathcal{L}_{\mathrm{int}}\left[\frac{\partial_\mu a}{f_a}; \psi\right]$$

[2] doi:10.1103/PhysRevLett.124.081803

Axion-Like Dark-Matter Search

Motivation to Search for Axions



- **axion-gluon coupling**
  ➔ oscillating neutron EDM[3]

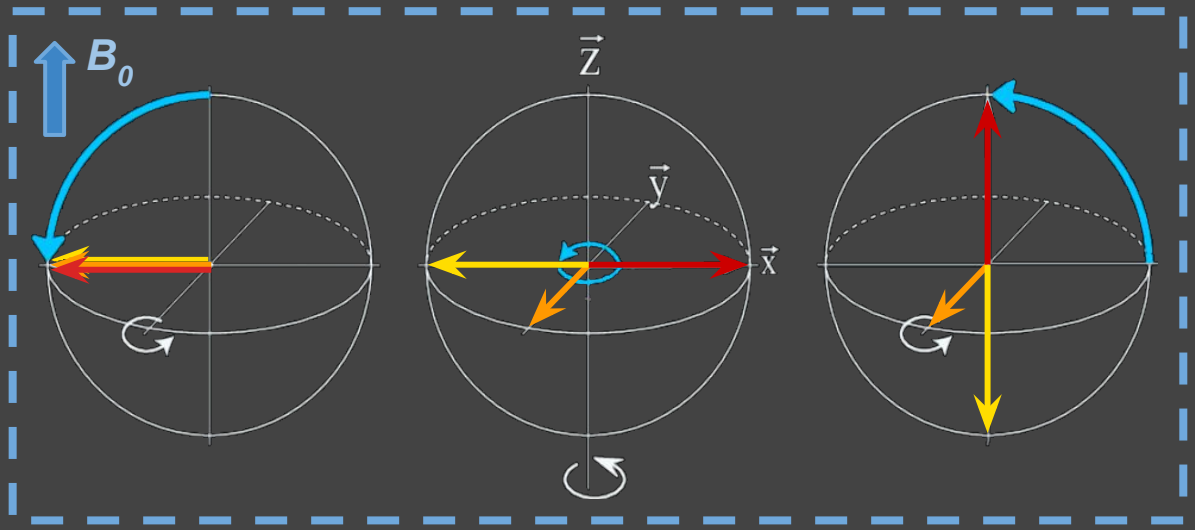
- $d_n(t) \approx \frac{C_G}{f_a} a_0 \cos(m_a t) \cdot 2.4 \times 10^{-16} e \cdot \mathrm{cm}$

  C_G: model dependent parameter
  f_a: axion decay constant
  a_0: axion field amplitude
  m_a: axion mass

[3] doi:10.1103/PhysRevD.89.043522

Measurement Technique

Ramsey's Method of Oscillatory Fields



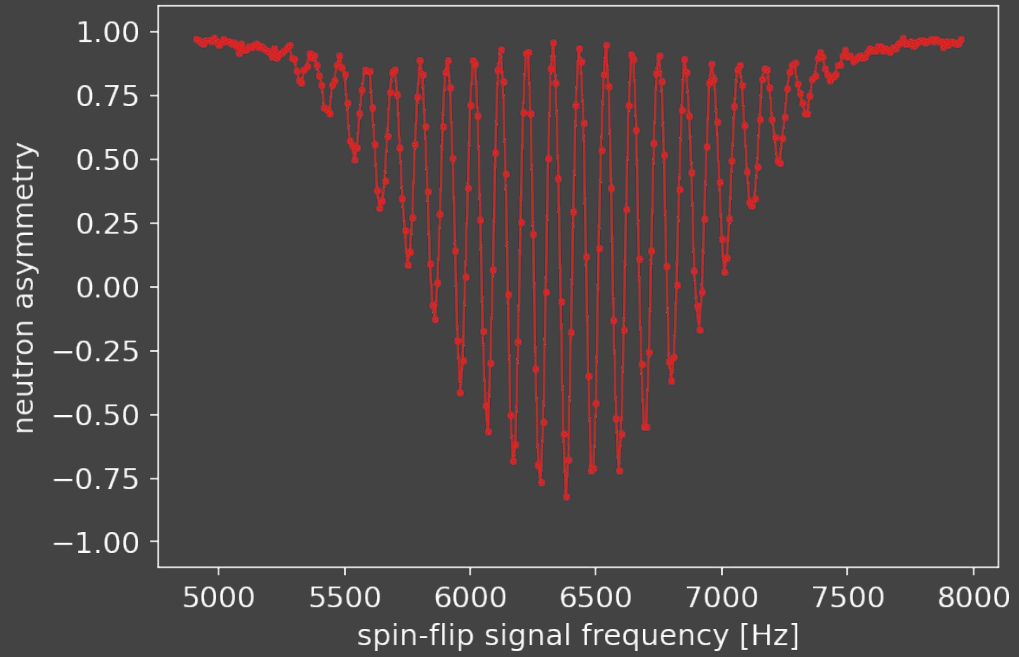
Larmor precession: $\hbar\omega = 2\,\mu\,B_0$

$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)}$$

picture adapted from:
J. Lisenfeld thesis - Fig. 4.25

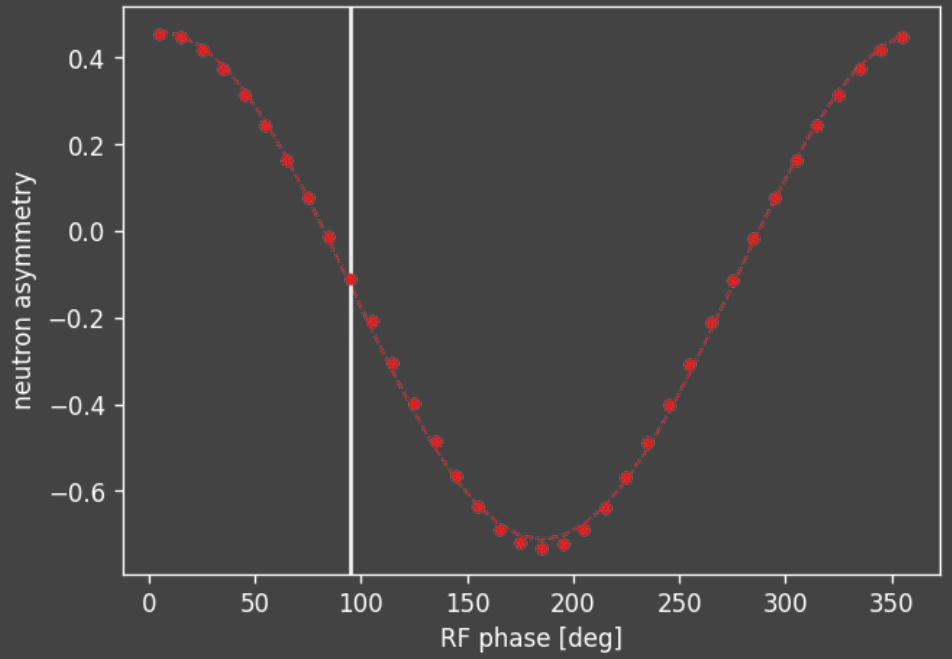
Measurement Technique

Ramsey's Method of Oscillatory Fields



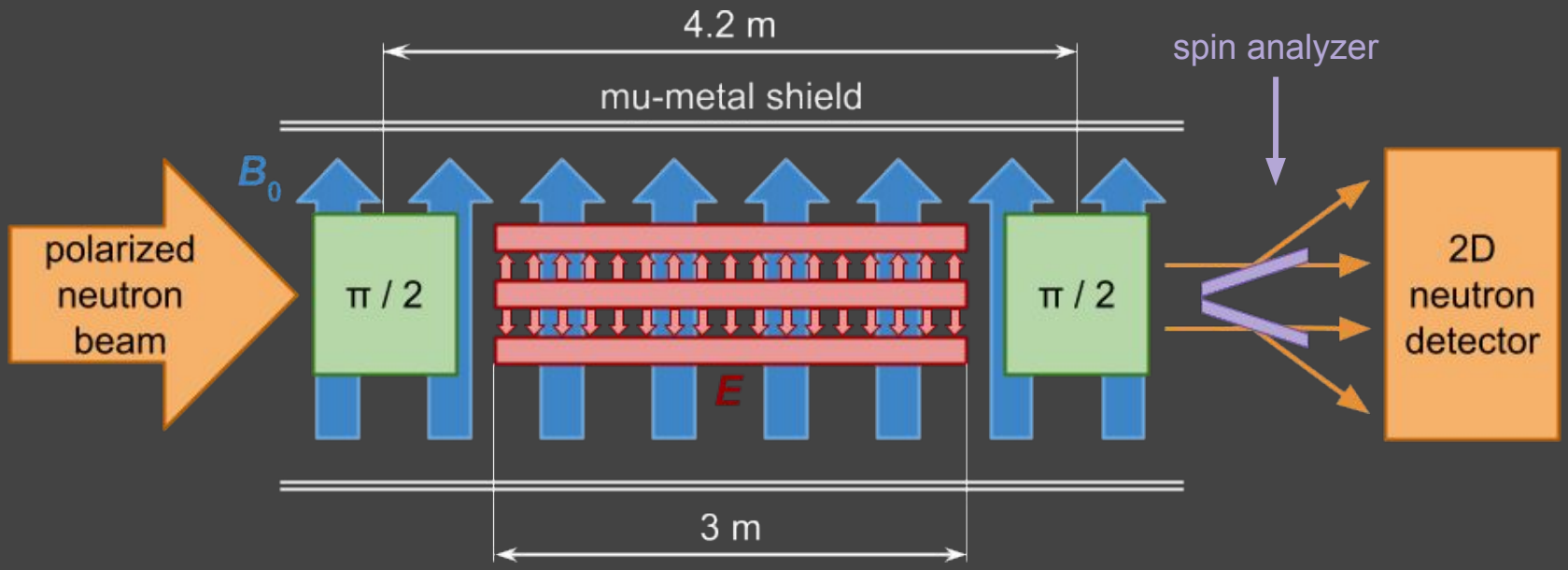
Measurement Technique

Ramsey's Method of Oscillatory Fields



The *Beam EDM* Apparatus

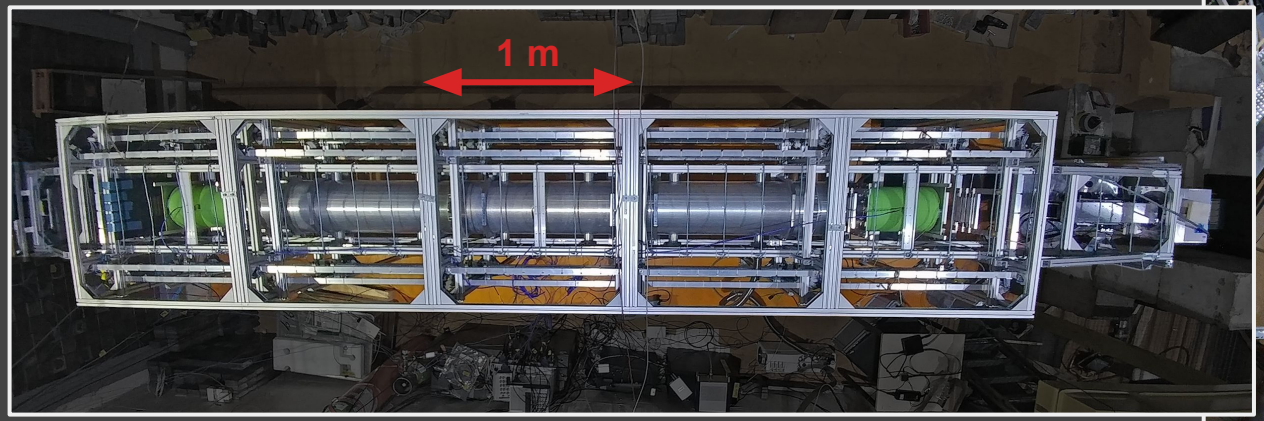
Experiment Schematic

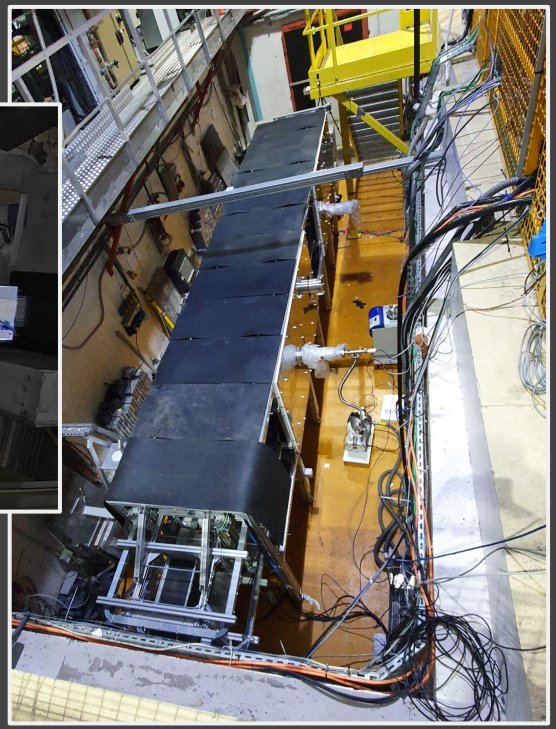


Larmor precession: $\hbar\omega = 2\,\mu\,B_0 \pm 2\,d\,E$

The *Beam EDM* Apparatus

Experimental Setup





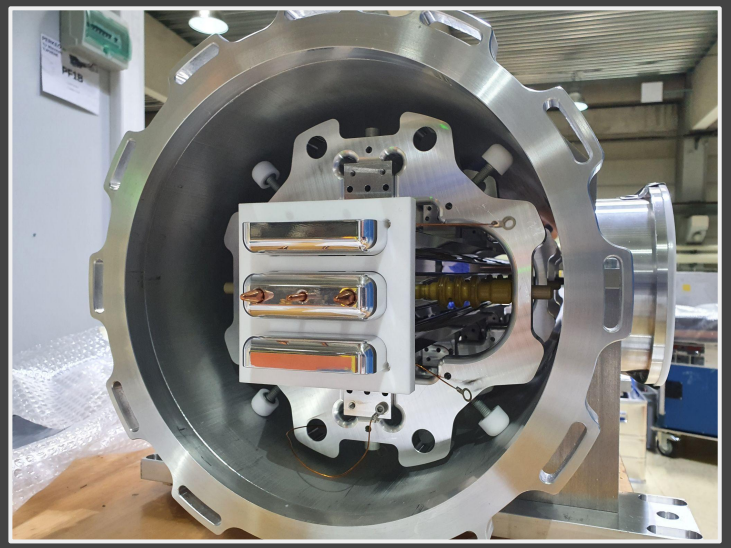
PAUL SCHERRER INSTITUT

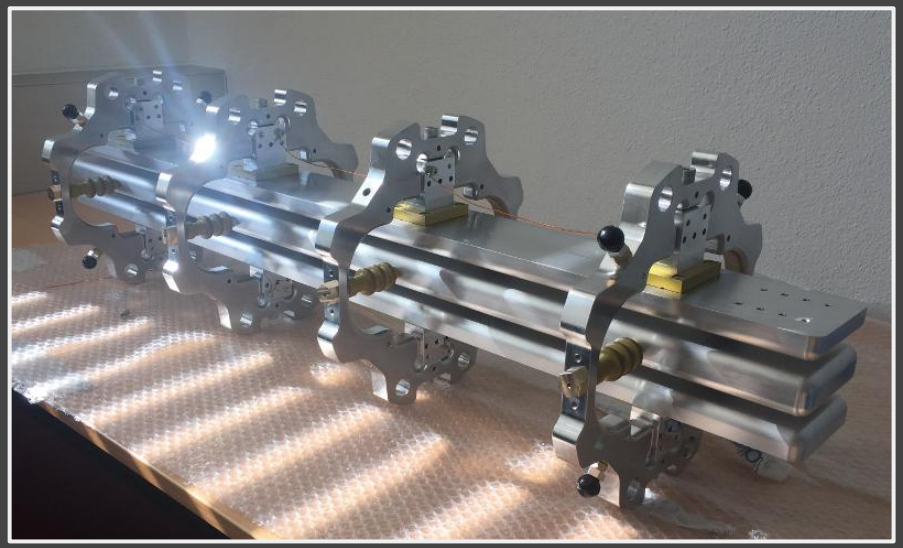
PSI

NEUTRONS FOR SOCIETY

The *Beam EDM* Apparatus

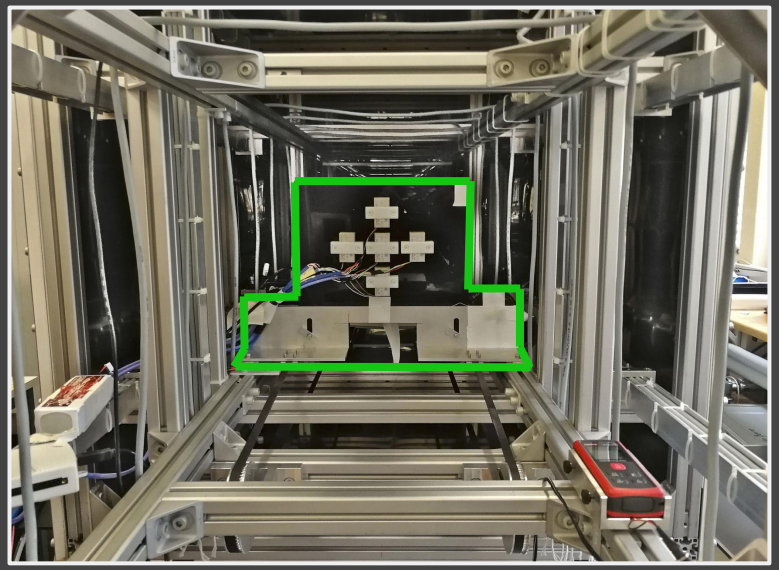
Experimental Setup

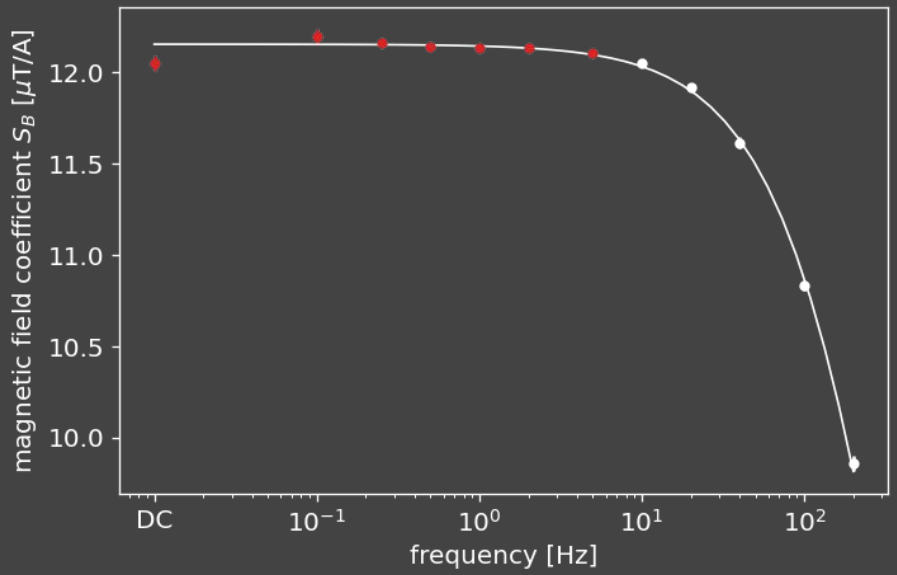




Axion-Like Dark-Matter Search

Characterization of the Experimental Apparatus

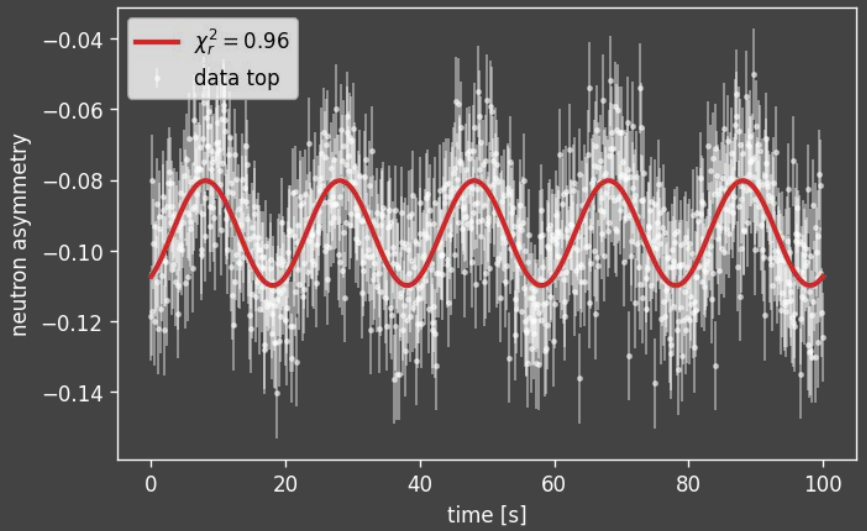


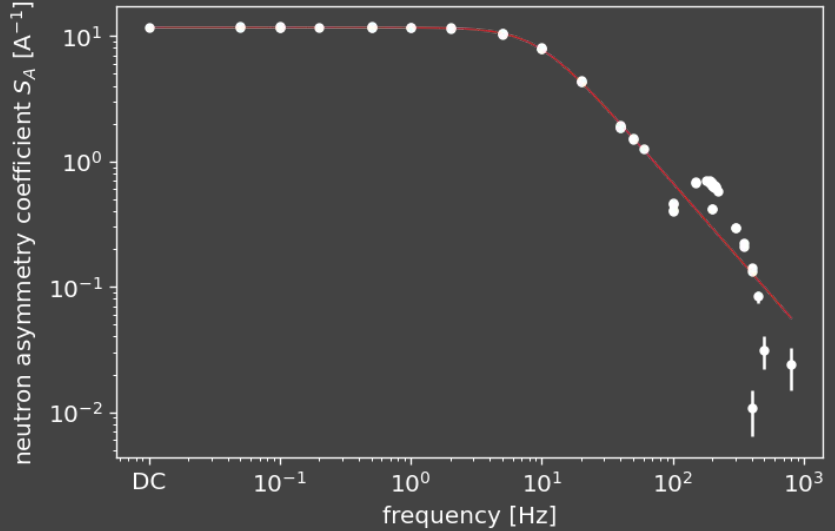


Axion-Like Dark-Matter Search

Characterization of the Experimental Apparatus

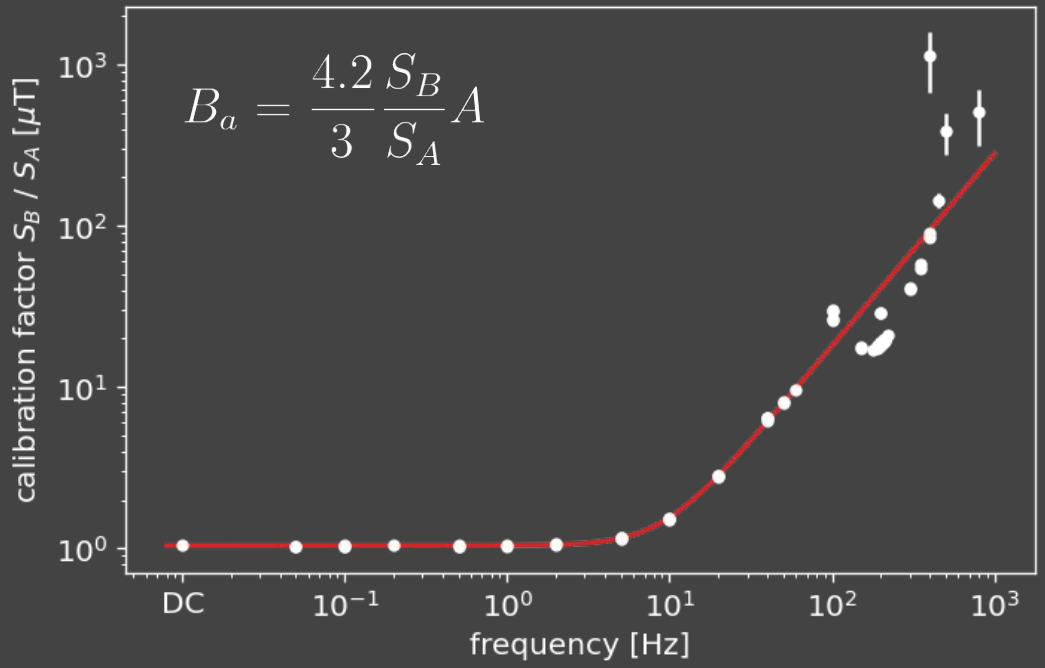
f = 50 mHz, A = 2.5 mA





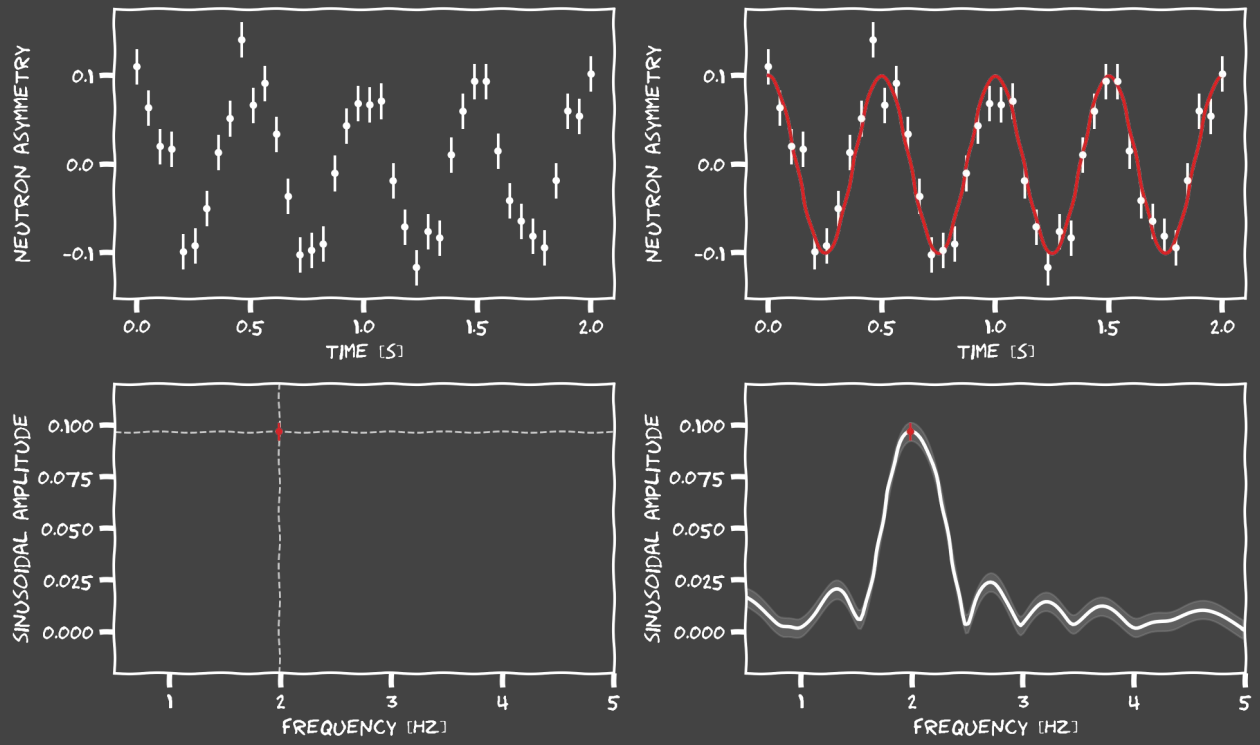
Axion-Like Dark-Matter Search

Characterization of the Experimental Apparatus



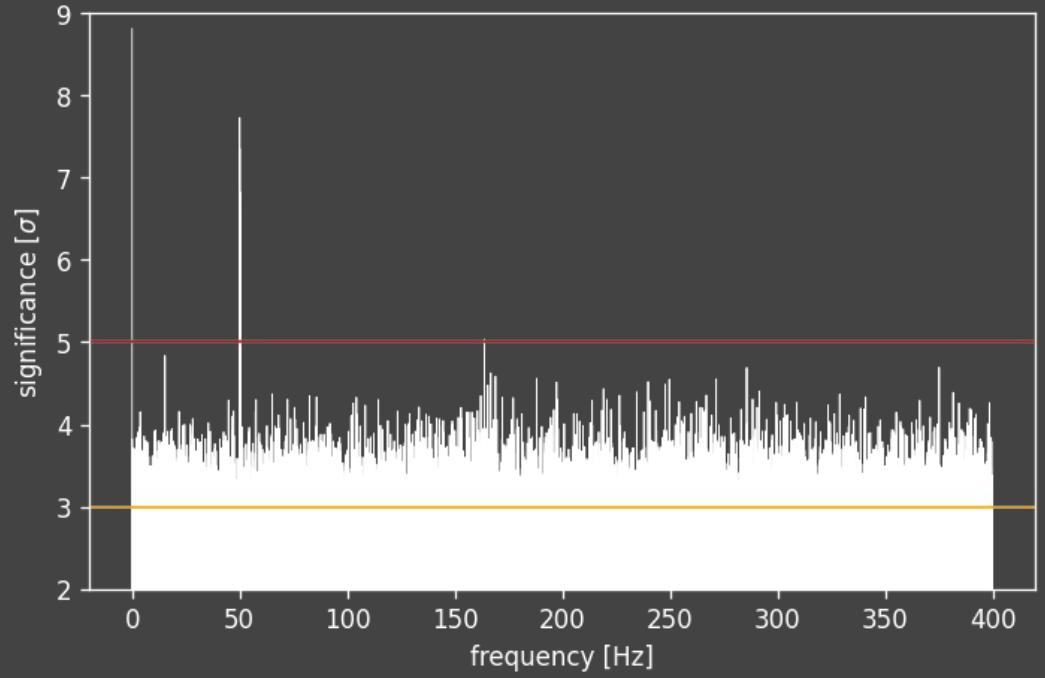
Axion-Like Dark-Matter Search

Data Processing



Axion-Like Dark-Matter Search

Data Processing

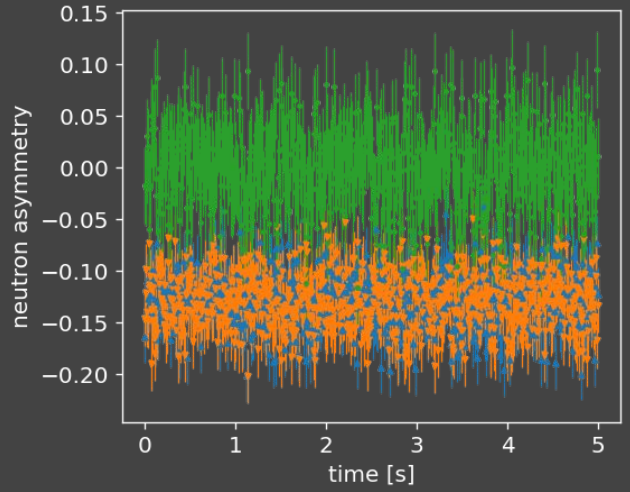


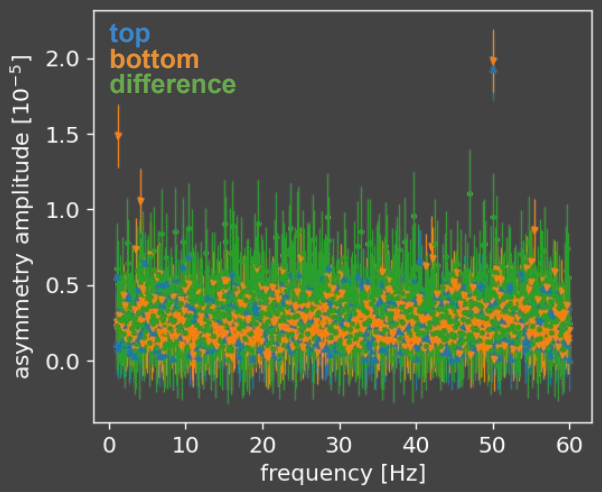
conditions for an axion signal:

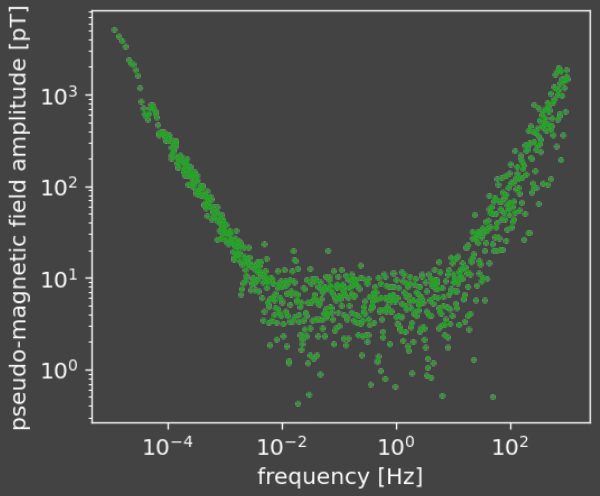
1. no signal for E = 0
2. peak with same amplitude for B↑↑E and B↑↓E
3. 180° phase shift for B↑↑E compared to B↑↓E

Axion-Like Dark-Matter Search

Data Processing

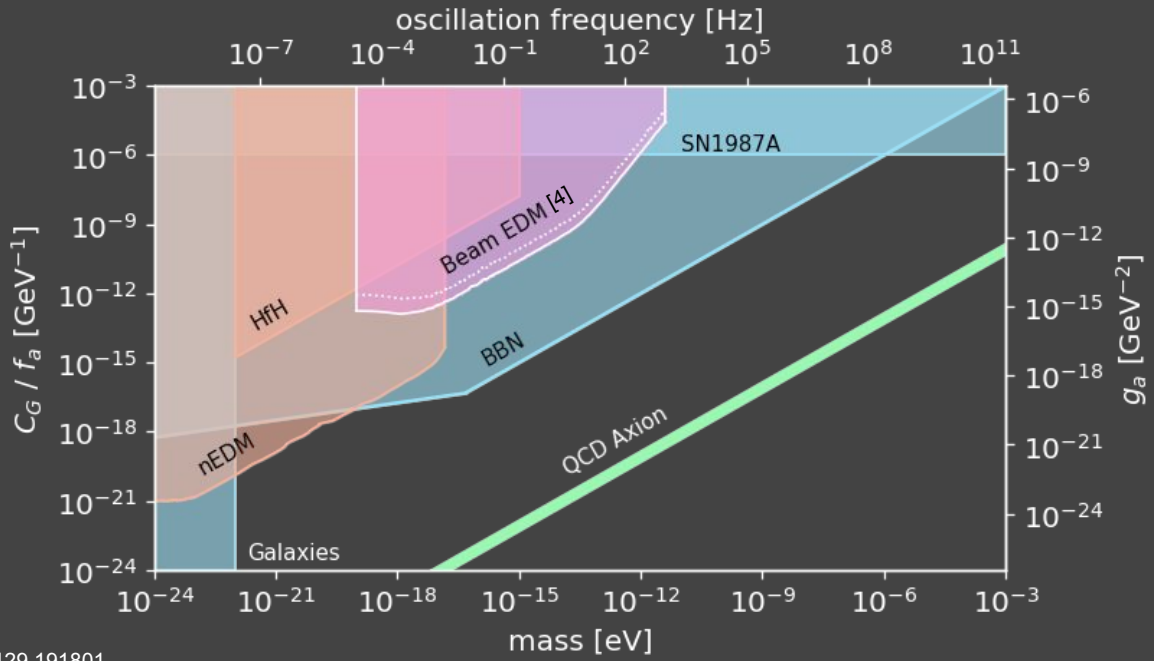






Axion-Like Dark-Matter Search

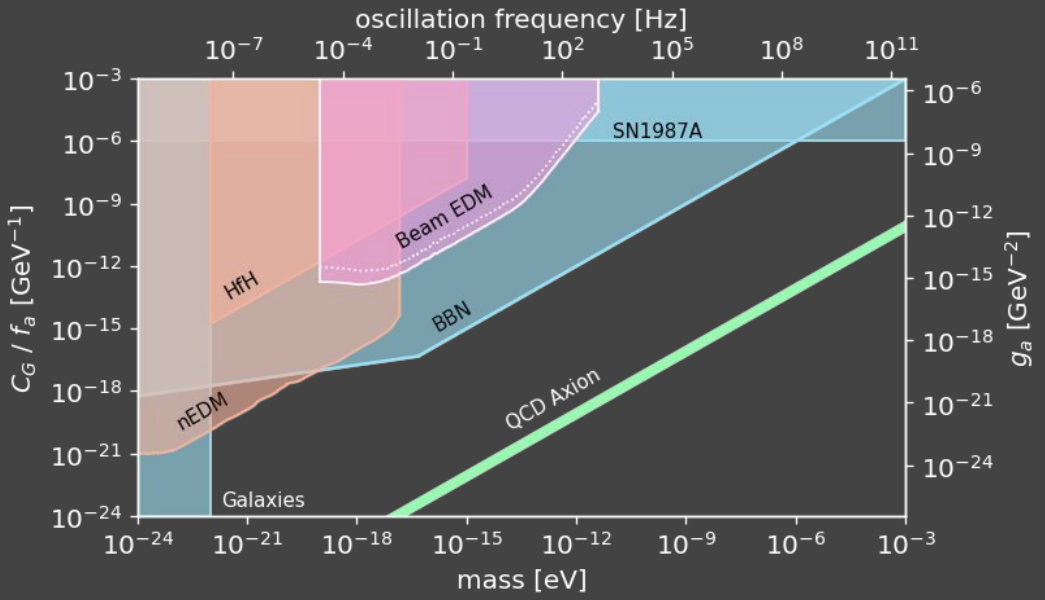
Results



[4] doi:10.1103/PhysRevLett.129.191801

Axion-Like Dark-Matter Search

Conclusion



- set a new limit on the existence of axion-like dark matter in a yet unexplored mass range[4]
- benefits from existing *Beam EDM* apparatus
- only 24 hours ➔ 8 orders of magnitude in m_a

[4] doi:10.1103/PhysRevLett.129.191801

Exotic Yukawa-Like Interaction

Exotic Yukawa-Like Interaction

Properties of the Interaction

- **search for BSM physics**
- **interaction** under test:
  - spin-dependent interaction of two fermions
  - momentum dependent
  - new massive spin 1 exchange boson
  - non-relativistic limit

$$V_\perp = \frac{f_\perp}{8\pi m}\frac{e^{-r/\lambda}}{r}\left(\frac{1}{r}+\frac{1}{\lambda}\right)\vec{\sigma}\cdot(\vec{v}\times\vec{r})$$

$$V = -\mu_p B^*$$

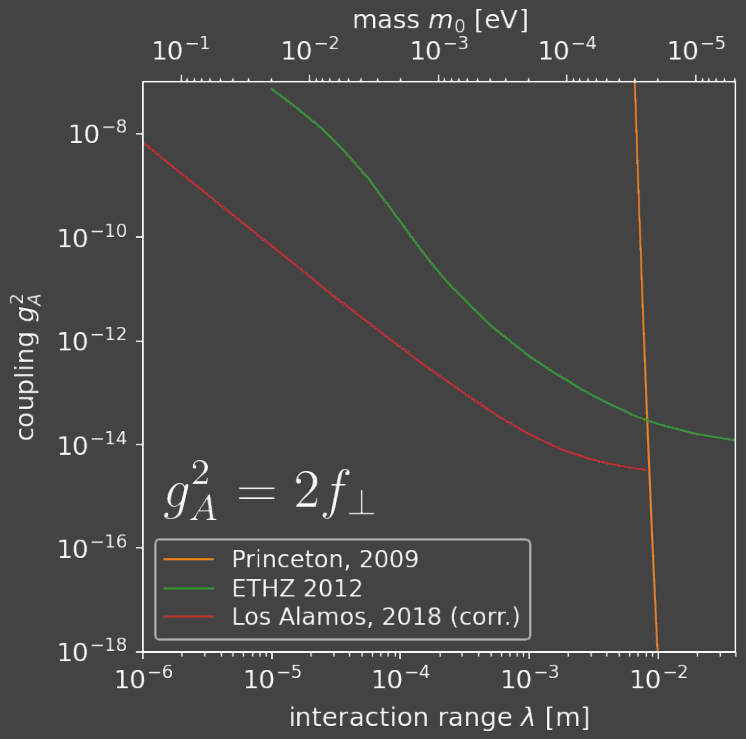
Exotic Yukawa-Like Interaction

Properties of the Interaction

- **search for BSM physics**
- **interaction** under test:
  - spin-dependent interaction of two fermions
  - momentum dependent
  - new massive spin 1 exchange boson
  - non-relativistic limit

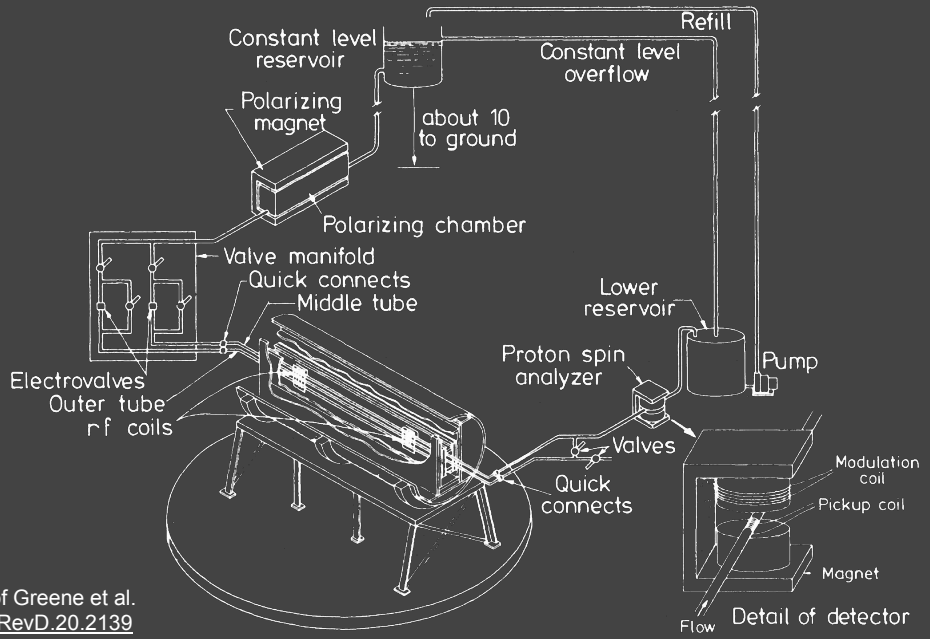
$$V_\perp = \frac{f_\perp}{8\pi m}\frac{e^{-r/\lambda}}{r}\left(\frac{1}{r}+\frac{1}{\lambda}\right)\vec{\sigma}\cdot(\vec{v}\times\vec{r})$$

$$V = -\mu_p B^*$$



Exotic Yukawa-Like Interaction

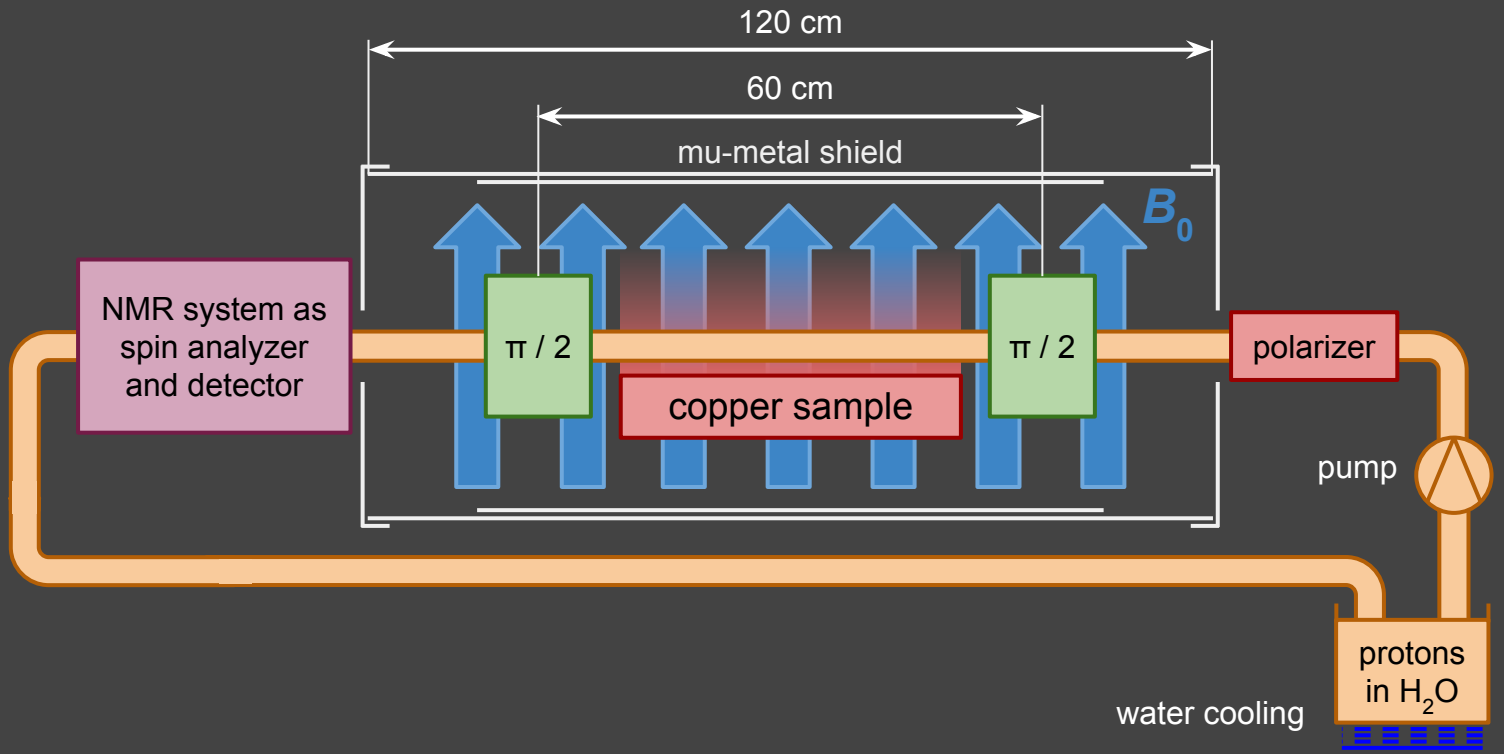
Experiment Idea



picture courtesy of Greene et al.
doi:10.1103/PhysRevD.20.2139

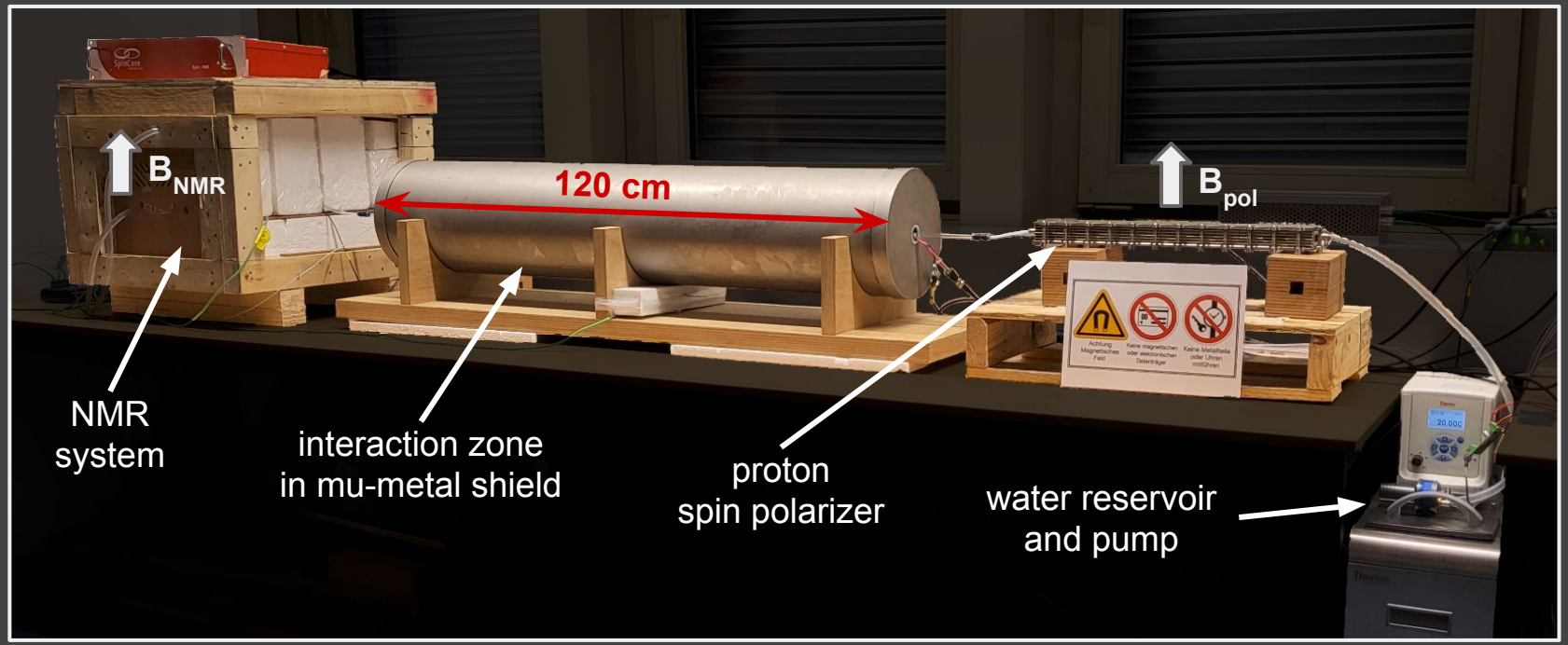
The *Proton NMR* Apparatus

Experiment Schematic



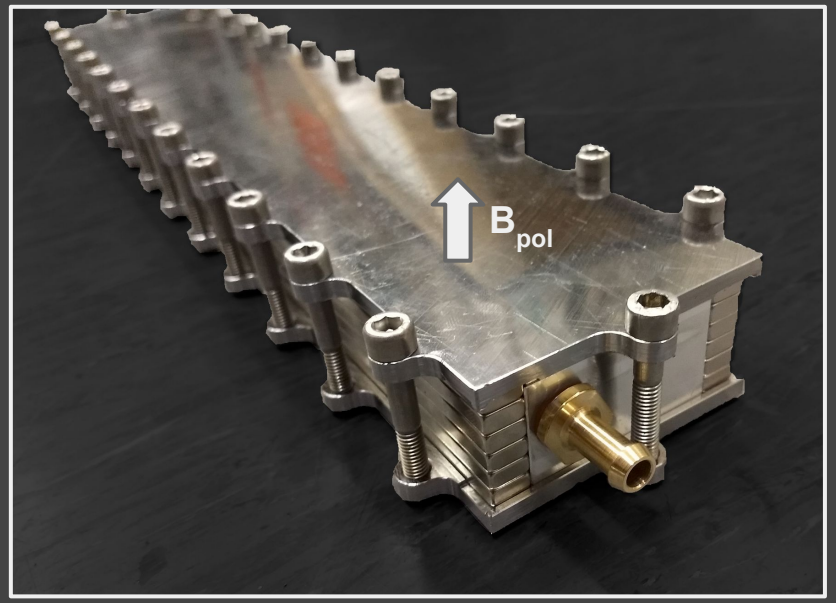
The *Proton NMR* Apparatus

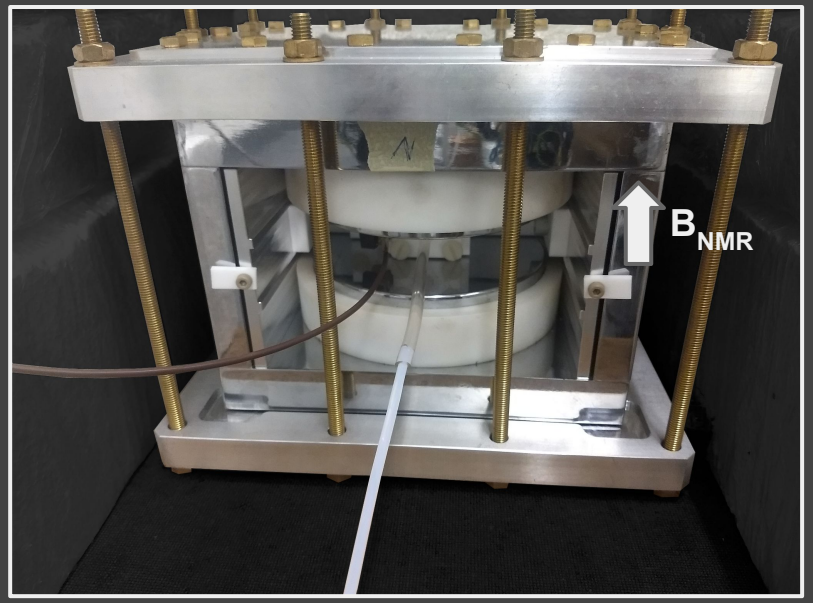
Experimental Setup



The *Proton NMR* Apparatus

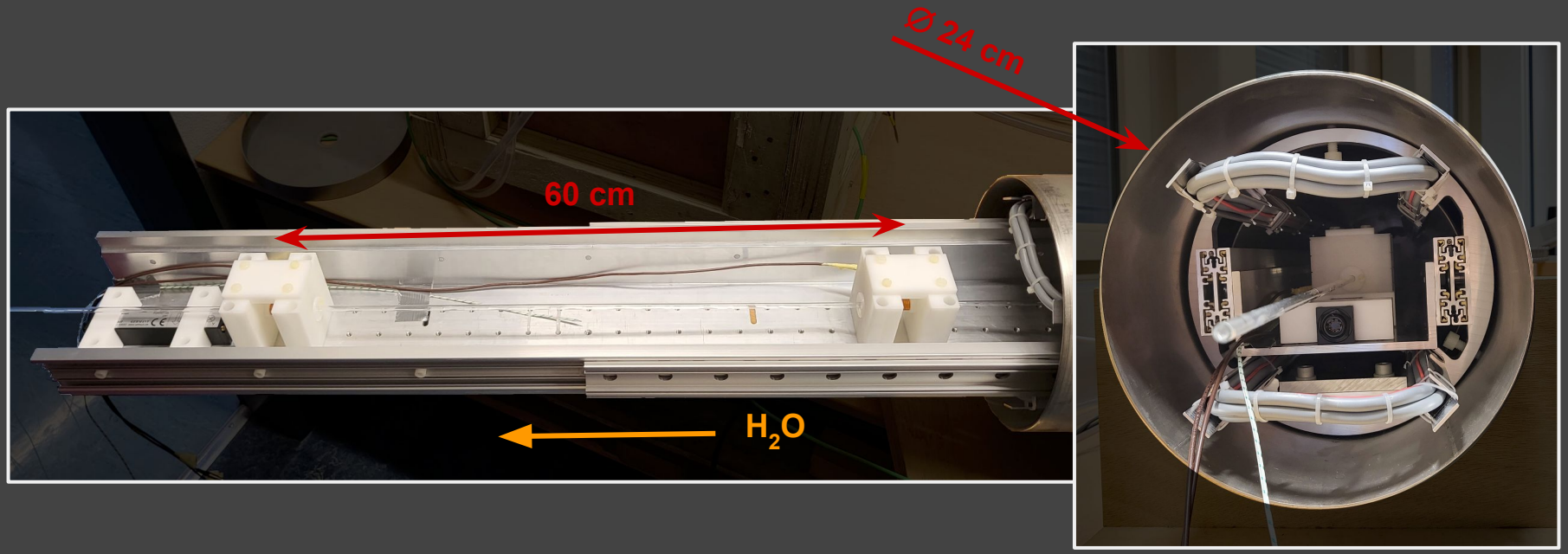
Experimental Setup





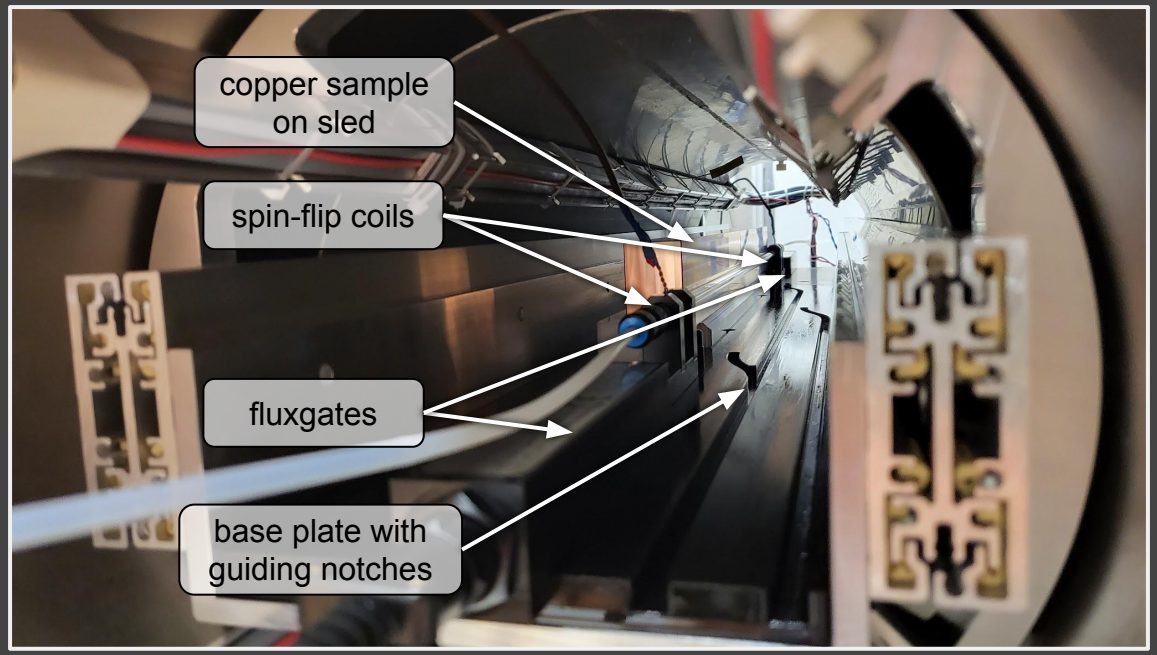
The *Proton NMR* Apparatus

Experimental Setup



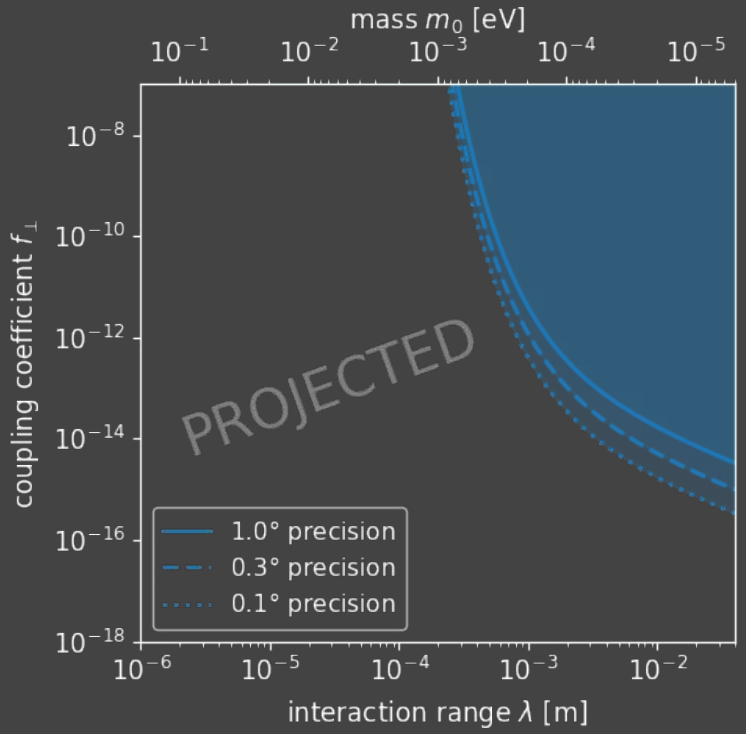
Exotic Yukawa-Like Interaction

Copper Sample Setup



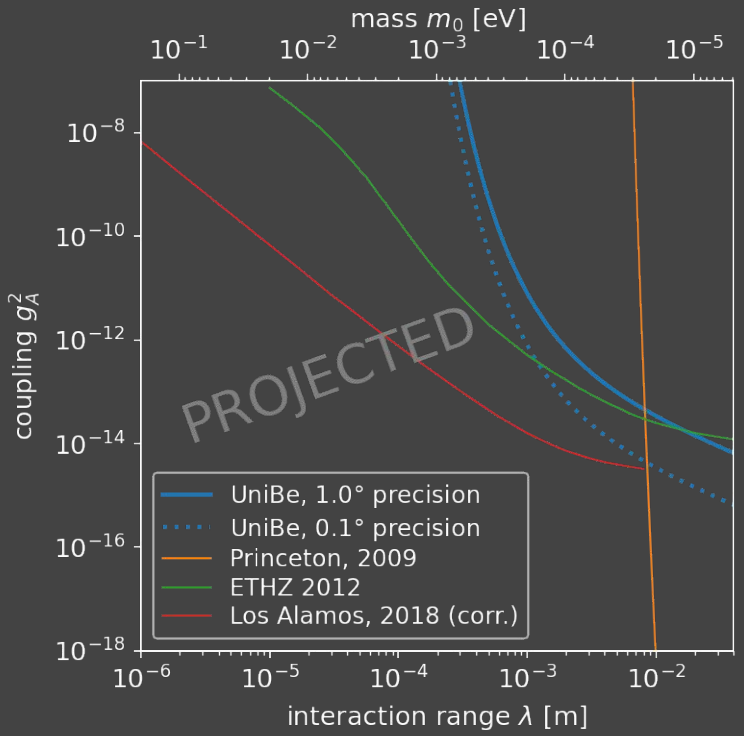
Exotic Yukawa-Like Interaction

Results and Conclusion



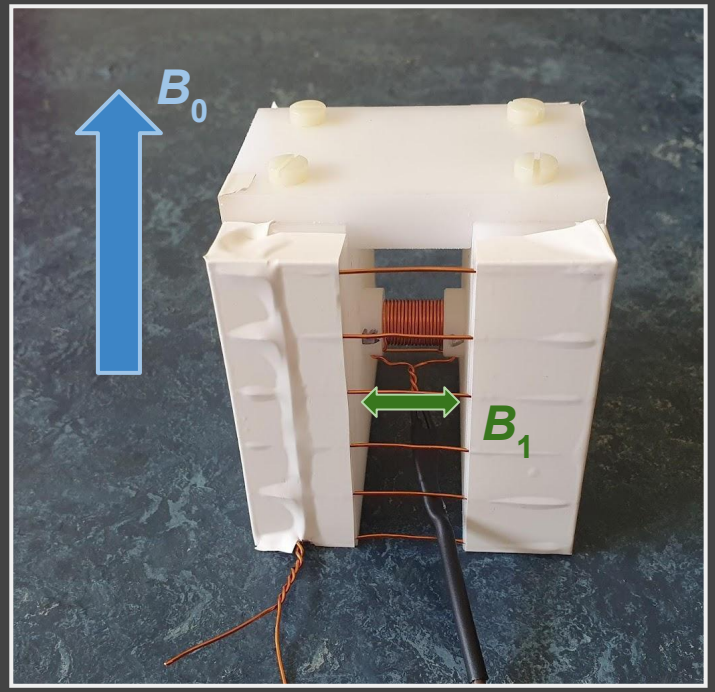
Exotic Yukawa-Like Interaction

Results and Conclusion



Measurement of Resonance Effects

Bloch-Siegert Shift



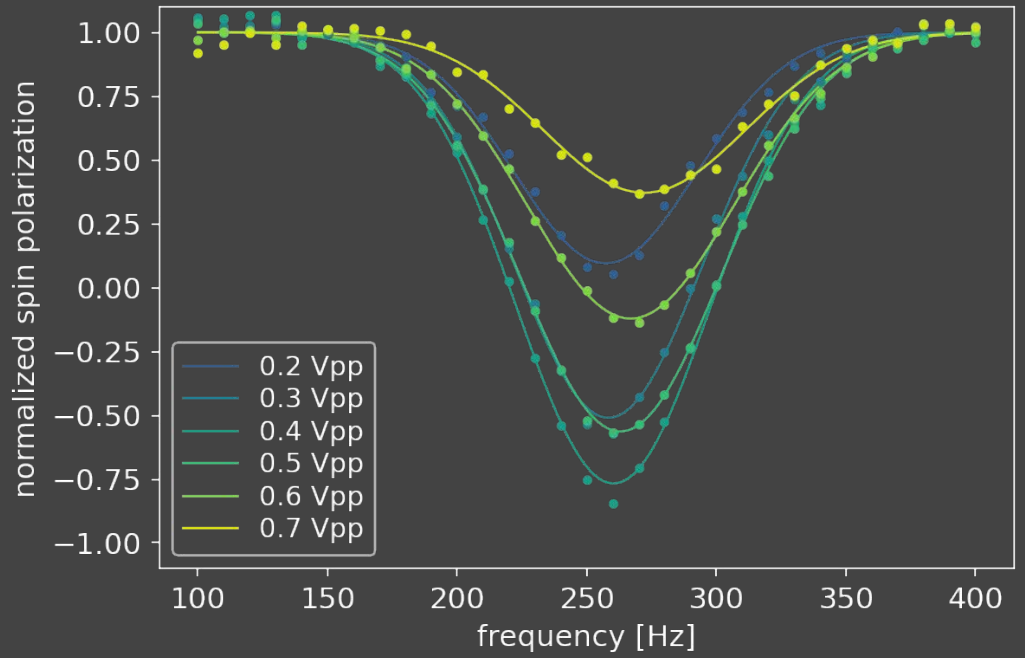
$\omega_0 = -\gamma B_0$

$\omega_1 = -\gamma B_1$

$$\delta\omega = \frac{\omega_1^2}{4\omega_0}$$

Measurement of Resonance Effects

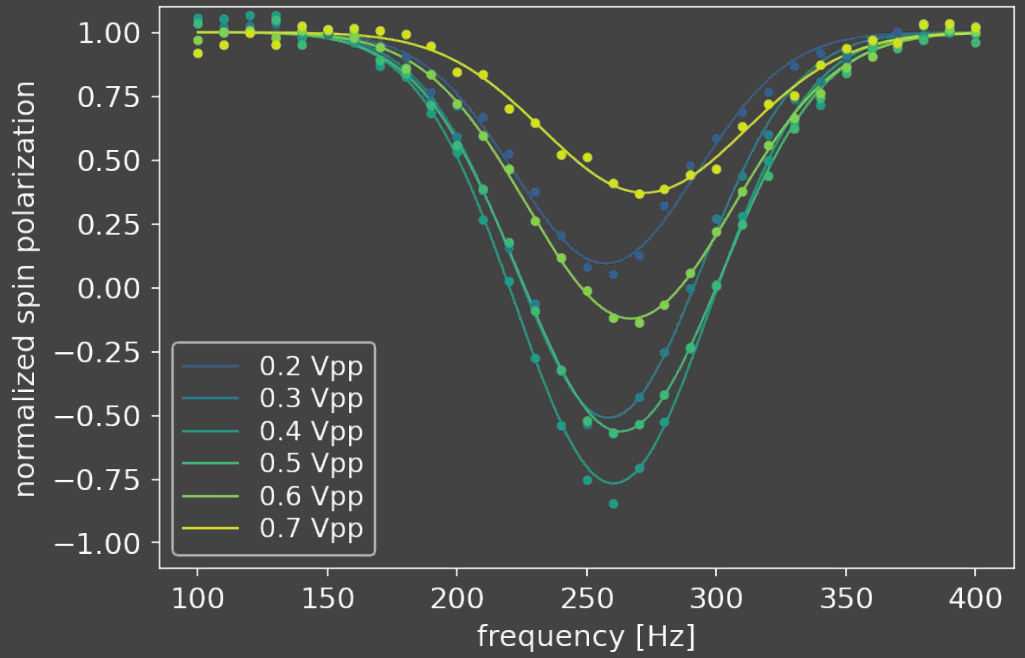
Bloch-Siegert Shift



- $\delta\omega = \dfrac{\omega_1^2}{4\omega_0}$
- can be compensated using additional RF signals

Measurement of Resonance Effects

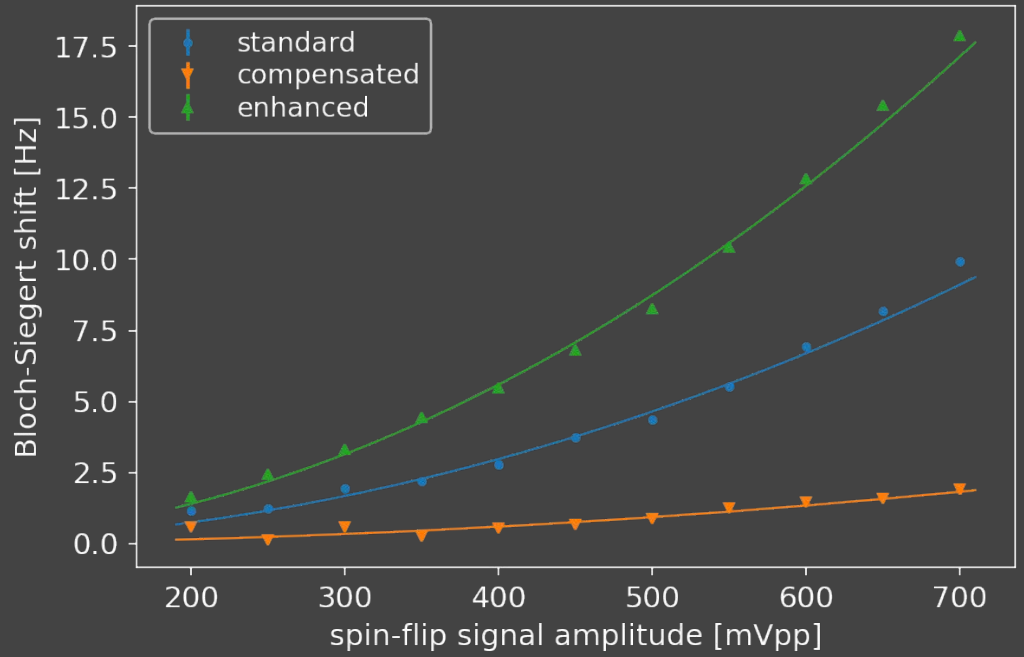
Bloch-Siegert Shift



$$\delta\omega = \frac{1}{2}\left(\frac{\omega_1^2}{2\omega_0} + \frac{(a\omega_1)^2}{\omega_0(1-b)} + \frac{(a\omega_1)^2}{\omega_0(1+b)}\right)$$
$$= \frac{1}{4}\frac{\omega_1^2}{\omega_0}\left(1 - \frac{4a^2}{b^2-1}\right)$$

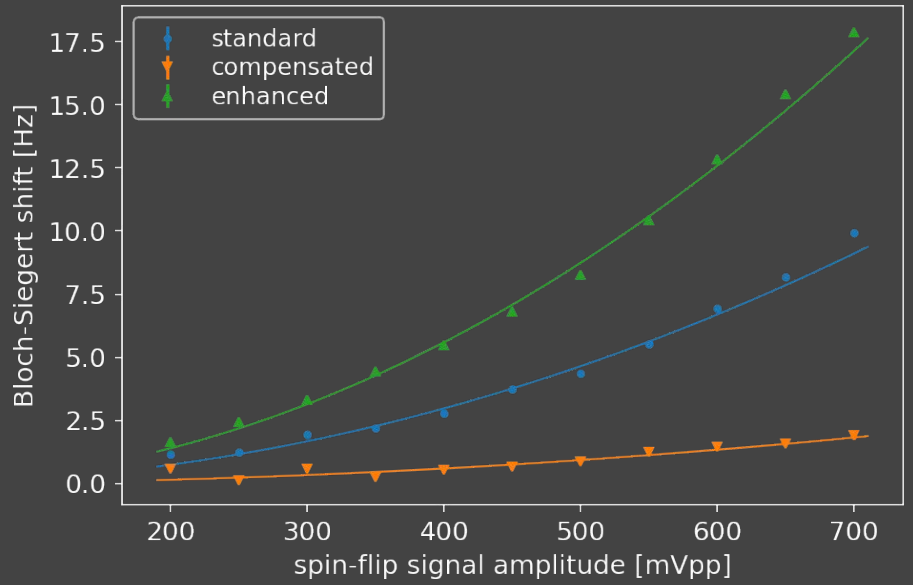
Measurement of Resonance Effects

Bloch-Siegert Shift Results



Exotic Interaction and Resonance Effects

Conclusion



- developed and built the *Proton NMR* apparatus
- performed proof-of-principle search for exotic Yukawa-like interaction
- investigated the Bloch-Siegert shift and its compensation and enhancement
- improved setup currently under development

Fundamental Neutron and Precision Physics

Acknowledgments