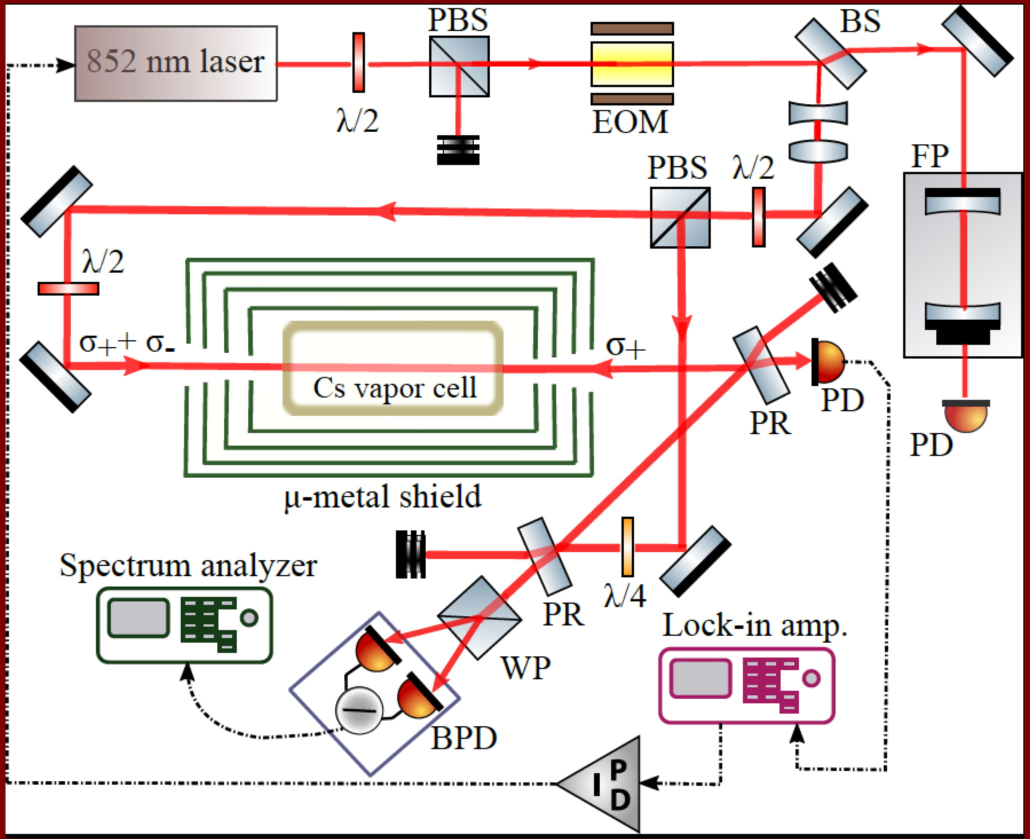
Some new ways to look for dark matter



Dmitry Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz

&

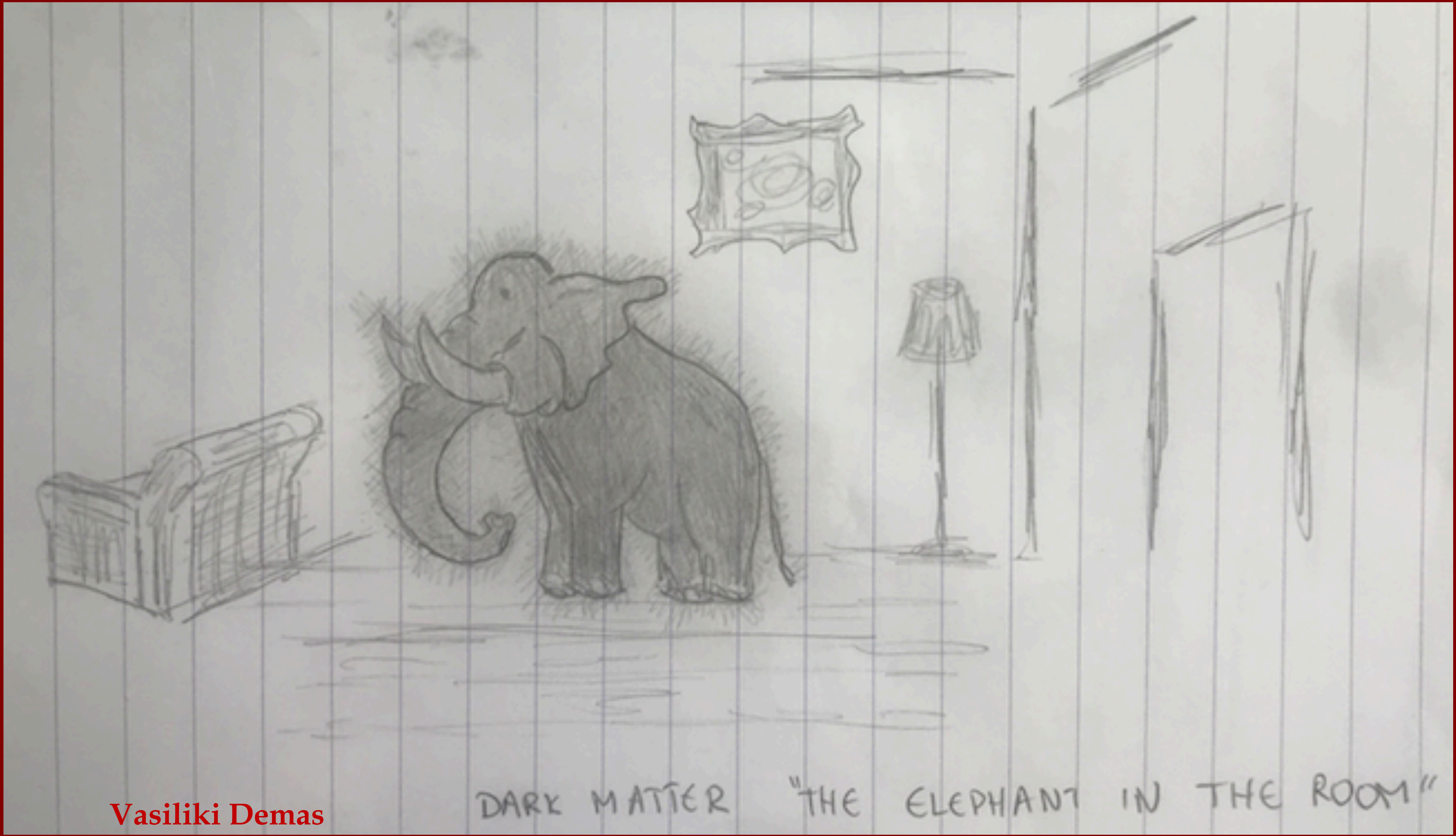
Department of Physics, UC Berkeley

Some new ways to look for dark matter

- NMR based searches
- Atomic clock searches
- Sensor networks
- Fast oscillation of fundamental constants (WRESL)
- Gravimeters
- Axion Quark Nuggets (AQN)
- Dark Matter search with antimatter

Dark Matter and axions


Axel Lindner
Marie Curie
Bela Majorowits
Ariel Zhitnitsky
Pierre Sikivie



Vasiliki Demas

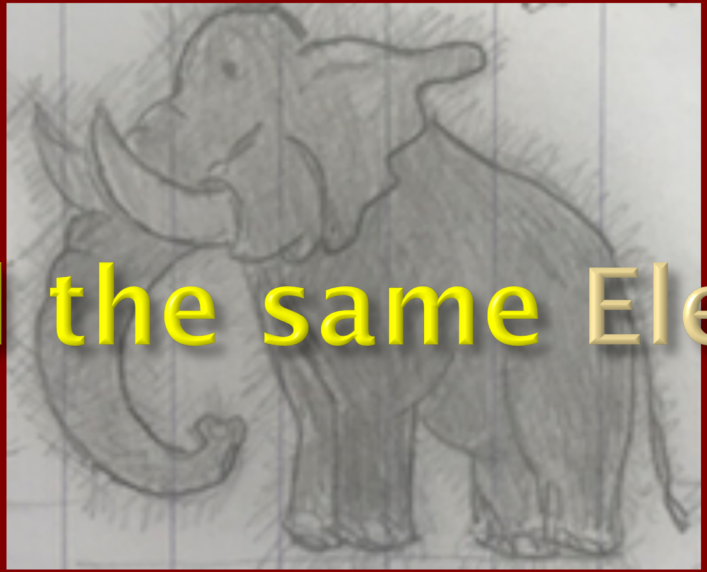
More Elephants!

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) !!!☺!!!

"Most Wanted" file on DM
What do we know?

- Galactic DM density: ~0.4 GeV/cm^3 (10 GeV/cm^3 d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be bosonic if $m < \sim 20$ eV (1 keV dwarf galaxies)
- "Bosonic Oscillator" with Q ~ $(v/c)^{-2} \sim 10^6$
- Cannot be lighter than ~ 10^{-22} eV
- … (e.g., BEC ?)

Ultralight Bosonic DM

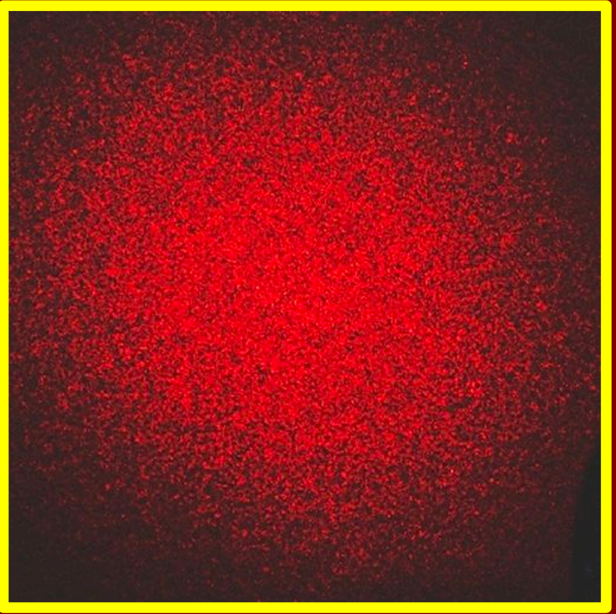
Density

(a) The number density of the dark-matter particles, under the assumption that all dark matter consists of particles of the same mass m is

$$\boxed{n_{dm} \approx \frac{0.4\ \mathrm{GeV/cm}^3}{mc^2}.} \tag{3.13}$$

The 1 MHz frequency corresponds to about $4{\cdot}10^{-9}$ eV, so the density of such particles should be $\boxed{\approx 10^{17}\ \mathrm{cm}^{-3}.}$ One cubic centimeter of air contains about $3 \cdot 10^{19}$ molecules, the majority of which are nitrogen with 28 nucleons each, which comes to about 10^{21} nucleons per cm^3, several orders of magnitude more than the above estimate for 1 MHz dark-matter particles.

Spatial pattern = speckle



Coherence time and length

(b) The total energy of a nonrelativistic dark-matter particle is dominated by the rest energy mc^2 with an additional correction on the order of mv^2, which comes to about 10^{-6} of the rest energy for $v \approx 10^{-3}c$. This means that the de Broglie waves dephase during roughly 10^6 periods of the oscillation whose frequency corresponds to the energy of mc^2, so that the *coherence time* is

$$\tau_c \approx 10^6 \cdot \left(\frac{mc^2}{2\pi\hbar}\right)^{-1}. \tag{3.14}$$

For 1 MHz dark-matter particles, this comes to $\boxed{\tau_c \approx 1\ \mathrm{s}.}$

Coherence length L_c can be estimated as a product of τ_c and the particle velocity v (we invite the reader to derive this result using the concepts of *phase velocity* and *group velocity* of the de Boglie waves), so that

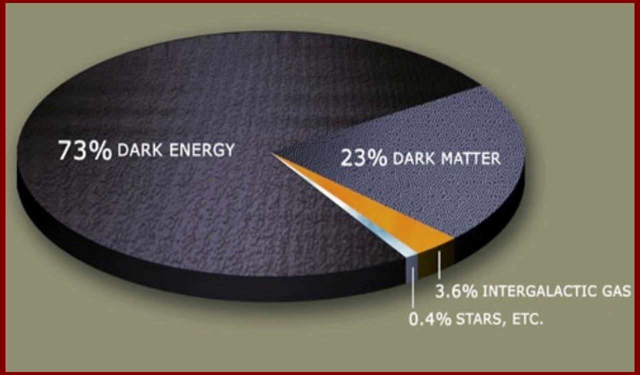
$$L_c \approx 10^3 \cdot \left(\frac{mc^2}{2\pi\hbar c}\right)^{-1}. \tag{3.15}$$

For 1 MHz dark-matter particles, this comes to $\boxed{L_c \approx 300\ \mathrm{km}.}$

From: D. Budker and A. Sushkov *Physics on Your Feet*, 2nd Edition, OUP (forthcoming)

Why Axions (ALPs) ?

- Big clean-up ?
  - Strong CP problem
  - Dark Matter
  - Dark Energy
  - Baryon asymmetry of the Universe
  - Hierarchy?
  - …



http://earthsky.org/space/

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

Gauge Fields

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

Most Searches, **DM** radio

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

(nEDM, CASPEr-E)

Fermions

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

(CASPEr-Wind, GNOME, QUAX)

Dark Matter search with NMR

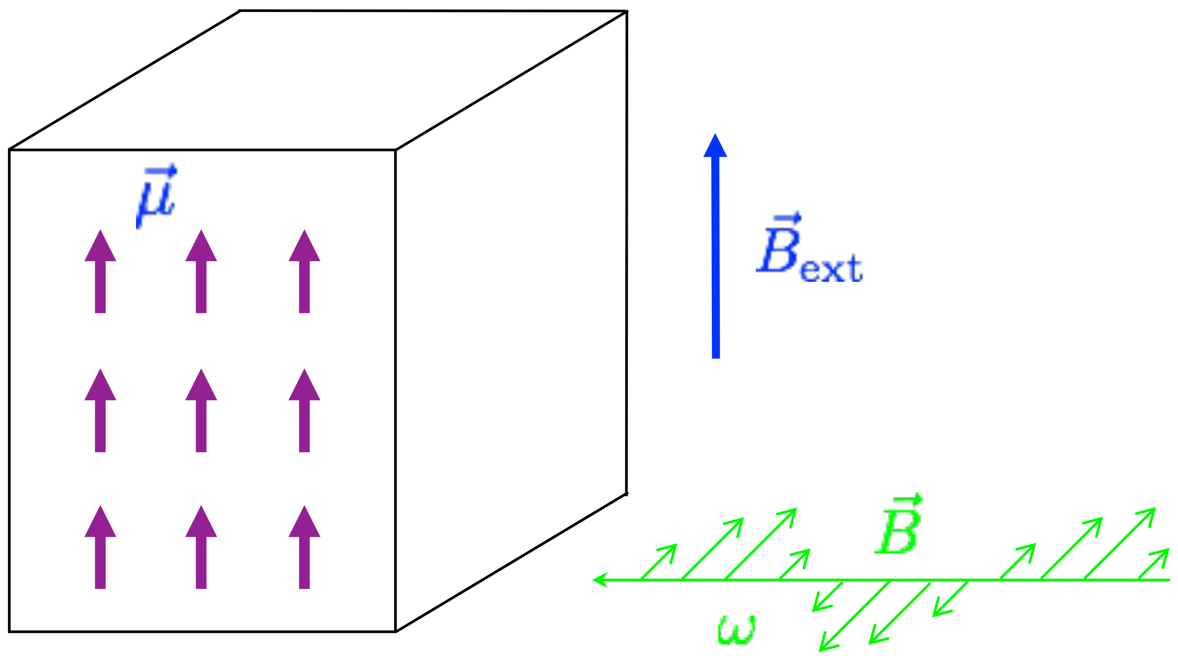
Key Ideas:

- **Dark Matter** could be a "classical" field
- Not screened by shielding
- Oscillating at frequency: mc^2/h
- Relatively narrow line: $\Delta\nu/\ \nu \sim 10^{-6}$

➙ Cosmic Axion Spin-Precession Experiment(s)

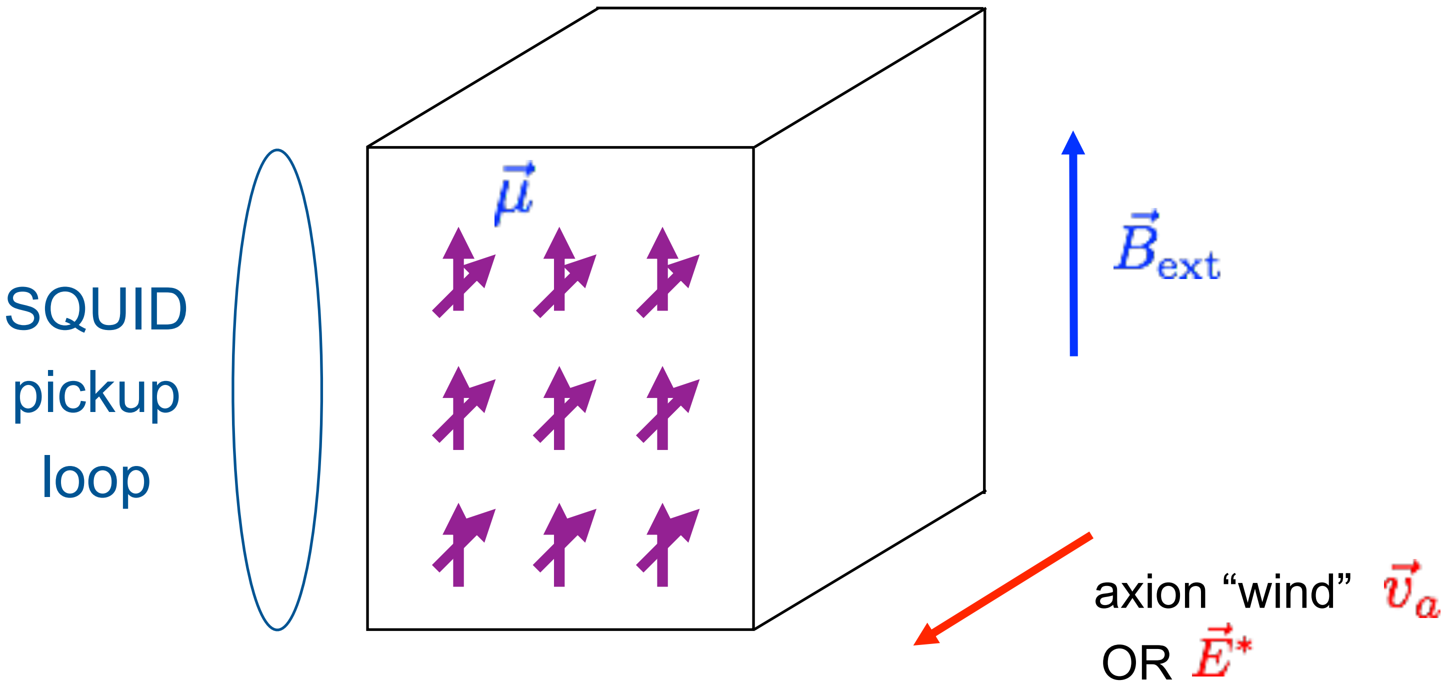
CASPEr

Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\text{ext}} = \omega$

CASPEr

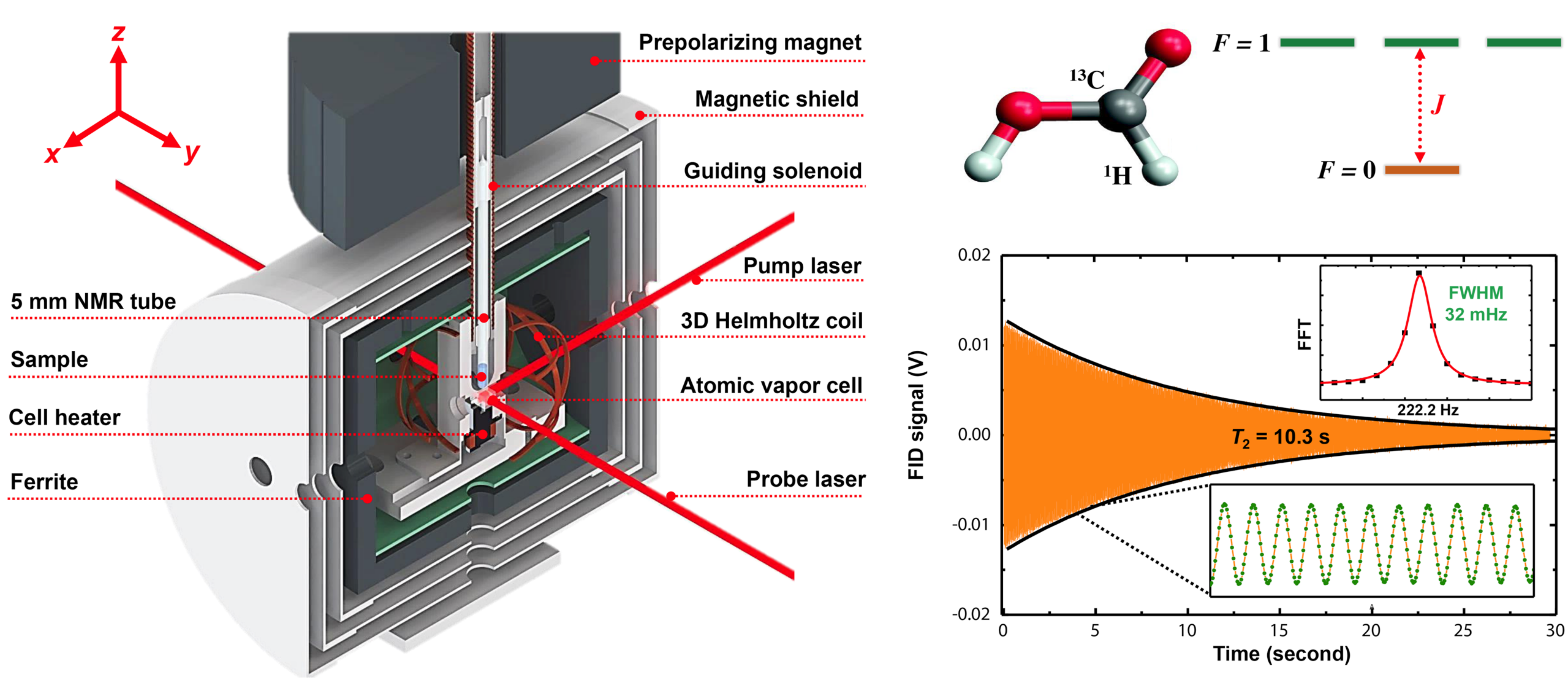


Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

Zero-field NMR



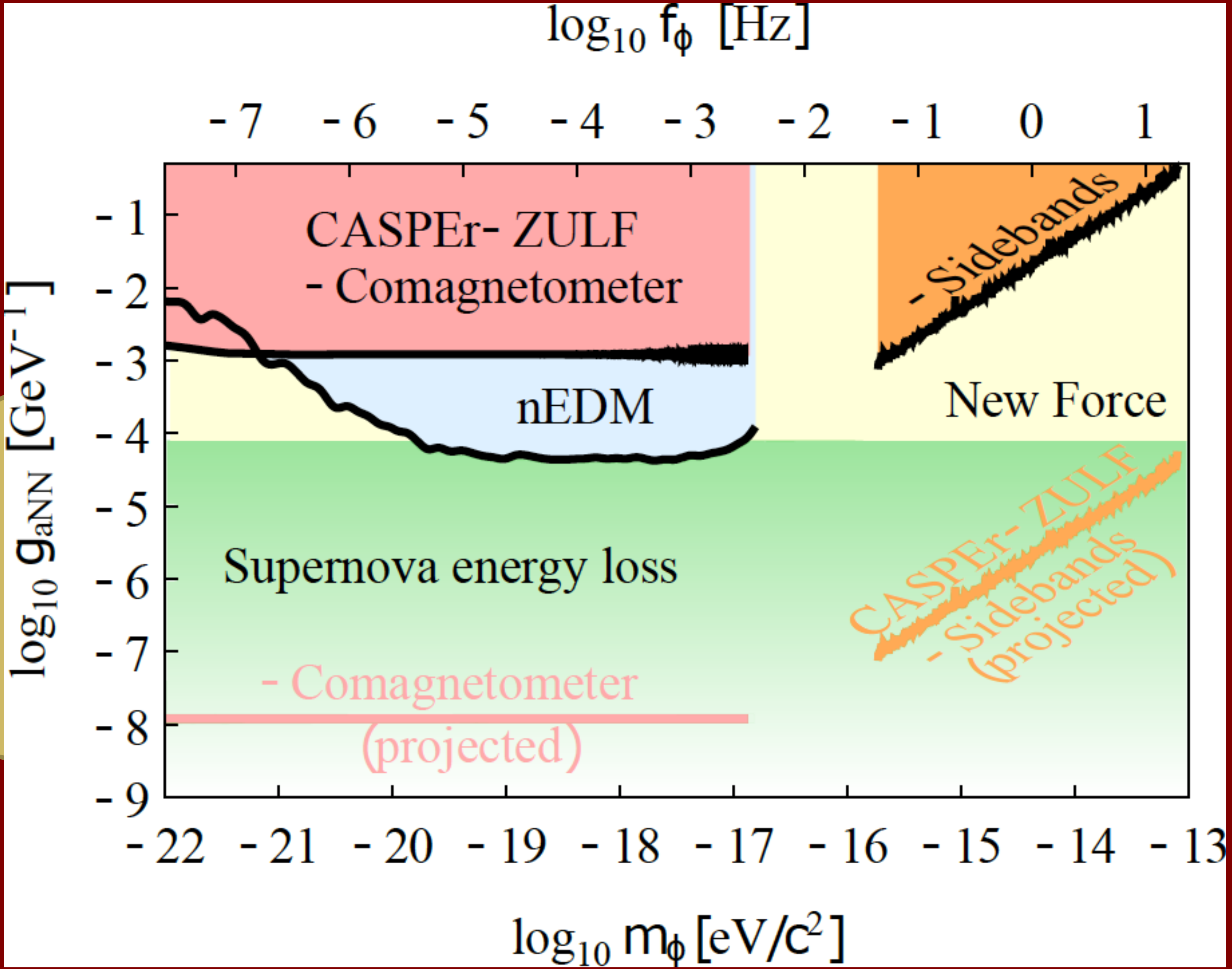
CASPEr: NMR based ALP-search program

- First results (2019!):

Antoine Garcon *et al*, Sci. Adv. 2019 **5**: eaax4539
arXiv:1902.04644;

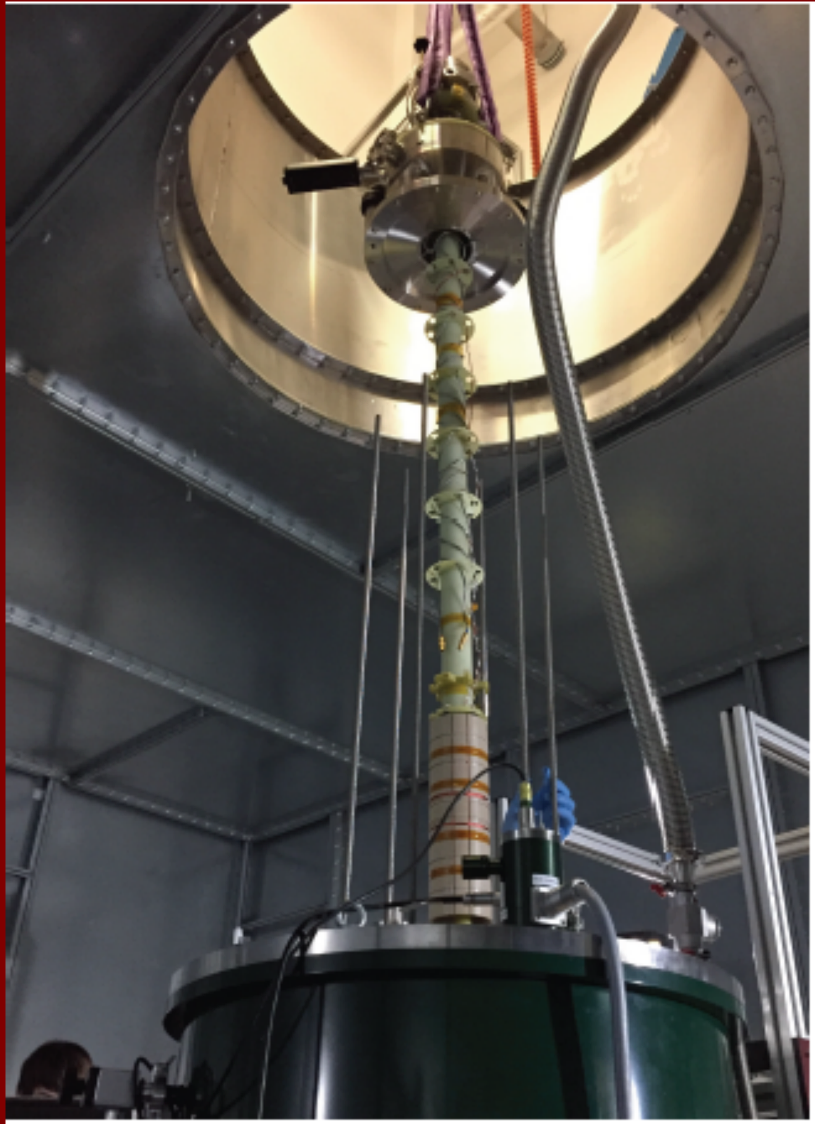
Teng Wu *et al*, **Phys. Rev. Lett. 122**, 191302 (2019);
arXiv:1901.10843

Low-frequency results should be taken with !caution!



CASPEr: NMR based ALP-search program

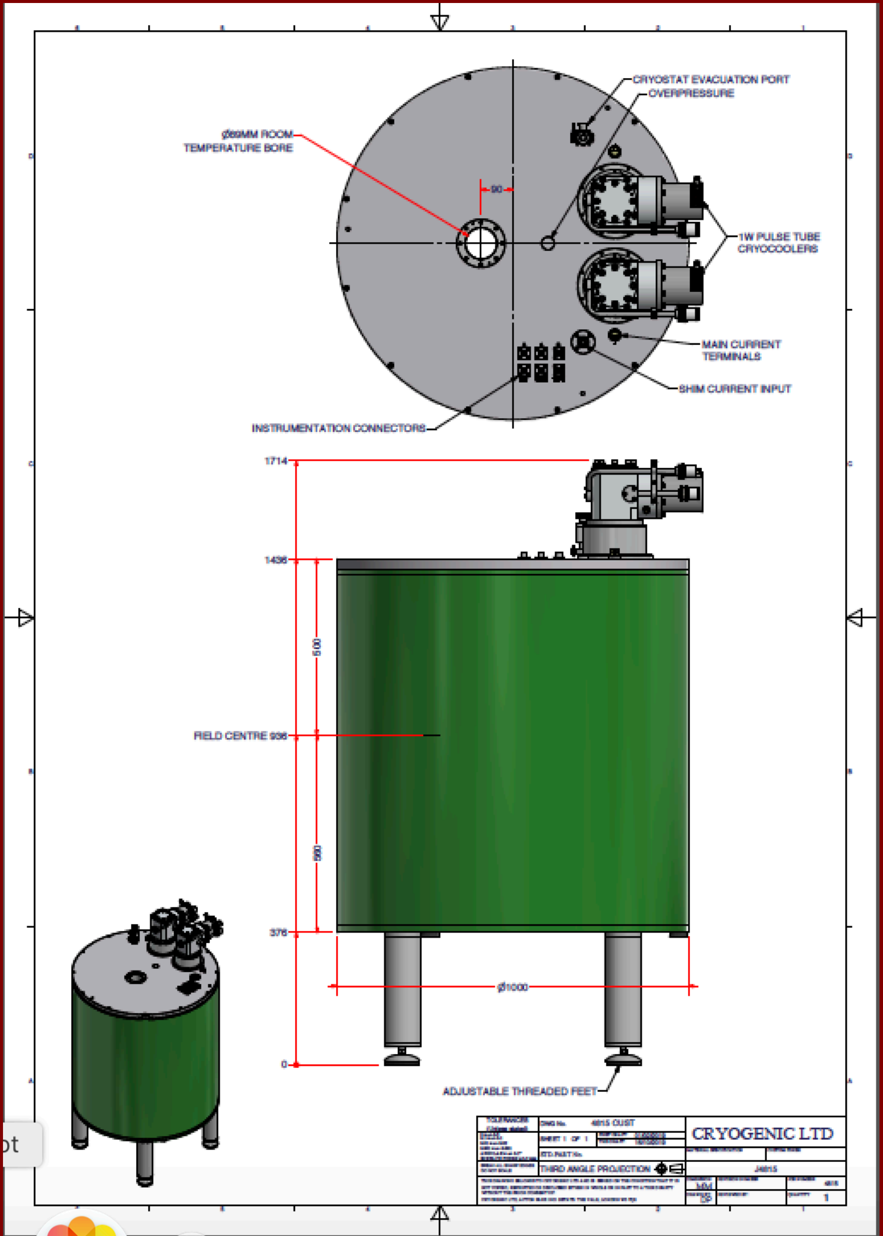
- Higher frequencies: data runs start in 2020 (virus permitting)!

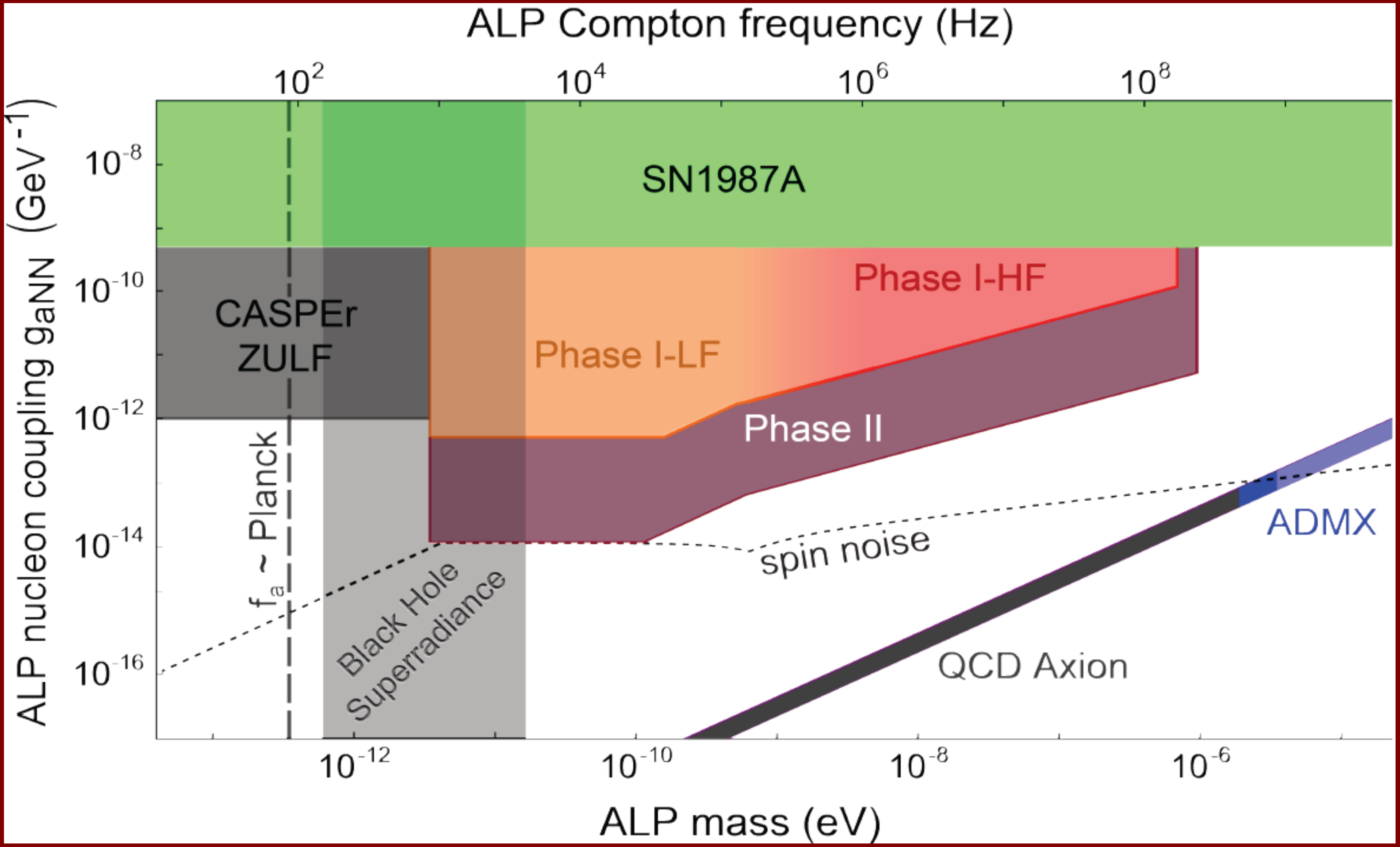


Cryogenics magnet; B < 0.15 T (<1.6 MHz for ^{129}Xe)

CASPEr: NMR based ALP-search program

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

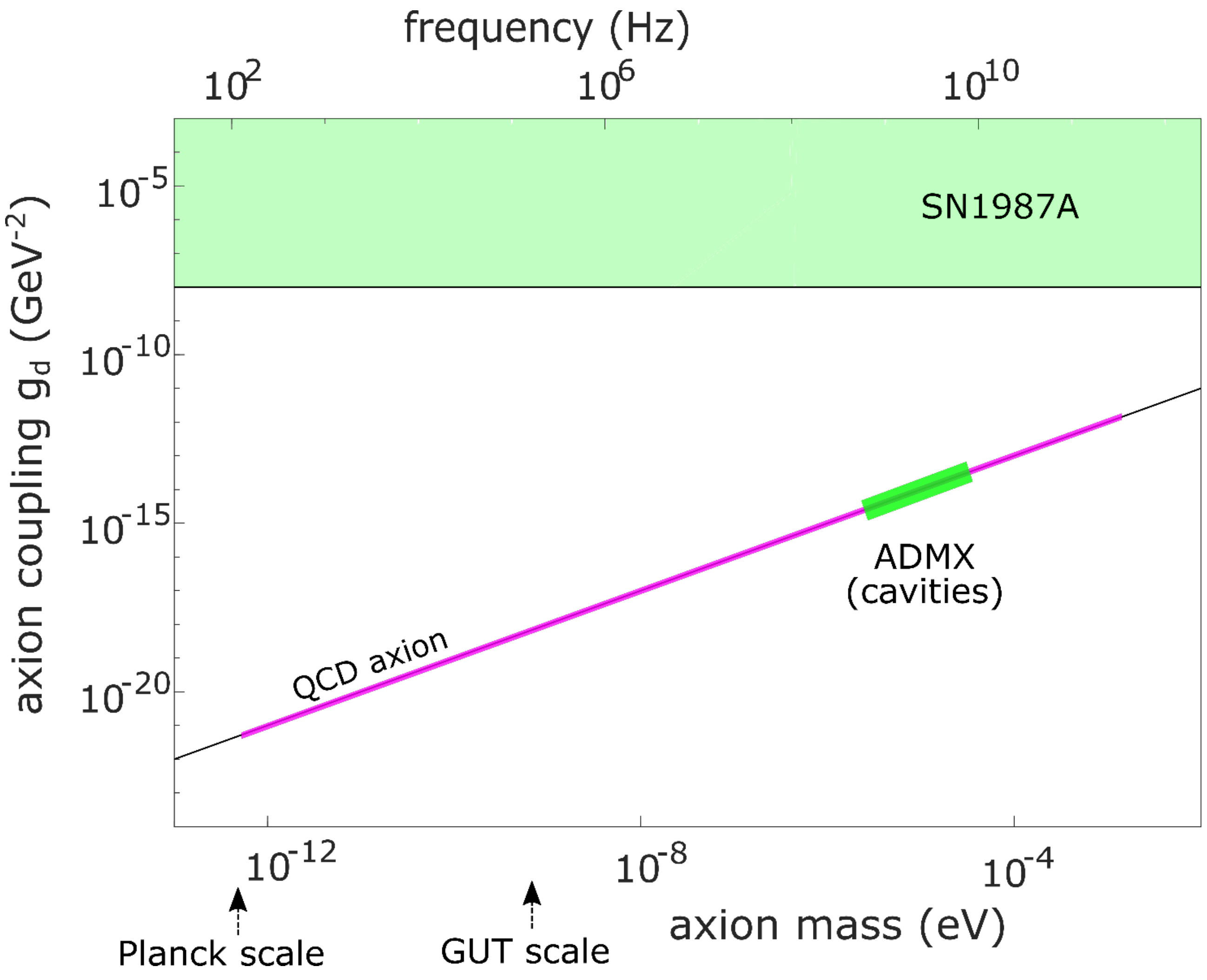




Cryogenics magnet; B < 14.1 T (166 MHz for ^{129}Xe)

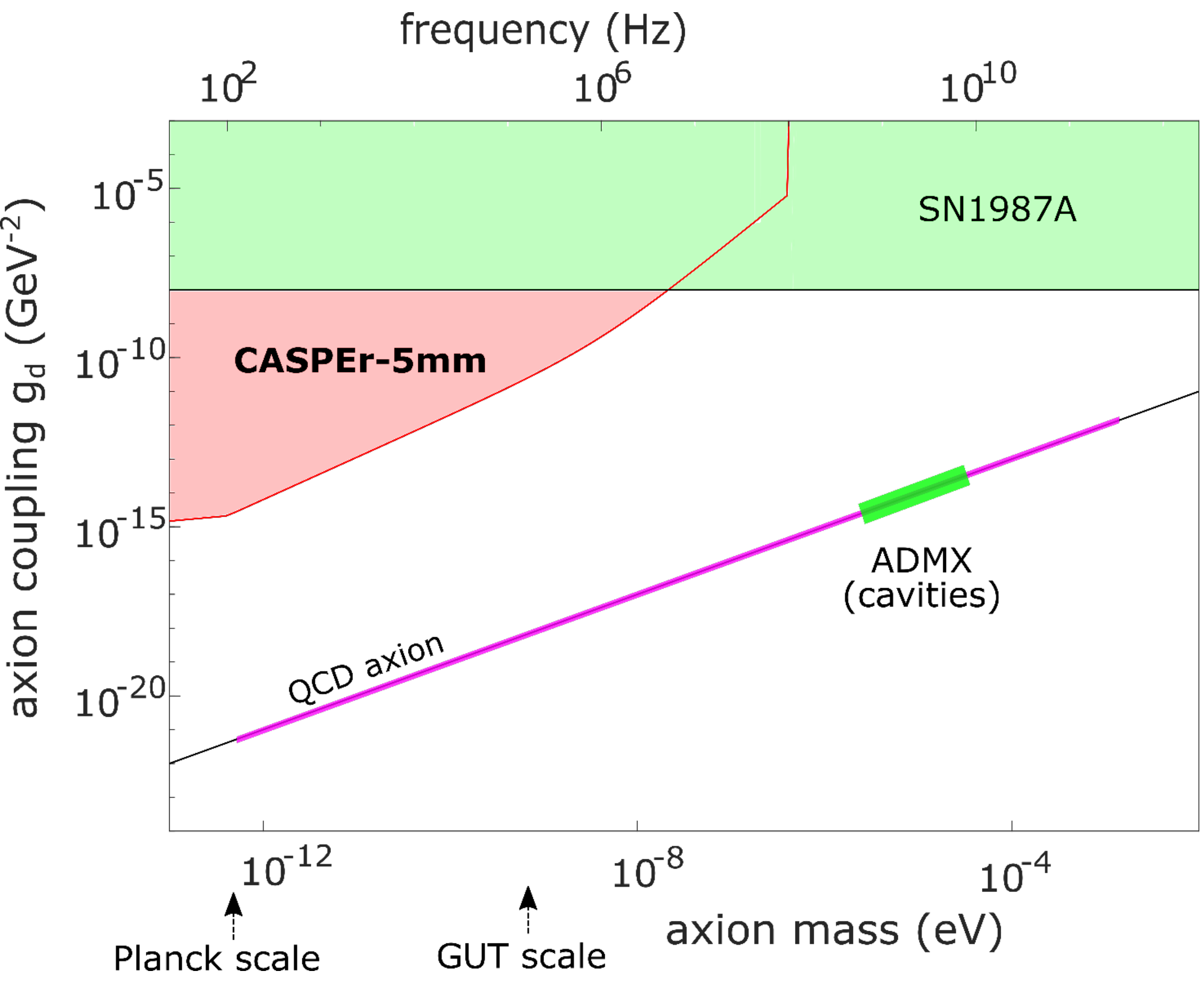
Alexander Sushkov

CASPEr-e, 5mm



Alexander Sushkov

CASPEr-e, 5mm

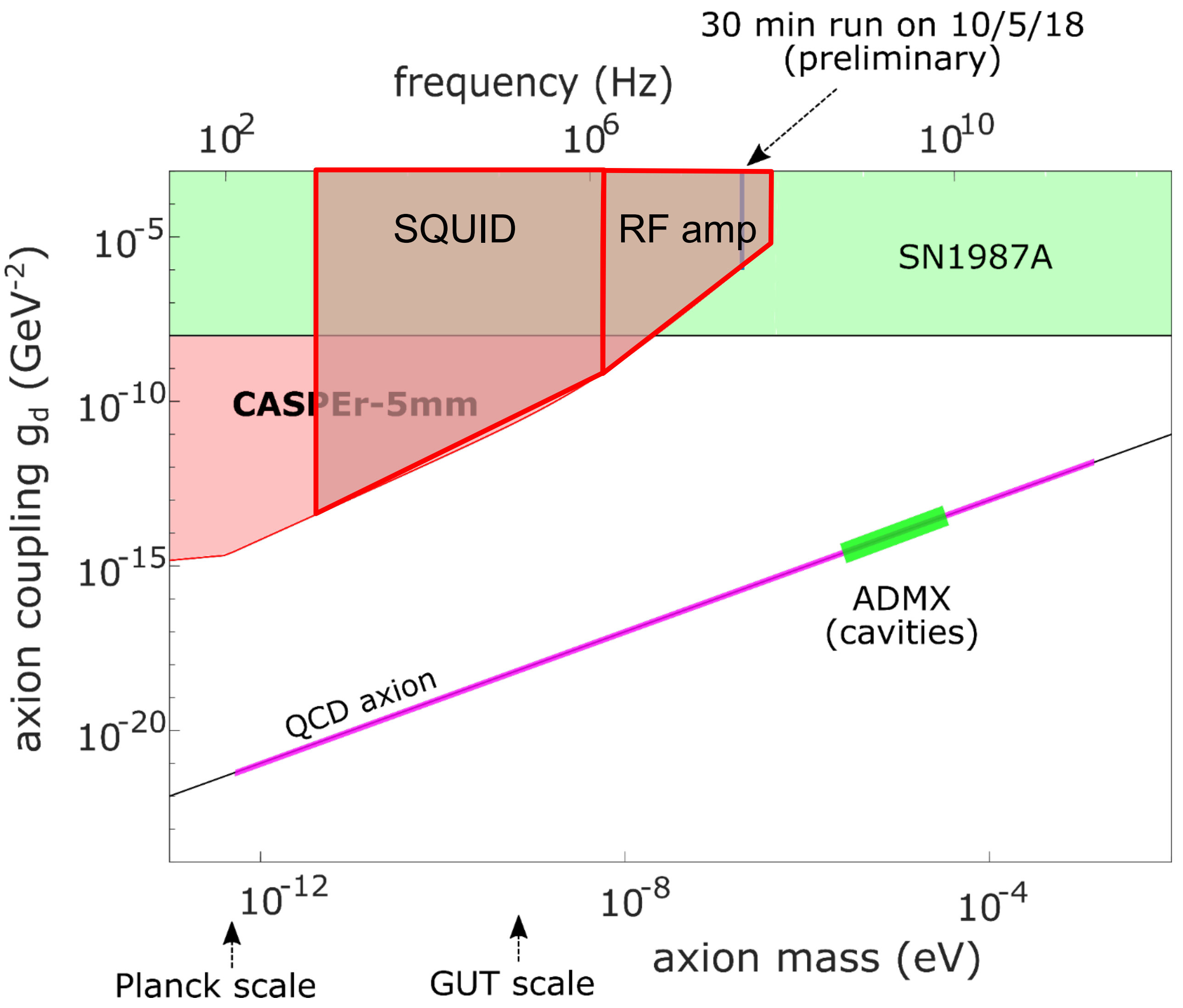


CASPEr-5mm at Boston University:

- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm

Alexander Sushkov

CASPEr-e, 5mm

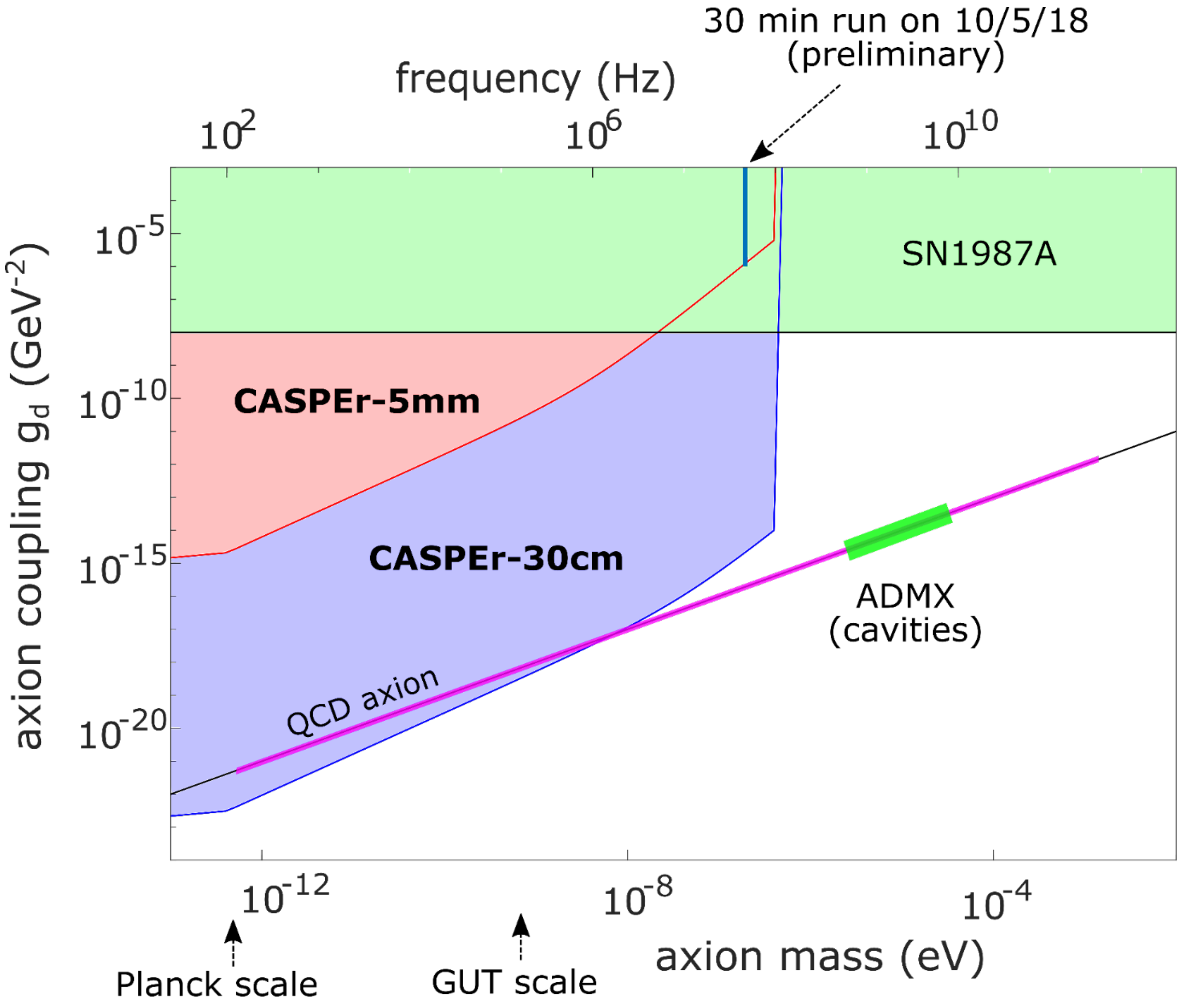


CASPEr-5mm at Boston University:

- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm
- pathfinder experiment operational at design sensitivity

Alexander Sushkov

The experimental reach of CASPEr-e



CASPEr-5mm at Boston University:

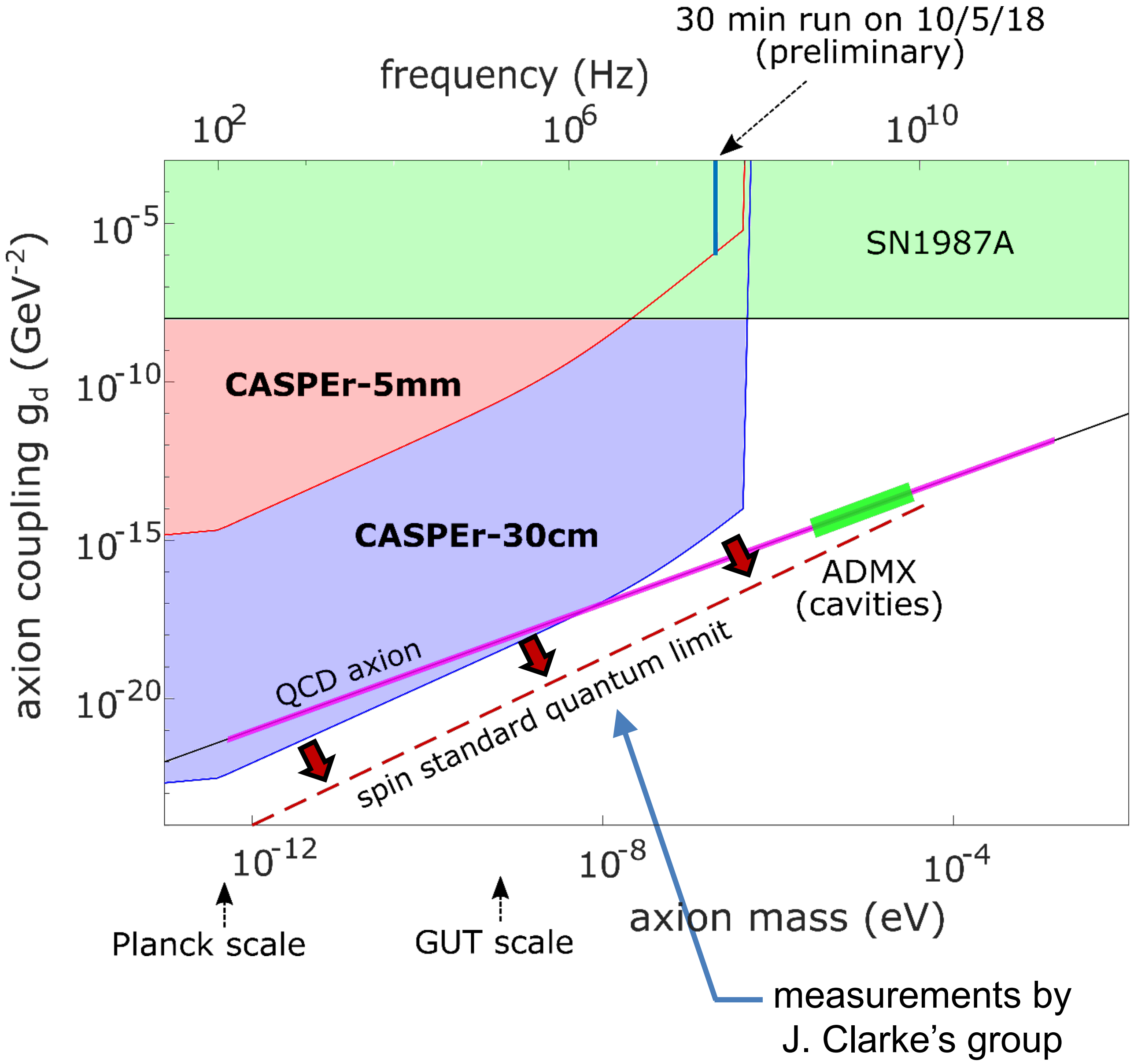
- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm
- pathfinder experiment operational at design sensitivity

CASPEr-30cm:

- thermal spin polarization, 300 mK
- 30 cm sample size,
- 15T magnet
- optimized magnetic sensor (with SLAC)
- sensitivity reaches QCD axion

Alexander Sushkov

The experimental reach of CASPEr-e



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

<u>CASPEr-5mm</u> at Boston University:

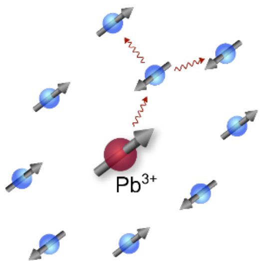
- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm
- pathfinder experiment operational at design sensitivity

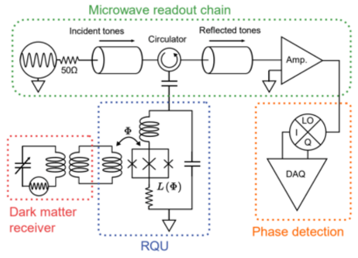
<u>CASPEr-30cm</u>:

- thermal spin polarization, 300 mK
- 30 cm sample size,
- 15T magnet
- optimized magnetic sensor (with SLAC)
- sensitivity reaches QCD axion

<u>ultimate sensitivity</u>:

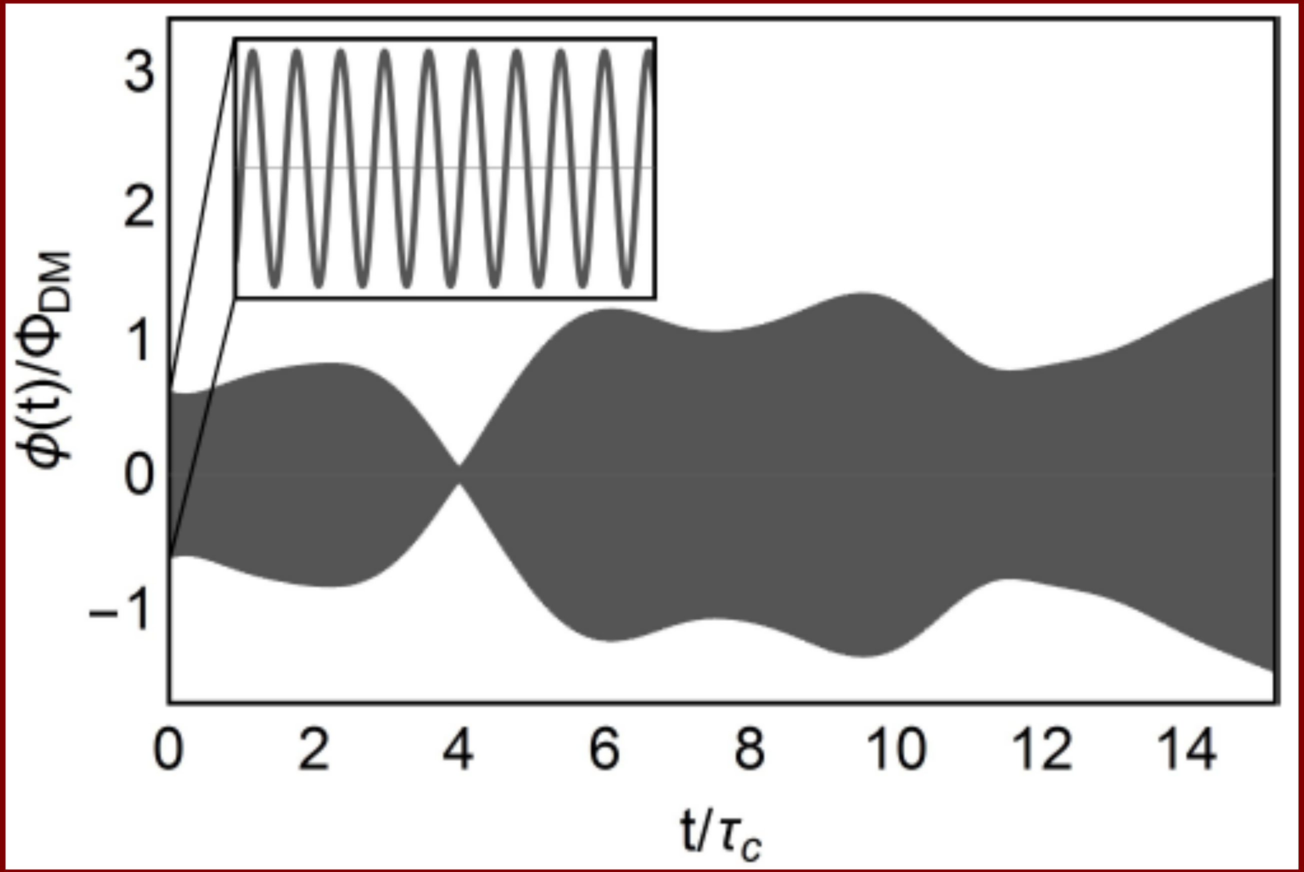
- spin standard quantum limit
- hyperpolarization, dynamical decoupling
- spin squeezing with RF resonant circuits? (with SLAC)





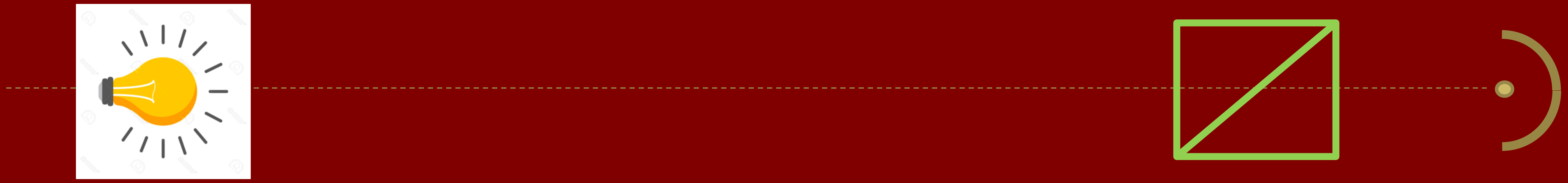
[*Phys. Rev. X* **4**, 021030 (2014)]

Stochastic nature of bosonic DM important for measurements not longer than coherence time

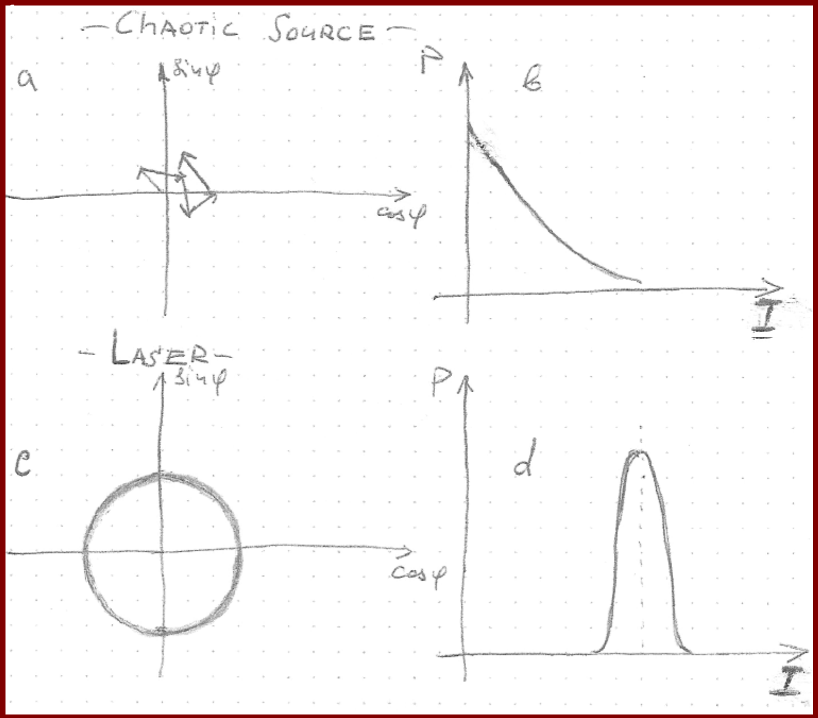


Gary P. Centers et al , **arXiv:1905.13650** (2019)

Analogy with chaotic light



- Q: What is the most probable instantaneous intensity ?
- A: zero



$$p(\mathrm{E}_s) \propto \exp\left\{-\frac{\mathrm{E}_s^2}{2N\mathrm{E}_0^2}\right\}d\mathrm{E}_s. \tag{5.26}$$

The combined probability distribution for the independent cosine and sine amplitudes is then

$$p(\mathrm{E}_c, \mathrm{E}_s) \propto \exp\left\{-\frac{\mathrm{E}_s^2+\mathrm{E}_c^2}{2N\mathrm{E}_0^2}\right\}d\mathrm{E}_s d\mathrm{E}_c = \exp\left\{-\frac{I}{\overline{I}}\right\}d\varphi \mathrm{E} d\mathrm{E}, \tag{5.27}$$

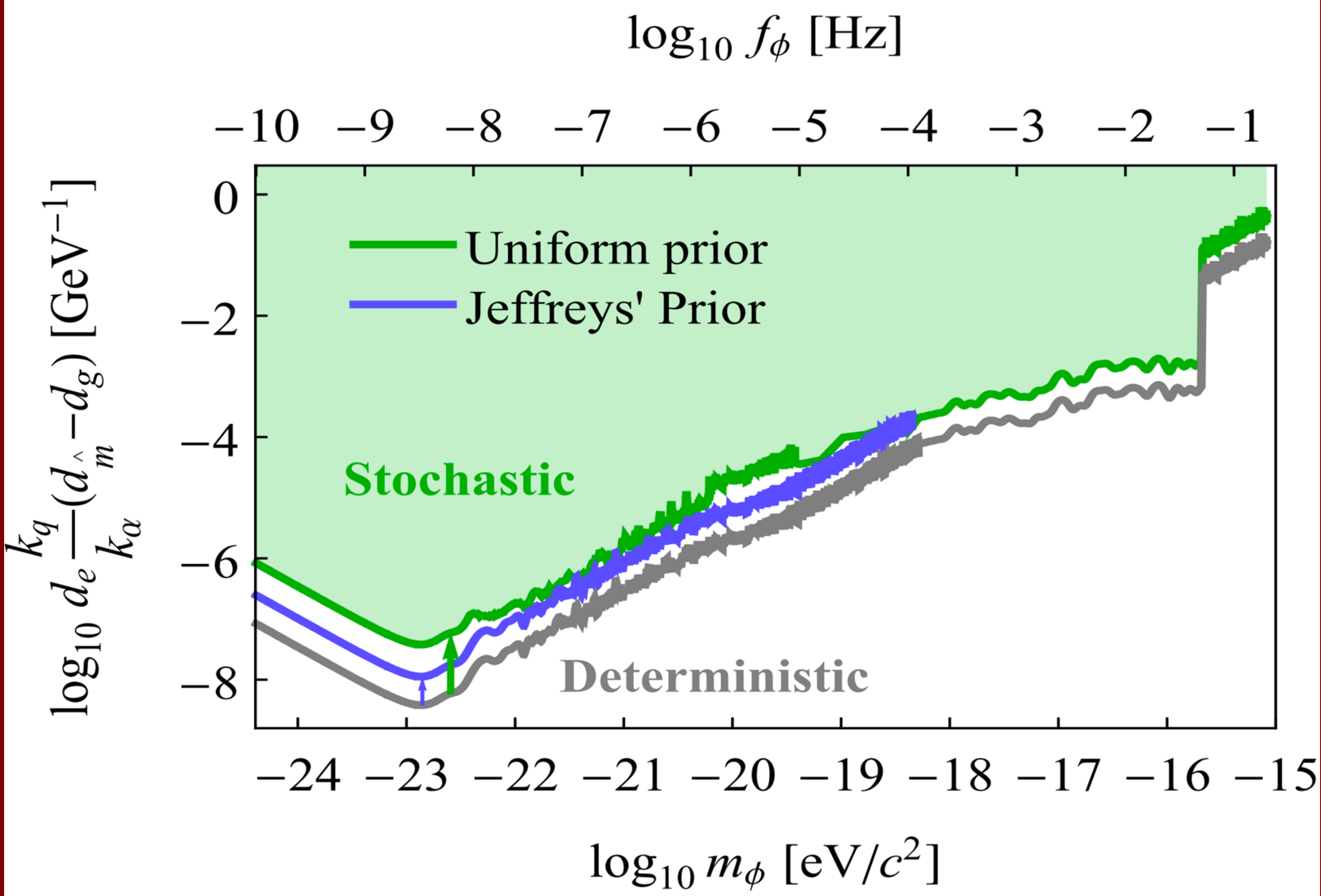
where we have introduced the instantaneous cycle-averaged intensity I, its mean value $\overline{I}$, the *phase angle* φ, and the total field amplitude E, which is non-negative.

We can now convert this into a distribution of cycle-averaged instantaneous intensity by integrating over φ and using the fact that $I \propto \mathrm{E}^2$, so, correspondingly, $dI \propto 2\mathrm{E}d\mathrm{E}$. With this, Eq. (5.27) becomes

$$p(I) \propto \exp\left\{-\frac{I}{\overline{I}}\right\}dI, \tag{5.28}$$

From: D. Budker and A. Sushkov *Physics on Your Feet*, OUP 2015

Significant effect on low-frequency DM searches



- Also velocity
  (magnitude and direction)

Gary P. Centers, John W. Blanchard, Jan Conrad, Nataniel L. Figueroa, Antoine Garcon, Alexander V. Gramolin, Derek F. Jackson Kimball, Matthew Lawson, Bart Pelssers, Joeseph A. Smiga, Yevgeny Stadnik, Alexander O. Sushkov, Arne Wickenbrock, Dmitry Budker, and Andrei Derevianko, *Stochastic fluctuations of bosonic dark matter*, arXiv:1905.13650 (2019)

Atomic clock searches for scalar DM

DILATON DM ?

Searching for dilaton dark matter with atomic clocks

Asimina Arvanitaki*

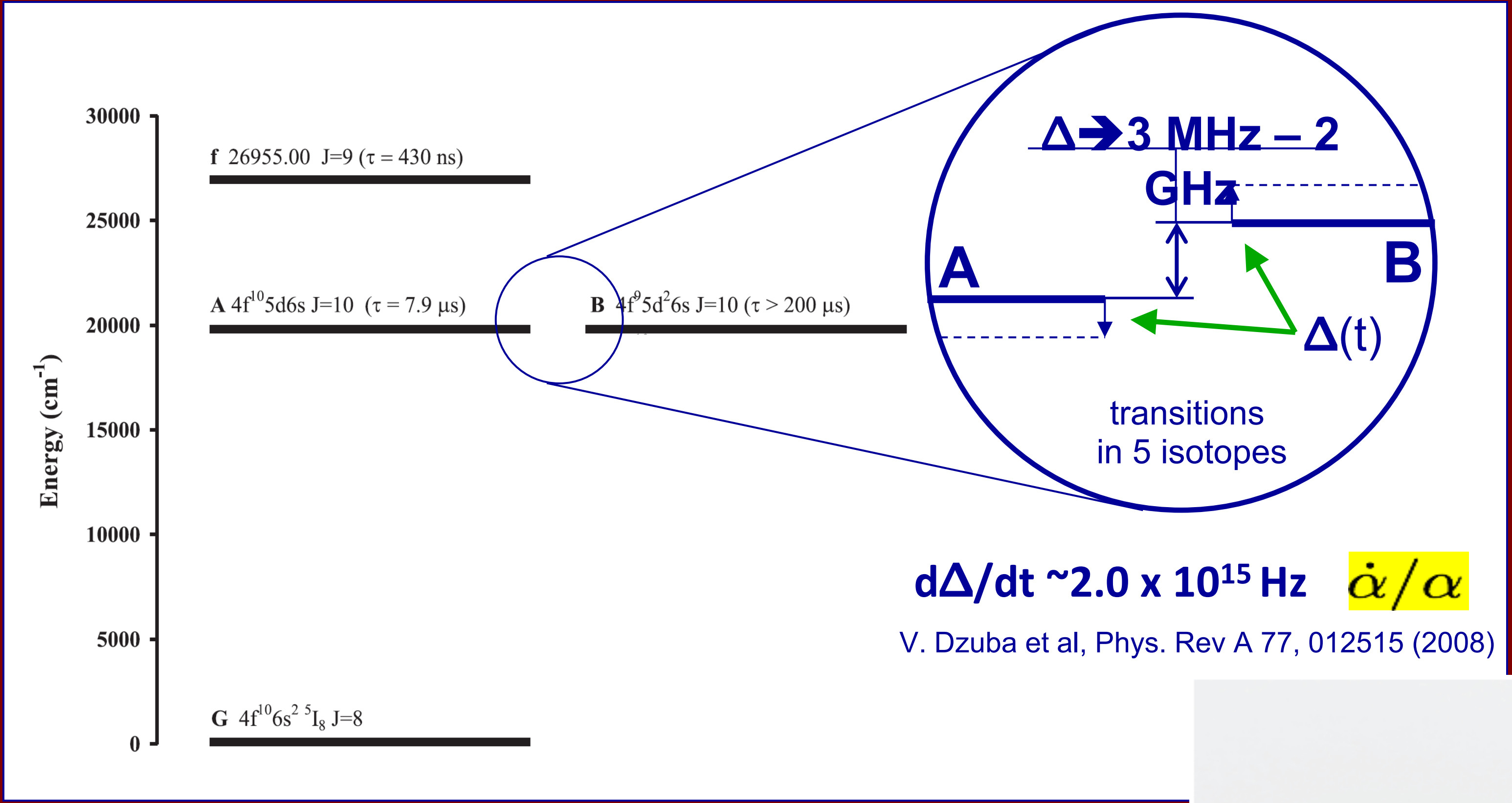
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

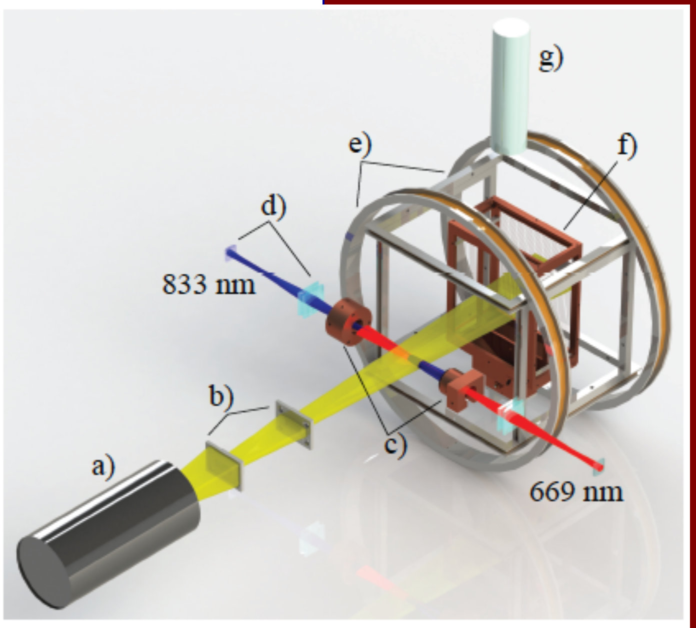
Junwu Huang† and Ken Van Tilburg‡

Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA

(Dated: May 14, 2014)

Dy as "Alpha Variometer"

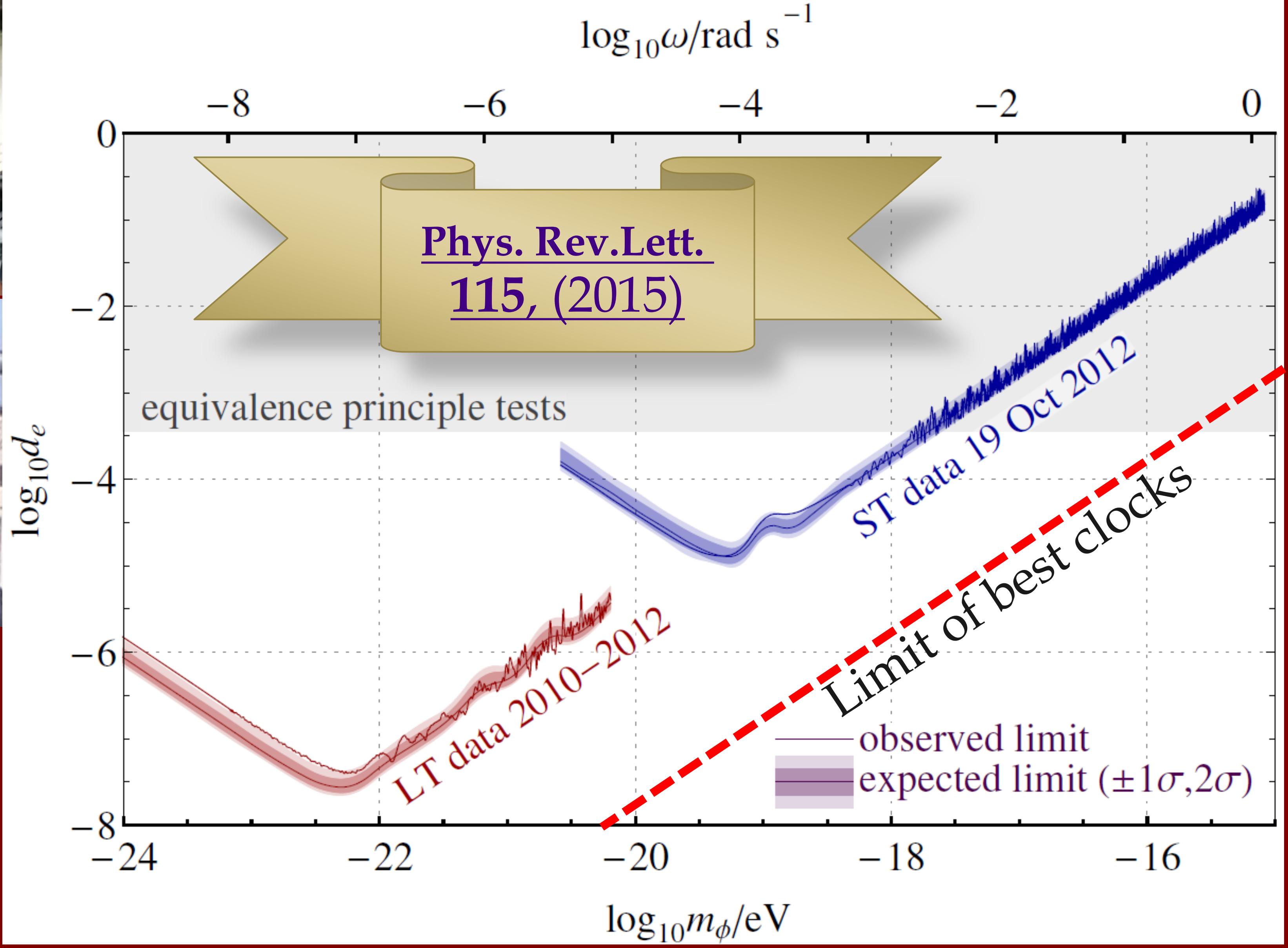




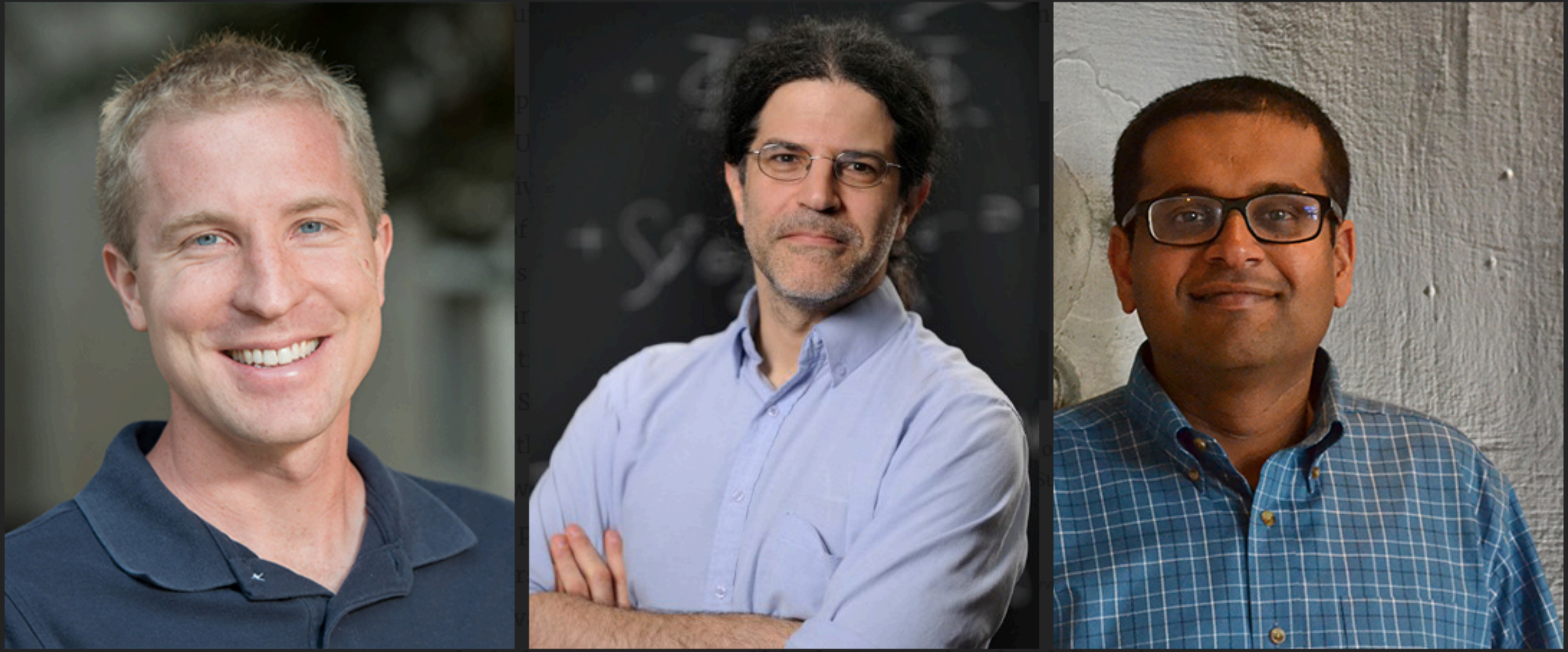
- Limits on alpha variation
- Dependence on gravitational potential
- Lorentz-Invariance violation (for electrons)
- …

Search for ultralight dark matter with dilaton-like photon couplings using atomic spectroscopy in dysprosium

Ken Van Tilburg,[1,*] Nathan Leefer,[2,†] Lykourgos Bougas,[2,‡] and Dmitry Budker[2,3,4,§]



Relaxions in the dark



From left: Peter Graham of Stanford University, David Kaplan of Johns Hopkins University and Surjeet Rajendran of the University of California, Berkeley.

—

Linda A. Cicero/Stanford News Service, Will Kirk/Johns Hopkins University, Sarah Wittmer

Gilad Perez
Weizmann Institute

RELAXION

- Relaxion => solves hierarchy and strong CP problems

  Graham, Kaplan & Rajendran (15); Hook,Marques-Tavares; Gupta, Komargodski, Perez & Ubaldi (16); Davidi, Gupta, Perez, Redigolo & Shalit; Gupta; Nelson & Prescod-Weinstein (17)

- Axion-like particle but mixes with the Higgs => has scalar interactions

  Flacke, Frugiuele, Fuchs, Gupta & Perez; Choi & Im (16)

- Minimal model provides viable axion-like dark matter (DM); for:

$$10^{-10}\text{eV} \lesssim m_{\phi\equiv\text{relax}} \lesssim 10^{-3}\text{eV}$$

  Banerjee, Kim & Perez (18)

- DM can form stars & halos around Earth \w large over densities

Relaxion stars and their detection via atomic physics
Abhishek Banerjee, Dmitry Budker, Joshua Eby, Hyungjin Kim & Gilad Perez
COMMUNICATIONS PHYSICS (2020) 3:1 arXiv:1902.08212

FAST OSCILLATING SCALAR DM

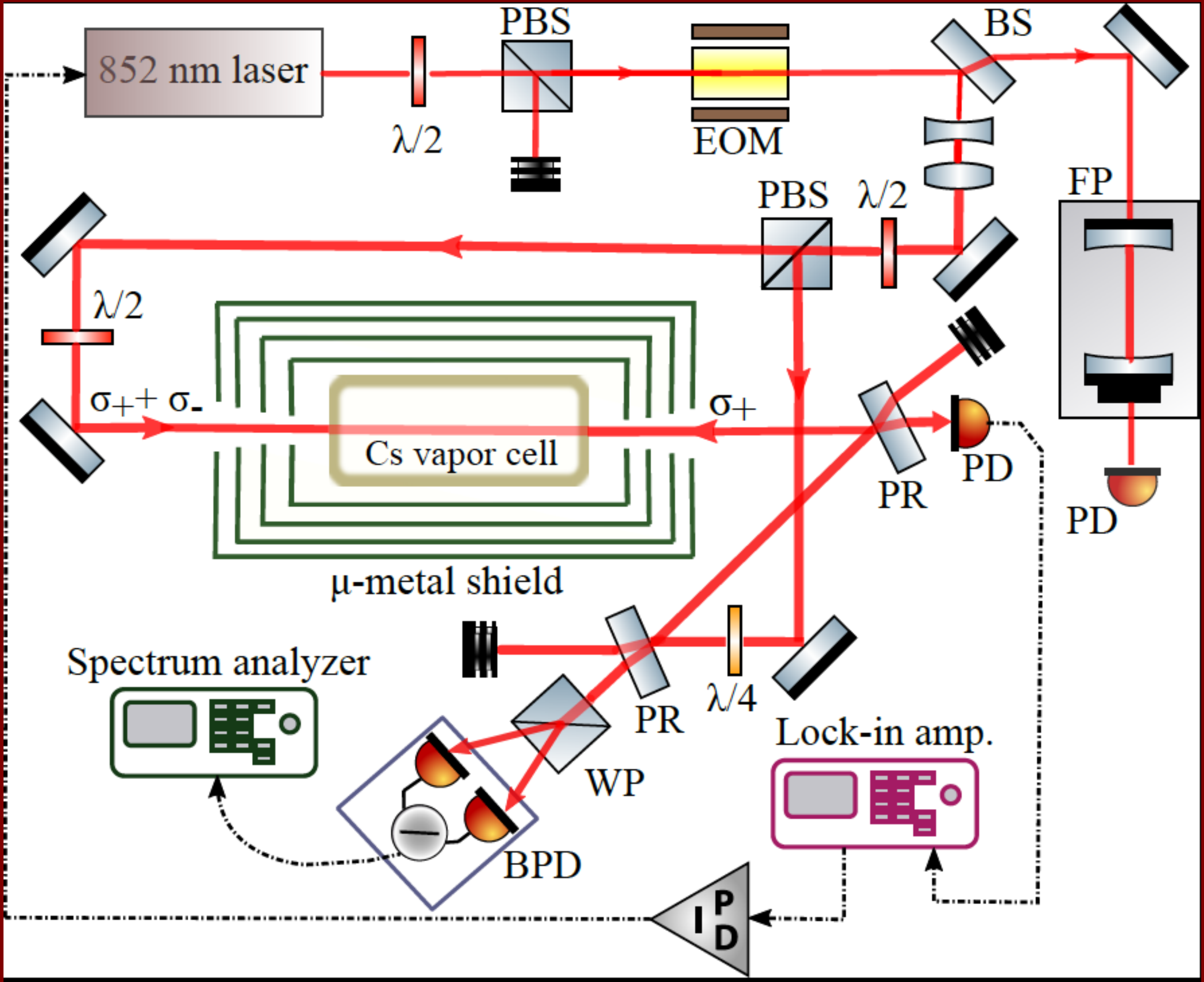
Weekend Relaxion e Search Laboratory

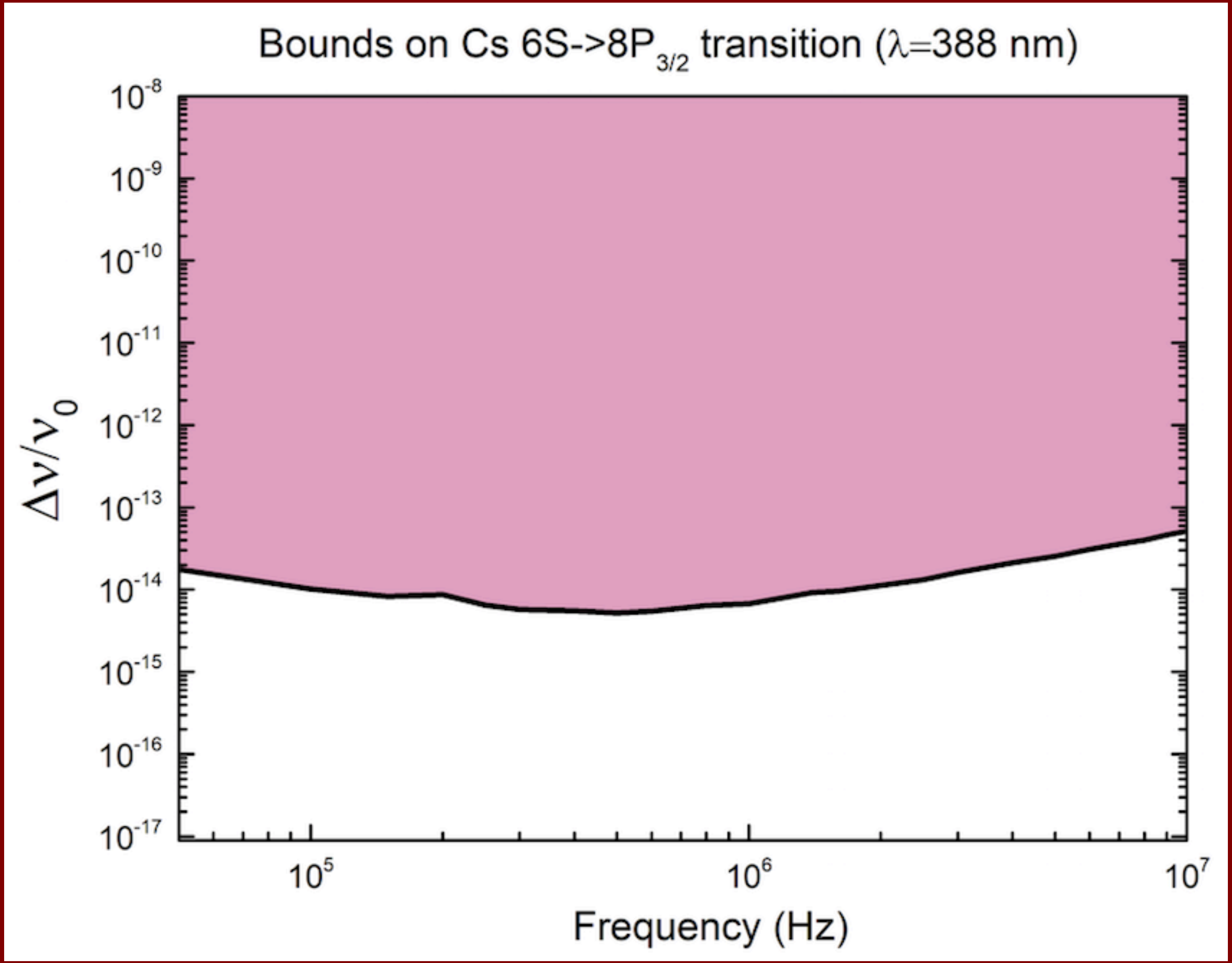
Fast changing “constants” ?

- Jun Ye *et al*: cavity-clock comparison
- Even faster: A “weekend” experiment @ Mainz ?



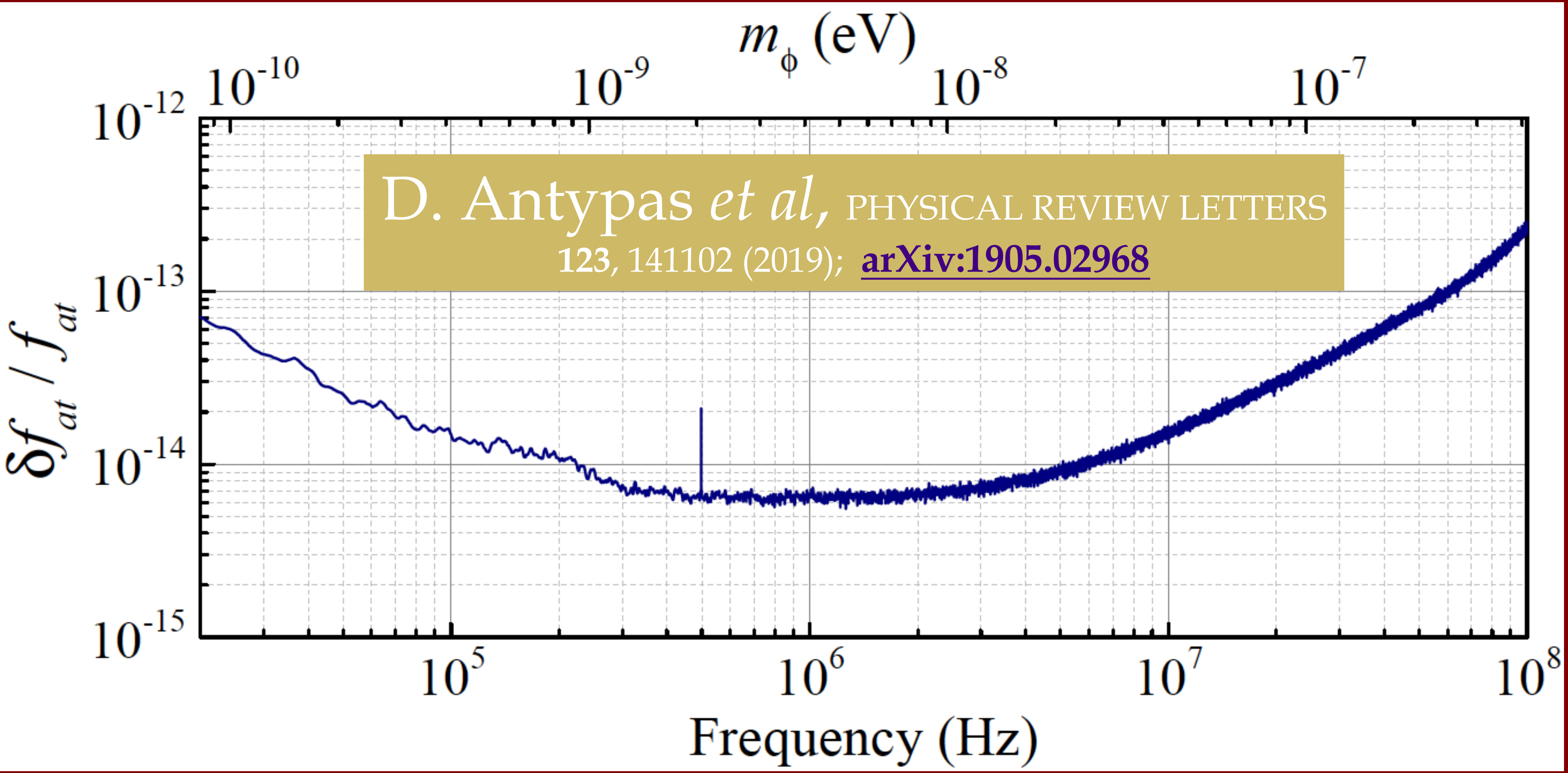

Dr. Dionysis Antypas	**Oleg Tretiak**	**Prof. Roee Ozeri**	**Antoine Garcon**
Helmholtz Institute, JGU Mainz	HIM, JGU Mainz	Weizmann Institute	HIM, JGU Mainz


852 nm laser
λ/2
PBS
EOM
BS
FP
PBS
λ/2
λ/2
σ+ + σ-
σ+
Cs vapor cell
μ-metal shield
PR
PD
PD
PR
λ/4
Spectrum analyzer
WP
BPD
Lock-in amp.
P
I
D



* Sensitive to variation of **α** and m_e $2d_\alpha + d_{m_e}$

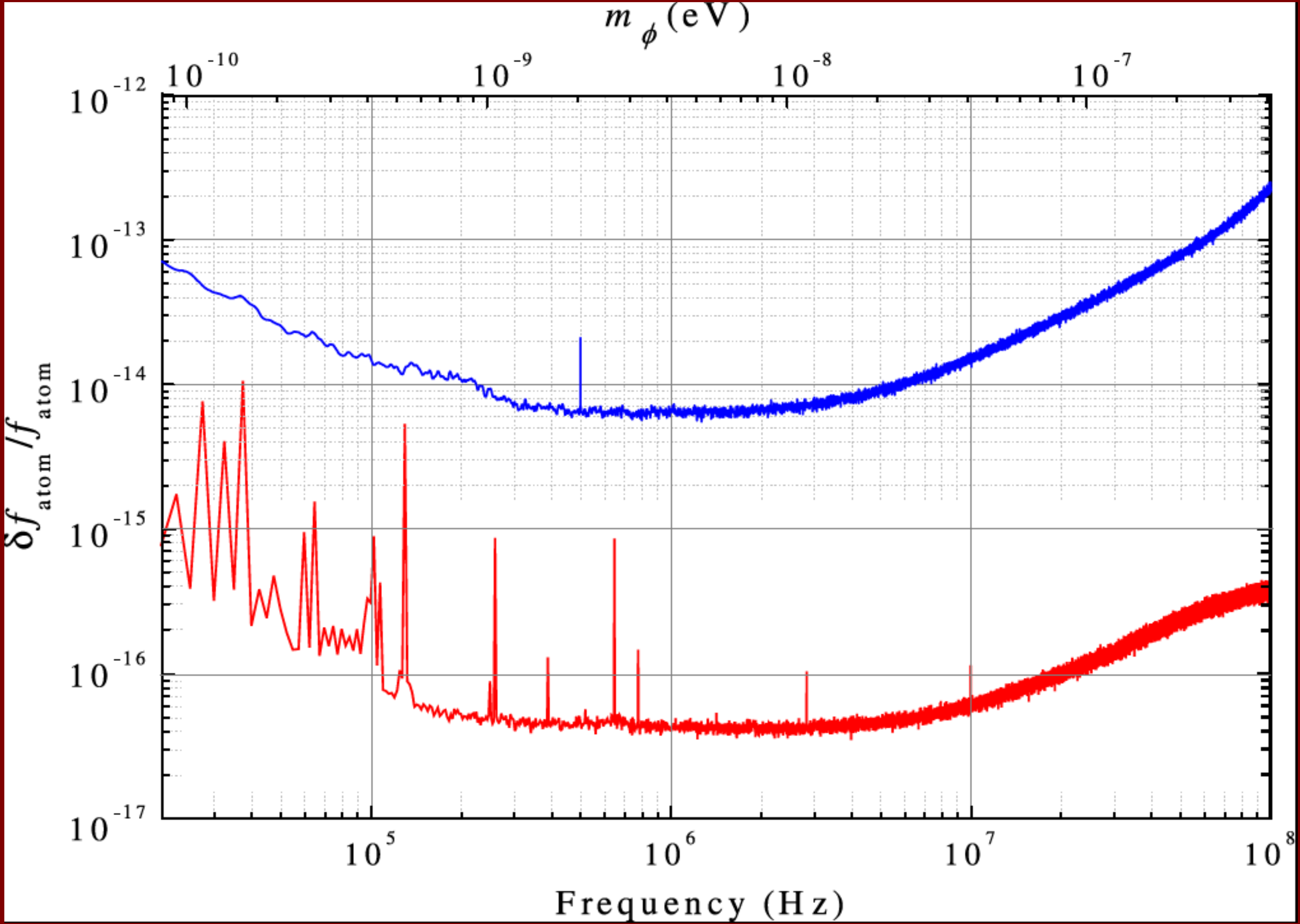
Cs D2 line (852 nm)



D. Antypas *et al*, PHYSICAL REVIEW LETTERS **123**, 141102 (2019); [**arXiv:1905.02968**]

* Sensitive to variation of **α** and m_e $2d_\alpha + d_{m_e}$

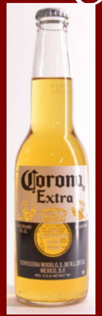
WReSL - 2



WRESL-1

WReSL-2 (preliminary)

- 500 s averaging
- Planning a 13+ hr run after



Fast Variation of Fundamental "Constants"

- Dionysios Antypas, Dmitry Budker, Victor V. Flambaum, Mikhail G. Kozlov, Gilad Perez, and Jun Ye,

  ANNALEN DER PHYSIK 2020, 1900566; arXiv:1912.01335
- Old thinking: only *dimensionless* constants may vary
- New thinking: $m_e / < m_e >$; $\boldsymbol{\alpha} / < \boldsymbol{\alpha} >$, ... are OK
- Origin of apparent variations: bosonic fields
- BSM (and BBSM) physics is tricky!

$$\mathcal{L}_{\text{free}} = -\frac{1}{4\alpha} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \left(\partial_\mu \varphi \, \partial^\mu \varphi - m^2 \varphi^2 \right) + \mathcal{L}_{\text{kin}}^{\text{SM}} - \sqrt{2} \frac{m_e}{v} H \bar{L}_e e_R + h.c. - \mu^2 H^\dagger H + \lambda \left(H^\dagger H \right)^2 + \mu_{\phi h} \phi H^\dagger H$$

Network searches for topological DM

Global **N**etwork of **O**ptical **M**agnetometers for **E**xotic searches

Idea and proof-of-concept: Annalen der Physik **525**(8-9), 659–70 (2013); Phys. Rev. Lett. **110**, 021803 (2013)

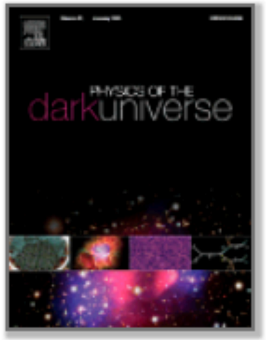
System description: Physics of the Dark Universe **22**, 162-180 (2018), **arXiv:1807.09391**

- Network of shielded, GPS-synchronized magnetometers + clocks, interferometers,...
- Sensitive to **topological Dark Matter**: domain walls, axion (ALP) stars, Phys. Rev. D (2018)
- Multi-messenger astronomy (e.g., look for ALPs from sources of gravitational waves)
- Sensor-correlation techniques resembling those of LIGO/Virgo
- Status: Science Run 2 complete, results to be announced; Run 3: ongoing

GNOME NETWORK 2017

Physics of the Dark Universe

Volume 28, May 2020, 100494

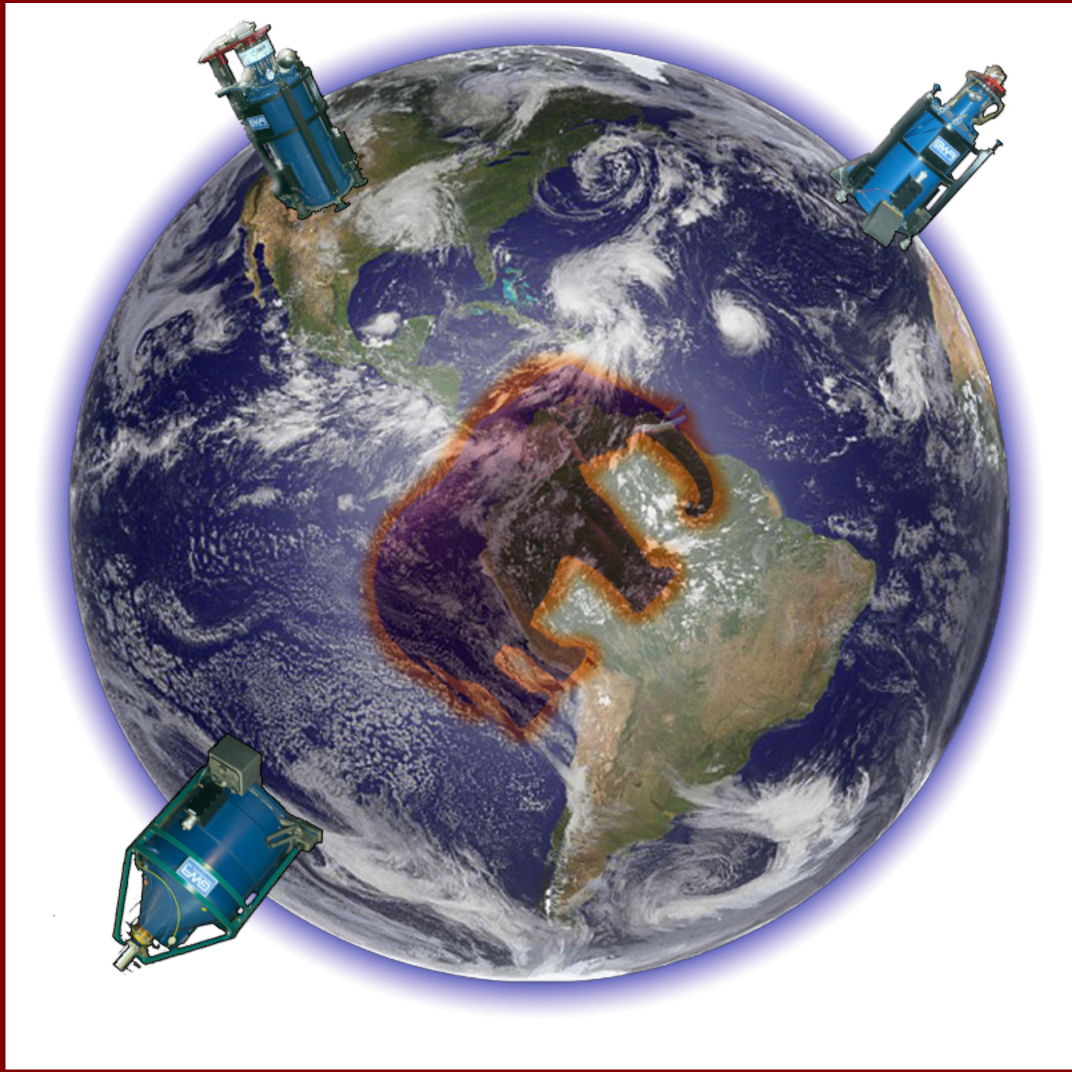


Analysis method for detecting topological defect dark matter with a global magnetometer network

arXiv:1912.08727

Hector Masia-Roig [a], Joseph A. Smiga [a], Dmitry Budker [a, b, c], Vincent Dumont [b], Zoran Grujic [d], Dongok Kim [e, f], Derek F. Jackson Kimball [g], Victor Lebedev [d], Madeline Monroy [g], Szymon Pustelny [h], Theo Scholtes [d, i, 1], Perrin C. Segura [j], Yannis K. Semertzidis [e, f], Yun Chang Shin [e], Jason E. Stalnaker [j], Ibrahim Sulai [k], Antoine Weis [d], Arne Wickenbrock [a]

Hypothetical Internal Object search with superconducting gravimeters



A network of superconducting gravimeters as a detector of matter with feeble nongravitational coupling

arXiv:1912.01900

Wenxiang Hu[1], Matthew Lawson[2,3], Dmitry Budker[3,4], Nataniel L. Figueroa[3], Derek F. Jackson Kimball[5], Allen P. Mills Jr.[6], and Christian Voigt[7]

- Tunnel-through-the-Earth problem (*T*≈80 min)
- Generalization to

Hypothetical Internally Orbiting matter (HIO)

- Earth is NOT of uniform density
- Small amplitude, near center:

$$T = \frac{2\pi}{\omega_h} = \frac{2\pi}{\sqrt{\frac{4\pi}{3} G\rho_0}} \approx 55\,\mathrm{min}$$

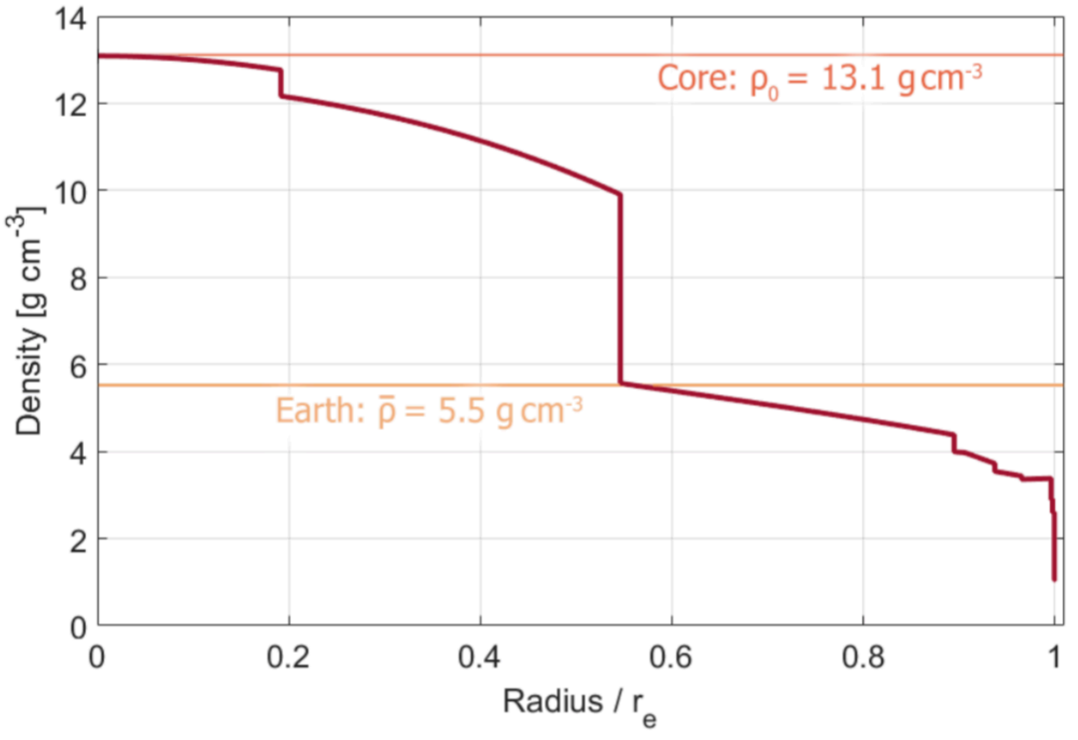


Figure 1: The density profile of the Earth based on the Preliminary Reference Earth model (PREM) [5]. $r_e = 6371$ km is the mean radius of the Earth, $\bar{\rho} = 5.51\,\mathrm{g\,cm^{-3}}$ is the average density of the Earth, and $\rho_0 = 13.1\,\mathrm{g\,cm^{-3}}$ is the density at the Earth's center.

Gravimeter Network

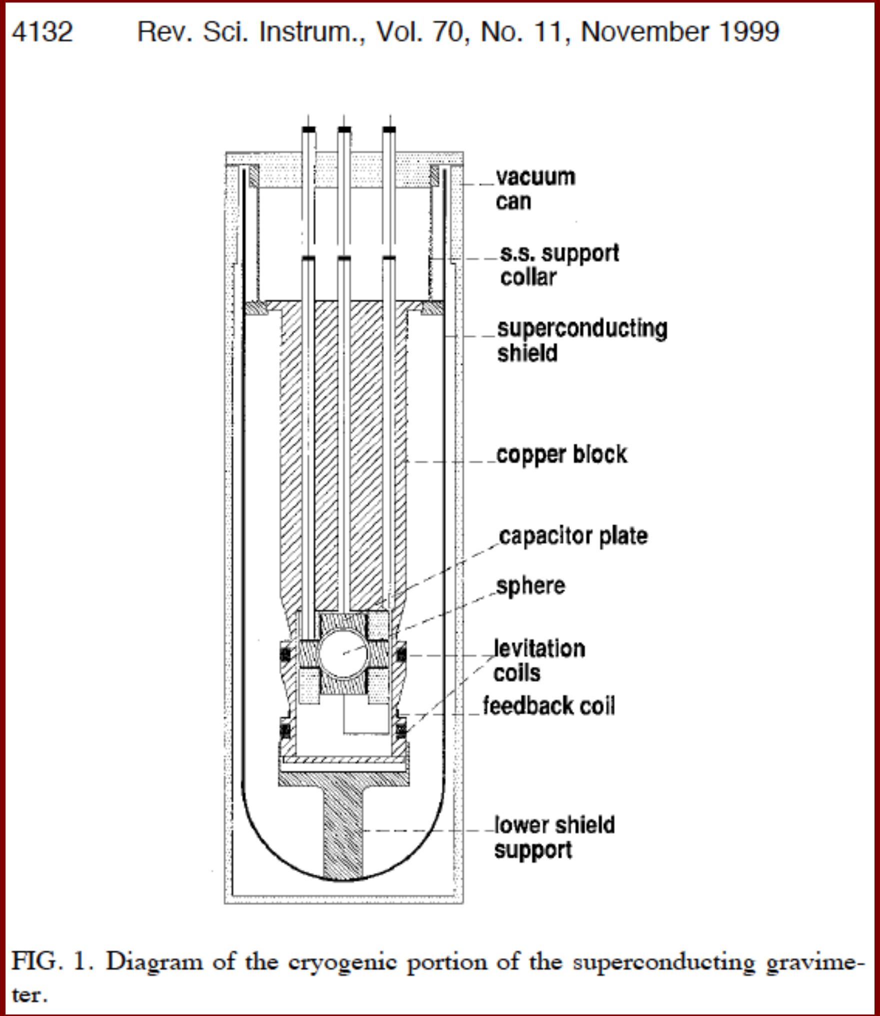


FIG. 1. Diagram of the cryogenic portion of the superconducting gravimeter.

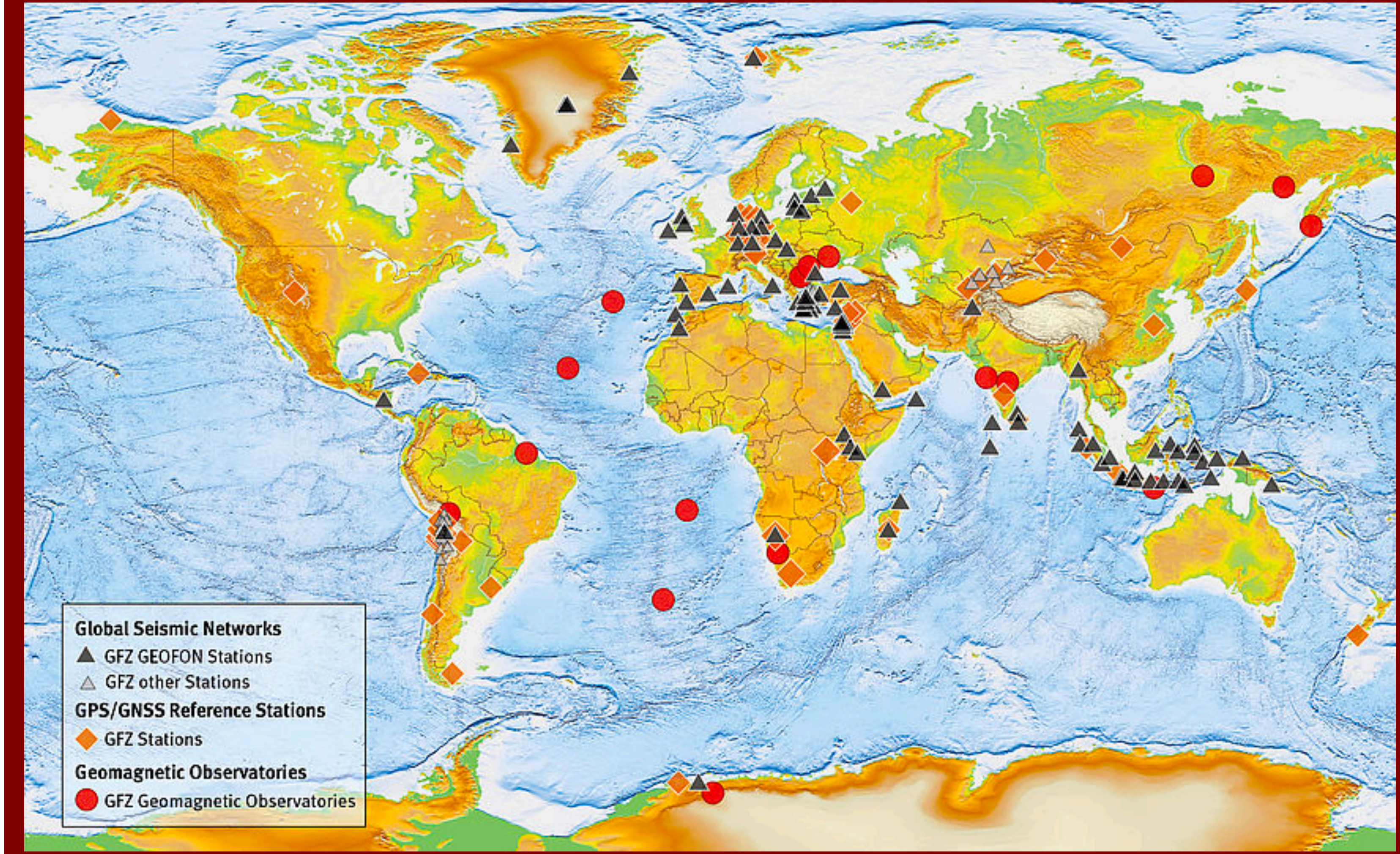


Figure credit: https://www.gfz-potsdam.de/en/scientific-infrastructure/research-infrastructures/global-observatories/

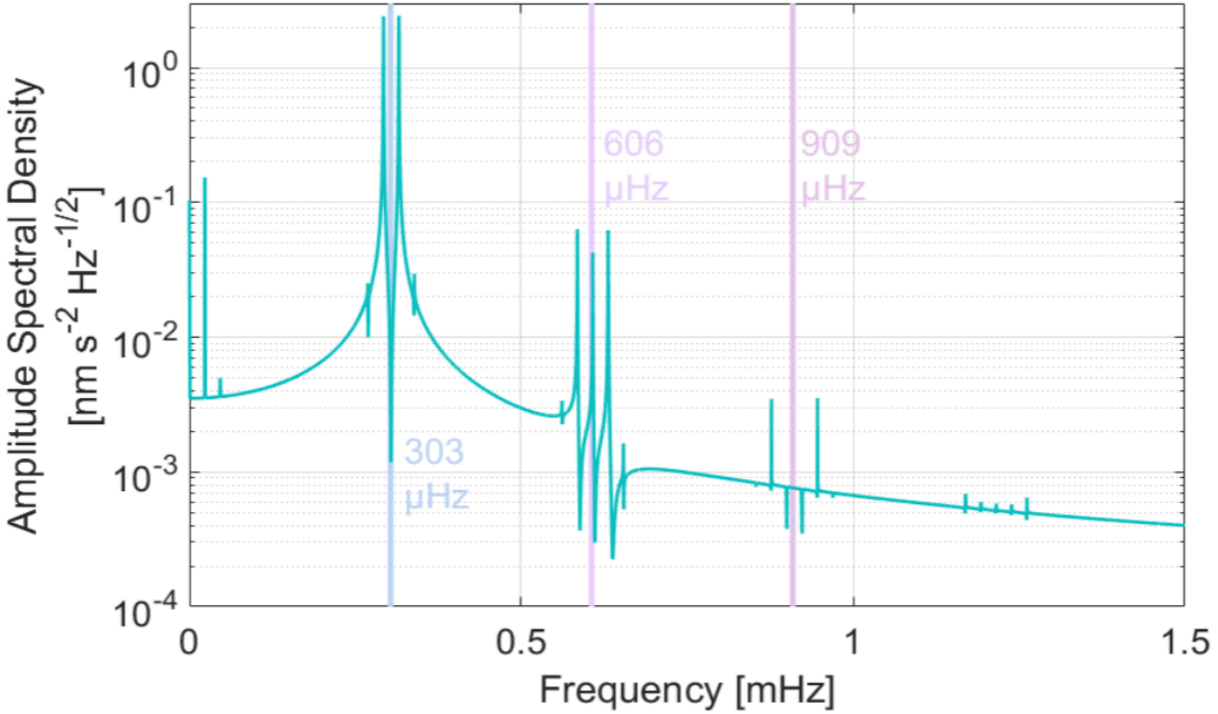


Figure 3: The theoretical spectrum of the HIO orbiting near the center of the Earth, the supposed mass of HIO here is 10^{16} kg, and the amplitude of the oscillation is $0.1\,r_e$. In the spectrum, there are signals centered near the first (around $303\,\mu$Hz) and higher (around $606\,\mu$Hz and $909\,\mu$Hz) harmonics due to the non-linearity of the force. Rotation of the Earth (seen as a small lowest-frequency peak) also leads to splitting of the first- and second-harmonic lines.

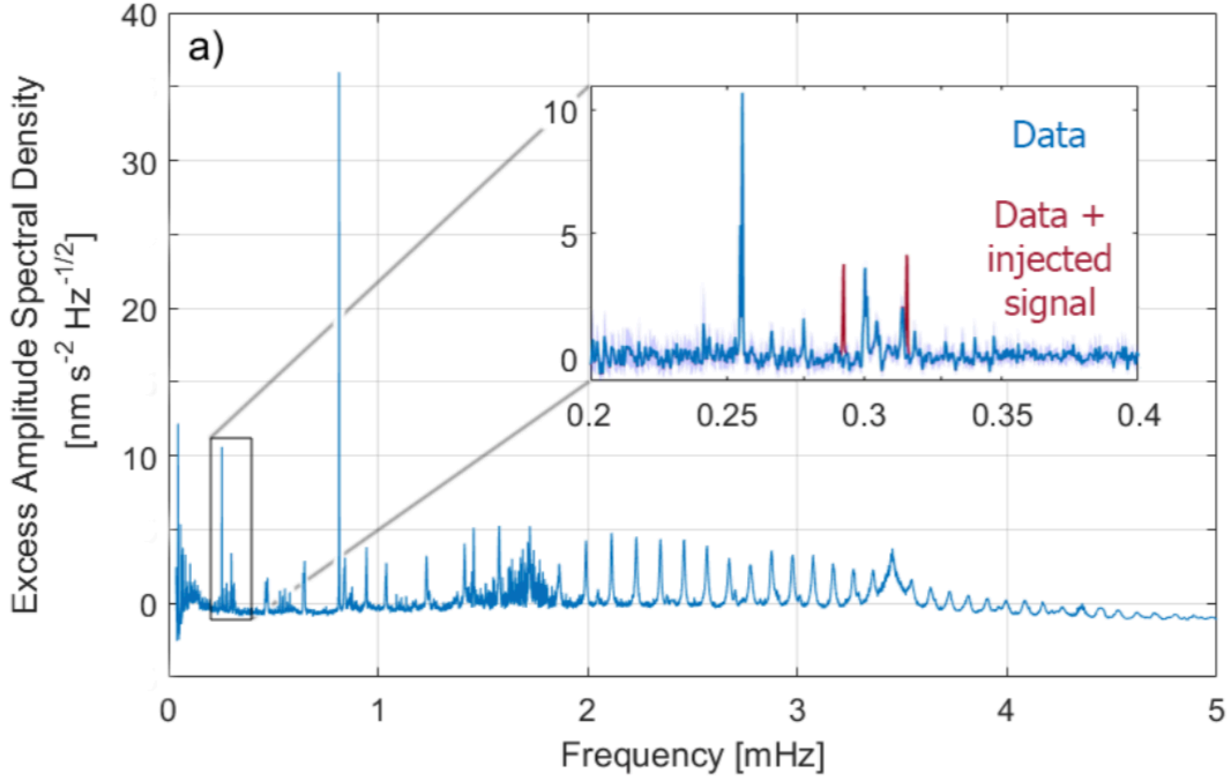


Figure 4: (a) The amplitude spectral density of the IGETS level 3 data sets, with baseline removal performed after the averaging. The large spike around $800\,\mu$Hz is due to the $_0S_0$ "breathing" mode of Earth [22, 2, 23]. The inset (b) shows details around $303\,\mu$Hz, where the signal from a HIO orbiting near the center of the Earth would lie. The dark red line corresponds to the data with the minimum-detectable signal ($m = 10^{14}$ kg) injected into it.

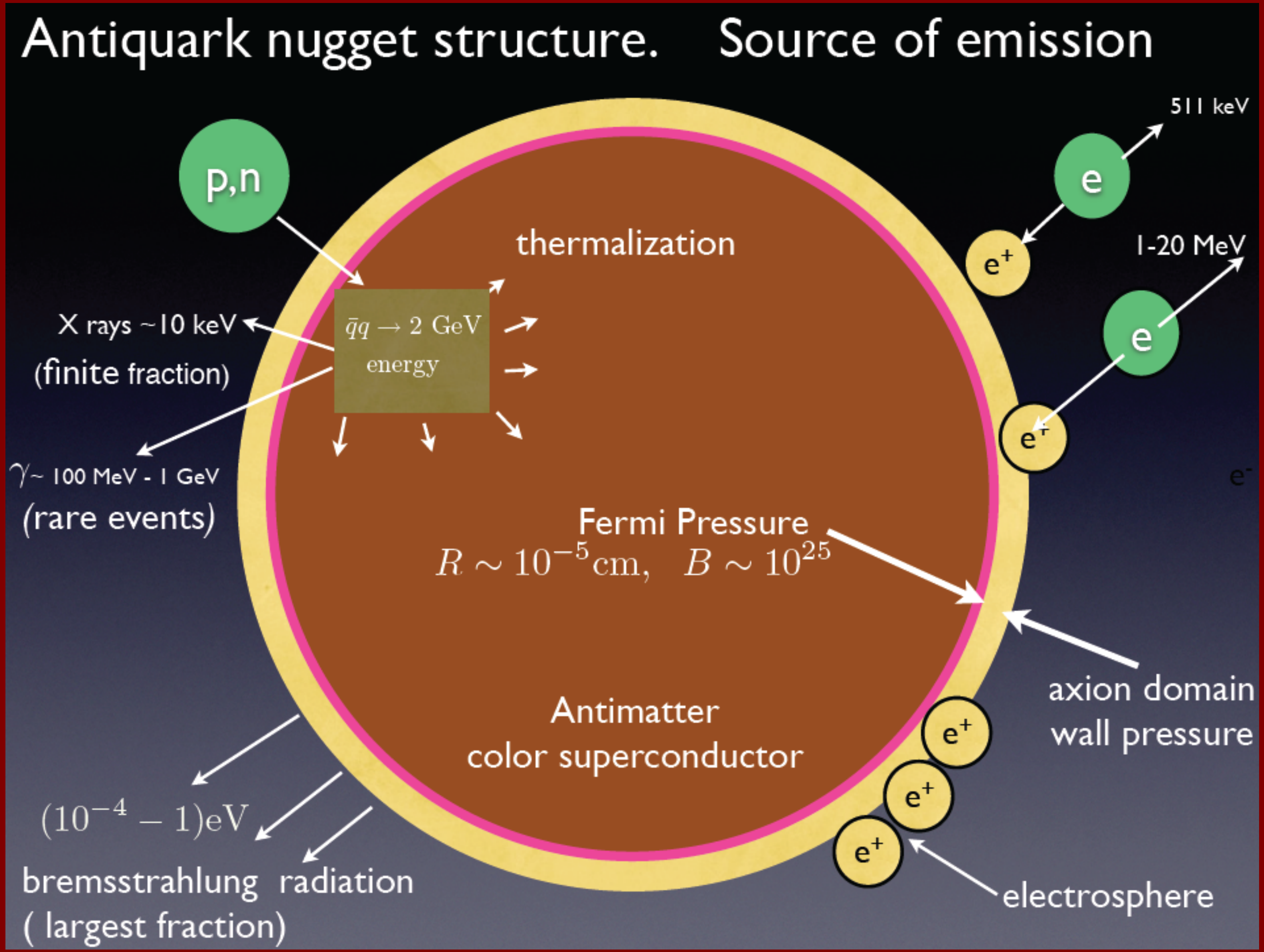
See also: C. J. Horowitz and R. Widmer-Schnidrig
Gravimeter Search for Compact Dark Matter Objects Moving in the Earth
Phys. Rev. Lett. **124**, 051102 (2020)

Axion Quark Nuggets

A radically different framework

Ariel Zhitnitsky

DFSZ (Dine–Fischler–Srednicki–Zhitnitsky)



No BSM physics (except the axion) and they explain everything ?

PHYSICAL REVIEW D **101,** 043012 (2020)

Axion quark nuggets and how a global network can discover them

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https://arxiv.org/abs/2003.07363

Axion Quark Nuggets. SkyQuakes and Other Mysterious Explosions

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AQN detected?

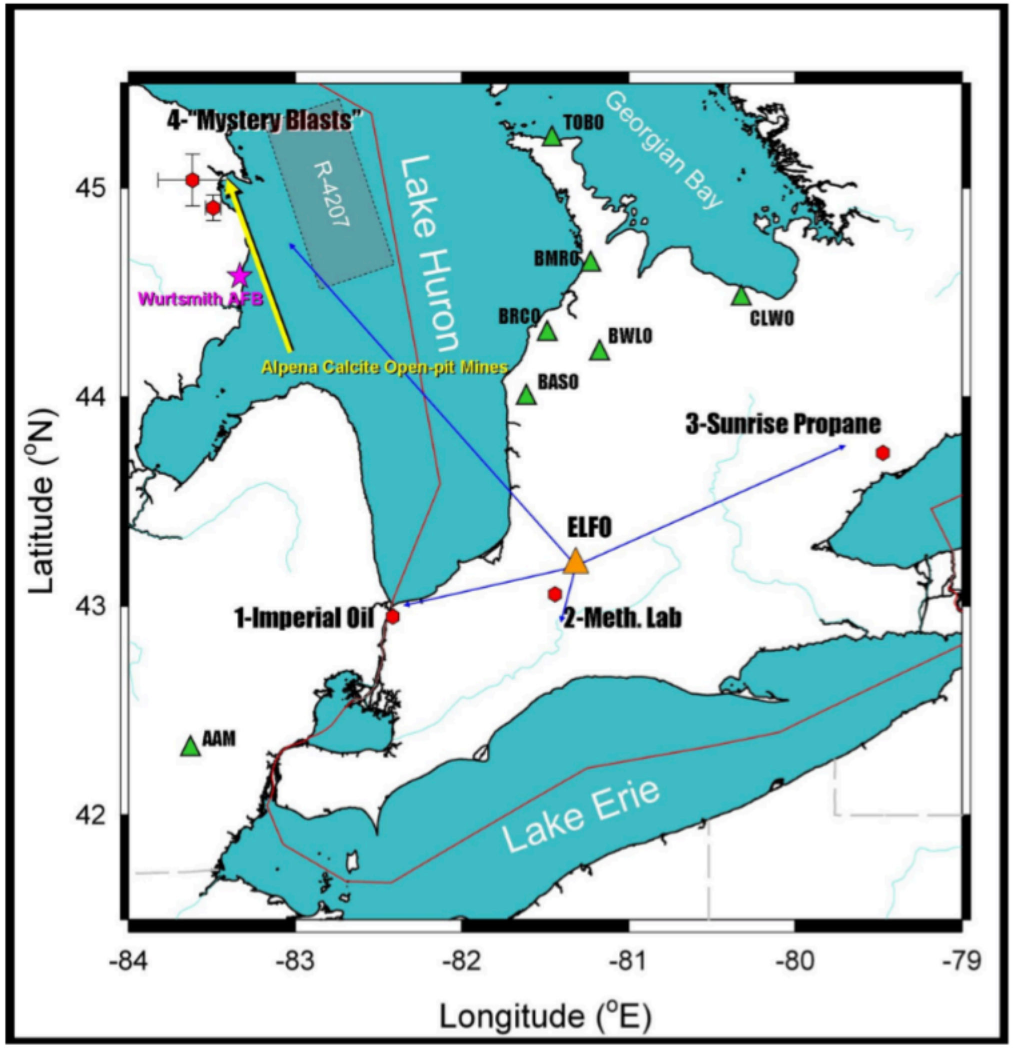


FIG. 1. Location of ELFO and seismic stations in the area, adopted from [4]. One degree along the latitude corresponds to 112 km. i.e. $1^0 \approx 112$ km, while along the longitude $1^0 \approx 82$ km. It explains our benchmark 300 km in eqs. (29) and (30) which covers the relevant area shown on the map.

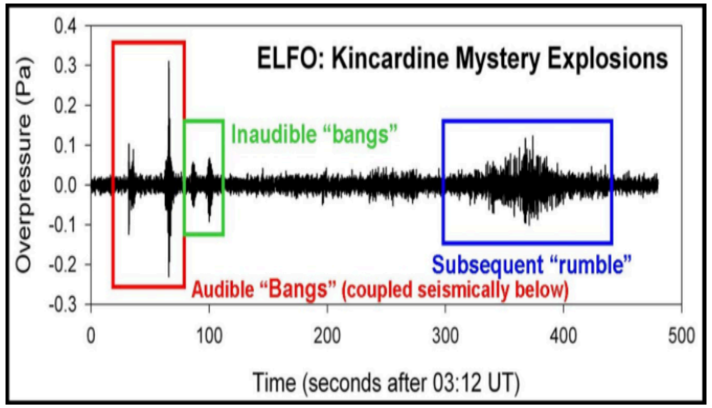
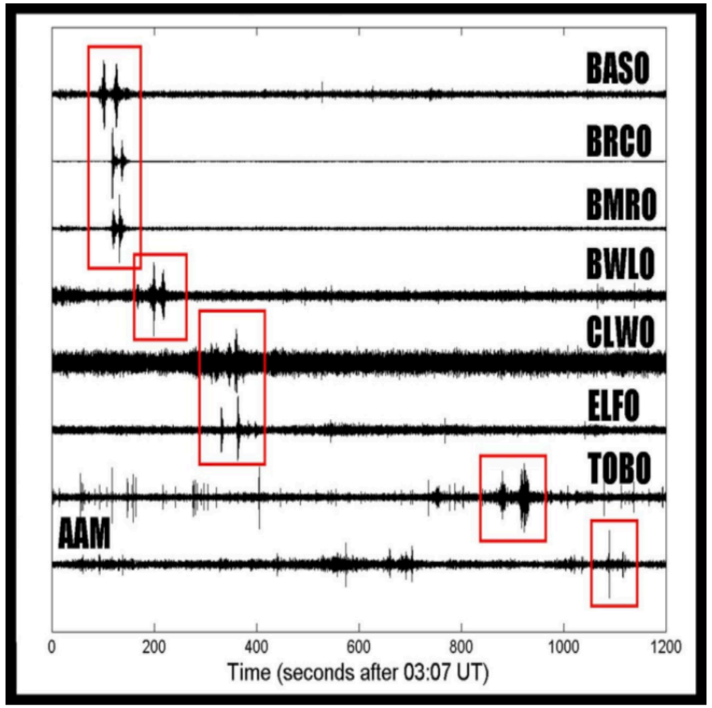


Figure 4a (observed blast)

Acoustic



reenshot

Figure 4b

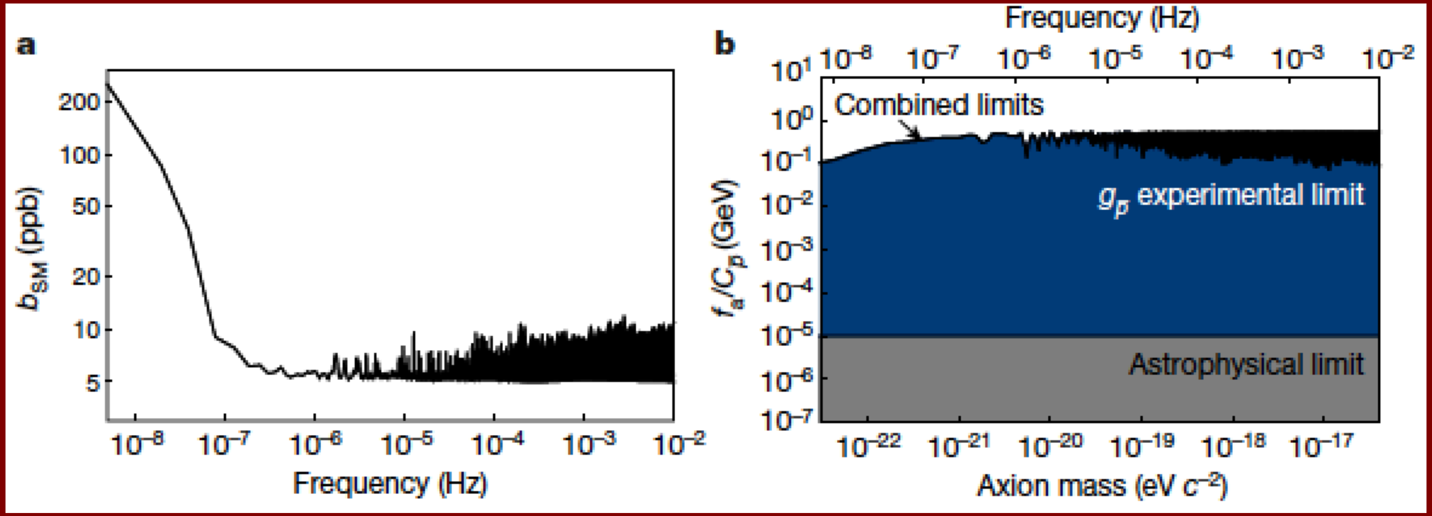
Seismic

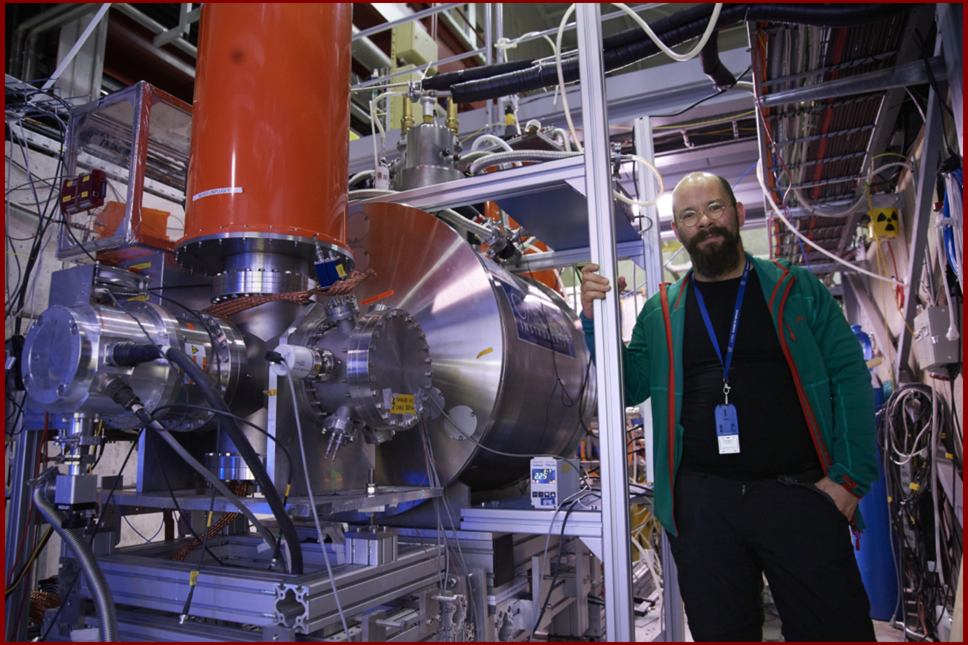
Dark Matter search with antimatter

Dark-matter search with antimatter !

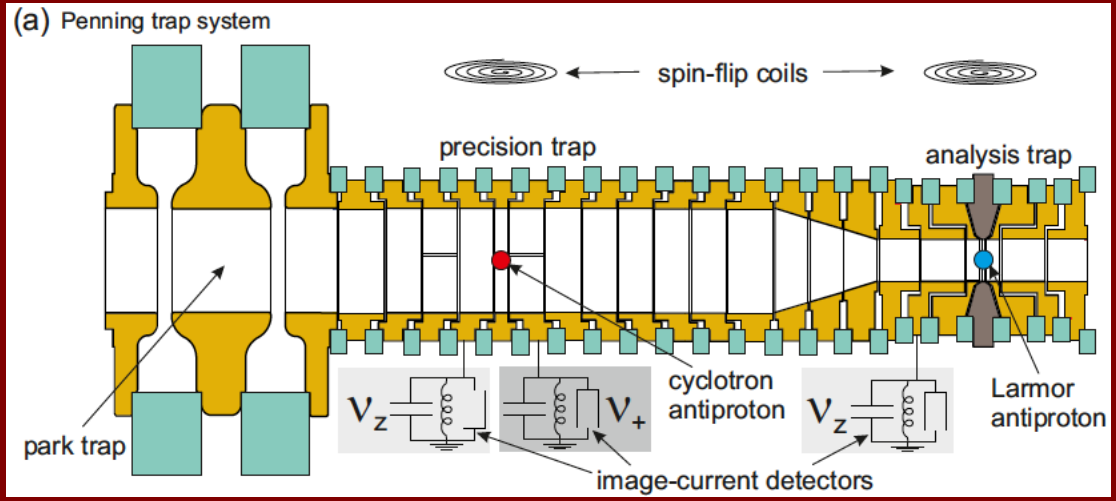
Direct limits on the interaction of antiprotons with axion-like dark matter

310 | Nature | Vol 575 | 14 November 2019





Stefan Ulmer



Ch. Smorra

Y. Stadnik

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

More developing stories...

Novel MASER for DM searches:

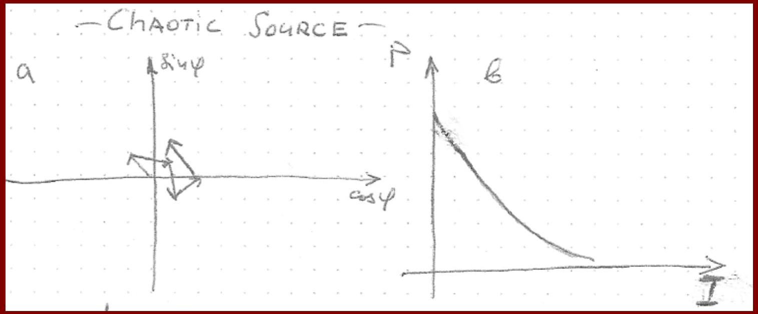
Min Jiang *et al*, Floquet-state Maser under Real-time Quantum Feedback Control, **arXiv:1901.00970**

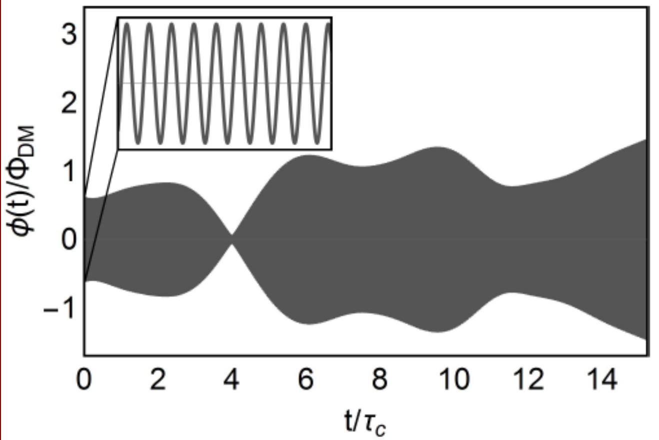
Guide to indirect new-particle searches :

Pavel Fadeev *et al*, Revisiting spin-dependent forces mediated by new bosons: Potentials in the coordinate-space representation for macroscopic- and atomic-scale experiments, **Phys. Rev. A** **99**, 022113 (2019)

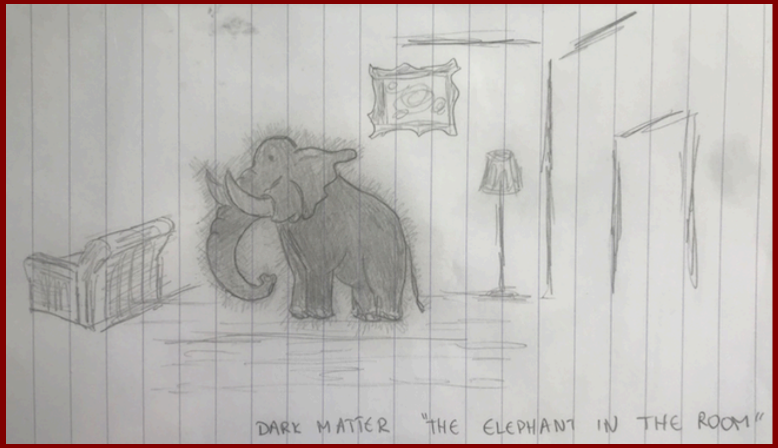
Summary

Ultralight bosonic DM is similar to chaotic light

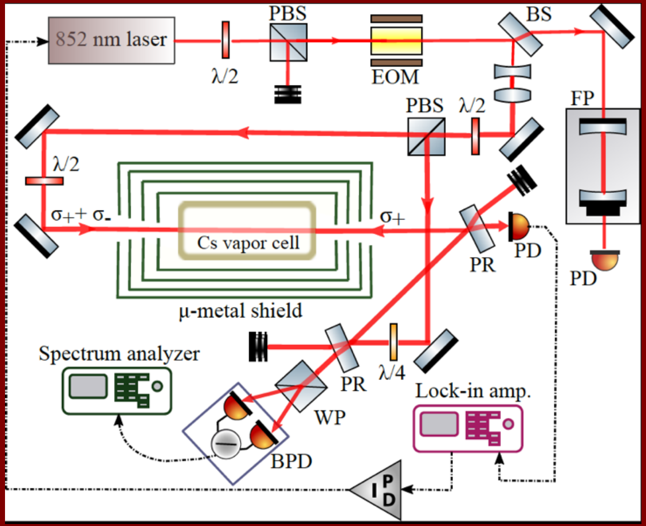




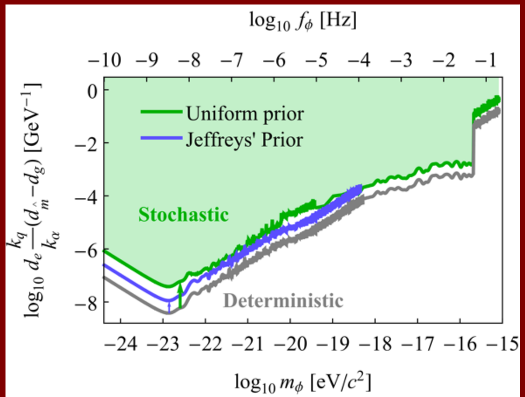
Elephants…



Recent DM searches with (anti)matter



Fluctuations affect DM searches



Gravimeters!

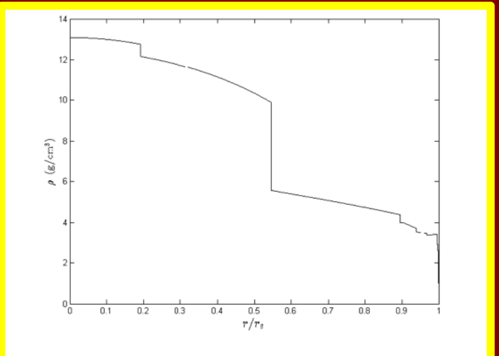


Figure 1: The density profile of the Earth based on the Preliminary Reference Earth model (PREM) [1]. r_e is the radius of the Earth.

Antiquark Nuggets