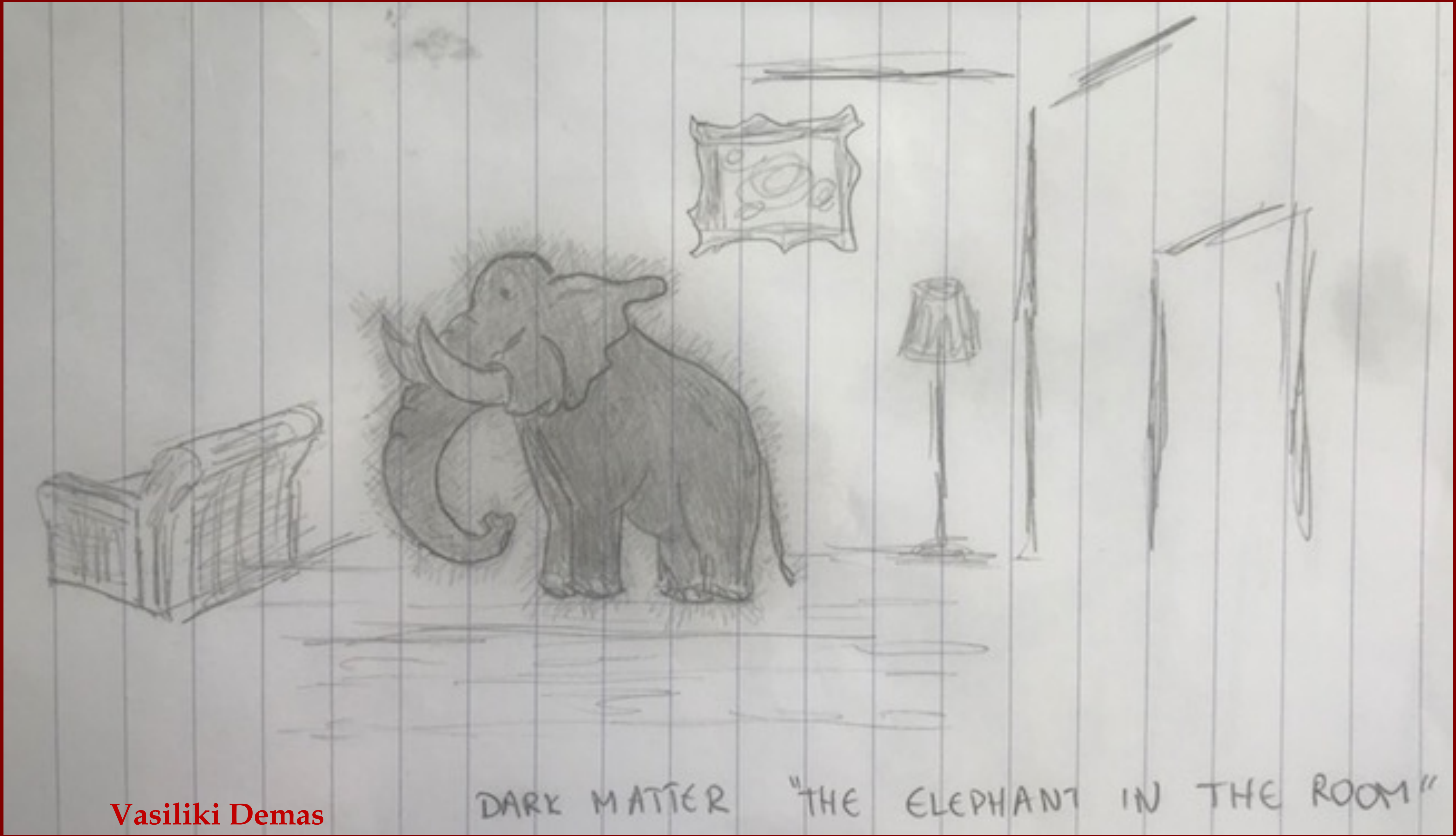
In search for ultralight bosonic fields, etc

Dmitry Budker

Helmholtz Institute, JGU Mainz & Department of Physics, UC Berkeley

PASCOS, June 17, 2021, S. Korea (via Zoom)



Vasiliki Demas

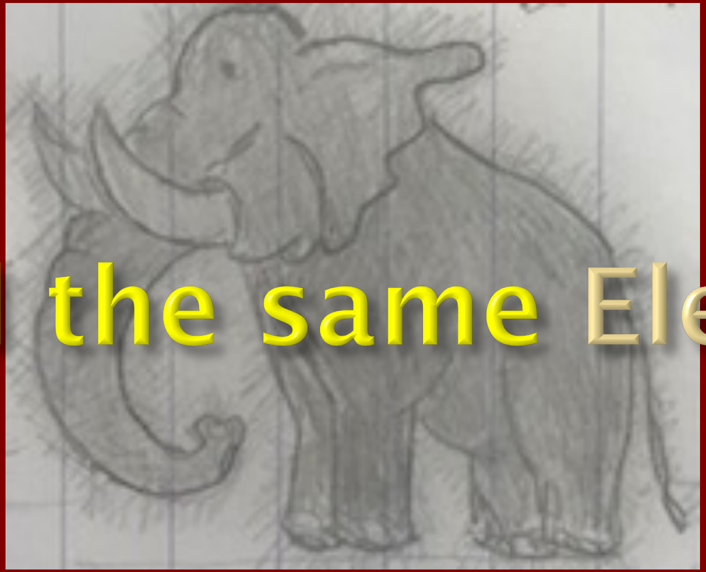
More Elephants!

Matter-antimatter Asymmetry

Similar amount of matter and DM

Dark Energy

Strong-CP problem



Hierarchy problem

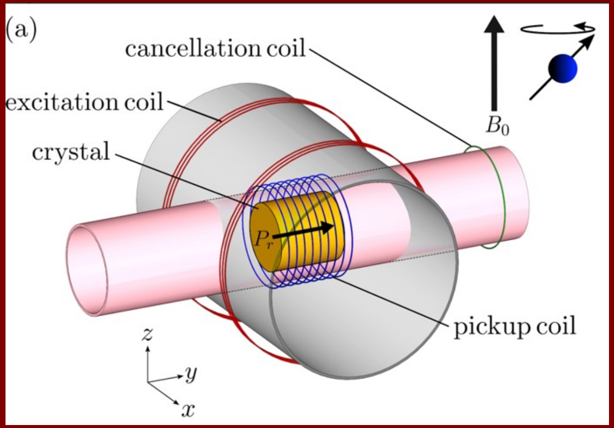
One and the same Elephant ?

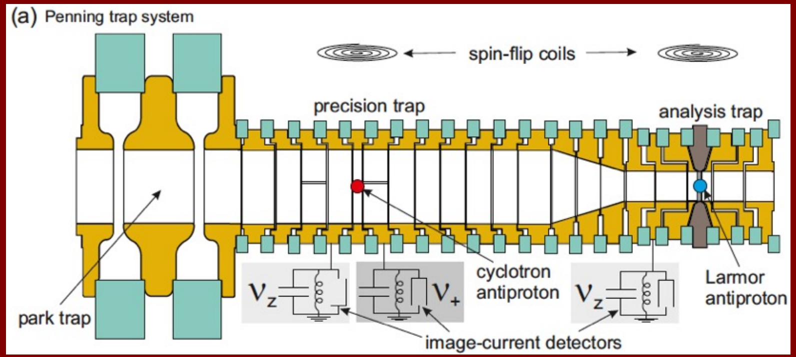
So what is DM or what mimics it ?

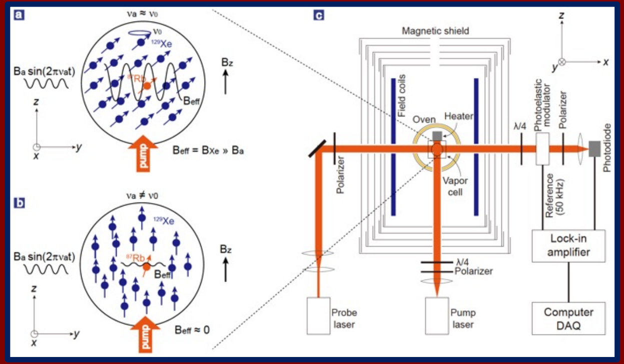
- A gross misunderstanding of gravity (MOND, …) ???
- Proca MHD (finite photon mass) ☹?
- Black holes, dark planets, interstellar gas, … ☹?
- WIMPS ☺
- Ultralight bosonic particles
  - Axions (pseudoscalar) ☺
  - ALPs (pseudoscalar) ☺
  - Dilatons (scalar) ☺
  - Vector particles ☺
  - Tensor particles ???
- Antiquark Nuggets (AQN) !!!☺!!!

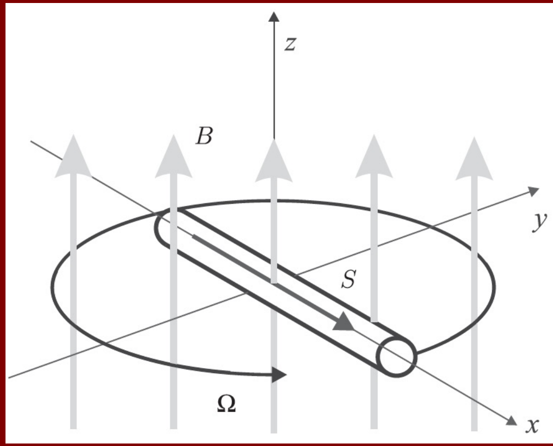
Searching for Ultralight Bosonic (and other) DM

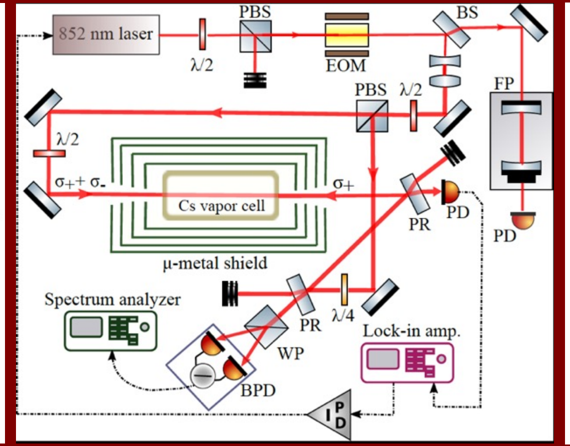
- NMR (CASPEr)
- Spin-based sensors for DM: masers, spin amplifiers
- Spin-based sensors for fifth-force searches (single NV, cells)
- GNOME, clock networks, hybrid networks
- Gravimeters
- Atomic spectroscopy
- Antimatter
- Levitated magnets

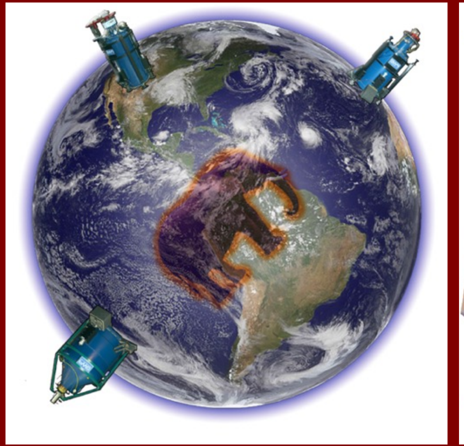


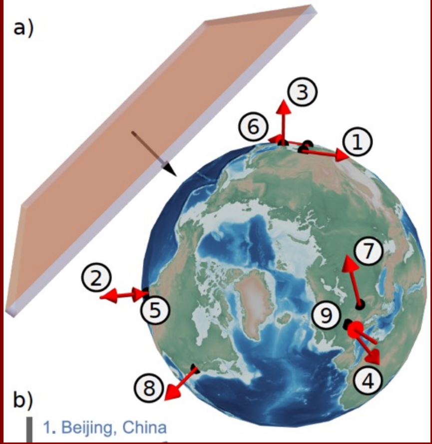


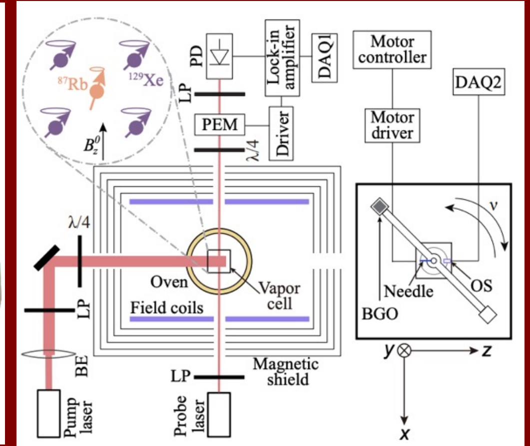










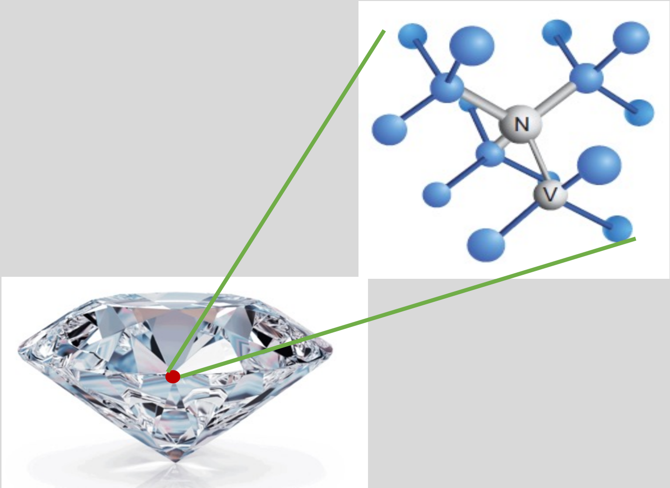


GNOME NETWORK 2017

Animation: Arne Wickenbrock

THE SMALLEST “TABLETOP”
ATOMIC SCALE

Utilizing single-spin sensor to search for exotic interactions



NV centers in diamond: single-spin sensors

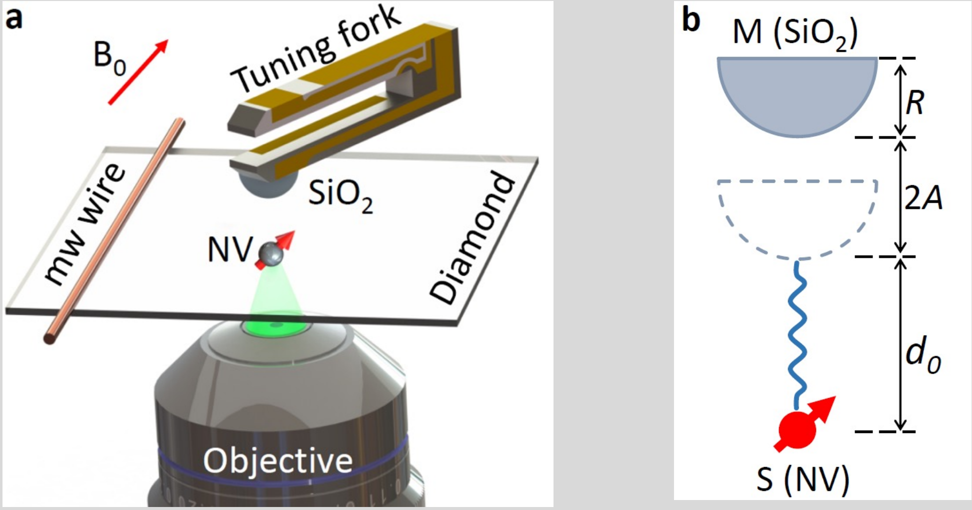


Diagram of the setup: NV sensor + AFM

Features

- ✓ Atomic scale
- ✓ Near surface
- ✓ Precise quantum control
- ✓ NV + AFM

Atomic scale, Near surface → Shorter force range

Precise quantum control → Good sensitivity

NV + AFM → Cancel unwanted signals

Prof. Xing Rong (USTC)

The latest catalog of EXOTIC potentials

PHYSICAL REVIEW A **99**, 022113 (2019)

Revisiting spin-dependent forces mediated by new bosons: Potentials in the coordinate-space representation for macroscopic- and atomic-scale experiments

Pavel Fadeev,[1] Yevgeny V. Stadnik,[1] Filip Ficek,[2] Mikhail G. Kozlov,[3,4] Victor V. Flambaum,[1,5] and Dmitry Budker[1,6,7]

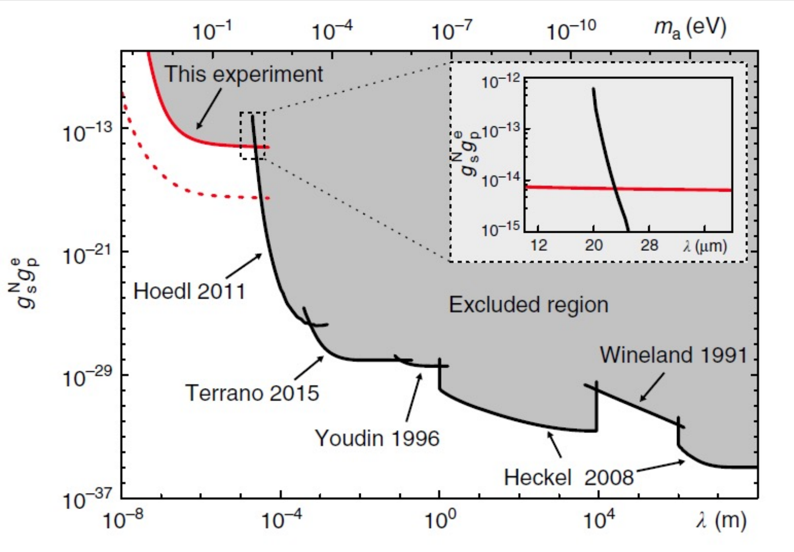
Previous catalogs:

- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984)
- B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006)

Search results with NV sensors

Monopole-dipole interaction

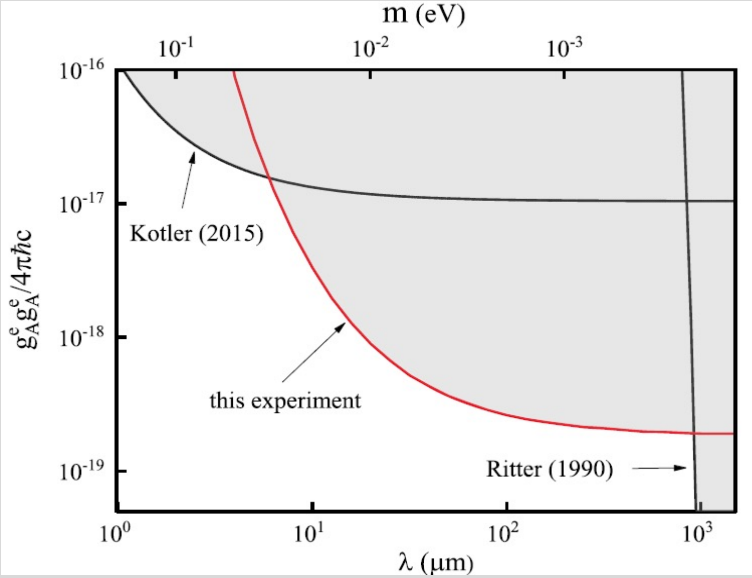
$$V_{sp}(\mathbf{r}) = \frac{\hbar^2 g_s^N g_p^e}{8\pi m}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda}} \boldsymbol{\sigma} \cdot \mathbf{e}_r,$$



Nature Communications 9,739 (2018)

Dipole-dipole interaction

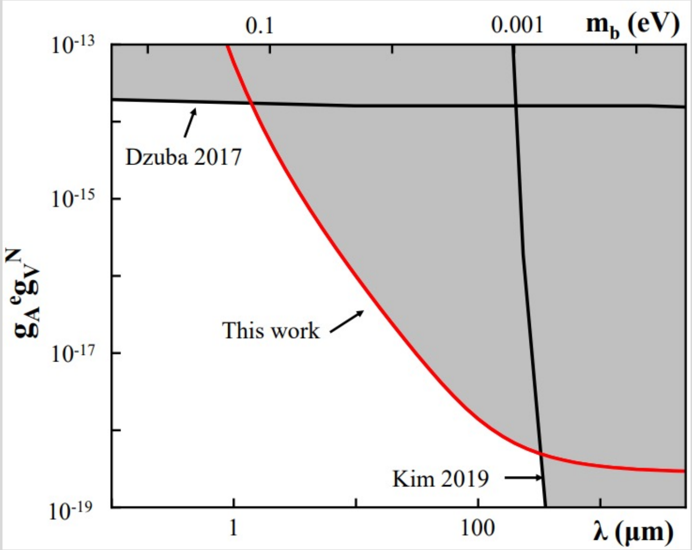
$$H_2 = \frac{g_A^e g_A^e}{4\pi\hbar c} \frac{\hbar c}{r} (\vec{\sigma_1} \cdot \vec{\sigma_2}) e^{-\frac{r}{\lambda}},$$



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

Velocity-dependent monopole-dipole interaction

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



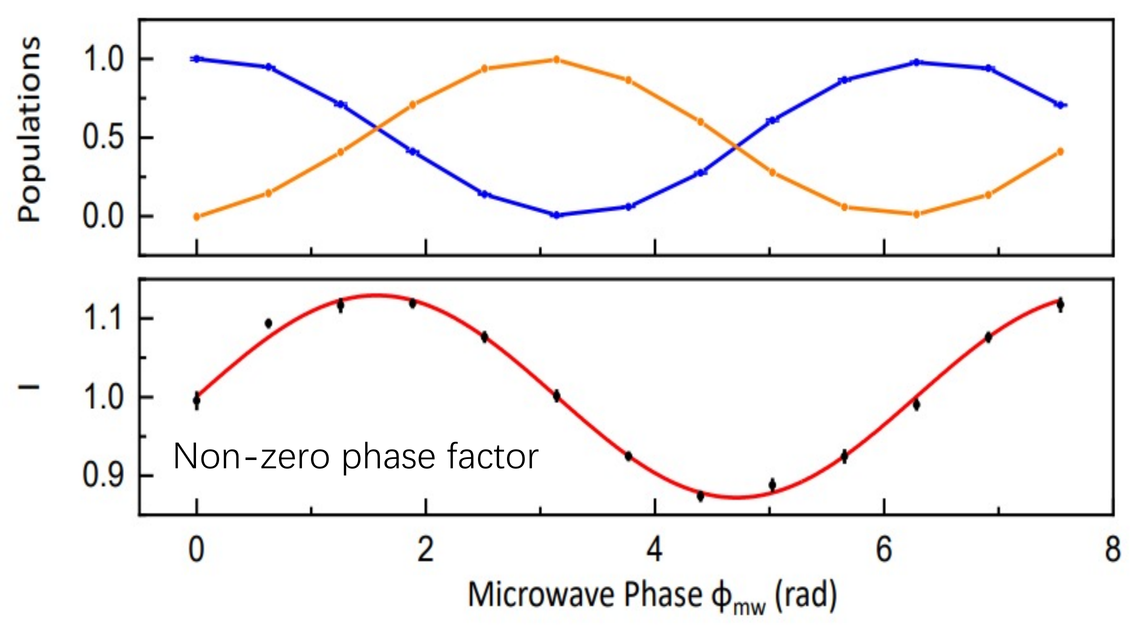
arXiv : 2009.09257 (2020)

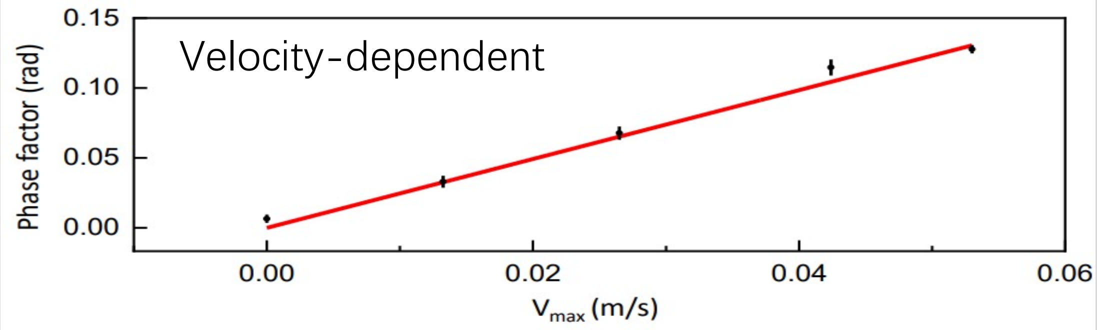
Prof. Xing Rong (USTC)

One search yields nonzero signal !

Velocity-dependent monopole-dipole interaction

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





arXiv : 2010.15667 (2020)

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.

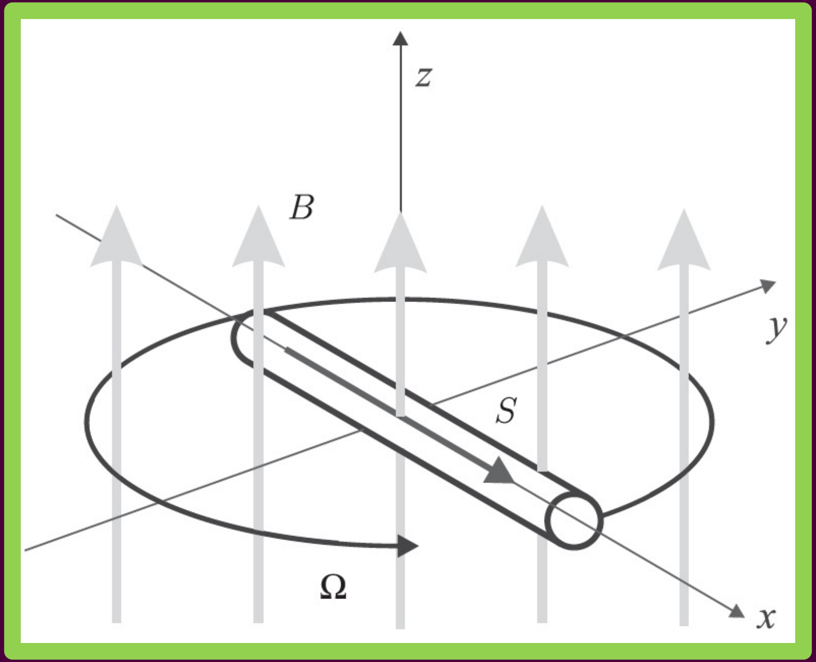
Possible sources	Contribution to the phase factor（rad）
Tuning fork	$< 10^{-3}$
Charges on the mass	$< 10^{-4}$
Casimir Force	$< 10^{-5}$
Diamagnetism of the mass	$< 10^{-10}$
Effect due to the moving dielectric	$< 10^{-15}$
Nuclear spin in the mass	$< 10^{-15}$

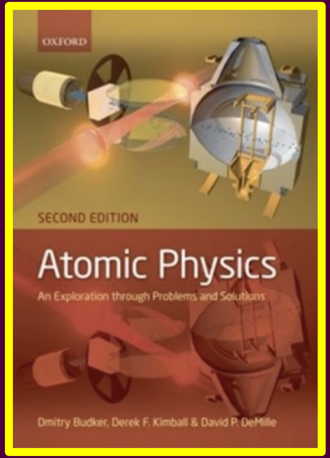
Prof. Xing Rong (USTC)

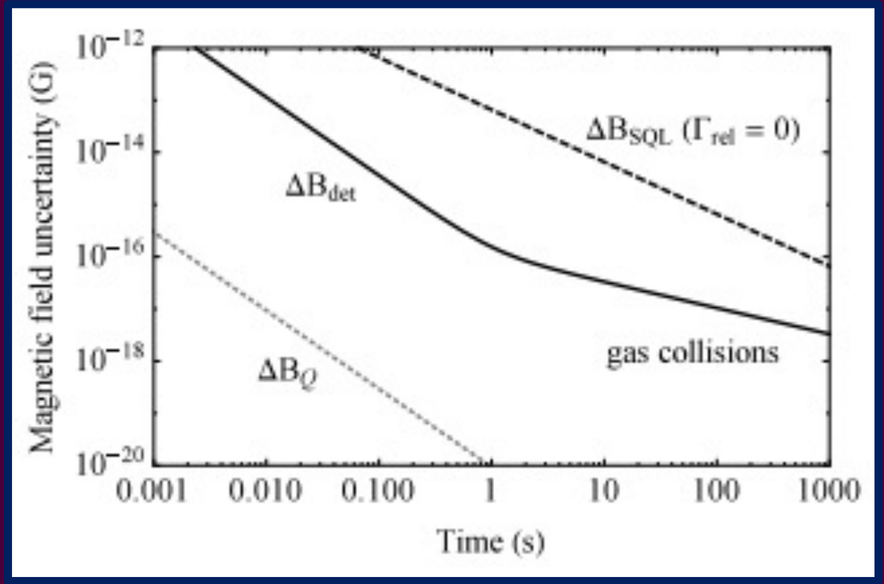
PRL 116, 190801 (2016) PHYSICAL REVIEW LETTERS week ending 13 MAY 2016

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 Timberlake[3], Tao Wang[4], Andrea Vinante[3,5], Y B Band[6], Dmitry Budker[1,2,7], Alexander O Sushkov[8], Hendrik Ulbricht[3] and Derek F Jackson Kimball[9]

Quantum Sci. Technol. **6** (2021) 024006

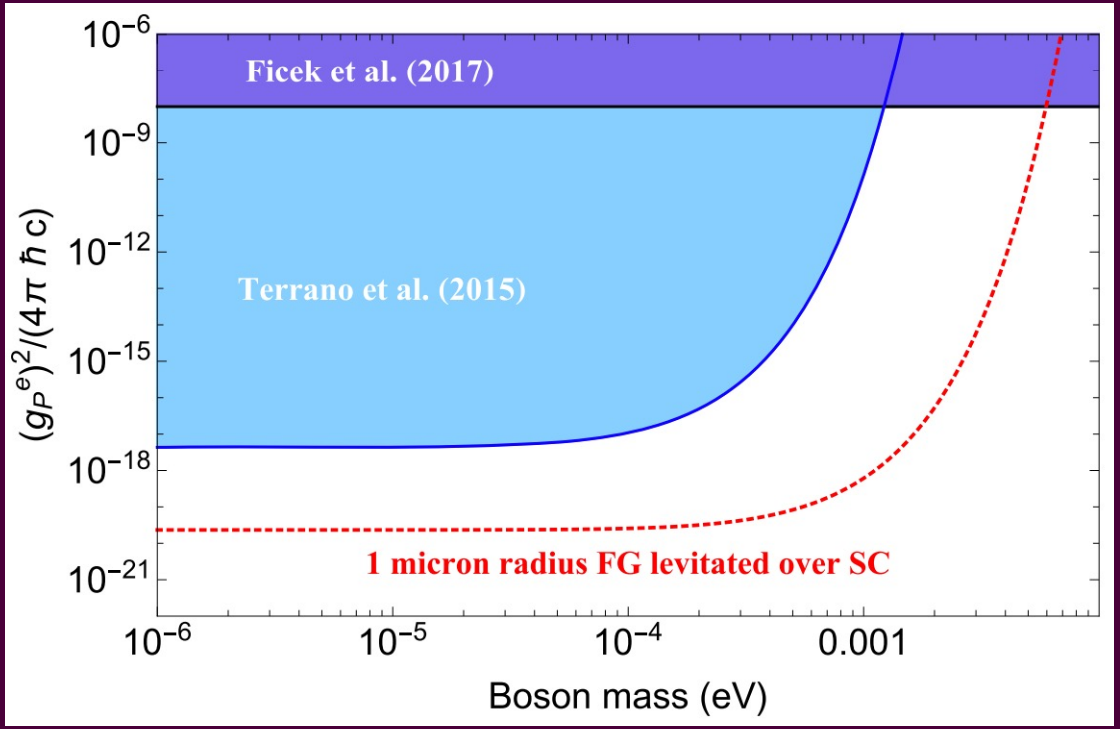
Experiments @ SOTON, Trento, Paris, Harvard …

"Exotic" potentials:

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

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

Promising projections!



Spin source:1 mm radius SmCo sphere; 1 mm from FG; integration time t = 10^6 s

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 Wang,[2] Y. B. Band,[3] Dmitry Budker,[1,4] Peter W. Graham,[5] Alexander O. Sushkov,[6] and Derek F. Jackson Kimball[7,†]

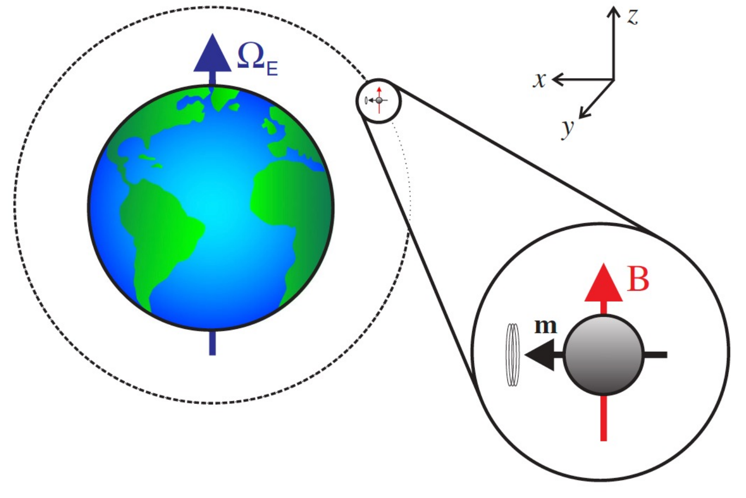


FIG. 2. Conceptual schematic diagram of a "Gravity Probe Spin" experiment. A freely floating spherical FG located within a superconducting shield is in a circular polar orbit. The magnetic field **B** (from the frozen flux in the superconducting shields) is oriented parallel to the direction of Earth's rotation axis $\mathbf{\Omega}_E$, 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.

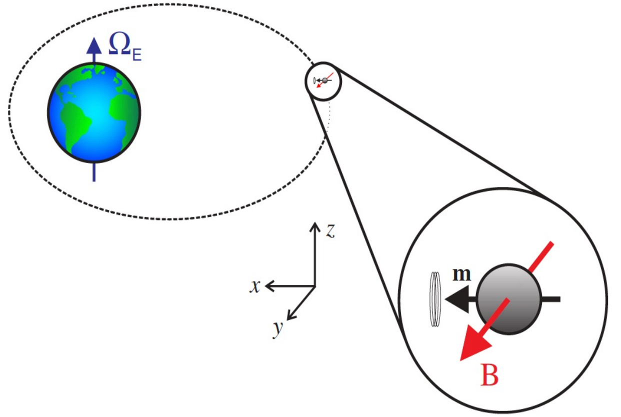
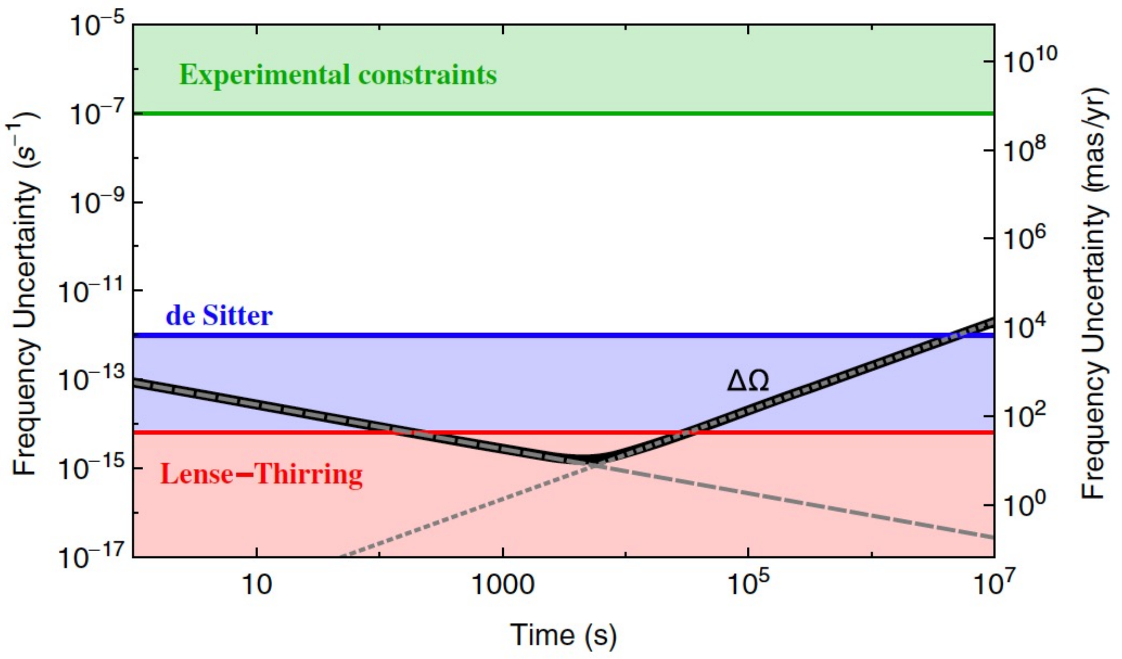


FIG. 6. Conceptual schematic diagram of a "Gravity Probe Spin" experiment similar to that shown in Fig. 2 except that the orbit is elliptical and the magnetic field **B** is directed along the y-axis, perpendicular to the orbital plane. This geometry is designed for the detection of the de Sitter effect.



Another (sneaky) way to search for axions and other exotic particles

Constraints on exotic spin-dependent interactions between electrons from helium fine-structure spectroscopy

Filip Ficek[1],* Derek F. Jackson Kimball[2], Mikhail Kozlov[3,4],
Nathan Leefer[5], Szymon Pustelny[1], and Dmitry Budker[5,6,7]

[1] Institute of Physics, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland
tment of Physics, California State University - East Bay, Hayward, California 94542-308
[3] Petersburg Nuclear Physics Institute, Gatchina 188300, Russia
[4] St. Petersburg Electrotechnical University LETI, Prof. Popov Str. 5, 197376 St. Petersburg
[5] Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany
[6] Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA
[7] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Dated: August 23, 2016)

TABLE I: Comparison of theoretical (QED-based) and experimental transition energies values between various helium states.

	Theoretical		Experimental		Difference	ΔE
$2^3P_1 - 2^3P_2$	2 291 178.9(1.7) kHz	[35]	2 291 177.69(36) kHz	[30]	1.2(1.7) kHz	4.6 kHz
$2^3P_0 - 2^3P_2$	31 908 131.2(1.8) kHz	[35]	31 908 131.25(30) kHz	[32]	0.1(1.8) kHz	3.2 kHz
$2^3P_0 - 2^3P_1$	29 616 952.3(1.7) kHz	[35]	29 616 951.66(70) kHz	[33]	0.6(1.8) kHz	3.7 kHz
$2^3P_0 - 2^3S_1$	276 764 094.7(3.0) MHz	[36]	276 764 094.7073(21) MHz	[31]	0.0(3.0) MHz	
$2^3P_1 - 2^3S_1$	276 734 477.7(3.0) MHz	[36]	276 734 477.7525(20) MHz	[31]	0.1(3.0) MHz	
$2^3P_2 - 2^3S_1$	276 732 186.1(2.9) MHz	[36]	276 732 186.621(15) MHz	[31]	0.5(2.9) MHz	

Phys. Rev. A **95**, 032505 (2017)

Pachucki & Yerokhin

A sneaky way to look for ALPs

$$V_2 = \frac{g_2^e g_2^e}{4\pi\hbar c}\hbar c\,(\mathbf{s}_1\cdot\mathbf{s}_2)\,\frac{e^{-r_{12}/\lambda}}{r_{12}},$$

$$V_3 = \frac{g_3^e g_3^e}{4\pi\hbar c}\frac{\hbar^3}{4m_e^2 c}\left[\mathbf{s}_1\cdot\mathbf{s}_2\left(\frac{1}{\lambda r_{12}^2}+\frac{1}{r_{12}^3}\right)-(\mathbf{s}_1\cdot\mathbf{e}_{12})(\mathbf{s}_2\cdot\mathbf{e}_{12})\left(\frac{1}{\lambda^2 r_{12}}+\frac{3}{\lambda r_{12}^2}+\frac{3}{r_{12}^3}\right)\right]e^{-r_{12}/\lambda},$$

$$V_4 = \frac{g_4^e g_4^e}{4\pi\hbar c}\frac{i\hbar^3}{4m_e^2 c}(\mathbf{s}_1+\mathbf{s}_2)\cdot\left[(\nabla_1-\nabla_2)\times\mathbf{r}_{12},\left(\frac{1}{r_{12}^3}+\frac{1}{\lambda r_{12}^2}\right)e^{-r_{12}/\lambda}\right]_+,$$

$$V_8 = \frac{g_8^e g_8^e}{4\pi\hbar c}\frac{\hbar^3}{4m_e^2 c}\left[\mathbf{s}_1\cdot(\nabla_1-\nabla_2),\left[\mathbf{s}_2\cdot(\nabla_1-\nabla_2),\frac{e^{-r_{12}/\lambda}}{r_{12}}\right]_+\right]_+,$$

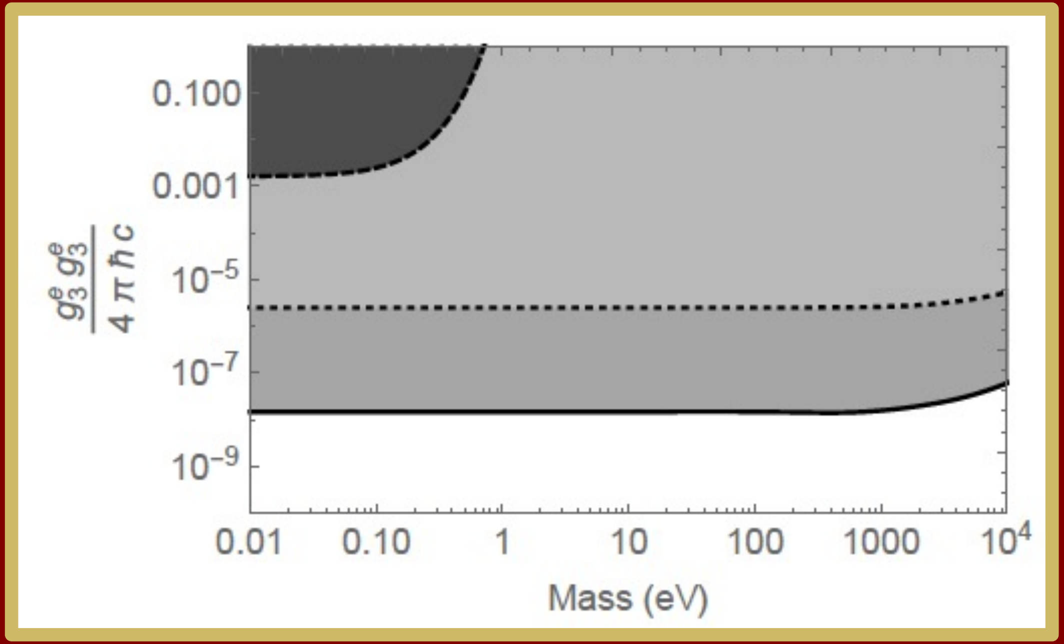


FIG. 1: Constraints (at the 90% confidence level) on the dimensionless coupling constant $g_3^e g_3^e/(4\pi\hbar c)$ as a function of the boson mass. The dashed line and dark gray fill shows the constraint for electrons from Ref. [35]. The dotted line and light gray fill show the constraint derived from analysis of positronium, also discussed in [35]. The solid line and medium gray fill shows the constraint from a comparison between theory and experiment for the $2^3P_2 - 2^3P_1$ transition frequency in He.

In progress: antiprotonic He $(\bar{p}, He^{++}, e^-)$

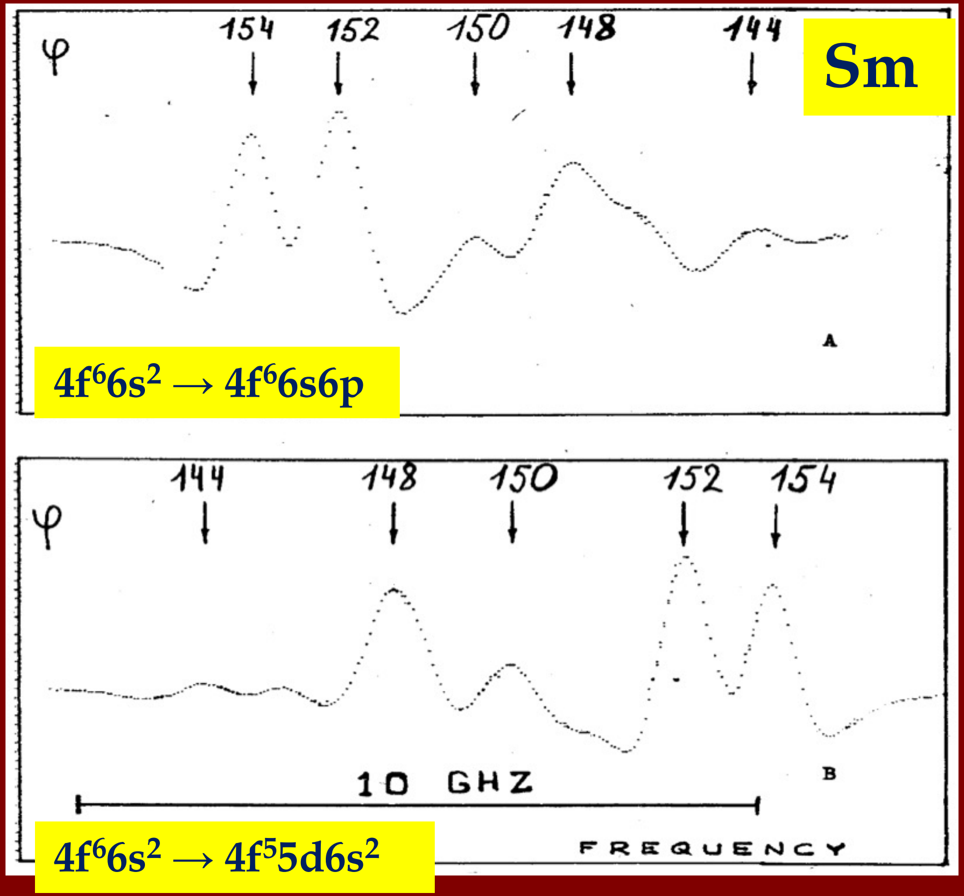
Another sneaky way to look for new physics

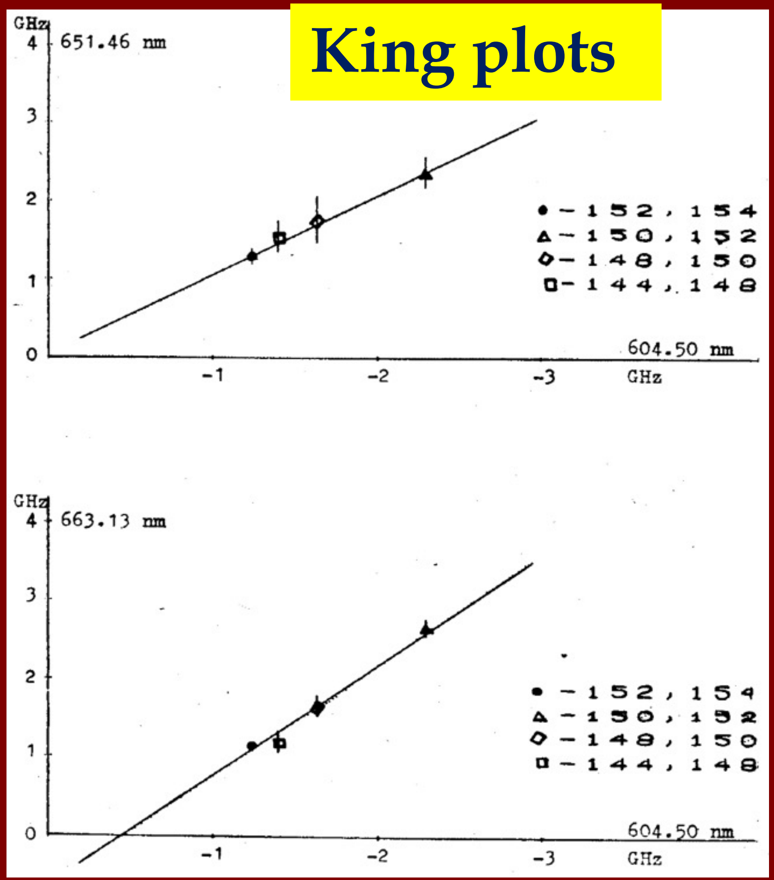
PHYSICAL REVIEW LETTERS **120**, 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,‖] Elina Fuchs,[6,¶] Christophe Grojean,[7,8,**] Roni Harnik,[9,††] Roee Ozeri,[10,‡‡] Gilad Perez,[6,§§] and Yotam Soreq[11,‖‖]

Isotope Shifts: a century of FUN





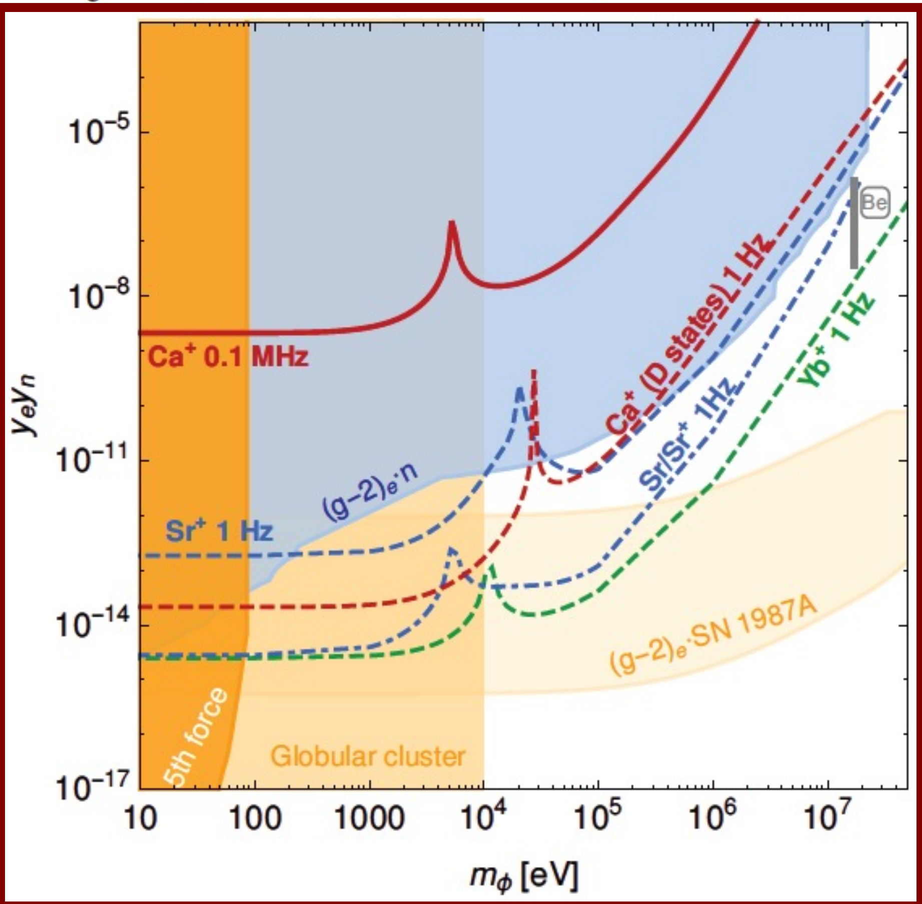
Plots from DB's Diploma Thesis (Novosibirsk, 1985)

Another sneaky way to look for new physics

PHYSICAL REVIEW LETTERS **120,** 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

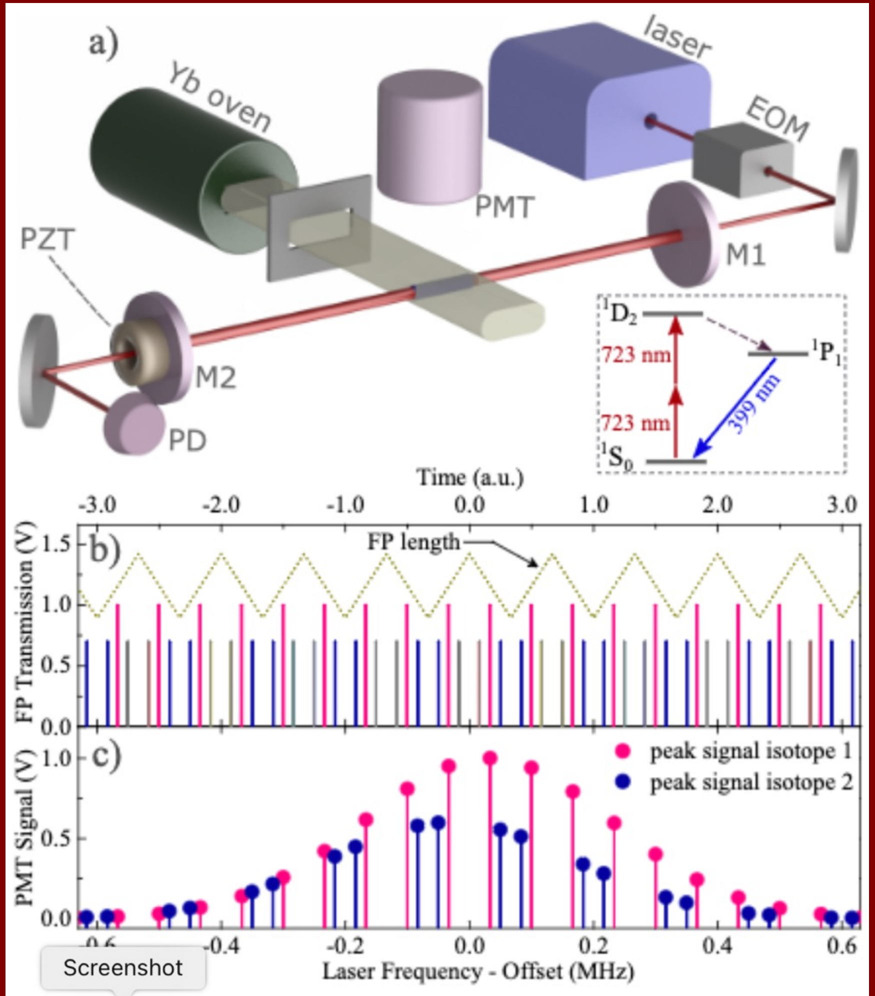
Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,‖] Elina Fuchs,[6,¶] Christophe Grojean,[7,8,**] Roni Harnik,[9,††] Roee Ozeri,[10,‡‡] Gilad Perez,[6,§§] and Yotam Soreq[11,‖‖]



Precision isotope shifts in ytterbium and implications for new physics

N. L. Figueroa,* D. Budker, and D. Antypas
Johannes Gutenberg-Universität Mainz, Helmholtz-Institut Mainz, Mainz 55128, Germany

J. C. Berengut, V. A. Dzuba, and V. V. Flambaum
School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
(Dated: June 8, 2021)



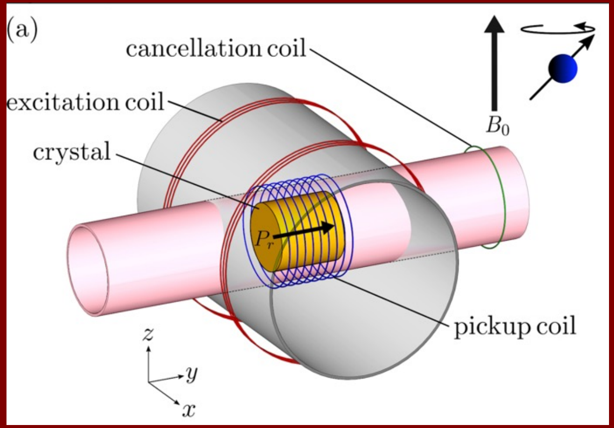
King Plot

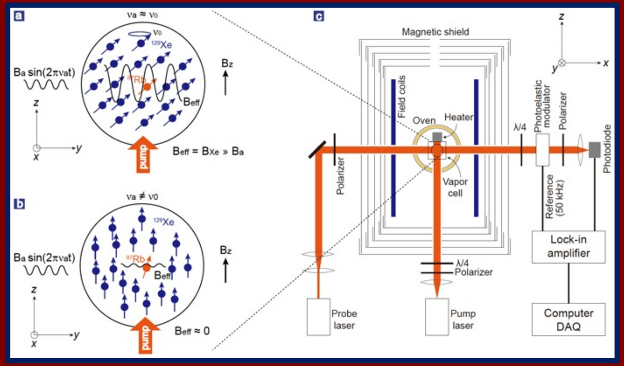
Coming here soon

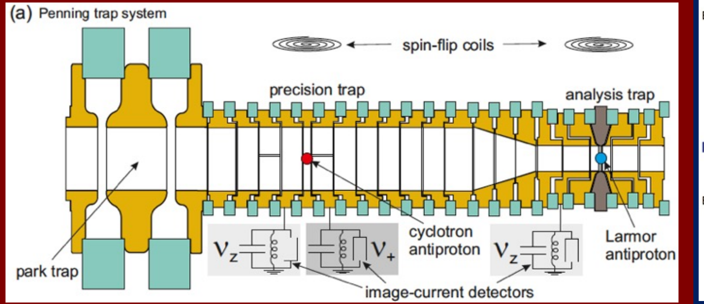
~300 Hz per isotope pair

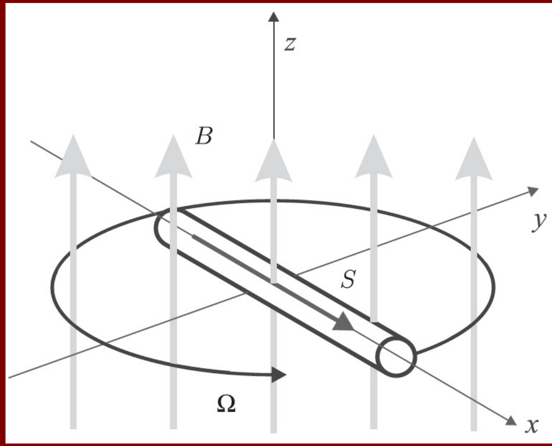
In search…

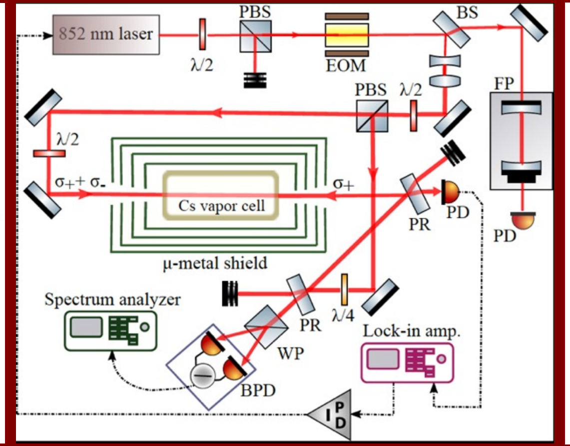
- *D. Aybas, et al, Search for axion-like dark matter using solid-state nuclear magnetic resonance,* *Phys. Rev. Lett.* **126**, 141802 (2021)
- *M. Jiang, H. Su, A. Garcon, X. Peng, and D. Budker, Search for axion-like dark matter with spin-based amplifiers,* *arXiv:2102.01448* (2021)
- *H. Su, et al, Search for exotic spin-dependent interactions with a spin-based amplifier,* *arXiv:2103.15282* (2021)
- *S. Afach, et al, Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches (GNOME);* *arXiv:2102.13379* (2021)
- *N. L. Figueroa, et al, Dark matter searches using accelerometer-based networks,* *Quantum Sci. Technol*. **6** 034004 (2021)
- *D. Antypas, et al, Fast apparent oscillations of fundamental constants,* *ANNALEN DER PHYSIK* 1900566 (2020)
- P. Fadeev, *et al,* Ferromagnetic Gyroscopes for Tests of Fundamental Physics, *Quant. Sci. Tech*. **6**(2) 024006 (2021)
- C. Smorra, *et al,* Direct limits on the interaction of antiprotons with axion-like dark matter. Nature **575**, 310-314 (2019)

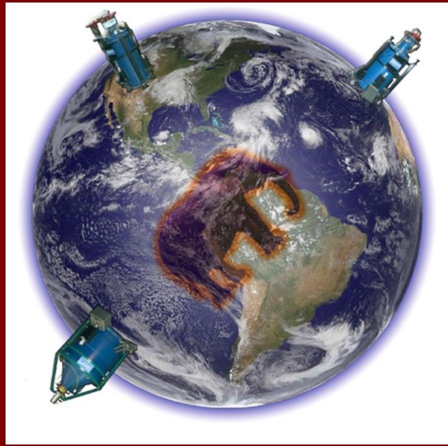


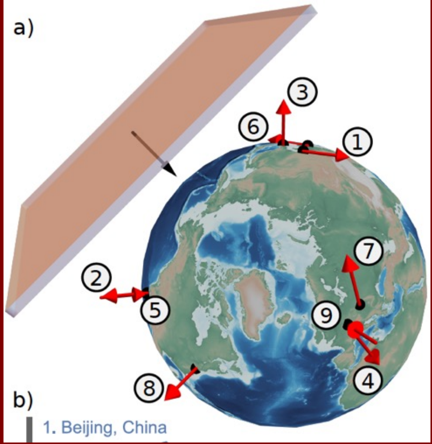


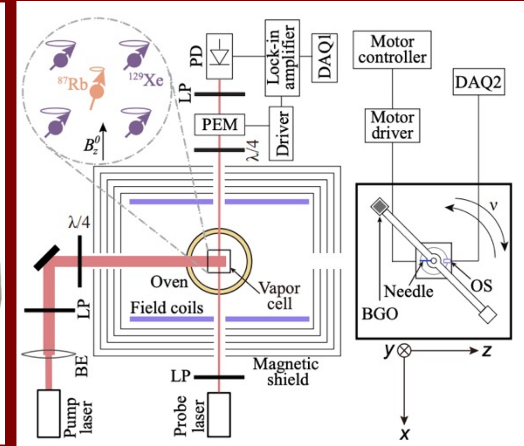












CASPEr searches for DM via:

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

coupling to gluons

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

→ spin $\boldsymbol{\sigma}$ to axion coupling:

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

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 $\boldsymbol{\sigma}$ to axion gradient coupling:

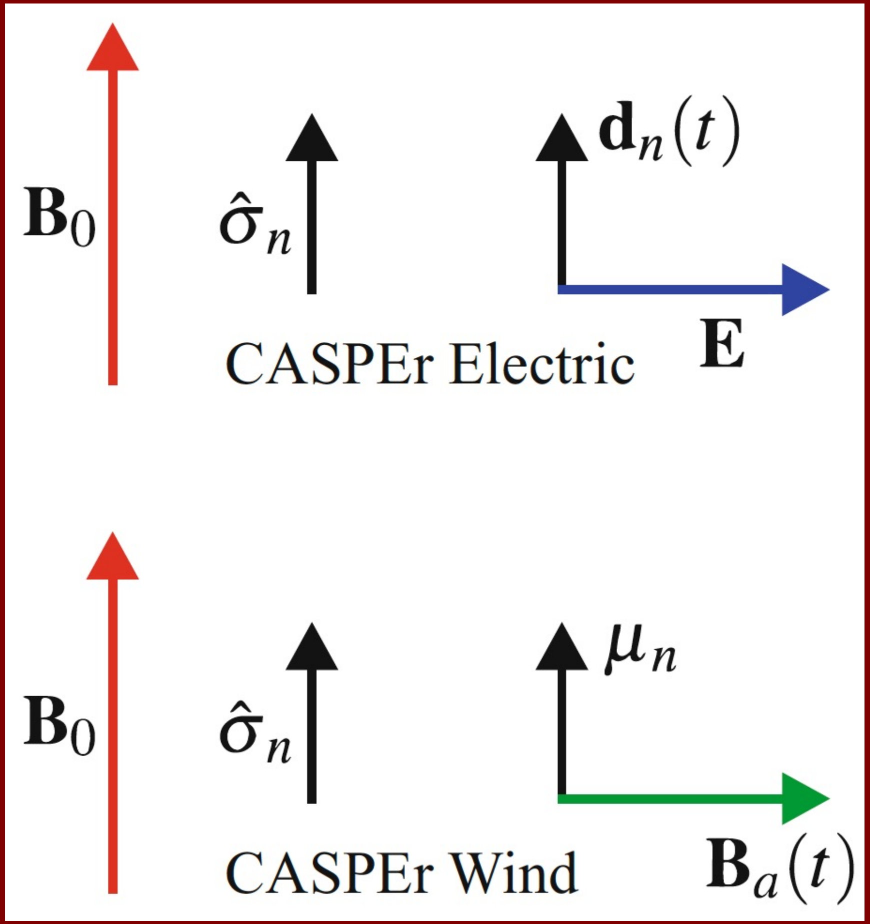
$$H_g \propto \boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a$$

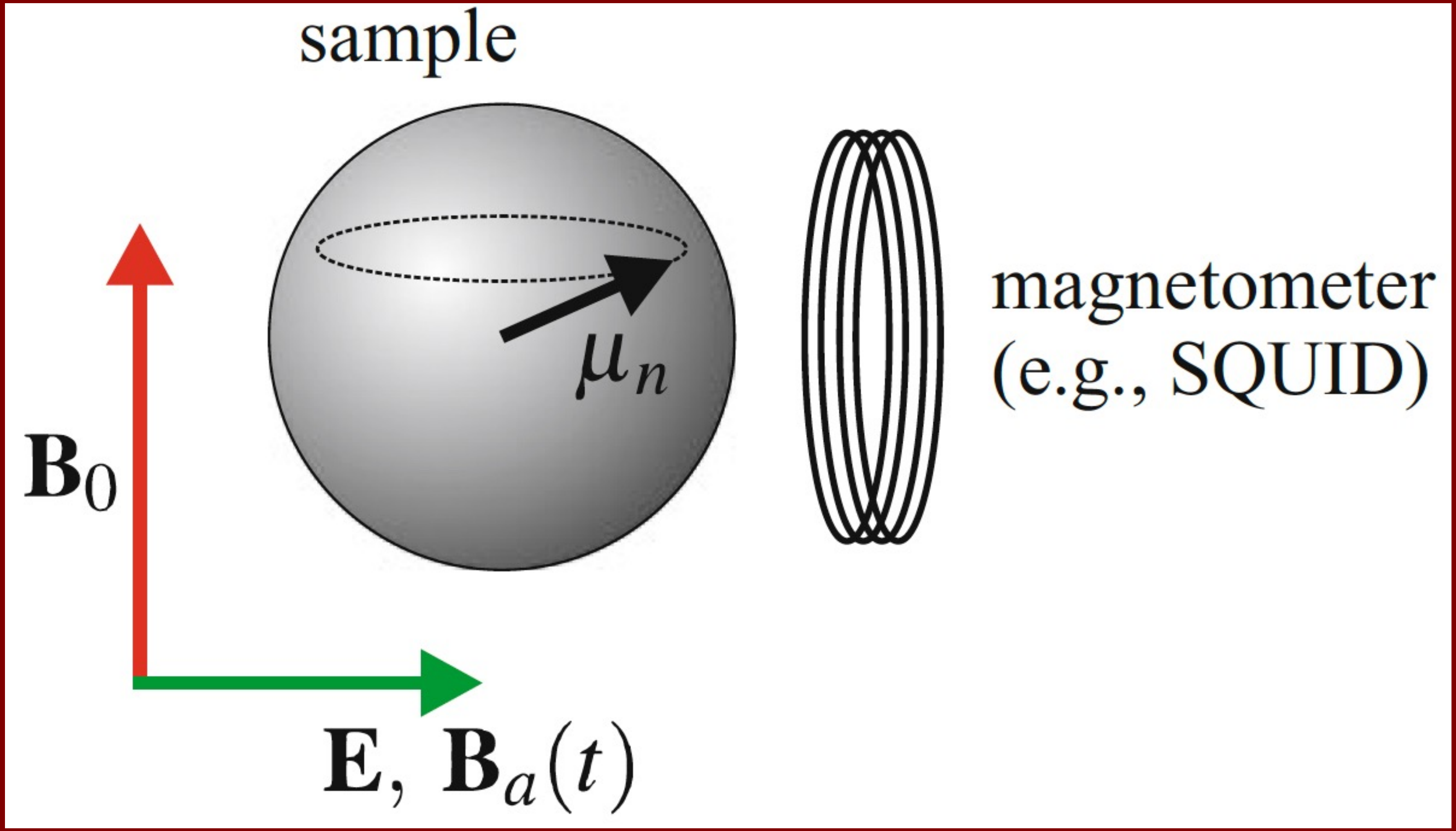
CASPEr-gradient

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

Deniz Aybas, *et al*, PRL **126**, 141802 (2021)

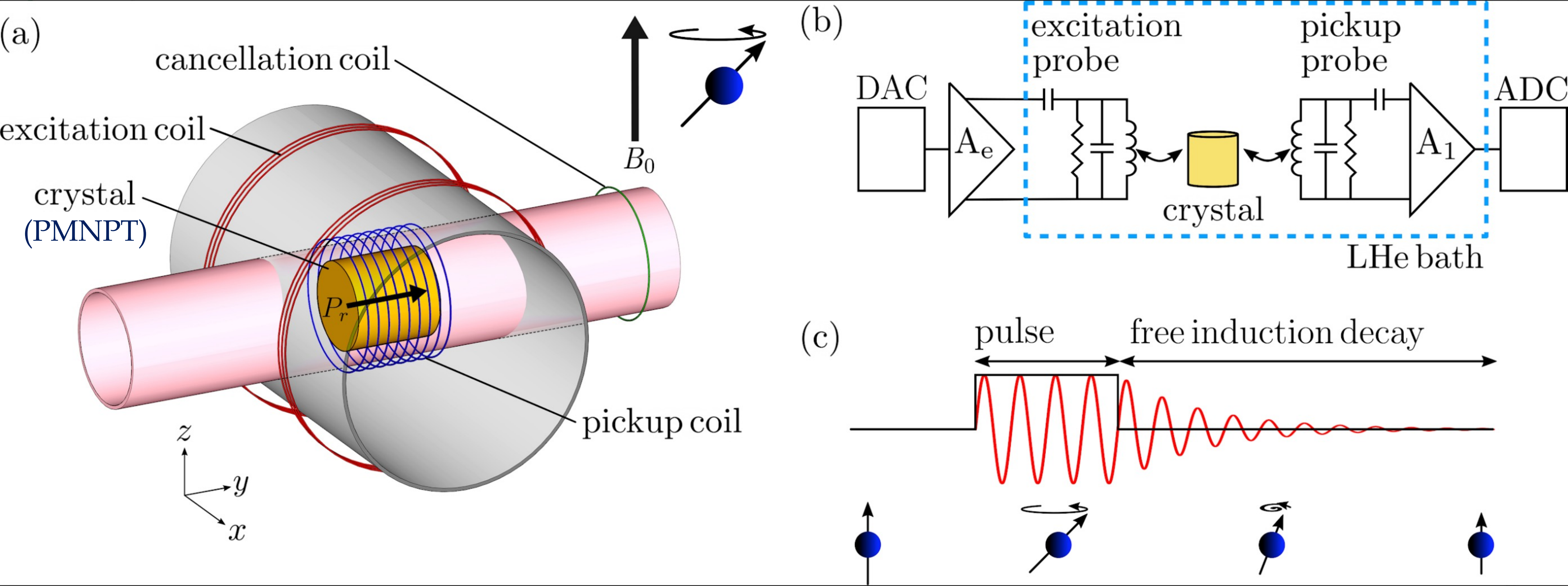
DM search with NMR (CASPEr)





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

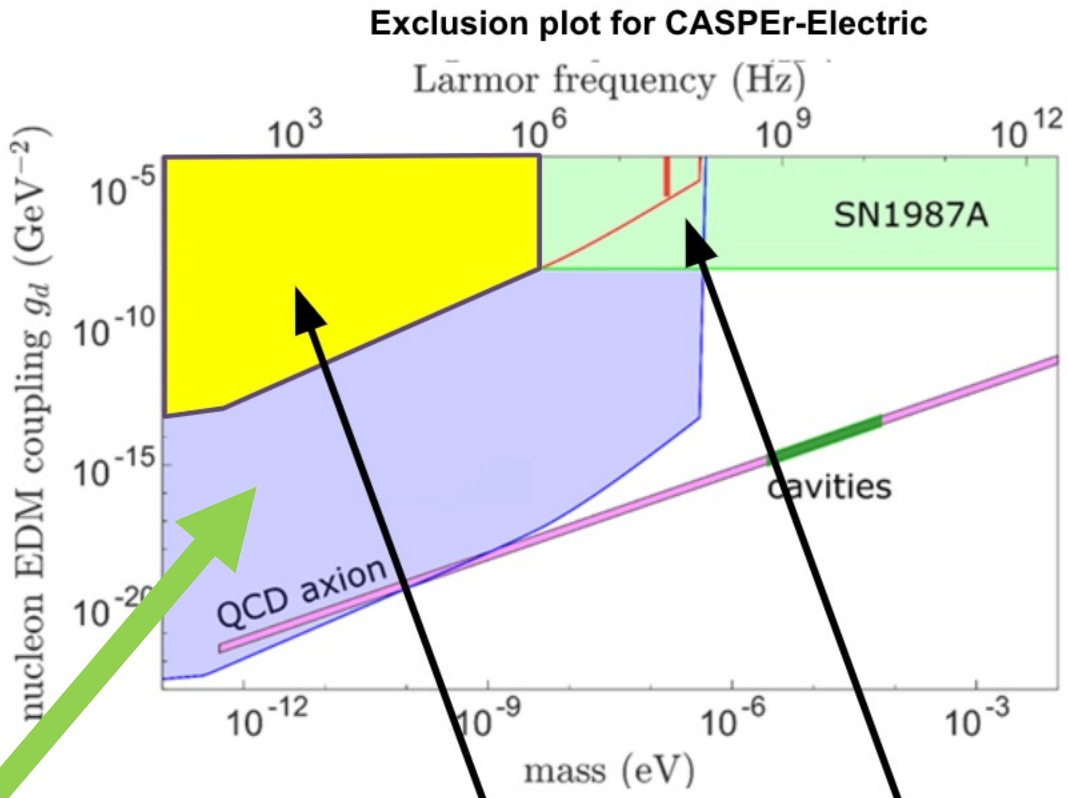


Deniz Aybas, *et al*, PRL **126**, 141802 (2021)

CASPEr-Boston

CASPEr-Electric Generation 2 – Low Field

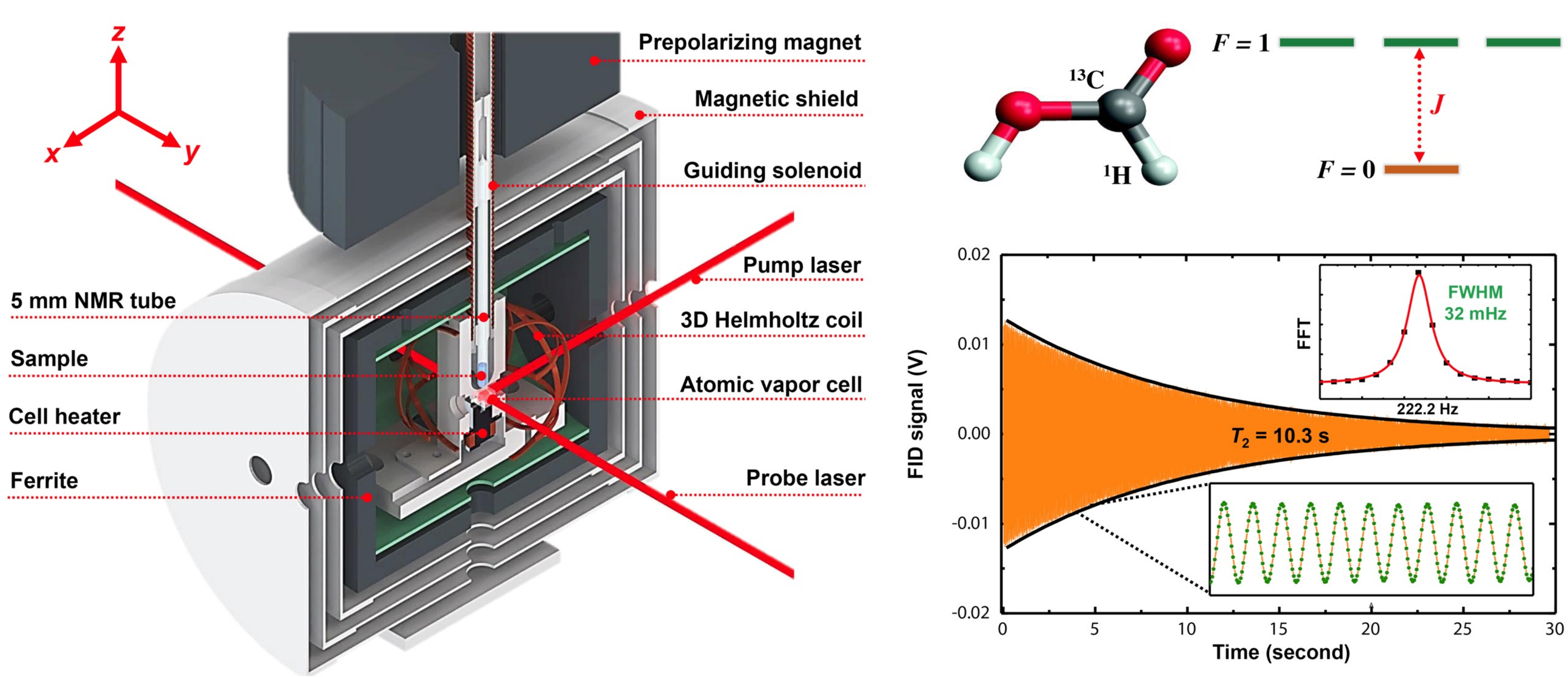
- Successful Gen 1 – High field
- **<u>Generation 2 – Low field</u>**
- **Frequency:** up to 1 MHz
- Goes below astronomical limits
- **Differences:**
  - Pickup: SQUID
  - SC wires



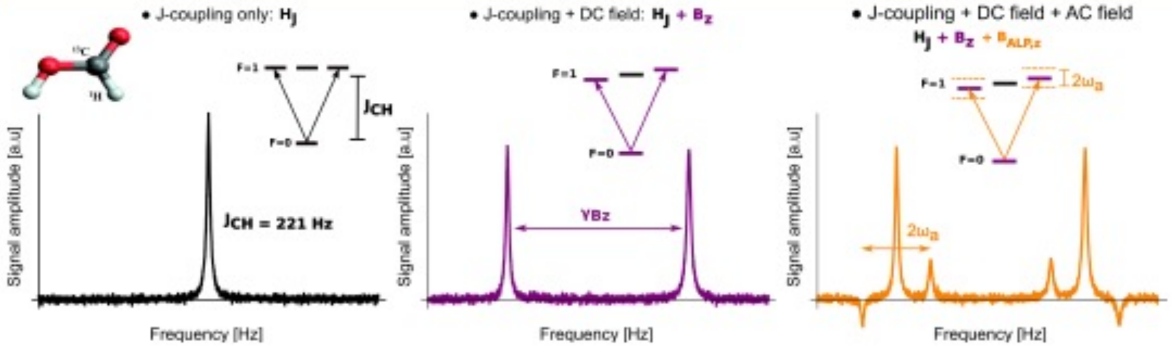
Gen 2 is looking for ALPs below 1 MHz with SQUIDs

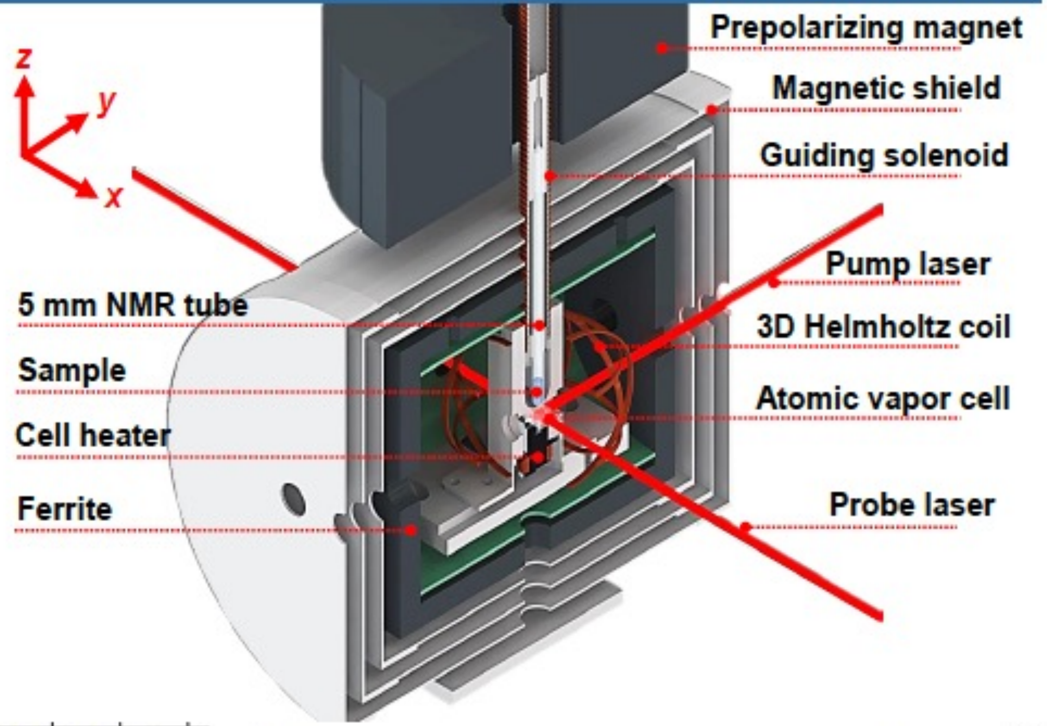
Gen 3 : Big Sample + Hyperpolarization !

Zero-field NMR

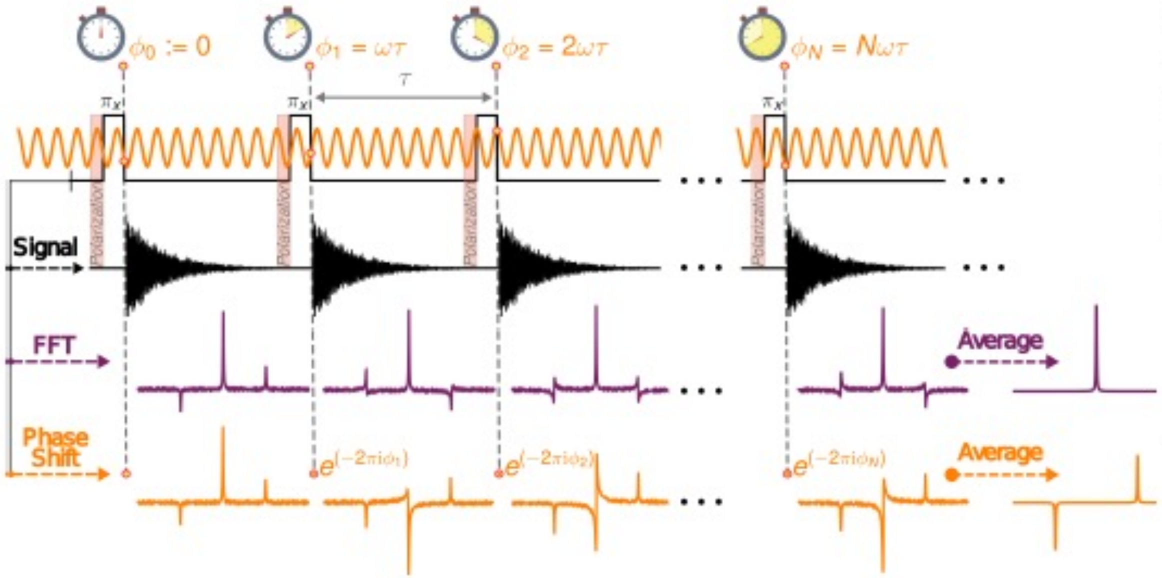


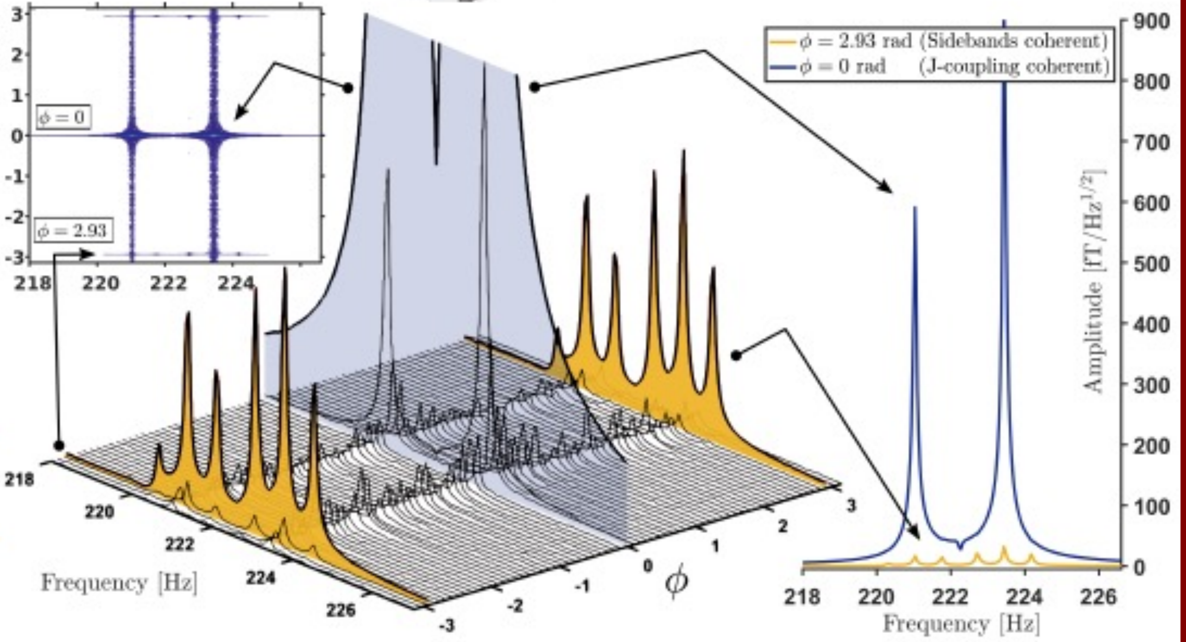
CASPEr With Zero- to Ultralow-Field NMR





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





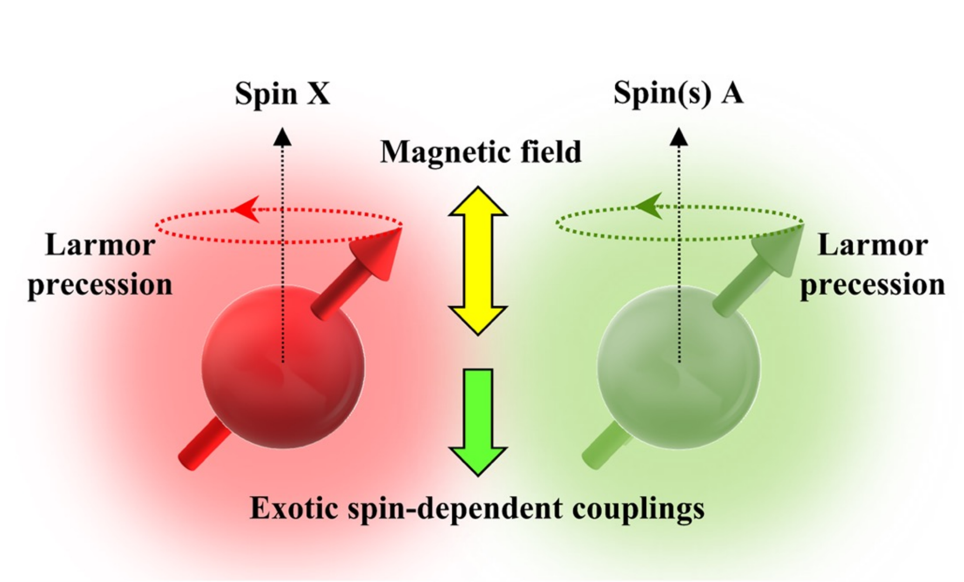
PHYSICAL REVIEW LETTERS

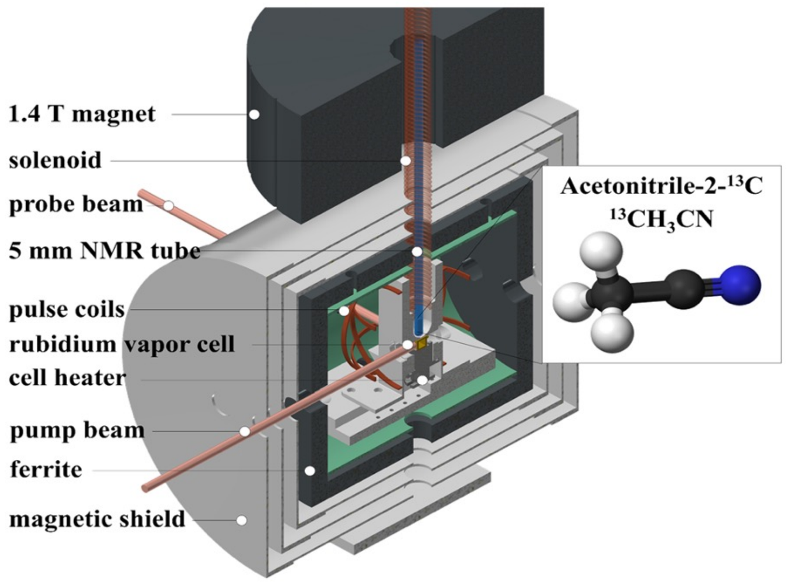
Nuclear-spin comagnetometer based on a liquid of identical molecules

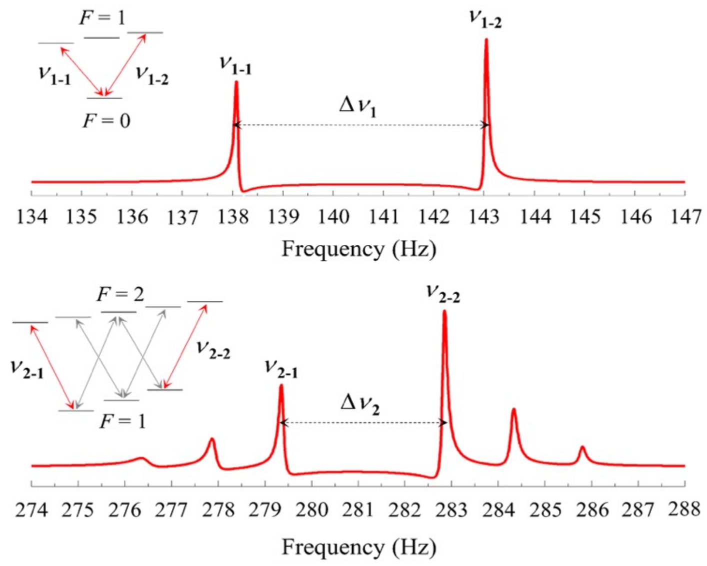
Phys. Rev. Lett.

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

Accepted 15 June 2018







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Nuclear-spin comagnetometer based on a liquid of identical molecules

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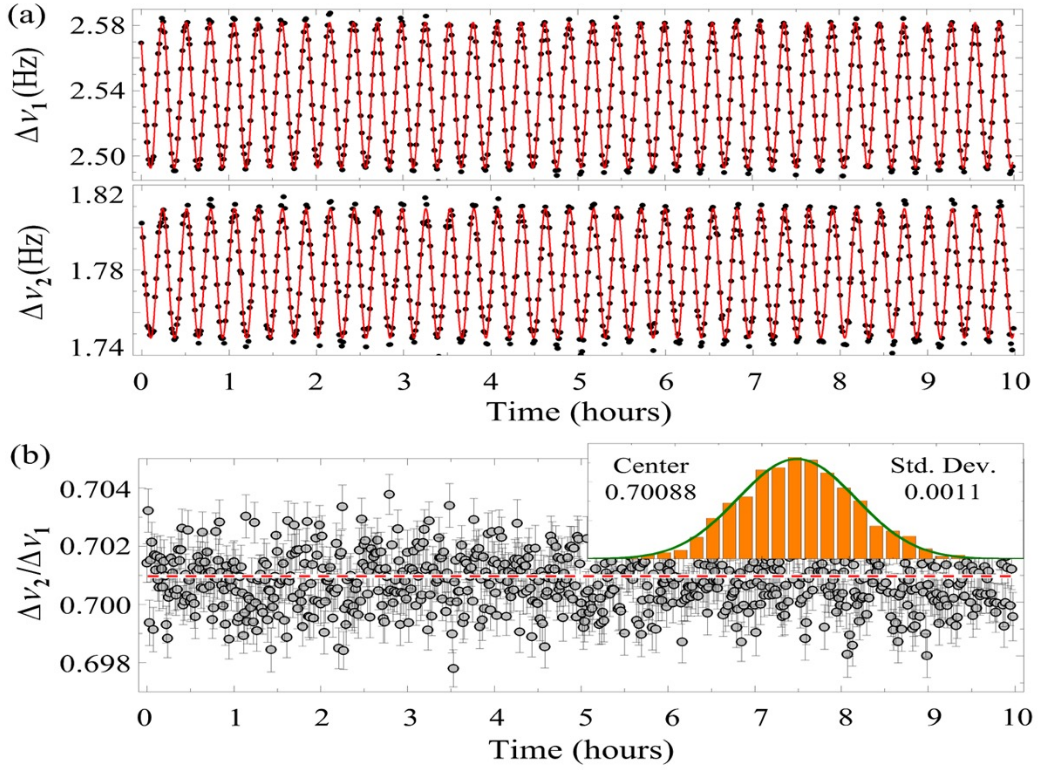
✓ Suppression of Magnetic Field Fluctuations

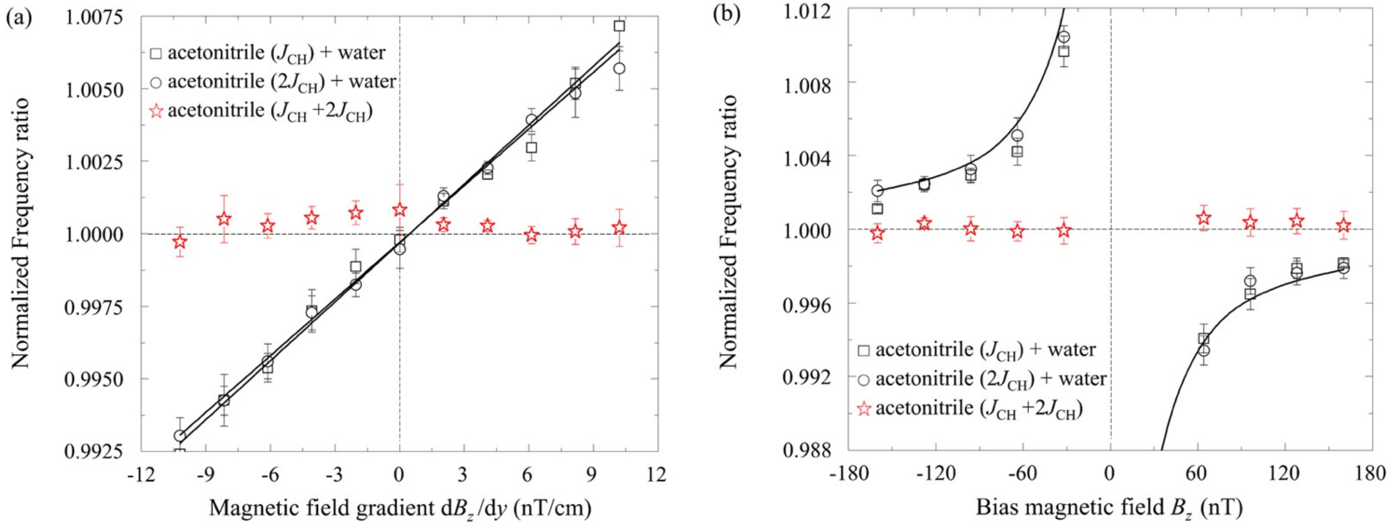


Sample: 2-^{13}C-acetonitrile (^{13}**CH$_3$**CN), ~ 100 μL, 5 mm NMR tube

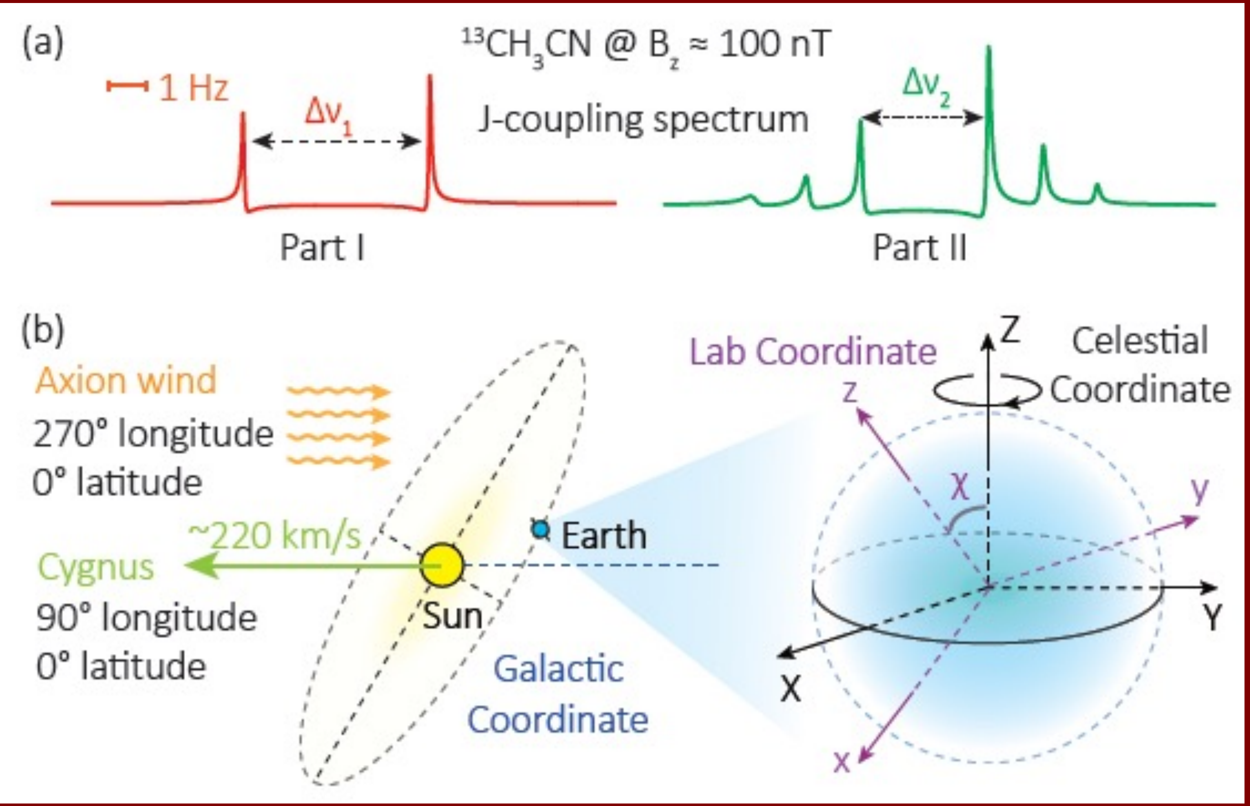
Polarization method: 1.4 Tesla Halbach magnet

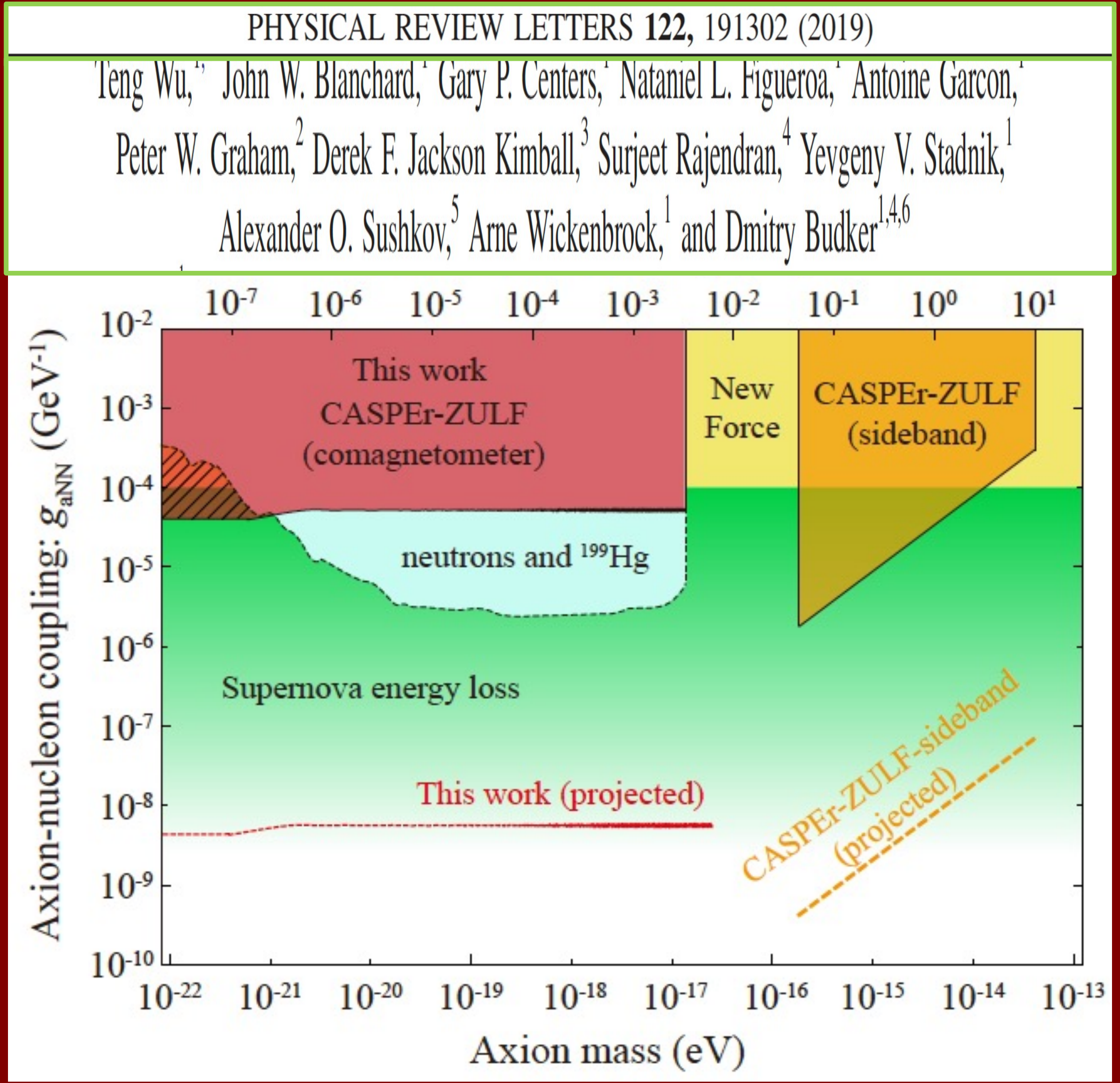
Detection method: Rubidium atomic magnetometer (10 fT/Hz$^{1/2}$)

✓ 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

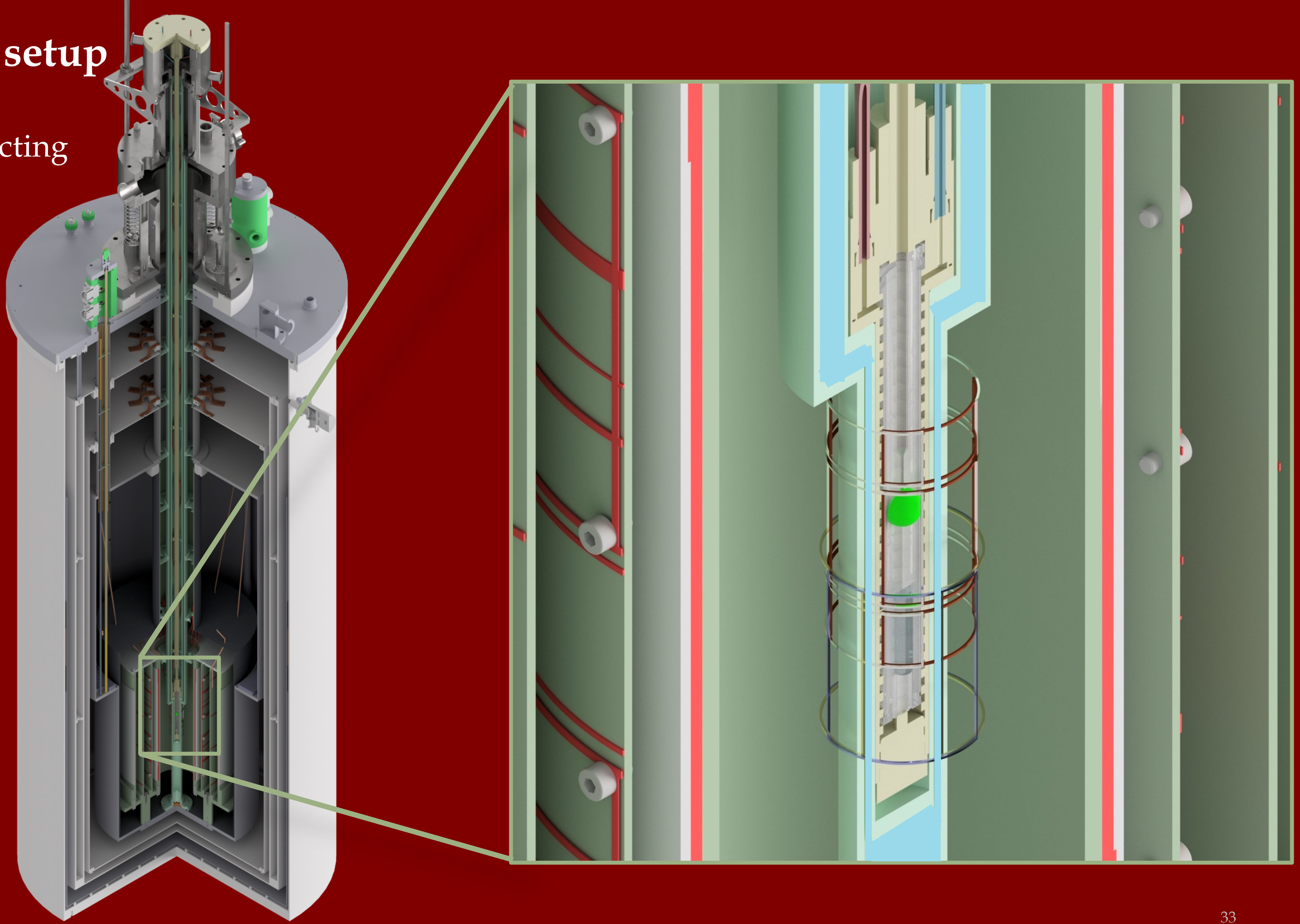
CASPEr: NMR based ALP-search program

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

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

CASPEr-gradient setup

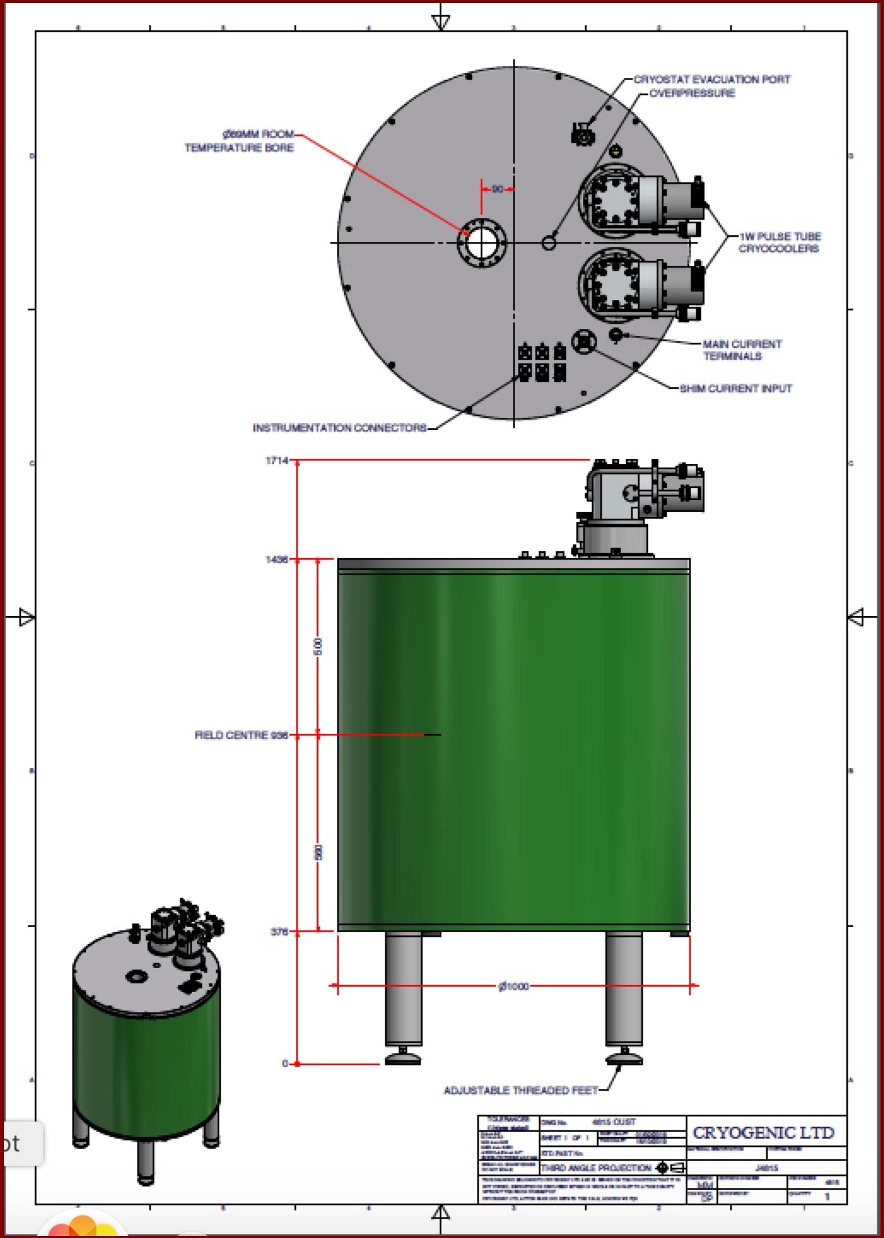
Cryogenics Lt.
0.1 T (1 kG) superconducting
Cold, wet bore
Superconducting shield

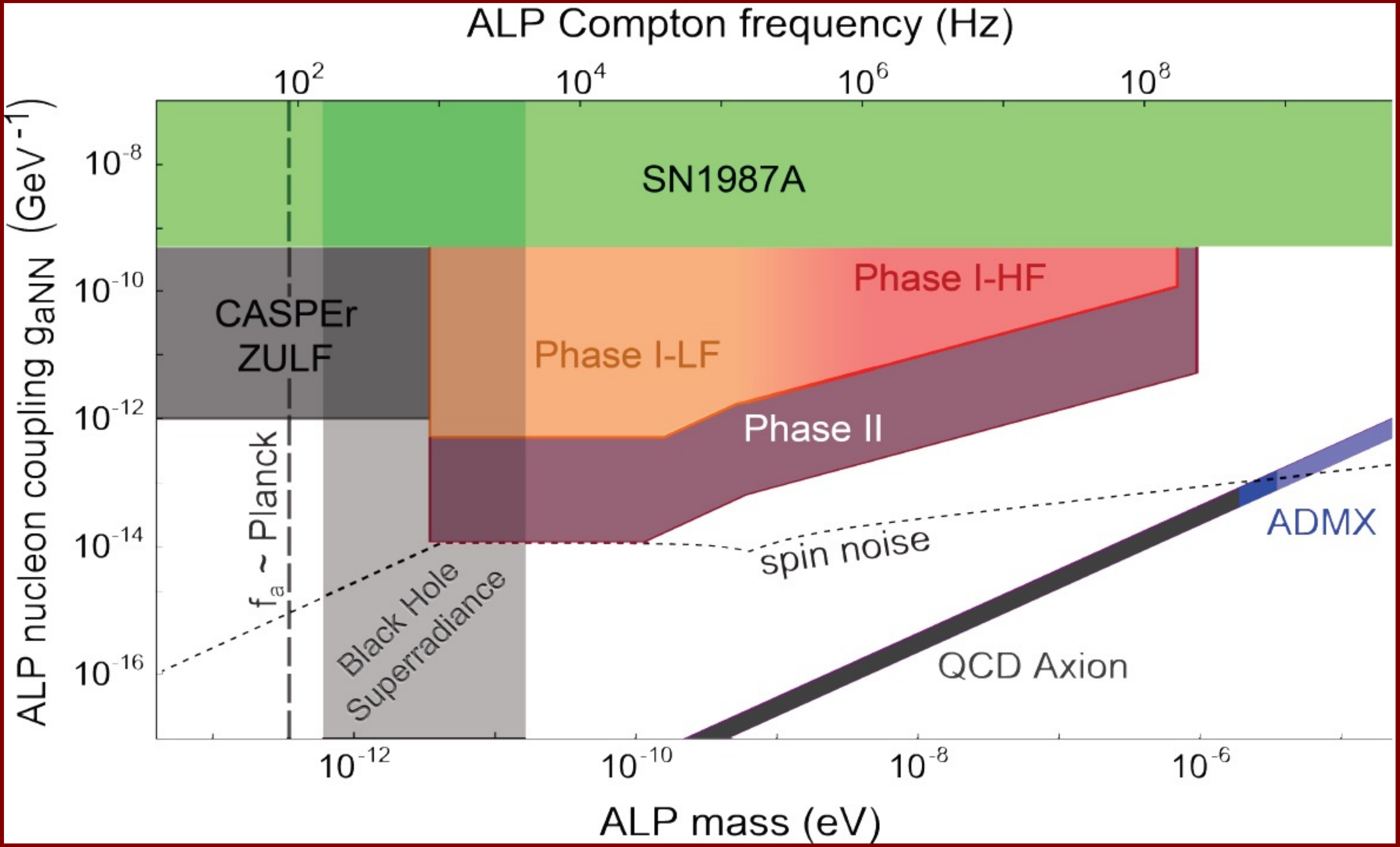


H. Bekker

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 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*

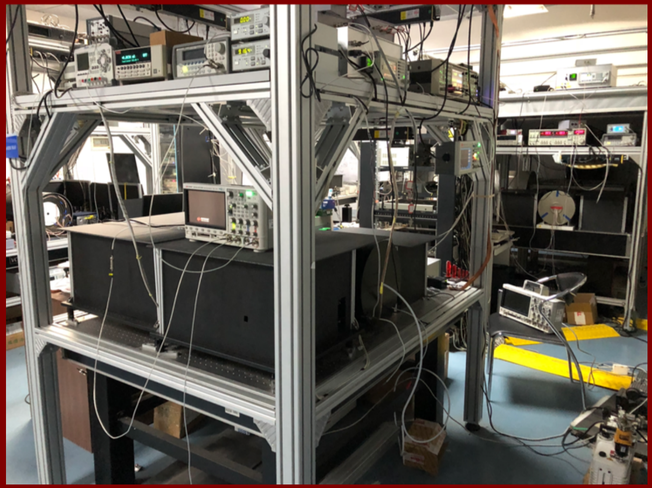
[3)] *Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

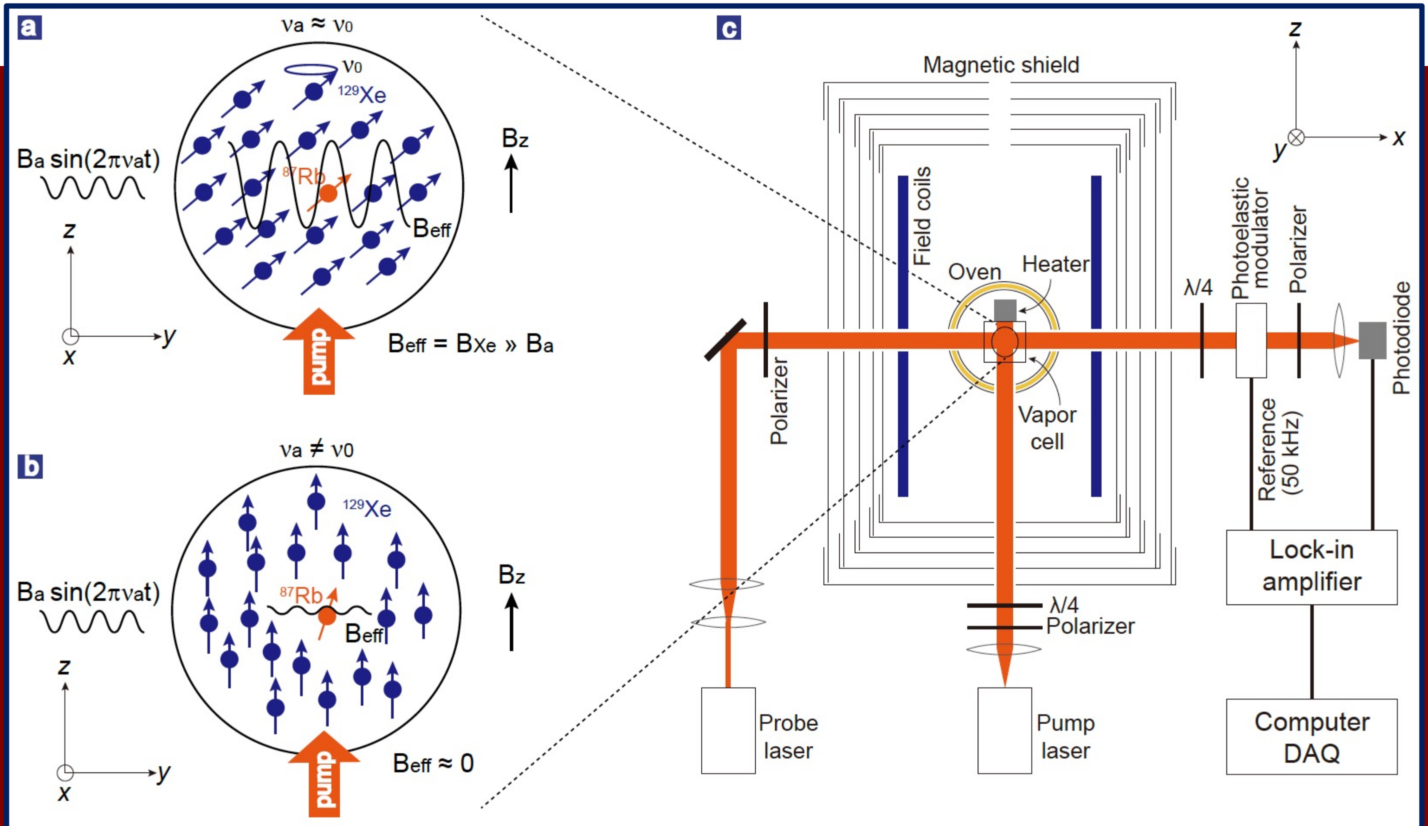
[4)] *Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, Mainz 55128, Germany*

[5)] *Johannes Gutenberg University, Mainz 55128, Germany*

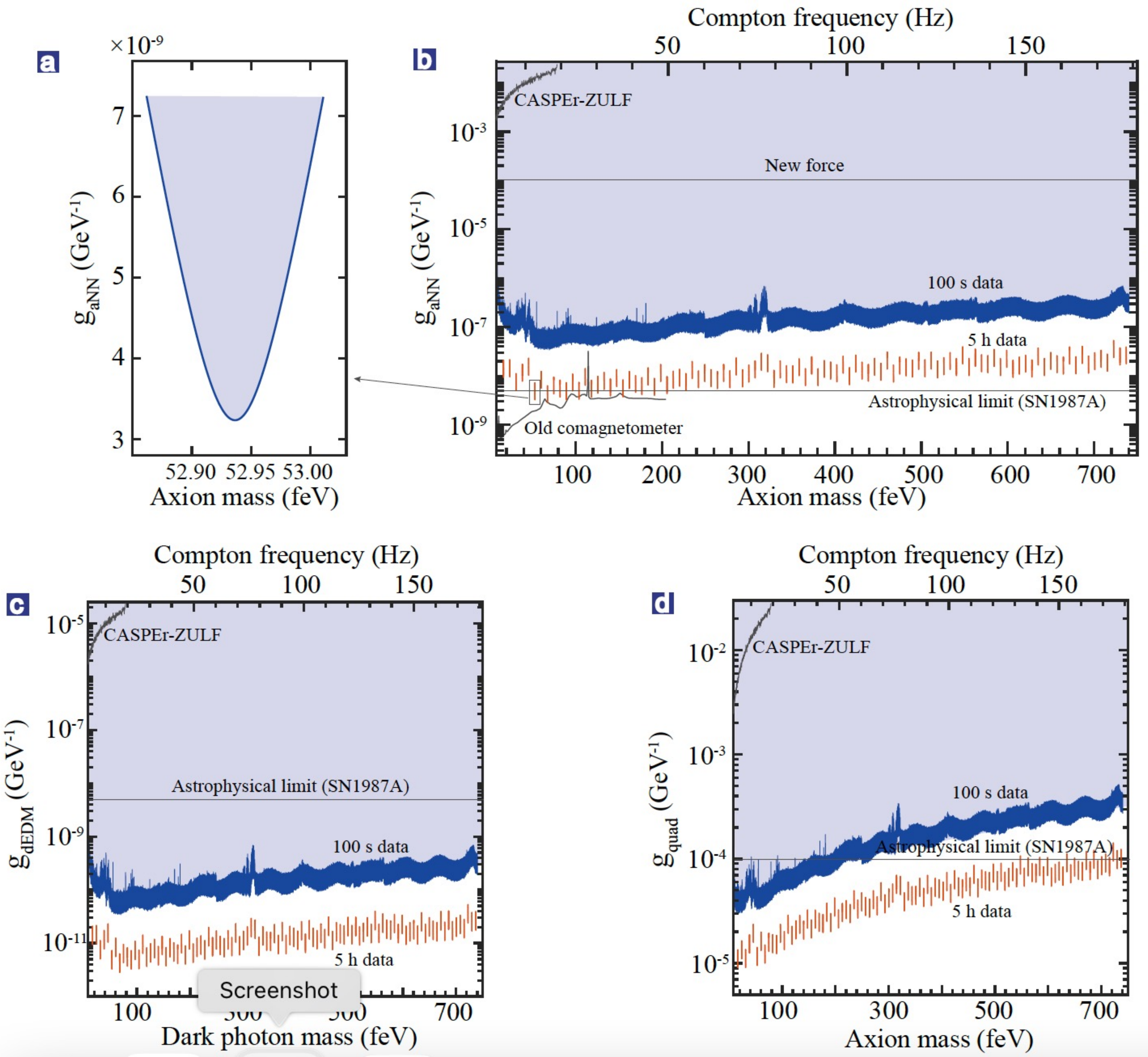
[6)] *Department of Physics, University of California, Berkeley, CA 94720-7300, USA*

(Dated: 3 February 2021)





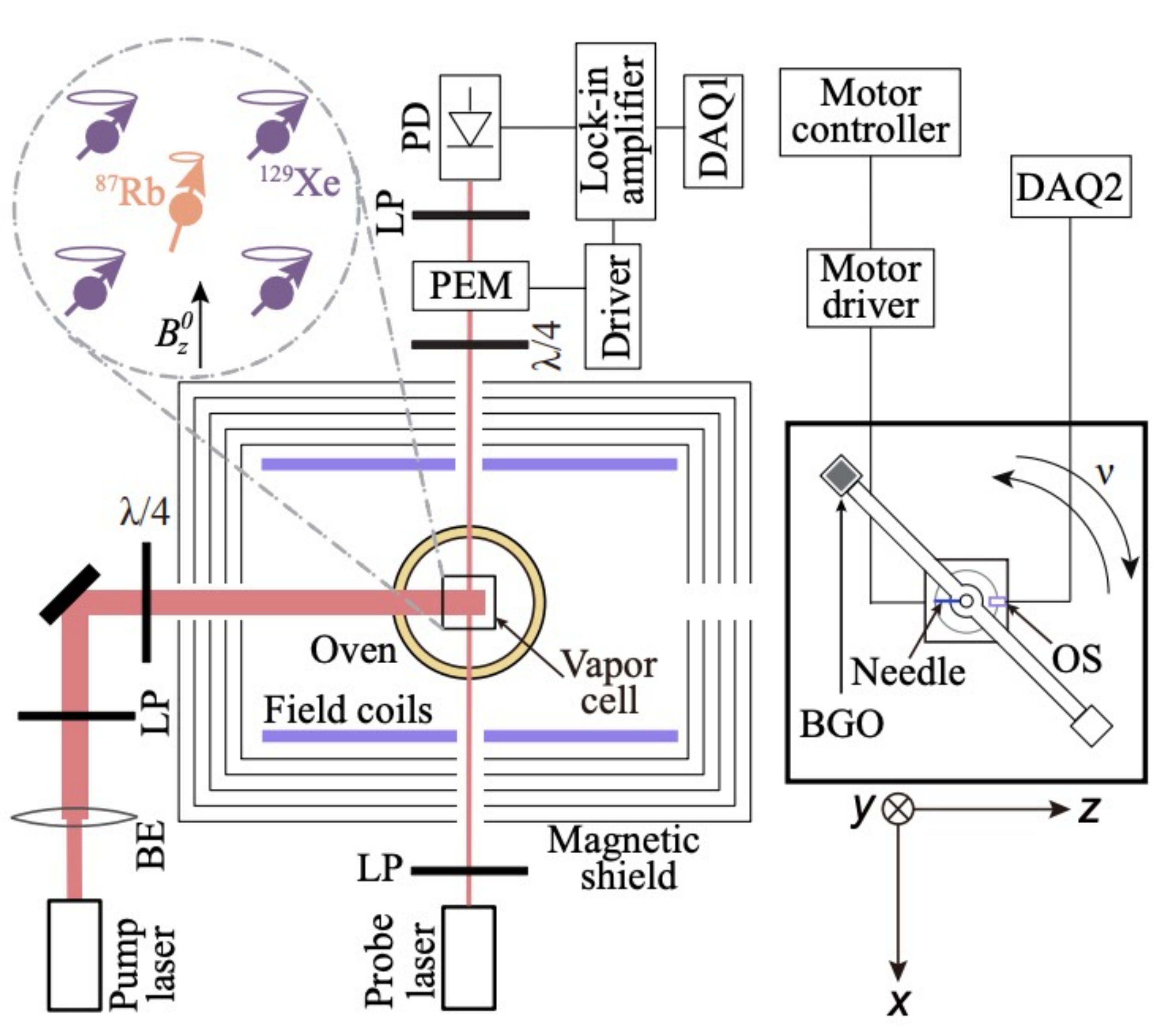
arXiv:2102.01448

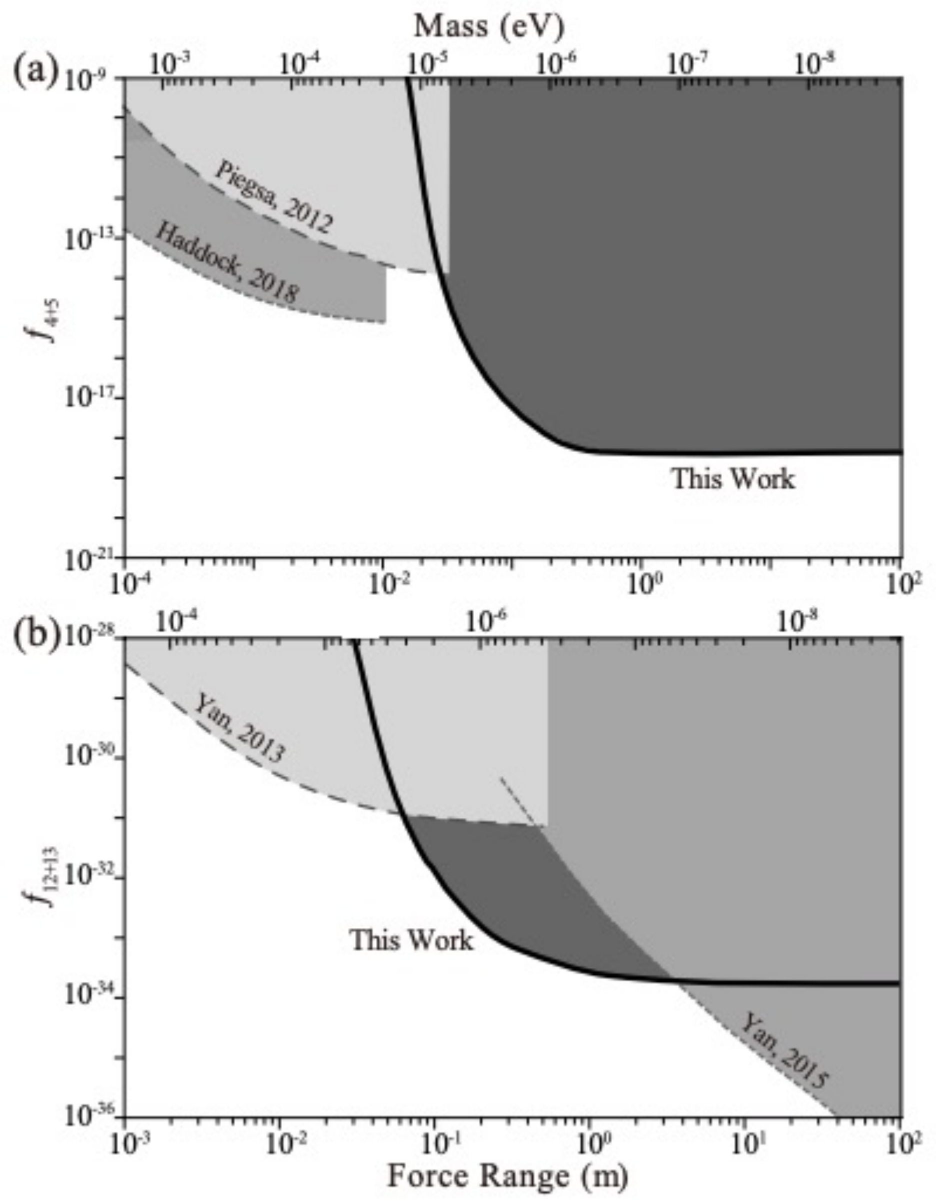


arXiv:2102.01448

Screenshot

Spin-Amplifier search for "fifth forces" (USTC)



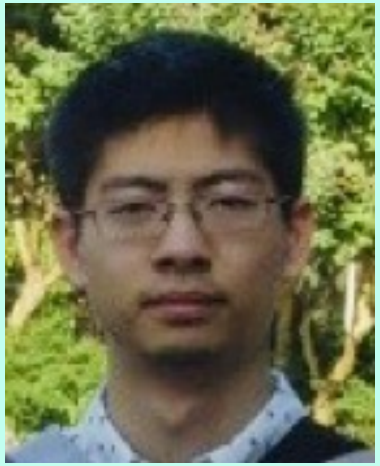


[Haowen Su, *et* al, arXiv:2103.15282]

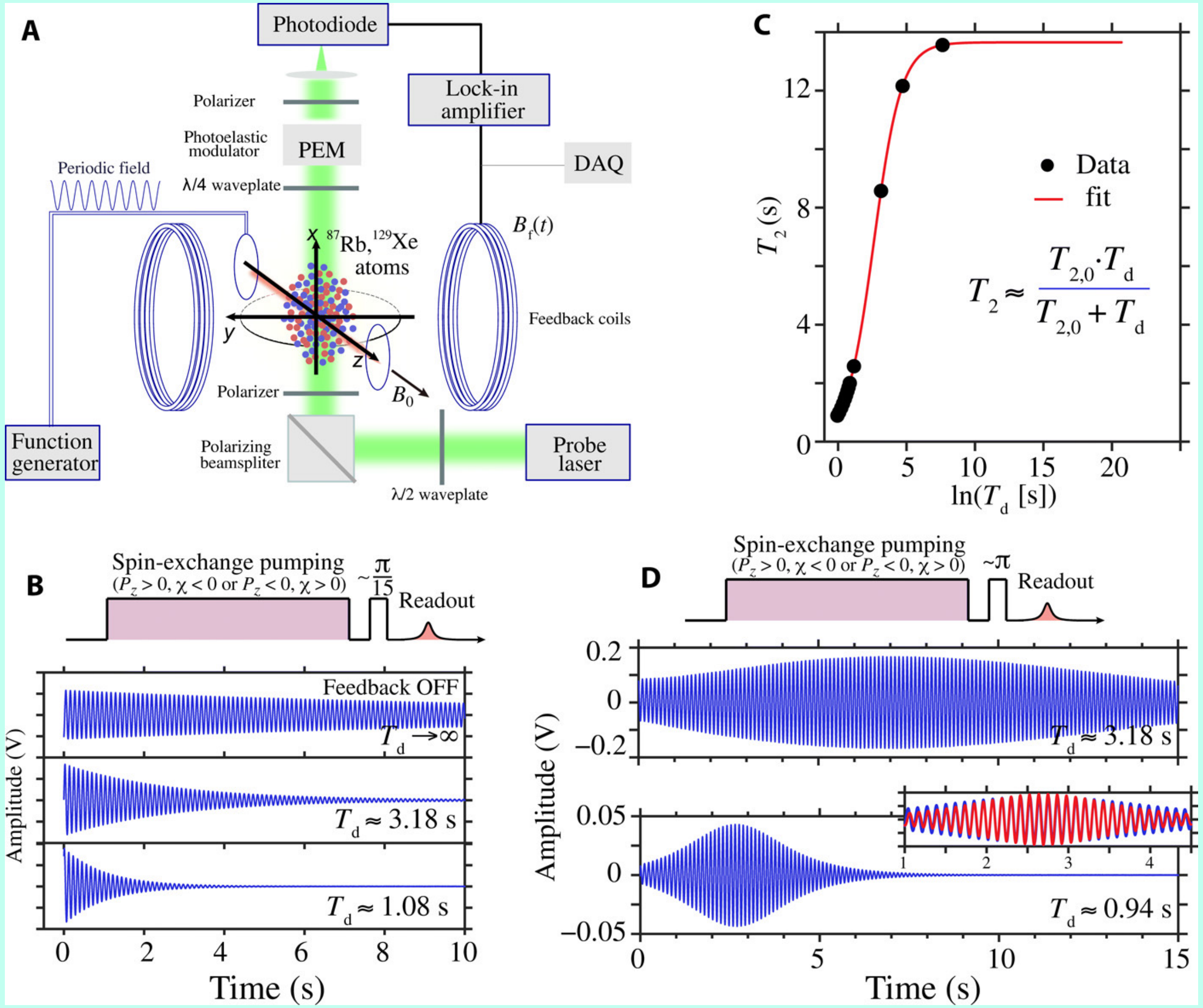
Floquet maser

Science Advances 17 Feb 2021:
Vol. 7, no. 8, eabe0719
DOI: 10.1126/sciadv.abe0719

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



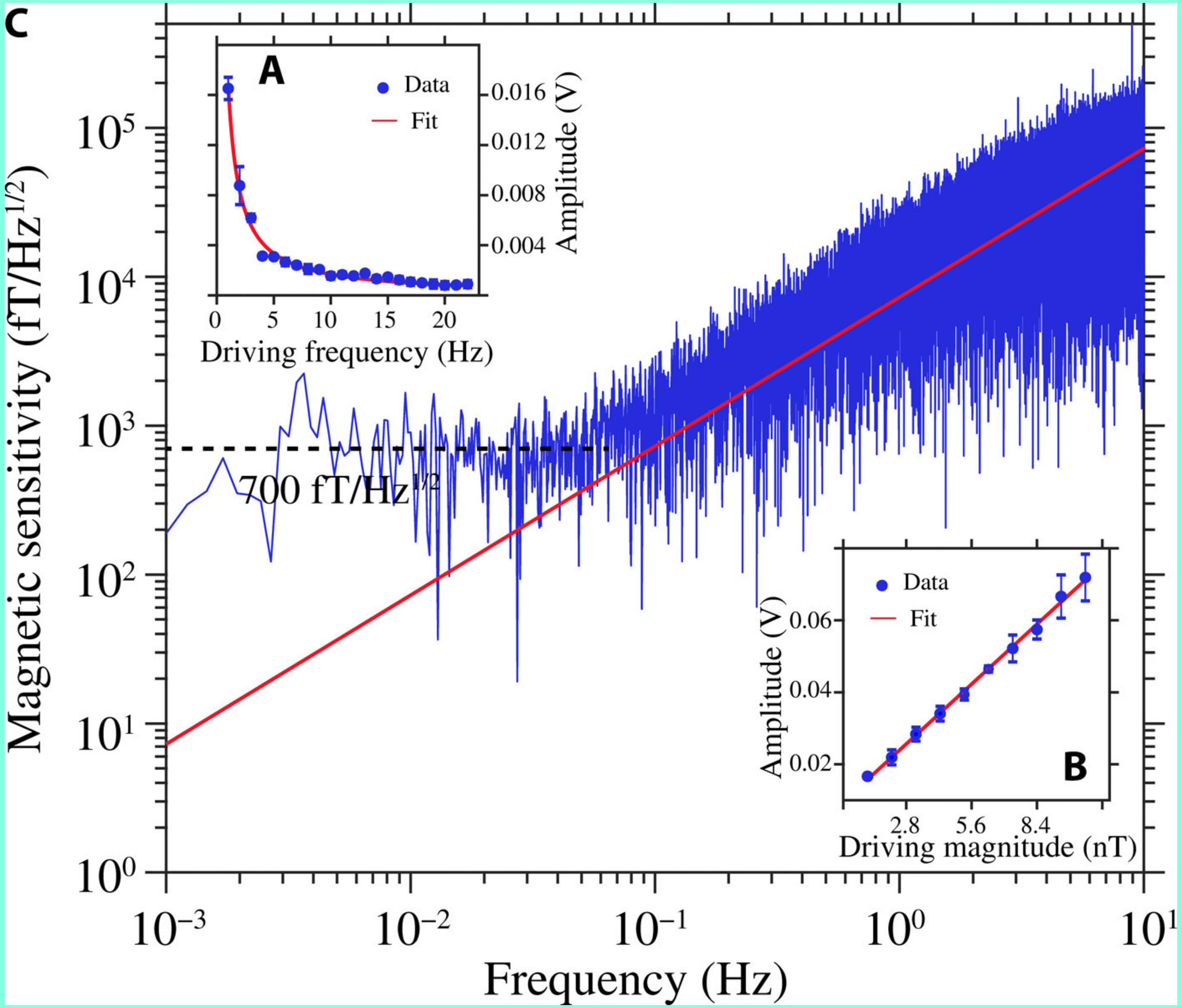
Schematic of experimental setup and damping feedback mechanism



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

ScienceAdvances AAAS

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



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

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