Search for axion-induced oscillating electric dipole moments (**CASPEr-Electric**)

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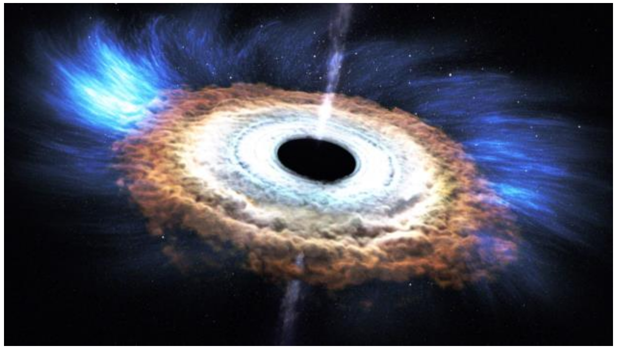
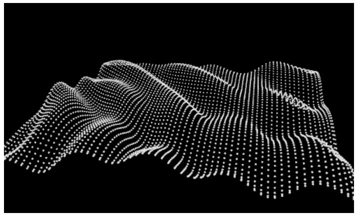
Outline

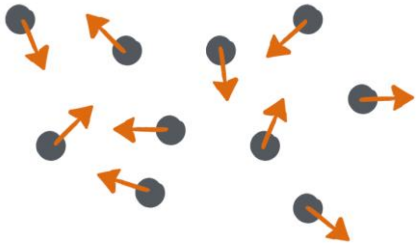
- Axion Dark Matter
  - Oscillating EDM
  - Nuclear Magnetic Resonance (NMR)
- Cosmic Axion Spin Precession Experiment (CASPEr-Electric)
  - Setup
  - Current Status
  - Future

What is **Dark Matter**?



- We don't know!
- Some candidates:
  - Massive Compact Halo Object (**MACHO**)
  - Weakly Interacting Massive Particle (**WIMP**)
  - **Axion**





Axion

- Spin = 0
- Charge = 0
- Mass = ?
- Its particle field can be expressed as an oscillating field

$$a(t) \sim a_0 \cos(\omega_a t) \qquad \omega_a = \frac{m_a c^2}{\hbar}$$

- Energy density stored in the oscillations can be **dark matter**

$$\rho_{DM} \sim m_a^2 a_0^2$$

[*PRD* **88**, 035023, (2013)]
[*arXiv* 1707.04591, (2017)]

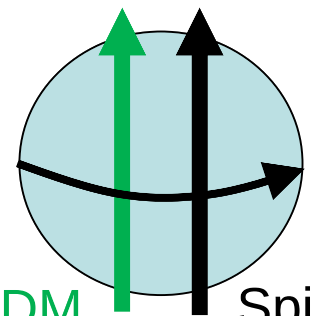
Axion couplings

Photon Coupling	Gluon Coupling	Fermion Coupling
$\mathcal{L} \sim aF_{\mu\nu}\tilde{F}^{\mu\nu}$	$\mathcal{L} \sim aG_{\mu\nu}\tilde{G}^{\mu\nu}$	$\mathcal{L} \sim (\partial_\mu a)\tilde{\Psi}_f\gamma^\mu\gamma_5\Psi_f$
↓	↓	↓
$H \sim a\overrightarrow{E} \cdot \overrightarrow{B}$	$H \sim a\overrightarrow{\sigma} \cdot \overrightarrow{E}$	$H \sim \nabla a \cdot \overrightarrow{\sigma}$
ADMX, HAYSTAC, ABRACADABRA, LC Circuit, DM Radio, …	CASPEr Electric, nEDM	CASPEr Wind, Atom Interferometry, ARIADNE, …

[PRD 88, 035023]

Axion and Electric Dipole Moment (**EDM**)

- Neutron and proton EDM are due to charge distribution



- Experiments so far have searched for **static** EDM to a lower limit that is close to zero.
- Axion would induce an **oscillatory** nuclear EDM:

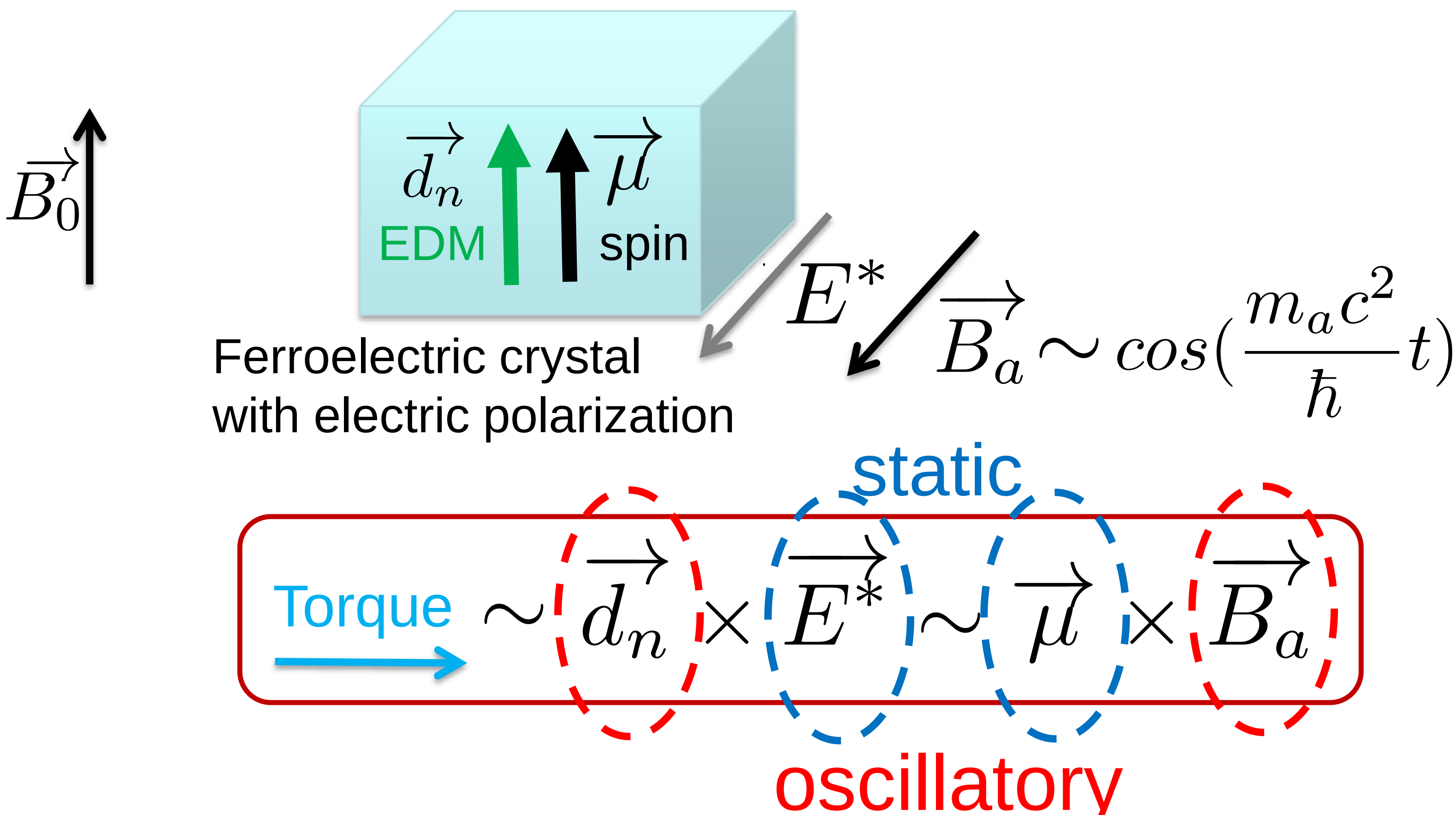
$$d_n \sim cos(\frac{m_a c^2}{\hbar} t)$$

$$H \sim a\vec{\sigma} \cdot \vec{E}$$

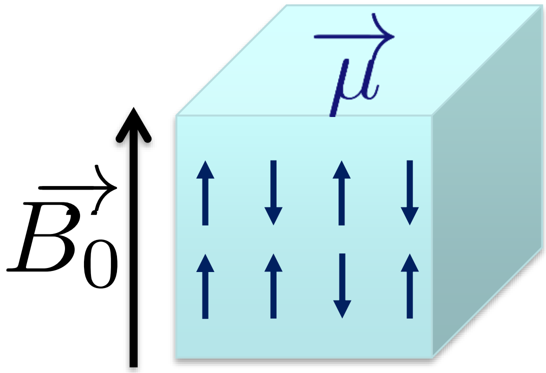
[PRD 88, 035023]

Oscillatory **EDM** and **Torque**

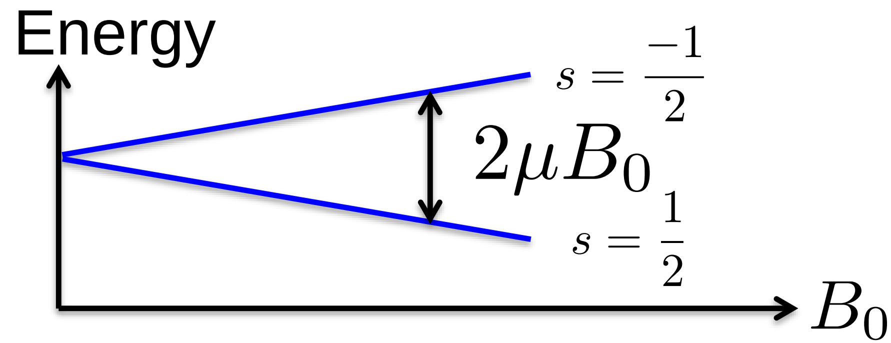
- When there is an Electric field orthogonal to an EDM, there is torque acting upon EDM and spin.



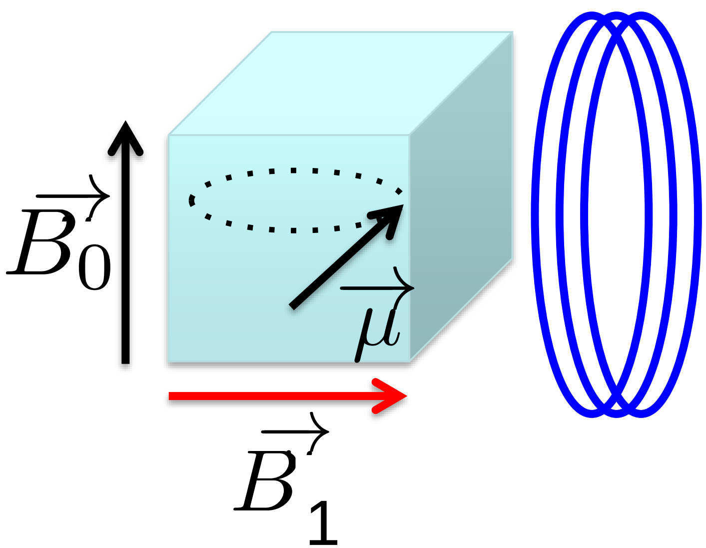
Nuclear Magnetic Resonance **(NMR)**



Static magnetic field



Spin polarization $p \sim \frac{\mu B_0}{k_B T}$



Time-varying magnetic field

Spin precession at Larmor frequency

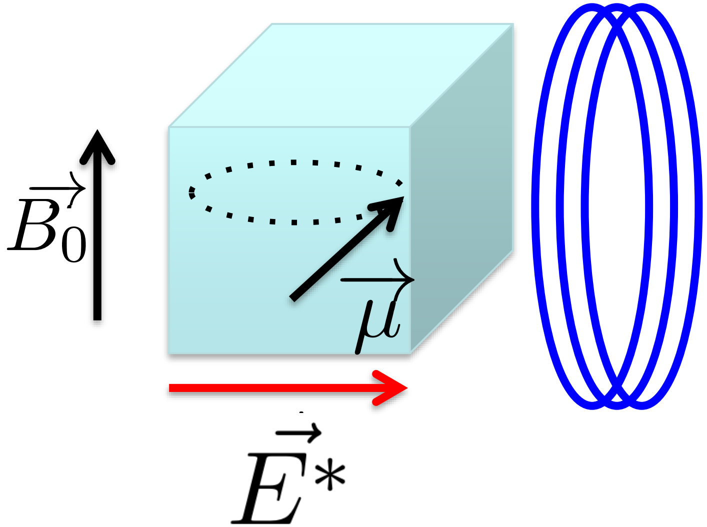
$$\Omega_L = \gamma_n B_0$$

How can we measure **Axion**?

time-varying magnetic field in NMR $H \sim \vec{\mu} \cdot \vec{B}_1$

↓ ↓

axion-nuclear spin interaction under an Electric field $H \sim a \overrightarrow{\sigma} \cdot \vec{E}^*$



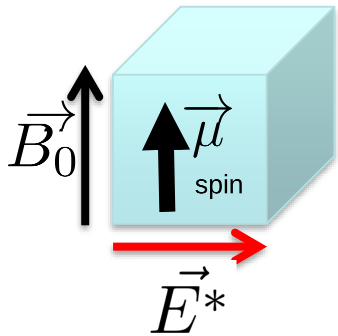
Torque $\sim \overrightarrow{\mu} \times \overrightarrow{B_1}$

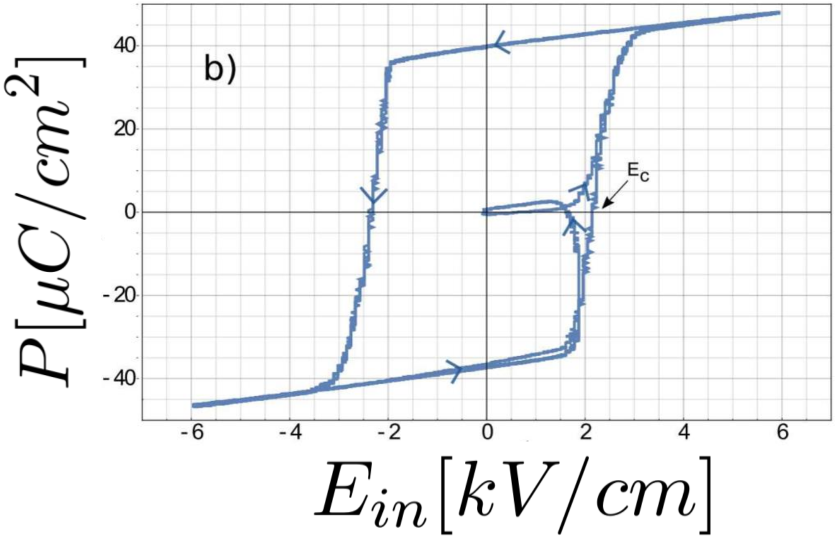
$\sim \overrightarrow{d_n} \times \overrightarrow{E^*}$

[*PRX* **4**, 021030, (2014)]

Sample for **CASPEr-Electric** $H \sim a\vec{\sigma} \cdot \vec{E}^*$

PMN-PT
^{207}Pb Spin ½





spontaneous polarization $\vec{P}$

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

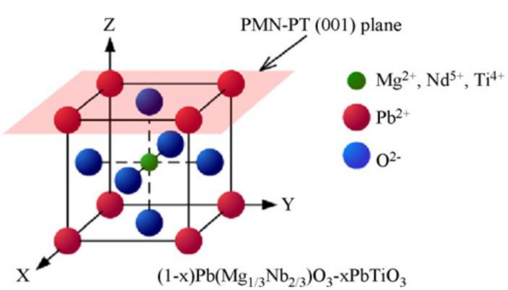
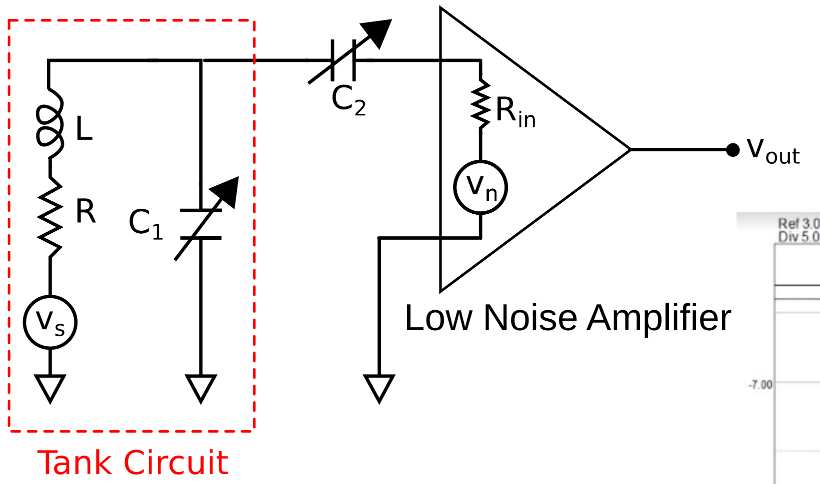
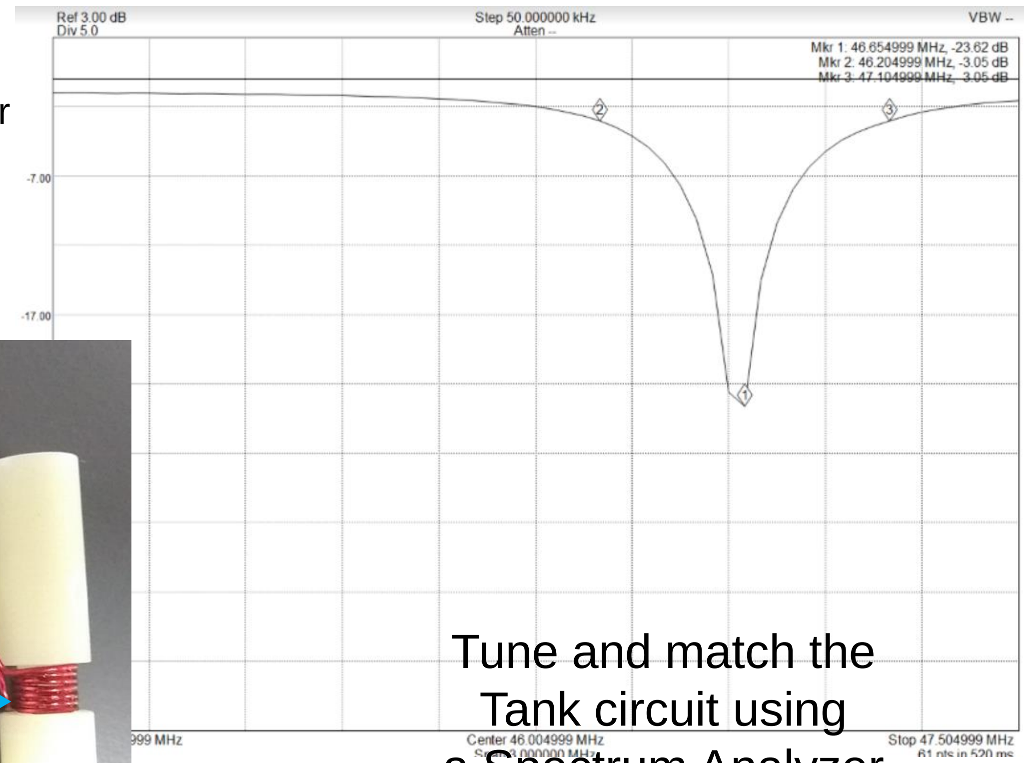


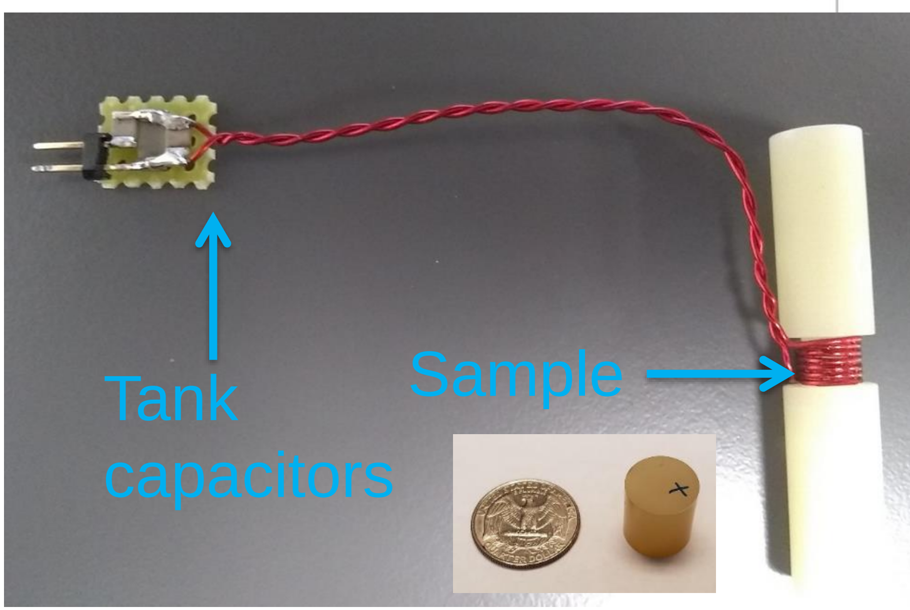
Fig. 1. Crystal structure of PMN-PT.

[*PRX* **4**, 021030, (2014)]

Inductive **Pickup** circuit

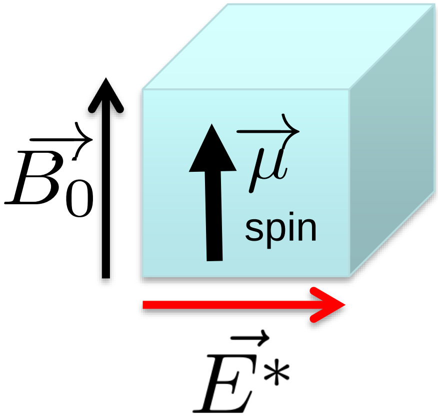


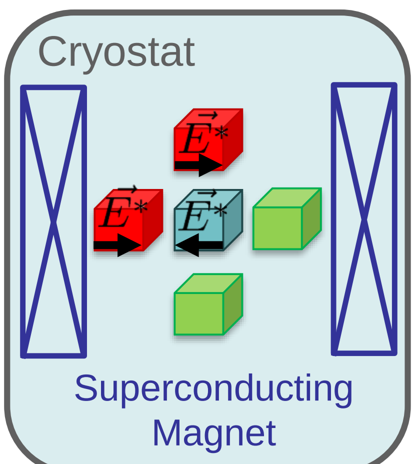


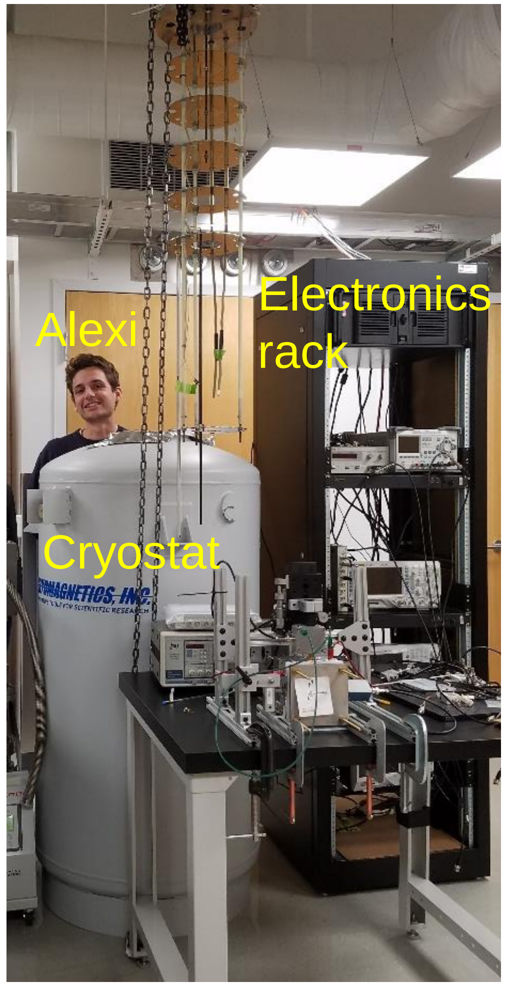


Tune and match the Tank circuit using a Spectrum Analyzer
Q ~ 50 at 300K

CASPEr **Phase 0** Setup

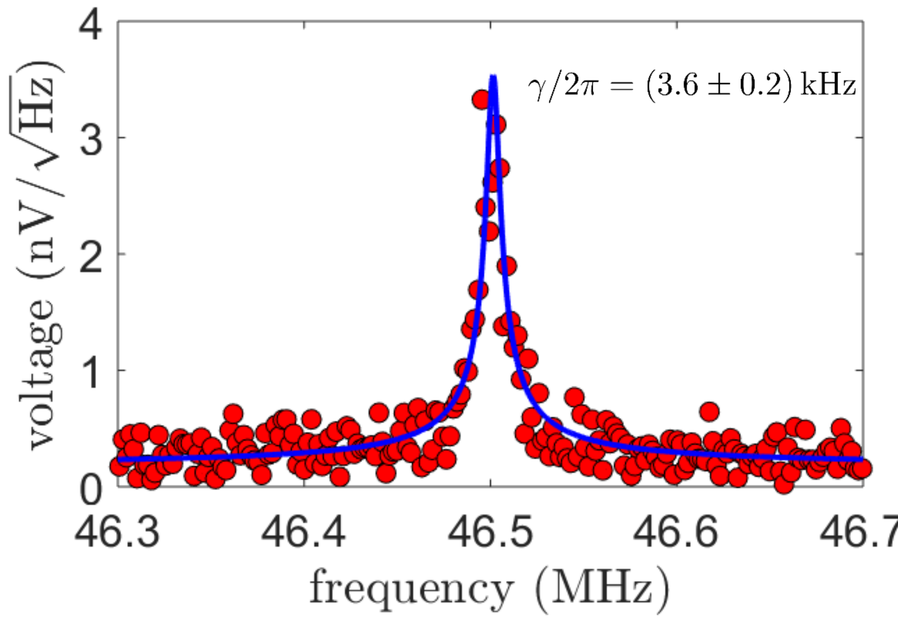






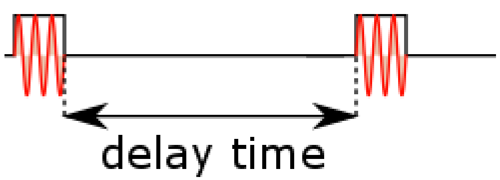
Main results from **Phase 0**

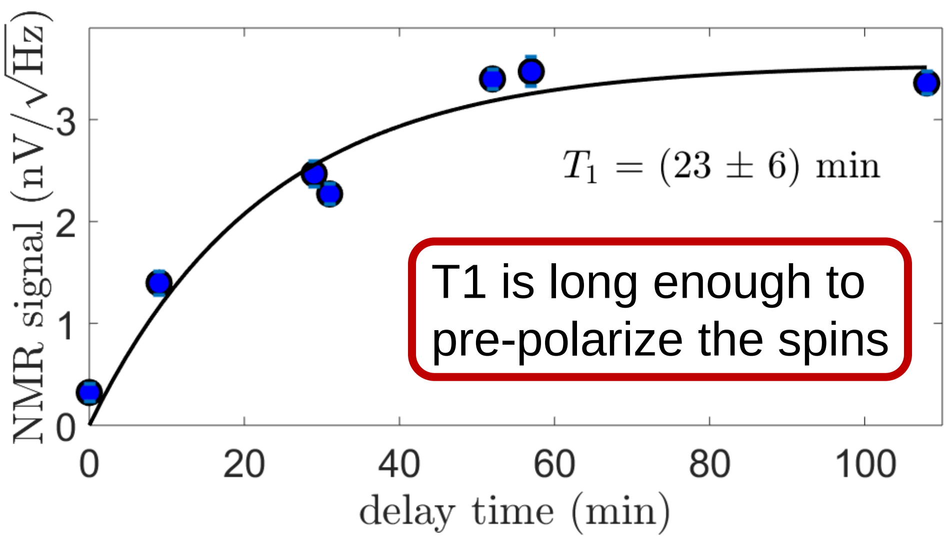
Measurement of Pb207 NMR in PMN-PT



Measurement at 5.2T

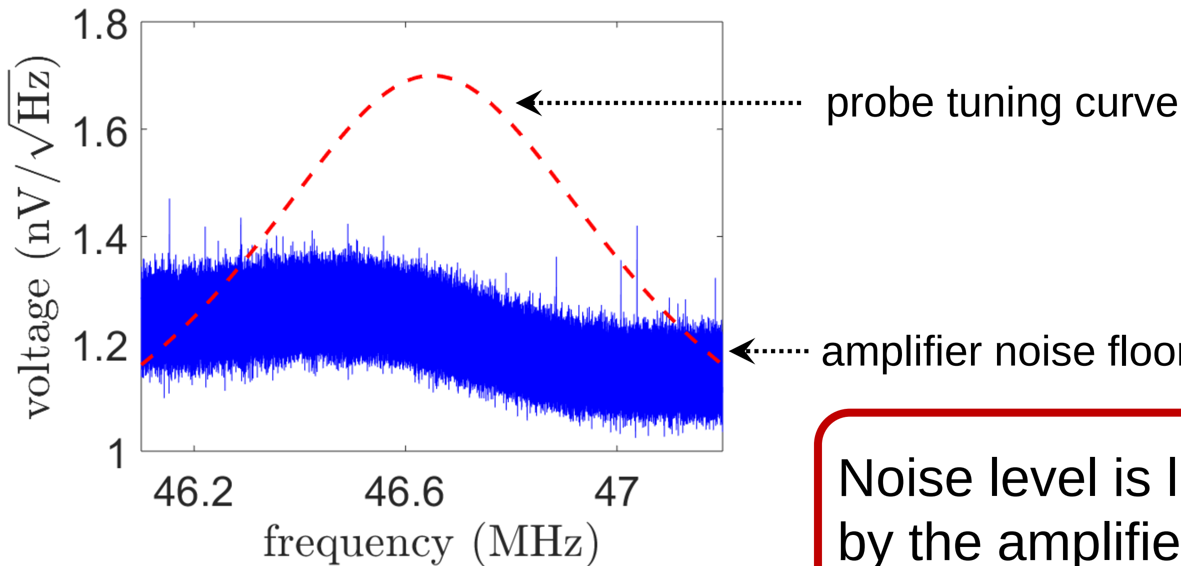
Pb207 T1 spin relaxation time measurement in PMN-PT with Saturation Recovery





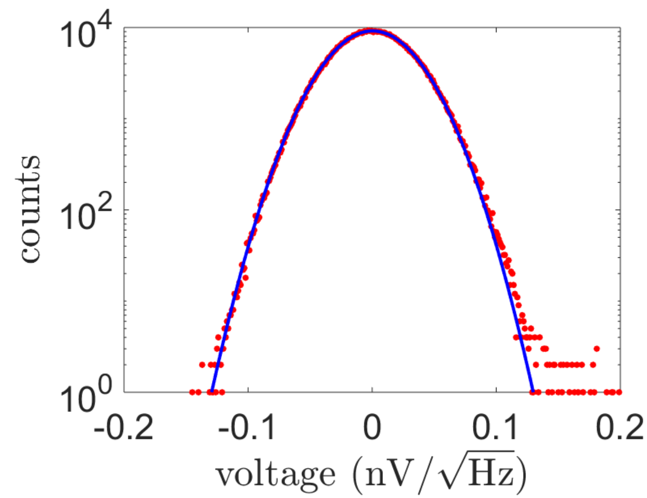
Main results from **Phase 0**

Axion measurements



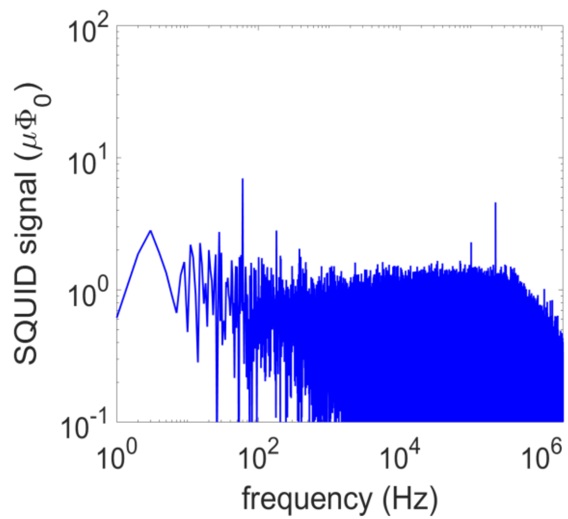
Noise level is limited by the amplifier input

Noise distribution

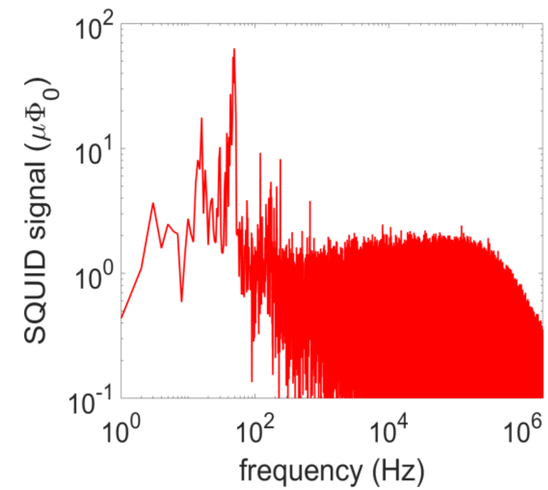


Noise is nearly Gaussian distributed after 30 min of averaging

Superconducting Quantum Interference Device (**SQUID**) for pickup



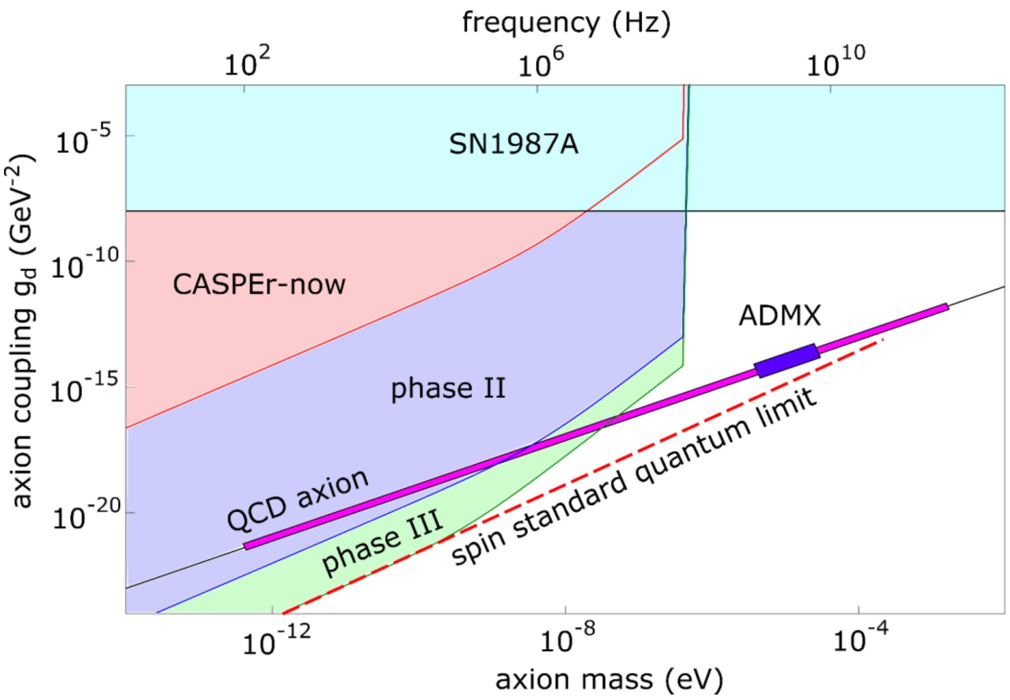
intrinsic SQUID noise
(no pickup coil)



SQUID noise coupled
with a pickup coil

- Measured noise level on order of $\mu\Phi_0/\sqrt{Hz}$
- Broadband
- Vibrations below 1 kHz

Sensitivity of CASPEr



CASPEr-now:

- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- Tuned Tank circuits for detection
- Soon: broadband SQUID detection

phase II:

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

phase III:

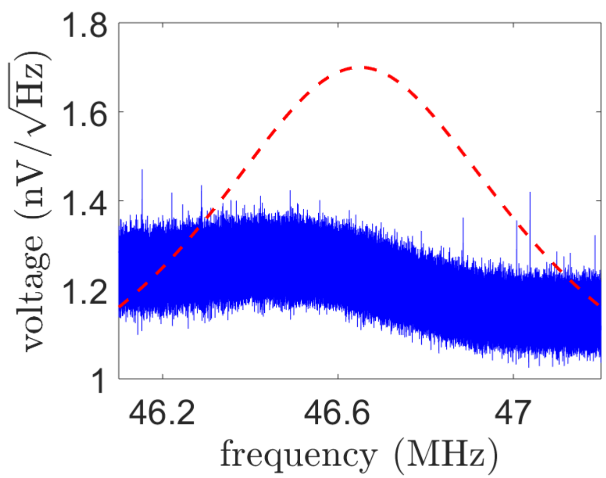
- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

We are planning to search for axion in several orders of magnitude range of mass.

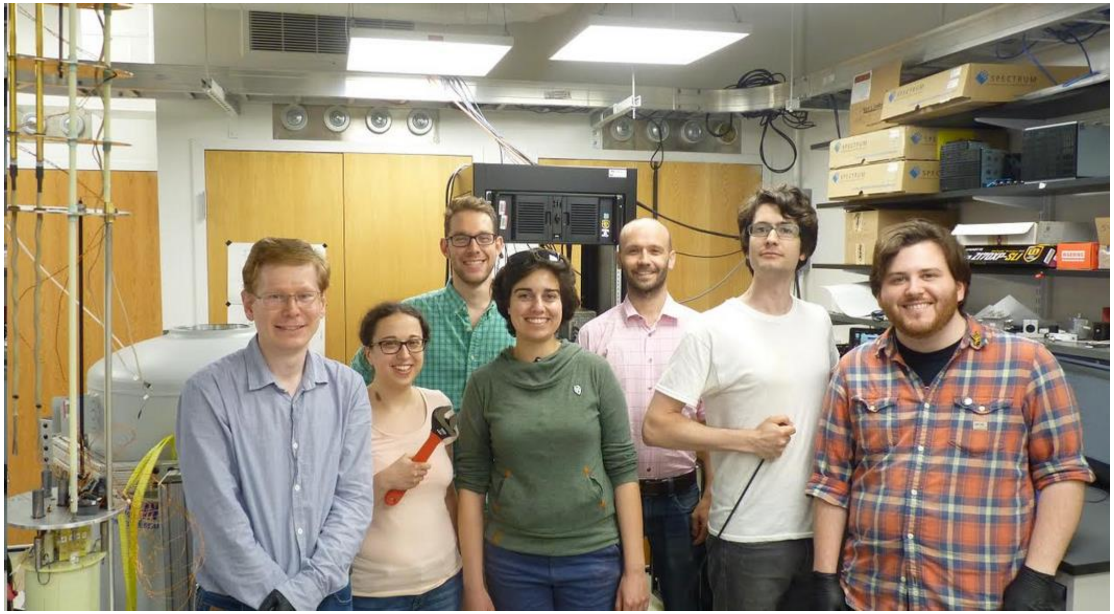
[*PRX* **4**, 021030, (2014)]

Current status of **CASPEr-Electric**

- Developed NMR electronics and software
- Developed setup for electrical polarization of Pb crystals
- Purchased SQUIDs, tested their operation
- Designed and used a cryogenic insert for CASPEr
- Ran phase 0, performed Axion measurements around 46.6 MHz +- 0.5 MHz. Axion coupling plot to be calculated.

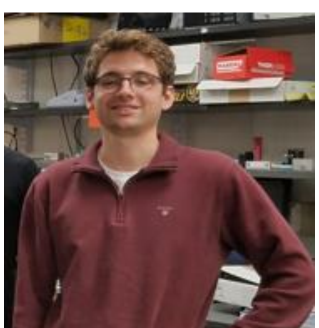


Thank you!



Sushkov Lab @ BU:
Sasha Gramolin, Deniz Aybas, Eric Boyers, Kristine Rezai,
Alex Sushkov, Jack Stropko, and **Dorian Johnson**

Not in photo: **Alexi Wilzewski, Janos Adam,** and **Annalies Kleyheeg**



HEISING-SIMONS FOUNDATION

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

HIM Helmholtz-Institut Mainz


CASPEr Collaboration

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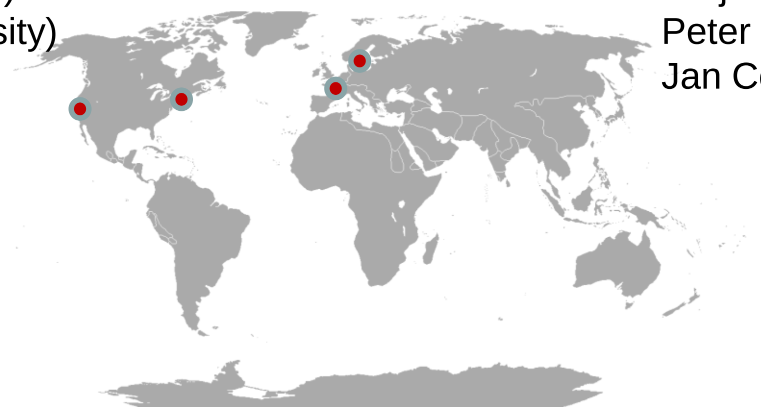
Jan Conrad (Stockholm)



Boston University: CASPEr-electric using spins in solids

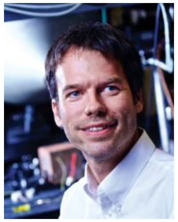
Alfred P. Sloan FOUNDATION

SIMONS FOUNDATION

HEISING - SIMONS FOUNDATION

Mainz: CASPEr-wind using liquid Xenon

Stanford, Berkeley, CSUEB, Stockholm:



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Some images are taken from NASA.gov