AXION SEARCHES

SEARCHING FOR ULTRALIGHT DARK MATTER WITH ATOMIC SPECTROSCOPY AND NUCLEAR RESONANCE

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Johannes Gutenberg U. **NSD LBNL**

Aspen, January 2016

The plan

- ✧ Why axions (or Axion-Like Particles) ?
- ✧ How to search for them ?
- ✧ A few ongoing and planned experiments
  - ADMX and ADMX-HF
  - ALPS-2
  - IAXO
- ✧ Cosmic Axion Spin Precession Experiment
- ✧ Global Network of Optical Magnetometers for Exotic physics searches
- ✧ Beyond Axions: e.g., dilatons
- ✧ 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?
  - …

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

P. Graham
S. Rajendran

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

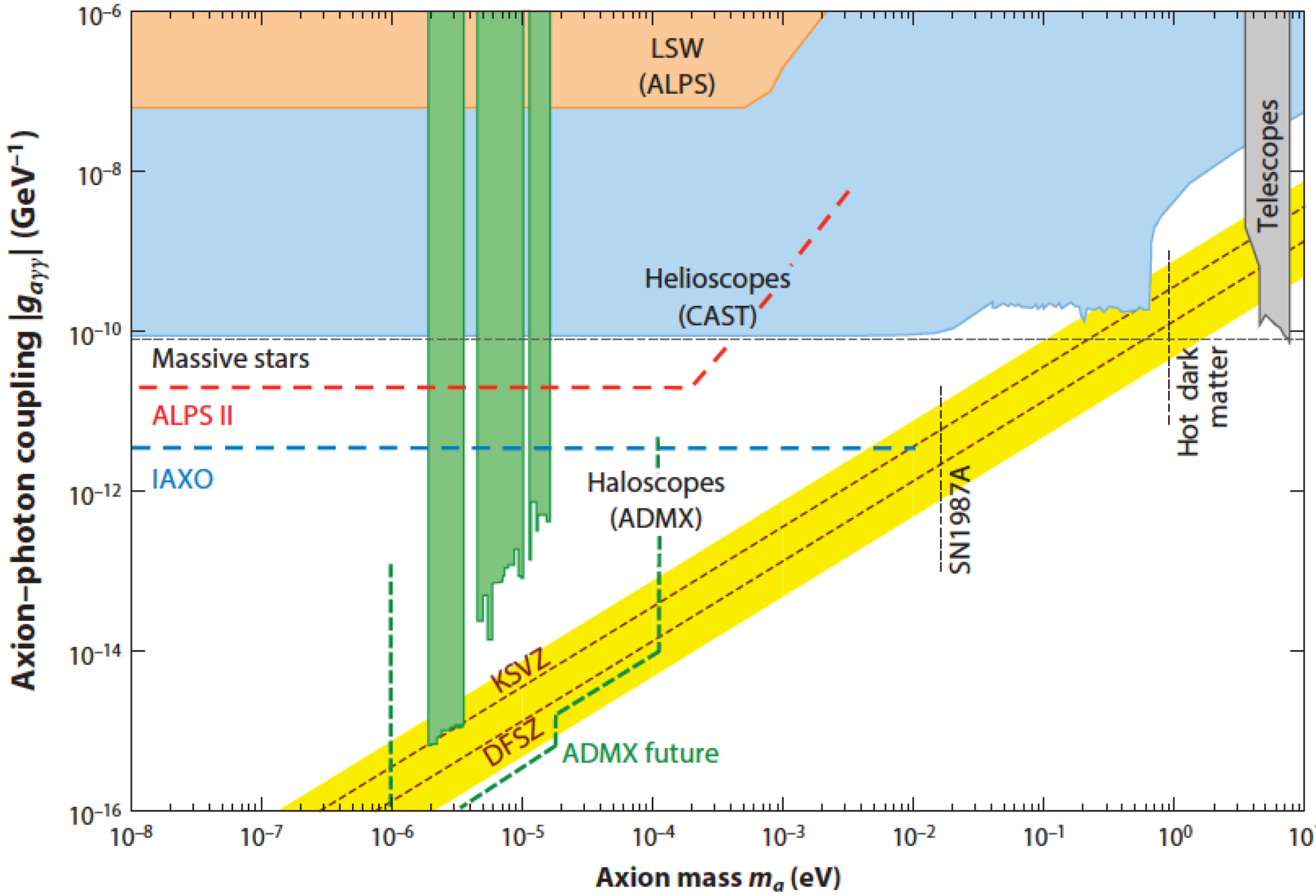
$$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Current Searches

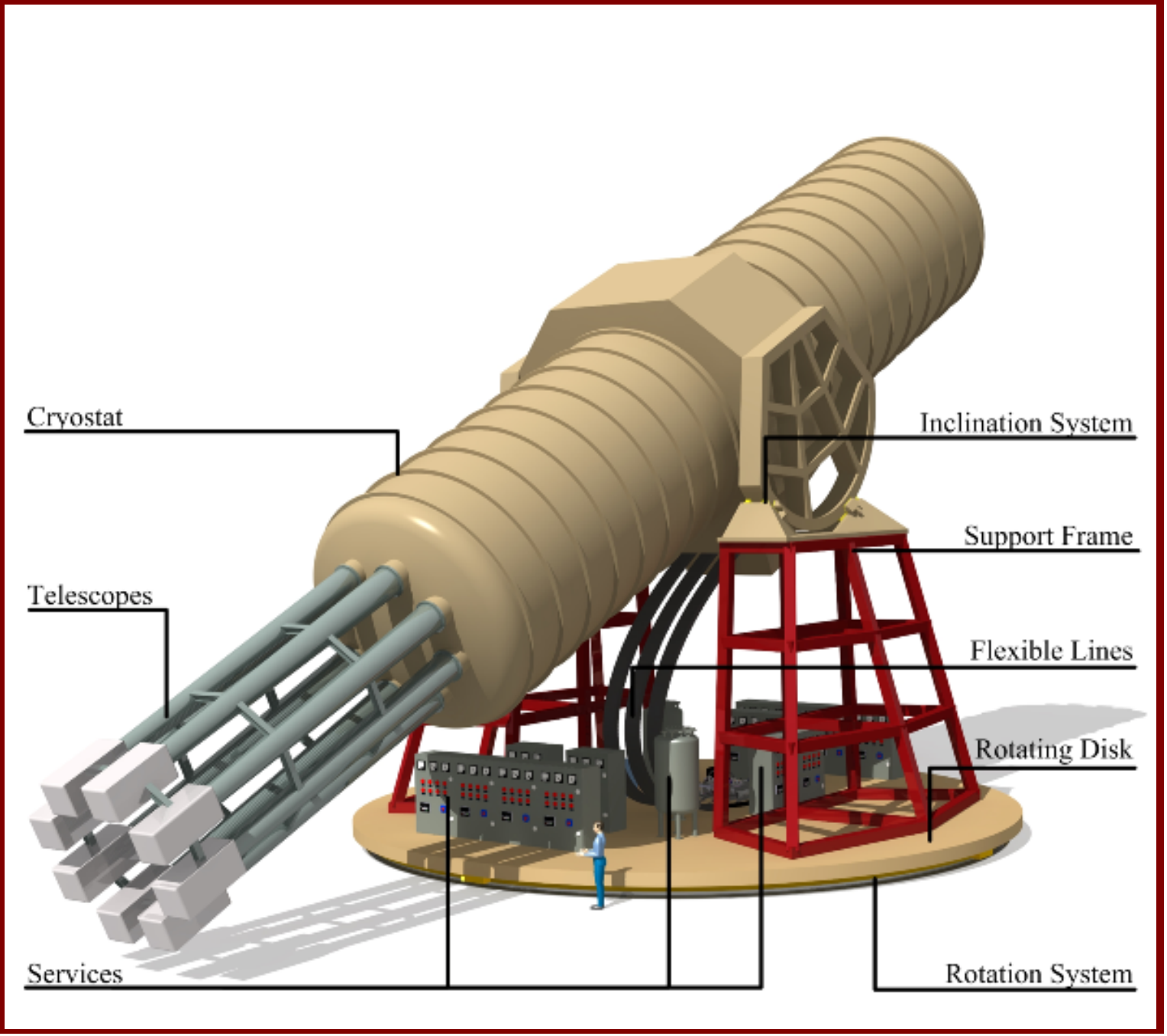
QCD axion (CASPEr-E)

Axion-like Particles (CASPEr-Wind, GNOME)

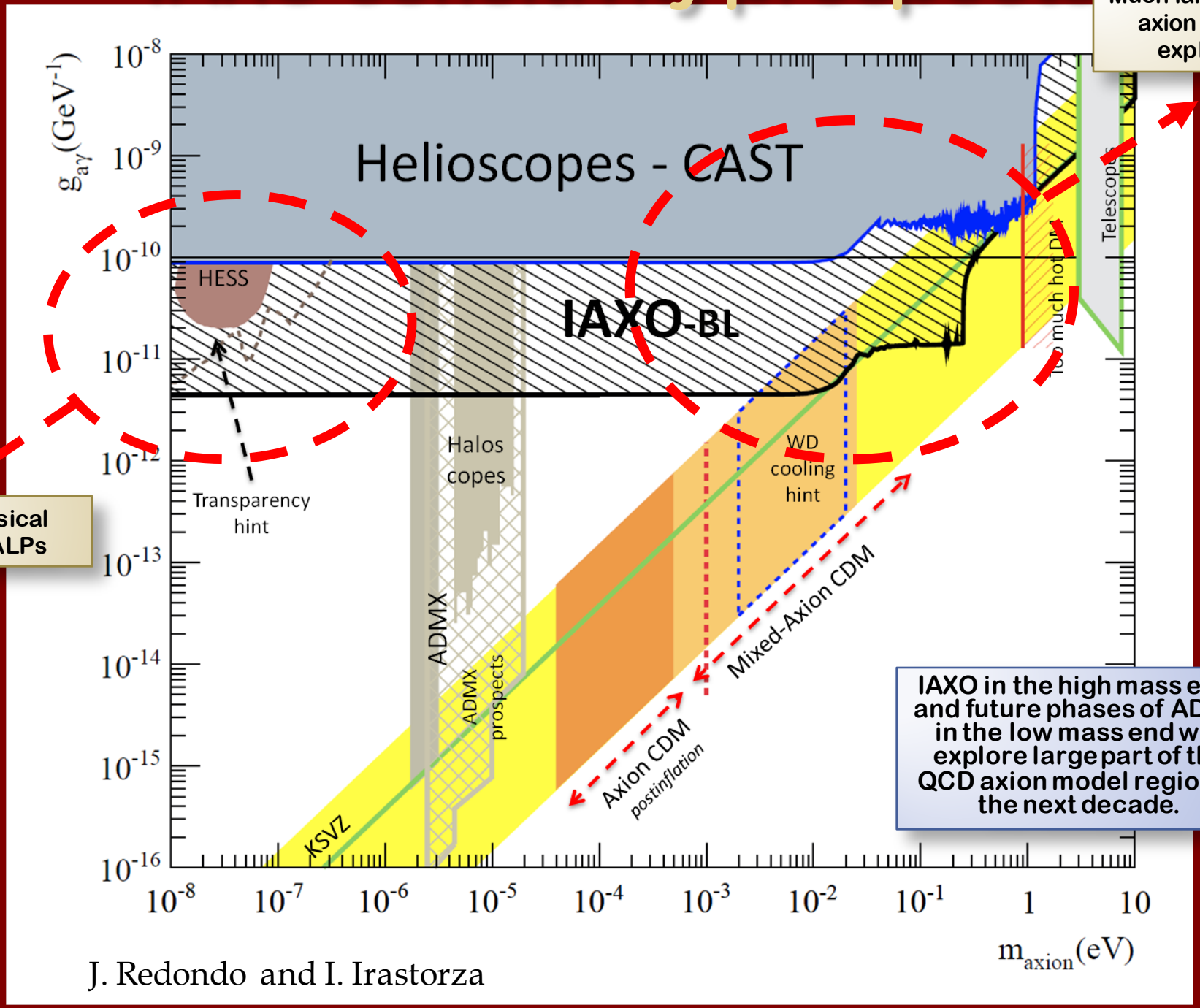
A few Axion/ALP experiments


LSW
(ALPS)
Telescopes
Helioscopes
(CAST)
Massive stars
ALPS II
IAXO
Haloscopes
(ADMX)
SN1987A
Hot dark
matter
KSVZ
DFSZ
ADMX future
Axion–photon coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
Axion mass m_a (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Helioscope of the future: IAXO

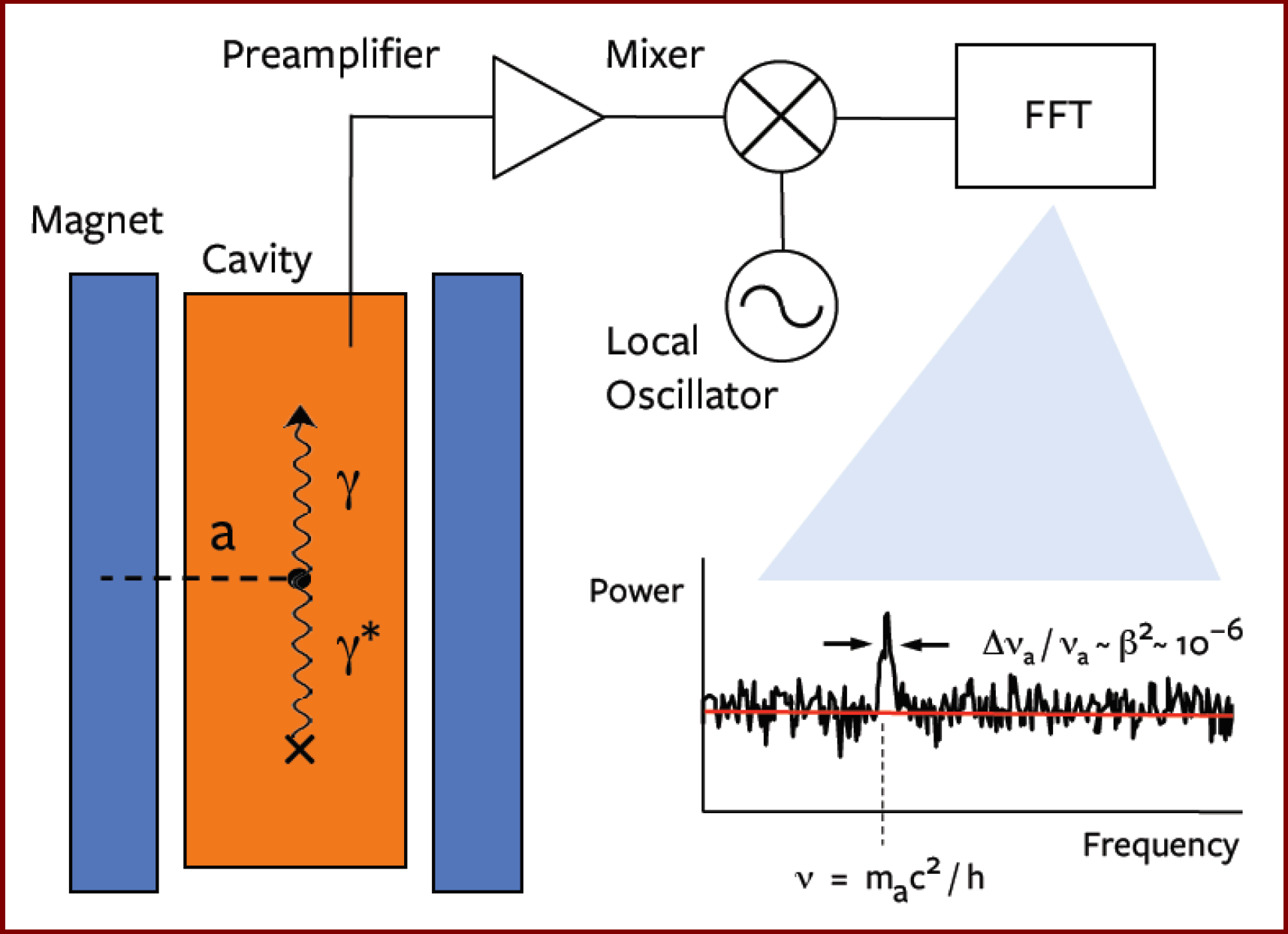


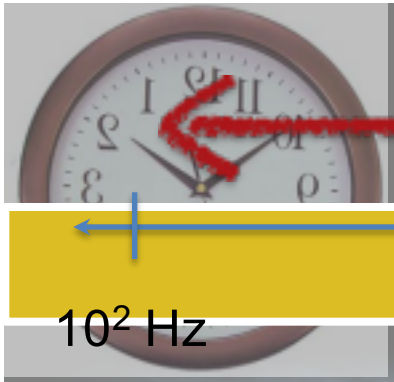
IAXO sensitivity prospects



J. Redondo and I. Irastorza

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





CASPEr

ADMX

10^2 Hz 10^4 Hz 10^6 Hz 10^8 Hz 10^{10} Hz 10^{12} Hz

axion mass (frequency)

Cosmic Axion Spin Precession Experiment (CASPEr)

Proposal:

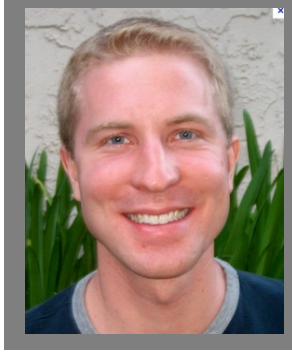
Peter Graham

Surjeet Rajendran

Alex Sushkov

Micah Ledbetter

Dmitry Budker



PRD **88** (2013) arXiv:1306.6088,

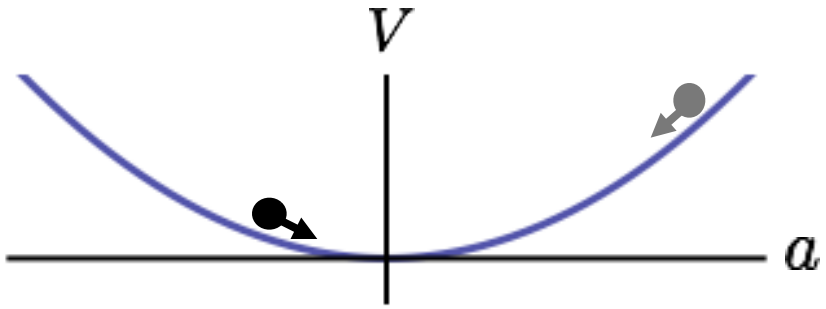
PRX (2014) arxXiv:1306.6089,

PRD **84** (2011) arXiv:1101.2691

Axion Dark Matter

Misalignment production:

Early Universe: Field has some initial value ➔ oscillations carry energy density ➔ natural dark matter



$$a(t) \sim a_0 \cos(m_a t)$$

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

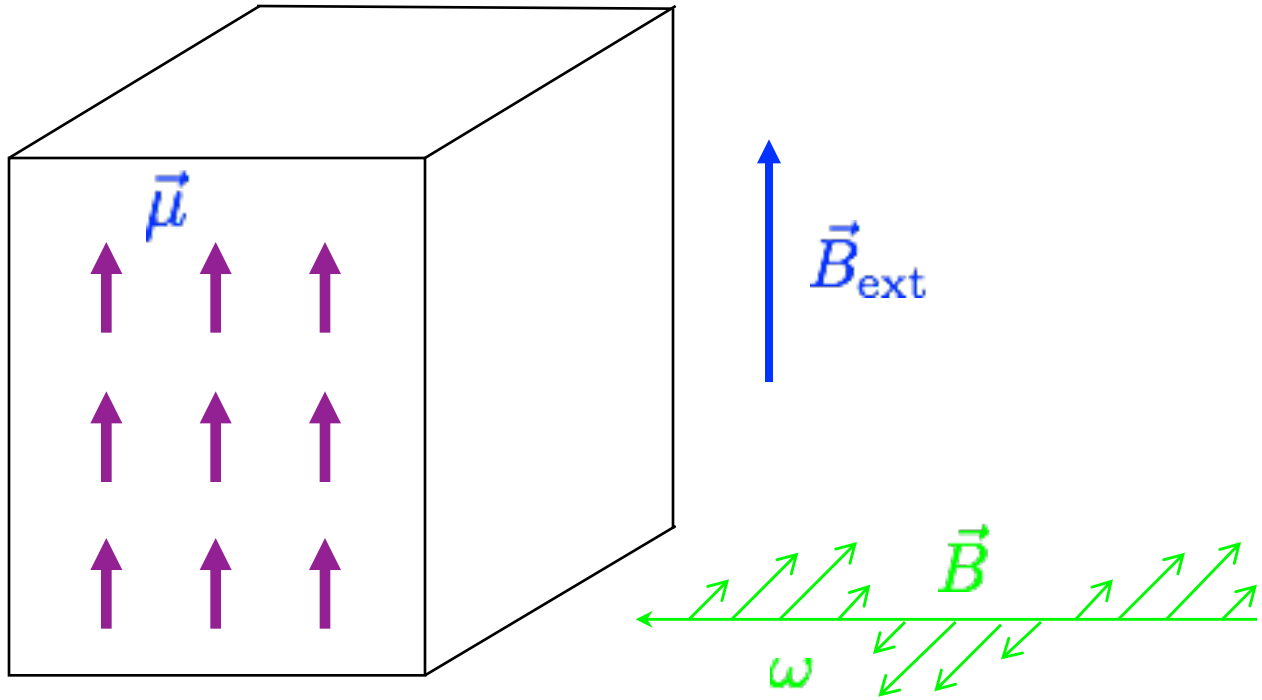
Axion easily produces correct abundance $\rho = \rho_{\rm DM}$

Many experiments search for WIMPs, only a few (ADMX, ADMX-HF, CAPP) can search for axion DM

Currently challenging to discover axions in much of parameter space

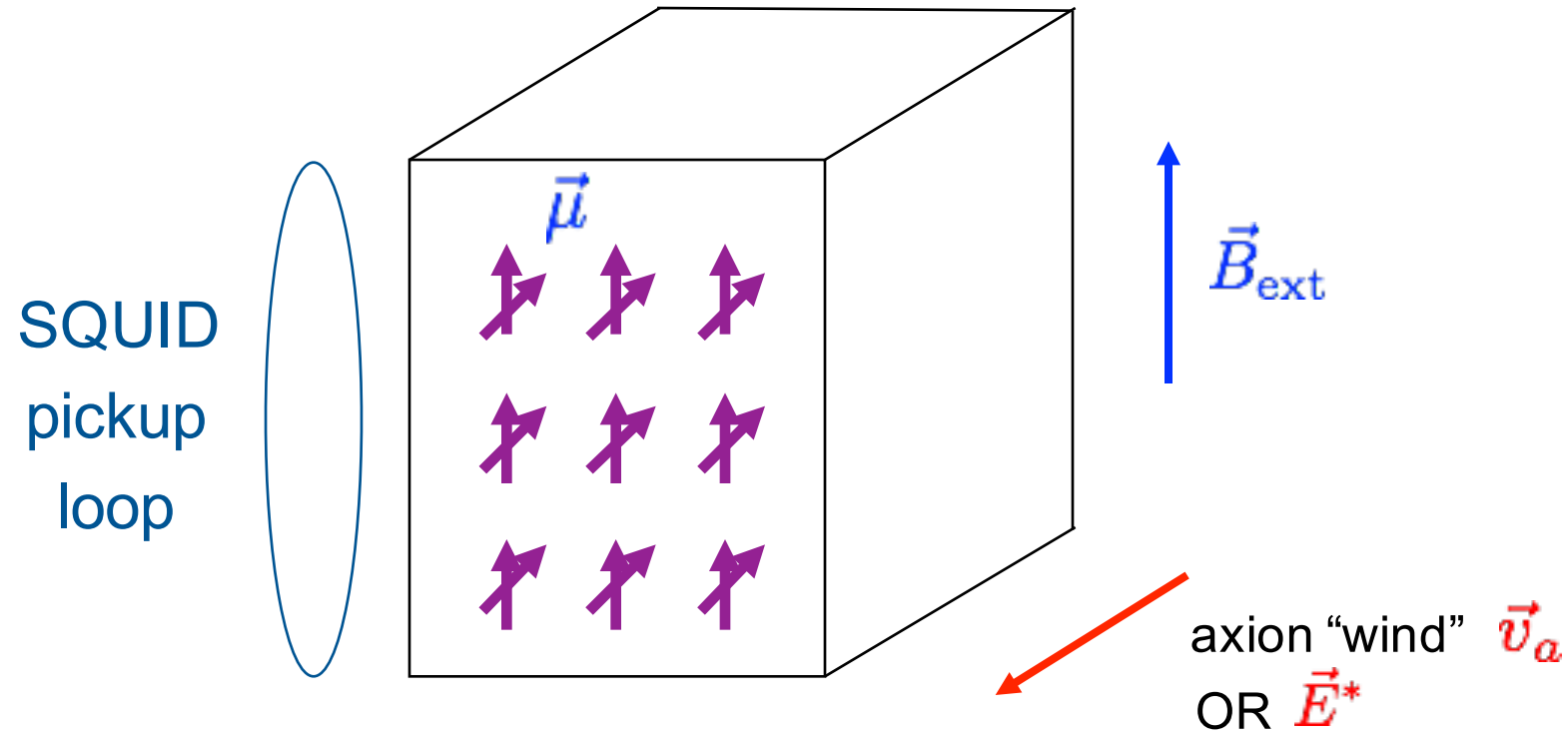
Important to find new ways to detect axions

Nuclear Magnetic Resonance (NMR)



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

CASPEr



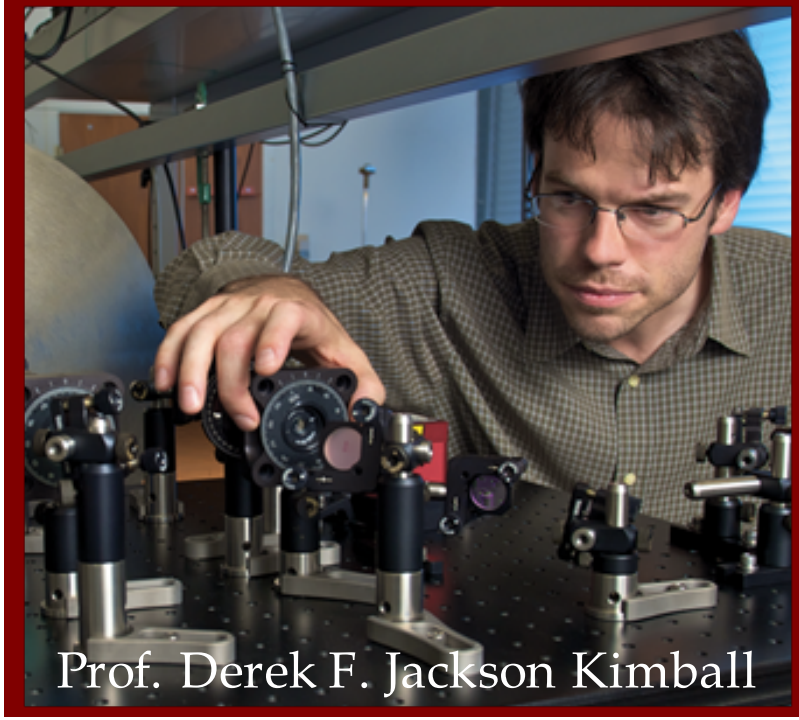
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

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

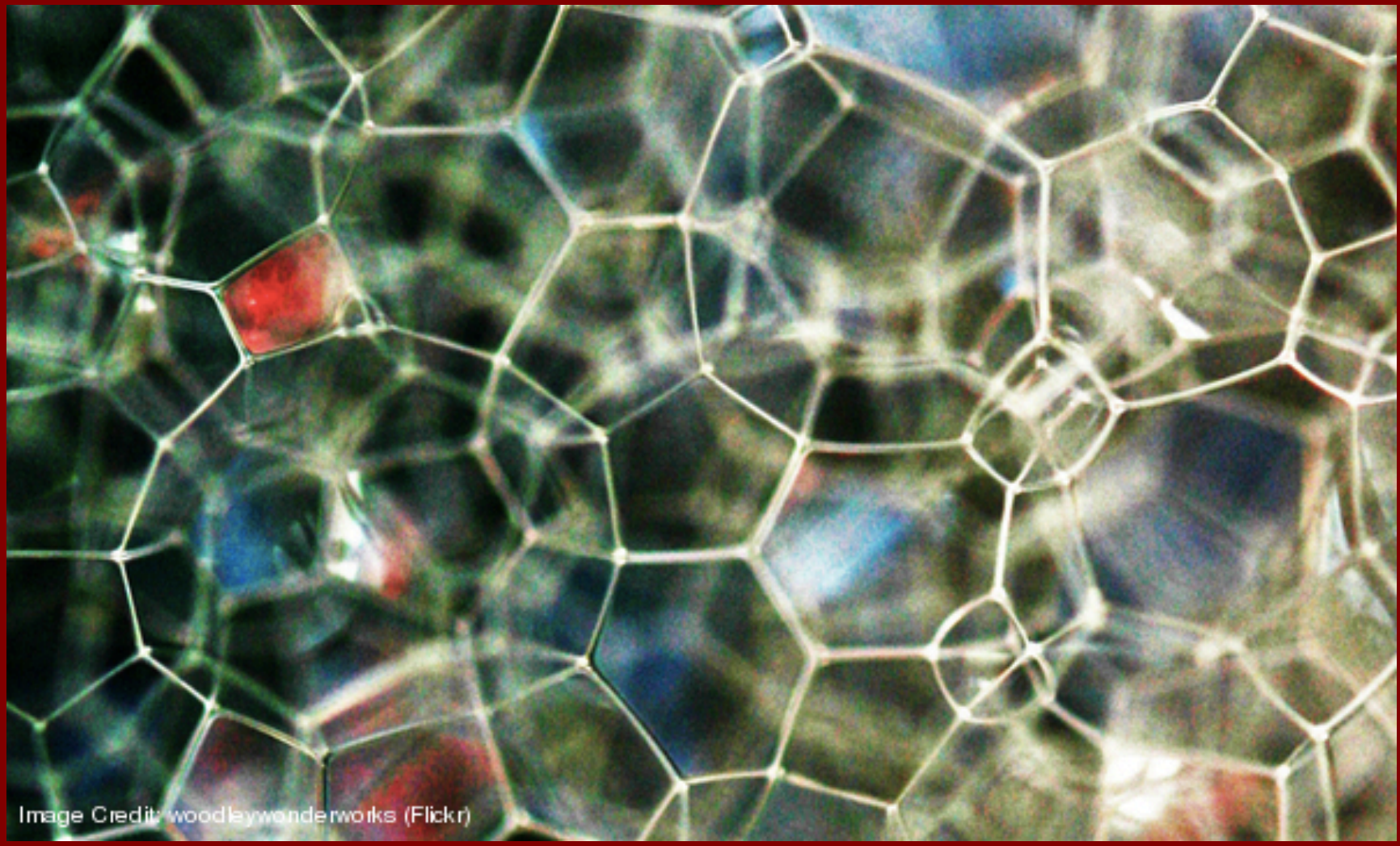
And another story called…

GLOBAL NETWORK OF OPTICAL MAGNETOMETERS FOR EXOTIC PHYSICS SEARCHES



Prof. Derek F. Jackson Kimball

ALPs may form domains

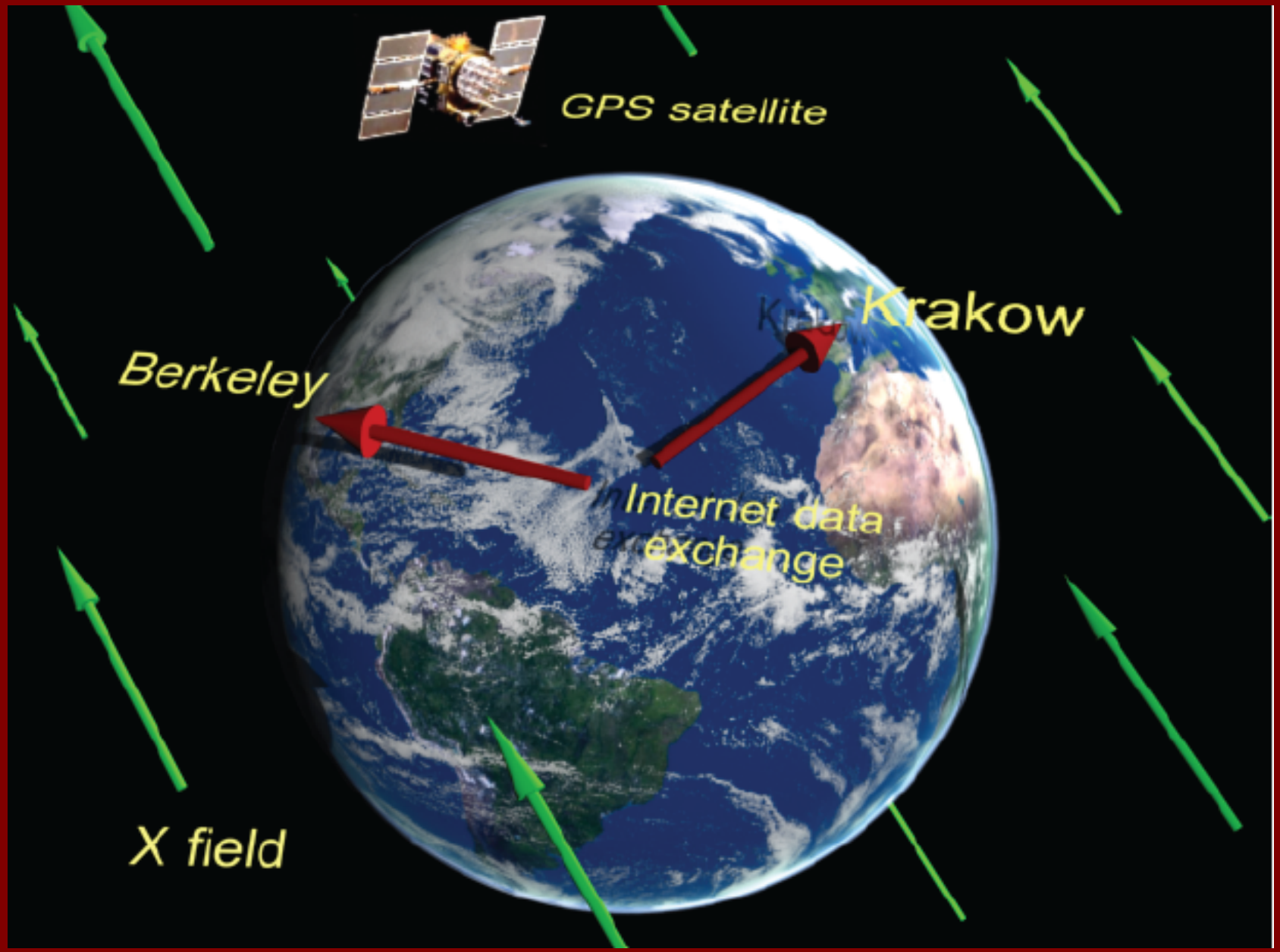


But how to detect them?

Correlated magnetometers…

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

Search for exotic fields: GNOME



PRL 110, 021803 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Detecting Domain Walls of Axionlike Models Using Terrestrial Experiments

M. Pospelov,[1,2] S. Pustelny,[3,4,*] M. P. Ledbetter,[4] D. F. Jackson Kimball,[5] W. Gawlik,[3] and D. Budker[4,6,†]

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[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
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[4]*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300*
[5]*Department of Physics, California State University - East Bay, Hayward, California 94542-3084, USA*
[6]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

(Dated: April 11, 2012)

- Ultralight (m_a~neV) axion-like fields forming domain networks
- Wall thickness $d \sim 2/m_a$ (~200 m)
- Domain size $L = 10^{-2}$ ly consistent with Dark Energy density constraints
- We may be going through a wall every 10 y or so!
- Bottom line: **GNOME** is quite sensitive to such events!

Ann. Phys. (Berlin), 1–12 (2013) / DOI 10.1002/andp.201300061

annalen der physik

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

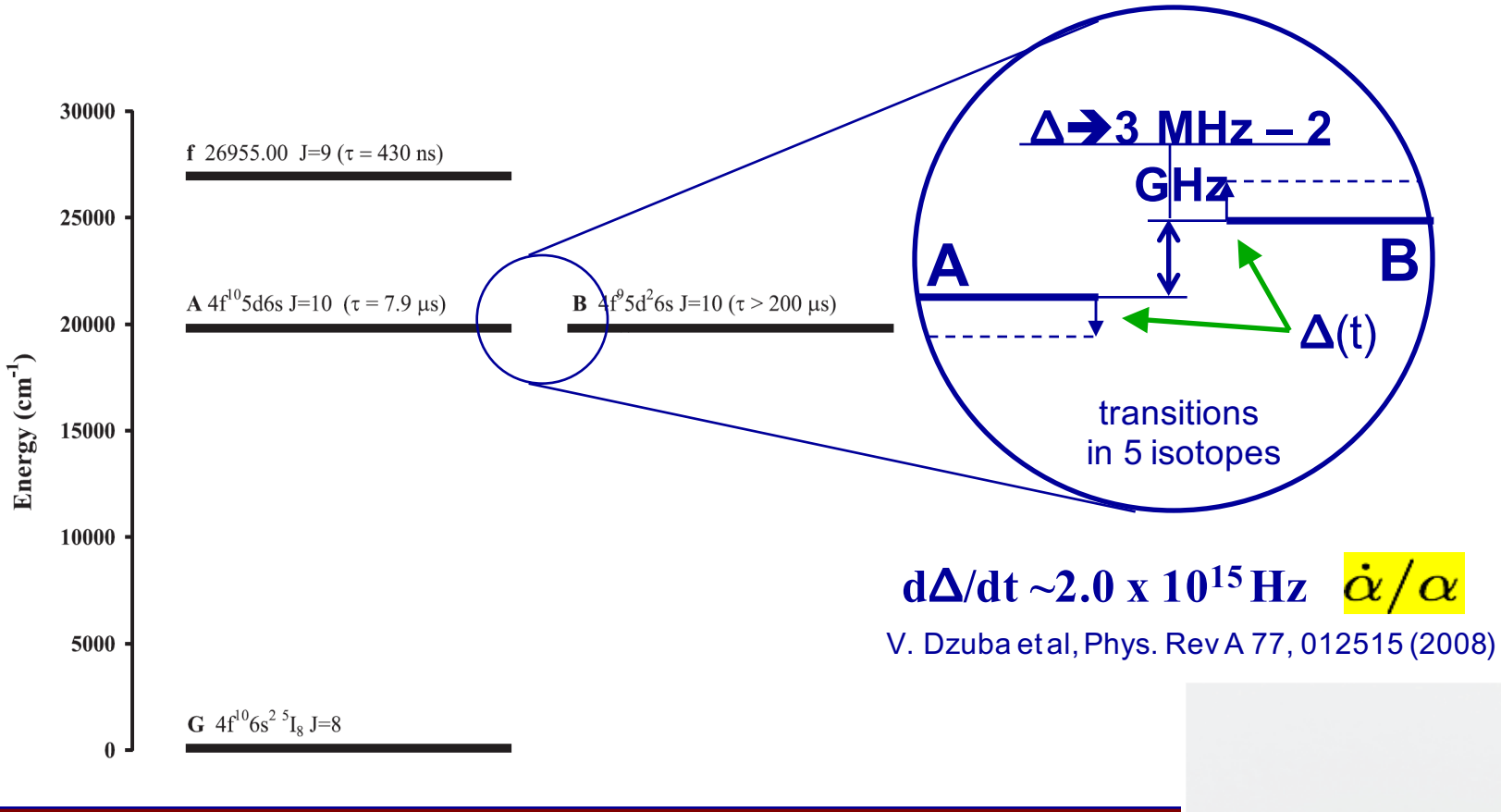
The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model

Szymon Pustelny[1,2,], Derek F. Jackson Kimball[3], Chris Pankow[4], Micah P. Ledbetter[2,**], Przemyslaw Wlodarczyk[5], Piotr Wcislo[1,6], Maxim Pospelov[7,8], Joshua R. Smith[9], Jocelyn Read[9], Wojciech Gawlik[1], and Dmitry Budker[2,10]*

- Current collaboration: Berkeley / Mainz, CSUEB, Krakow, USTC, U.Fribourg, TUM, KAIST, members of the LIGO analysis team, M. Pospelov
- Future members: PU, BGU, UW, Oberlin, PTB…
- Test runs done and analyzed (no wall **yet**)
- Taking data now!
- Also clocks! (A. Derevianko and M. Pospelov, 2014)

Beyond ALPs: dilatons

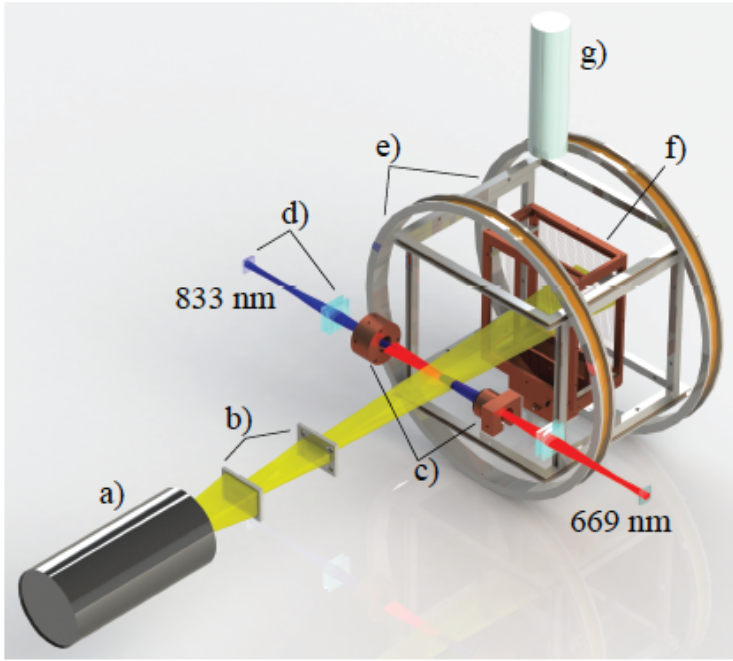
Dy as "Alpha Variometer"



$d\Delta/dt \sim 2.0 \times 10^{15}\,\mathrm{Hz}$ $\dot{\alpha}/\alpha$

V. Dzuba et al, Phys. Rev A 77, 012515 (2008)

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



DILATON DM ?

Searching for dilaton dark matter with atomic clocks

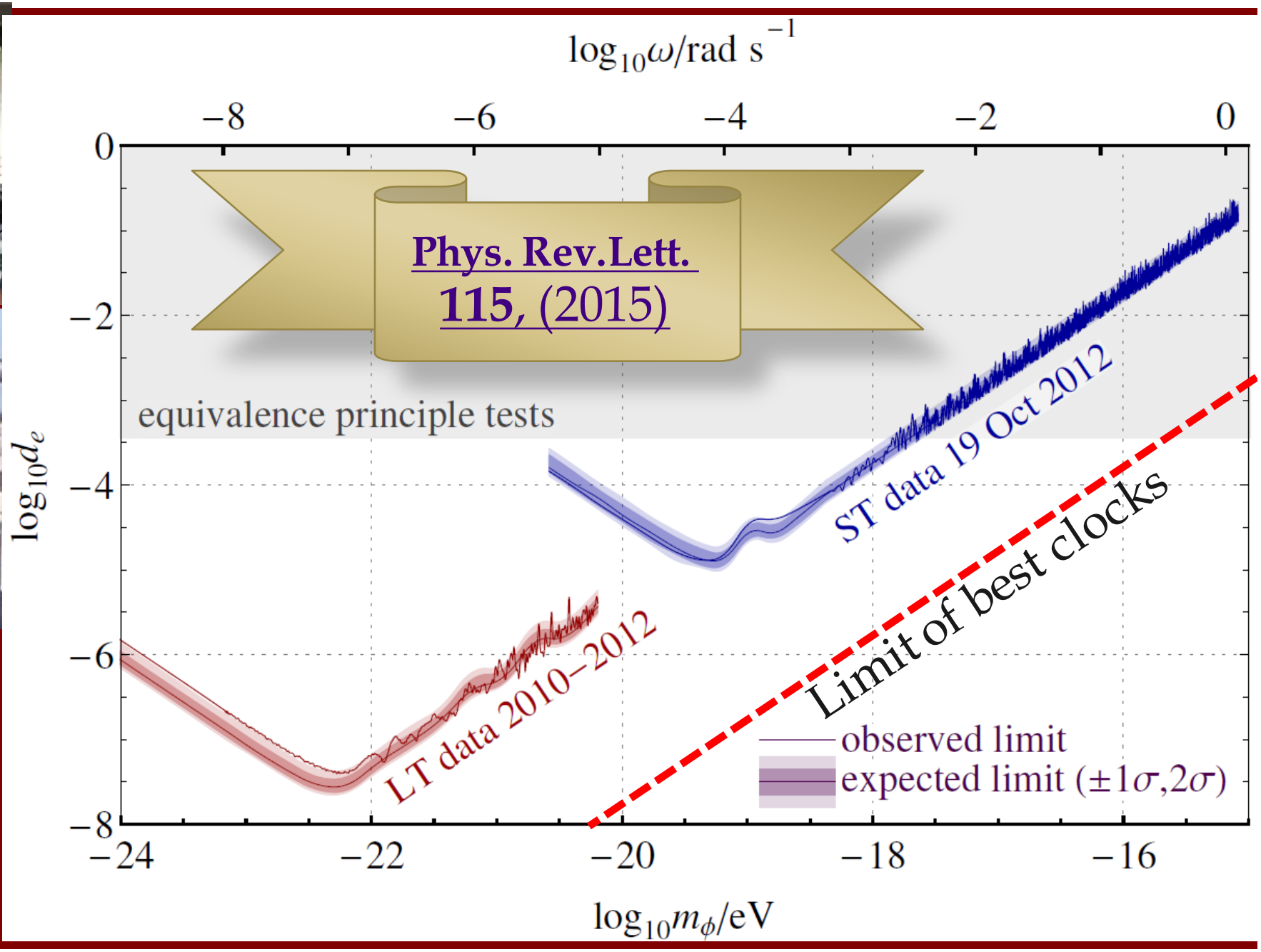
Asimina Arvanitaki*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

Junwu Huang† and Ken Van Tilburg‡
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA

(Dated: May 14, 2014)

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,§]



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)]

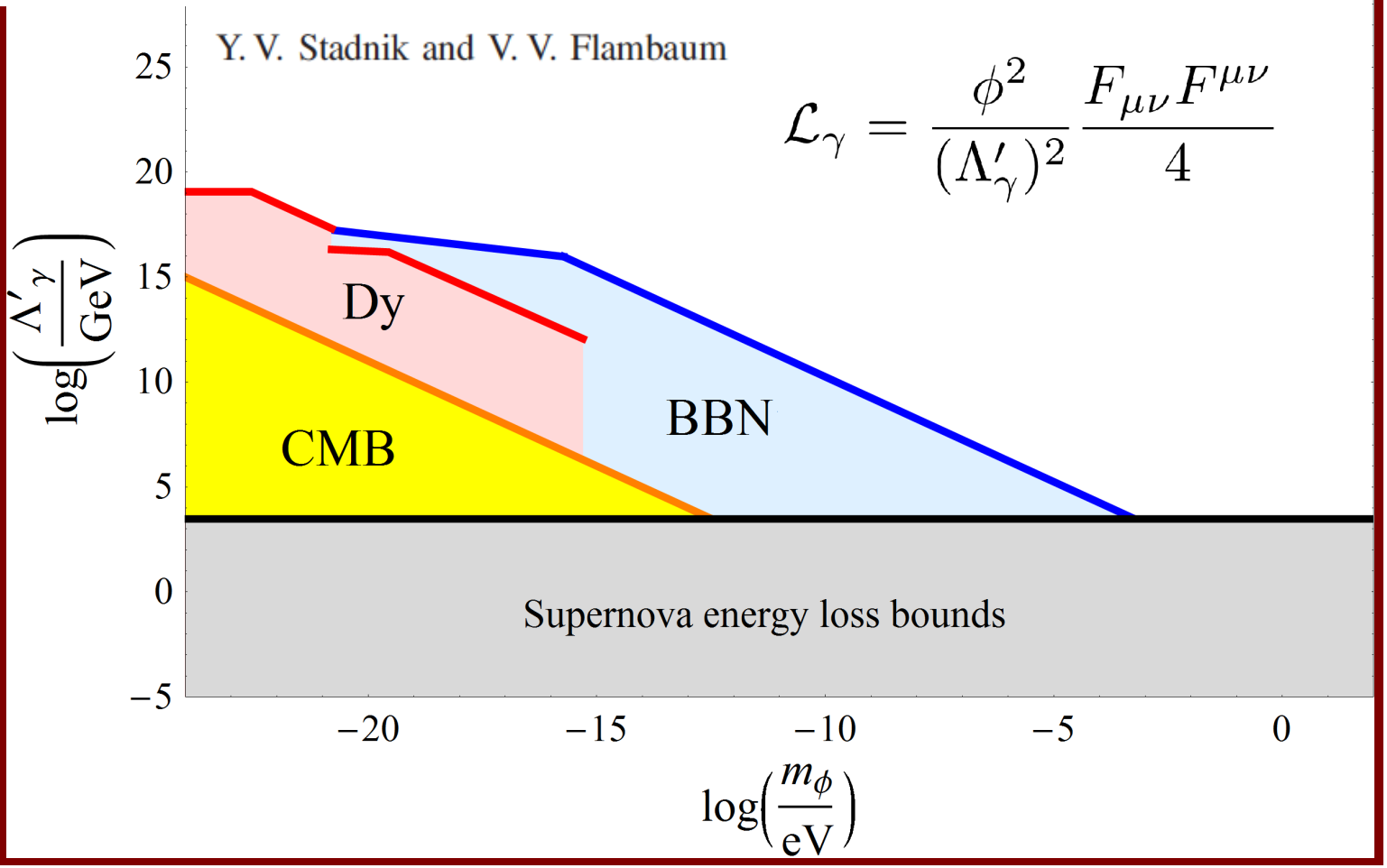
PRL 115, 201301 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

Victor V. Flambaum

Can Dark Matter Induce Cosmological Evolution of the Fundamental Constants of Nature?

Y. V. Stadnik and V. V. Flambaum

$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

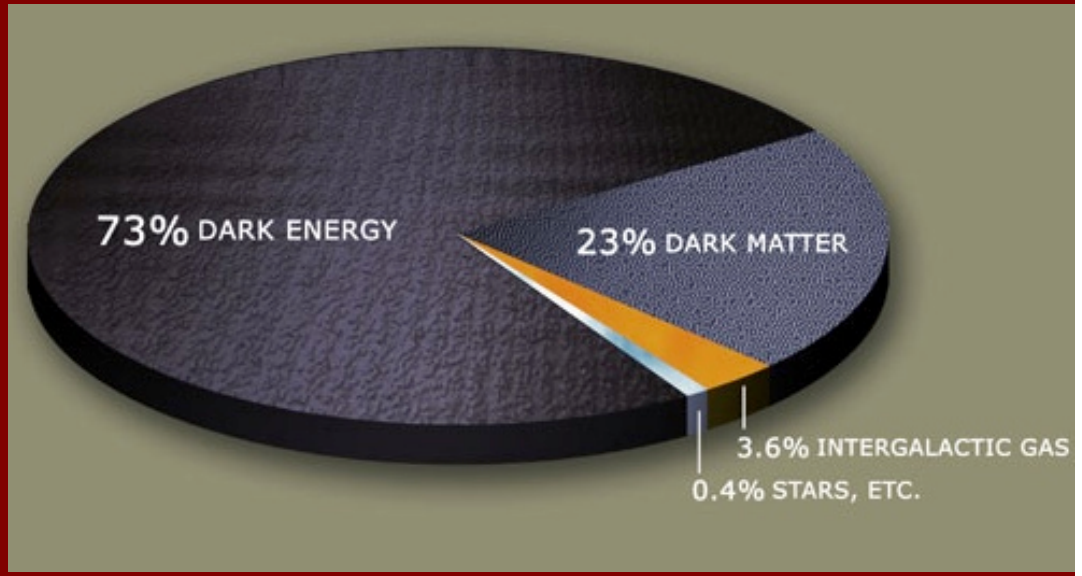


DARK-SIDE CONNECTION ?

- *Apparent* violations/variations of "constants" may be due to "cosmic fields"
- Oscillating or transient effects !

Dark Matter

Dark Energy



http://earthsky.org/space/

Phys. Rev. Lett. 113; Phys. Rev. D 90 (2014)

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

B. M. Roberts,[1,*] Y. V. Stadnik,[1,†] V. A. Dzuba,[1] V. V. Flambaum,[1,2] N. Leefer,[3] and D. Budker[3,4,5]

[1] *School of Physics, University of New South Wales, Sydney 2052, Australia*
[2] *New Zealand Institute for Advanced Study, Massey University, Auckland 0745, New Zealand*
[3] *Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
[4] *Department of Physics, University of California at Berkeley, Berkeley, CA 94720-7300, USA*
[5] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: April 15, 2014)

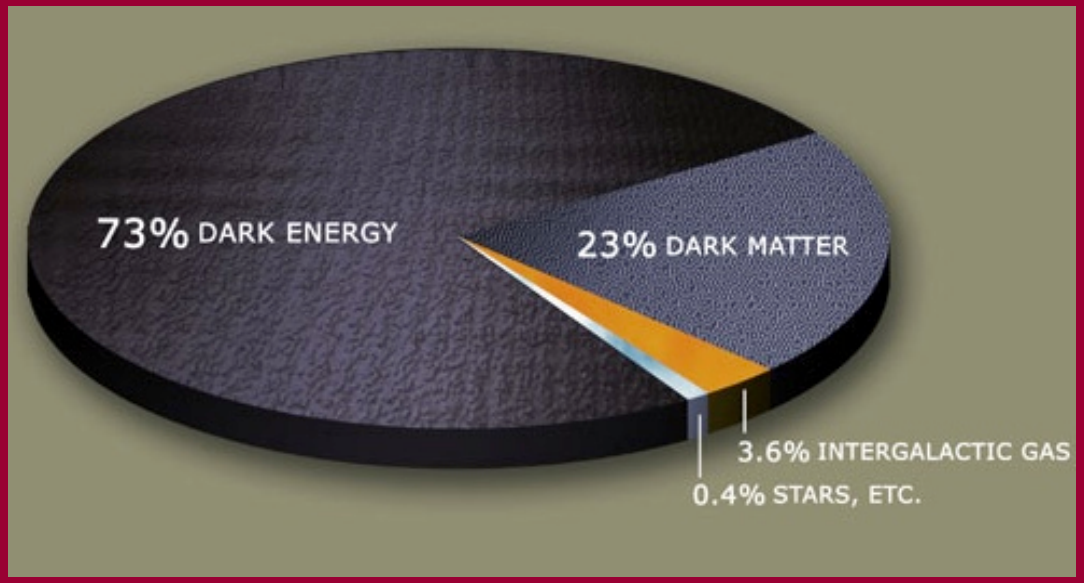
We propose methods for extracting limits on the strength of $\mathcal{P}$-odd interactions of pseudoscalar and pseudovector cosmic fields with electrons, protons and neutrons. Candidates for such fields are dark matter (including axions) and dark energy, as well as several more exotic sources described 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.

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

From nuclear anapoles

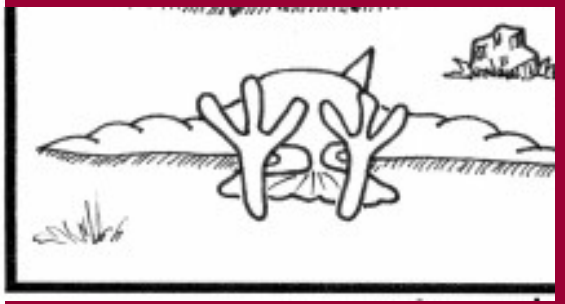
CONCLUSIONS I

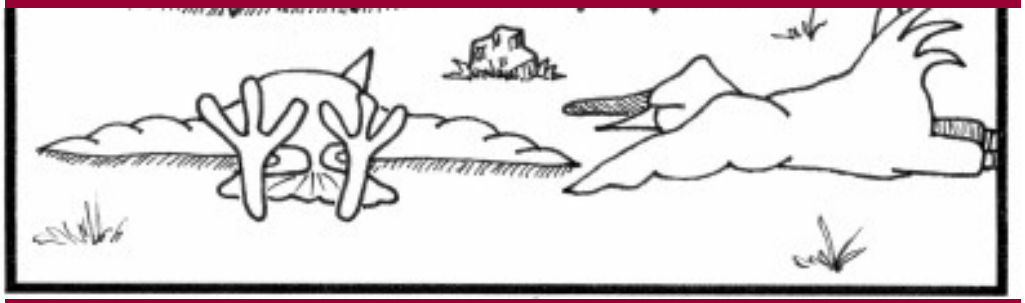


http://earthsky.org/space/

Dark-side
connection

CONCLUSIONS II





Thanks to Prof. G. Raffelt

Light axions may solve all our problems…

… and we are looking for them!

CONCLUSIONS III

All precision-measurement data need to be

- Time stamped
- Stored

SIMONS FOUNDATION

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