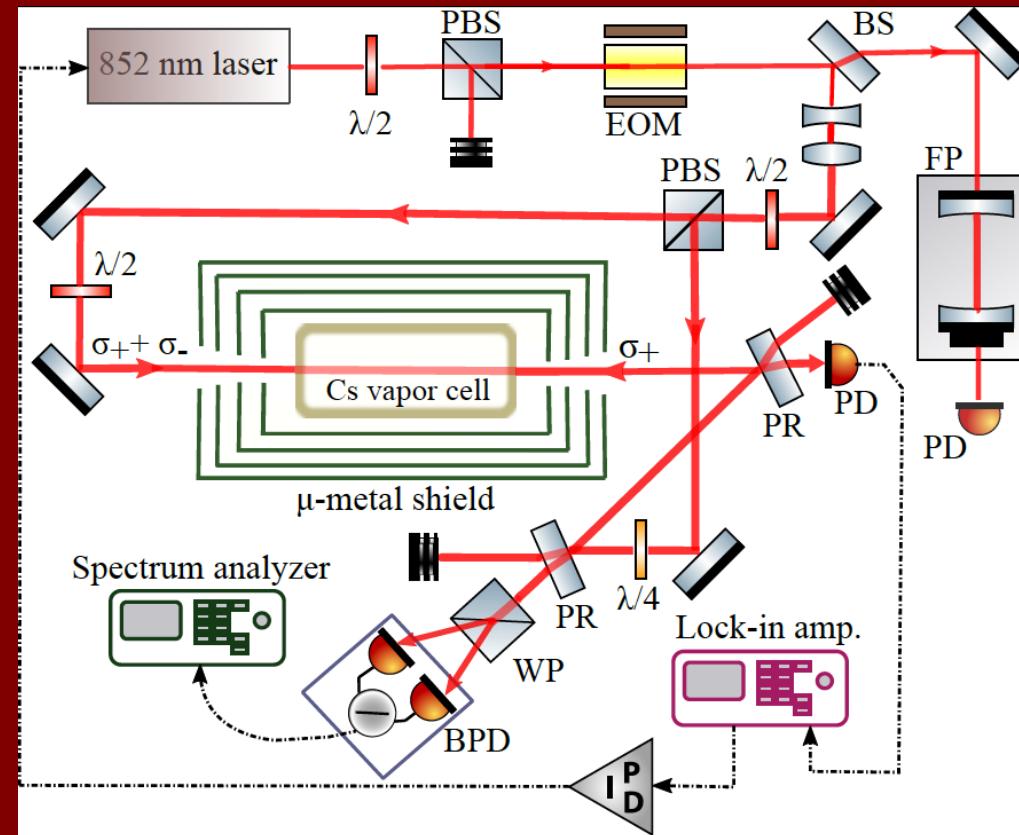


# Some recent and less so ways to look for Dark Matter



Dmitry Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz

&

Department of Physics, UC Berkeley

# The Plan

- ❑ Briefly: DM candidates
- ❑ Ultralight DM: analogy with chaotic light
- ❑ Some recent experiments



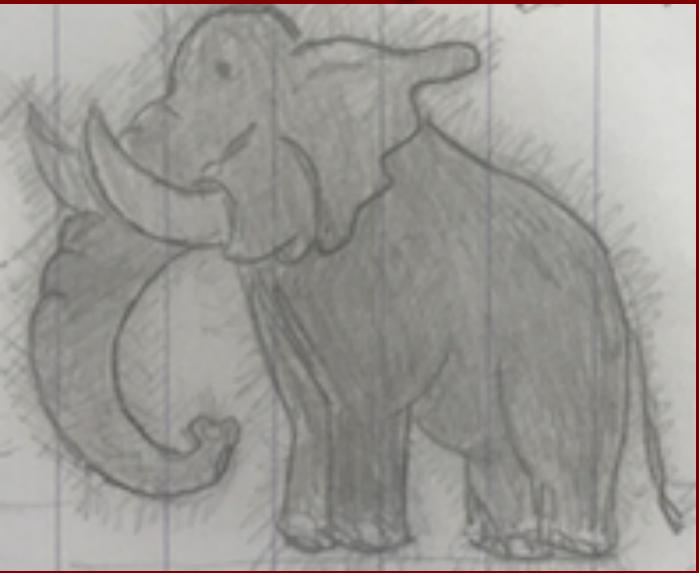
Vasiliki Demas

DARK MATTER "THE ELEPHANT IN THE ROOM"

# More Elephants!



Matter-antimatter Asymmetry



Similar amount of matter and DM



Dark Energy



Strong-CP problem



Hierarchy problem

# So what is DM or what mimics it ?

- ❑ A gross misunderstanding of gravity (MOND, ...) ☹?
- ❑ Proca MHD (finite photon mass) ☹?

THE ASTROPHYSICAL JOURNAL, 871:218 (13pp), 2019 February 1

<https://doi.org/10.3847/1538-4357/aaf63a>

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## A Hypothetical Effect of the Maxwell–Proca Electromagnetic Stresses on Galaxy Rotation Curves

D. D. Ryutov<sup>1</sup> , Dmitry Budker<sup>1,2,3</sup> , and V. V. Flambaum<sup>1,4</sup> 

- ALPs (pseudoscalar) ☺
- Dilatons (scalar) ☺
- Vector particles ☺
- Tensor particles ???
- ❑ Antiquark Nuggets (AQN) !!!☺!!!

# Ultralight Bosonic DM

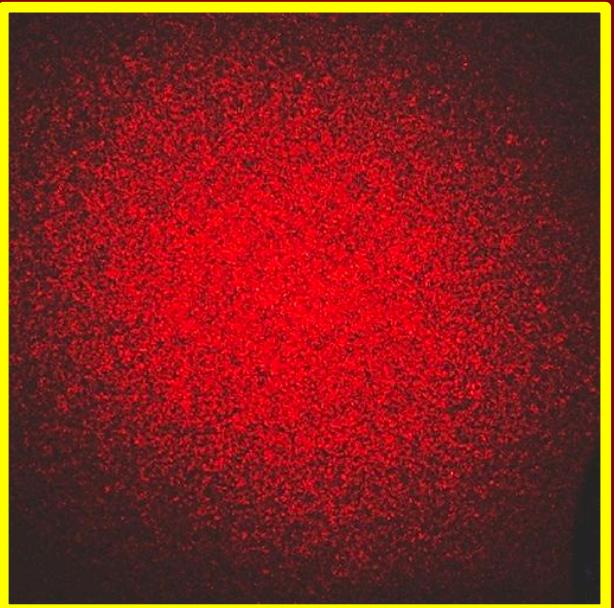
## Density

(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

$$n_{dm} \approx \frac{0.4 \text{ GeV/cm}^3}{mc^2}. \quad (3.13)$$

The 1 MHz frequency corresponds to about  $4 \cdot 10^{-9}$  eV, so the density of such particles should be  $\approx 10^{17} \text{ cm}^{-3}$ . 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  $\text{cm}^3$ , 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

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

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

*Coherence length*  $L_c$  can be estimated as a product of  $\tau_c$  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 Broglie waves), so that

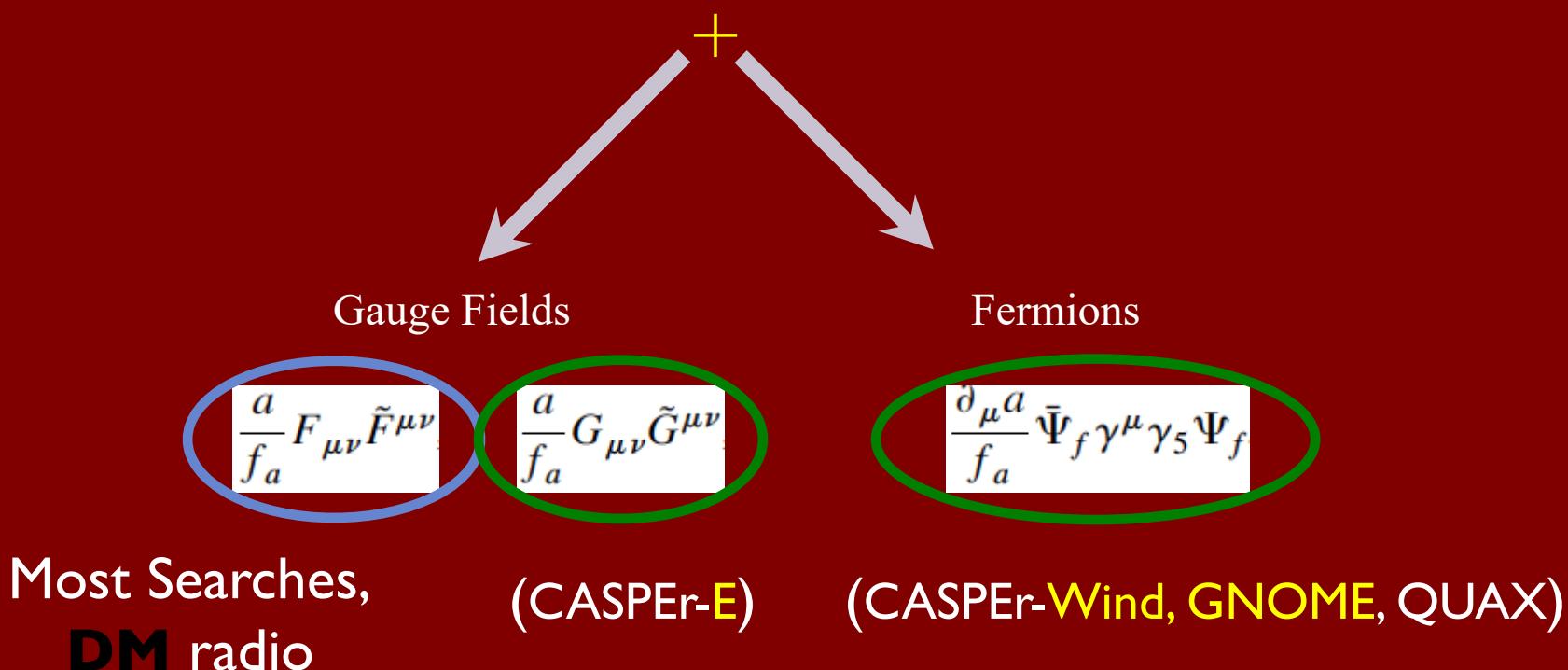
$$L_c \approx 10^3 \cdot \left( \frac{mc^2}{2\pi\hbar c} \right)^{-1}. \quad (3.15)$$

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

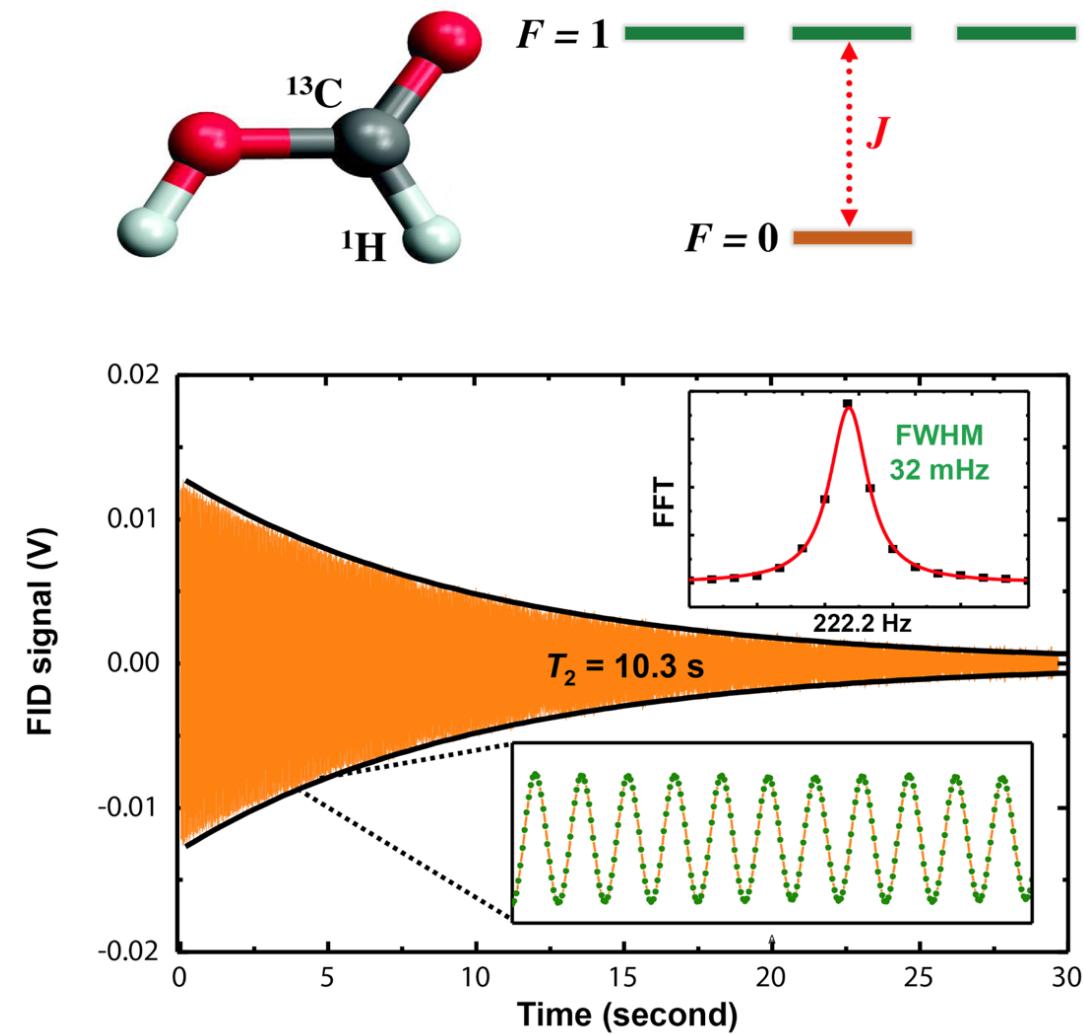
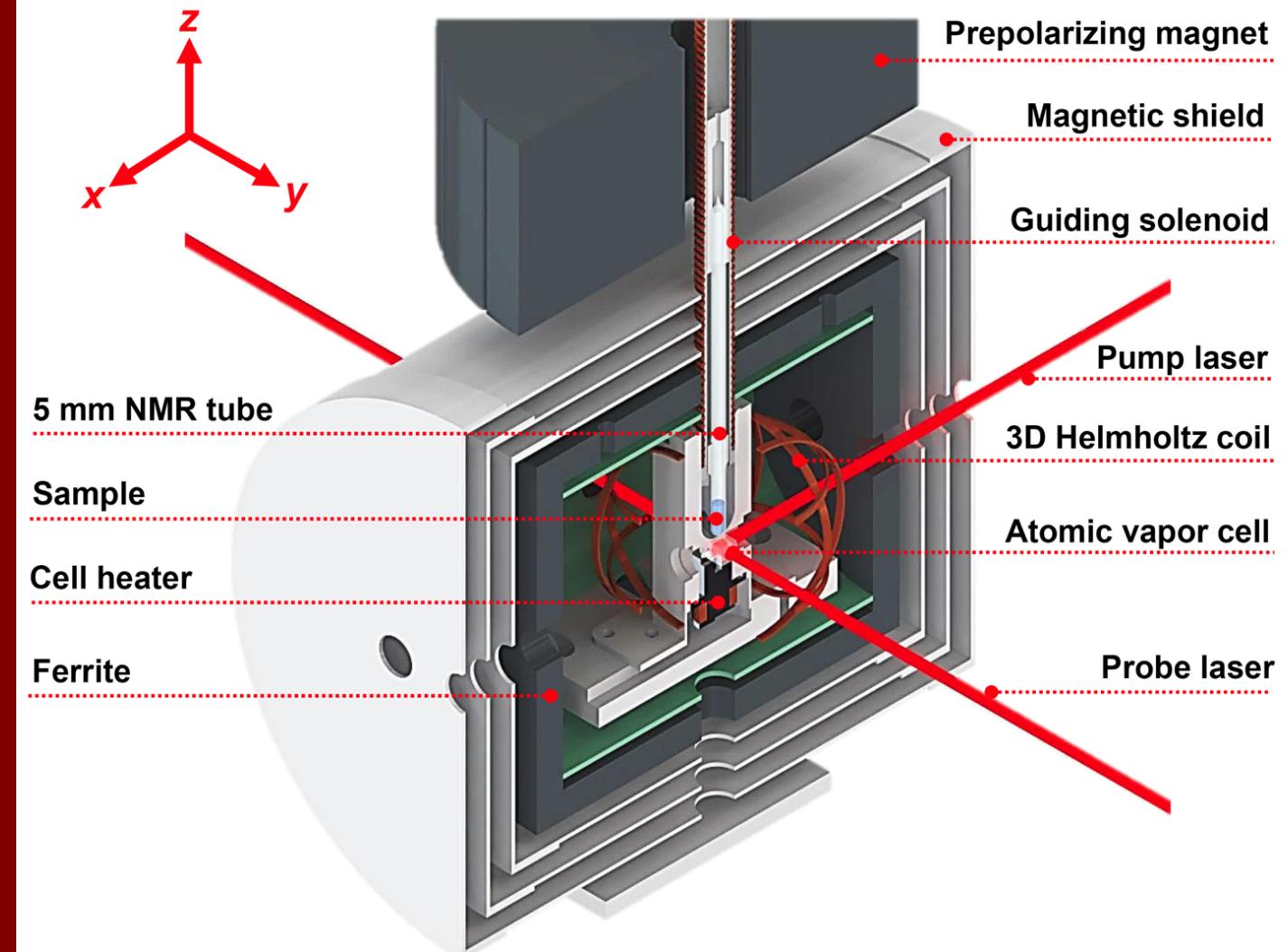
# How to search for Axions (ALPs) ?

## Axion (ALP) Interactions

### Gravity



# Zero-field NMR



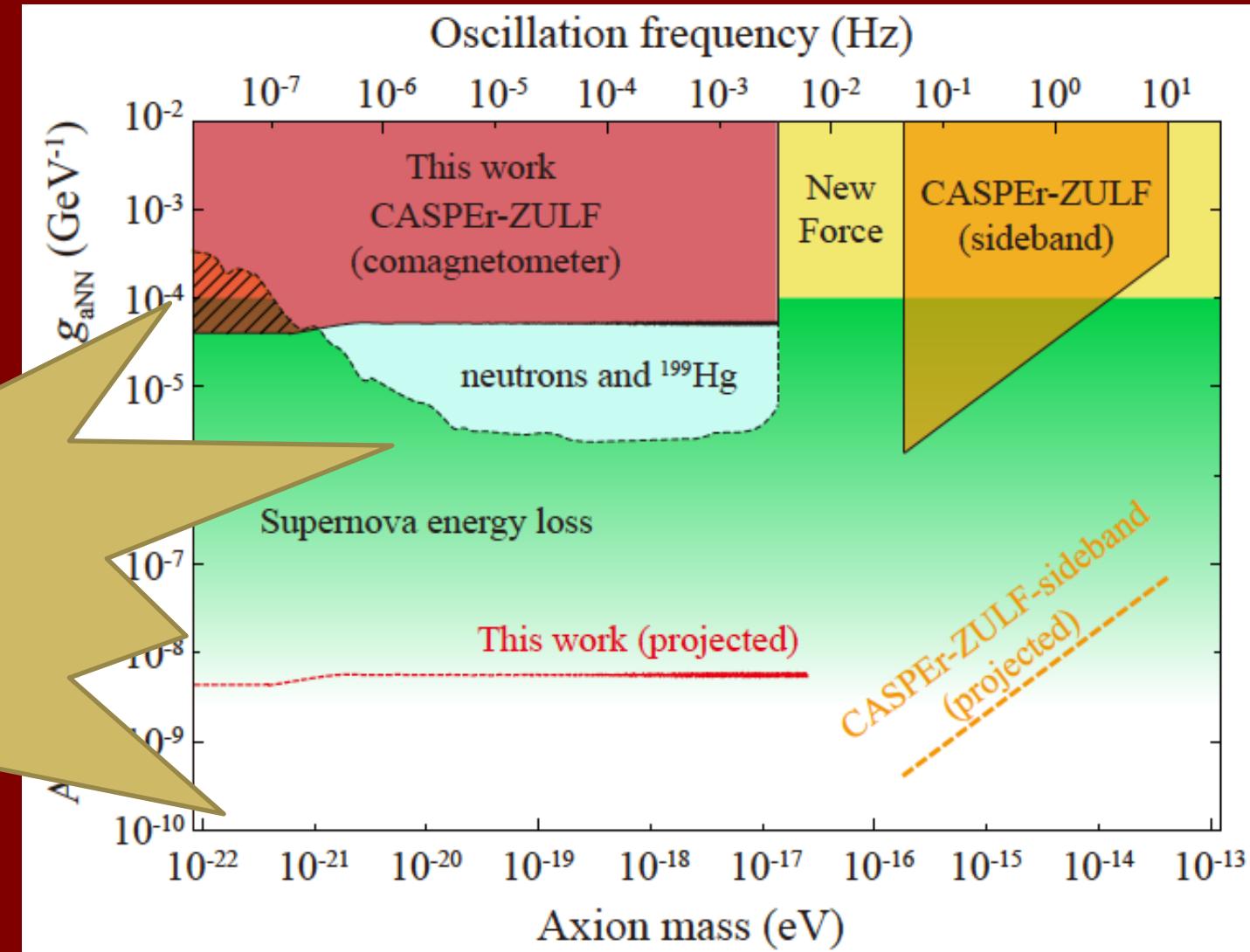
# CASPER: NMR based ALP-search program

- First results (2019!):

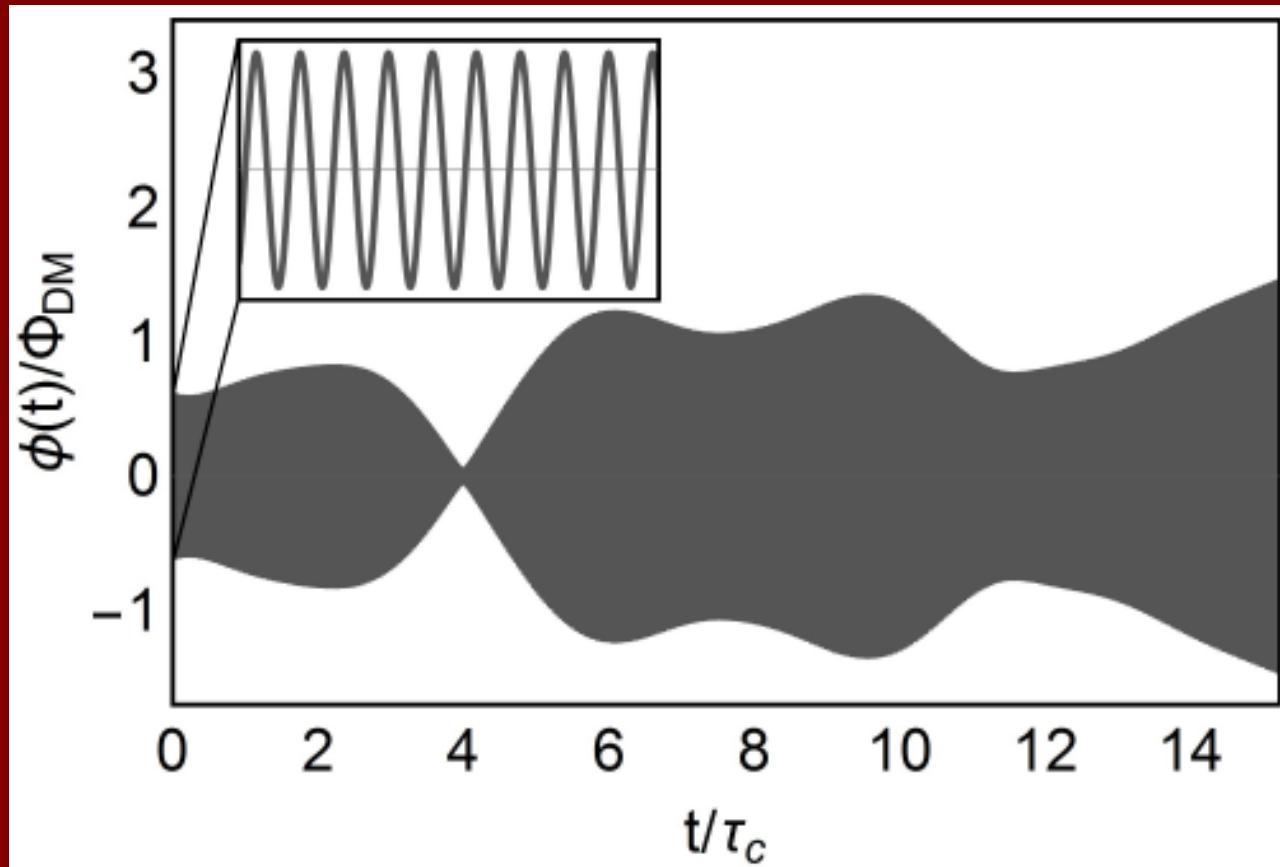
Antoine Garcon *et al*, Science Advances (in press)  
[arXiv:1902.04644](https://arxiv.org/abs/1902.04644);

Teng Wu *et al*, **Phys. Rev. Lett.** **122**, 191302 (2019);  
[arXiv:1901.10843](https://arxiv.org/abs/1901.10843)

Low-frequency  
results should  
be taken with  
**!caution!**



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

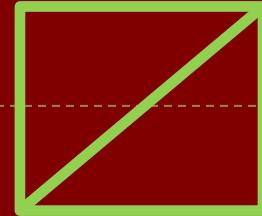


Gary P. Centers et al , [arXiv:1905.13650](https://arxiv.org/abs/1905.13650) (2019)

# Analogy with chaotic light



Thermal light source



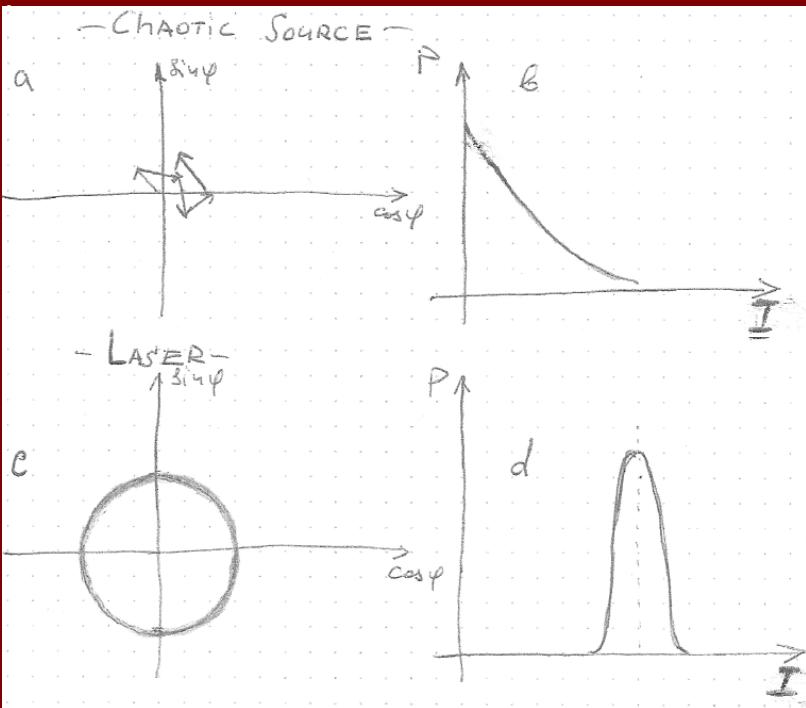
Polarizer



Detector

➤ Q: What is the most probable **instantaneous intensity** ?

➤ A: **zero**



$$p(E_s) \propto \exp\left\{-\frac{E_s^2}{2NE_0^2}\right\} dE_s. \quad (5.26)$$

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

$$p(E_c, E_s) \propto \exp\left\{-\frac{E_s^2 + E_c^2}{2NE_0^2}\right\} dE_s dE_c = \exp\left\{-\frac{I}{\bar{I}}\right\} d\varphi dE, \quad (5.27)$$

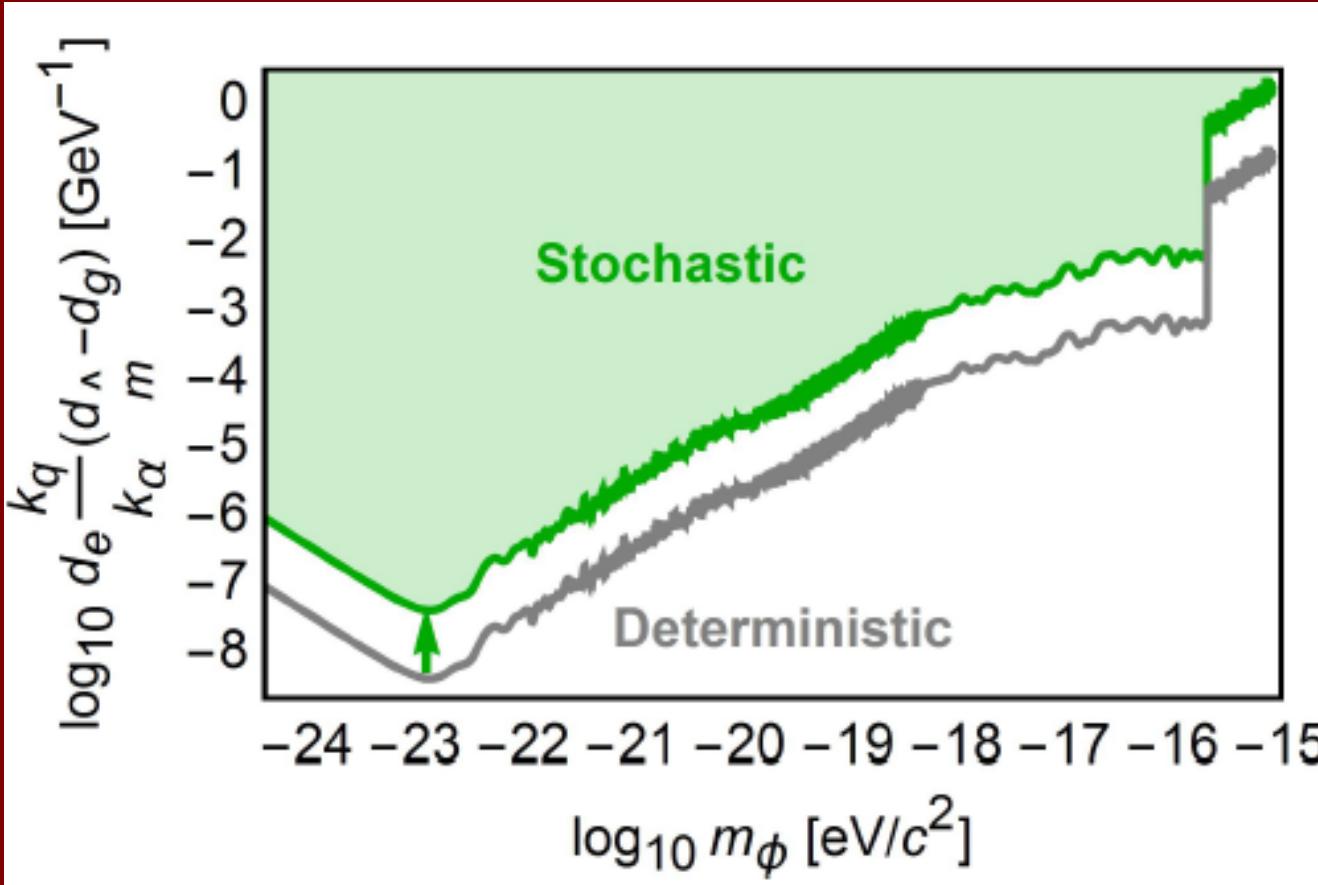
where we have introduced the instantaneous cycle-averaged intensity  $I$ , its mean value  $\bar{I}$ , the *phase angle*  $\varphi$ , and the total field amplitude  $E$ , which is non-negative.

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

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

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

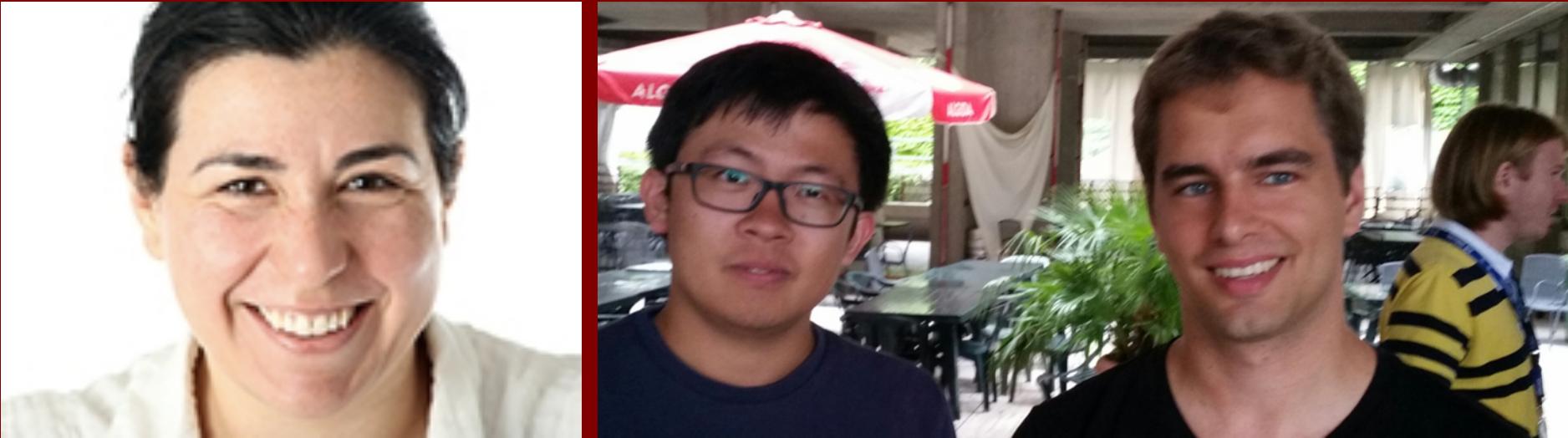
# Significant effect on low-frequency DM searches



- 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](https://arxiv.org/abs/1905.13650) (2019)

# DILATON DM ?



## Searching for dilaton dark matter with atomic clocks

Asimina Arvanitaki\*

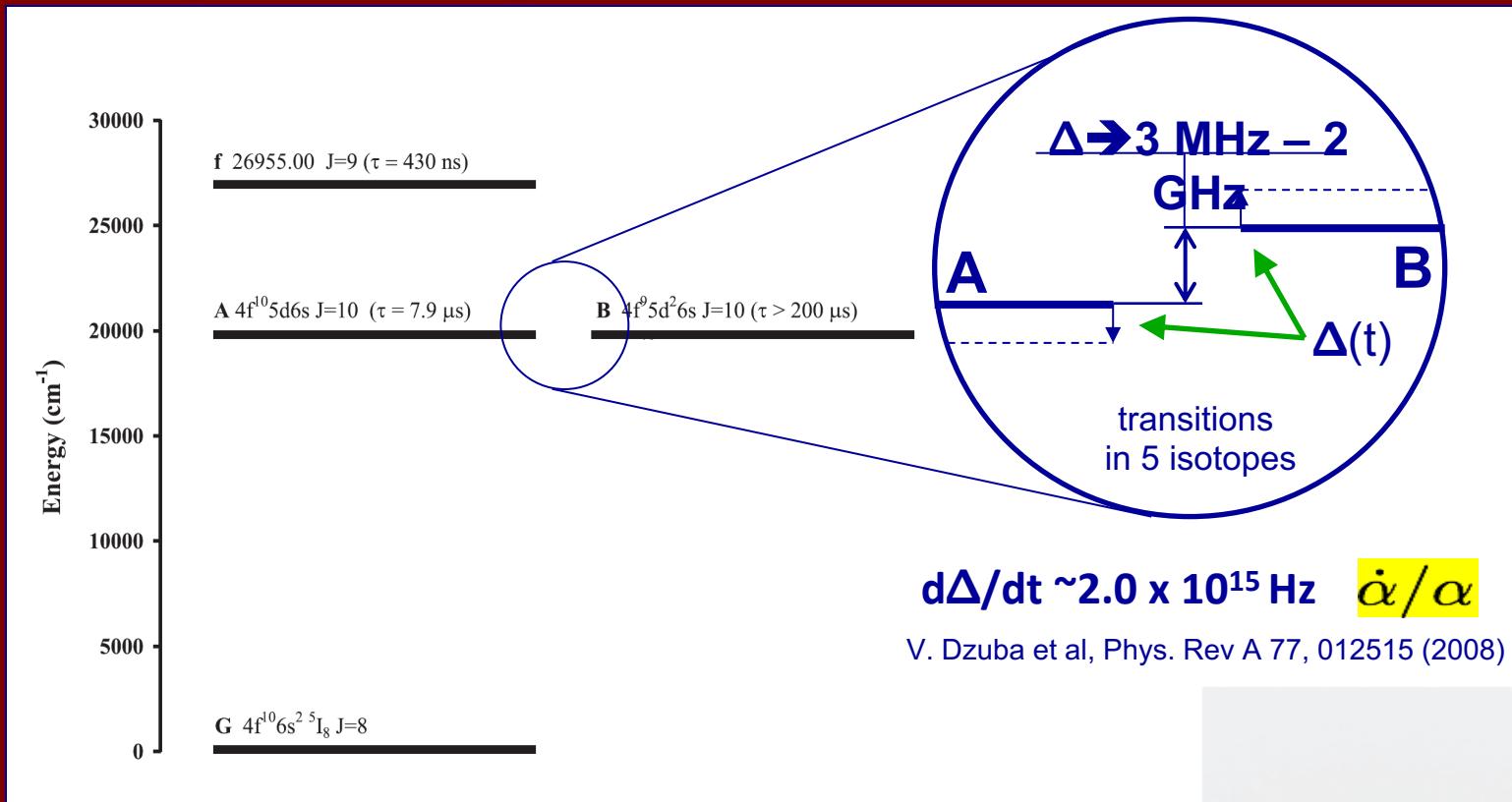
*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*

Junwu Huang<sup>†</sup> and Ken Van Tilburg<sup>‡</sup>

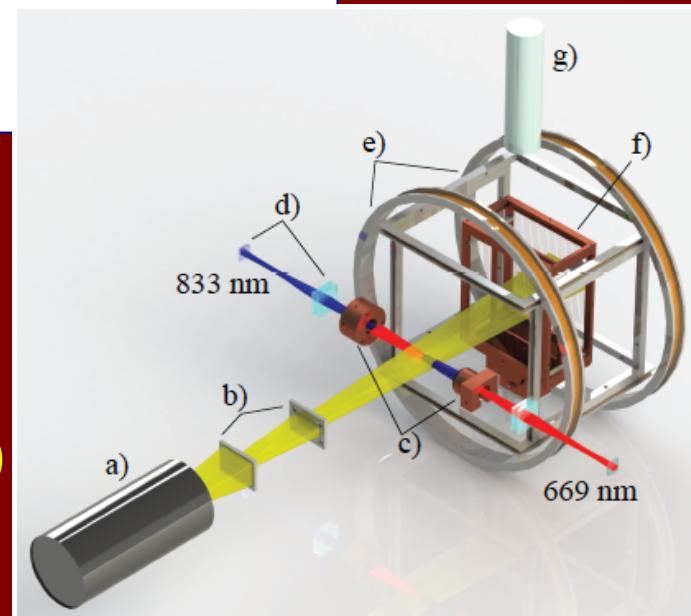
*Stanford Institute for Theoretical Physics, Department of Physics,  
Stanford University, Stanford, CA 94305, USA*

(Dated: May 14, 2014)

# Dy as “Alpha Variometer”

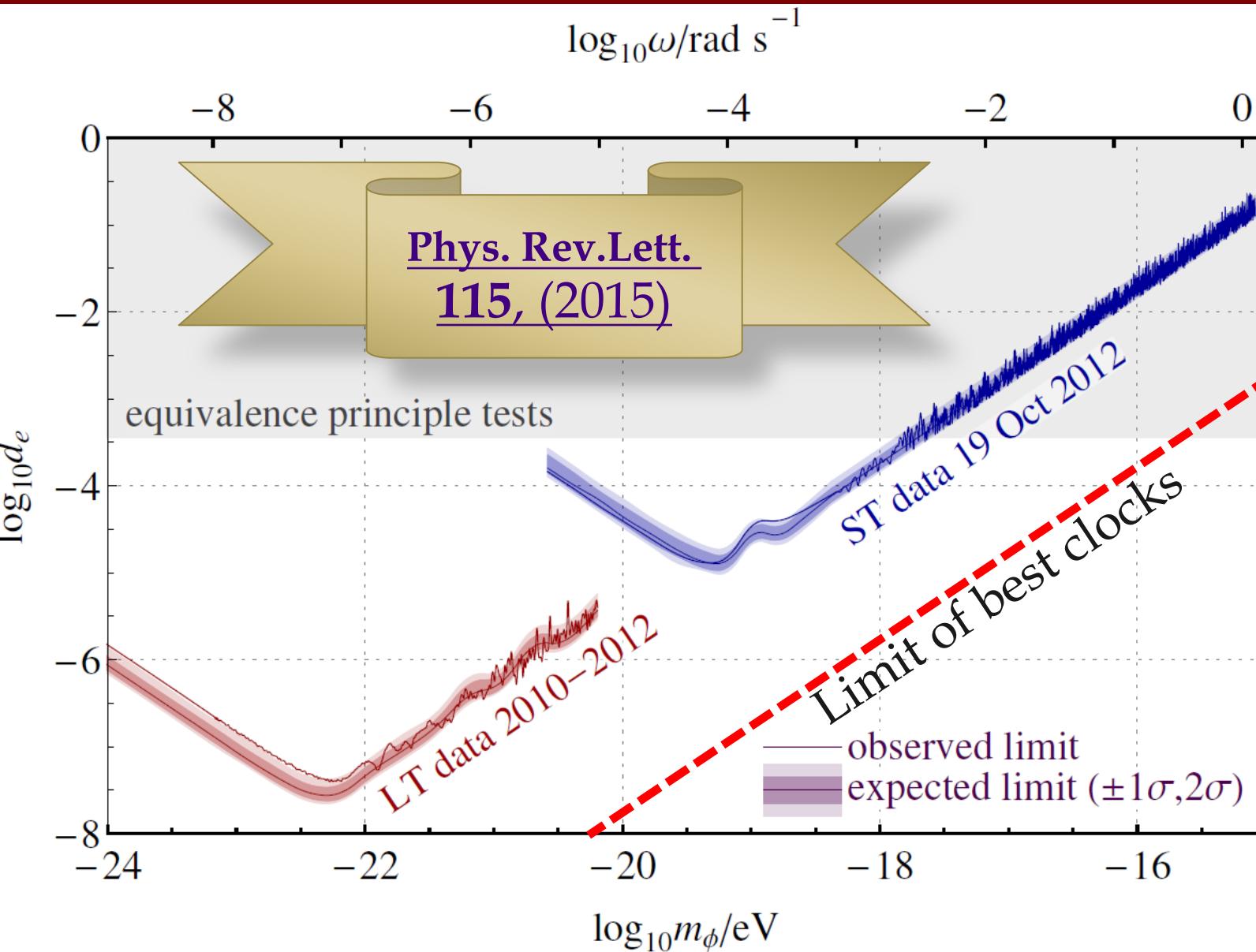
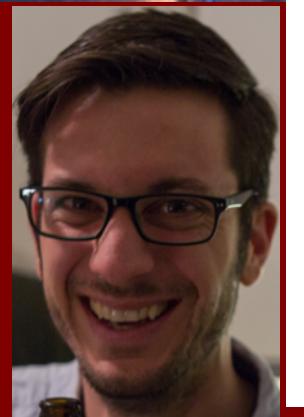


- Limits on alpha variation
- Dependence on gravitational potential
- Lorentz-Invariance violation (for electrons)
- ...



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

Ken Van Tilburg,<sup>1,\*</sup> Nathan Leefer,<sup>2,†</sup> Lykourgos Bougas,<sup>2,‡</sup> and Dmitry Budker<sup>2,3,4,§</sup>



# 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, Fruguele, 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

Abhishek Banerjee, Dmitry Budker, Joshua Eby,  
Hyungjin Kim, and Gilad Perez, Relaxion Stars and  
their detection via Atomic Physics, [arXiv:1902.08212](https://arxiv.org/abs/1902.08212)

# Fast changing “constants” ?

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



**Dr. Dionysis Antypas**  
Helmholtz Institute, JGU Mainz



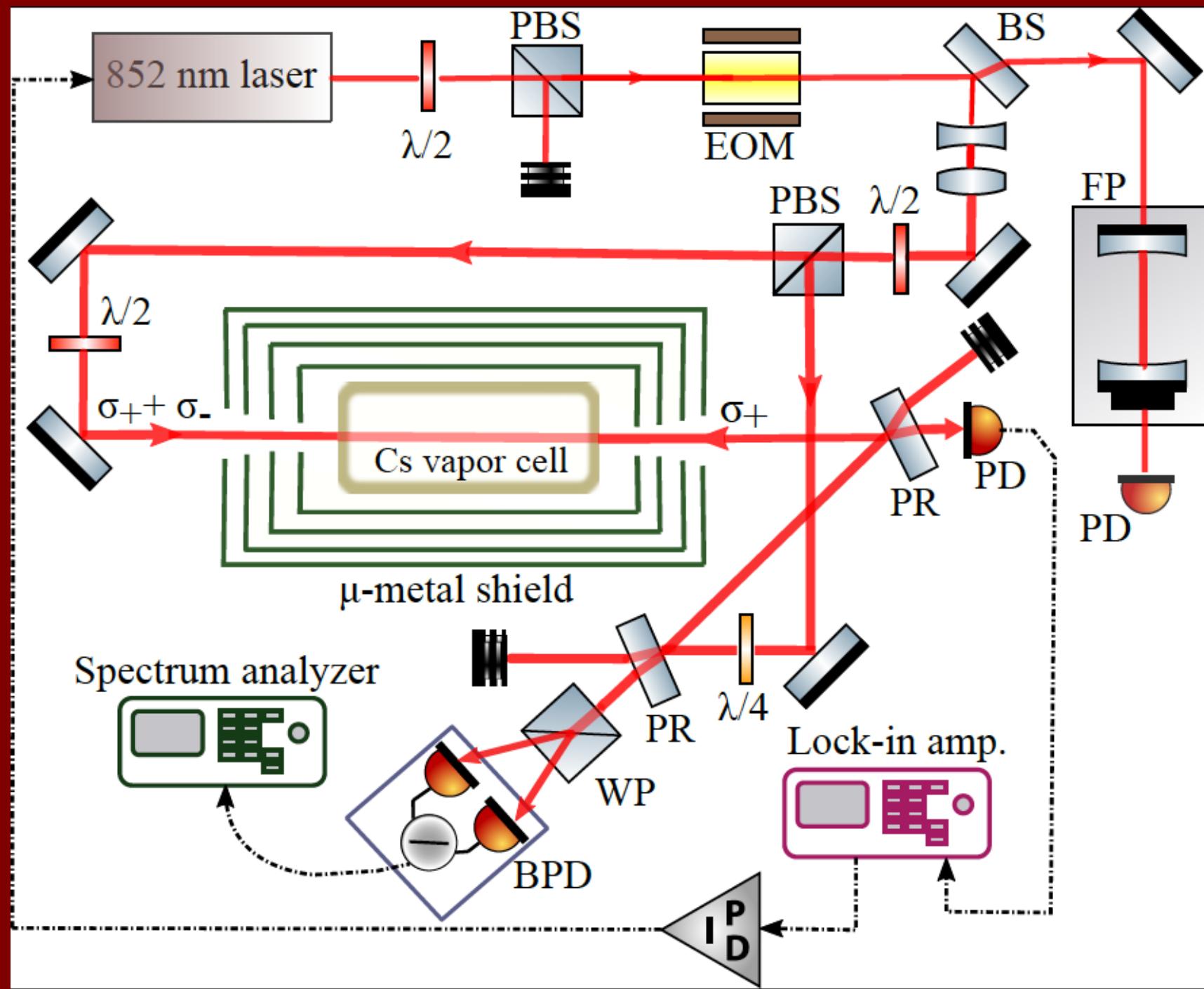
**Oleg Tretiak**  
HIM, JGU Mainz



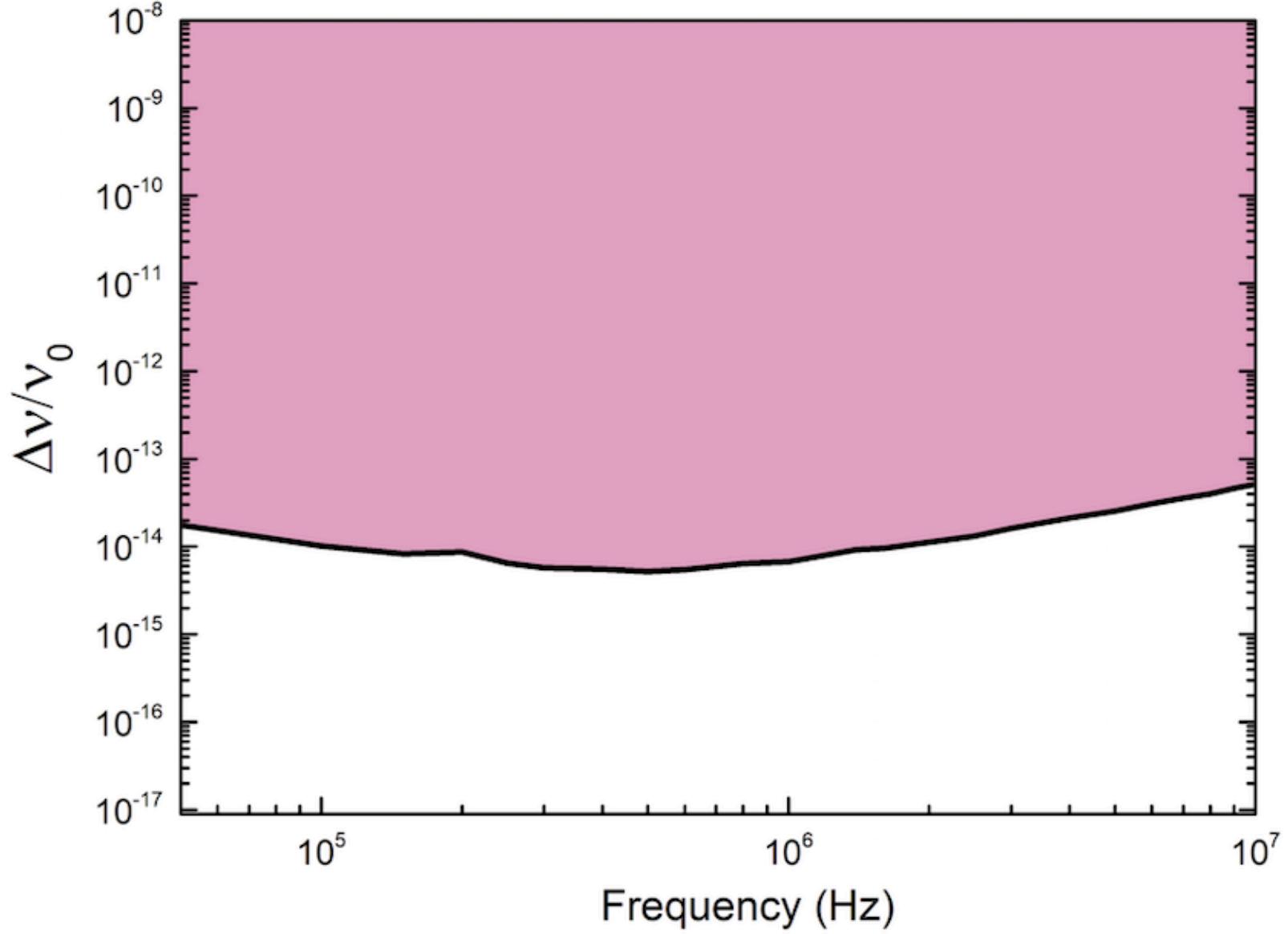
**Prof. Roee Ozeri**  
Weizmann Institute



**Antoine Garcon**  
HIM, JGU Mainz

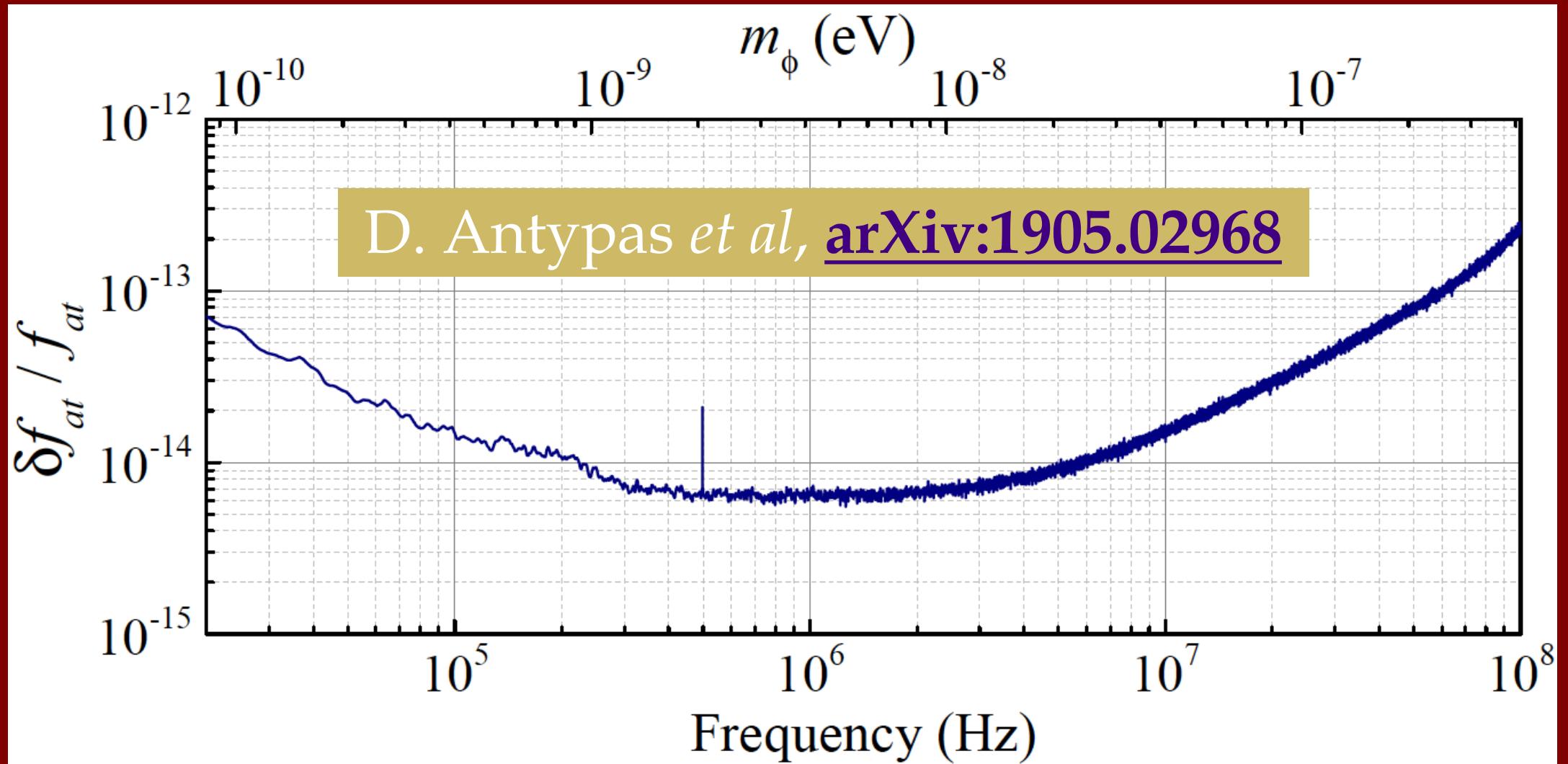


### Bounds on Cs 6S->8P<sub>3/2</sub> transition ( $\lambda=388$ nm)



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

# Cs D2 line (852 nm)



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

# Network searches for topological DM



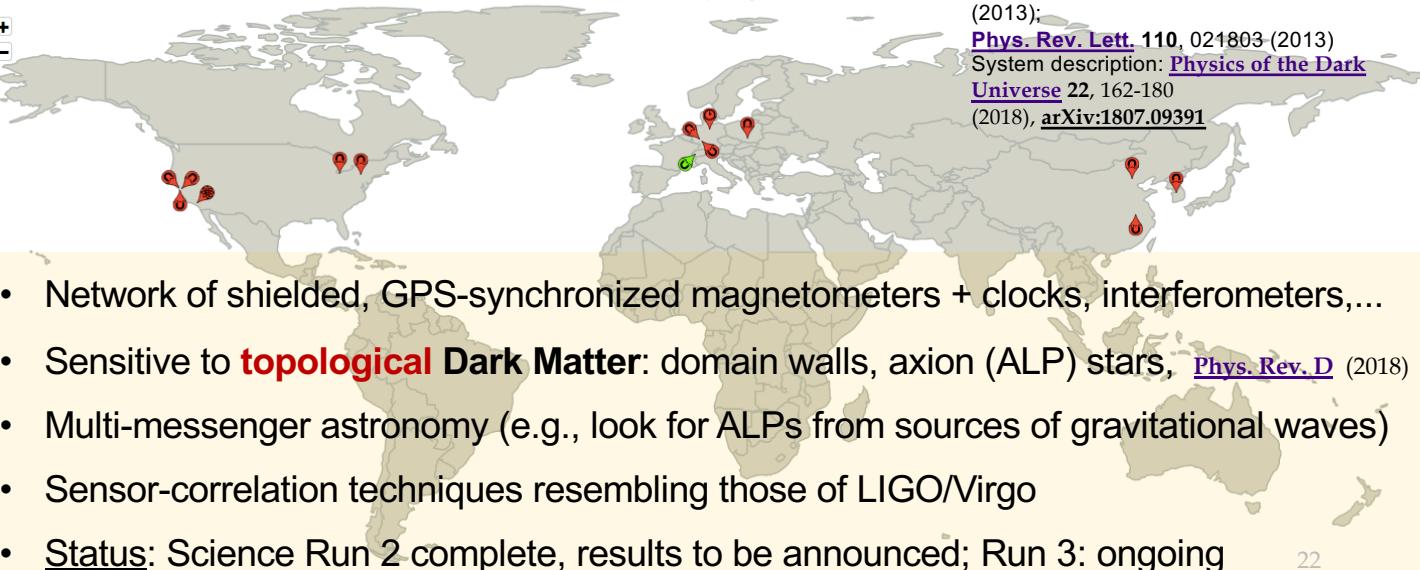
# The GNOME Experiment

Collaboration website

Global Network of Optical Magnetometers for Exotic searches

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

Show Map Legend



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



Wenxiang Hu<sup>1</sup>, Matthew Lawson<sup>2,3</sup>, Dmitry Budker<sup>3,4</sup>, Nataniel L. Figueroa<sup>3</sup>, Derek F. Jackson Kimball<sup>5</sup>, and Allen P. Mills Jr.<sup>6</sup>

- Tunnel-through-the-Earth problem ( $T \approx 80$  min)
  - Generalization to
- Hypothetical Internally Orbiting matter (HIO)
- Earth is NOT of uniform density
  - Small amplitude, near center:

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

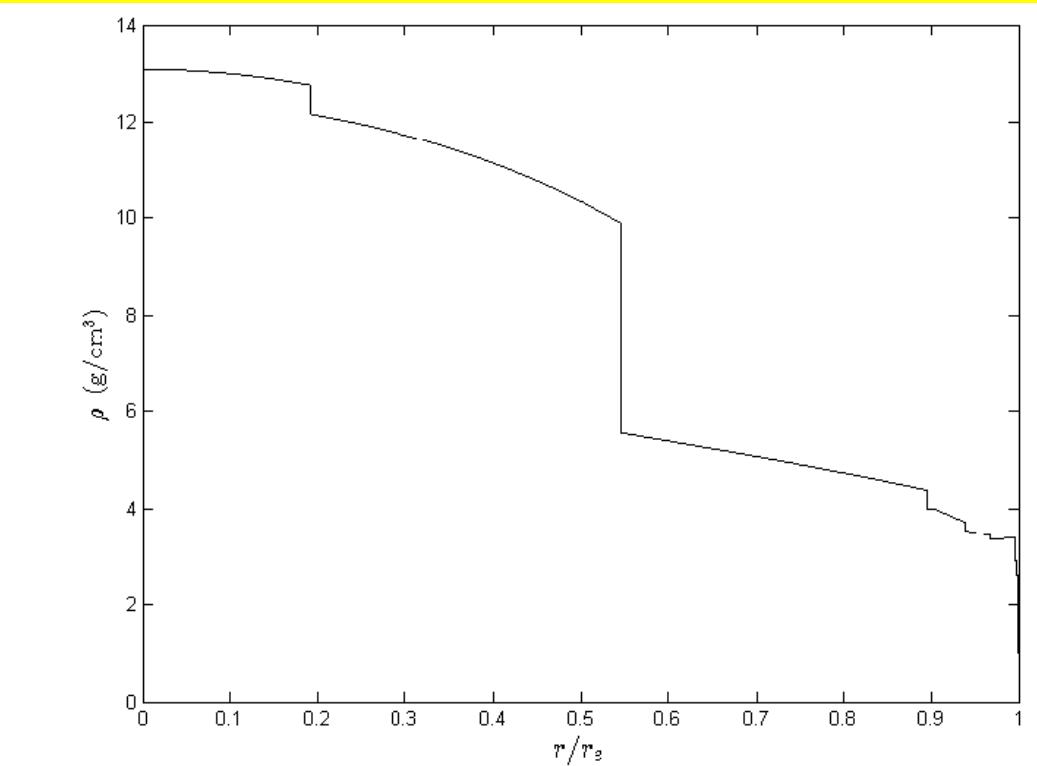


Figure 1: The density profile of the Earth based on the Preliminary Reference Earth model (PREM) [1].  $r_e$  is the radius of the Earth.

# Gravimeter Network

4132 Rev. Sci. Instrum., Vol. 70, No. 11, November 1999

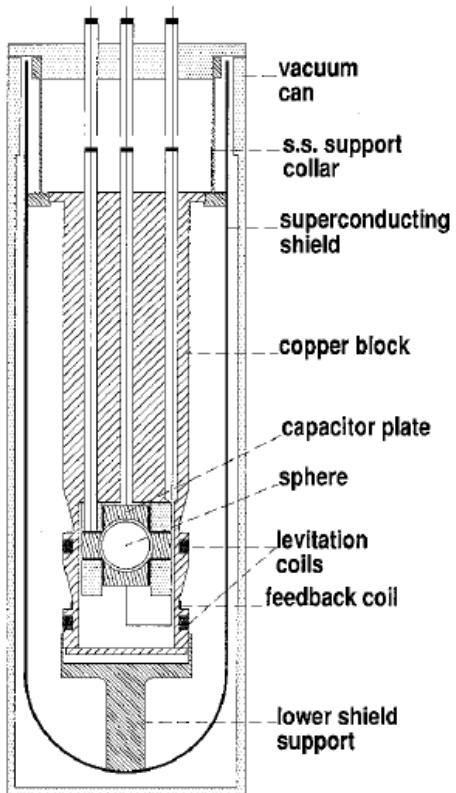


FIG. 1. Diagram of the cryogenic portion of the superconducting gravimeter.

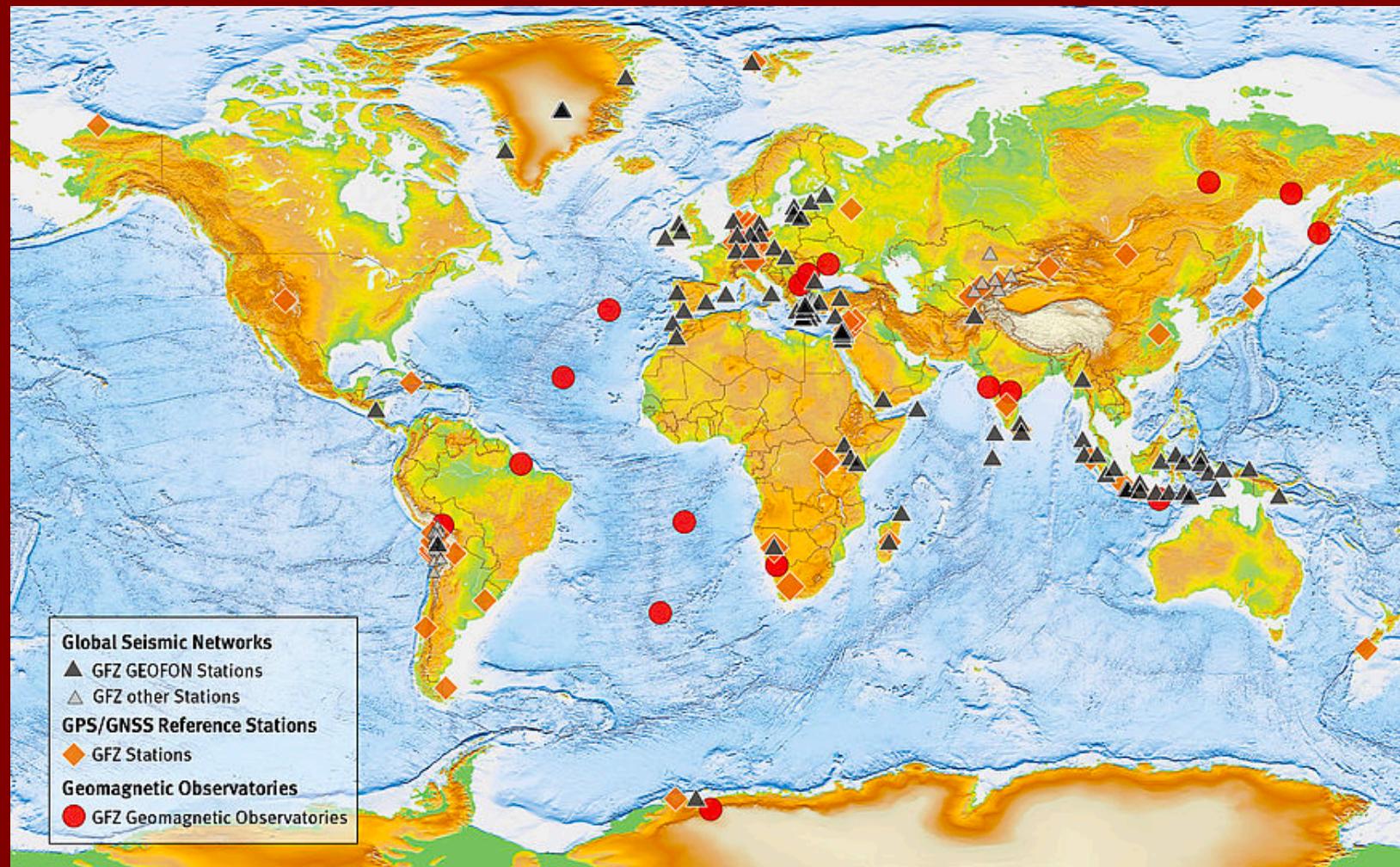
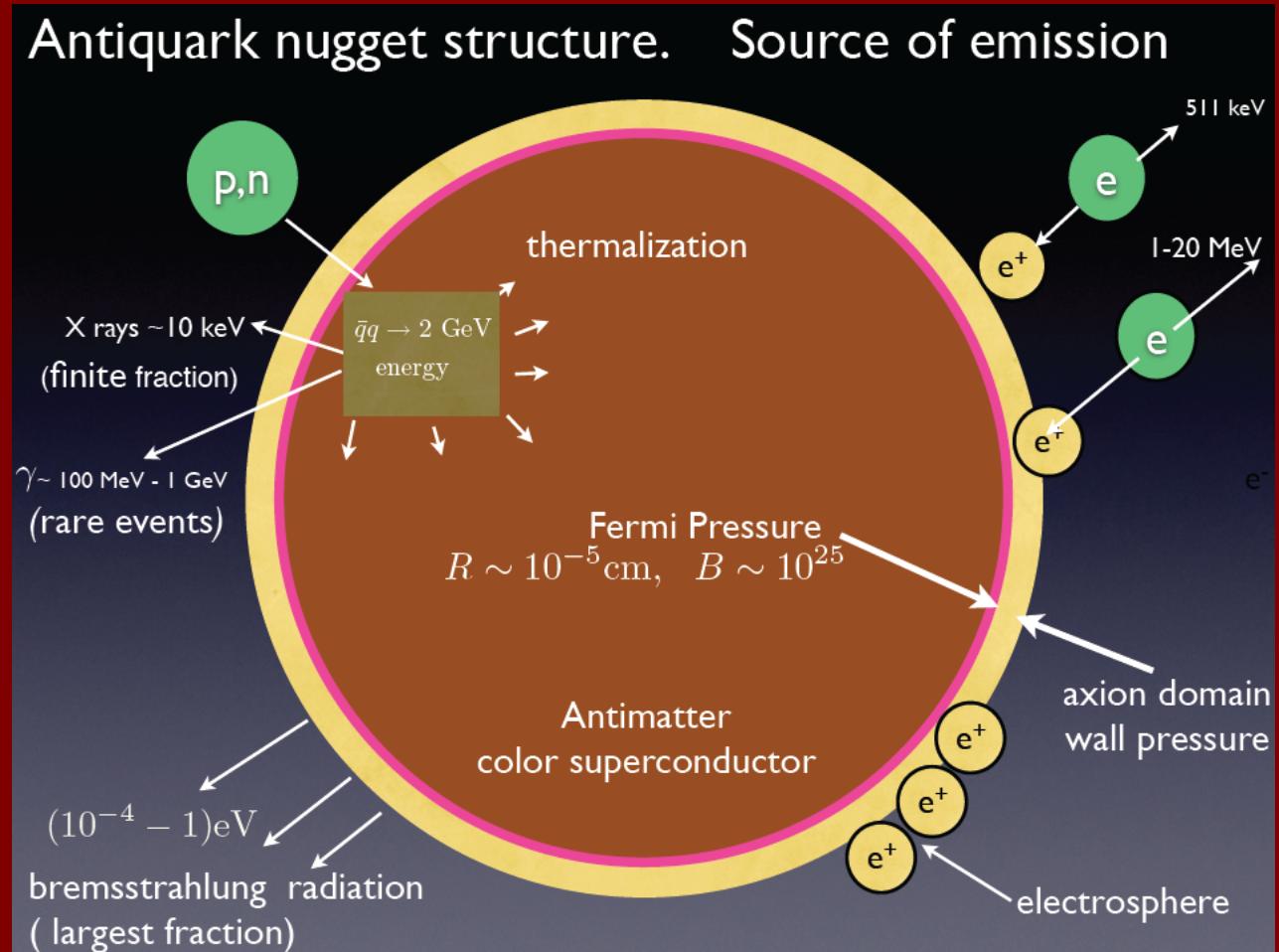


Figure credit: <https://www.gfz-potsdam.de/en/scientific-infrastructure/research-infrastructures/global-observatories/>

# A radically different framework



**Ariel Zhitnisky**  
DFSZ (Dine–Fischler–Srednicki–Zhitnitsky)



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

# Axion Quark Nuggets and how a Global Network can discover them

Dmitry Budker\*

*Johannes Gutenberg-Universitt Mainz (JGU) - Helmholtz-Institut, 55128 Mainz, Germany  
Department of Physics, University of California, Berkeley, CA, 94720-7300, USA*

Victor V. Flambaum†

*School of Physics, University of New South Wales, Sydney 2052, Australia  
Johannes Gutenberg-Universitt Mainz (JGU) - Helmholtz-Institut, 55128 Mainz, Germany*

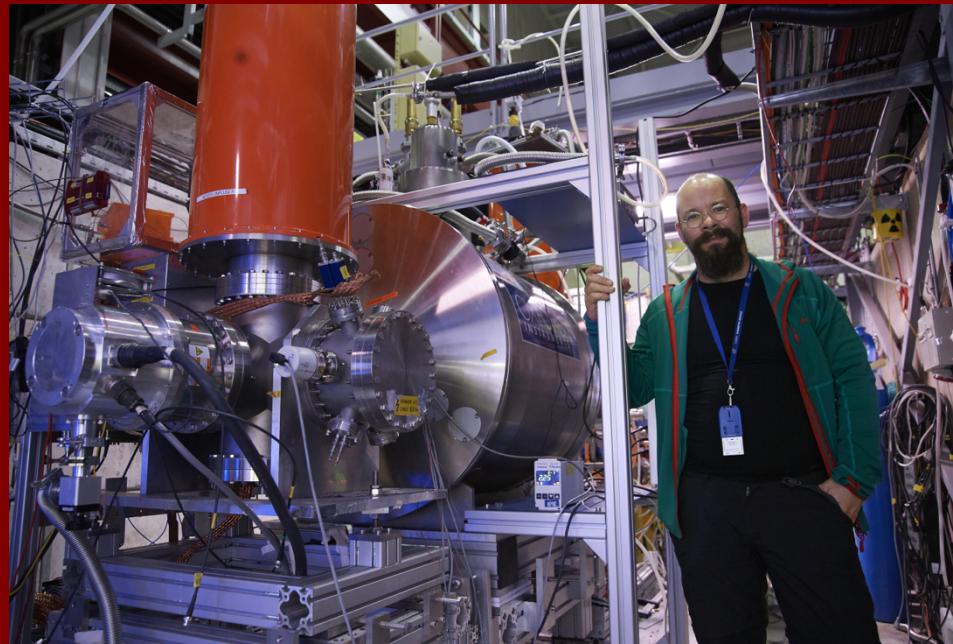
Xunyu Liang‡ and Ariel Zhitnitsky§

*Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada*

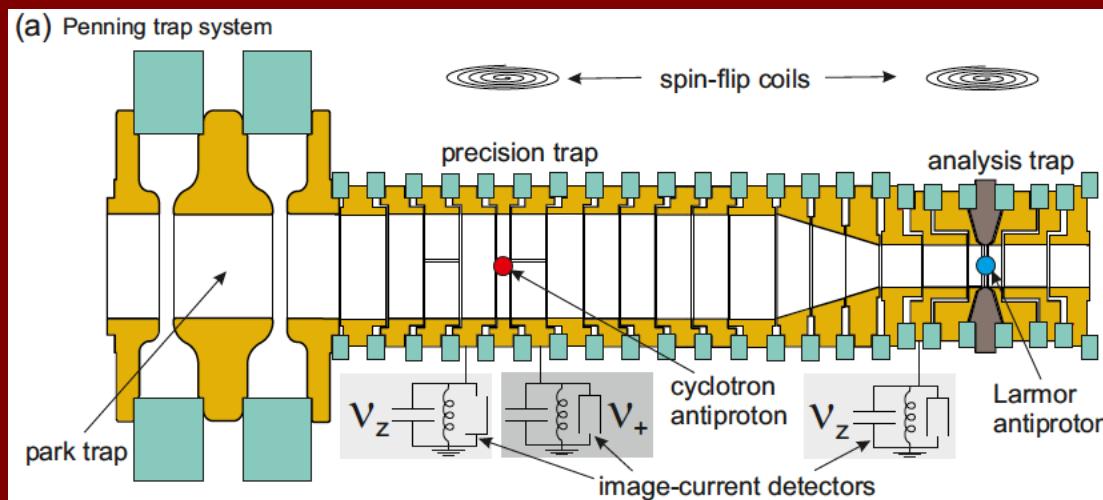
**arXiv:1909.09475** (*Submitted on 19 Sep 2019*)

# Dark-matter search with antimatter !

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



Stefan Ulmer



Ch. Smorra



Y. Stadnik

# Breaking news, developing stories...

Dark-matter search with **antimatter**

An important realization regarding slow oscillating DM (it is like chaotic light):

Gary P. Centers *et al*, Stochastic fluctuations of bosonic dark matter, [arXiv:1905.13650](https://arxiv.org/abs/1905.13650)

First limit on DM fields oscillating at frequencies up to 100 MHz:

D. Antypas *et al*, A search for light scalar dark matter in the radio-frequency band with atomic spectroscopy, [arXiv:1905.02968](https://arxiv.org/abs/1905.02968)

Possible DM enhancement by Earth and Sun:

Abhishek Banerjee *et al*, Relaxion Stars and their detection via Atomic Physics, [arXiv:1902.08212](https://arxiv.org/abs/1902.08212)

Novel MASER for DM searches:

Min Jiang *et al*, Floquet-state Maser under Real-time Quantum Feedback Control, [arXiv:1901.00970](https://arxiv.org/abs/1901.00970)

Is fast oscillating DM like variation of “constants” ?

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 \(2019\)](https://doi.org/10.1103/PhysRevA.99.022113)

## Search for new physics with atoms and molecules

M. S. Safronova

*University of Delaware, Newark, Delaware 19716, USA*

*and Joint Quantum Institute, National Institute of Standards and Technology  
and the University of Maryland, College Park, Maryland 20742, USA*

D. Budker

*Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,  
University of California, Berkeley, California 94720, USA,  
and Nuclear Science Division, Lawrence Berkeley National Laboratory,  
Berkeley, California 94720, USA*

D. DeMille

*Yale University, New Haven, Connecticut 06520, USA*

Derek F. Jackson Kimball

*California State University, East Bay, Hayward, California 94542, USA*

A. Derevianko

*University of Nevada, Reno, Nevada 89557, USA*

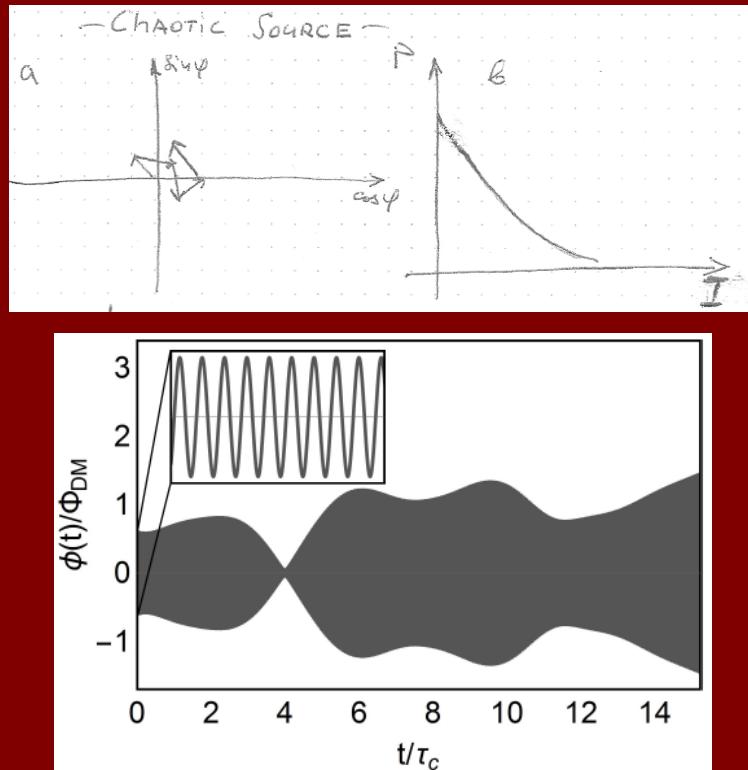
Charles W. Clark

*Joint Quantum Institute, National Institute of Standards and Technology  
and the University of Maryland, College Park, Maryland 20742, USA*

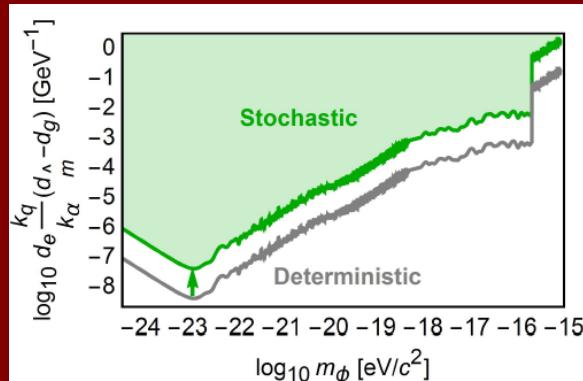


Marianna Safronova with Erwin L.  
Hahn and the Budker Group,  
Berkeley, 2006

Ultralight bosonic DM  
is similar to chaotic light

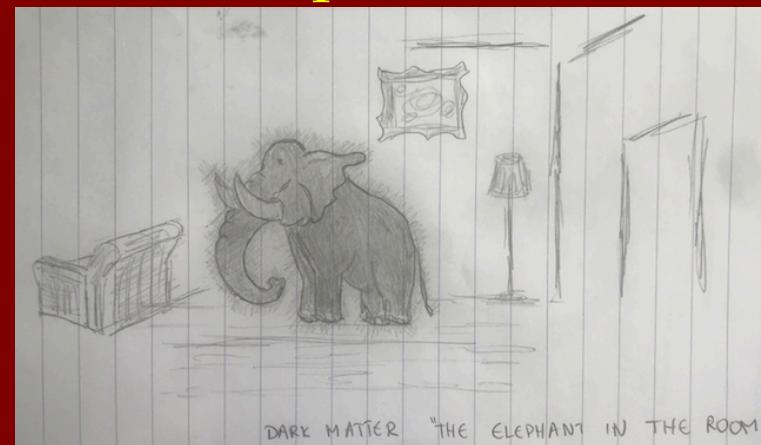


Fluctuations affect DM searches

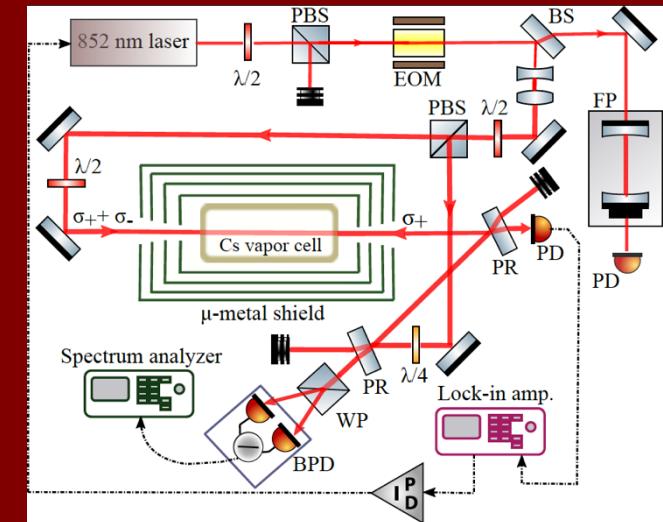


## Summary

Elephants...

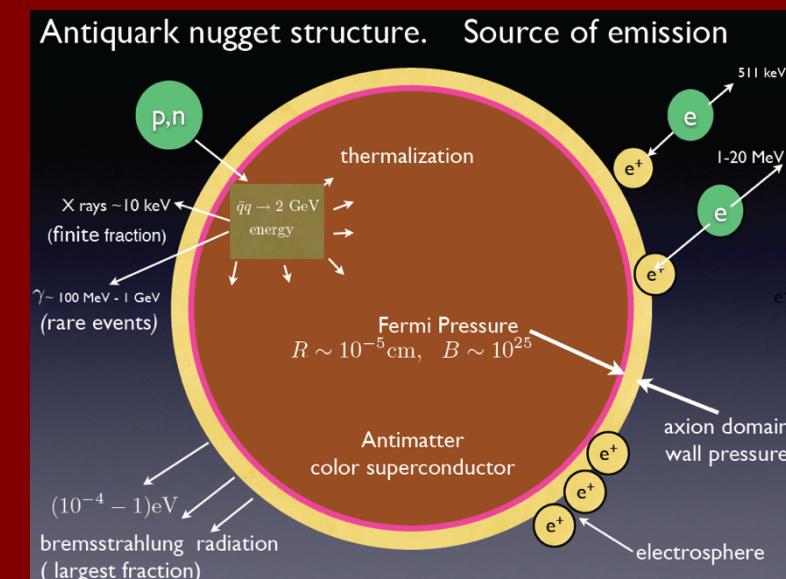
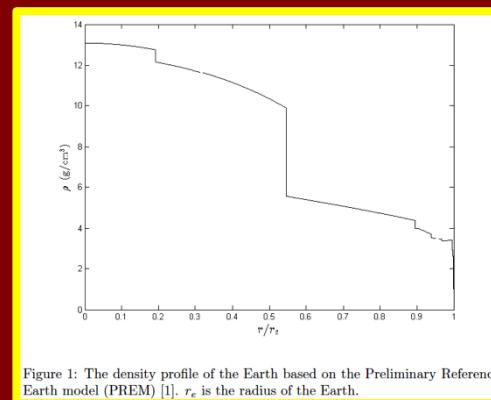


Recent DM  
searches with (anti)matter



Antiquark Nuggets

Gravimeters!





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