

Spin-based techniques, NV-diamonds, Magnetometry



Dmitry Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz

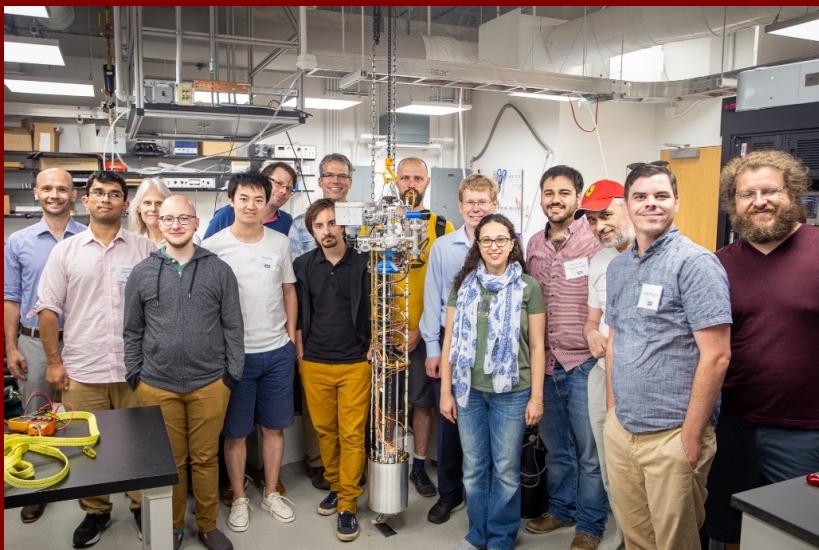
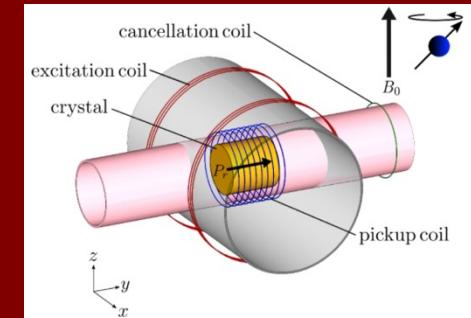
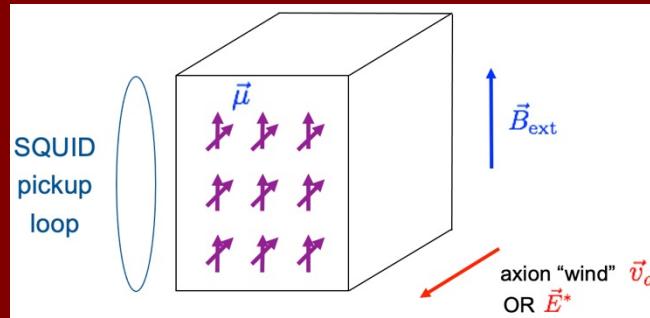
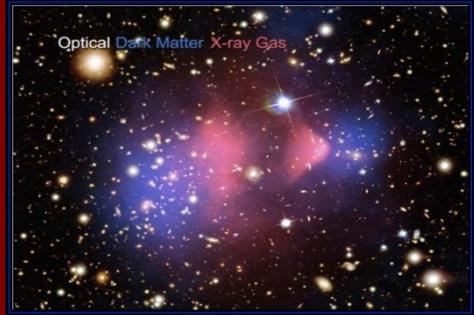
&

Department of Physics, UC Berkeley

Agenda

- NMR in search of DM (CASPER)
- Search for Halo Axions with Ferromagnetic Toroids (BU)
- Spin-based sensors for DM: GNOME, masers, spin amplifiers
- Spin-based sensors for fifth-force searches
- Fifth-force searches with NV-diamond sensors
- New (or very old) sensors: levitated magnets

Cosmic Axion Spin-Precession Experiment(s)



The CASPER collaboration

*Boston University; Helmholtz Institute, Johannes Gutenberg University, Mainz;
Department of Physics, UC Berkeley; Stockholm University*

CASPER searches for DM via:

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



coupling to gluons

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

→ spin σ to axion coupling:

$$H_e \propto a \sigma \cdot E^*$$

CASPER-electric

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



coupling to fermions

→ via axion field gradient

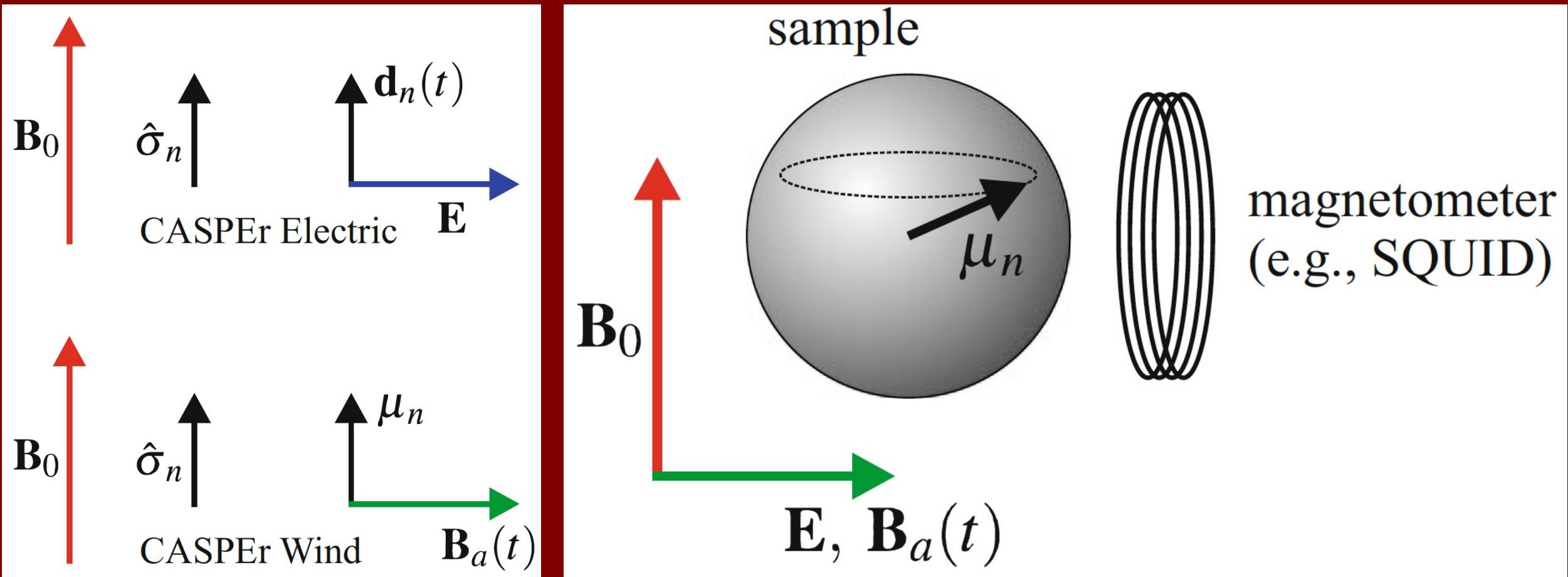
→ spin σ to axion gradient coupling:

$$H_g \propto \sigma \cdot \nabla a$$

CASPER-gradient

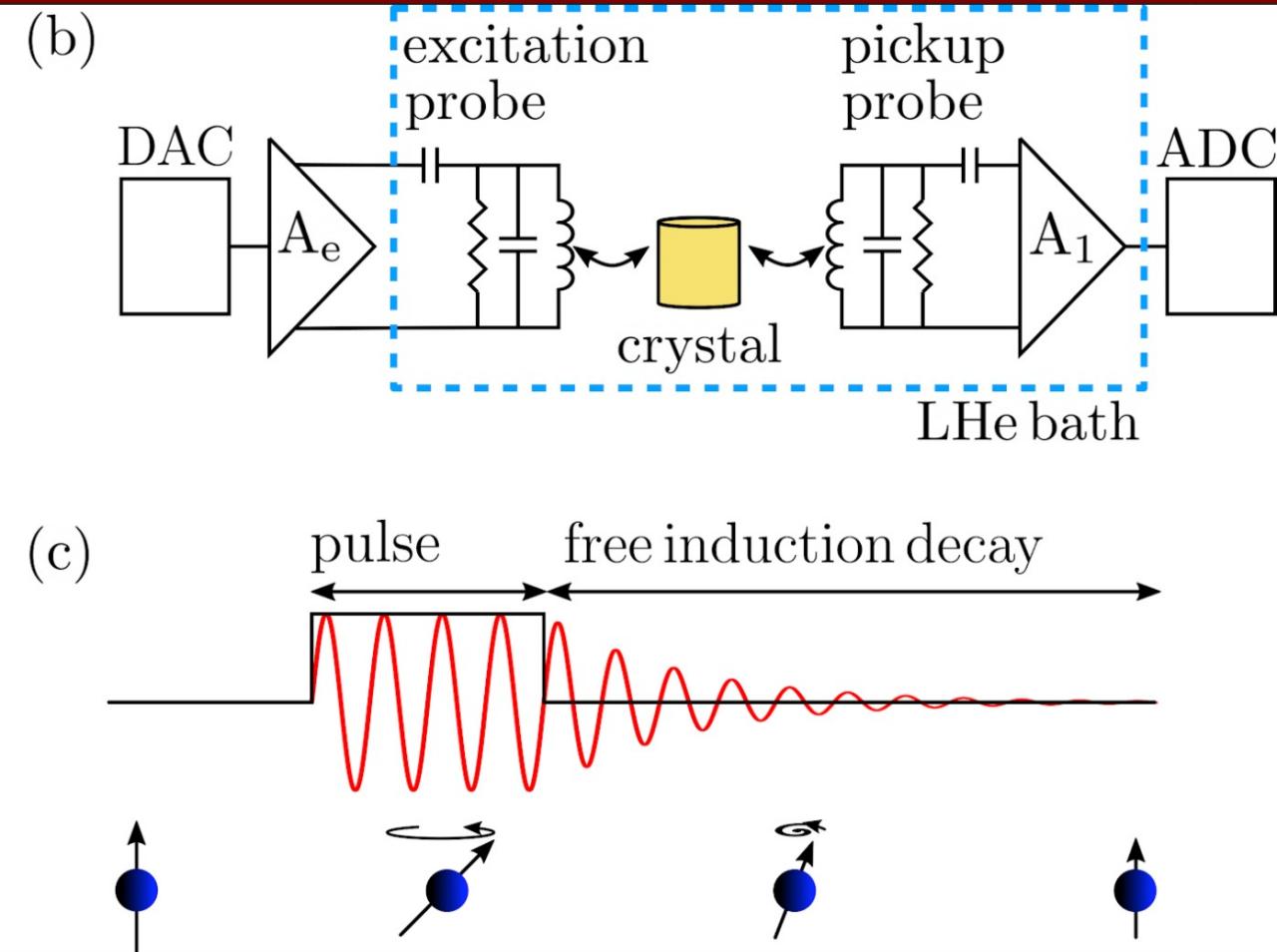
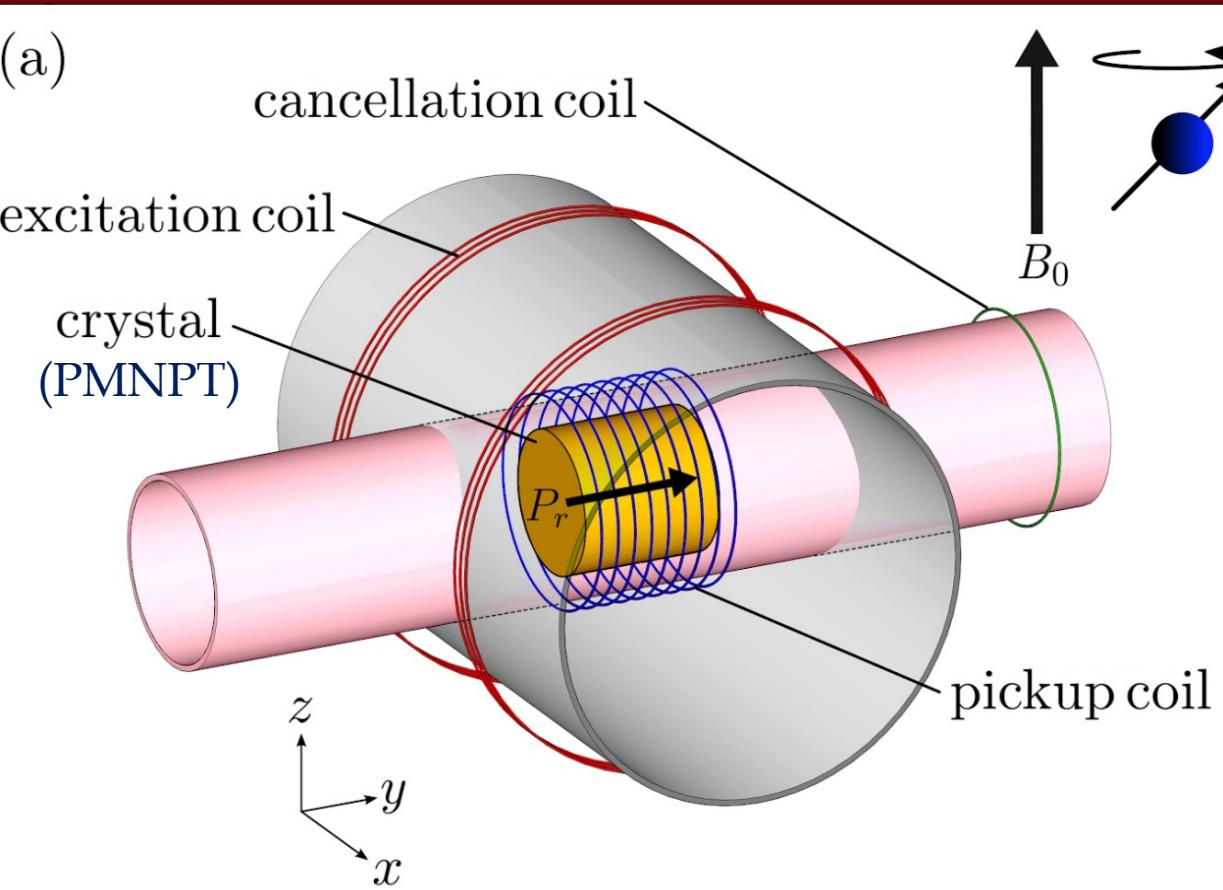
CASPER (Cosmic Axion Spin Precession Experiments) searches for experimental signatures of these couplings

DM search with NMR (CASPER)



D. F. Jackson Kimball *et. al.* in G. Carosi, G. Rybka (eds.), Microwave Cavities and Detectors for Axion Research, Springer Proceedings in Physics 245, https://doi.org/10.1007/978-3-030-43761-9_13

CASPEr-Boston

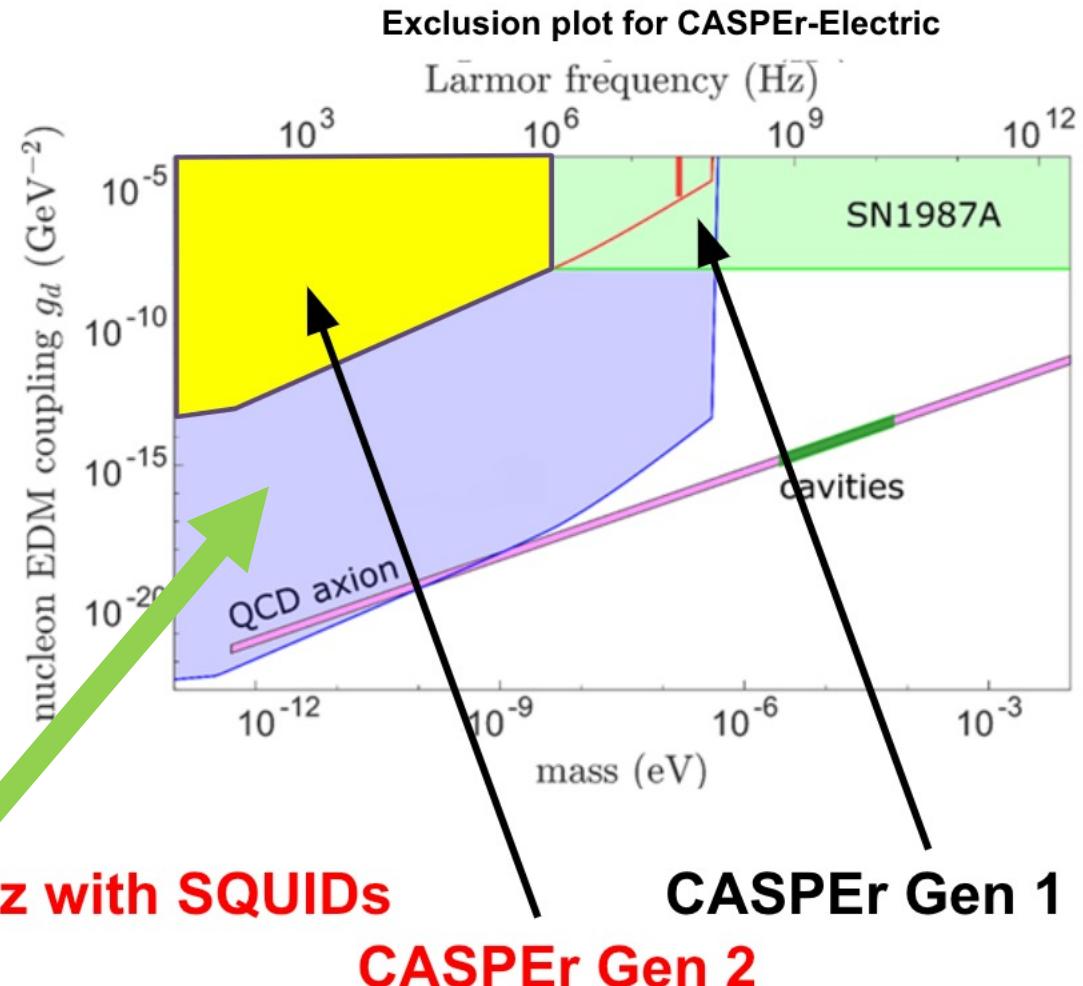




CASPER-Electric Generation 2 – Low Field

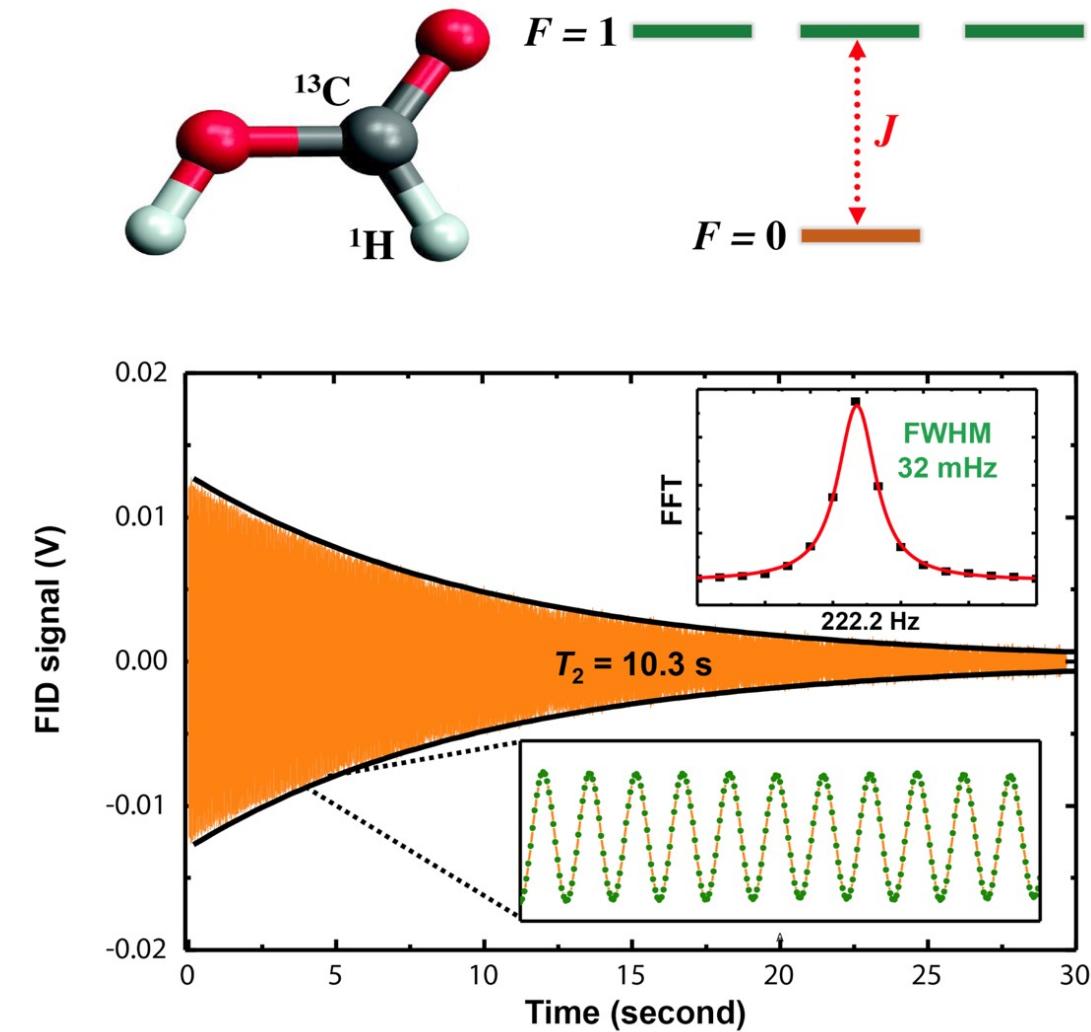
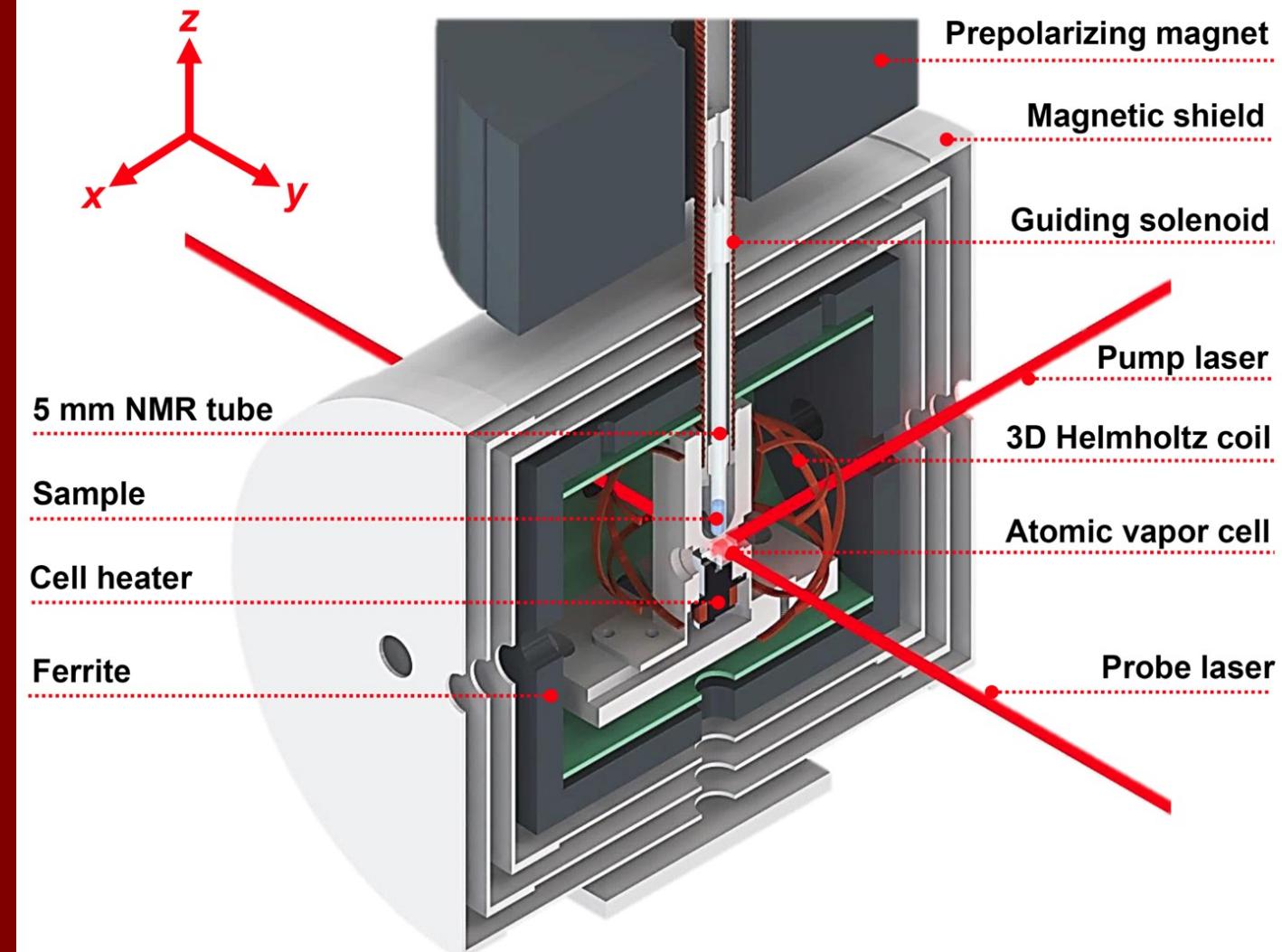
- Successful Gen 1 – High field
- **Generation 2 – Low field**
- **Frequency:** up to 1 MHz
- Goes below astronomical limits
- **Differences:**
 - Pickup: SQUID
 - SC wires

Gen 2 is looking for ALPs below 1 MHz with SQUIDs

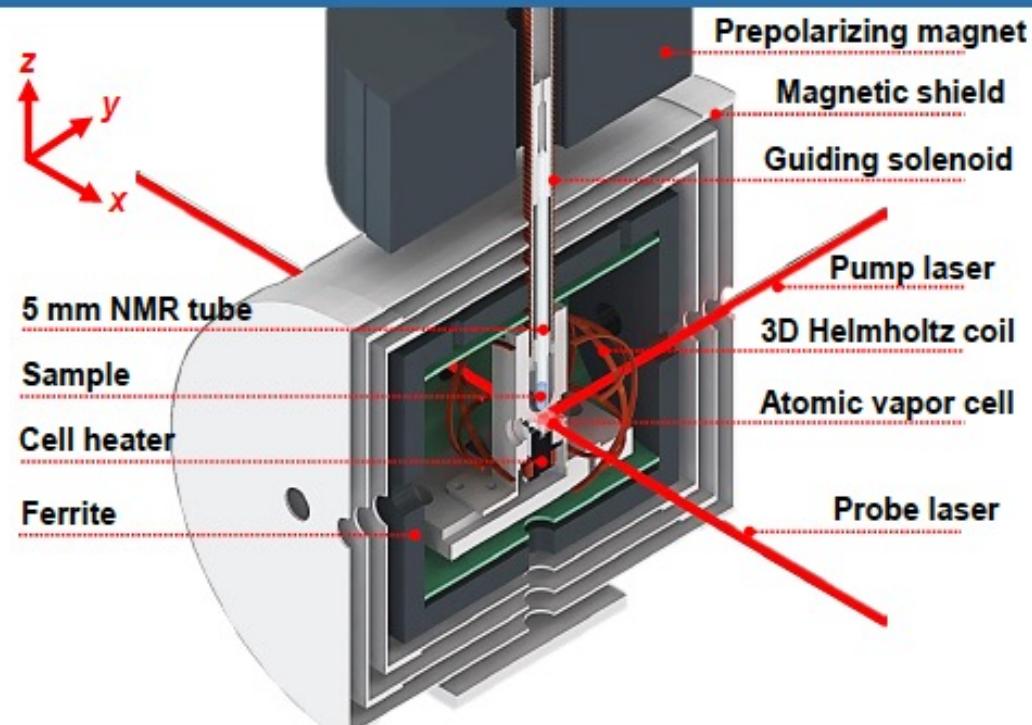
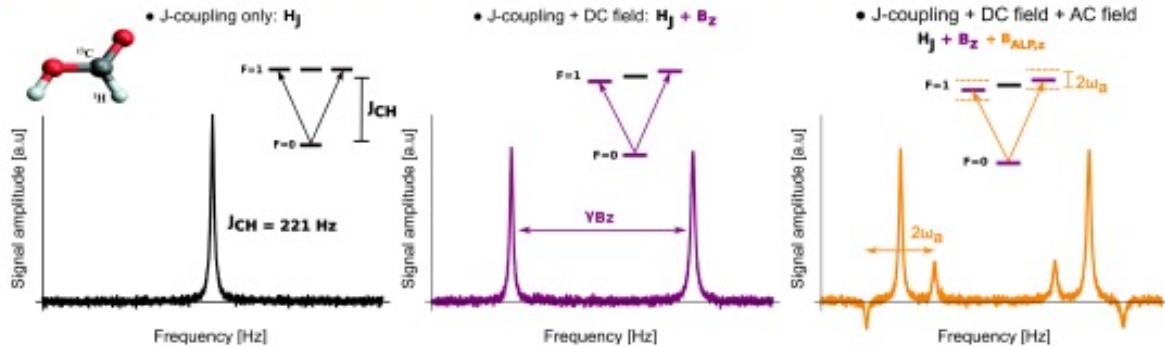


Gen 3 : Big Sample + Hyperpolarization !

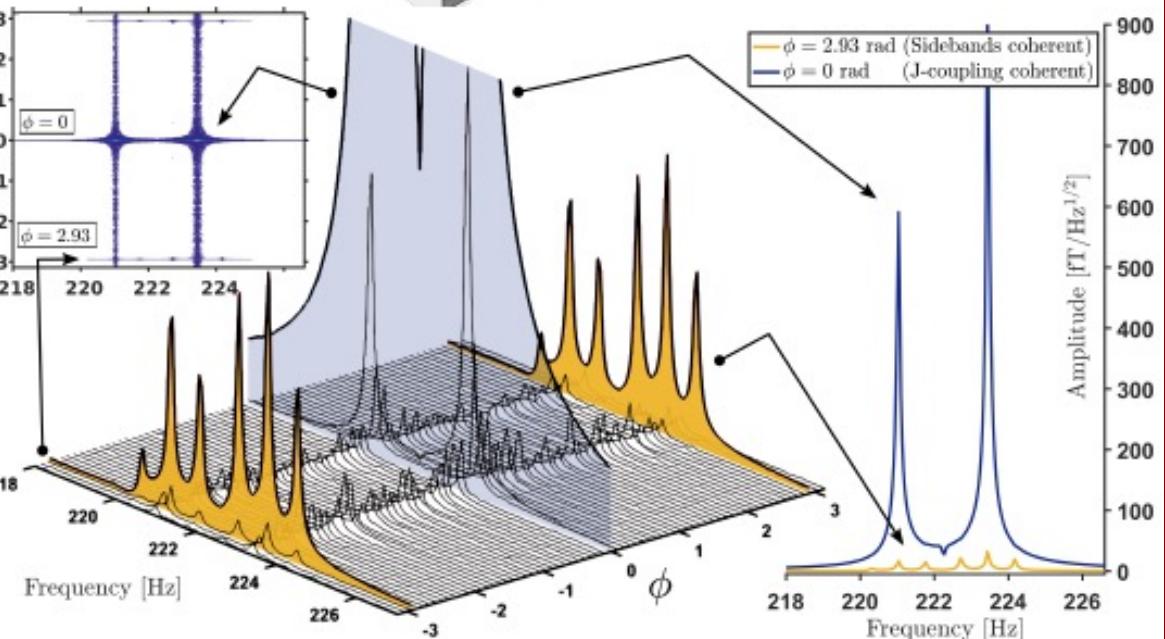
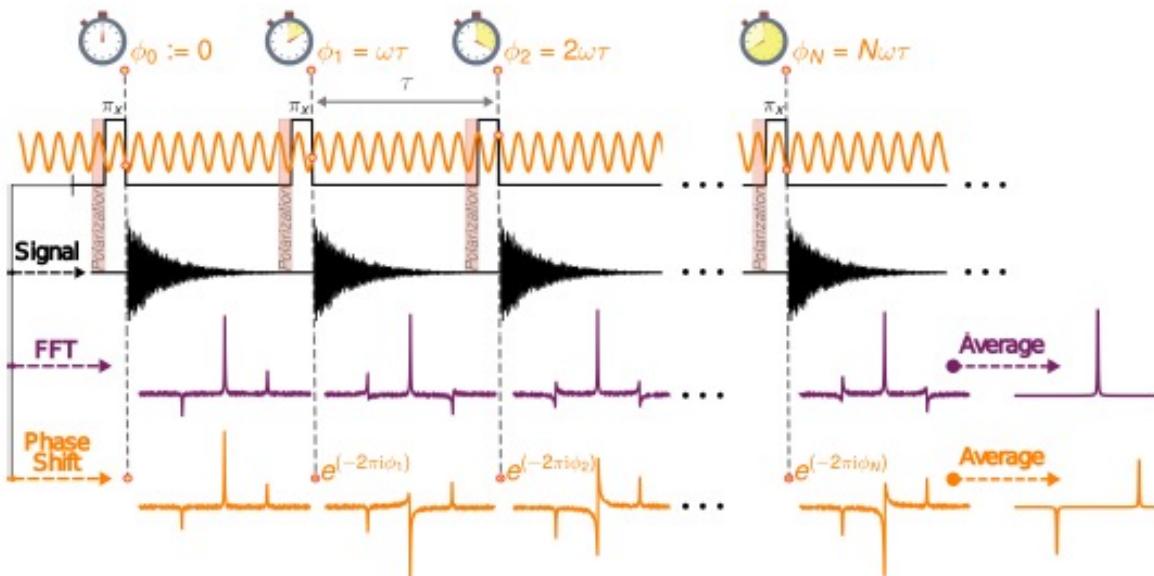
Zero-field NMR



CASPER With Zero- to Ultralow-Field NMR



- ▶ Search for dark-matter-induced sidebands
- ▶ Coherent averaging of arbitrary frequency via post-processing phase cycling
- ▶ Upcoming sensitivity improvements with PHIP

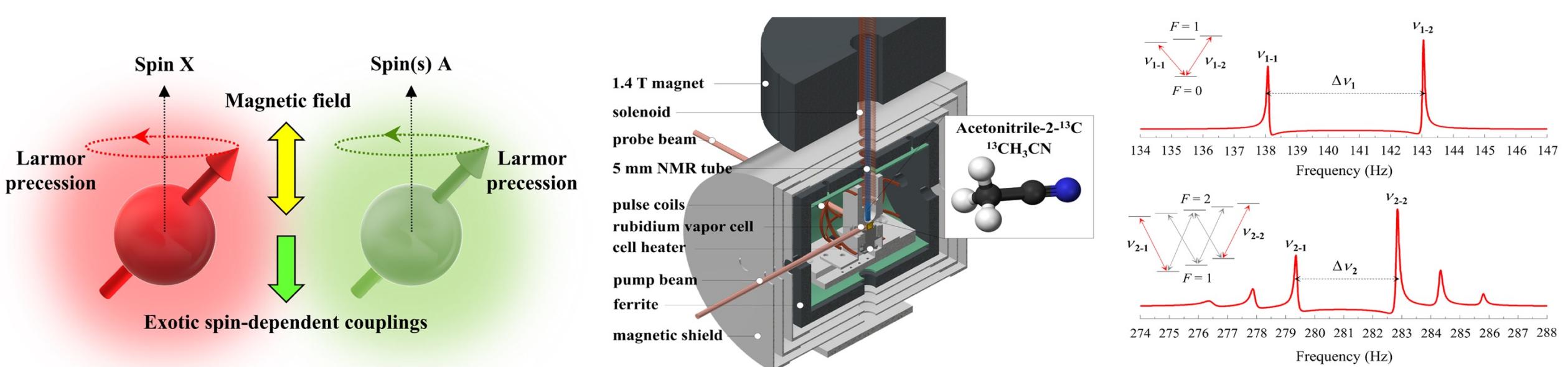


Nuclear-spin comagnetometer based on a liquid of identical molecules

Phys. Rev. Lett.

Teng Wu, John W. Blanchard, Derek F. Jackson Kimball, Min Jiang, and Dmitry Budker

Accepted 15 June 2018



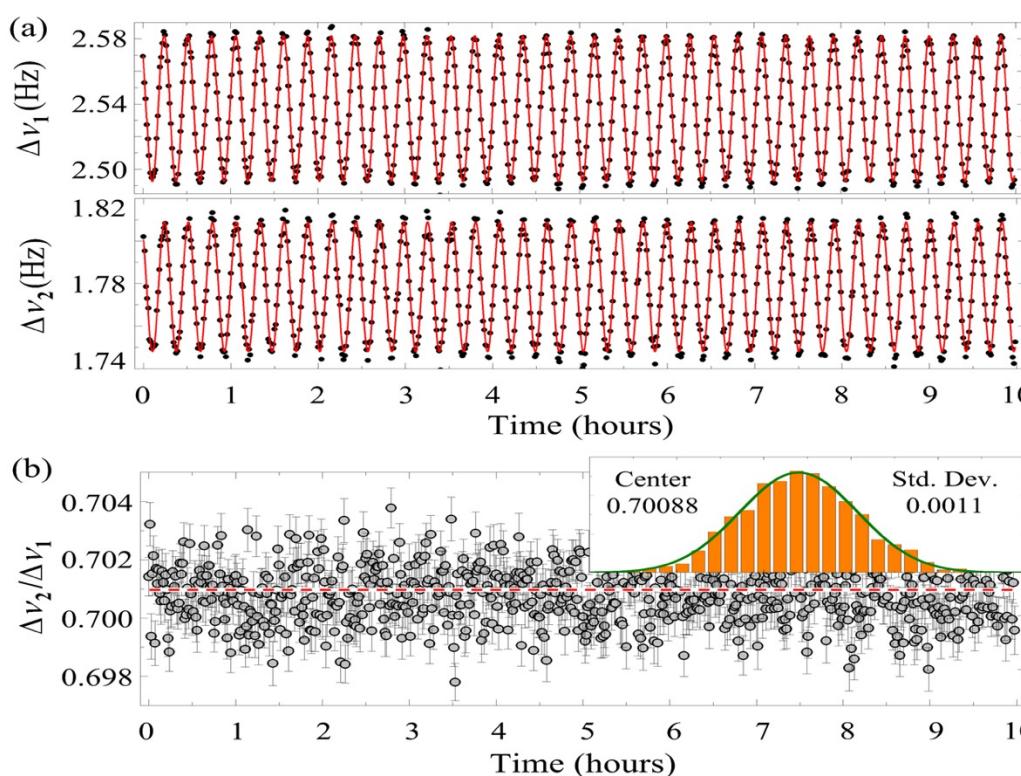
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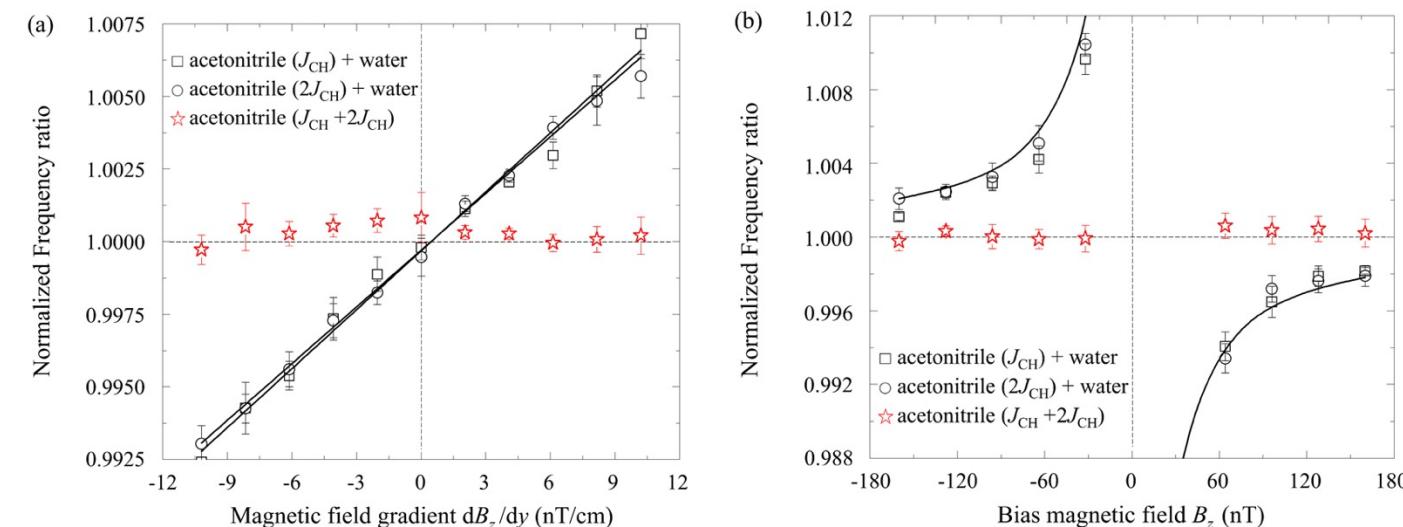
✓ Suppression of Magnetic Field Fluctuations

Sample: $2\text{-}^{13}\text{C}$ -acetonitrile ($^{13}\text{CH}_3\text{CN}$), $\sim 100 \mu\text{L}$, 5 mm NMR tube

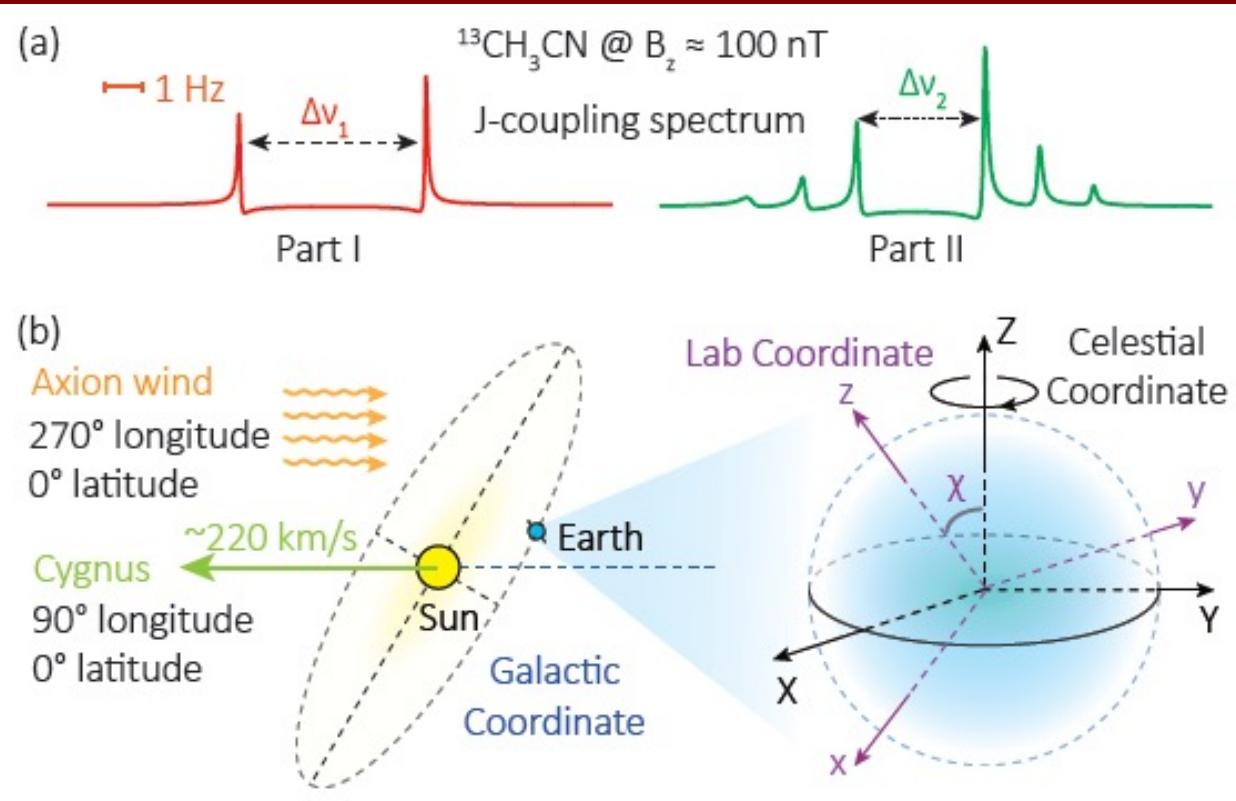
Polarization method: 1.4 Tesla Halbach magnet

Detection method: Rubidium atomic magnetometer ($10 \text{ fT/Hz}^{1/2}$)

✓ Suppression of Magnetic Field Gradient Systematic Effects

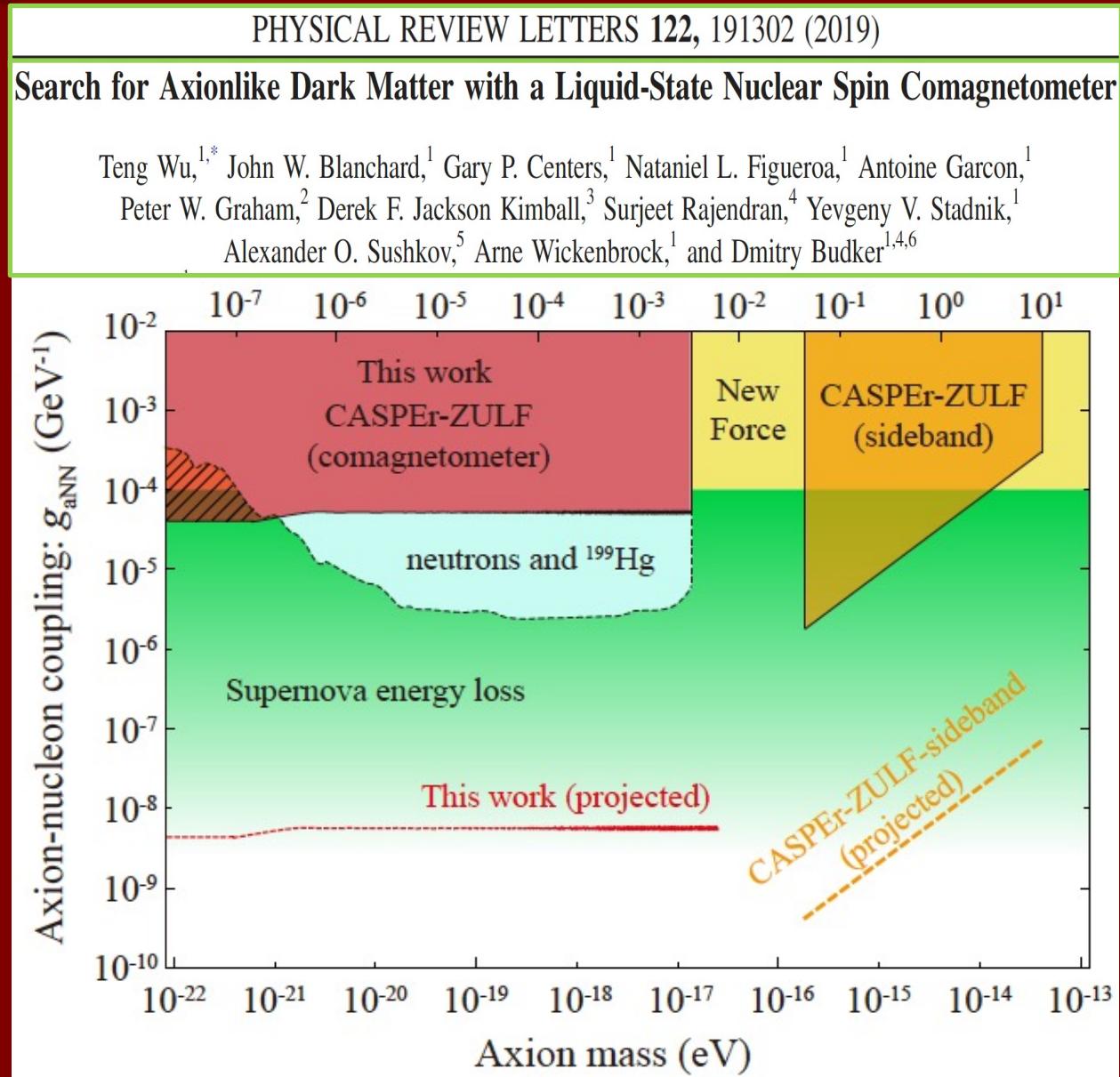


ZULF-comagnetometer



Recent strong limits (not CASPER):

- I. M. Bloch, Y. Hochberg *et al* (2020)
comagnetometer analysis
- Jiang Min *et al* (2021)
spin amplifier + maser



CASPER: NMR based ALP-search program

- ❑ Higher frequencies: data runs start in 2021 (virus permitting)!



Cryogenics magnet; $B < 0.15 \text{ T}$ ($< 1.6 \text{ MHz}$ for ^{129}Xe)

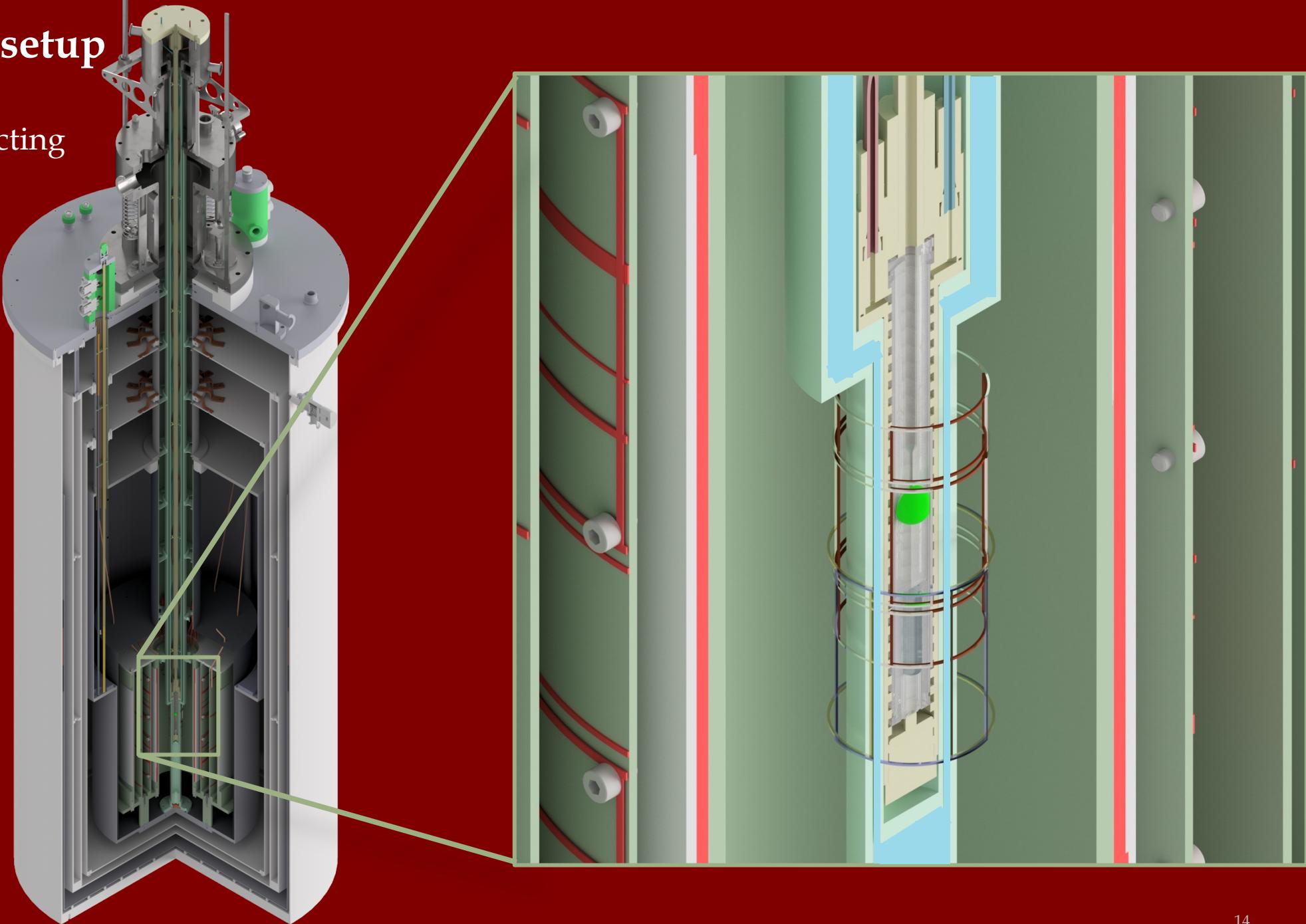
CASPer-gradient setup

Cryogenics Lt.

0.1 T (1 kG) superconducting

Cold, wet bore

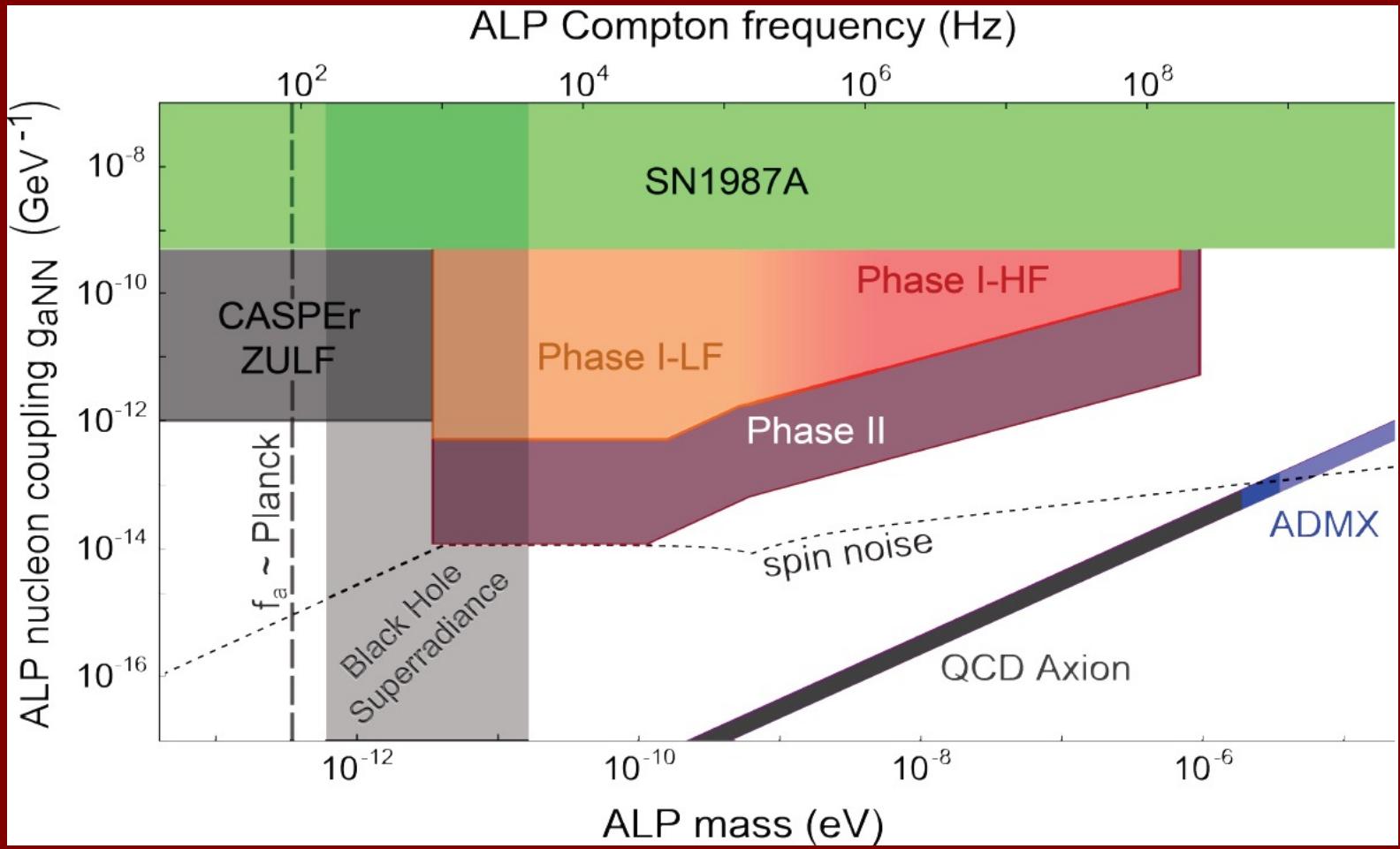
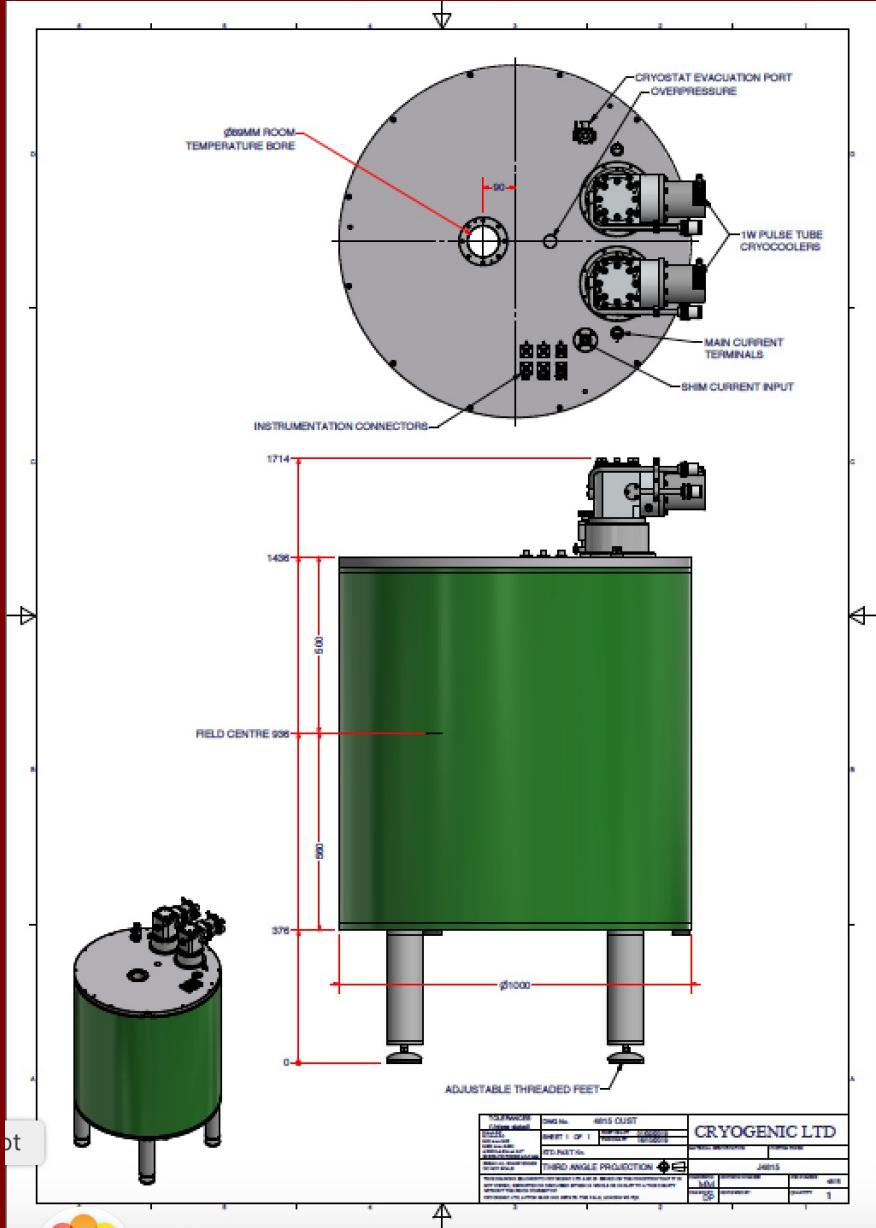
Superconducting shield



H. Bekker

CASPER: NMR based ALP-search program

- Even higher frequencies are in the plan (~ 2 years):

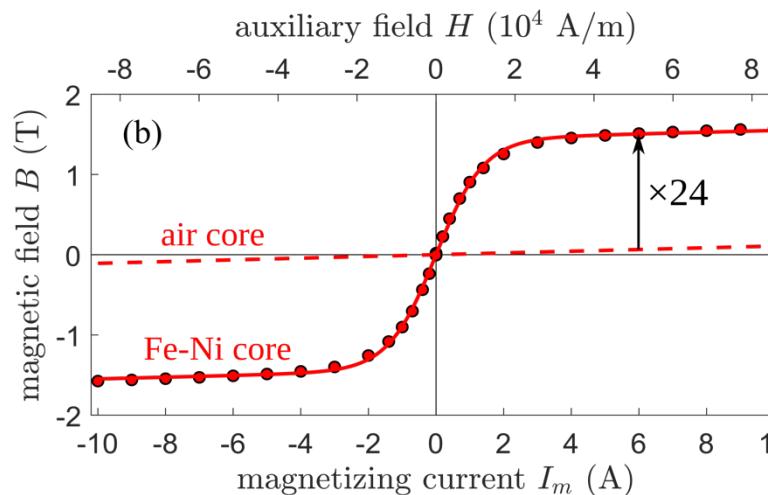
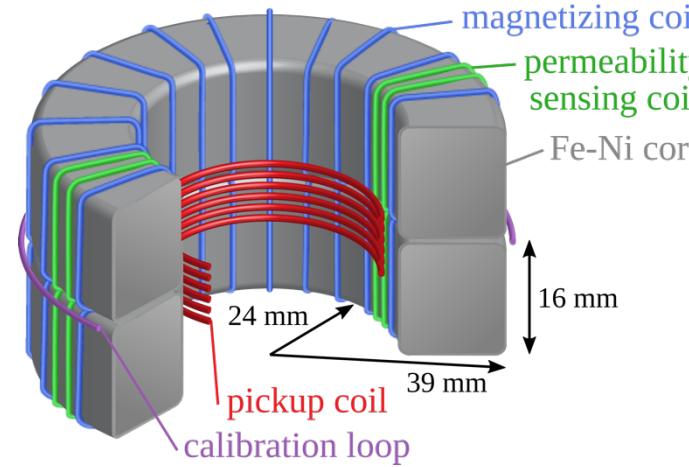


Cryogenics magnet; $B < 14.1$ T (166 MHz for ^{129}Xe)

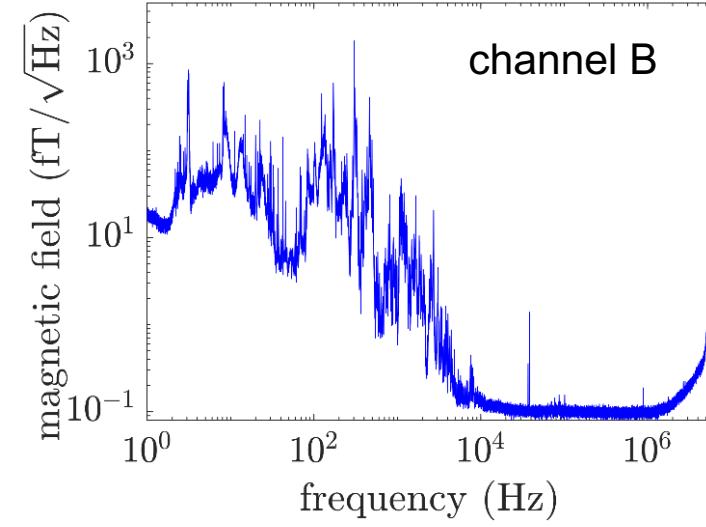
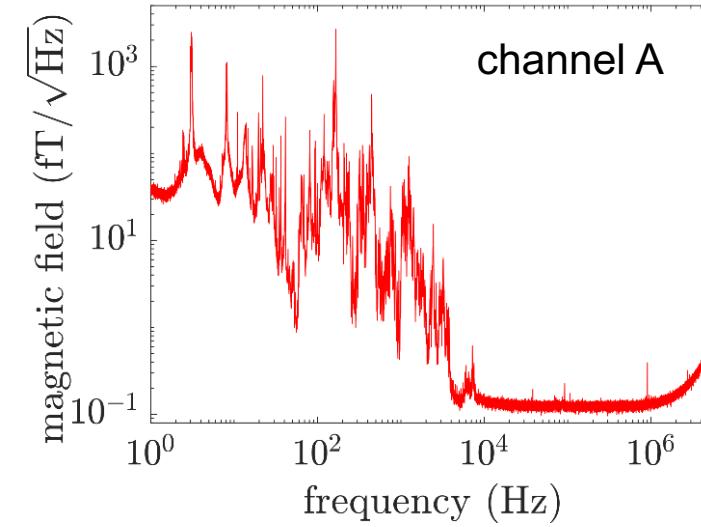


Search for Halo Axions with Ferromagnetic Toroids (SHAFT) at BU

search for electromagnetic coupling $\rightarrow \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$



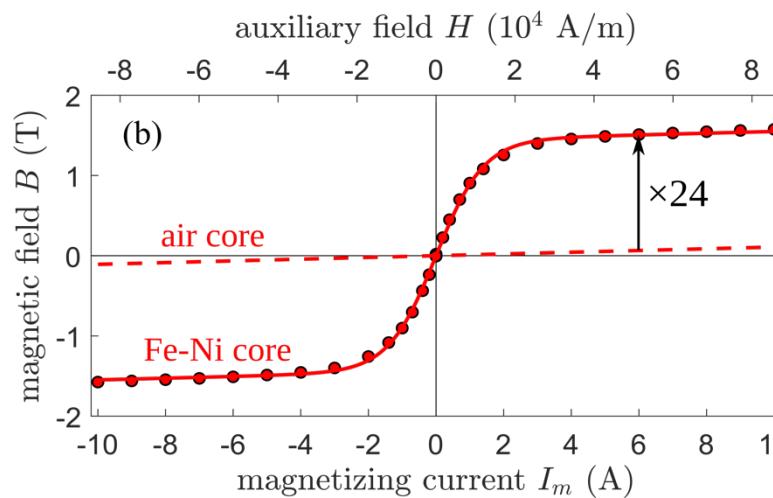
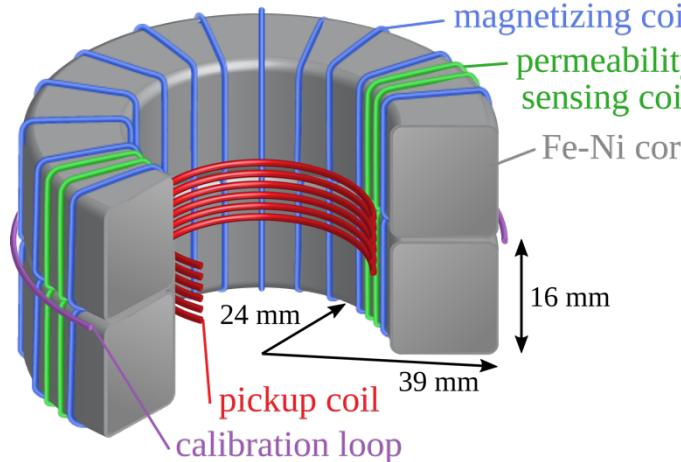
- Fe-Ni toroid powder cores provide $\times 24$ enhancement
- 1.5 T magnetic field at 6 A magnetizing current
- Two channels allow for rejection of systematics
- Magnetic field sensitivity $150 \text{ aT}/\sqrt{\text{Hz}}$ using DC SQUIDs at 4.2 K





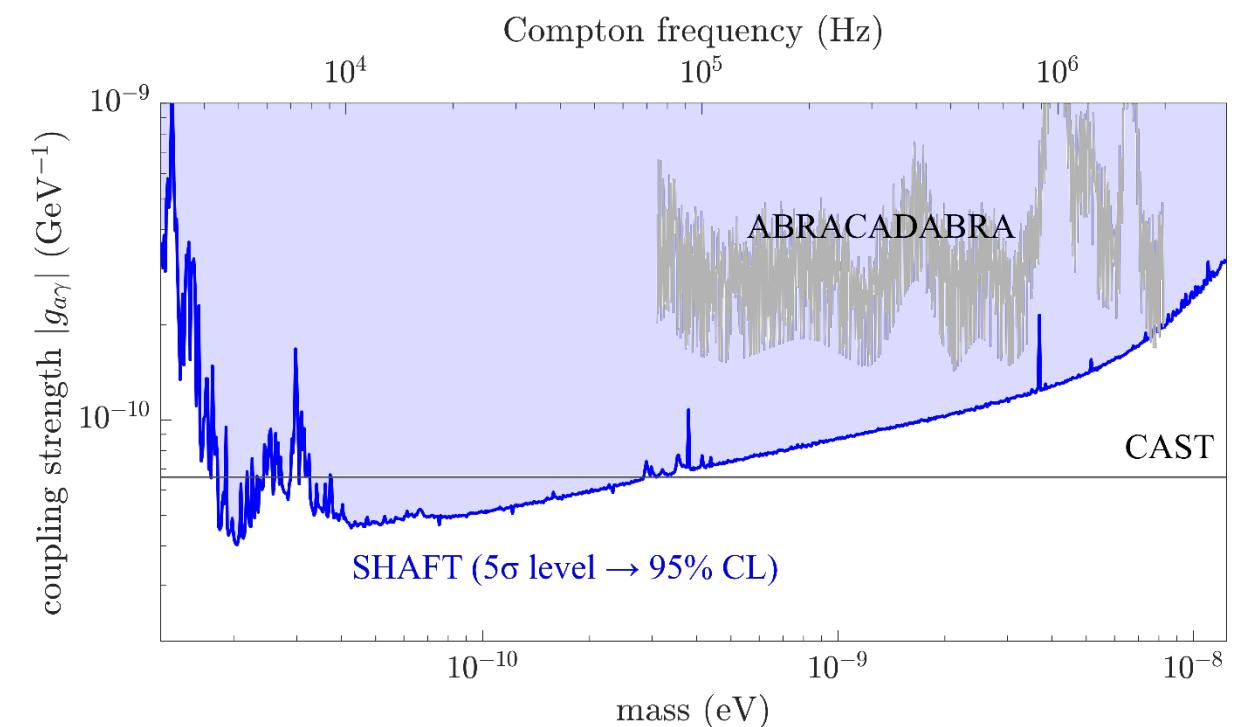
Search for Halo Axions with Ferromagnetic Toroids (SHAFT) at BU

search for electromagnetic coupling $\rightarrow \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$



Prof. A. Sushkov (BU)

- Fe-Ni toroid powder cores provide $\times 24$ enhancement
- 1.5 T magnetic field at 6 A magnetizing current
- Two channels allow for rejection of systematics
- Magnetic field sensitivity $150 \text{ aT}/\sqrt{\text{Hz}}$ using DC SQUIDs at 4.2 K
- 41 hours of ALP search data, 12 peV to 12 neV mass range
- Limits reach (at 5σ level): $|g_{a\gamma}| = 4.0 \times 10^{-11} \text{ GeV}^{-1}$



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

Search for axion-like dark matter with spin-based amplifiers

Min Jiang,^{1, 2, 3, a)} Haowen Su,^{1, 2, 3, a)} Antoine Garcon,^{4, 5} Xinhua Peng,^{1, 2, 3, b)} and Dmitry Budker^{4, 5, 6}

¹⁾Hefei National Laboratory for Physical Sciences at the Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

²⁾CAS Key Laboratory of Microscale Magnetic Resonance, University of Science and Technology of China, Hefei 230026, China

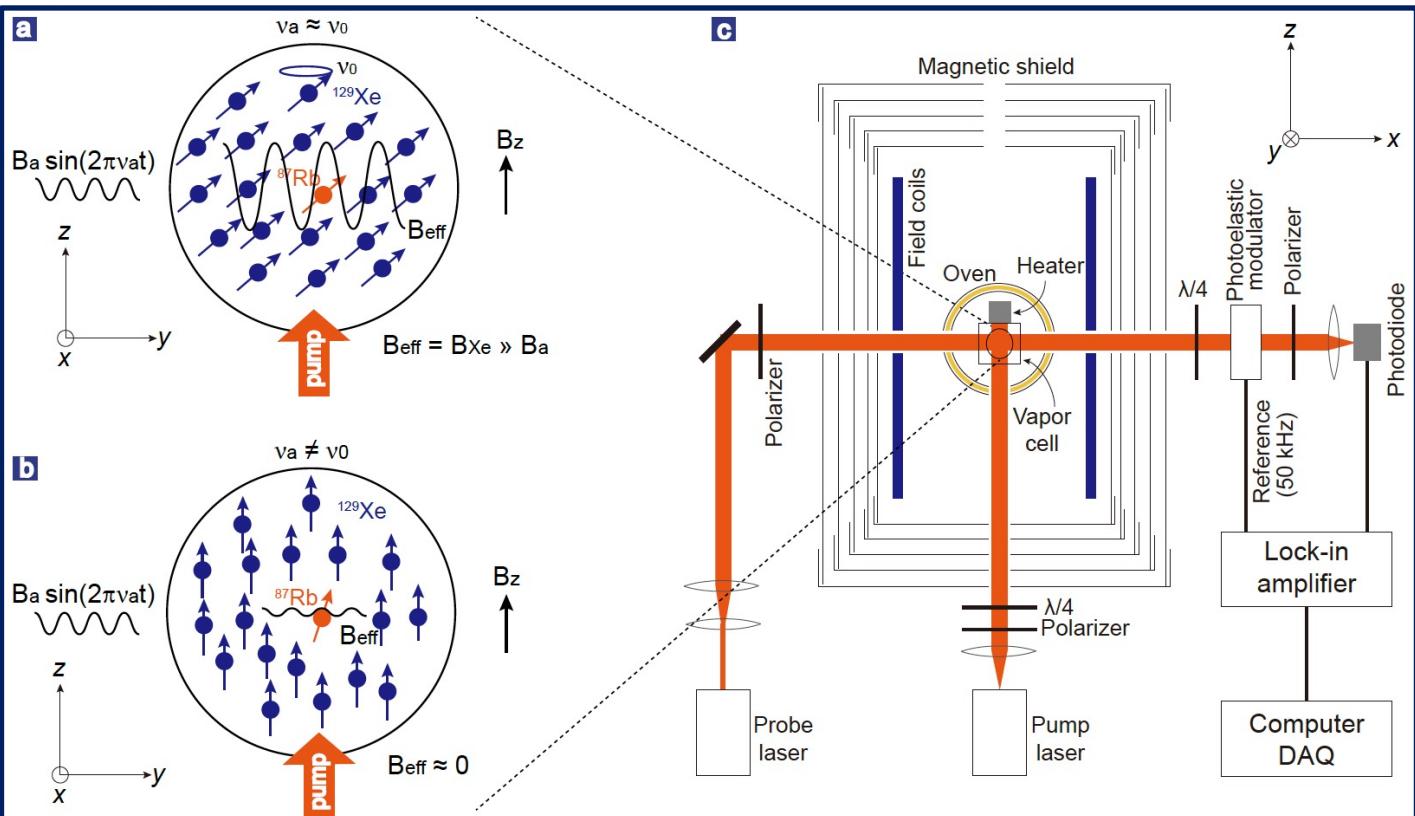
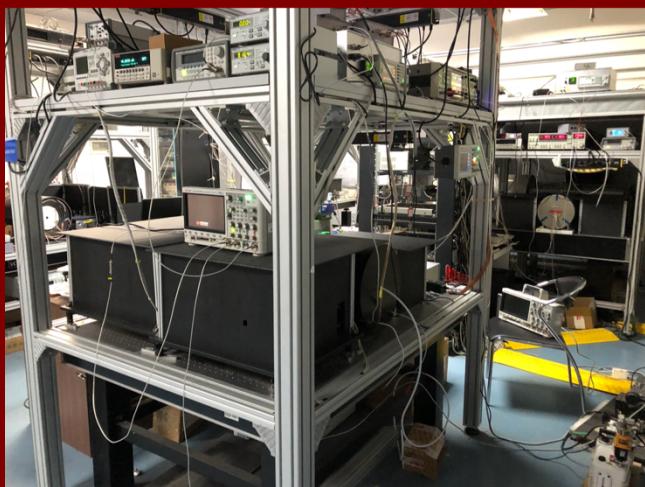
³⁾Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China

⁴⁾Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, Mainz 55128, Germany

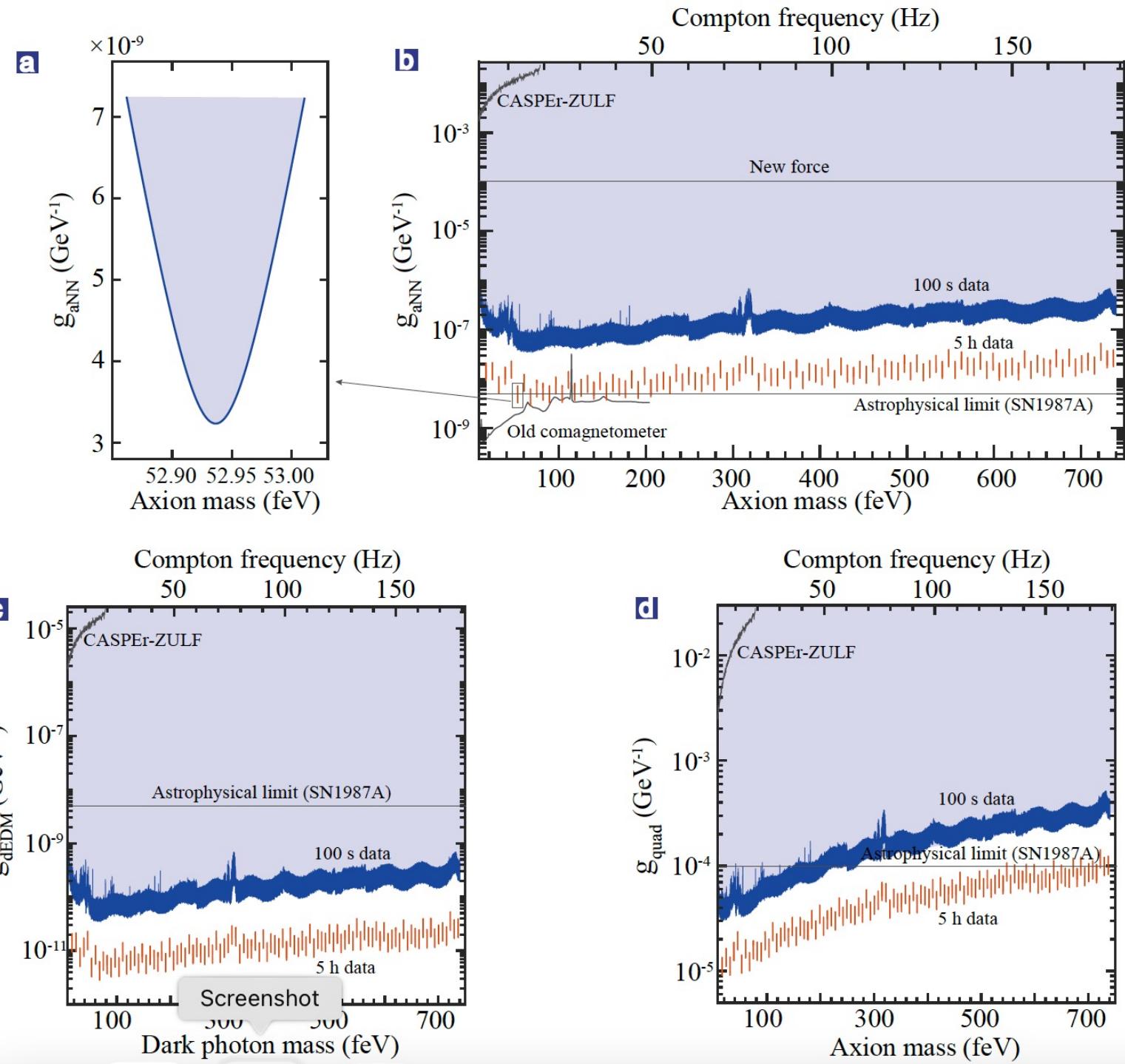
⁵⁾Johannes Gutenberg University, Mainz 55128, Germany

⁶⁾Department of Physics, University of California, Berkeley, CA 94720-7300, USA

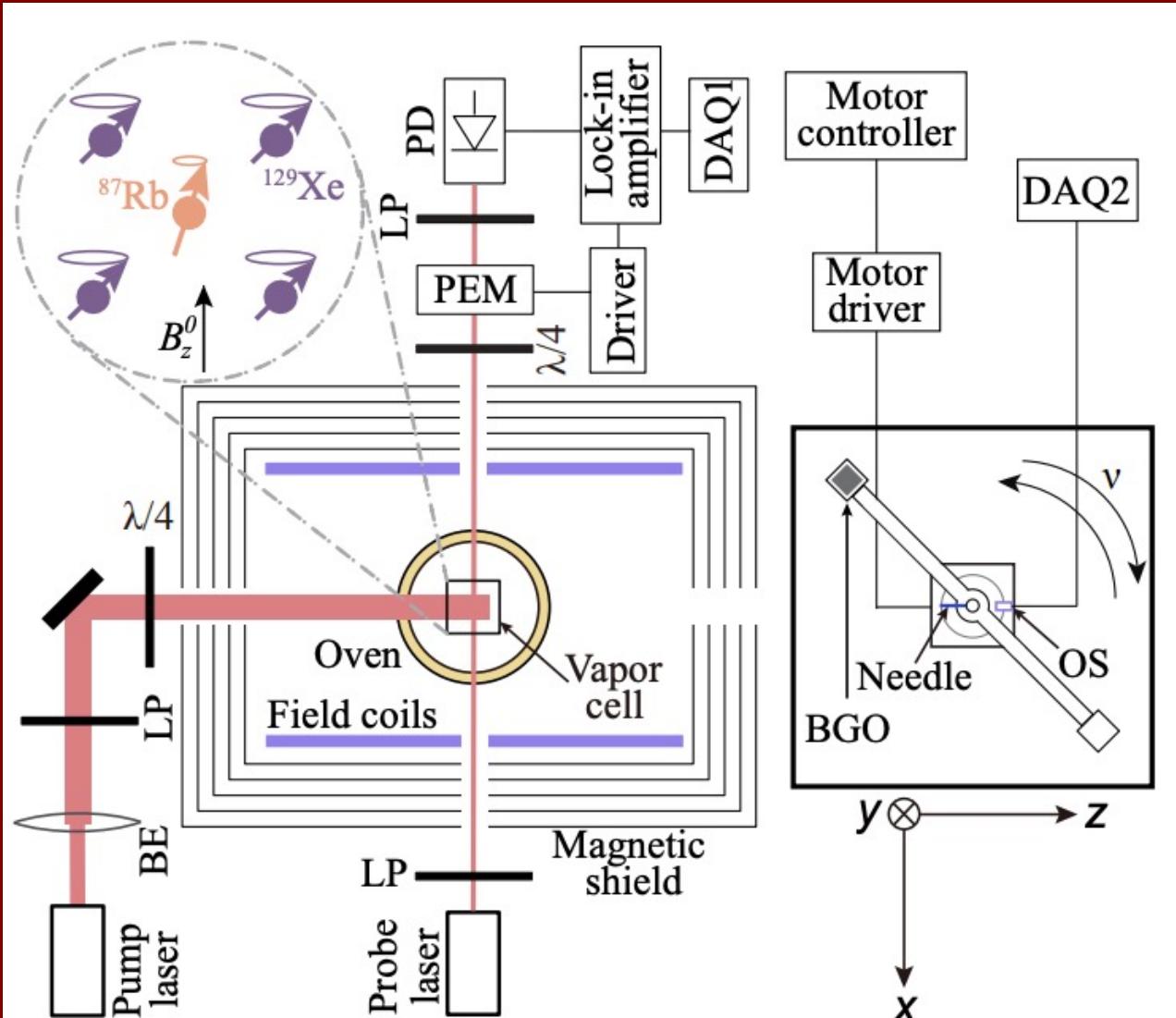
(Dated: 3 February 2021)



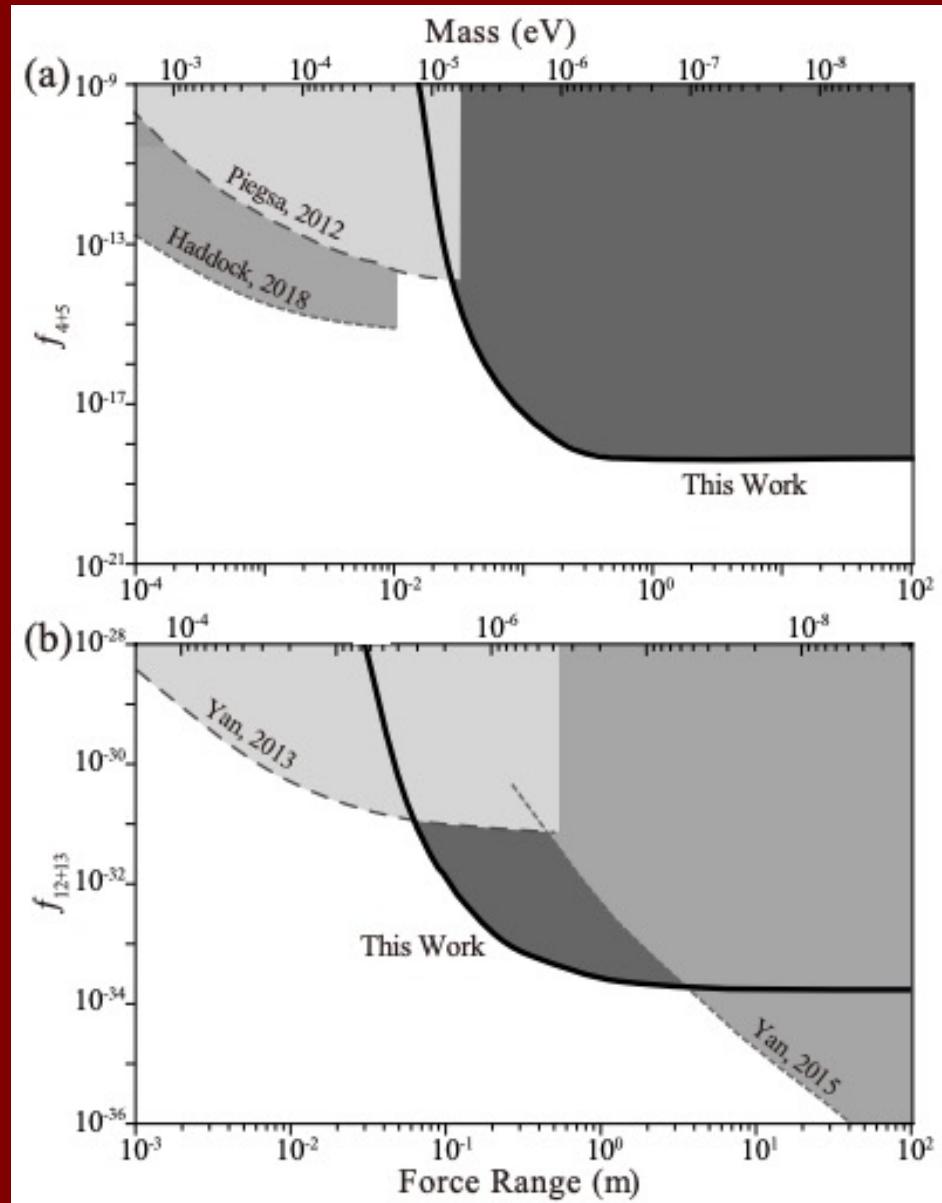
arXiv:2102.01448



Spin-Amplifier search for “fifth forces” (USTC)



Haowen Su, et al, arXiv:2103.15282

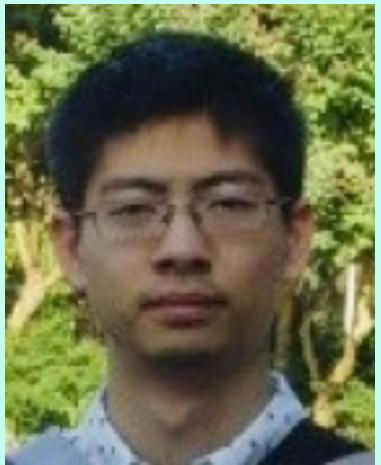


Floquet maser

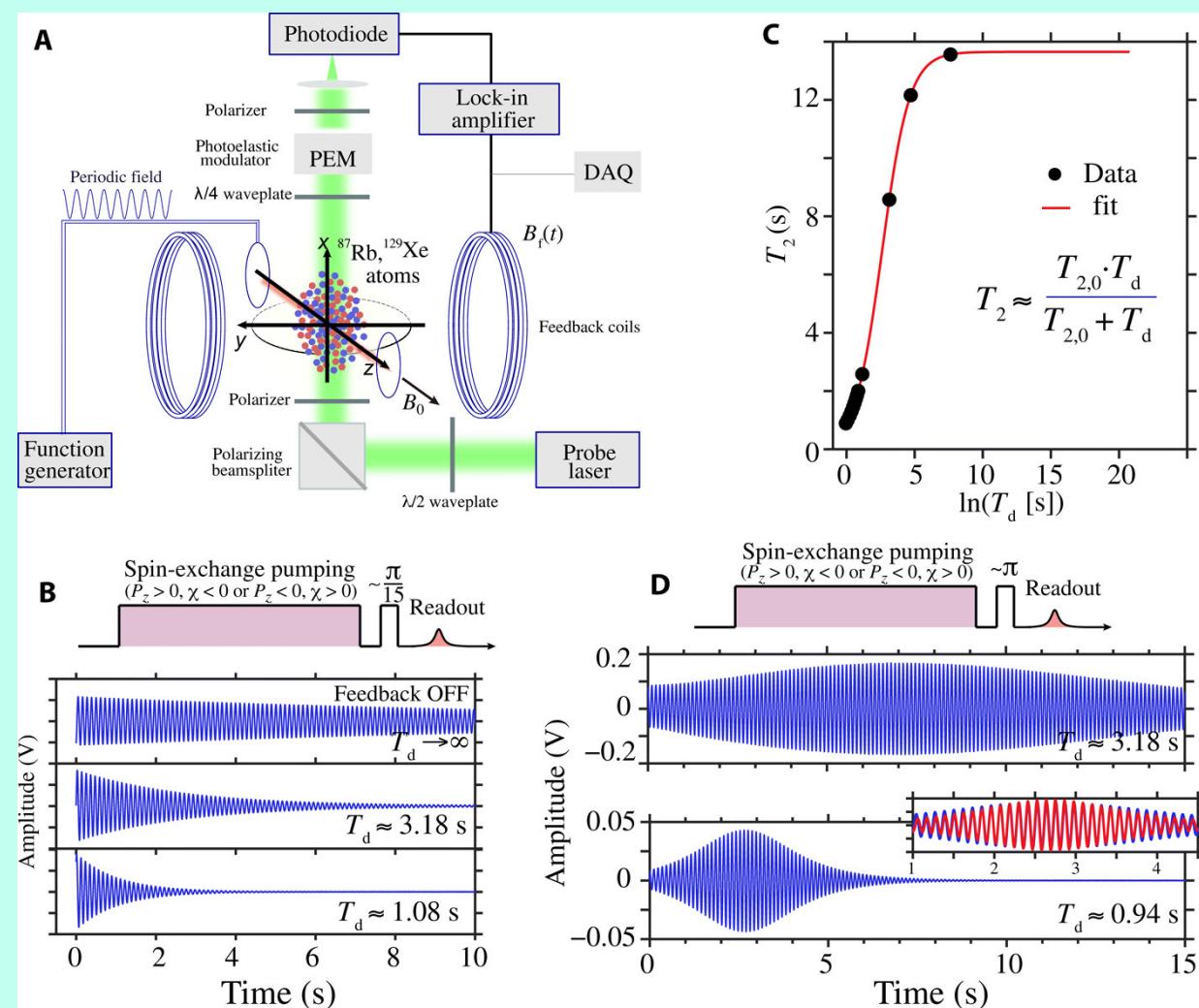
Science Advances 17 Feb 2021:
Vol. 7, no. 8, eabe0719
DOI: 10.1126/sciadv.eabe0719

Min Jiang^{1,2,3}, Haowen Su^{1,2,3}, Ze Wu^{1,2,3}, Xinhua Peng^{1,2,3,*} and Dmitry Budker^{4,5,6}

* See all authors and affiliations

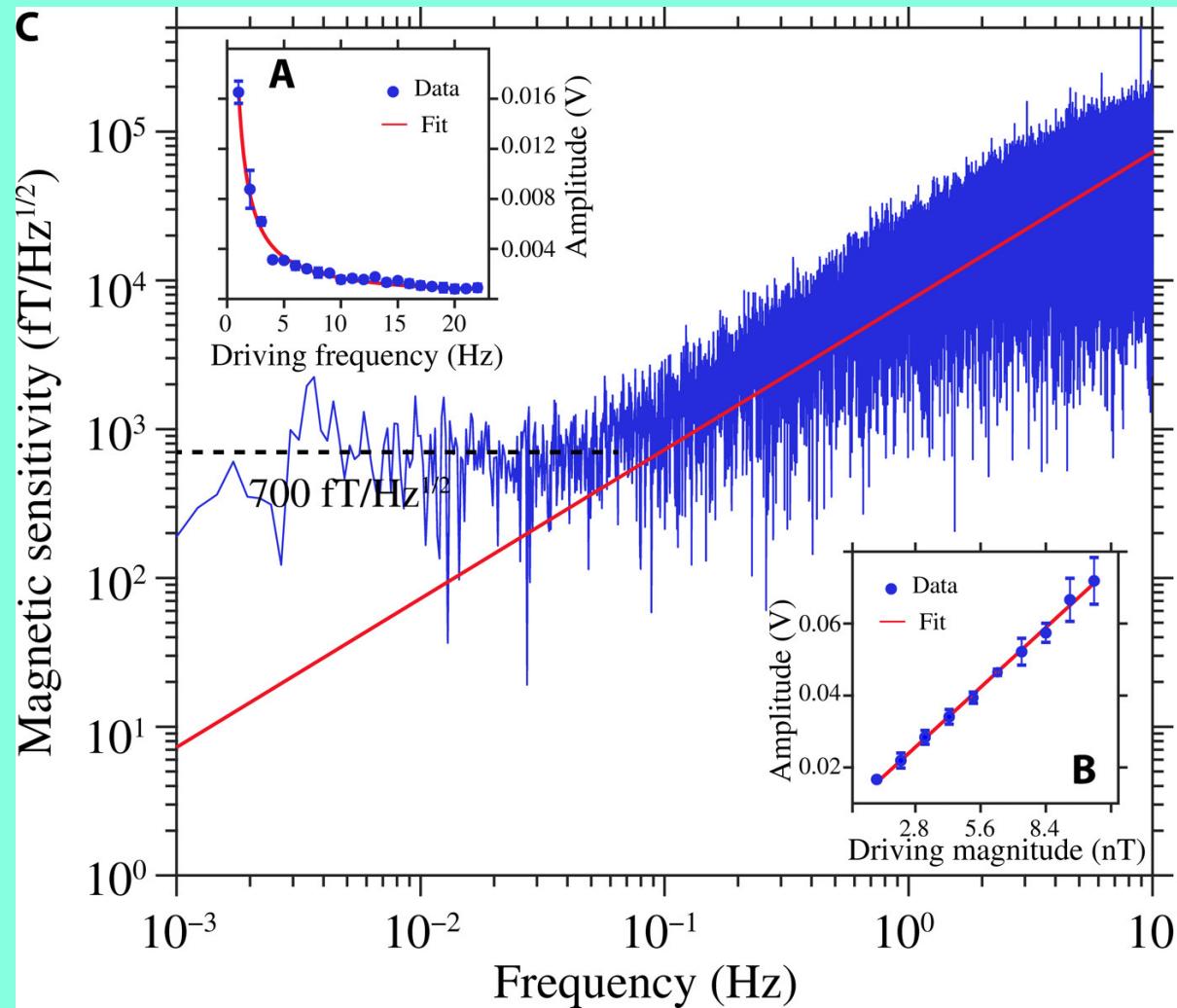


Schematic of experimental setup and damping feedback mechanism



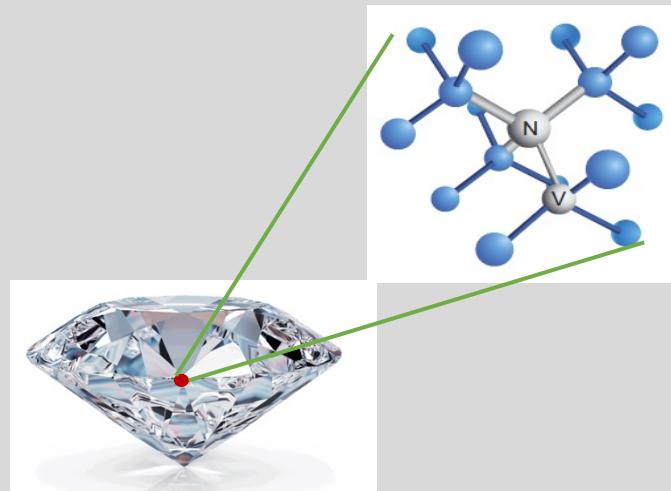
Min Jiang et al. Sci Adv 2021;7:eabe0719

Maser-based magnetometry on the first-order Floquet sideband of ^{129}Xe



Min Jiang et al. Sci Adv 2021;7:eabe0719

Utilizing single-spin sensor to search for exotic interactions



NV centers in diamond: single-spin sensors

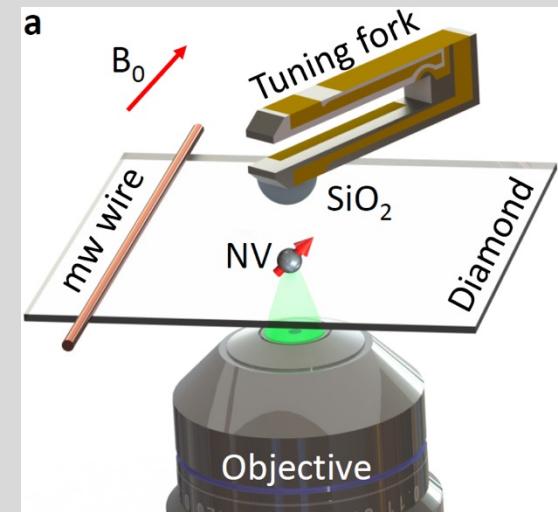
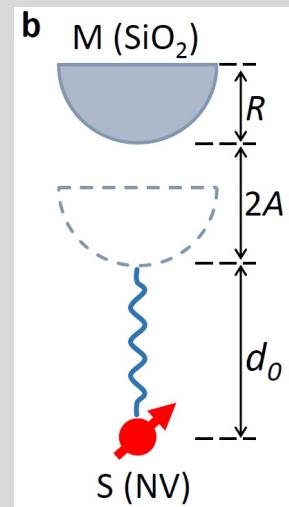


Diagram of the setup: NV sensor + AFM



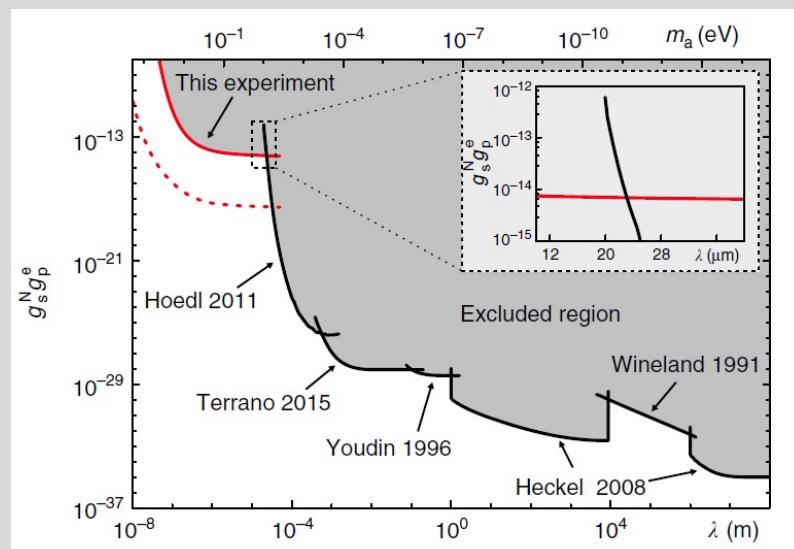
Features

- ✓ Atomic scale
 - ✓ Near surface
 - ✓ Precise quantum control
 - ✓ NV + AFM
- } → Shorter force range
- Good sensitivity
- Cancel unwanted signals

Several searching results with NV sensors

Monopole-dipole interaction

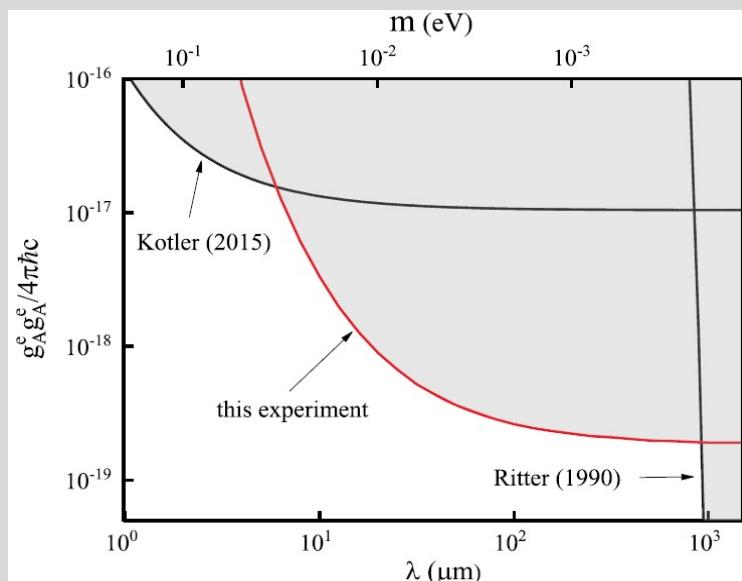
$$V_{\text{sp}}(\mathbf{r}) = \frac{\hbar^2 g_s^N g_p^e}{8\pi m} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda}} \boldsymbol{\sigma} \cdot \mathbf{e}_r,$$



Nature Communications 9,739 (2018)

Dipole-dipole interaction

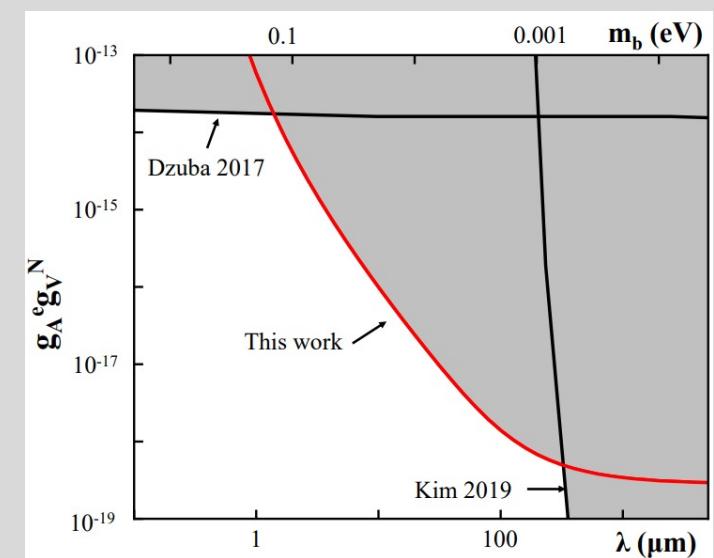
$$H_2 = \frac{g_A^e g_A^e \hbar c}{4\pi \hbar c} \frac{1}{r} (\vec{\sigma}_1 \cdot \vec{\sigma}_2) e^{-\frac{r}{\lambda}},$$



Phys. Rev. Lett. 121, 080402 (2018)

Velocity-dependent monopole-dipole interaction

$$V = g_A^e g_V^N \frac{\hbar}{4\pi} (\boldsymbol{\sigma} \cdot \mathbf{v}) \left(\frac{e^{-\frac{r}{\lambda}}}{r} \right),$$

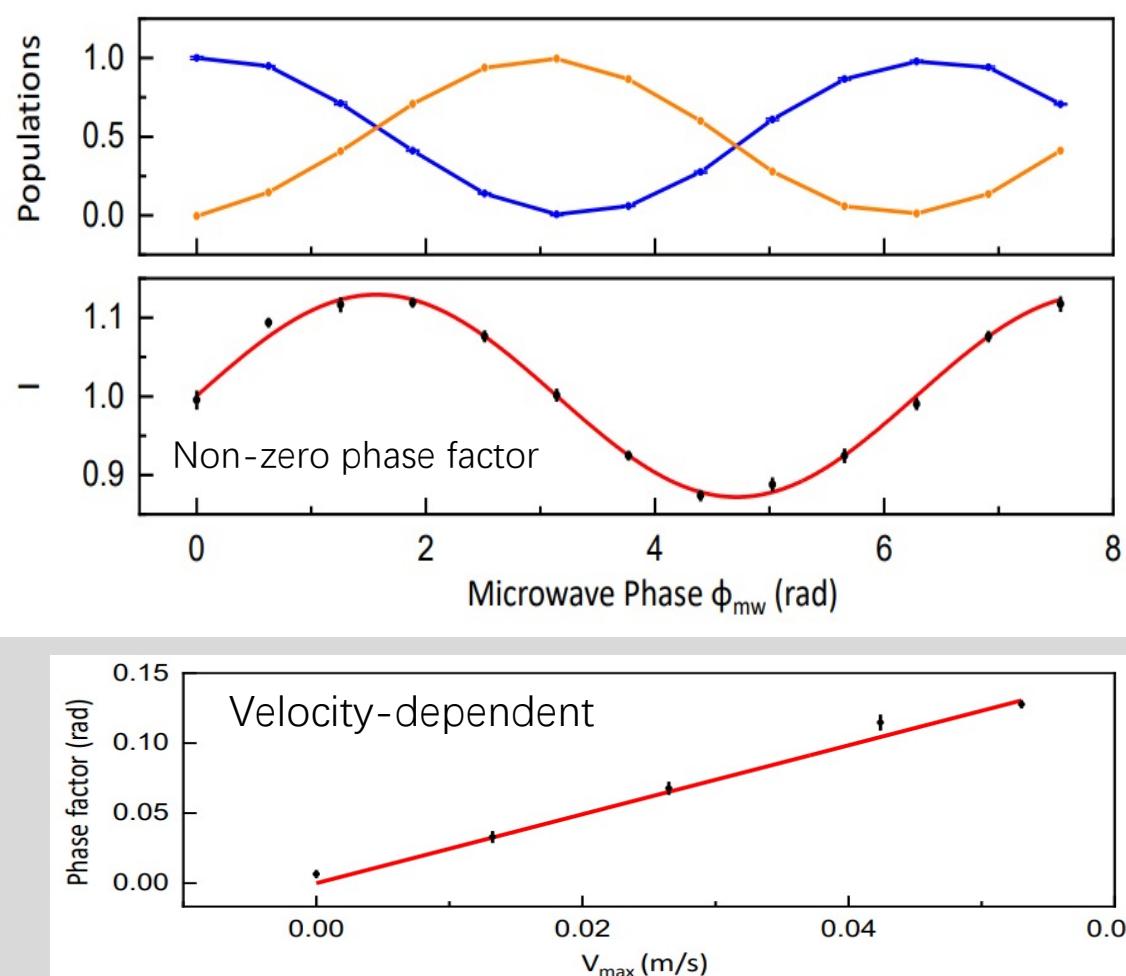


arXiv : 2009.09257 (2020)

One search yields nonzero signal !

Velocity-dependent monopole-dipole interaction

$$V = f^\perp \frac{\hbar^2}{4\pi m_e c} \boldsymbol{\sigma} \cdot \mathbf{v} \times \hat{r} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda}},$$



We analyzed several possible sources of the observed signal and they cannot explain the nonzero signal. Further experiments are being carried out to figure out the possible source of this signal.

Possible sources	Contribution to the phase factor (rad)
Tuning fork	$< 10^{-3}$
Charges on the mass	$< 10^{-4}$
Casimir Force	$< 10^{-5}$
Diamagnetism of the mass	$< 10^{-10}$
Effect due to the moving dielectric	$< 10^{-15}$
Nuclear spin in the mass	$< 10^{-15}$



Samer Afach, *et al*, Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches (GNOME); [arXiv:2102.13379](https://arxiv.org/abs/2102.13379) (2021)

The GNOME Experiment

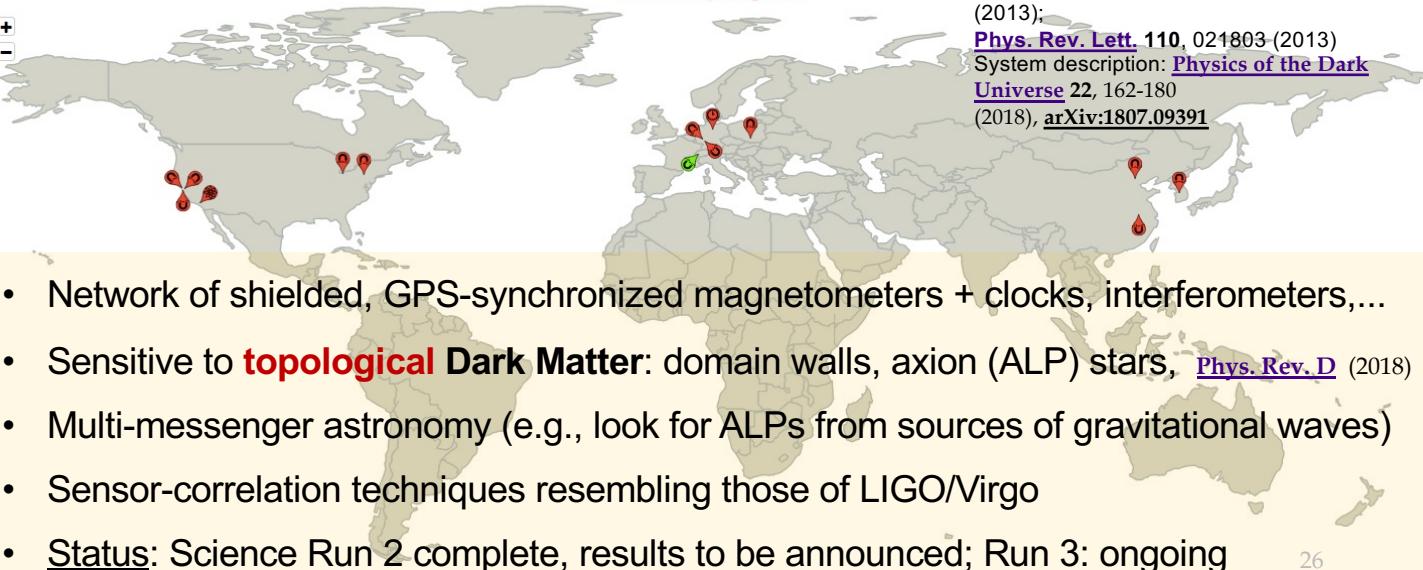
Collaboration website

Global Network of Optical Magnetometers for Exotic searches

Current date: 2017/09/28 21:54:36 GPS

Show Map Legend

Idea and proof-of-concept:
Annalen der Physik **525**(8-9), 659–70 (2013);
[Phys. Rev. Lett.](#) **110**, 021803 (2013)
System description: [Physics of the Dark Universe](#) **22**, 162–180 (2018), [arXiv:1807.09391](https://arxiv.org/abs/1807.09391)

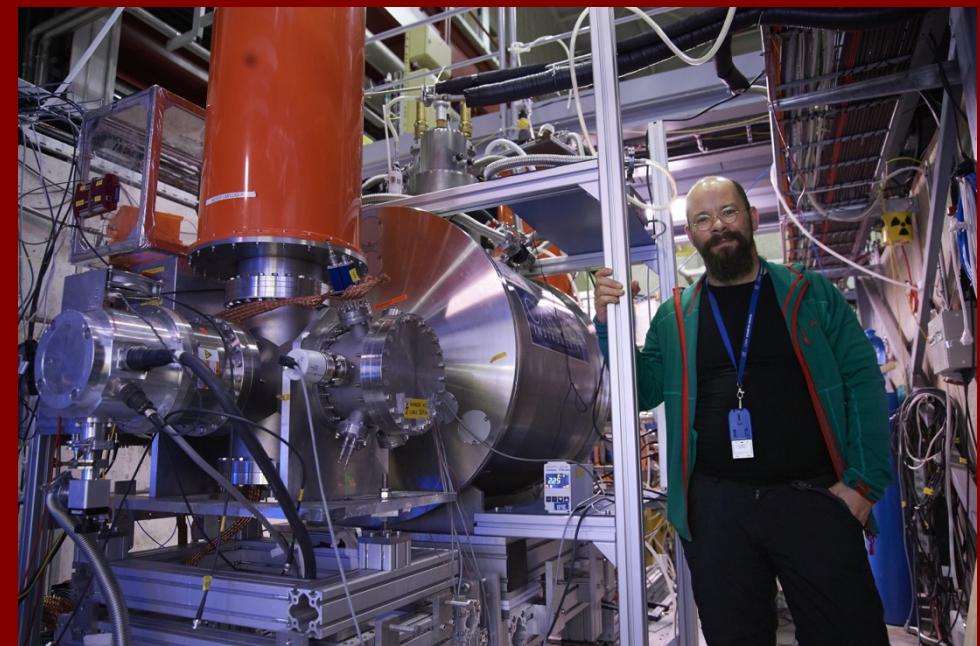
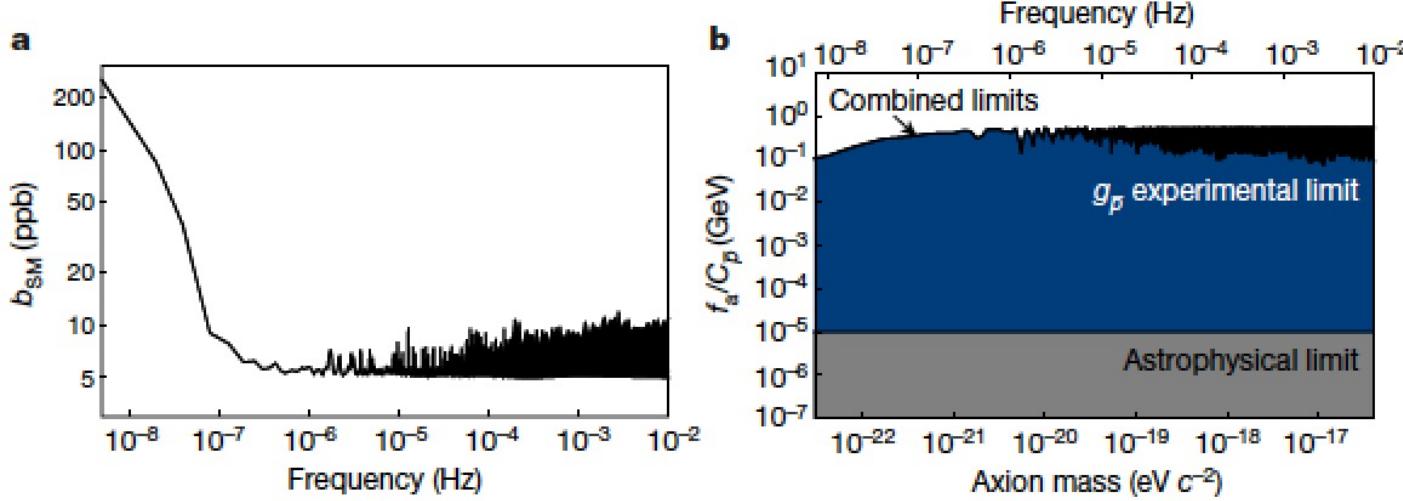


- Also **clock** networks!
- **Hybrid** networks
- E.g.: GPS.DM+GNOME+PTB

Dark-matter search with antimatter !

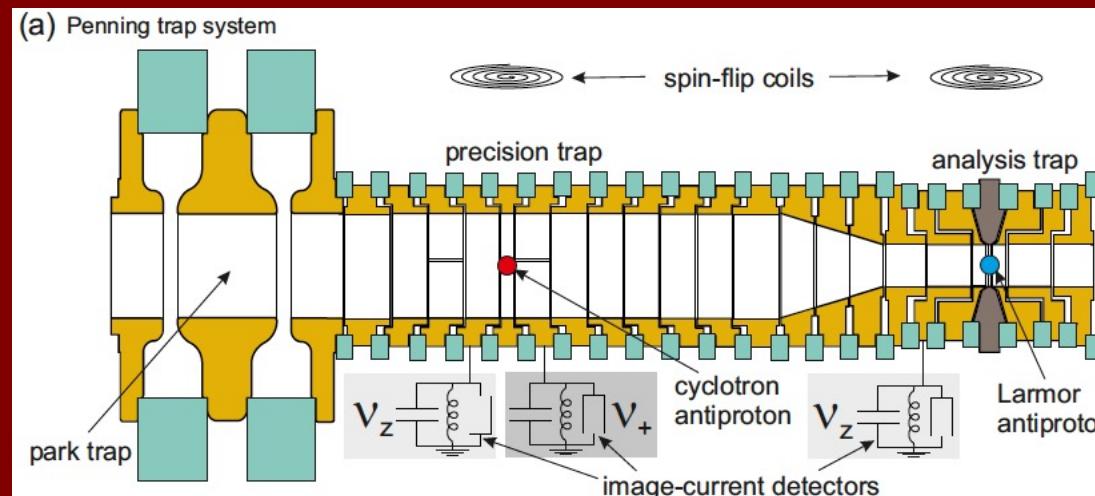
Direct limits on the interaction of antiprotons with axion-like dark matter

310 | Nature | Vol 575 | 14 November 2019



Stefan Ulmer

- Collaboration with BASE
- Search for ALP-induced antiproton spin precession



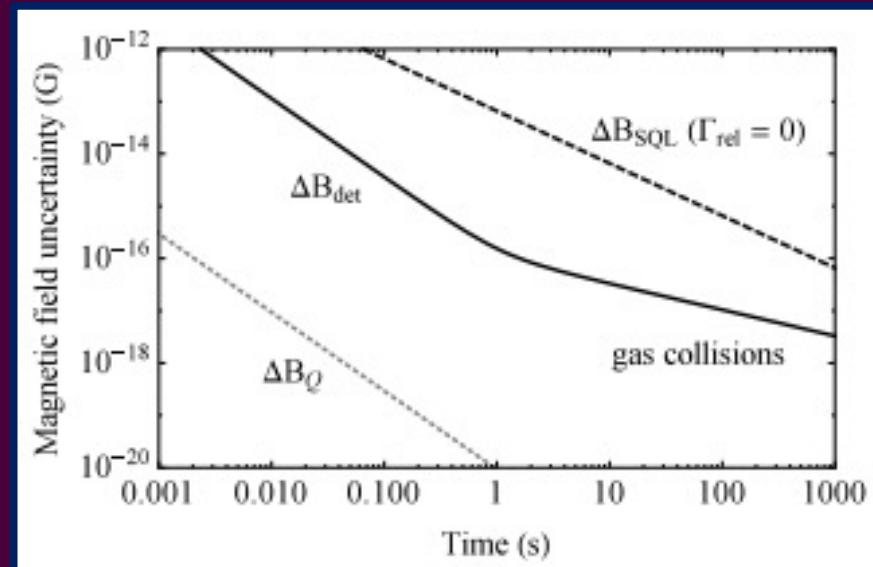
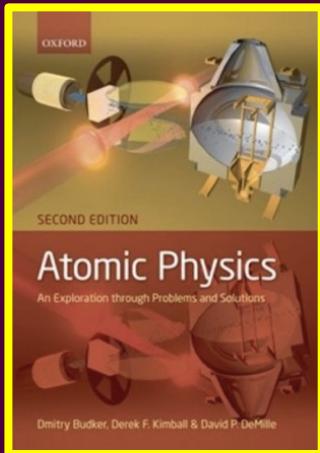
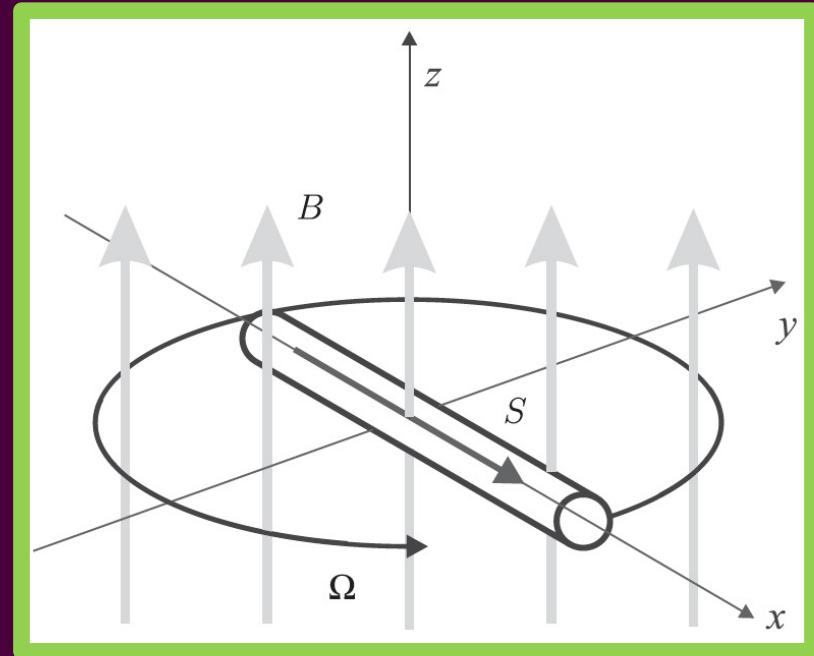
Ch. Smorra



Y. Stadnik 27



Precessing Ferromagnetic Needle Magnetometer

Derek F. Jackson Kimball,¹ Alexander O. Sushkov,² and Dmitry Budker^{3,4,5}

Levitated Ferromagnets as novel sensors

PHYSICAL REVIEW APPLIED 11, 044041 (2019)

Dynamics of a Ferromagnetic Particle Levitated over a Superconductor

Tao Wang,^{1,*} Sean Lourette,¹ Sean R. O’Kelley,¹ Metin Kayci,^{1,2} Y.B. Band,³
Derek F. Jackson Kimball,⁴ Alexander O. Sushkov,⁵ and Dmitry Budker^{1,6,7}

Ferromagnetic gyroscopes for tests of fundamental physics

Pavel Fadeev^{1,2,*}, Chris Timberlake³, Tao Wang⁴, Andrea Vinante^{3,5}, Y B Band⁶, Dmitry
Budker^{1,2,7} , Alexander O Sushkov⁸, Hendrik Ulbricht³  and Derek F Jackson
Kimball⁹ 

Quantum Sci. Technol. 6 (2021) 024006

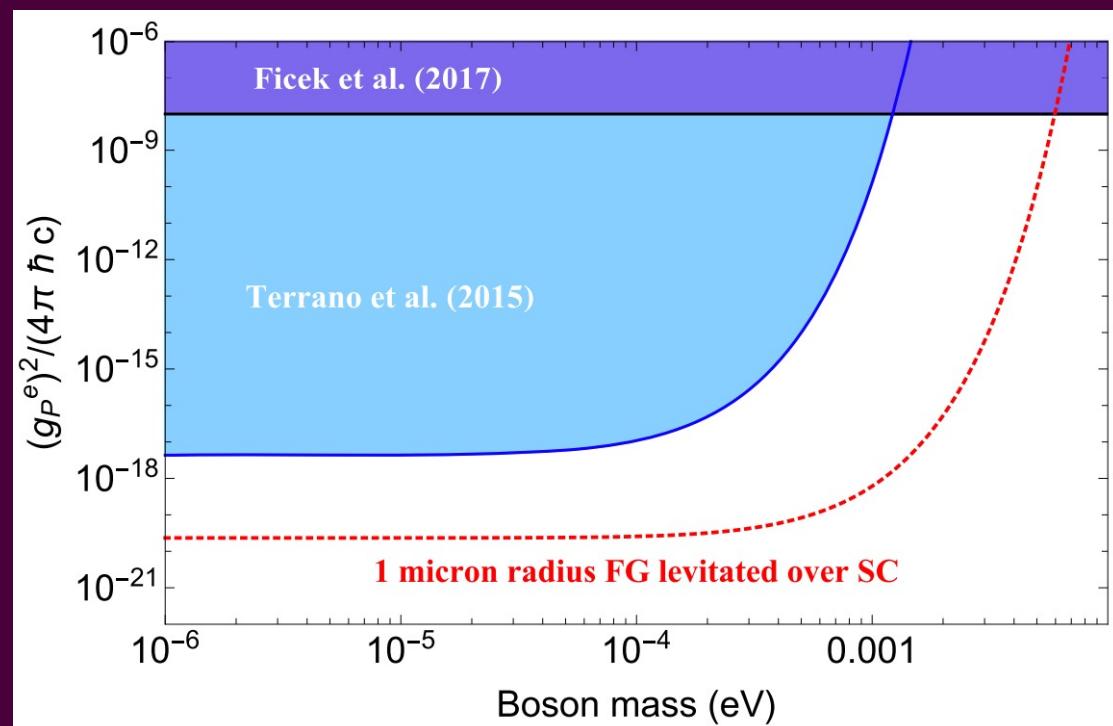
“Exotic” potentials:

(P. Fadeev *et al* 2019 *Phys. Rev. A* **99** 022113)

$$\begin{aligned} \mathcal{V}_{PP}(\mathcal{R}) = & \frac{(g_P^e)^2}{4\pi\hbar c} \frac{\hbar^3}{4m_e^2c} \left[\mathbf{S}_1 \cdot \mathbf{S}_2 \left(\frac{m_b c}{\hbar \mathcal{R}^2} + \frac{1}{\mathcal{R}^3} + \frac{4\pi}{3} \delta^3(\mathcal{R}) \right) \right. \\ & \left. - (\mathbf{S}_1 \cdot \hat{\mathbf{R}})(\mathbf{S}_2 \cdot \hat{\mathbf{R}}) \left(\frac{m_b^2 c^2}{\hbar^2 \mathcal{R}} + \frac{3m_b c}{\hbar \mathcal{R}^2} + \frac{3}{\mathcal{R}^3} \right) \right] e^{-m_b c \mathcal{R}/\hbar} \end{aligned}$$

Experiments @ SOTON, Trento,
Paris, Harvard ...

Promising projections!



Levitated Ferromagnets as novel sensors

PHYSICAL REVIEW D 103, 044056 (2021)

Gravity Probe Spin: Prospects for measuring general-relativistic precession of intrinsic spin using a ferromagnetic gyroscope

Pavel Fadeev^{1,*}, Tao Wang², Y. B. Band³, Dmitry Budker^{1,4}, Peter W. Graham⁵, Alexander O. Sushkov⁶, and Derek F. Jackson Kimball^{7,†}

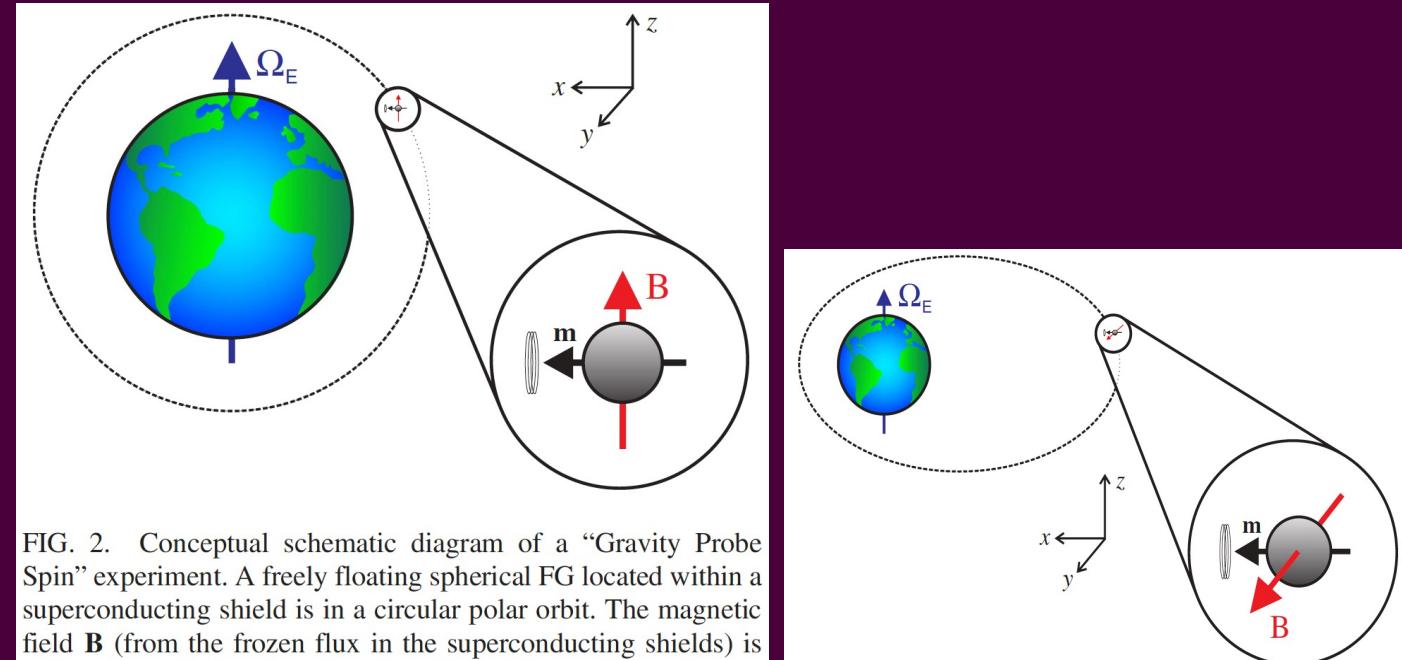
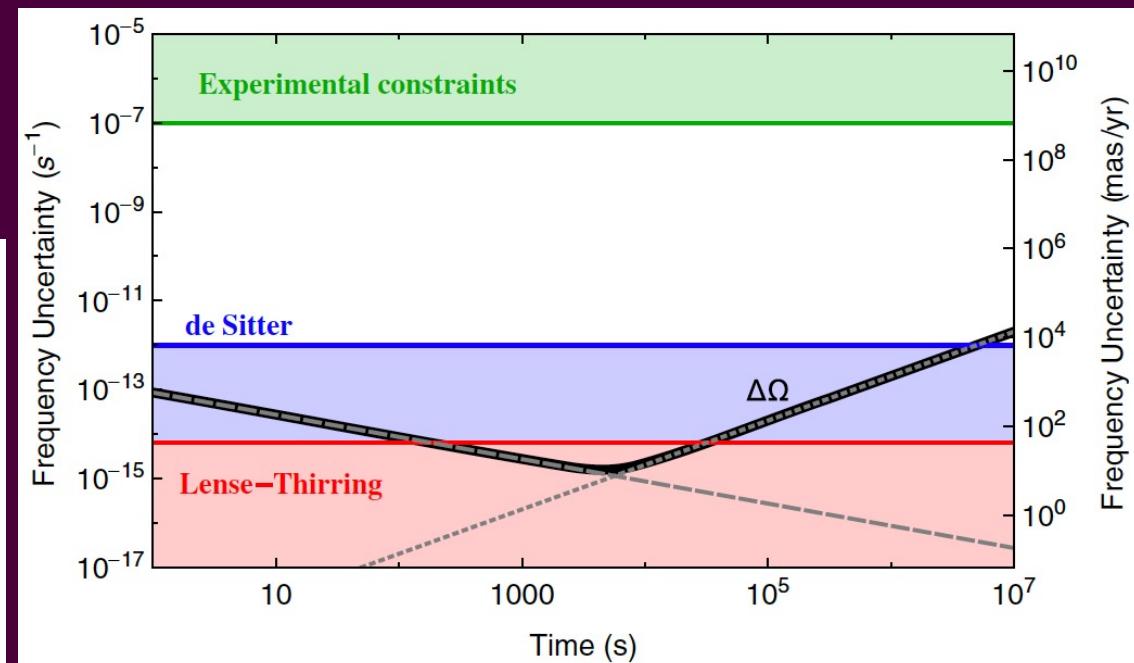


FIG. 2. Conceptual schematic diagram of a “Gravity Probe Spin” experiment. A freely floating spherical FG located within a superconducting shield is in a circular polar orbit. The magnetic field \mathbf{B} (from the frozen flux in the superconducting shields) is oriented parallel to the direction of Earth’s rotation axis Ω_E , both designated to point along z . The insert shows the initial orientation of the FG’s magnetic moment and spin m along the x axis. The pick-up coil measures the FG’s magnetization along x . This geometry is designed for the detection of the Lense-Thirring effect.

FIG. 6. Conceptual schematic diagram of a “Gravity Probe Spin” experiment similar to that shown in Fig. 2 except that the orbit is elliptical and the magnetic field \mathbf{B} is directed along the y -axis, perpendicular to the orbital plane. This geometry is designed for the detection of the de Sitter effect.



Timeline

- Difficult: Yogi Berra effect
- Hopeless: no NV sensing before 2008 (e.g., J.M. Taylor *et al*, Nature Physics **4**, 810 - 816, 2008)
- Unnecessary for non-accelerator physics ? (but 3 y funding cycle is too short!)
- This said:
 - ➡ Commercial research-grade Optically Pumped Magnetometers ~now!
 - ➡ Hyperpolarization enhanced NMR for Fund. Phys. ~now!
 - ➡ Ensemble NV sensors reach “Eq. (1)” ~5 years
 - ➡ Precessing ferromagnets proof-of-principle ~2 years
 - ➡ precision measurements ~5 years
 - ➡ space missions ~5-20 years
 - ➡ Useful squeezing/entanglement in vapor and NV sensors ~5 years
 - ➡ 10-100 improvement in spin amplifiers and masers ~1-2 years

Other Technologies (some examples)

- SQUIDs
- Clocks, interferometers
- Gravimeters and seismometers
- Ion traps
- Anything on a chip, including antimatter (AMOC)
- Gamma Factory (“table-top” physics with LHC)

