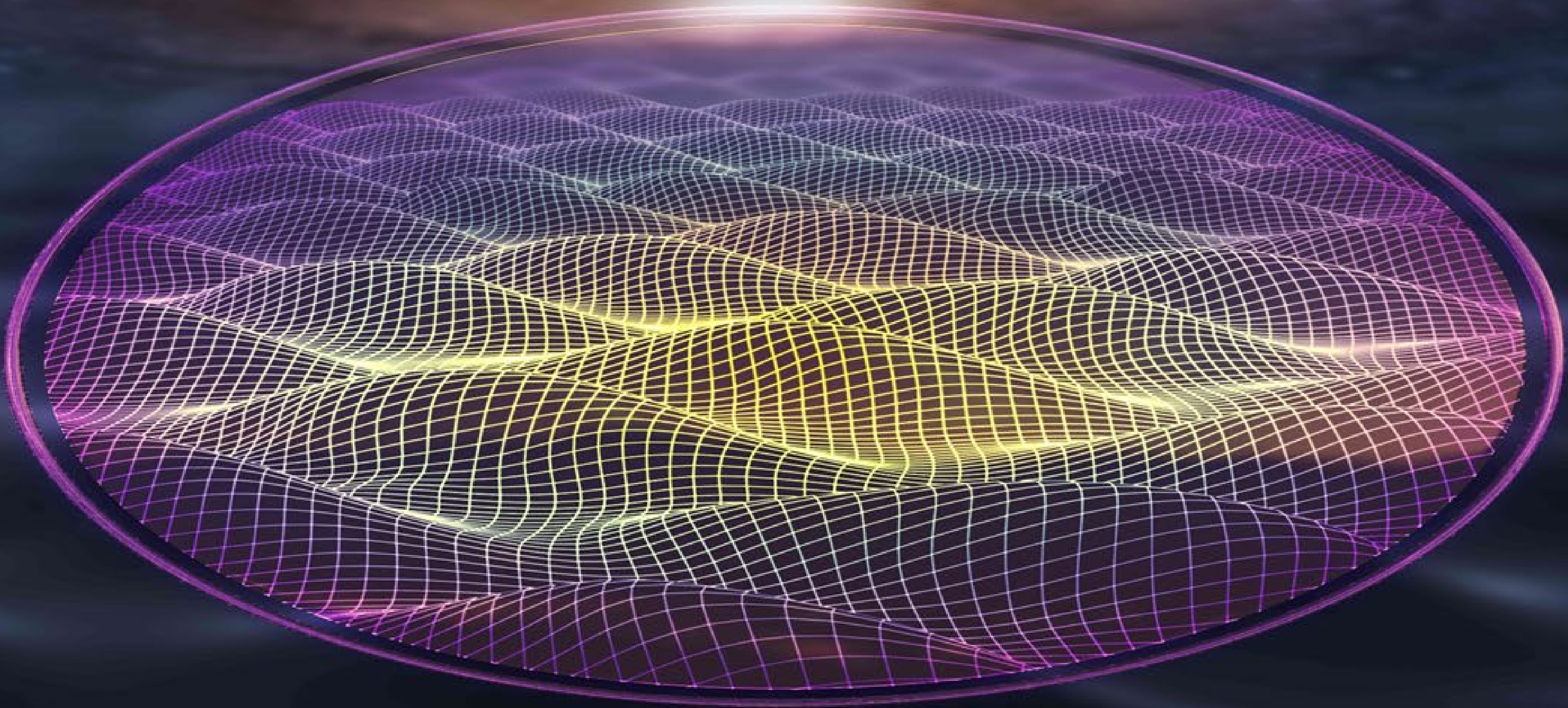
Searching for time-varying nuclear electric dipole moments using precision magnetic resonance

Alex Sushkov (for the CASPEr collaboration)



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Alfred P. Sloan FOUNDATION

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BOSTON UNIVERSITY

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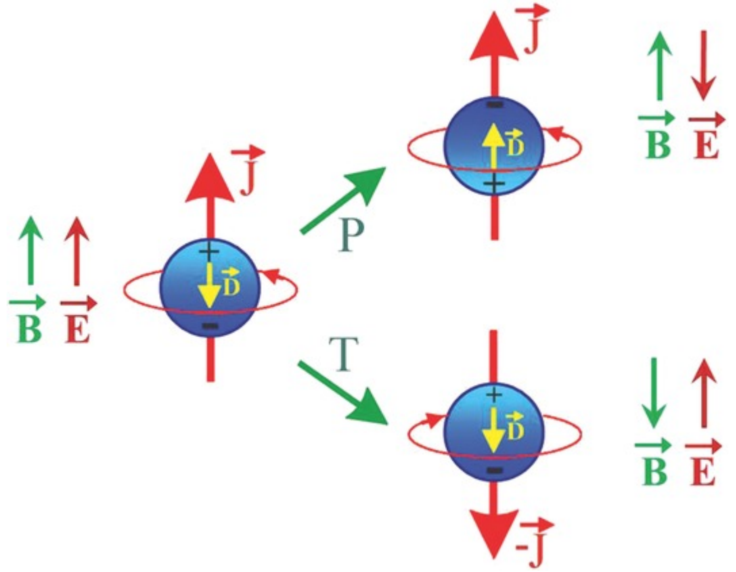
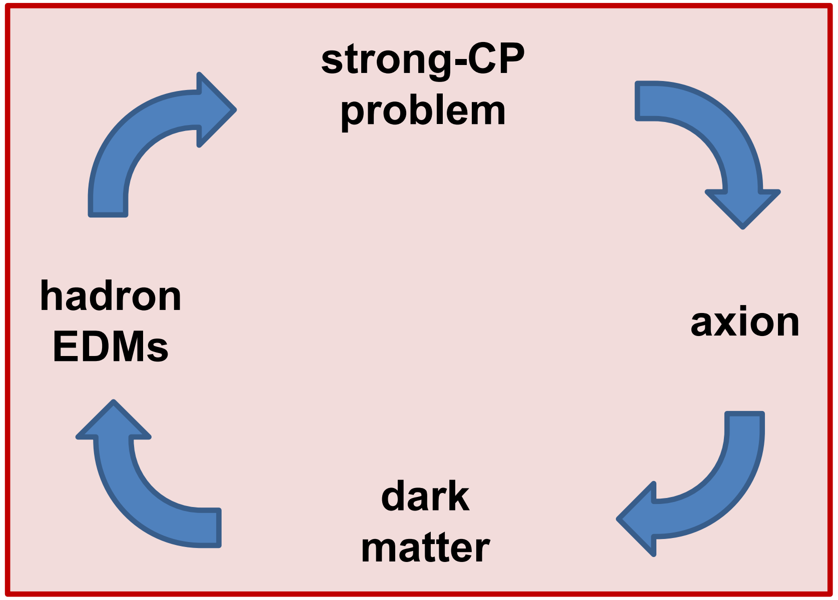
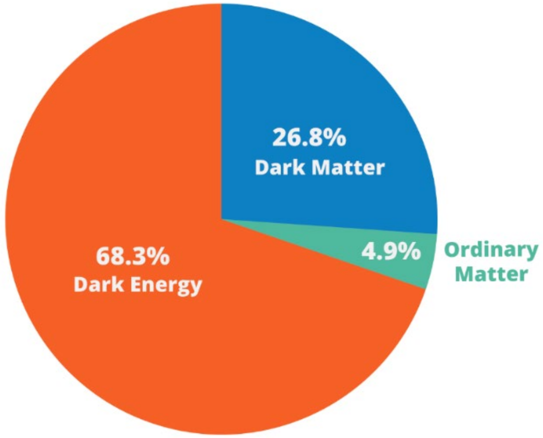
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

EDM, discrete symmetries, axions, and dark matter

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$







Axions and axion-like particles, axion-like dark matter

1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [Phys. Rev. Lett. **38**, 1440 (1977)]
3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken up to GUT (10^{16} GeV), Planck (10^{19} GeV) scales

axion-like dark matter

ALP mass range
$$m_a c^2 < \mathrm{meV}$$

+

dark matter energy density:
$$\rho_{\mathrm{DM}} \approx 0.4\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.05\,\mathrm{eV})^4$$

↓

large number of particles per de Bloglie wavelength

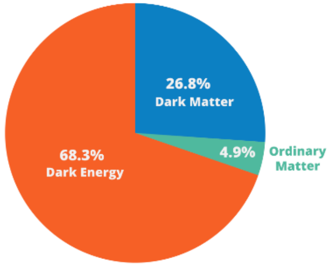
↓

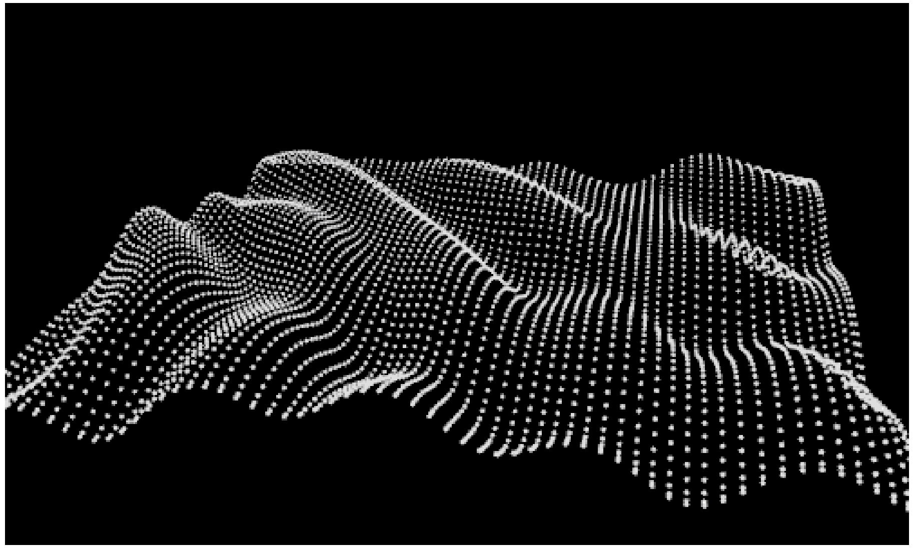
ALP dark matter acts as a classical field

axion-like field: $a(t) = a_0 \cos \omega_a t$

$\omega_a = m_a c^2/\hbar$ → ALP Compton frequency

$\rho_{\mathrm{DM}} \propto a_0^2$ → dark matter density





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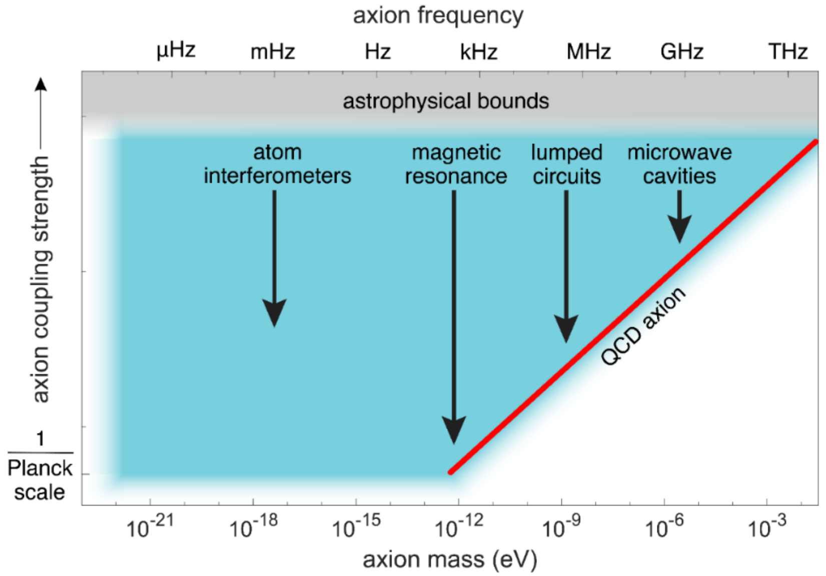
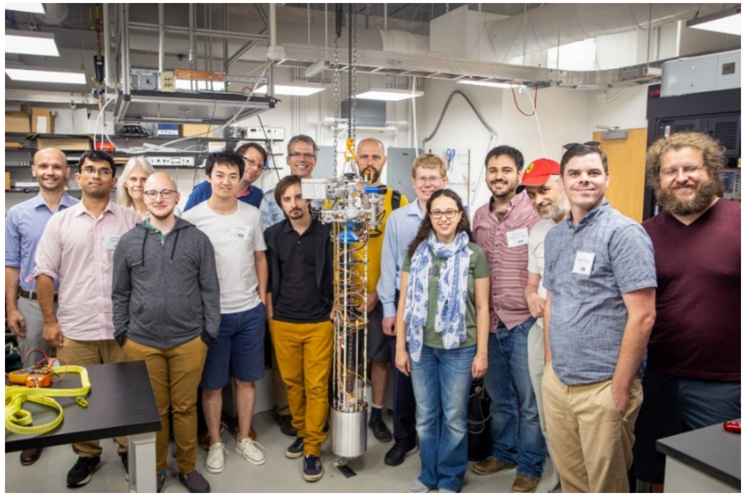
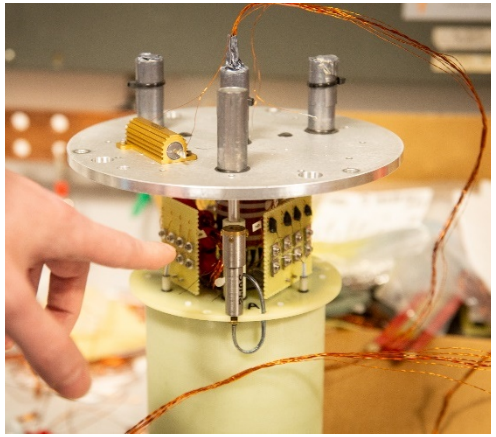


laboratory-scale experiments using quantum-limited sensors (and beyond)





[*DOE BRN report:* Dark Matter Small Projects, New Initiatives (2018)] [*DOE BRN report:* High Energy Physics Detector Research and Development (2020)] [*Science* **357**, 990 (2017)]

Axions and axion-like particles, axion-like dark matter

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

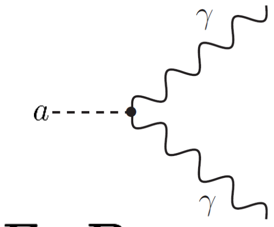
1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [Phys. Rev. Lett. **38**, 1440 (1977)]
3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken at GUT (10^{16} GeV) or Planck (10^{19} GeV) scales
4. Possible interactions with standard model particles:

interaction with photons:

ALP field amplitude → a

symmetry breaking scale → f_a

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



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

→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

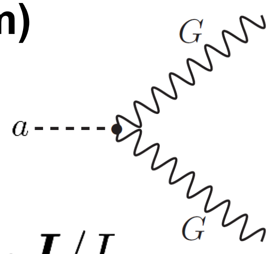
ADMX, HAYSTAC, DMradio, SHAFT, ABRA, ALPS, CAST, IAXO, CAPP, ORGAN, BREAD, SLIC, LC circuit, MADMAX, KLASH, BRASS, many others

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

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

interaction with gluons: (strong-CP problem)

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$



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

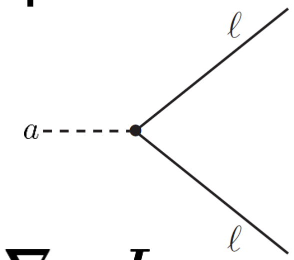
→ nuclear spin $\boldsymbol{I}$ interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of effective electric field $\boldsymbol{E}^*$.

CASPEr-electric

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

interaction with leptons:

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



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

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

force mediator → ARIADNE
electron spin → QUAX

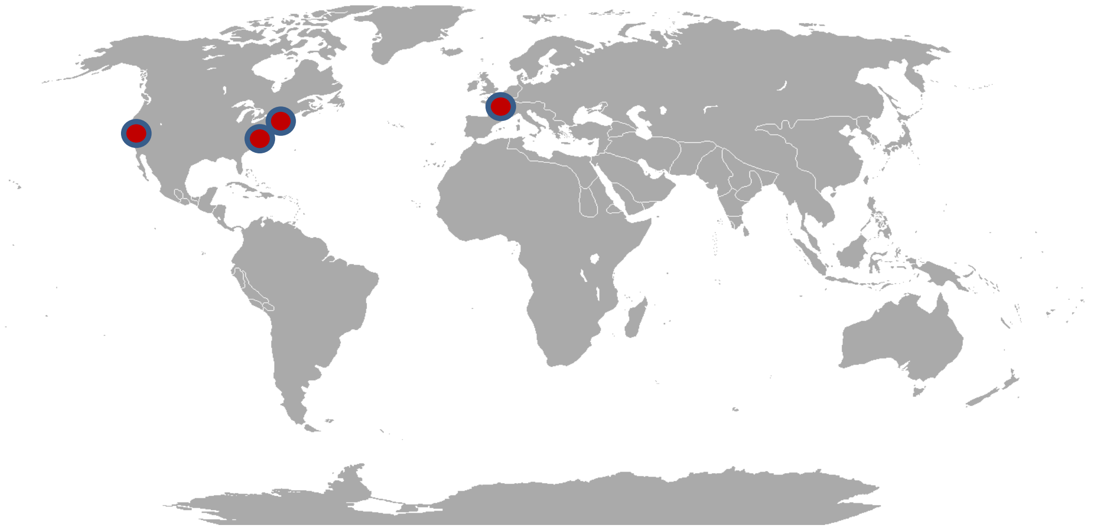
CASPEr-gradient

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

[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]
[A. Garcon et al., Sci. Adv. **5**, eaax4539 (2019)]

CASPEr program

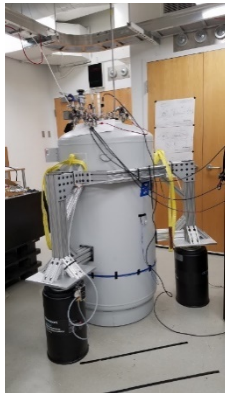
Deniz Aybas
Alex Wilzewski
Janos Adam
Sasha Gramolin
Dorian Johnson
Annalies Kleyheeg
Arne Wickenbrock
John Blanchard
Hendrik Bekker
Antoine Garcon
Gary Centers
Nataniel Figueroa
Marina Gil Sendra
Teng Wu
Alfredo Ferella
Matthew Lawson



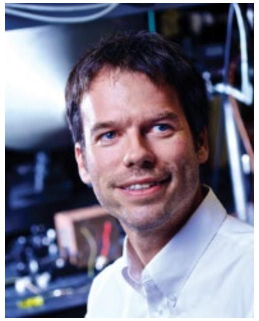
Dmitry Budker
Peter Graham
Derek Kimball
Surjeet Rajendran
Alex Sushkov

Alfred P. Sloan Foundation
Heising - Simons Foundation
Simons Foundation
erc
Deutsche Forschungsgemeinschaft DFG
HIM Helmholtz-Institut Mainz

Boston University: CASPEr-electric using spins in solids

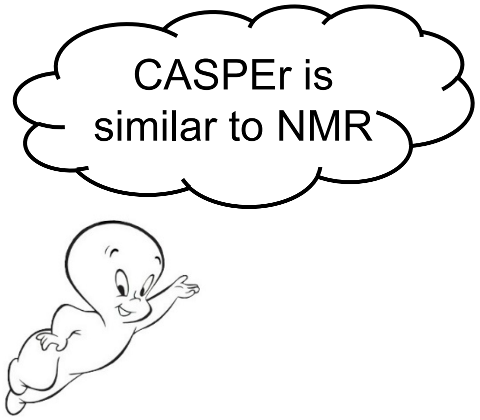



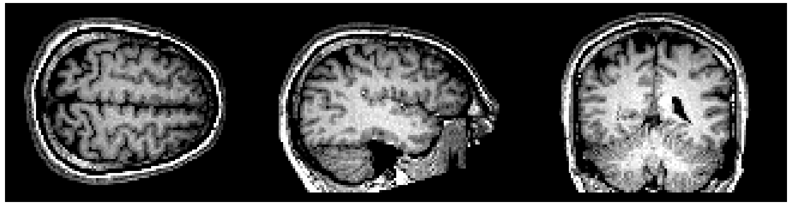




Mainz: CASPEr-gradient using hyperpolarized liquids


Aside: magnetic resonance





a very useful tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

Aside: magnetic resonance

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

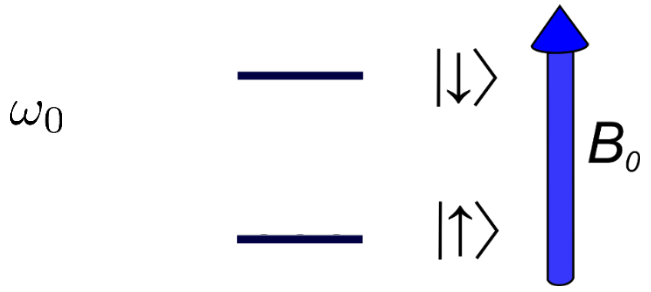
CASPEr is similar to NMR

(nuclear gyromagnetic ratio)

interaction: $\mathcal{H}_{\rm NMR} = -\hbar\gamma_I \boldsymbol{B} \cdot \boldsymbol{I}$

$$\mathcal{H}_{\rm NMR} = -\hbar\gamma_I \boldsymbol{B}_0 \cdot \boldsymbol{I} - \hbar\gamma_I (\boldsymbol{B}_1 \cos\omega_0 t) \cdot \boldsymbol{I}$$

- constant bias magnetic field $\boldsymbol{B}_0$
- radiofrequency (RF) magnetic field $\boldsymbol{B}_1 \cos\omega_0 t$

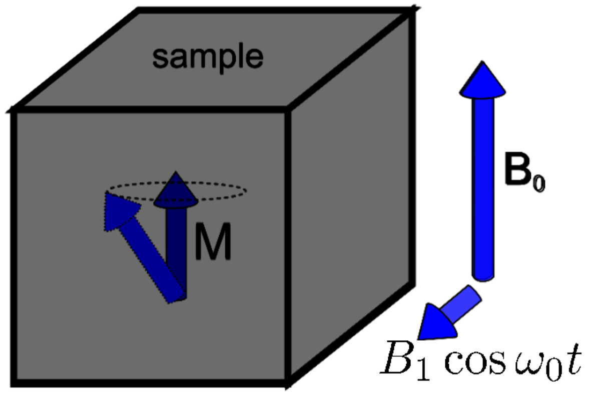


1) place a spin-1/2 into an external magnetic field splits the spin states by $\gamma_I B_0$

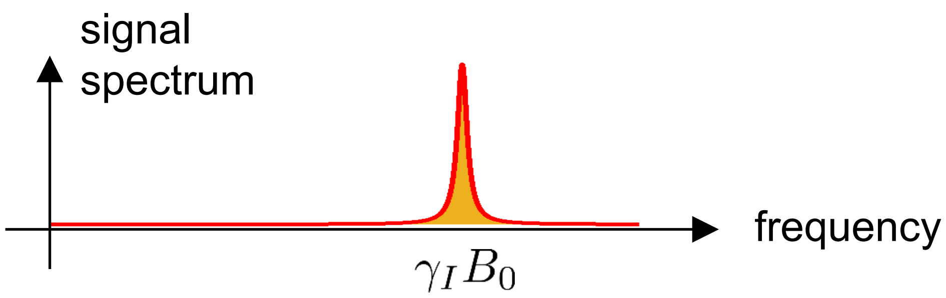
2) spin polarization (thermal or optical) in a cm^3 sample

3) resonance: $\omega_0 = \gamma_I B_0$

- RF magnetic field 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



a very useful tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

Axion-like dark matter → pseudo-magnetic field

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

CASPEr-electric

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

CASPEr-gradient

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

axion (or ALP) field

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

$\omega_a = m_a c^2/\hbar$ → ALP Compton frequency

$\rho_{\mathrm{DM}} \propto a_0^2$ → dark matter density

$$\mathcal{H}_{\mathrm{EDM}} = (g_d a_0 \boldsymbol{E}^* \cos\omega_a t) \cdot \boldsymbol{I}/I$$

$$\mathcal{H}_{aNN} = (g_{aNN} \boldsymbol{\nabla} a_0 \cos\omega_a t) \cdot \boldsymbol{I}$$

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

effective magnetic field due to ALP dark matter

oscillating at ALP Compton frequency

nuclear spin

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

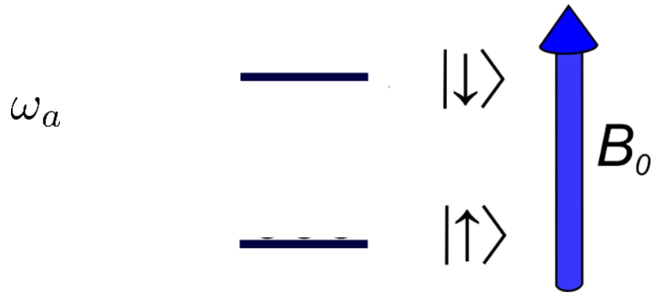
Searching for axionic coupling to spin with magnetic resonance

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

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

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

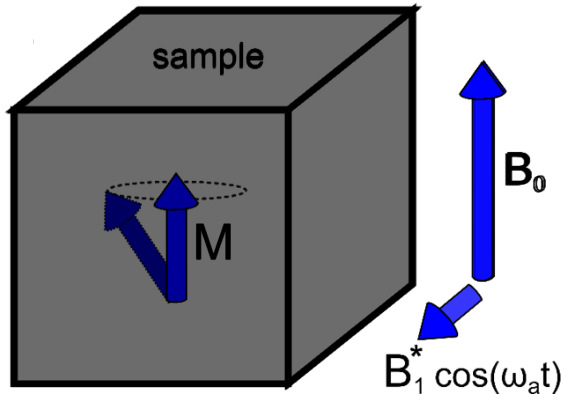
1) placing a spin-1/2 into an external magnetic field splits the spin states by $\gamma_I B_0$



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

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

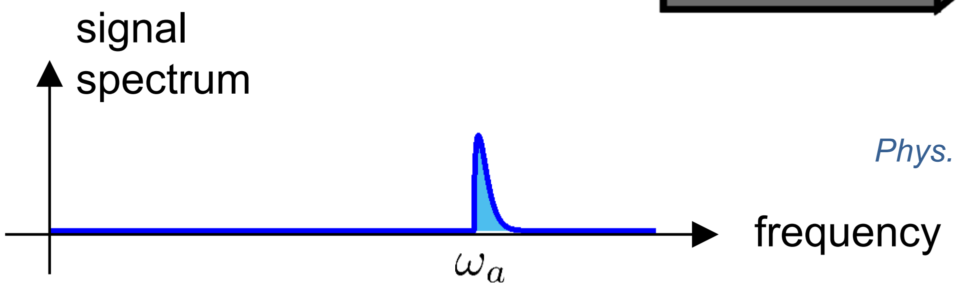
- axion-spin interaction can now flip spins!
- sample magnetization tilts and precesses



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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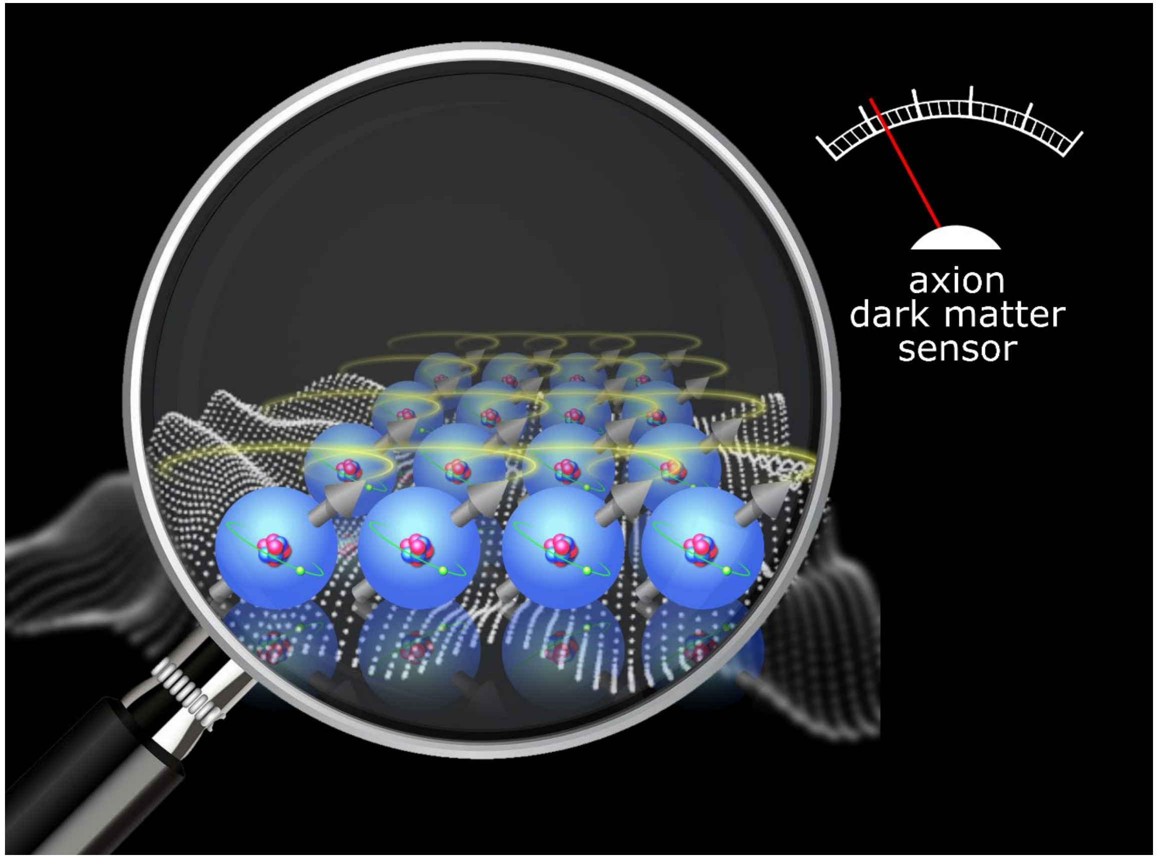
⬇

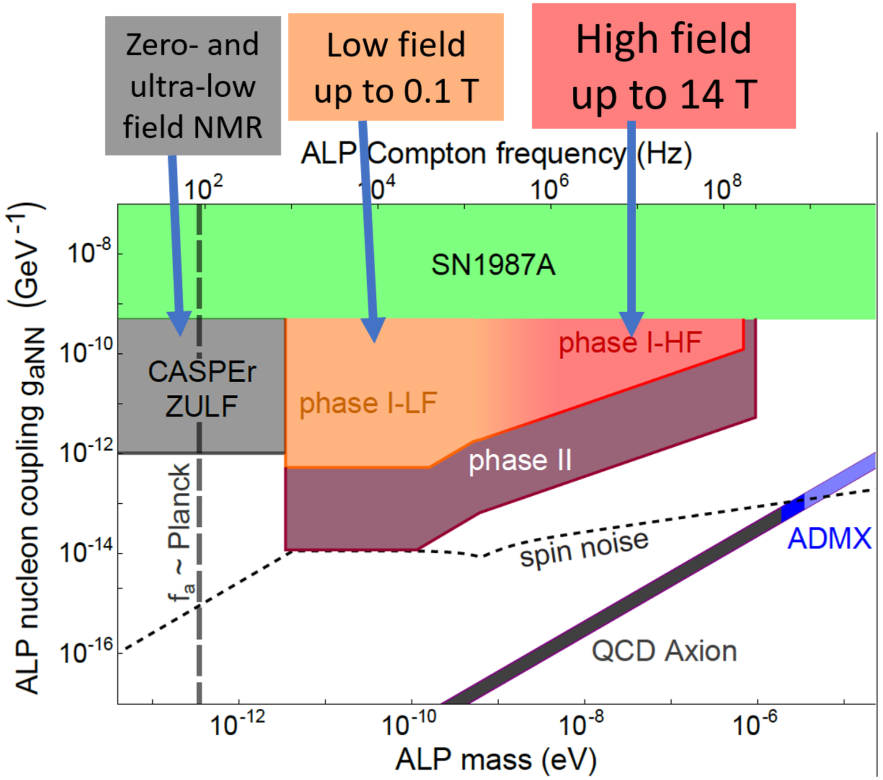
an NMR experiment with no RF magnetic field, instead axion-like dark matter flips spins



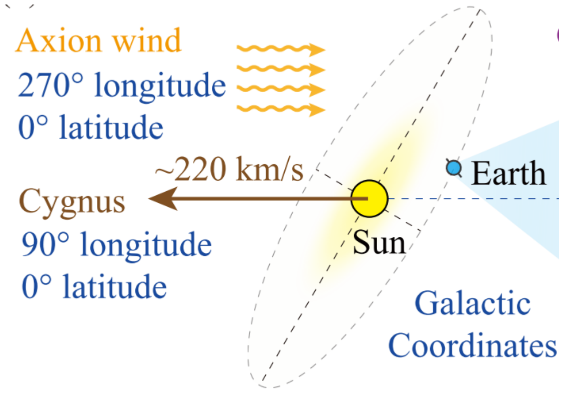
[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]

CASPEr-gradient

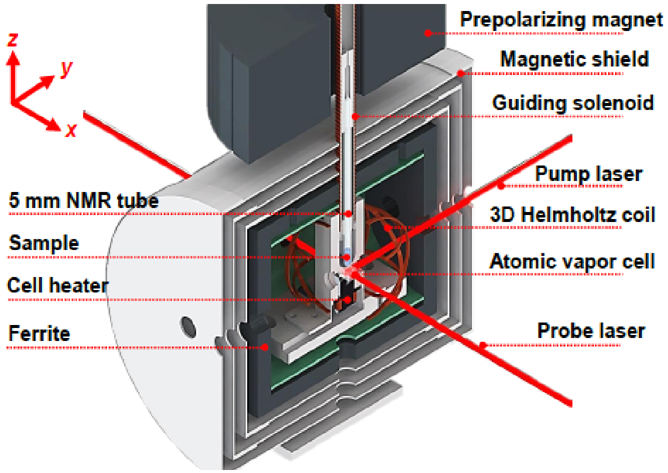
led by Dima Budker's group
(JGU Mainz & UC Berkeley)



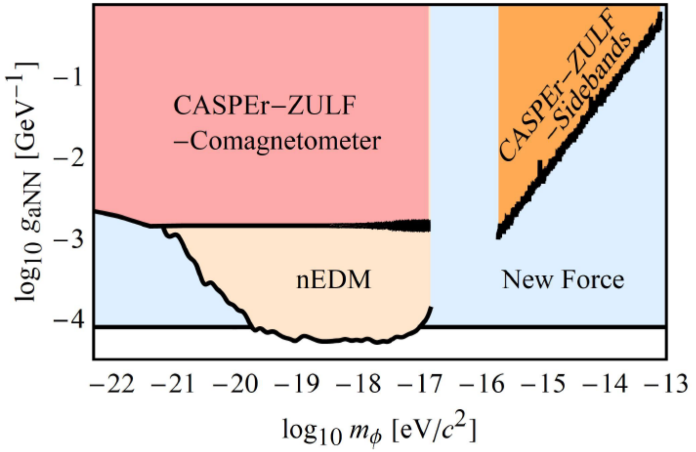
$$\vec{B}_1^* \propto \vec{\nabla} a$$

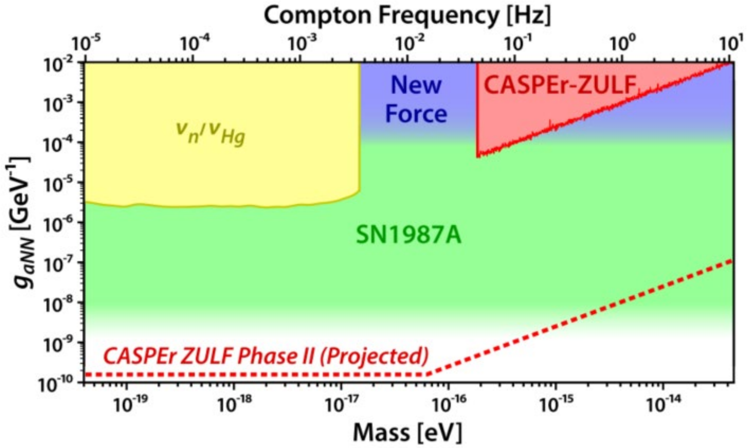


CASPEr-ZULF: axion-gradient search using existing infrastructure + ^{13}C-enriched formic acid



recent experimental limits:

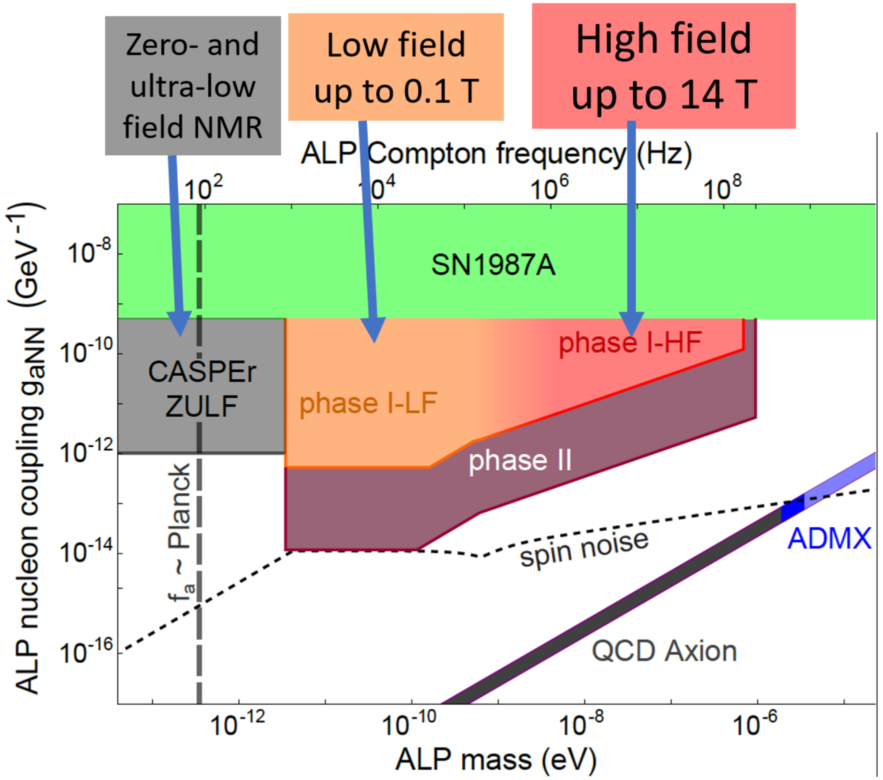




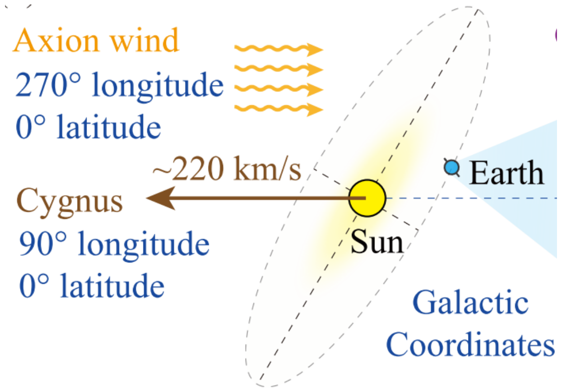
[T. Wu et al., *Phys. Rev. Lett.* **122**, 191302 (2019)]
[A. Garcon et al., *Science Adv.* **5**, eaax4539 (2019)]
[G. Centers et al., *arXiv: 1905.13650* (2019)]

CASPEr-gradient

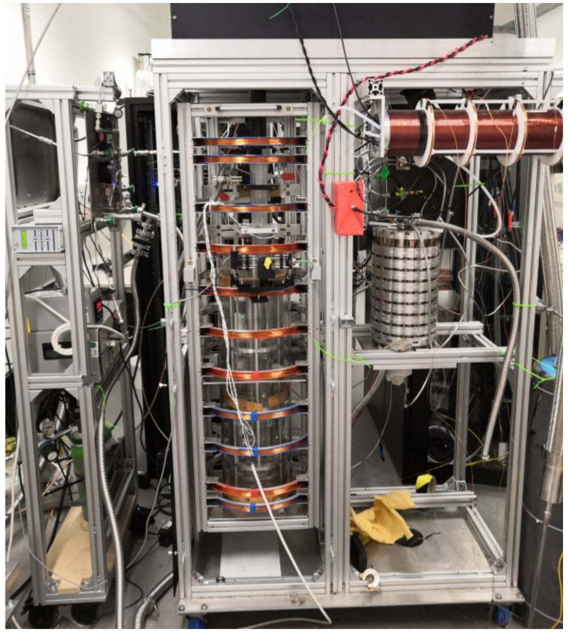
led by Dima Budker's group
(JGU Mainz & UC Berkeley)



$$\vec{B}_1^* \propto \vec{\nabla} a$$



ongoing experimental work



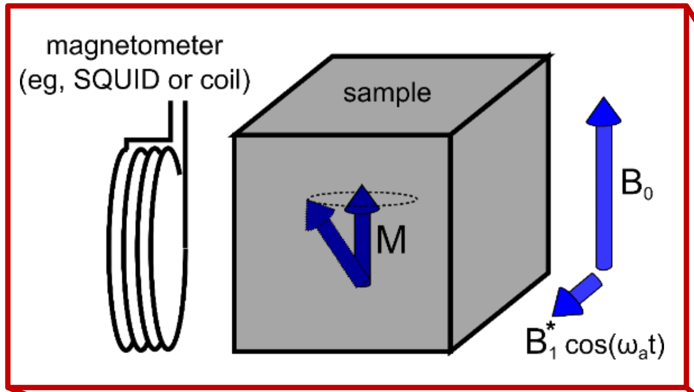
CASPEr-gr-HF: axion-gradient search using liquid Xe

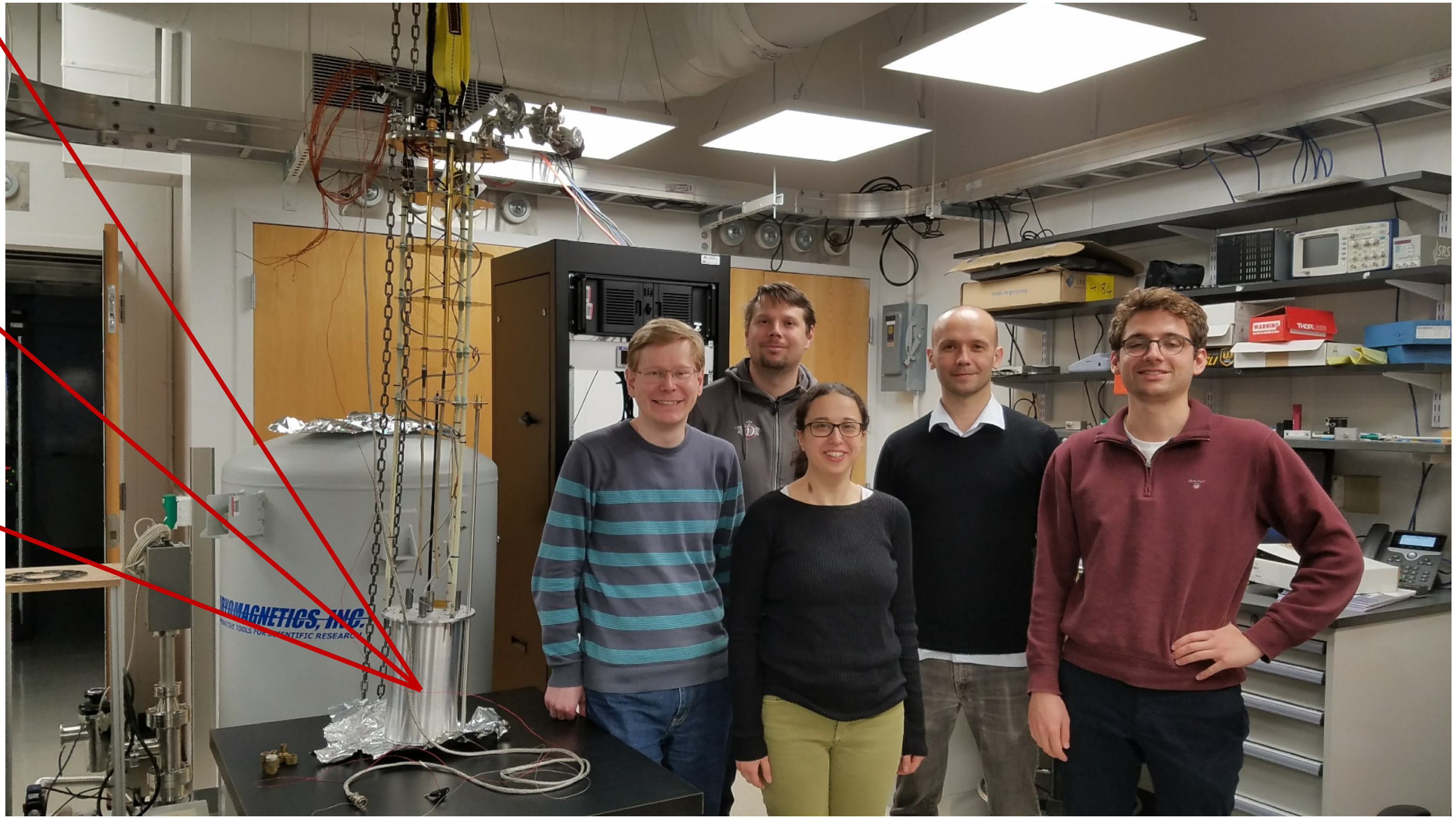
CASPEr-electric

$$\vec{B}_1^* \propto a\vec{E}^*$$

led by the Boston University group

→ searching for an oscillating nuclear EDM





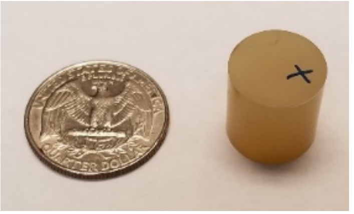
left to right: CASPEr-e, Sasha Gramolin, Janos Adam, Deniz Aybas, Alex Sushkov, Alexi Wilzewski
not shown: Dorian Johnson, Annalies Kleyheeg, Emmy Blumenthal

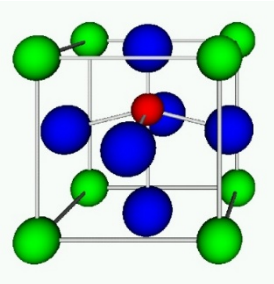
First results from CASPEr-e

sample: 5mm

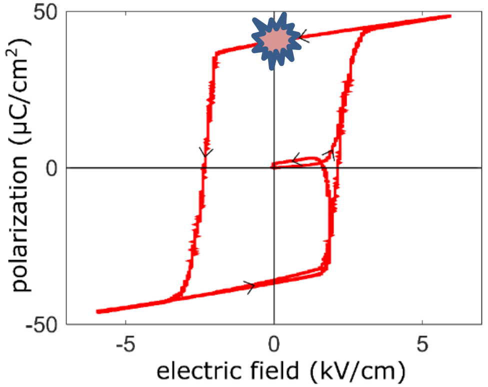
^{207}Pb nuclear spins in ferroelectrically-polarized PMN-PT

$(\mathrm{PbMg}_{1/3}\mathrm{Nb}_{2/3}\mathrm{O}_3)_{2/3}(\mathrm{PbTiO}_3)_{1/3}$





3×10^{20} spins



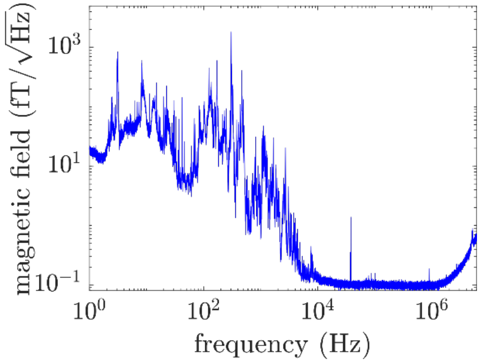
$$E^* = 340\,\mathrm{kV/cm}$$

(similar to a polar molecule

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

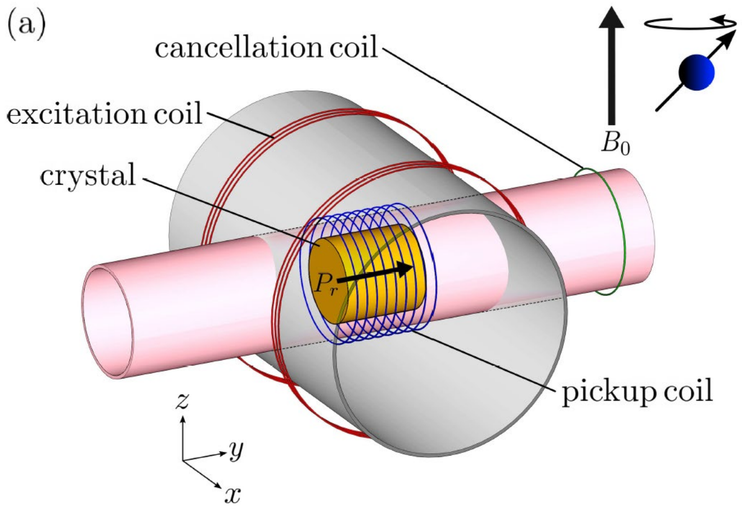
sensor:

SQUID or low-noise RF amplifier (depending on frequency)

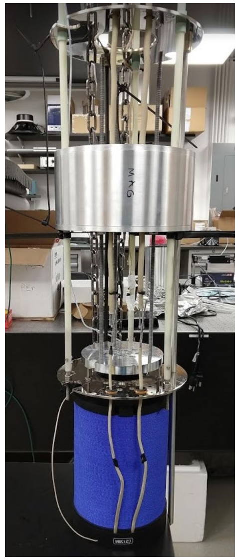


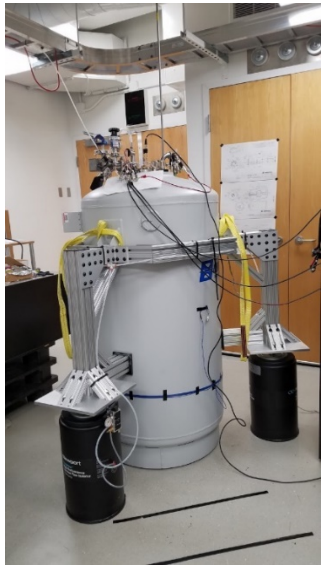
NMR calibration

crossed excitation and pickup coils



liquid helium bath cryostat with 9T magnet

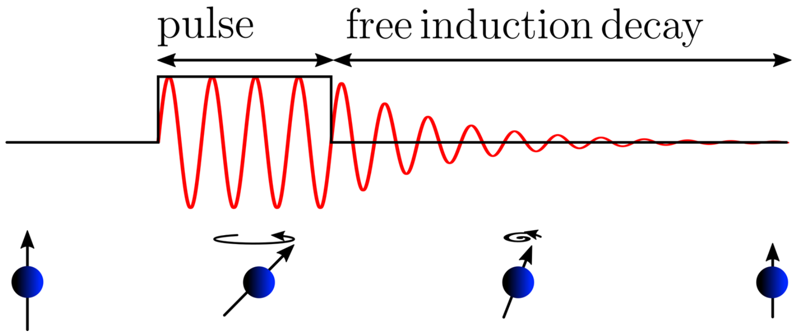




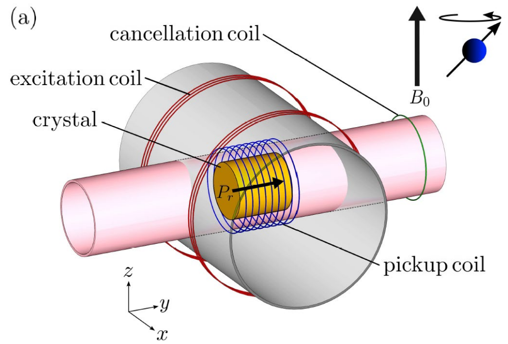
first-generation proof-of-principle CASPEr-e search based on nuclear magnetic resonance

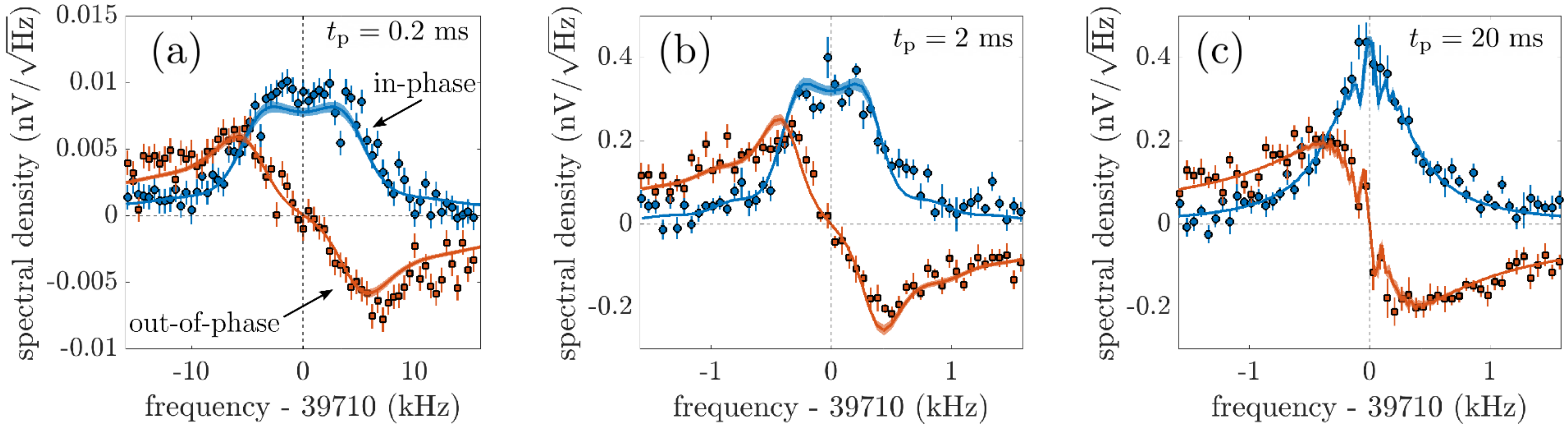
[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

^{207}Pb NMR: sensitivity calibration, characterization of PMN-PT



^{207}Pb NMR: free induction decay (FID) after small-tip angle pulses
(we use small-tip angle pulses so that spin polarization is not diminished after FID acquisition)

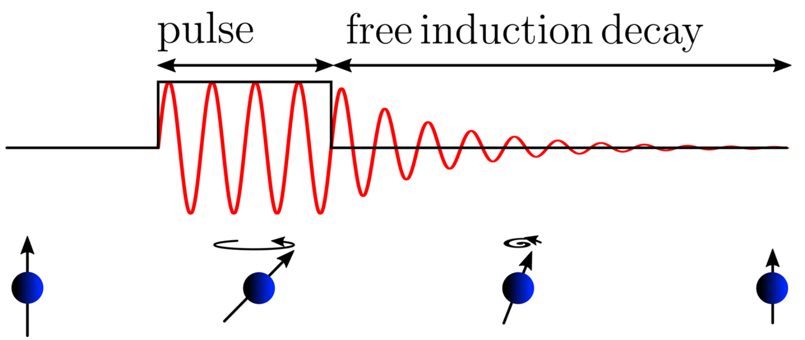




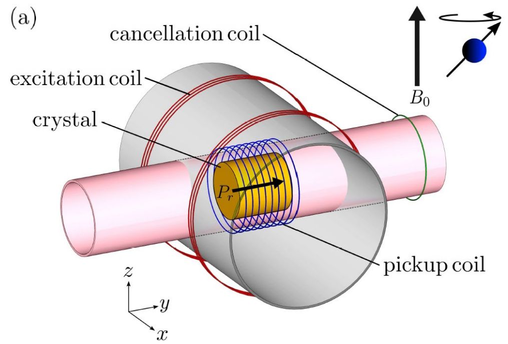
- successful modeling of spin dynamics and FID data using Bloch equations
- measurement of nuclear spin coherence time → $T_2 = (16.7 \pm 0.9)$ ms
- calibration of sensitivity to axion-like dark matter by measuring FID after small-tip angle pulse

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

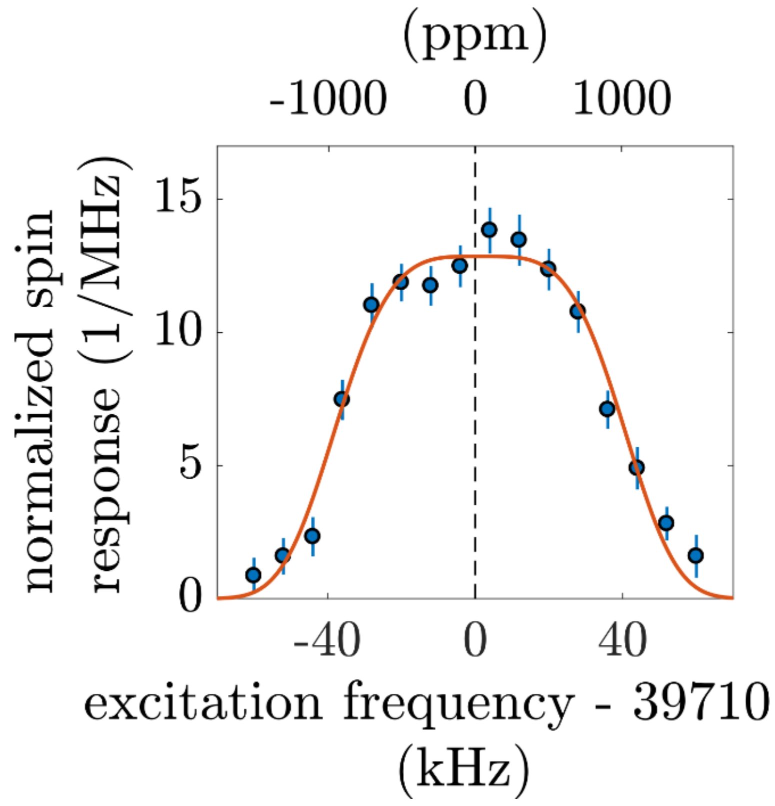
^{207}Pb NMR: sensitivity calibration, characterization of PMN-PT



^{207}Pb NMR: free induction decay (FID) after small-tip angle pulses
(we use small-tip angle pulses so that spin polarization is not diminished after FID acquisition)



measurement of excitation spectral profile



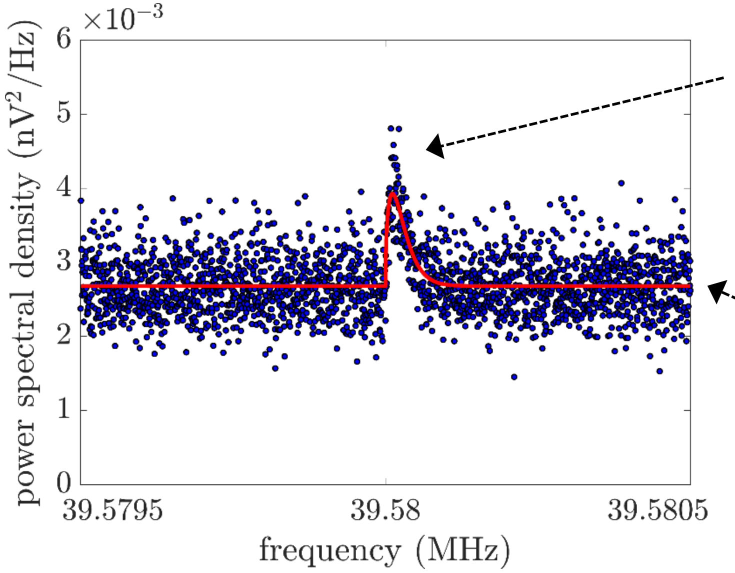
excitation bandwidth → $\Gamma/(2\pi) = (78 \pm 2)\,\mathrm{kHz}$
(consistent with chemical shift anisotropy ≈ 1500 ppm)

at each magnetic field CASPEr-e is sensitive to ALP signal within this window

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

First CASPEr-e axion-like dark matter search

38 min of data taken in October 2019
spin Larmor frequency tuned between 39.2 and 40.2 MHz



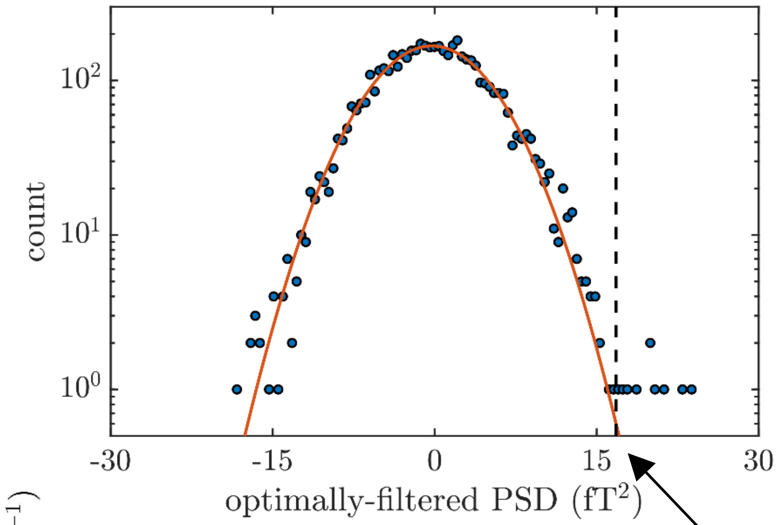
injected ALP dark matter signal:

$$m_a c^2/h = 39.58\,\mathrm{MHz}$$
$$g_d = 3\times10^{-3}\,\mathrm{GeV}^{-2}$$

amplifier noise floor:

$$0.05\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$$

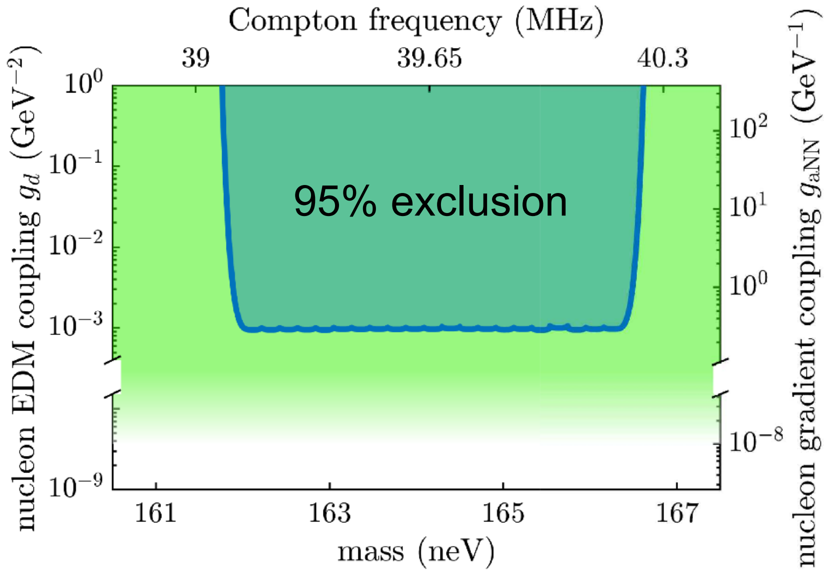
histogram after optimal filtering



3.35σ candidate threshold

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

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

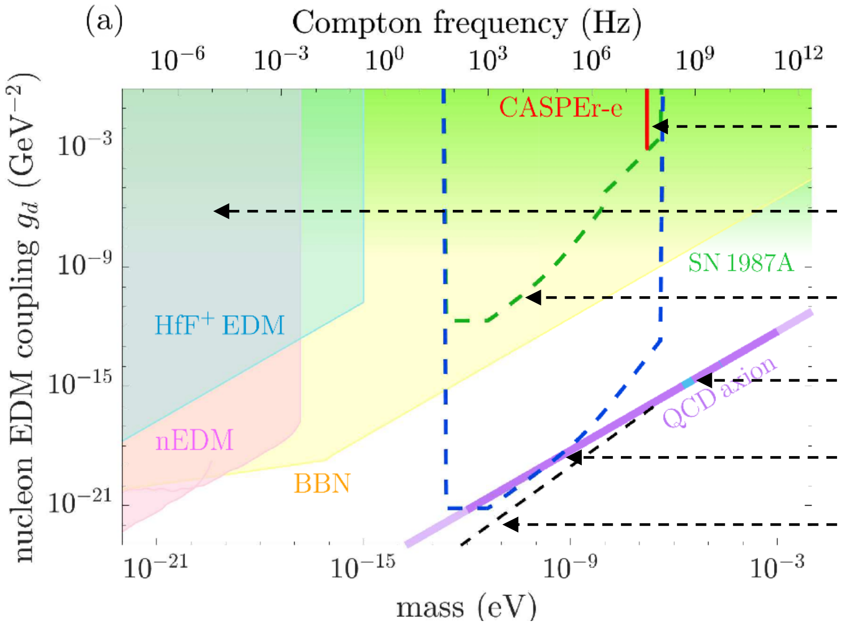


$$|d_n| < 1.0\times10^{-21}\,\mathrm{e}\cdot\mathrm{cm}$$
$$|\theta| < 4.3\times10^{-6}$$

amplitudes of oscillations near 40 MHz

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

The bigger picture



our present limits

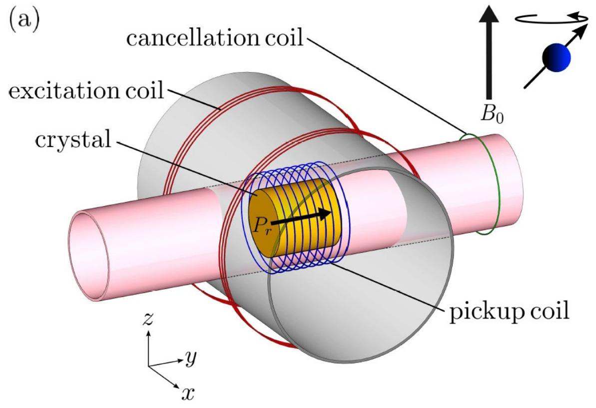
other experimental constraints

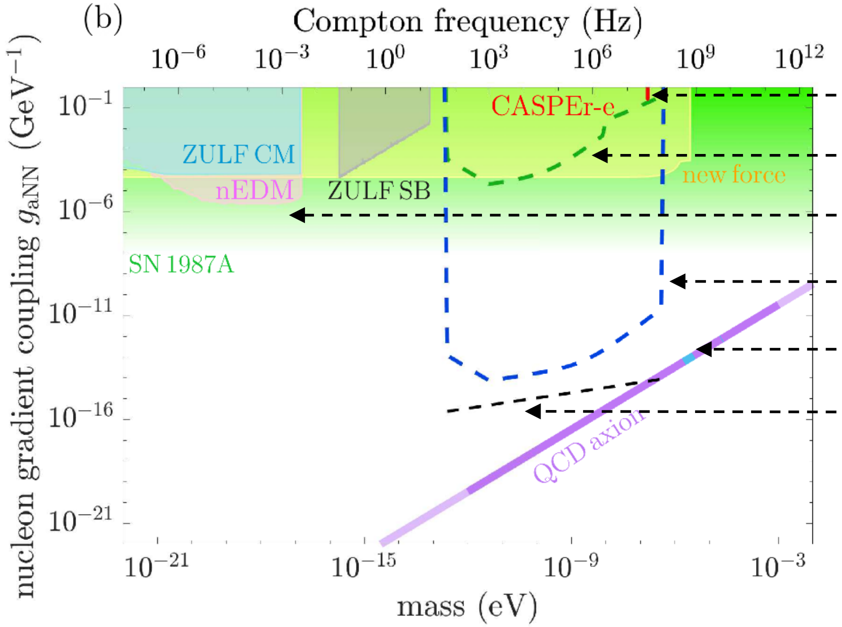
our sensitivity with current setup

QCD axion band

our sensitivity with upgraded setup: 80 cm sample, 100 mK temperature

spin projection noise quantum sensitivity limit





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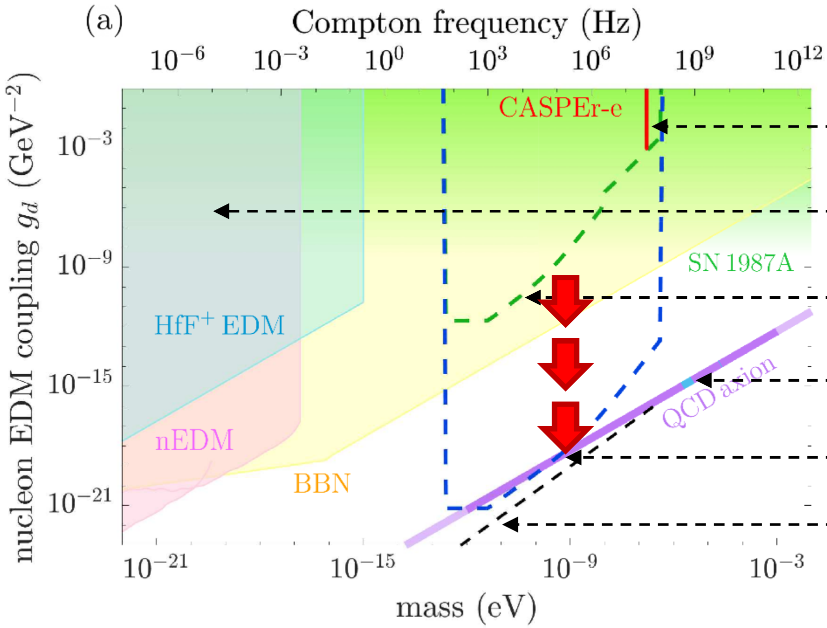
[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

CASPEr: towards the QCD axion



our present limits

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our sensitivity with current setup

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our sensitivity with upgraded setup: 80 cm sample, 100 mK temperature

spin projection noise quantum sensitivity limit

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

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

ongoing work:

1) sweep the full frequency range → current results at 40 MHz, we are sweeping down to kHz

2) increase sample size → currently $N = 3 \times 10^{20}$ spins

3) improve material → currently ferroelectric PMN-PT ➡ non-centrosymmetric ionic crystals

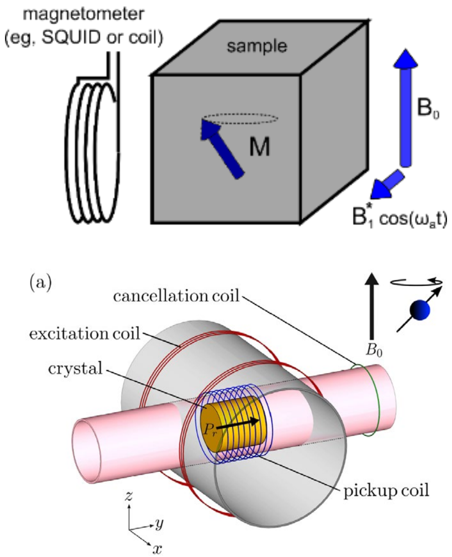
4) improve sensor → currently RF amp/SQUID ➡ collaboration with SLAC to couple RQUs

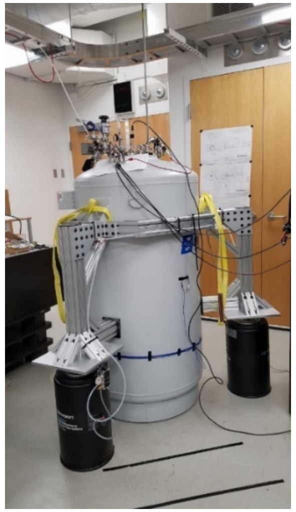
5) increase spin polarization (quantum state control) → currently $\approx 10^{-4}$ ➡ optical control of spin thermalization

➡ optical spin hyperpolarization

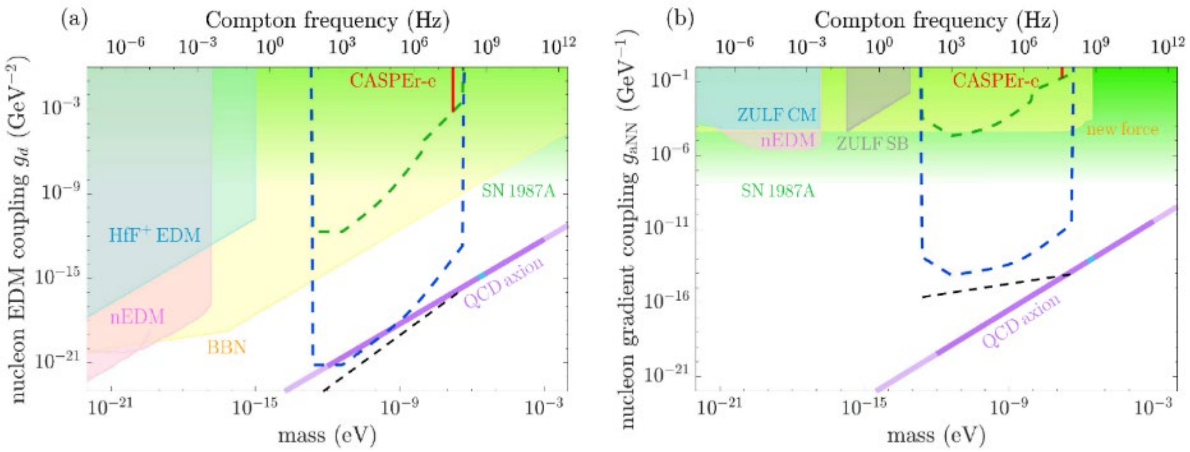
CASPEr-e has the potential to reach QCD axion sensitivity in the peV – neV band ⟺ $|d_n| \sim 10^{-34}\,\mathrm{e \cdot cm}$

Alex Sushkov (Boston University):
Searching for time-varying nuclear electric dipole moments using precision magnetic resonance





Planck scale



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

Thank you!

$$|d_n| < 1.0 \times 10^{-21}\ \mathrm{e \cdot cm}$$
$$|\theta| < 4.3 \times 10^{-6}$$

amplitudes of oscillations near 40 MHz

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Dorian Johnson,
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Tao Wang,
John Blanchard,
Hendrik Bekker,
Gary Centers,
Nate Figueroa,
Antoine Garcon,
Marina Gil Sendra,
Teng Wu,
Alfredo Ferella
Matthew Lawson,
Arne Wickenbrock,
Derek Kimball,
Surjeet Rajendran,
Peter Graham,
Dmitry Budker