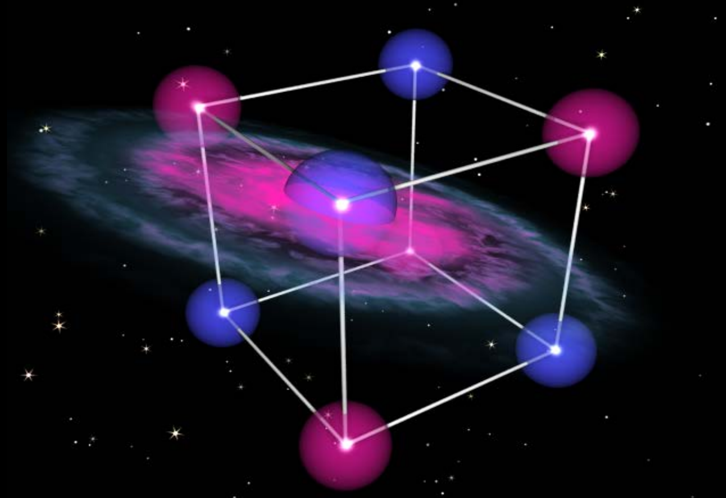

Cosmic Axion Spin Precession Experiment (CASPEr)

Alex Sushkov
Deniz Aybas, Alex Wilzewski, Janos Adam, Hannah Mekbib, Adam Pearson
CASPEr collaboration

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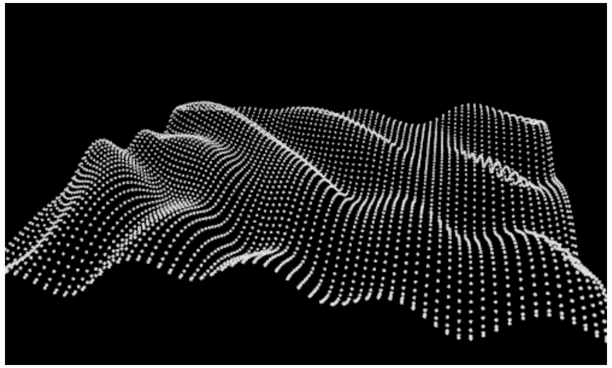
SIMONS FOUNDATION
BOSTON UNIVERSITY
Alfred P. Sloan FOUNDATION

Some of the candidates for dark matter

Weakly Interacting Massive Particles (WIMPs):
mass ~ 100 GeV

[Phys. Rev. Lett. **118**, 021303 (2017)]

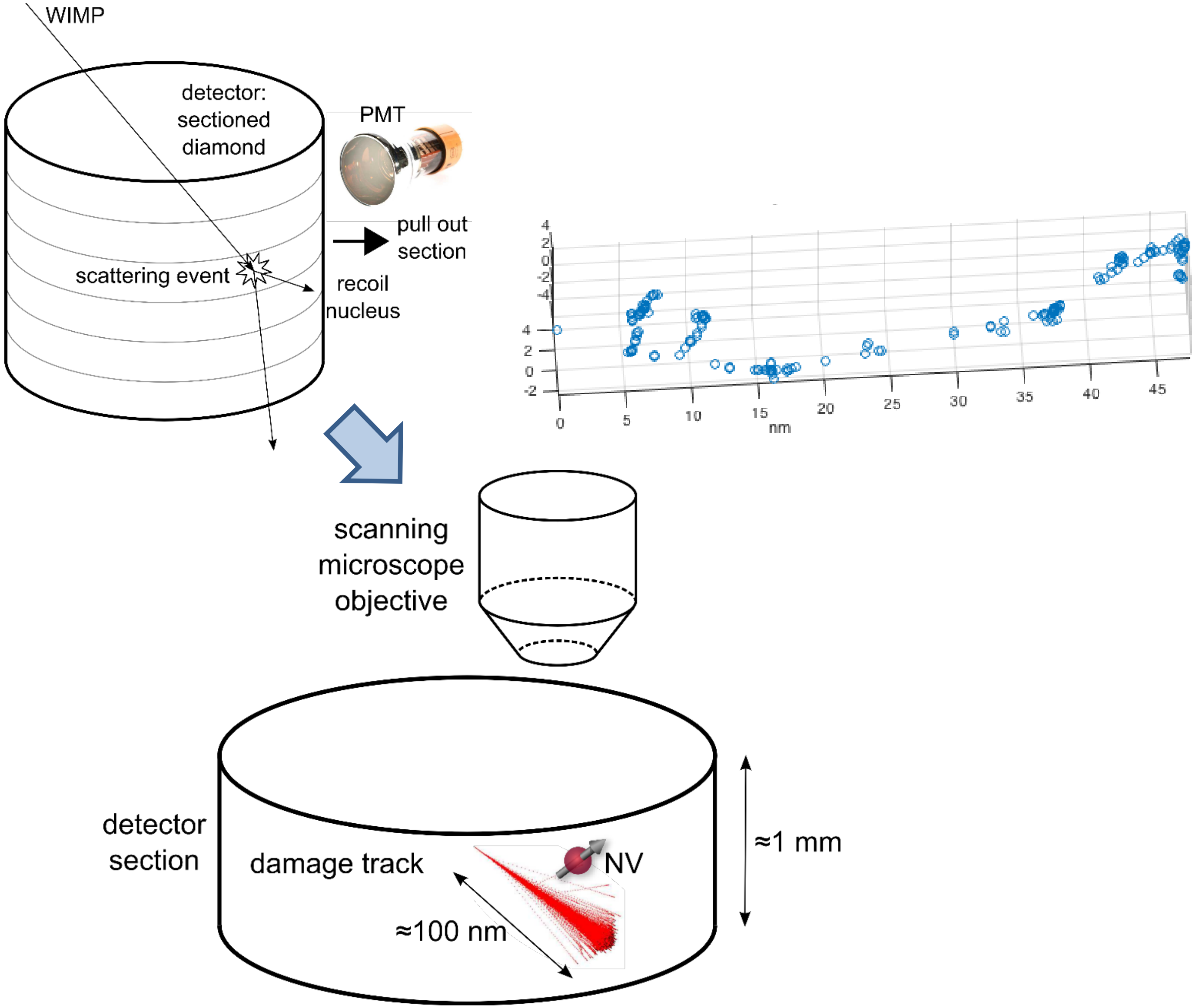


Light candidates
(eg: axions, dark photons)
mass ~ μeV

[Phys. Rev. Lett. **118**, 061302 (2017)]

Direction-sensitive WIMP detector based on diamond

1. detector volume is made up of diamond sections, surrounded by PMTs and/or charge readout sensors
2. a WIMP scattering event is detected and localized via charge collection and scintillation
3. the recoil nucleus produces a track of vacancies ≈ 100 nm long
4. the detector section where the scattering event occurred is pulled out and examined
5. measurements of crystal strain using NV centers allow reconstruction of vacancy distribution, and hence the WIMP momentum direction



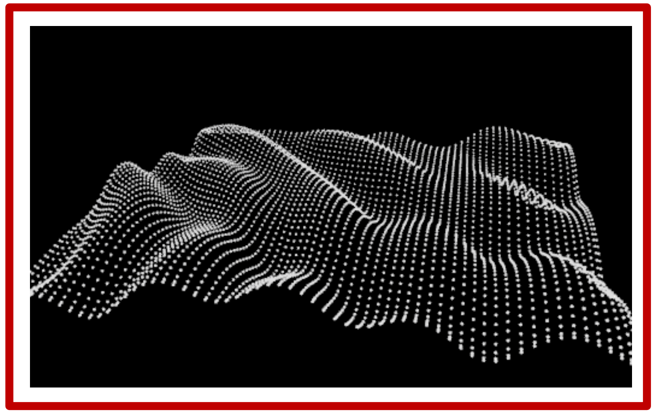
a directional dark matter detector

details: [arxiv:1705.09760 (2017)]

Some of the candidates for dark matter

Weakly Interacting Massive
Particles (WIMPs):
mass ~ 100 GeV

[Phys. Rev. Lett. **118**, 021303 (2017)]



Light candidates
(eg: axions, dark photons)
mass ~ μeV

[Phys. Rev. Lett. **118**, 061302 (2017)]

Axions

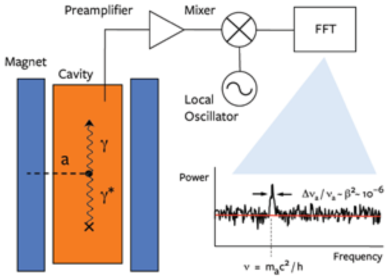
1. Pseudoscalar light field: spin = 0, odd under parity
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [PRL 38, 1440 (1977)]
3. Axion-like particles (ALPs) arise very naturally in string theories, symmetries broken at GUT (10^{16} GeV) or Planck (10^{19} GeV) scales
4. Possible couplings to standard model particles:

axion field amplitude

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

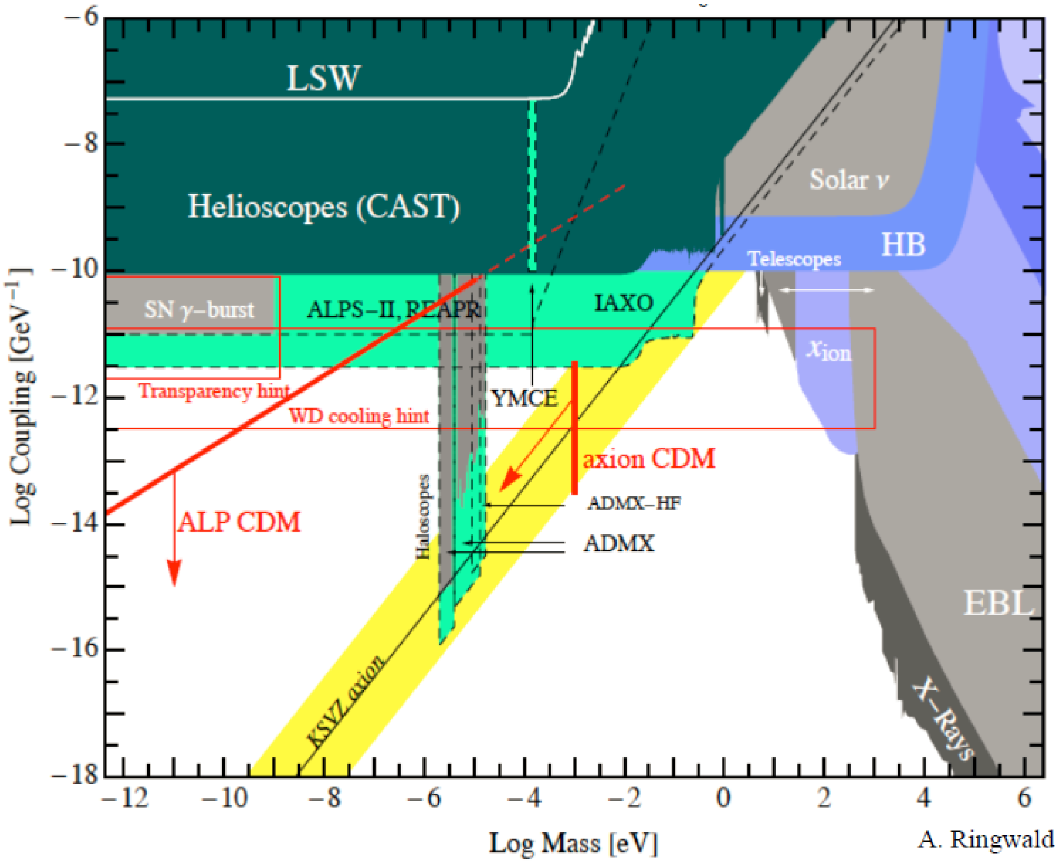
coupling to photons

□ Primakoff effect



most axion searches:
ADMX, HAYSTAC, …
(sensitivity all the way down to the QCD axion coupling!)

[Phys. Rev. Lett. **118**, 061302 (2017)]



A. Ringwald (2012)

Axions

1. Pseudoscalar light field: spin = 0, odd under parity
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4. Possible couplings to standard model particles:

axion field amplitude

$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

coupling to photons

☐ Primakoff effect

most axion searches:
ADMX, HAYSTAC, …
(sensitivity all the way down to the QCD axion coupling!)

coupling to gluons

☐ creates nucleon EDM (electric dipole moment)
this is why axions were invented

☐ spin to axion coupling:

$$\boxed{H_\mathrm{e} \propto a\vec{\boldsymbol{\sigma}}\cdot\vec{\boldsymbol{E}}^*}$$

CASPEr-electric

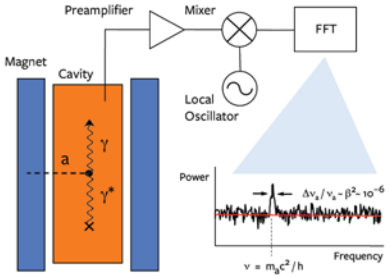
coupling to fermions

☐ creates axion "wind"

☐ spin to axion "wind" coupling:

$$\boxed{H_\mathrm{wind} \propto \vec{\boldsymbol{\sigma}}\cdot\vec{\boldsymbol{\nabla}}a}$$

CASPEr-wind

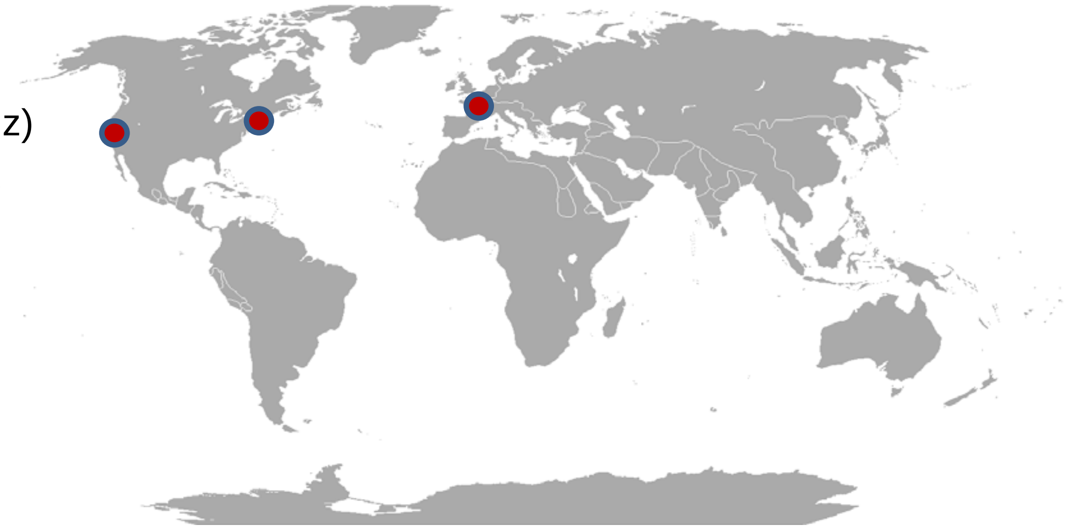


[Phys. Rev. Lett. **115**, 201301 (2015)]
[Phys. Rev. Lett. **118**, 061302 (2017)]

CASPEr (Cosmic Axion Spin Precession Experiments) will search for experimental signatures of these couplings

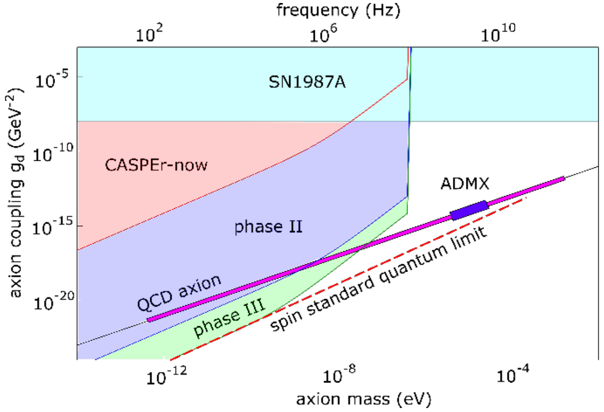
Our collaboration

Deniz Aybas (Boston University)
Alex Wilzewski (Boston University & Mainz)
Janos Adam (Boston University)
Arne Wickenbrock (Mainz)
John Blanchard (Mainz)
Gary Centers (Mainz)
Nataniel Figueroa (Mainz)
Marina Gil Sendra (Mainz)
Tao Wang (UC Berkeley)



Surjeet Rajendran (UC Berkeley),
Peter Graham (Stanford)
Dmitry Budker (UC Berkeley & Mainz)
Alex Sushkov (Boston University)
Derek Kimball (CSUEB)

Boston University:
CASPEr-electric using
spins in solids



Alfred P. Sloan FOUNDATION

SIMONS FOUNDATION

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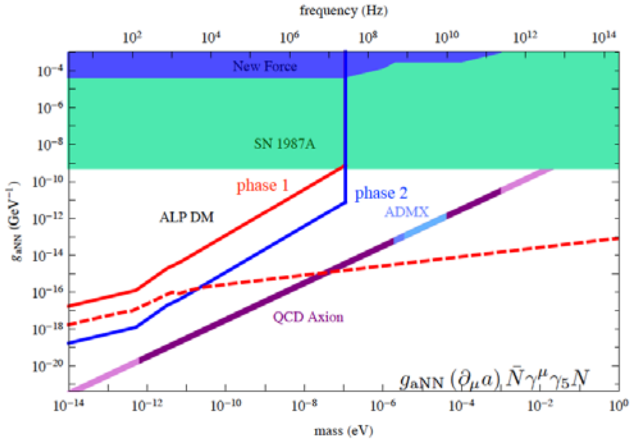
Stanford, Berkeley, CSUEB:

Mainz:
CASPEr-wind using
liquid Xenon



Axion coupling to spin: CASPEr-electric

spin to axion coupling: $H_{\mathrm{e}} \propto a\vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{E}}^{*}$

axion (or ALP) field

spin

effective electric field

dark matter energy density:
$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$

+

ALP mass range:
$m_a c^2 \approx \mu\mathrm{eV}$

large number of particles per de Bloglie wavelength

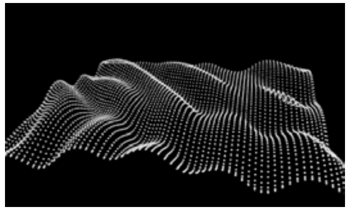
ALP dark matter acts as a classical field: $a(t) = a_0 \cos \omega_a t$

$\omega_a = m_a c^2/\hbar$

ALP Compton frequency

coupling constant

spin to axion coupling: $H_{\mathrm{e}} = g_d (a_0 \cos \omega_a t) \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{E}}^{*}$



effective interaction: $H_{\mathrm{e}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^{*} \cos \omega_a t$

spin “feels” an effective magnetic field: $\vec{\boldsymbol{B}}_1^{*} \cos \omega_a t = g_d a_0 \vec{\boldsymbol{E}}^{*} \cos \omega_a t$

[*Phys. Rev. X* **4**, 021030 (2014)]

Experimental search for axion coupling to spin

effective interaction: $H_\mathrm{e} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos\omega_a t$

search for this effective magnetic field using magnetic resonance

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

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

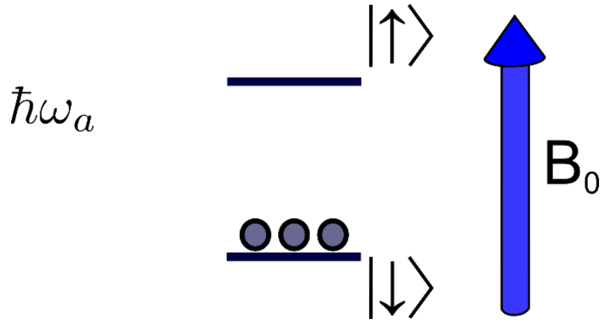
3) resonance: $\hbar\omega_a = g\mu B_0$

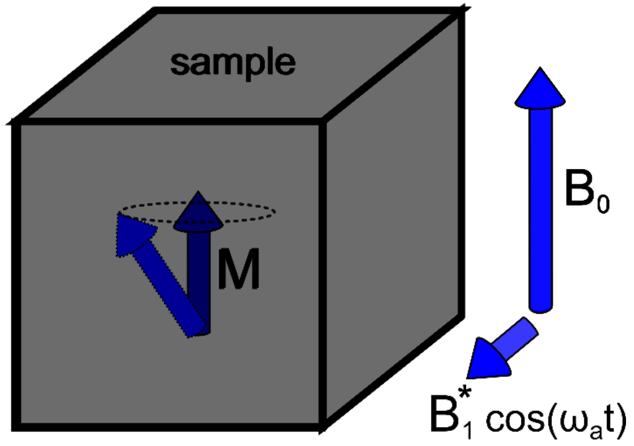
- ➡ axion-spin interaction can now flip spins!
- ➡ sample magnetization tilts and precesses

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

⬇

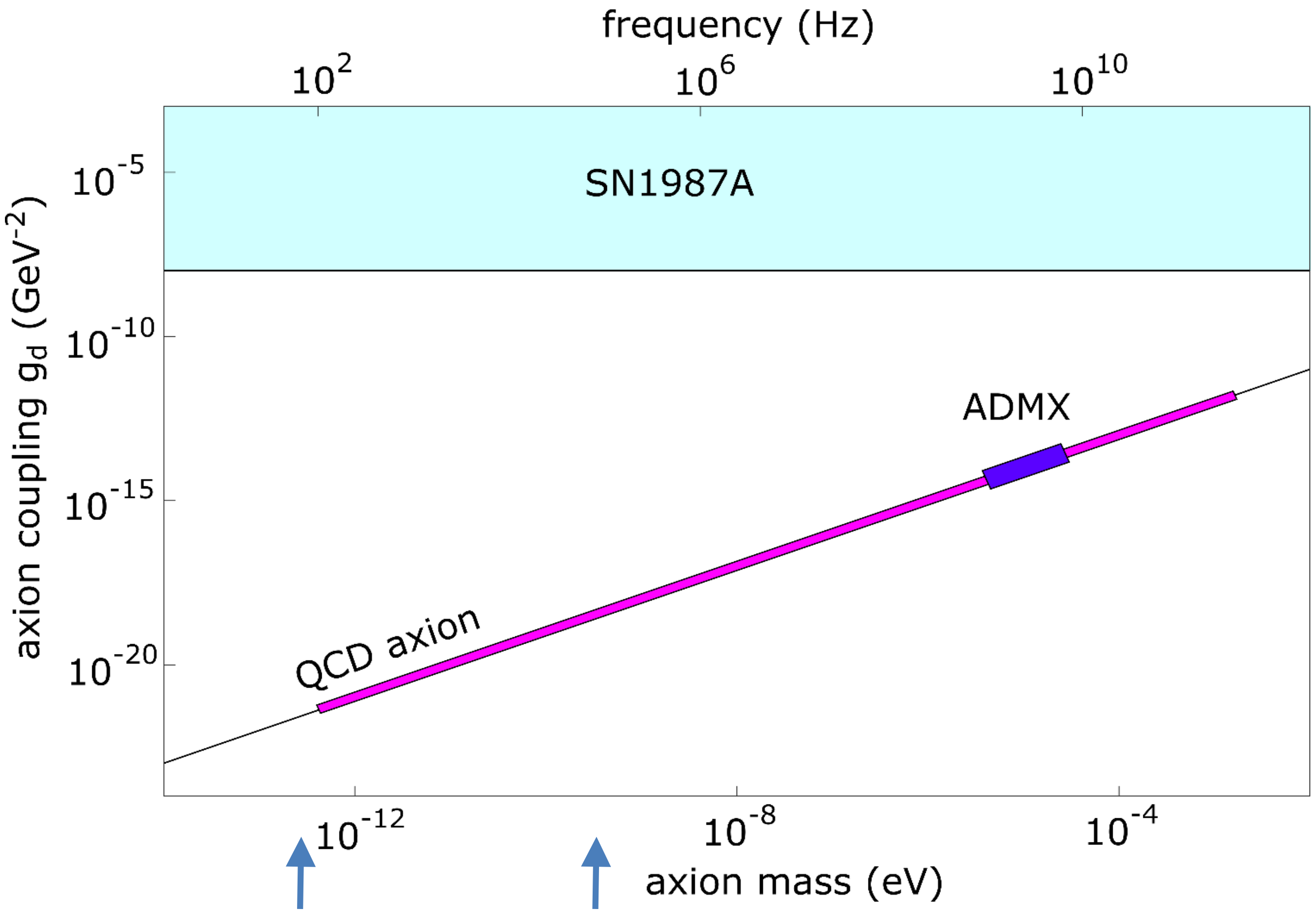
basically an NMR experiment





[*Phys. Rev. X* **4**, 021030 (2014)]

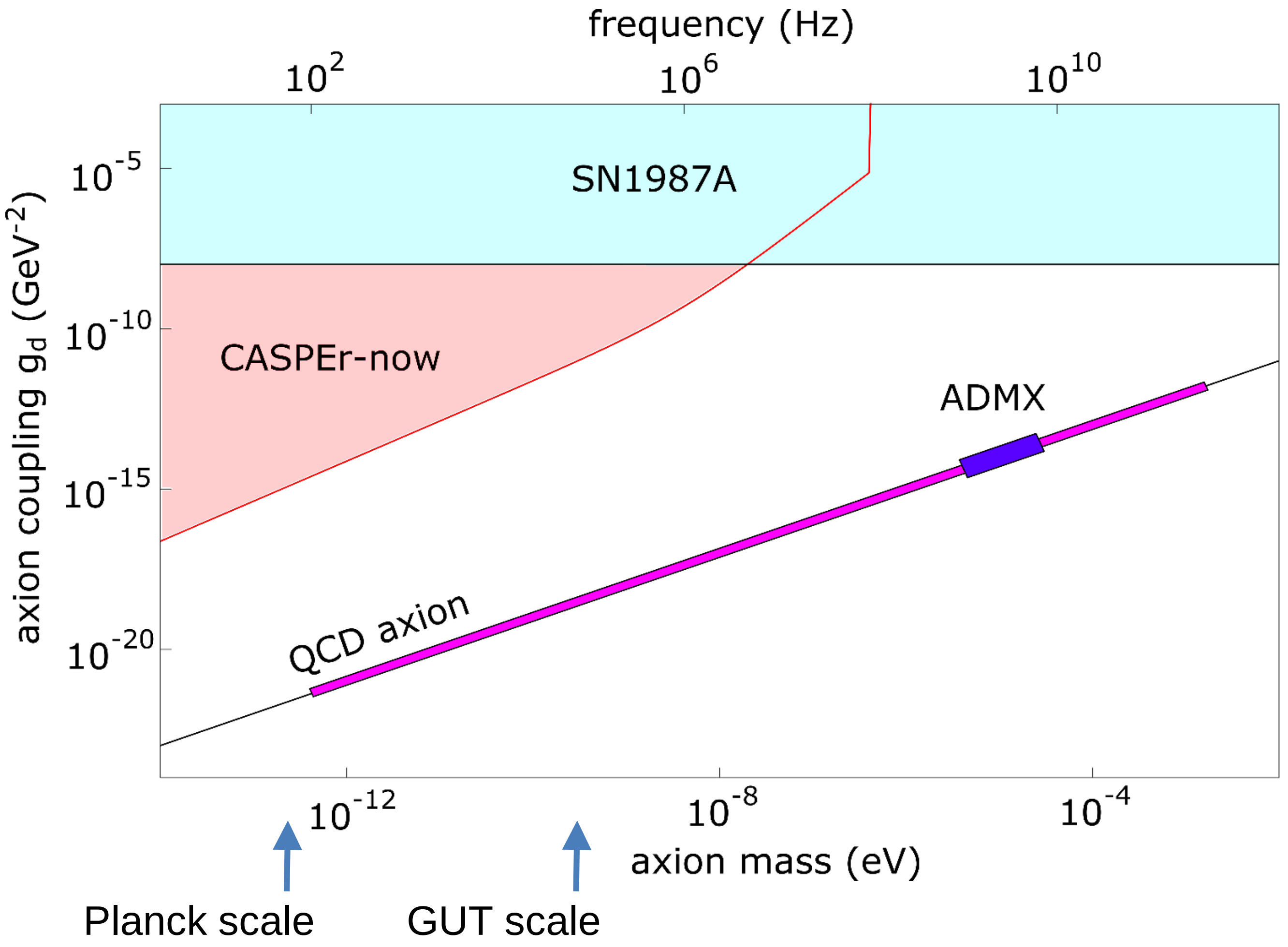
The experimental reach of CASPEr



Planck scale

GUT scale

The experimental reach of CASPEr

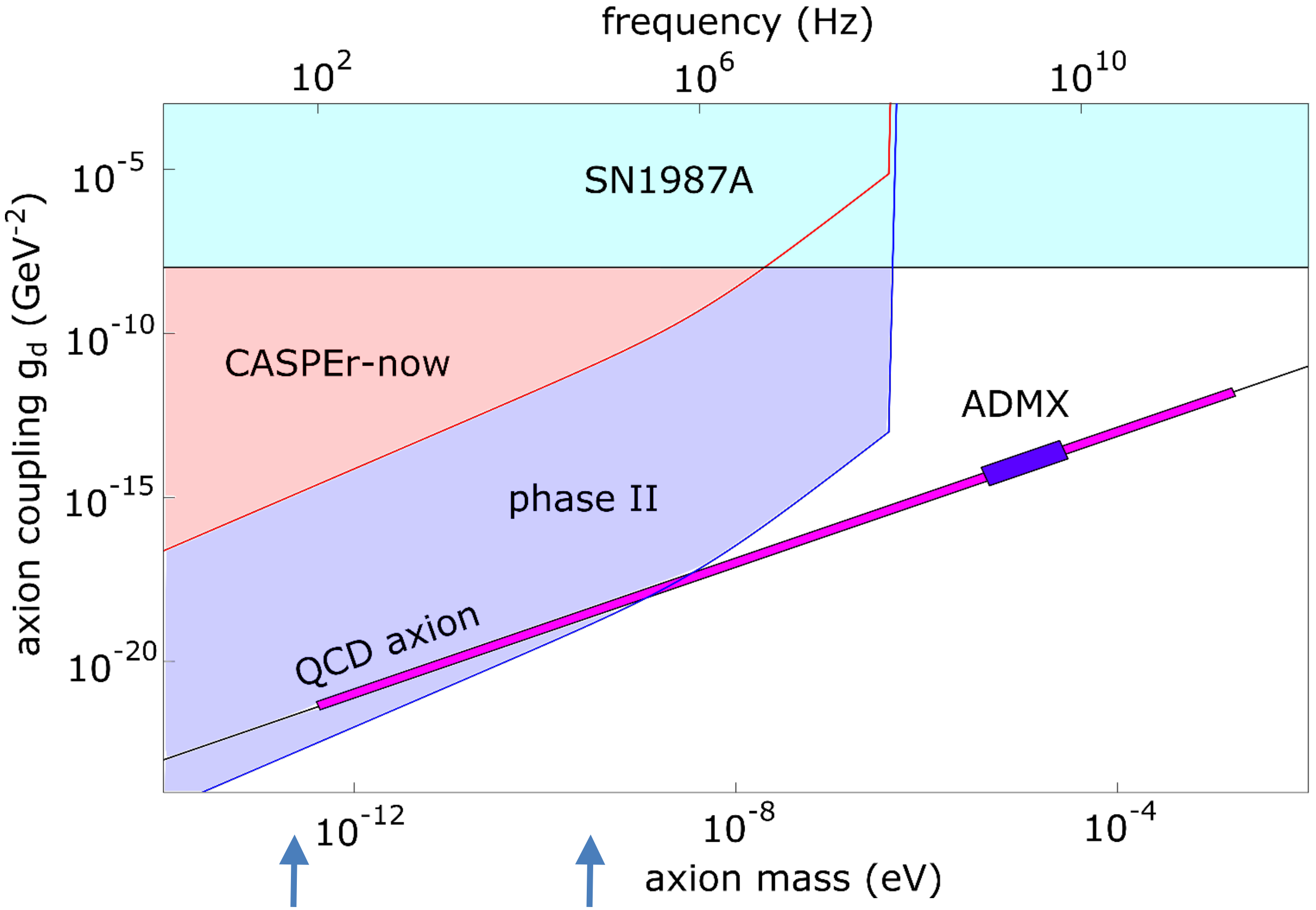


<u>CASPEr-now</u> at BU:

- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

[*Phys. Rev. X* **4**, 021030 (2014)]

The experimental reach of CASPEr



Planck scale GUT scale

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- thermal spin polarization,
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<u>phase II</u>:
- optically enhanced spin polarization (first results: 2/17)
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit

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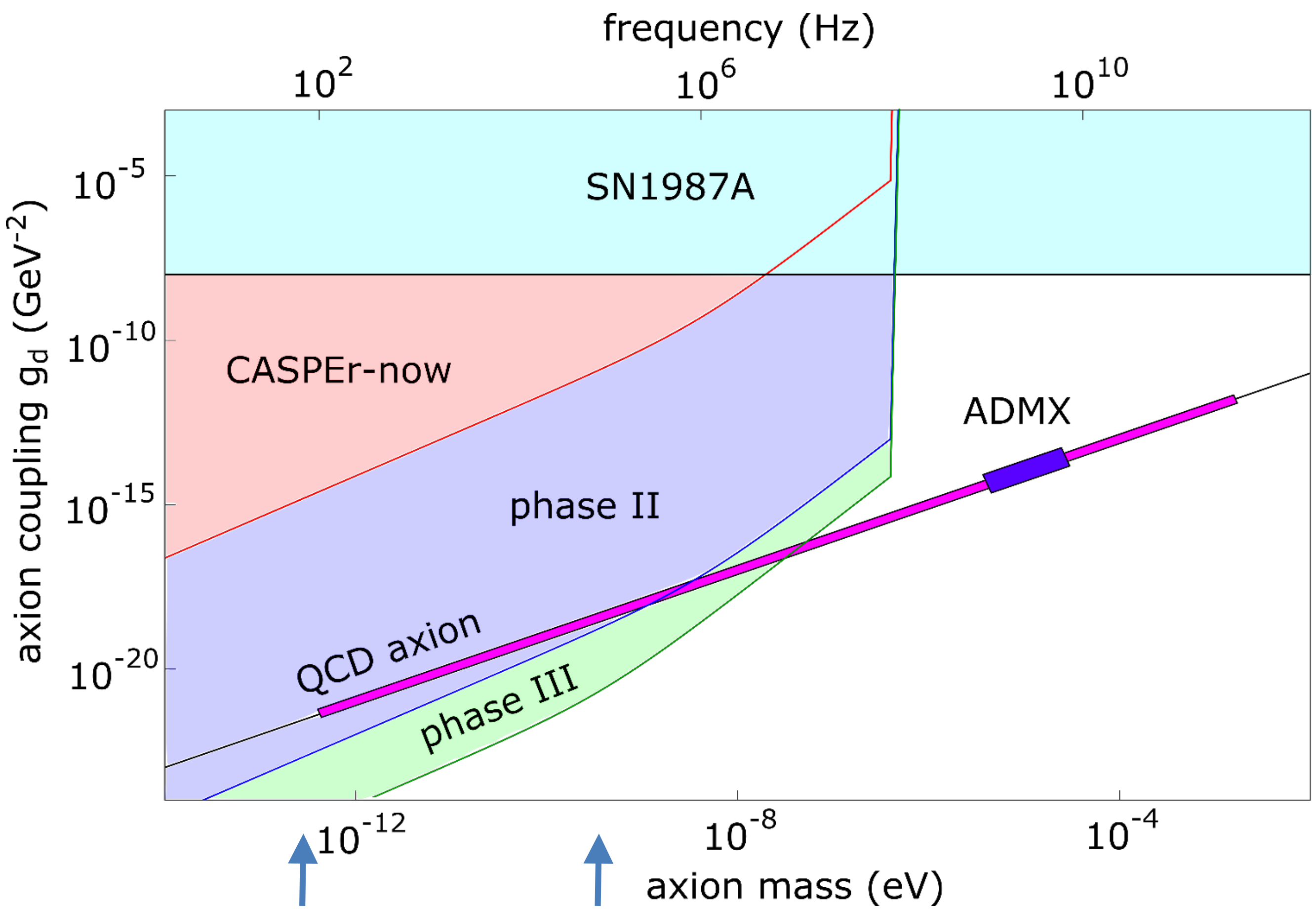
[*Phys. Rev. X* **4**, 021030 (2014)]

The experimental reach of CASPEr



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<u>phase II</u>:

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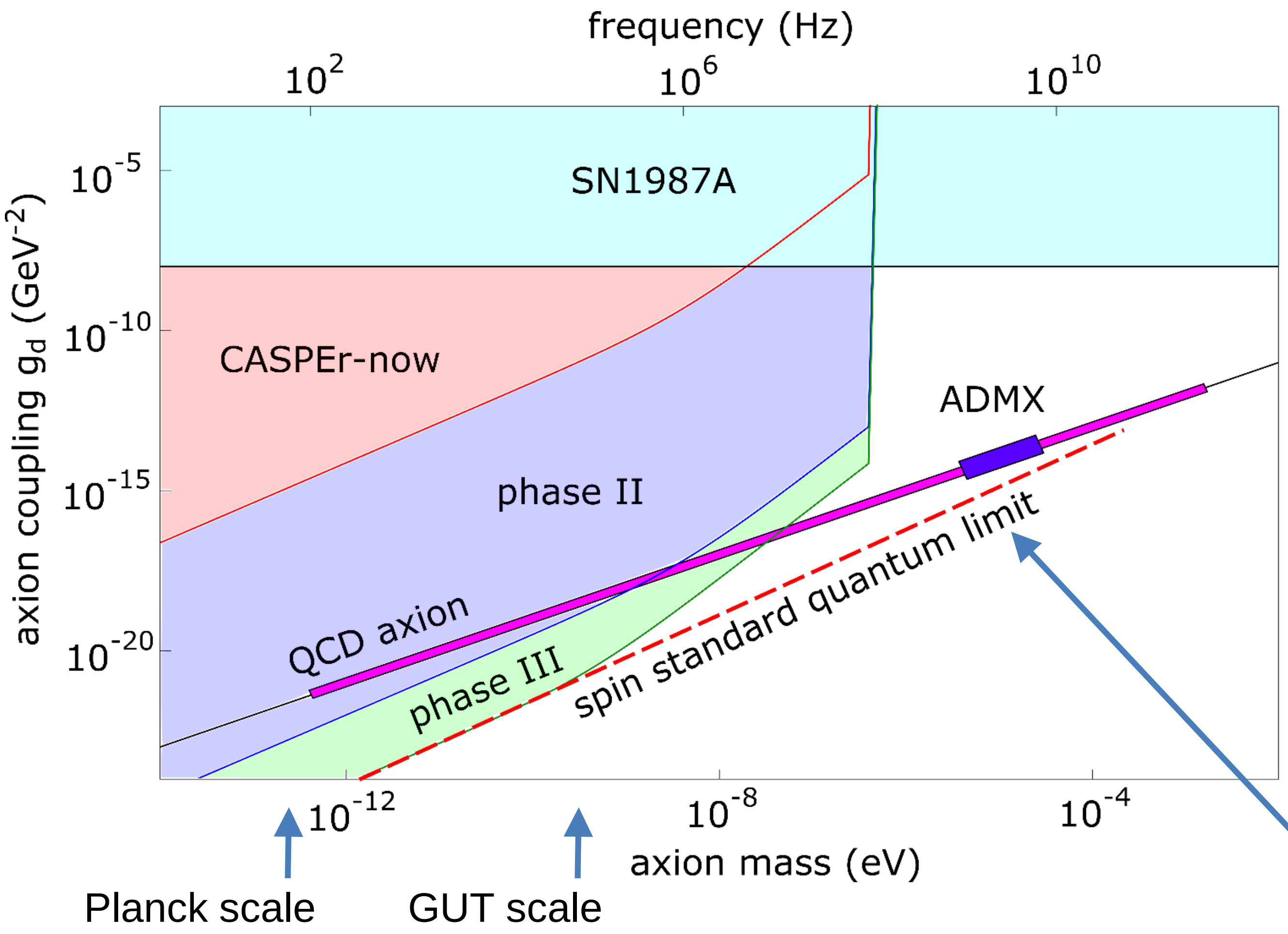
<u>phase III</u>:

- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit

[*Phys. Rev. X* **4**, 021030 (2014)]

The experimental reach of CASPEr



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[*Phys. Rev. X* **4**, 021030 (2014)]

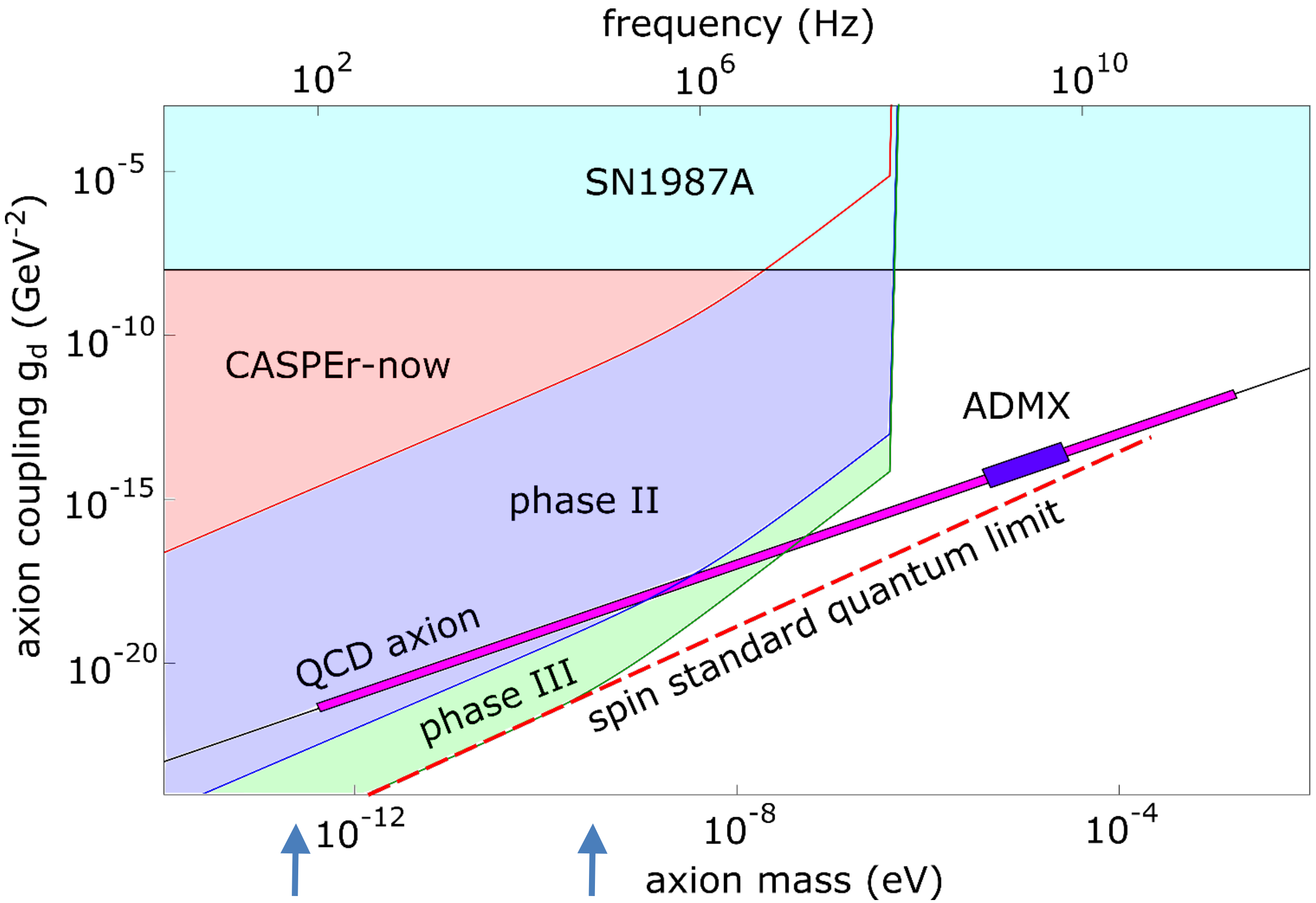
1. use <u>existing technology</u>, mostly commercial
2. search in a <u>wide range</u> of masses and couplings
3. sensitivity reaches <u>QCD axion</u> down to Planck and GUT scales

the most sensitive NMR experiment in history*

experimentally measurable

[*Phys. Rev. Lett.* **55**, 1742 (1985)]

The experimental reach of CASPEr



Planck scale GUT scale

1. use existing technology, mostly commercial
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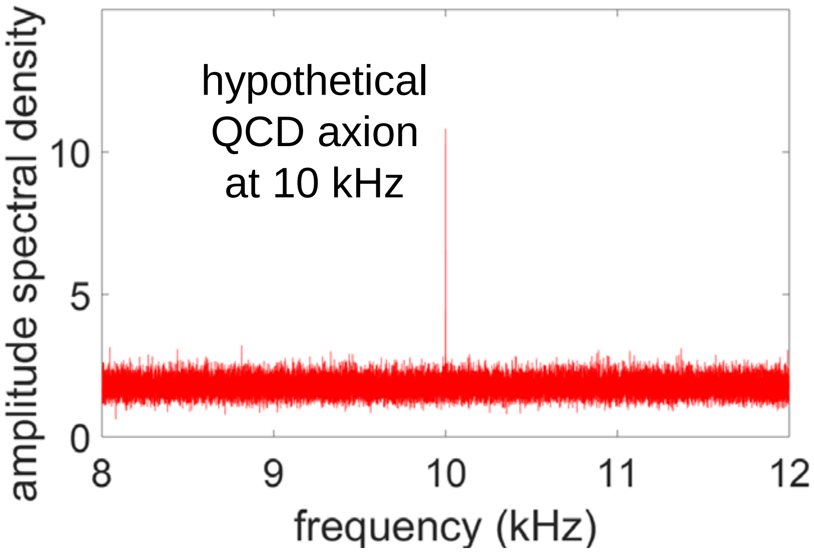
3. sensitivity reaches QCD axion down to Planck and GUT scales

phase II sensitivity simulation:



[*Phys. Rev. X* **4**, 021030 (2014)]

the most sensitive NMR experiment in history*

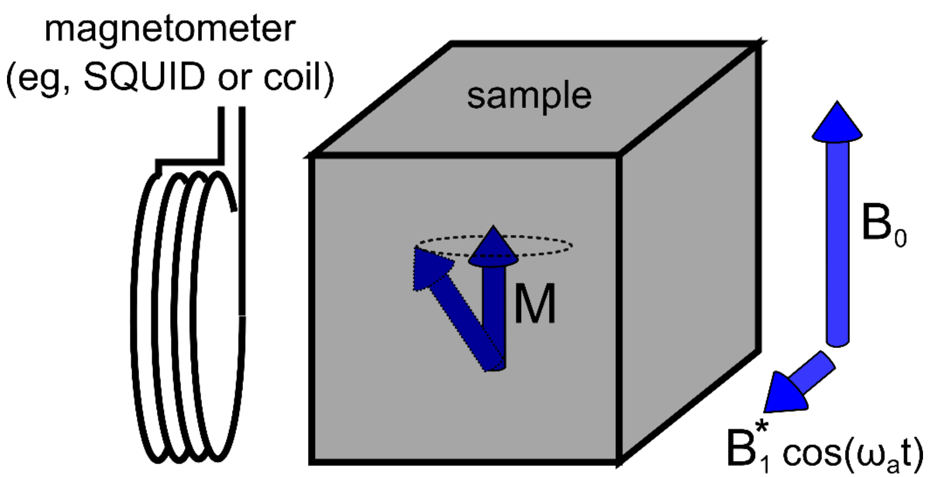
Sample material

effective interaction: $H_{\mathrm{e}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

1) maximize $\vec{\boldsymbol{B}}_1^* = g_d a_0 \vec{\boldsymbol{E}}^*$

2) maximize spin density

3) optimize spin coherence time



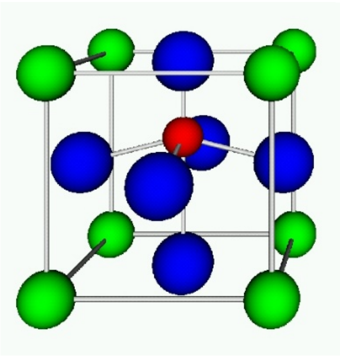
1) use a **ferroelectric solid** where nuclear spin are subject to effective electric fields

$$E^* \approx 10^8\,\mathrm{V/cm}$$

similar to a polar molecule: ACME [Science 343, 269 (2013)]

2) nuclear spin **density**: $n \approx 3 \times 10^{21}\,\mathrm{cm}^{-3}$

3) nuclear spin **coherence time**: $T_2^* \approx 1\,\mathrm{ms}$



materials: $\mathrm{PbTiO_3}$

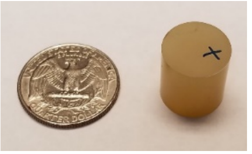
$\mathrm{Pb(Zr,Ti)O_3}\ (PZT)$

$\boxed{\mathrm{(1-x)[Pb(Mg_{1/3}Nb_{2/3})O_3]/x[PbTiO_3]}\ (PMN-PT)}$

$\mathrm{Pb_5Ge_3O_{11}}$

used for novel piezoelectric transducers

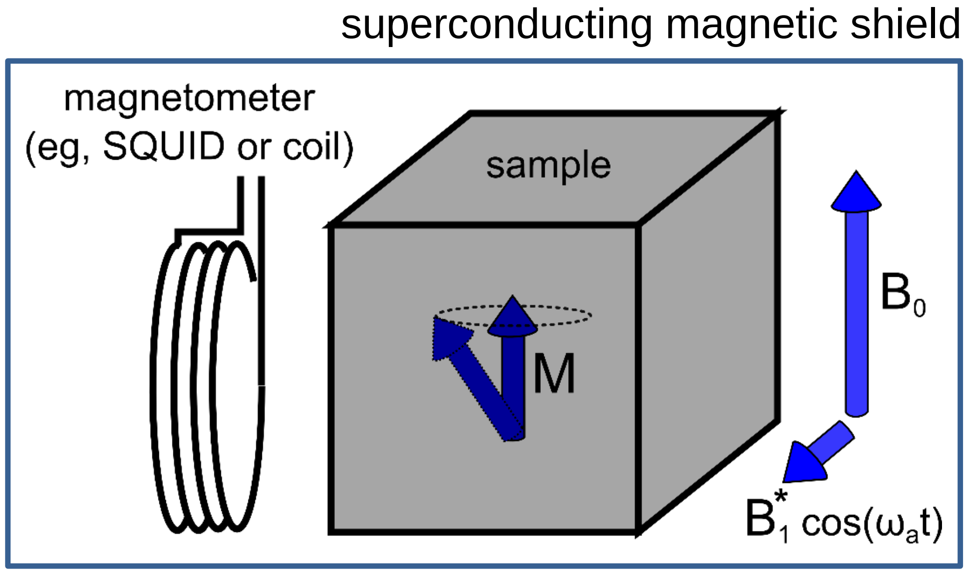
commercially available



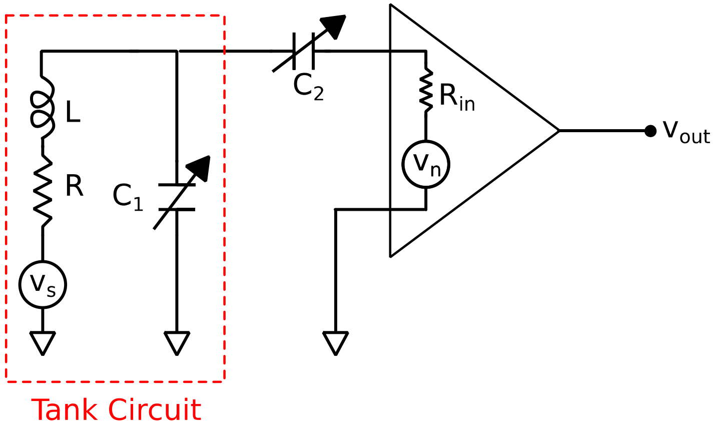
[*Phys. Rev. X* **4**, 021030 (2014)]

Magnetometry

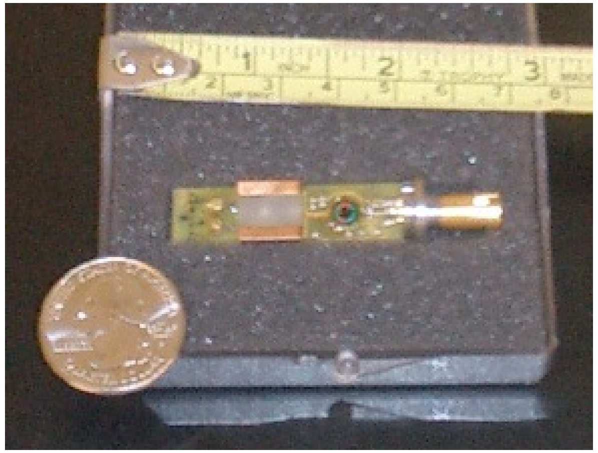
effective interaction: $H_{\mathrm{e}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

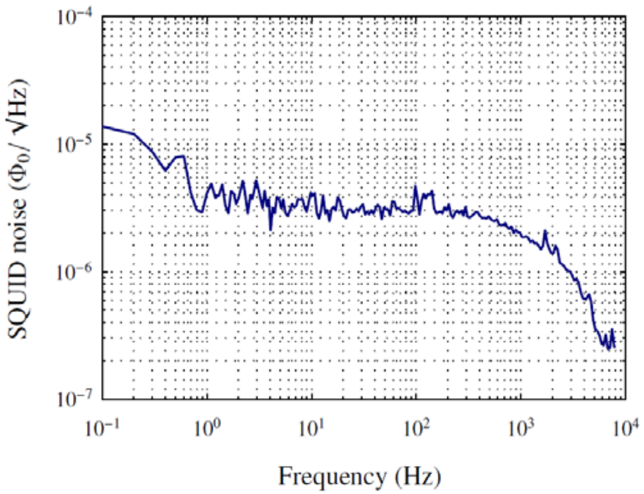


inductive (Faraday) detection:



SQUID:

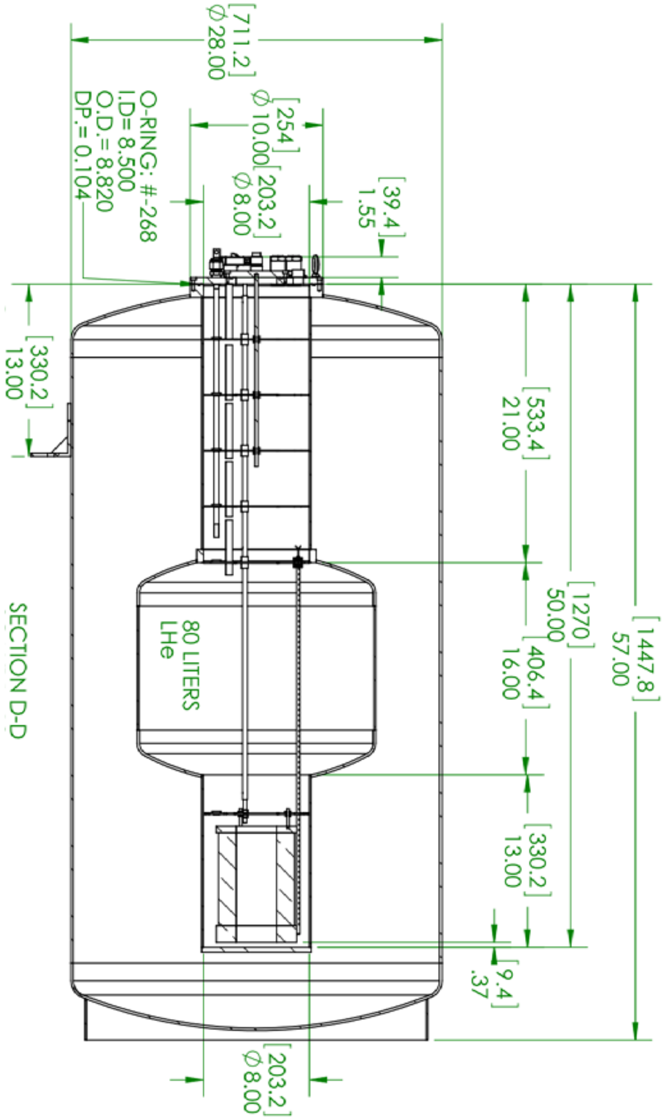


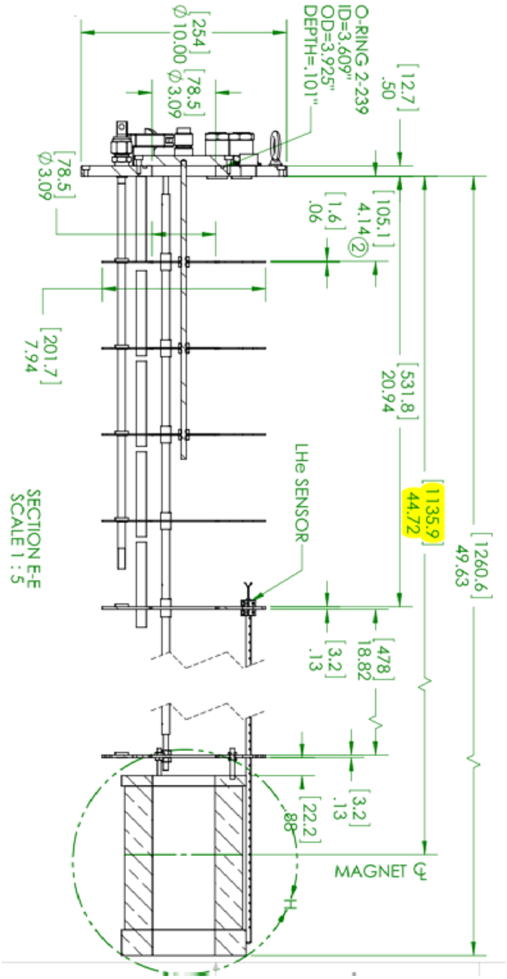


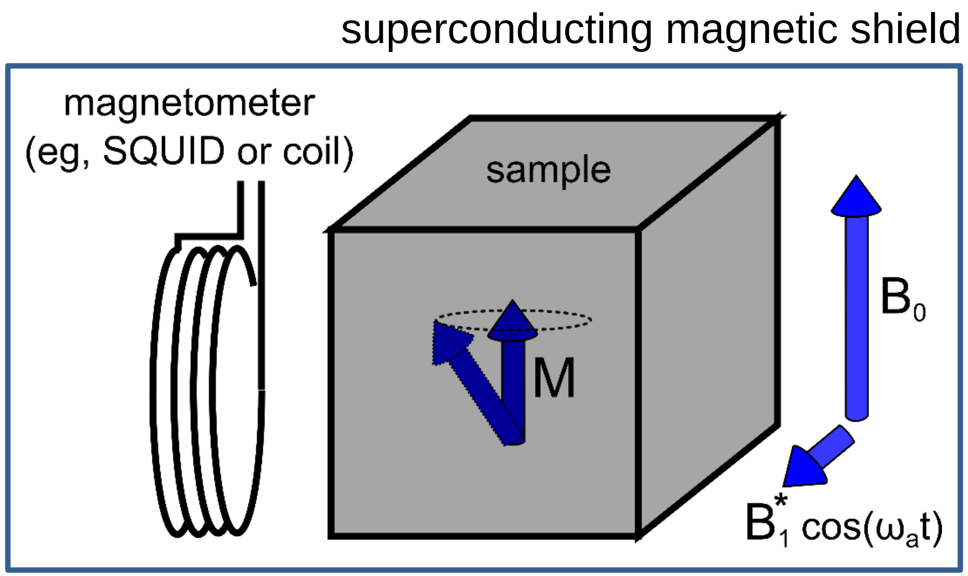
used for precision magnetometry, RF amplifiers, …

→ commercially available

Cryostat and magnet for CASPEr-now



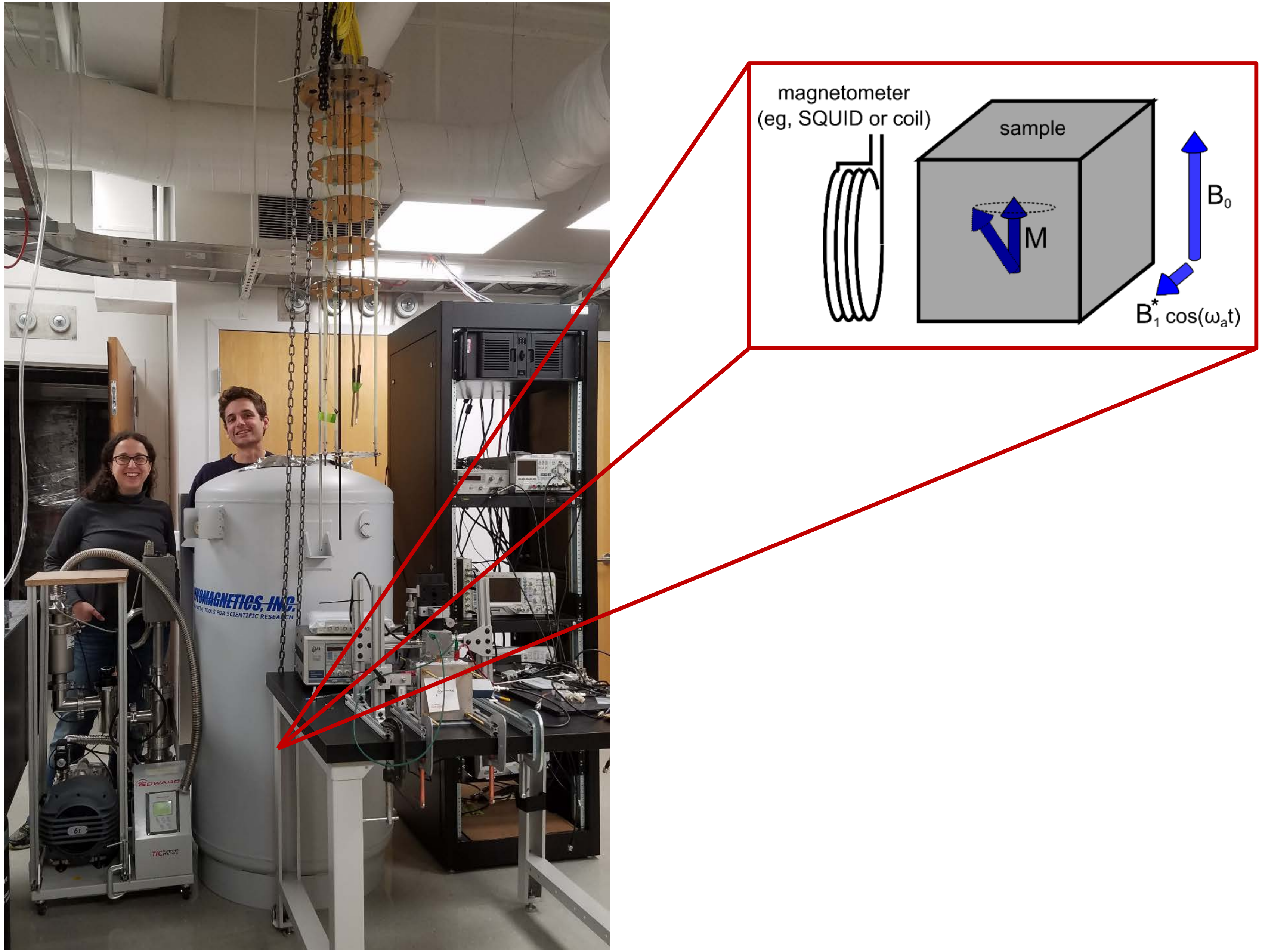




9T magnet with 3” bore, 1000 ppm
homogeneity over 1cm DSV
(Cryomagnetic Inc.)

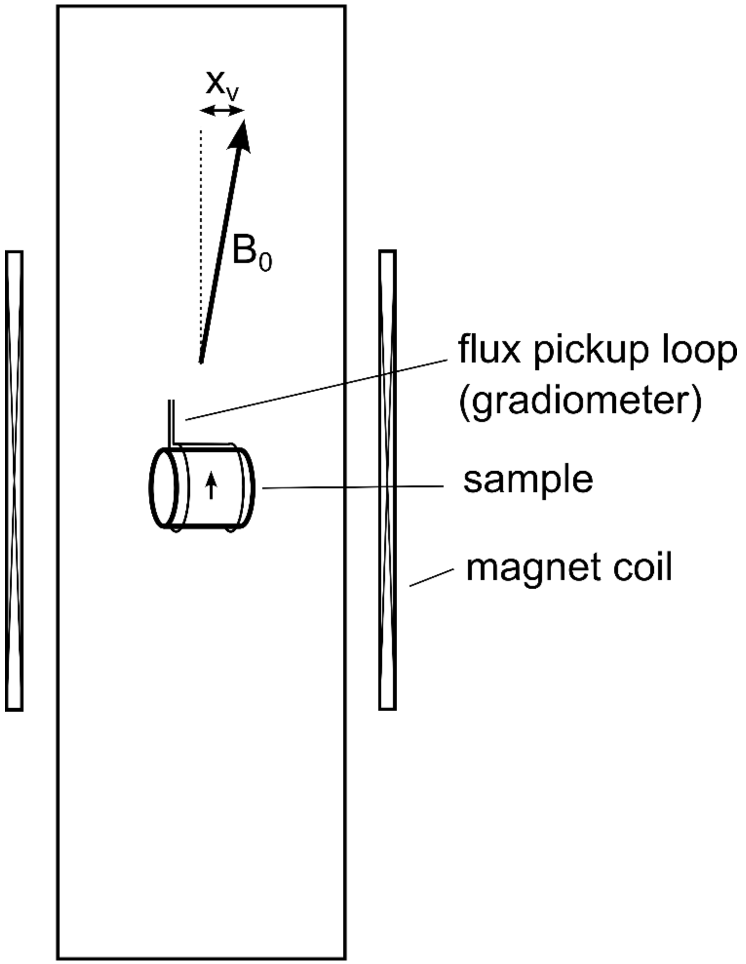
CASPEr-now in Feb 2016

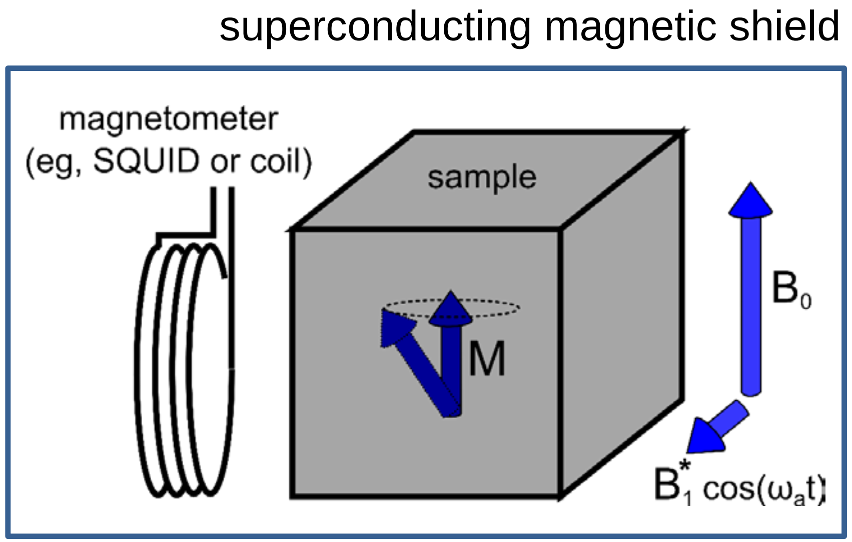
CASPEr-now in July 2017



Systematics

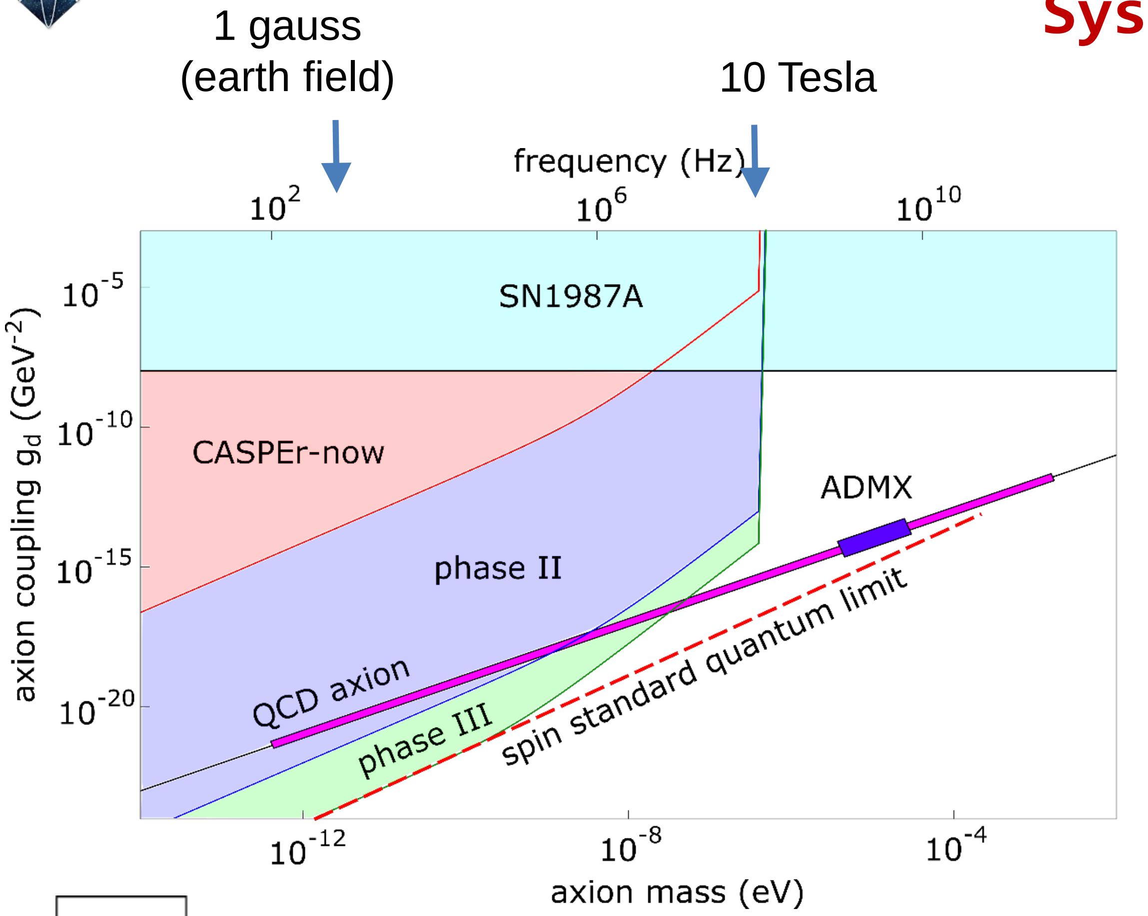
main systematic: vibrations

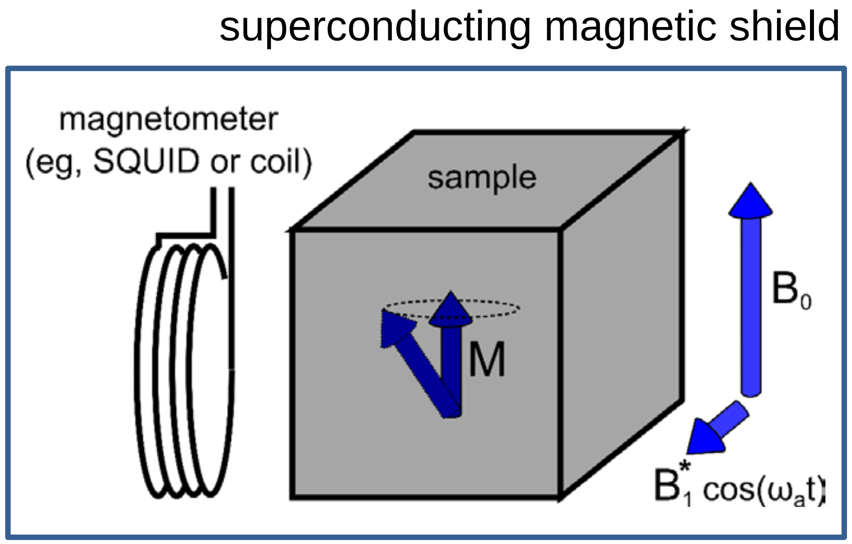




vibrations (~100Hz → kHz) of the magnetometer pickup loop with respect to the applied magnetic field will show up as oscillating signals mimicking the axion signature

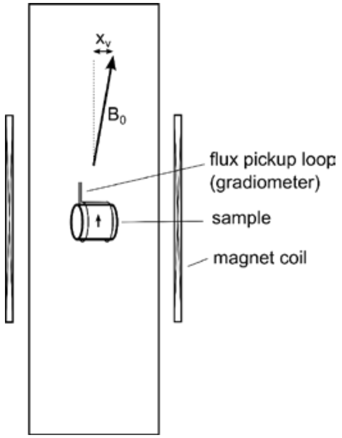
Systematics





vibrations (~100Hz → kHz) of the magnetometer pickup loop with respect to the applied magnetic field will show up as oscillating signals mimicking the axion signature

- small B_0 → searching for axions at small mass (low frequency, close to vibration peaks), but signal due to vibrations is small
- large B_0 → larger signal due to vibrations, but searching for axions at large mass (high frequency, far from vibration peaks)

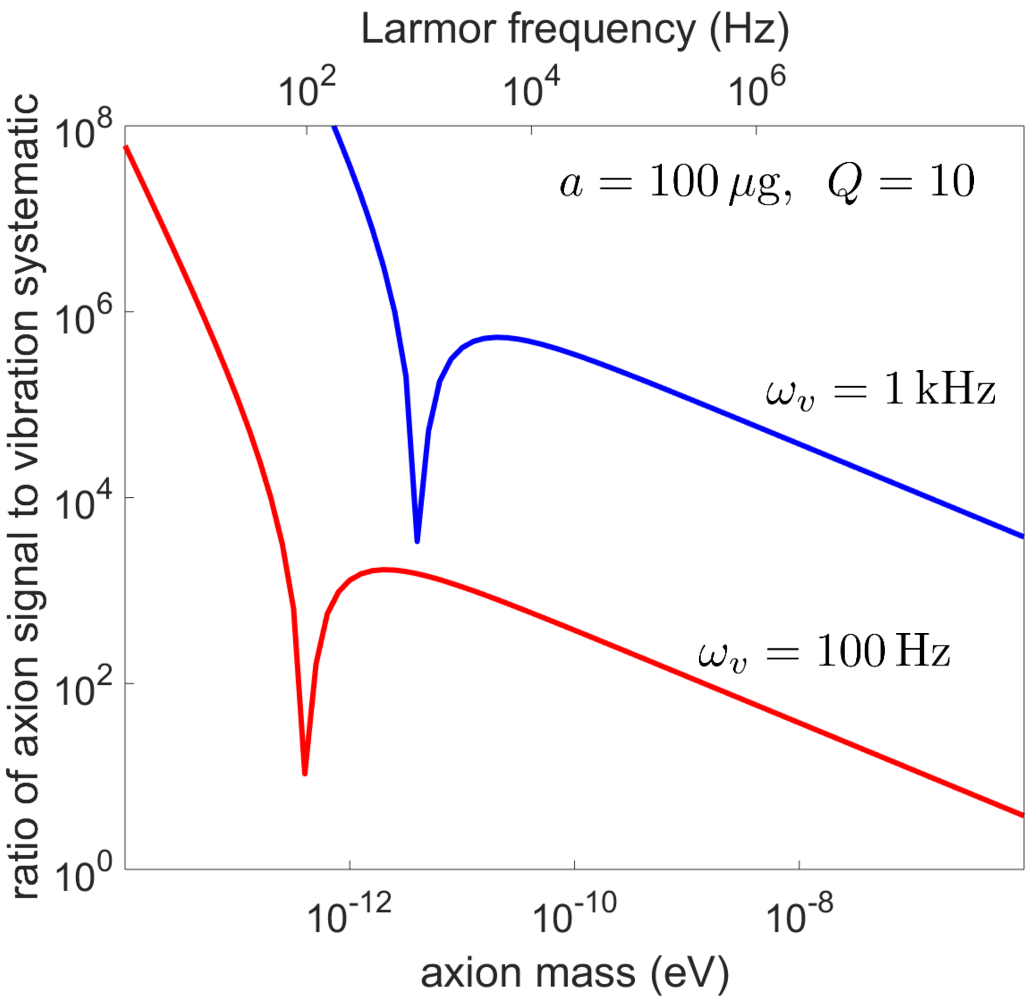


axion Q ~ 10^6, vibration Q ~ 10

➡ careful spectral analysis

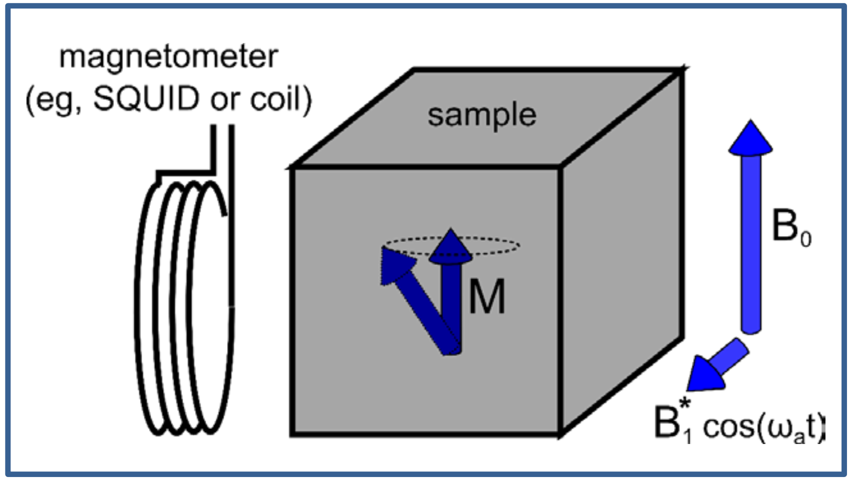
gradiometer pickup loop configuration

Systematics



vibrations on the level of 100 μg, at frequencies ~kHz are acceptable

superconducting magnetic shield



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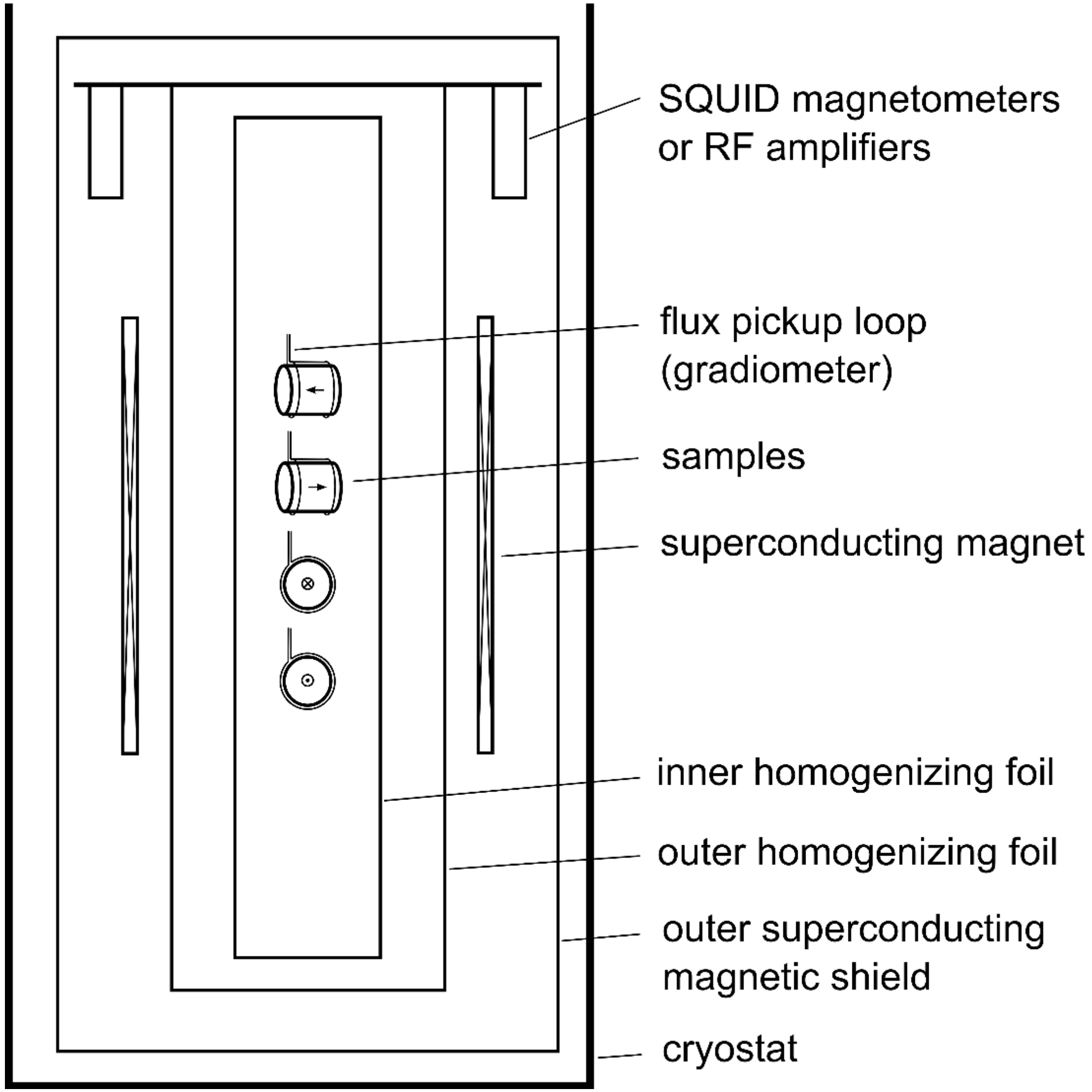

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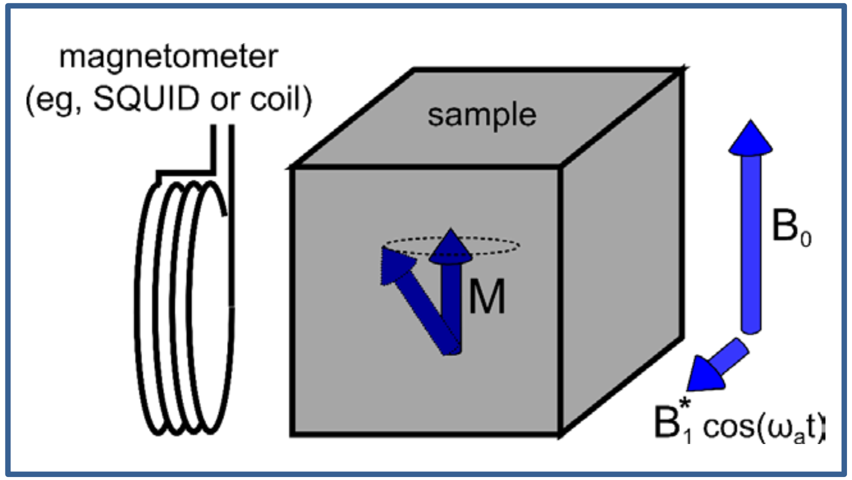


in order to reject systematics, we have several samples:
axions will couple identically (in-phase)

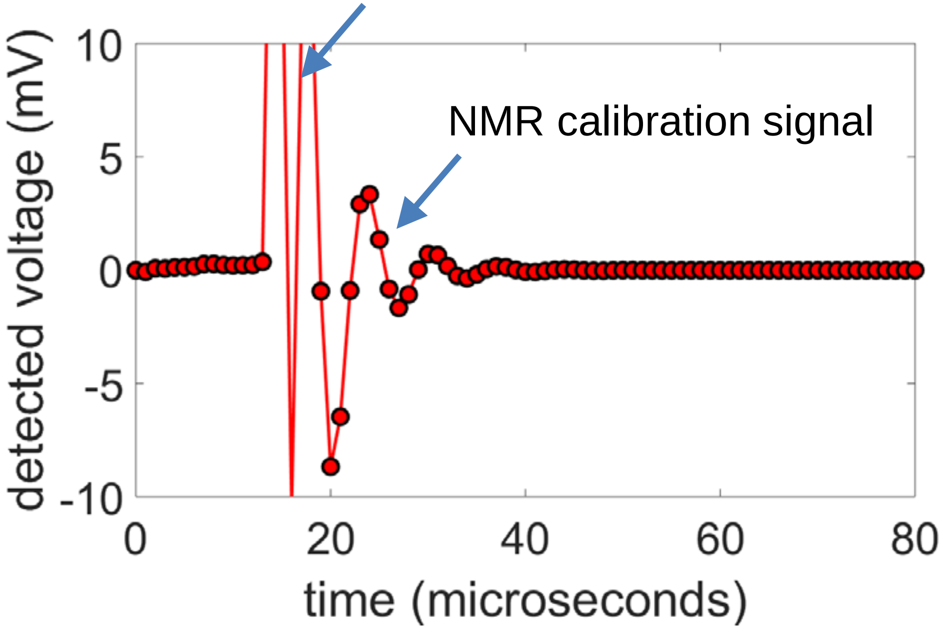
if we have a detection, axion Compton frequency (inverse mass) must be the same in independent experiments

Current status

assembly and testing of magnetic resonance electronics and DAQ system at Boston University

probe ringing during excitation pulse

NMR calibration signal

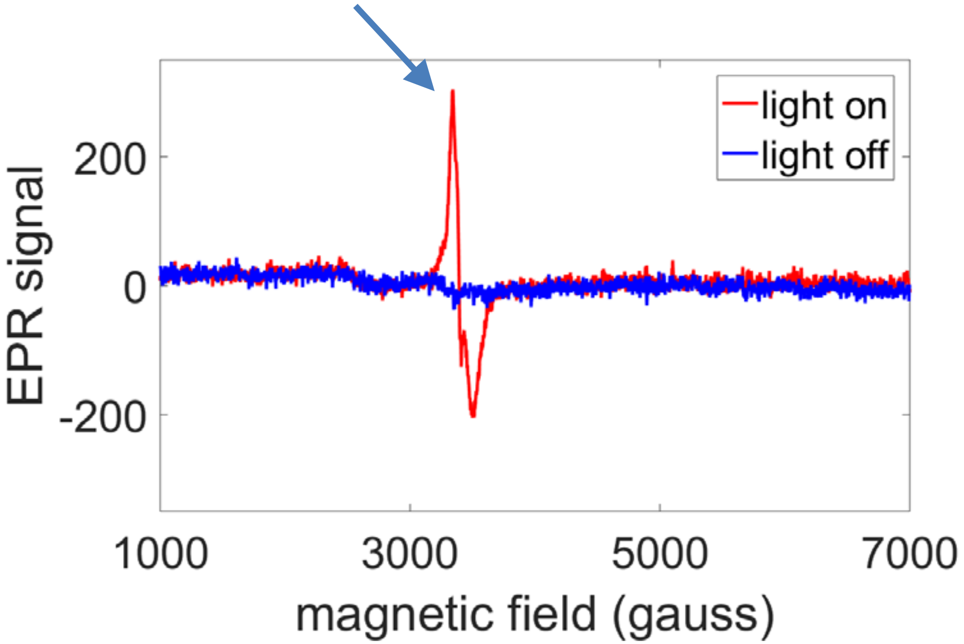


➡ integrate into the apparatus

first results on optically-excited transient paramagnetic centers in PMN-PT at EPFL

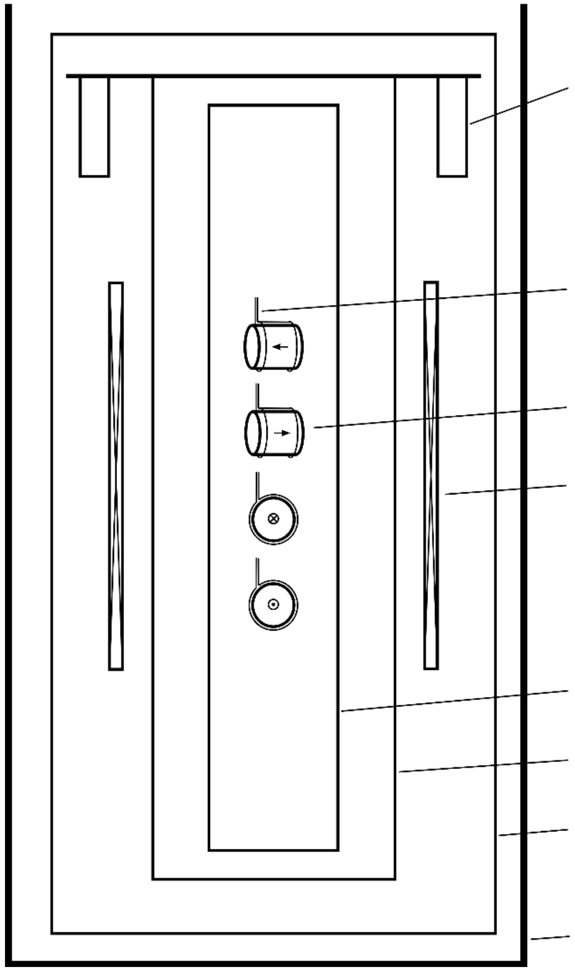
Dr. Bálint Náfrádi, EPFL
Dr. Claudia Avalos, EPFL
Prof. Lyndon Emsley, EPFL

EPR signal due to g=2 transient paramagnetic centers after 405nm laser excitation, lifetime ~ 10 seconds



➡ optically-assisted hyperpolarization

Current status



SQUID magnetometers or RF amplifiers → in place at BU

flux pickup loop (gradiometer)

samples → in place at BU

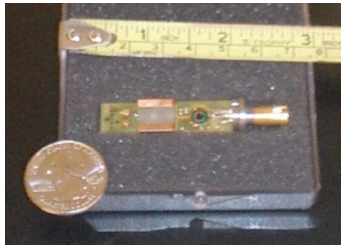
superconducting magnet → in place at BU

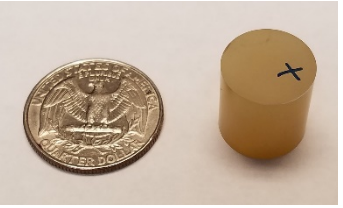
inner homogenizing foil

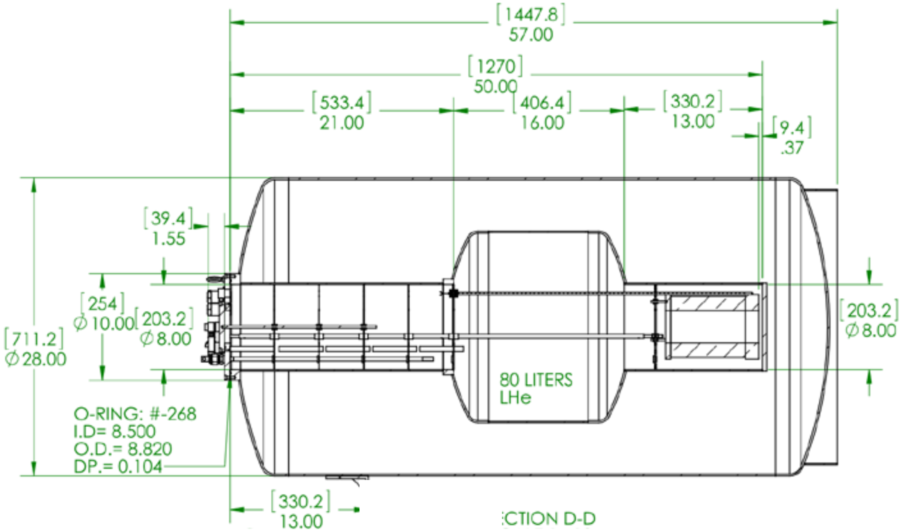
outer homogenizing foil

outer superconducting magnetic shield

cryostat → in place at BU



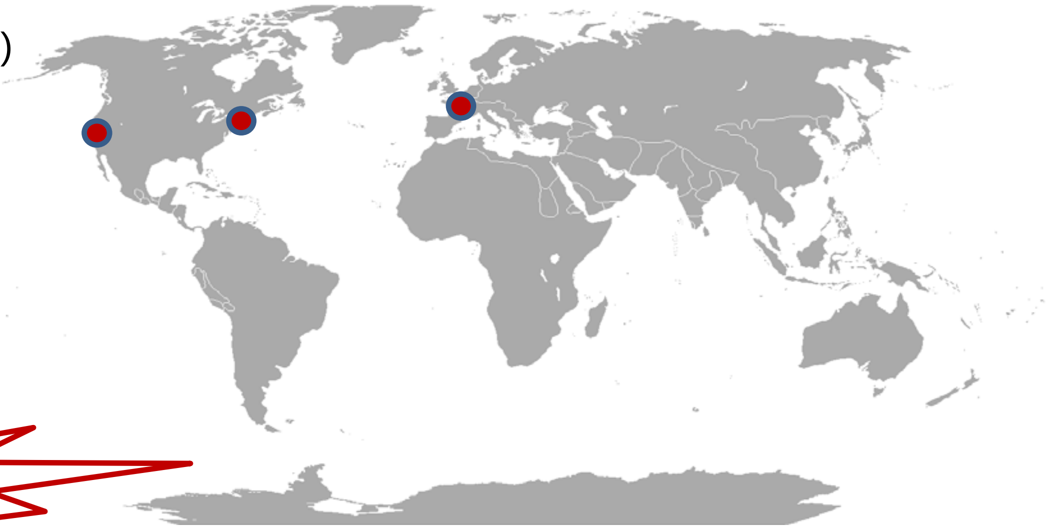




ongoing assembly and testing

Our collaboration

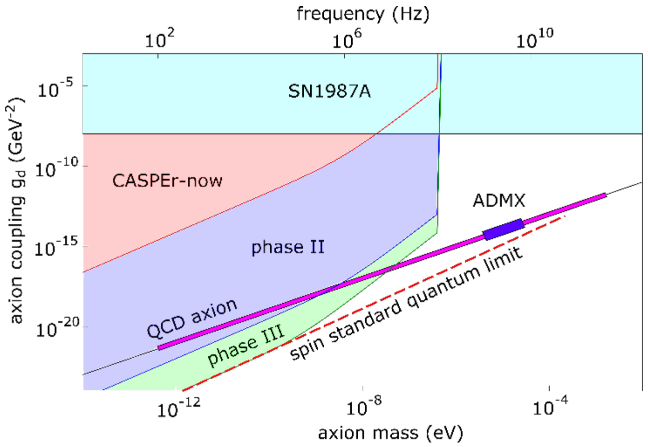
Deniz Aybas (Boston University)
Alex Wilzewski (Boston University & Mainz)
Janos Adam (Boston University)
Arne Wickenbrock (Mainz)
John Blanchard (Mainz)
Gary Centers (Mainz)
Nataniel Figueroa (Mainz)
Marina Gil Sendra (Mainz)
Tao Wang (UC Berkeley)



Surjeet Rajendran (UC Berkeley),
Peter Graham (Stanford)
Dmitry Budker (UC Berkeley & Mainz)
Alex Sushkov (Boston University)
Derek Kimball (CSUEB)

postdoc & student opportunities

Boston University:
CASPEr-electric using spins in solids

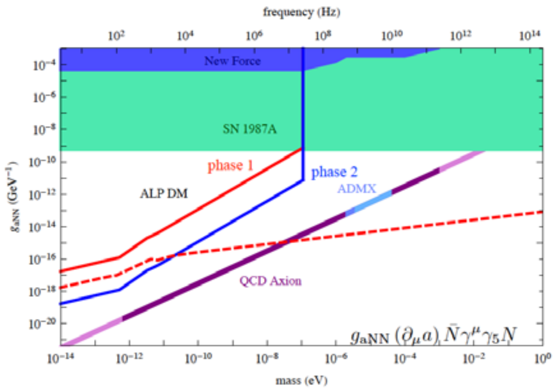


Alfred P. Sloan FOUNDATION

SIMONS FOUNDATION

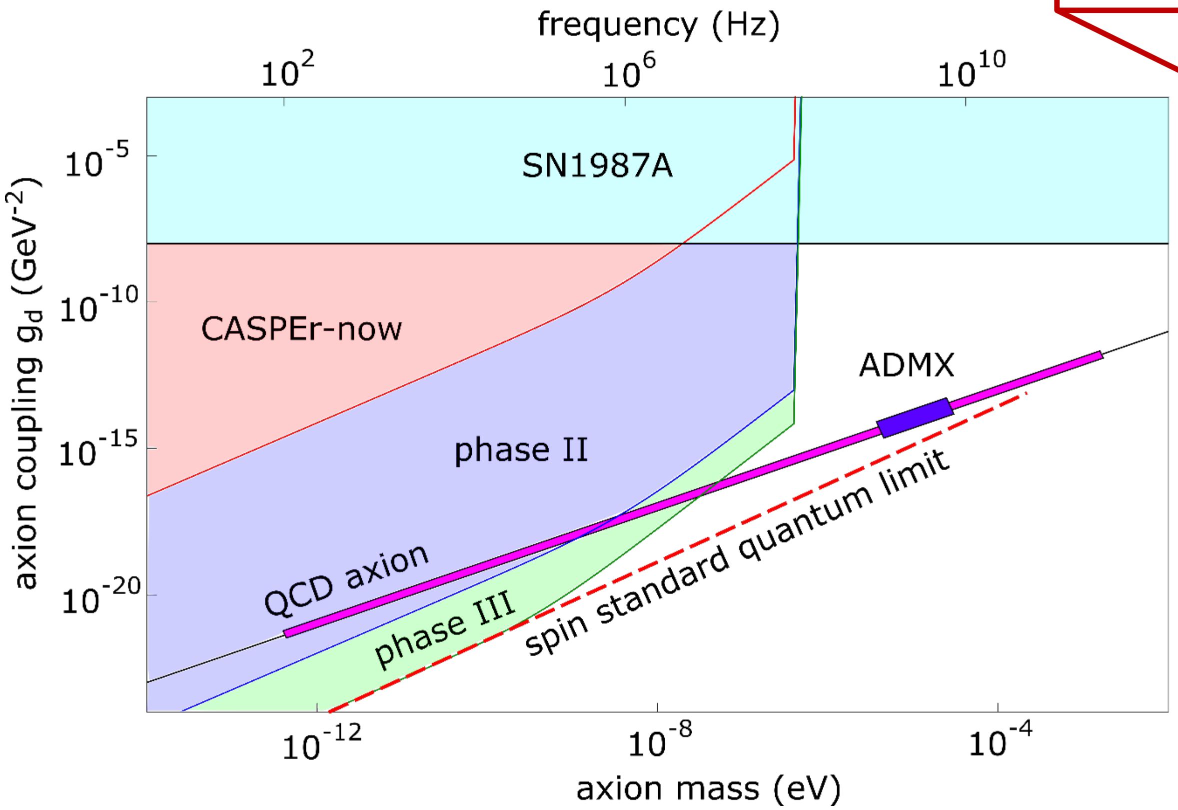
HEISING - SIMONS FOUNDATION

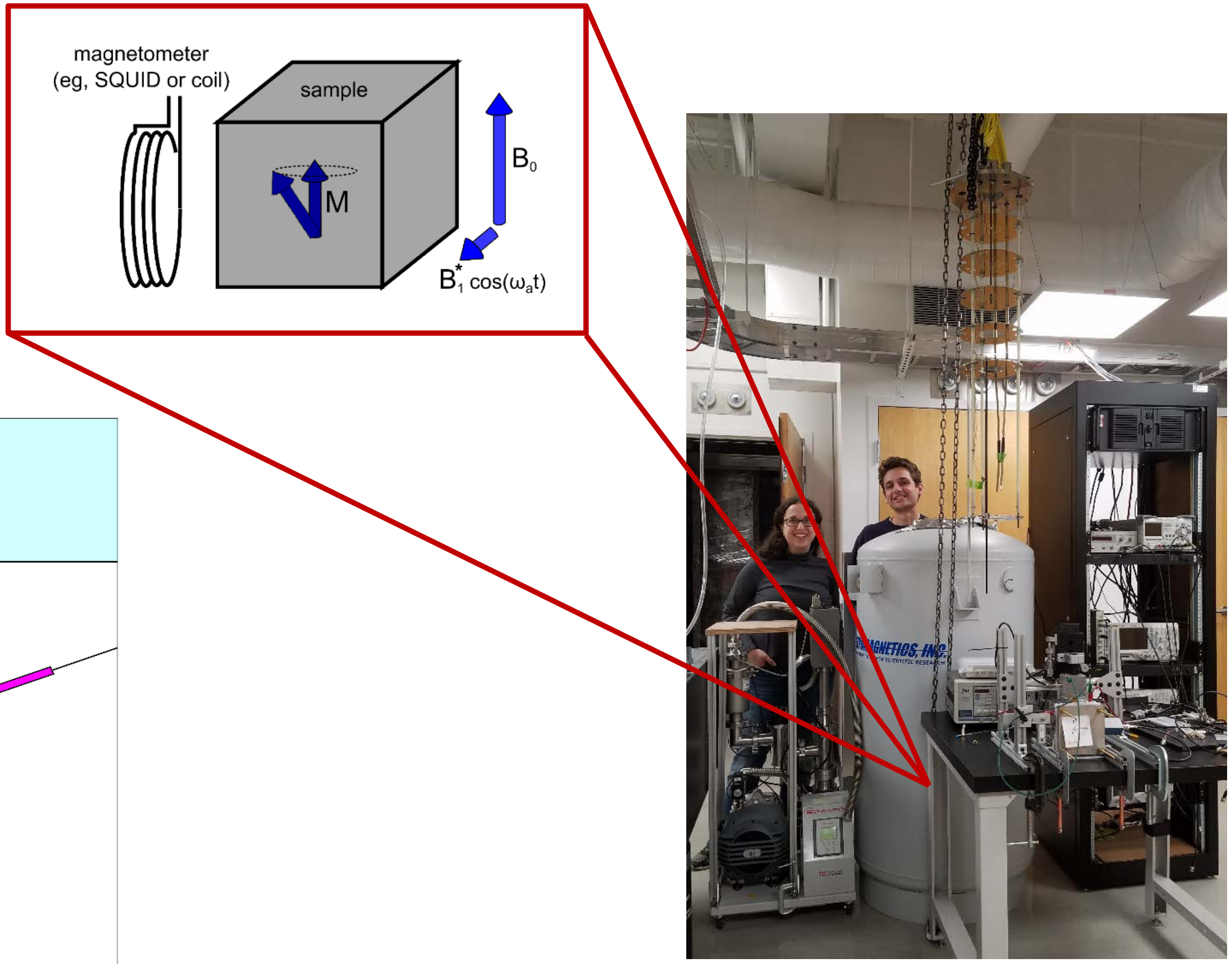
Mainz:
CASPEr-wind using liquid Xenon



Stanford, Berkeley, CSUEB:

Thank you





[*Phys. Rev. X* **4**, 021030 (2014)]