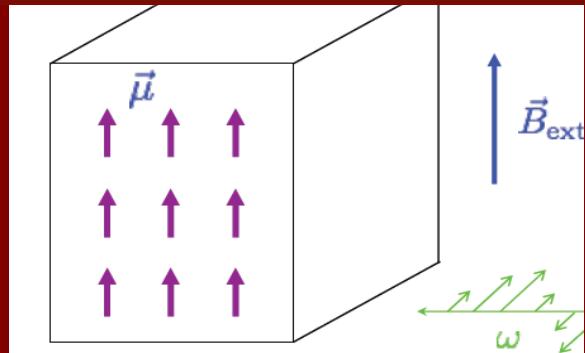


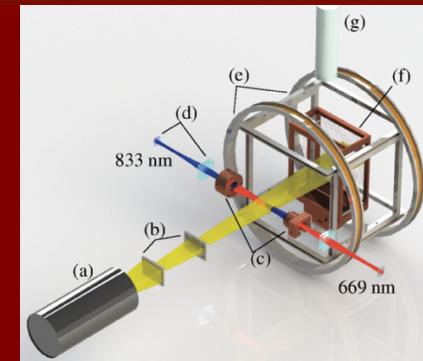
SEARCHING FOR ULTRALIGHT DARK MATTER

WITH

nuclear resonance & atomic spectroscopy



Dmitry Budker
Helmholtz-Institute Mainz
UC Berkeley Physics



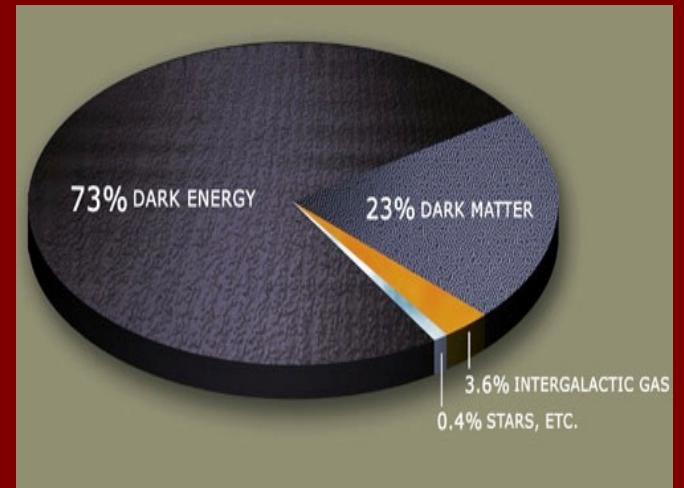
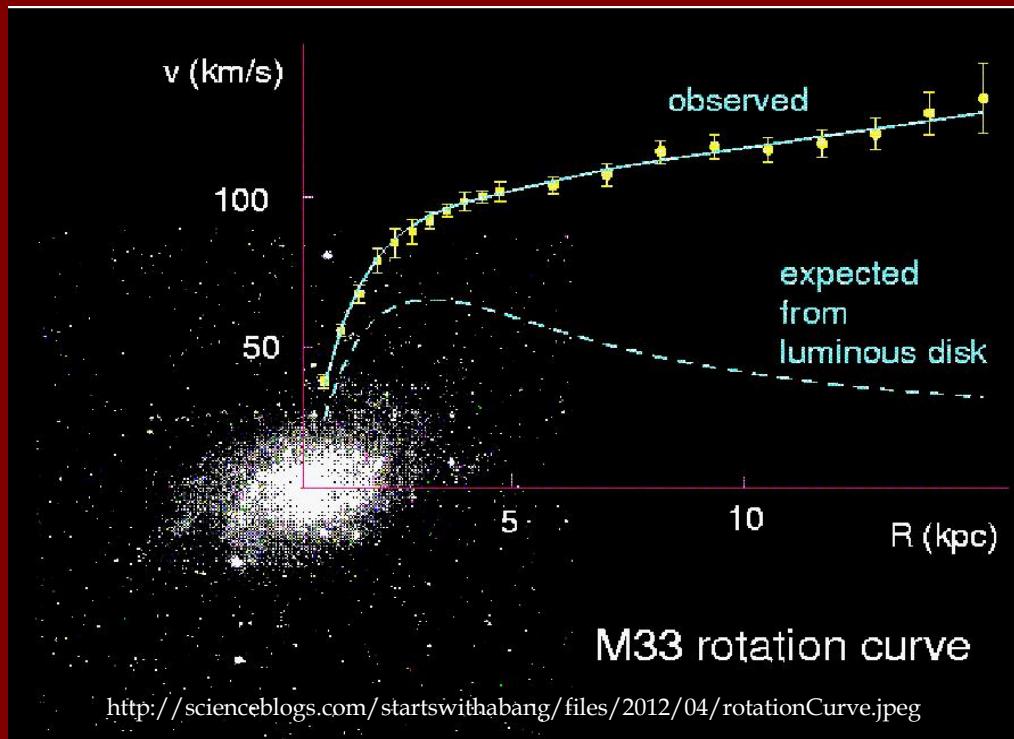
Seminar organized within the project: "Hunt for the "impossible atoms": the quest for a tiny violation of the Pauli Exclusion Principle. Implications for physics, cosmology and philosophy,"
ID 58158, funded by the John Templeton Foundation

Frascati, May 15, 2017



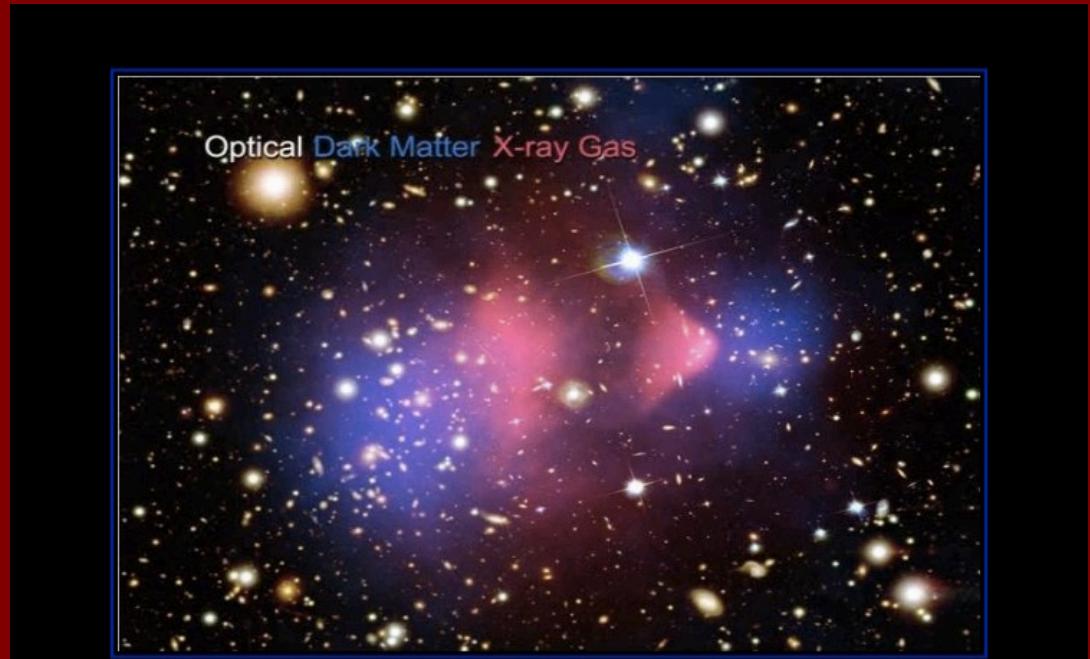
Houston, we've got problems...

1. What is $> 80\%$ of matter ?



IS IT POSSIBLE...

- ...there is no DM, but we do not get gravity?
- Perhaps, not



DARK MATTER

Most of the universe can't even be bothered to interact with you.

[Sean Carroll's blog](#)

So what is DM ?

- A gross misunderstanding of gravity (MOND, ...) ☹?
- Black holes, dark planets, interstellar gas, ... ☹
- WIMPS ☺
- Ultralight bosonic particles
 - Axions (pseudoscalar) ☺
 - ALPs (pseudoscalar) ☺
 - Dilatons (scalar) ☺
 - Vector particles ☺
 - Tensor particles ???

“Most Wanted” file on DM What do we know?

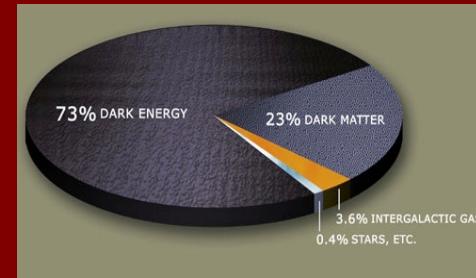
- Galactic DM density: $\sim 0.4 \text{ GeV/cm}^3$ (10 GeV/cm^3 d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be **bosonic** if $m < \sim 20 \text{ eV}$ (1 keV dwarf galaxies) 
- Cannot be lighter than $\sim 10^{-22} \text{ eV}$
- ... (e.g., BEC ?)

The plan

- ✧ How to search for axions (or Axion-Like Particles) ?
- ✧ Cosmic Axion Spin Precession Experiment
- ✧ Global Network of Optical Magnetometers for
Exotic physics searches
- ✧ Dilatons
- ✧ Scalar sourcing by masses
- ✧ Cosmic Parity Violation
- ✧ Dark Sector searches and fundamental symmetries
- ✧ Conclusions

Why Axions (ALPs) ?

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



<http://earthsky.org/space/>

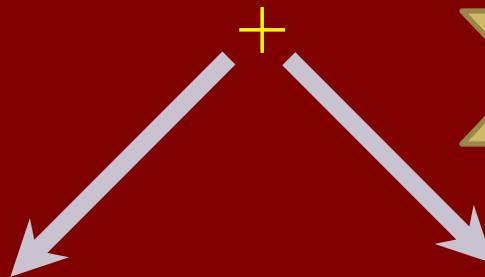
How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

P. Graham
S. Rajendran

2017
New Horizons
In Physics
Prize



Gauge Fields

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

Most
Searches

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

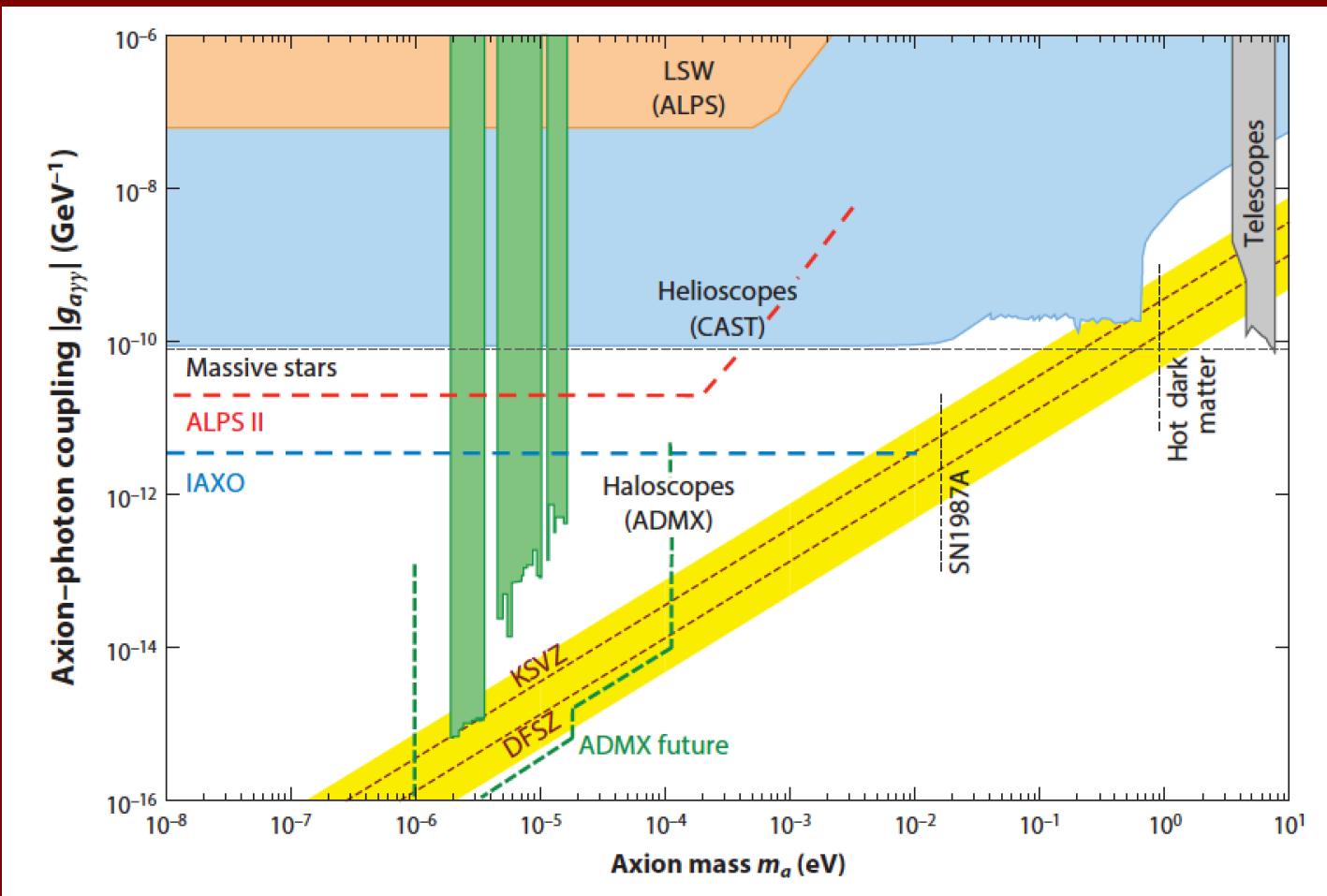
QCD axion
(CASPEr-E)

Fermions

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

Axion-like Particles
(CASPEr-Wind, GNOME, QUAX)

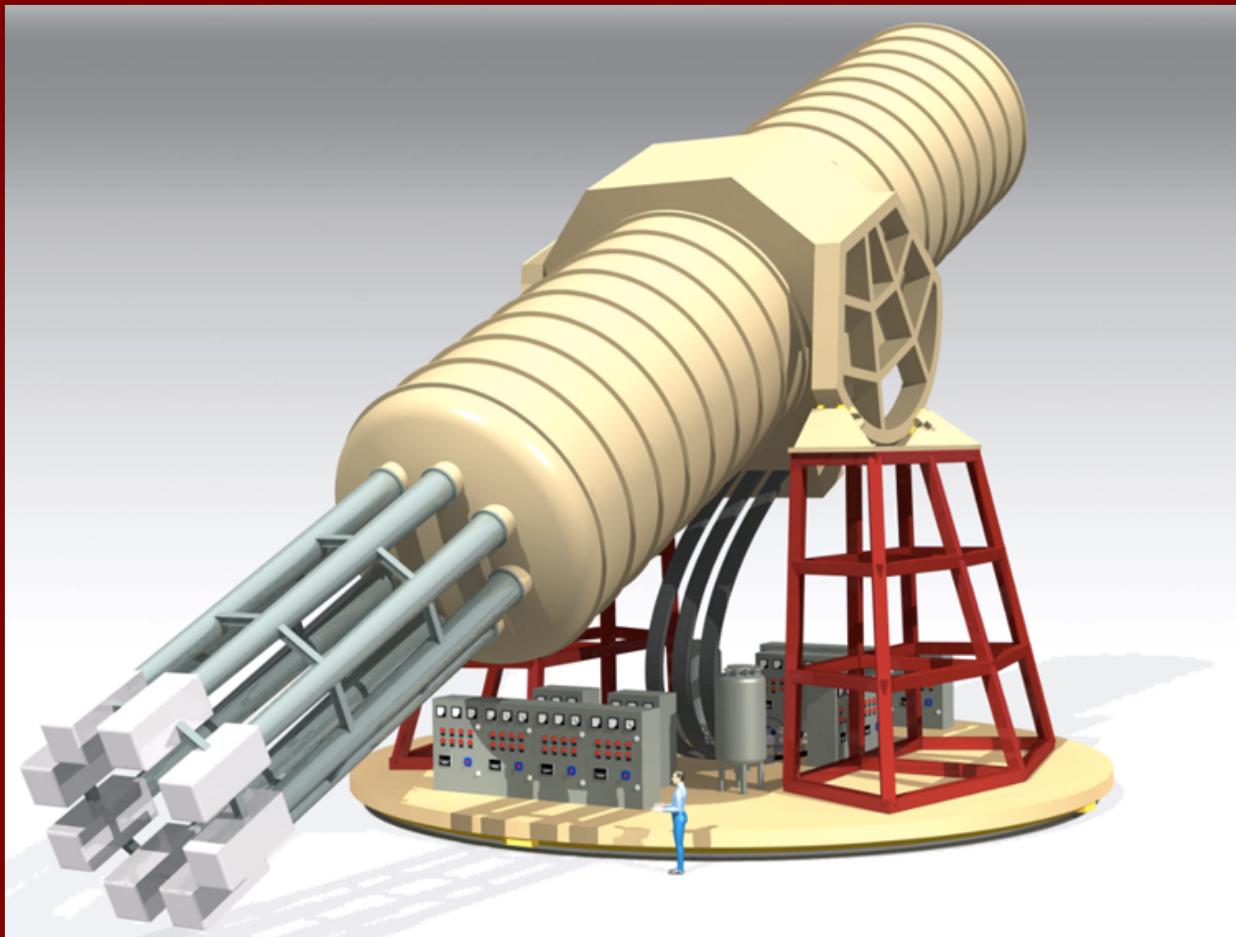
A few Axion/ALP experiments

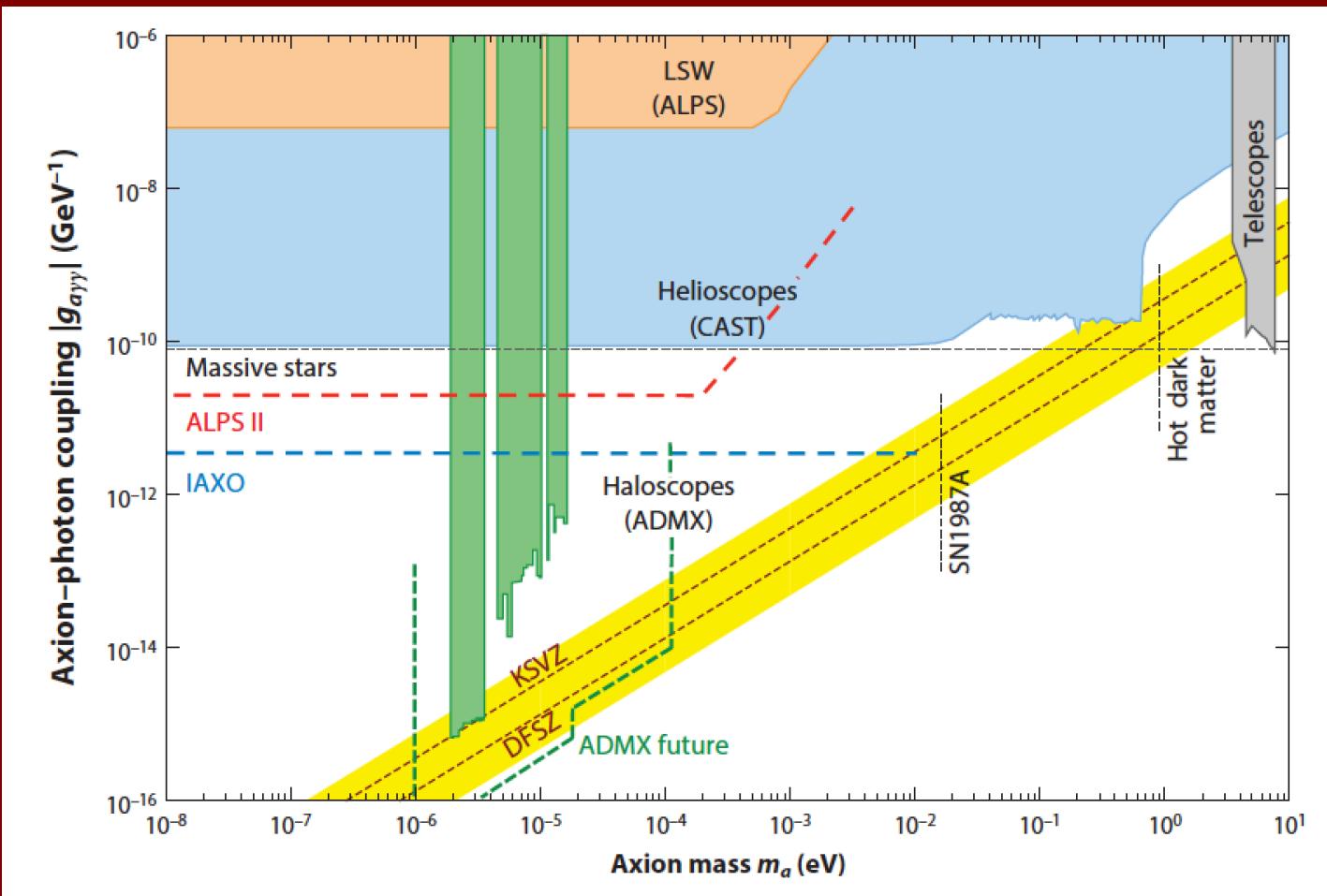


Karl van Bibber

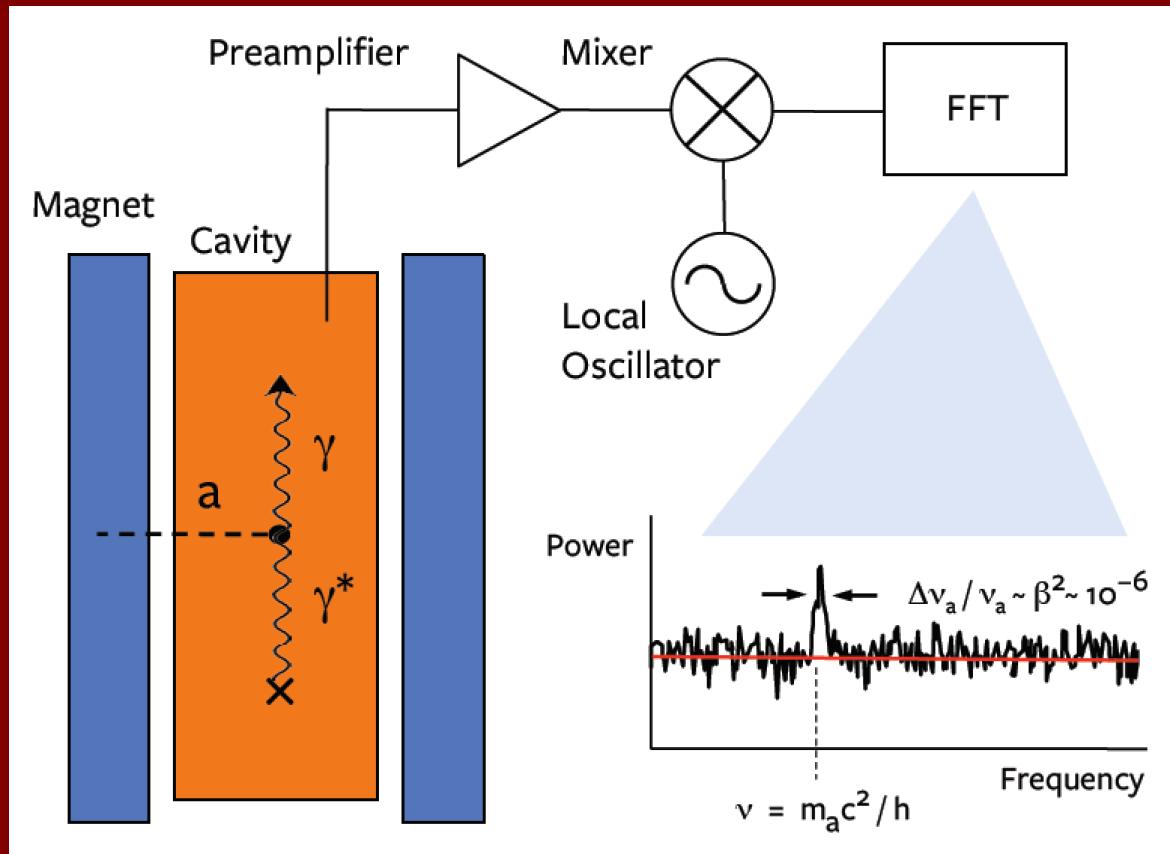
10

Helioscope of the future: IAXO

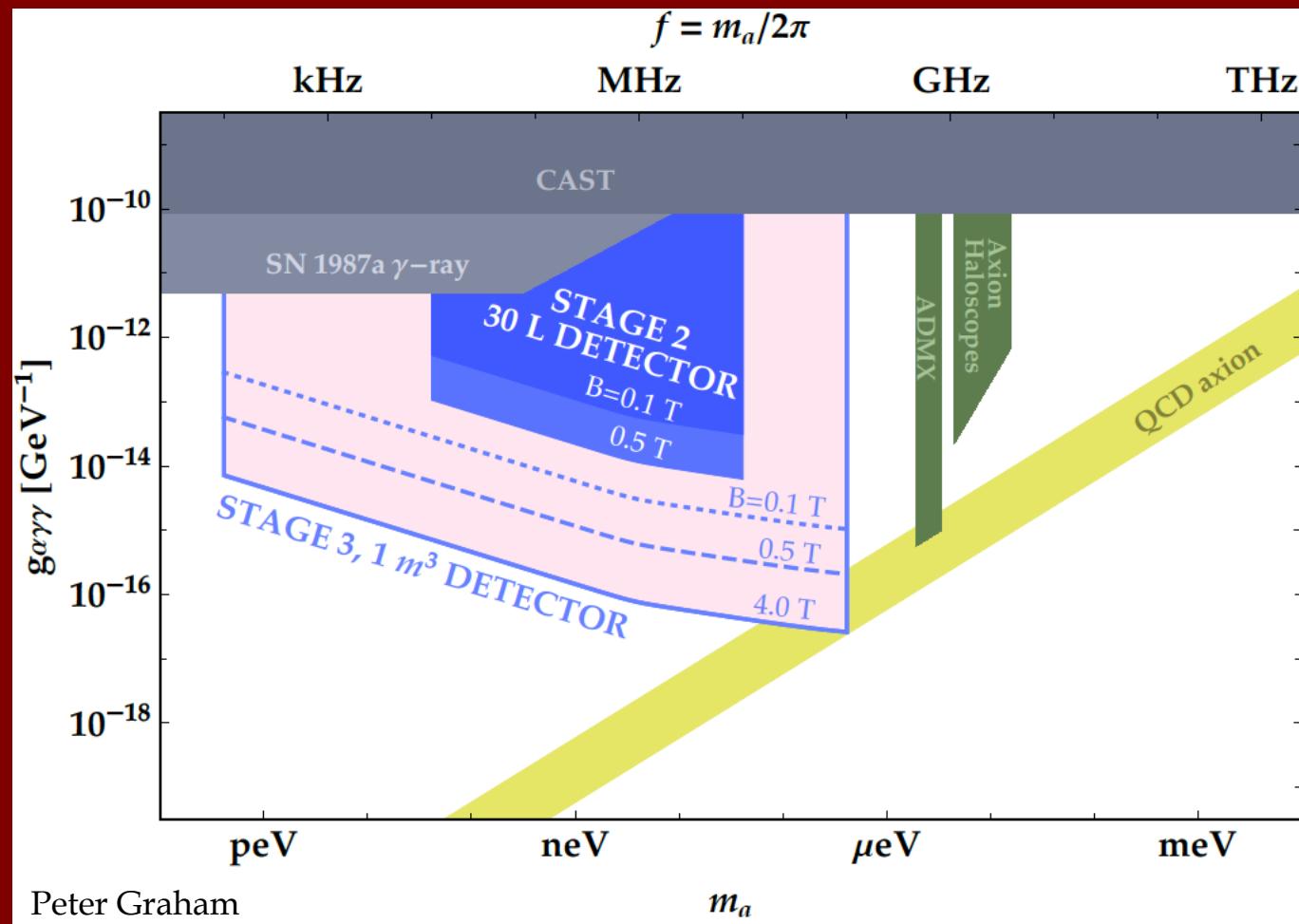




The principle of the microwave-cavity haloscopes: ADMX, ADMX-HF, CAPP, ORGAN



New Haloscope Proposals: ABRACADABRA (MIT) and DM Radio



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 Kimball², Mikhail Kozlov^{3,4},

Nathan Leefer⁵, Szymon Pustelný¹, and Dmitry Budker^{5,6,7}

¹ Institute of Physics, Jagiellonian University, Lojasiewicza 11, 30-348 Kraków, Poland

² Department of Physics, California State University - East Bay, Hayward, California 94542-3081

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	

A sneaky way to look for ALPs

$$\begin{aligned}
V_2 &= \frac{g_3^e g_2^e}{4\pi\hbar c} \hbar c (\mathbf{s}_1 \cdot \mathbf{s}_2) \frac{e^{-r_{12}/\lambda}}{r_{12}}, \\
V_3 &= \frac{g_3^e g_3^e}{4\pi\hbar c} \frac{\hbar^3}{4m_e^2 c} \left[\mathbf{s}_1 \cdot \mathbf{s}_2 \left(\frac{1}{\lambda r_{12}^2} + \frac{1}{r_{12}^3} \right) - (\mathbf{s}_1 \cdot \mathbf{e}_{12}) (\mathbf{s}_2 \cdot \mathbf{e}_{12}) \left(\frac{1}{\lambda^2 r_{12}} + \frac{3}{\lambda r_{12}^2} + \frac{3}{r_{12}^3} \right) \right] e^{-r_{12}/\lambda}, \\
V_4 &= \frac{g_4^e g_4^e}{4\pi\hbar c} \frac{i\hbar^3}{4m_e^2 c} (\mathbf{s}_1 + \mathbf{s}_2) \cdot \left[(\nabla_1 - \nabla_2) \times \mathbf{r}_{12}, \left(\frac{1}{r_{12}^3} + \frac{1}{\lambda r_{12}^2} \right) e^{-r_{12}/\lambda} \right]_+, \\
V_8 &= \frac{g_8^e g_8^e}{4\pi\hbar c} \frac{\hbar^3}{4m_e^2 c} \left[\mathbf{s}_1 \cdot (\nabla_1 - \nabla_2), \left[\mathbf{s}_2 \cdot (\nabla_1 - \nabla_2), \frac{e^{-r_{12}/\lambda}}{r_{12}} \right]_+ \right]_+,
\end{aligned}$$

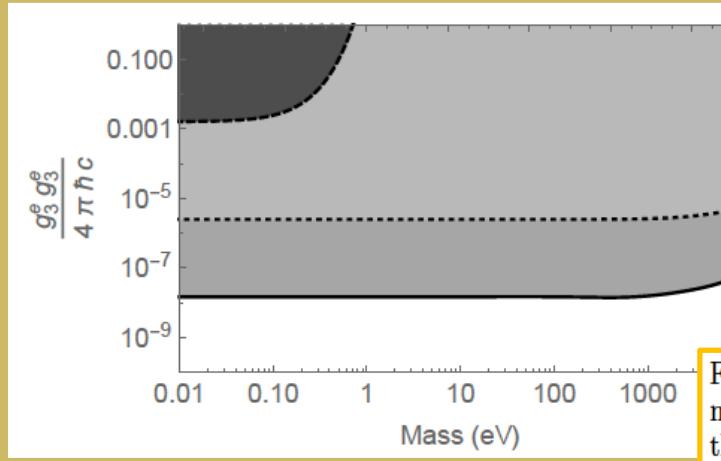


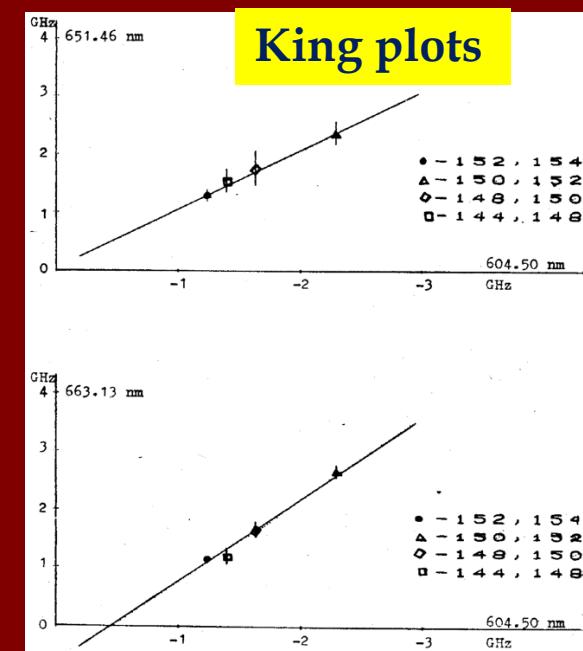
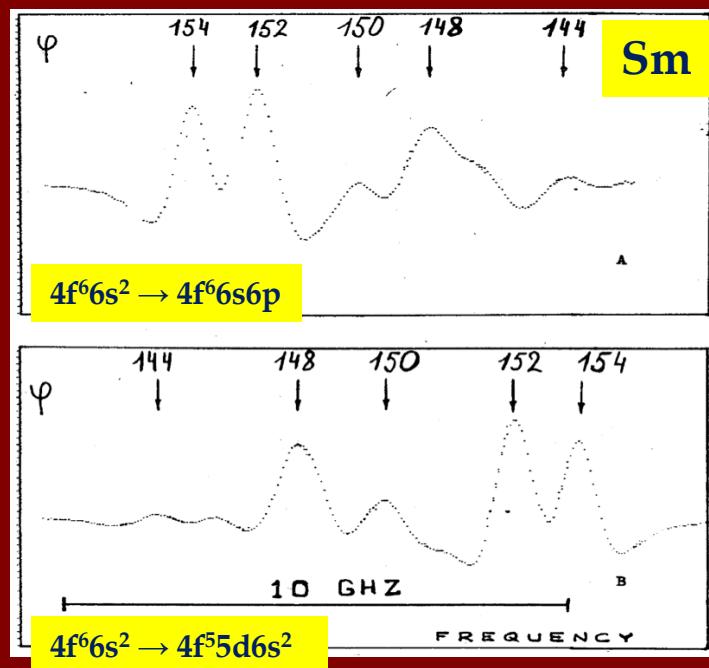
FIG. 1: Constraints (at the 90% confidence level) on the dimensionless coupling constant $g_3^e g_3^e / (4\pi\hbar c)$ as a function of the boson mass. The dashed line and dark gray fill shows the constraint for electrons from Ref. [35]. The dotted line and light gray fill show the constraint derived 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.

Another sneaky way to look for new physics

Probing new light force-mediators by isotope shift spectroscopy

Julian C. Berengut,^{1,*} Dmitry Budker,^{2,3,4,†} Cédric Delaunay,^{5,‡} Victor V. Flambaum,^{1,§} Claudia Frugueule,^{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

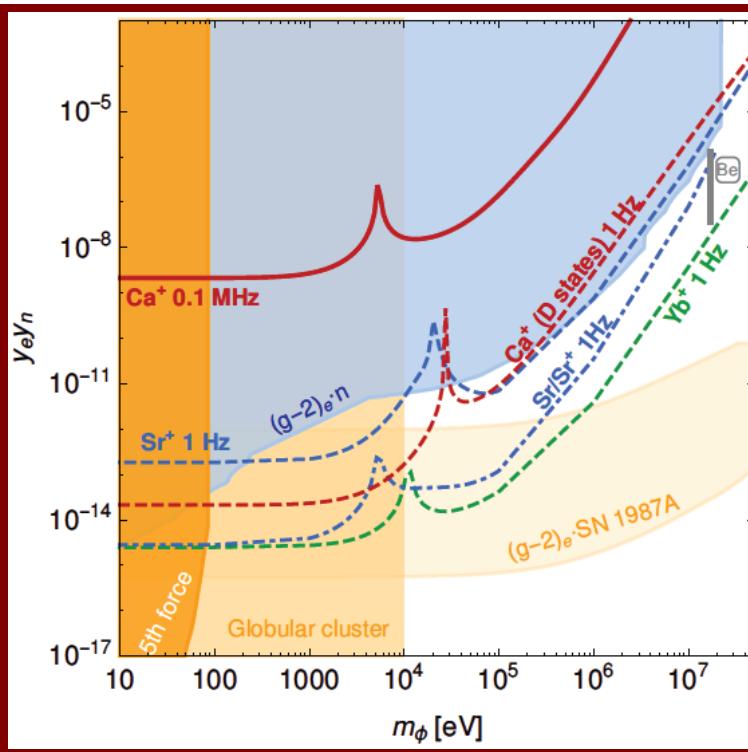


Plots from DB's Diploma Thesis (Novosibirsk, 1985)

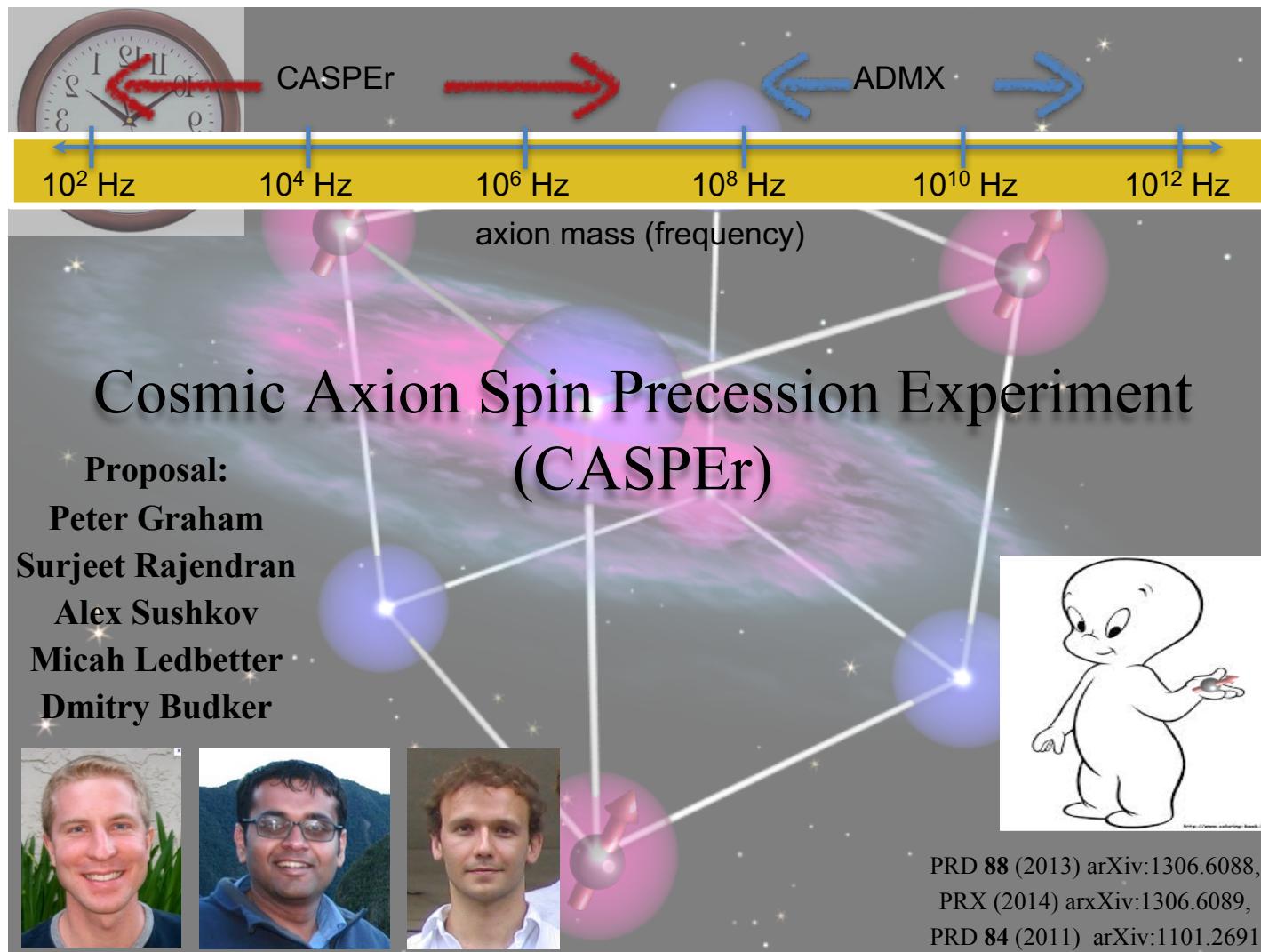
Another sneaky way to look for new physics

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[arXiv:1704.05068](https://arxiv.org/abs/1704.05068)

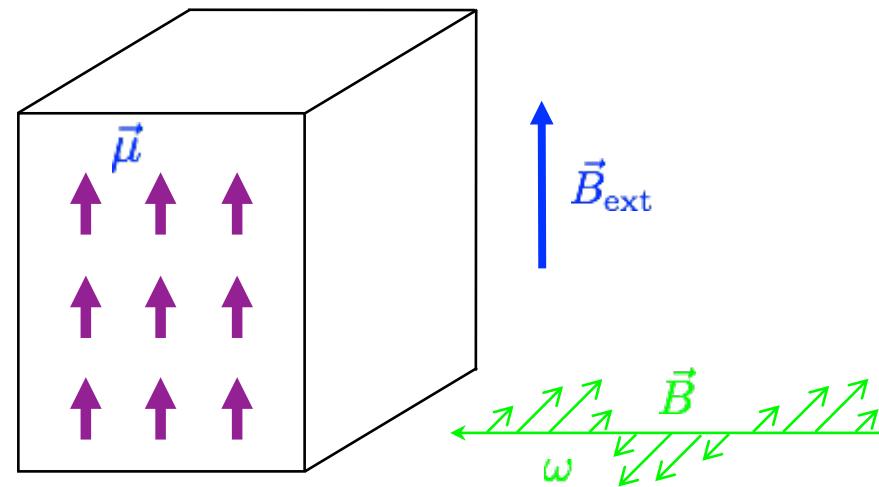


CASPEr Overview

Key ideas:

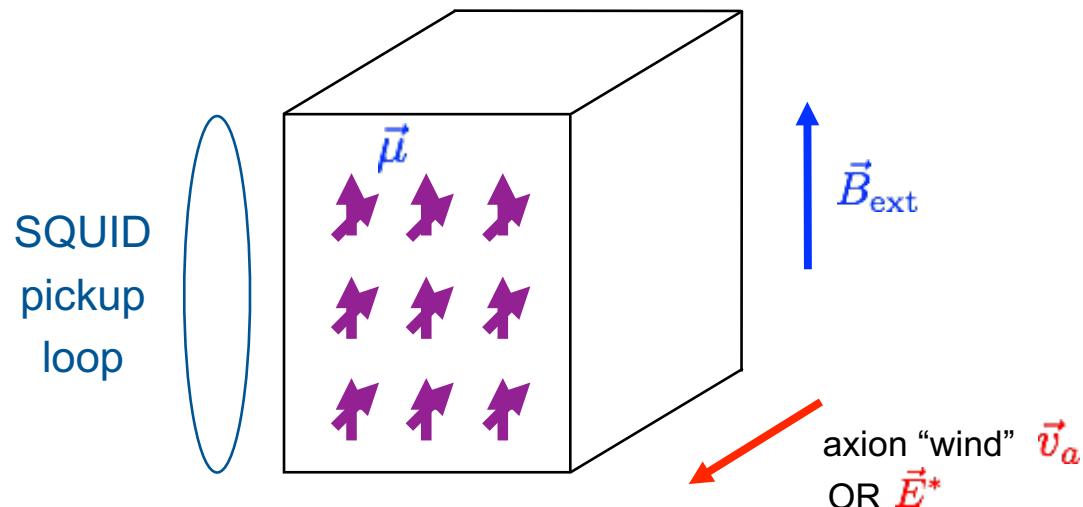
- Axion (ALP) field oscillates
- at a frequency equal to its mass (Hz to GHz)
- → time varying CP-odd nuclear moments:
- nEDM, Schiff, ... 
- Also: axion wind (like a magnetic field) 
- $v \sim 10^{-3} c$ (virial velocity)
- Coherence time: $[m_a(v/c)^2]^{-1} \rightarrow Q \sim 10^6$

Nuclear Magnetic Resonance (NMR)



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

CASPER



Larmor frequency = axion mass → resonant enhancement

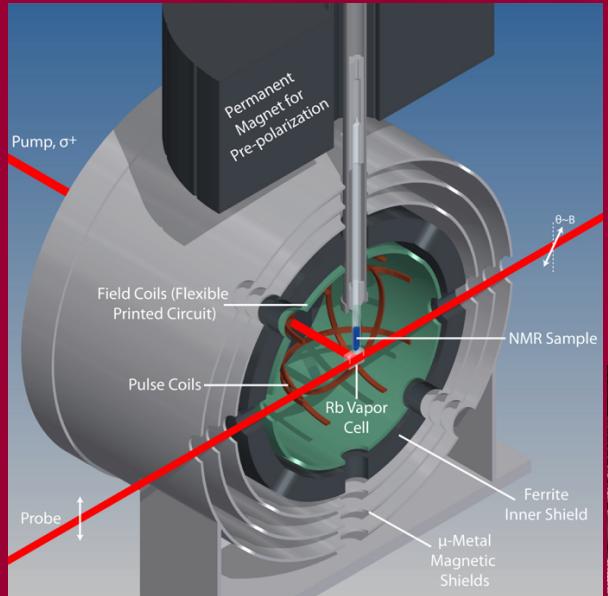
SQUID measures resulting transverse magnetization

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

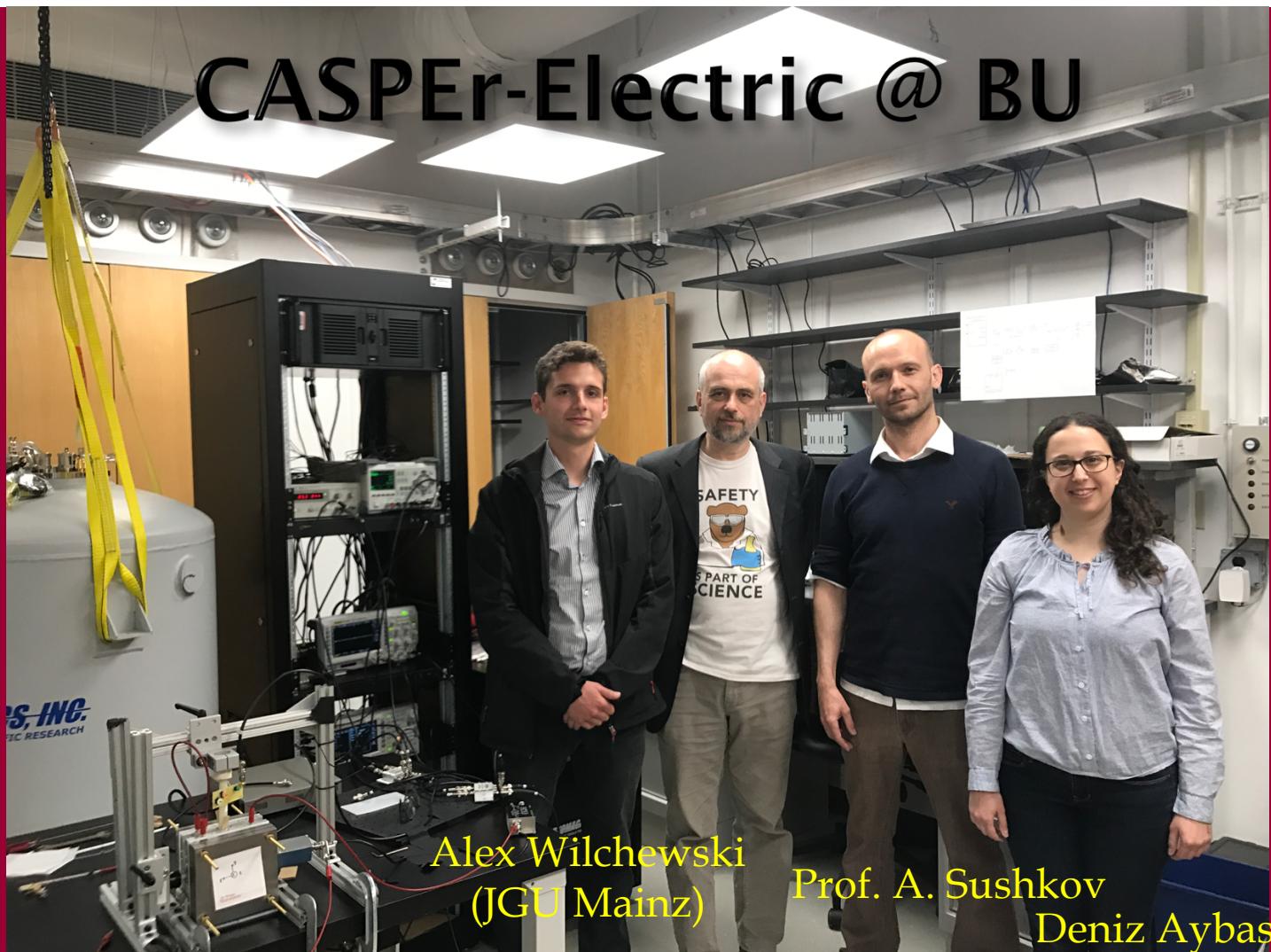
Xe hyperpolarizer @ Mainz



CASPER-NOW with ZULF NMR



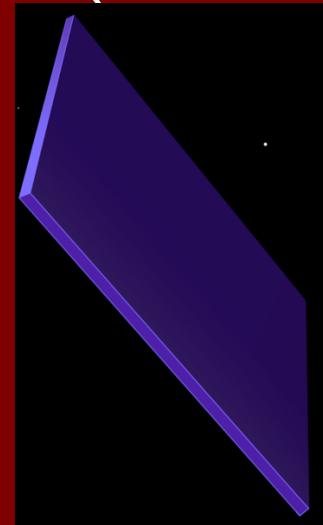
CASPEr-Electric @ BU



Alex Wilchewski
(JGU Mainz)

Prof. A. Sushkov
Deniz Aybas

And now, another story...
ALPs may form domains (or clumps, strings, ...)

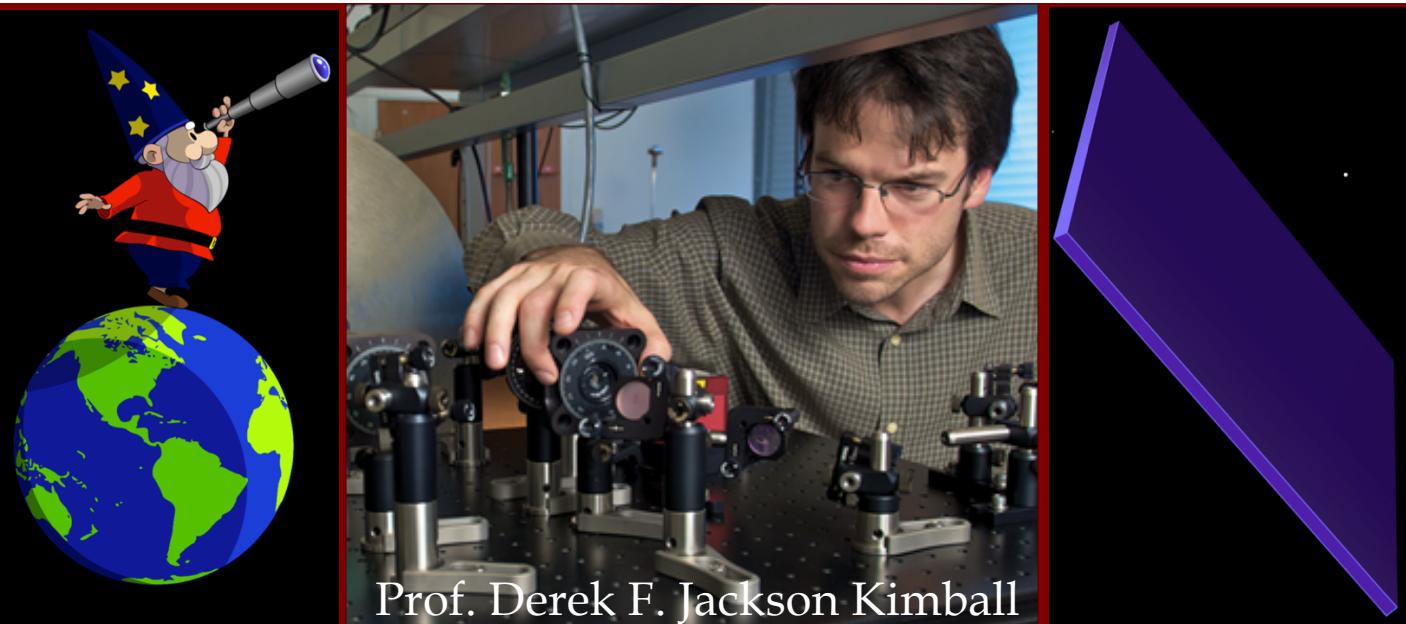


But how to detect them?

Issue edited by: Klaus Blaum, Holger Müller, Nathal Severijns

The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model

Szymon Pustelny^{1,2,*}, Derek F. Jackson Kimball³, Chris Pankow⁴, Micah P. Ledbetter^{2,**},
Przemyslaw Włodarczyk⁵, Piotr Wcislo^{1,6}, Maxim Pospelov^{7,8}, Joshua R. Smith⁹, Jocelyn Read⁹,
Wojciech Gawlik¹, and Dmitry Budker^{2,10}



Correlated magnetometers...

- Synchronized separated, shielded mags
- Detect pseudomagnetic field from wall crossing
- Modern atomic magnetometers are sensitive !
 $<1 \text{ fT/Hz}^{1/2}$
- Electron and nuclear spin based mags

GNOME station @ Mainz



Hector Masia Roig



Arne Wickenbrock

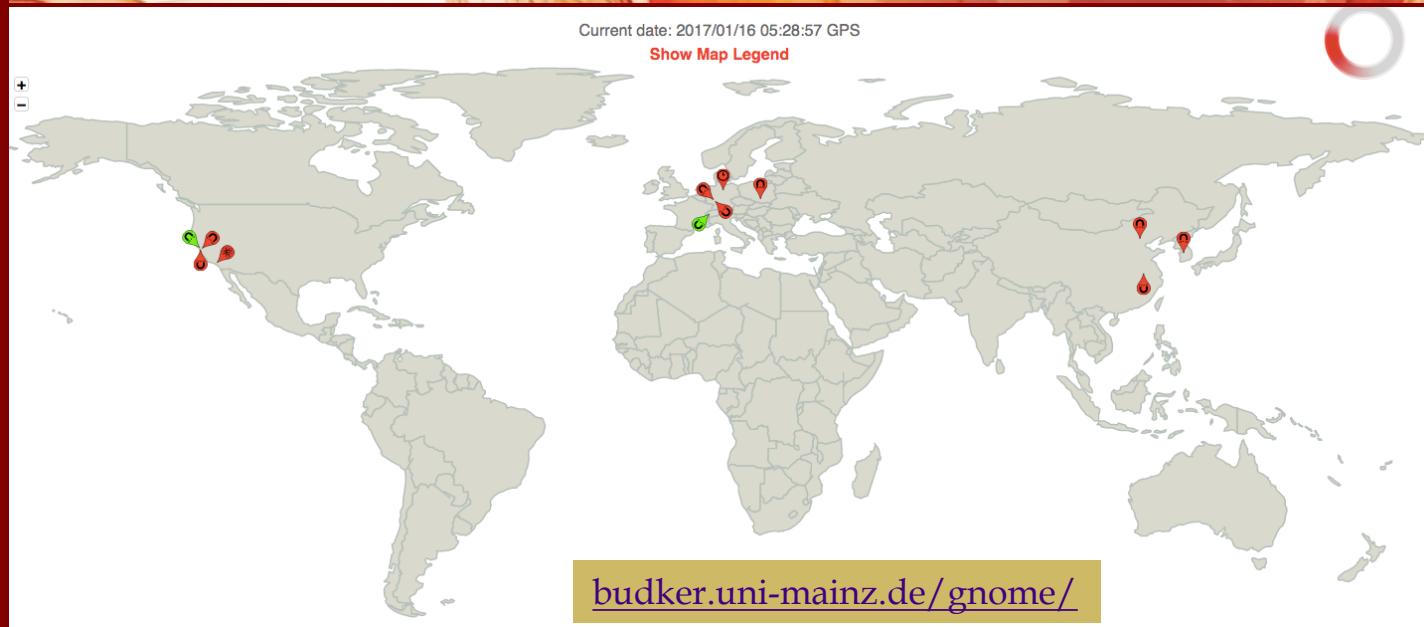


Samer Afach

Mainz GNOME team

The GNOME Experiment

Collaboration website



- Taking data now! (Coordinated runs: July&Nov, 2016; also NOW)
- Also clocks! (A. Derevianko and M. Pospelov, 2014)

DILATON DM ?



2017
New Horizons
In Physics
Prize

ton dark matter with atomic clocks

Asimina Arvanitaki*

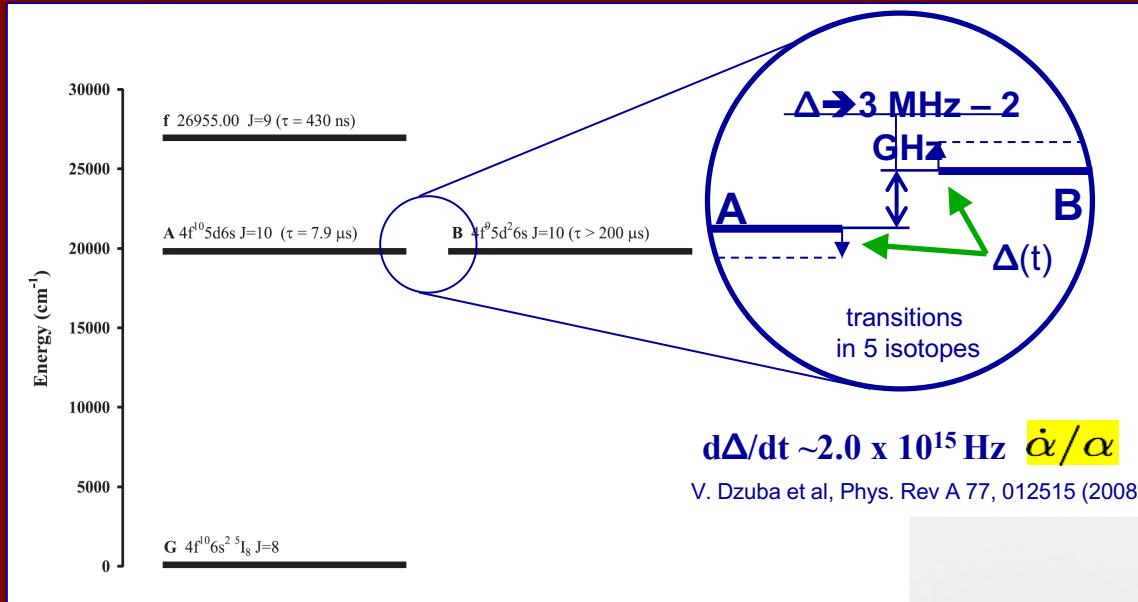
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

Junwu Huang[†] and Ken Van Tilburg[‡]

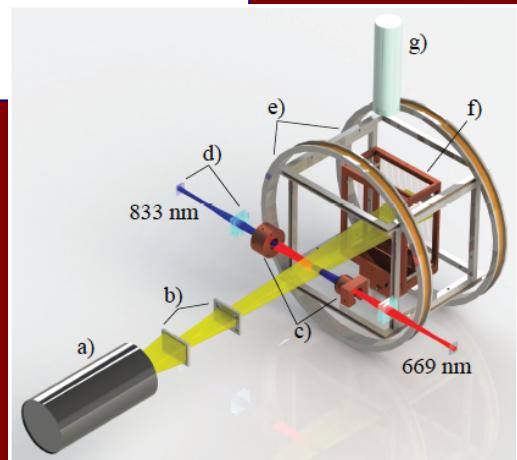
*Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, USA*

(Dated: May 14, 2014)

Dy as “Alpha Variometer”

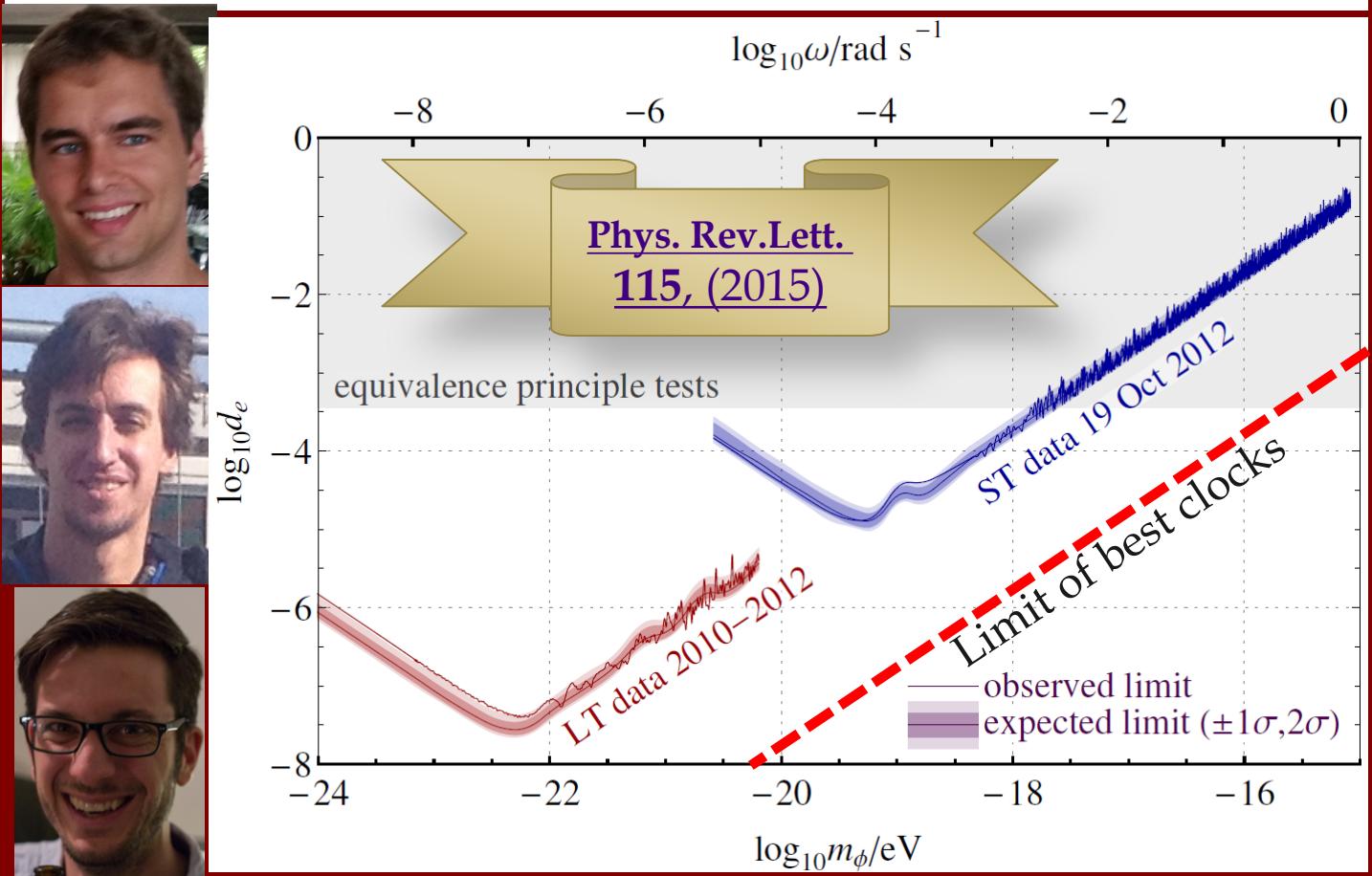


- Limits on alpha variation
- Dependence on gravitational potential
- Lorentz-Invariance violation (for electrons)
- ...



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,§}

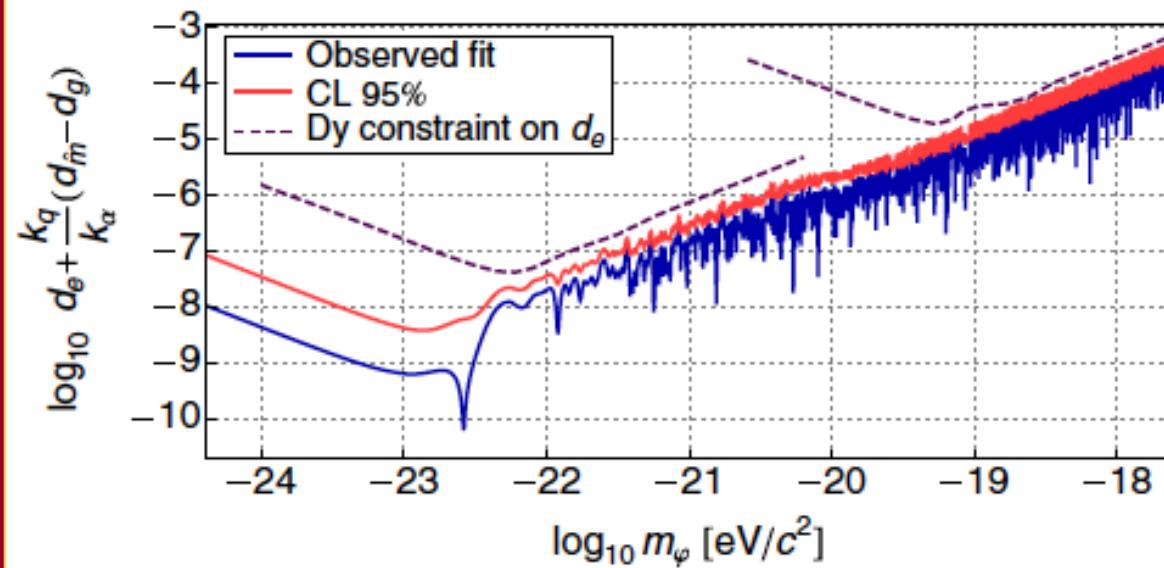


Searching for an Oscillating Massive Scalar Field as a Dark Matter Candidate Using Atomic Hyperfine Frequency Comparisons

A. Hees,^{1,2,*} J. Guéna,^{1,†} M. Abgrall,^{1,‡} S. Bize,^{1,§} and P. Wolf^{1,||}

¹SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 61 avenue de l'Observatoire, 75014 Paris, France

²Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA



Constraints on Scalar/Pseudoscalar Quadratic Interaction with the Photon

BBN, CMB and Dy: [Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

Supernova energy loss bounds: [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Victor V. Flambaum

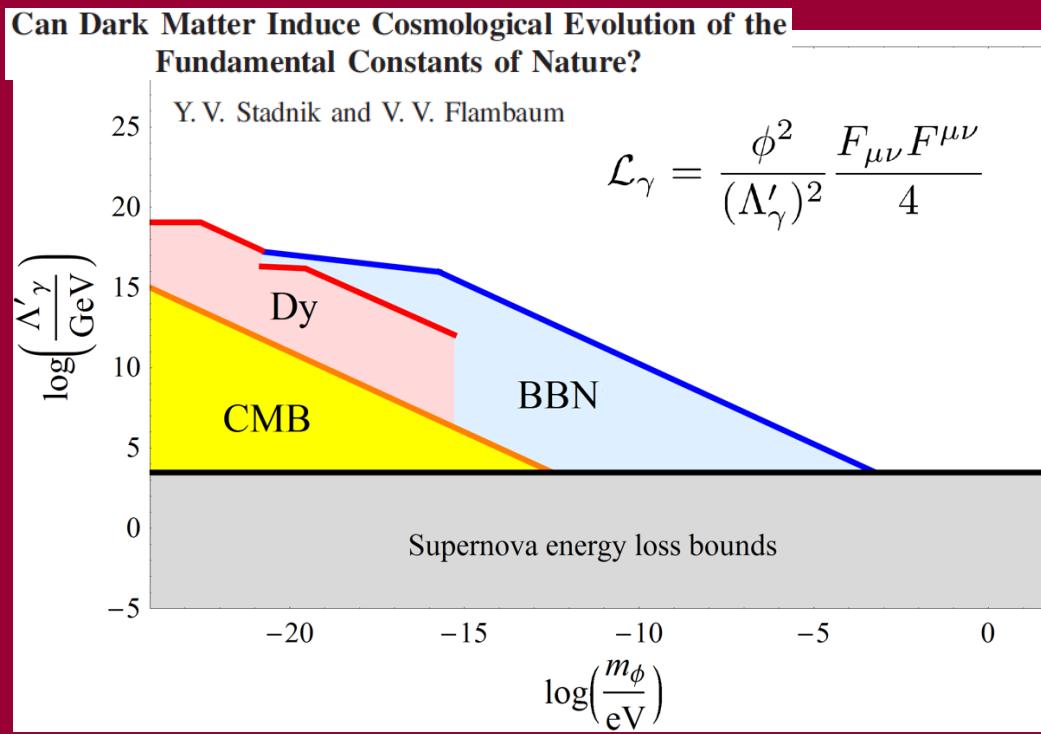


Yevgeny Stadnik

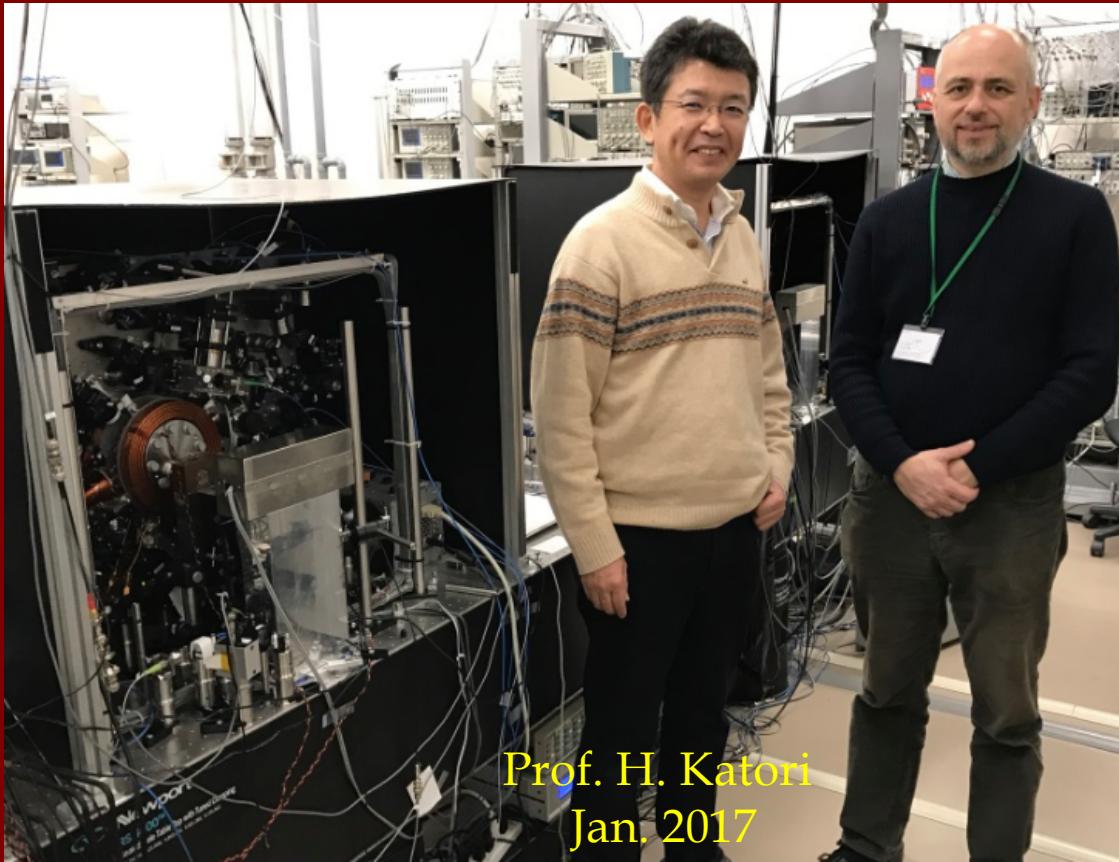
PRL 115, 201301 (2015)

PHYSICAL REVIEW LETTERS

week ending
13 NOVEMBER 2015



Clock comparison (at 10^{-18} level) @ RIKEN



An now, the latest...

Search for the effect of massive bodies on atomic spectra and constraints on Yukawa-type interactions of scalar particles

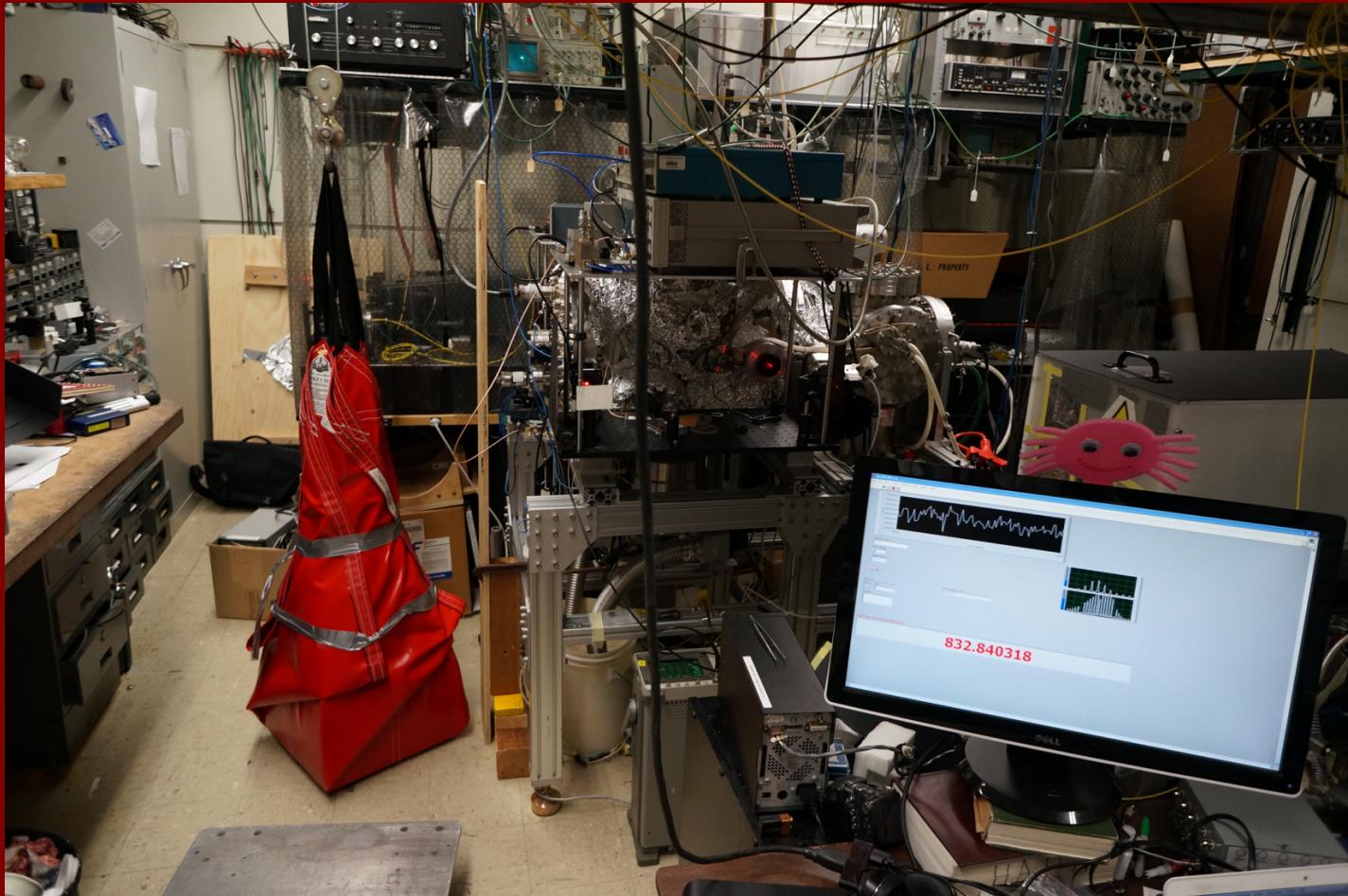
N. Leefer,^{1,*} A. Gerhardus,^{2,†} D. Budker,^{1,3,4} V. V. Flambaum,^{1,5} and Y. V. Stadnik^{5,‡}

$$\mathcal{L}_{\text{int}} = - \sum_f \frac{\phi}{\Lambda_f} m_f \bar{f} f + \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4}$$

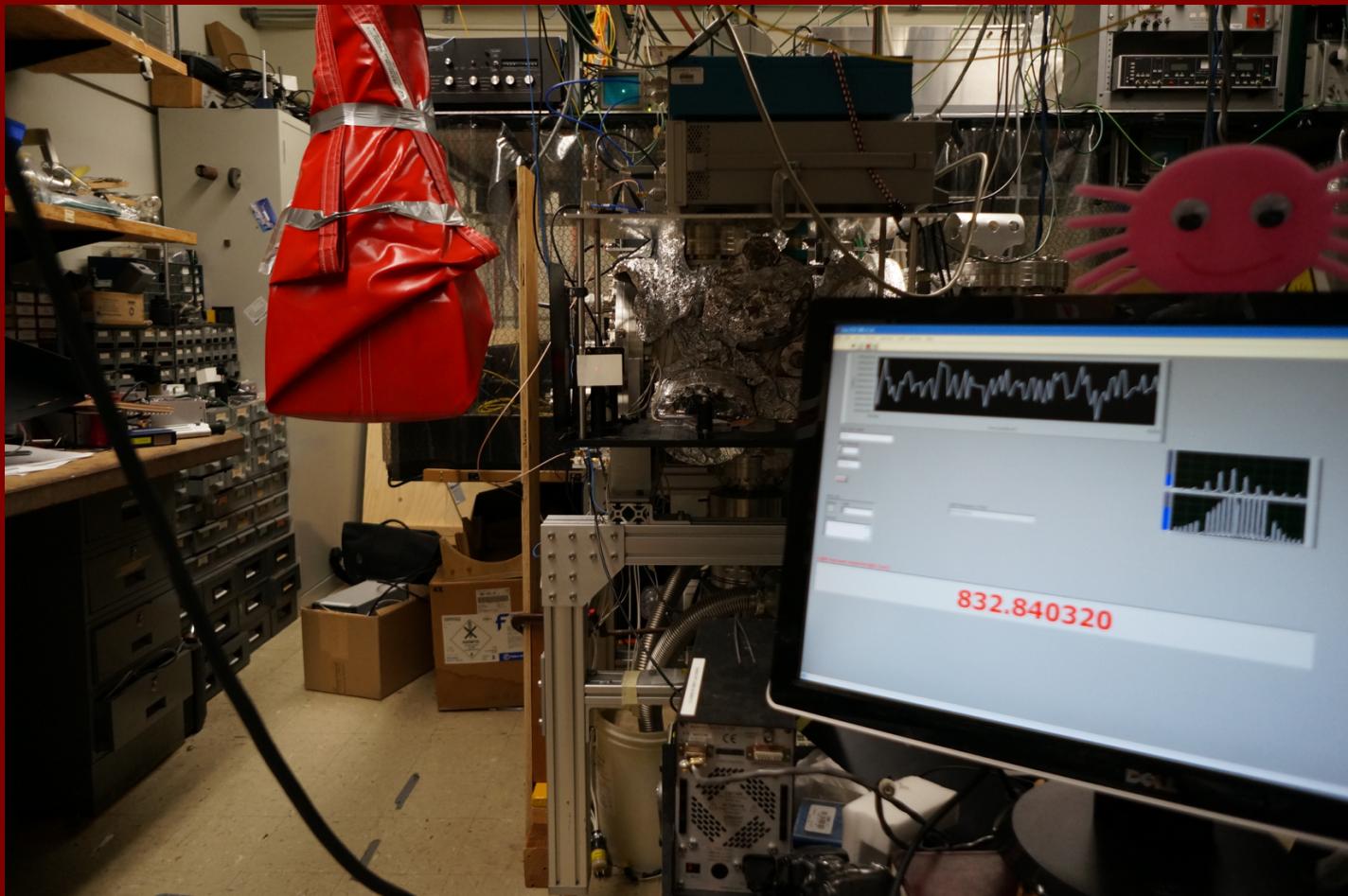
$$m_f \rightarrow m_f \left(1 + \frac{\phi}{\Lambda_f} \right), \quad \alpha \rightarrow \frac{\alpha}{1 - \phi/\Lambda_\gamma} \simeq \alpha \left(1 + \frac{\phi}{\Lambda_\gamma} \right)$$



Does heavy weight affect α ?



Does heavy weight affect α ?



Dy and the masses...

PRL 117, 271601 (2016)

PHYSICAL REVIEW LETTERS

week ending
30 DECEMBER 2016

Search for the Effect of Massive Bodies on Atomic Spectra and Constraints on Yukawa-Type Interactions of Scalar Particles

N. Leefer,¹ A. Gerhardus,² D. Budker,^{1,3,4} V. V. Flambaum,^{1,5} and Y. V. Stadnik⁵

¹Helmholtz-Institut Mainz, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

²Bethe Center for Theoretical Physics, Physikalisches Institut der Universität Bonn, 53115 Bonn, Germany

³Physics Department, University of California, Berkeley 94720-7300, USA

⁴Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

⁵School of Physics, University of New South Wales, Sydney 2052, Australia

(Received 25 July 2016; revised manuscript received 27 October 2016; published 29 December 2016)

TABLE I. Summary of source body parameters, and atomic dysprosium transition frequency variation constraints. The results here can be combined with Eq. (8) to give constraints on the new-physics energy scales that appear in Eq. (1), as a function of the scalar-particle mass m_ϕ . We have assumed that the elemental composition of the Sun is 75% ^1H and 25% ^4He by mass, and that the elemental composition of the Moon is a 1:1 ratio of $^{24}\text{Mg}^{16}\text{O}$ and $^{28}\text{Si}^{16}\text{O}_2$ by number.

Source	β/m_N	M (kg)	Size (m)	$ \mathbf{r}_1 $ (m)	$ \mathbf{r}_2 $ (m)	$ \Delta\nu $ (Hz)	Ref.
Sun	$\frac{0.15}{\Lambda_n} + 1.1 \left(\frac{1}{\Lambda_p} + \frac{5 \times 10^{-4}}{\Lambda_e} \right) + \frac{8 \times 10^{-4}}{\Lambda_\gamma}$	2.0×10^{30}	7.0×10^8	1.47×10^{11}	1.52×10^{11}	< 0.7	[11]
Moon	$\frac{10}{\Lambda_n} + 10 \left(\frac{1}{\Lambda_p} + \frac{5 \times 10^{-4}}{\Lambda_e} \right) + \frac{0.03}{\Lambda_\gamma}$	7.3×10^{22}	1.7×10^6	3.69×10^8	3.99×10^8	< 0.6	[32]
Lead	$\frac{126}{\Lambda_n} + 82 \left(\frac{1}{\Lambda_p} + \frac{5 \times 10^{-4}}{\Lambda_e} \right) + \frac{0.9}{\Lambda_\gamma}$	300	$0.38 \times 0.38 \times 0.18$	0.95	1.34	< 0.3	This work

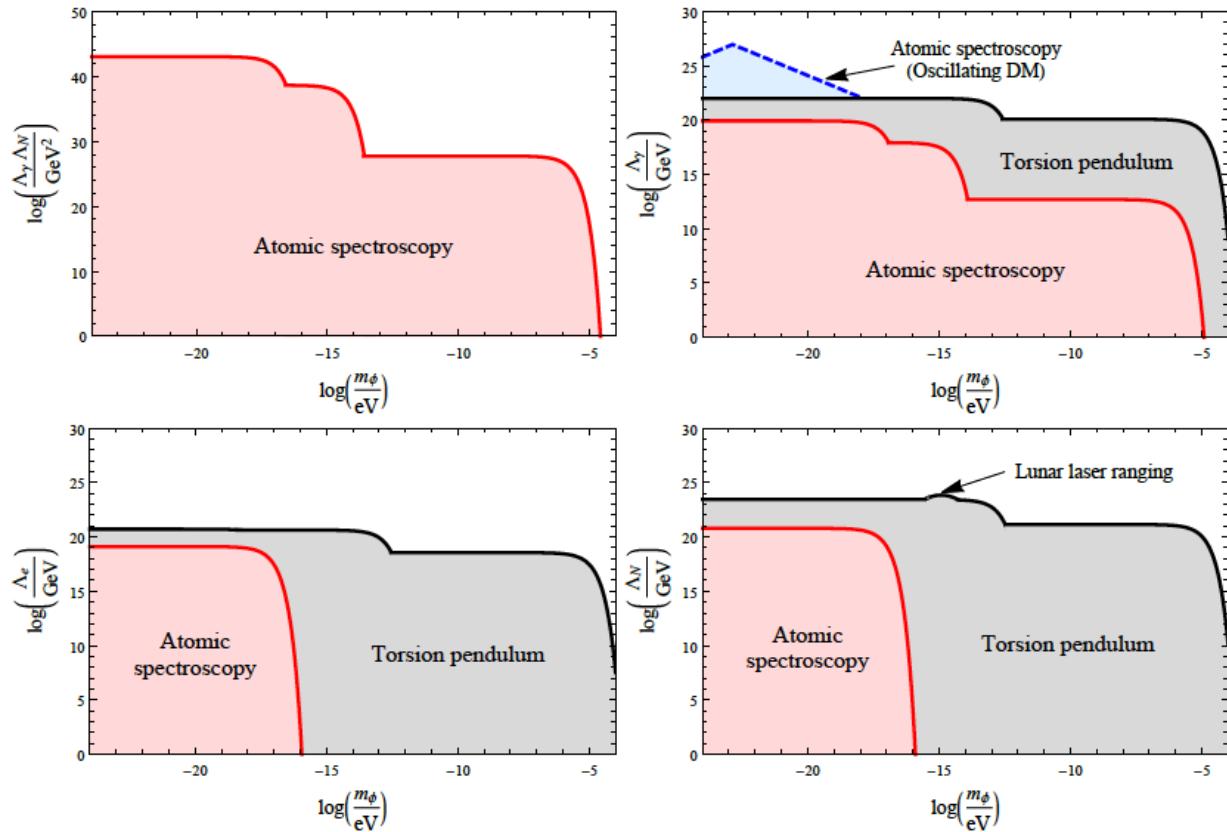
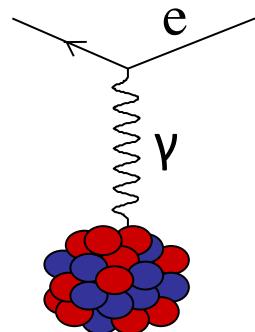


FIG. 2. (Color online) Limits on the Yukawa-type interactions of the scalar field ϕ with the photon, electron and nucleons (assuming an isotopically-invariant interaction), as defined in Eq. (1). The regions in red correspond to regions of parameters excluded by the present work. The regions in grey correspond to existing constraints from searches for anomalous forces due to the exchange of virtual ϕ quanta [17–20, 24]. See Table II for further details. A detailed geological and topographical analysis in combination with existing torsion pendulum measurements gives additional constraints (not shown) for $1/R_{\text{Earth}} \lesssim m_\phi \lesssim 10^{-7}$ eV (see Refs. [19–21] and the references therein for more details). The region in blue corresponds to existing constraints from atomic spectroscopy measurements that search for the effects of a relic coherently oscillating field $\phi = \phi_0 \cos(m_\phi t)$, which saturates the local cold dark matter content [32, 37].

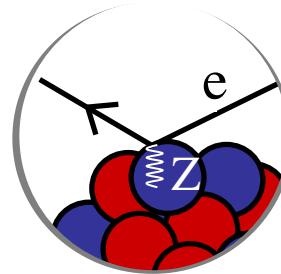
A story of an open question:
Is parity conserved by gravitation?

ATOMIC PARITY VIOLATION

- Main Source: Z exchange



Electromagnetic
interaction
(conserves parity)



Weak
interaction
(violates parity)

- P-odd, T-even correlation $\vec{\sigma} \cdot \vec{p}$

ONE THING LEADS TO ANOTHER

- Is parity conserved by gravitation ?
- How to check? \Rightarrow centrifuge (EEP)

$$\vec{\sigma} \cdot (\vec{\Omega} \times \vec{r}) = \vec{\sigma} \cdot \vec{v} = \vec{\sigma} \cdot \vec{p} / m$$

- Can we test gravity via APV ?
- Probably not...
- ... but can look for exotic cosmic fields

COSMIC PARITY VIOLATION

Limits on \mathcal{P} -odd interactions of cosmic fields with electrons, protons and neutrons

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We propose methods for extracting limits on the strength of \mathcal{P} -odd interactions of pseudoscalar and pseudovector cosmic fields with electrons, protons and neutrons. Candidates for such fields are dark matter (including axions) and dark energy, as well as several more exotic sources described by standard-model extensions. Calculations of parity nonconserving amplitudes and atomic electric dipole moments induced by these fields are performed for Li, Na, K, Rb, Cs, Ba⁺, Tl, Dy, Fr, and Ra⁺. From these calculations and existing measurements in Dy and Cs, we constrain the parity-violating interaction of a static pseudovector cosmic field at 2.1×10^{-19} GeV for the electron, and 3.1×10^{-8} GeV for the proton.

[Phys. Rev. Lett. 113; Phys. Rev. D 90 \(2014\)](#)

TABLE II. Limits on the dimensionless constants b_0^e and b_0^p quantifying the interaction strength of a PV cosmic field with electrons and protons, respectively.

PNC quantity	Limits	
	$ b_0^e $	$ b_0^p $
Cs $E_{\text{PNC}}(6s-7s)$	21×10^4	5.1×10^{13}
Tl $E_{\text{PNC}}(6p_{1/2}-6p_{3/2})$	95×10^4	1.4×10^{14}
Dy $\langle A \hat{h} B \rangle$	340	

From nuclear anapoles

Summary

- ✧ DM and Axions/ ALPs
- ✧ How to look for Axions/ ALPs
- ✧ Sneaky ways (atomic spectroscopy)
- ✧ Cosmic Axion Spin Precession Experiment
- ✧ Global Network of Optical Magnetometers for
Exotic physics searches
- ✧ Beyond Axions: dilatons, scalar sourcing by masses
- ✧ Dark Sector searches and fundamental symmetries



Thanks!



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