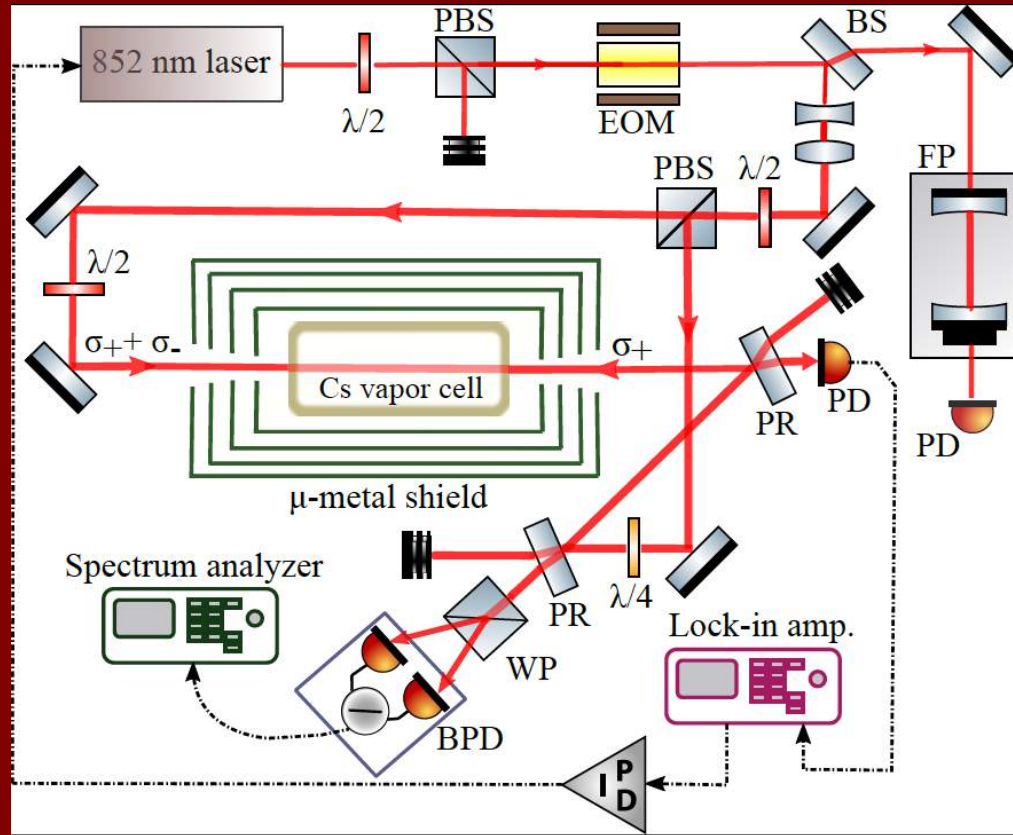


Some recent ways to look for Dark Matter



Dmitry Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz

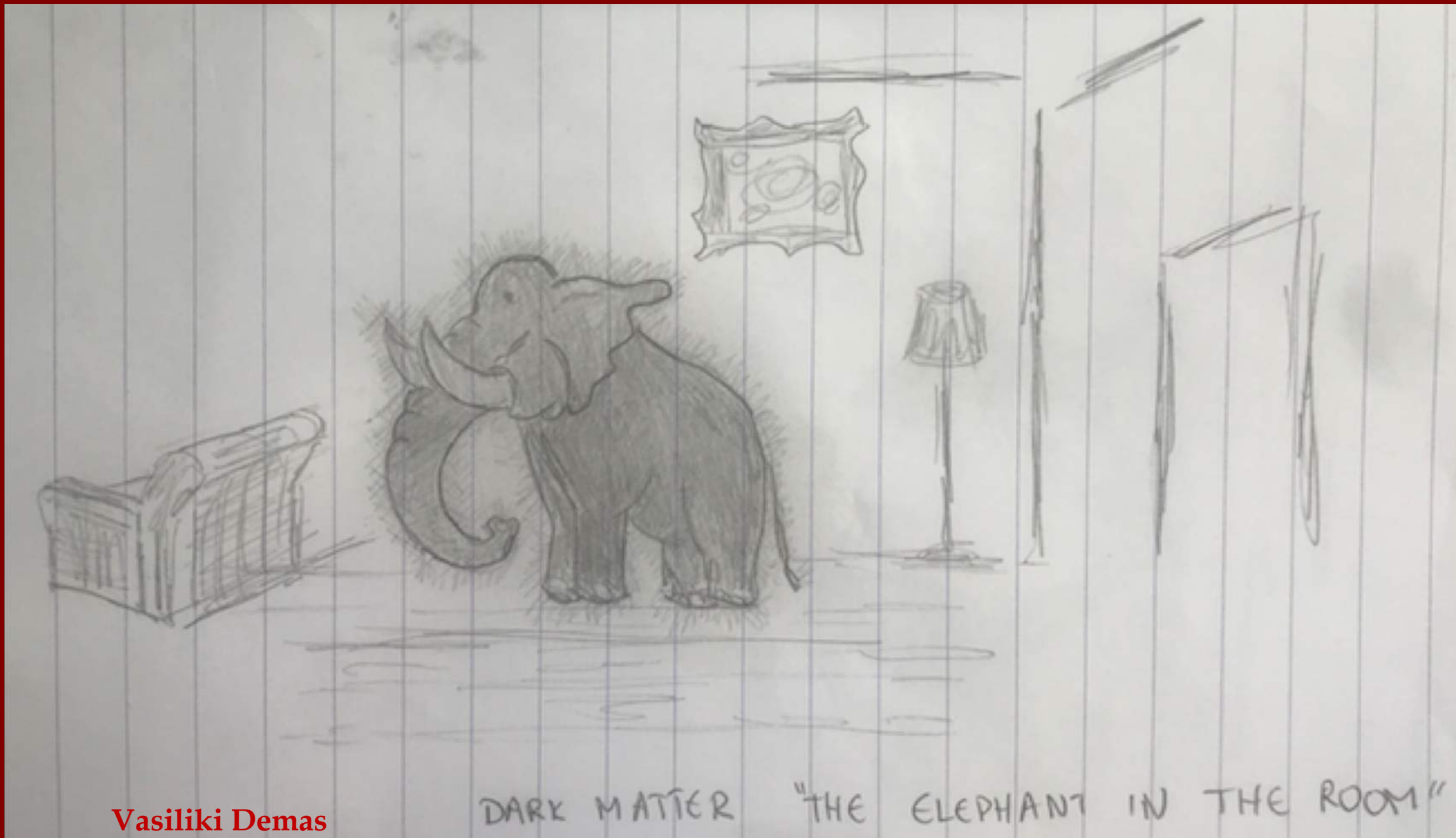
&

Department of Physics, UC Berkeley



The Plan

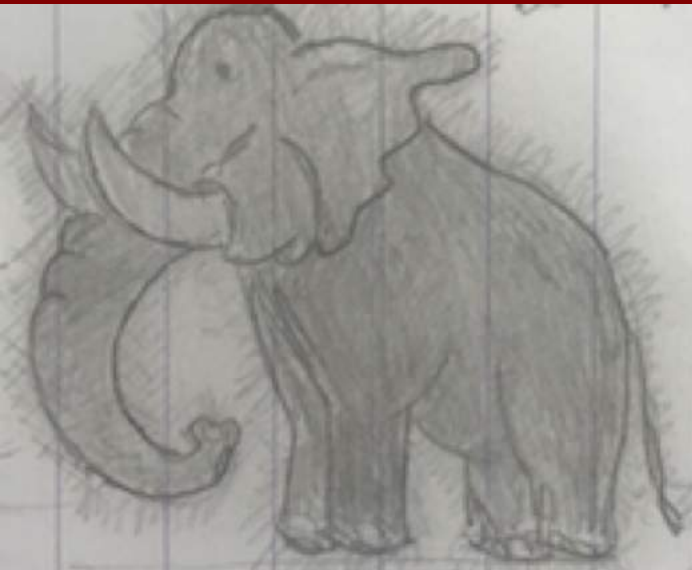
- ▣ Briefly: DM candidates
- ▣ Ultralight DM: analogy with chaotic light
- ▣ Some recent experiments
- ▣ Gamma Factory @ CERN



Vasiliki Demas

DARK MATTER "THE ELEPHANT IN THE ROOM"

More Elephants!



Matter-antimatter Asymmetry

Similar amount of matter and DM

Dark Energy



One and the same Elephant ?

Strong-CP problem

Hierarchy problem

So what is DM or what mimics it ?

▣ A gross misunderstanding of gravity (MOND, ...) ☹?

▣ Proca MHD (finite photon mass) ☹?

11
THE ASTROPHYSICAL JOURNAL, 871:218 (13pp), 2019 February 1
© 2019, The American Astronomical Society. All rights reserved.

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



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

D. D. Ryutov¹ , Dmitry Budker^{1,2,3} , and V. V. Flambaum^{1,4}

■ Dilatons (scalar) ☺

■ Vector particles ☺

■ Tensor particles ???

▣ Antiquark Nuggets (AQN) !!!☺!!!

▣

Ultralight Bosonic DM

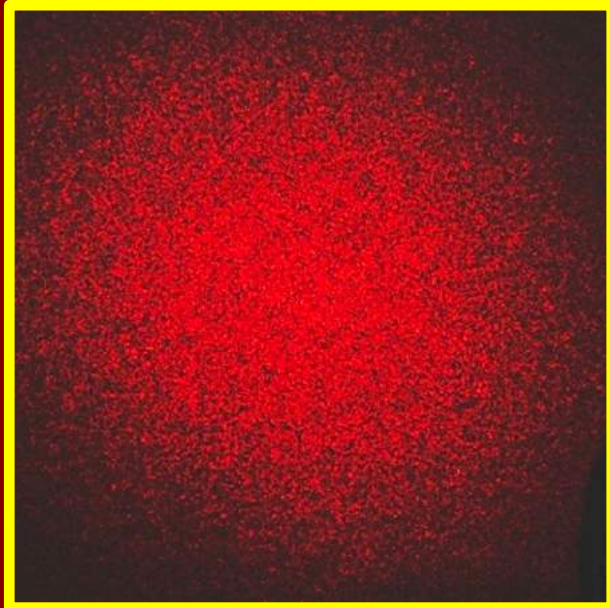
Density

(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 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 $\tau_c \approx 1 \text{ s}$.

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 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 $L_c \approx 300 \text{ km}$.

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

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

Gauge Fields

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

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

Fermions

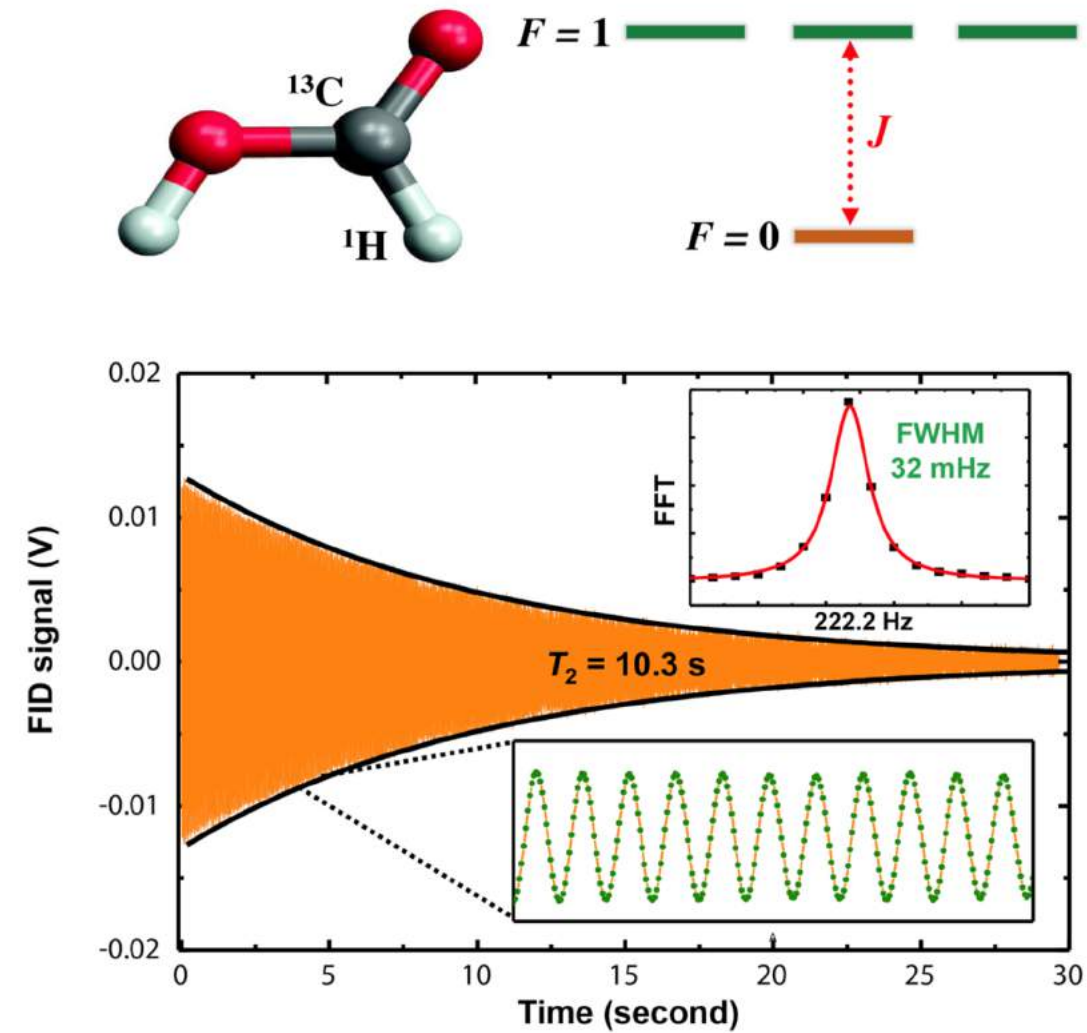
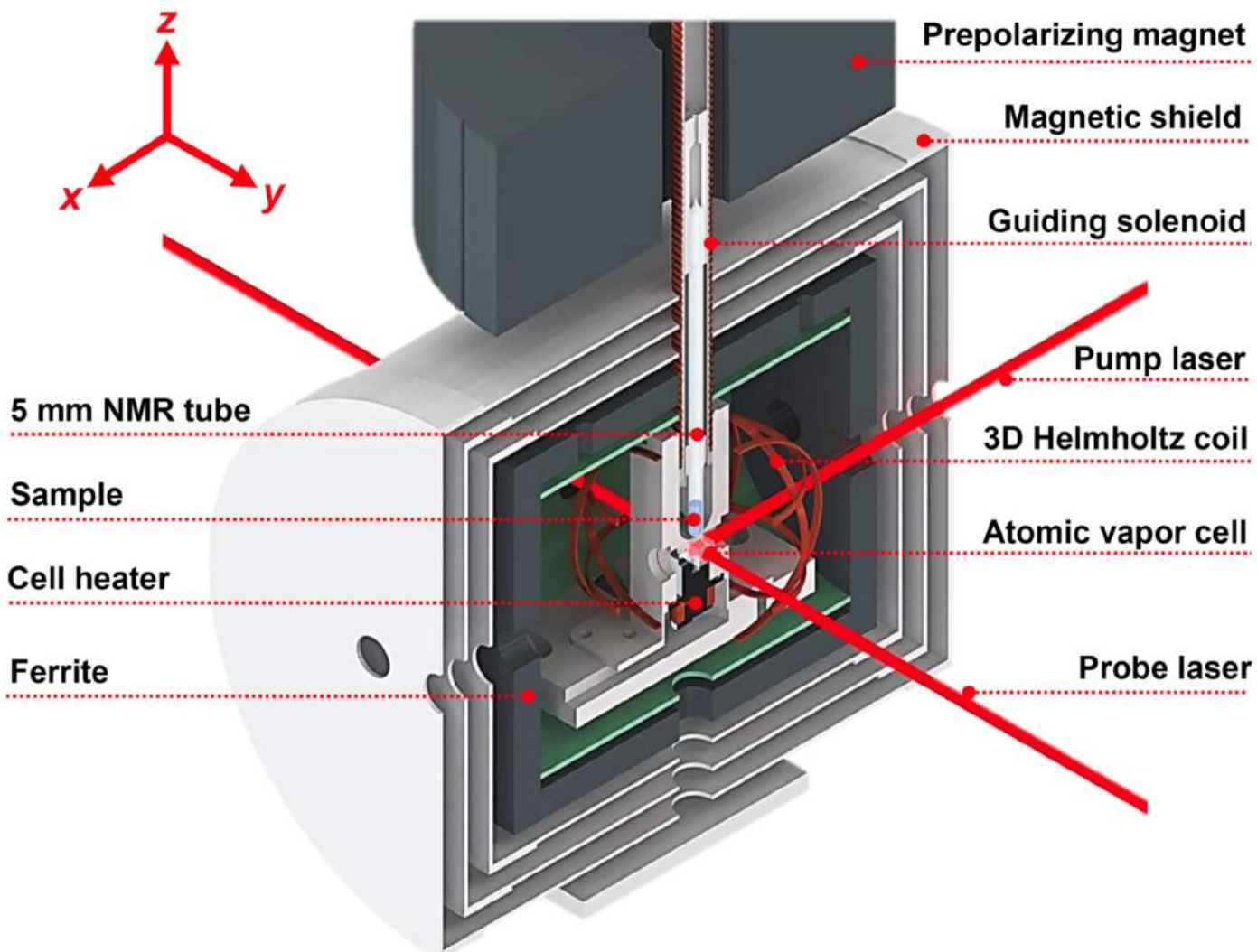
$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Most Searches,
DM radio

(nEDM, CASPER-**E**)

(CASPER-**Wind**, **GNOME**, QUAX)

Zero-field NMR



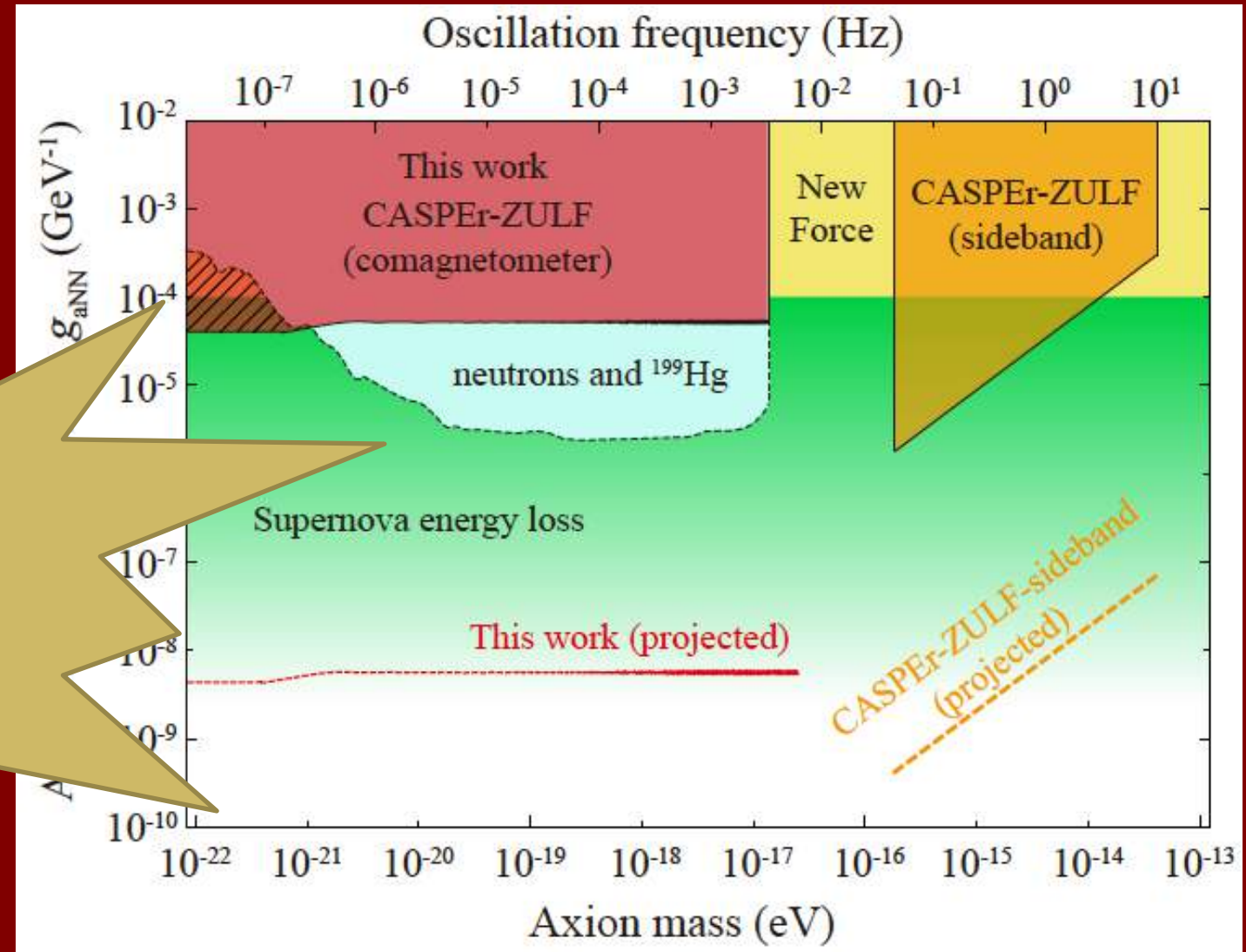
CASPER: NMR based ALP-search program

- ▣ First results (2019!):

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

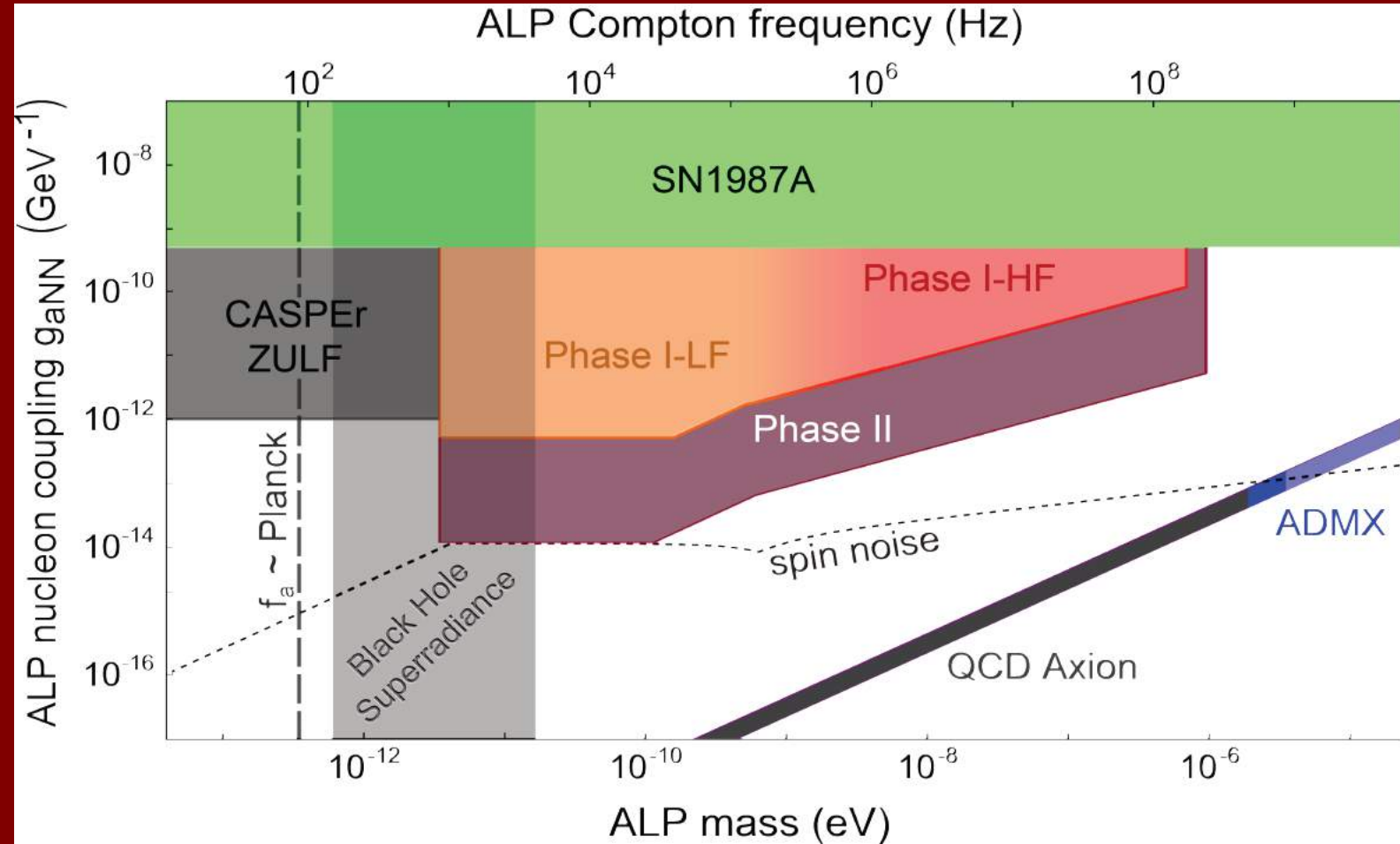
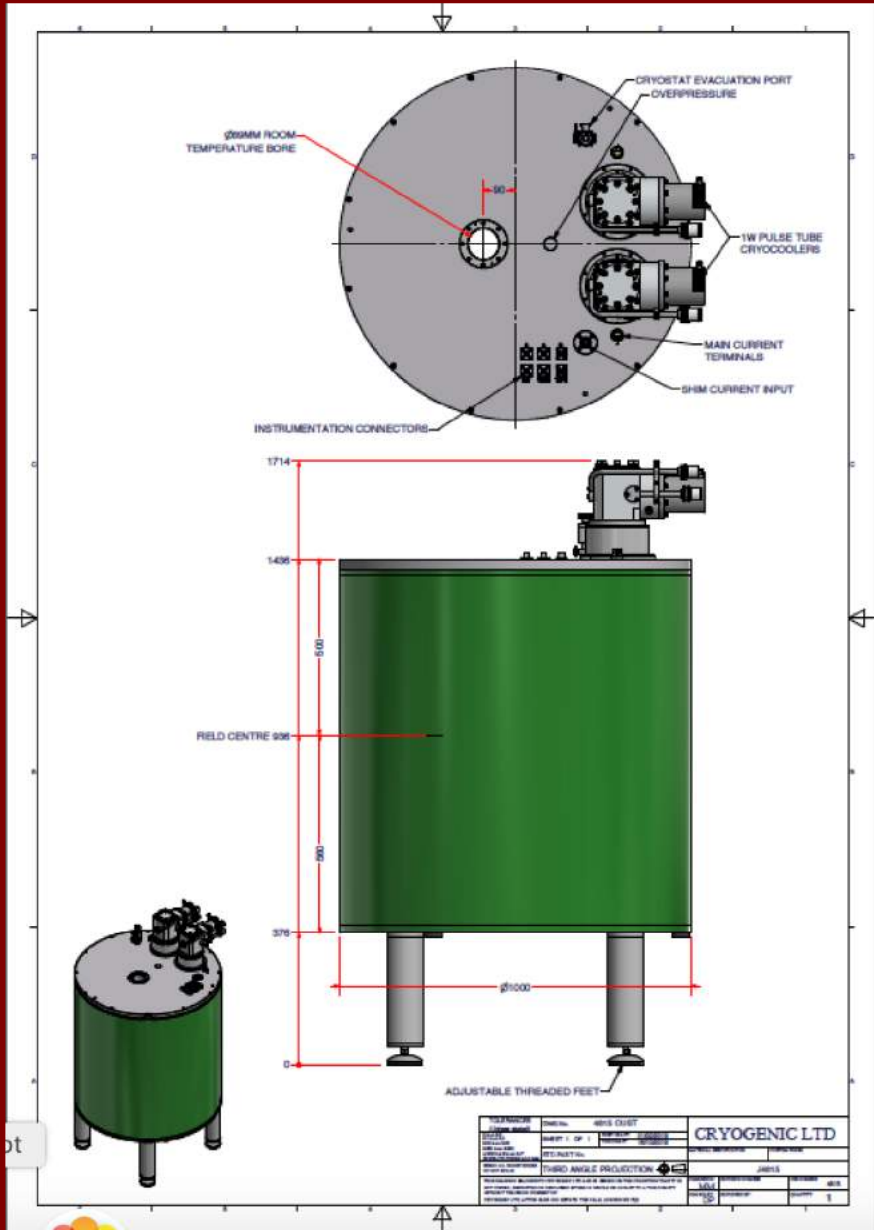
Teng Wu *et al*, **Phys. Rev. Lett.** **122**, 191302 (2019).
[arXiv:1901.10843](https://arxiv.org/abs/1901.10843)

Low-frequency
results should
be taken with
!caution!



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)

CASPER: NMR based ALP-search program

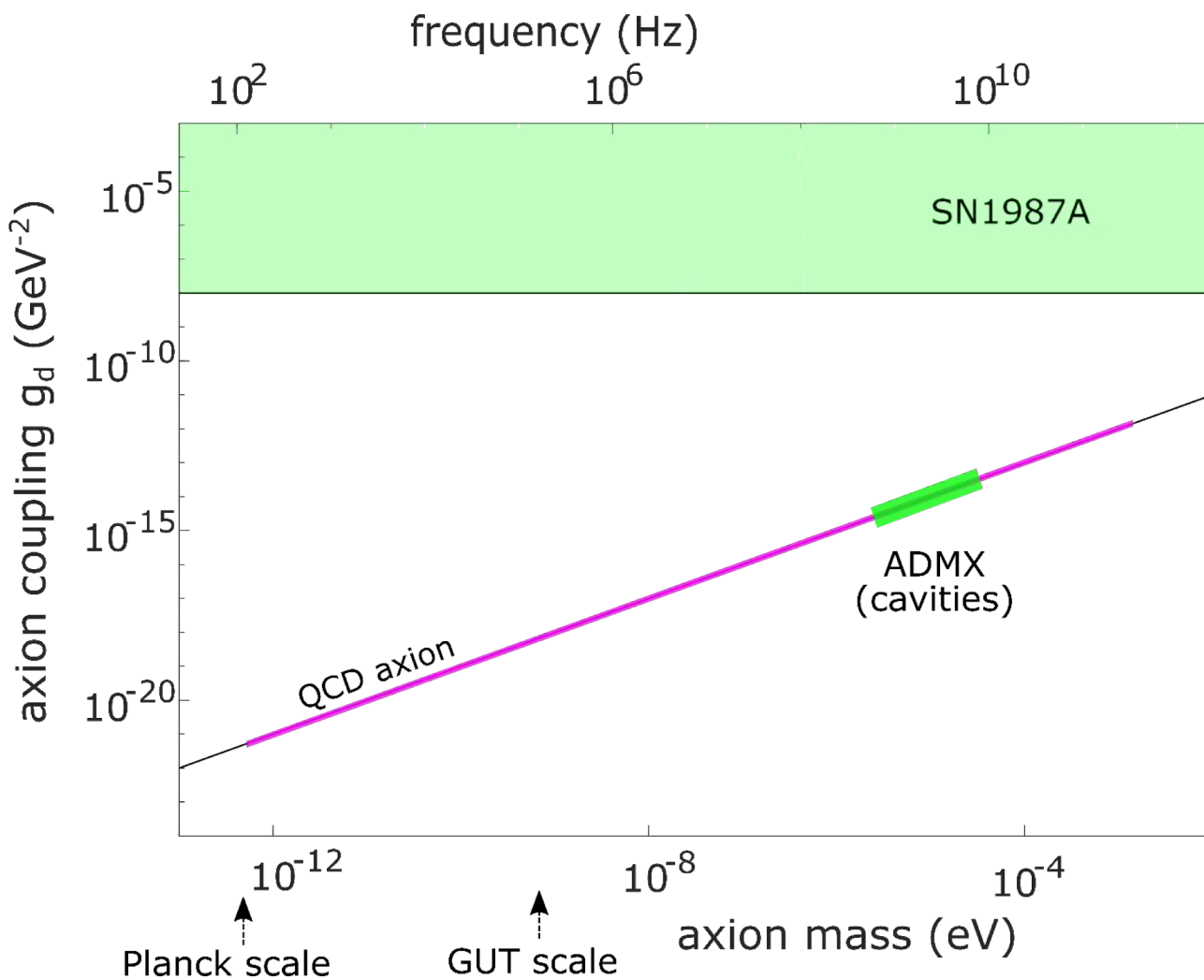
- Higher frequencies: data runs start in 2020!



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

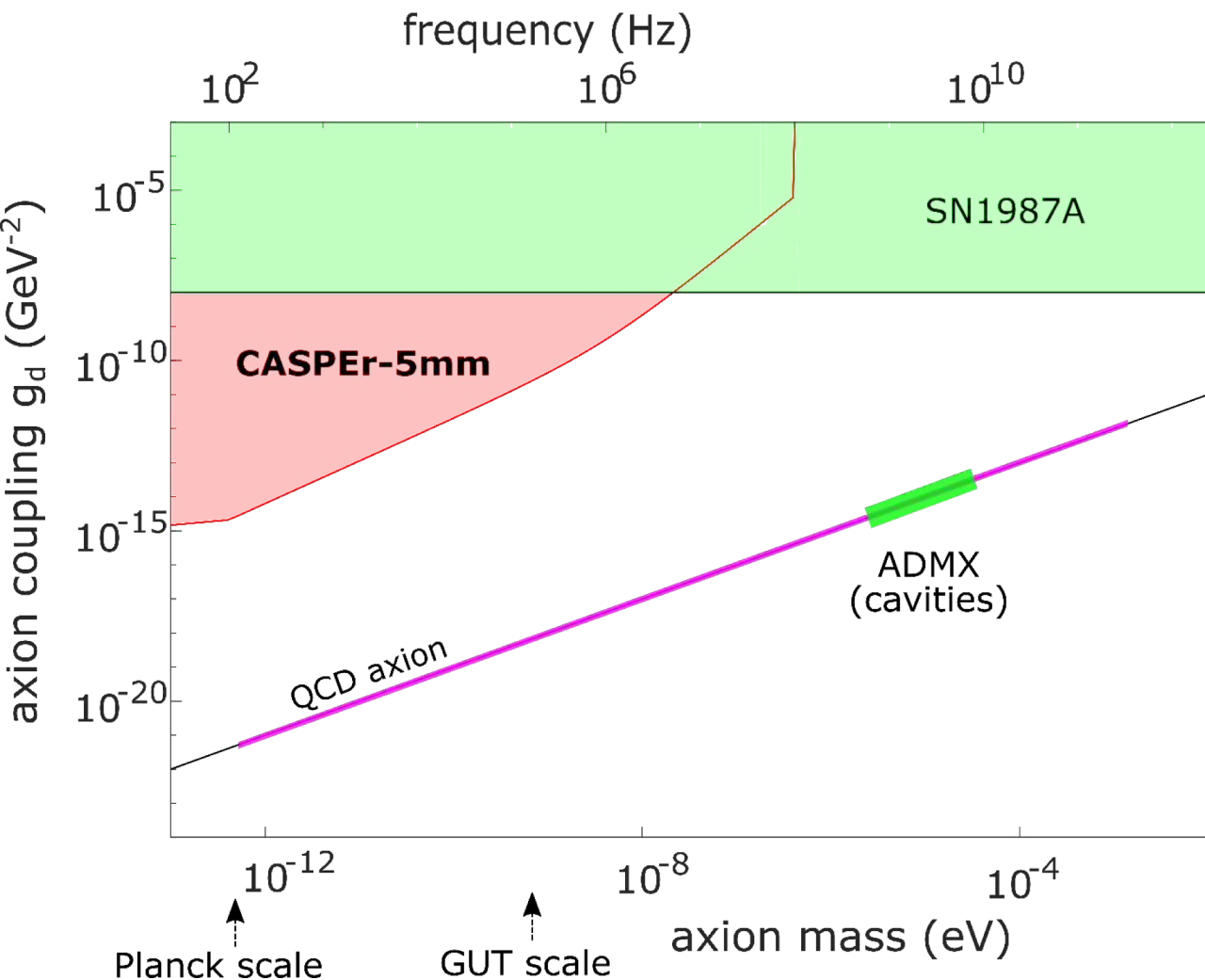


CASPER-e, 5mm





CASPER-e, 5mm

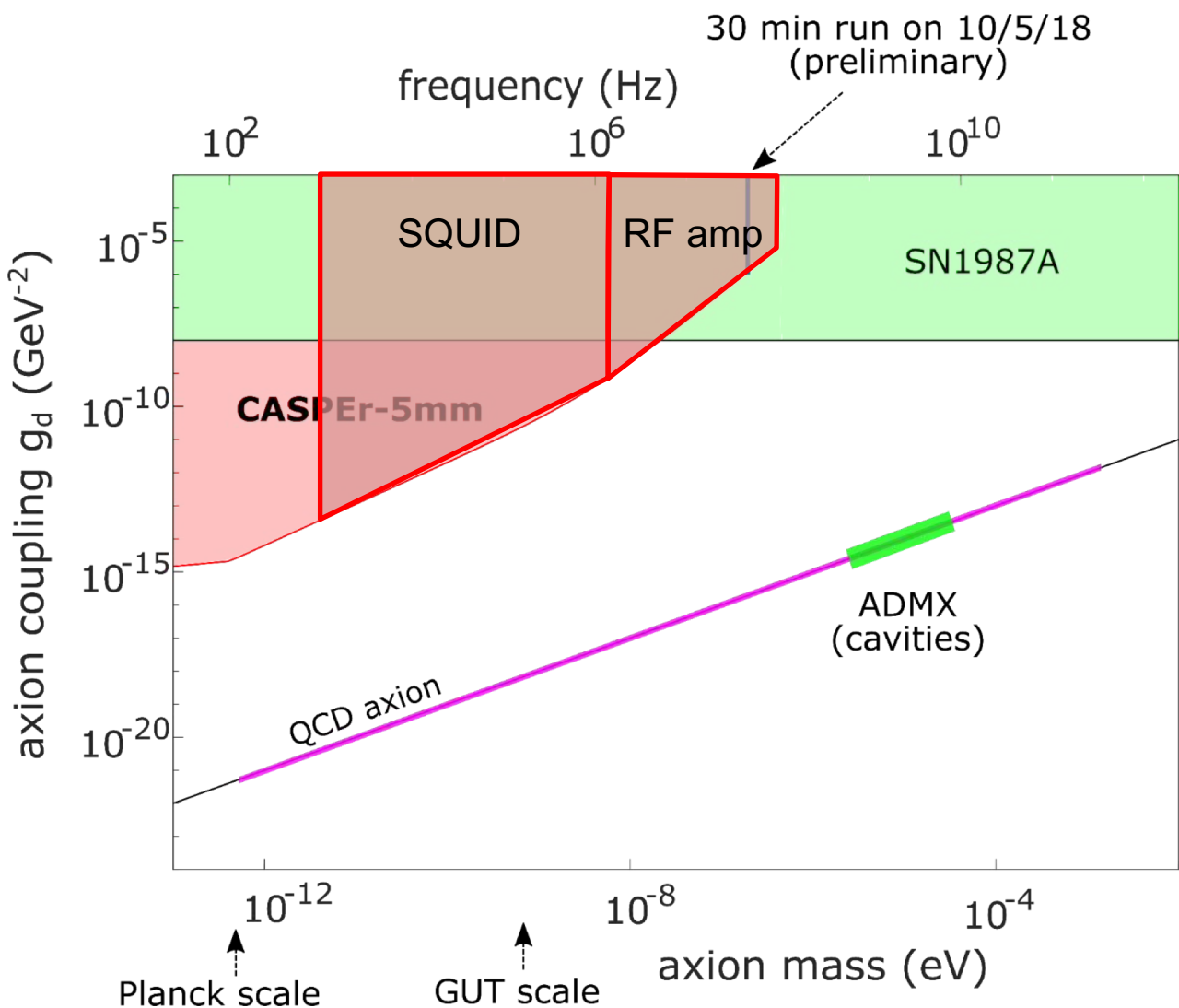


CASPER-5mm at Boston University:

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



CASPER-e, 5mm

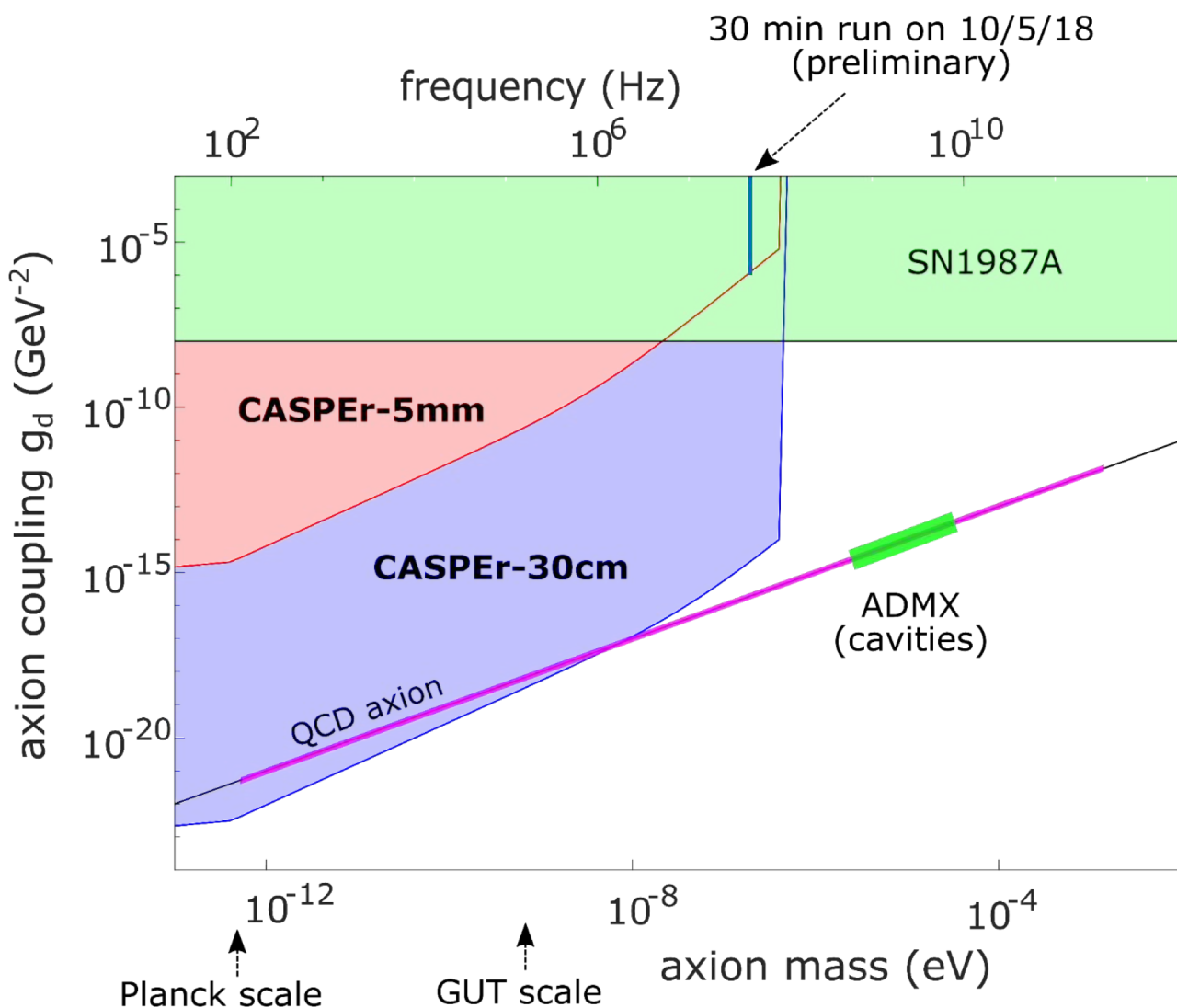


CASPER-5mm at Boston University:

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



The experimental reach of CASPEr-e



CASPEr-5mm at Boston University:

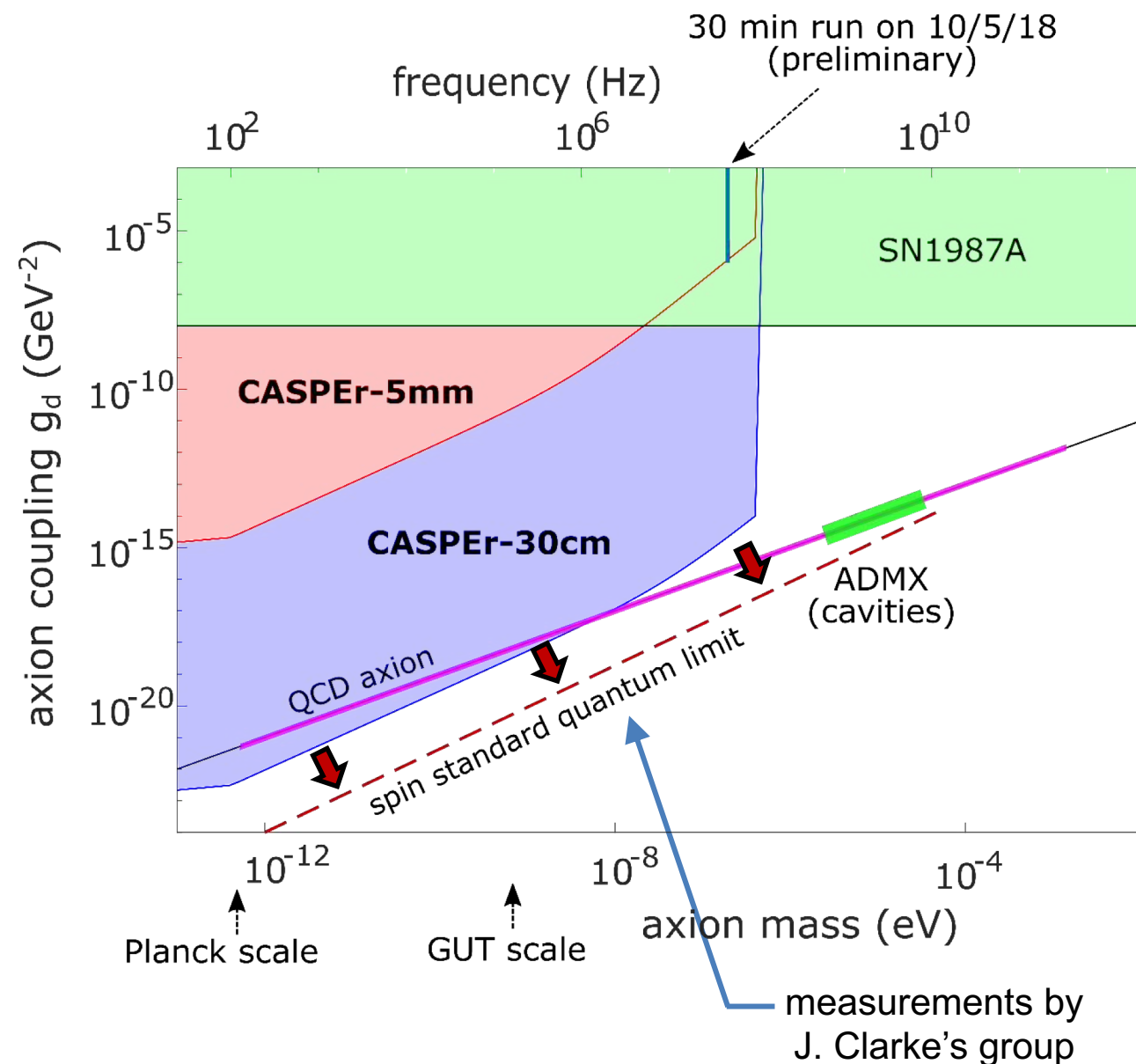
- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm
- pathfinder experiment operational at design sensitivity

CASPEr-30cm:

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



The experimental reach of CASPER-e



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

CASPER-5mm at Boston University:

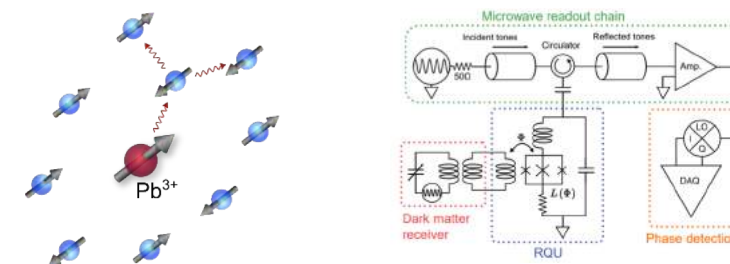
- thermal spin polarization, 4 K
- 5 mm sample size,
- 8T magnet, homogeneity 1000 ppm
- pathfinder experiment operational at design sensitivity

CASPER-30cm:

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

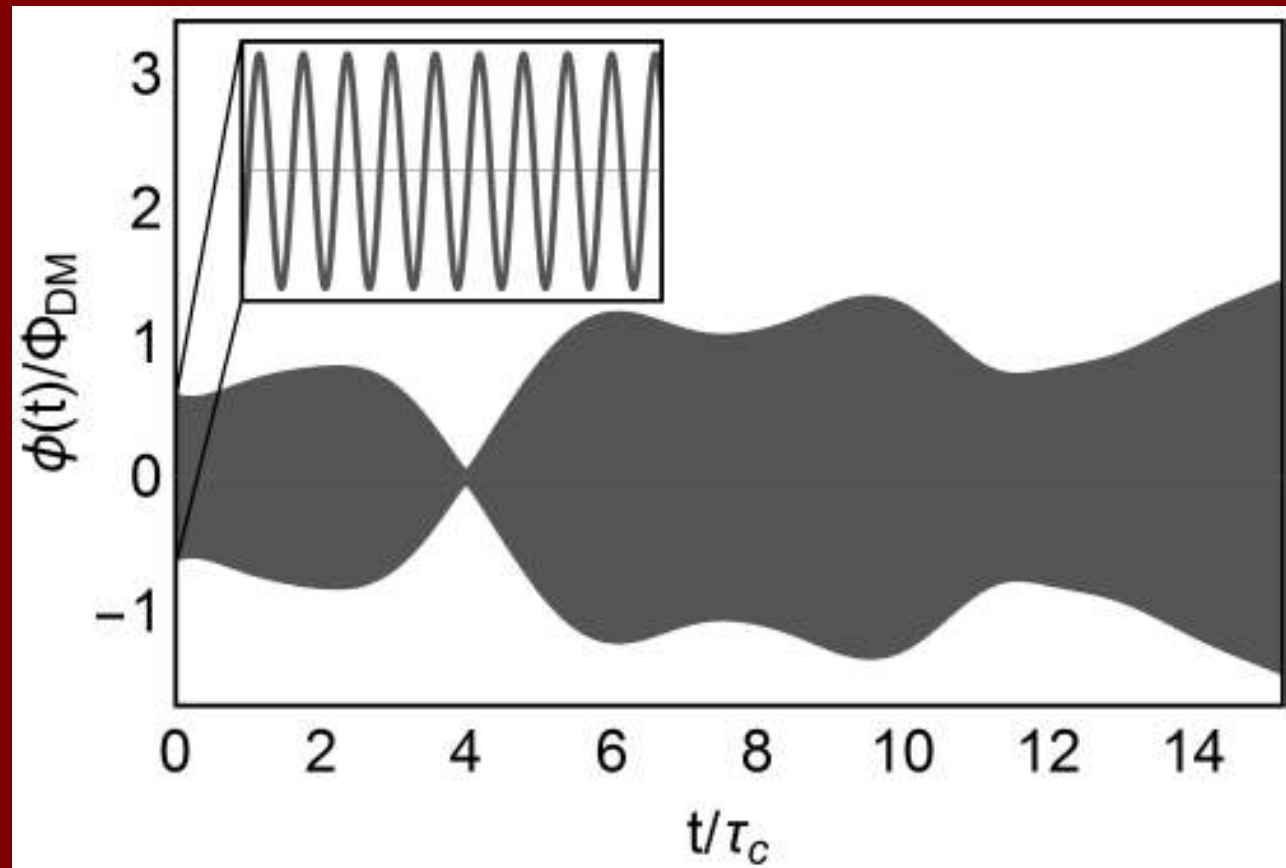
ultimate sensitivity:

- 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

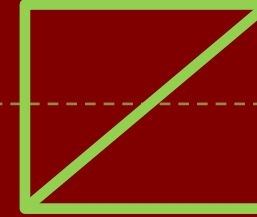


Gary P. Centers et al , [arXiv:1905.13650](https://arxiv.org/abs/1905.13650) (2019)

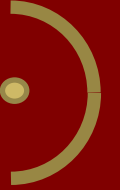
Analogy with chaotic light



Thermal light source



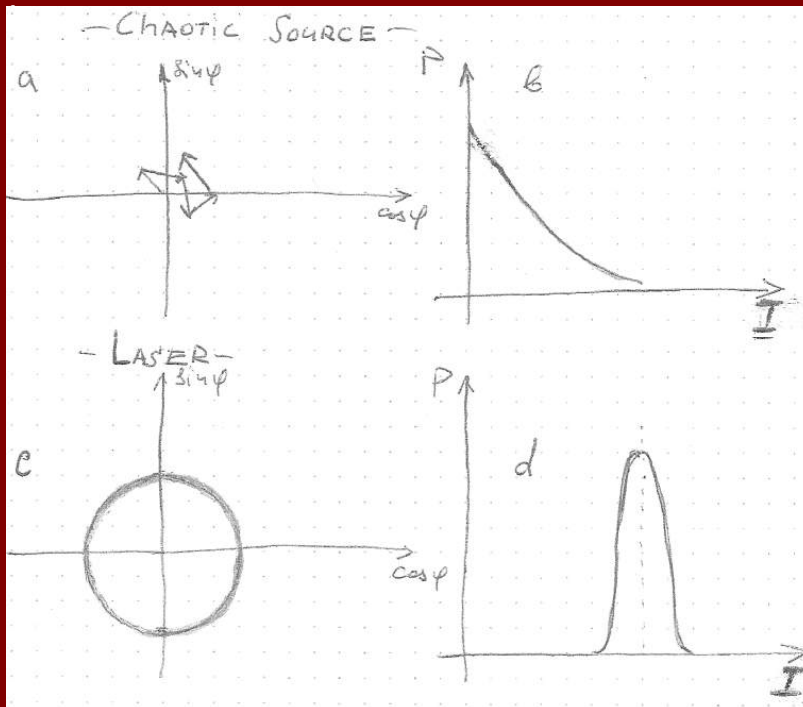
Polarizer



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

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

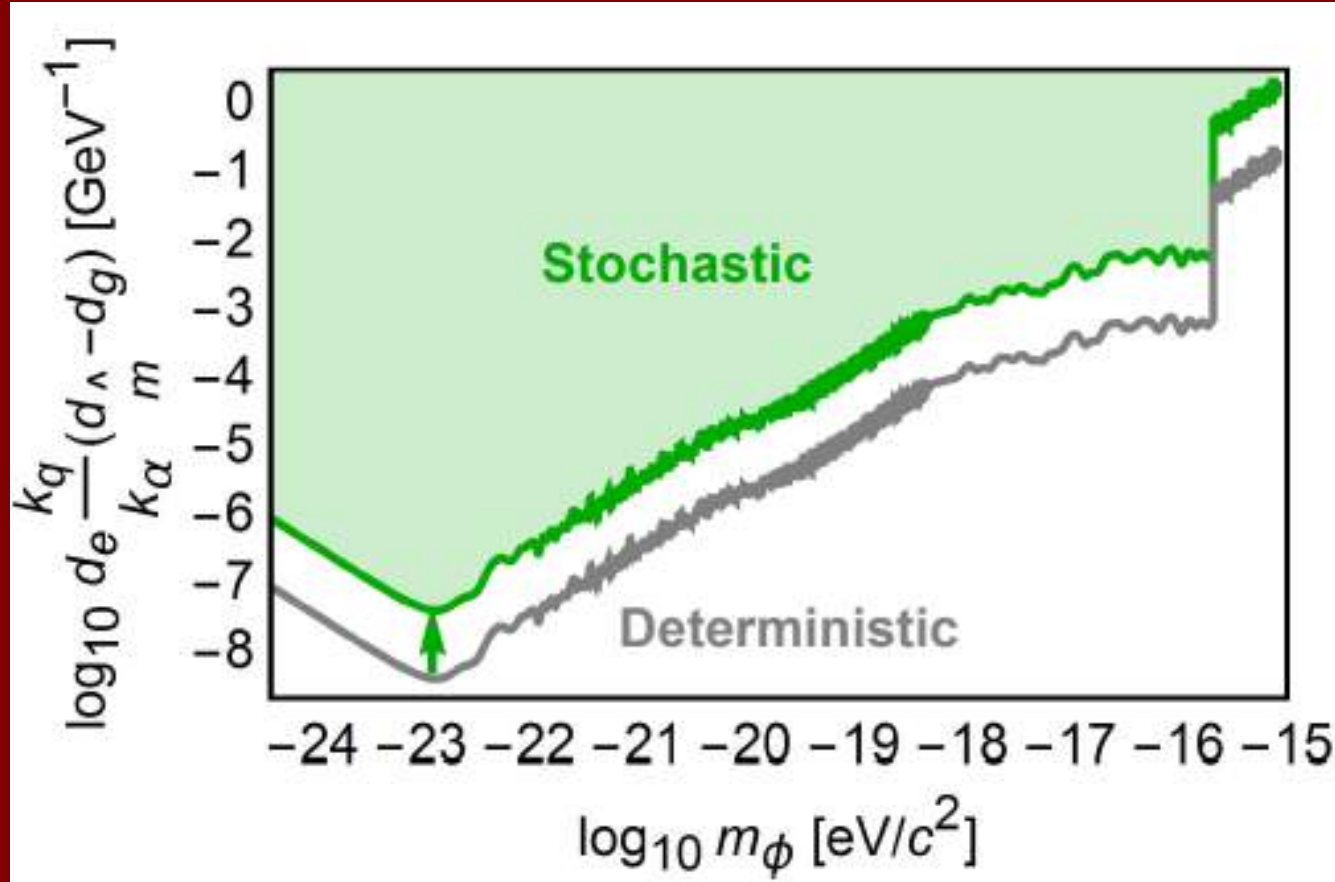
where we have introduced the instantaneous cycle-averaged intensity I , its mean value $\bar{I}$, the *phase angle* φ , and the total field amplitude E , which is non-negative.

We can now convert this into a distribution of cycle-averaged instantaneous intensity by integrating over φ and using the fact that $I \propto E^2$, 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, Joeseeph 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*

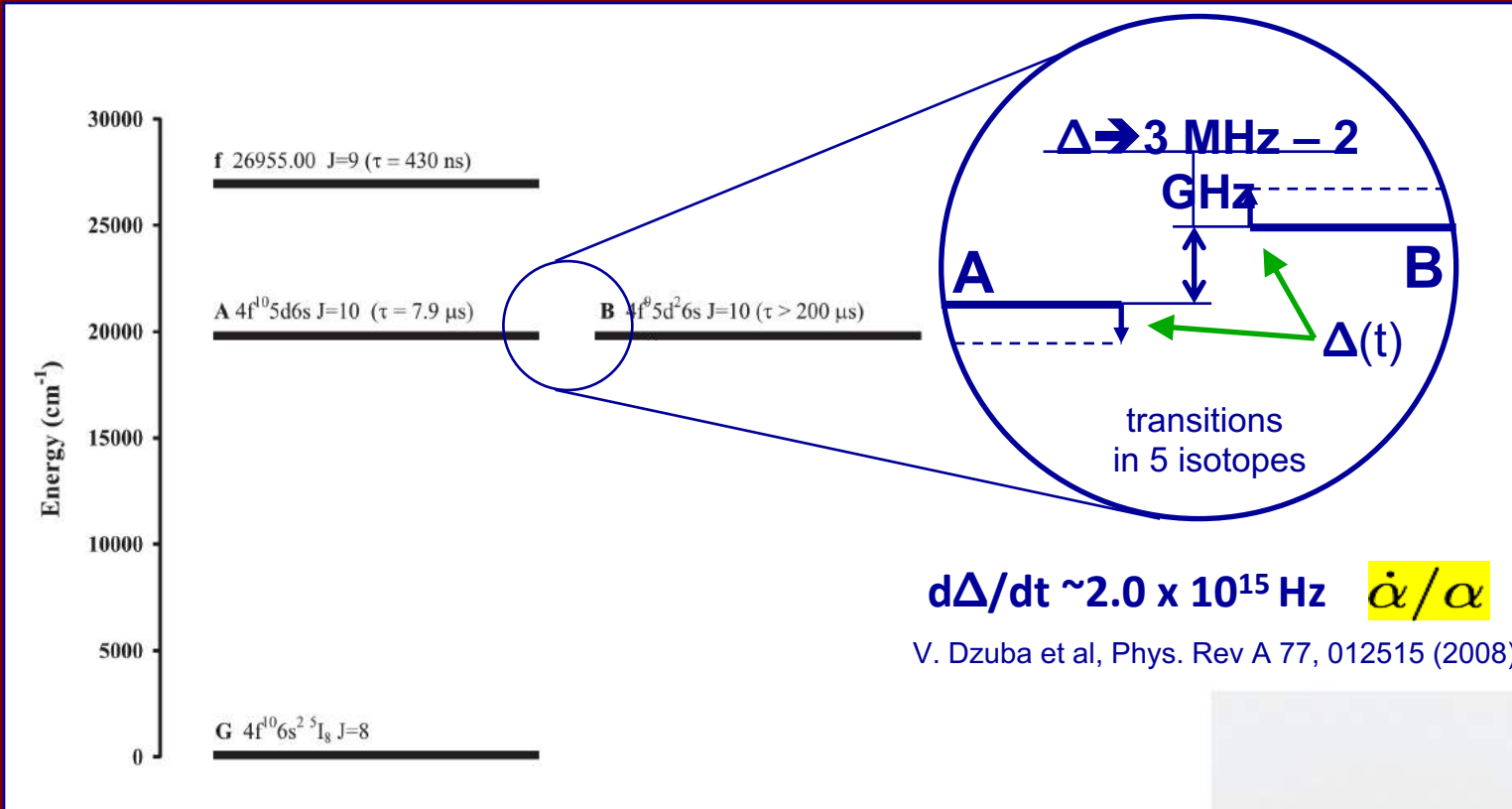
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

Junwu Huang[†] and Ken Van Tilburg[‡]

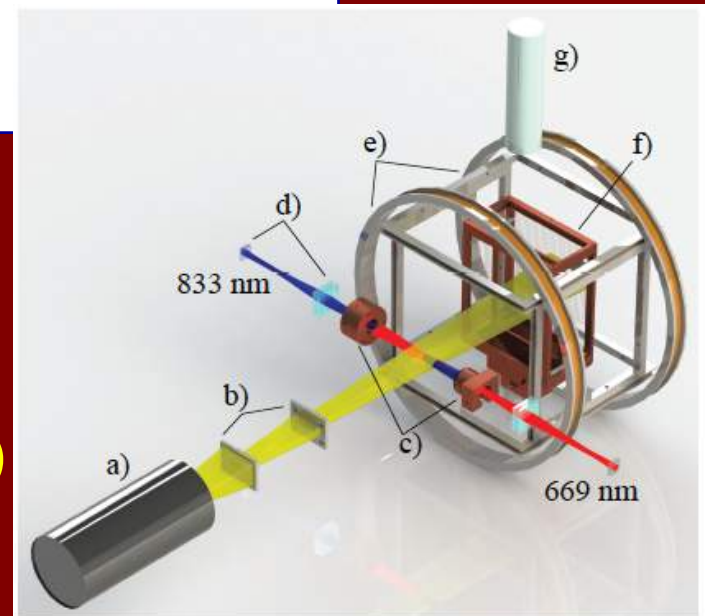
*Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, USA*

(Dated: May 14, 2014)

Dy as “Alpha Variometer”

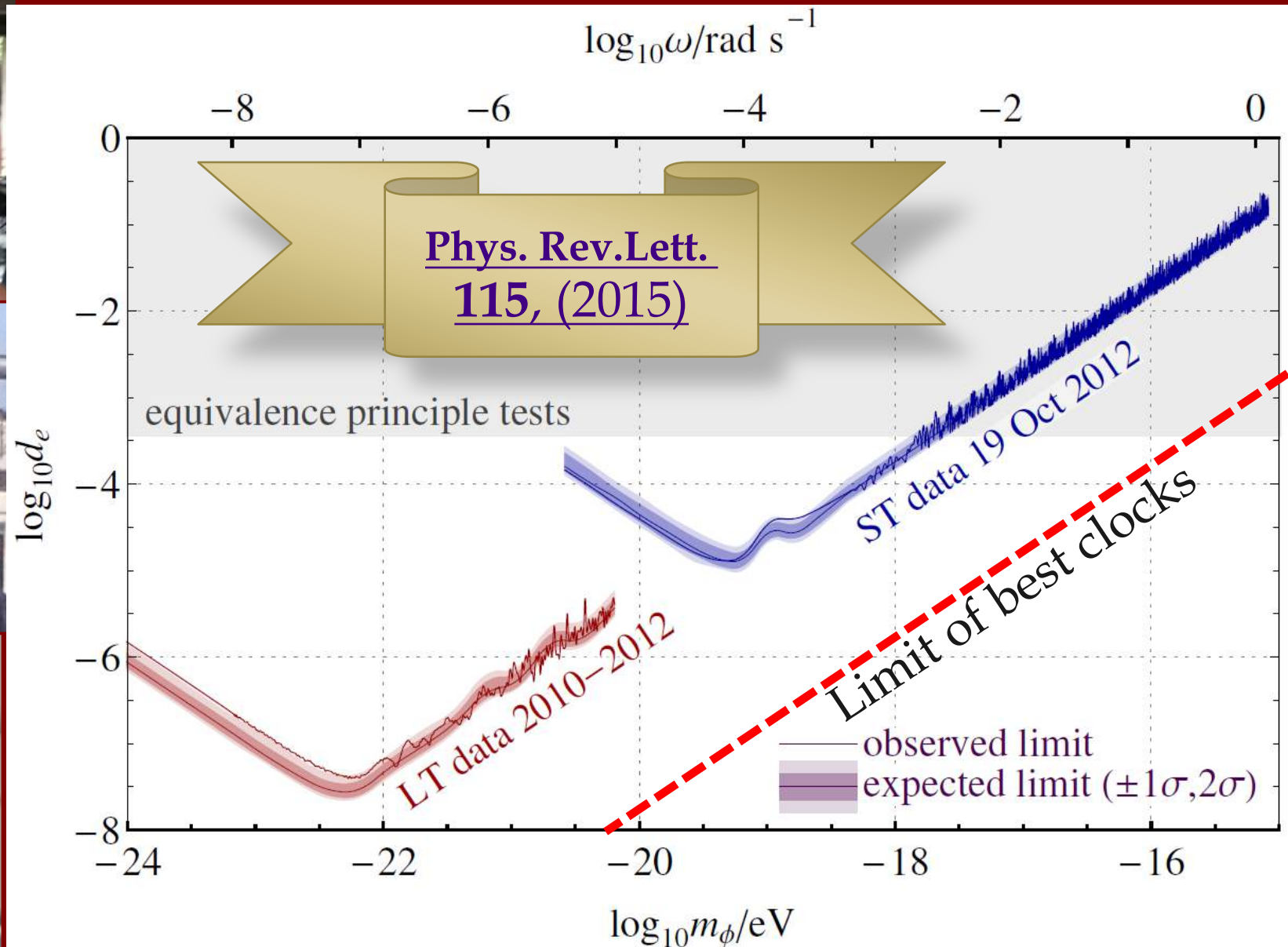


- Limits on alpha variation
- Dependence on gravitational potential
- Lorentz-Invariance violation (for electrons)
- ...



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,§}



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

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



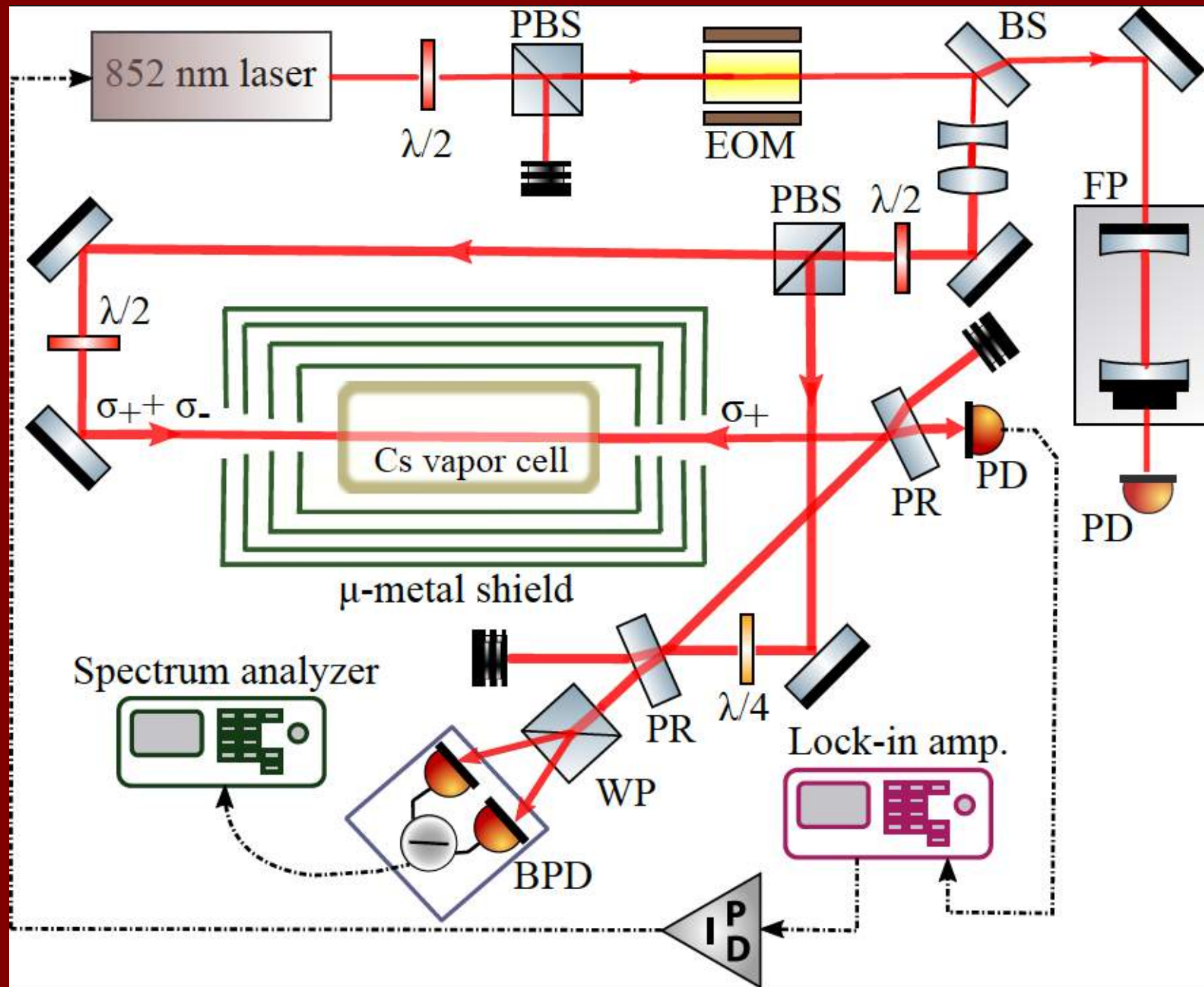
Oleg Tretiak
HIM, JGU Mainz

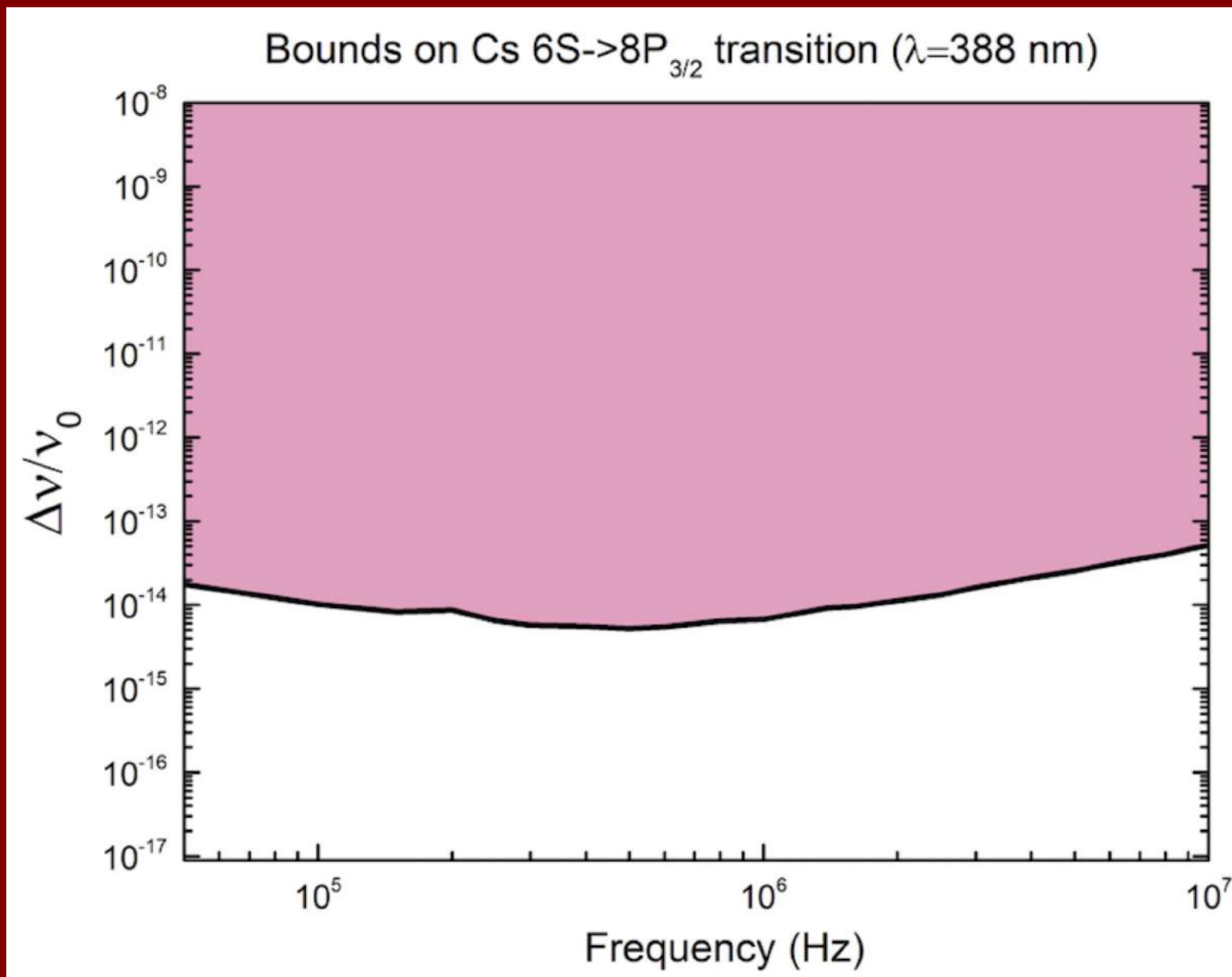


Prof. Roee Ozeri
Weizmann Institute



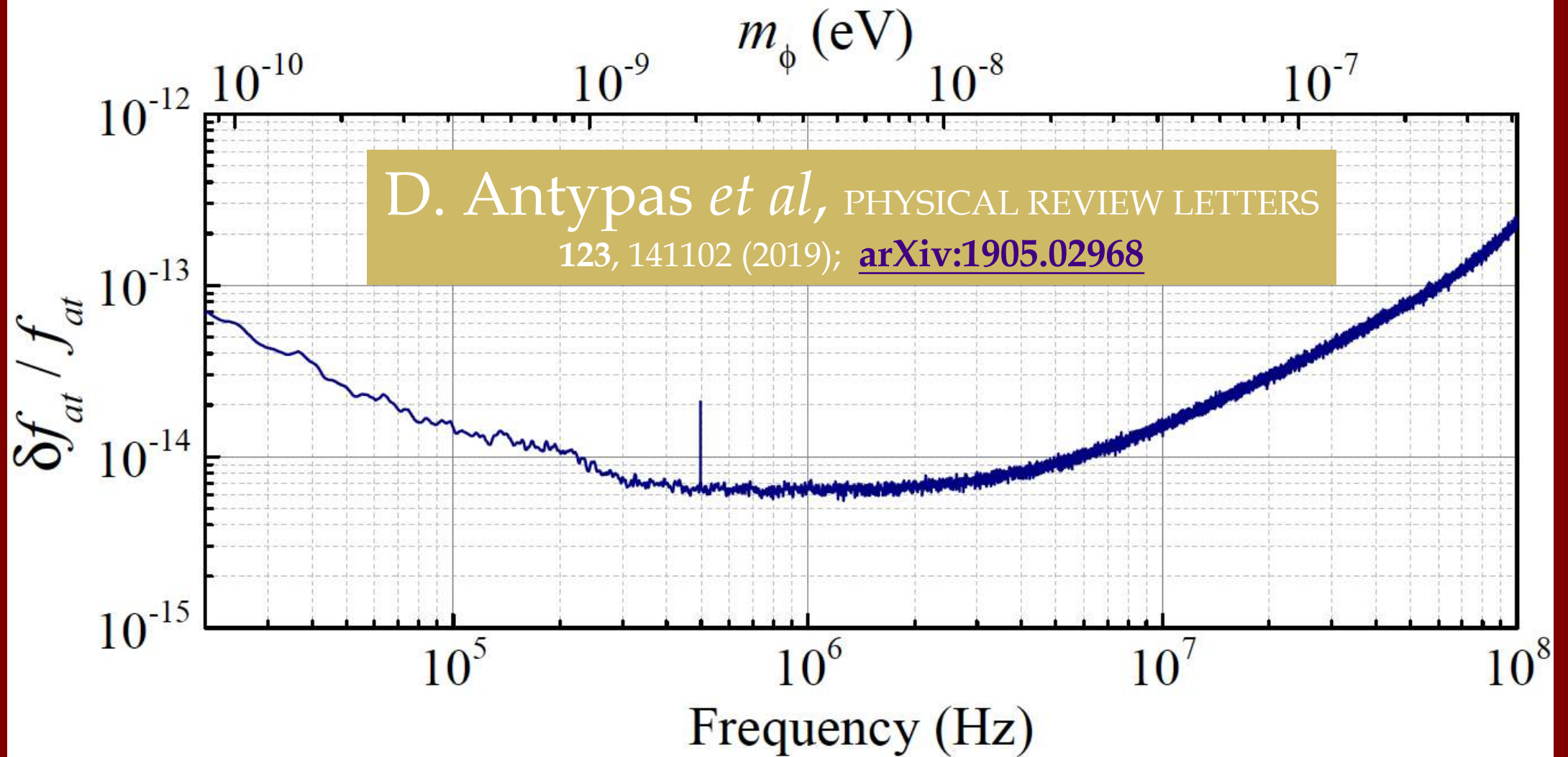
Antoine Garcon
HIM, JGU Mainz





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

Cs D2 line (852 nm)



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

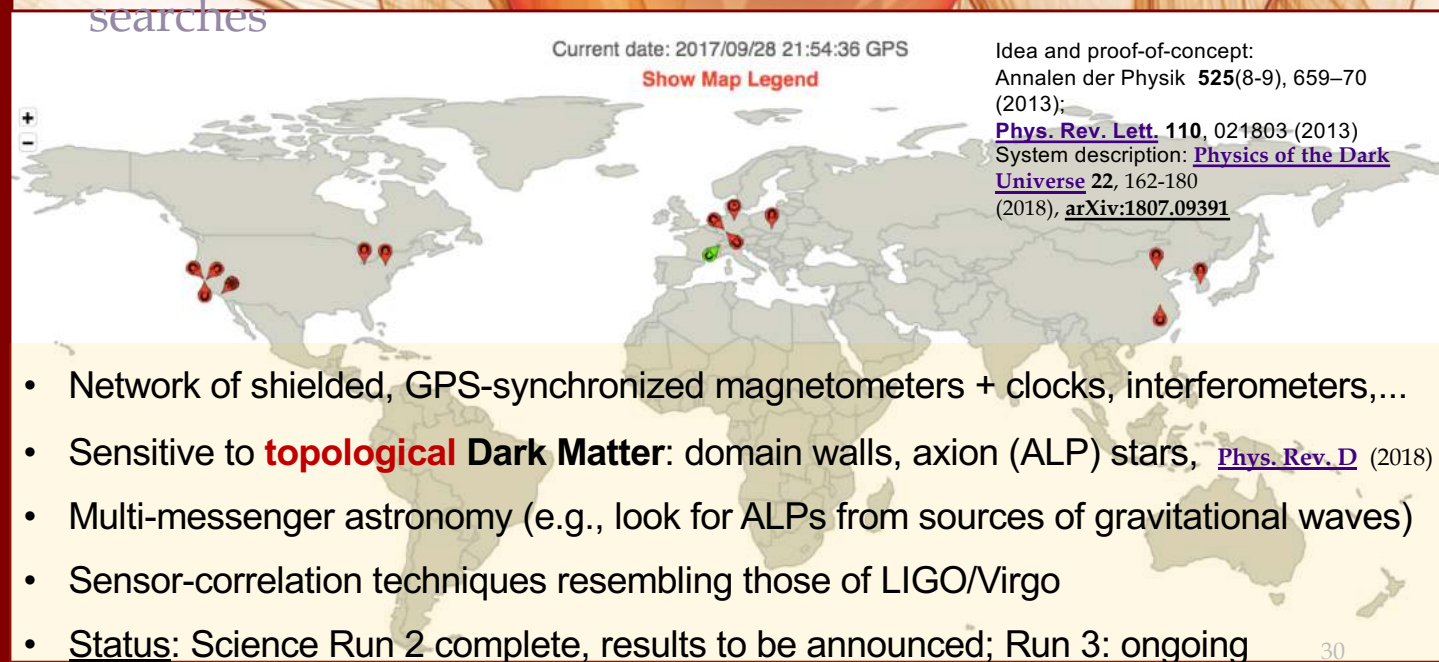
Network searches for topological **DM**



The GNOME Experiment

Collaboration website

Global Network of Optical Magnetometers for Exotic searches



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

Wenxiang Hu¹, Matthew Lawson^{2,3}, Dmitry Budker^{3,4}, Nataniel L. Figueroa³, Derek F. Jackson Kimball⁵, and Allen P. Mills Jr.⁶



- 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:

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

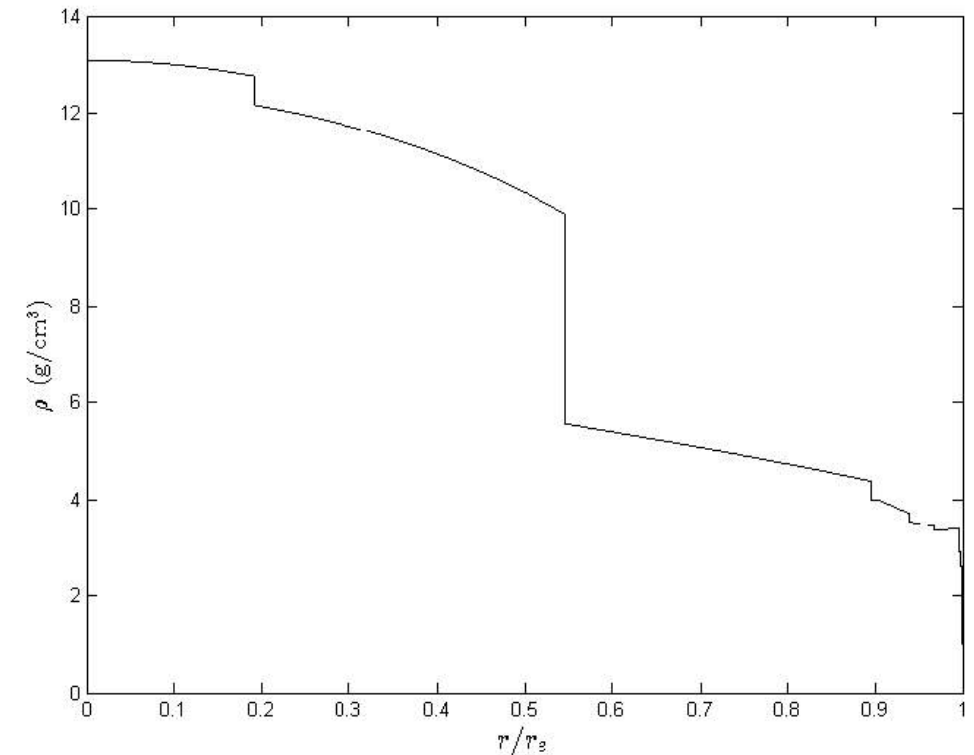


Figure 1: The density profile of the Earth based on the Preliminary Reference Earth model (PREM) [1]. r_e is the radius of the Earth.

Gravimeter Network

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

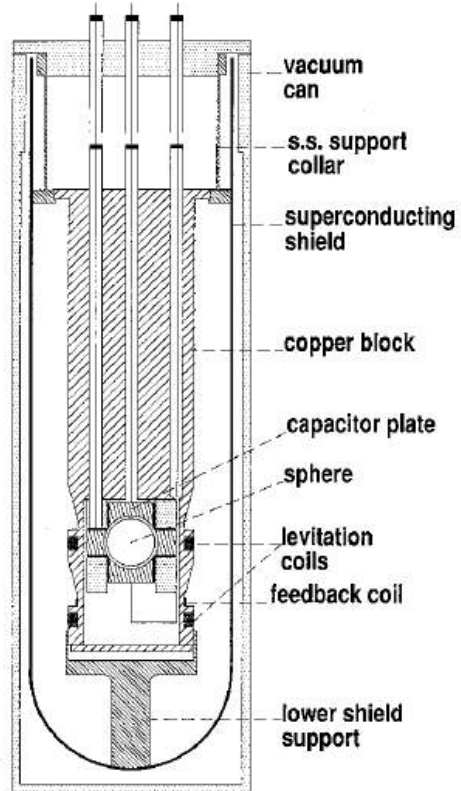


FIG. 1. Diagram of the cryogenic portion of the superconducting gravimeter.

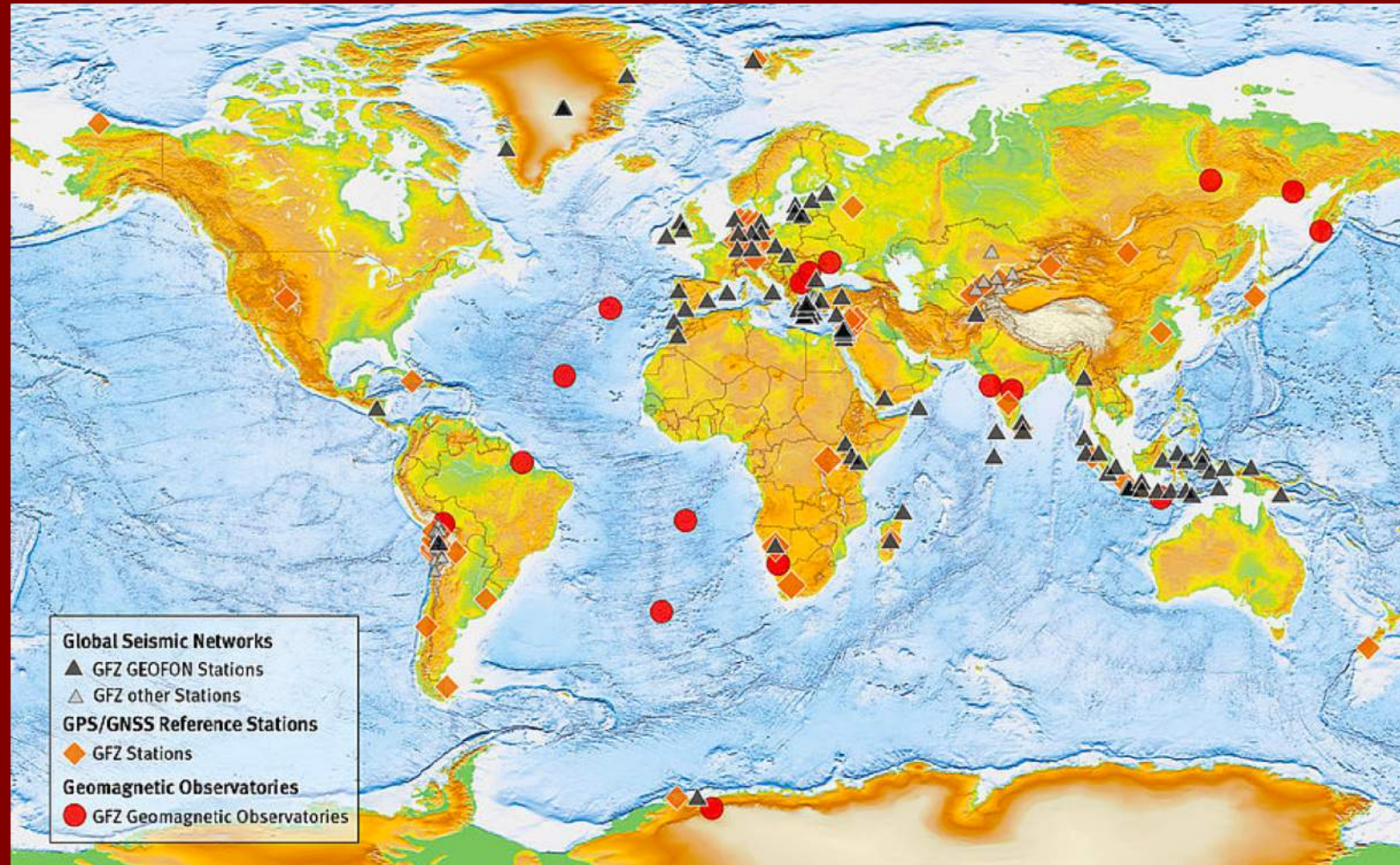


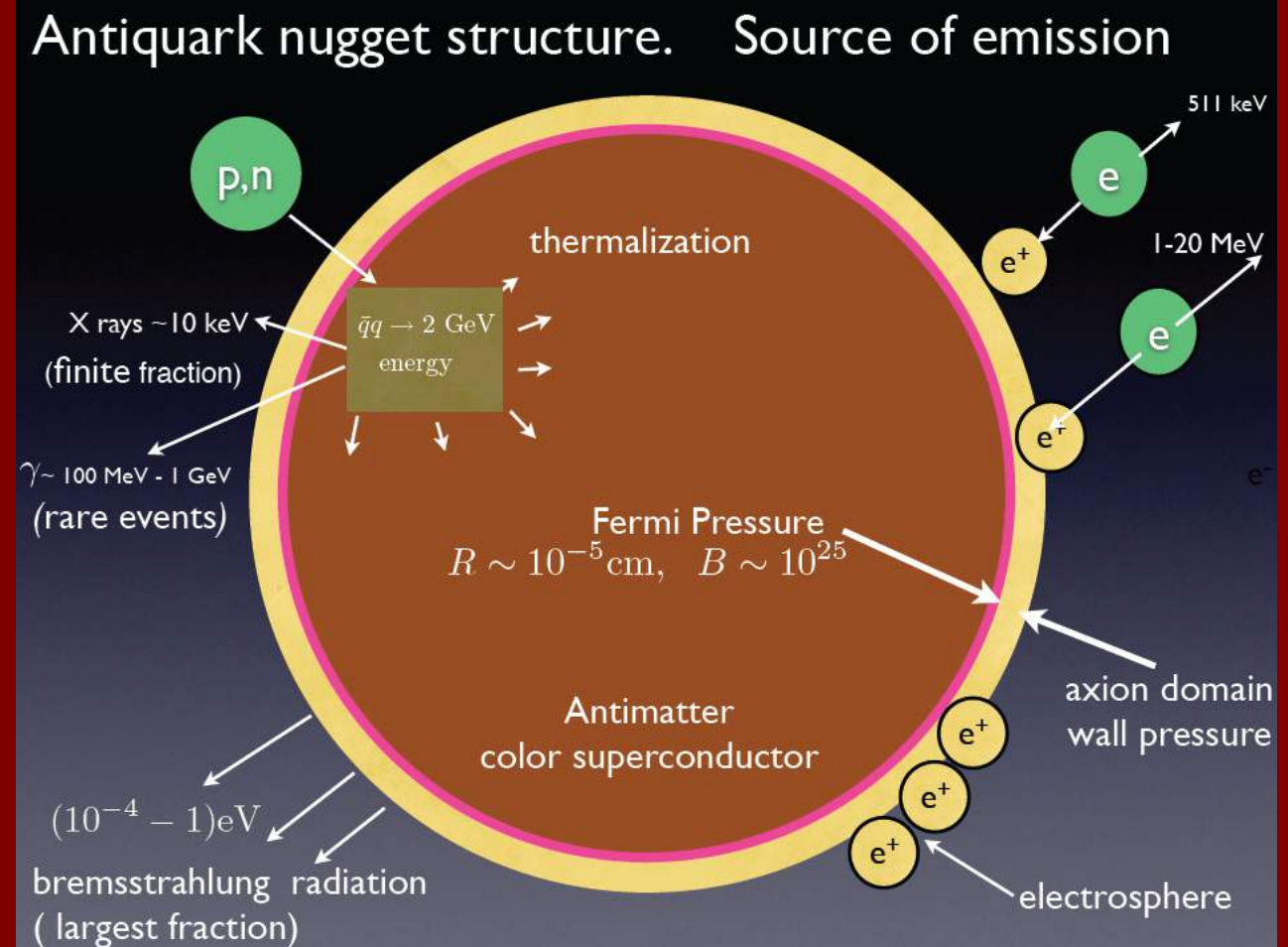
Figure credit: <https://www.gfz-potsdam.de/en/scientific-infrastructure/research-infrastructures/global-observatories/>

A radically different framework



Ariel Zhitnitsky

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*

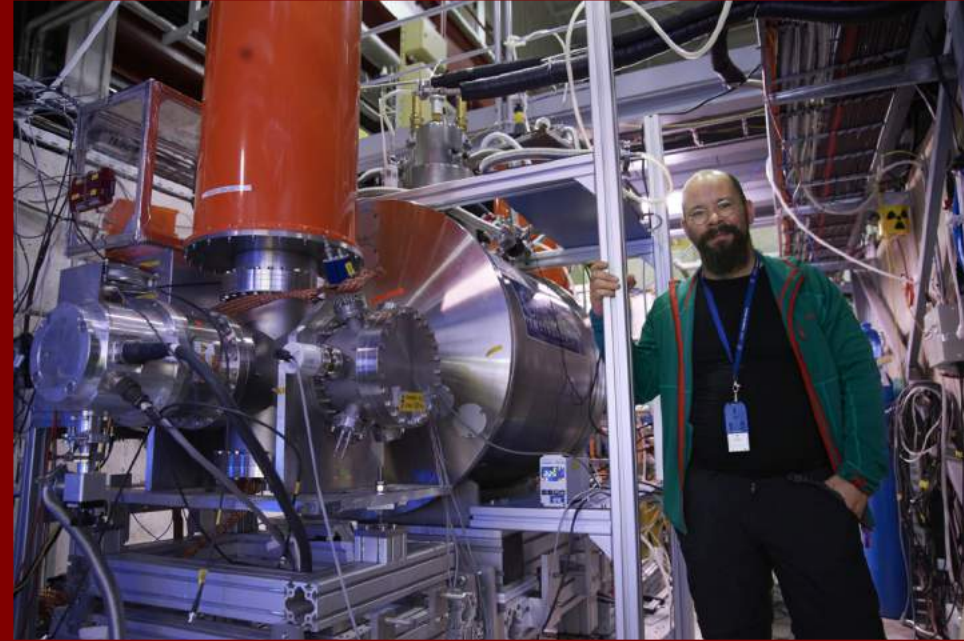
Xunyu Liang[‡] and Ariel Zhitnitsky[§]

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

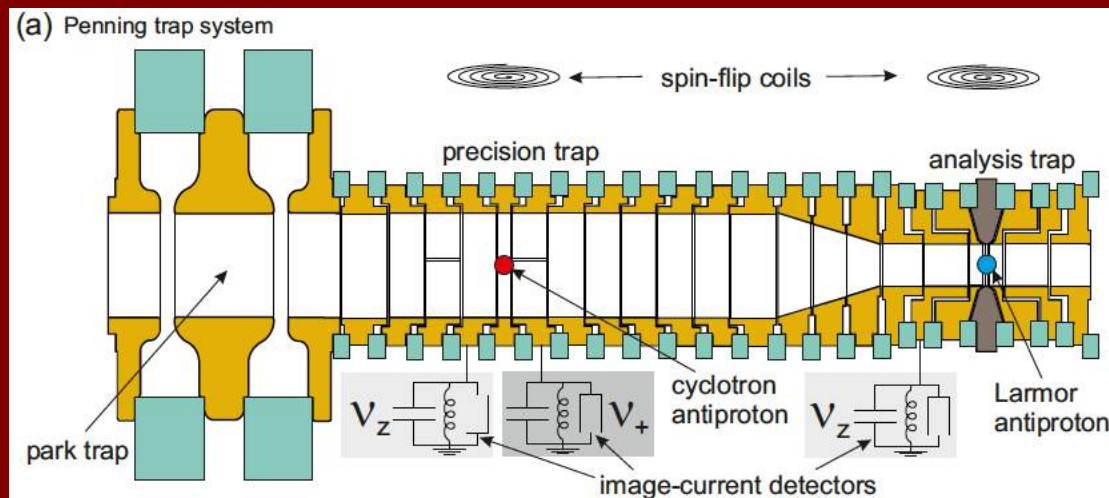
arXiv:1909.09475 (Submitted on 19 Sep 2019)

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**

Possible DM enhancement by Earth and Sun:

Abhishek Banerjee *et al*, Relaxion Stars and their detection via Atomic Physics, [arXiv:1902.08212](#)

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](#)

Novel MASER for DM searches:

Min Jiang *et al*, Floquet-state Maser under Real-time Quantum Feedback Control, [arXiv:1901.00970](#)

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

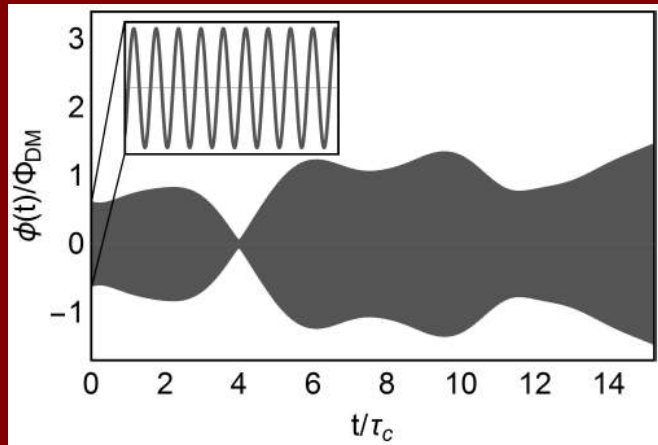
D. Antypas *et al*, A search for light scalar dark matter in the radio-frequency band with atomic spectroscopy, [arXiv:1905.02968](#)

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)

Recent DM searches with (anti)matter

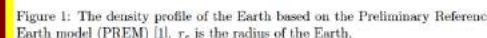
[illegible]

Antiquark Nuggets

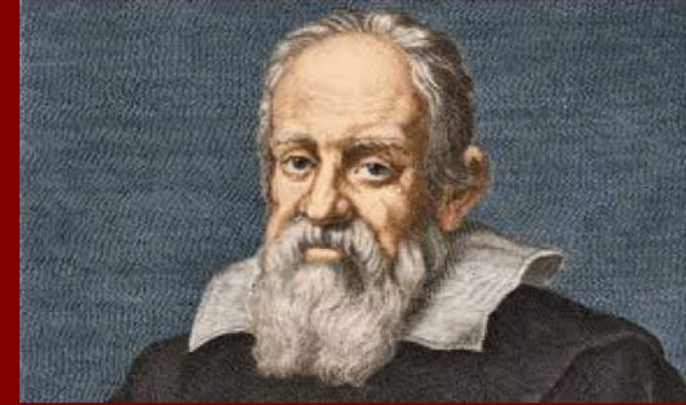
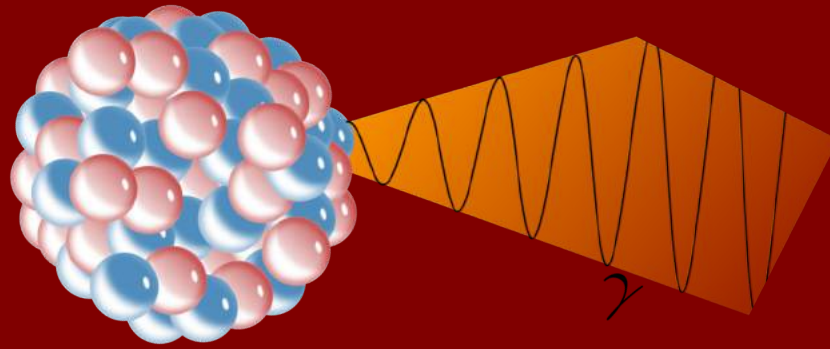
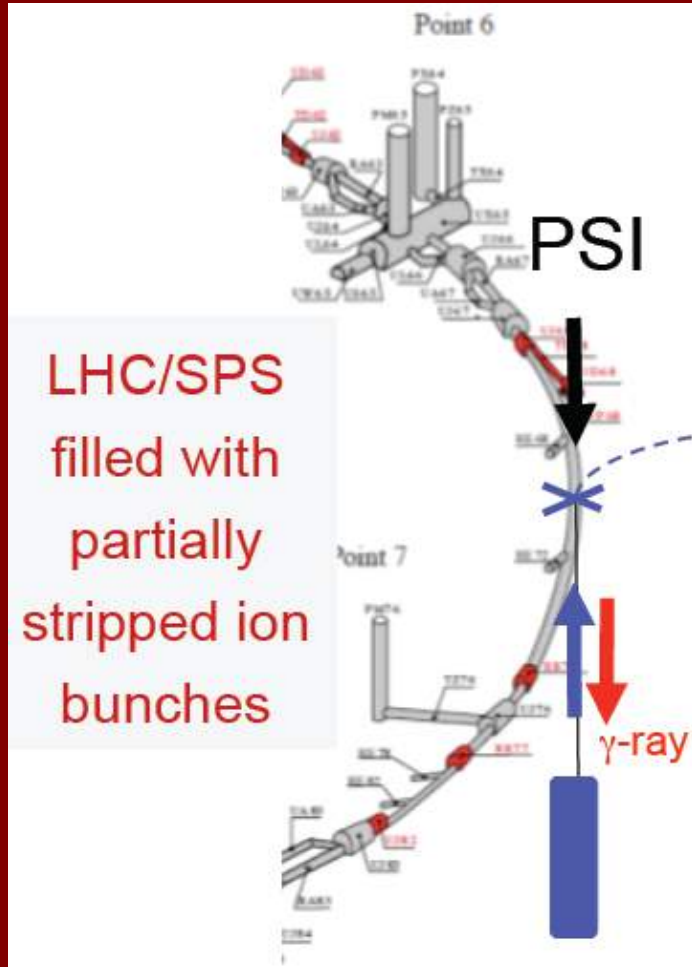
The diagram illustrates the internal structure and emission sources of an antineutron. It is a large sphere with a brown core and a yellow outer shell. The core is labeled "Antimatter color superconductor" and contains "Fermi Pressure" with parameters $R \sim 10^{-5} \text{ cm}$ and $B \sim 10^{25}$. A central box labeled " $\bar{q}q \rightarrow 2 \text{ GeV}$ energy" has arrows pointing outwards, labeled "thermalization". Various emission sources are shown around the sphere:

- Top left: A green circle labeled "p,n" with an arrow pointing to the core.
- Top right: A green circle labeled "e" with an arrow pointing away, labeled "511 keV". Below it, a yellow circle labeled "e⁺" with an arrow pointing towards the core, labeled "1-20 MeV".
- Bottom right: A yellow circle labeled "e⁺" with an arrow pointing towards the core, labeled "axion domain wall pressure". Below it, a yellow circle labeled "e⁺" with an arrow pointing away, labeled "electrosphere".
- Bottom left: Three arrows pointing away from the core, labeled "(10⁻⁴ - 1) eV", "bremsstrahlung radiation", and "(largest fraction)".
- Left side: Two arrows pointing away from the core, labeled "X rays ~ 10 keV (finite fraction)" and " $\gamma \sim 100 \text{ MeV} - 1 \text{ GeV}$ (rare events)".

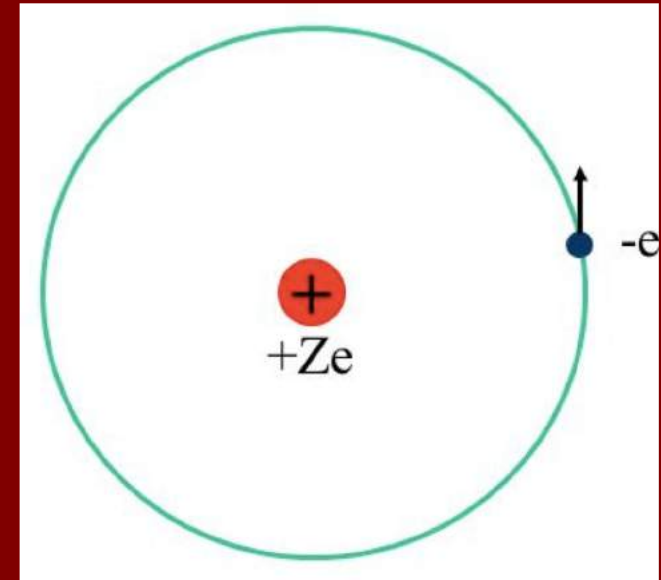
Gravimeters!



37



Atomic Physics with the Gamma Factory



Dmitry Budker

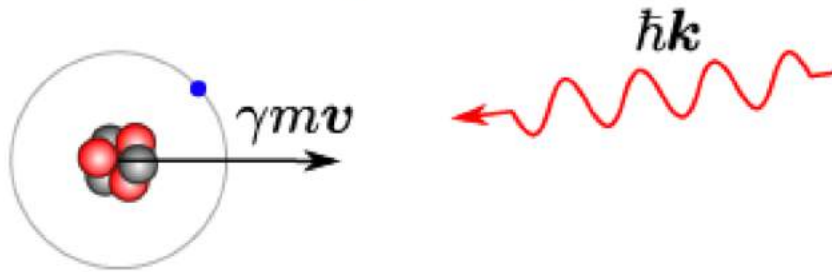
Helmholtz Institute, JGU Mainz & UC Berkeley, Physics

CAPP, Daejeon, November 2019

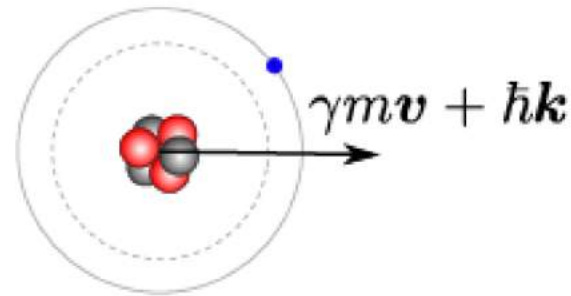
Photon scattering on relativistic ions

In the laboratory reference frame:

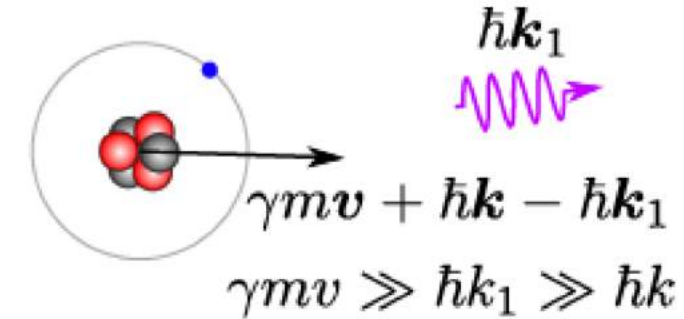
Before photon absorption



Excited ion



After photon emission

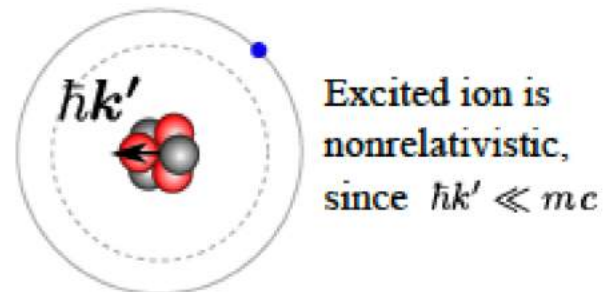


In the initial ion reference frame:

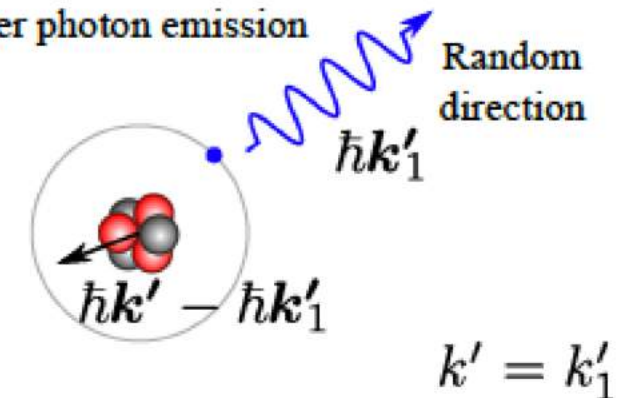
Before photon absorption



Excited ion

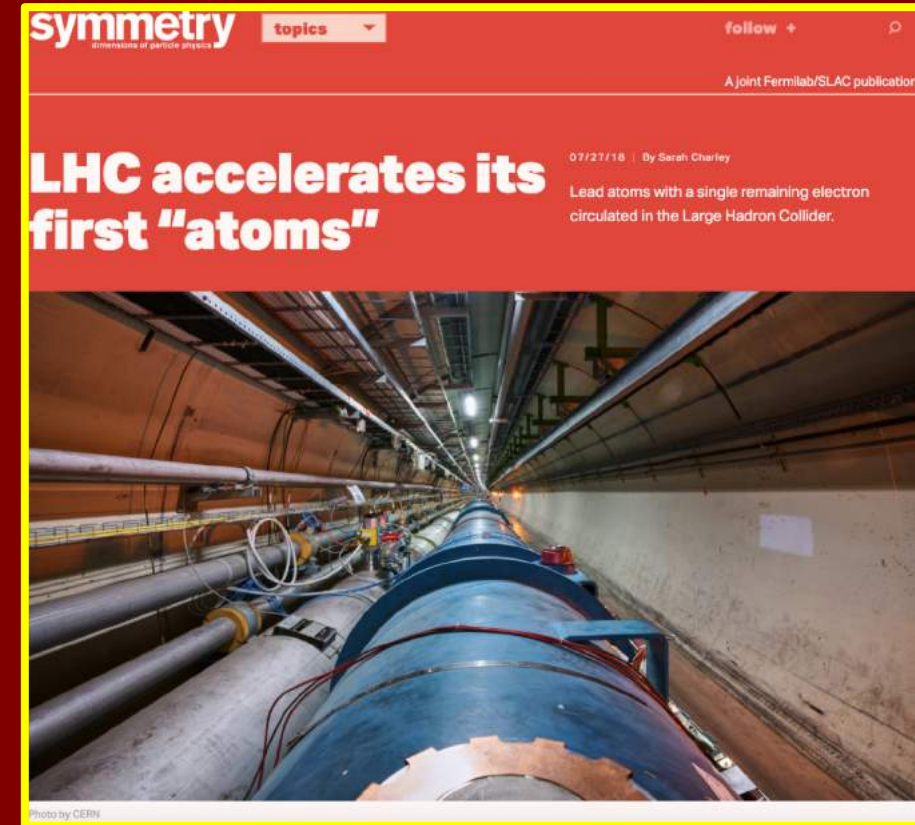


After photon emission



Summary:

- ▣ Gamma Factory: primary and secondary beams
- ▣ Spectroscopy of partially stripped ions (PSI)
- ▣ Tests of fundamental symmetries
- ▣ Neutron skins
- ▣ Spin-polarized PSI
 - ▣ Fundamental physics
 - ▣ Beam-dump
 - ▣ Quark-gluon plasma from spin-polarized ion collisions?
- ▣ Vortex-beam x-rays and gamma-rays
- ▣ Photon scattering



Atomic physics studies at the Gamma Factory

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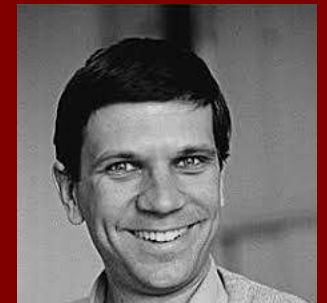
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How to make discoveries?

Following Galileo:

- New instrumentation and techniques
- New ideas



Summary:

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