Constancy of the Constants of Nature: Update

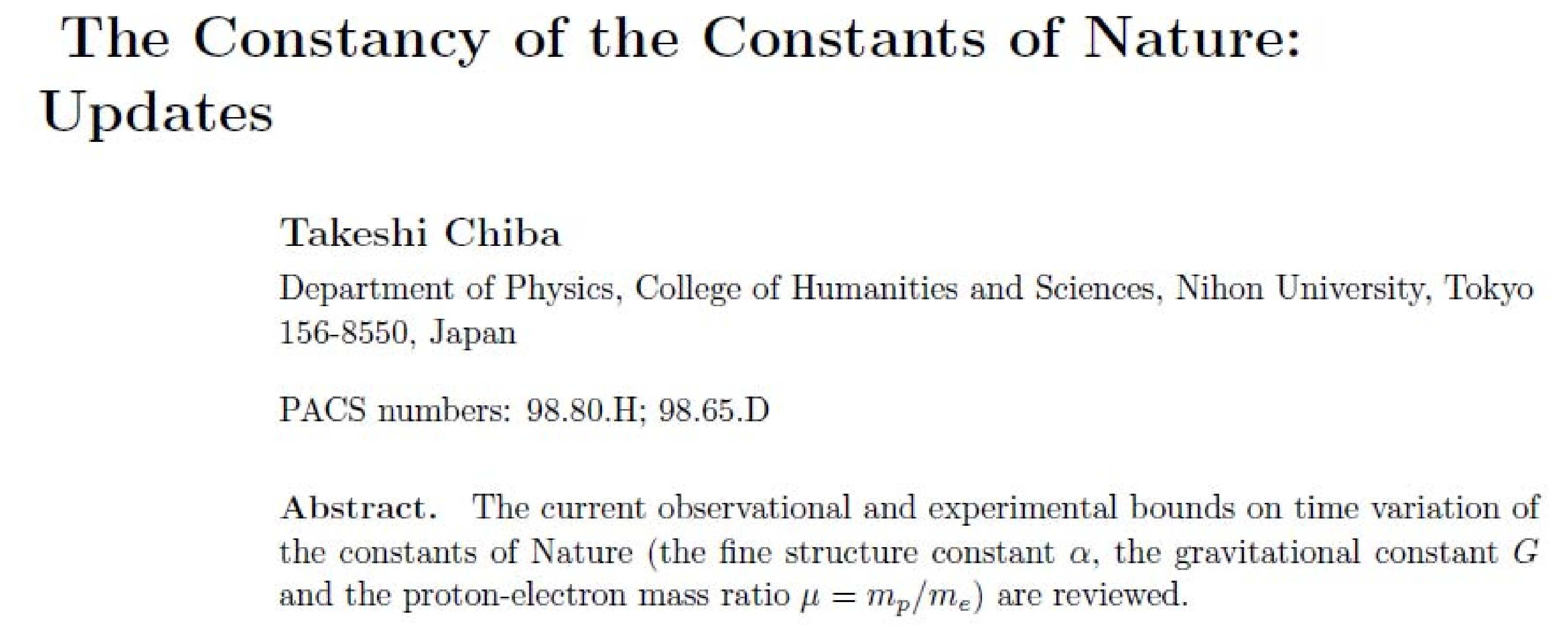
Nihon University

Takeshi Chiba

- motivation
  - Large Number Hypothesis
  - Mach's Principle
  - Unification
  - Null Tests
- G
- α
- conclusion

Reference

- TC, gr-qc/0110118, in the proceedings of Frontier of Cosmology and Gravitation (in the honor of Prof. Tomita's 60 birthday)



The Constancy of the Constants of Nature: Updates

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PACS numbers: 98.80.H; 98.65.D

Abstract. The current observational and experimental bounds on time variation of the constants of Nature (the fine structure constant α, the gravitational constant G and the proton-electron mass ratio $\mu = m_p/m_e$) are reviewed.

Motivation

- Dirac's Large Number Hypothesis:

$N_1 = e^2/Gm_pm_e$ (=elemag. force/grav. force) $\sim 10^{39}$

$N_2 = H_0^{-1}/e^2m_e^{-1}$ (=Hubble radius/classical electron radius) $\sim 10^{40}$

"Any two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity." (Dirac, 1938)

$N_1 = N_2$!

- If $N_1=N_2$,

then $G \propto 1/t$ (Dirac)

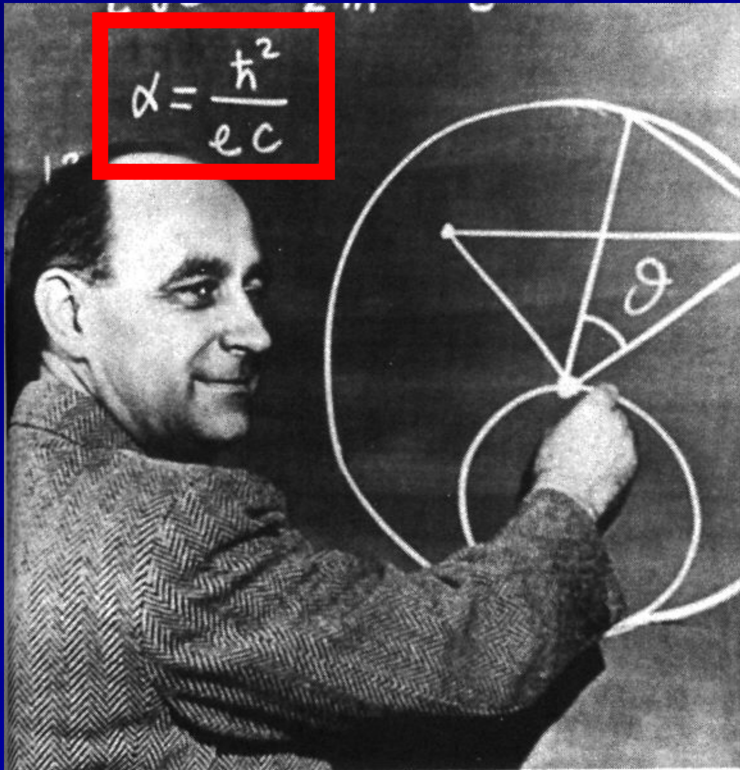
or $\alpha \propto t^{1/2}$ (Gamov)

cf.

$\alpha = e^2/\hbar c$ (cgs Gauss)

$\alpha = e^2/(4\pi\epsilon_0 \hbar c)$ (S.I.)

$\simeq 1/137$



Mach’s Principle:

Local Physics ← global mass
(inertia) distribution
in the Universe

The Universe determines the physics on the earth

Brans-Dicke theory(1959):

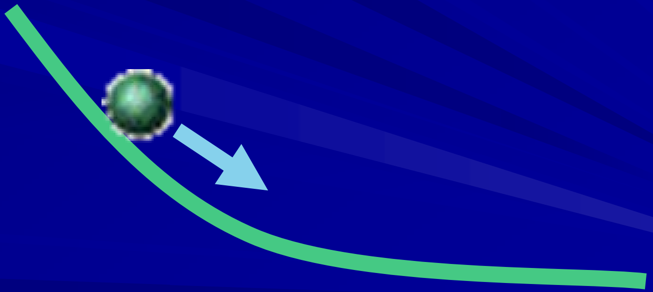
$$\Box\Phi \sim T, \quad G=1/\Phi$$

Modern Motivation

- Unification :

String Theory(Higher Dimensional Theory)

(VEVs of) Dilaton and Moduli(extra dimensions) determine gauge coupling constants



The Universe is expanding

→ Physical constants can be space-time varying

softening of physics?

	spacetime	laws of physics
Newton	rigid	rigid
Einstein	soft	rigid
String	soft	soft

Importance of null tests

- Inverse square law
- Equivalence Principle

To what extent do they hold? (null tests)

It is of fundamental importance to check the constancy of the fundamental constants to the ultimate precision.

Let’s shake the pillars to make sure they are rigid!

Use of Cosmology

$$\frac{\Delta \alpha}{\alpha \Delta t}$$

Laboratory : $\Delta\alpha$ small, but $\Delta t \sim$ yr

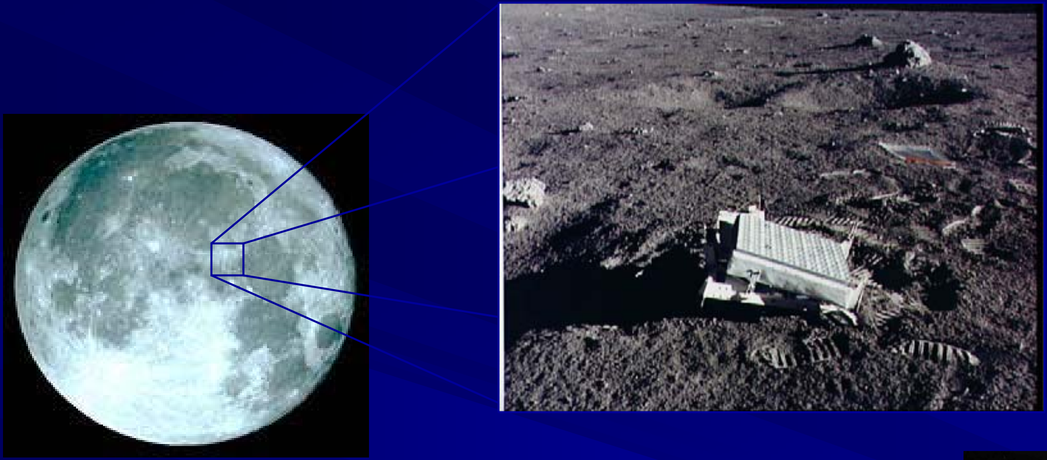
Cosmology: $\Delta\alpha \sim 1$, but $\Delta t \sim H_0^{-1} \sim 10^{10}$yr

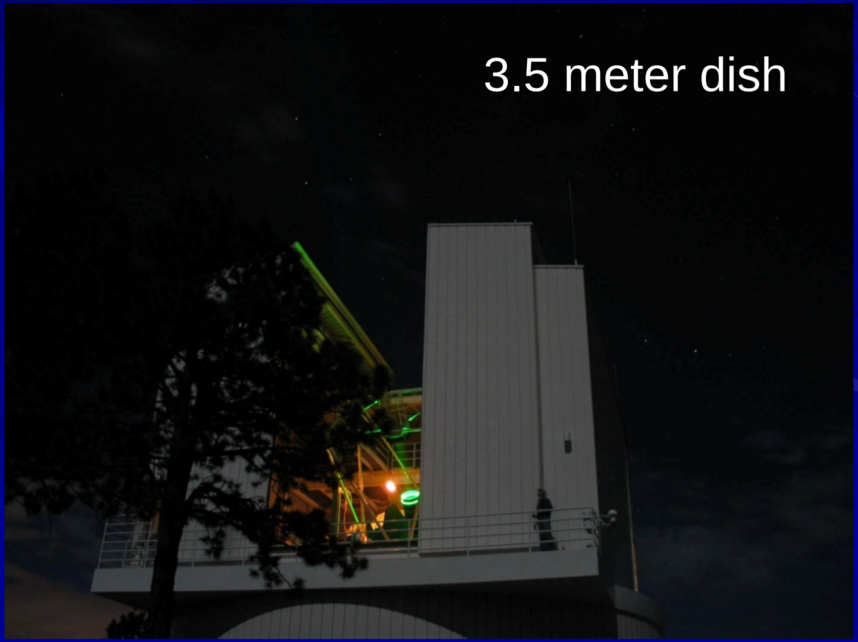
G

G

- Solar System Experiments
- Cosmology(BBN,CMB)

Solar System Experiments: Lunar Laser Ranging





3.5 meter dish

2cm/385,000 km

Solar System Experiments

- Lunar Laser Ranging(1970-:Apollo11)

$G=G_0+(dG/dt)\ (t-t_0)$

$$\frac{d^2\mathbf{x}}{dt^2} = -\frac{GM\mathbf{x}}{r^3} = -\frac{G_0M\mathbf{x}}{r^3} - \frac{\dot{G}_0}{G_0}\frac{G_0M}{r}\frac{\mathbf{x}(t-t_0)}{r^2}$$

$dG/dt/G=(1 \pm 8)\times 10^{-12}\ \mathrm{yr}^{-1}$ (up to 1994)

(Williams et al., PRD('96))

$dG/dt/G=(4 \pm 9)\times 10^{-13}\ \mathrm{yr}^{-1}$ (up to 2004)

(Williams et al., PRL('04))

binary pulsar

- timing of orbital period of binary pulsars:

$$P_b = 2\pi \left(\frac{a^3}{Gm}\right)^{1/2} = \frac{2\pi\ell^3}{G^2m^2(1-e^2)^{3/2}}$$ (Newtonian)

$$\frac{\dot{P}}{P} \cong -2\frac{\dot{G}}{G}$$

PSR 1913+16: dG/dt/G= $=(1.10 \pm 1.07)\times 10^{-11}\ \mathrm{yr}^{-1}$
(Damour-Taylor,91)

J0437-4715(NS-WD): dG/dt/G= $=(-5 \pm 18)\times 10^{-12}\ \mathrm{yr}^{-1}$
(Verbiest et al.,08)

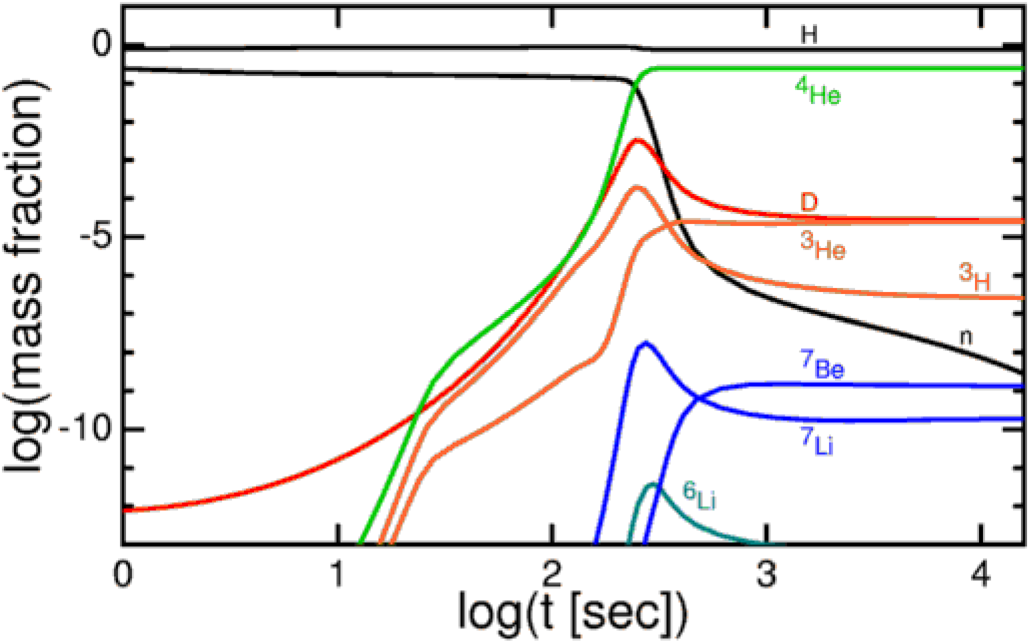
Cosmology: BBN

- only p and n at T>1MeV (weak interaction)
- cools down by the adiabatic expansion of the universe
- freeze out of n/p ratio: $T_f \sim 0.8$MeV

interaction $n\sigma v \sim T_f^3 G_F^2 T_f^2 \sim H \sim \sqrt{G} T_f^2$ expansion

$n/p = \exp(-(m_n - m_p)/T_f)$

$Y_p = 2(n/p)/(1+(n/p))$



BBN

- Larger G ↑ → H ↑

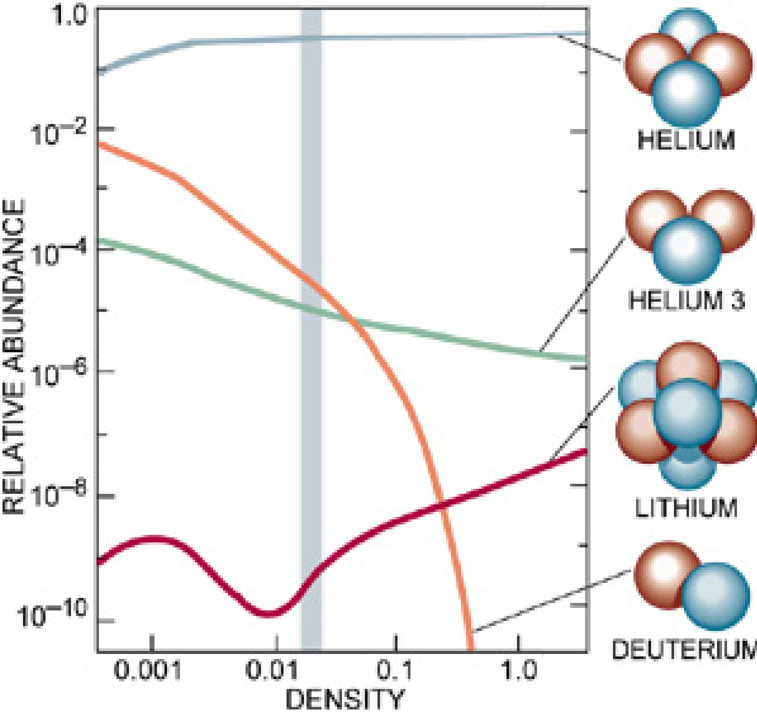
results in earlier freeze out of n/p ratio: T_f ↑

$$n/p=\exp(-(m_n-m_p)/T_f)$$

$$n\sigma v \sim T_f^3 G_F^2 T_f^2 \sim H \sim \sqrt{G} T_f^2$$

- results in larger amount of ^{4}He: Yp ↑

spoiling the success of BBN



- Copi-Davis-Krauss,PRL,92(04)171301

  assuming WMAP value of $\Omega_B h^2$

  and comparing with D/H constrains ΔG

  (inconsistent: neglecting the effect of the dynamics of varying G field on CMB):

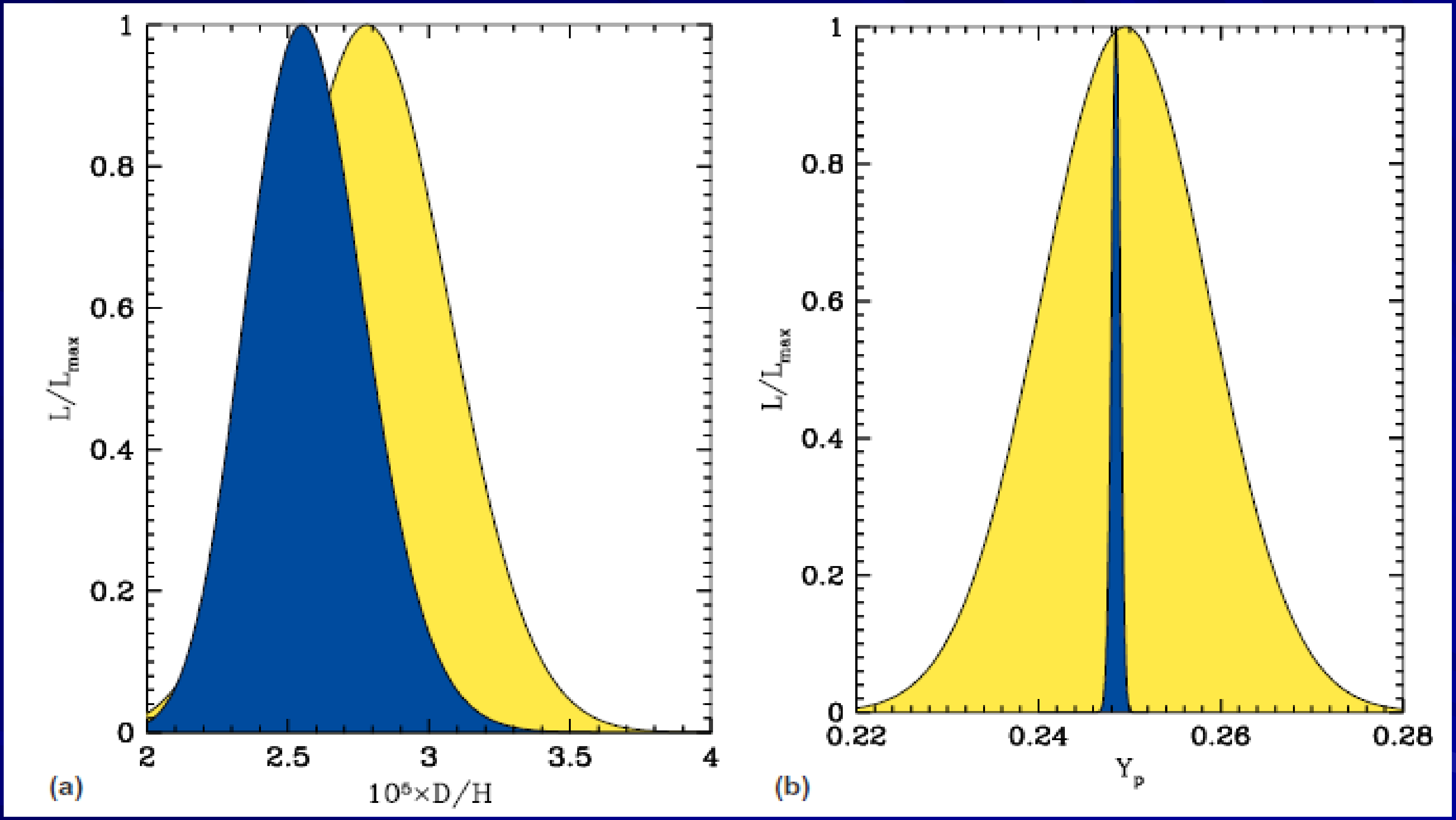
  $-0.15<(G_{BBN}-G_0)/G_0<0.21$ (1 sigma)

- Cyburt et al.,Astropart.Phys.,23(05)313

  assuming WMAP value of $\Omega_B h^2$

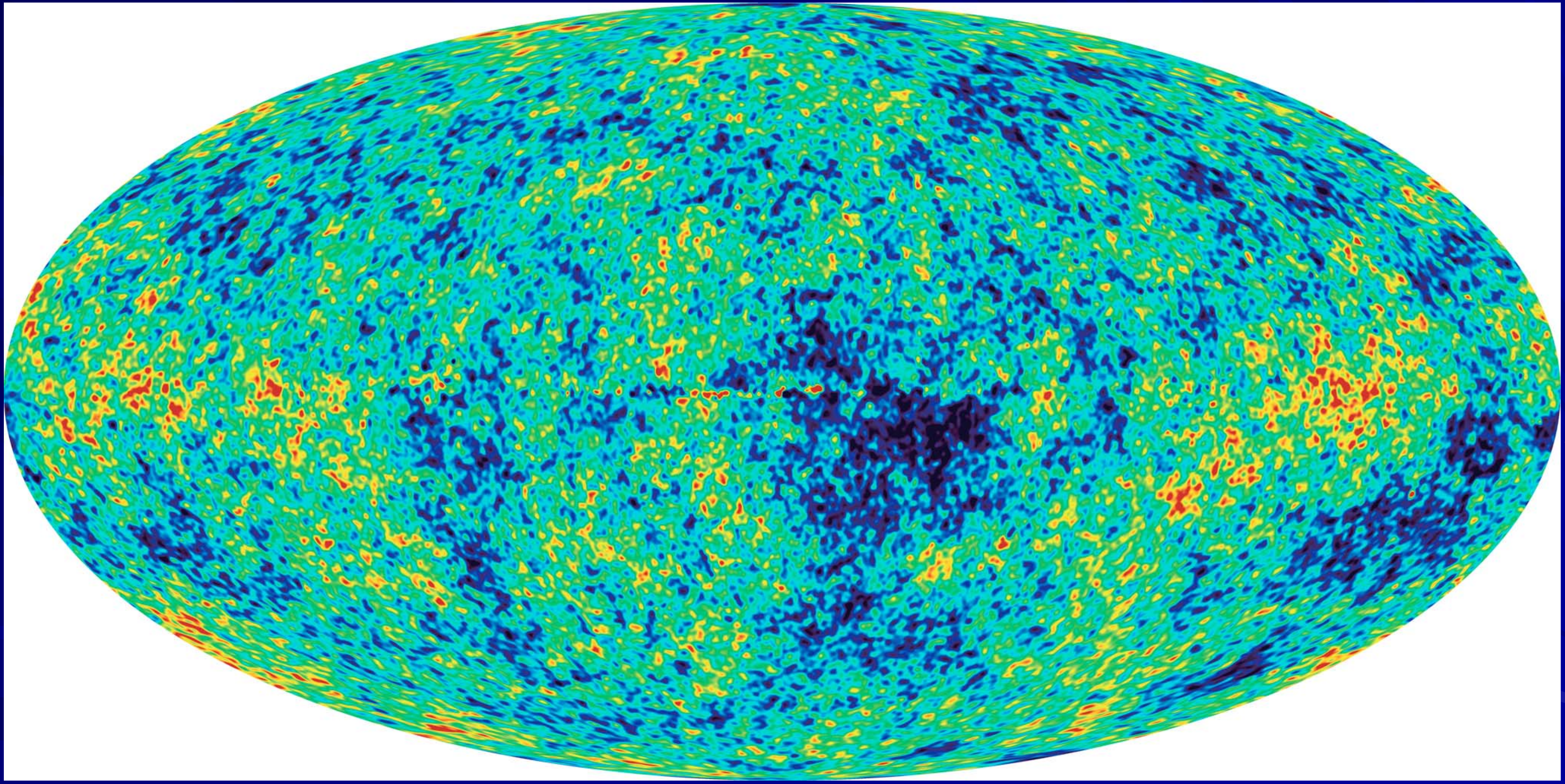
  and comparing with ^{4}He :

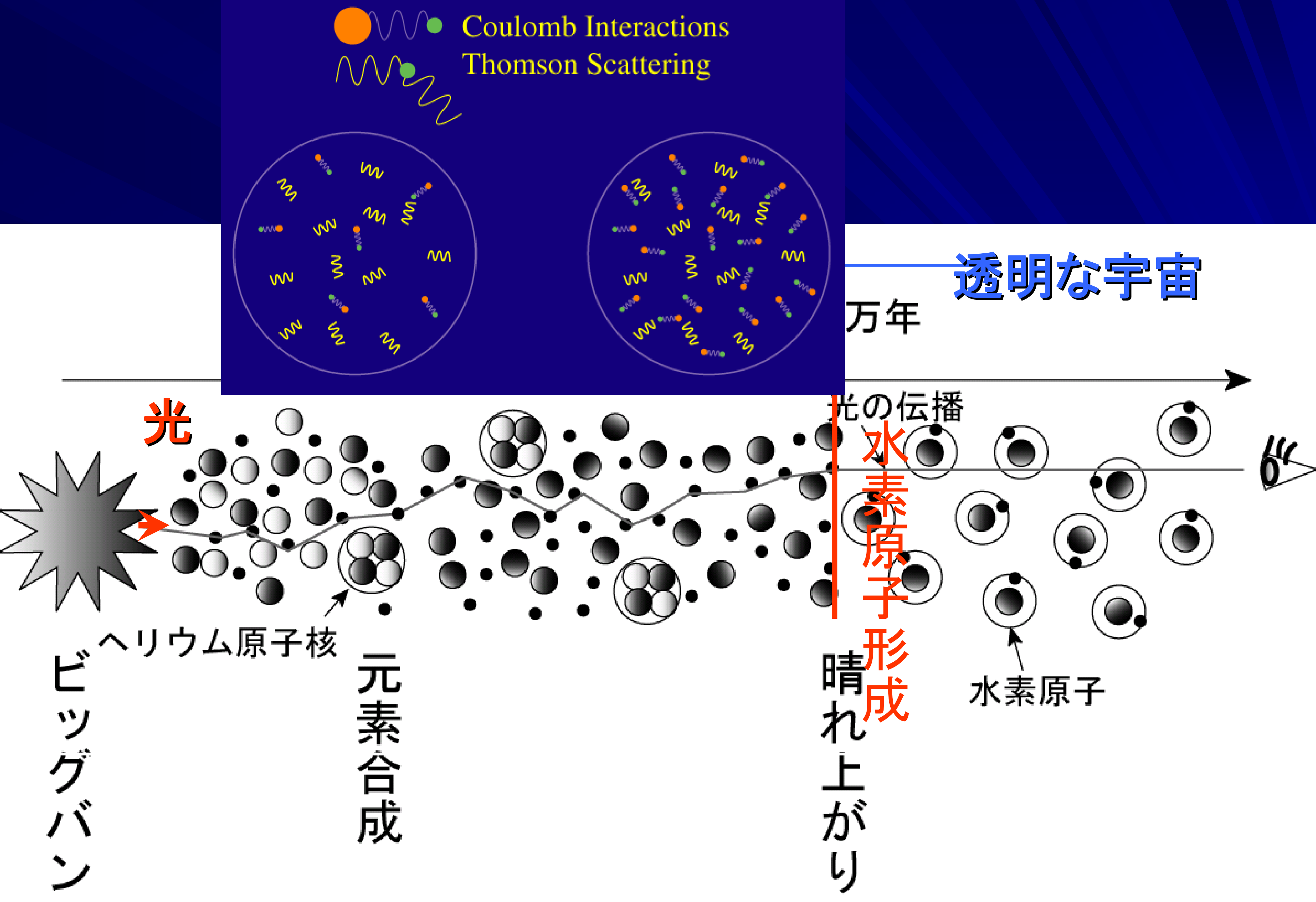
  $-0.10<(G_{BBN}-G_0)/G_0<0.13$ (1 sigma)



blue: BBN prediction from WMAP; yellow : observations (from Cyburt et al.(05))

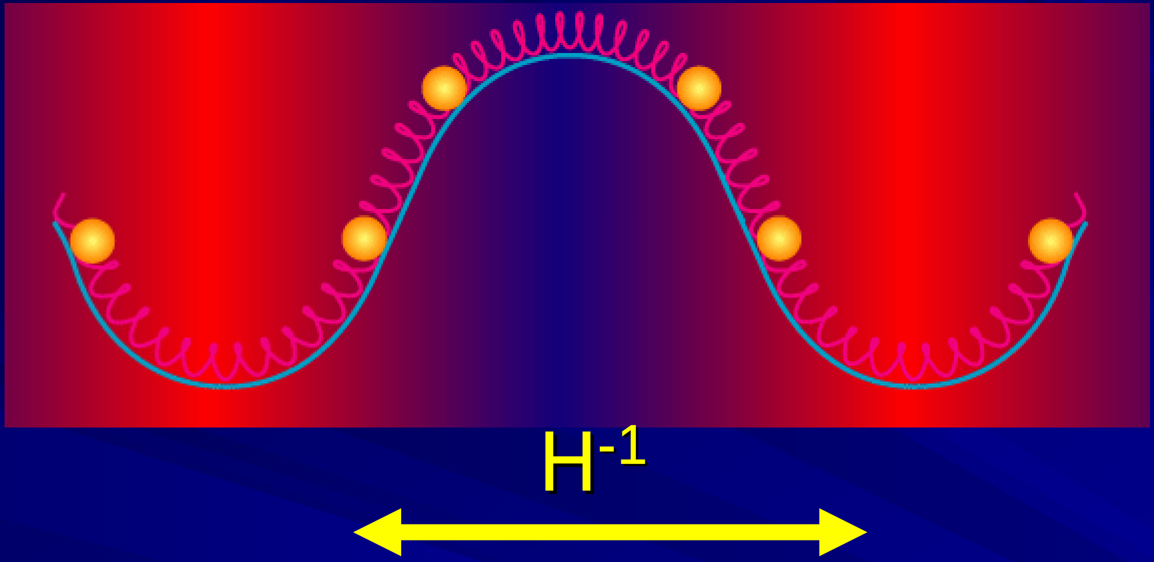
CMB



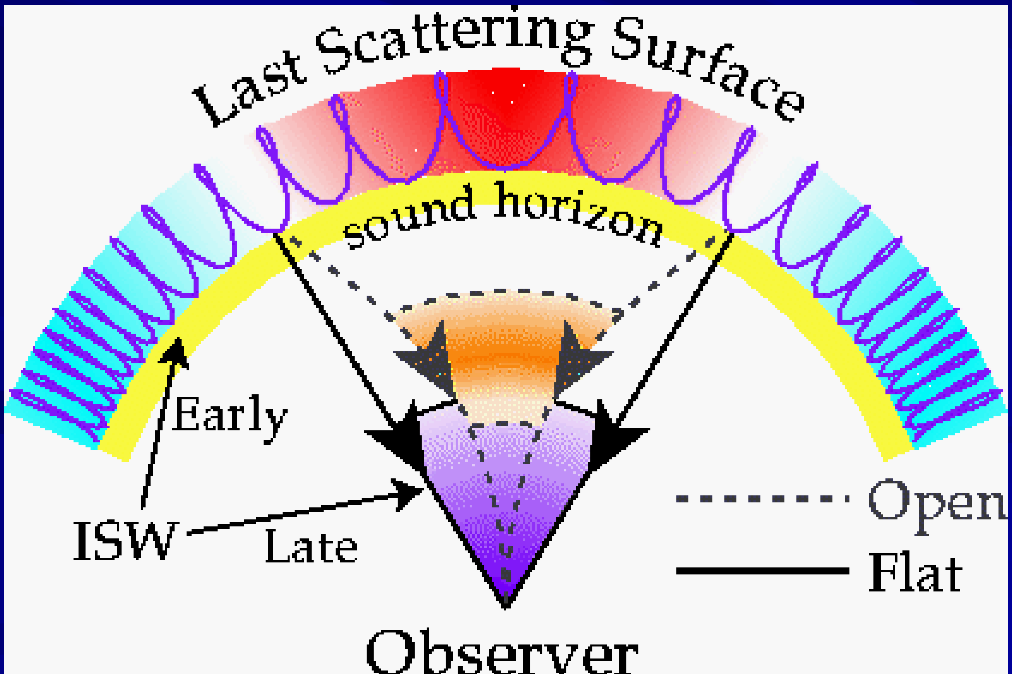


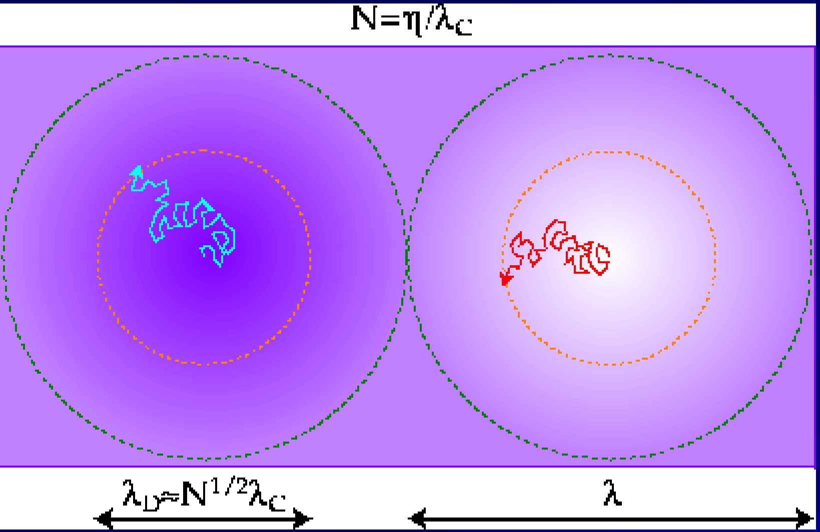
温度 **10億K** **3000K** **2.725K**

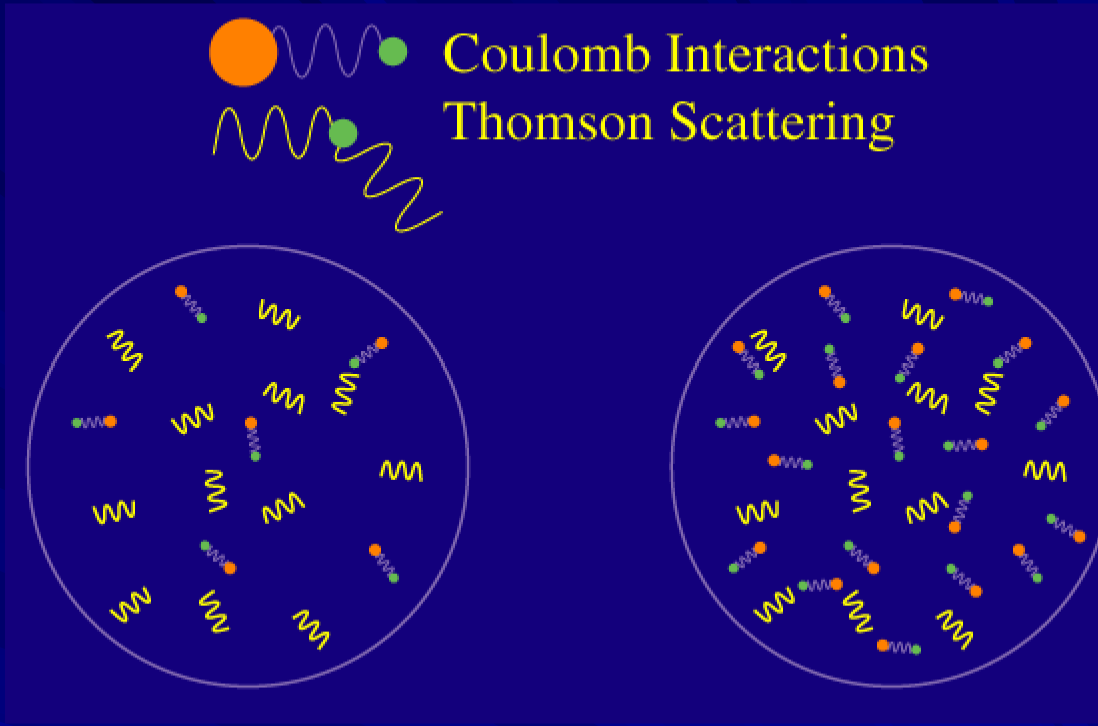
CMB



赤（温度低い）
青（高い）





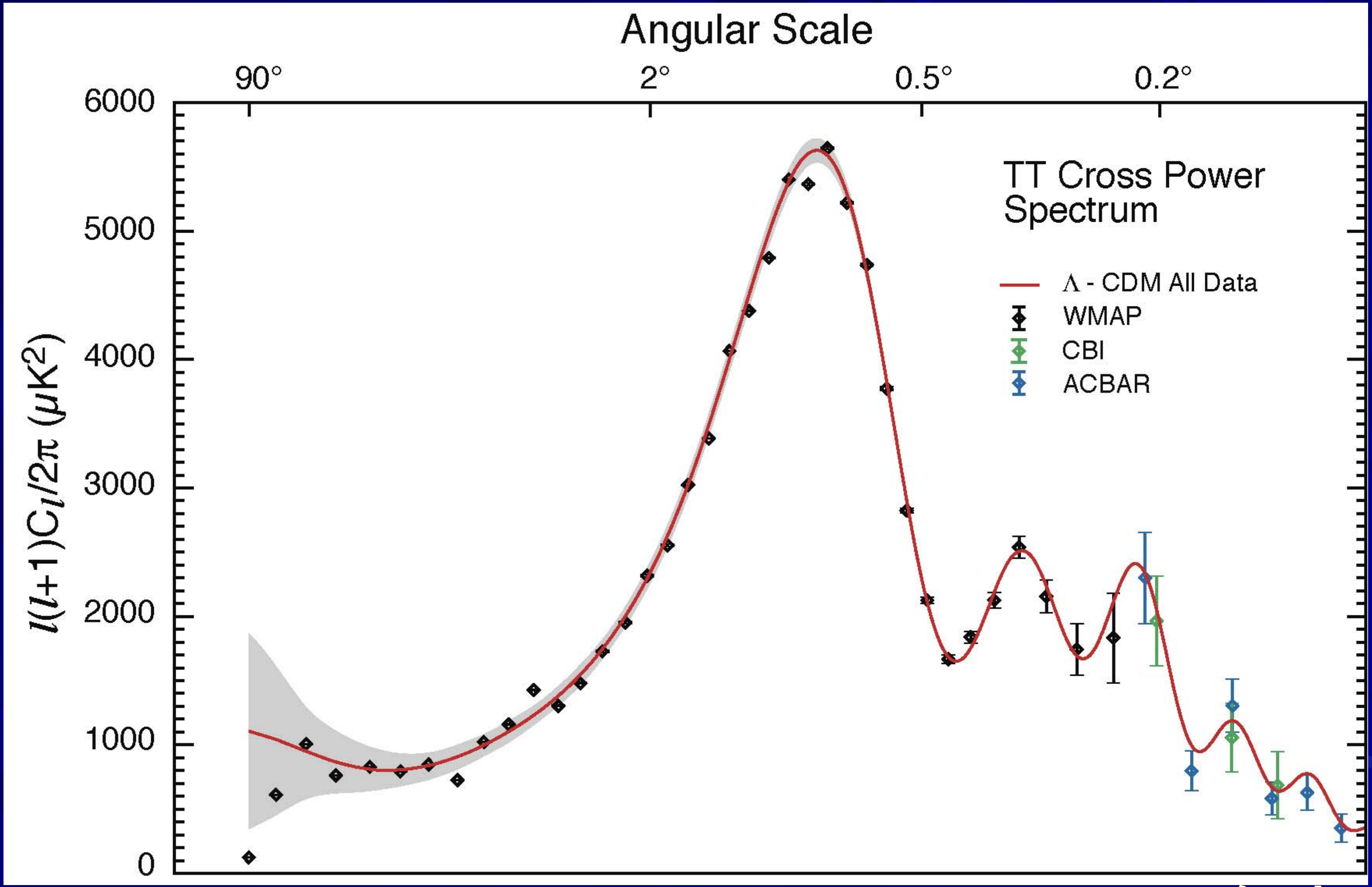

Coulomb Interactions

Thomson Scattering

$$\lambda_D = \sqrt{N}\,\ell_{mfp} \quad (\ell_{mfp} = 1/n\underline{\sigma_T})$$

$$H^{-1} = N\ell_{mfp}$$

$$\lambda_D = \sqrt{\underline{H^{-1}}\,\ell_{mfp}}$$


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi\ (\mu K^2)$
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR

大角度　　　　　　　　　　　　小角度

Cosmology:CMB

- Larger G shortens the horizon radius $H^{-1}\downarrow$

- Projection effect(first acoustic peak, $H^{-1}\downarrow$)
- Shift of zero point of oscillation($\cong\Omega_B h^2\uparrow$)
- Diffusion damping($\lambda_D \sim \surd\, H^{-1} l_{mfp}\downarrow$)

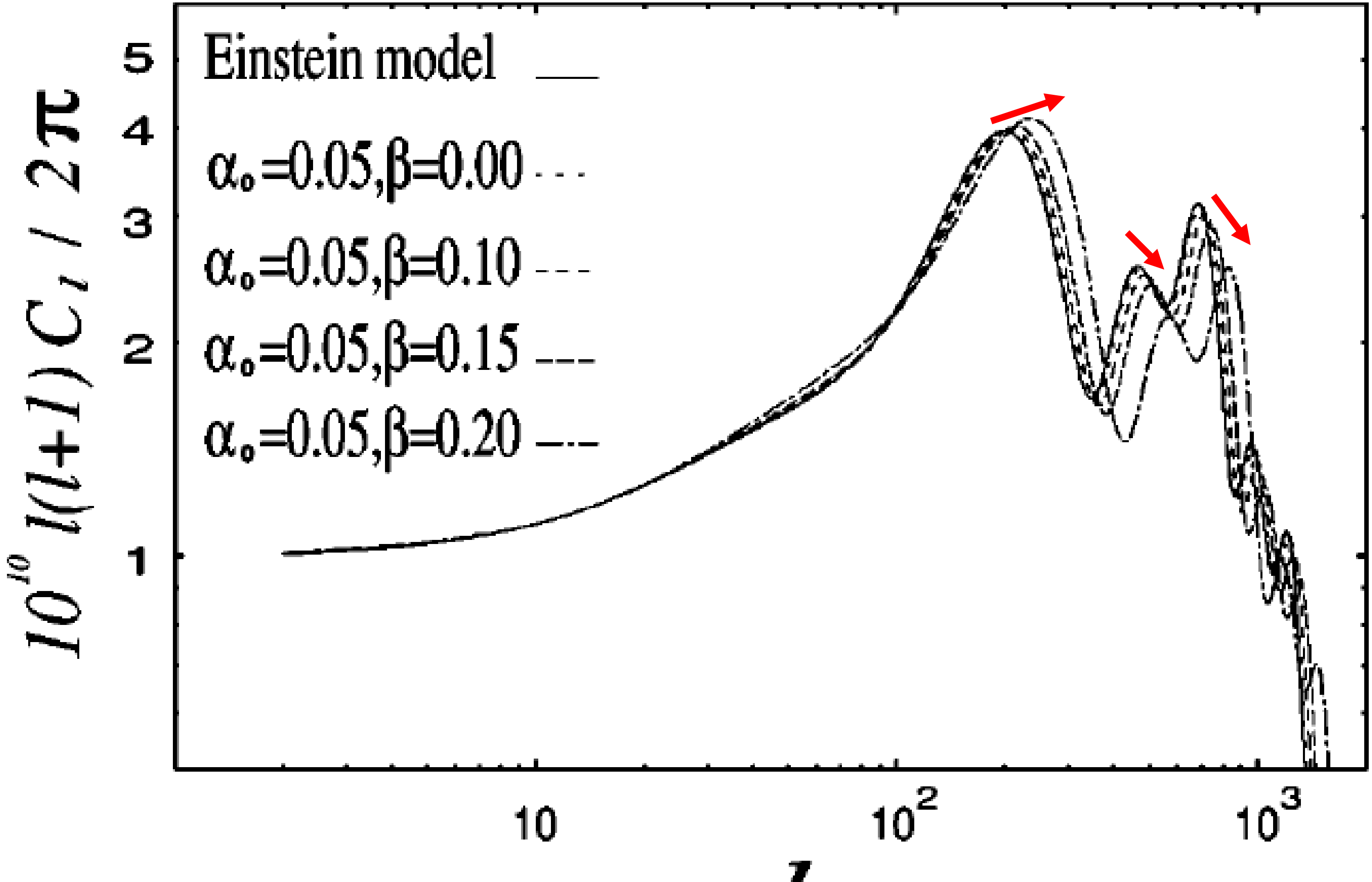
  (damping factor at peaks ($\lambda \propto H^{-1}$):

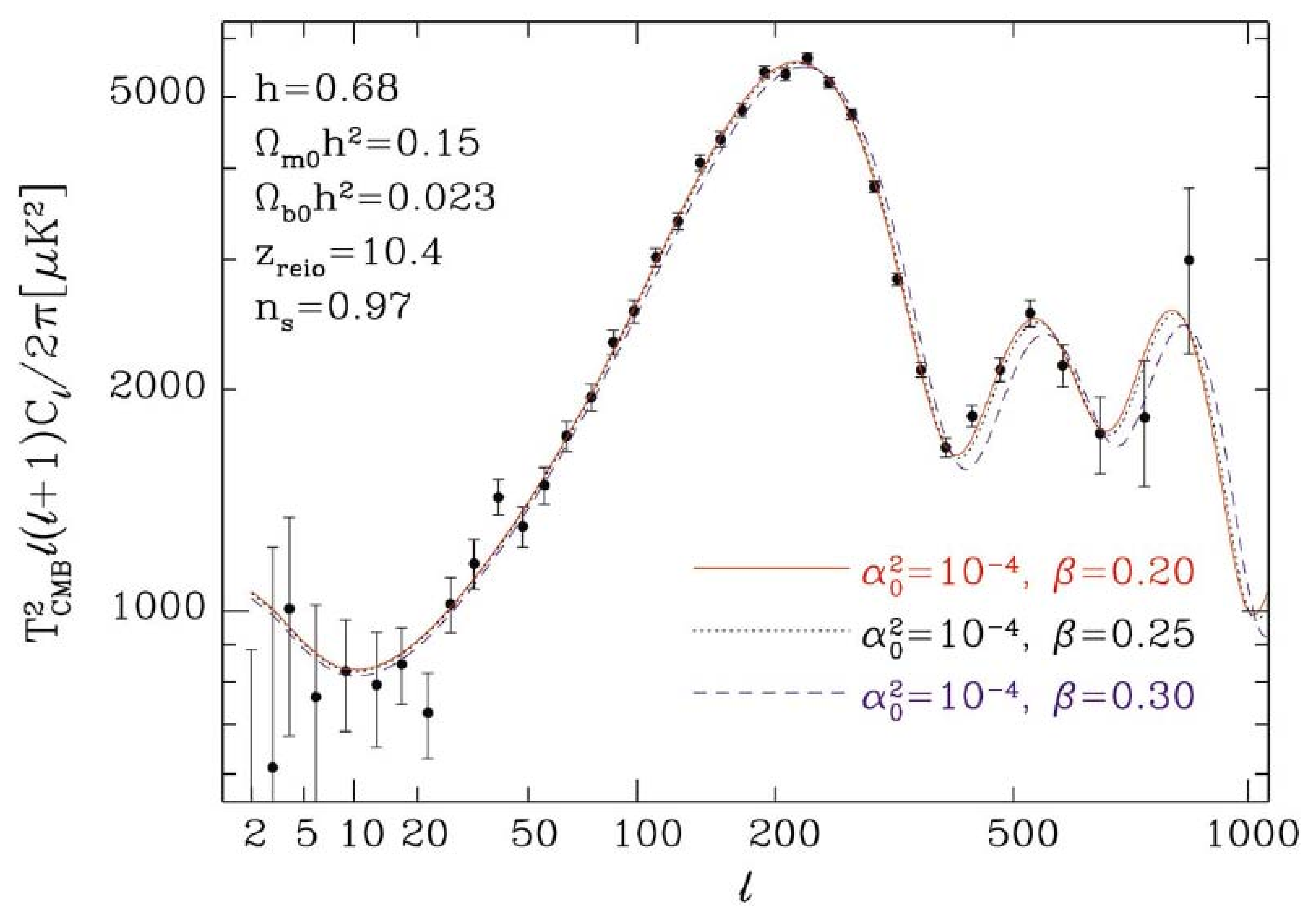
  $\exp(-\lambda_D^2/\lambda^2)\downarrow$)
- Decay of gravitational potential

  ($\delta\Phi\neq0$, ISW)

Nagata-TC-Sugiyama(2002)

PHYSICAL REVIEW D **66**, 103510 (2002)





$(G_{recom}-G_0)/G_0<0.05$

(Nagata-TC-Sugiyama,2004)

Conclusion:G

- G: $z=10^{10}$ (BBN) $-0.10<(G_{BBN}-G_0)/G_0<0.13$

  $z=1100$ (CMB) $(G_{recom}-G_0)/G_0<0.05$

  $z=0$ (LRR) $dG/dt/G=(4\pm9)\times10^{-13}\ yr^{-1}$

  (pulsar) $dG/dt/G=(1\pm1)\times10^{-11}\ yr^{-1}$

  - $\Delta G/\Delta t/G < 10^{-3\sim-1}\ H_0$
  - Dirac's larger number hypothesis is ruled out
  - Modified gravity theories should satisfy these bounds

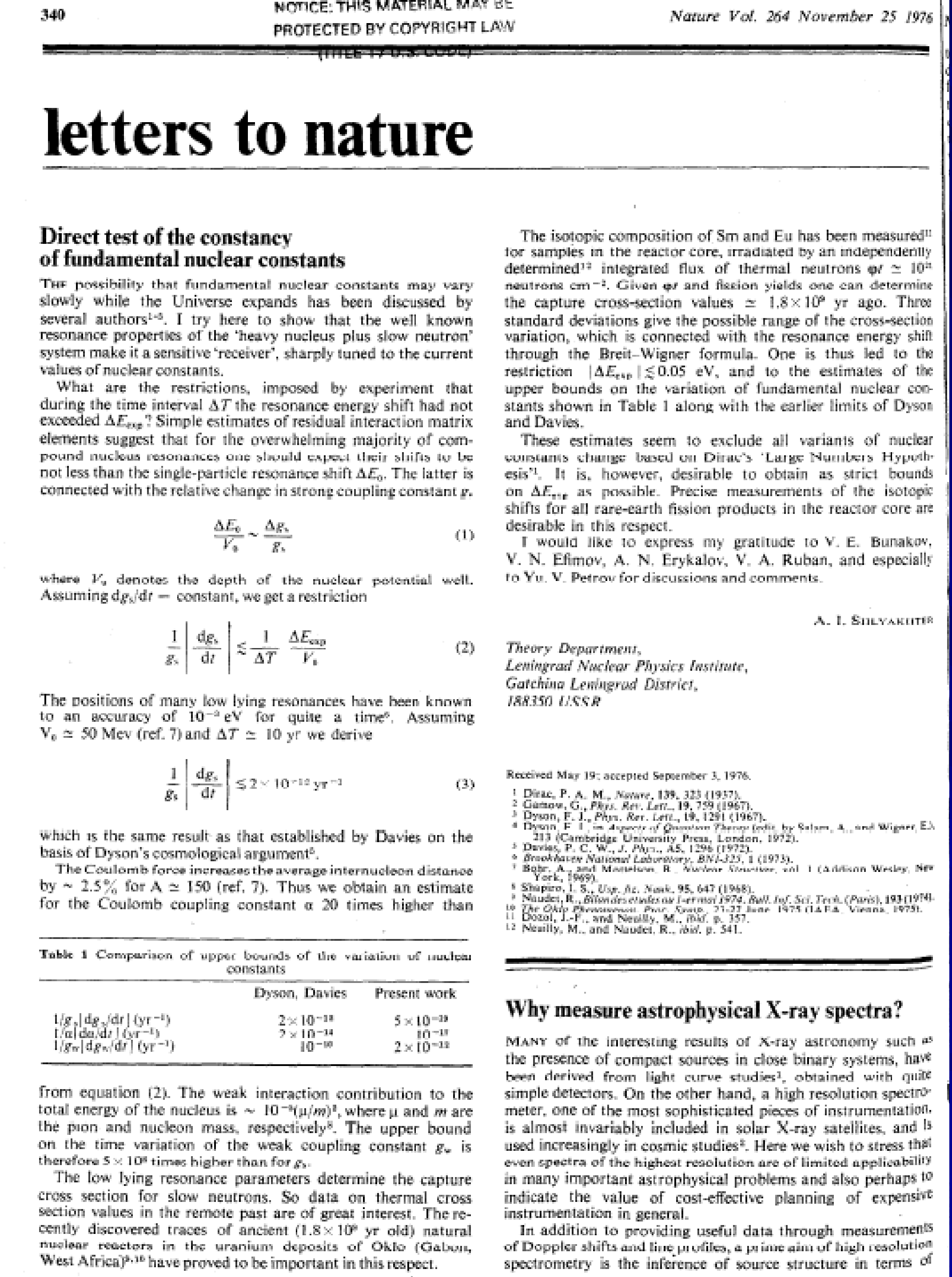
α

α

- Oklo(Natural Nuclear Reactor)
- Absorption lines
- Cosmology(BBN, CMB)
- Laboratory Tests(Clock comparison)

Oklo:

Shlyakhter's famous paper(1976)



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letters to nature

Direct test of the constancy of fundamental nuclear constants

The possibility that fundamental nuclear constants may vary slowly while the Universe expands has been discussed by several authors[1–5]. I try here to show that the well known resonance properties of the 'heavy nucleus plus slow neutron' system make it a sensitive 'receiver', sharply tuned to the current values of nuclear constants.

What are the restrictions, imposed by experiment that during the time interval ΔT the resonance energy shift had not exceeded ΔE_{exp}? Simple estimates of residual interaction matrix elements suggest that for the overwhelming majority of compound nucleus resonances one should expect their shifts to be not less than the single-particle resonance shift ΔE_0. The latter is connected with the relative change in strong coupling constant g_s

$$\frac{\Delta E_0}{V_0} \sim \frac{\Delta g_s}{g_s} \qquad (1)$$

where V_0 denotes the depth of the nuclear potential well. Assuming $\mathrm{d}g_s/\mathrm{d}t$ = constant, we get a restriction

$$\frac{1}{g_s}\left|\frac{\mathrm{d}g_s}{\mathrm{d}t}\right| \lesssim \frac{1}{\Delta T}\,\frac{\Delta E_{\text{exp}}}{V_0} \qquad (2)$$

The positions of many low lying resonances have been known to an accuracy of 10^{-3} eV for quite a time[6]. Assuming $V_0 \simeq 50$ Mev (ref. 7) and $\Delta T \simeq 10$ yr we derive

$$\frac{1}{g_s}\left|\frac{\mathrm{d}g_s}{\mathrm{d}t}\right| \lesssim 2\times10^{-12}\ \text{yr}^{-1} \qquad (3)$$

which is the same result as that established by Davies on the basis of Dyson's cosmological argument[5].

The Coulomb force increases the average internucleon distance by ~ 2.5% for A ≃ 150 (ref. 7). Thus we obtain an estimate for the Coulomb coupling constant α 20 times higher than from equation (2). The weak interaction contribution to the total energy of the nucleus is $\sim 10^{-8}(\mu/m)^2$, where μ and m are the pion and nucleon mass, respectively[8]. The upper bound on the time variation of the weak coupling constant g_w is therefore 5×10^8 times higher than for g_s.

Table 1 Comparison of upper bounds of the variation of nuclear constants

	Dyson, Davies	Present work
$1/g_s\,\lvert \mathrm{d}g_s/\mathrm{d}t\rvert$ (yr^{-1})	2×10^{-18}	5×10^{-19}
$1/\alpha\,\lvert \mathrm{d}\alpha/\mathrm{d}t\rvert$ (yr^{-1})	2×10^{-14}	10^{-17}
$1/g_w\,\lvert \mathrm{d}g_w/\mathrm{d}t\rvert$ (yr^{-1})	10^{-10}	2×10^{-12}

The low lying resonance parameters determine the capture cross section for slow neutrons. So data on thermal cross section values in the remote past are of great interest. The recently discovered traces of ancient (1.8×10^9 yr old) natural nuclear reactors in the uranium deposits of Oklo (Gabon, West Africa)[9,10] have proved to be important in this respect.

The isotopic composition of Sm and Eu has been measured[11] for samples in the reactor core, irradiated by an independently determined[12] integrated flux of thermal neutrons $\varphi t \simeq 10^{21}$ neutrons cm^{-2}. Given φt and fission yields one can determine the capture cross-section values $\simeq 1.8\times10^9$ yr ago. Three standard deviations give the possible range of the cross-section variation, which is connected with the resonance energy shift through the Breit–Wigner formula. One is thus led to the restriction $\lvert\Delta E_{\text{exp}}\rvert \lesssim 0.05$ eV, and to the estimates of the upper bounds on the variation of fundamental nuclear constants shown in Table 1 along with the earlier limits of Dyson and Davies.

These estimates seem to exclude all variants of nuclear constants change based on Dirac's 'Large Numbers Hypothesis'[1]. It is, however, desirable to obtain as strict bounds on ΔE_{exp} as possible. Precise measurements of the isotopic shifts for all rare-earth fission products in the reactor core are desirable in this respect.

I would like to express my gratitude to V. E. Bunakov, V. N. Efimov, A. N. Erykalov, V. A. Ruban, and especially to Yu. V. Petrov for discussions and comments.

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Received May 19; accepted September 3, 1976.

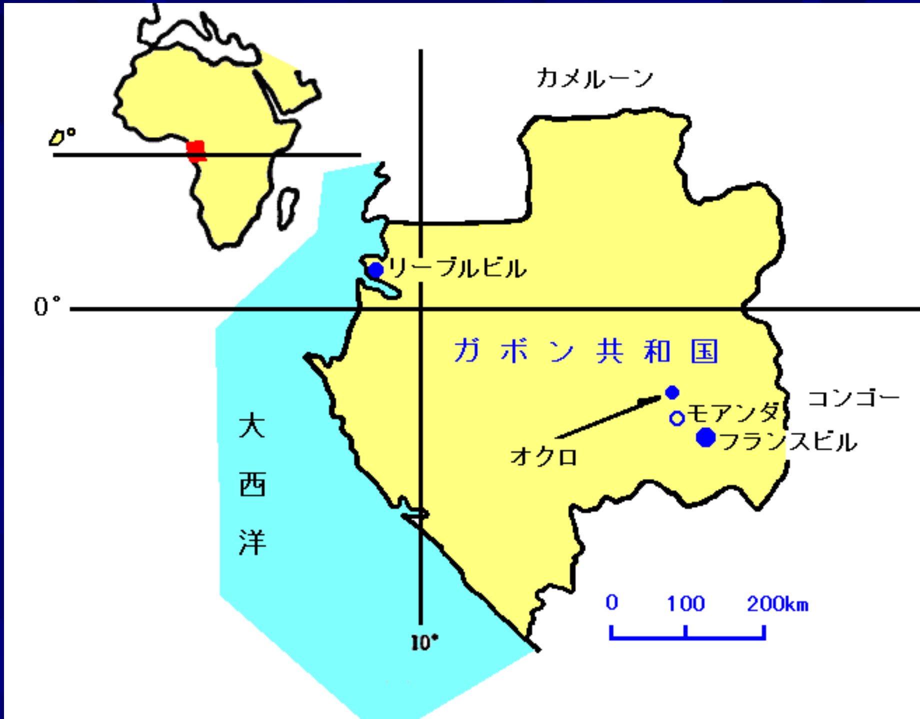
1. Dirac, P. A. M., *Nature*, 139, 323 (1937).
2. Gamow, G., *Phys. Rev. Lett.*, 19, 759 (1967).
3. Dyson, F. J., *Phys. Rev. Lett.*, 19, 1291 (1967).
4. Dyson, F. J., in *Aspects of Quantum Theory* (edit. by Salam, A., and Wigner, E.), 213 (Cambridge University Press, London, 1972).
5. Davies, P. C. W., *J. Phys.*, A5, 1296 (1972).
6. *Brookhaven National Laboratory, BNL-325*, 1 (1973).
7. Bohr, A., and Mottelson, B., *Nuclear Structure*, vol. 1 (Addison Wesley, New York, 1969).
8. Shapiro, I. S., *Usp. fiz. Nauk*, 95, 647 (1968).
9. Naudet, R., *Bilan des etudes au 1 er mai 1974, Bull. Inf. Sci. Tech. (Paris)*, 193 (1974).
10. *The Oklo Phenomenon, Proc. Symp.*, 23-27 June 1975 (IAEA, Vienna, 1975).
11. Dozol, J.-F., and Neuilly, M., *ibid.* p. 357.
12. Neuilly, M., and Naudet, R., *ibid.* p. 541.

Why measure astrophysical X-ray spectra?

Many of the interesting results of X-ray astronomy such as the presence of compact sources in close binary systems, have been derived from light curve studies[1], obtained with quite simple detectors. On the other hand, a high resolution spectrometer, one of the most sophisticated pieces of instrumentation, is almost invariably included in solar X-ray satellites, and is used increasingly in cosmic studies[2]. Here we wish to stress that even spectra of the highest resolution are of limited applicability in many important astrophysical problems and also perhaps to indicate the value of cost-effective planning of expensive instrumentation in general.

In addition to providing useful data through measurements of Doppler shifts and line profiles, a prime aim of high resolution spectrometry is the inference of source structure in terms of

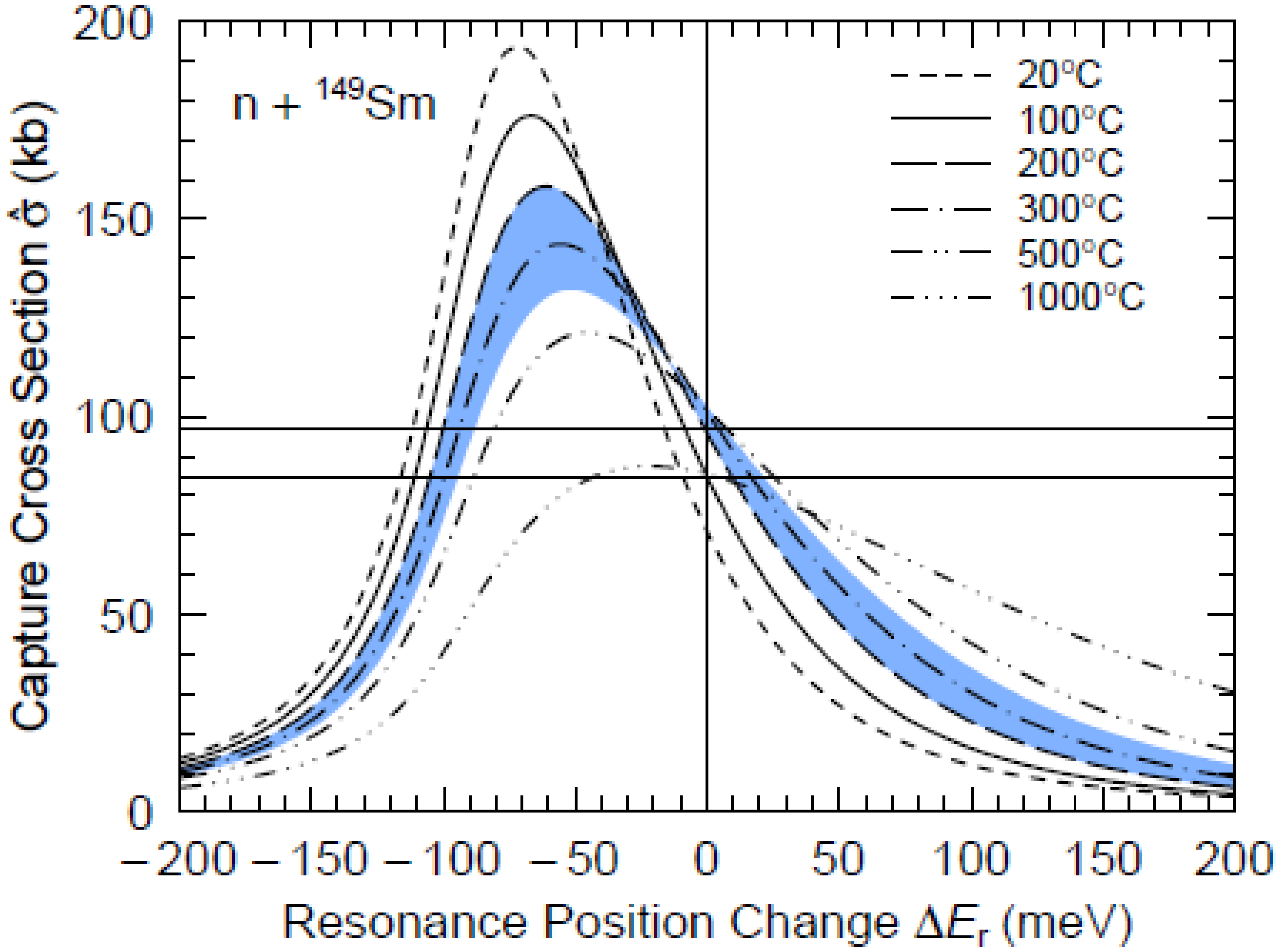
- Oklo natural nuclear reactor at Gabon (West Africa) operated 2Gyr ago



- Anomaly of the isotope ratio of Sm: $^{149}\mathrm{Sm}/^{147}\mathrm{Sm}=0.02$ (natural value:0.9)

$$^{149}\mathrm{Sm} + n \to \ ^{150}\mathrm{Sm} + \gamma$$

- Shlyakhter noticed the sensitivity of the cross section of neutron capture by Sm to the resonance energy $E_r \sim 97$ meV



Fujii et al. (2000)

$$\Delta Er = \Delta(E^{*}_{150} - E_{149} - m_{n}) \cong -1.1\,\mathrm{MeV}\,\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\alpha}{\alpha} \cong \frac{4 \pm 16\ \mathrm{meV}}{-1.1\ \mathrm{MeV}} \cong (-4 \pm 15) \times 10^{-9}$$

$$\frac{\dot{\alpha}}{\alpha} = -\frac{\Delta\alpha}{\alpha\,\Delta t} = (0.2 \pm 0.8) \times 10^{-17}\ \mathrm{yr}^{-1}$$

$\dot{\alpha}/\alpha$

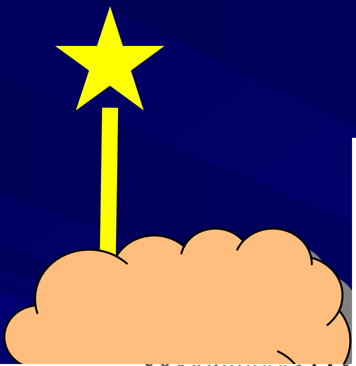
- Shlyakhter(1976)

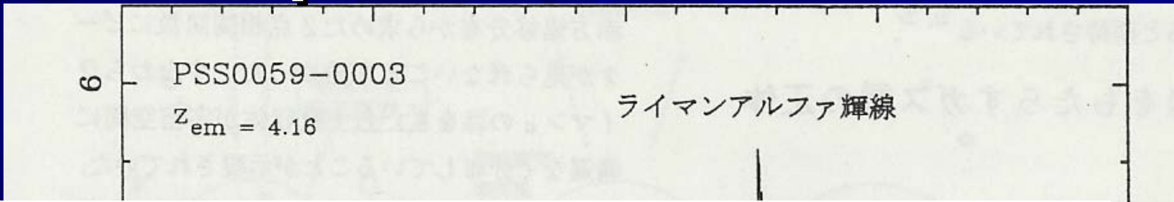
  1×10^{-17} /yr
- Damour-Dyson(1996)

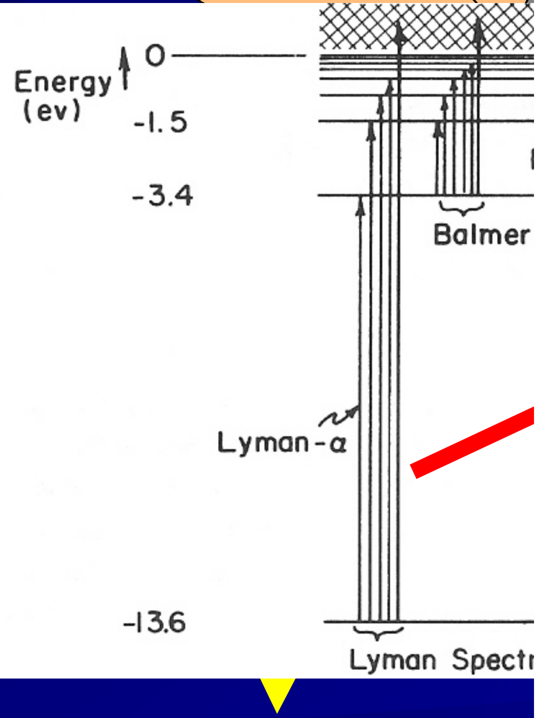
  $(-6.7 \sim 5.0) \times 10^{-17}$ /yr
- Fujii et al.(2000)

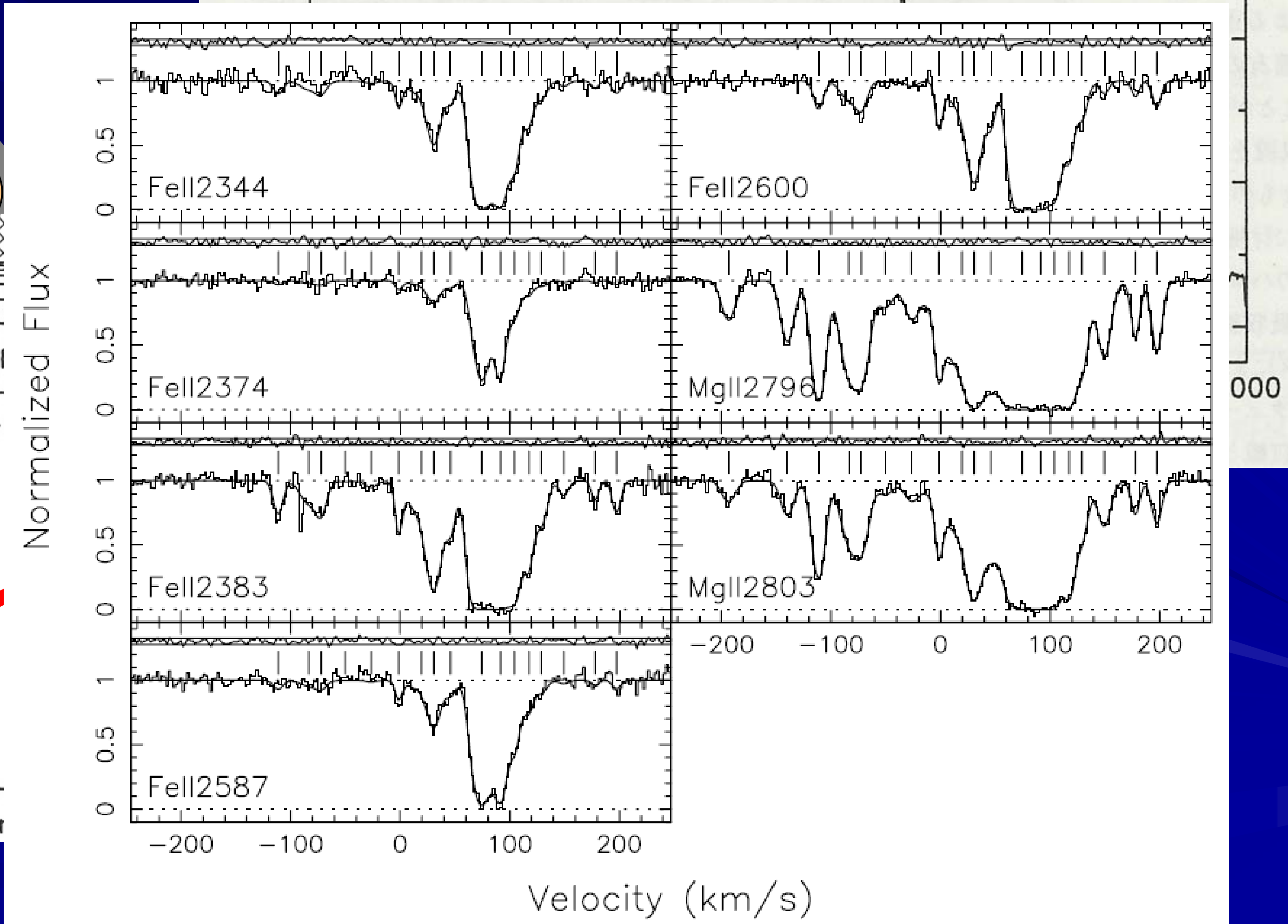
  $(2+-8)\text{x}10^{-18}$ /yr

Quasar Absorption Lines

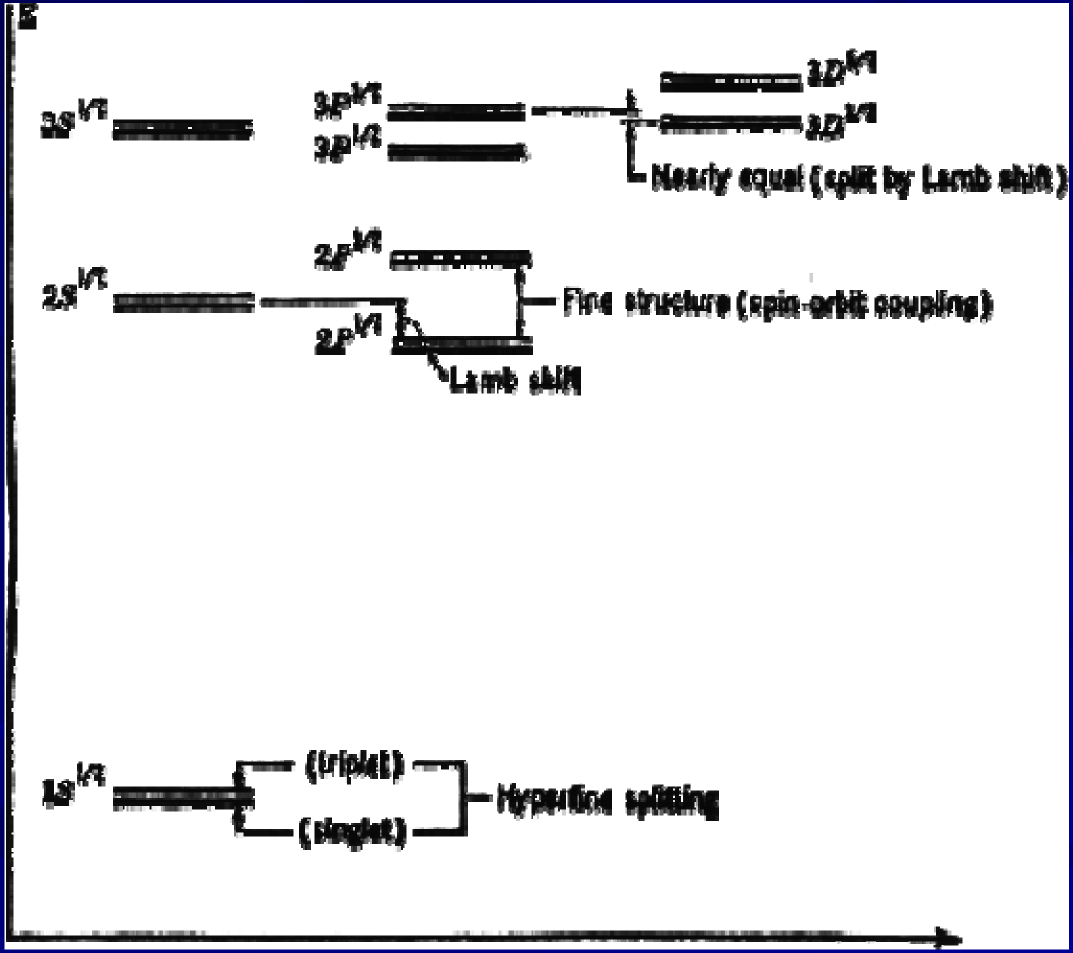








hydrogen atom: example



fine structure $\propto \alpha^4$

Lamb shift $\propto \alpha^5$

hyperfine $\propto \alpha^4 m_e/m_p$

(21cm)

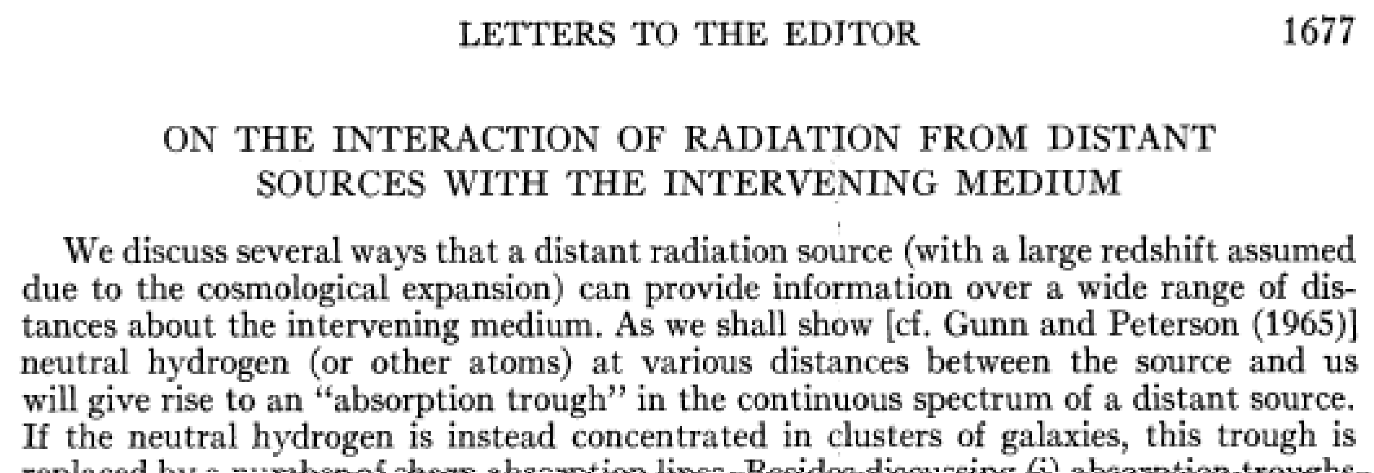
doublet vs. α

- fine structure:
  doublet splitting $(\lambda_1 - \lambda_2)/(\lambda_1 + \lambda_2) \propto \alpha^2$

$$2\Delta\alpha/\alpha = \Delta\lambda/\lambda = (\Delta v/c)/\lambda$$

Old Idea:

Bahcall-Salpeter (1965)



LETTERS TO THE EDITOR 1677

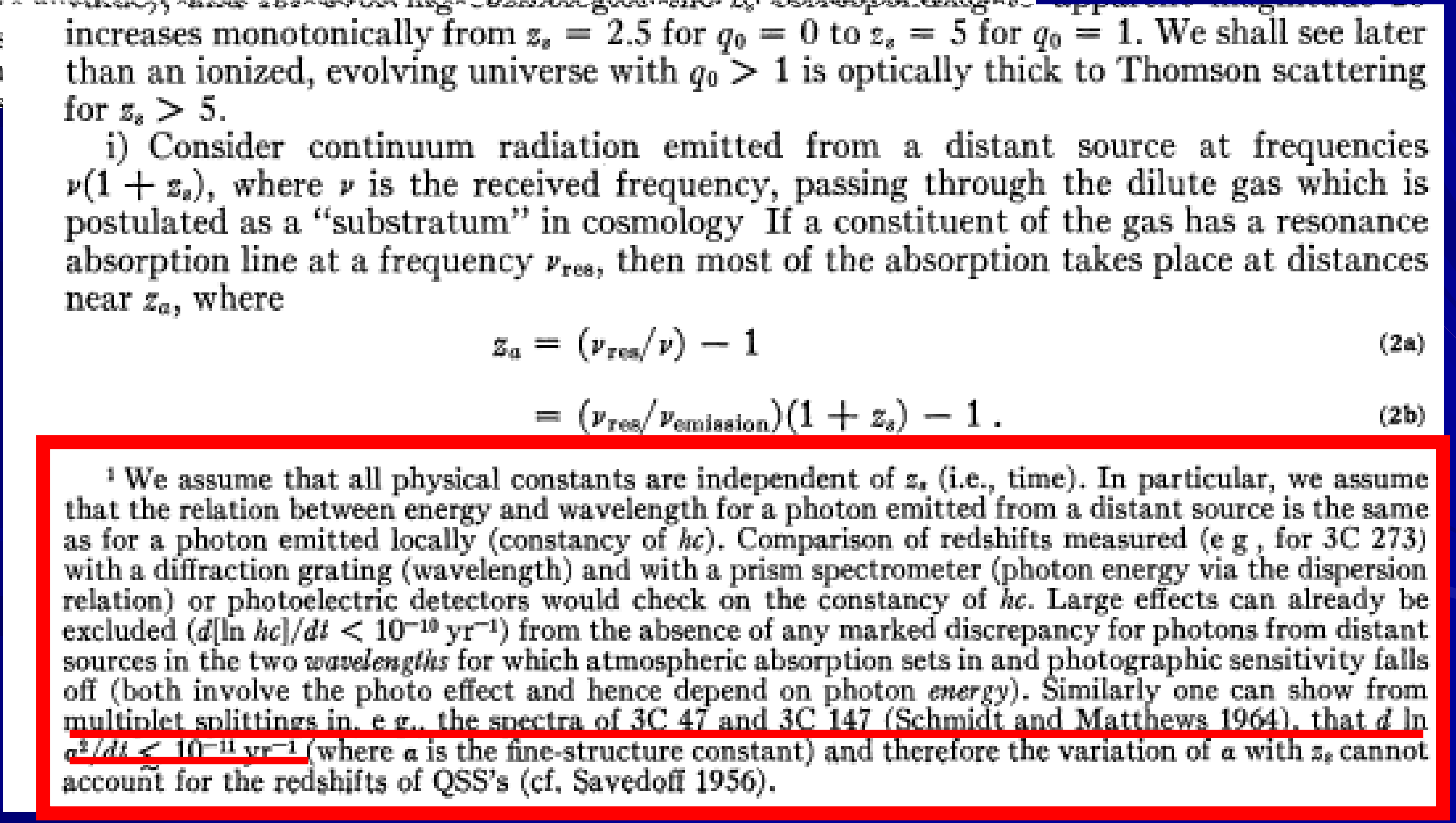
ON THE INTERACTION OF RADIATION FROM DISTANT SOURCES WITH THE INTERVENING MEDIUM

We discuss several ways that a distant radiation source (with a large redshift assumed due to the cosmological expansion) can provide information over a wide range of distances about the intervening medium. As we shall show [cf. Gunn and Peterson (1965)] neutral hydrogen (or other atoms) at various distances between the source and us will give rise to an "absorption trough" in the continuous spectrum of a distant source. If the neutral hydrogen is instead concentrated in clusters of galaxies, this trough is replaced by

and (ii) abs

electrons in

mogeneities



increases monotonically from $z_s = 2.5$ for $q_0 = 0$ to $z_s = 5$ for $q_0 = 1$. We shall see later than an ionized, evolving universe with $q_0 > 1$ is optically thick to Thomson scattering for $z_s > 5$.

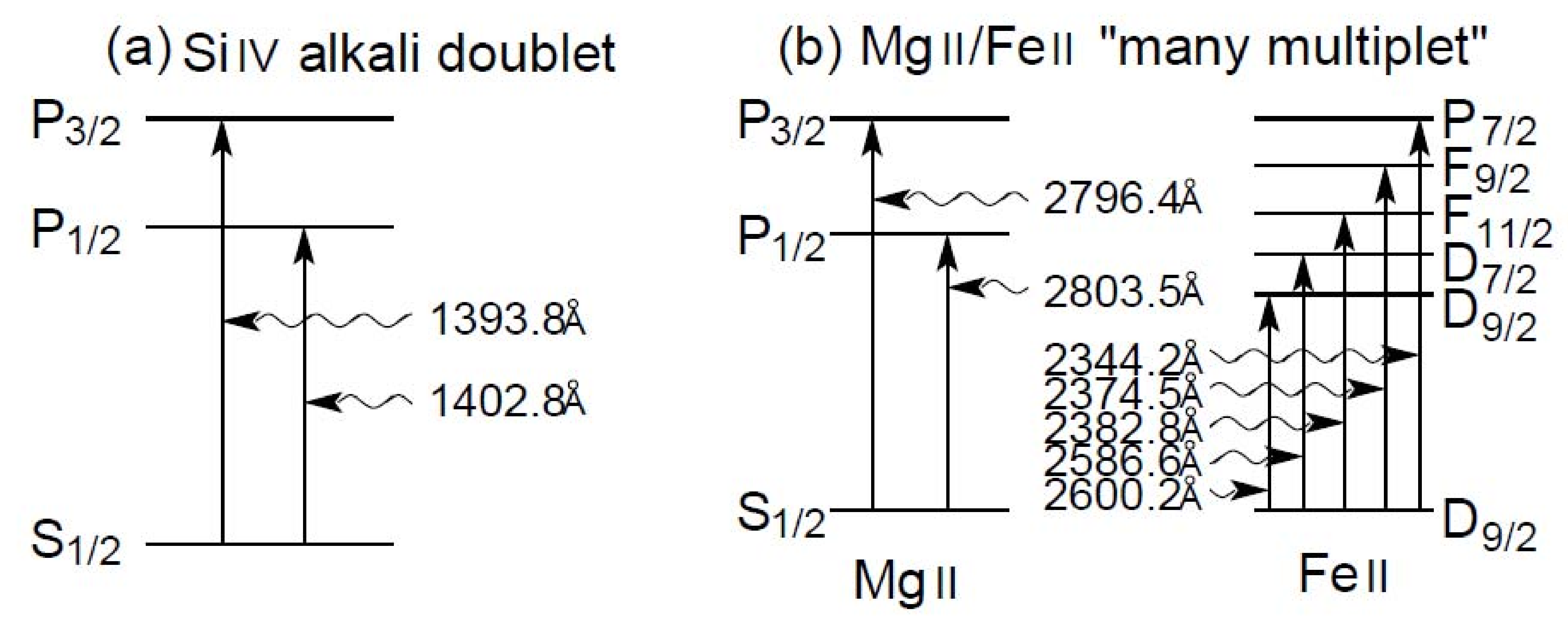
i) Consider continuum radiation emitted from a distant source at frequencies $\nu(1 + z_s)$, where ν is the received frequency, passing through the dilute gas which is postulated as a "substratum" in cosmology If a constituent of the gas has a resonance absorption line at a frequency $\nu_{\rm res}$, then most of the absorption takes place at distances near z_a, where

$$z_a = (\nu_{\rm res}/\nu) - 1 \tag{2a}$$

$$= (\nu_{\rm res}/\nu_{\rm emission})(1 + z_s) - 1\,. \tag{2b}$$

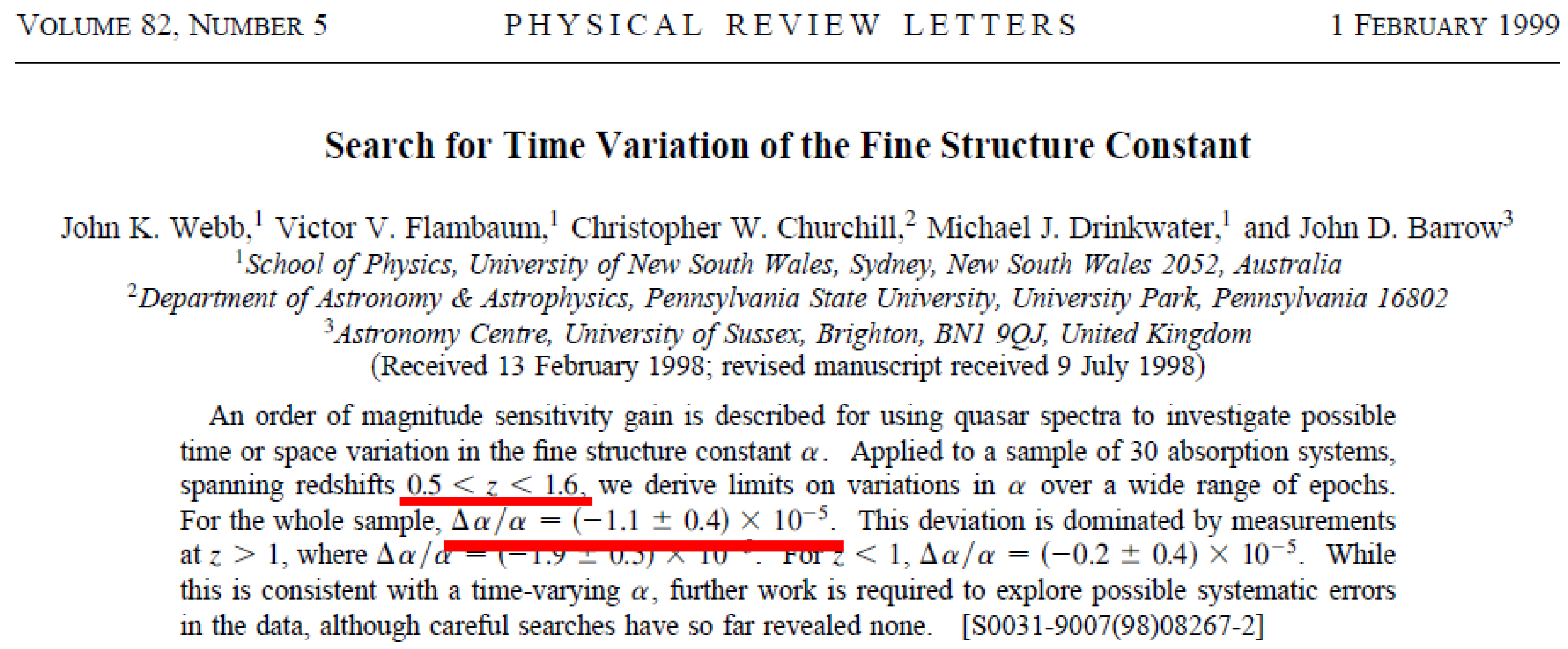
[1] We assume that all physical constants are independent of z_s (i.e., time). In particular, we assume that the relation between energy and wavelength for a photon emitted from a distant source is the same as for a photon emitted locally (constancy of hc). Comparison of redshifts measured (e g , for 3C 273) with a diffraction grating (wavelength) and with a prism spectrometer (photon energy via the dispersion relation) or photoelectric detectors would check on the constancy of hc. Large effects can already be excluded ($d[\ln hc]/dt < 10^{-10}$ yr^{-1}) from the absence of any marked discrepancy for photons from distant sources in the two *wavelengths* for which atmospheric absorption sets in and photographic sensitivity falls off (both involve the photo effect and hence depend on photon *energy*). Similarly one can show from multiplet splittings in, e g., the spectra of 3C 47 and 3C 147 (Schmidt and Matthews 1964), that $d \ln \alpha^2/dt \leq 10^{-11}$ yr^{-1} (where α is the fine-structure constant) and therefore the variation of α with z_s cannot account for the redshifts of QSS's (cf. Savedoff 1956).

alkali doublet vs. many multiplet



α-dependence depends on species

Webb et al.: Evidence for $\Delta\alpha \neq 0$ (first sample)



VOLUME 82, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1999

Search for Time Variation of the Fine Structure Constant

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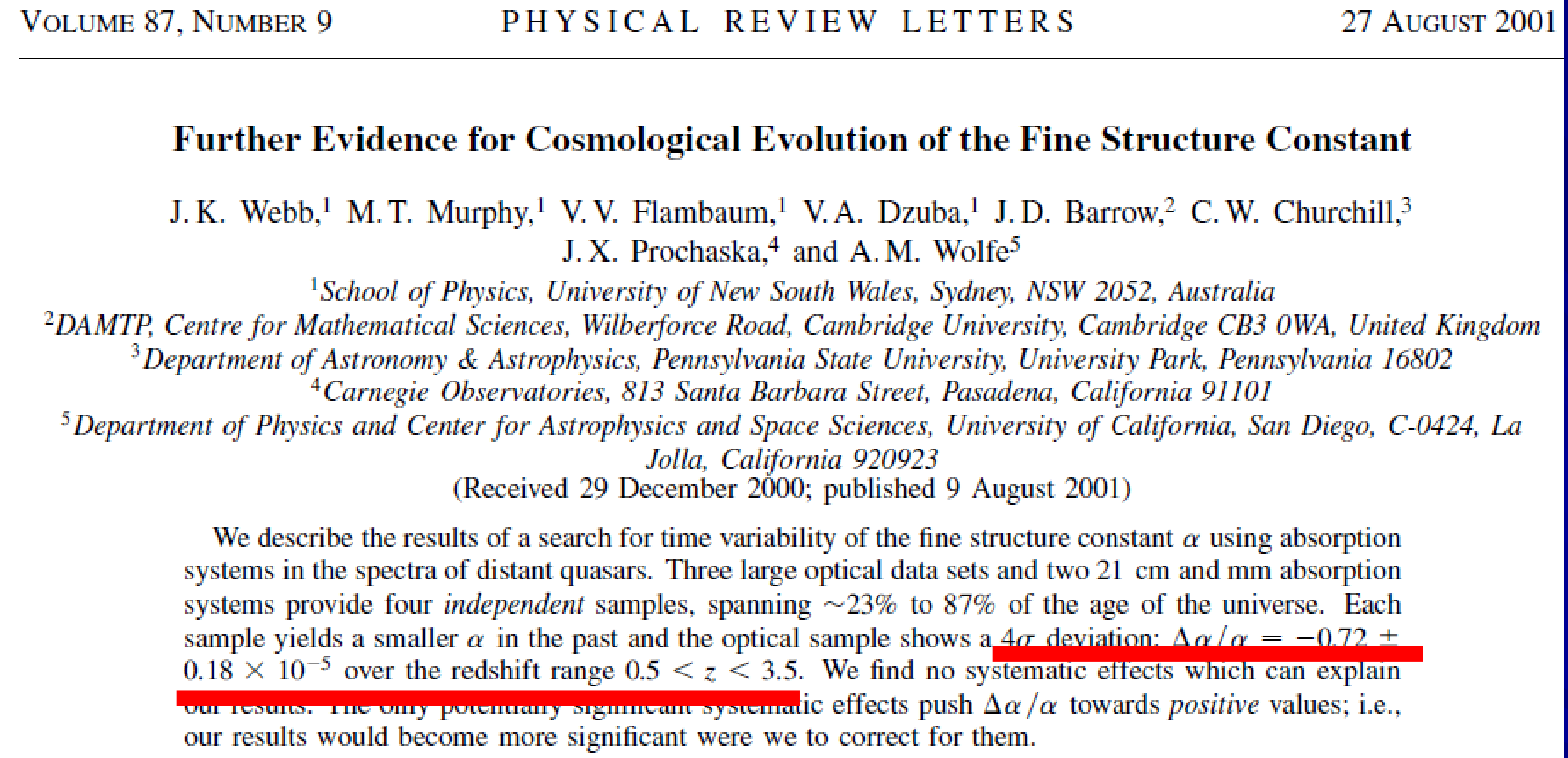
(Received 13 February 1998; revised manuscript received 9 July 1998)

An order of magnitude sensitivity gain is described for using quasar spectra to investigate possible time or space variation in the fine structure constant α. Applied to a sample of 30 absorption systems, spanning redshifts $0.5 < z < 1.6$, we derive limits on variations in α over a wide range of epochs. For the whole sample, $\Delta\alpha/\alpha = (-1.1 \pm 0.4) \times 10^{-5}$. This deviation is dominated by measurements at $z > 1$, where $\Delta\alpha/\alpha = (-1.9 \pm 0.5) \times 10^{-5}$. For $z < 1$, $\Delta\alpha/\alpha = (-0.2 \pm 0.4) \times 10^{-5}$. While this is consistent with a time-varying α, further work is required to explore possible systematic errors in the data, although careful searches have so far revealed none. [S0031-9007(98)08267-2]

- 30 absorption systems (FeII, MgI,II) at $0.5<z<1.6$ by Keck
- 3 sigma evidence for α is smaller in the past

2nd sample



VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Further Evidence for Cosmological Evolution of the Fine Structure Constant

J. K. Webb,[1] M. T. Murphy,[1] V. V. Flambaum,[1] V. A. Dzuba,[1] J. D. Barrow,[2] C. W. Churchill,[3]
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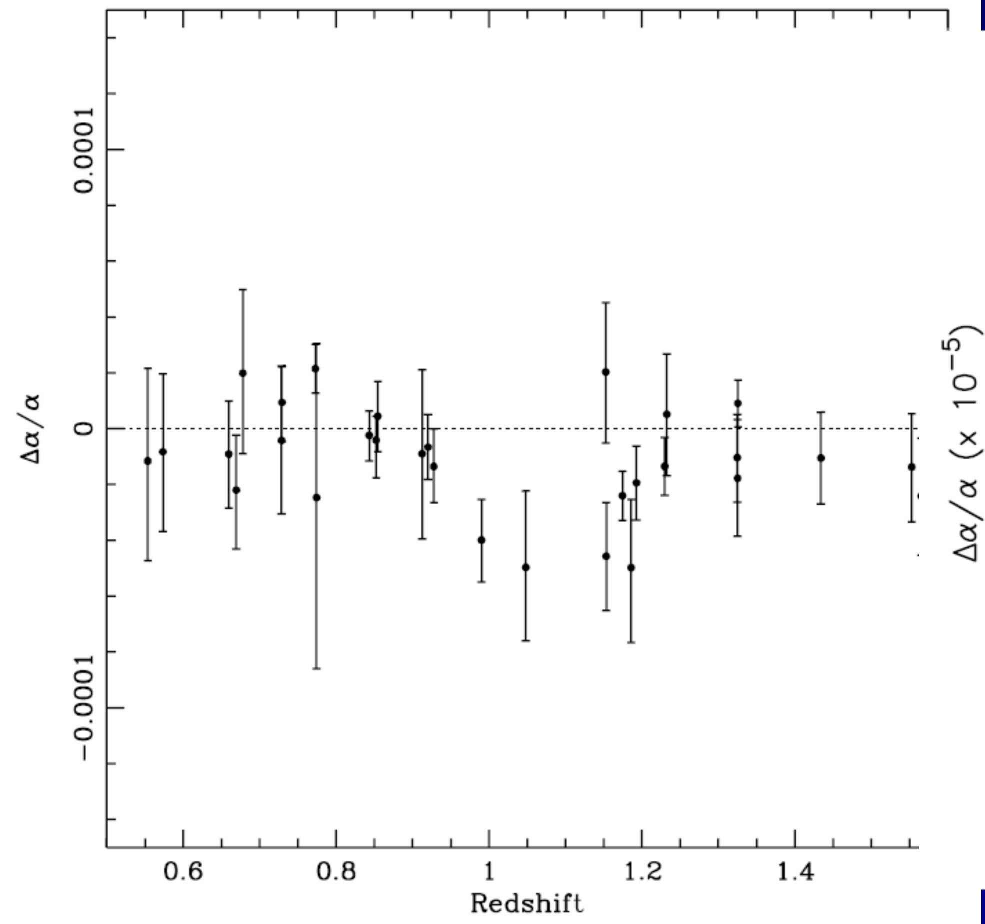
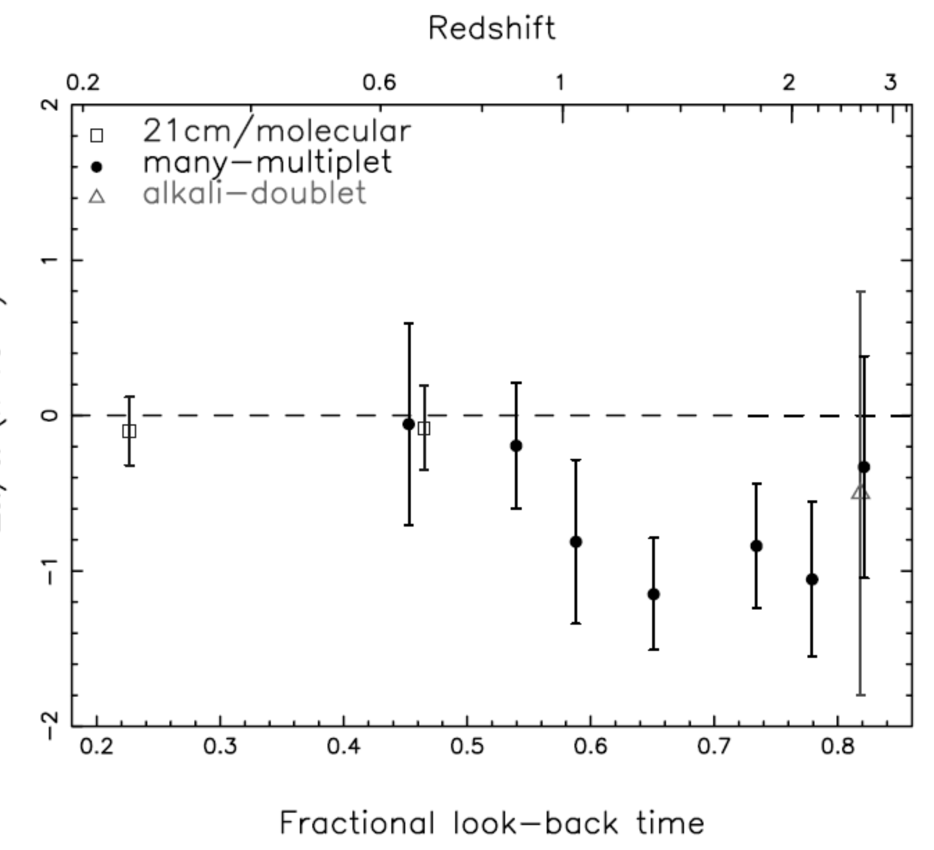
(Received 29 December 2000; published 9 August 2001)

We describe the results of a search for time variability of the fine structure constant α using absorption systems in the spectra of distant quasars. Three large optical data sets and two 21 cm and mm absorption systems provide four *independent* samples, spanning $\sim$23% to 87% of the age of the universe. Each sample yields a smaller α in the past and the optical sample shows a 4σ deviation: $\Delta\alpha/\alpha = -0.72 \pm 0.18 \times 10^{-5}$ over the redshift range $0.5 < z < 3.5$. We find no systematic effects which can explain our results. The only potentially significant systematic effects push $\Delta\alpha/\alpha$ towards *positive* values; i.e., our results would become more significant were we to correct for them.

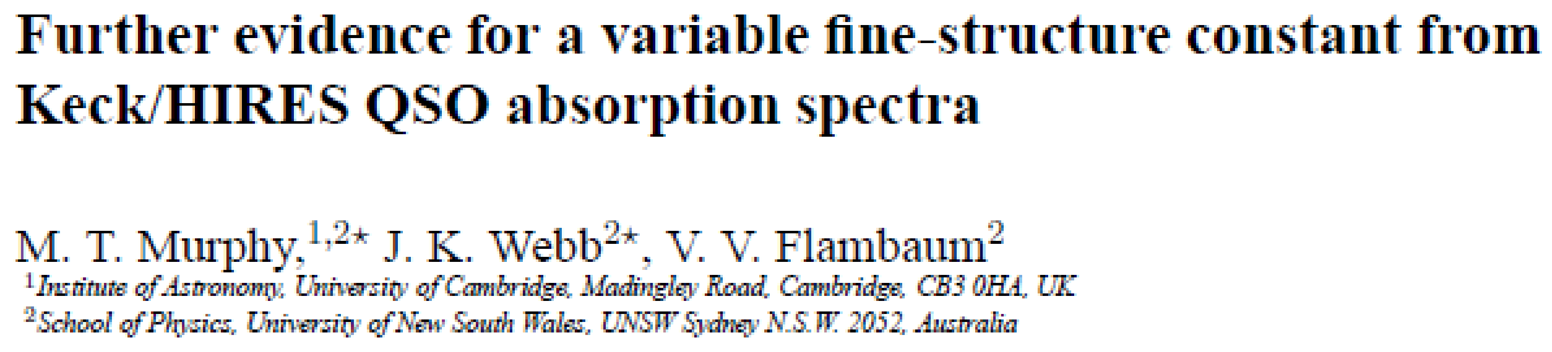
- 72 absorption systems
  (FeII, MgI,II, SiII,NiII,CrII,ZnII,AlII,III)
- 4.1 sigma evidence for α is smaller in the past





$\Delta\alpha/\alpha=(-1.1\pm0.4)\times10^{-5}$ $\Delta\alpha/\alpha=(-0.72\pm0.18)\times10^{-5}$

third sample



Further evidence for a variable fine-structure constant from Keck/HIRES QSO absorption spectra

M. T. Murphy,[1,2⋆] J. K. Webb[2⋆], V. V. Flambaum[2]

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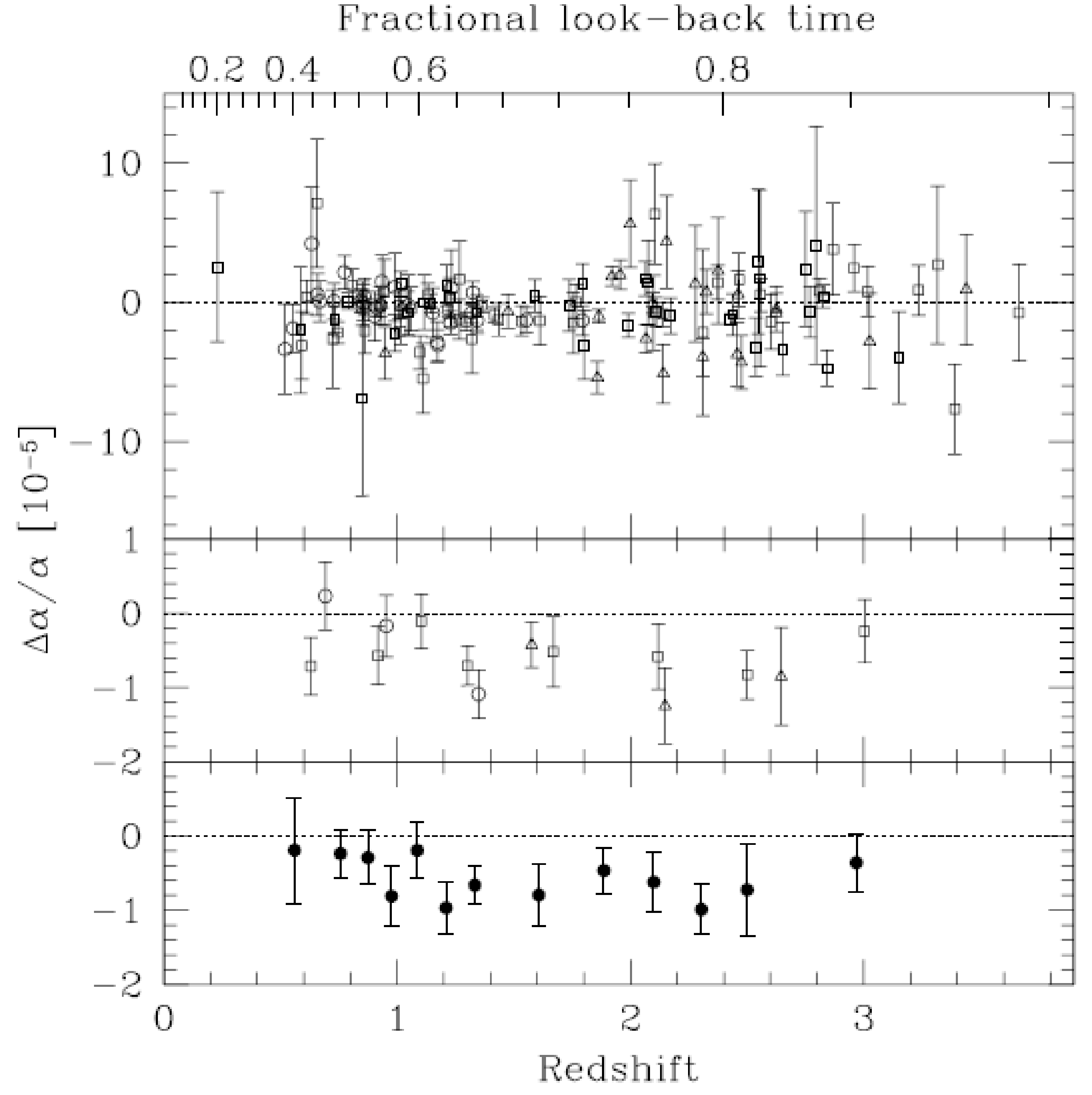
[2] *School of Physics, University of New South Wales, UNSW Sydney N.S.W. 2052, Australia*

- Murphy et al., MNRAS,345(03)609
- 128 absorption systems over 0.2< z< 3.7
- 4.7 sigma evidence for α is smaller is the past

$$\Delta\alpha/\alpha = (-0.543 \pm 0.116) \times 10^{-5}$$


Fractional look-back time
0.2
0.4
0.6
0.8
10
0
−10
1
0
−1
−2
0
−1
−2
Δα/α [10⁻⁵]
0
1
2
3
Redshift

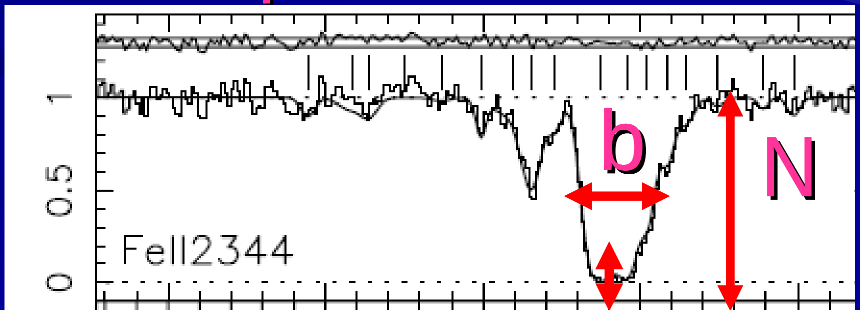
any systematic errors?

- (Webb et al. claim) all sources of systematic only strengthen the result

However...

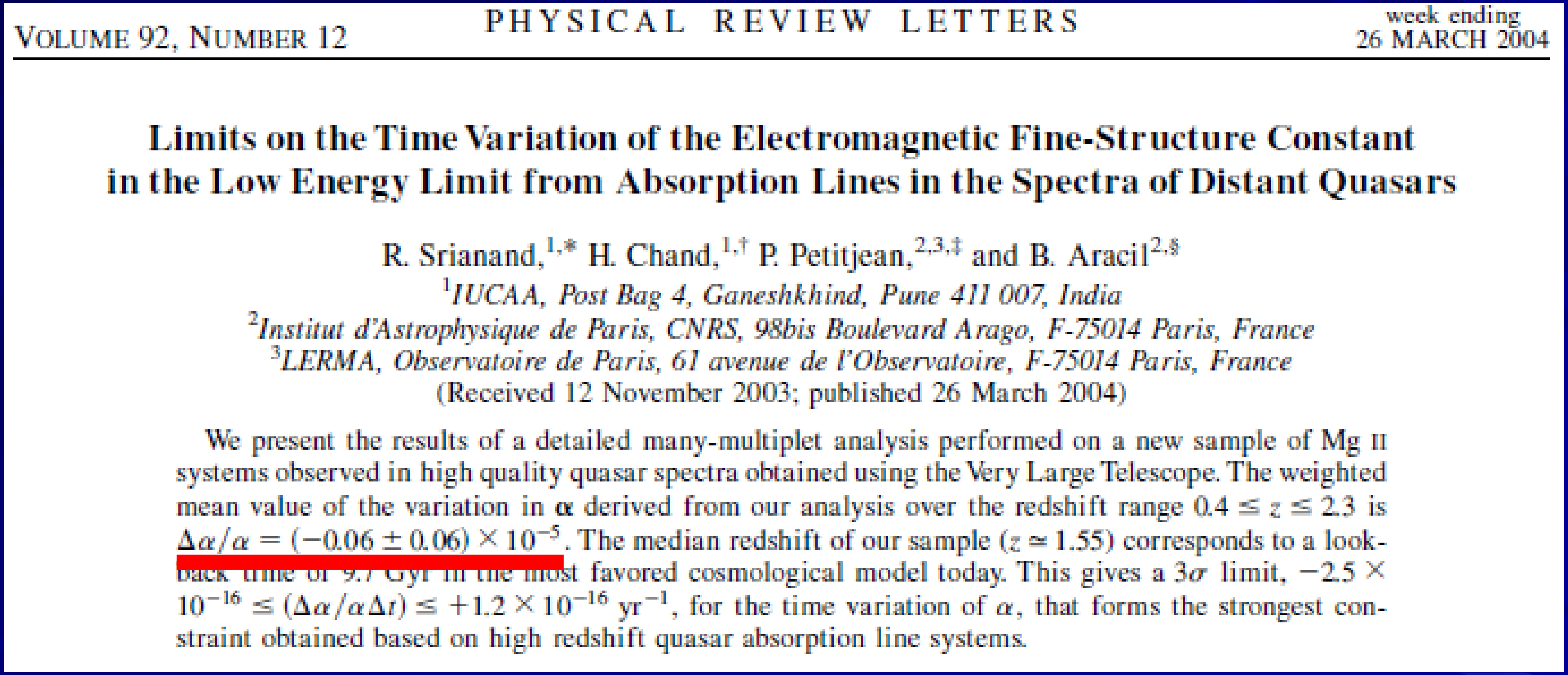
- Many multiplet method suffers from systematic: comparing lines between different species →
- absolute value of wavelength is important
- velocity width of absorption line (of different species) is fitted by common parameter

$b^2 = 2kT/M + b^2_{turb}$



The game is over?

- Srianand et al.,PRL(04)



VOLUME 92, NUMBER 12 PHYSICAL REVIEW LETTERS week ending 26 MARCH 2004

Limits on the Time Variation of the Electromagnetic Fine-Structure Constant in the Low Energy Limit from Absorption Lines in the Spectra of Distant Quasars

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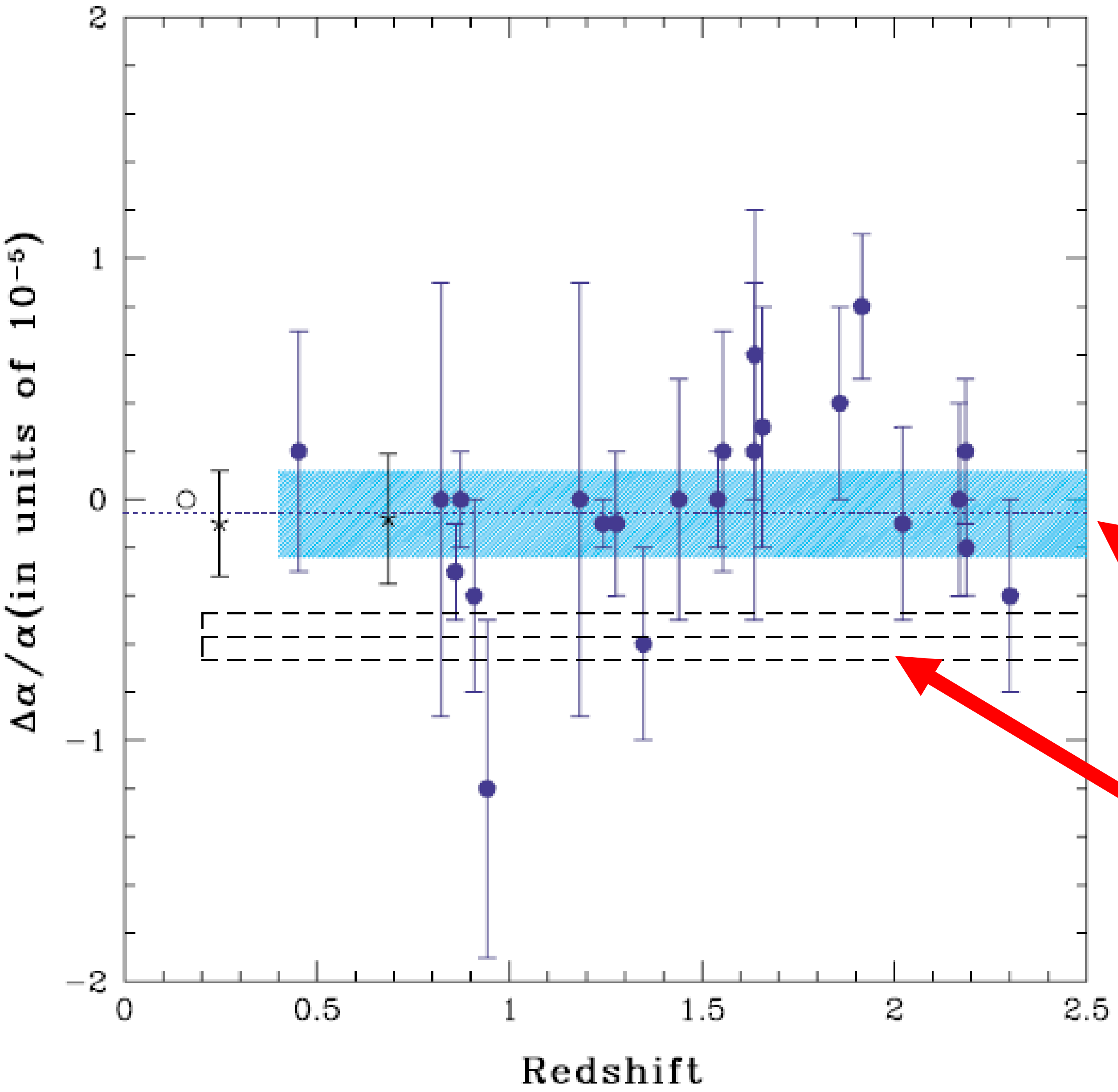
(Received 12 November 2003; published 26 March 2004)

We present the results of a detailed many-multiplet analysis performed on a new sample of Mg II systems observed in high quality quasar spectra obtained using the Very Large Telescope. The weighted mean value of the variation in α derived from our analysis over the redshift range $0.4 \le z \le 2.3$ is $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$. The median redshift of our sample ($z \simeq 1.55$) corresponds to a look-back time of 9.7 Gyr in the most favored cosmological model today. This gives a 3σ limit, $-2.5 \times 10^{-16} \le (\Delta\alpha/\alpha\Delta t) \le +1.2 \times 10^{-16}$ yr^{-1}, for the time variation of α, that forms the strongest constraint obtained based on high redshift quasar absorption line systems.

- 23 absorption systems (MgII only) over $0.4<z<2.3$ by VLT



mean value is inconsistent with Webb et al.

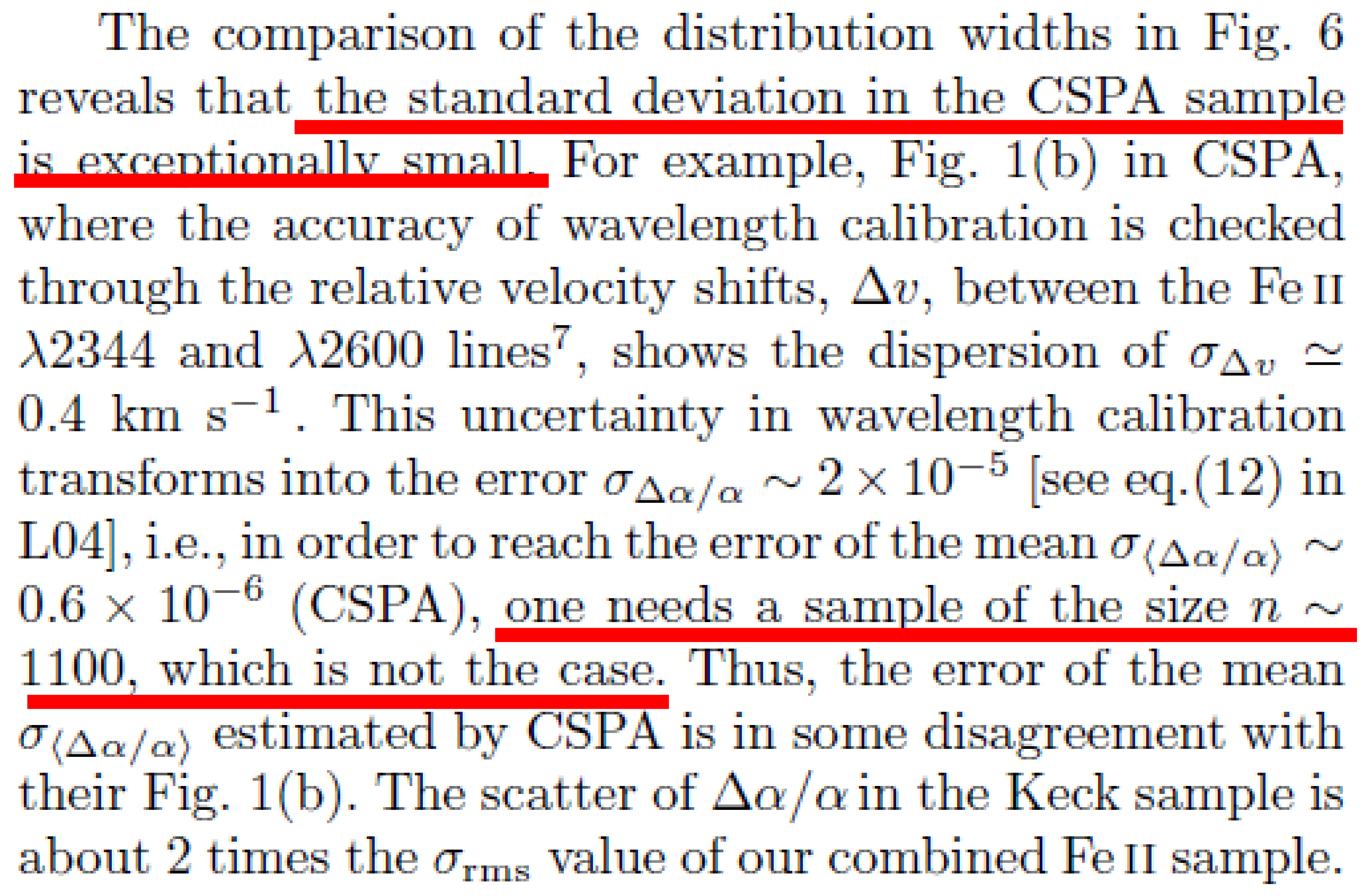
3 sigma region

1 sigma region of Murphy et al (third sample)

$$\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$$

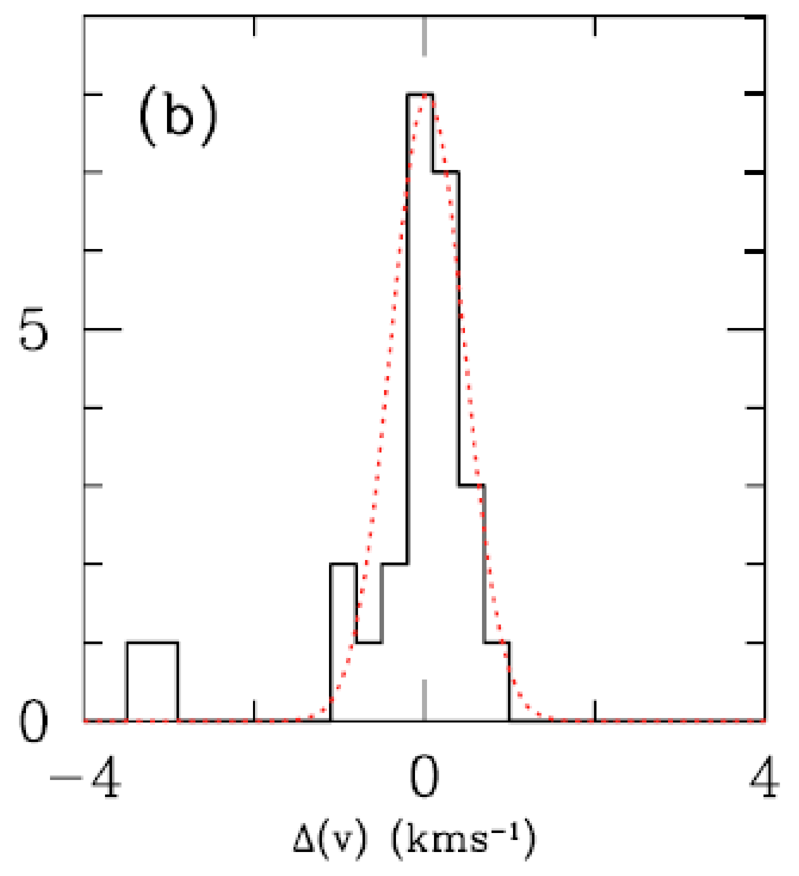
life is not so easy!

Levshakov et al.A&A,434(05)827 (VLT)



The comparison of the distribution widths in Fig. 6 reveals that the standard deviation in the CSPA sample is exceptionally small. For example, Fig. 1(b) in CSPA, where the accuracy of wavelength calibration is checked through the relative velocity shifts, Δv, between the Fe II $\lambda2344$ and $\lambda2600$ lines[7], shows the dispersion of $\sigma_{\Delta v} \simeq 0.4$ km s^{-1}. This uncertainty in wavelength calibration transforms into the error $\sigma_{\Delta\alpha/\alpha} \sim 2 \times 10^{-5}$ [see eq.(12) in L04], i.e., in order to reach the error of the mean $\sigma_{\langle\Delta\alpha/\alpha\rangle} \sim 0.6 \times 10^{-6}$ (CSPA), one needs a sample of the size $n \sim 1100$, which is not the case. Thus, the error of the mean $\sigma_{\langle\Delta\alpha/\alpha\rangle}$ estimated by CSPA is in some disagreement with their Fig. 1(b). The scatter of $\Delta\alpha/\alpha$ in the Keck sample is about 2 times the $\sigma_{\rm rms}$ value of our combined Fe II sample.

trouble in error analysis
(too small error bars)

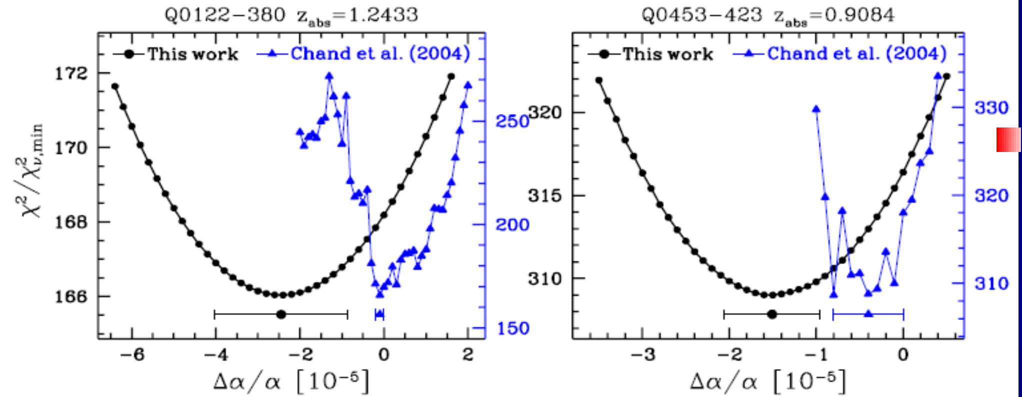


- Chand et al. A&A,417(04)853

sigma(Δv)~0.4 km/s
→sigma($\Delta\alpha/\alpha$)~2x10^{-5}

In order to reduce the dispersion below 0.06x10^{-5},
N~1100 samples are required
(from 2x$10^{-5}/\sqrt{N}=0.06$x10^{5})
↔ only 23 samples are used

Debate between
Murphy et al. and Srianand et al. (2007)



- Srianand's χ^2 curves zigzagged：presumably due to the small number of iteration
- In fact, our minimization of χ^2 using Srianand's data with their best fit as the initial guess gives smooth χ^2 curves and different best fitting values and different error bars
- Our reanalysis gives

$\Delta\alpha/\alpha$=(-0.44±0.16)x10^{-5}

Srianand's error bar was underestimated

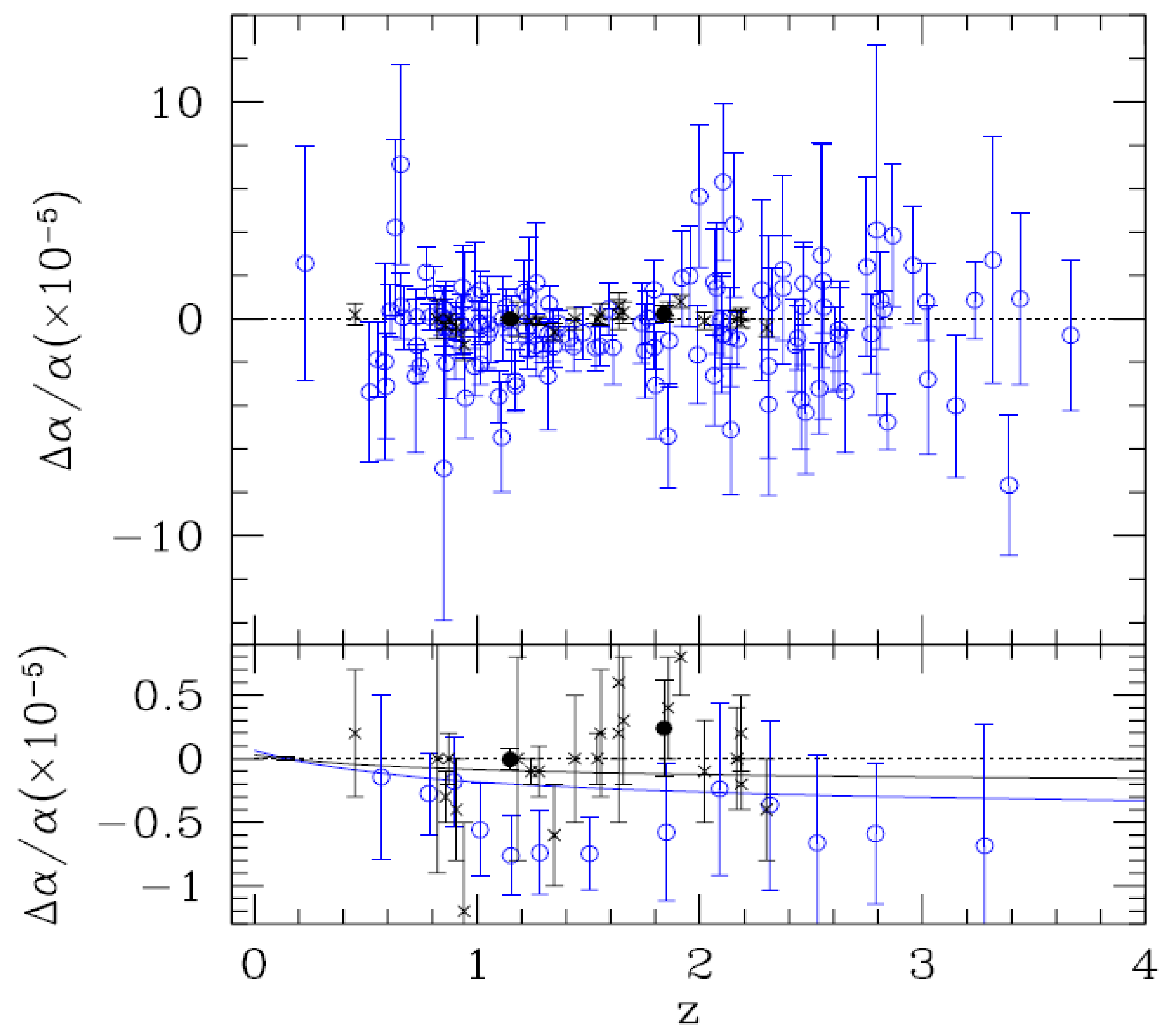
- χ^2 curves get smoothed after the large number of iteration, but the new results are consistent with Murphy's and with our original ones within1σ
- The errors used by Murphy are underestimated（？）
- Murphy's measurements match ours at <1σ for 16 systems（？）
- Only 2 system >4 σ deviant systems dominate the result by Murphy ：

Excluding these systems gives

$\Delta\alpha/\alpha$=(0.01±0.15)x10^{-5} ????

⇔their original claim:

$\Delta\alpha/\alpha$=(-0.06±0.06)x10^{-5}



○（blue）Webb e
(Keck)

× Srianand et a
(VLT)

● Levshakov et
(VLT)

binned data

$$\Delta\alpha/\alpha = 2.93(\pm 1.80)\times 10^{-7} - 2.31(\pm 1.01)\times 10^{-6}(1-a)$$

$$\Delta\alpha/\alpha = 6.08(\pm 2.22)\times 10^{-7} - 4.85(\pm 1.46)\times 10^{-6}(1-a)$$

(when used Murphy et al.(2008) which reanalyzed Srianand et al.)

$\Delta\alpha/\alpha$ = (-0.543+-0.116)x10^{-5}

(Murphy et al.)

?? (0.06+-0.06) x10^{-5}

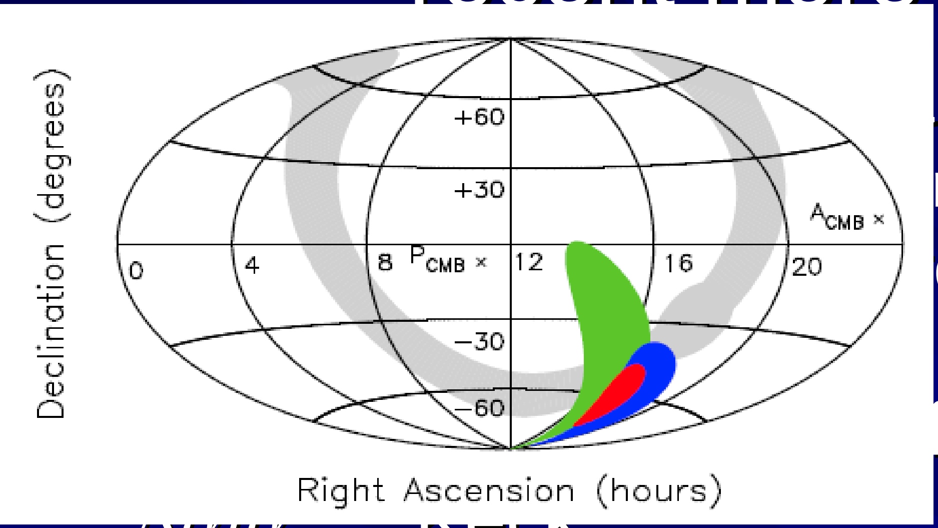
(Srianand et al.)??

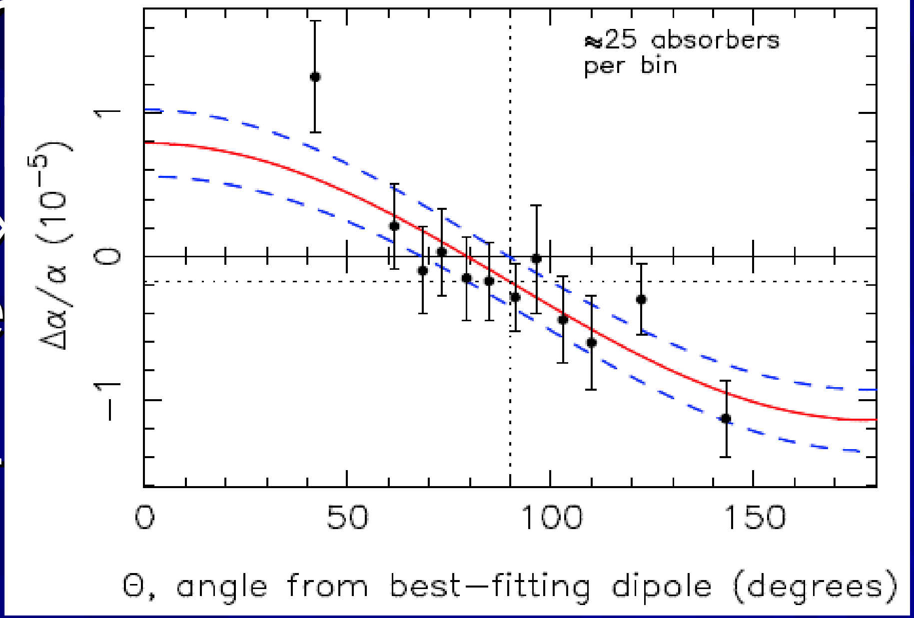
(0.4+-1.5)x10^{-6}

(Levshakov et al.)

FeII at z=1.84,1.15

recent more r





$\Delta\alpha/\alpha$	Keck	
z<1.8	$(-0.54\pm0.12)\mathrm{x}10^{-5}$	$(-0.06\pm0.16)\mathrm{x}10^{-5}$
z>1.8	$(-0.74\pm0.17)\mathrm{x}10^{-5}$	$(+0.61\pm0.20)\mathrm{x}10^{-5}$

- Keck: α was smaller in the past

  VLT: α was larger in the past!

  →consistent with zero when averaged?
- Both observed different directions

  → spatial dependence
- $\Delta\alpha/\alpha=(1.10\pm0.25)\mathrm{x}10^{-6}\ r/(\mathrm{Glyr})\cos\theta$

CMB

- changing α affects recombination process of hydrogen

via changing the binding energy of hydrogen:

$$B = \alpha^2 m_e^2 / 2$$

and changing the Thomson cross section and hence optical depth:

$$\sigma_T = 8\pi\alpha^2 / 3m_e^2$$

$$\tau = \int^{t0} x_e n_e \sigma_T dt$$

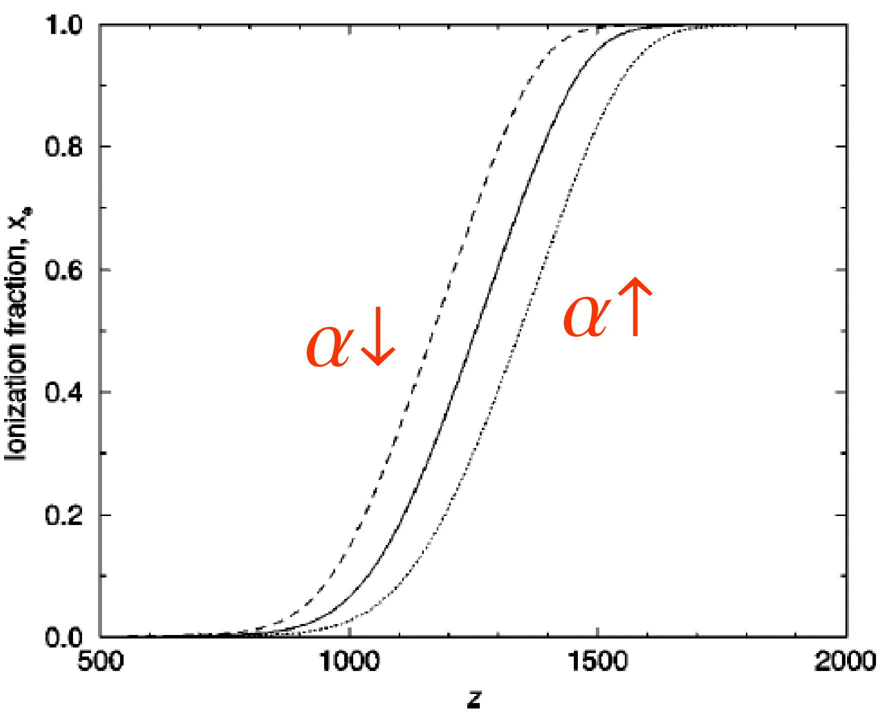
- from Saha equation,

the ionization fraction x_e is

$$\frac{x_e^2}{1-x_e} = \frac{1}{n}\left(\frac{m_e T}{2\pi}\right)^{3/2} \exp(-B/T)$$

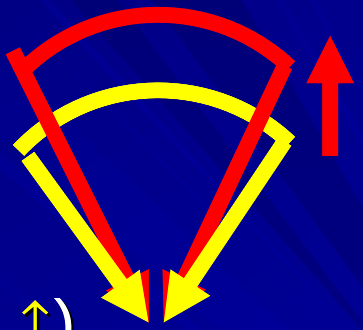
- larger α results in smaller

ionization fraction x_e ↑ and hence in earlier recombination



CMB: Effects on CMB spectrum

- peak location: larger α changes the sustaining angle of the last scattering surface (peak location is shifted toward higher multipole)
- amplitutde:



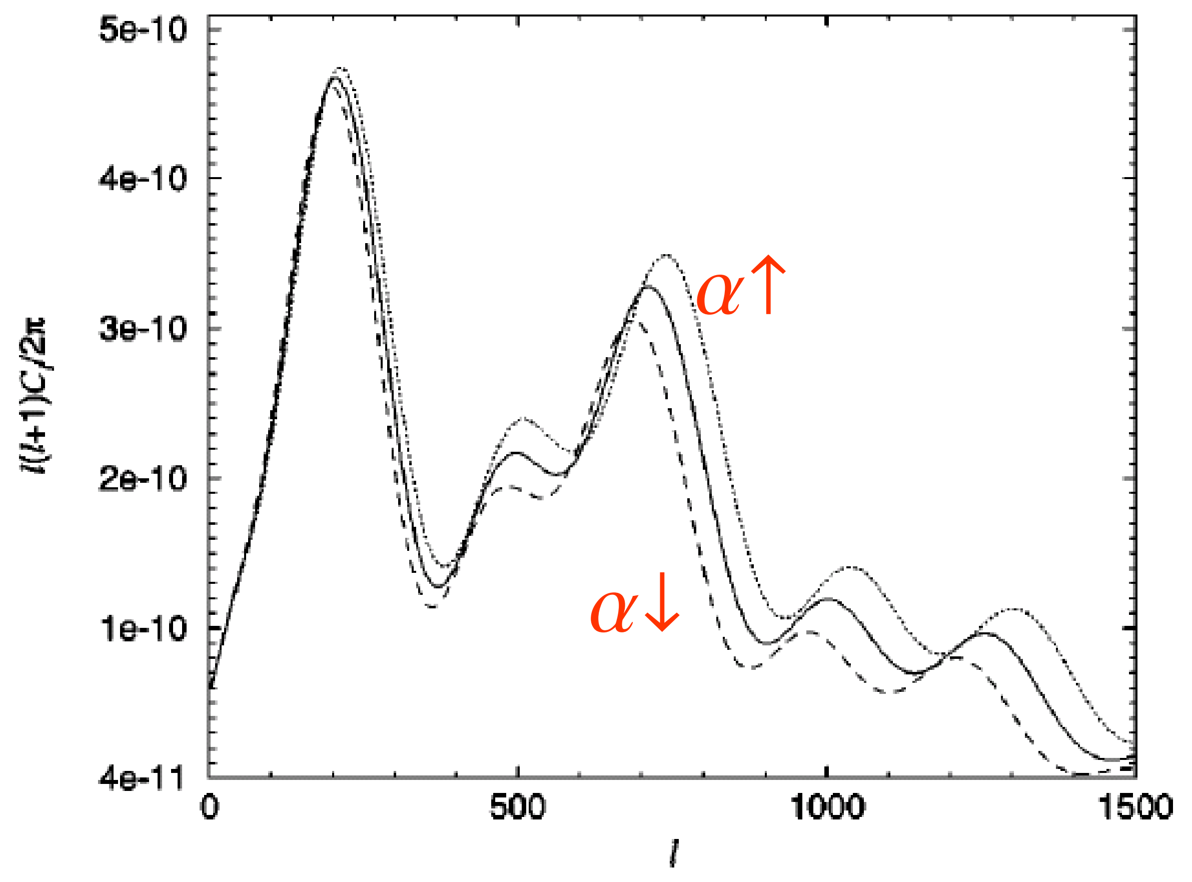
first peak: early ISW ↑(blueshift due to
the decay of grav. pot.) (z_{rec} ↑ for α ↑)

beyond the first: diffusion damping due to
the thickness of the last scattering surface

Damping factor $\propto$ $\exp(-\lambda_D^2/\lambda^2)$; $\lambda_D \sim \sqrt{(H^{-1}/x_e n_e \sigma_T)}$

for α ↑ ⇒ thickness of LSS ↓ ⇒ D ↓

CMB



Kaplinghat et al. (1999)

$-0.06<(\alpha_{\rm dec}-\alpha_0)/\alpha_0<0.01$ (2 sigma) (WMAP1)(Martins et al.,04)

$-0.028<(\alpha_{\rm dec}-\alpha_0)/\alpha_0<0.026$ (WMAP5+HST) (Nakashima et al. ,08)

$-0.013<(\alpha_{\rm dec}-\alpha_0)/\alpha_0<0.015$

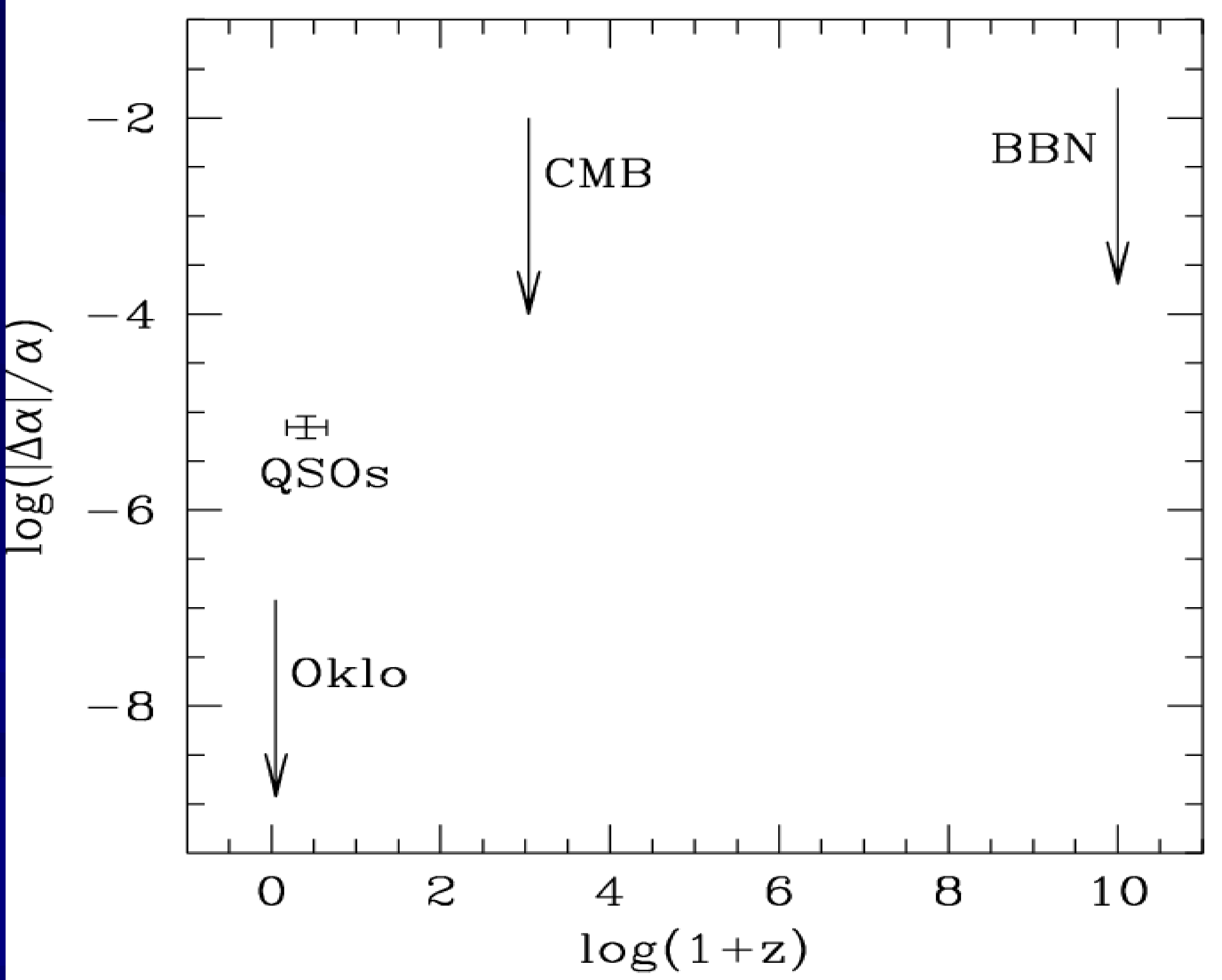
(WMAP5+ACBAR/QUAD/BICEP+HST, Menegoni et al., 09)

BBN

- affects the neutron-proton mass difference Q(=1.29MeV)
- larger α results in smaller Q:
  $Q=1.29 - 0.76\ \Delta\alpha/\alpha\,(\mathrm{MeV})$ (Gasser-Leutwyler(82))
- results in larger amount of ^{4}He:
  $n/p \sim \exp(-Q/T_f)$

$|\Delta\alpha/\alpha| < 0.06$ (Cyburt et al.2005)

QSO and Oklo



Atomic Clock

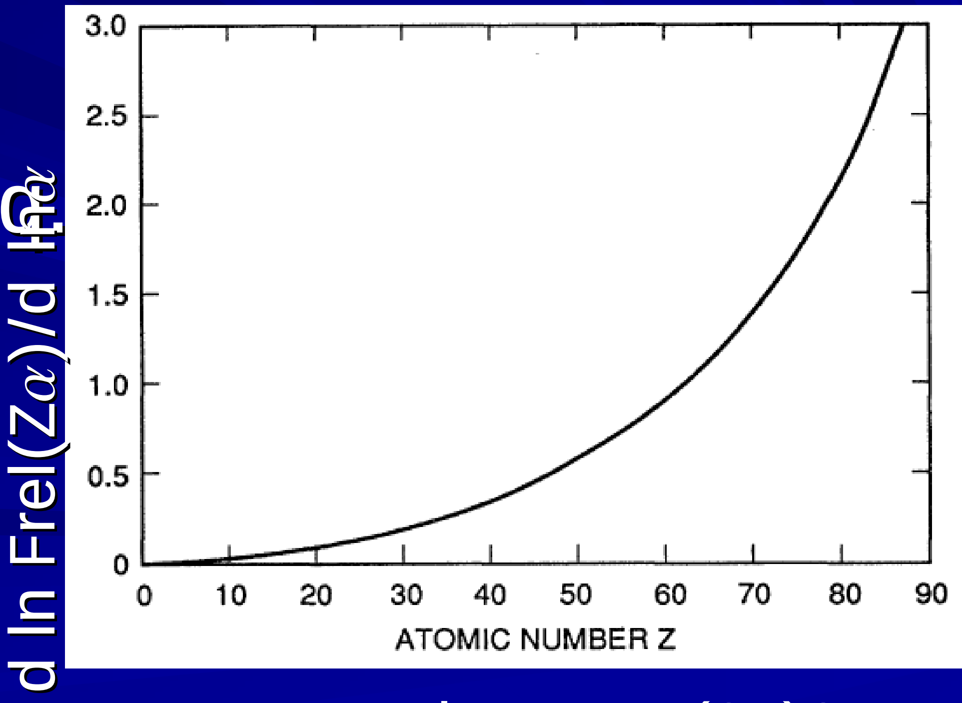
- Definition of the second: “the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom”

- hyperfine transition freq.

$\propto Z\alpha^2 \mu_N (m_e/m_p) F_{rel}(Z\alpha)$

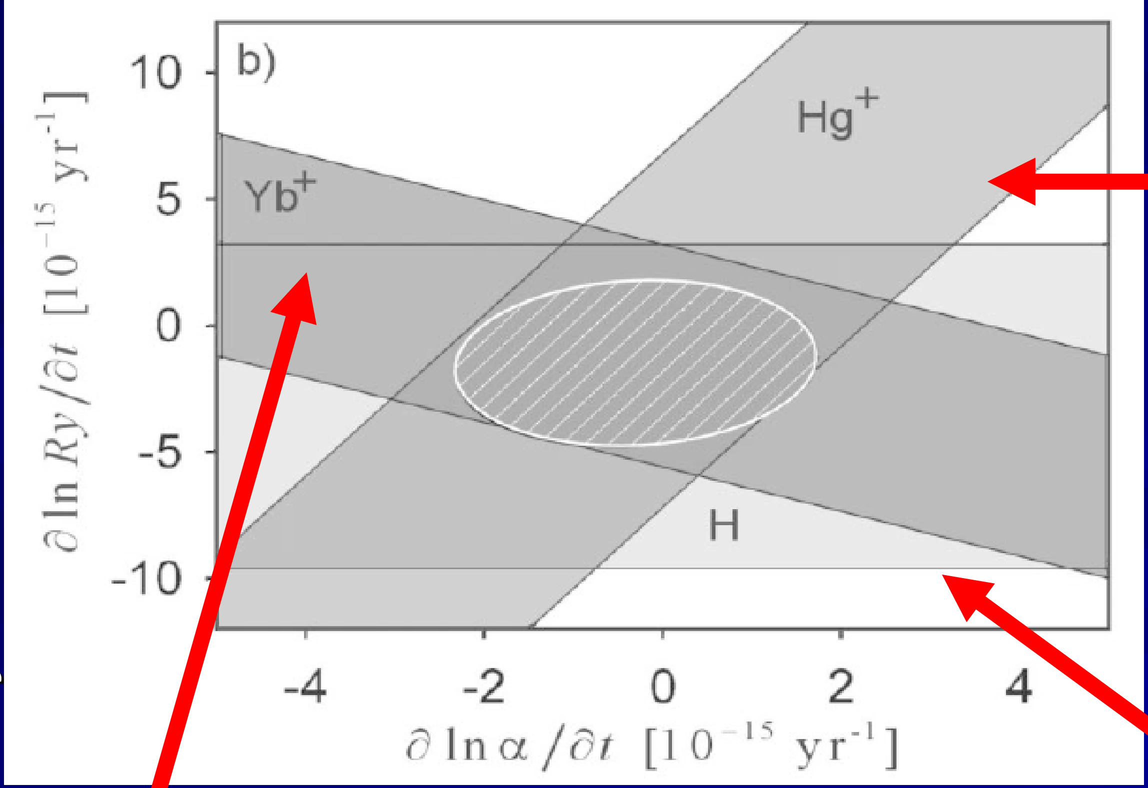
- clock comparison

→ constraint on time varying α



Prestage et al.,PRL,74(95)3511

$R_y = \alpha^2 m_e c / 4\pi\hbar$



Bize et al.,
PRL,90(03)150802

Fisher et al.,
PRL,92(04)230802

Peik et al.,PRL,93(04)170801

Cs ~ 9GHz(microwave) ; optical~ 10^5GHz

- H-maser vs. Hg^+ clock (140 days):

  $|d\alpha/dt/\alpha| < 3.7 \times 10^{-14}\ yr^{-1}$

  Prestage et al., PRL,74(95)3511
- Hg^+ optical clock vs. Cs hyperfine (2 yrs):

  $|d\alpha/dt/\alpha| < 1.2 \times 10^{-15}\ yr^{-1}$

  Bize et al.,PRL,90(03)150802
- Comparing above two with the comparison of 1S-2S in H with Cs hyperfine (3.7 yrs):

  $d\alpha/dt/\alpha = (-0.9\pm2.9) \times 10^{-15}\ yr^{-1}$

  Fisher et al.,PRL,92(04)230802
- Yb optical clock vs. Hg^+ optical clock (2.8 yrs):

  $d\alpha/dt/\alpha = (-0.3\pm2.0) \times 10^{-15}\ yr^{-1}$

  Peik et al.,PRL,93(04)170801
- Al+ optical clock vs. Hg+ optical clock(1 yr):

  $d\alpha/dt/\alpha = (-1.6\pm2.3) \times 10^{-17}\ yr^{-1}$

  Rosenband et al., Science 319(08)808

  ($\Delta\nu/\nu$=5.2x10^{-7}; cf. grav. redshift $\Delta\nu/\nu \simeq 10^{-8}$

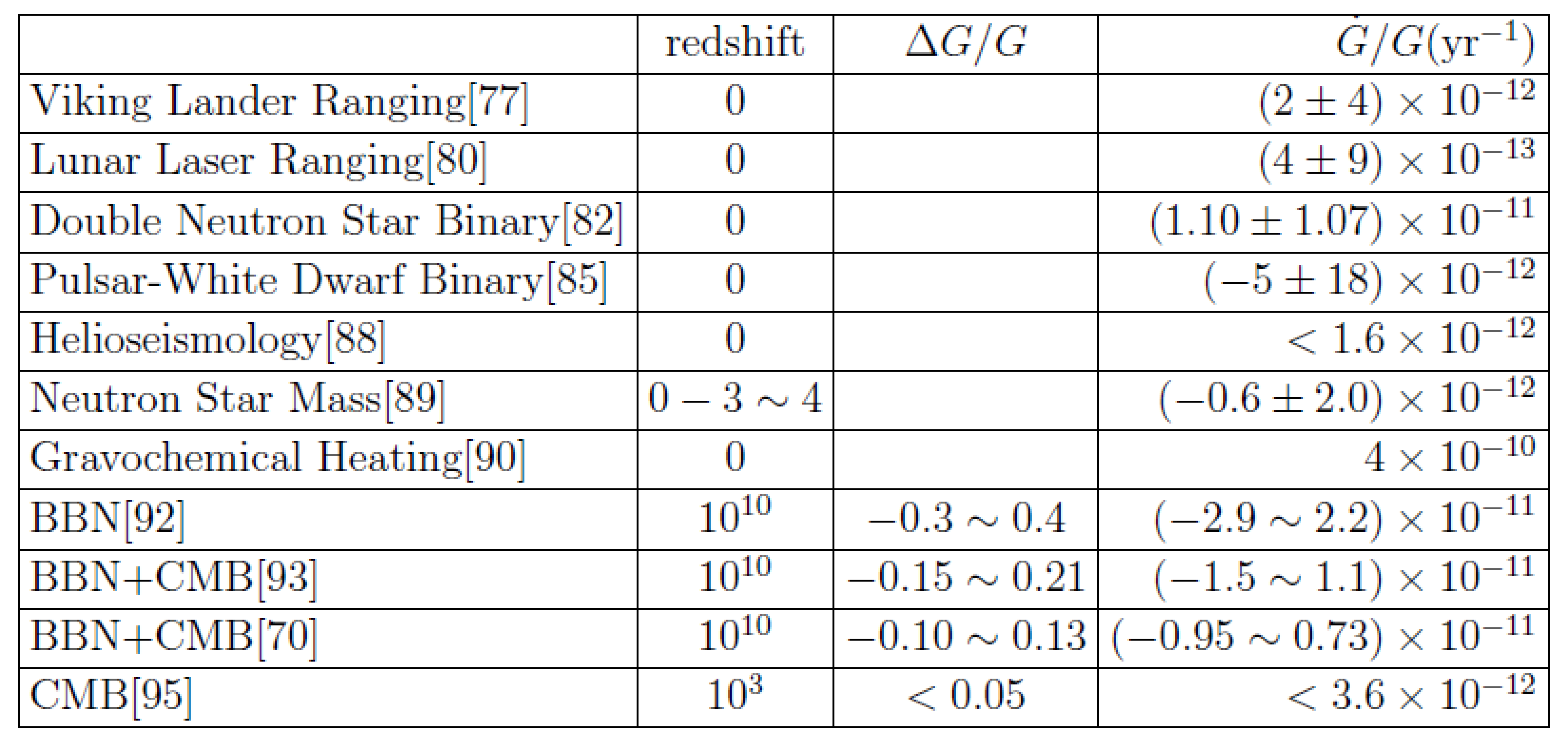
  geoid map via optical clock?)

Conclusion:G

- G: $z=10^{10}$ (BBN) $-0.10<(G_{BBN}-G_0)/G_0<0.13$
  $z=1100$ (CMB) $(G_{recom}-G_0)/G_0<0.05$
  $z=0$ (LRR) $dG/dt/G=(4\pm9)\times10^{-13}\ yr^{-1}$
  (pulsar) $dG/dt/G=(1\pm1)\times10^{-11}\ yr^{-1}$

$\Delta G/\Delta t/G < 10^{-3\sim-1}\ H_0$

Dirac's larger number hypothesis is ruled out



	redshift	$\Delta G/G$	$\dot{G}/G(\mathrm{yr}^{-1})$
Viking Lander Ranging[77]	0		$(2 \pm 4) \times 10^{-12}$
Lunar Laser Ranging[80]	0		$(4 \pm 9) \times 10^{-13}$
Double Neutron Star Binary[82]	0		$(1.10 \pm 1.07) \times 10^{-11}$
Pulsar-White Dwarf Binary[85]	0		$(-5 \pm 18) \times 10^{-12}$
Helioseismology[88]	0		$< 1.6 \times 10^{-12}$
Neutron Star Mass[89]	$0 - 3 \sim 4$		$(-0.6 \pm 2.0) \times 10^{-12}$
Gravochemical Heating[90]	0		4×10^{-10}
BBN[92]	10^{10}	$-0.3 \sim 0.4$	$(-2.9 \sim 2.2) \times 10^{-11}$
BBN+CMB[93]	10^{10}	$-0.15 \sim 0.21$	$(-1.5 \sim 1.1) \times 10^{-11}$
BBN+CMB[70]	10^{10}	$-0.10 \sim 0.13$	$(-0.95 \sim 0.73) \times 10^{-11}$
CMB[95]	10^{3}	< 0.05	$< 3.6 \times 10^{-12}$

Conclusion: α

- α:

  $z=10^{10}$ (BBN) $|\Delta\alpha/\alpha| < 0.06$

  $z=1100$ (CMB) $-0.013<(\alpha_{recom}- \alpha_0)/\alpha_0 <0.015$

  $z=1\sim3$ (QSO) $\Delta\alpha/\alpha = (-0.543 \pm 0.116)\mathrm{x}10^{-5}$ (Murphy et al.)

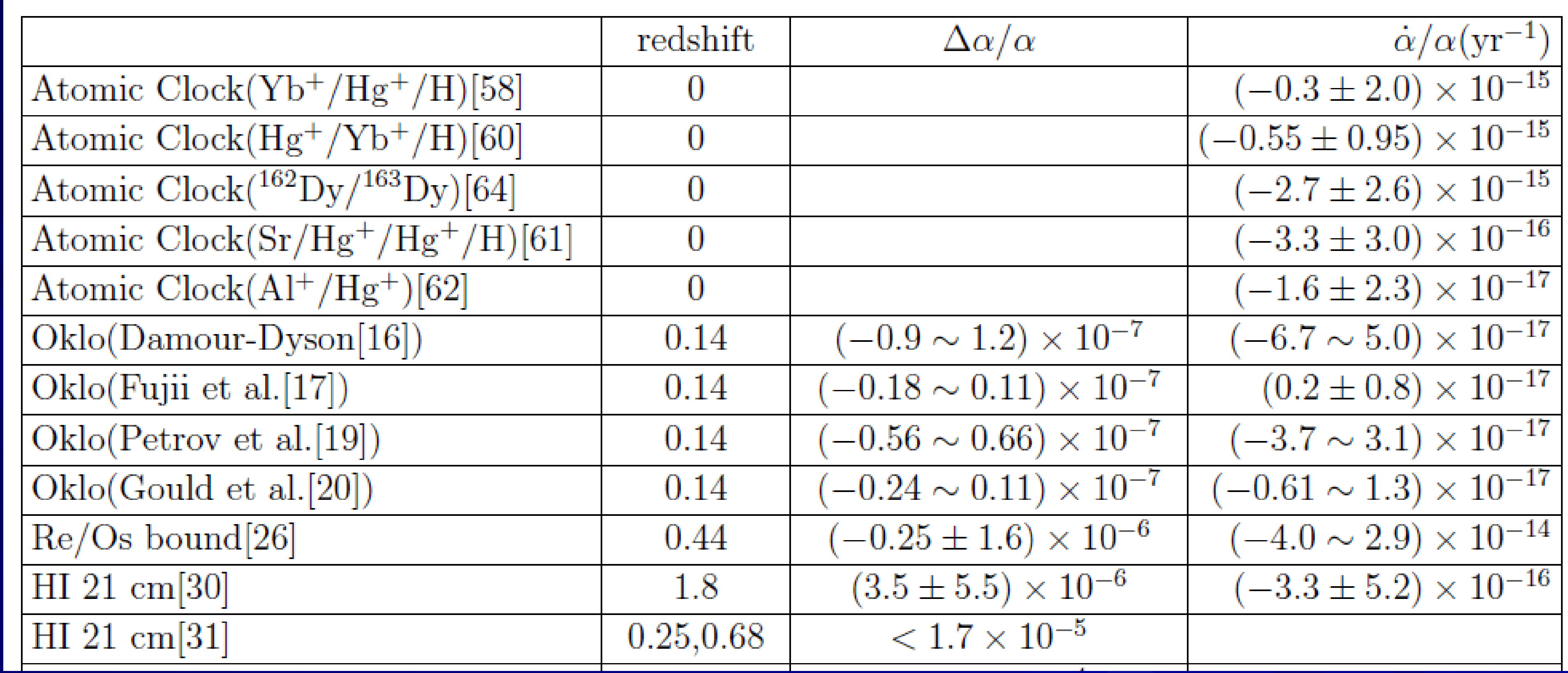
  $(0.4 \pm 1.5)\mathrm{x}10^{-6}$ (Levshakov et al.)

  $z=0.14$ (Oklo) $\Delta\alpha/\alpha = (0.4 \pm 1.6)\mathrm{x}10^{-8}$

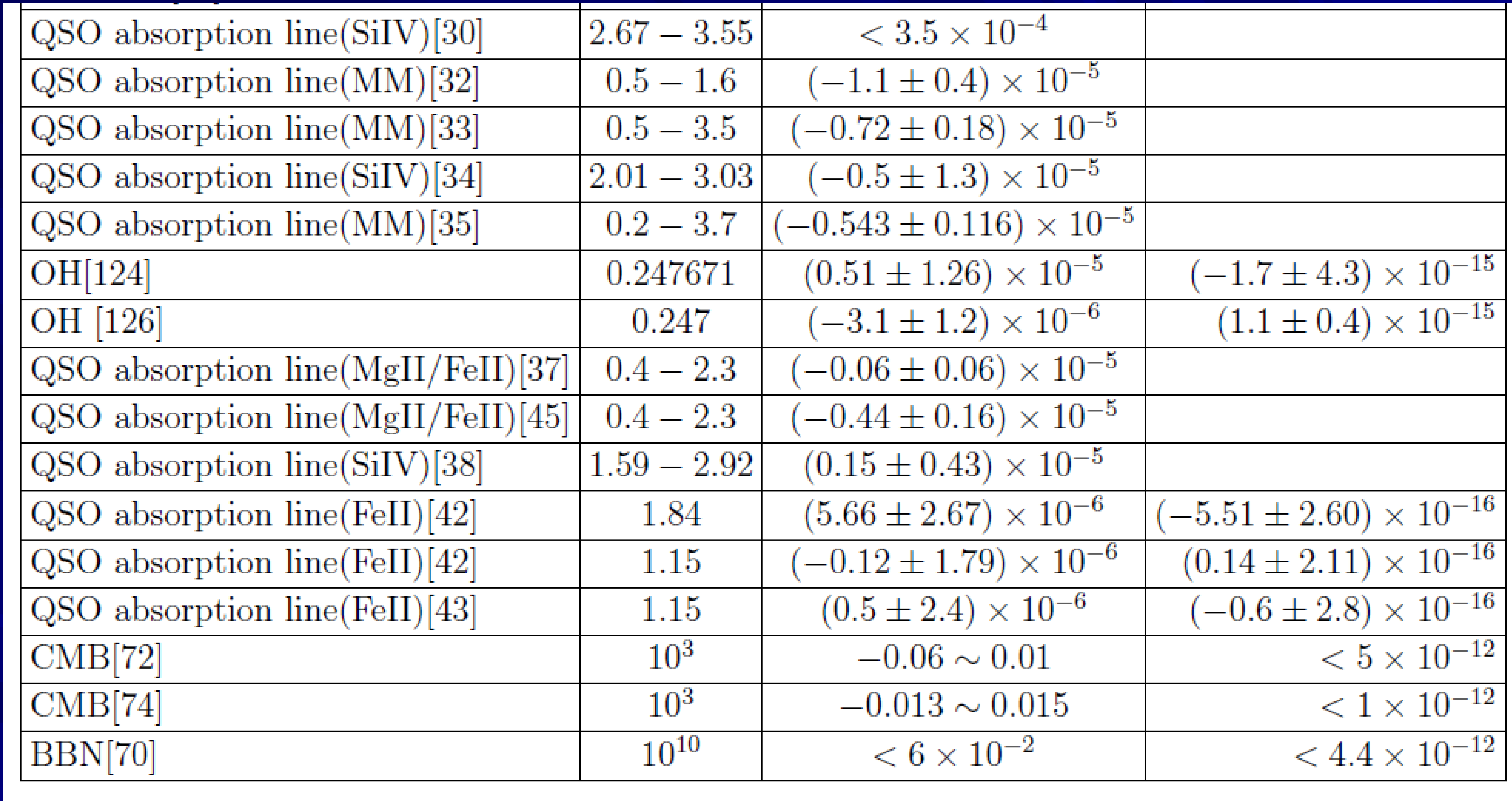
  $\Delta\alpha/\Delta t/\alpha < 10^{-2\sim-8} H_0$

  $z=0$ (Atomic clock)

  $|d\alpha/dt/\alpha| < 3.9 \times 10^{-17}\ \mathrm{yr}^{-1}$



	redshift	$\Delta\alpha/\alpha$	$\dot{\alpha}/\alpha(\mathrm{yr}^{-1})$
Atomic Clock($Yb^+/Hg^+/H$)[58]	0		$(-0.3 \pm 2.0) \times 10^{-15}$
Atomic Clock($Hg^+/Yb^+/H$)[60]	0		$(-0.55 \pm 0.95) \times 10^{-15}$
Atomic Clock($^{162}Dy/^{163}Dy$)[64]	0		$(-2.7 \pm 2.6) \times 10^{-15}$
Atomic Clock($Sr/Hg^+/Hg^+/H$)[61]	0		$(-3.3 \pm 3.0) \times 10^{-16}$
Atomic Clock(Al^+/Hg^+)[62]	0		$(-1.6 \pm 2.3) \times 10^{-17}$
Oklo(Damour-Dyson[16])	0.14	$(-0.9 \sim 1.2) \times 10^{-7}$	$(-6.7 \sim 5.0) \times 10^{-17}$
Oklo(Fujii et al.[17])	0.14	$(-0.18 \sim 0.11) \times 10^{-7}$	$(0.2 \pm 0.8) \times 10^{-17}$
Oklo(Petrov et al.[19])	0.14	$(-0.56 \sim 0.66) \times 10^{-7}$	$(-3.7 \sim 3.1) \times 10^{-17}$
Oklo(Gould et al.[20])	0.14	$(-0.24 \sim 0.11) \times 10^{-7}$	$(-0.61 \sim 1.3) \times 10^{-17}$
Re/Os bound[26]	0.44	$(-0.25 \pm 1.6) \times 10^{-6}$	$(-4.0 \sim 2.9) \times 10^{-14}$
HI 21 cm[30]	1.8	$(3.5 \pm 5.5) \times 10^{-6}$	$(-3.3 \pm 5.2) \times 10^{-16}$
HI 21 cm[31]	0.25,0.68	$< 1.7 \times 10^{-5}$	

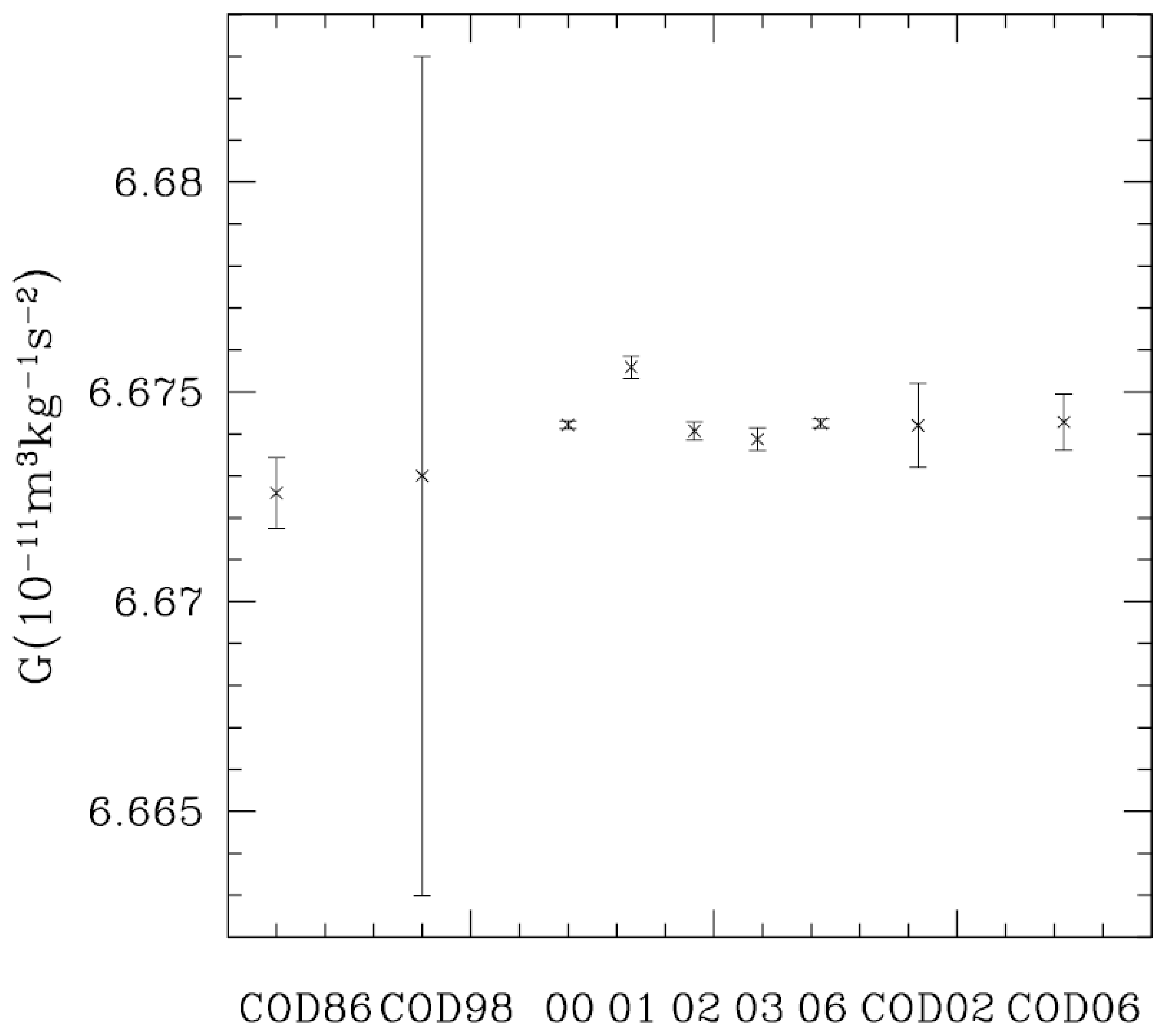


QSO absorption line(SiIV)[30]	$2.67 - 3.55$	$< 3.5 \times 10^{-4}$	
QSO absorption line(MM)[32]	$0.5 - 1.6$	$(-1.1 \pm 0.4) \times 10^{-5}$	
QSO absorption line(MM)[33]	$0.5 - 3.5$	$(-0.72 \pm 0.18) \times 10^{-5}$	
QSO absorption line(SiIV)[34]	$2.01 - 3.03$	$(-0.5 \pm 1.3) \times 10^{-5}$	
QSO absorption line(MM)[35]	$0.2 - 3.7$	$(-0.543 \pm 0.116) \times 10^{-5}$	
OH[124]	0.247671	$(0.51 \pm 1.26) \times 10^{-5}$	$(-1.7 \pm 4.3) \times 10^{-15}$
OH [126]	0.247	$(-3.1 \pm 1.2) \times 10^{-6}$	$(1.1 \pm 0.4) \times 10^{-15}$
QSO absorption line(MgII/FeII)[37]	$0.4 - 2.3$	$(-0.06 \pm 0.06) \times 10^{-5}$	
QSO absorption line(MgII/FeII)[45]	$0.4 - 2.3$	$(-0.44 \pm 0.16) \times 10^{-5}$	
QSO absorption line(SiIV)[38]	$1.59 - 2.92$	$(0.15 \pm 0.43) \times 10^{-5}$	
QSO absorption line(FeII)[42]	1.84	$(5.66 \pm 2.67) \times 10^{-6}$	$(-5.51 \pm 2.60) \times 10^{-16}$
QSO absorption line(FeII)[42]	1.15	$(-0.12 \pm 1.79) \times 10^{-6}$	$(0.14 \pm 2.11) \times 10^{-16}$
QSO absorption line(FeII)[43]	1.15	$(0.5 \pm 2.4) \times 10^{-6}$	$(-0.6 \pm 2.8) \times 10^{-16}$
CMB[72]	10^{3}	$-0.06 \sim 0.01$	$< 5 \times 10^{-12}$
CMB[74]	10^{3}	$-0.013 \sim 0.015$	$< 1 \times 10^{-12}$
BBN[70]	10^{10}	$< 6 \times 10^{-2}$	$< 4.4 \times 10^{-12}$

Other Issues/Future

- m_p/m_e via
- laboratory

$\Delta G/G \sim 10^{-4}$



$10^{-4} \rightarrow 10^{-3} \rightarrow 10^{-5} \quad (10^{-4})$

We need independent measurements of $\Delta\alpha/\alpha \neq 0$

because

extraordinary claims require extraordinary evidence (Carl Sagan)

(Page 1)

Subaru Telescope
National Astronomical Observatory of Japan

Semester	S04a
Proposal ID	048
Received	/ /

Application Form for Telescope Time

1. Title of Proposal

Testing the Possible Time Variation of Fine Structure Constant

2. Principal Investigator

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3. Scientific Category

☐ Solar System
☐ Compact Objects and SNe
☐ Nearby Galaxies
☐ Clusters of Galaxies
☐ Large-Scale Structure
☐ Normal Stars
☐ Milky Way
☐ Starburst Galaxies
☐ Gravitational Lenses
☐ Cosmological Parameters
☐ Extrasolar Planets
☐ Local Group
☐ AGN and QSO Activity
☐ High-z Galaxies
☐ Miscellaneous
☐ Star and Planet Formation
☐ ISM
☑ QSO Absorption Lines and IGM
☐ Deep Surveys

4. Abstract *(approximately 200 words)*

We propose to launch a program aiming at studying the time variation of fine structure constant ($\alpha = 2\pi e^2/hc$) over cosmological time-scale by measuring absolute wavelengths of QSO metal absorption lines at high redshift. Recently John Webb's group found a possible time variation $\Delta\alpha/\alpha = -0.57 \pm 0.10 \times 10^{-5}$ at $0.2 \leq z \leq 3.7$ using Keck HIRES data. If this variation is confirmed, it will have a huge impact on cosmology. However, their results are relying only on a single instrument and a single group and it is essential to conduct an independent research from Webb's group to confirm or refute the time variation of α. We propose to obtain high quality spectra of a large number of QSO absorption lines utilizing the high-spectral resolution and high sensitivity of Subaru HDS. Subaru HDS is the unique independent instrument for this purpose. Thanks to better spectral resolution (R > 75,000 compared to R=45,000 of Kech HIRES data) and the fine pixel sampling (0.9 km s^{-1} for Subaru HDS while 2.2 km s^{-1} for Keck HIRES), we can achieve roughly twice better accuracy for α measurement per object. With these advantages, we even hope to constrain some of the basic assumptions in Webb's analysis, to which others questioned.

5. Co-Investigators

Name	Institute	Name	Institute
Takeshi Chiba	Kyoto University	Naoshi Sugiyama	NAOJ
Masanori Iye	NAOJ	Yosuke Minowa	Tokyo University
Yuzuru Yoshii	IoA, University of Tokyo		
Chris Churchill	Penn State Univ.		
Takuji Tsujimoto	NAOJ		

6. List of Applicants' Related Publications *(last 5 years)*

- Chiba, Takeshi; Kohri, Kazunori 2002, Prog. of Theor. Phys., 107, 631, *Quintessence Cosmology and Varying α*
- Chiba, Takeshi 2001, gr-qc/0110118, in the proceedings of Frontier of Cosmology and Gravitation, *The Constancy of the Constants of Nature*
- Chiba, Takeshi 1999, Phys. Rev. D, 60, 083508, *Quintessence, the Gravitational Constant, and Gravity*
- Kobayashi, N., Terada, H., Goto, M., & Tokunaga, A. T. 2002, ApJ, 569, 676, *"Mg II Absorption Lines in z=2.974 Damped Lyman-α system toward Gravitationally Lensed QSO APM 08279+5255: Detection of Small-scale Structure in Mg II Absorbing Clouds"*
- Misawa, Toru; Tytler, David; Iye, Masanori; Storrie-Lombardi, Lisa J.; Suzuki, Nao; Wolfe, Arthur M. 2002, AJ, 123, 1847, *C IV and other Metal Absorption Line Systems in 18 z=4 Quasars*
- Churchill, C. W., et al. 2000, ApJ, 543, 577, *Low and High Ionization Absorption Properties of Mg II Absorption Selected Galaxies II. Taxonomy, Kinematics, and Galaxies*
- Churchill, C. W., et al. 2000, ApJS, 130, 91, *Low and High Ionization Absorption Properties of Mg II Absorption Selected Galaxies I. General Properties*

Last modified 08/22/03

We have observed QSO absorption lines by Subaru
(PI Naoto Kobayashi)
(Aug,2004)

the result is...

not yet to come
(sorry)

varying alpha via runaway dilaton

- predicts the violation of weak equivalence principle (Dvali-Zaldarriaga;Chiba-Kohri):

α dependence of proton mass is different from that of neutron mass

$\eta=(a_1-a_2)/a\sim10^{-17}$

← potentially detectable by STEP