New physics searches with atomic dysprosium

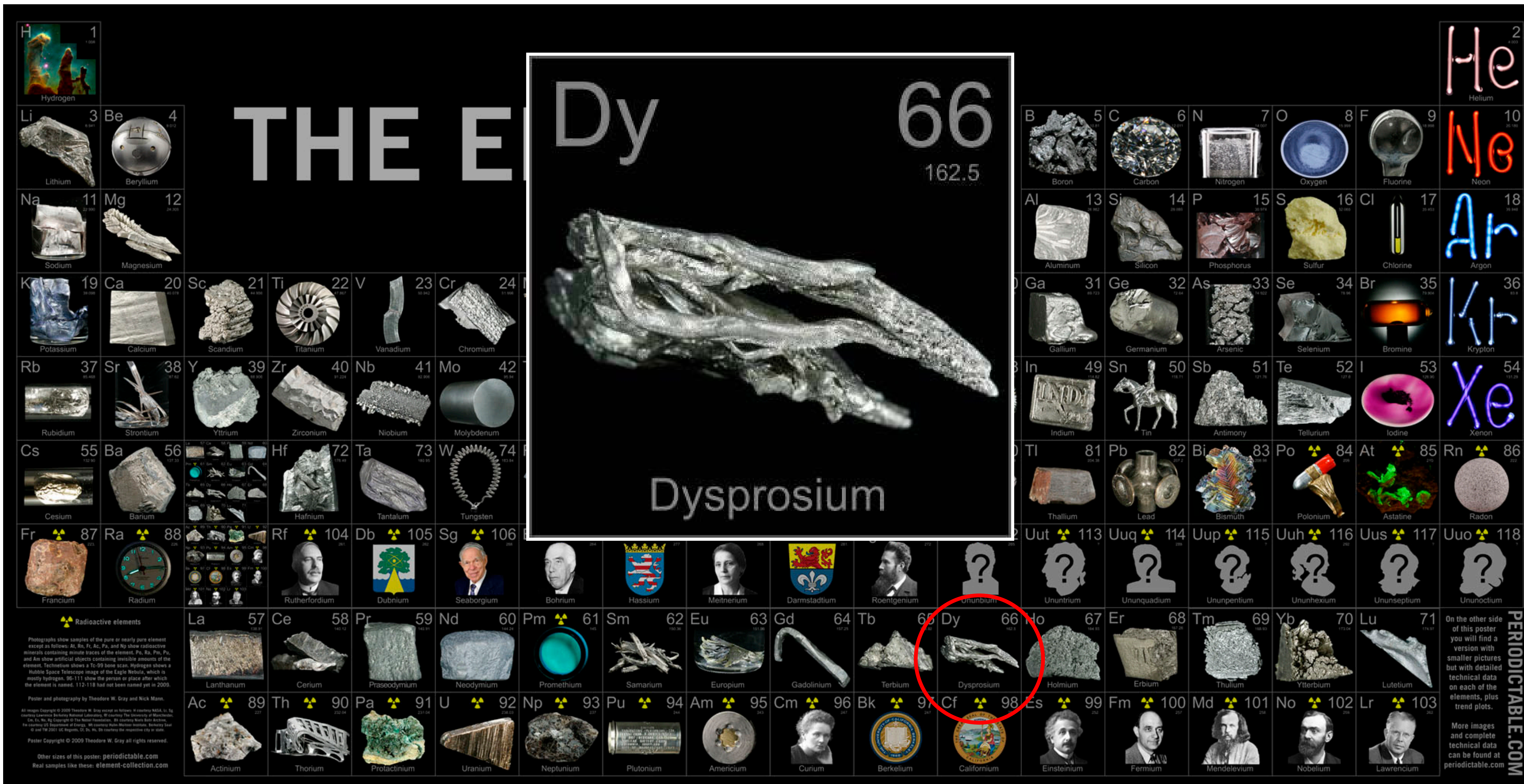
Nathan Leefer **(HIM/JGU)**
Ken Van Tilburg **(Stanford)**
Lykourgos Bougas **(HIM/JGU)**
Dmitry Budker (**HIM/JGU/UC Berkeley)**

HIM
Helmholtz-Institut Mainz

SEVENTH FRAMEWORK PROGRAMME

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

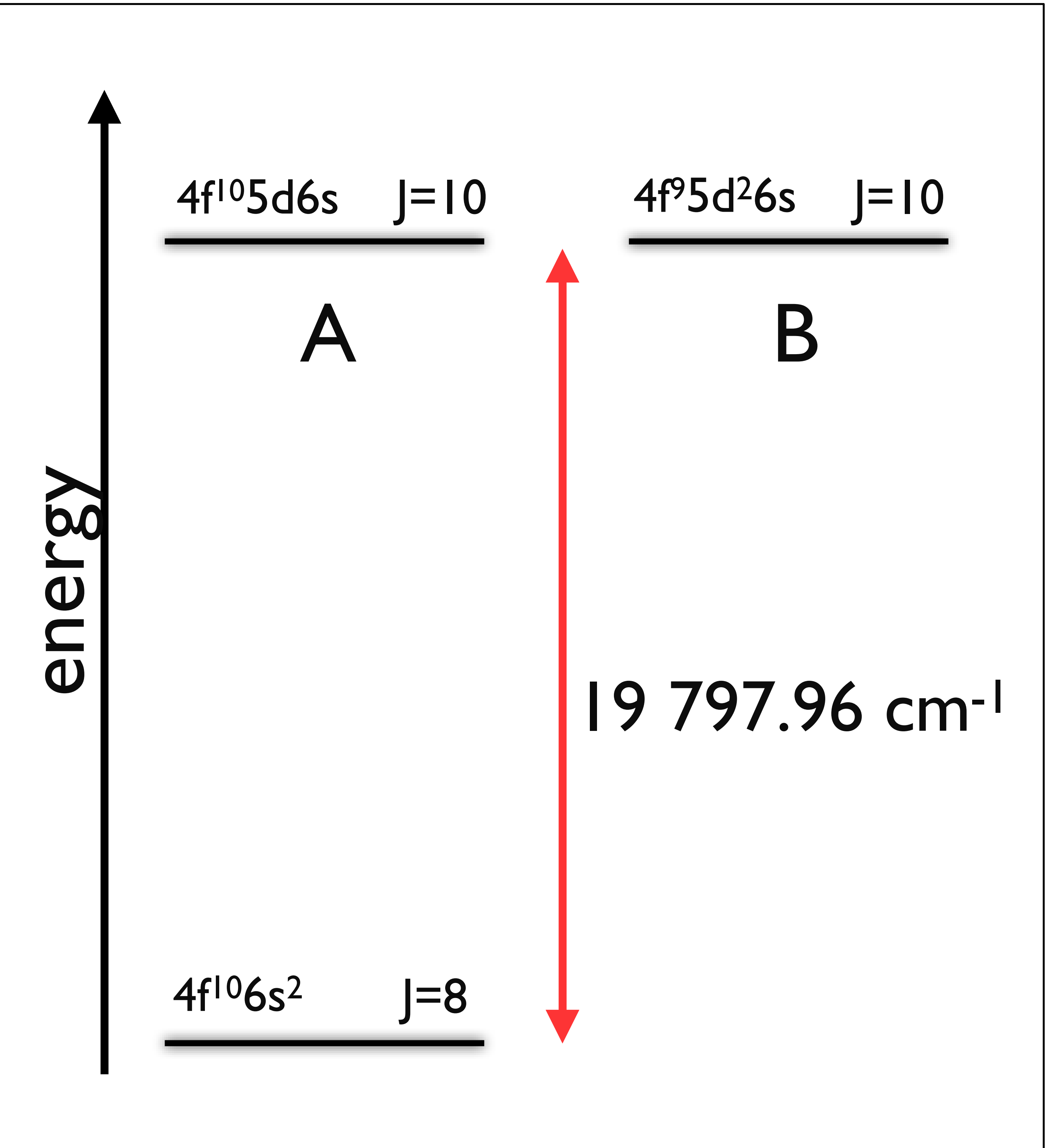
What is dysprosium?



PHYSICAL REVIEW A VOLUME 50, NUMBER 1 JULY 1994

Experimental investigation of excited states in atomic dysprosium

Dmitry Budker, David DeMille, and Eugene D. Commins



- state lifetimes

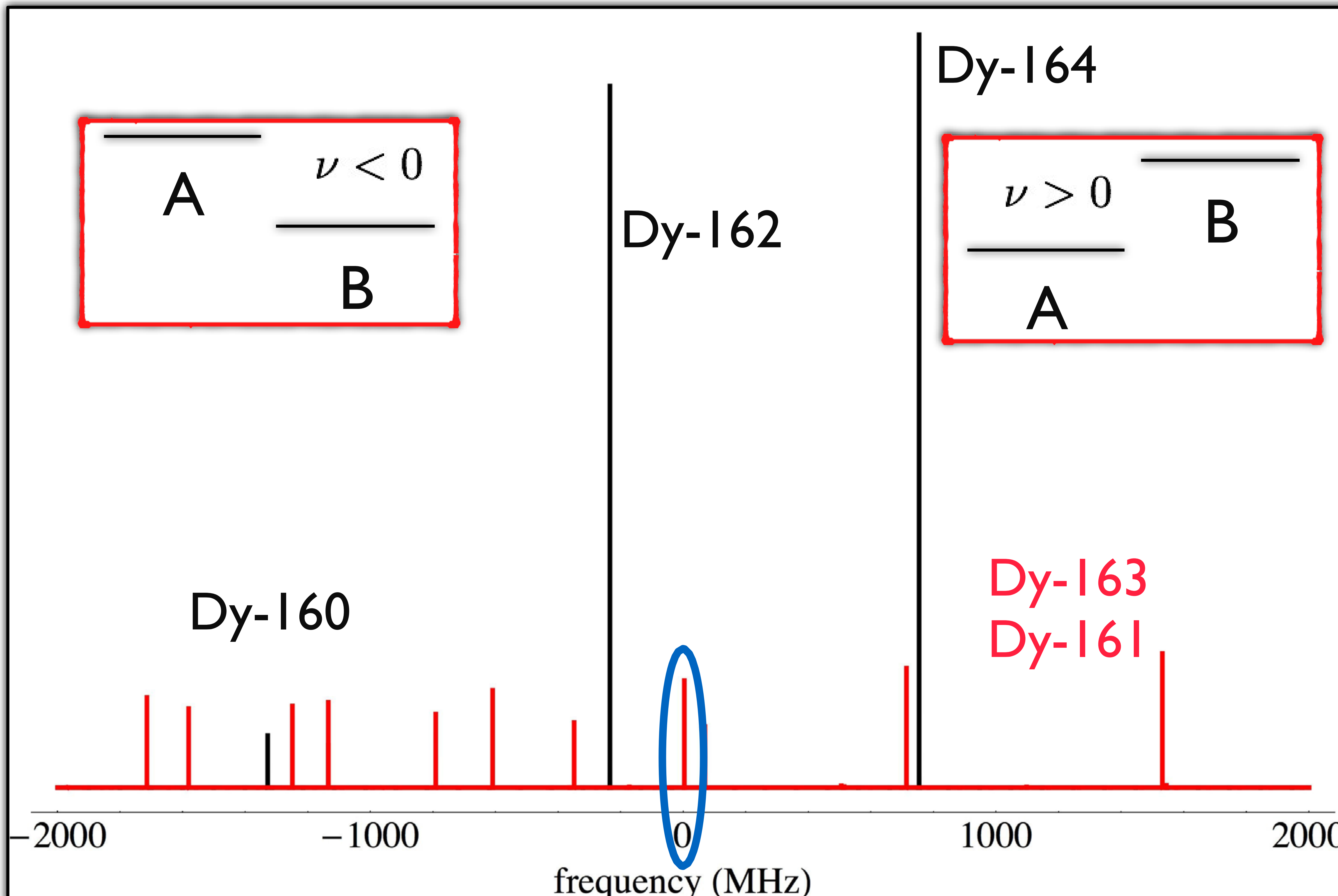
$$\tau_A \sim 8\,\mu s$$
$$\tau_B > 200\,\mu s$$

- dipole matrix element

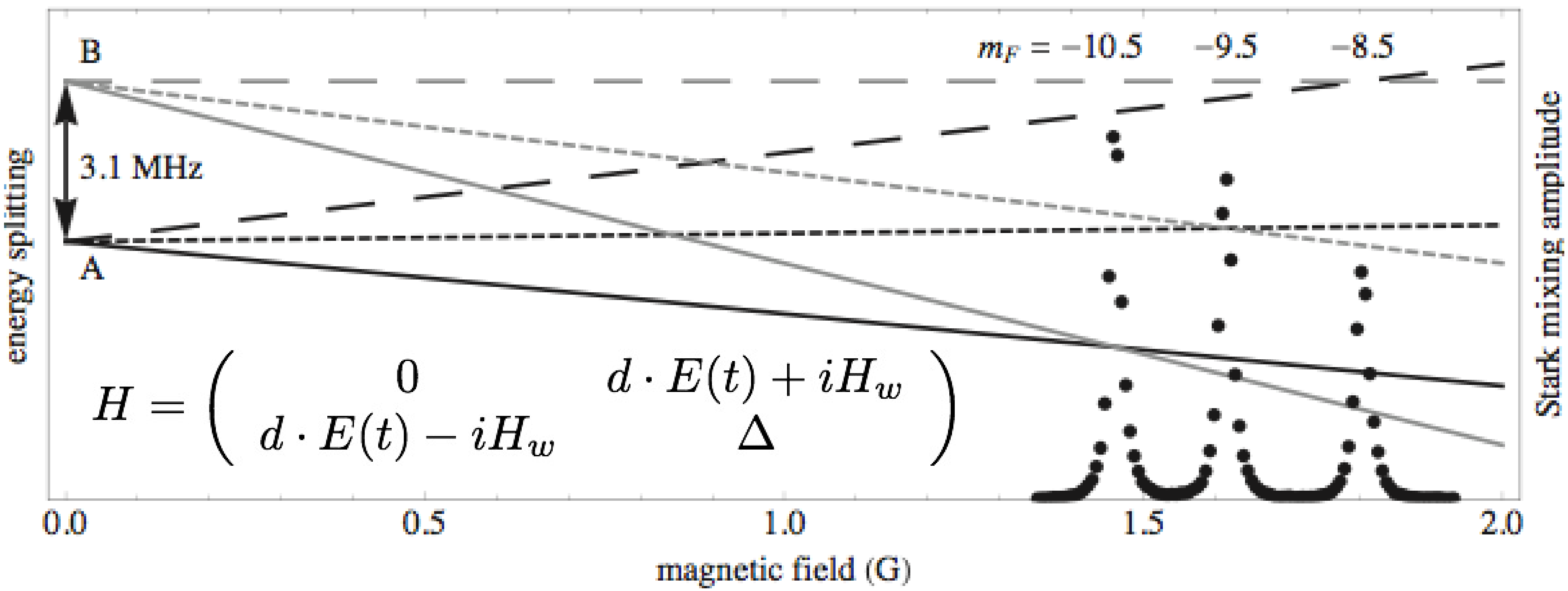
$$\langle B||d||A\rangle = 0.015(1)\,ea_0$$

- isotope shifts and hyperfine coefficients

Radio-frequency spectrum



The Dy parity violation experiment



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]

$$|H_w| = |2.3 \pm 2.9(\text{statistical}) \pm 0.7(\text{systematic})|\ \text{Hz}$$

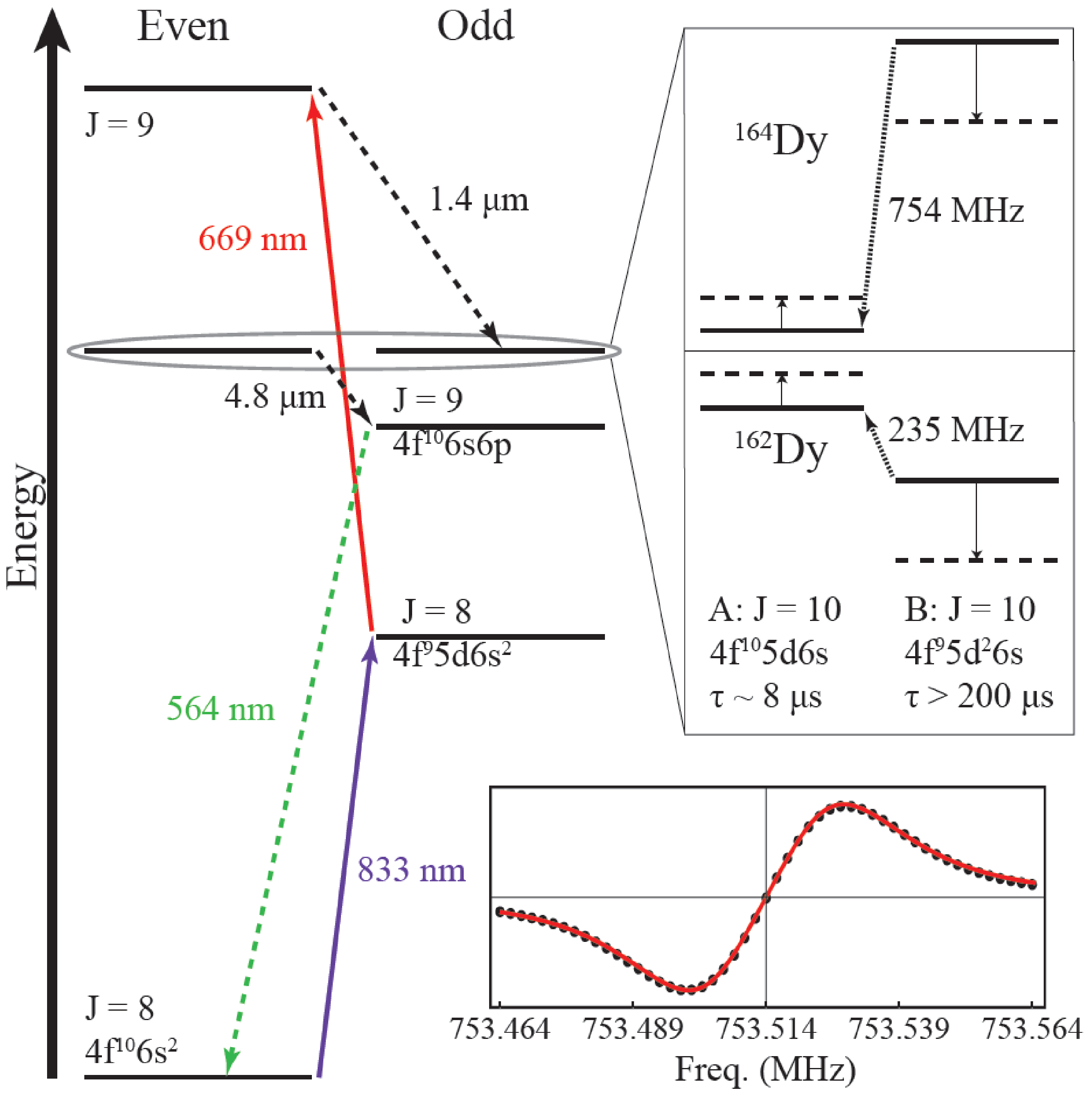
PRL **113,** 081601 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

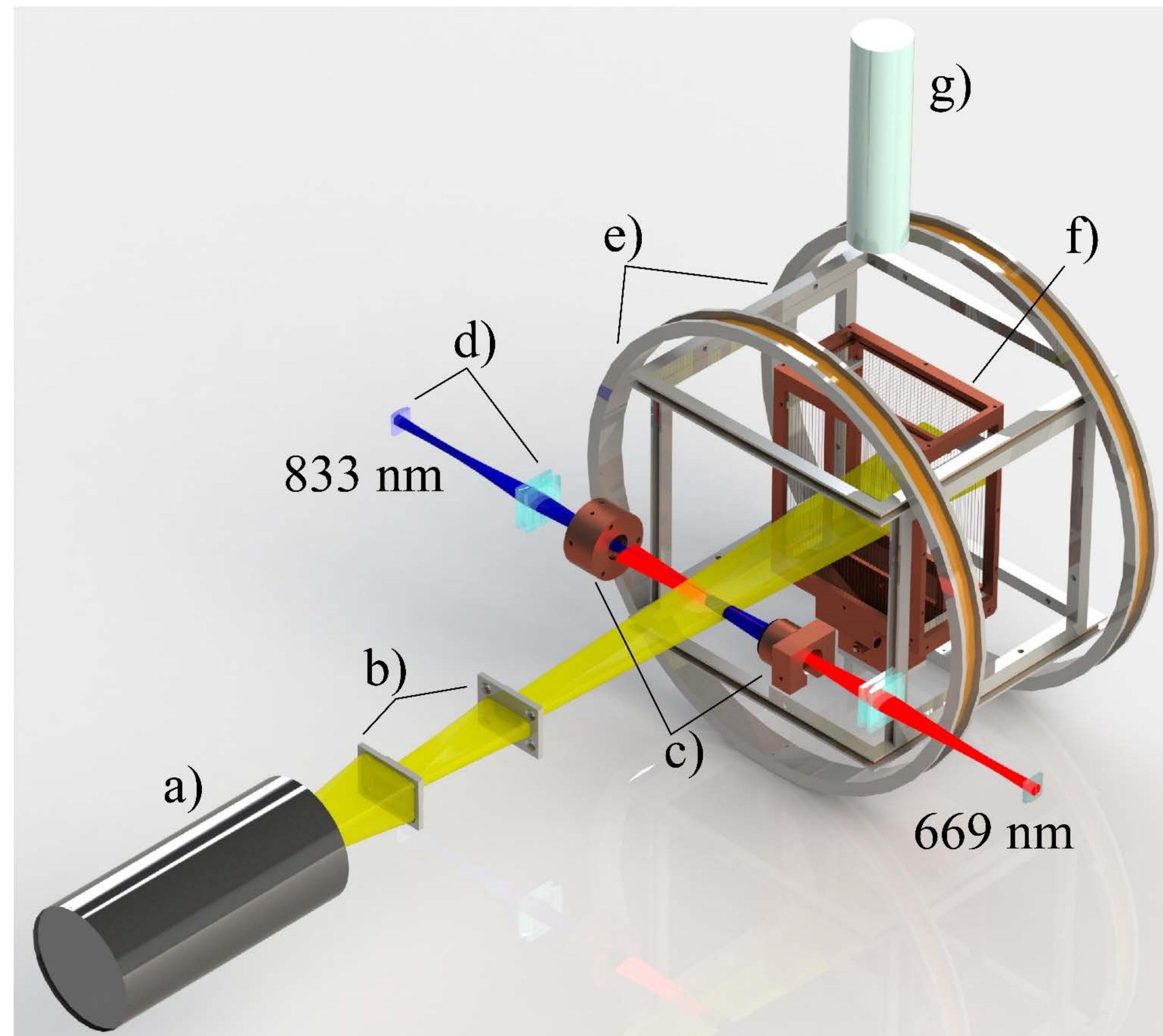
Limiting *P*-Odd Interactions of Cosmic Fields with Electrons, Protons, and Neutrons

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]

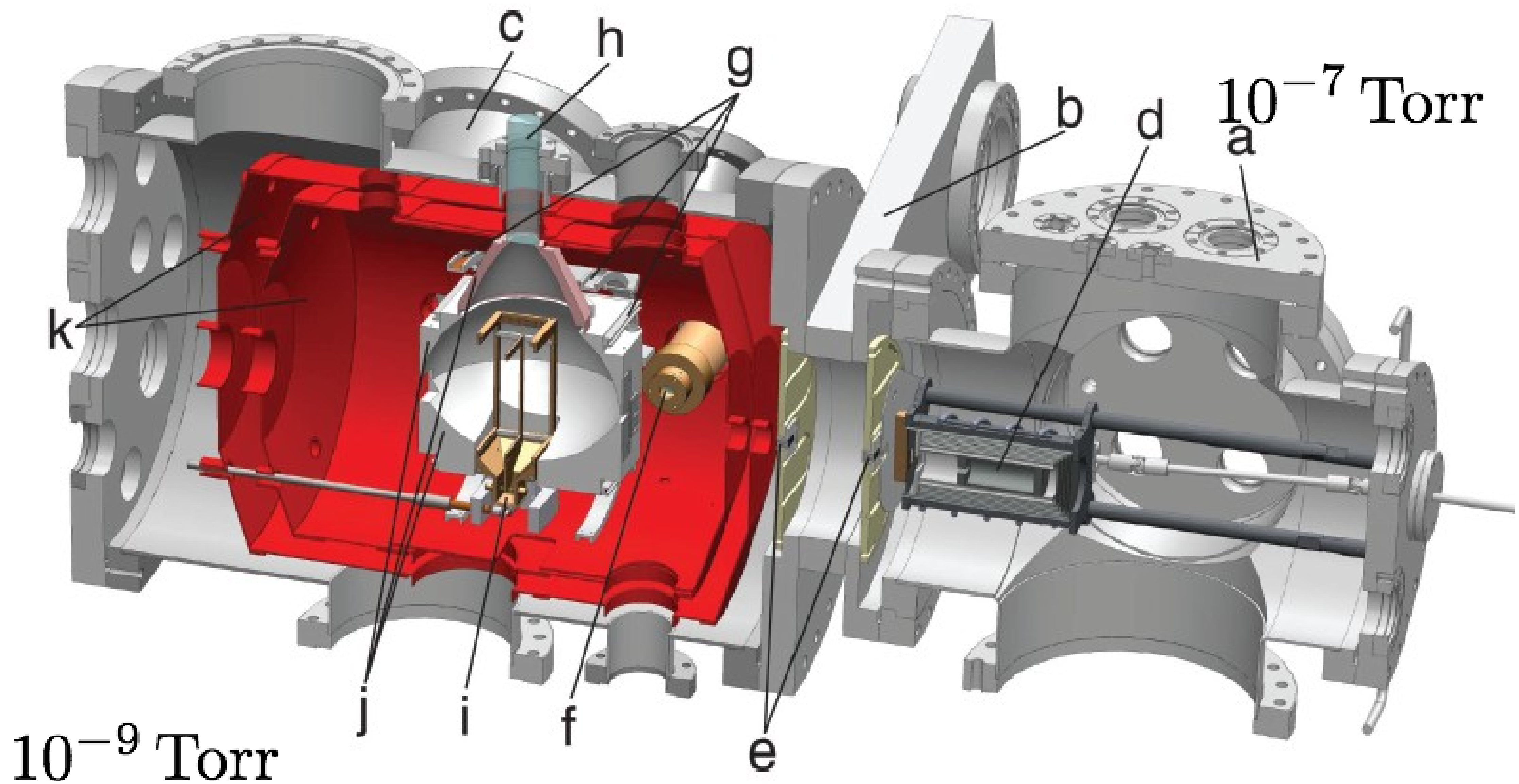
also
PRD **90**, 096005 (2014)

Experimental details





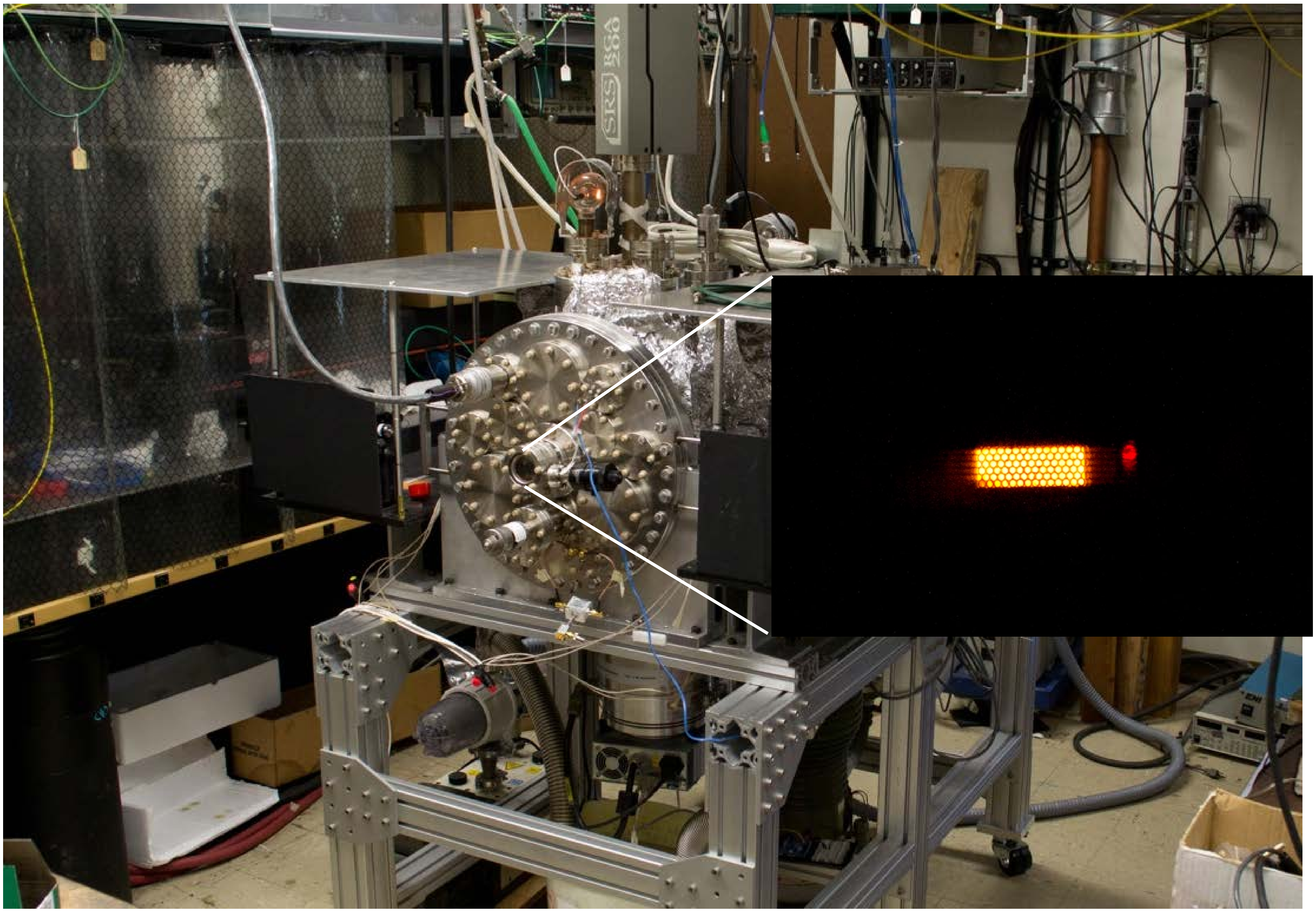
Atomic beam apparatus



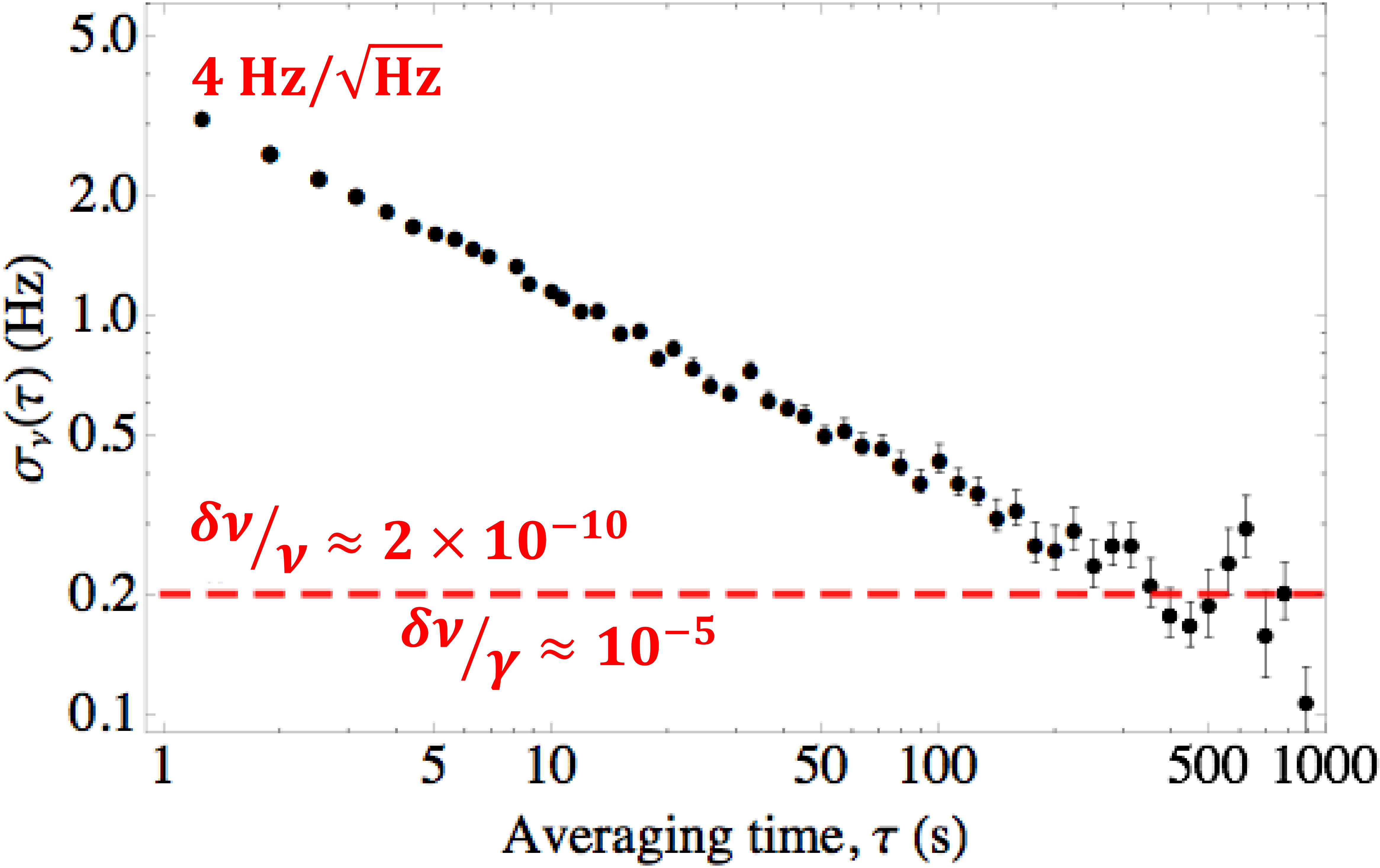
$(\delta\nu \sim \text{Hz}/10^{-6}\ \text{Torr})$ A. Cingoz, *et. al.*, **Phys. Rev. A** **72**, 063409 (2005)

a) oven chamber
b) gate valve
c) interaction-region chamber
d) Dy oven
e) vacuum chokes
f) laser access/in-vacuum polarizer
g) magnetic-field coils
h) light pipe
i) rf electrodes
j) light-collection mirrors
k) two-layer magnetic shielding

Atomic beam apparatus



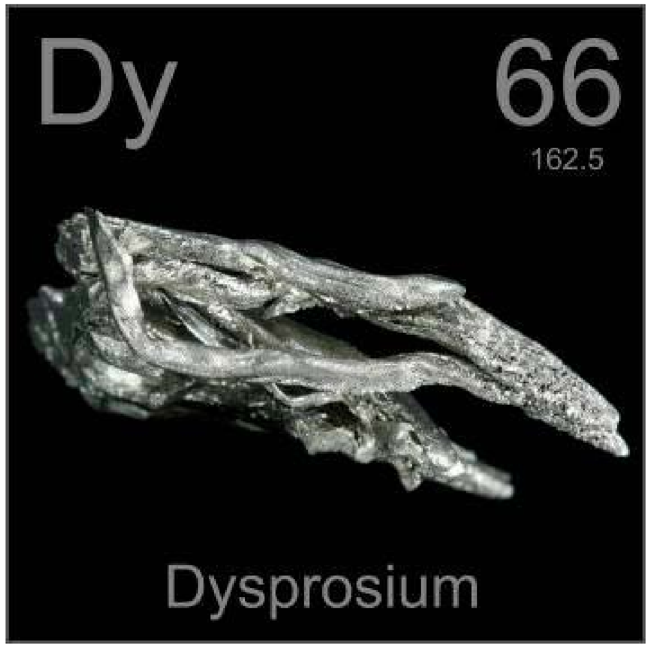
Sensitivity



DM constraints

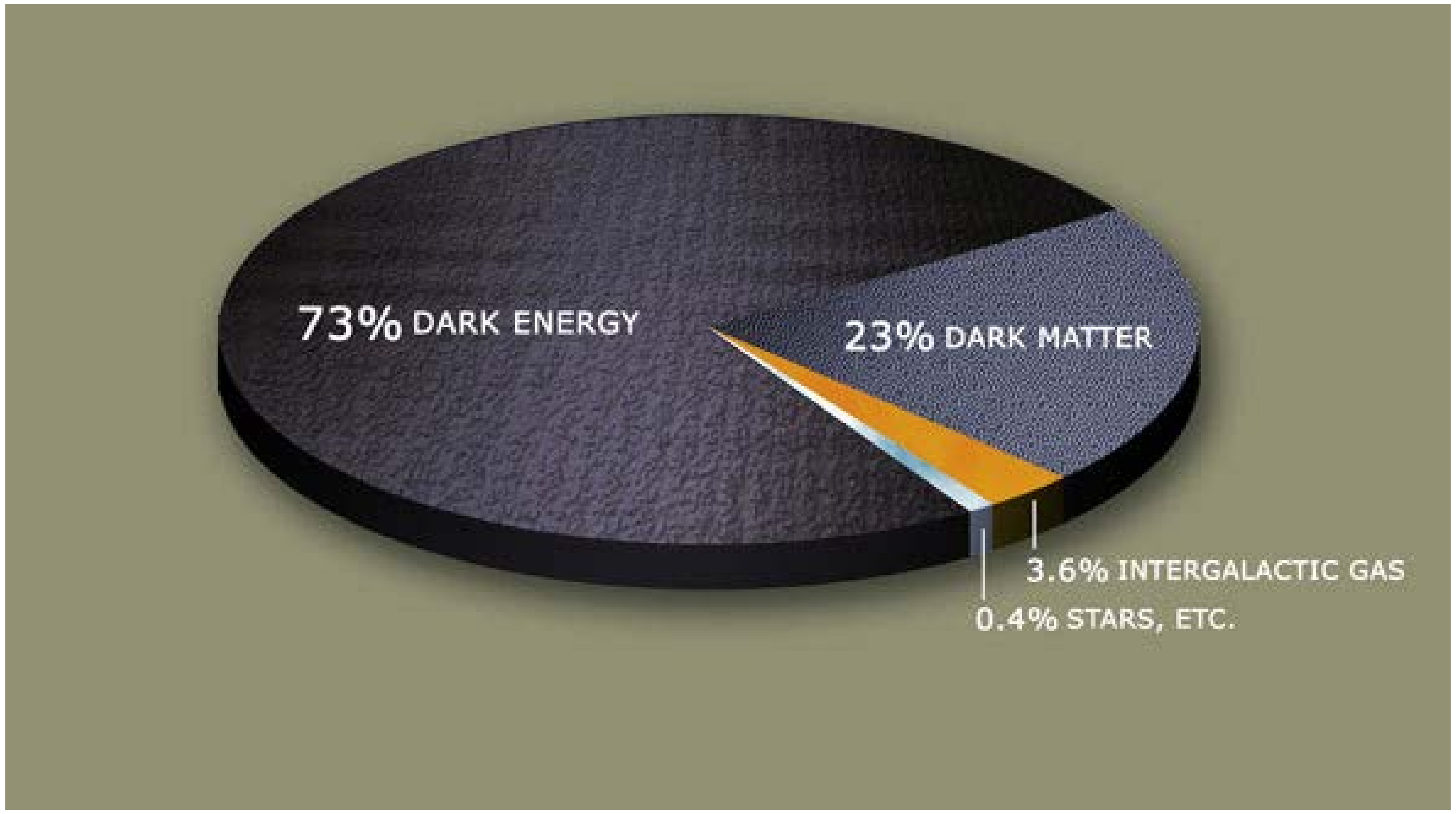
variation of constants

Lorentz symmetry tests



atomic parity violation

Why look for variation?



J.-P. Uzan, Rev. of Mod. Phys. **75** (2003)

- There is no reason to expect parameters of our theories to be constant.
- Astrophysics evidence

$$\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$$

10 billion year time scale

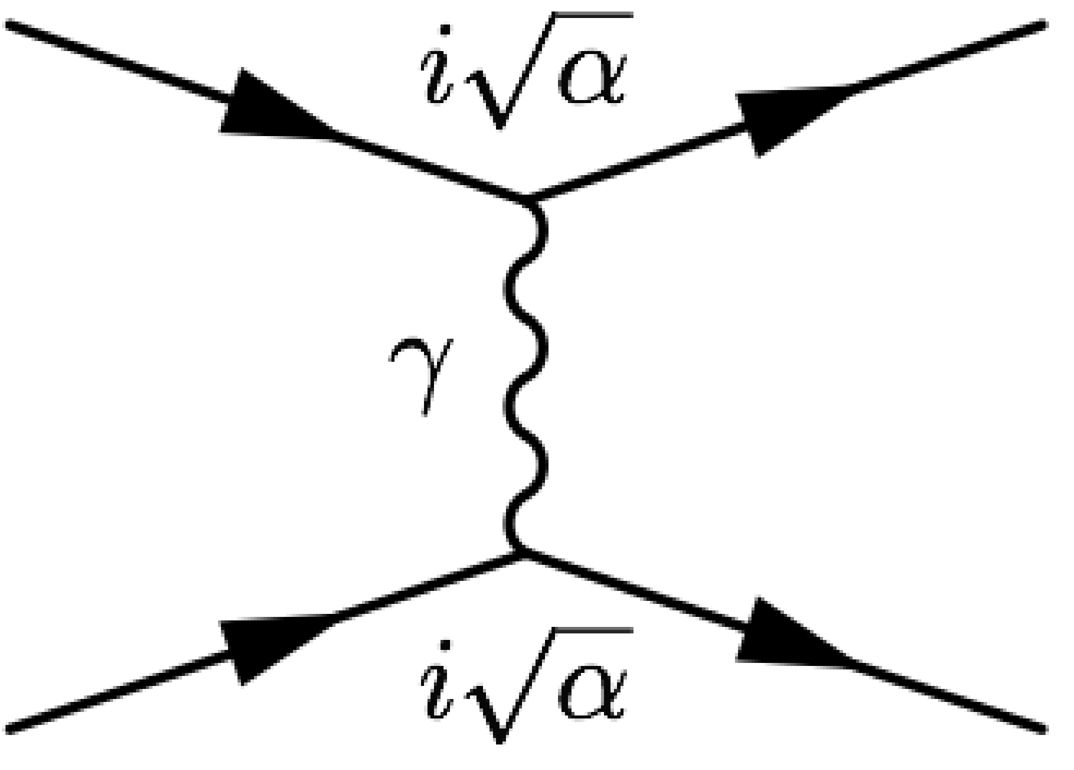
How do we look?

- Direct methods
- Indirect methods

Method: Direct measurement

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137.035\,999\,074(44)}$$

- Precise measurement at 0.5 ppb level by electron g-factor



$$\left|\dot{\alpha}/\alpha\right| \leq 5\times10^{-10}/\,yr$$

- We can do better!

Method: Indirect measurement

$$E_{atom} = K m_e c^2 \alpha^2 Z^2 \left(1 + k_{fs} \alpha^2 Z^2 + k_{hfs} g \left(\frac{m_e}{m_p} \right) \alpha^2 Z^2 + \cdots \right)$$

- Look for relative shift of atomic transition energies

$$E = E_o + q \left(\frac{\alpha^2}{\alpha_o^2} - 1 \right)$$

V. A. Dzuba *et. al.*, Phys. Rev. A **68**, 022506 (2003)

Requires theory input

Laboratory searches

- Every frequency measurement is a ratio

$$\upsilon_a / \upsilon_b$$

- Look for fractional changes of ratio

$$\frac{\Delta(\upsilon_a/\upsilon_b)}{\upsilon_a/\upsilon_b} = \frac{\Delta\upsilon_a}{\upsilon_a} - \frac{\Delta\upsilon_b}{\upsilon_b} = \underbrace{\left(\frac{2\,q_a}{\upsilon_a} - \frac{2\,q_b}{\upsilon_b}\right)}_{K_\alpha}\frac{\Delta\alpha}{\alpha}$$

- Any comparison can be written

$$\frac{\Delta(\upsilon_a/\upsilon_b)}{\upsilon_a/\upsilon_b} = K_\alpha\frac{\Delta\alpha}{\alpha} + K_e\frac{\Delta(m_e/m_p)}{m_e/m_p} + K_q\frac{\Delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}}$$

Laboratory searches

$$\frac{\Delta(\upsilon_a/\upsilon_b)}{\upsilon_a/\upsilon_b} = K_\alpha \frac{\Delta\alpha}{\alpha} + K_e \frac{\Delta(m_e/m_p)}{m_e/m_p} + K_q \frac{\Delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}}$$

Ratio	K_α	K_e	K_q	Reference
^{164,162}Dy/Cs	$(-2.6, +8.5) \times 10^6$	-1	-0.002	This work
Rb/Cs	-0.49	0	-0.021	[10]
Yb^+/Cs	-1.83	-1	-0.002	[11]
CSO/Cs	3	-1	0.1	[12]
Hg^+/Al^+	-2.95	0	0	[13]
Sr/Cs	-2.77	-1	-0.002	[14]
H(1S-2S)/Cs	-2.83	-1	-0.002	[16]

Laboratory searches

- Short time scale, high precision
- Controlled environment

<u>Single ion clocks</u>

Al+,Yb+,Hg+….

Optical frequency

$$\frac{\Delta v}{v} \sim 10^{-17}$$

<u>Optical lattice clocks (ensemble)</u>

Sr, Yb, Hg

Optical frequency

$$\frac{\Delta v}{v} \sim 10^{-17}$$

<u>Atomic fountain clocks</u>

Rb, Cs

Microwave frequency

$$\frac{\Delta v}{v} \sim 10^{-16}$$

<u>Dysprosium thermal beam</u>

Radio-frequency

$$\frac{\Delta v}{v} \sim 10^{-10}$$

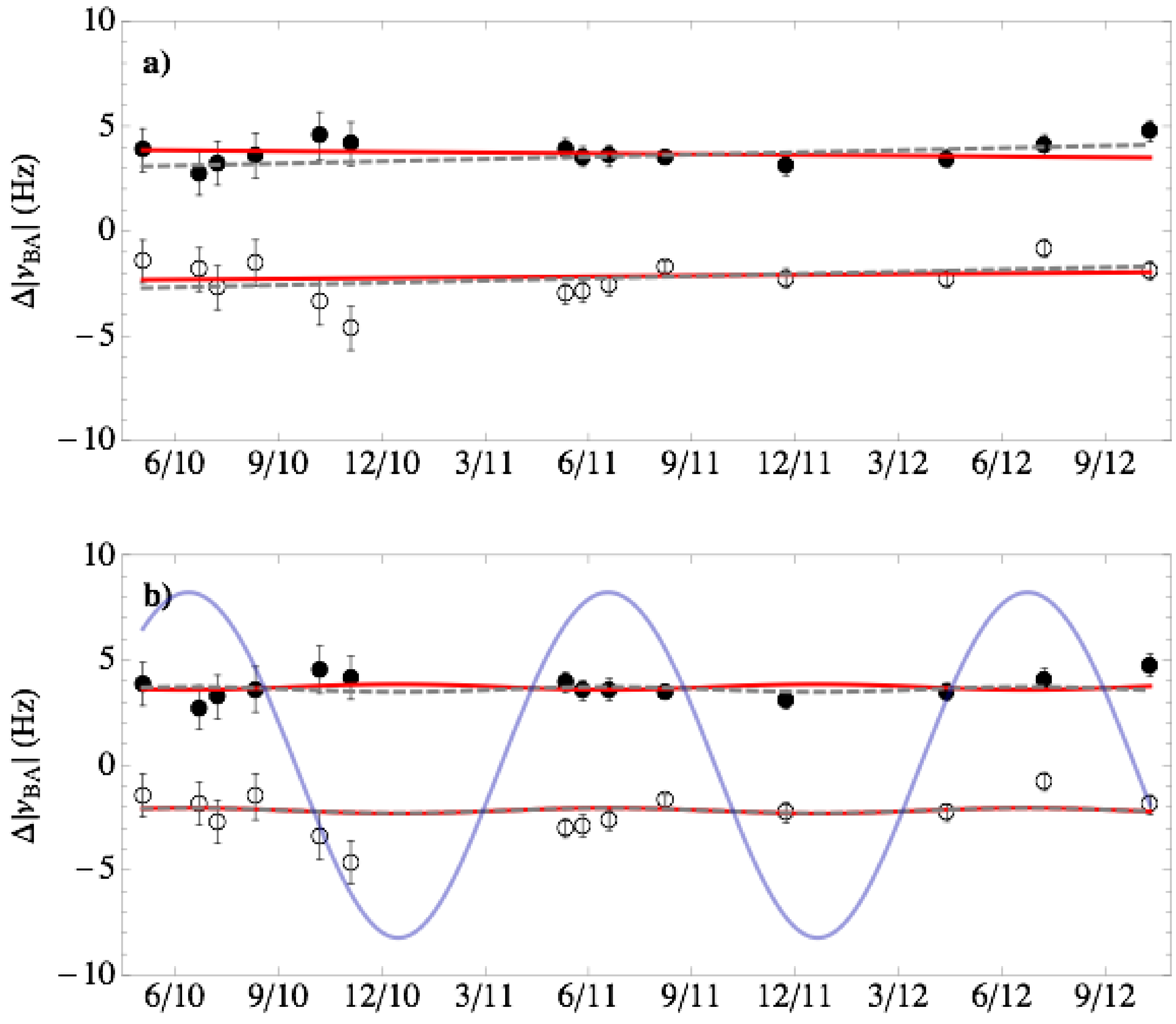
PRL 111, 060801 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

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

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

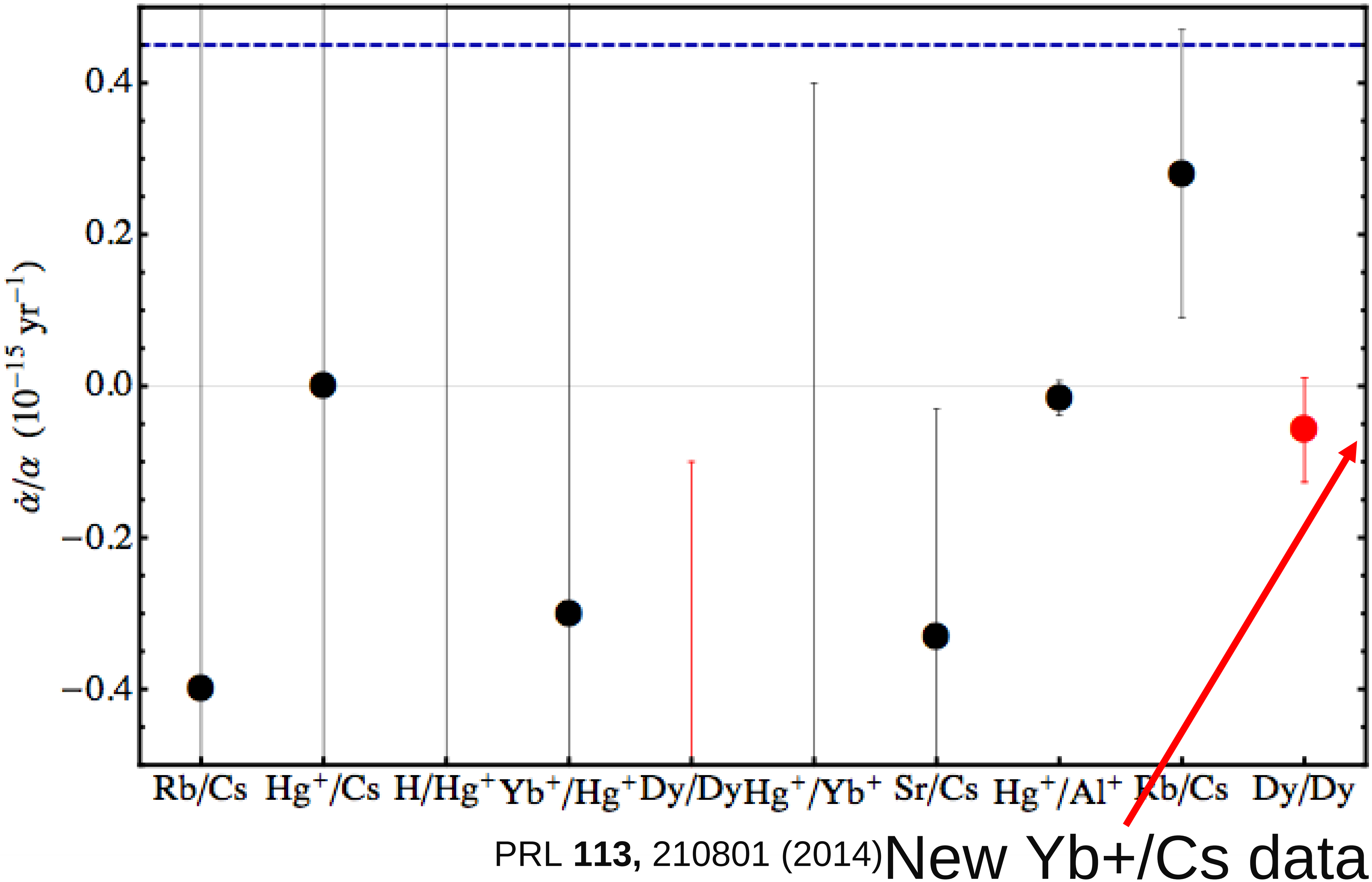


$$\frac{\Delta\alpha}{\alpha} = k_\alpha \frac{\Delta U}{c^2}$$

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

Systematics Limited!

Summary of results

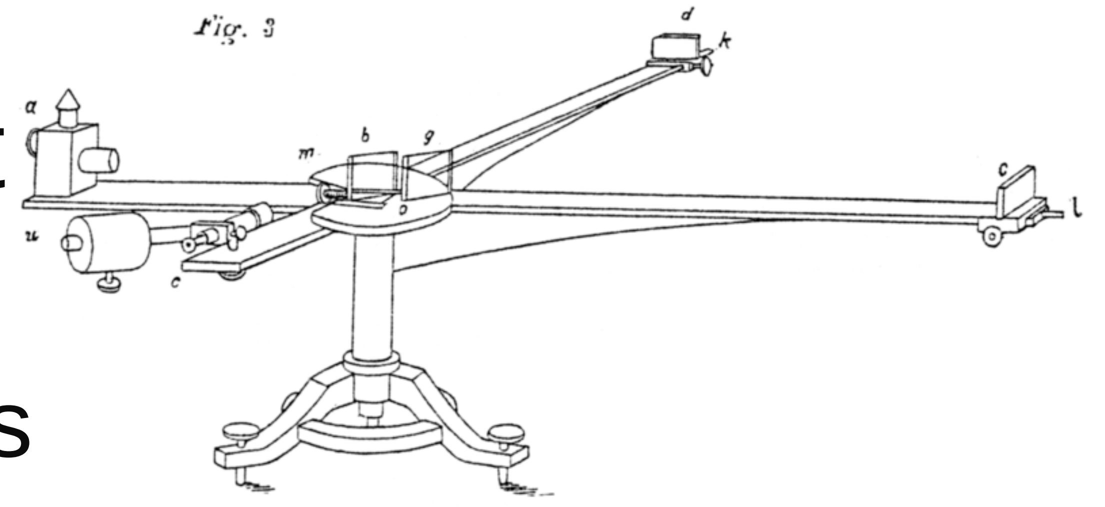


PRL **113,** 210801 (2014)
PRL **113,** 210802 (2014)

Test of Lorentz symmetry

Special relativity: laws of physics are invariant under Lorentz transformations.

1) Anisotropy of speed of light



Michelson-Morley experiments

2) Anisotropy of maximum speed in particle Lorentz transformation

kinematic constraints, Hughes-Drever experiments

Test of Lorentz symmetry for electrons

modified electron Lagrangian V. A. Kostelecký and C. D. Lane, Phys. Rev. D, **60** (1999)

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} (\gamma_\nu + c_{\mu\nu} \gamma^\mu) \overleftrightarrow{D}^\nu \psi - \bar{\psi} m \psi$$

modified maximum speed of electron

$$(v_j \hat{e}_j)_{\max} = 1 - c_{jk} \hat{e}_j \hat{e}_k - c_{0j} \hat{e}_j$$

For a bound electron

$$\delta H = (c_{11} + c_{22} - 2c_{33}) \langle p_1^2 + p_2^2 - 2p_3^2 \rangle$$

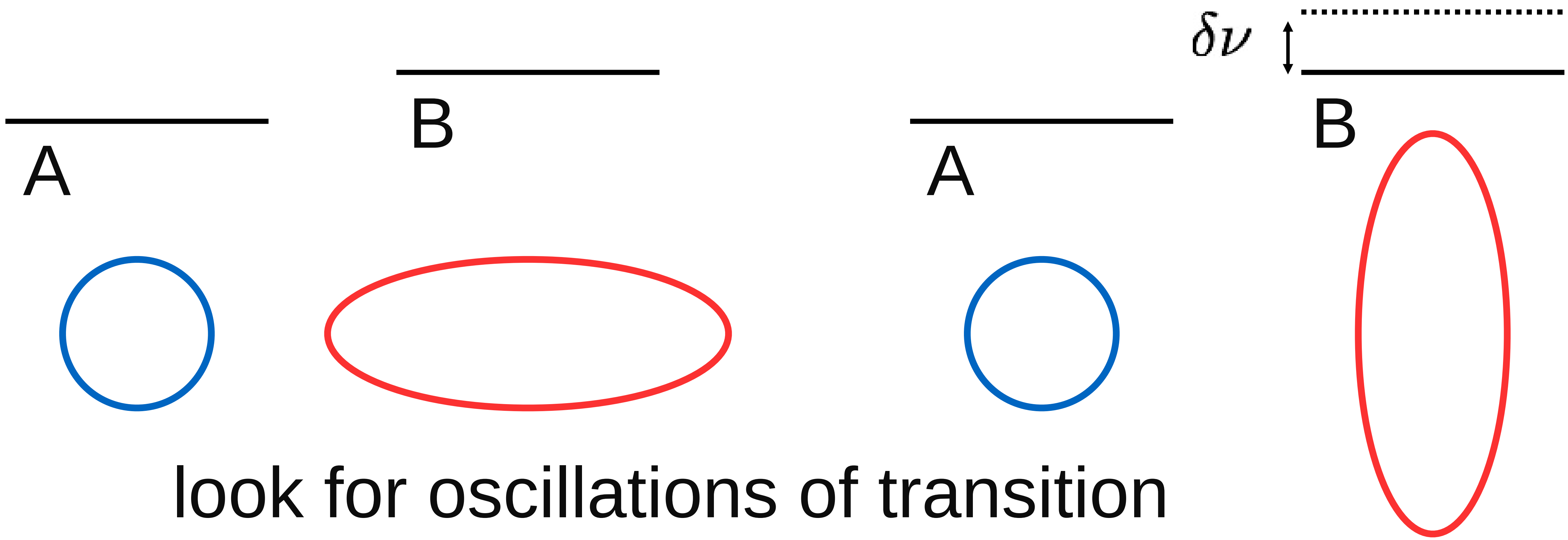
Test of Lorentz symmetry for electrons

For a bound electron

atomic calculations

$$\delta H = (c_{11} + c_{22} - 2c_{33})\langle p_1^2 + p_2^2 - 2p_3^2 \rangle$$

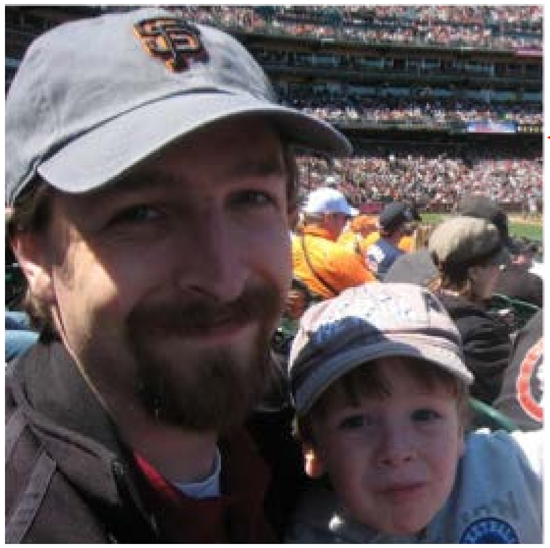
energy shift of anisotropic electron orbital depends on alignment of quantization axis



look for oscillations of transition frequencies at sidereal day

PRL 111, 050401 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

Limits on Violations of Lorentz Symmetry and the Einstein Equivalence Principle using Radio-Frequency Spectroscopy of Atomic Dysprosium



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

C. Harabati, V. A. Dzuba, and V. V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia
(Received 14 March 2013; published 29 July 2013)

Combination	New limit	Existing limit
$0.10c_{X-Y} - 0.99c_{XZ}$	-9.0 ± 11	$27 \pm 19 \times 10^{-17}$
$0.99c_{X-Y} + 0.10c_{XZ}$	3.8 ± 5.6	$-32 \pm 62 \times 10^{-17}$
$0.94c_{XY} - 0.35c_{YZ}$	-0.4 ± 2.8	$43 \pm 19 \times 10^{-17}$
$0.35c_{XY} + 0.94c_{YZ}$	3.2 ± 7.0	$5.3 \pm 23 \times 10^{-17}$
$0.18c_{TX} - 0.98c_{T(Y+Z)}$	$0.95 \pm 18(3.3)$	$-0.7 \pm 1.3 \times 10^{-15}$
$0.98c_{TX} + 0.18c_{T(Y+Z)}$	$5.6 \pm 7.7(2.4)$	$-1.4 \pm 5.4 \times 10^{-15}$
$c_{T(Y-Z)}$	$-21 \pm 19(2.2)$	$.002 \pm .004 \times 10^{-13}$
c_{TT}	$-8.8 \pm 5.1(4)$	$10^{-6}(2 \pm 2) \times 10^{-9}$
c_{TT} (gravitational)	$-14 \pm 28(9)$	$4600 \pm 4600 \times 10^{-9}$

Best limit at time

$$c_{X-Y} \equiv c_{XX} - c_{YY}$$

$$c_{T(Y+Z)} \equiv c_{TY} \cos\eta + c_{TZ} \sin\eta$$

$$c_{T(Y-Z)} \equiv c_{TY} \sin\eta - c_{TZ} \cos\eta$$

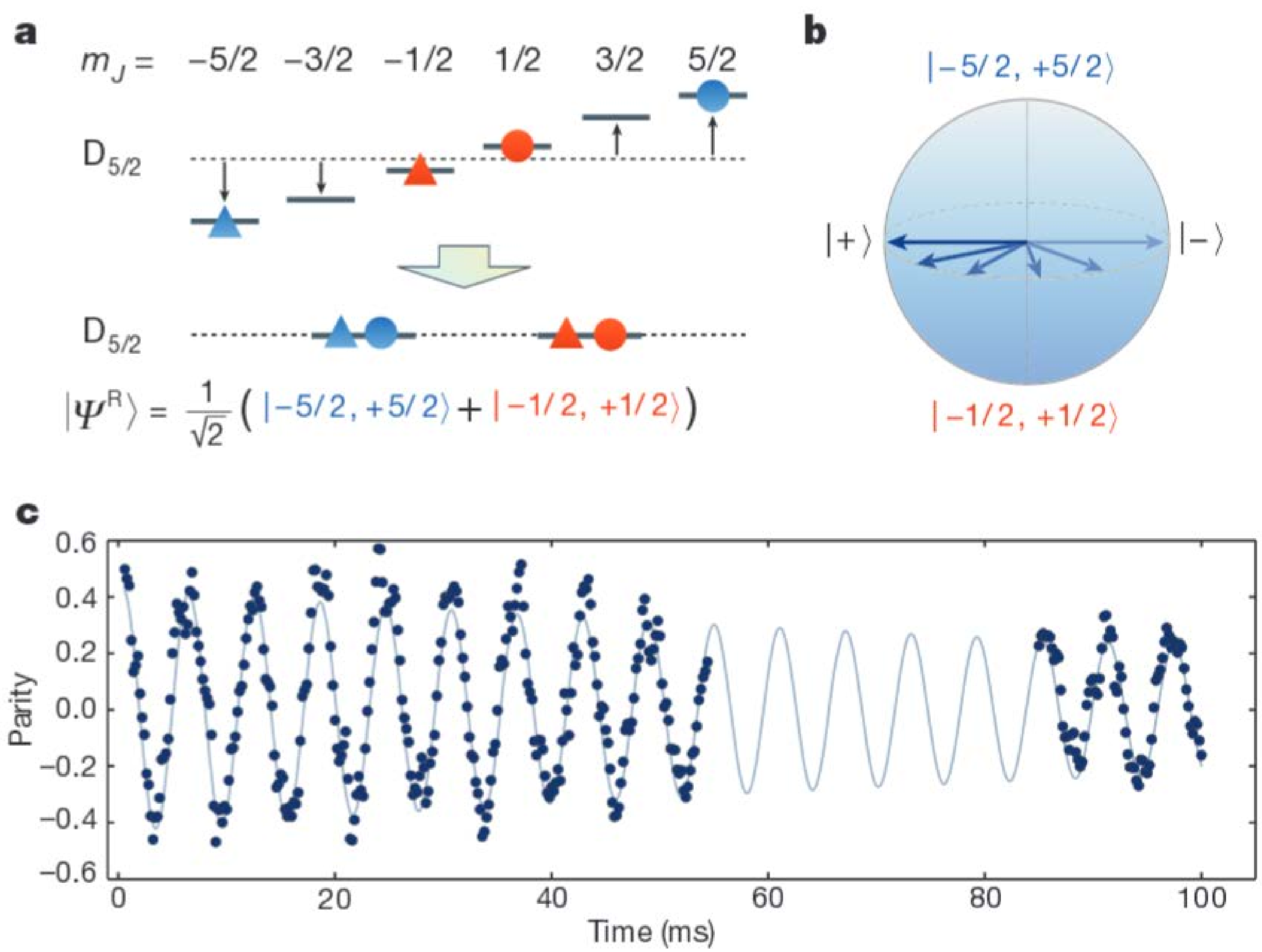
η = Earth's axial tilt

LETTER

doi:10.1038/nature14091

Michelson–Morley analogue for electrons using trapped ions to test Lorentz symmetry

T. Pruttivarasin[1,2], M. Ramm[1], S. G. Porsev[3,4], I. I. Tupitsyn[5], M. S. Safronova[3,6], M. A. Hohensee[1,7] & H. Häffner[1]



Improved constraints
on LV for electrons by up to
two orders of magnitude

Searching for dilaton dark matter with atomic clocks

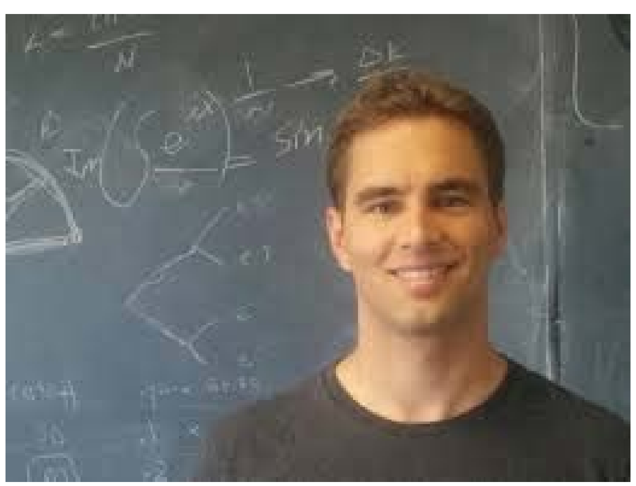
Asimina Arvanitaki*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

Junwu Huang† and Ken Van Tilburg‡
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA
(Dated: February 3, 2015)

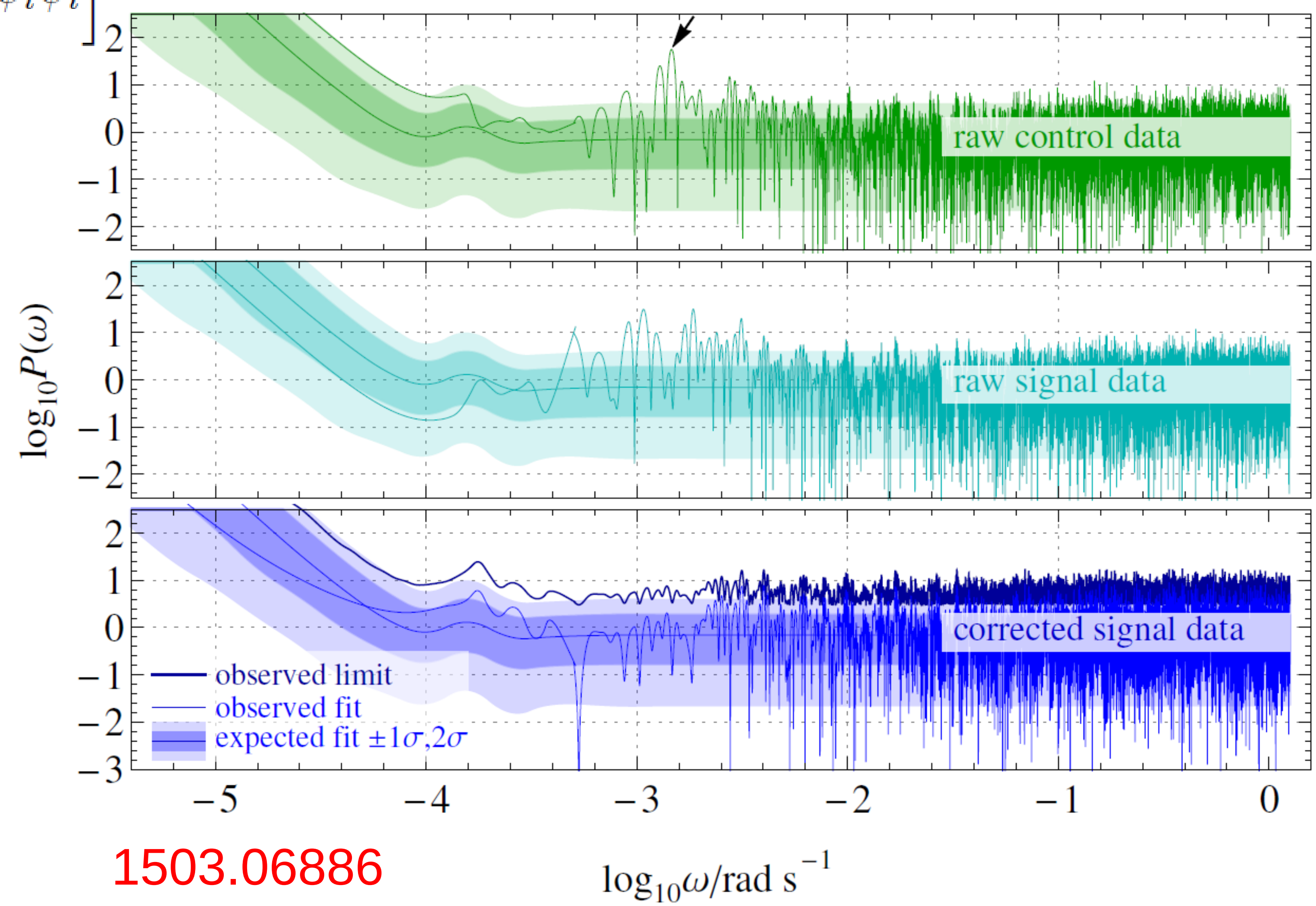
1405.2925
PRD **91** 015015 (2015)

$$\mathcal{L}_\phi = \kappa\phi\left[+ \frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu} G^{A\mu\nu} - d_{m_e} m_e \bar{e} e - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$

$$\frac{\partial \ln \alpha}{\partial(\kappa\phi)} = d_e$$



K. van Tilburg

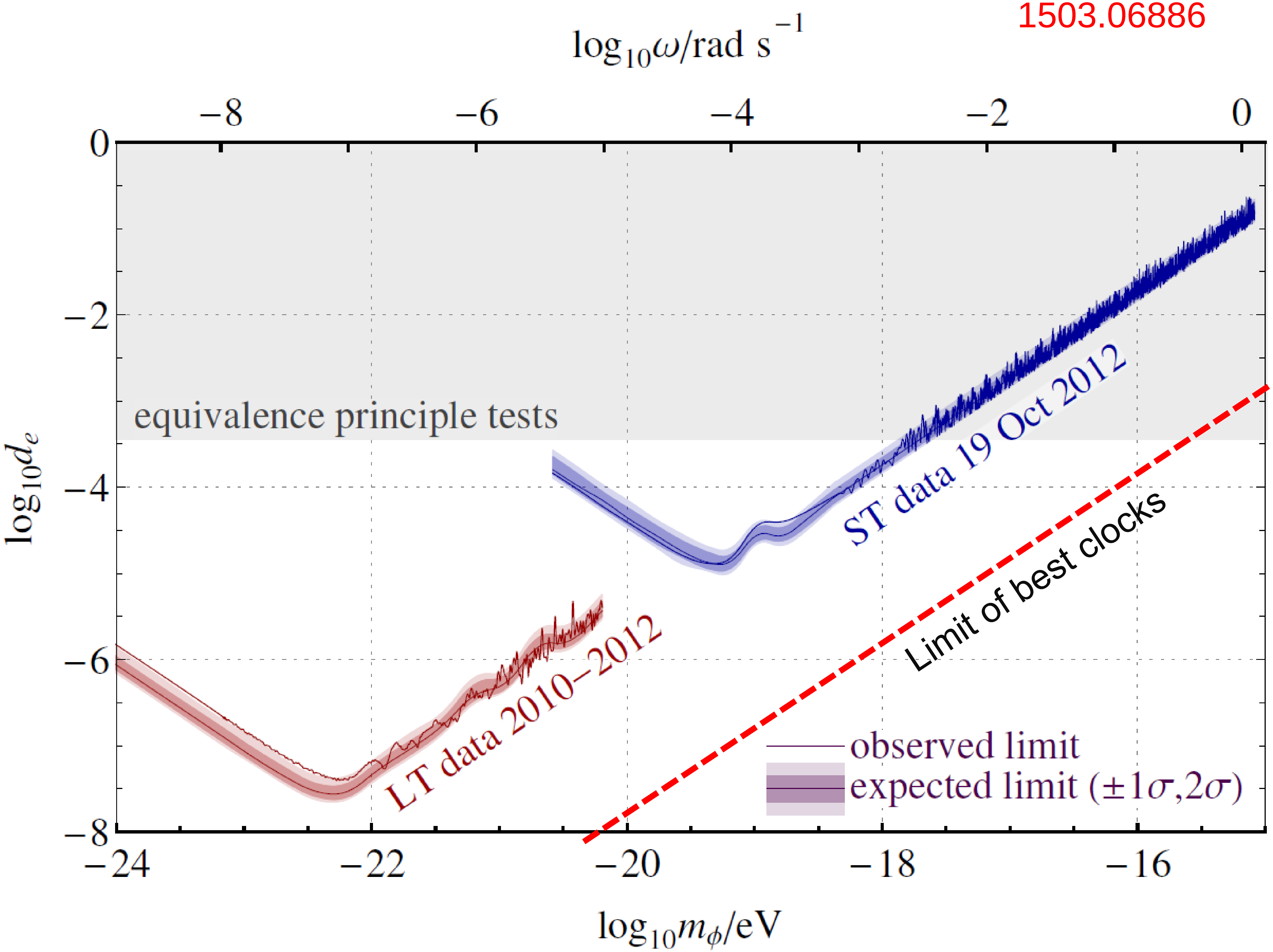


1503.06886

Search for ultralight scalar dark matter with atomic spectrosopy

Ken Van Tilburg,[1,*] Nathan Leefer,[2,†] Lykourgos Bougas,[2,‡] and Dmitry Budker[2,3,4,§]

1503.06886



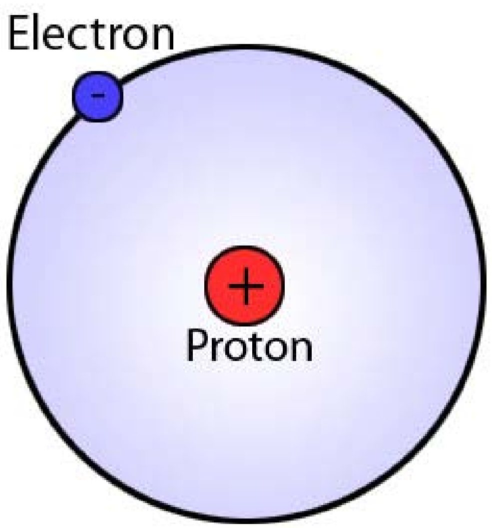
Summary and Outlook

- With a single experiment we have placed constraints on a wide range of ‘new’ physics
  - Results are applicable for any metrological spectroscopy
  - We did not foresee 2/3 of results presented here
- With large model space for DM/DE, documenting and storing data is extremely important

Thank you!

- Michael Hohensee
- Andreas Gerhardus
- Christian Weber
- Dimitri Dounas-Frazer
- Damon English
- Uttam Paudel
- Adrian de Nijs
- Vladimir Dzuba
- Celal Harabati
- Julian Berengut
- Misha Kozlov
- Bevan Gerber-Siff
- Arijit Sharma
- Sarah Ferrell
- Alain Lapierre
- Arman Cingoz
- Justin Torgerson
- Tuan Nguyen
- Victor Flambaum
- Valeriy Yashchuk
- Ben Roberts
- Yevgeny Stadnik

Why look for variation?



$$\frac{F_{EM}}{F_G} = \frac{e^2/a_0^2}{Gm_e m_p/a_0^2} \approx 10^{40}$$

$$\frac{\text{age of universe}}{\text{period of orbit}} \approx \frac{10^{18}\ \text{s}}{a_0/\alpha c} \approx 10^{40}$$

$$\dot{G}/G \approx -10^{-10}\,\text{yr}^{-1}$$

Dirac, 1937, Large Numbers Hypothesis

Ruled out by lunar laser-ranging: $\dot{G}/G \leq 10^{-12}\,\text{yr}^{-1}$

J. Müller and L. Biskupek, Class. Quant. Grav. **24**, 4533 (2007)

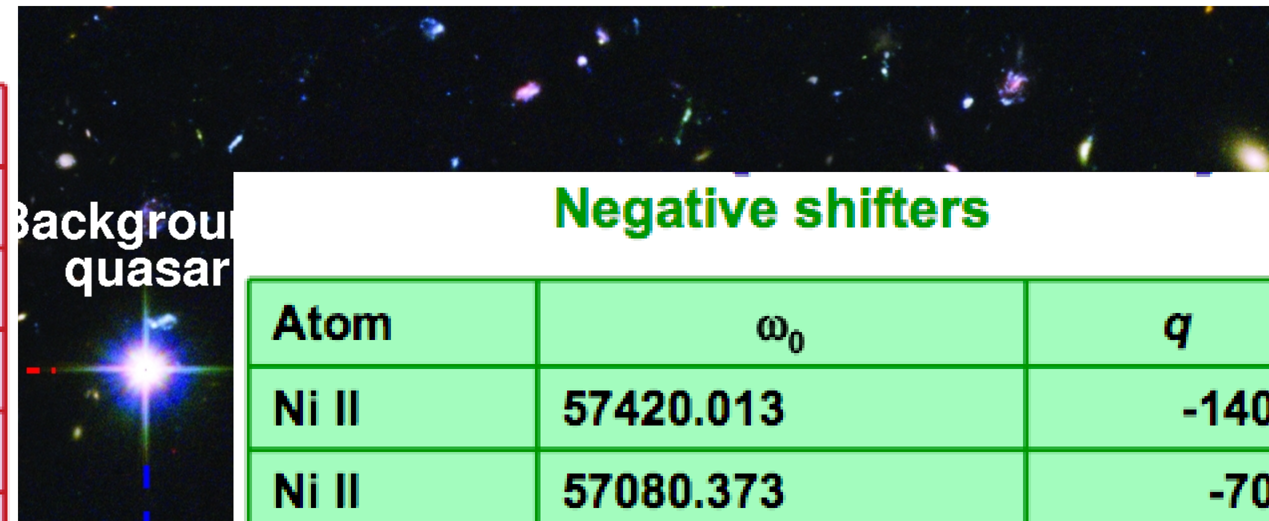
Astrophysics searches

Absorption features in quasar spectra encode local value of α throughout the universe

M.T. Murphy

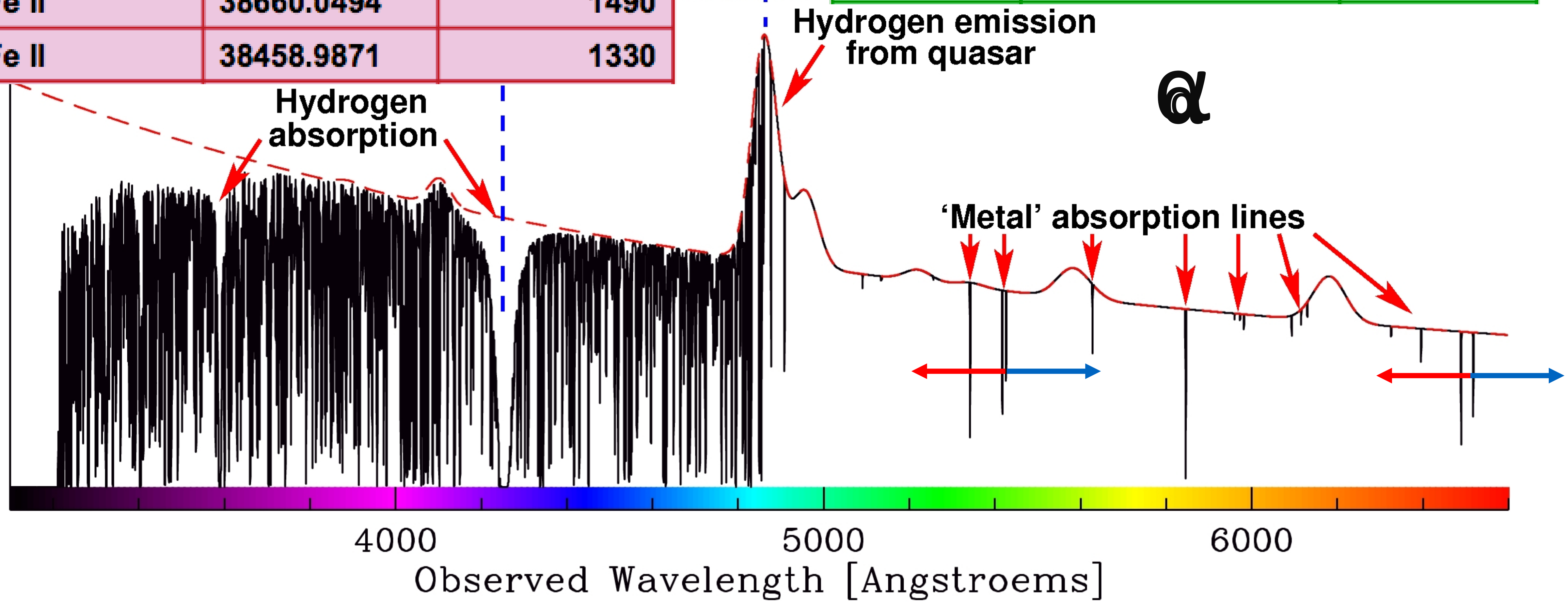
Positive shifters

Atom	ω_0	q
Fe II	62065.528	1100
Fe II	42658.2404	1210
Fe II	42114.8329	1590
Fe II	41968.0642	1460
Fe II	38660.0494	1490
Fe II	38458.9871	1330



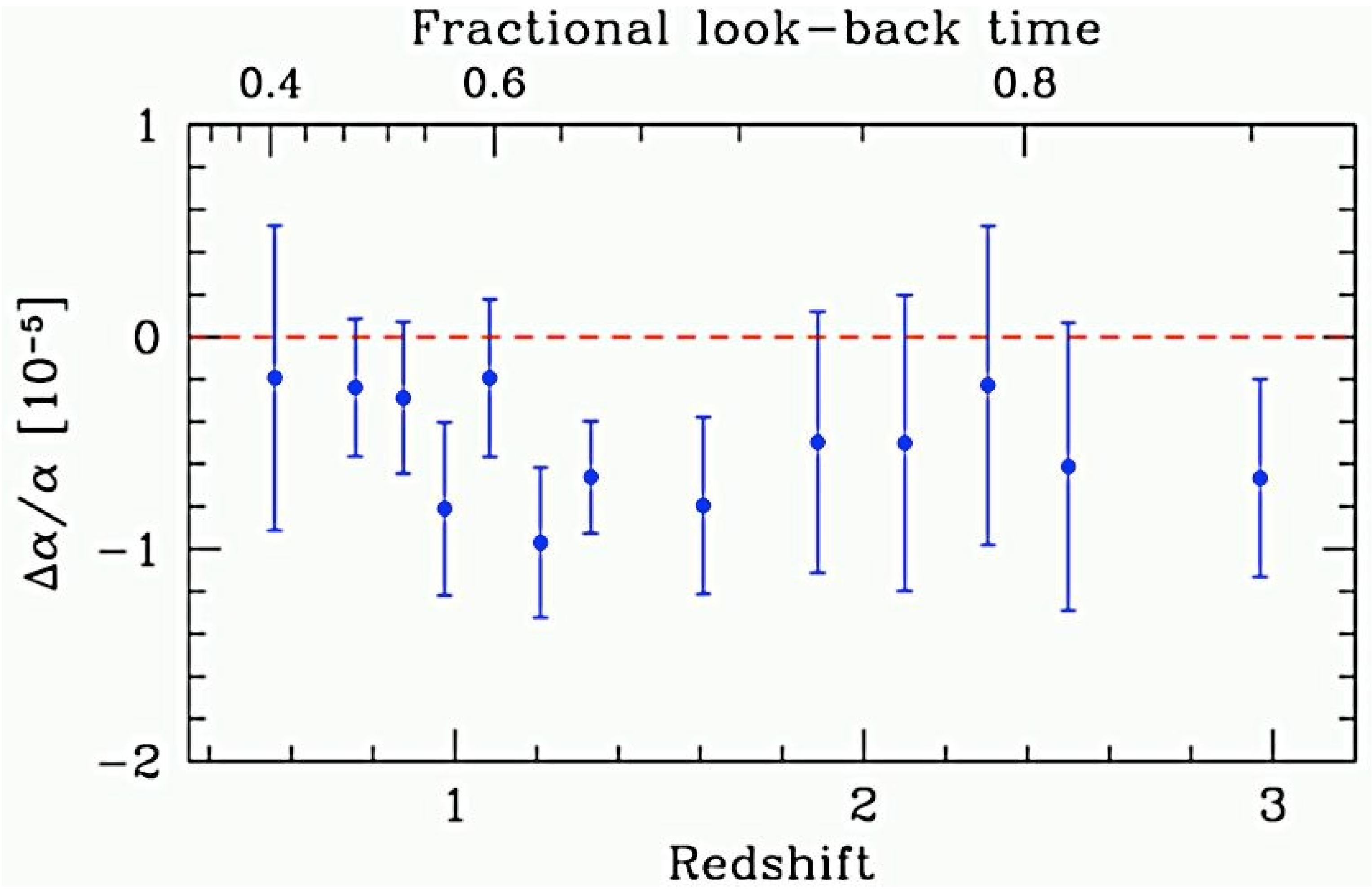
Negative shifters

Atom	ω_0	q
Ni II	57420.013	-1400
Ni II	57080.373	-700



Astrophysics searches

Absorption features in quasar spectra encode local value of α throughout the universe



M.T. Murphy, *et. al.*, ACFC Proceedings **74**, 131 (2004)

$$\boldsymbol{\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}}$$

10 billion year time scale

Astrophysical searches

Year	Method	$\Delta\alpha/\alpha$ $(\times 10^{-5})$	Redshift	$\dot{\alpha}/\alpha$ $(\times 10^{-15}/\text{yr})$
2006	CMB	-800 ± 1850	$z = 1100$	584 ± 1350
2004	CMB	-1500 ± 1750	$z = 1100$	1095 ± 1277
2005	OIII	6 ± 16	$0.3 < z < 0.8$	-8.7 ± 23
2004	QSO Abs.	-0.04 ± 0.33	$z = 1.15$	0.05 ± 0.4
2004	QSO Abs.	1.1 ± 1.1	$z = 1.149$	-1.3 ± 1.3
2004	QSO Abs.	-0.06 ± 0.06	$0.4 < z < 2.3$	0.06 ± 0.06
2003	QSO Abs.	-0.543 ± 0.116	$0.2 < z < 3.7$	0.45 ± 0.097
2001	QSO Abs.	-0.72 ± 0.18	$0.5 < z < 3.5$	$\simeq 0.61 \pm 0.15$
1999	QSO Abs.	-1.1 ± 0.4	$0.5 < z < 1.6$	$\simeq 1.2 \pm 0.4$

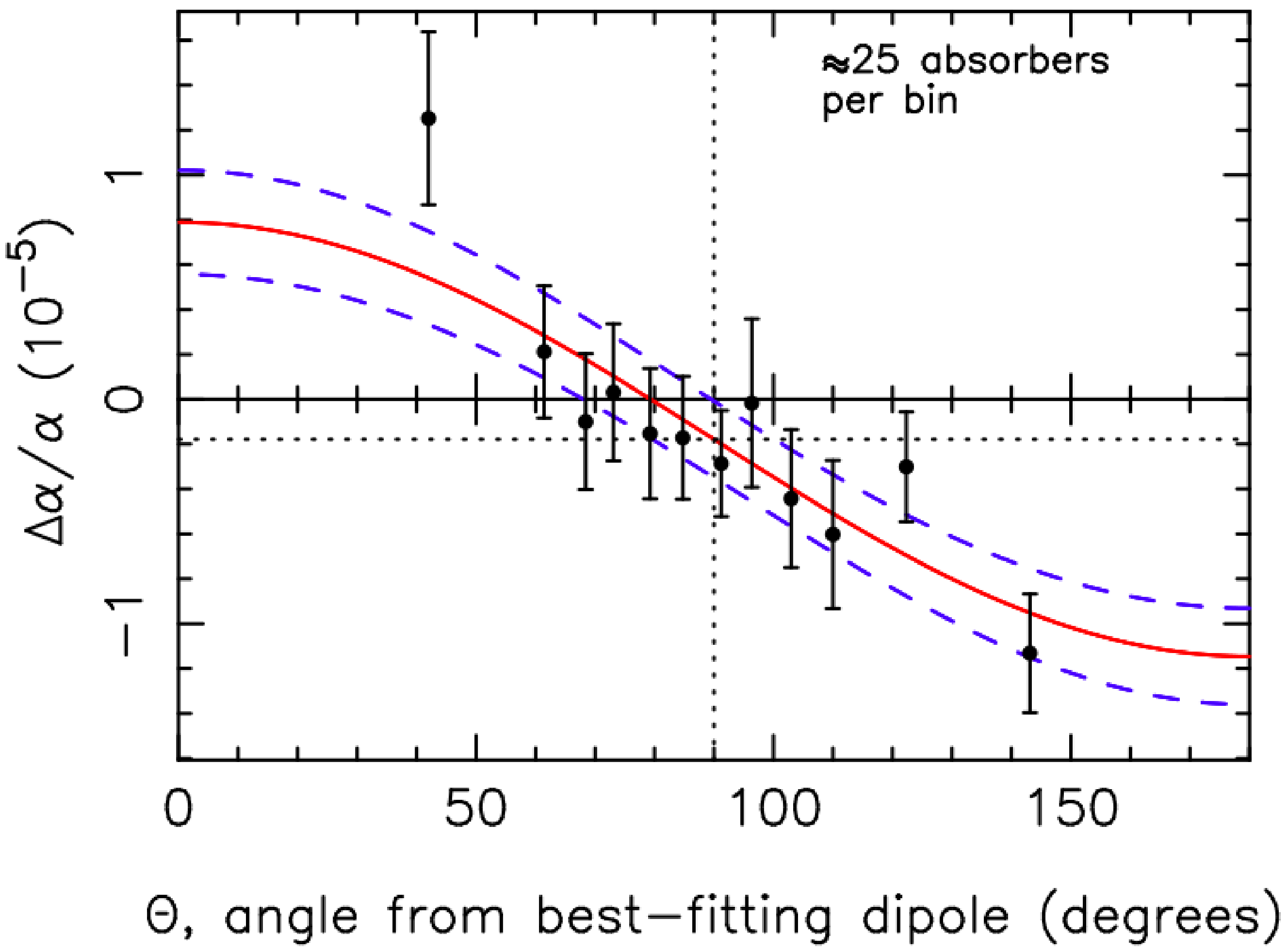
VLT

KECK

- Conflicting data come from different telescopes, observing <u>different regions of the sky</u>

revisited in 2011

Spatial variation?



J. K. Webb, *et. al.* (2011) Phys. Rev. Lett.

$$\frac{\Delta\alpha}{\alpha} = (1.1 \pm 0.25) \times 10^{-6}\, r \cos\theta$$

J. C. Berengut and V. V. Flambaum (2012) Euro. Phys. Lett.

$$\dot{\alpha}/\alpha|_{lab} = 1.35 \times 10^{-18} \cos\theta_{lab}\ \mathrm{yr}^{-1}$$

$$\cos\theta_{lab} \sim 0.07$$

Analysis of absorption lines in north and south hemispheres

Movement of Sun relative to CMB

Oklo natural reactor

- 1976: Y. Petrov and A. Shlyakhter propose using isotopic abundances to search for α variation

$$\mathbf{n} + {}^{149}\mathbf{Sm} \rightarrow {}^{150}\mathbf{Sm} + \gamma$$

- Resonance energy of reaction is **97.3 meV**

➡ Cancellation of strong nuclear force by coulomb interaction

➡ Neutron capture cross section very sensitive to changes in resonance energy, i.e. changes in α and α_S

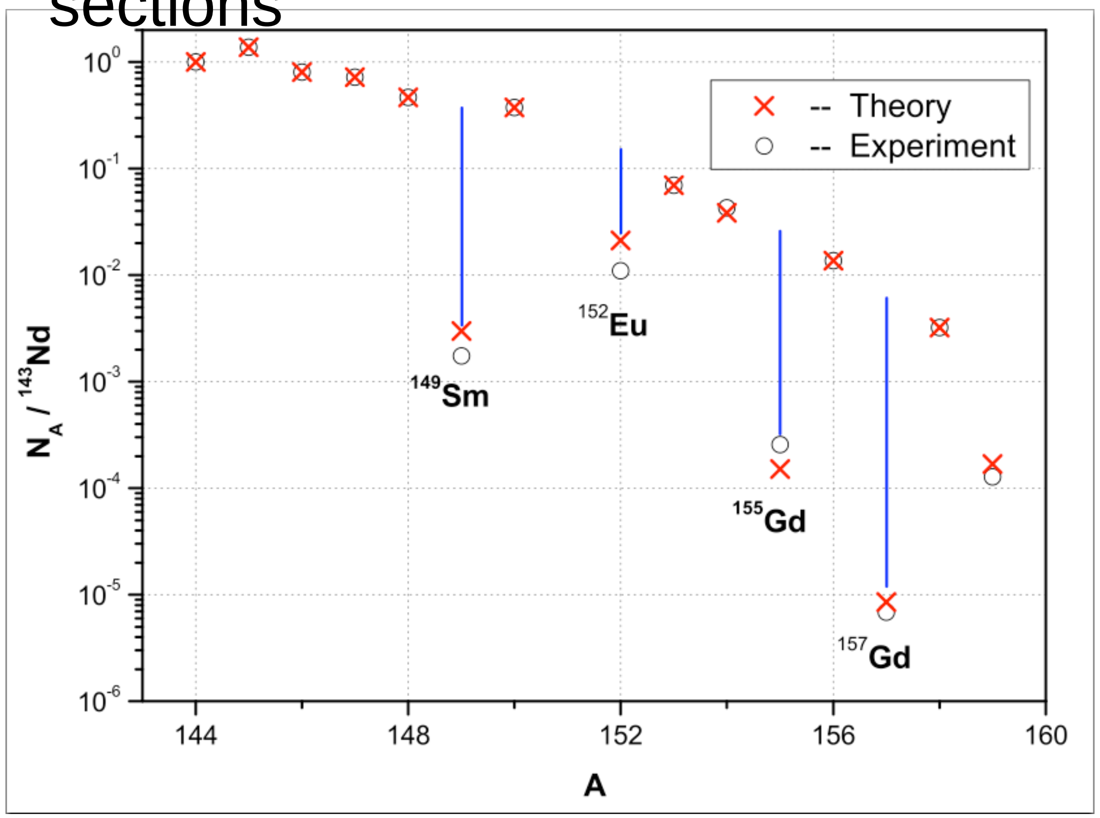
The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.

$$1972 : 0.717\,\%\ {}^{235}U \text{ found}$$

$$0.720\,\%\ {}^{235}U \text{ expected}$$

Oklo natural reactor

- Isotopic abundances of strong vs weak absorbers to calculate cross sections

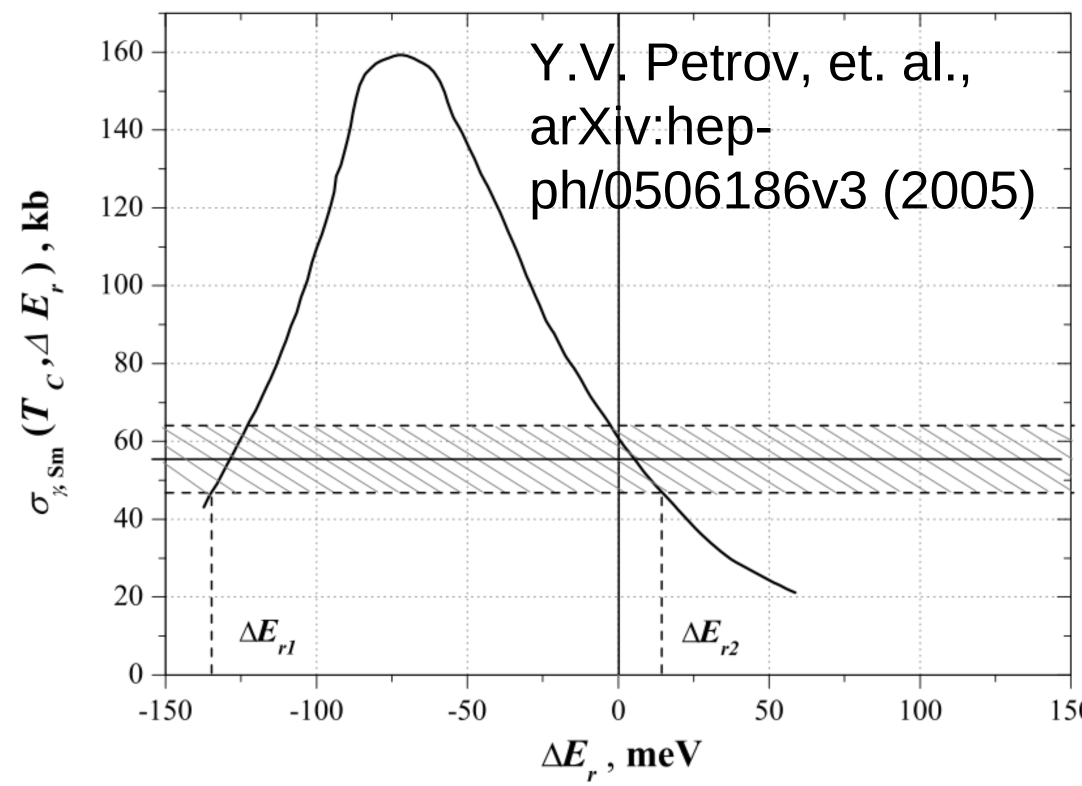


$$\frac{\Delta\alpha}{\alpha} \sim \frac{\Delta E_r}{1.1\,\mathrm{MeV}}$$

T. Damour and F. Dyson, Nuclear Physics, **B480**, 37 (1996)

- Model dependent, large uncertainties due to reactor models

- Dependence of cross section on energy shift



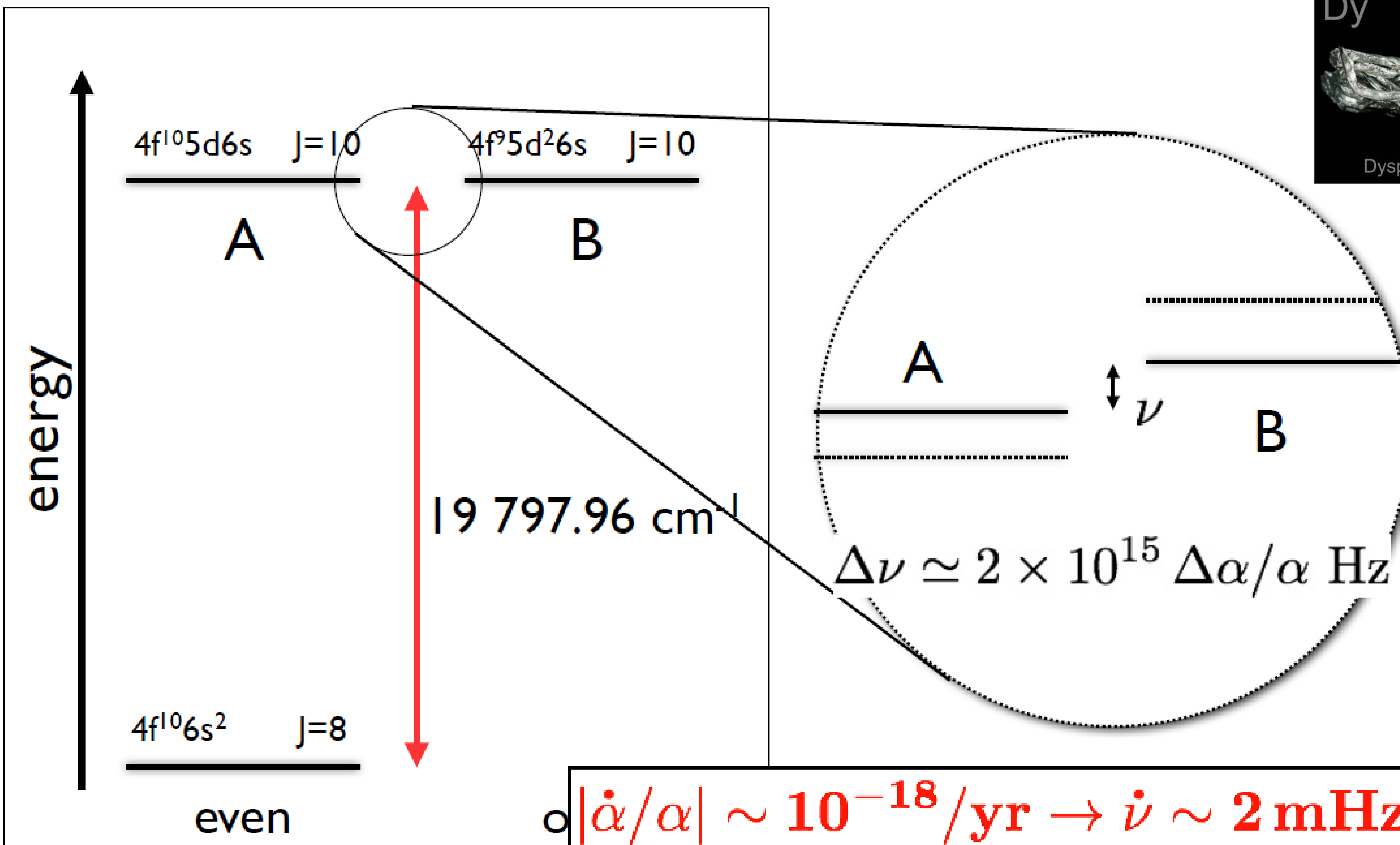
Y.V. Petrov, et. al., arXiv:hep-ph/0506186v3 (2005)

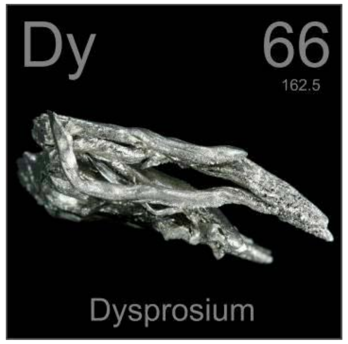
$$|\dot{\alpha}/\alpha| \leq 4.6 \times 10^{-17}\, yr^{-1}$$

C.R. Gould, *et. al.*, Phys. Rev. C **74**, 024607 (2006)

2 billion year time scale

Search in dysprosium





$$|\dot{\alpha}/\alpha| \sim 10^{-18}/\mathrm{yr} \rightarrow \dot{\nu} \sim 2\,\mathrm{mHz/yr}$$

Atomic beam apparatus

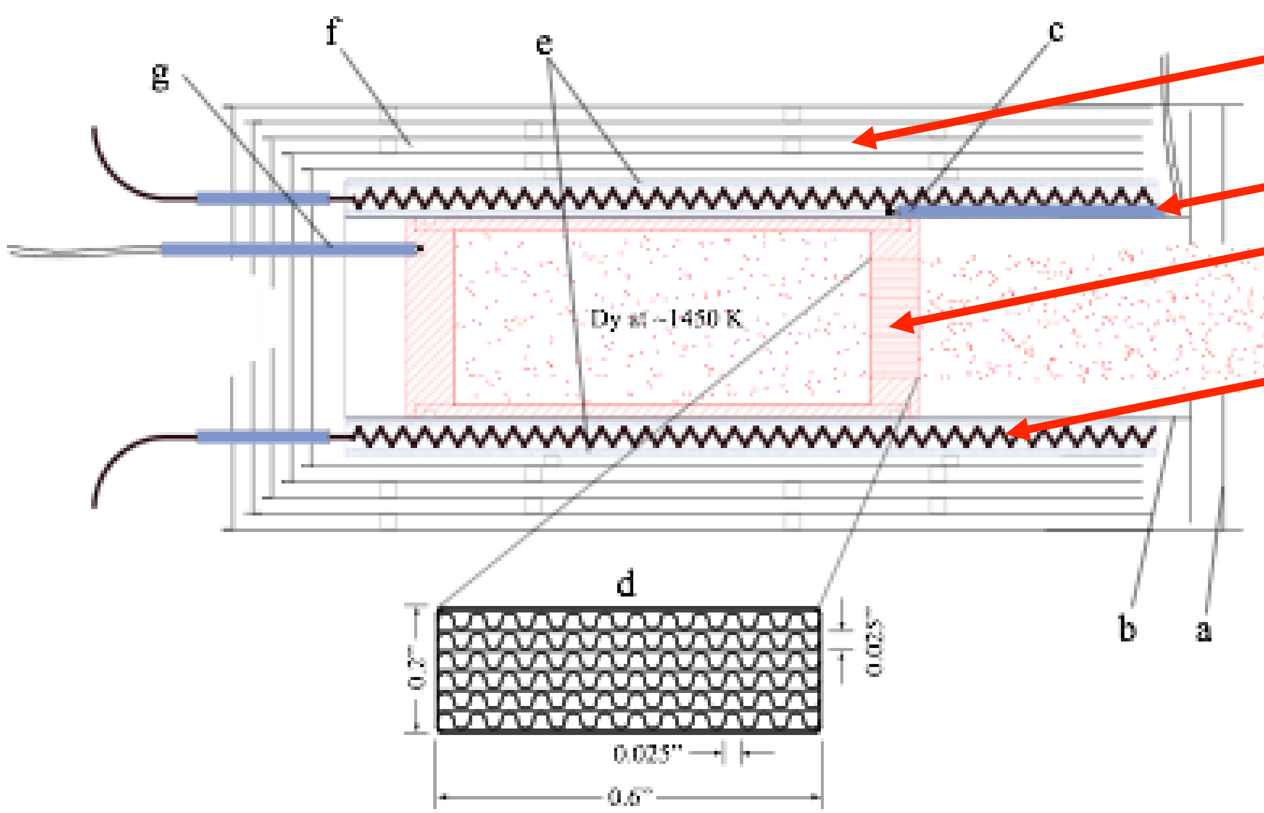
oven

5 layer, Ta heat shield

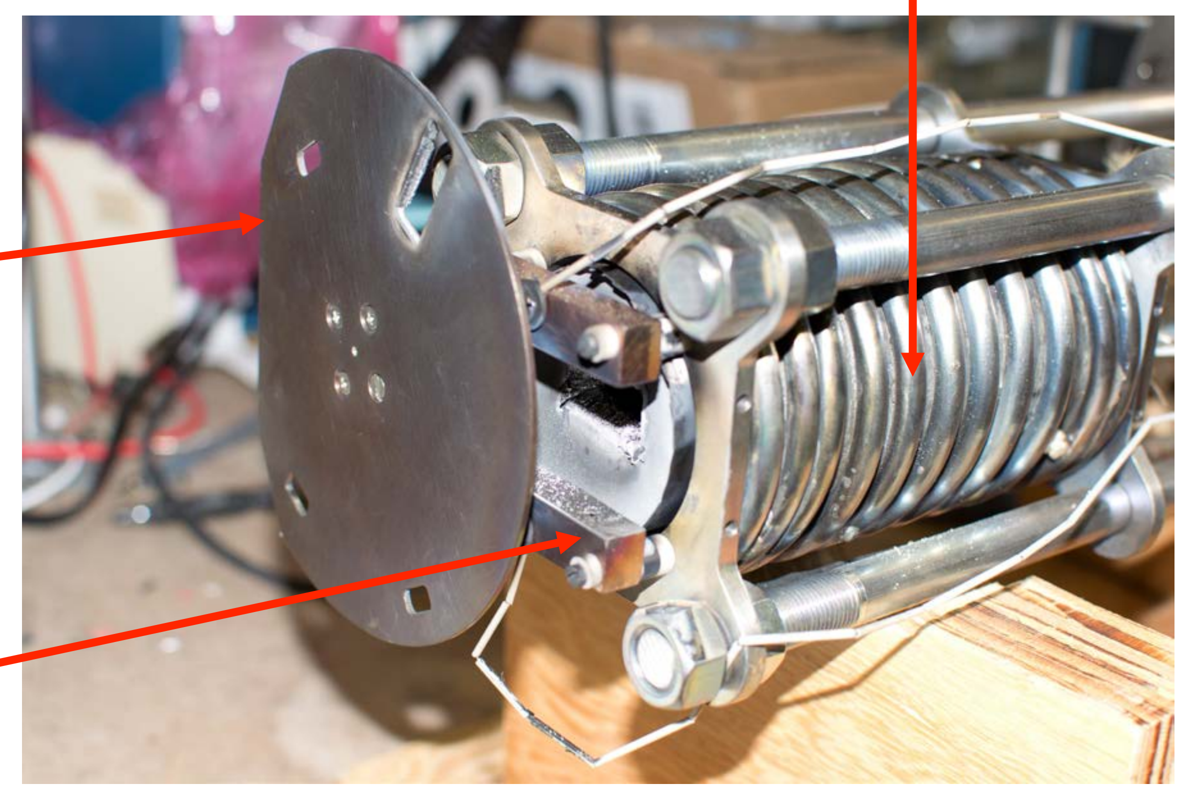
thermocouple

Mo oven tube

Ta heater coil



water cooled jacket

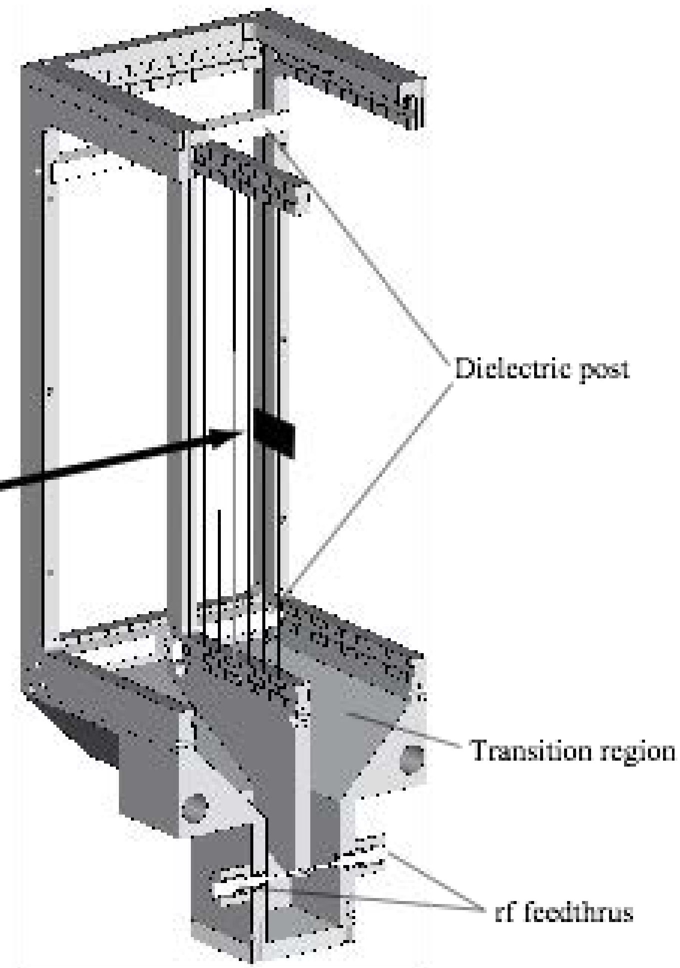


beam flag

sweep electrode

Atomic beam apparatus

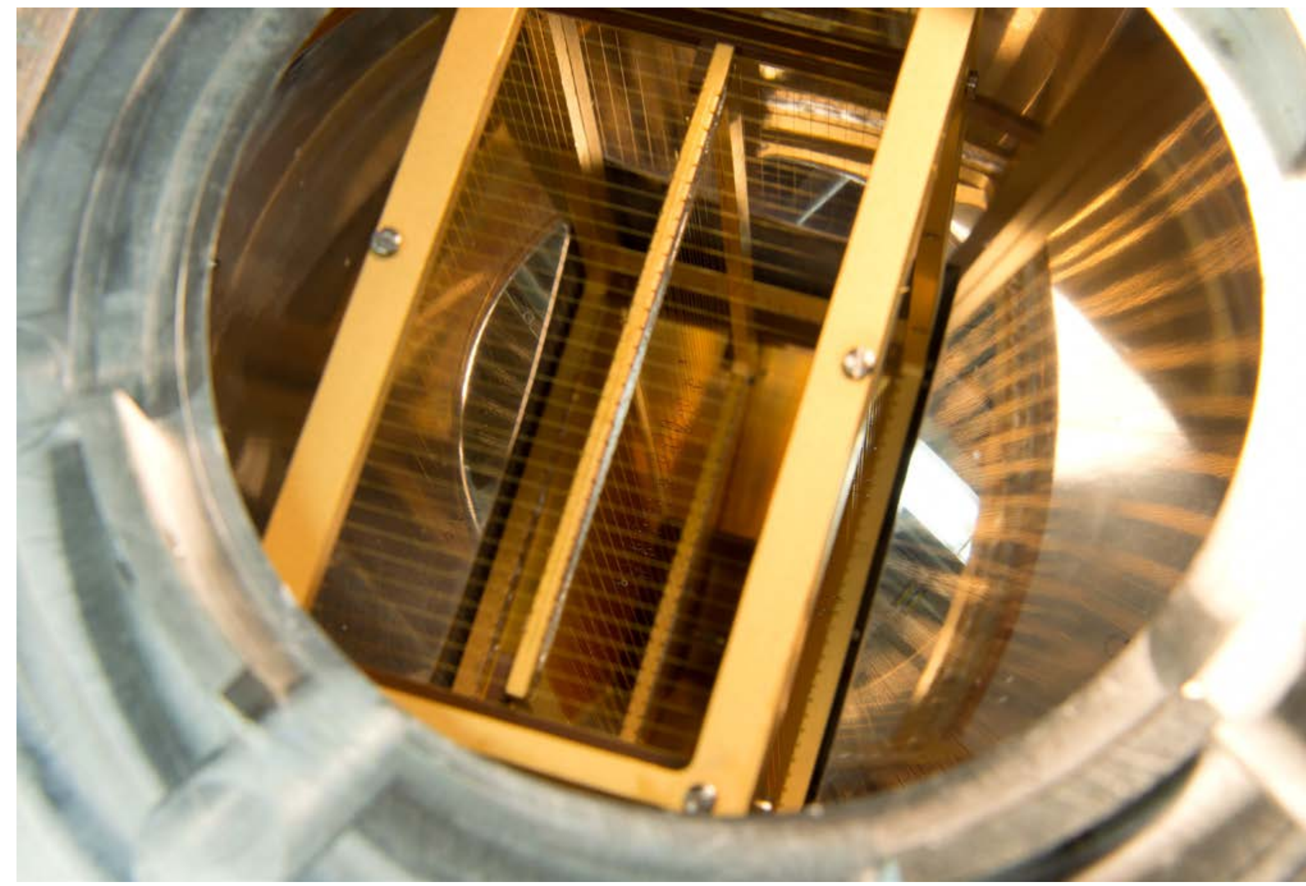
(a)



A. Cingoz

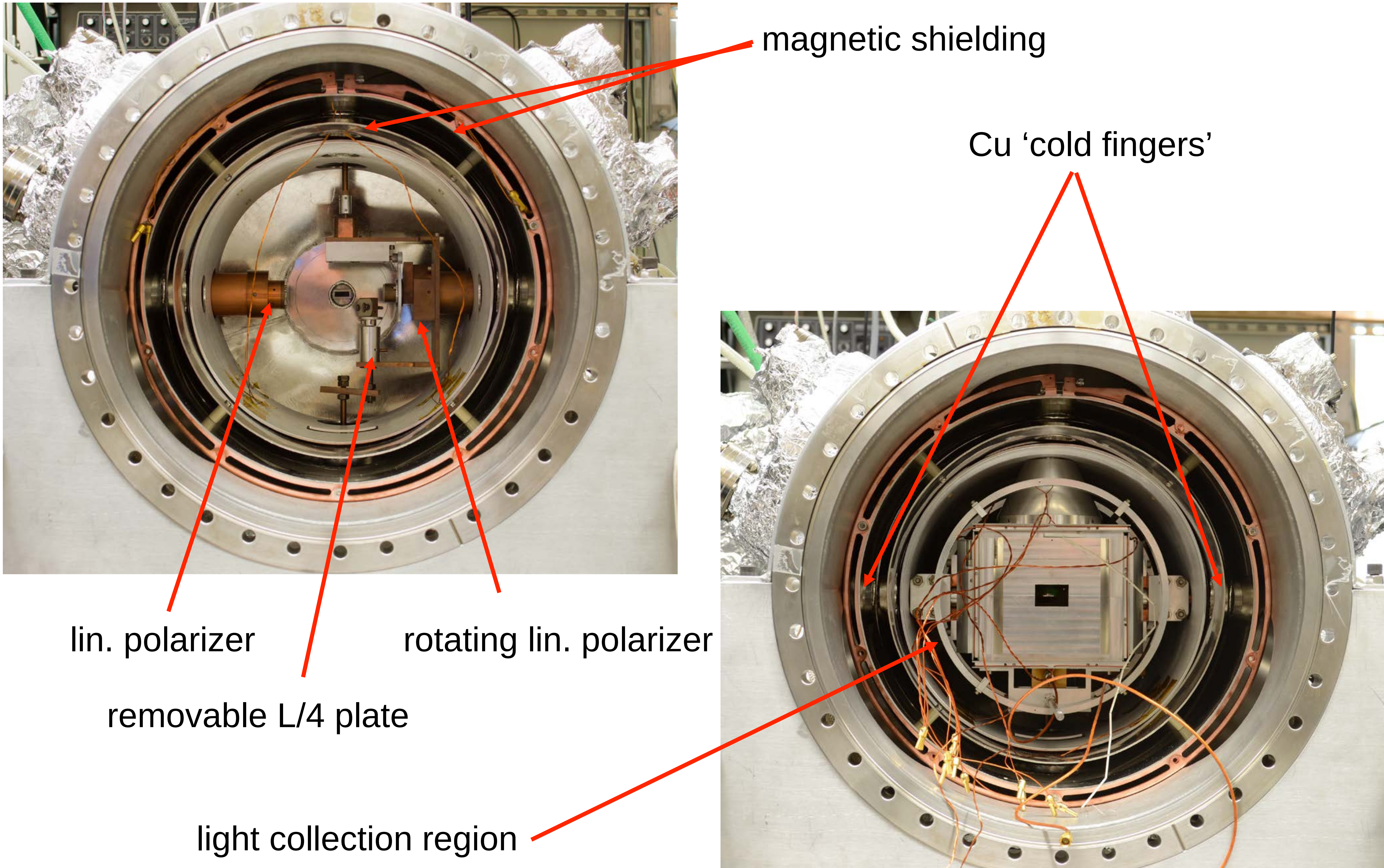
(b)

rf electrodes



polished Al light collector

Atomic beam apparatus



Lock-in detection

- First harmonic, H1, is odd function of detuning around resonance
- variable detection phase for characterizing systematics