Title: Introduction, Scope and goals of the workshop, Open questions in the field

Date: Jun 16, 2014 09:10 AM

URL: http://pirsa.org/14050149

Abstract:

# New Ideas in Low-Energy Tests of Fundamental Physics

## General Thoughts

Derek F. Jackson Kimball
California State University

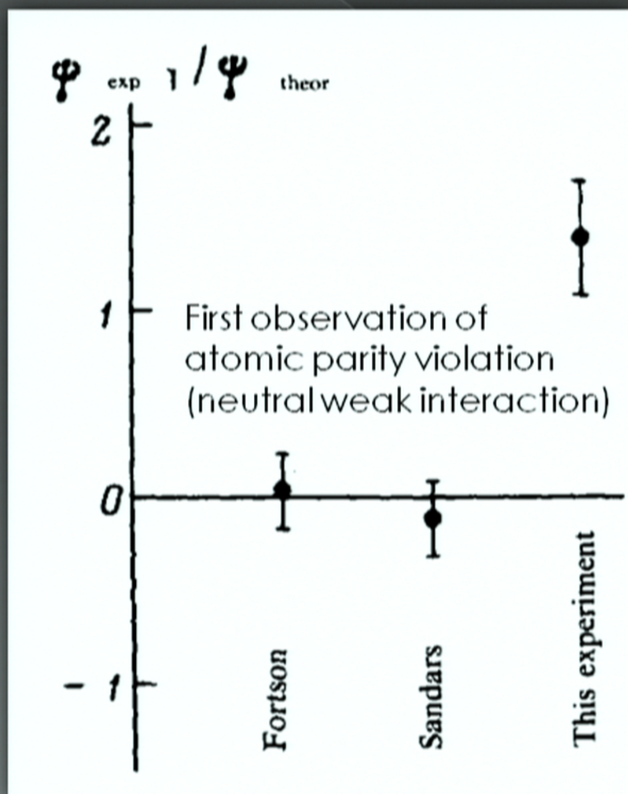
# Origins…

# Origins…

Max Zolotorev

Eugene Commins

# Origins…




Barkov & Zolotorev, JETP Lett. **27**, 357 (1978).

Max Zolotorev

Eugene Commins

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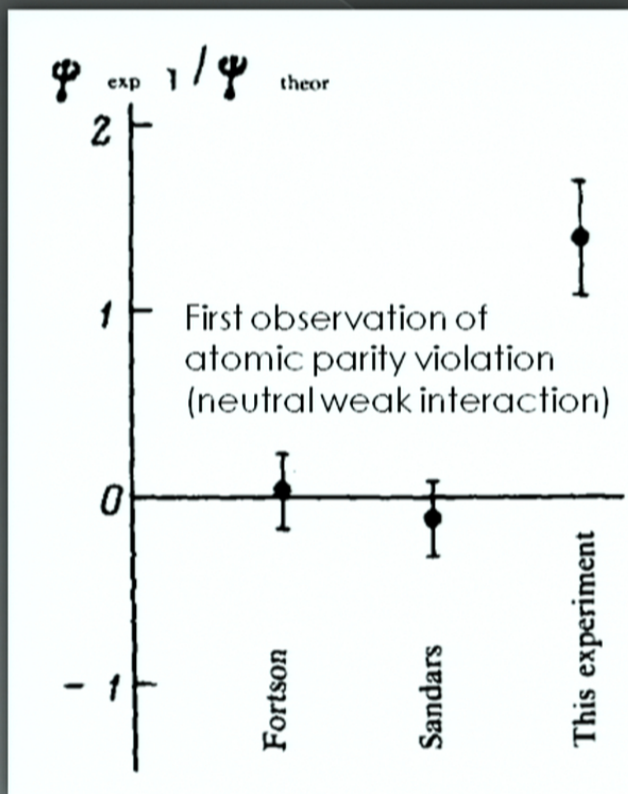


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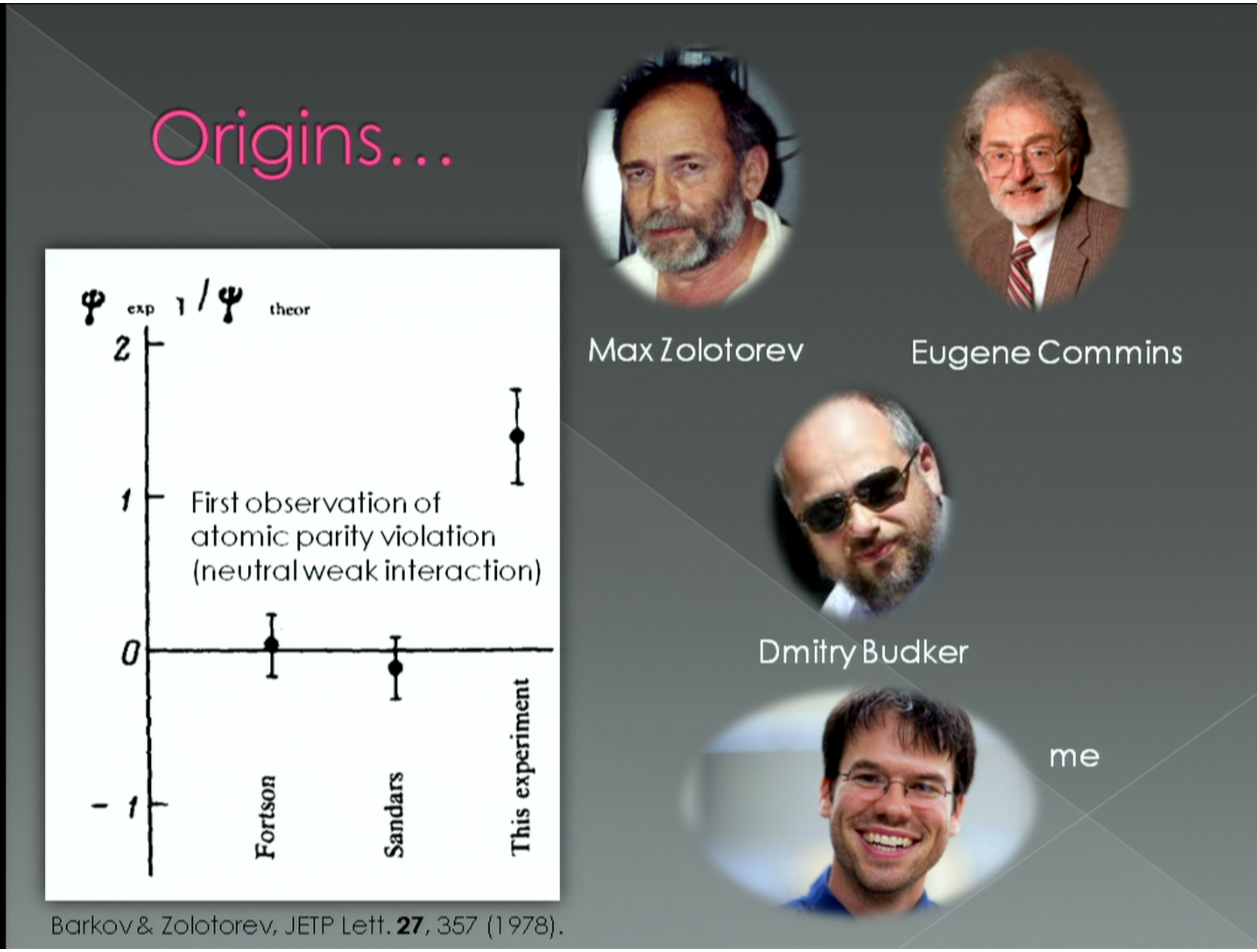
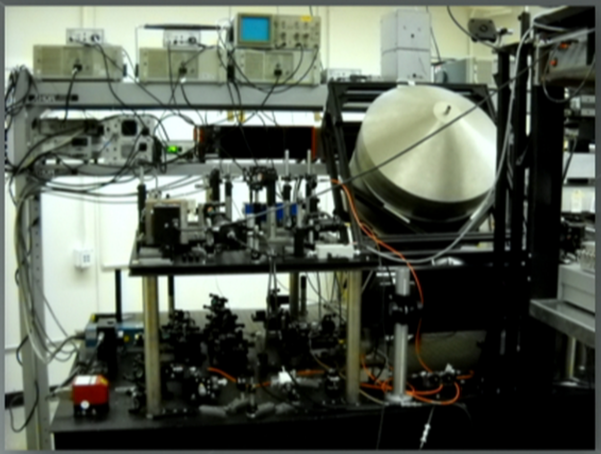

Origins...
theor
2
1
0
-1
First observation of
atomic parity violation
(neutral weak interaction)
Fortson
Sandars
This experiment
Barkov & Zolotorev, JETP Lett. 27, 357 (1978).
Max Zolotorev
Eugene Commins
Dmitry Budker
me

# Interface between theorists and experimentalists

# Interface between theorists and experimentalists

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi);$$

$$V(\phi) = \frac{\lambda}{S_0^{2N-4}} |2^{N/2}\phi^N - S_0^N|^2,$$



# The state of particle physics?

James Chadwick
discovered neutron 1932

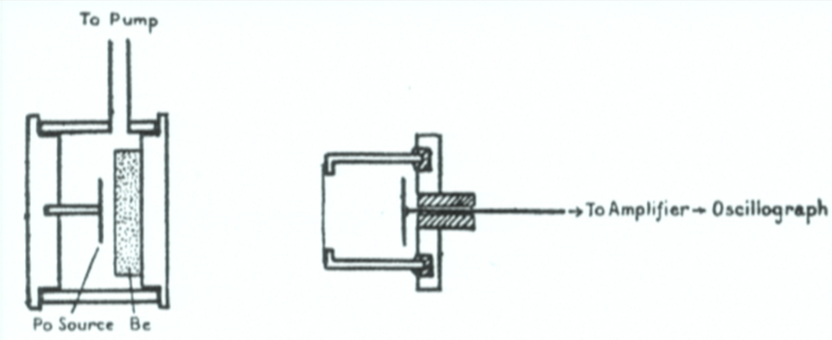



FIG. 1.

# The state of particle physics?

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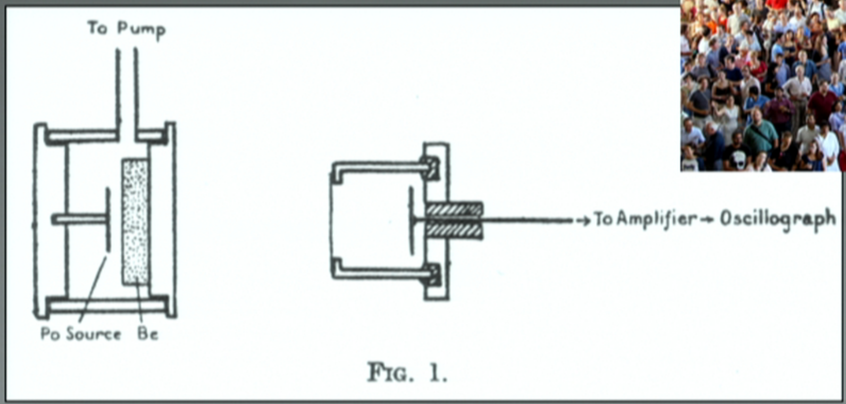



Fig. 1.

CERN team
discovered Higgs 2013

# Confusion is preface to discovery!

# Motivated by great mysteries

- Missing CP-violation for baryogenesis,
- Strong CP problem,
- Dark matter,
- Dark energy,
- etc.

# Finite set of parameters to explore with atomic experiments?

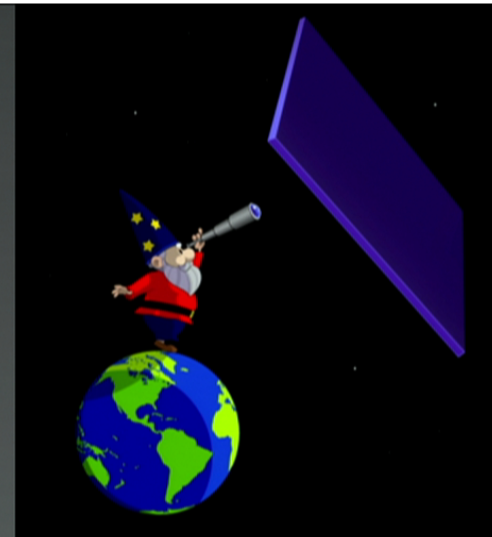
- Elementary fermions have only monopole (charge/mass) and dipole (spin) moments.
- Elementary particles can be in relative motion.
- Quantum field theory, with general assumptions, allows only a finite number of possible spin-0 and spin-1 potentials.

# A new direction in low-energy tests of fundamental physics…

- Instead of searching for local or universal signatures of new physics in atomic systems, search for transient signatures of astrophysical origin…

- But where to search, how to search, and what to search for? Motivation and connections between different measurements come from theory.

# Global Network of Optical Magnetometers to search for Exotic Physics (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]

[1]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 1A1, Canada*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada*
[3]*Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Kraków, Poland*
[4]*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA*
[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, USA*

(Received 23 July 2012; revised manuscript received 4 November 2012; published 11 January 2013)

# Cosmic Axion Spin Precession Experiment (CASPEr)

PHYSICAL REVIEW X **4,** 021030 (2014)

## Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

[2]*Department of Physics, Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*

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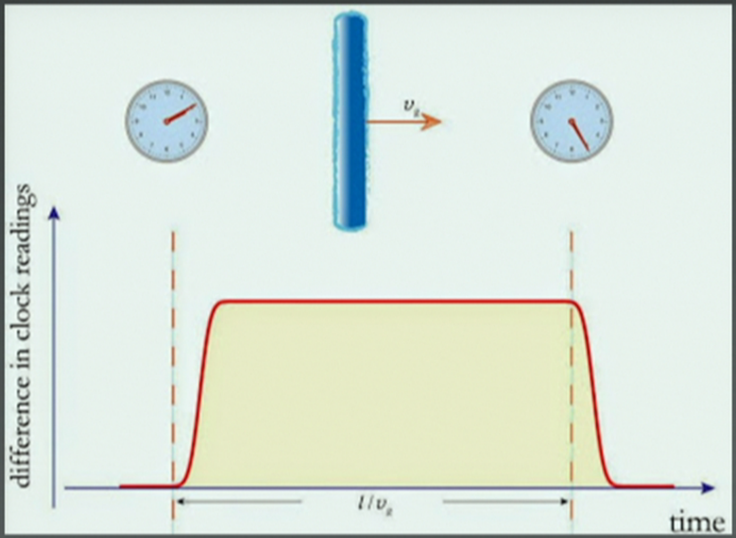
[4]*Department of Physics and Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, USA*

[5]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*

(Received 9 July 2013; published 19 May 2014)

# Network of atomic clocks




**Hunting for topological dark matter with atomic clocks**

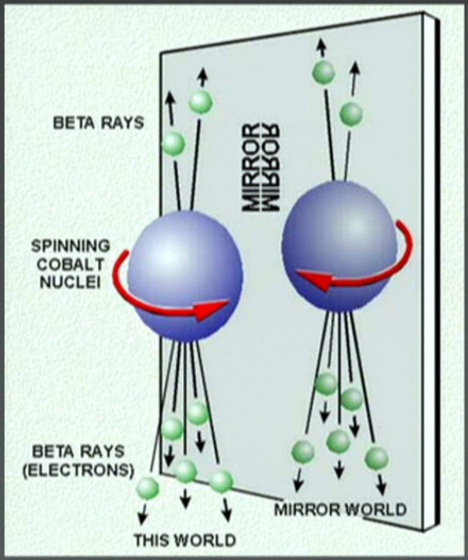

A. Derevianko
*Department of Physics, University of Nevada, Reno, NV 89557, USA*

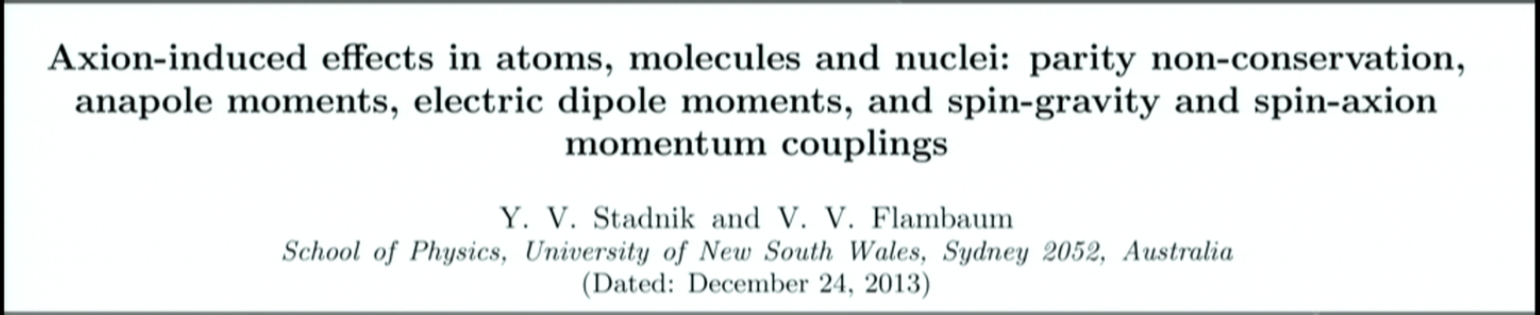
M. Pospelov
*Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada and Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*

(Dated: November 7, 2013)

Derevianko and Pospelov, arXiv:1311.1244 (2013).

# Astrophysically induced parity violating effects





**Axion-induced effects in atoms, molecules and nuclei: parity non-conservation, anapole moments, electric dipole moments, and spin-gravity and spin-axion momentum couplings**

Y. V. Stadnik and V. V. Flambaum
*School of Physics, University of New South Wales, Sydney 2052, Australia*
(Dated: December 24, 2013)

Stadnik and Flambaum, arXiv:1312.6667 (2013).

# Transient violations of physical laws?

- Broadly speaking, it seems possible that many physical laws could be subject to transient, small violations from some unknown astrophysical effects, and violations could easily have escaped detection!

- But given difficulty of experiments and our finite resources, what are the most promising laws to test? What are the most promising systems with which to perform tests?

# OPEN QUESTIONS

**Dmitry Budker**

**Helmholtz Institute Mainz**
**Johannes Gutenberg U.**

**UC Berkeley Physics**
**NSD LBNL**

Perimeter Institute, June 2014

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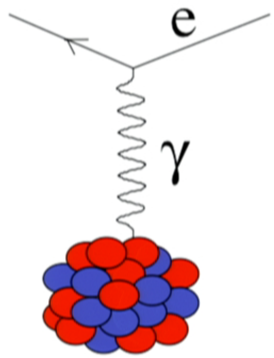
Perimeter Institute, June 2014

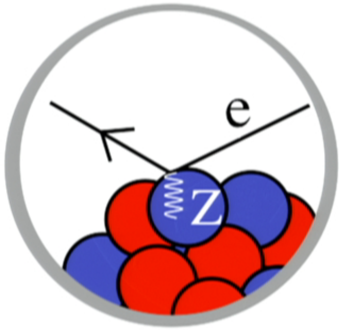
# THE PLAN …

- Gravity tests with $\dot{\alpha}$ ?
- Does gravity respect parity ?
- Cosmic parity violation ?
- Antimatter tests beyond $\overline{g}$ ?
- Open GNOME & CASPEr Qns

# ATOMIC PARITY VIOLATION

- Main Source: Z exchange



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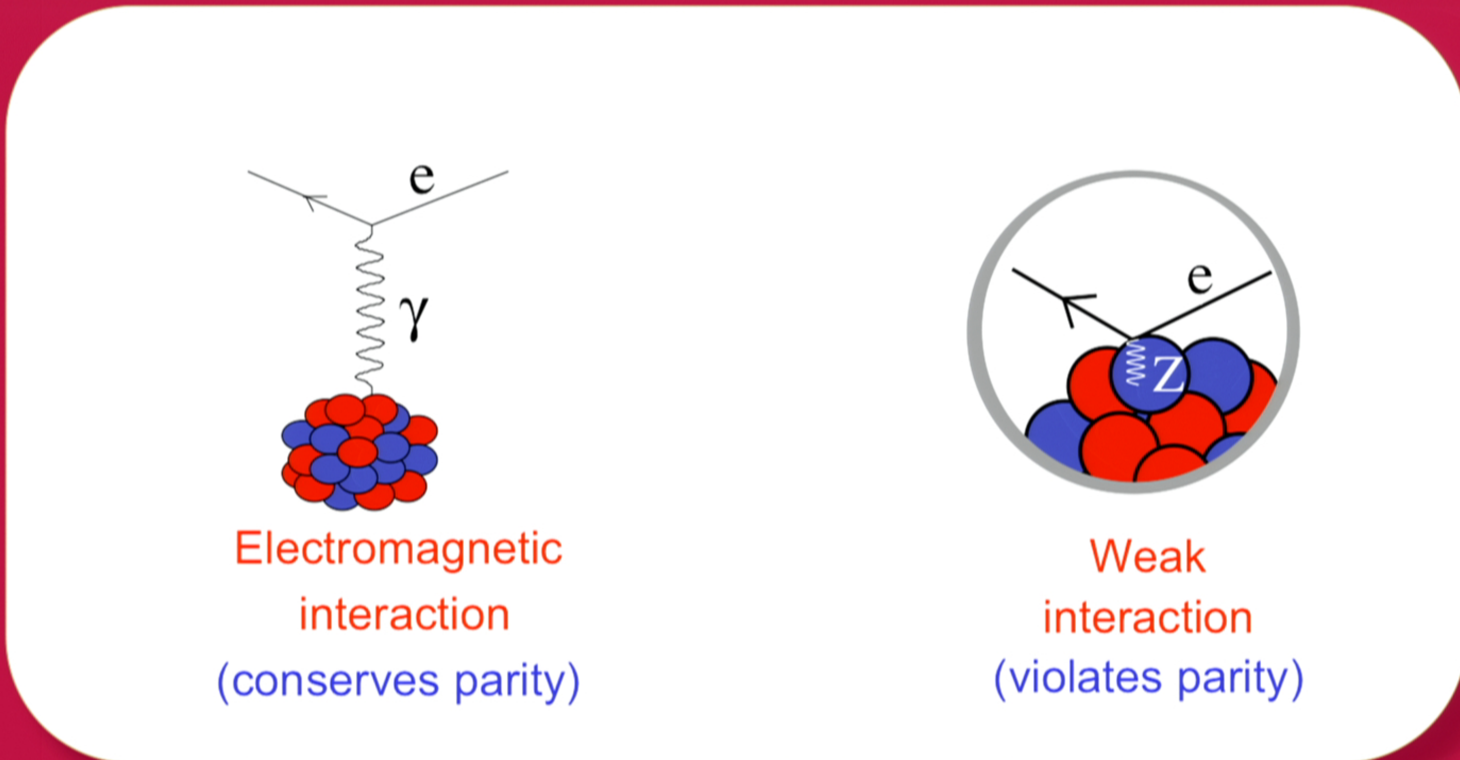


- P-odd, T-even correlation $\vec{\sigma} \cdot \vec{p}$

# Dy

- Ideal APV amplifier? Dzuba, Flambaum, Khriplovich (1986)
  - Fully degenerate opposite-parity levels
  - Large $Z^3$ (Z=66)

4

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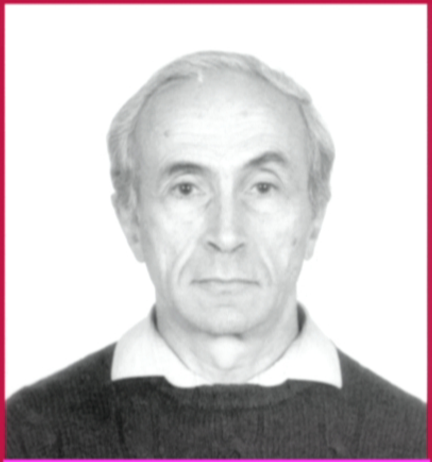

Prof. Iosif B. Khriplovich

4

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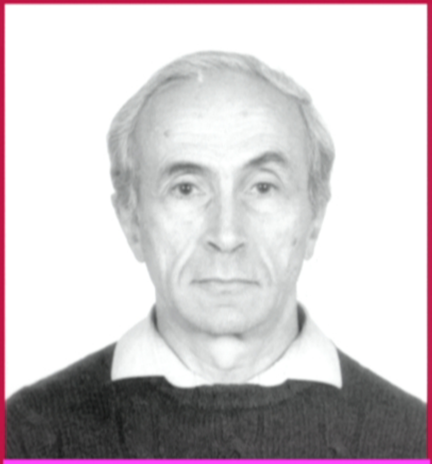
- Also
  - Many stable isotopes: A=164-156
  - Two $I$=5/2 isotopes (anapole)



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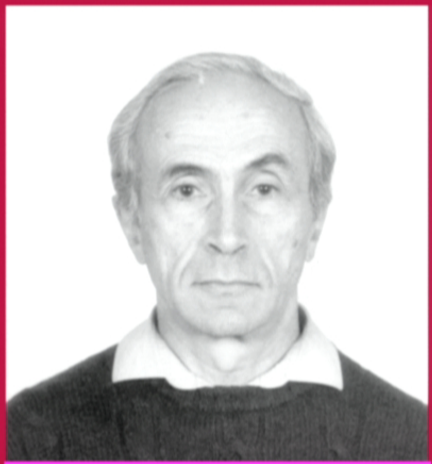

Prof. Iosif B. Khriplovich

- Degenerate levels require quantum juggling to measure APV

4

# The parity violation experiment in Dy

PHYSICAL REVIEW A VOLUME 56, NUMBER 5 NOVEMBER 1997

## Search for parity nonconservation in atomic dysprosium

A. T. Nguyen,[1] D. Budker,[1,2] D. DeMille,[1,*] and M. Zolotorev[3]
[1]*Physics Department, University of California, Berkeley, California 94720-7300*
[2]*Nuclear Science Division, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[3]*Center for Beam Physics, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720*
(Received 2 June 1997)

Results of a search for parity nonconservation (PNC) in a pair of nearly degenerate opposite-parity states in atomic dysprosium are reported. The sensitivity to PNC mixing is enhanced in this system by the small energy separation between these levels, which can be crossed by applying an external magnetic field. The metastable odd-parity sublevel of the nearly crossed pair is first populated. A rapidly oscillating electric field is applied to mix this level with its even-parity partner. By observing time-resolved quantum beats between these sublevels, we look for interference between the Stark-induced mixing and the much smaller PNC mixing. To guard against possible systematic effects, reversals of the signs of the electric field, the magnetic field, and the decrossing of the sublevels are employed. We report a value of $|H_w| = |2.3 \pm 2.9$ (statistical) $\pm 0.7$(systematic)$|$ Hz for the magnitude of the weak-interaction matrix element. A detailed discussion is given of the apparatus, data analysis, and systematic effects. [S1050-2947(97)02111-2]



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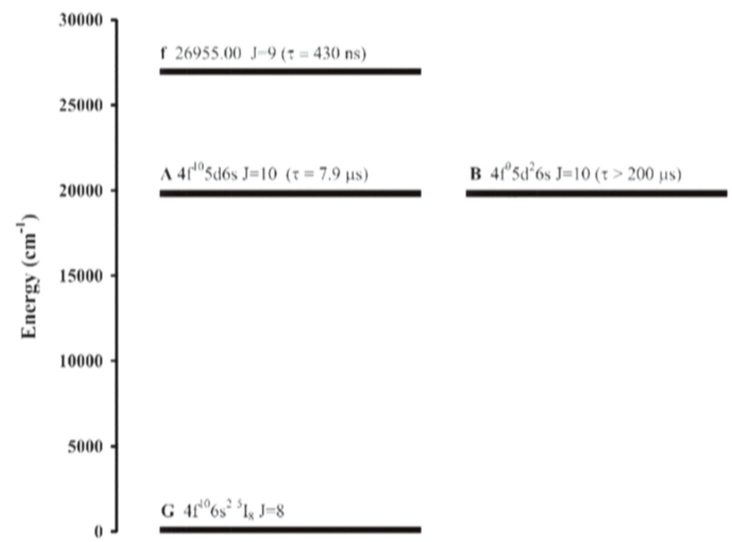
# Search in Atomic Dy



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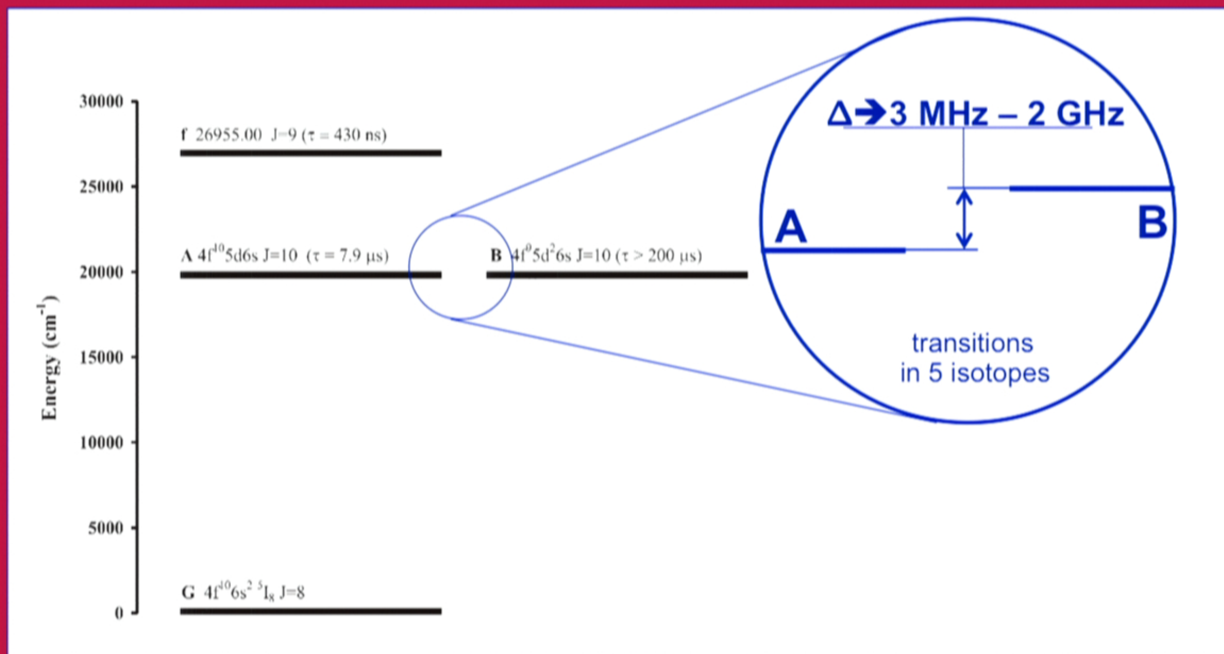

# Sensitivity

- Transition linewidth $\gamma$ determined by lifetime of A ($\tau$ =7.9 $\mu$s) and transit broadening: $\gamma \sim 40$ kHz
- Counting rate ~ $10^9$ $s^{-1}$
- 10 mHz sensitivity in 6 hours of averaging

$$\delta\nu \sim \frac{\gamma}{\sqrt{N}} \sim \frac{1.3}{\sqrt{T_{avg}}}\,\mathrm{Hz}$$

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$$\frac{\delta\nu}{\nu} \sim 10^{-11}$$

fractional frequency stability

Easy

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Easy

fractional frequency stability

$$\frac{\delta\nu}{\gamma} \sim 3 \times 10^{-7}$$

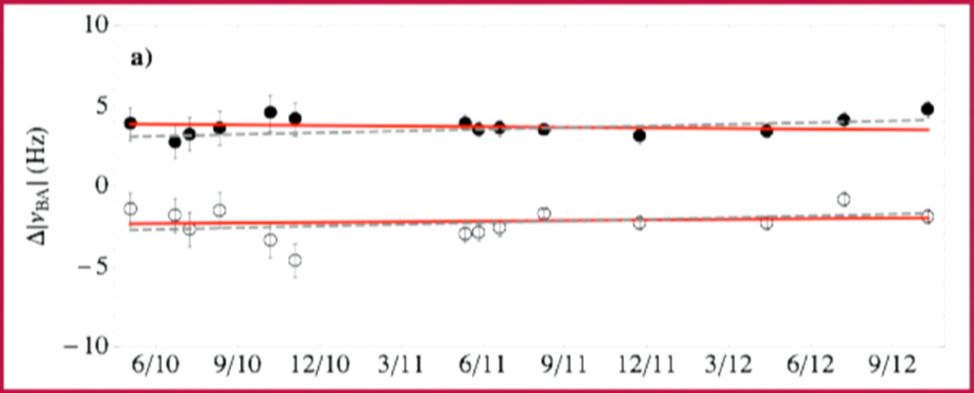
Difficult

"splitting the line"

PRL 111, 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

**New Limits on Variation of the Fine-Structure Constant Using Atomic Dysprosium**

N. Leefer,[1] C. T. M. Weber,[2] A. Cingöz,[3] J. R. Torgerson,[4] and D. Budker[1,5]




## Isotope Comparison

$$\dot{\alpha}/\alpha = (-5.8 \pm 6.9) \times 10^{-17}$$

PRL **111,** 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

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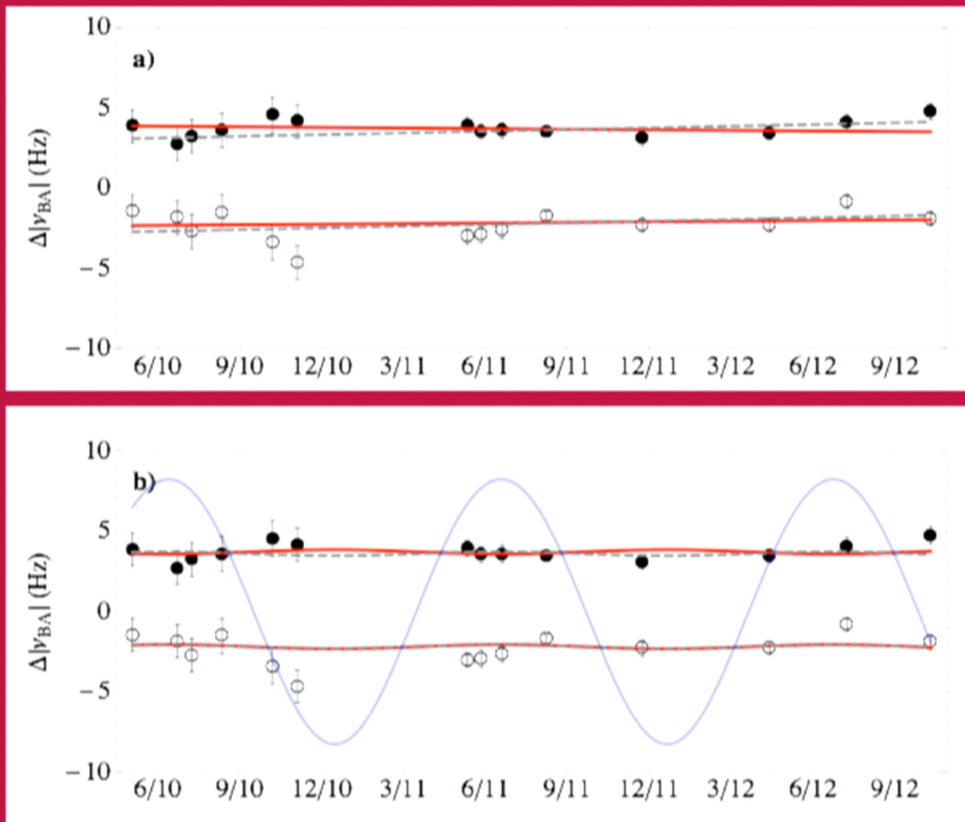


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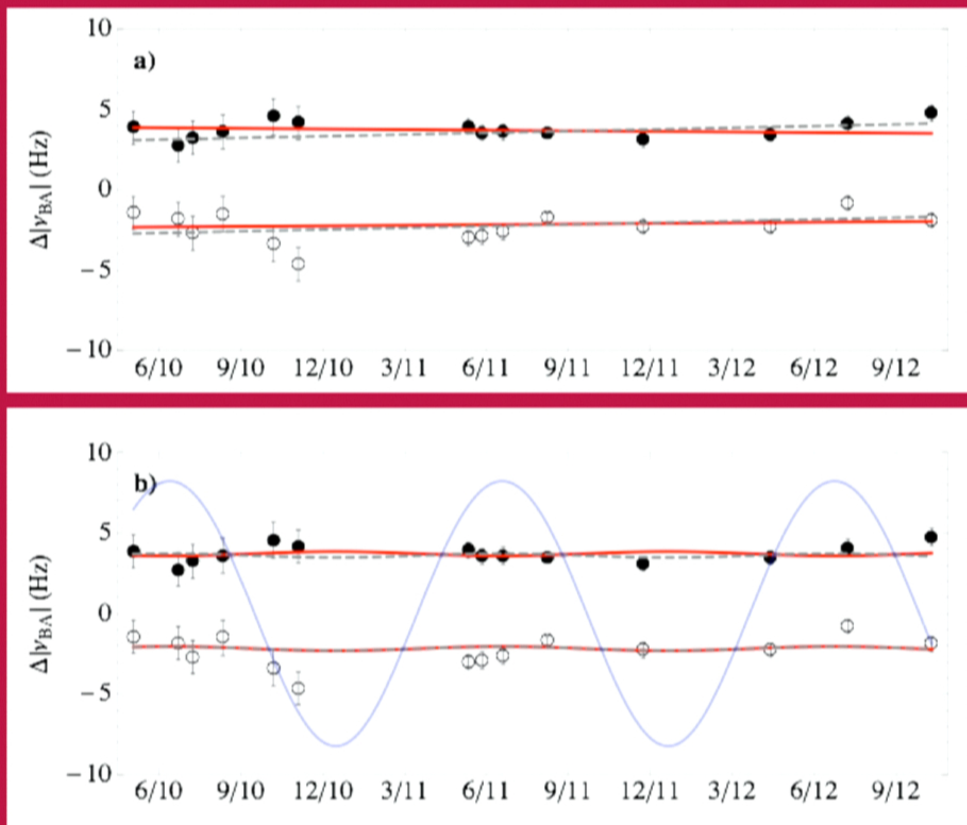


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$$\frac{\Delta\alpha}{\alpha} = k_\alpha \frac{\Delta U}{c^2}$$

$$k_\alpha = (-5.5 \pm 5.2) \times 10^{-7}$$

PRL **111,** 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

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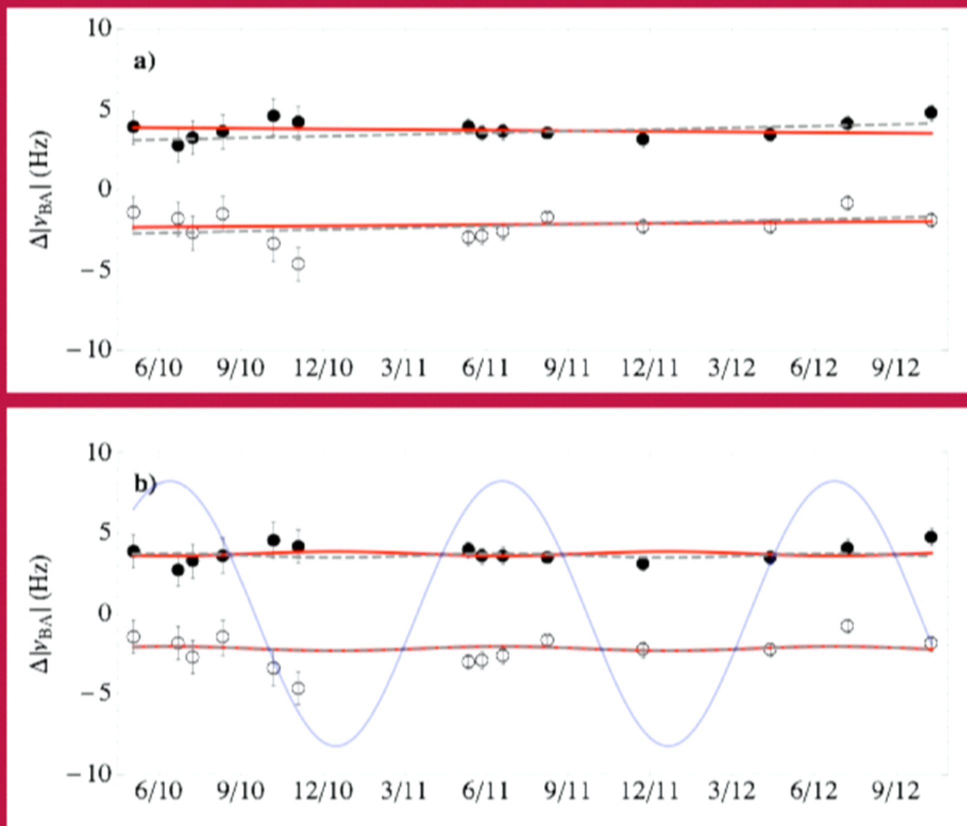


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## The effect of gravitational field gradient on atomic energies

A. Gerhardus,* N. Leefer,† M. Hohensee, and D. Budker
*Physics Department, University of California, Berkeley 94720-7300, USA*

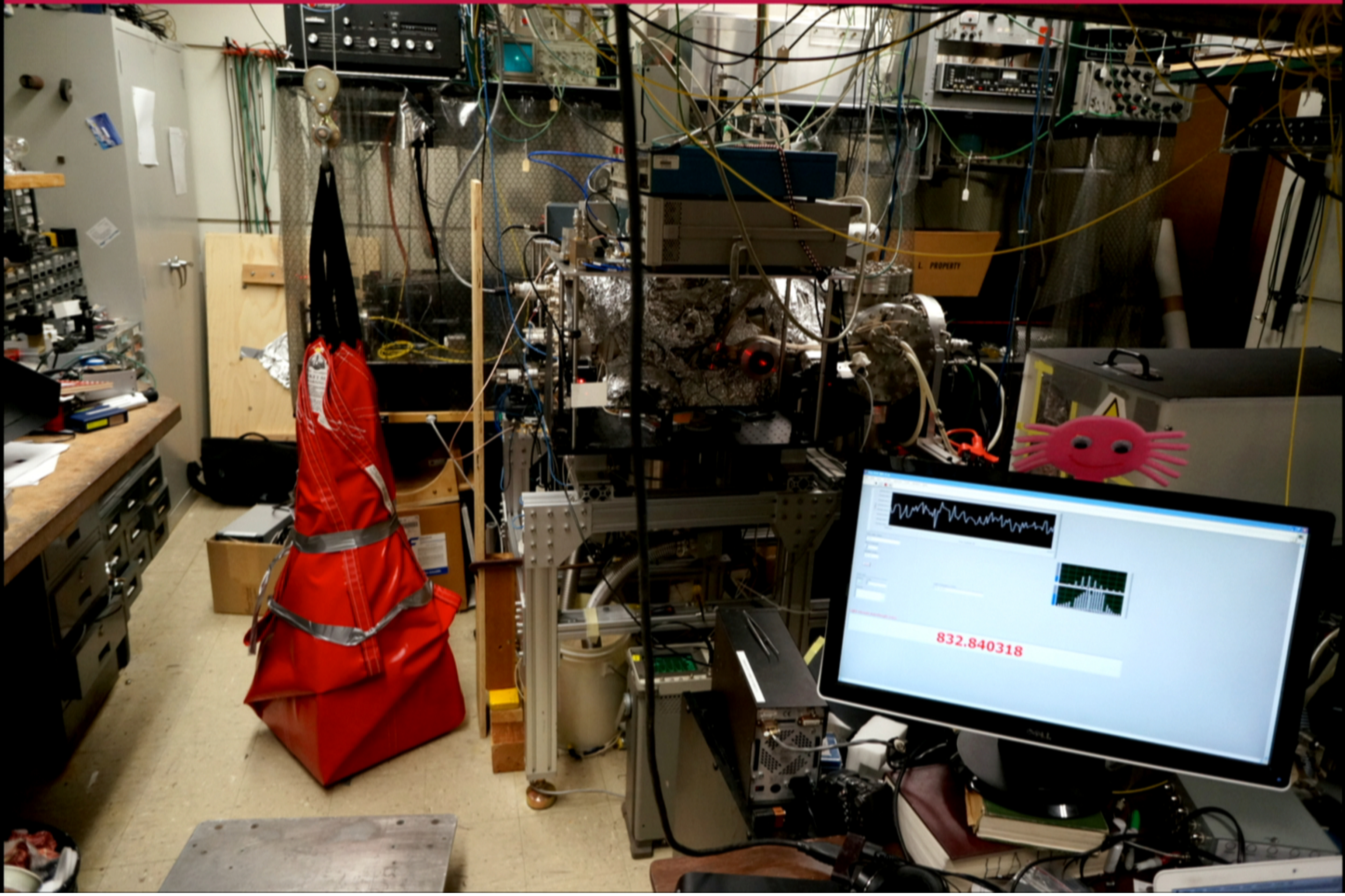
P. Graham
*Department of Physics, Stanford University, Stanford 94305, USA*
(Dated: November 24, 2013)

$$\alpha = \frac{e^2}{4\pi}\left(1 + D^{ij} g_{ij}\right)$$

Background tensor field

Gravitational-field gradient

# Search for background tensor field



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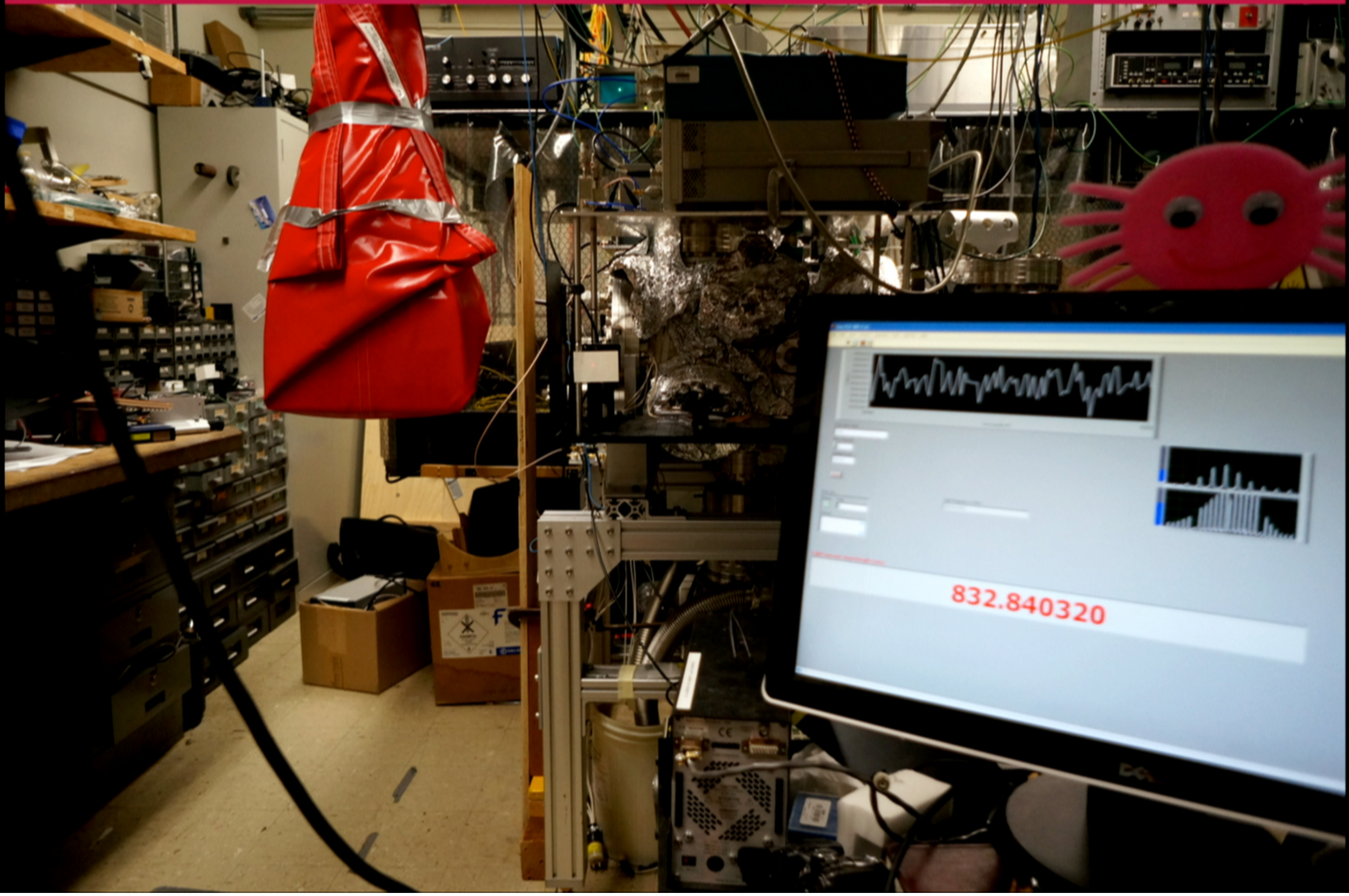

# Search for background tensor field

- Move the 300 kg mass
- ➔ $D^{ij} < 10^{21}$ eV$^{-2}$ (exptl limits)
- Can also wait for earth to rotate w.r.t. cosmic gradient

# Q: Does such search make sense ?

$$\alpha = \frac{e^2}{4\pi}\left(1 + D^{ij} g_{ij}\right)$$

Background tensor field

Gravitational-field gradient

- Is parity conserved by gravitation ?

- Is parity conserved by gravitation ?
- How to check?

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(GDMs are T-odd,…) → centrifuge (EEP)

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

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

- Can we test gravity via APV ?

- Is parity conserved by gravitation ?
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(GDMs are T-odd,…) → centrifuge (EEP)

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- Can we test gravity via APV ?
- Probably not…

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

**DM, DE, …**

# ONE THING LEADS TO ANOTHER

- Is parity conserved by gravitation ?
- How to check?

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**DM, DE, …**

arXiv:1404.2723

# 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*
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(Dated: June 13, 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 H, 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 $9 \times 10^{-15}$ GeV for the electron, and $3.1 \times 10^{-8}$ GeV for the proton.

arXiv:1404.2723

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

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TABLE II. Limits ($1\sigma$) on the interaction strengths of a PV cosmic field with electrons ($b_0^e$) and protons ($b_0^p$) in GeV.

| | PNC quantity | $\lvert b_0^e \rvert$ | $\lvert b_0^p \rvert$ |
|---|---|---|---|
| Cs | $E_{\rm PNC}(6s\text{-}7s)$ | $1.5 \times 10^{-14}$ | $3.1 \times 10^{-8}$ |
| Tl | $E_{\rm PNC}(6p_{1/2}\text{-}6p_{3/2})$ | $2.2 \times 10^{-12}$ | $8.5 \times 10^{-8}$ |
| Dy | $\langle A \lvert \hat{h} \rvert B \rangle$ | $7 \times 10^{-15}$ | |

Q: How do cosmic PNC searches fare compared to other searches ?

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Q: Any unique capabilities ?

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Q: Any unique capabilities ?

Q: So how do we test parity in gravity?

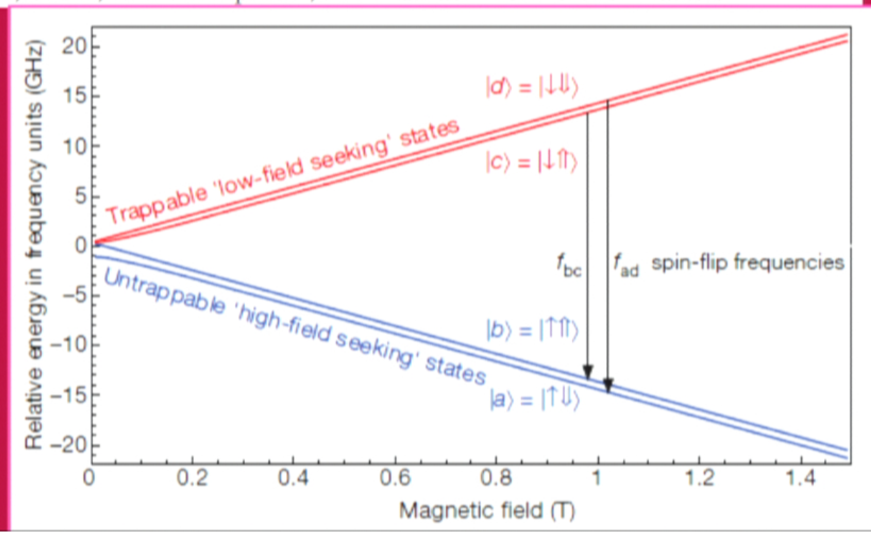
# Search for Exotic Physics with Antiatoms ?

# A New Era...

LETTER 22 MARCH 2012 | VOL 483 | NATURE | 439
doi:10.1038/nature10942

## Resonant quantum transitions in trapped antihydrogen atoms

C. Amole[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5,6], P. D. Bowe[7], E. Butler[8], A. Capra[1], C. L. Cesar[9], M. Charlton[4], A. Deller[4], P. H. Donnan[10], S. Eriksson[4], J. Fajans[3,11], T. Friesen[12], M. C. Fujiwara[12,13], D. R. Gill[13], A. Gutierrez[14], J. S. Hangst[7], W. N. Hardy[14,15], M. E. Hayden[2], A. J. Humphries[4], C. A. Isaac[4], S. Jonsell[16], L. Kurchaninov[13], A. Little[3], N. Madsen[4], J. T. K. McKenna[17], S. Menary[1], S. C. Napoli[4], P. Nolan[17], K. Olchanski[13], A. Olin[13,18], P. Pusa[17], C. Ø. Rasmussen[7], F. Robicheaux[10], E. Sarid[19], C. R. Shields[4], D. M. Silveira[20]†, S. Stracka[13], C. So[3], R. I. Thompson[12], D. P. van der Werf[4] & J. S. Wurtele[3,11]



# WHAT ELSE IN ADDITION TO FALLING UP AND 1S-2S (CPT)?

# WHAT ELSE IN ADDITION TO FALLING UP AND 1S-2S (CPT)?

It difficult to come up with a scenario that will have exotic physics with antimatter that would not “leak” into the ordinary-matter sector without “fine tuning”

# CPT and Lorentz Invariance

VOLUME 89, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 2002

## *CPT* Violation Implies Violation of Lorentz Invariance

O.W. Greenberg*
*Center for Theoretical Physics, Department of Physics, University of Maryland, College Park, Maryland 20742-4111*
(Received 28 January 2002; published 18 November 2002)

A interacting theory that violates *CPT* invariance necessarily violates Lorentz invariance. On the other hand, *CPT* invariance is not sufficient for out-of-cone Lorentz invariance. Theories that violate *CPT* by having different particle and antiparticle masses must be nonlocal.

~~CPT~~ → ~~LI~~

# CPT and Lorentz Invariance

Physics Letters B 699 (2011) 177–180

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Physics Letters B

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## CPT violation does not lead to violation of Lorentz invariance and vice versa

Masud Chaichian [a,*], Alexander D. Dolgov [b,c,d], Victor A. Novikov [d], Anca Tureanu [a]

$$\cancel{\text{CPT}} \nrightarrow \cancel{\text{LI}}$$

# CPT and Lorentz Invariance

**CPT, Lorentz invariance, mass differences, and charge non-conservation**

A.D. Dolgov, V.A. Novikov

**April 26, 2012**

arxiv.org/abs/1204.5612v1

$$\not{CPT} \not\leftrightarrow \not{LI}$$

$$LI \leftrightarrow m=\bar{m}$$

(even with $\not{CPT}$)

# Search for Exotic Physics with Antiatoms ?

Personal opinion:

pay no attention to what theorists (or astronomers) say, and measure what is important

# Fun stuff to do with (anti)atomic clocks…

- Dependence on gravitational potential and gradients
- Anomalous spin-mass and spin-spin couplings
- Noise correlations?
- Temporal variation

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- Dependence on gravitational potential and gradients
- Anomalous spin-mass and spin-spin couplings
- Noise correlations?
- Temporal variation

**But** many (most?) specific models are already constrained by experiments with ordinary matter, positrons, and antiprotons!

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Finally…

Why stop at antihydrogen?

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# ANTI ENERGY SECRETARY

# Q: What tests should be done with antimatter beyond $\bar{g}$ ?

# GNOME & CASPEr Open Qns

# GNOME & CASPEr Open Qns

- Axion "g" factors for $^{129}$Xe, $^{3}$He, $^{87}$Rb, …
- Optimal experimental strategy for "GNOME now"
- "GNOME-AC" ?