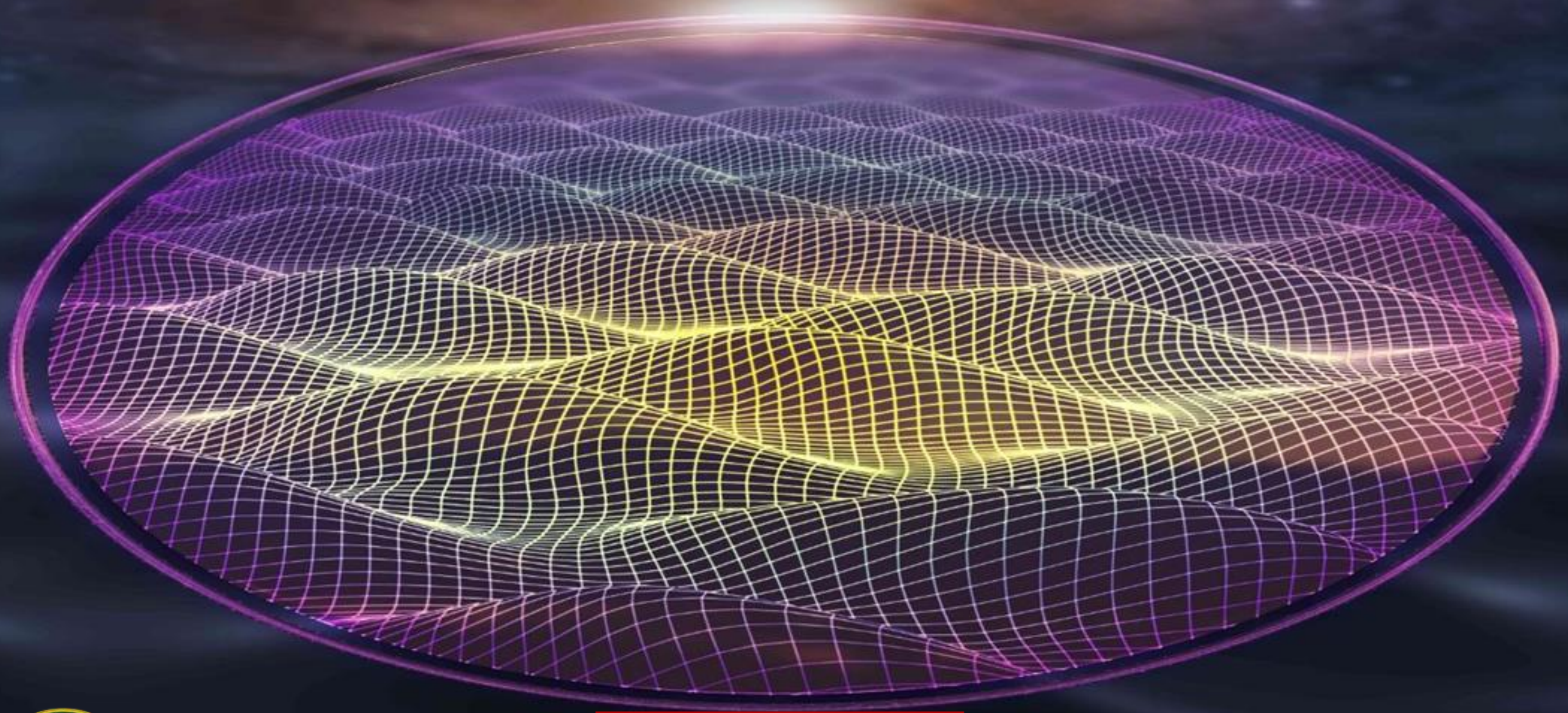
Searching for axion-like dark matter with precision NMR: the Cosmic Axion Spin Precession Experiments

Alex Sushkov (CASPEr collaboration)



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Department of Energy, United States of America
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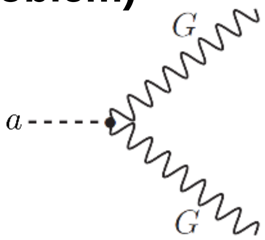
Searching for interactions of axions and axion-like particles

1. Proposed to solve the **strong CP problem** of Quantum Chromodynamics [Phys. Rev. Lett. **38**, 1440 (1977)]
2. Well-motivated and thoroughly-studied **dark matter** candidate: $a(t) \approx a_0 \cos \omega_a t$
3. 3 possible (non-gravitational) interactions with standard model particles:

defining QCD axion interaction with gluons: (solves strong-CP problem)

axion field amplitude → $\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$ ← symmetry breaking scale



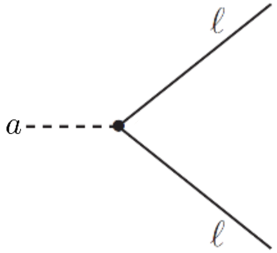
$$\mathcal{H}_{\text{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ nuclear spin $\boldsymbol{I}$ interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of effective electric field $\boldsymbol{E}^*$.

CASPEr-electric

interaction with fermions:

$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

→ nuclear spin $\boldsymbol{I}$ interacts with an effective magnetic field $\boldsymbol{\nabla} a$.

co-magnetometers
force mediator → ARIADNE
electron spin → QUAX

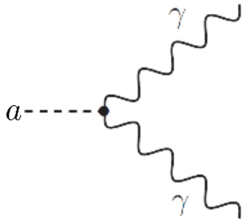
CASPEr-gradient

CASPEr (Cosmic Axion Spin Precession Experiments) search for experimental signatures of these interactions using precision magnetic resonance

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]
[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]
[A. Garcon et al., Sci. Adv. **5**, eaax4539 (2019)]

interaction with photons:

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ ALP ↔ electromagnetic field mixing
→ precision electromagnetic sensors

ADMX, HAYSTAC, DMradio, SHAFT, ABRA, ALPS, CAST, IAXO, CAPP, ORGAN, BREAD, SLIC, LC circuit, MADMAX, KLASH, BRASS, many others

SHAFT → a kHz-MHz search using SQUIDs and ferromagnetic toroidal cores

[A.Gramolin et al., *Nature Physics* **17**, 79 (2021)]

Searching for interactions of axions and axion-like particles

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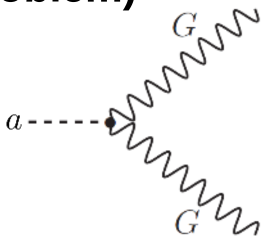

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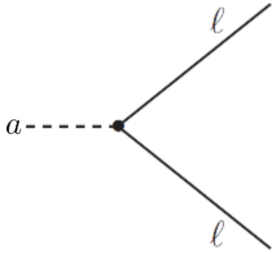

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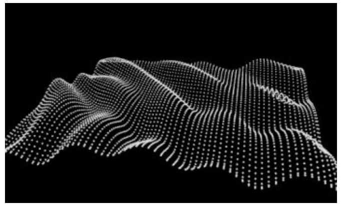
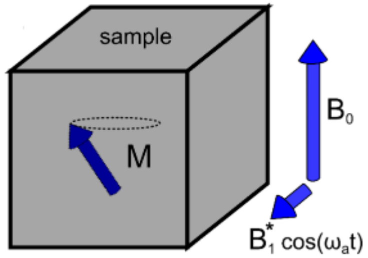


axion-like field

+



spin ensemble acts as the transducer

+

electromagnetic sensor measures spin ensemble evolution

flexibility to optimize spin ensemble parameters to optimize transducer efficiency → maximize sensitivity

Searching for axionic coupling to spin with magnetic resonance

effective interaction: $\mathcal{H}_{\mathrm{CASPEr}} = -(\hbar\gamma_I \boldsymbol{B}_1^* \cos\omega_a t)\cdot \boldsymbol{I}$

$$\mathcal{H} = -\hbar\gamma_I \boldsymbol{B}_0 \cdot \boldsymbol{I} - (\hbar\gamma_I \boldsymbol{B}_1^* \cos\omega_a t)\cdot \boldsymbol{I}$$

- constant bias magnetic field $\boldsymbol{B}_0$
- spin-axion interaction plays the role of the RF field $\boldsymbol{B}_1$

1) placing a spin-1/2 into an external magnetic field splits the spin states by $\gamma_I B_0$

2) spin polarization (thermal or optical) in a cm^3 sample

3) resonance: $\omega_a = \gamma_I B_0$

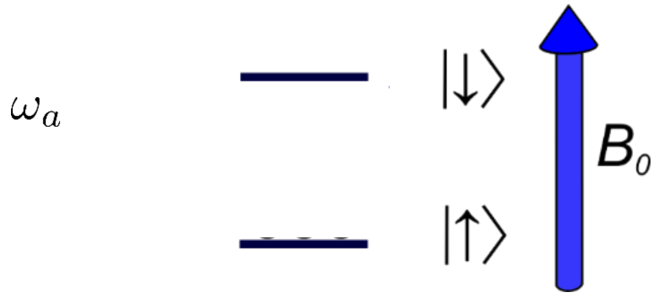
- ⇨ axion-spin interaction can now flip spins!
- ⇨ sample magnetization tilts and precesses

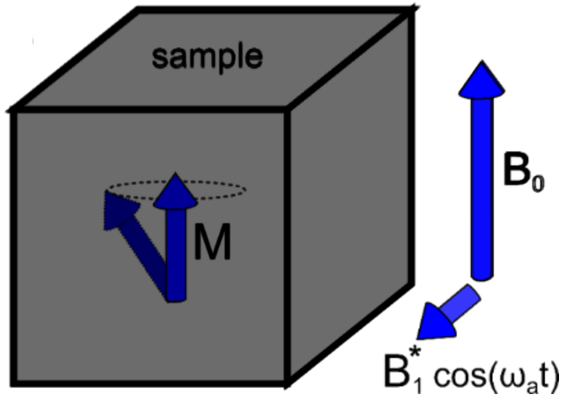
4) a magnetometer next to the sample detects the magnetic field created by this precessing magnetization

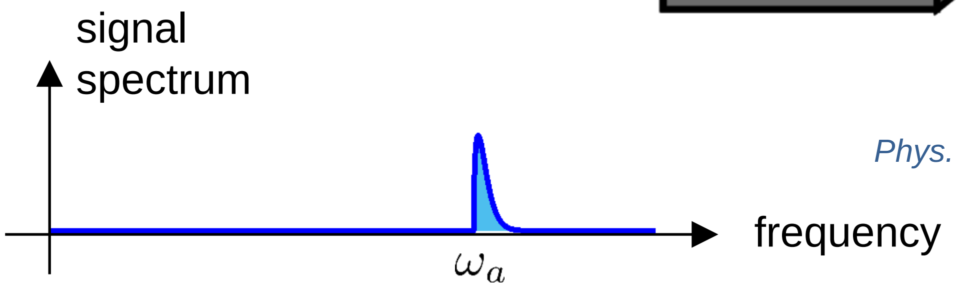
5) search for unknown frequency ω_a by sweeping bias magnetic field B_0, look for resonance

⇩

an NMR experiment with no RF magnetic field, instead axion-like dark matter flips spins







[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]

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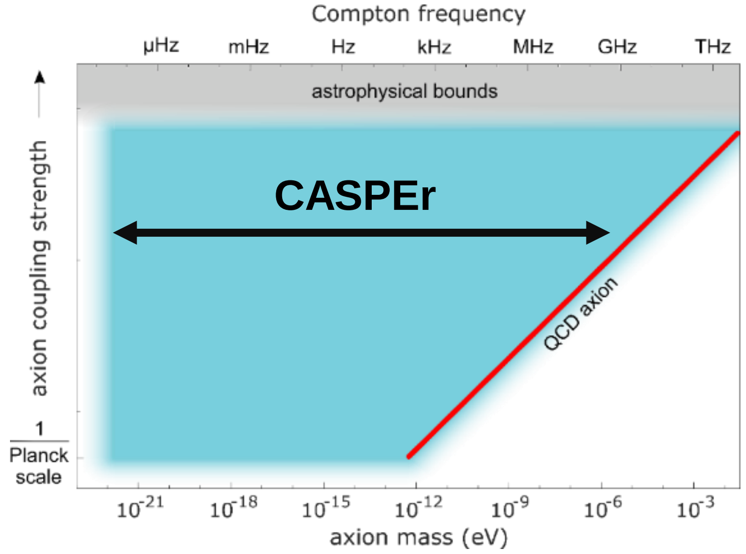
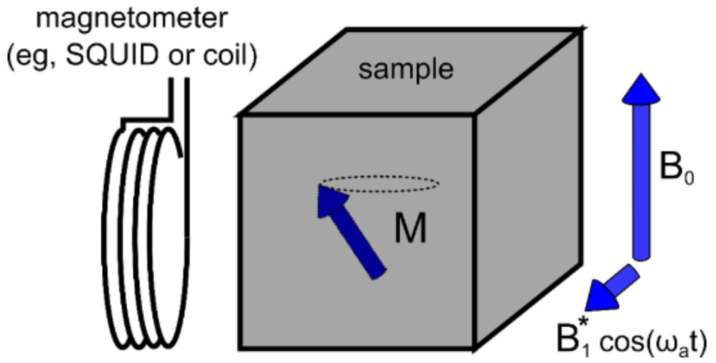




ultimate goal: QCD axion

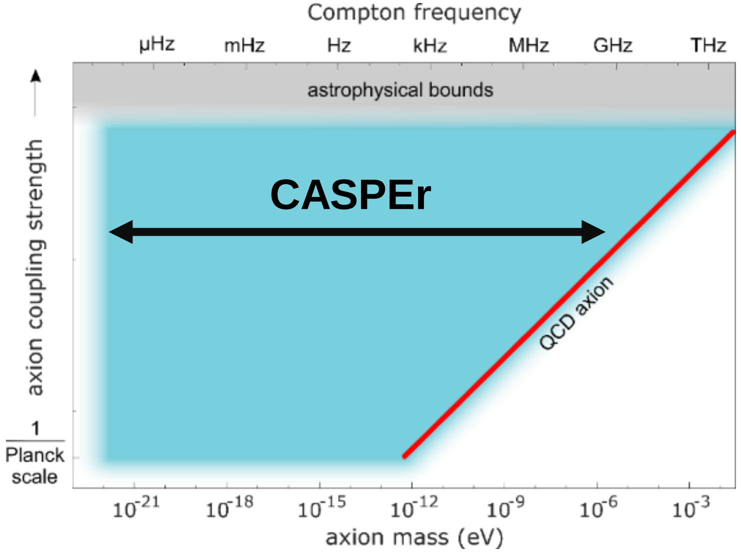
$$B_1^* \approx 10^{-20}\,\mathrm{T}$$
$$\gamma_I B_1^* \approx 10^{-13}\,\mathrm{rad/s}$$
$$\gamma_I B_1^* T_2 \approx 10^{-15}\,\mathrm{rad}$$

in SHAFT we achieved sensitivity $\approx 10^{-18}\,\mathrm{T}$

[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]

CASPEr program

Boston University:
CASPEr-electric using spins in solids
→ sensitive to both $\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$
$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$



Mainz:
CASPEr-gradient using hyperpolarized liquids
→ sensitive to $\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$

Janos Adam
Stephen Kuenstner
Glenn Randall
Andrew Winter
Tanja Maric

Hendrik Bekker
Arne Wickenbrock
Yuzhe Zhang
John Blanchard
Deniz Aybas

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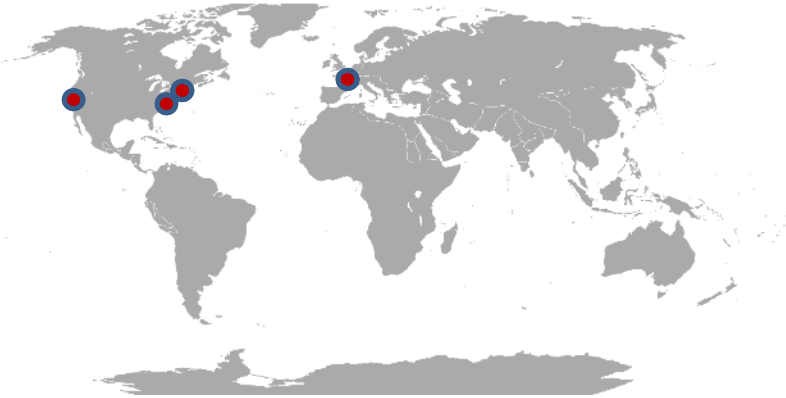
HIM Helmholtz-Institut Mainz
GORDON AND BETTY MOORE FOUNDATION
Alfred P. Sloan FOUNDATION
Deutsche Forschungsgemeinschaft DFG



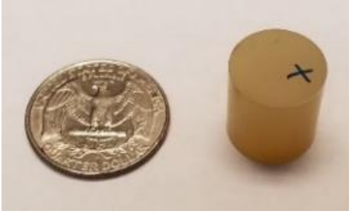
Dmitry Budker, Peter Graham, Derek Kimball, Surjeet Rajendran, Alex Sushkov

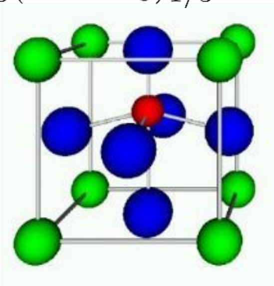
Millimeter-scale CASPEr-e axion-like dark matter search

sample: 4mm

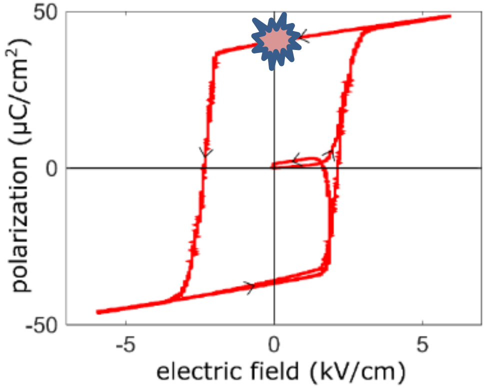
^{207}Pb nuclear spins in ferroelectrically-polarized PMN-PT

$(PbMg_{1/3}Nb_{2/3}O_3)_{2/3}(PbTiO_3)_{1/3}$





3×10^{20} spins



$$E^* = 340\,\mathrm{kV/cm}$$

[*Phys. Rev. A* **72**, 34501 (2005)]

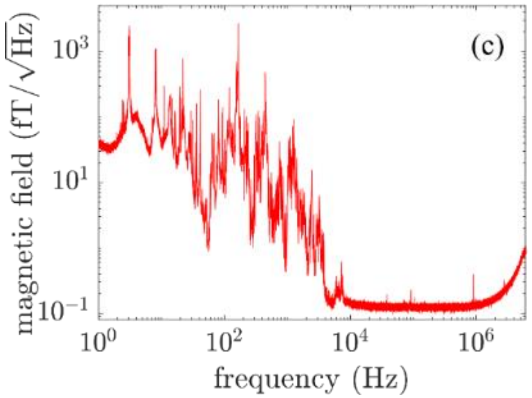
similar to a polar molecule

ACME [*Science* **343**, 269 (2013)]
[*Nature* **562**, 355 (2018)]

sensor:

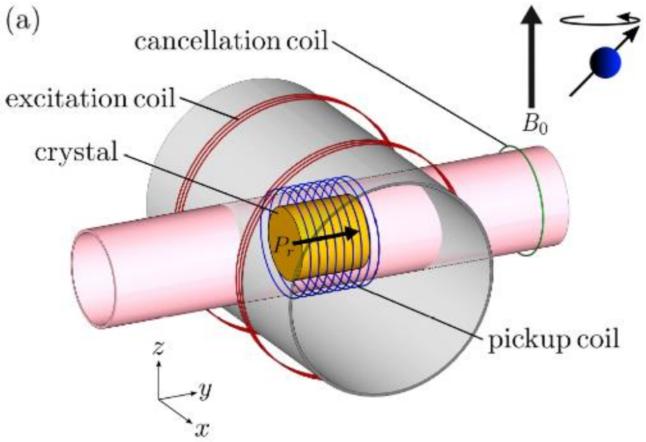
low-noise radiofrequency amplifier

SQUID



NMR calibration

crossed excitation and pickup coils



liquid helium (4 K) bath cryostat with 9T magnet

millimeter-scale CASPEr-e search based on nuclear magnetic resonance

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

Millimeter-scale CASPEr-e axion-like dark matter search

CASPEr-e limits on nucleon EDM and gradient interactions of axion-like dark matter

$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

→ limits on oscillation amplitudes of neutron EDM and θ_{QCD}:

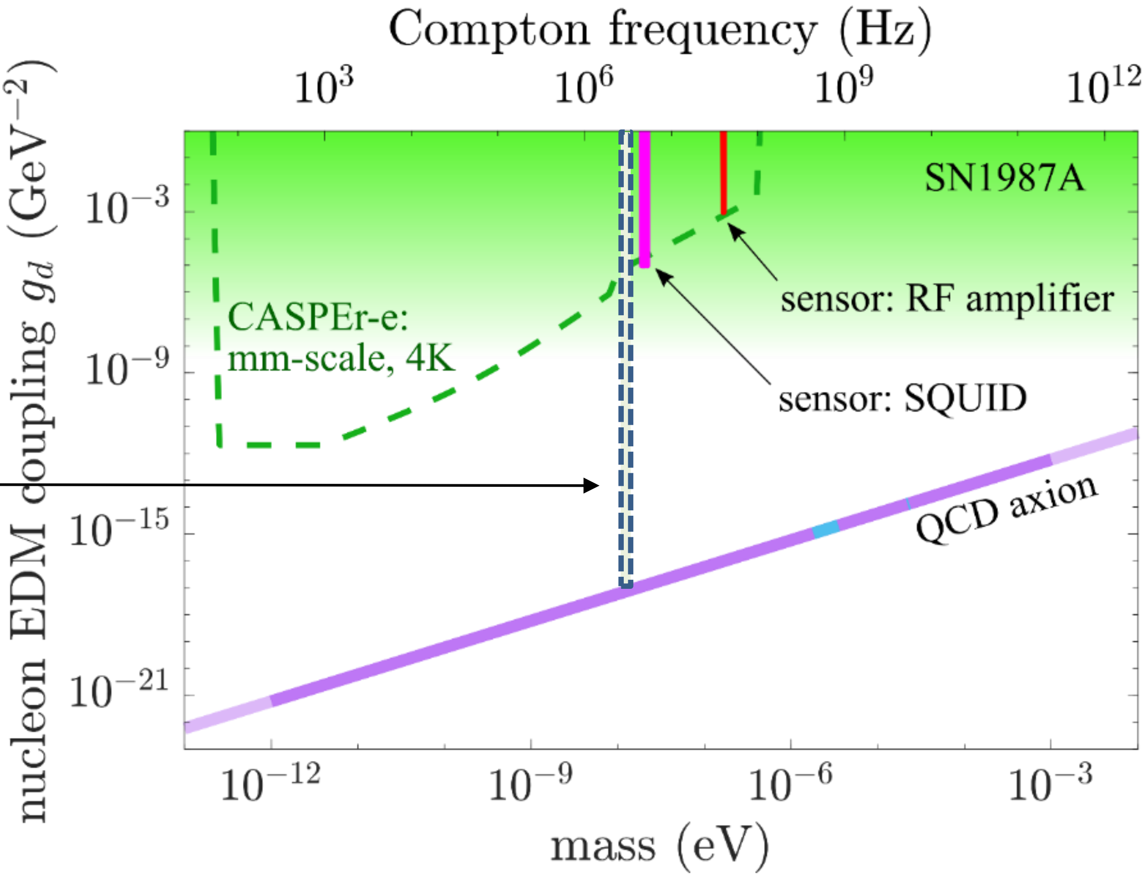
$$|d_n| < 1.0 \times 10^{-21}\ \mathrm{e \cdot cm}$$

$$|\theta| < 4.3 \times 10^{-6}$$

one possible path: scale up experimental volume

our next goal

our current approach: 1) optimize material properties
2) maximize sensitivity with resonant circuit



unique features of the magnetic resonance approach →

- <u>broad-band</u>: tune frequency by changing magnetic field (i.e. current) → can cover 4-5 decades in axion mass
- <u>flexible</u>: sensitivity can be improved by choice of material (→ *E**), as well as by scaling up the experimental volume
- <u>searching for QCD interaction</u>: this is the defining interaction of the QCD axion

our next goal:
reach QCD axion sensitivity with a cm-scale search:
1) resonant detection scheme in our dilution fridge
2) nuclear spin hyperpolarization

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Towards the centimeter-scale CASPEr-e QCD axion dark matter search

CASPEr-e limits on nucleon EDM and gradient interactions of axion-like dark matter

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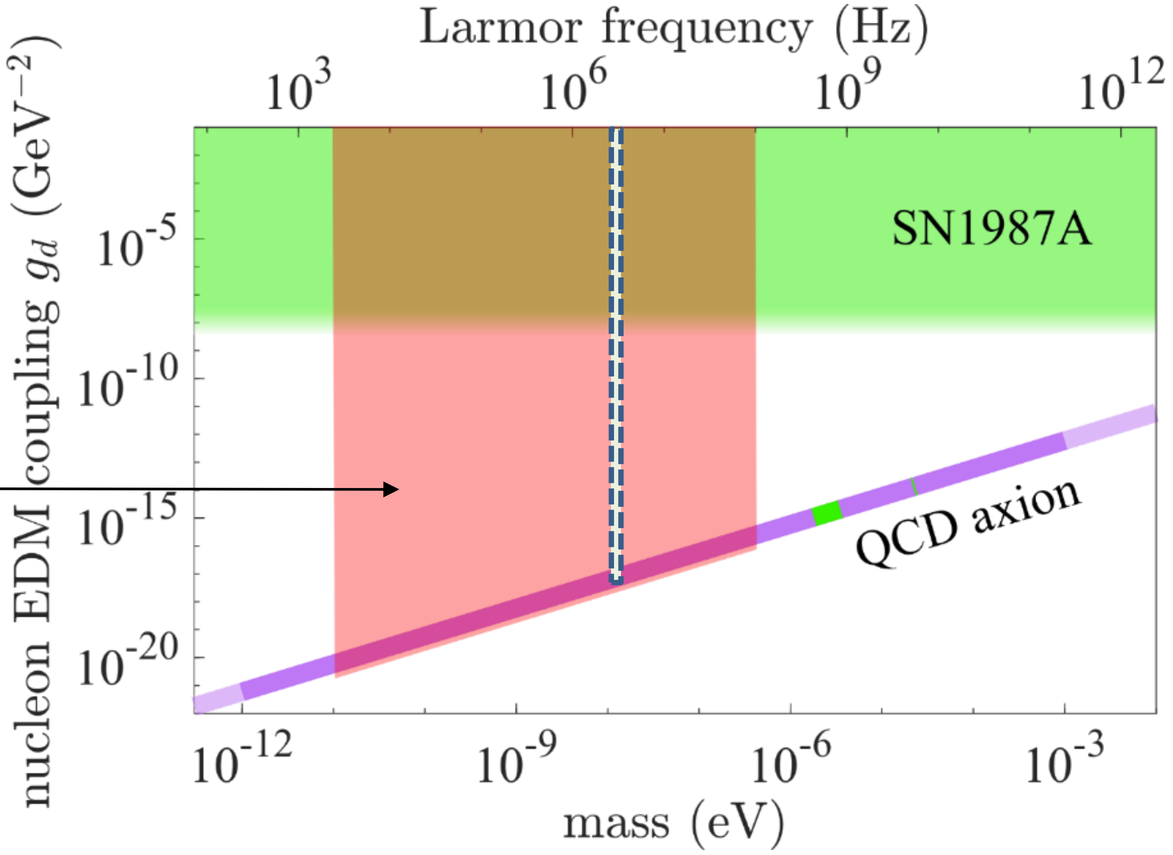
our long-term goal



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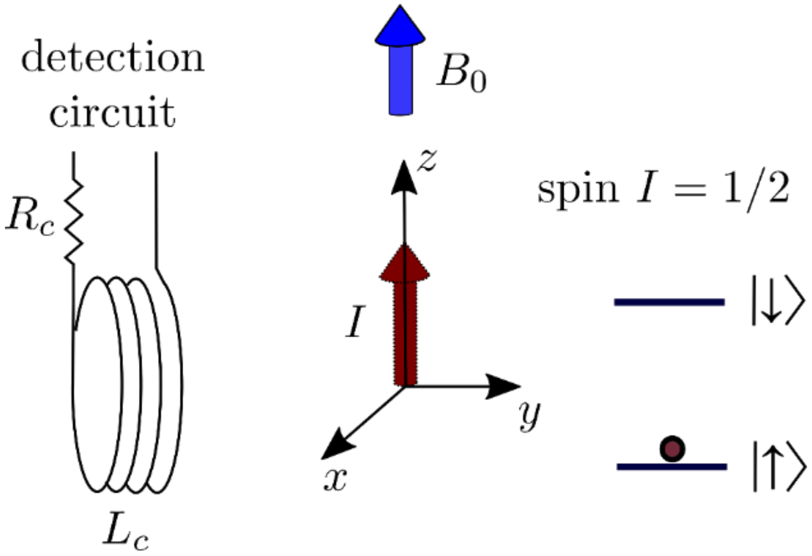
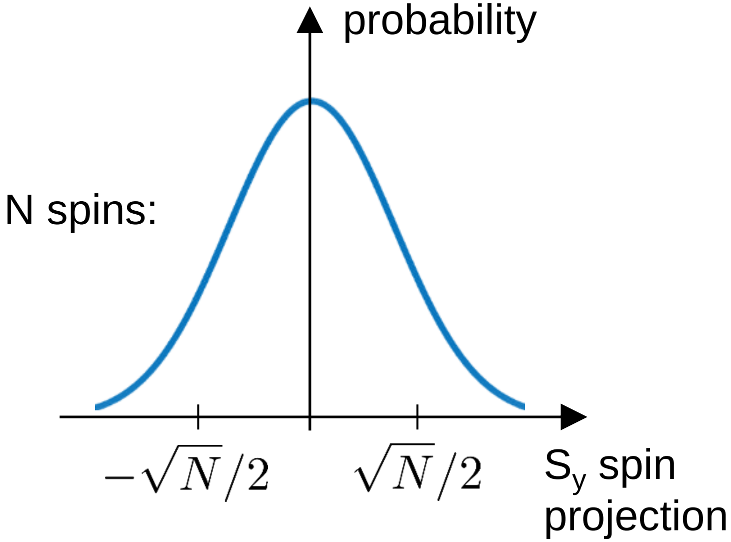
- flexible: sensitivity can be improved by choice of material (→ E^*), as well as by scaling up the experimental volume
- searching for QCD interaction: this is the defining interaction of the QCD axion

our long-term goal:
search for pre-inflationary QCD axion dark matter over multiple mass decades

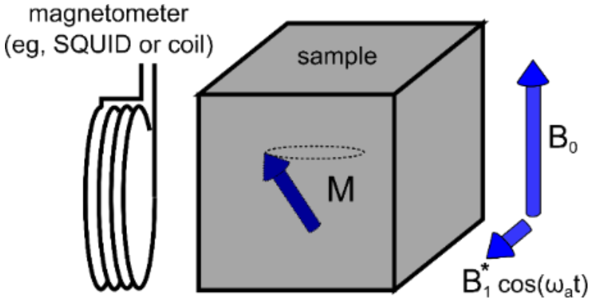
[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Fundamental quantum noise: spin projection noise (standard quantum limit)

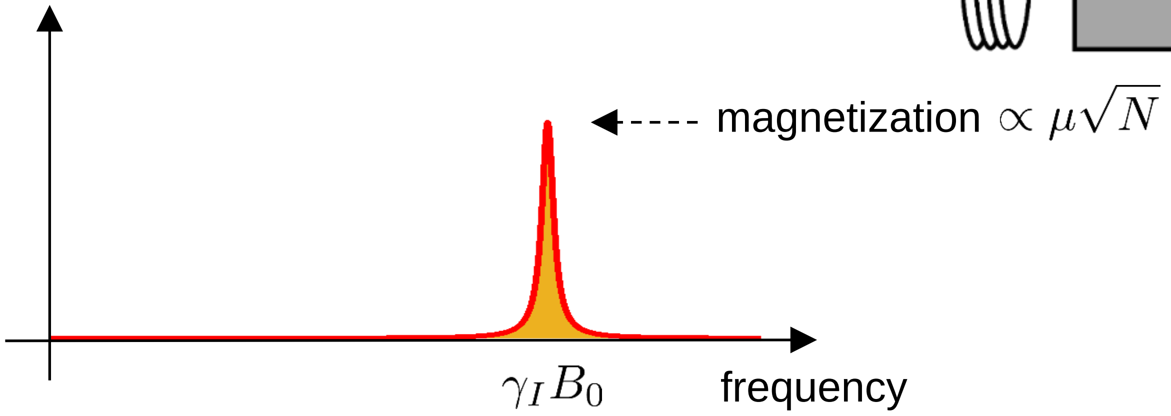




[F. Bloch, *Phys. Rev.* **7-8**, 460 (1946)]



detected spectrum with a <u>noiseless detection circuit</u>



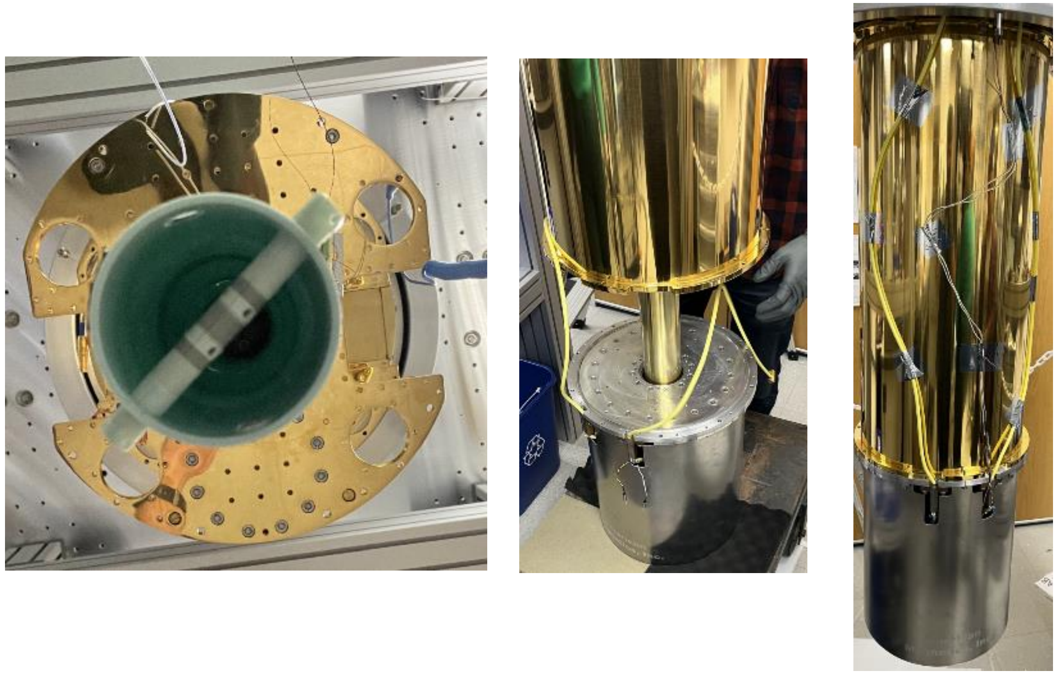
standard quantum limit (SQL): $\frac{\delta M_\perp}{M_0} \approx \frac{1}{\sqrt{N}}$ ◄--- spin projection measurement uncertainty

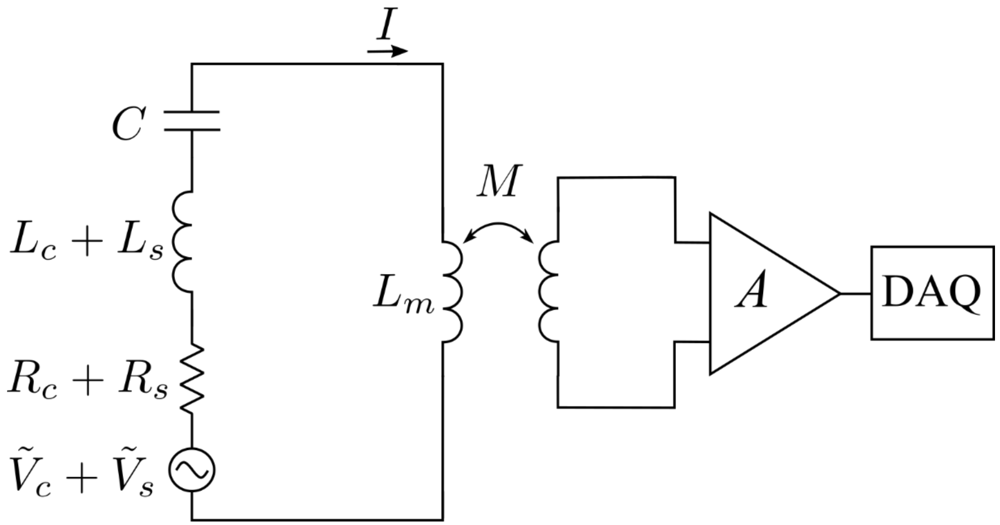
spin projection noise has been detected in NMR experiments

[T. Sleator et al., *Phys. Rev. Lett* **55**, 1742 (1985)]
[M.A. McCoy, R.R. Ernst., *Chem. Phys. Lett.* **159**.5, 587 (1989)]
[M. Gueron, J. L. Leroy., *J. Mag. Res.* **85**.1, 209 (1989)]

we are building CASPEr with sensitivity limited by spin projection noise

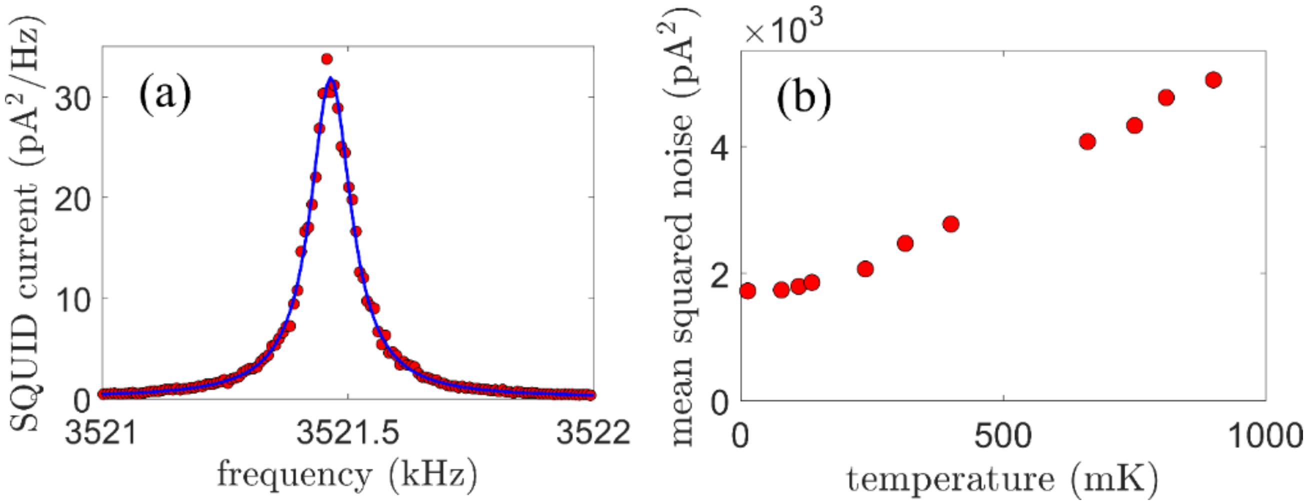
Boston CASPEr-electric search for the EDM coupling





- solid-state NMR apparatus in a dilution refrigerator
- spin projection noise-limited NMR search for axion-like dark matter

preliminary noise data:



condition for an experiment limited by spin projection noise:

$$\theta_c = 50\,\mathrm{mK}, \quad Q_c > 3 \times 10^4$$

[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]