Searching for temporal variation of the fine-structure "constant"

in

radio-frequency transitions of Dy

Dmitry Budker

http://socrates.berkeley.edu/~budker

Fine-Structure Constant α

- Dimensionless fundamental constant

- Characterizes the strength of all electromagnetic interactions

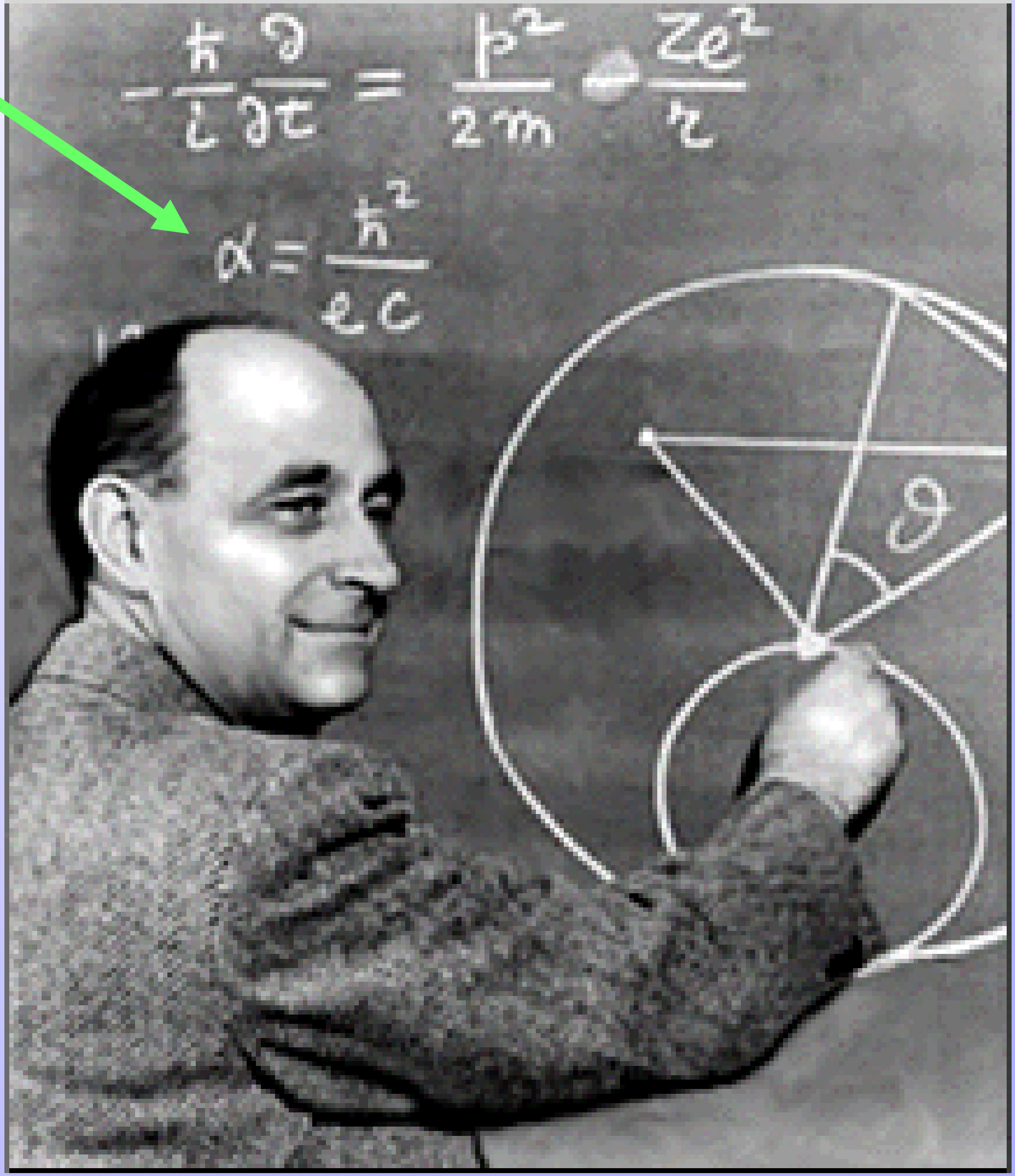
- Energy of atomic levels $\propto m_e c^2 \cdot \alpha^2 \cdot (1 + k\alpha^2 + \ldots)$

$$\boxed{\alpha = \frac{e^2}{\hbar c} = \frac{1}{137.035\ 999\ 710\ (96)} \quad [0.70\ \text{ppb}]}$$

G. Gabrielse *et al,* Phys. Rev. Lett. **97**, 030802 (2006)

A ***gross*** variation

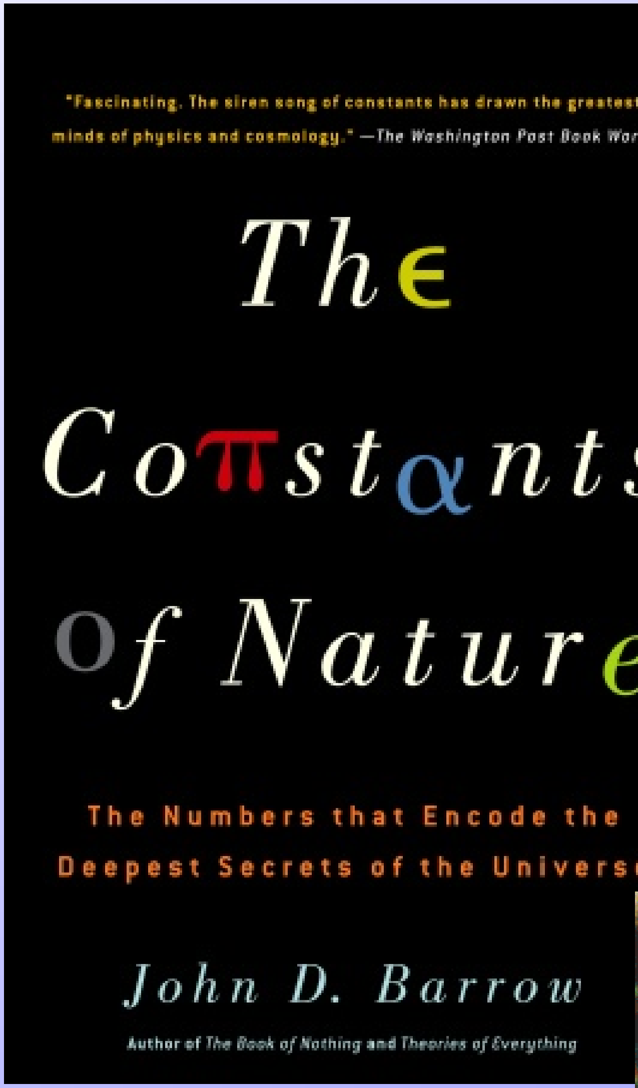
We search for *small* temporal variation of *α*



Professor Enrico Fermi

Are the constants of Nature constant?
(A fundamental question)

- Sir A. Eddington
- A. Einstein
- P. A. M. Dirac
- E. Teller
- G. Gamow
- R. H. Dicke
- …



"Fascinating. The siren song of constants has drawn the greatest minds of physics and cosmology." —*The Washington Post Book World*

The Constants of Nature

The Numbers that Encode the Deepest Secrets of the Universe

John D. Barrow

Author of *The Book of Nothing* and *Theories of Everything*

2006 Templeton Foundation Award

The constants:

1. $c = 3 \cdot 10^{10} cm \cdot sec^{-1}$, velocity of light
2. $\hbar = 1.05 \cdot 10^{-27} erg \cdot sec$, Planck's constant
3. $e = 4.8 \cdot 10^{-10} erg^{1/2} cm^{1/2}$, elementary charge
4. $m_p = 1.6 \cdot 10^{-24} gram$, mass of the proton
5. $g = 1.4 \cdot 10^{-49} erg \cdot cm^3$, Fermi's constant of weak interactions
6. $G = 6.7 \cdot 10^{-8} erg \cdot cm \cdot gram^{-2}$, constant of gravitation
7. $H = 1.6 \cdot 10^{-18} sec^{-1}$, Hubble's constant ($1/H \approx 2 \cdot 10^{10}$ years gives the "age" of the Universe)
8. $\rho = 10^{-31} gram \cdot cm^{-3}$, mean density of mass in the Universe

Dimensionless combinations do not depend on units :

1. $\alpha = e^2/\hbar c \approx 1/137$
2. $\beta = (g m_p^2 c)/\hbar^3 = 9 \cdot 10^{-6}$
3. $\gamma = (G m_p^2)/(\hbar c) = 5 \cdot 10^{-39}$
4. $\delta = (H \hbar)/(m_p c^2) = 10^{-42}$
5. $\epsilon = (G\rho)/H^2 = 2 \cdot 10^{-3}$

Conventional Wisdom:

α, β, γ-constant; $\delta \sim t^{-1}$, $\varepsilon \sim t^{-1}$

Dirac's Large Number Hypothesis and variations :

- Dirac (1937): $\alpha, \beta, \epsilon = const; \gamma \sim t^{-1}, \delta \sim t^{-1}$
- Teller (1948): $\beta, \epsilon = const, \alpha^{-1} \sim \ln(\gamma^{-1}), \gamma \sim t^{-1}, \delta \sim t^{-1}$
- Gamow (1967): $\beta, \gamma, \epsilon = const, \alpha \sim t, \delta \sim t^{-1}$

Ruled out as predict variations ~ 10^{-10}-10^{-12}/y

$$N_1 = \frac{\text{size of Universe}}{\text{classical electron radius}} = \frac{ct}{e^2 / m_e c^2} \approx 10^{40}$$

$$N_2 = \frac{\text{Electromagnetic force between } e, p}{\text{Gravitational force between } e, p} = \frac{e^2}{G m_e m_p} \approx 10^{40}$$

$$N = \text{Number of protons in Universe} \approx \frac{c^3 t}{G m_p} \approx 10^{80}$$

Dirac's Large Number Hypothesis:

$$N_1 \approx N_2 \approx \sqrt{N} \propto t$$

Large variations are out…

… but BIG QUESTIONS are in:

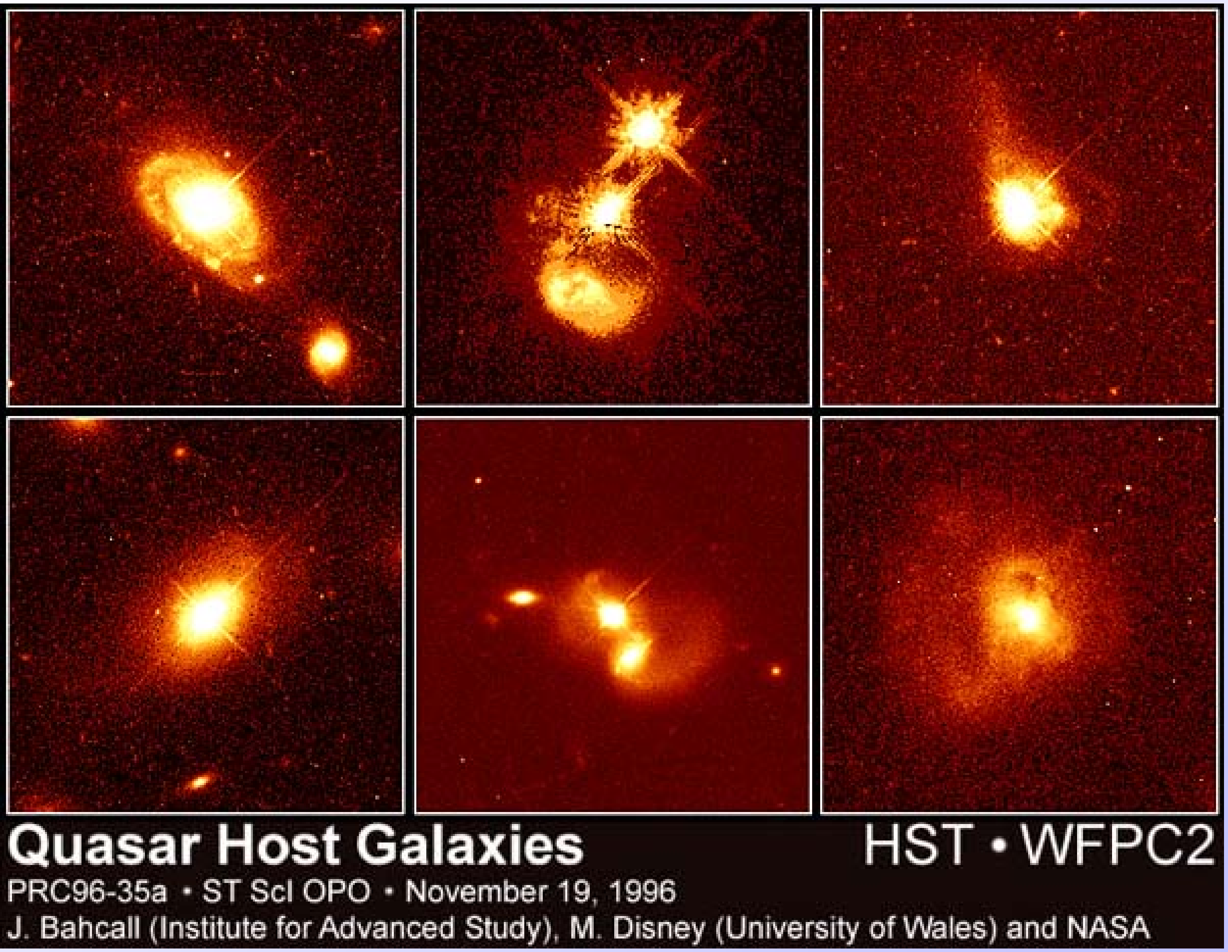
- Are there small changes of "constants" over the past 13 Gy or so ?

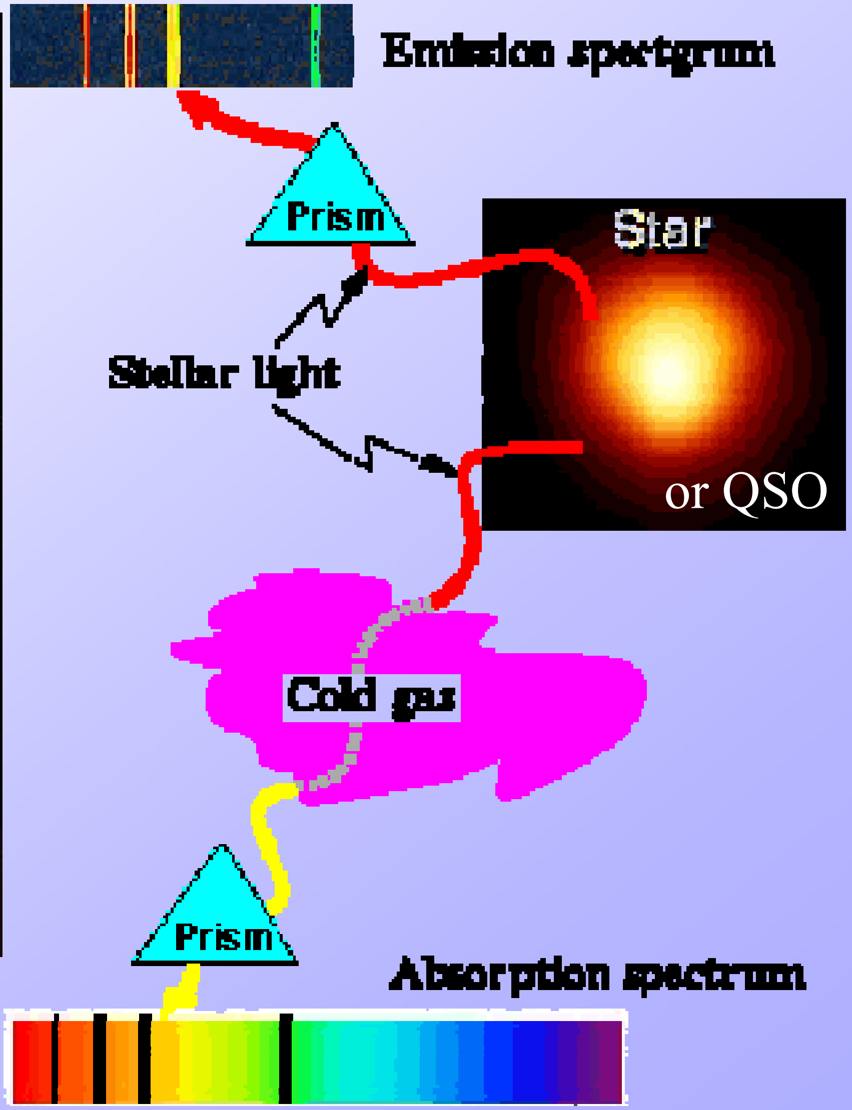
Observations

- May the "constants" be changing as we speak ?

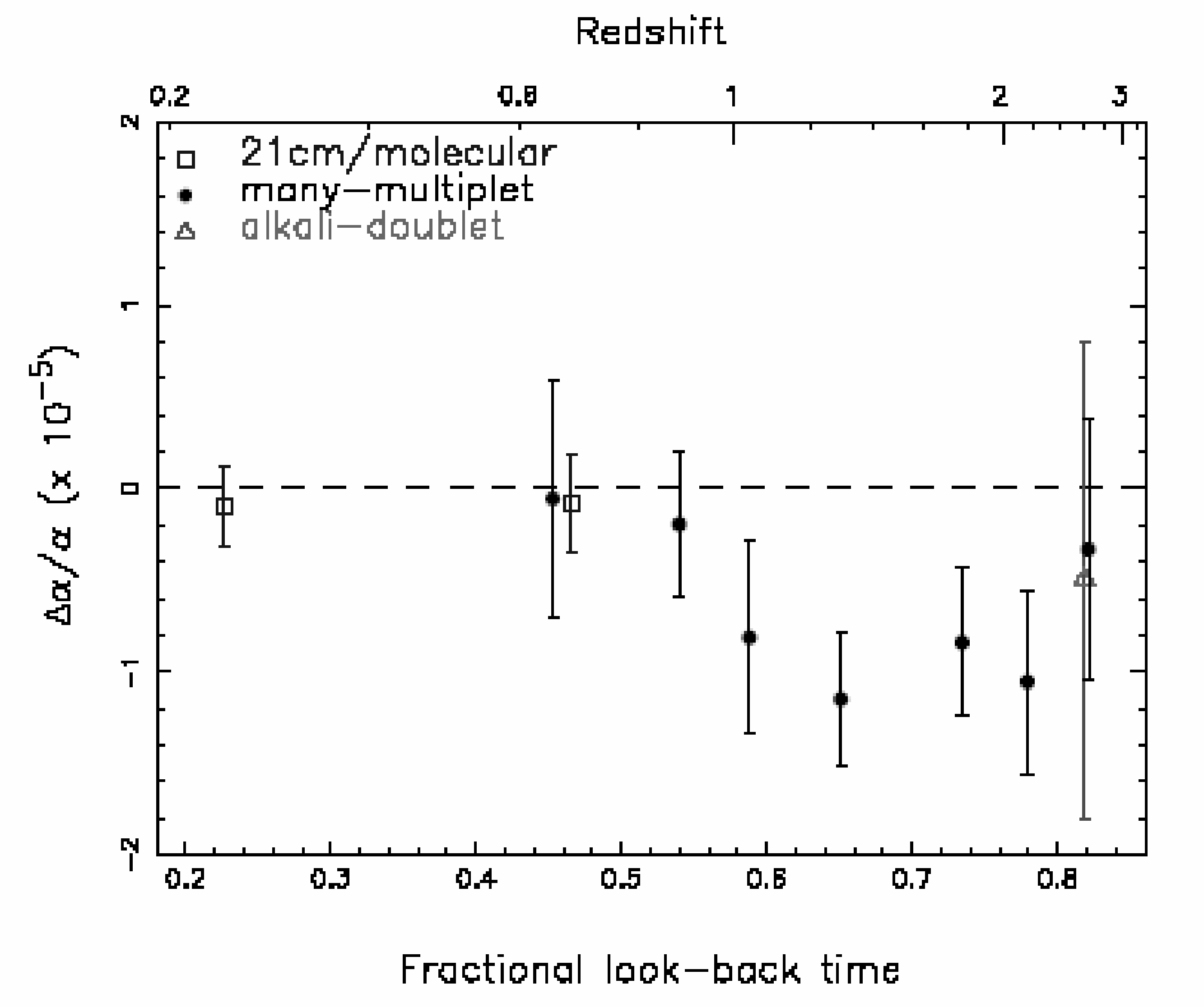
Laboratory ?

Astrophysical searches for α-variation





- Astrophysical evidence for smaller α in the past:



J. K. Webb, *et al.* , Phys. Rev. Lett. **87**, 091301 (2001)

- Astrophysical evidence for a smaller α in the past:

	$\dot{\alpha}/\alpha$ ($\times 10^{-16}$ /yr)	
1999	14 ± 5	J. K. Webb, *et al.* , Phys. Rev. Lett. **82**, 884 (1999)
2001	7.2 ± 1.8	J. K. Webb, *et al.* , Phys. Rev. Lett. **87**, 091301 (2001)
2003	6.4 ± 1.4	M. T. Murphy, *et al.* , Mon. Not. R. Astron. Soc. **345**, 609 (2003)

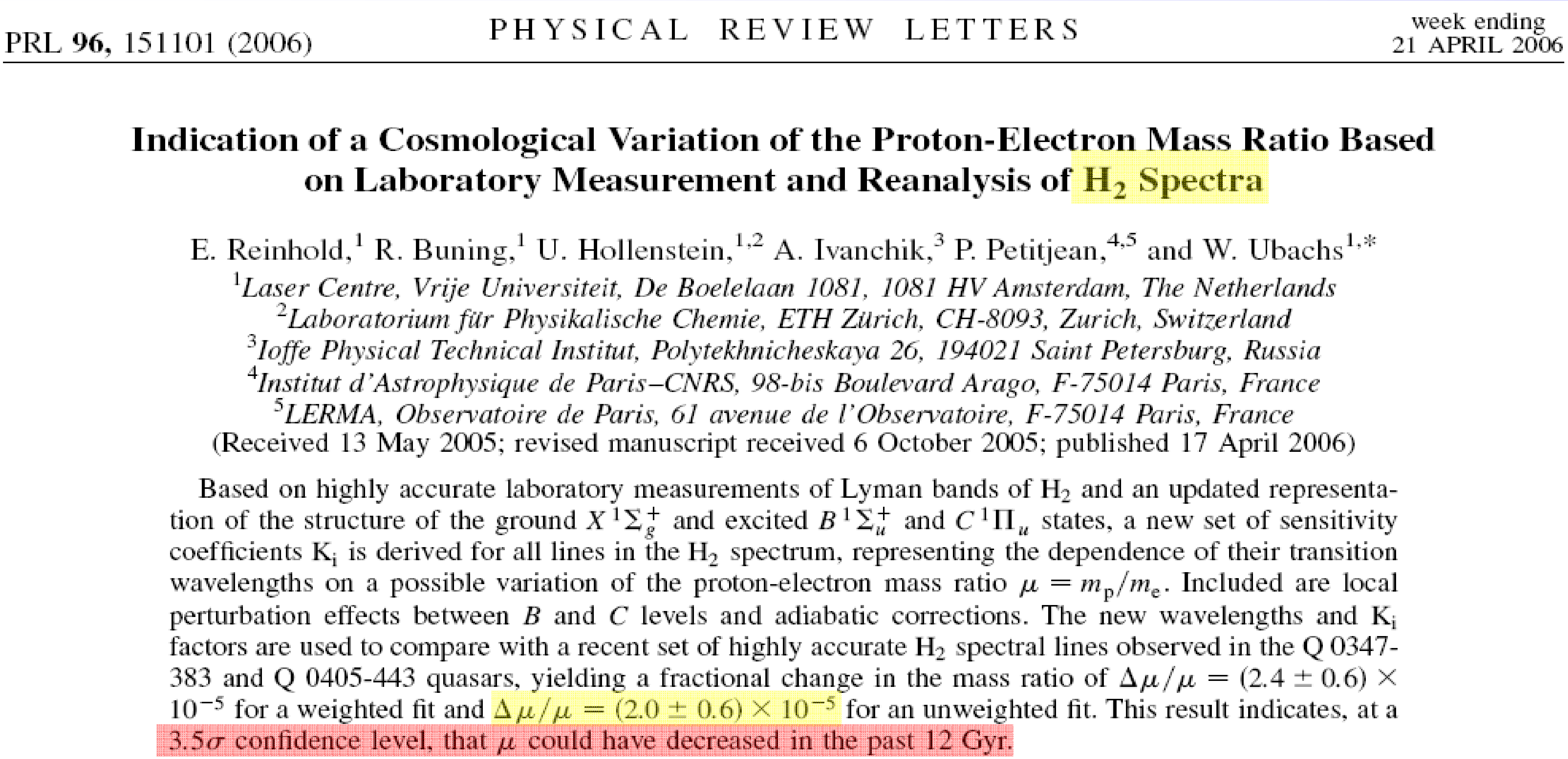
Victor V. Flambaum

- However, other groups see no variation:

(using a different telescope and higher quality but smaller data set)

	$\dot{\alpha}/\alpha$ ($\times 10^{-16}$ /yr)	
2004	0.5 ± 4	R. Quast, *et al.* , Astron. Astrophysics. **415**, L7 (2004)
2004	0.6 ± 0.6	R. Srianand, *et al.* , Phys. Rev. Lett. **92**, 121302 (2004)

More Controversy: claim for variation of $\mu = m_p / m_e$



PRL **96,** 151101 (2006) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2006

Indication of a Cosmological Variation of the Proton-Electron Mass Ratio Based on Laboratory Measurement and Reanalysis of H_2 Spectra

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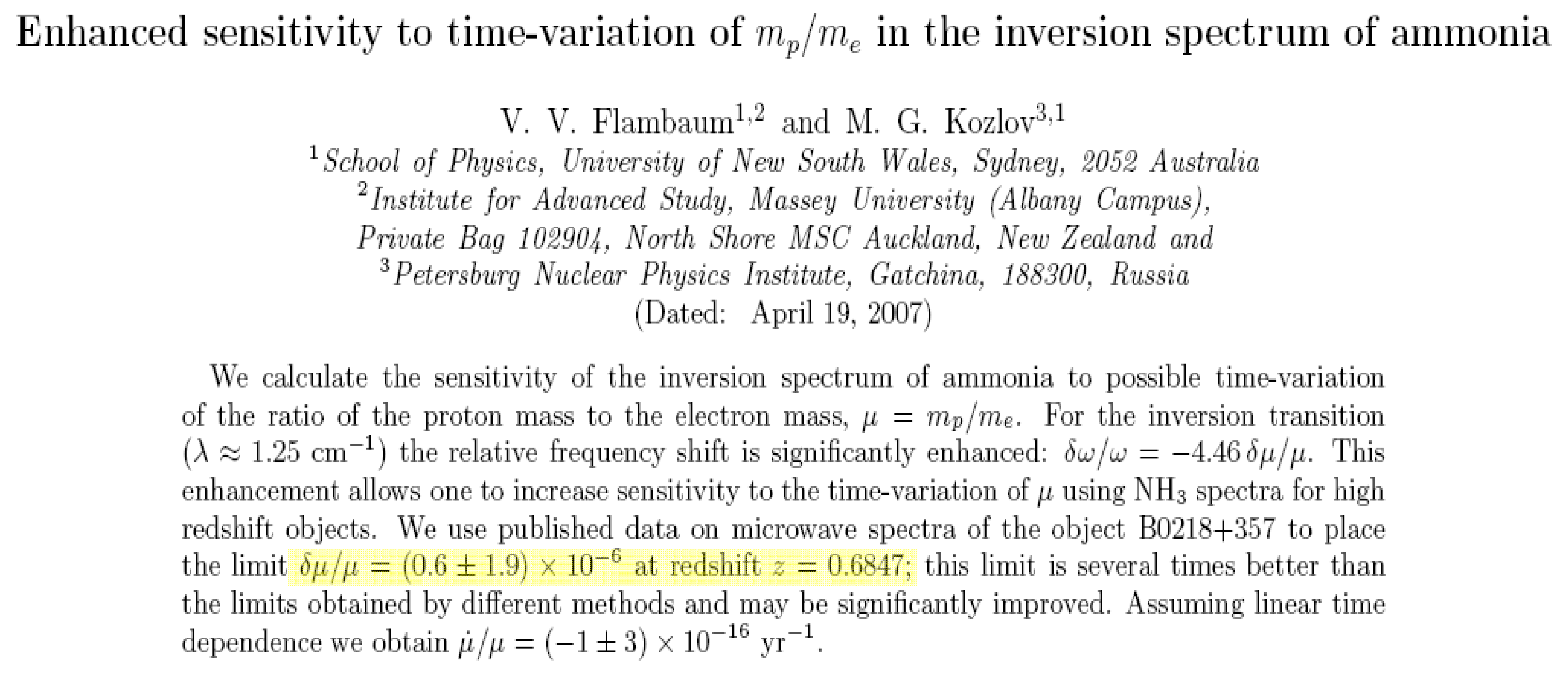
(Received 13 May 2005; revised manuscript received 6 October 2005; published 17 April 2006)

Based on highly accurate laboratory measurements of Lyman bands of H_2 and an updated representation of the structure of the ground $X\,^1\Sigma_g^+$ and excited $B\,^1\Sigma_u^+$ and $C\,^1\Pi_u$ states, a new set of sensitivity coefficients K_i is derived for all lines in the H_2 spectrum, representing the dependence of their transition wavelengths on a possible variation of the proton-electron mass ratio $\mu = m_p/m_e$. Included are local perturbation effects between B and C levels and adiabatic corrections. The new wavelengths and K_i factors are used to compare with a recent set of highly accurate H_2 spectral lines observed in the Q 0347-383 and Q 0405-443 quasars, yielding a fractional change in the mass ratio of $\Delta\mu/\mu = (2.4 \pm 0.6) \times 10^{-5}$ for a weighted fit and $\Delta\mu/\mu = (2.0 \pm 0.6) \times 10^{-5}$ for an unweighted fit. This result indicates, at a 3.5σ confidence level, that μ could have decreased in the past 12 Gyr.

These measurements are based on the different dependences of molecular energies on μ:

- Electronic $\propto m_e \alpha^2$
- Vibrational $\propto m_e \alpha^2 \sqrt{\frac{m_e}{m_p}}$
- Rotational $\propto m_e \alpha^2 \frac{m_e}{m_p}$

More **Controversy**: limit on variation of $\mu = m_p / m_e$



Enhanced sensitivity to time-variation of m_p/m_e in the inversion spectrum of ammonia

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Private Bag 102904, North Shore MSC Auckland, New Zealand and
[3] *Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia*
(Dated: April 19, 2007)

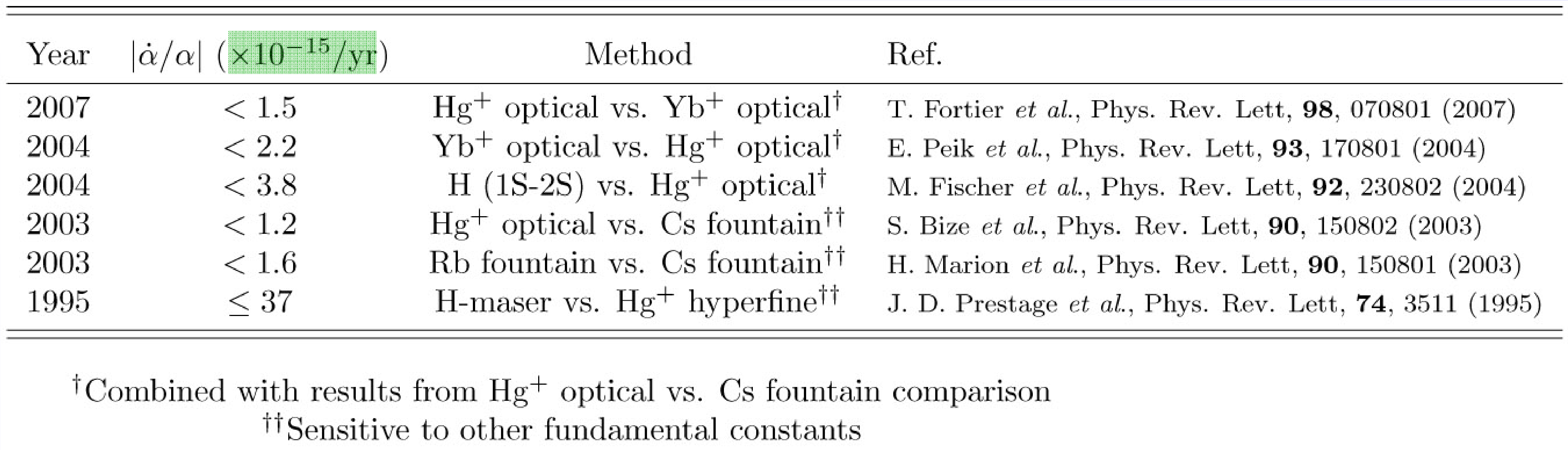
We calculate the sensitivity of the inversion spectrum of ammonia to possible time-variation of the ratio of the proton mass to the electron mass, $\mu = m_p/m_e$. For the inversion transition ($\lambda \approx 1.25$ cm^{-1}) the relative frequency shift is significantly enhanced: $\delta\omega/\omega = -4.46\,\delta\mu/\mu$. This enhancement allows one to increase sensitivity to the time-variation of μ using NH_3 spectra for high redshift objects. We use published data on microwave spectra of the object B0218+357 to place the limit $\delta\mu/\mu = (0.6 \pm 1.9) \times 10^{-6}$ at redshift $z = 0.6847$; this limit is several times better than the limits obtained by different methods and may be significantly improved. Assuming linear time dependence we obtain $\dot{\mu}/\mu = (-1 \pm 3) \times 10^{-16}$ yr^{-1}.

arXiv.org > astro-ph > arXiv:0704.2301

Laboratory Searches

- Looking for *present-day* variation [e.g., $\dot{\alpha}(t = now)$]
- Level of present interest: $1/10^5$ per 10 Gy
- Which is $1/10^{15}$ per year (assuming linear variation)
- This is about where **best atomic clocks** are today
- Clock laboratories search for variation of constants
- (We do not rely on fancy clock, but still would like to have one)

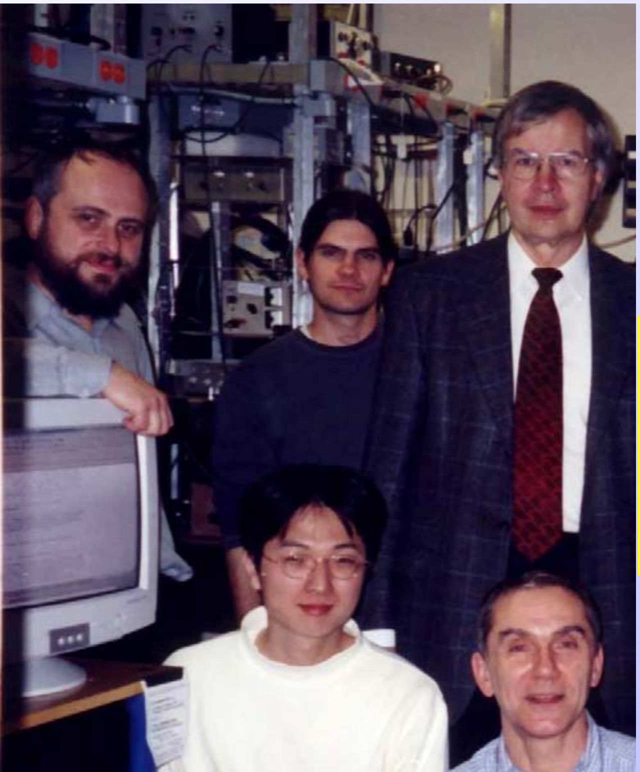
• Laboratory limits (1σ):



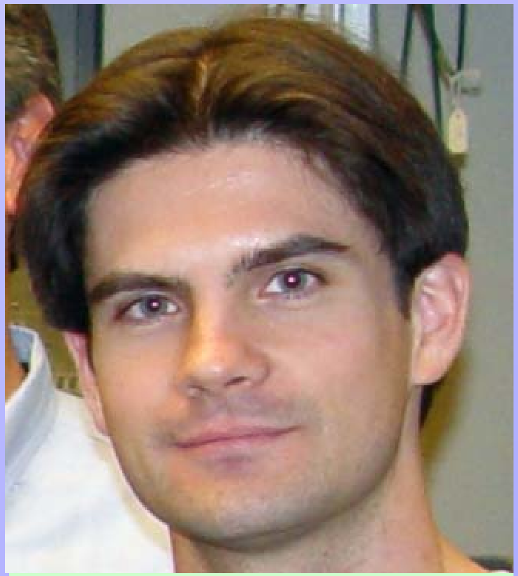
Year	$\lvert\dot{\alpha}/\alpha\rvert$ ($\times 10^{-15}$/yr)	Method	Ref.
2007	< 1.5	Hg^+ optical vs. Yb^+ optical†	T. Fortier *et al.*, Phys. Rev. Lett, **98**, 070801 (2007)
2004	< 2.2	Yb^+ optical vs. Hg^+ optical†	E. Peik *et al.*, Phys. Rev. Lett, **93**, 170801 (2004)
2004	< 3.8	H (1S-2S) vs. Hg^+ optical†	M. Fischer *et al.*, Phys. Rev. Lett, **92**, 230802 (2004)
2003	< 1.2	Hg^+ optical vs. Cs fountain††	S. Bize *et al.*, Phys. Rev. Lett, **90**, 150802 (2003)
2003	< 1.6	Rb fountain vs. Cs fountain††	H. Marion *et al.*, Phys. Rev. Lett, **90**, 150801 (2003)
1995	≤ 37	H-maser vs. Hg^+ hyperfine††	J. D. Prestage *et al.*, Phys. Rev. Lett, **74**, 3511 (1995)

†Combined with results from Hg^+ optical vs. Cs fountain comparison

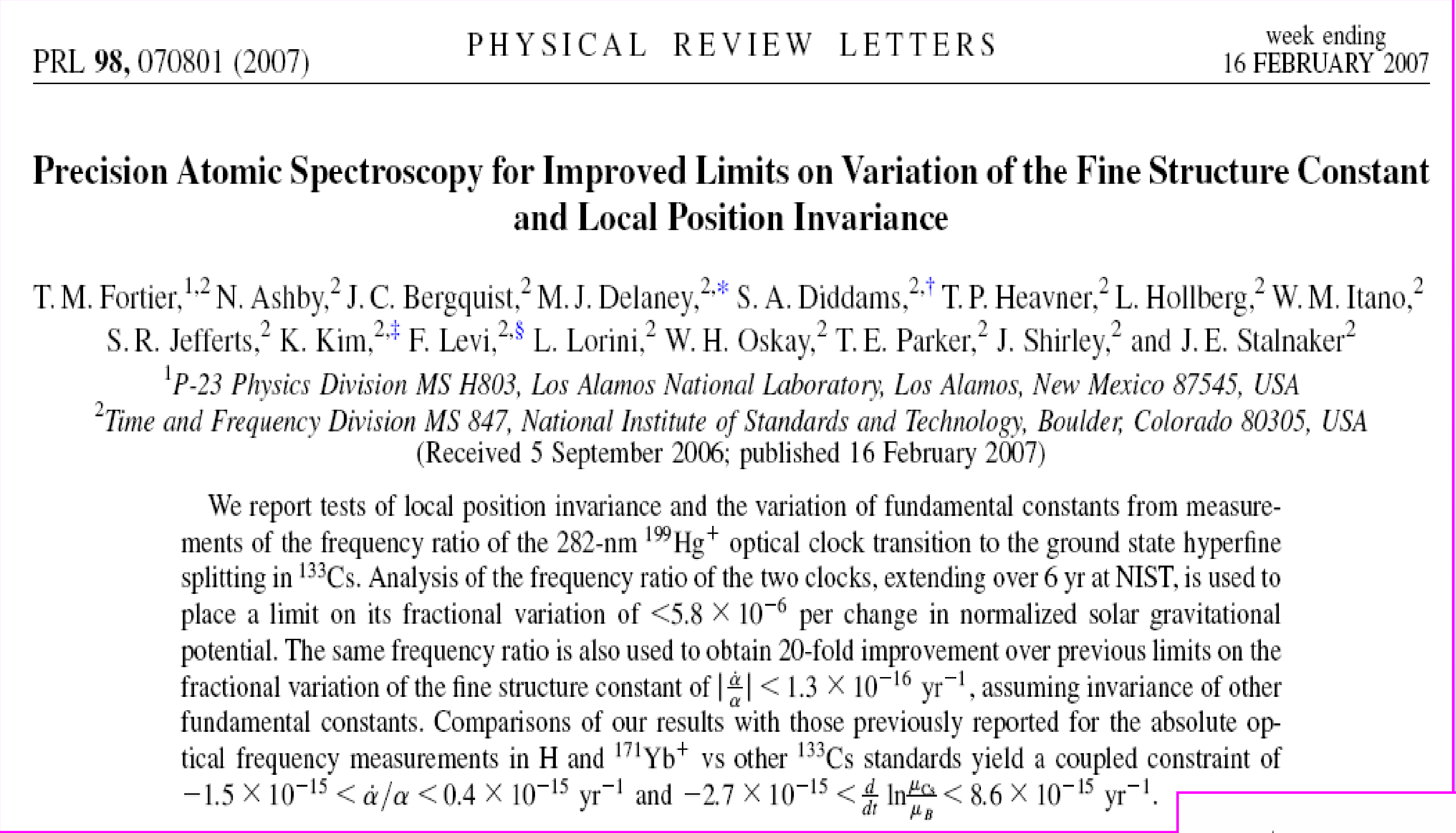
††Sensitive to other fundamental constants



Rapid progress with trapped single ions and femtosecond frequency combs !



Jason E. Stalnaker



PRL **98,** 070801 (2007) PHYSICAL REVIEW LETTERS week ending 16 FEBRUARY 2007

Precision Atomic Spectroscopy for Improved Limits on Variation of the Fine Structure Constant and Local Position Invariance

T. M. Fortier,[1,2] N. Ashby,[2] J. C. Bergquist,[2] M. J. Delaney,[2,*] S. A. Diddams,[2,†] T. P. Heavner,[2] L. Hollberg,[2] W. M. Itano,[2] S. R. Jefferts,[2] K. Kim,[2,‡] F. Levi,[2,§] L. Lorini,[2] W. H. Oskay,[2] T. E. Parker,[2] J. Shirley,[2] and J. E. Stalnaker[2]

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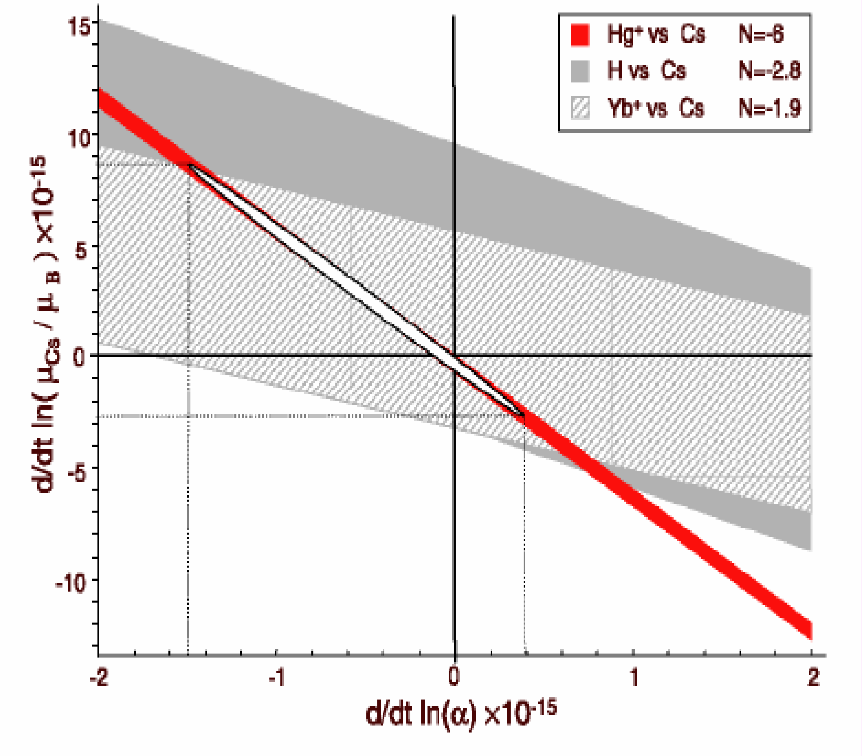
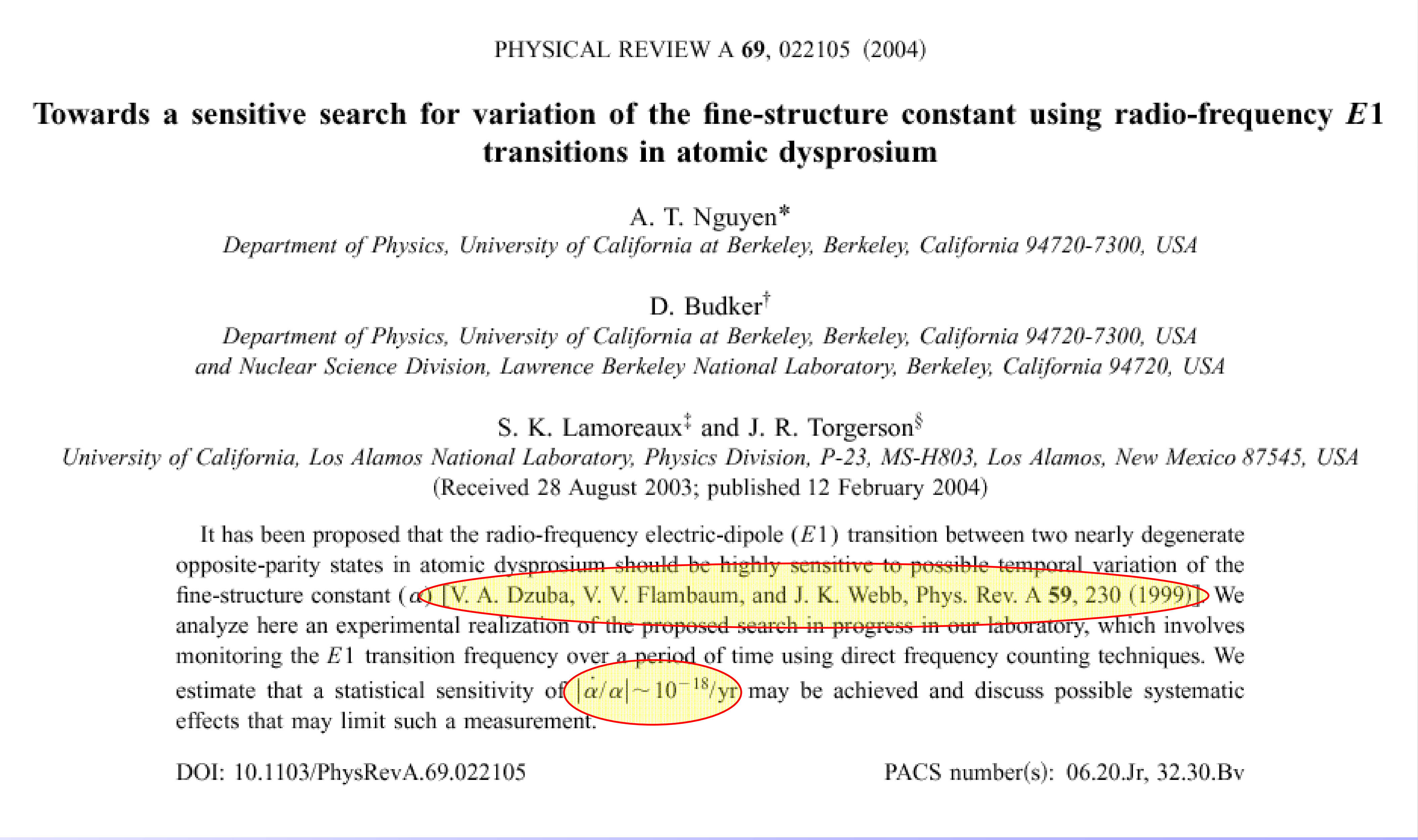
(Received 5 September 2006; published 16 February 2007)

We report tests of local position invariance and the variation of fundamental constants from measurements of the frequency ratio of the 282-nm $^{199}\mathrm{Hg}^+$ optical clock transition to the ground state hyperfine splitting in $^{133}\mathrm{Cs}$. Analysis of the frequency ratio of the two clocks, extending over 6 yr at NIST, is used to place a limit on its fractional variation of $<5.8 \times 10^{-6}$ per change in normalized solar gravitational potential. The same frequency ratio is also used to obtain 20-fold improvement over previous limits on the fractional variation of the fine structure constant of $|\frac{\dot{\alpha}}{\alpha}| < 1.3 \times 10^{-16}\ \mathrm{yr}^{-1}$, assuming invariance of other fundamental constants. Comparisons of our results with those previously reported for the absolute optical frequency measurements in H and $^{171}\mathrm{Yb}^+$ vs other $^{133}\mathrm{Cs}$ standards yield a coupled constraint of $-1.5 \times 10^{-15} < \dot{\alpha}/\alpha < 0.4 \times 10^{-15}\ \mathrm{yr}^{-1}$ and $-2.7 \times 10^{-15} < \frac{d}{dt} \ln\frac{\mu_{Cs}}{\mu_B} < 8.6 \times 10^{-15}\ \mathrm{yr}^{-1}$.





PHYSICAL REVIEW A **69**, 022105 (2004)

Towards a sensitive search for variation of the fine-structure constant using radio-frequency $E1$ transitions in atomic dysprosium

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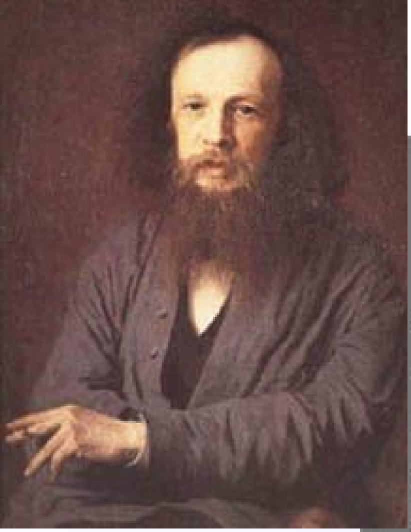
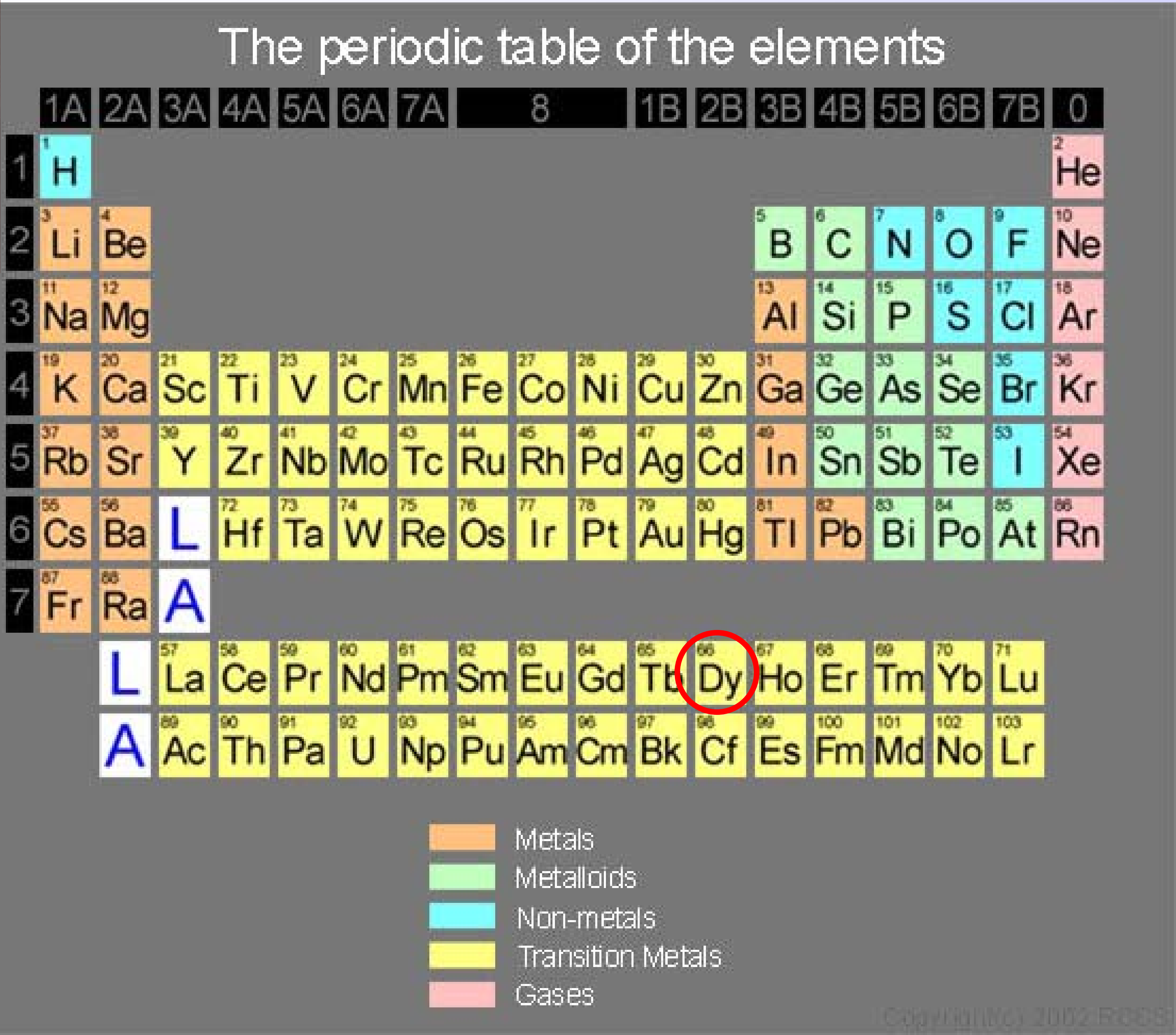
(Received 28 August 2003; published 12 February 2004)

It has been proposed that the radio-frequency electric-dipole ($E1$) transition between two nearly degenerate opposite-parity states in atomic dysprosium should be highly sensitive to possible temporal variation of the fine-structure constant (α) [V. A. Dzuba, V. V. Flambaum, and J. K. Webb, Phys. Rev. A **59**, 230 (1999)]. We analyze here an experimental realization of the proposed search in progress in our laboratory, which involves monitoring the $E1$ transition frequency over a period of time using direct frequency counting techniques. We estimate that a statistical sensitivity of $|\dot{\alpha}/\alpha| \sim 10^{-18}/\mathrm{yr}$ may be achieved and discuss possible systematic effects that may limit such a measurement.

DOI: 10.1103/PhysRevA.69.022105

PACS number(s): 06.20.Jr, 32.30.Bv





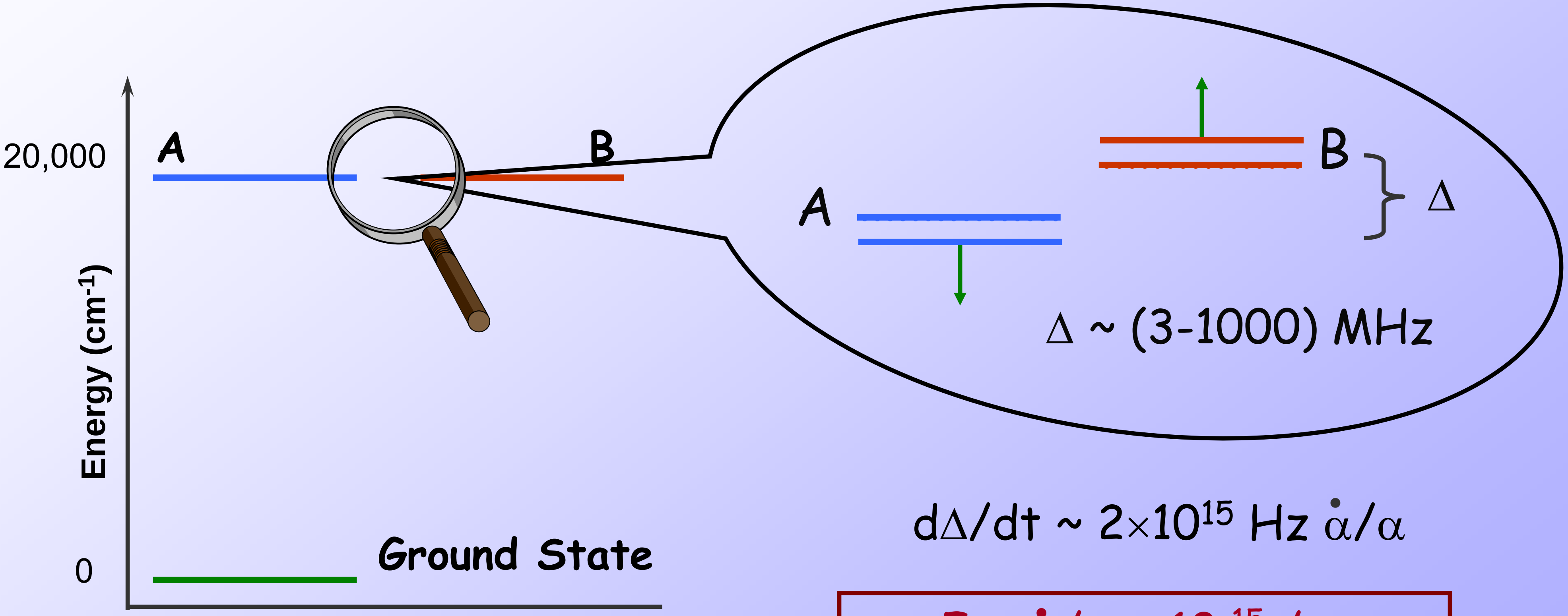
The periodic table of the elements

	1A	2A	3A	4A	5A	6A	7A	8			1B	2B	3B	4B	5B	6B	7B	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

🟧	Metals
🟩	Metalloids
🟦	Non-metals
🟨	Transition Metals
🟥	Gases

α-Variation in Atomic Dysprosium

- Two nearly degenerate states in dysprosium (Dy, Z=66) are highly sensitive to α-variation:



$\Delta \sim$ (3-1000) MHz

$d\Delta/dt \sim 2\times10^{15}$ Hz $\dot{\alpha}/\alpha$

For $\dot{\alpha}/\alpha \sim 10^{-15}$ /yr

$\Rightarrow$ $d\Delta/dt \sim$ 2 Hz/yr !!

Dzuba, Flambaum, Kozlov, et al

A and B States

- Opposite parity
- $\Delta E \sim$ 3-1000 MHz

⇒ E1 transition connecting the states can be driven with rf electric field

⇒ small enough to allow accurate direct counting of transition frequency

⇒ relaxed requirements on reference clock ($\Delta\upsilon / \upsilon$)

Statistical Sensitivity

- Transition linewidth ~ 20 kHz

- Counting rate ~ 10^9 s^{-1}

$\Rightarrow$ Sensitivity: $\delta\nu \sim \frac{0.6}{T^{1/2}}$ Hz $s^{1/2}$

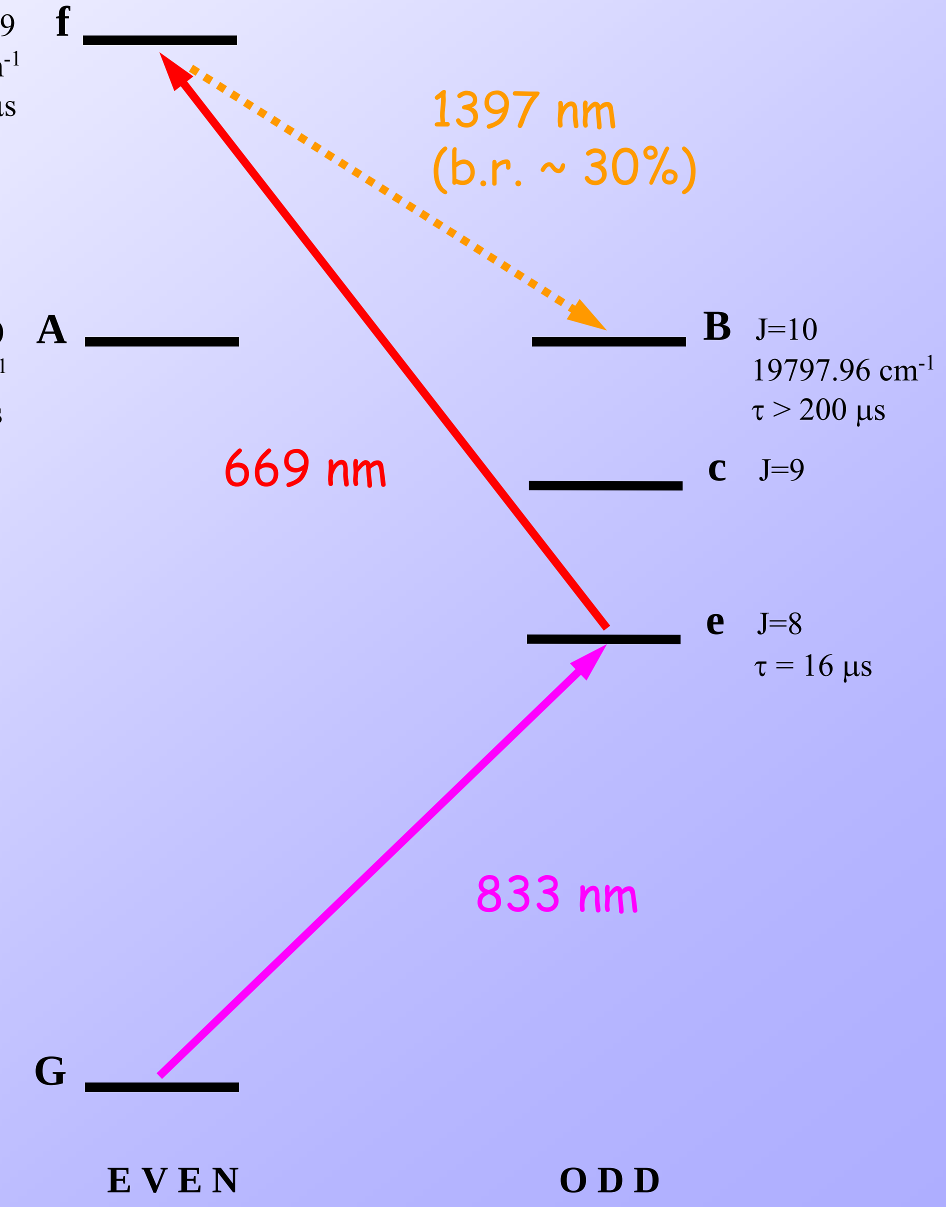
After an hour of data taking, $\delta\nu$ ~ 10 mHz which allows

for a sensitivity of

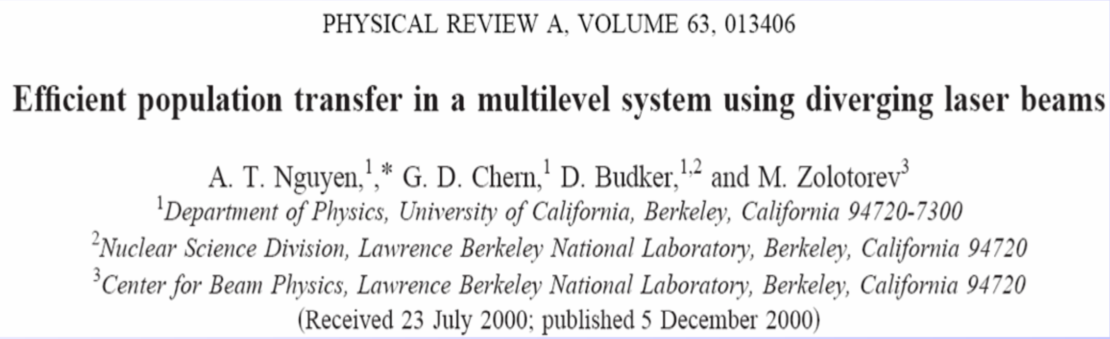
$$\boxed{|\dot{\alpha}/\alpha| \sim 5 \times 10^{-18}\ /\mathrm{yr}\ !!}$$

Population

- Three-step scheme:



1st & 2nd - cw laser excitation



PHYSICAL REVIEW A, VOLUME 63, 013406

Efficient population transfer in a multilevel system using diverging laser beams

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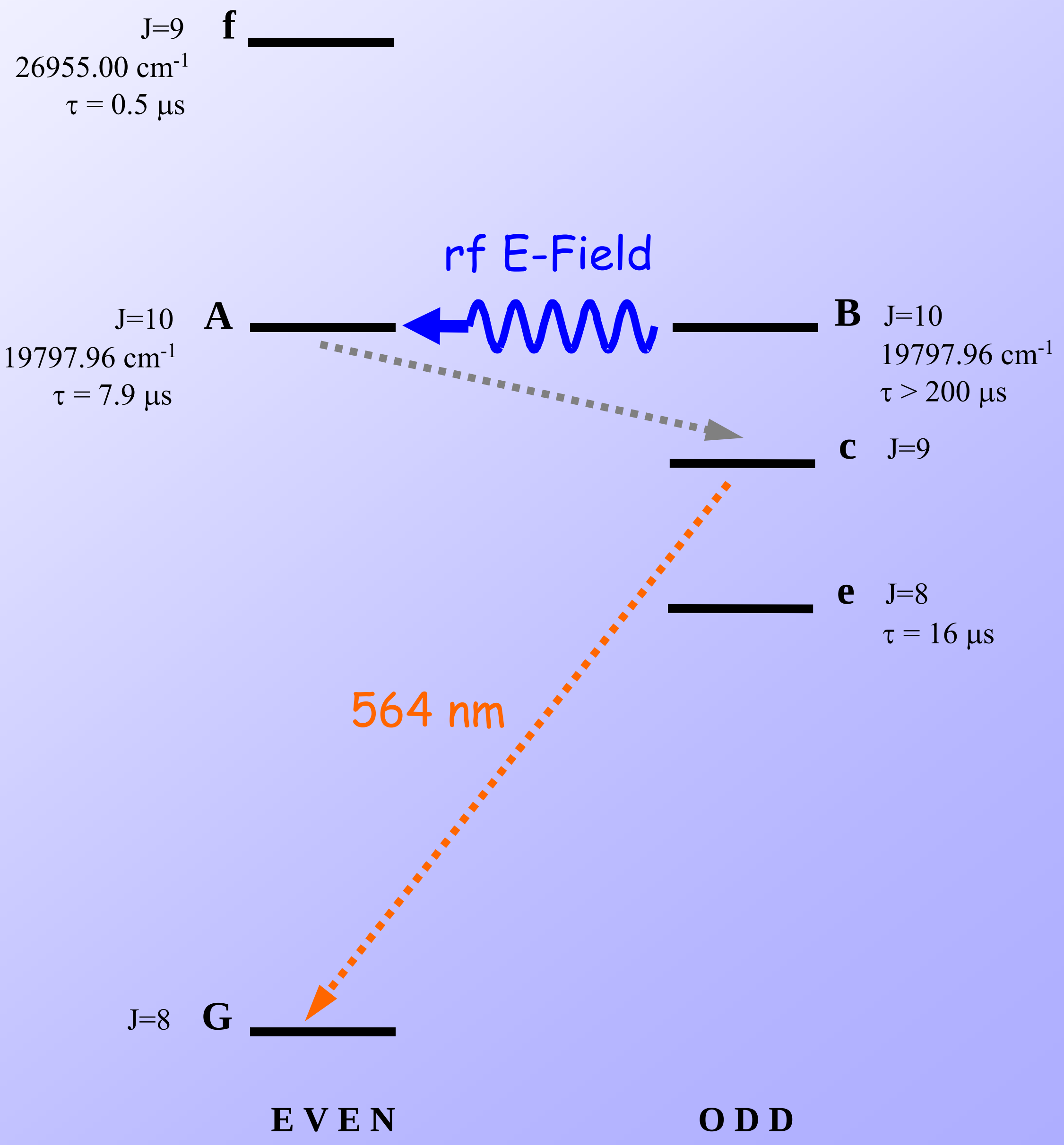
[3]*Center for Beam Physics, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
(Received 23 July 2000; published 5 December 2000)

3rd - spontaneous emission

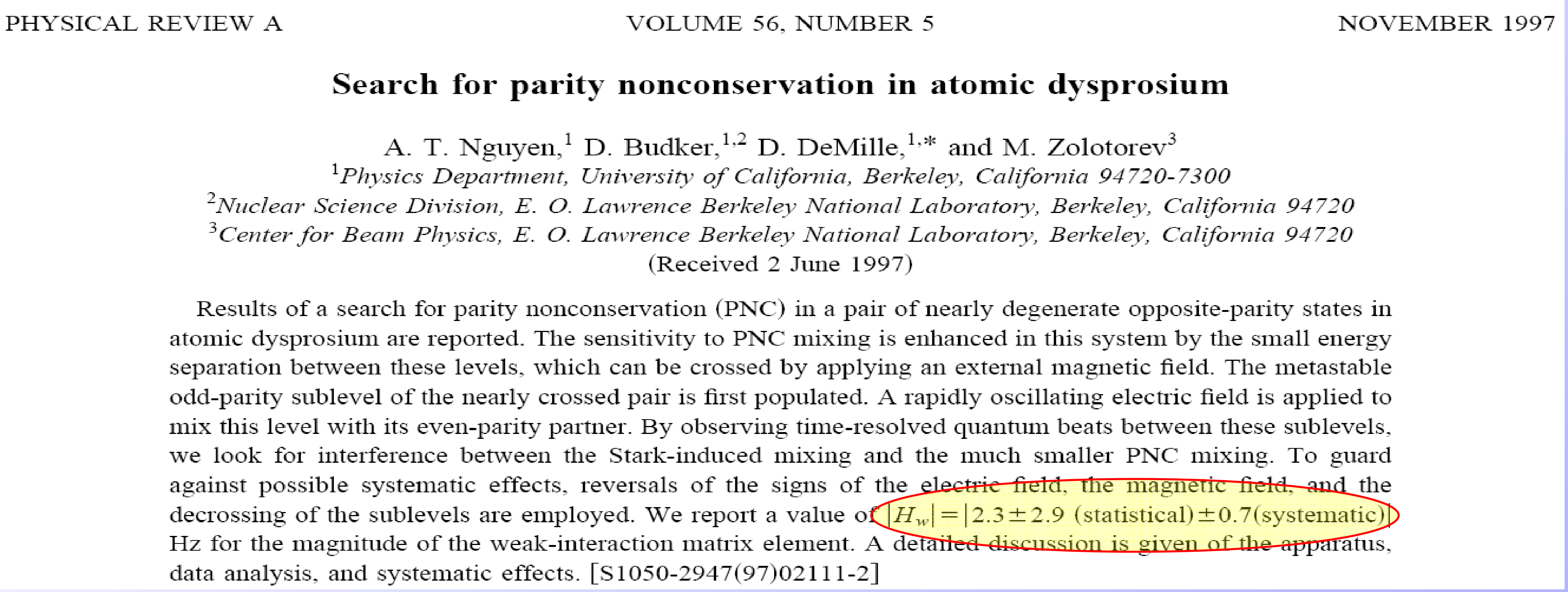
rf Transition and Detection

- rf E-field excites atoms to state A

- State A decays and 564-nm light is detected



The experiment evolved from a **parity nonconservation** search 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]
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[2] *Nuclear Science Division, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720*
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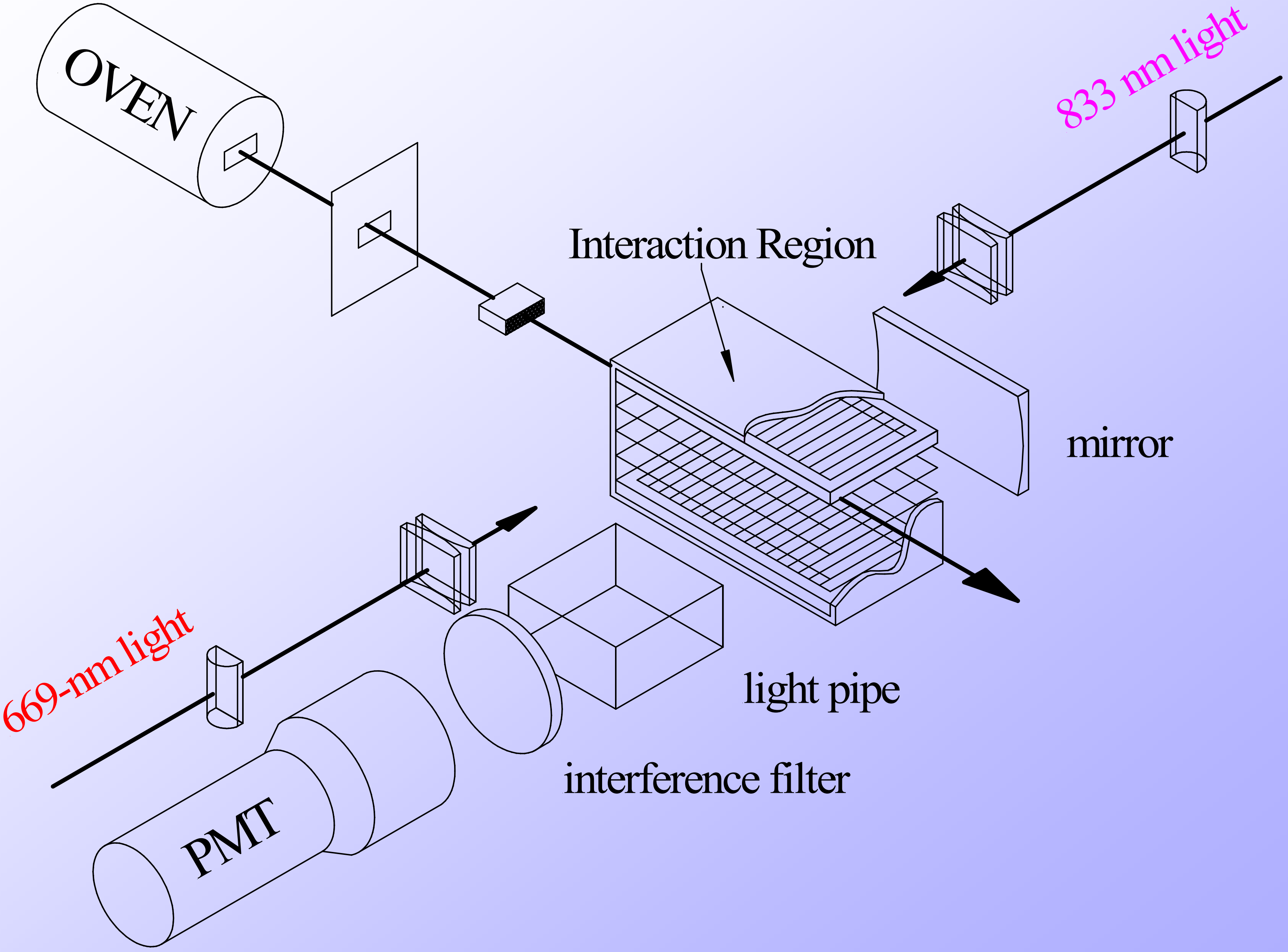
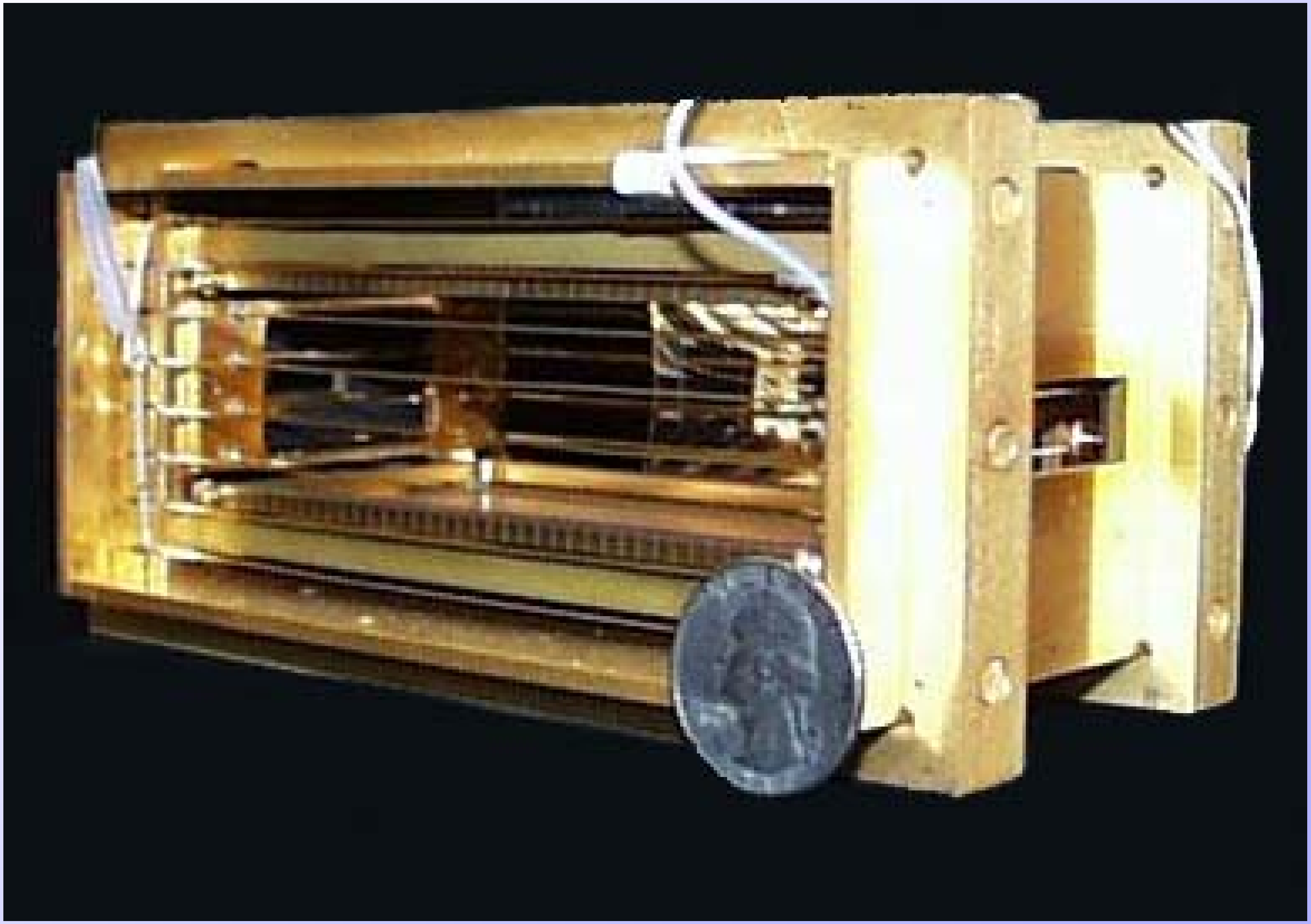
(Received 2 June 1997)

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

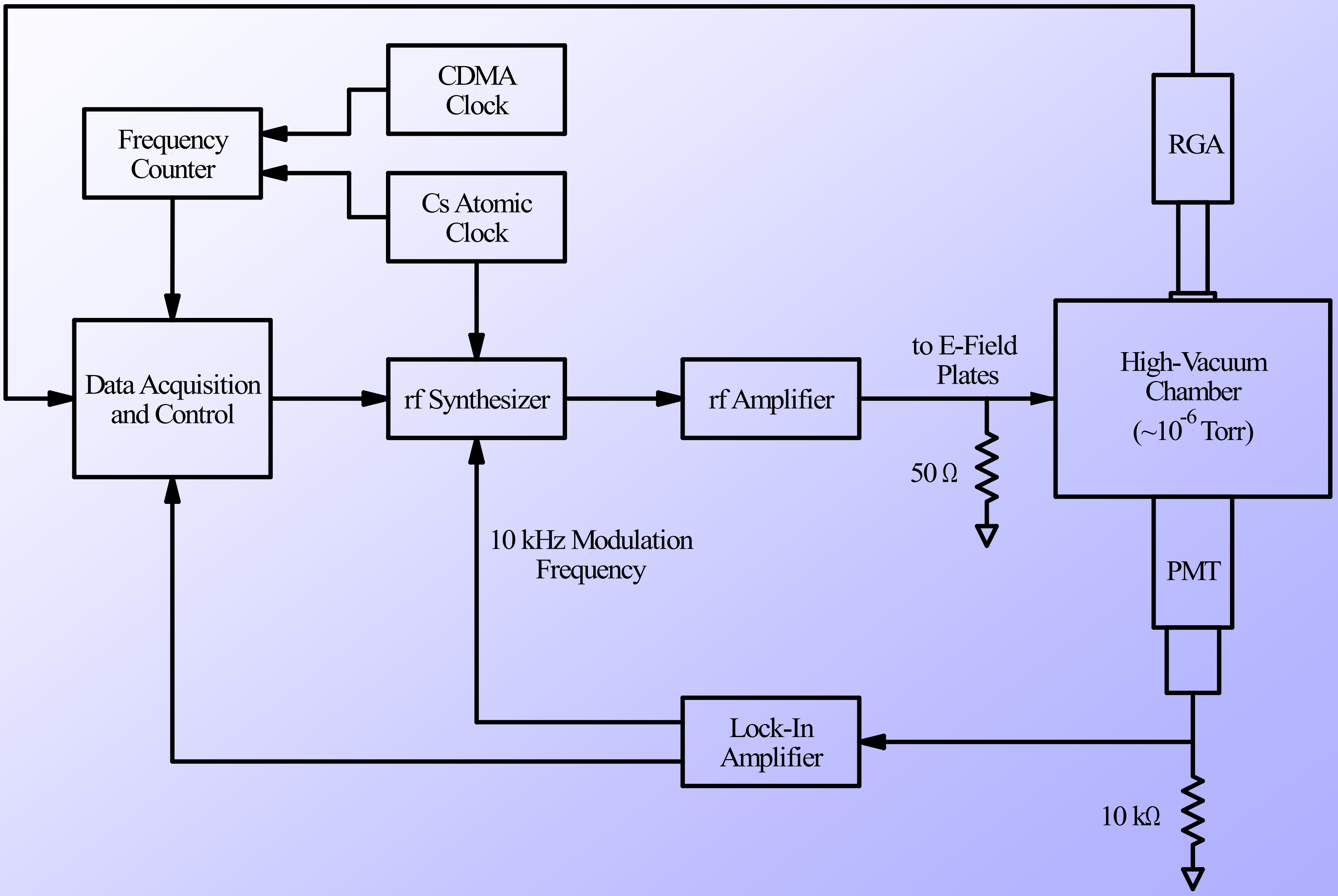
Apparatus


OVEN
833 nm light
Interaction Region
mirror
669-nm light
light pipe
interference filter
PMT

Interaction Region



Experimental Setup



CDMA Clock

Frequency Counter

Cs Atomic Clock

RGA

Data Acquisition and Control

rf Synthesizer

rf Amplifier

to E-Field Plates

High-Vacuum Chamber ($\sim 10^{-6}$ Torr)

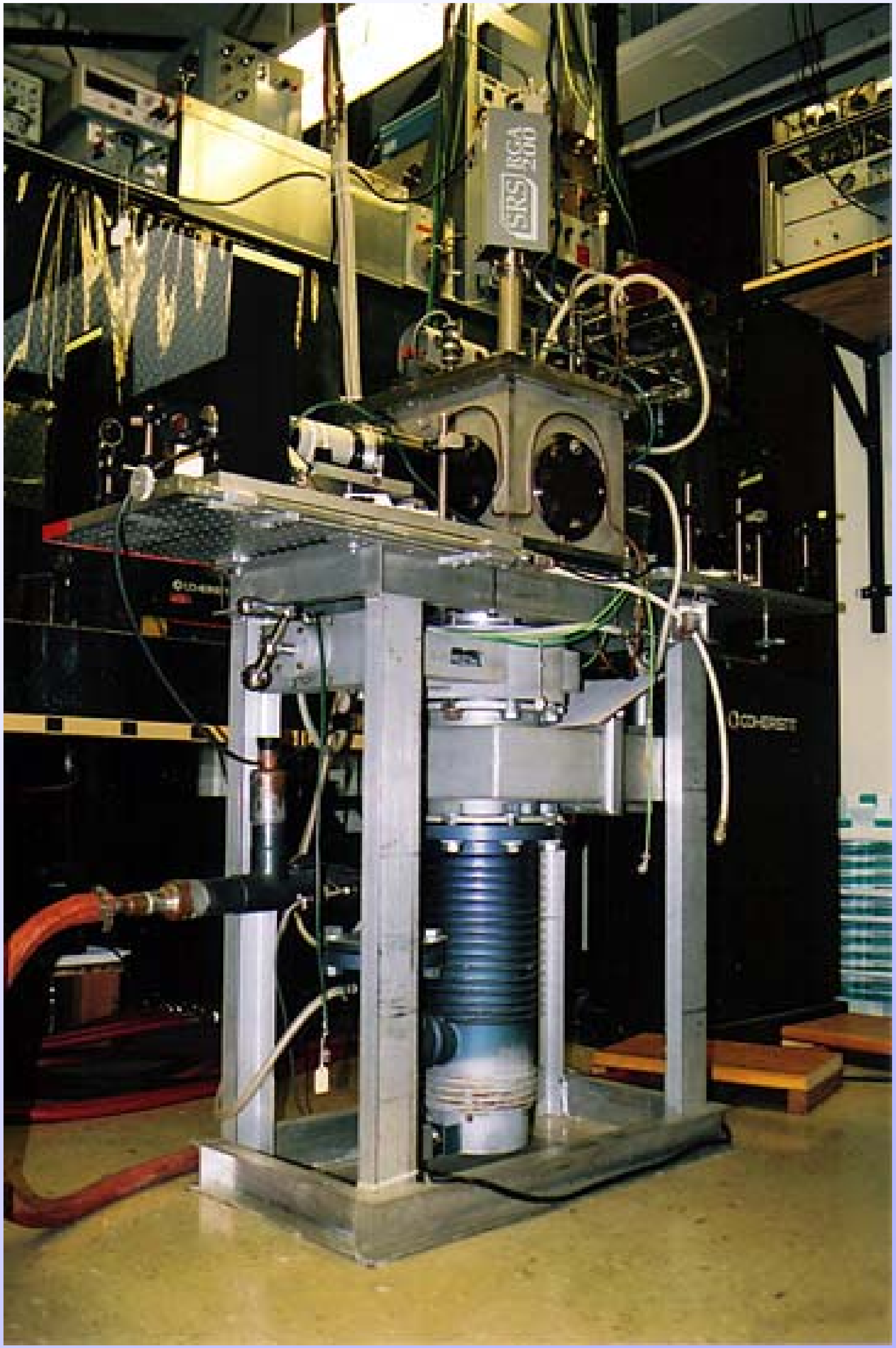
50 Ω

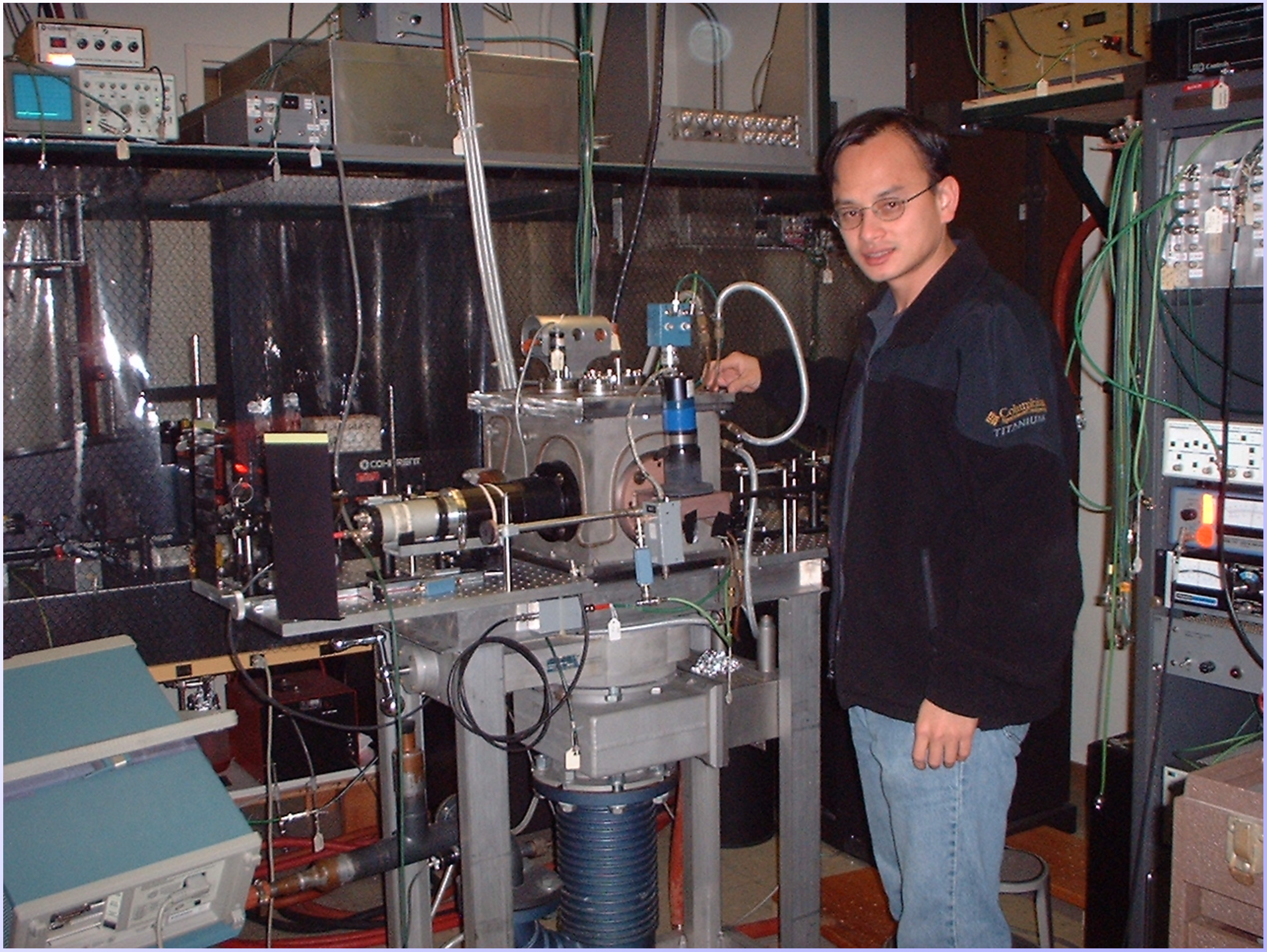
10 kHz Modulation Frequency

PMT

Lock-In Amplifier

10 kΩ


SRS RGA 200
COHERENT
COHERENT

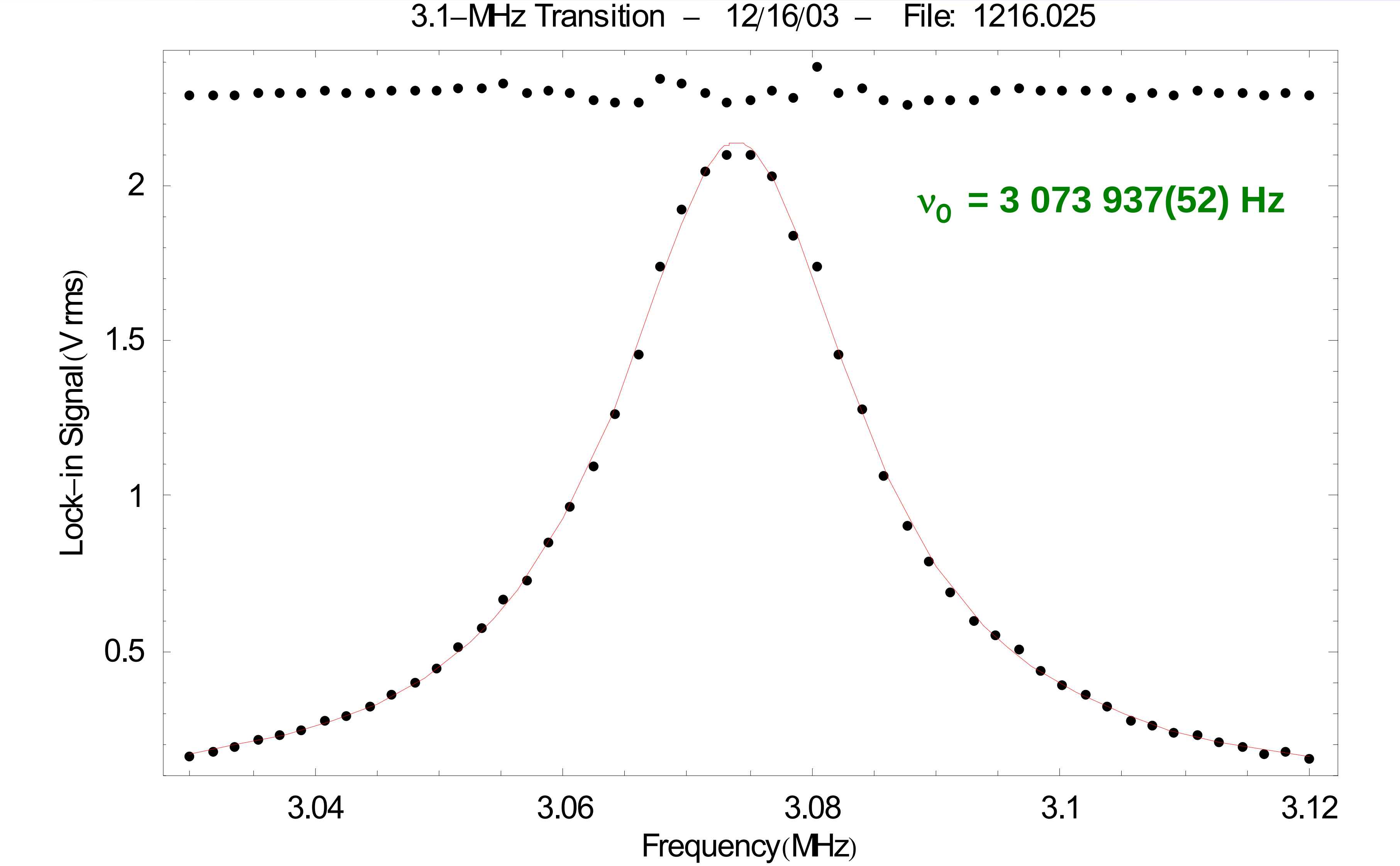


Dr. A.-T. Nguyen, UCB⟶LANL

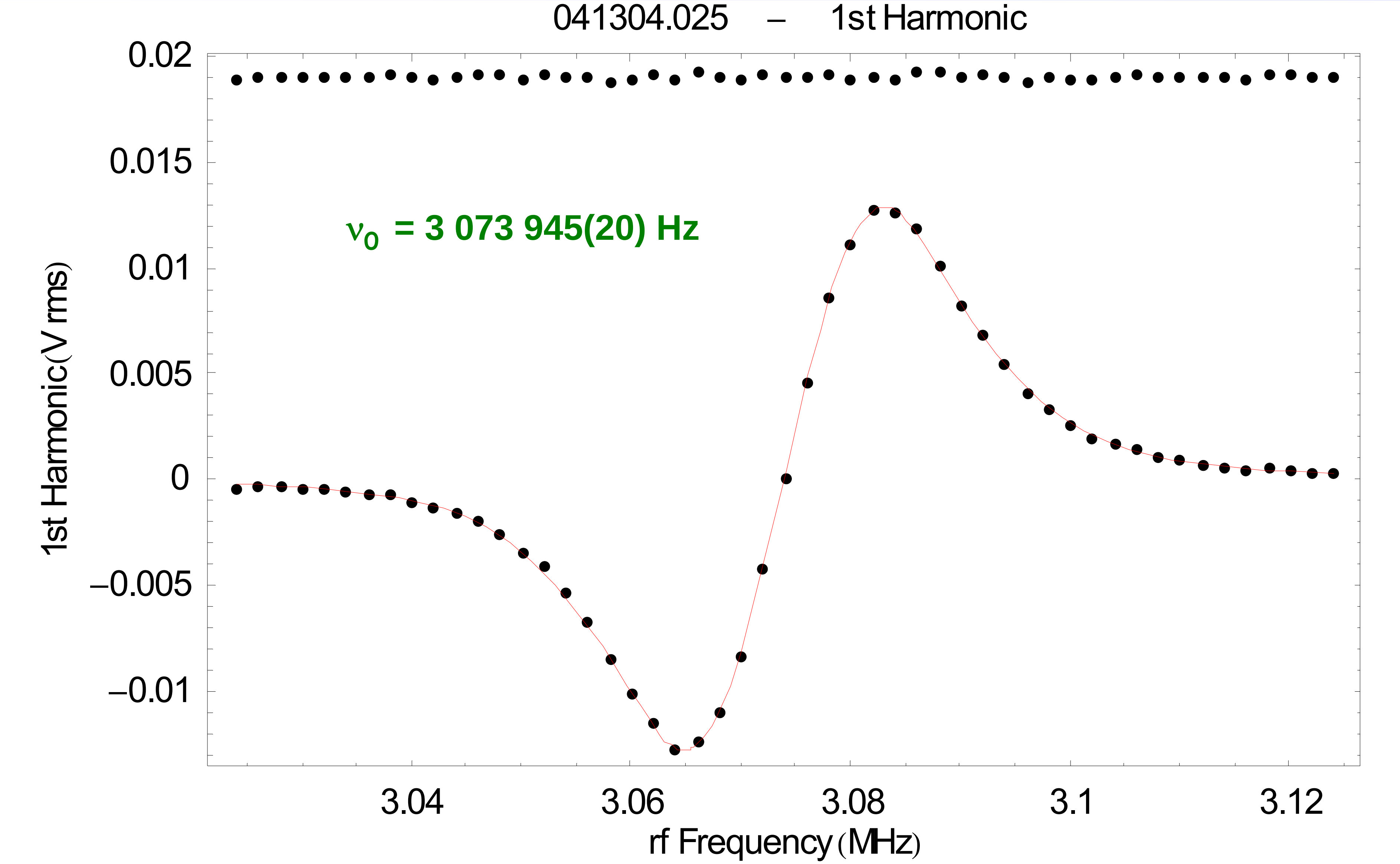
Arman Cingöz

First Data

Amplitude Modulation:

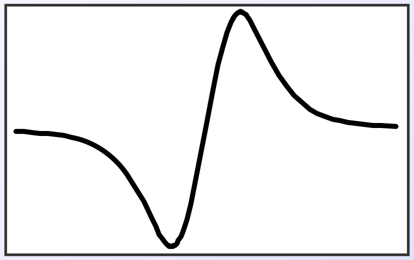


rf Frequency Modulation

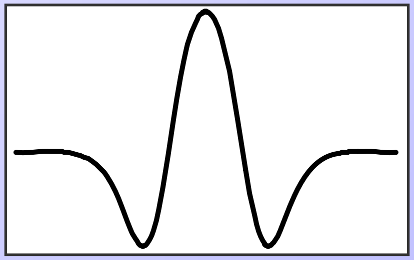


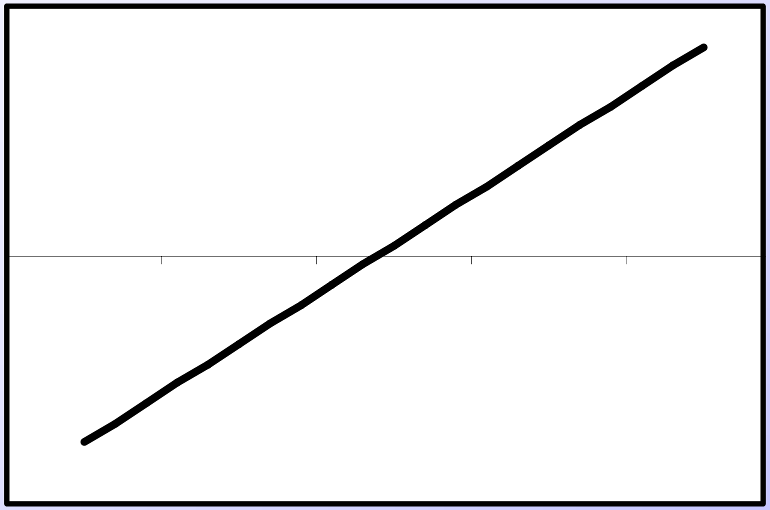
Fixed Frequency Technique

Measure the


1st Harmonic

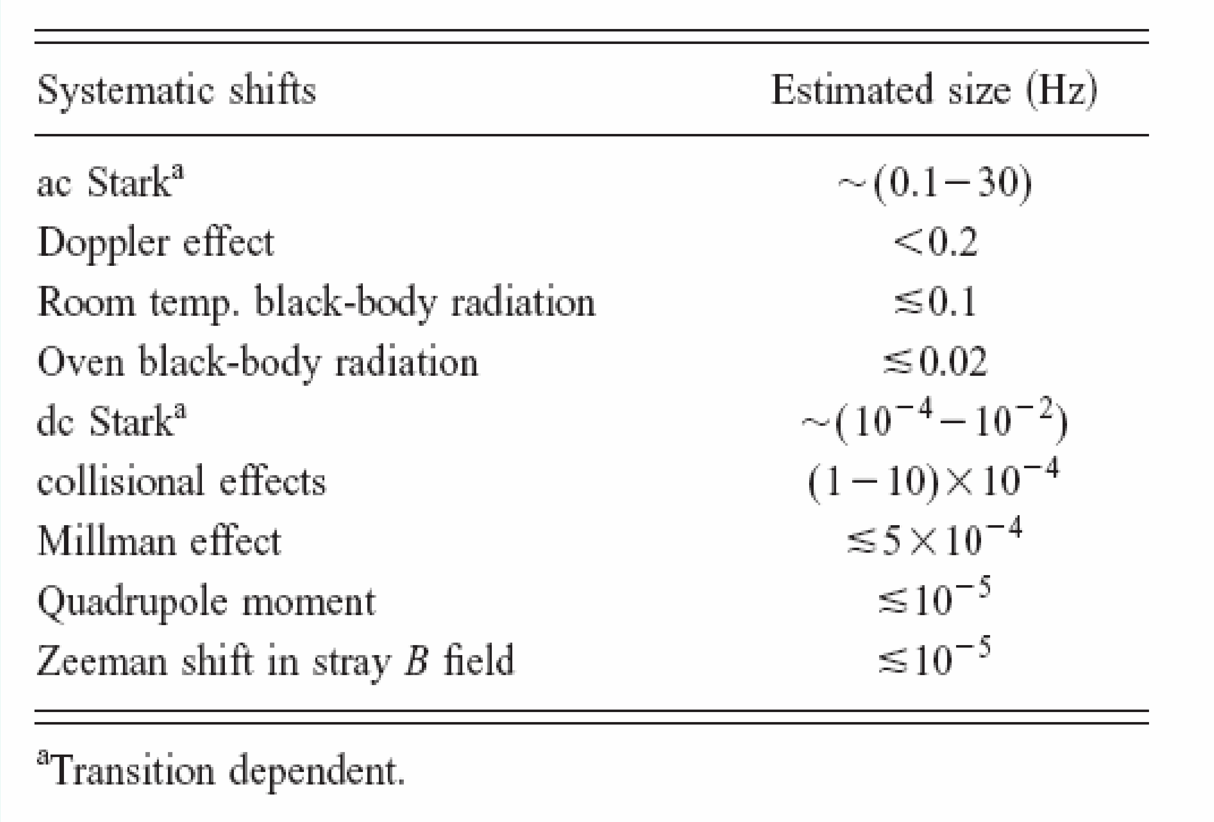
normalized by the


2nd Harmonic



Ratio $(1^{st}/2^{nd}) = const.(\nu - \nu_0)$

Systematic Effects



Systematic shifts	Estimated size (Hz)
ac Stark[a]	$\sim(0.1-30)$
Doppler effect	<0.2
Room temp. black-body radiation	$\lesssim 0.1$
Oven black-body radiation	$\lesssim 0.02$
dc Stark[a]	$\sim(10^{-4}-10^{-2})$
collisional effects	$(1-10)\times 10^{-4}$
Millman effect	$\lesssim 5\times 10^{-4}$
Quadrupole moment	$\lesssim 10^{-5}$
Zeeman shift in stray *B* field	$\lesssim 10^{-5}$

[a] Transition dependent.

A.- T. Nguyen *et al.* PRA Phys. Rev. A **69**, 022105 (2004)

- However, it is not the size but the stability of these effects that is important

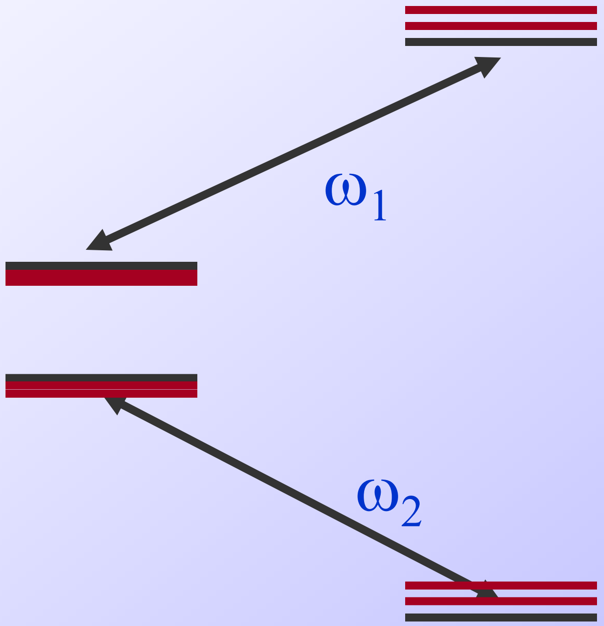
⇒ preliminary analysis shows that systematic effects can be controlled to

a level corresponding to $|\alpha/\alpha| \sim 5 \times 10^{-18}$ /yr

Powerful Check for Systematics

Since Dy has many isotopes (some with hfs), more than one rf transition frequency can be measured

For example, two transition frequencies can be simultaneously measured:



$\omega_1 + \omega_2 \Rightarrow$ insensitive to α variation

$\omega_1 - \omega_2 \Rightarrow$ α variation is twice as large

Collisional Effects

- Collisions with residual background atoms perturbs a radiating (absorbing) Dy atom

$\Rightarrow$ lineshape broadening and shift

- Collisional effects in high-vacuum (10^{-6} Torr) have rarely been measured

- Simple estimate:

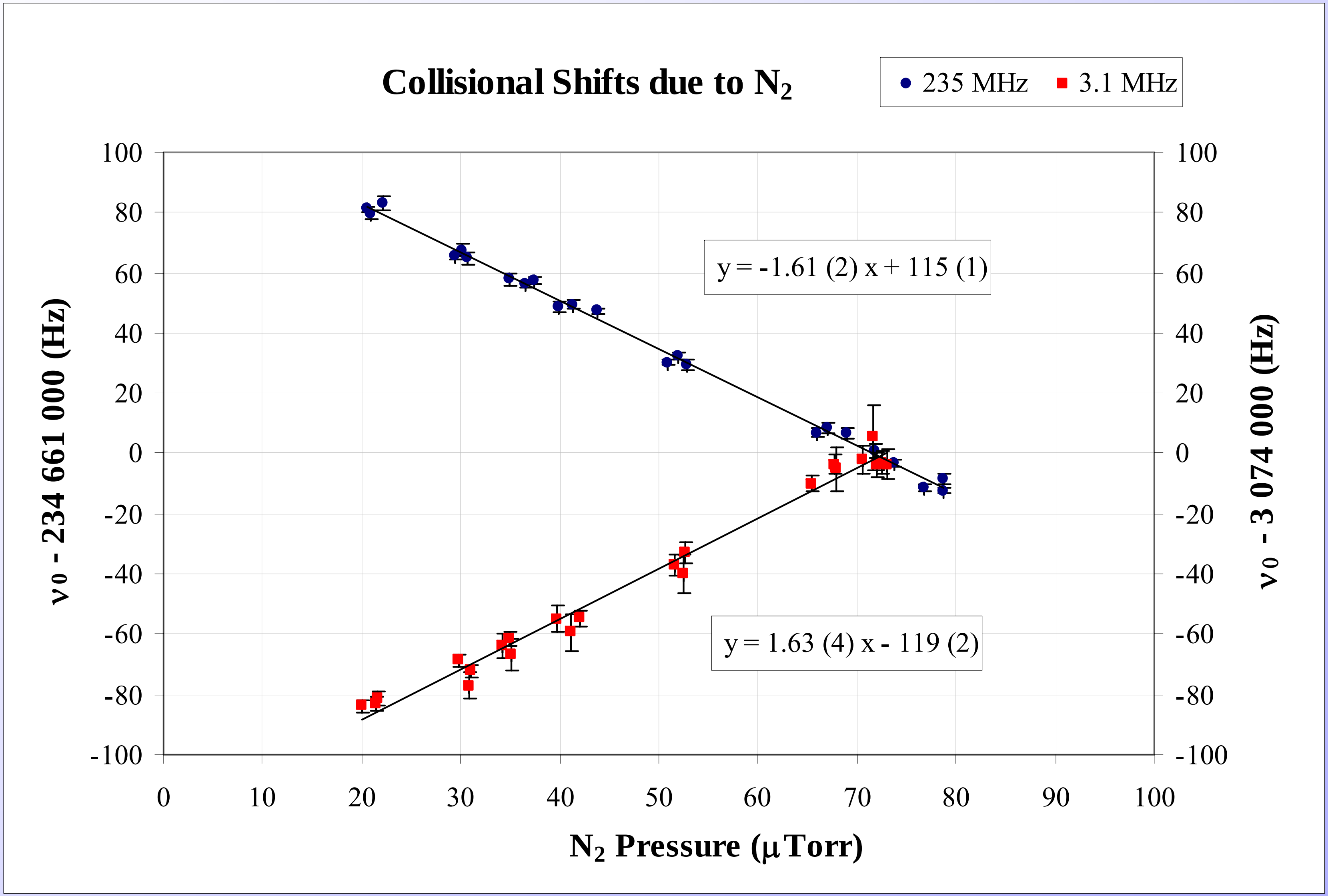
$\sigma \sim 10^{-14}$ cm^2

$n \simeq 3\times10^{10}$ molecules/cm^3 at 1μTorr

$v \simeq 4\times10^{4}$ cm/s

$$\Rightarrow \delta\nu \sim (2\pi)^{-1}\, n\, \sigma\, v = 2\ \text{Hz}$$

Collisional Data

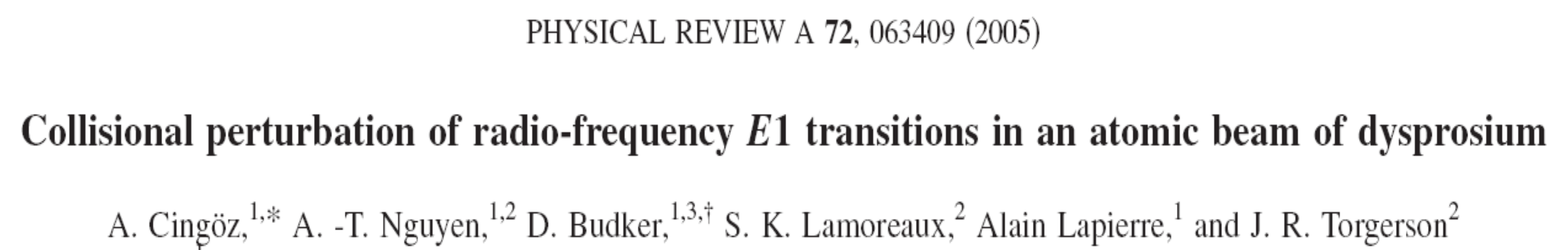


Collisional Shifts

Gas	Shift Coefficients (Hz/μTorr)	
	3.1-MHz	235-MHz
H_2	-0.09 (8)	-0.02 (4)
He	-1.27 (6)	+1.25 (3)
Ne	-0.02 (6)	-0.01 (3)
N_2	+1.72 (7)	-1.71 (5)
O_2	< 5	-1.97 (30)
Ar	+2.14 (11)	-2.21 (7)
Kr	+2.78 (9)	-2.78 (7)
Xe	+2.75 (10)	-2.74 (7)

- Conclusion:

⇒ collisional effects are consistent with those found in 1-Torr measurements

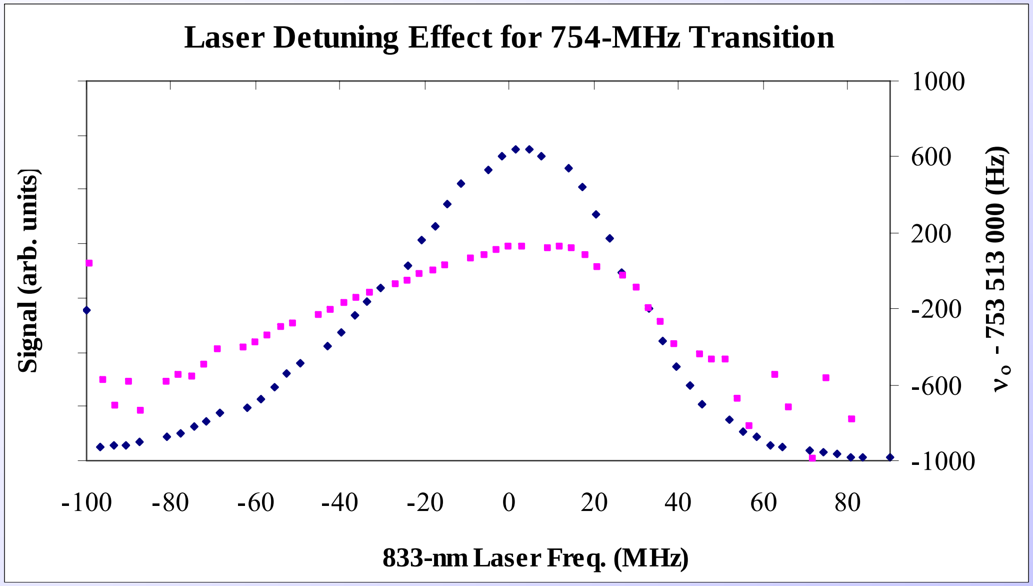


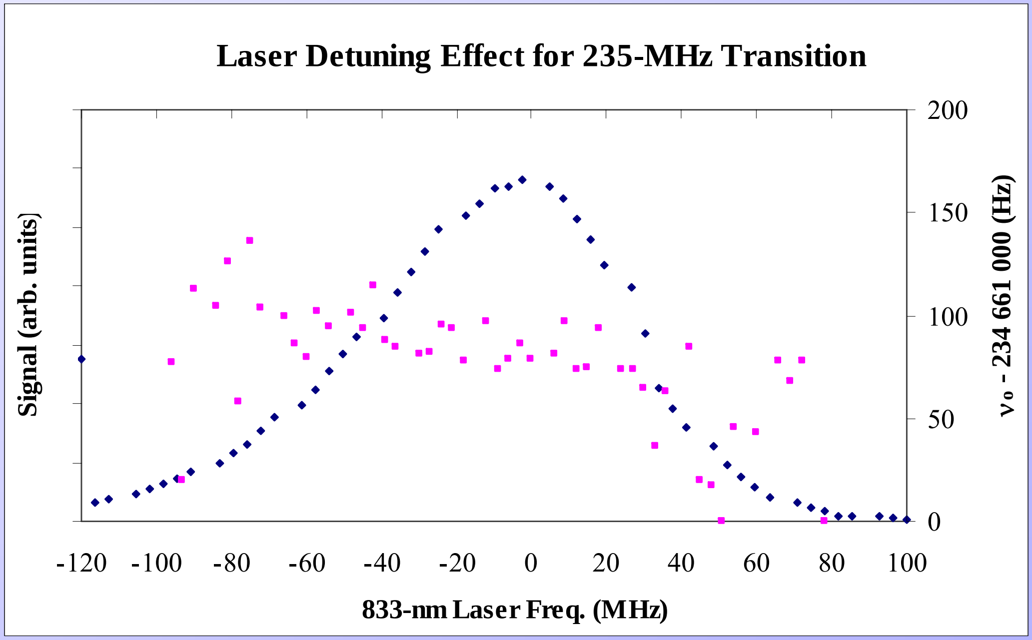
PHYSICAL REVIEW A **72**, 063409 (2005)

Collisional perturbation of radio-frequency *E*1 transitions in an atomic beam of dysprosium

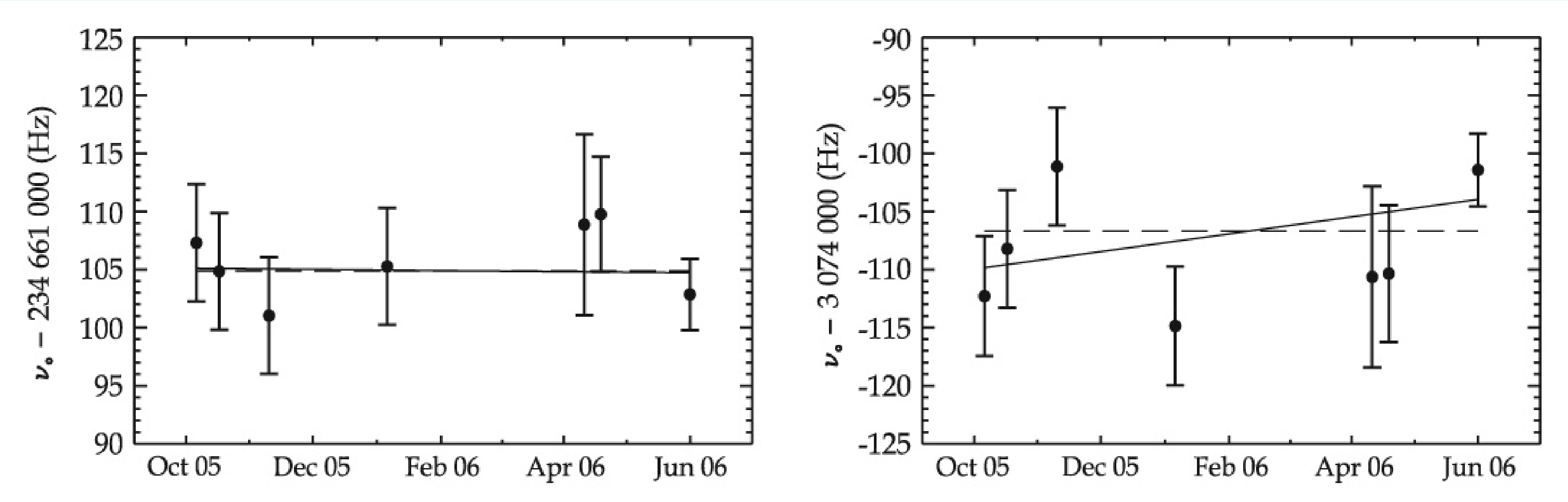
A. Cingöz,[1,*] A. -T. Nguyen,[1,2] D. Budker,[1,3,†] S. K. Lamoreaux,[2] Alain Lapierre,[1] and J. R. Torgerson[2]

Laser Detuning Effect





Results



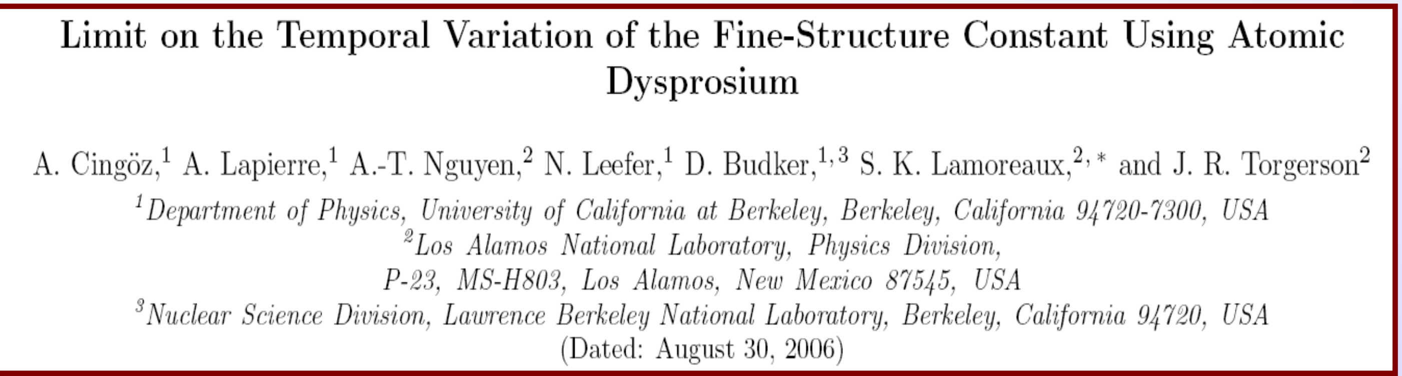
-0.6 ± 6.5 Hz/yr

9.0 ± 6.7 Hz/yr

$\dot{\alpha}/\alpha = (-0.3 \pm 3.6) \times 10^{-15}\ \mathrm{yr}^{-1}$

$(-5.0 \pm 3.7) \times 10^{-15}\ \mathrm{yr}^{-1}$

Result: Phys. Rev. Lett. **98**, 040801 (2007)



Limit on the Temporal Variation of the Fine-Structure Constant Using Atomic Dysprosium

A. Cingöz,[1] A. Lapierre,[1] A.-T. Nguyen,[2] N. Leefer,[1] D. Budker,[1,3] S. K. Lamoreaux,[2,*] and J. R. Torgerson[2]
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[2] *Los Alamos National Laboratory, Physics Division,*
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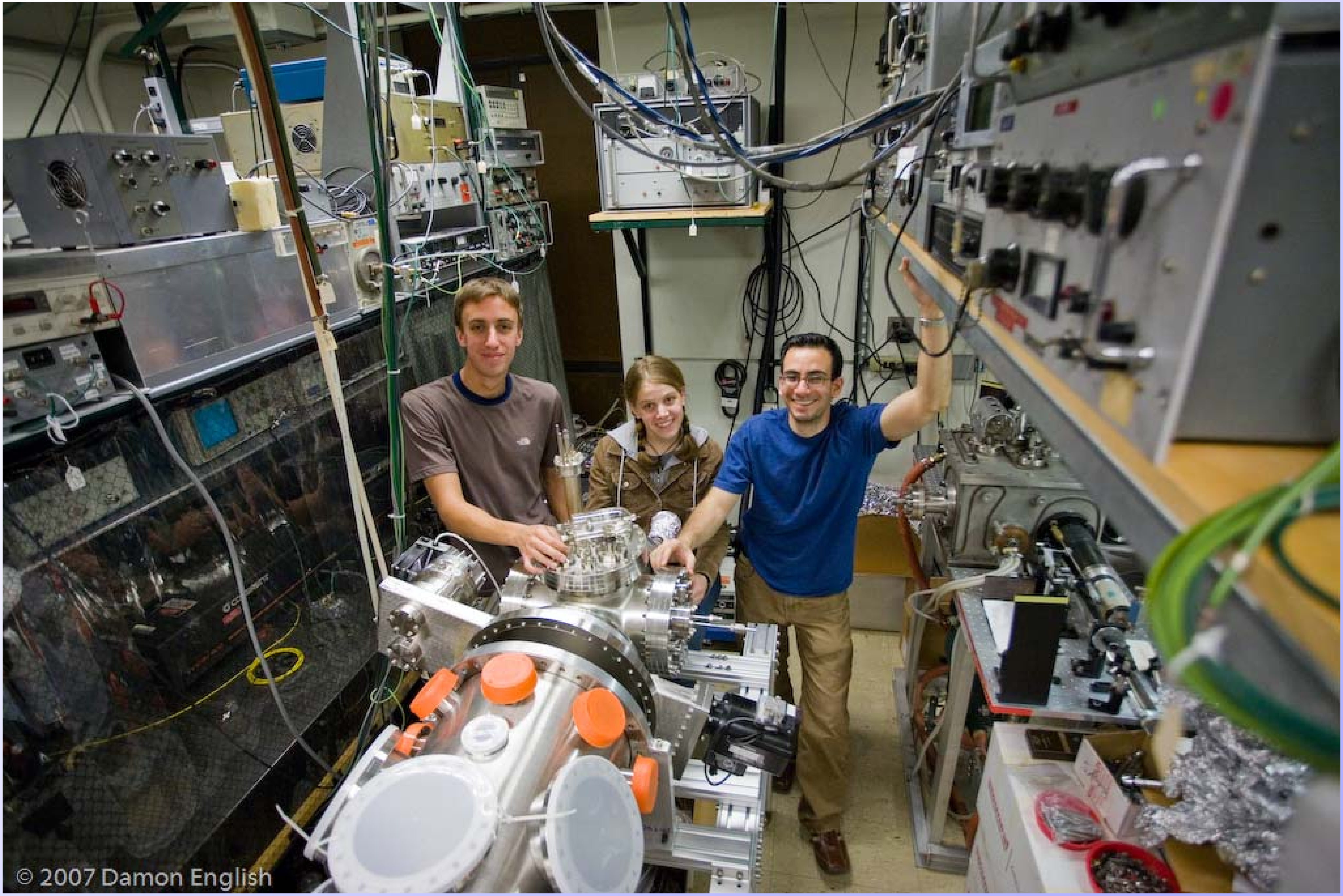
(Dated: August 30, 2006)

$$\dot{\alpha}/\alpha = (-2.9 \pm 2.6_{\text{mostly syst}}) \text{ x } 10^{-15}\ \text{yr}^{-1}$$

Independent of other fundamental constants

The Future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