Title: Cosmic Axion Spin Precession Experiment (CASPEr): Using the Tools of Quantum and Condensed Matter Physics to Search for Axion-Like Dark Matter

Date: Jun 19, 2018 11:00 AM

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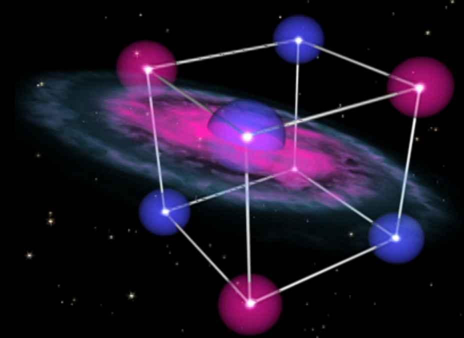
Abstract:

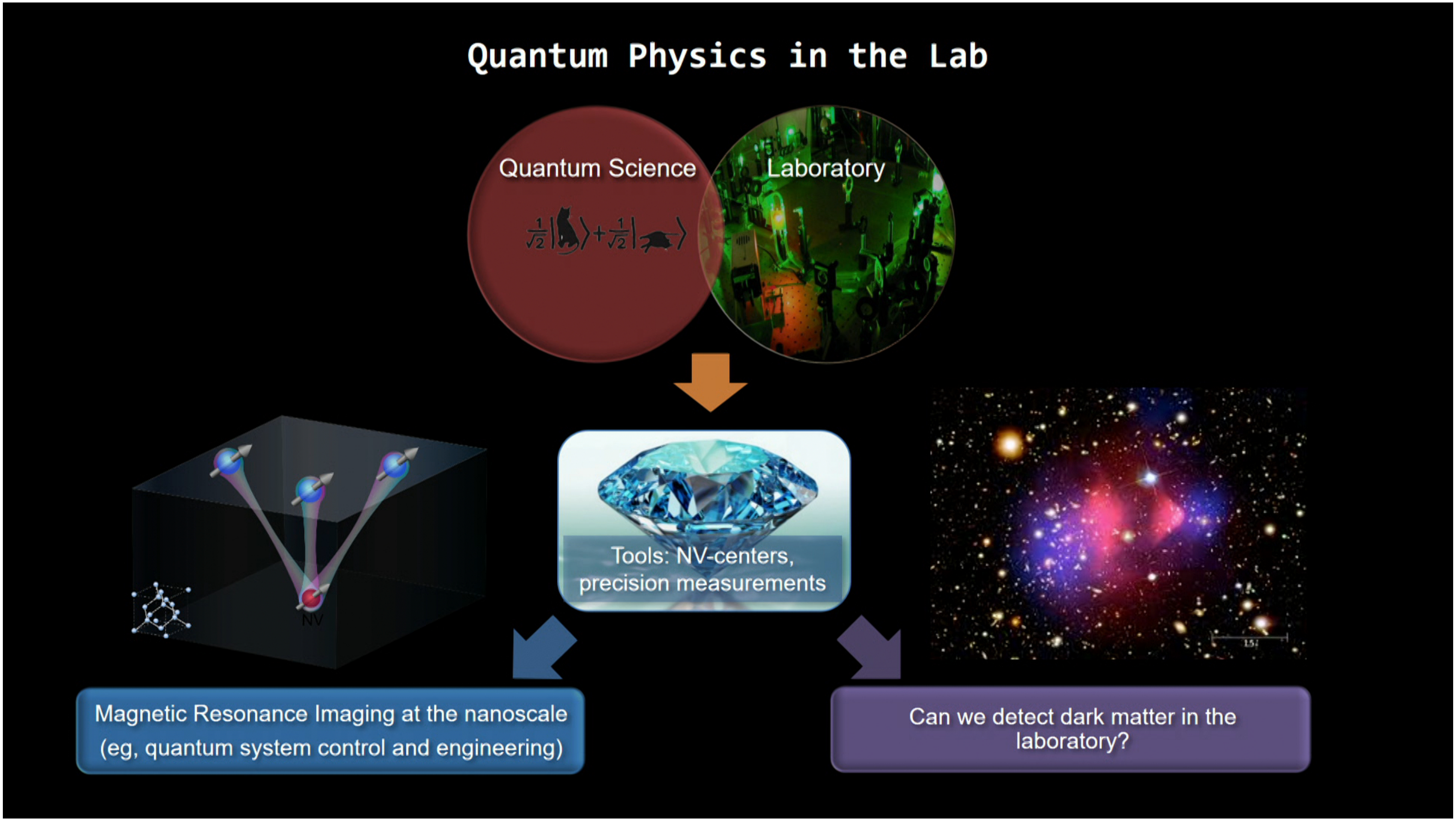


Cosmic Axion Spin Precession Experiment (CASPEr): using the tools of quantum and condensed matter physics to search for axion-like dark matter

Alex Sushkov

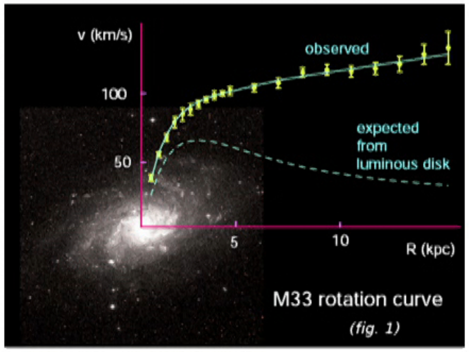
Deniz Aybas, Alex Wilzewski, Janos Adam, Sasha Gramolin, Hannah Mekbib, Adam Pearson, Annalies Kleyheeg
+ CASPEr collaboration

HEISING - SIMONS FOUNDATION
SIMONS FOUNDATION
BOSTON UNIVERSITY
Alfred P. Sloan FOUNDATION

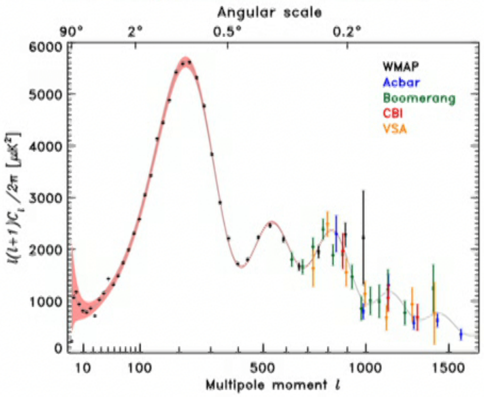

Quantum Physics in the Lab
Quantum Science
Laboratory
NV
Tools: NV-centers, precision measurements
Magnetic Resonance Imaging at the nanoscale (eg, quantum system control and engineering)
Can we detect dark matter in the laboratory?

Evidence for dark matter

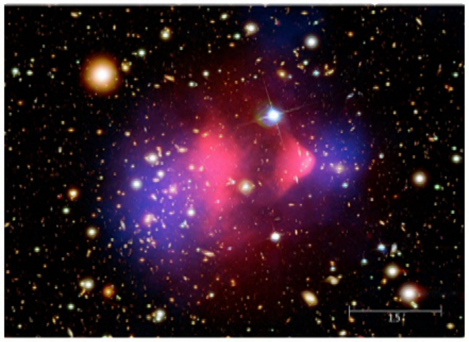
galaxy rotation curves



CMB angular power spectrum



galaxy clusters: Bullet cluster



+ gravitational lensing
+ structure formation
+ …

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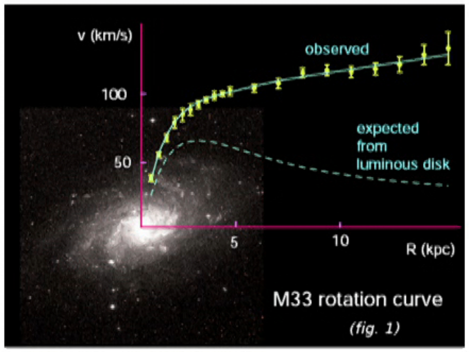

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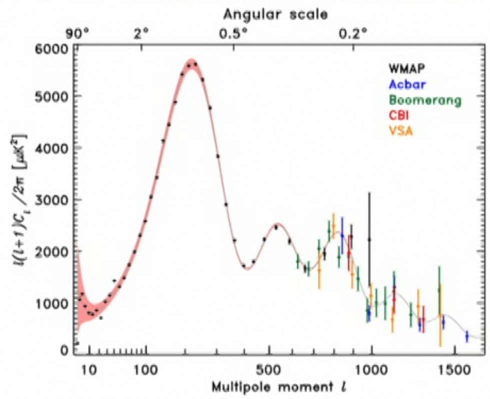

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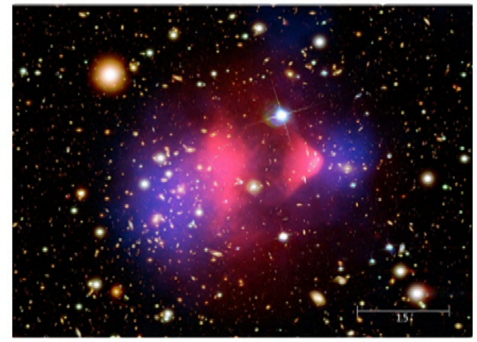

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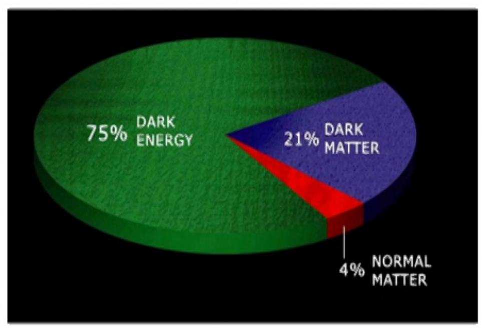
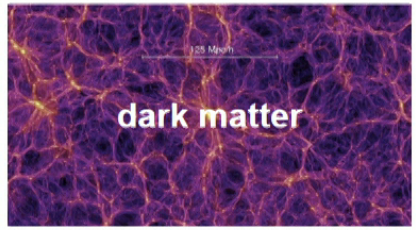


approximately 21% of energy in the Universe is in the form of dark matter: $\rho \approx 0.3\,\mathrm{GeV}/\mathrm{cm}^3$

Some of the candidates for dark matter



Weakly Interacting Massive
Particles (WIMPs):
mass ~ 100 GeV
[Phys. Rev. Lett. **118**, 021303 (2017)]

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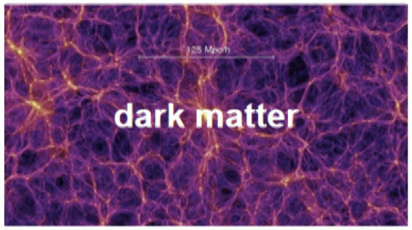

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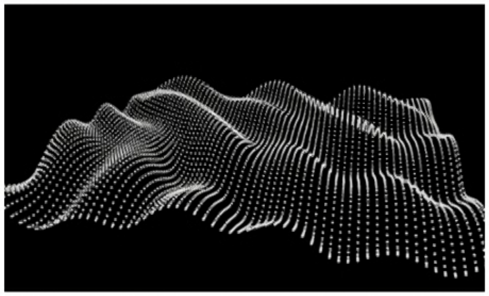

Light candidates
(eg: axions, dark photons)
mass ~ μeV
[Phys. Rev. Lett. **118**, 061302 (2017)]

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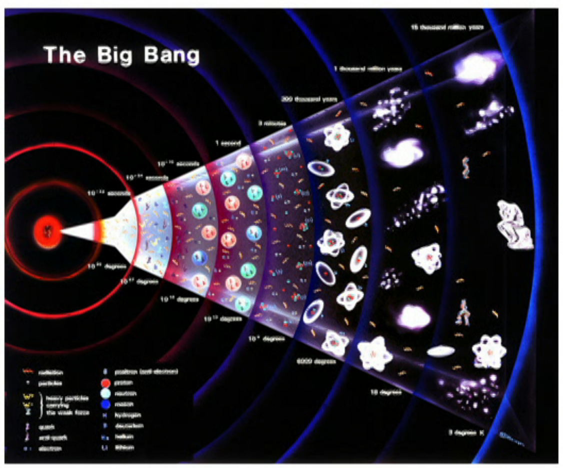
mass ~ 100 GeV

the WIMP miracle: weak interaction cross section gives correct abundance



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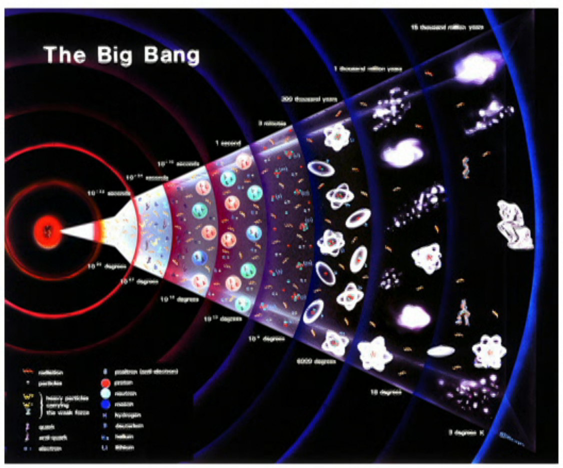
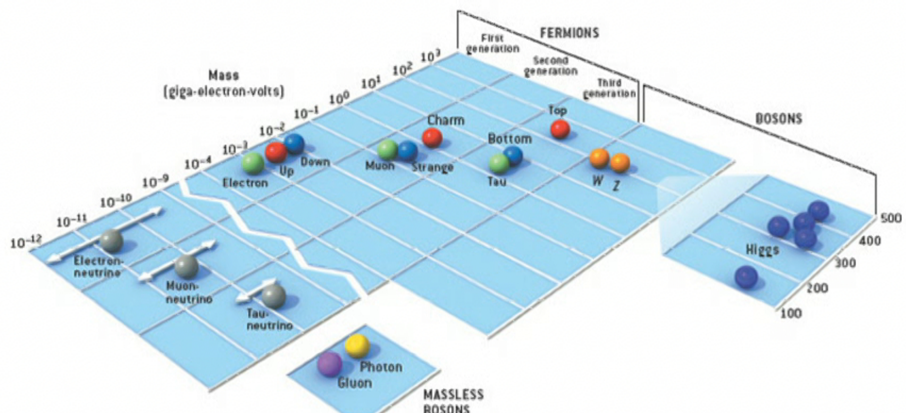


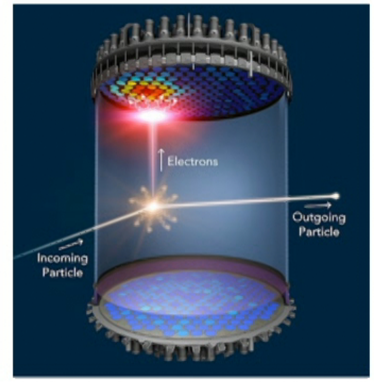
WIMP has the right properties to be the lightest supersymmetric particle

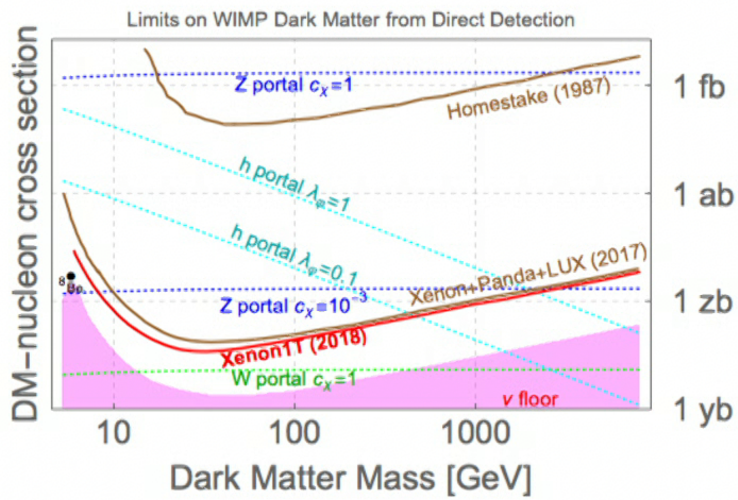


Searching for WIMPs

indirect detection

direct detection

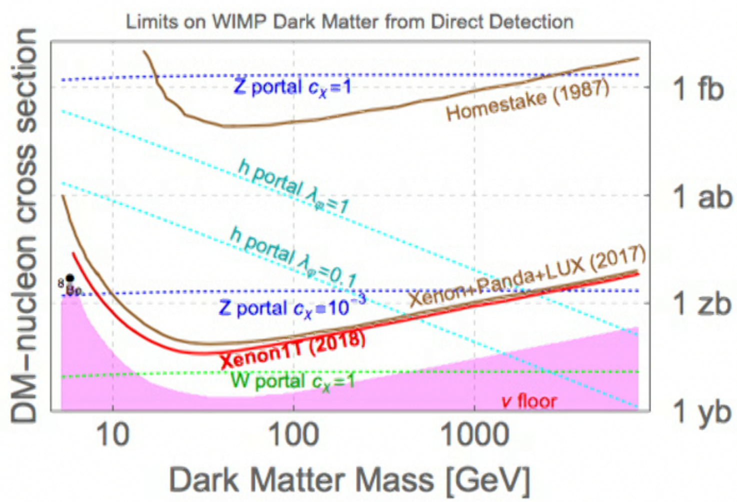




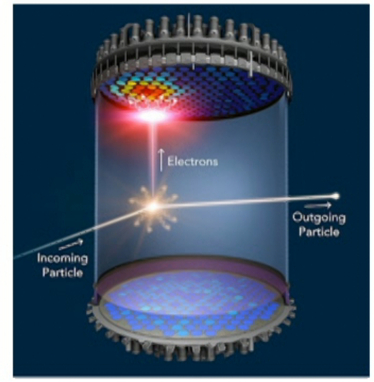
Searching for WIMPs

indirect detection

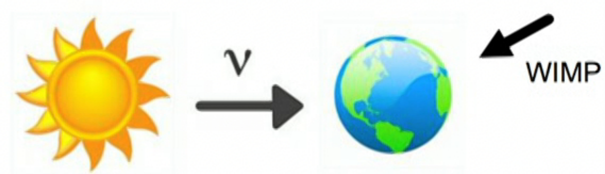
a number of extremely sensitive experimental searches (approaching the neutrino floor), but no clear detection so far



direct detection

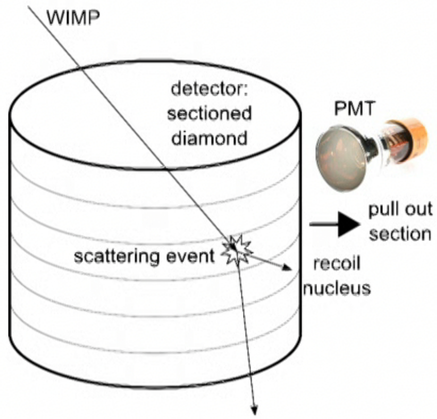


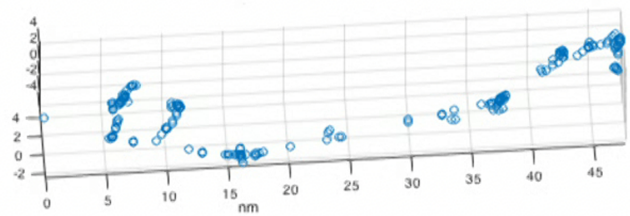
to go beyond the neutrino floor we need directional information



Idea: direction-sensitive WIMP detector based on quantum defects in 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





details: [*Phys. Rev. D* **96**, 035009 (2017)]
(collaboration with Ron Walsworth, Misha Lukin, Surjeet Rajendran)

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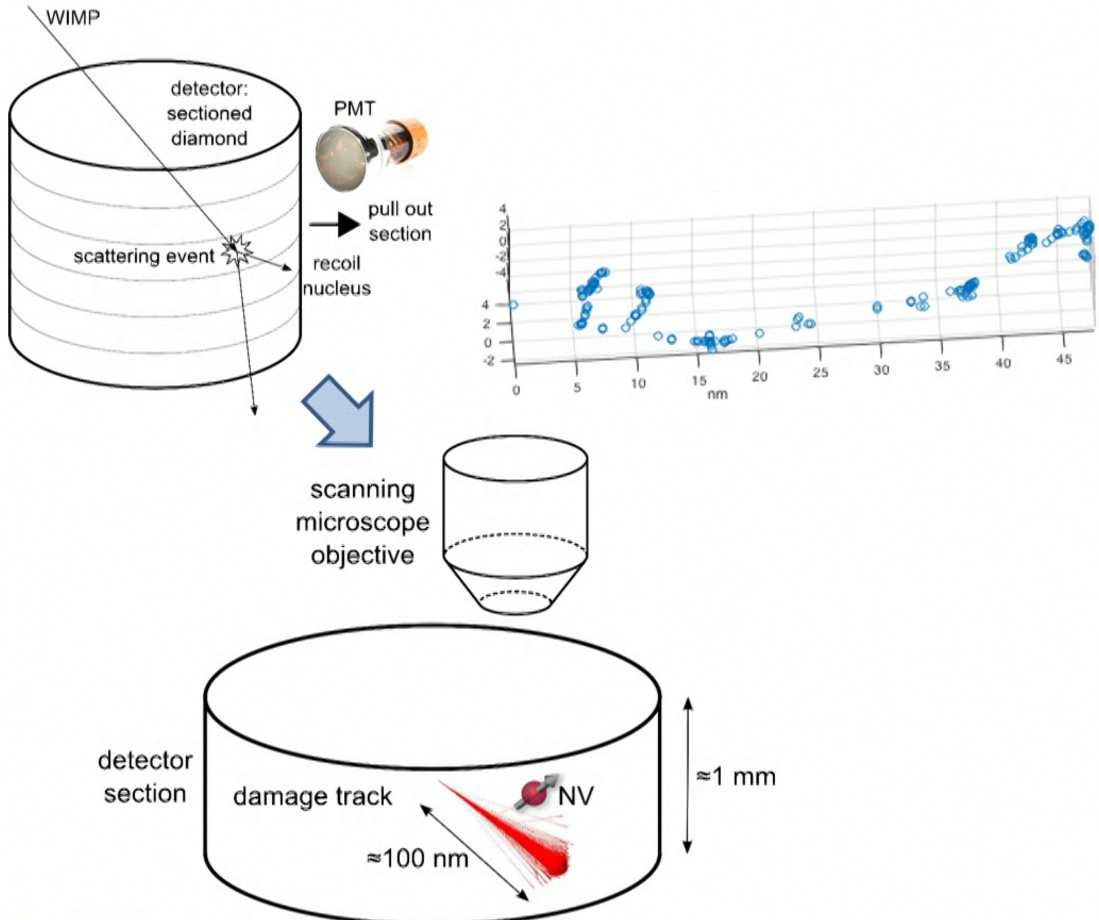

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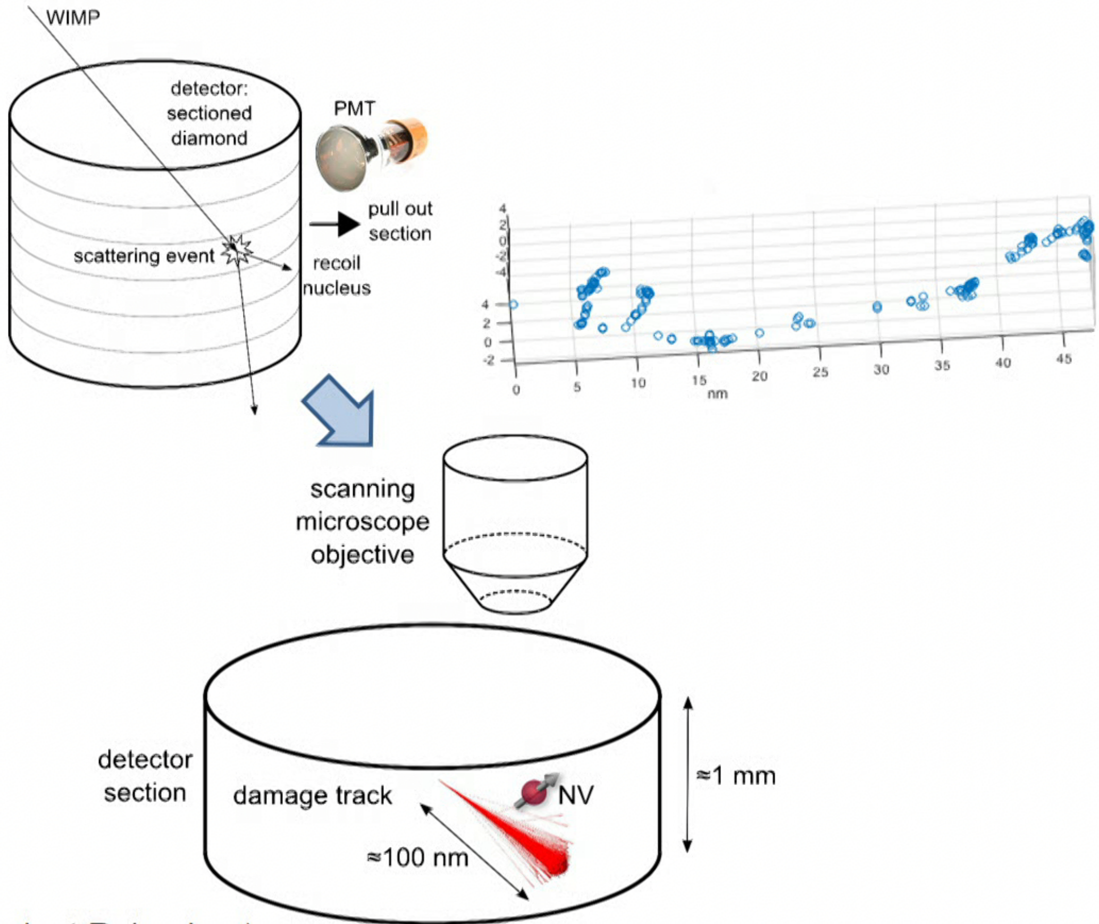

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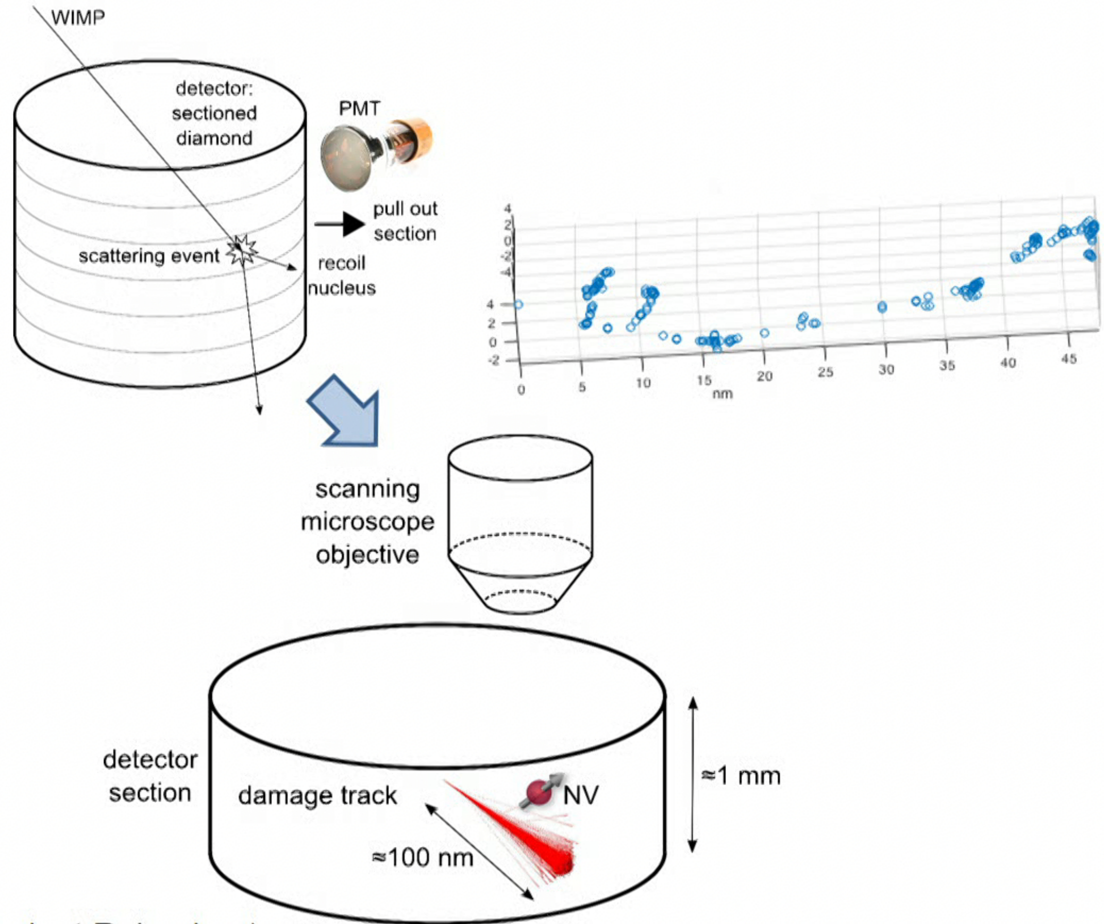

a directional detector for WIMP dark matter

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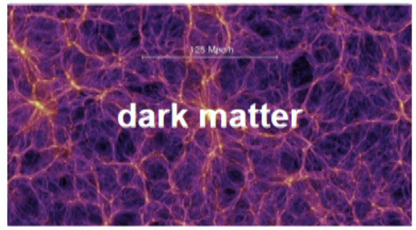

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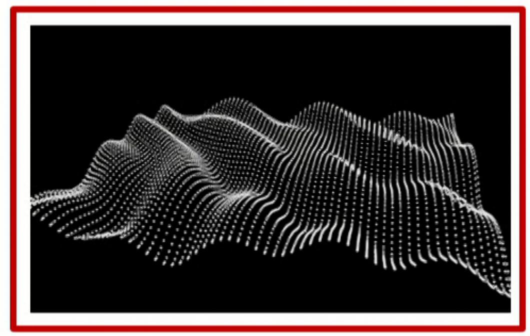

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Axions

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4. Possible couplings to standard model particles:

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

axion field amplitude → a

symmetry breaking scale → f_a

coupling to photons

→ Primakoff effect

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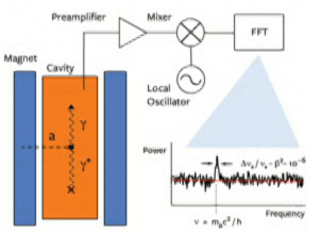
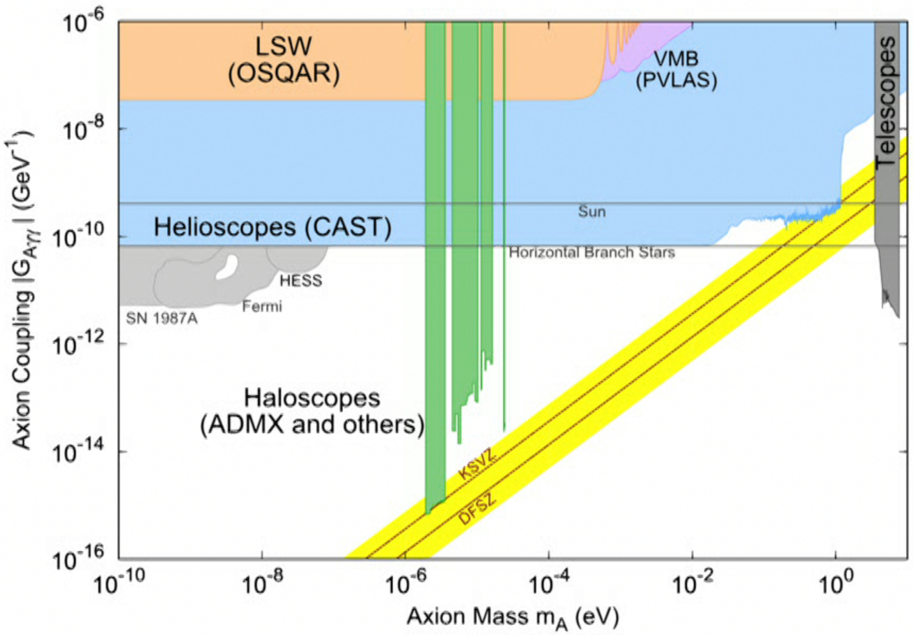


most axion DM searches:
ADMX, HAYSTAC, …
(sensitivity all the way down to the QCD axion coupling!)

[Phys. Rev. Lett. **120**, 151301 (2018)]



[C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update]

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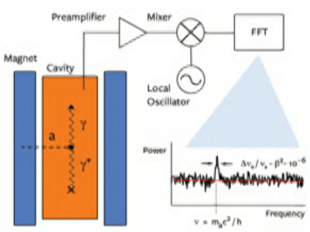

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[Phys. Rev. Lett. **115**, 201301 (2015)]
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coupling to gluons

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

→ spin to axion coupling:

$$H_e \propto a \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{E}}^*$$

CASPEr-electric

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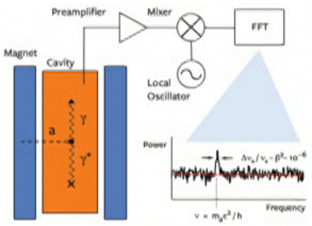

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CASPEr-electric

coupling to fermions
→ creates axion "wind"

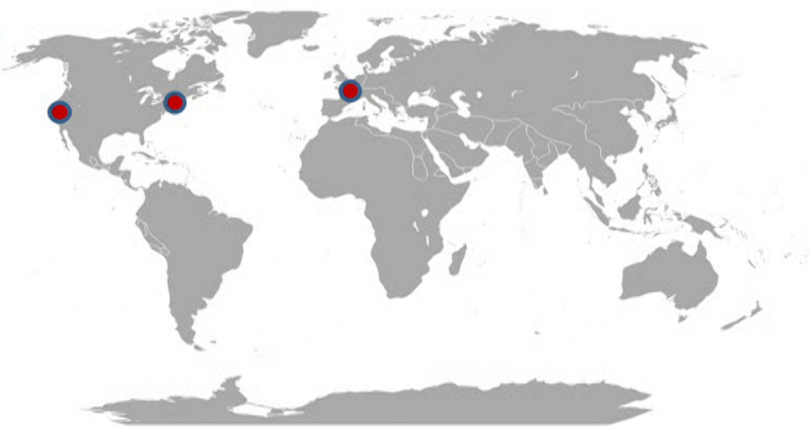
→ spin to axion "wind" coupling:

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

CASPEr-wind

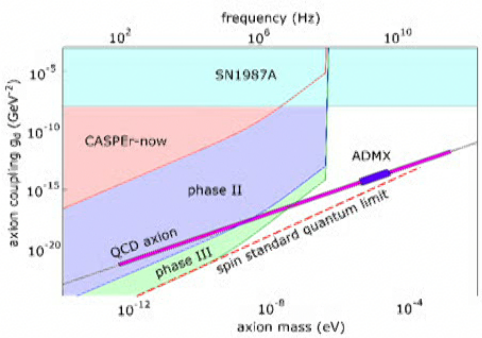
Our collaboration

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



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

Boston University:
CASPEr-electric using spins in solids



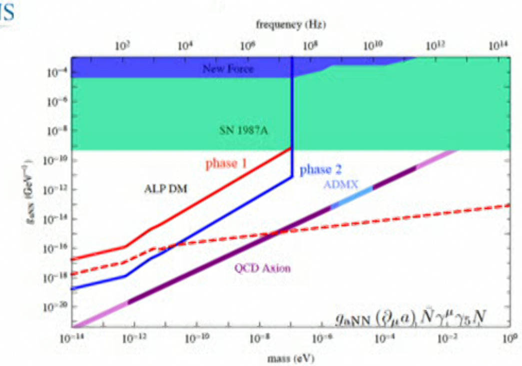
Alfred P. Sloan FOUNDATION

SIMONS FOUNDATION

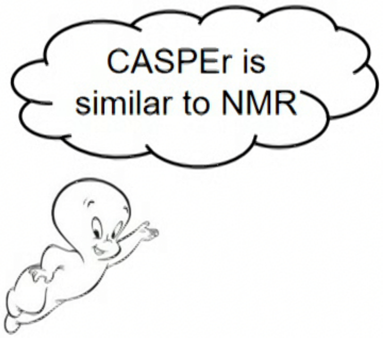
HEISING - SIMONS FOUNDATION

Stanford, Berkeley, CSUEB:

Mainz:
CASPEr-wind using liquid Xenon



Aside: magnetic resonance



Aside: magnetic resonance

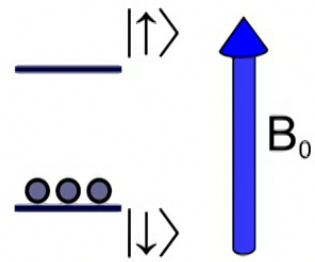
CASPEr is similar to NMR

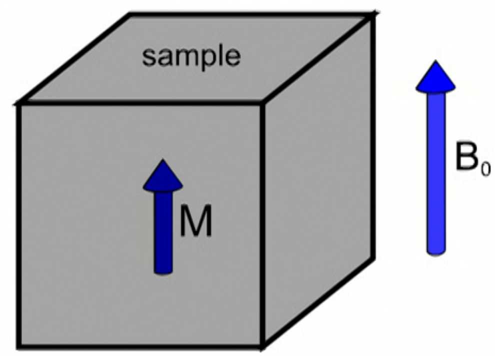
interaction: $H_{\rm NMR} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}$

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

1) place 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





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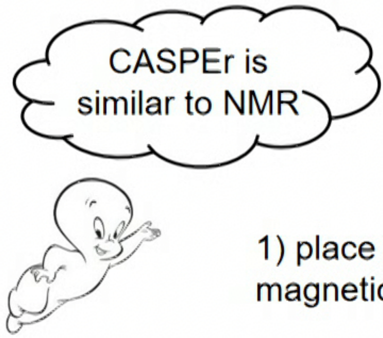

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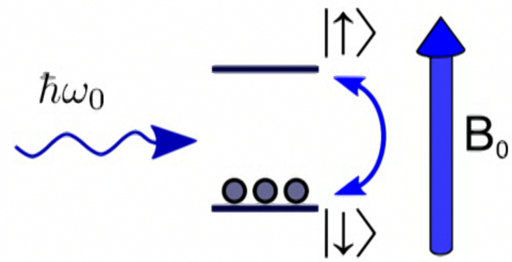
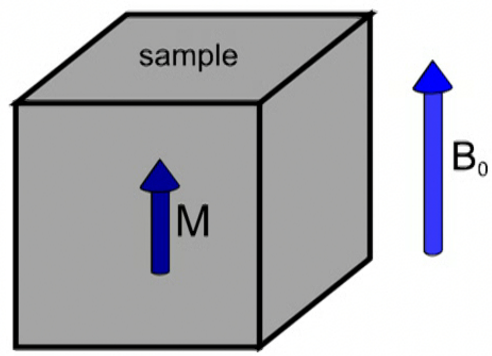
3) resonance: $\hbar\omega_0 = g\mu B_0$

➡ RF magnetic field can now flip spins!





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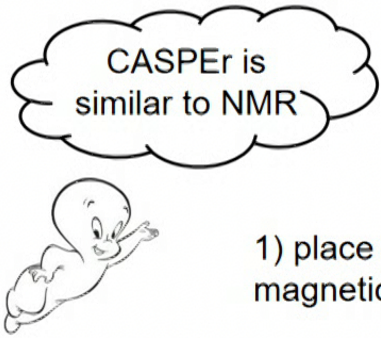

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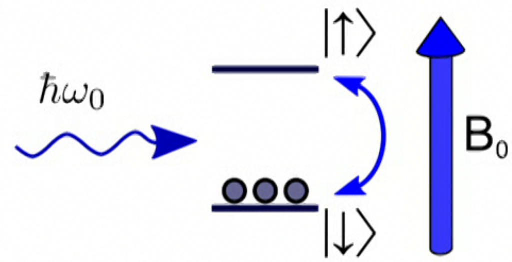

2) spin polarization (thermal or optical) in a cm^3 sample

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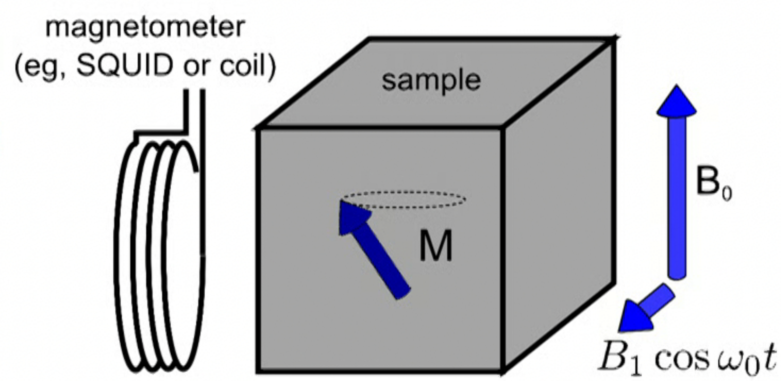
- RF magnetic field can now flip spins!
- sample magnetization tilts and precesses

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



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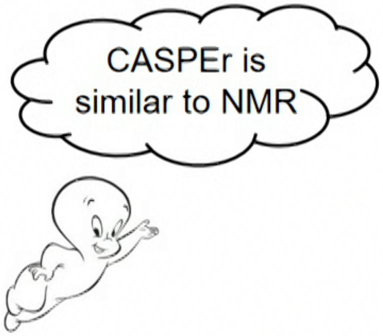

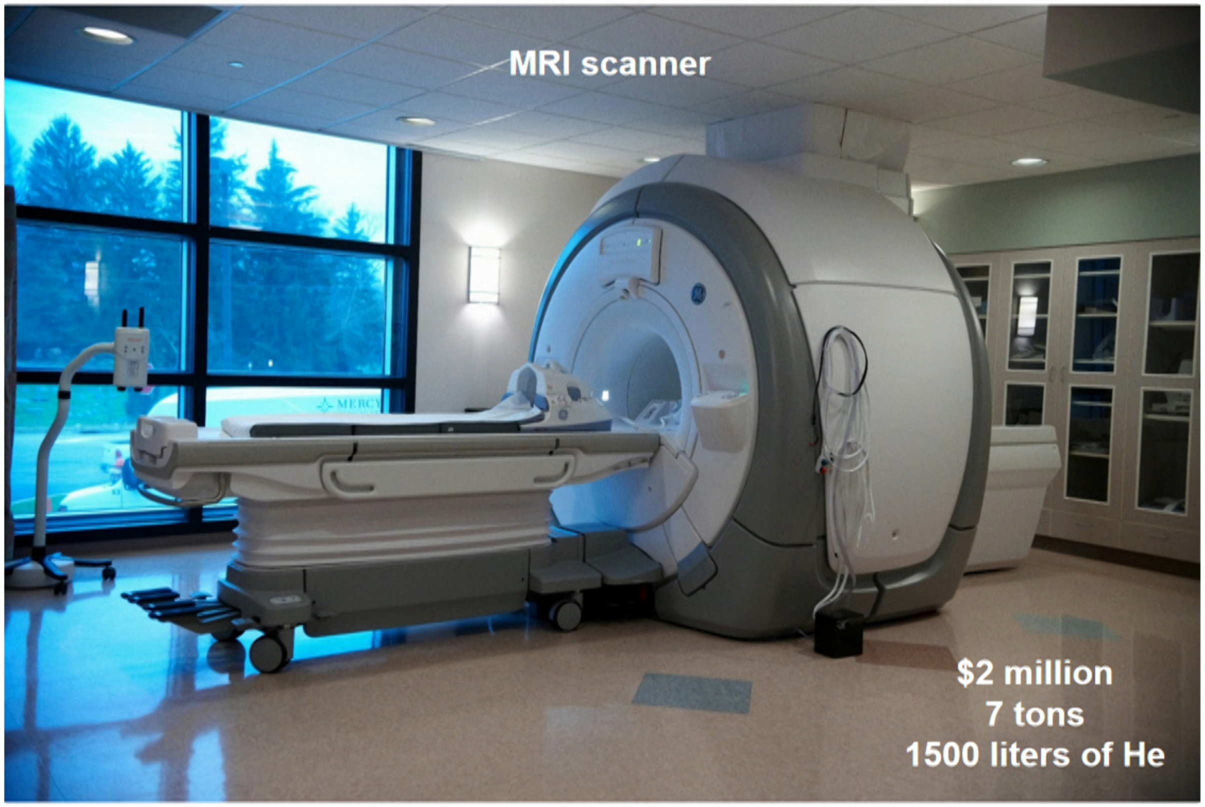

a very useful tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

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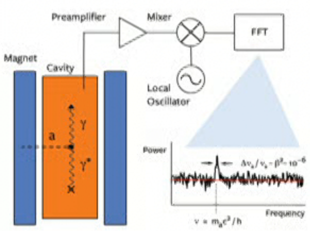
$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a}\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

coupling to photons
→ Primakoff effect



most axion DM 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:

$$H_e \propto a\vec{\sigma} \cdot \vec{E}^*$$

CASPEr-electric

coupling to fermions
→ creates axion "wind"

→ spin to axion "wind" coupling:

$$H_{\text{wind}} \propto \vec{\sigma} \cdot \vec{\nabla} a$$

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

Axion coupling to spin: CASPEr-electric

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

coupling constant — axion (or ALP) field — spin — effective electric field

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

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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

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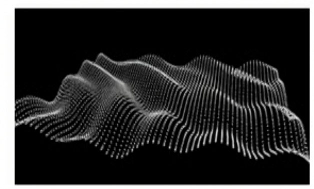

→ effective interaction: $H_{\mathrm{e}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

→ 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: $H_{\rm e} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

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

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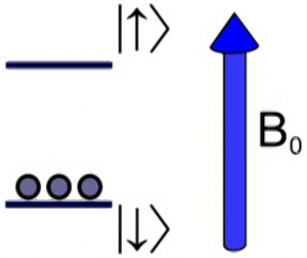

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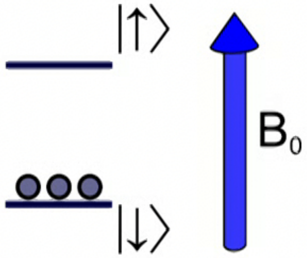

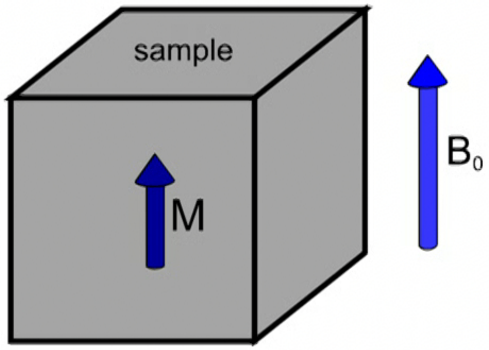

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- axion-spin interaction can now flip spins!
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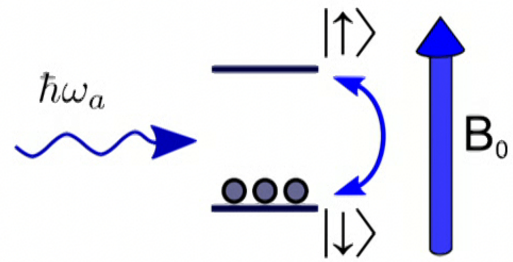

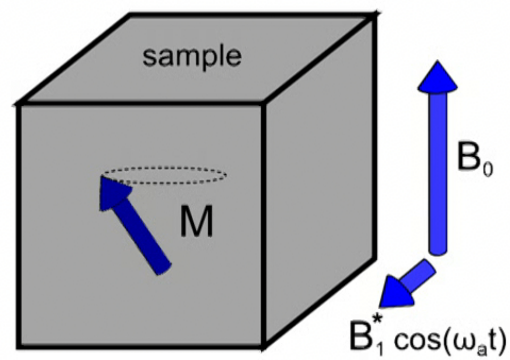

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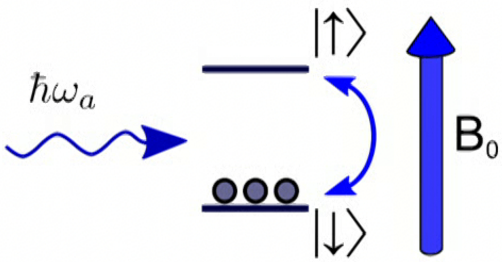

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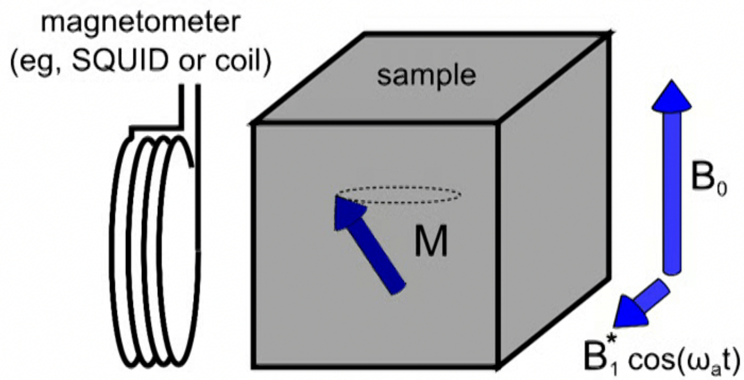
4) a magnetometer next to the sample detects the magnetic field created by this precessing magnetization

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



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

Choosing the sample material to maximize sensitivity

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

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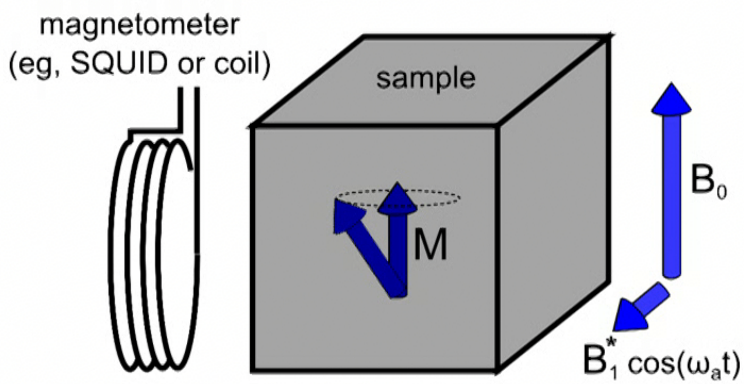
} important parameters



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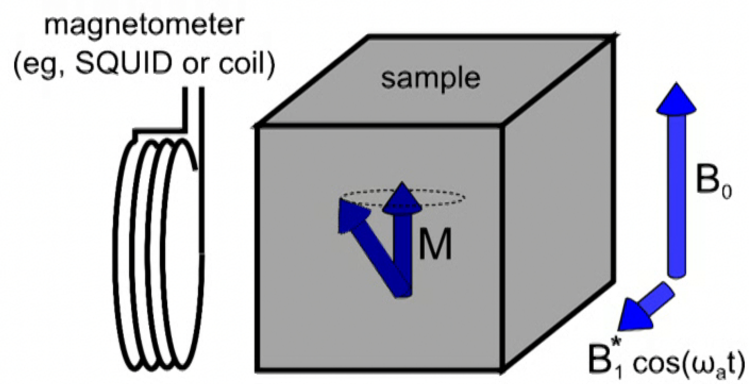

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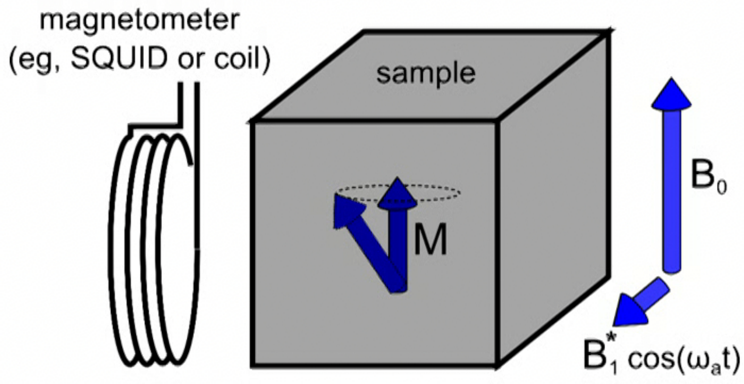

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acting on nuclear spins: $E^* \approx 10^8\ \mathrm{V/cm}$ (similar to a polar molecule ACME [Science 343, 269 (2013)])

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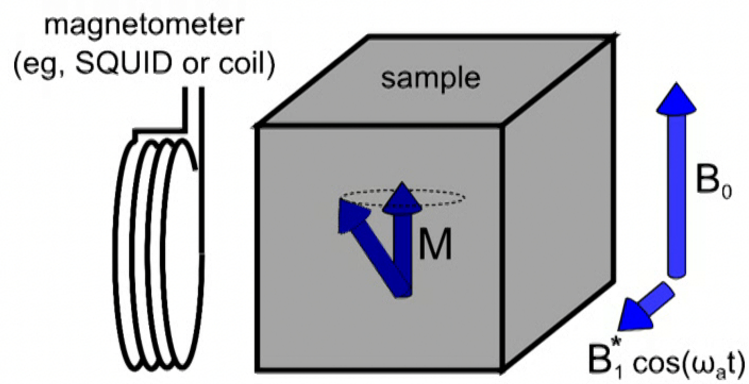

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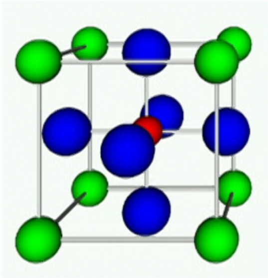

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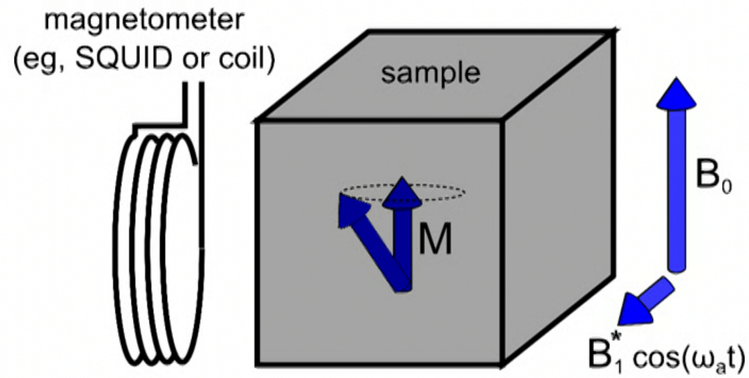

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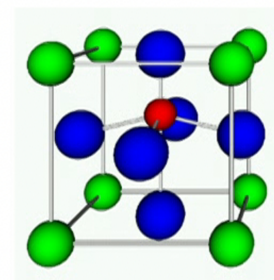

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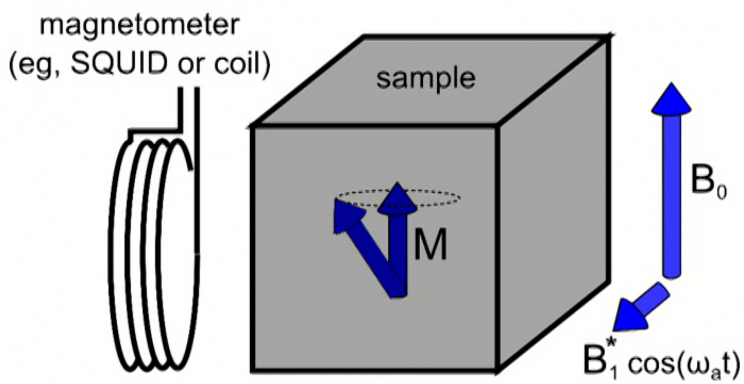

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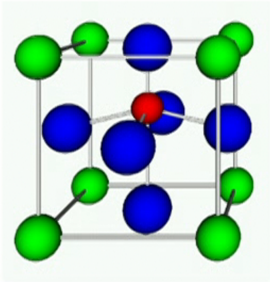

^{207}Pb spins in materials:

$PbTiO_3$
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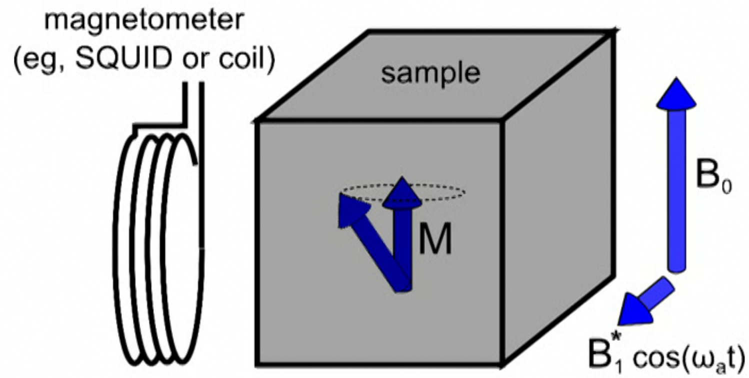

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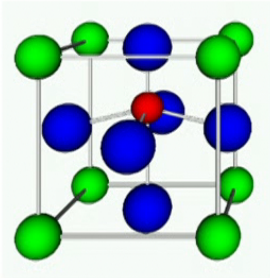

used for novel piezoelectric transducers

↓

commercially available

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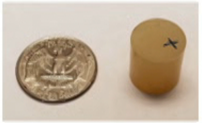
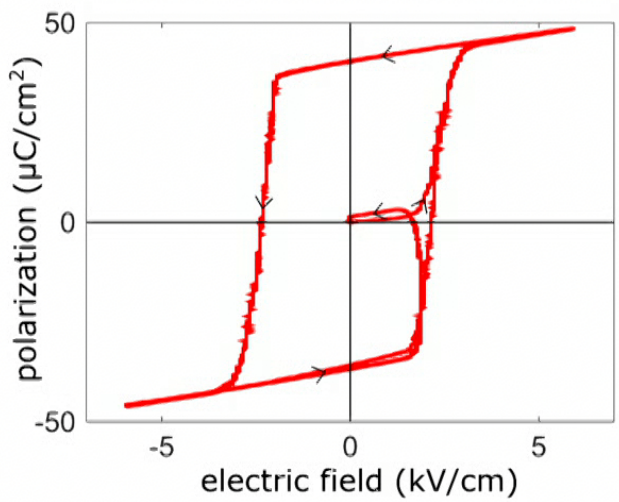


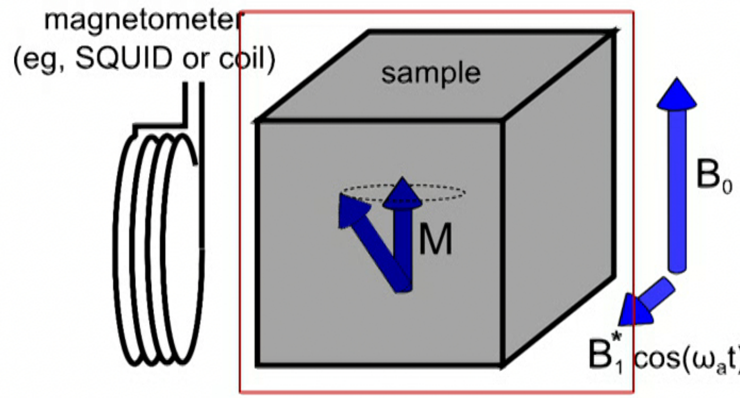
$\mathrm{Pb_5Ge_3O_{11}}$

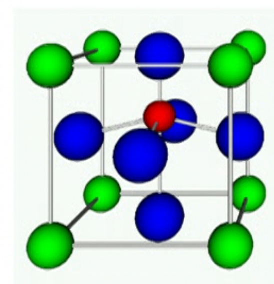
[*Phys. Rev. X* **4**, 021030 (2014)]

Ferroelectric polarization control of PMN-PT sample

our signal is $\propto E^* \propto$ ferroelectric polarization
↓
we should be able to polarize and depolarize our PMN-PT crystals







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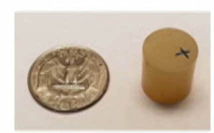

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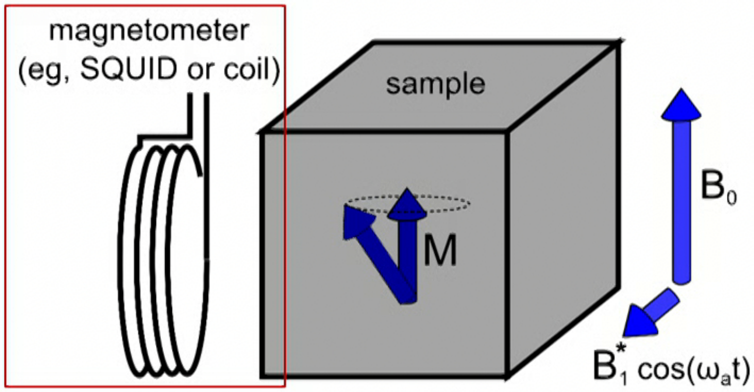
[*Phys. Rev. X* **4**, 021030 (2014)]

Optimizing the detector for maximum sensitivity

goal: detect sample spins tilting and precessing due to axion dark matter



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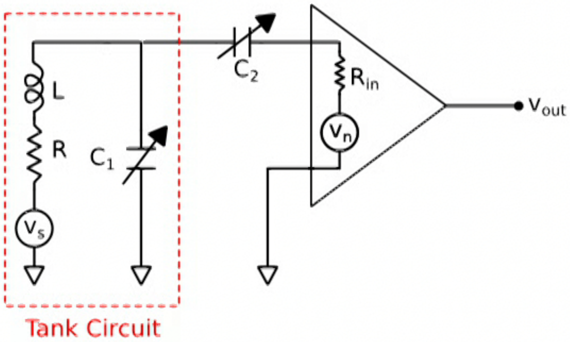
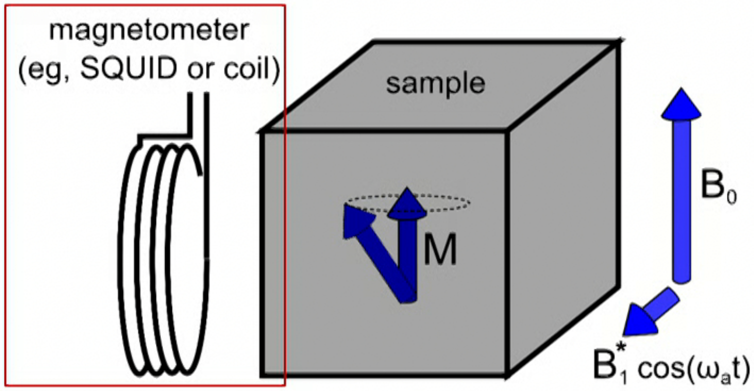
inductive (Faraday) detection:

pickup coil
+
matched tank circuit
+
RF amplifier

used for NMR at high frequencies





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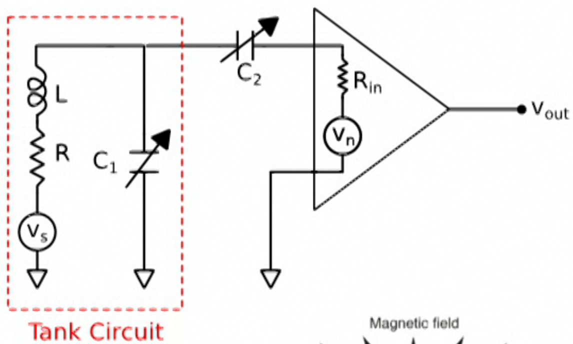
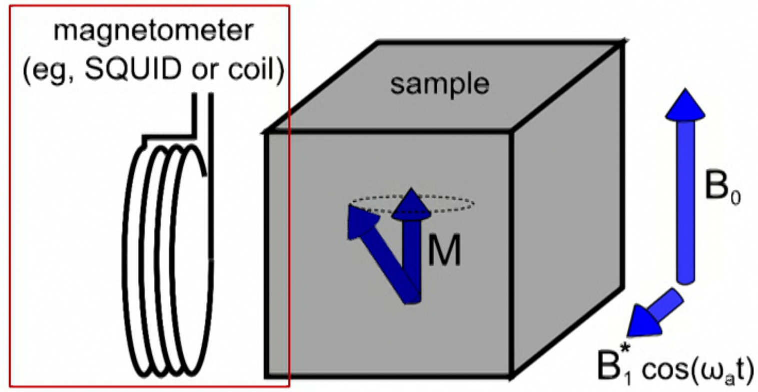
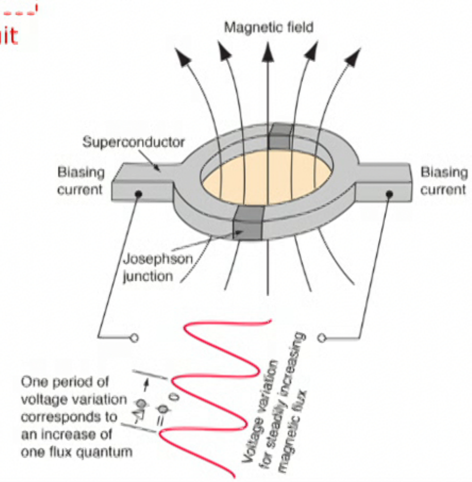




SQUID:

superconducting
pickup coil
+
commercial SQUID

used for precision magnetometry in a wide range of frequencies



Detection electronics test: proton NMR

goal: test room-temperature electronics and data acquisition

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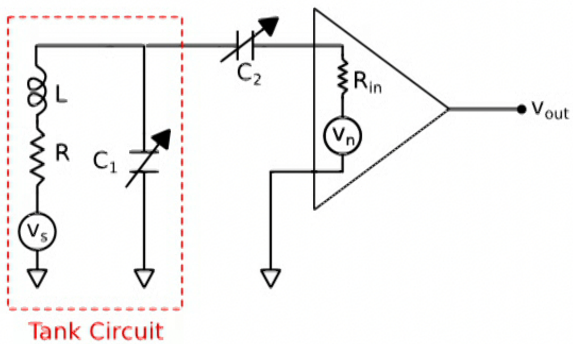

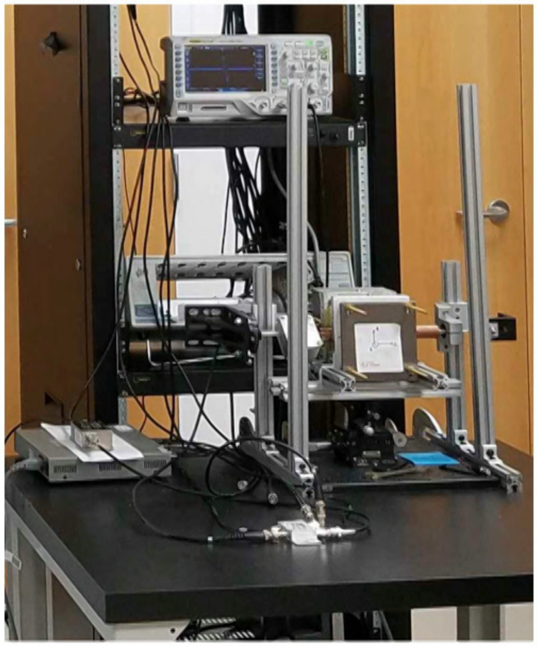

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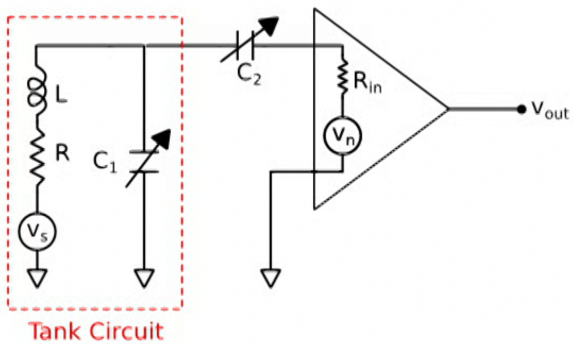
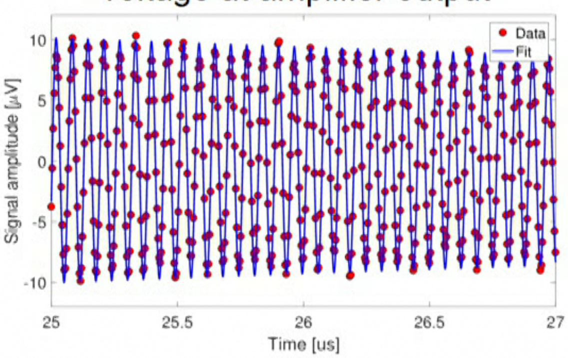
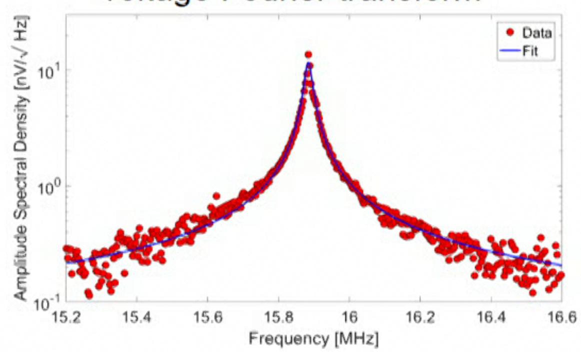


voltage at amplifier output



voltage Fourier transform



Detection electronics test: SQUID magnetometer noise at 4K

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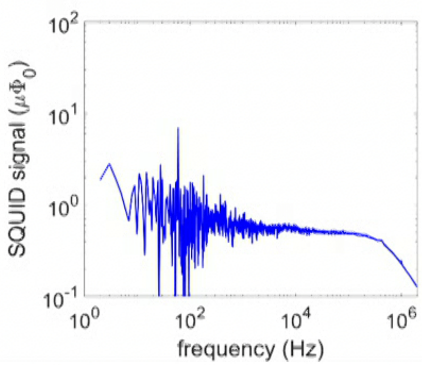
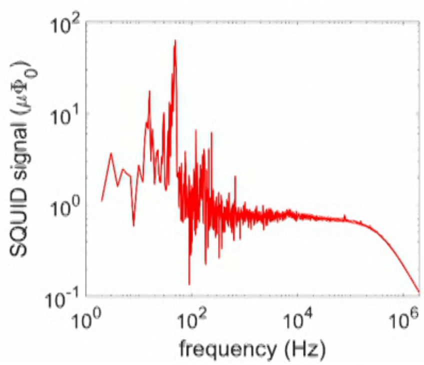
commercial SQUID

used for precision magnetometry in a wide range of frequencies

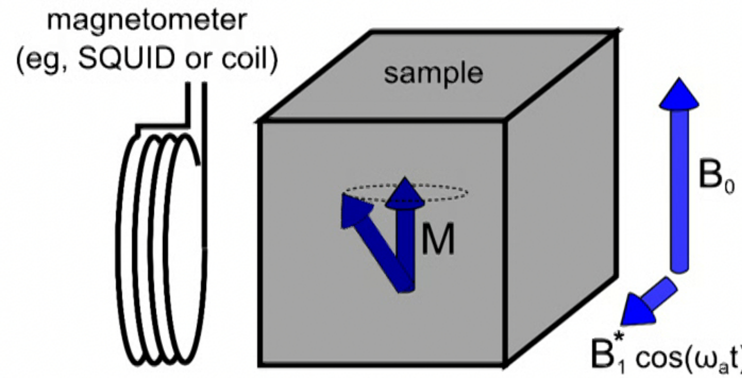
intrinsic SQUID noise (no pickup coil)



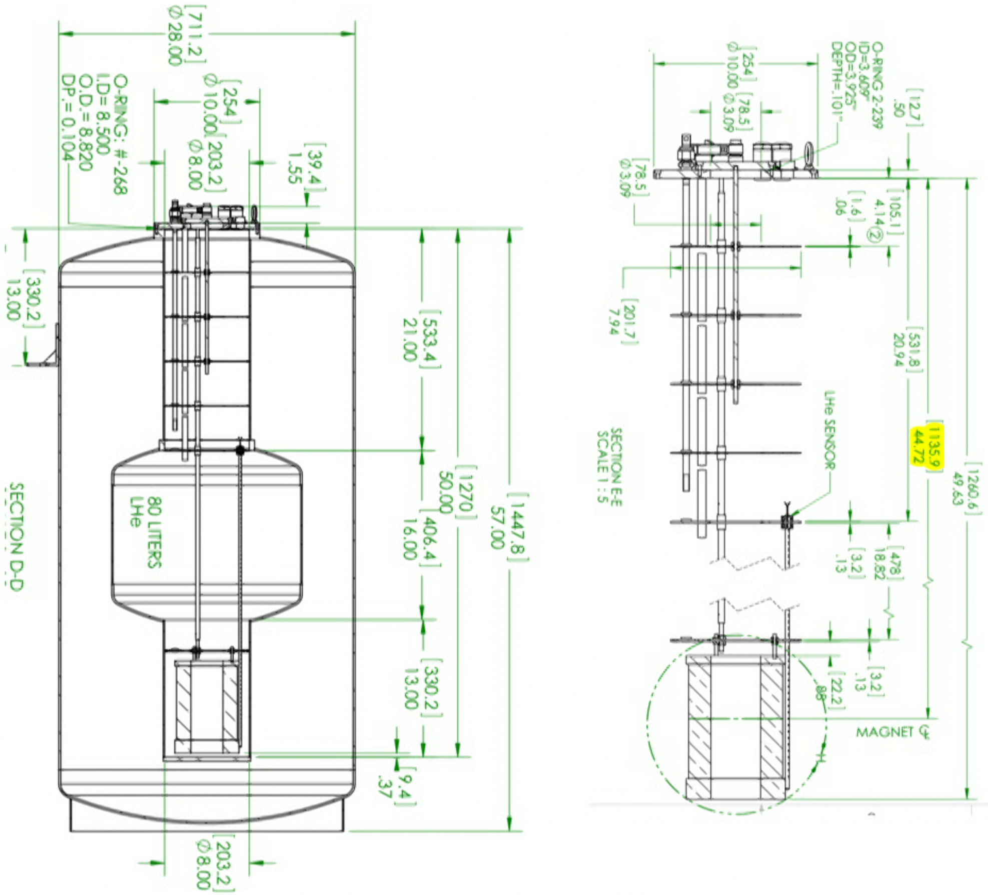
SQUID noise with a pickup coil

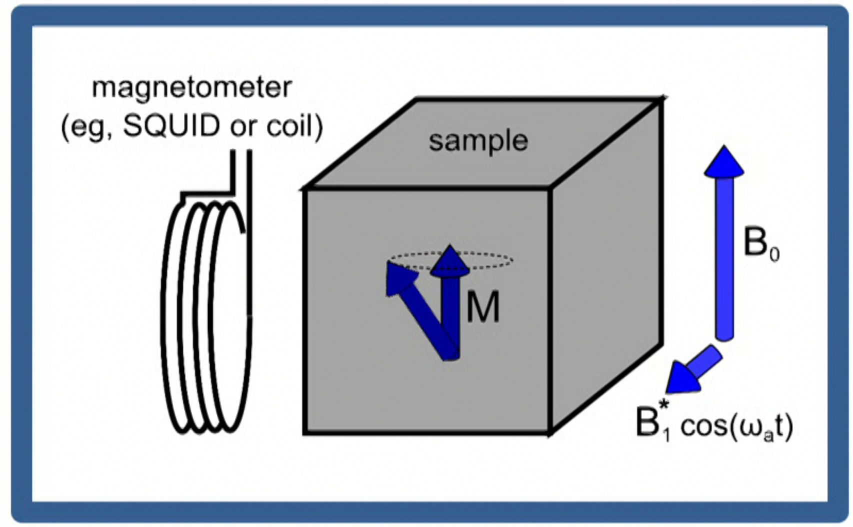


Suppressing external interference: superconducting magnetic shielding



CASPEr-e hardware: cryostat and magnet



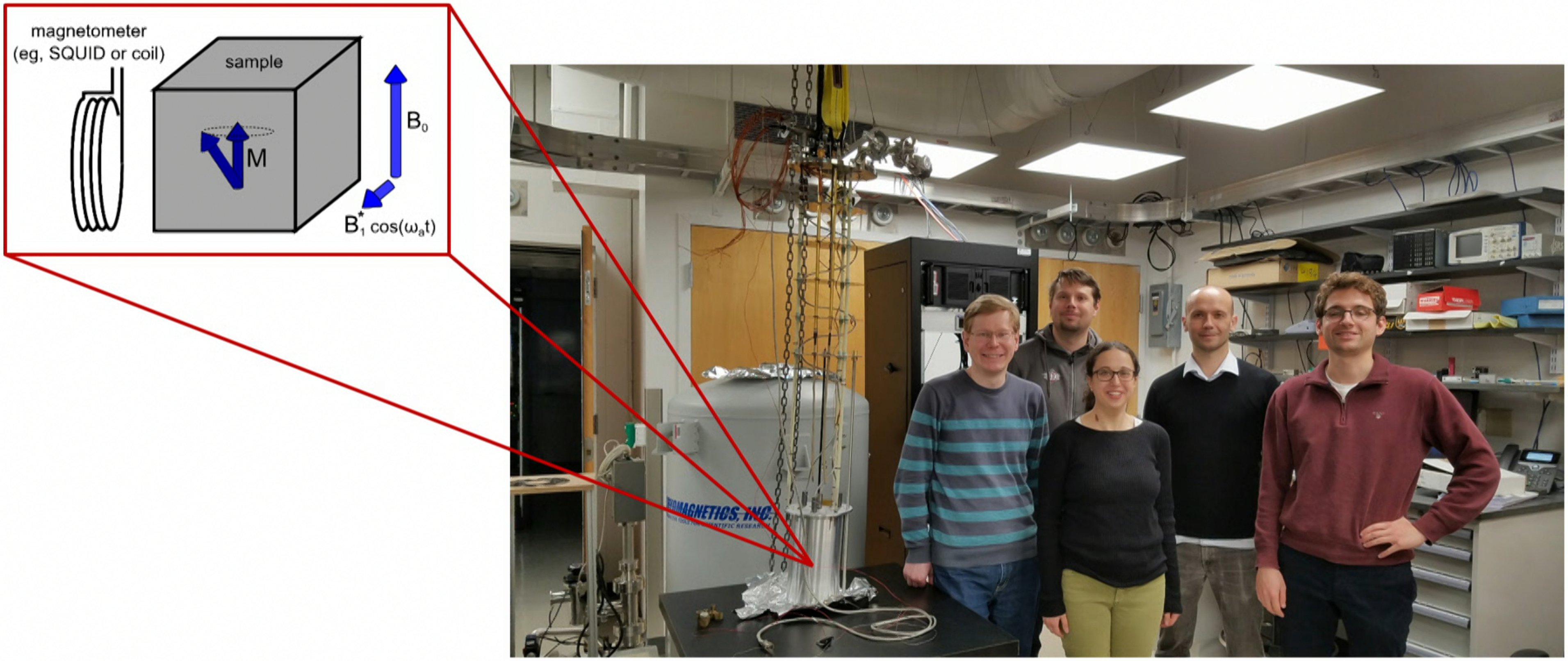


superconducting magnetic shield ⇨ screens external magnetic fields

(Meissner effect)

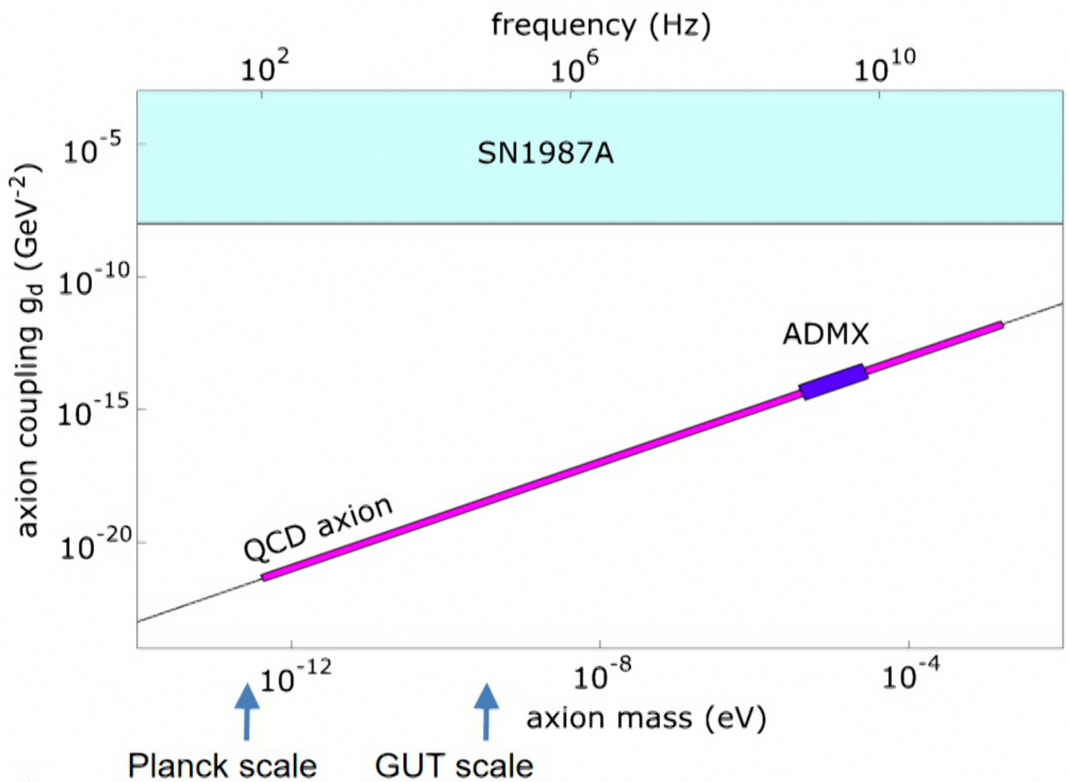
9T magnet with 3” bore, 1000 ppm homogeneity over 1cm DSV (Cryomagnetics Inc.)

CASPEr-e in November 2017



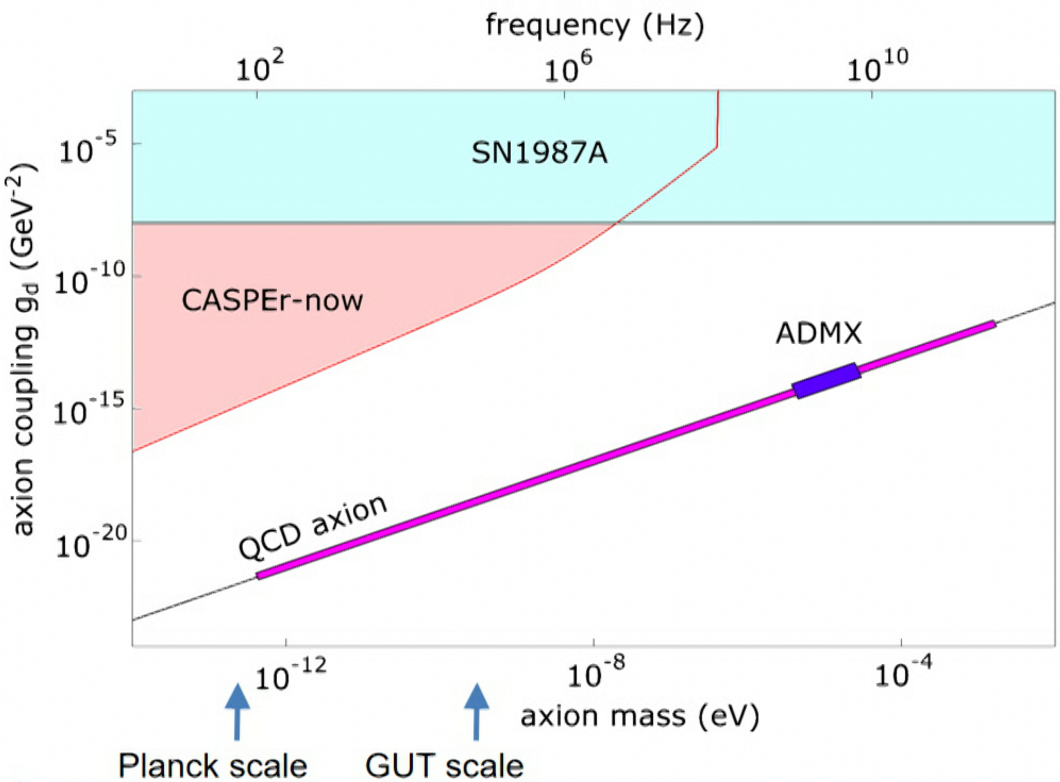
left to right: CASPEr-e, Sasha Gramolin, Janos Adam, Deniz Aybas, Alex Sushkov, Alexi Wilzewski

The experimental reach of CASPEr-e



new limits in ref:
[*Phys. Rev. X* **4**, 041034 (2017)]

The experimental reach of CASPEr-e



CASPEr-now at BU:

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

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

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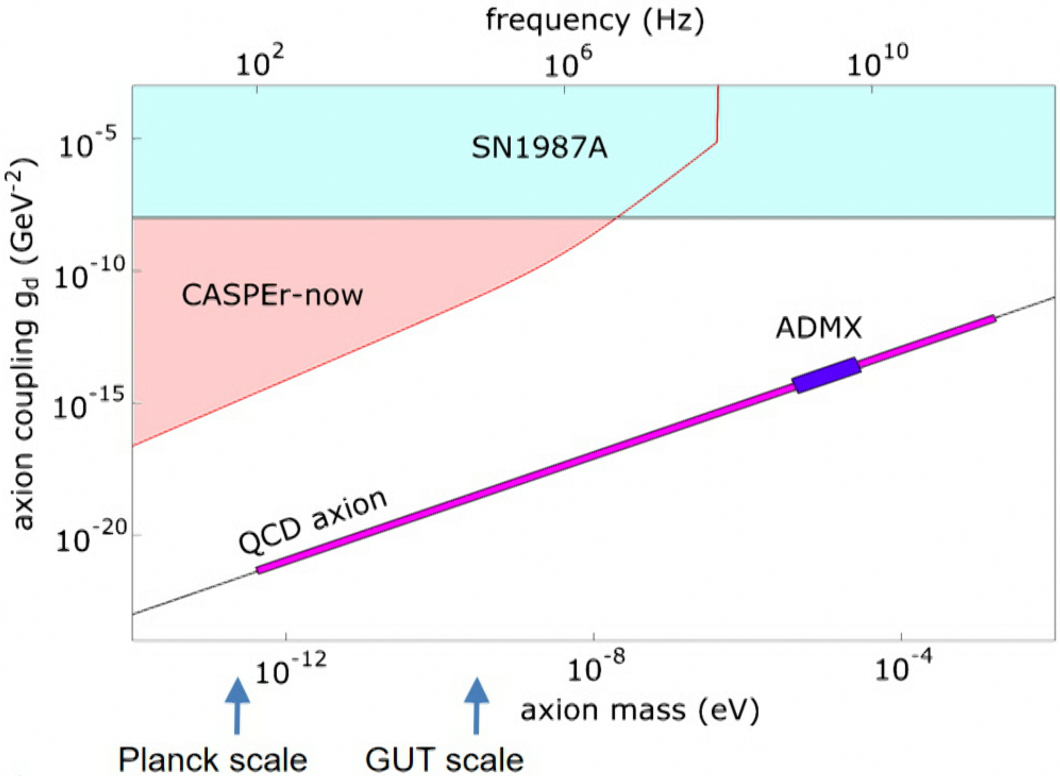

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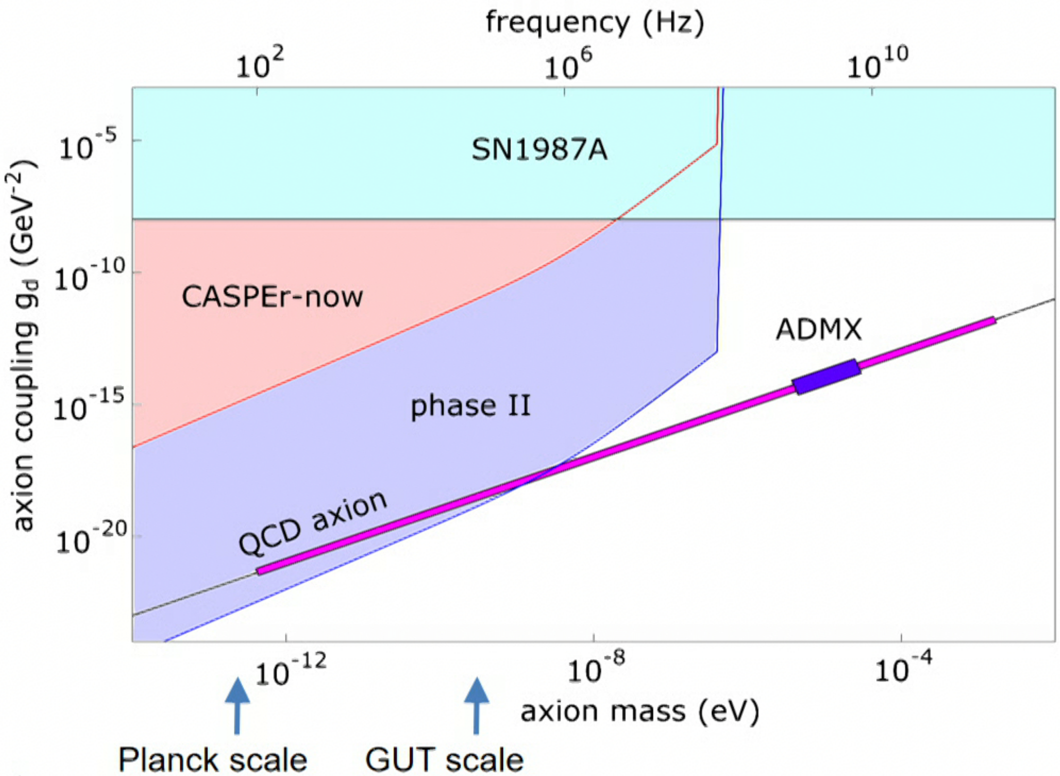

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phase II:

- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

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

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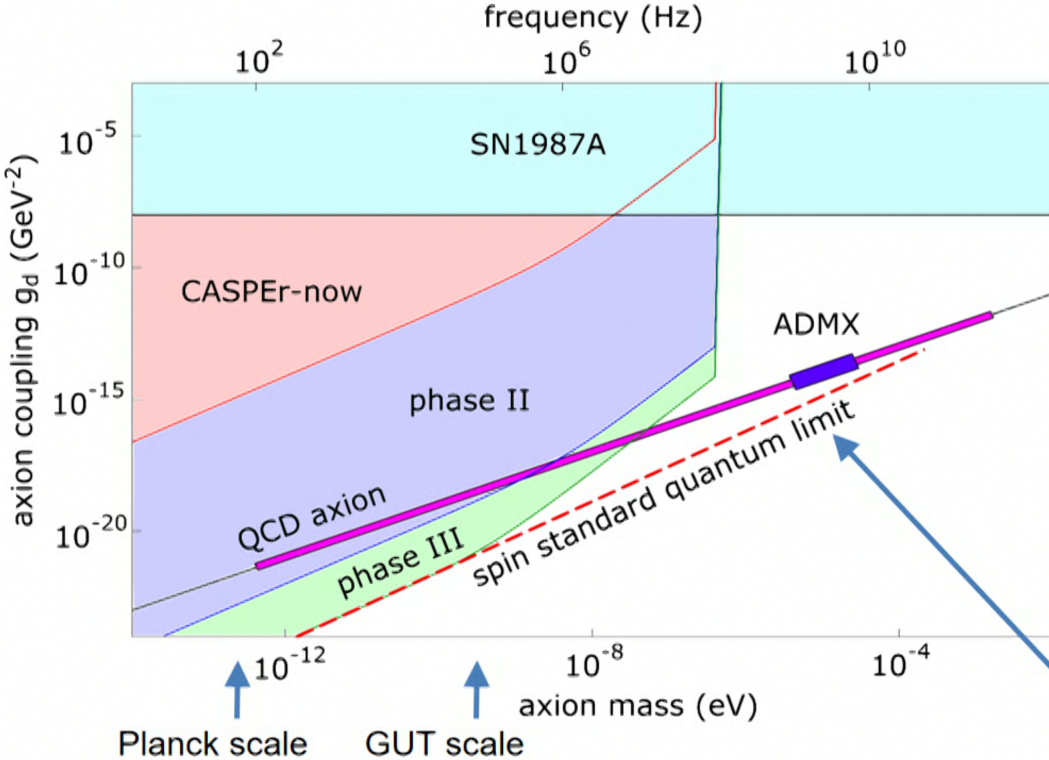

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[*Phys. Rev. X* **4**, 021030 (2014)]

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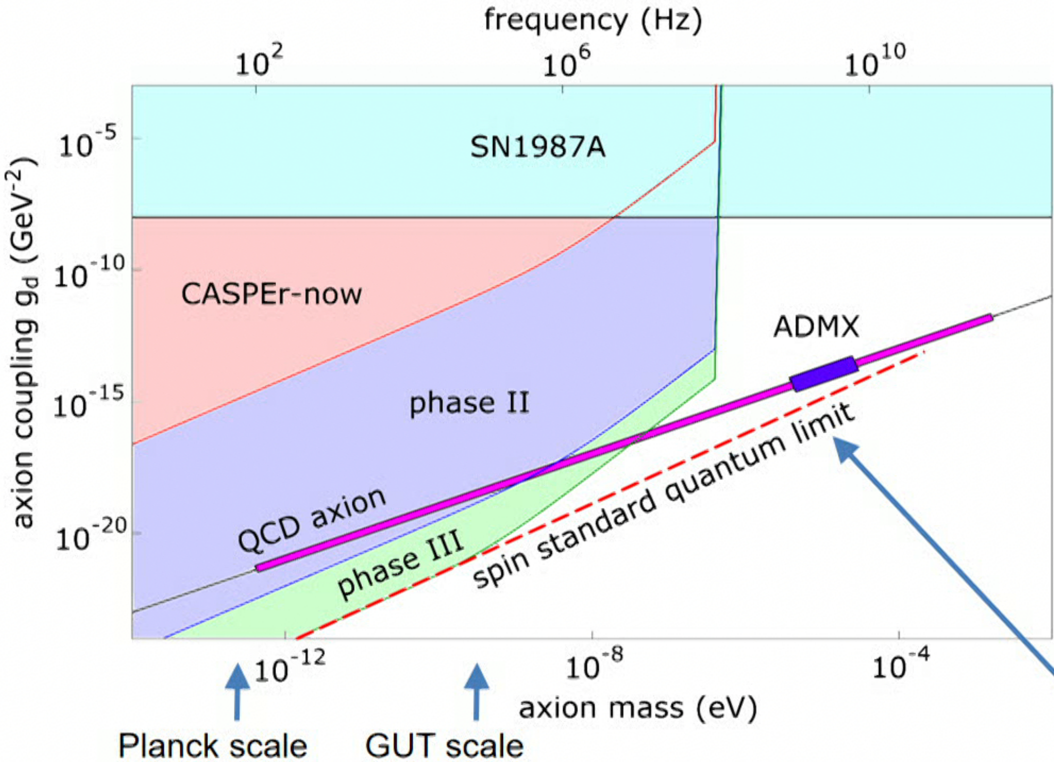
[*Phys. Rev. Lett.* **55**, 1742 (1985)]

The experimental reach of CASPEr-e



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2. search in a wide range of masses and couplings
3. sensitivity reaches QCD axion down to Planck and GUT scales

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

the most sensitive NMR experiment in history*

experimentally measurable

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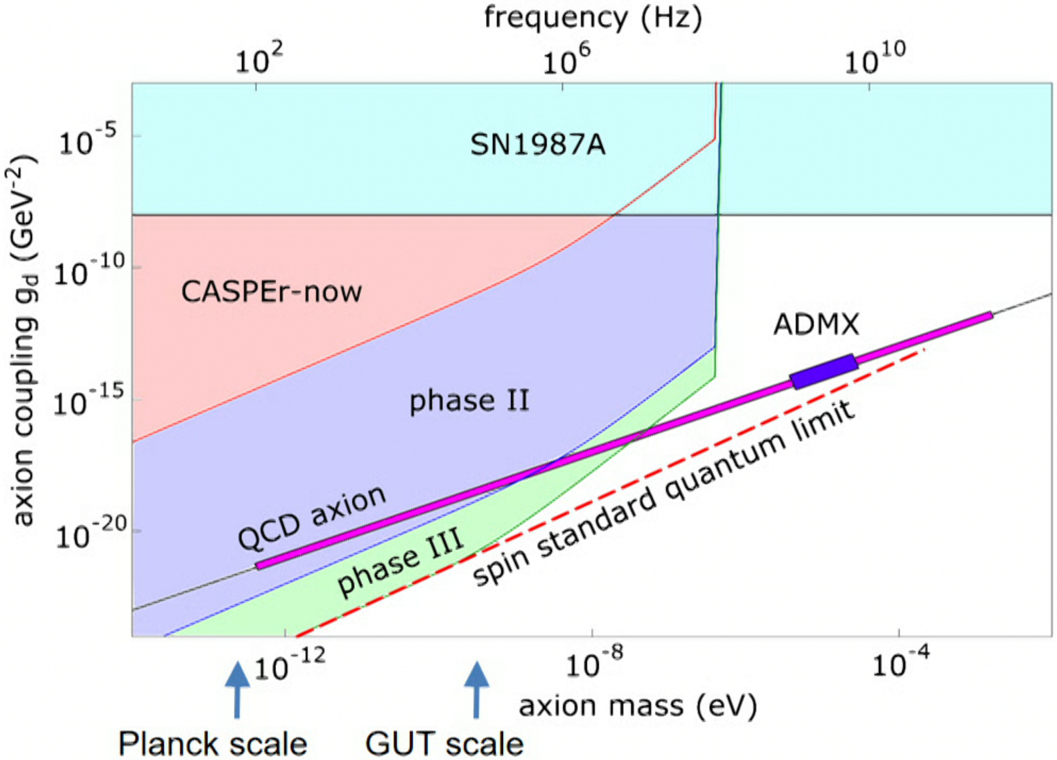

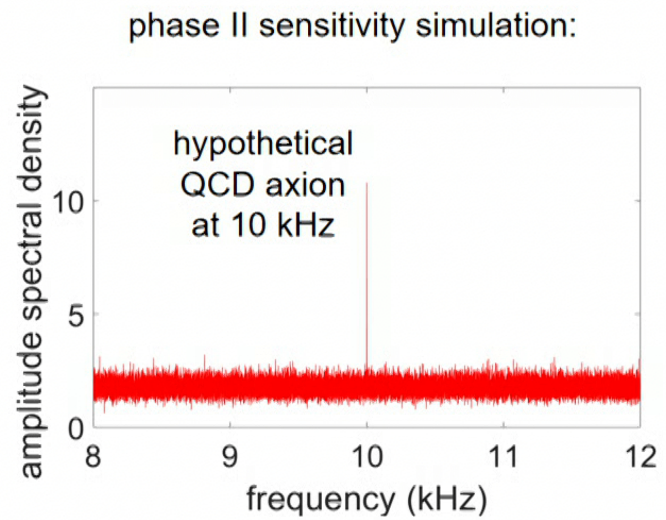

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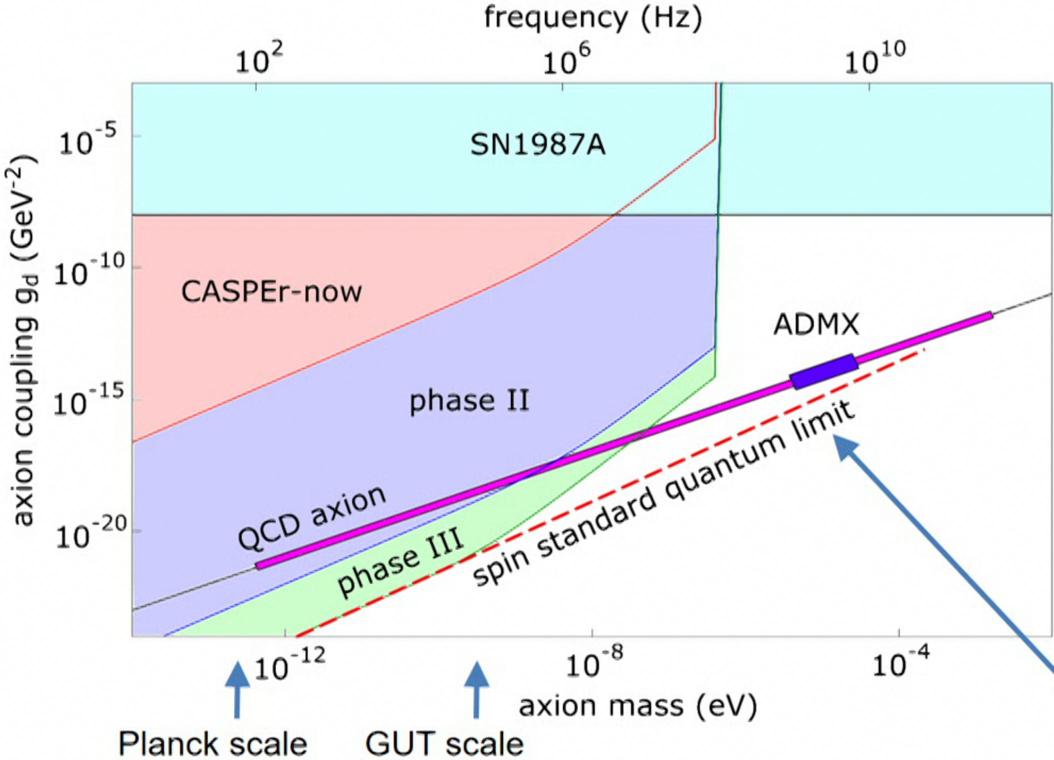

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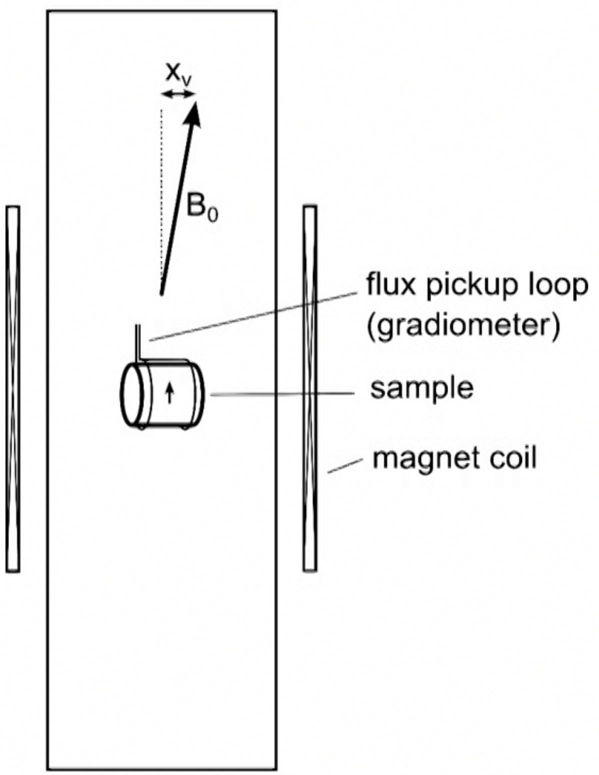
Systematics

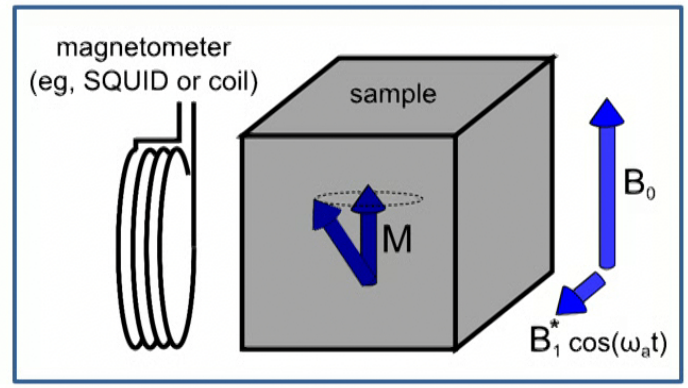
- electromagnetic interference from external sources

Systematics

main systematic: vibrations



superconducting magnetic shield



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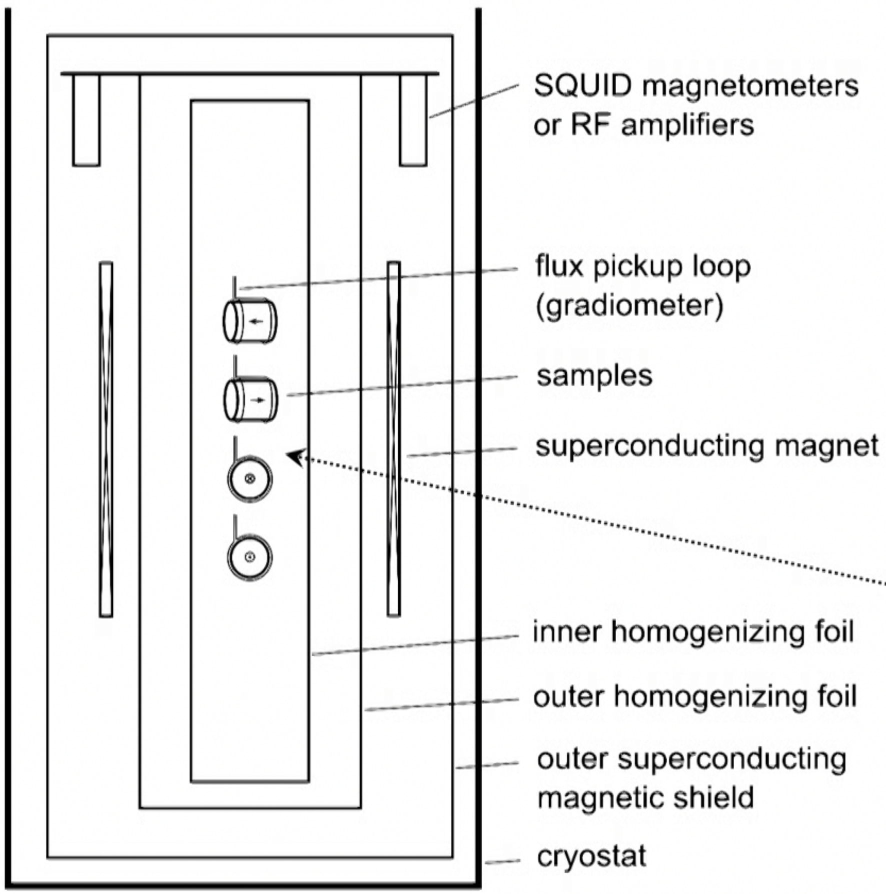
in order to reject systematics, we have several samples: axions will couple identically (in-phase)

Systematics



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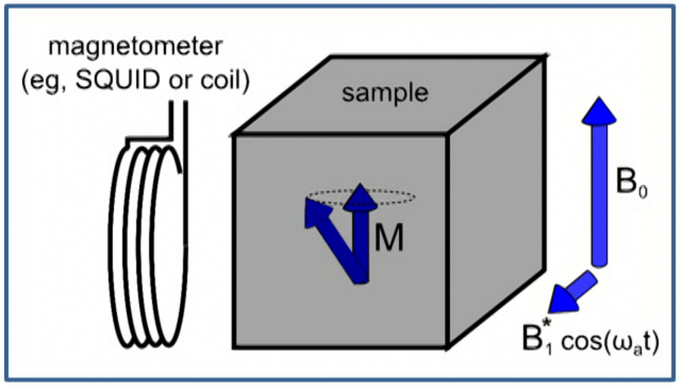

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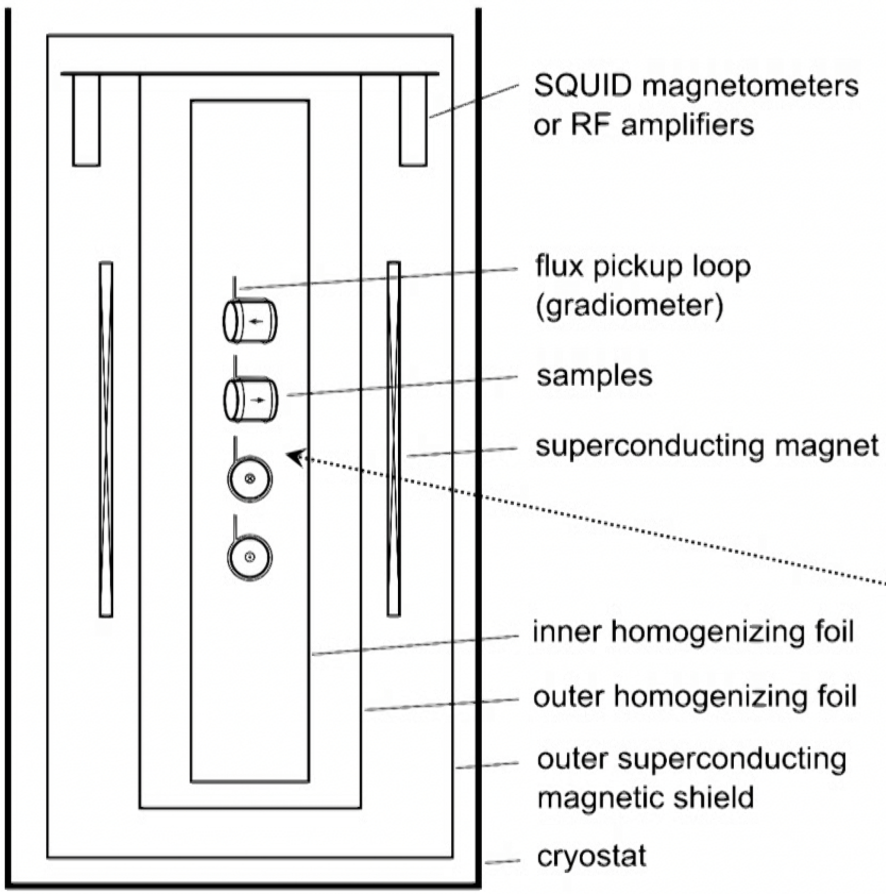

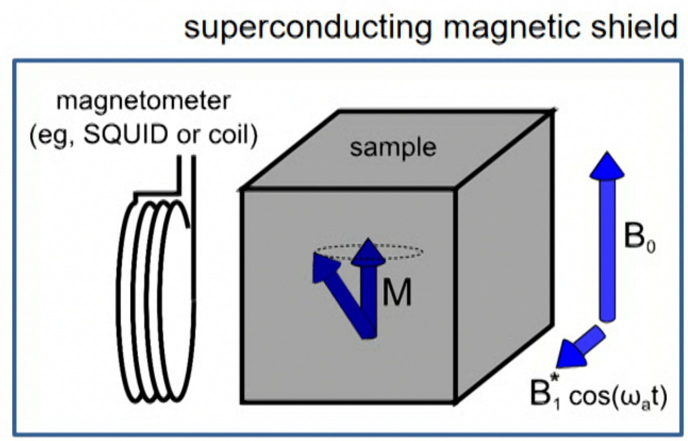

- electromagnetic interference from external sources
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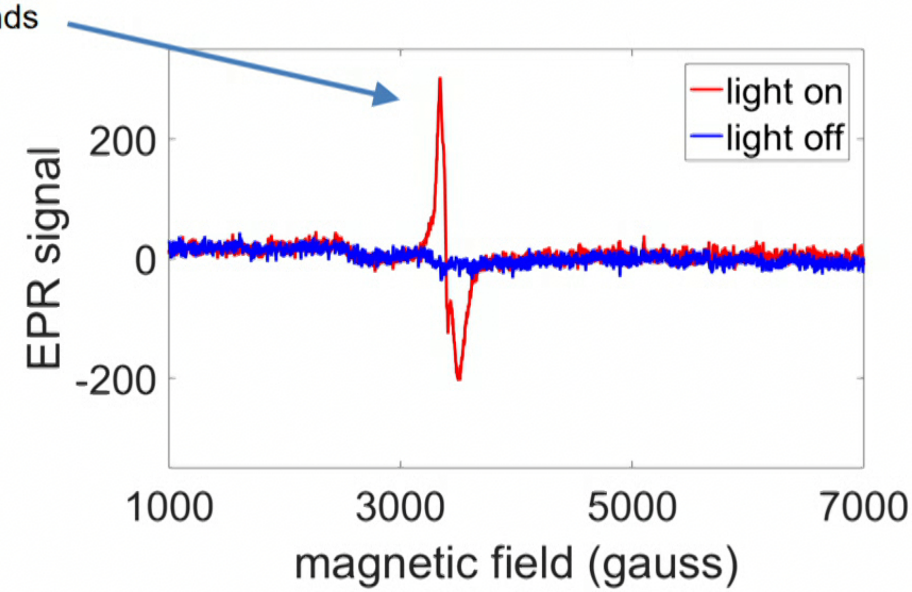
in order to reject systematics, we have several samples: axions will couple identically (in-phase)

ultimate check: if we have a detection, axion Compton frequency ($\propto$ axion mass) must be the same in independent experiments

Next-generation CASPEr: towards optically-assisted spin hyperpolarization

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

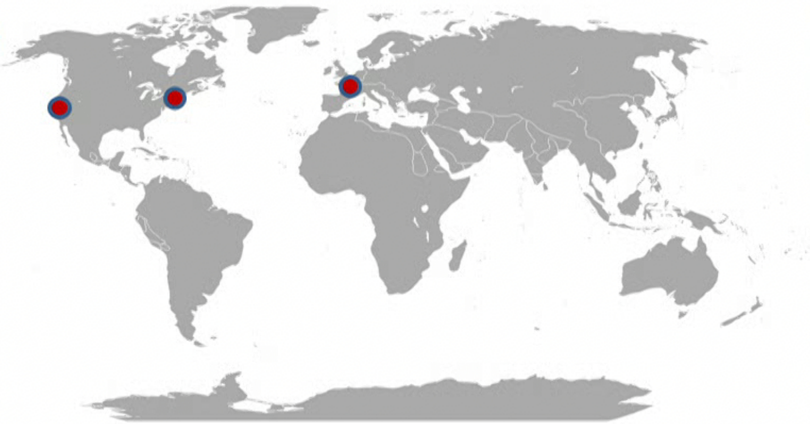
EPR signal due to g=2 transient paramagnetic centers after 405nm laser excitation, lifetime ~ 10 seconds



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

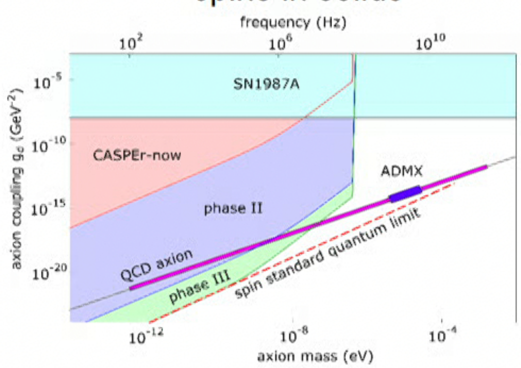
Our collaboration

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



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

Boston University:
CASPEr-electric using spins in solids



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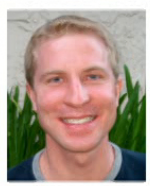
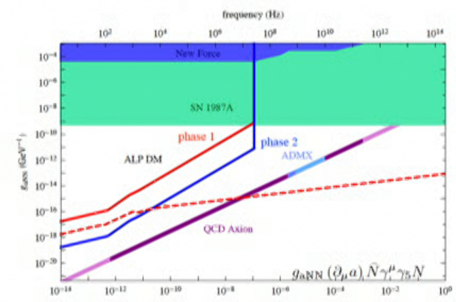
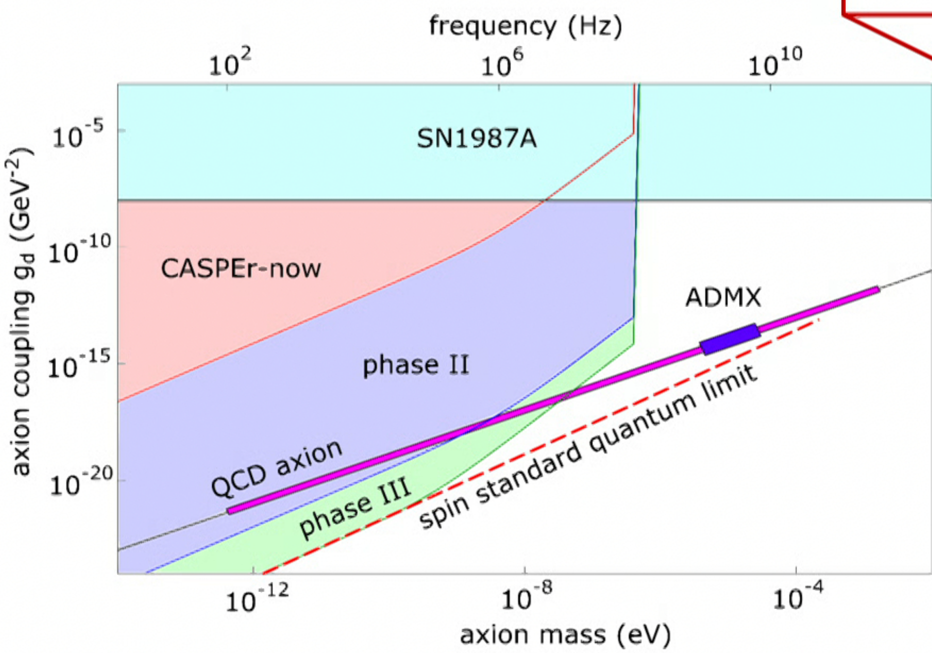
Stanford, Berkeley, CSUEB:

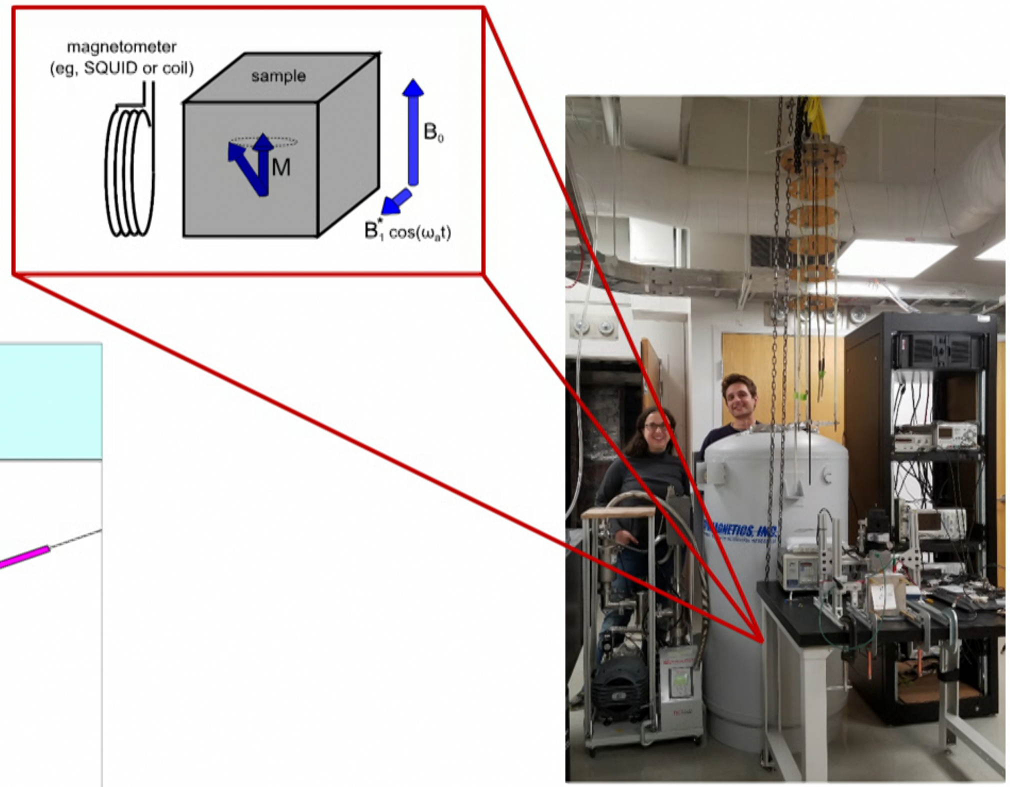


Mainz:
CASPEr-wind using liquid Xenon



Alex Sushkov (Boston University): CASPEr





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