物理"定数"の時間変化
と宇宙論

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Motivation

history

Dirac's large number hypothesis
(1938)

large dimensionless numbers including "G":

$$N_1 = \frac{(\text{Coulomb force})}{(\text{Gravity force})} = \frac{(\text{古典電子半径})}{(\text{proton の Sch. 半径})}$$

$$= \frac{e^2}{G m_p m_e} \approx 10^{40}$$

: Simply Gravity is weak!

$$N_2 = \frac{(\text{horizon radius})}{(\text{古典電子半径})}$$

$$= \frac{H_0^{-1}}{e^2/m_e} \approx 10^{40}$$

: Simply Universe is large!

cf. $\alpha = \frac{e^2}{\hbar c} = \frac{1}{137} \sim O(1)$

$m_p/m_e \simeq 1840 \sim O(1)$

" Any two of the very large dimensionless numbers occuring in Nature are connected by a single mathematical relation in which the coefficients are of the order of magnitude unity"

(Dirac "A new basis for cosmology" (1938))

$$N_1 = N_2 \times O(1)$$

!?

$$N_1 = \frac{e^2}{G m_p m_e}, \quad N_2 = \frac{H_0^{-1}}{e^2/m_e}$$

⇐ numerology !

$$\Rightarrow \quad G \propto t^{-1} \quad (\because H \propto t^{-1})$$

(Dirac (1937))

or

$$e^2 \propto t$$

(Gamow (1967))

Modern Motivation

- String theorists say ....

coupling const. $\Leftarrow$ $\langle\phi\rangle$

dilaton

moduli

\+ the Universe is expanding

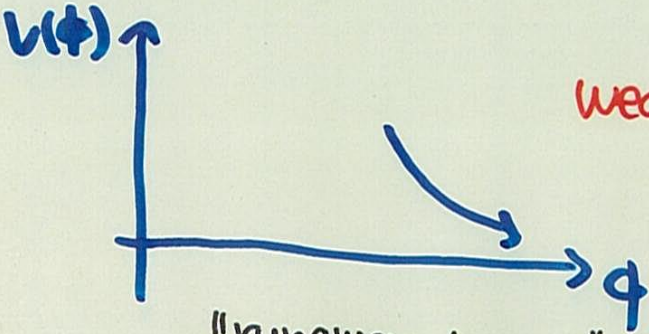
$\Rightarrow$ **Why not $\frac{d}{dt}$(coupling const.) $\neq 0$?**

$$\int d^4x\, \underline{d^6y}\, \sqrt{-g_{10}}\, \Phi^2 (R_{10} - F^2 + \cdots)$$

$\downarrow$ Y ↻ コンパクト化

$$\int d^4x \sqrt{-g_4}\, \Phi^2 Y^6 (R_4 - F^2 + \cdots)$$

$$\frac{\dot{G}}{G} \sim \frac{\dot{\alpha}}{\alpha}$$



weak coupling

$Y \to \infty$

$\Phi \to \infty$

"runaway vacuum" (Dine Seiberg 1985)

one of
null tests

- inverse square law
- equivalence principle
- post-Newtonian tests of gravity theories

....

~~High risk~~ High return

Low cost

- <u>Submm</u> での Newton law からのズレ → · Large extra dimension
  · quantum gravity at TeV

table top の実験 → 量子重力!

$$\left(\frac{M_{pl}}{10^{18}\,\mathrm{GeV}}\right)^2 = \left(\frac{R}{\mathrm{mm}}\right)^2 \left(\frac{M_f}{\mathrm{TeV}}\right)^4$$

- Coupling const. の時間変化

  → · extra dimension
  · dilaton
  · quintessence

Constraining $\dot{\alpha}$

$$\frac{d}{dt}\alpha = \frac{\Delta\alpha}{\Delta t}$$

$\Rightarrow$ $\Delta\alpha$ を小さくする

$\Leftarrow$ lab. exp

or

Δt を長くする

$\Leftarrow$ Cosmology

	Big Bang Nucleosynthesis	$z \sim 10^{10}$
	CMB	$z \sim 10^{3}$
	QSO 吸収線	$z \sim 1$
	Oklo	$z \sim 0.1$
	now	
t $\downarrow$		

§$\dot{\alpha}$ CMB

Hannestad (1999)

Kaplinghat et al. (1999)

$\dot{\alpha} \neq 0 \Rightarrow$

Thomson scattering :

$\alpha \nearrow$: tighter coupling

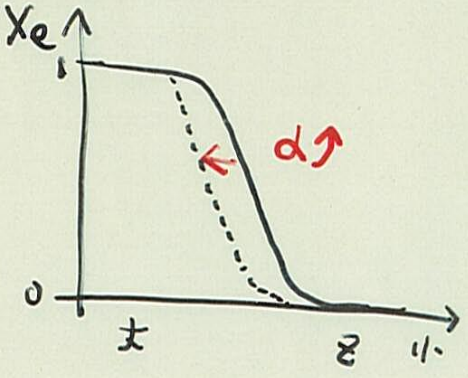
$$\sigma_T = \frac{8\pi}{3}\frac{\alpha^2}{m_e^2}$$

optical depth : $\tau = \int_t^{t_0} x_e n_e \sigma_T \, dt$

Recombination : $e + p \rightarrow H$

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

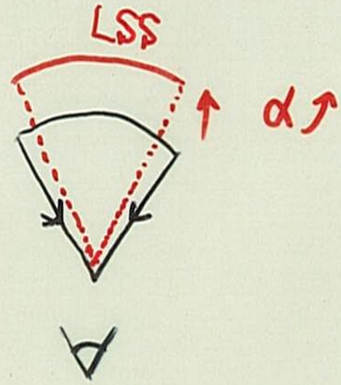
$$B = \frac{\alpha^2 m_e}{2}$$



$\alpha \nearrow \rightarrow z_{LSS} \nearrow$

Effects on CMB spectrum

peak location



$\alpha\uparrow \to \ell_{peak}\uparrow$ (角度小)

($z_{LSS}\uparrow$)

amplitude

first peak : early ISW $\uparrow$ ($\alpha\uparrow$)

$z_{rec}\uparrow$

beyond first : diffusion damping at recombination

damping factor

$$D = \int_0^{\eta} d\eta\, \dot{\tau} e^{-\tau} e^{-k^2/k_D^2}$$

$$k_D^{-2} = \left(\frac{H^{-1}}{n_e \sigma_T}\right)$$

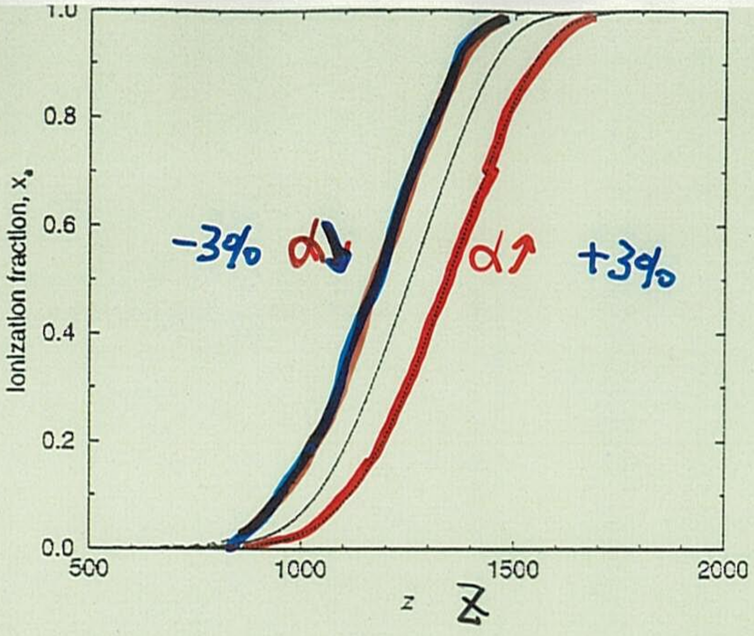
$\alpha\uparrow \Rightarrow$ thickness of LSS $\searrow$ ($k_D^{-1}\searrow$)

$\Rightarrow D\searrow$

イオン化率

X_e

Kaplinghat et al.



$g = e^{-\tau}\frac{d\tau}{dz}$

微分散乱確率

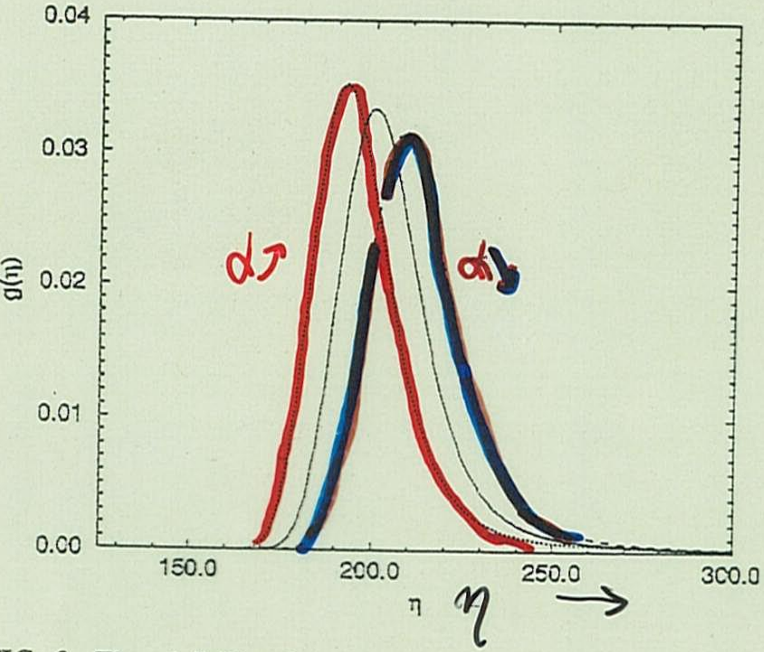


FIG. 3. The visibility function $g(\eta)=e^{-\tau}d\tau/d\eta$ as a function

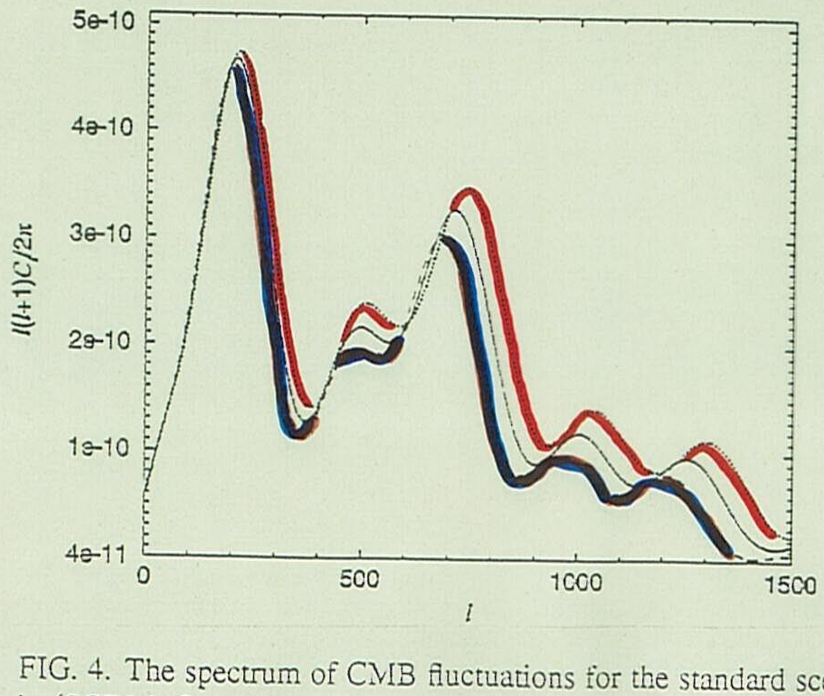
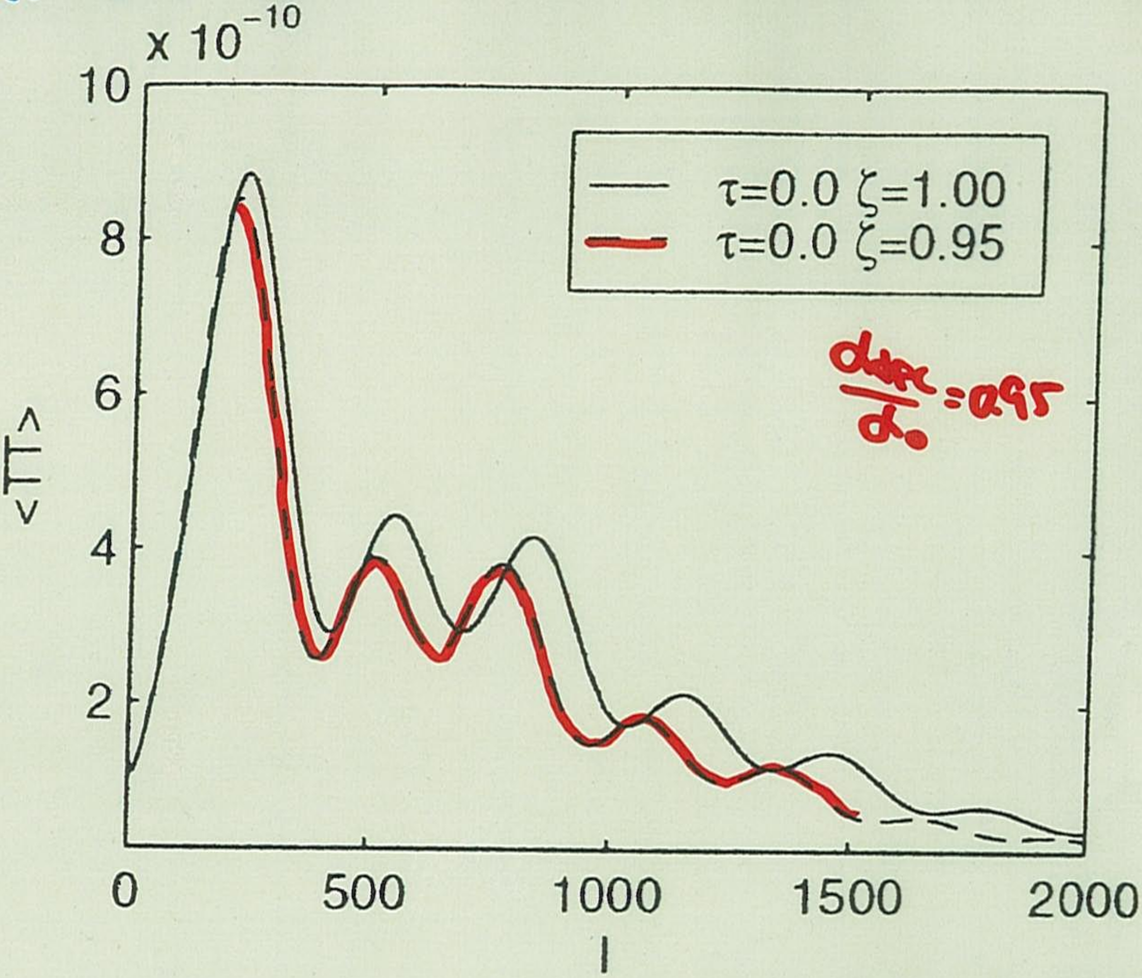
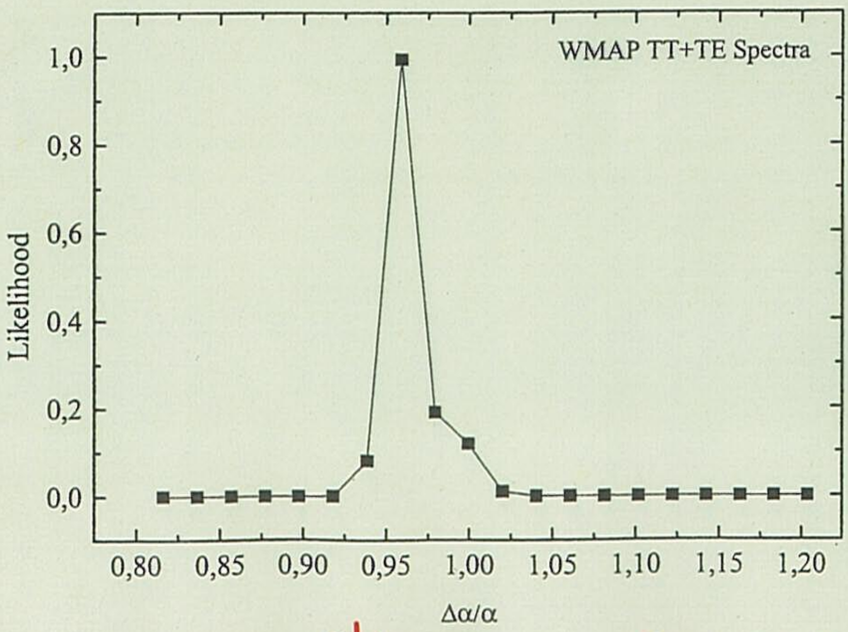


FIG. 4. The spectrum of CMB fluctuations for the standard sce-
nario (SCDM, $\Omega_b=0.05$, $h=0.65$) (solid curve), an increase of

WMAP and α

Martins et al. (2003)





$0.94 < \frac{\alpha_{dec}}{\alpha_0} < 1.01$ (95% C.L.)

BBN

Kolb-Perry-Walker (1986)

$$(n/p)_f = \exp\left(-\frac{Q}{T_f}\right)$$

freez-out

$G_F^2 T_f^5 \simeq H(T_f) \sim \frac{T_f^2}{M_{pl}}$ $Q = M_n - M_p = 1.29\,\mathrm{MeV}$

$Q \nearrow \Rightarrow n/p \searrow \rightarrow {}^4He \searrow$

elemag self-energy   quark mass difference

$$Q \sim \underbrace{a}_{\frac{-0.8\,\mathrm{MeV}}{\alpha\Lambda^0_{QCD}}} \Lambda_{QCD}\alpha + b \underbrace{v}_{\text{Higgs VEV}}$$

(Campbel-Olive 1995)

$$\Rightarrow (n/p)_f = (n/p)_{f0}\left(1 - \Delta Q/T_f\right)$$

$$Y_p \simeq 1 - \frac{n_p - n_n}{n_p + n_n} = \frac{2(n/p)_f}{1+(n/p)_f}$$

$$\frac{\Delta Y}{Y} \approx 2\frac{\Delta\alpha}{\alpha}$$

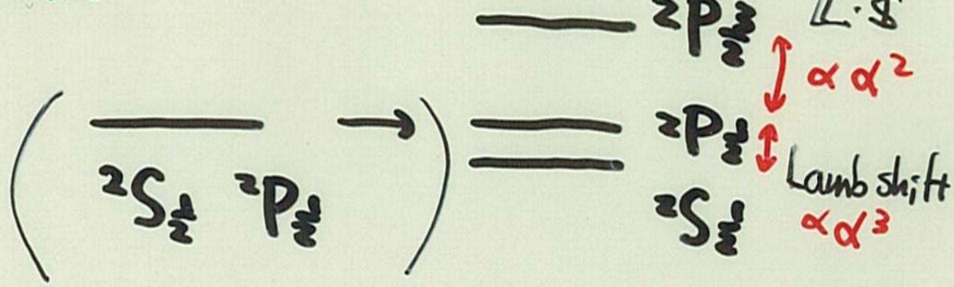
obs. $Y_p \sim 0.22 \sim 0.25$

$$-0.05 \lesssim \frac{\Delta\alpha}{\alpha} \lesssim 0.01$$

§ $\dot{\alpha}$

QSO と α

fine structure

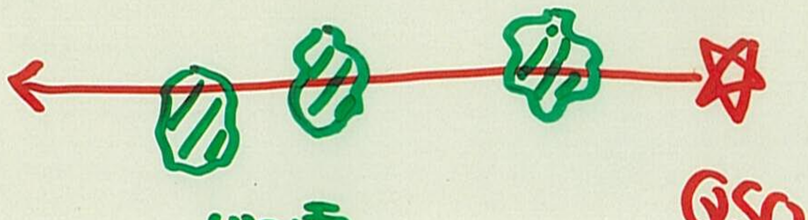


$\lambda_1 : {}^2S_{\frac{1}{2}} \to {}^2P_{\frac{3}{2}}$

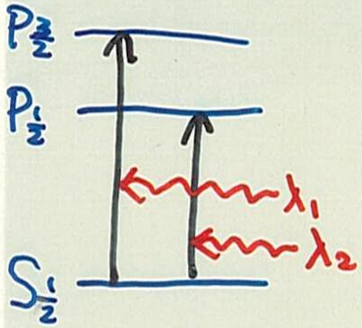
$\lambda_2 : {}^2S_{\frac{1}{2}} \to {}^2P_{\frac{1}{2}}$

$\lambda_1 - \lambda_2 \propto \alpha^2$

$$\boxed{\frac{\delta\alpha}{\alpha} = \frac{\delta(\Delta\lambda)}{2\Delta\lambda} \approx \frac{\lambda}{2\Delta\lambda}\frac{\delta v}{c}}$$



Cowie-Songaila (1995)



Si IV doublet

☺ λ_1 と λ_2 の差が大きい

1393.755 1402.770 Å

Keck HIRES を使って Si IV を同定

$z \sim 3$

$$\sqrt{(\delta v)^2} \lesssim 1.1 \text{ km s}^{-1}$$

systematic $\lesssim 1.0$ km s^{-1} (5mÅ)

(λ_1, λ_2 の不定性)

$$\frac{\delta\alpha}{\alpha} = \frac{\lambda}{2\Delta\lambda}\frac{\delta v}{c} \leftarrow \sqrt{(\delta v)^2_{obs} + (\delta v)^2_{sys}}$$

$$< 3.5\times10^{-4}$$

$z \sim 3$: $t \sim 11$ Gyr

$$\frac{\dot\alpha}{\alpha} < 3.4\times10^{-14} \text{ yr}^{-1}$$

QSO absorption line

- doublet splitting : $\frac{\Delta\lambda}{\lambda} \propto \alpha^2$

$$\frac{\delta\alpha}{\alpha} = \frac{\delta(\Delta\lambda)}{2\Delta\lambda}$$

$$E_{nJ} = -\frac{(Z\alpha)^2}{2n^2} - \frac{(Z\alpha)^4}{2n^4}\left(\frac{n}{J+\frac{1}{2}} - \frac{3}{4}\right) + \cdots$$

alkali-doublet : Mg II, Si IV, C IV, Al III
Si II
$Z \simeq 6 \sim 14$

many-multiplet method : Ni II, Cr II, Zn II
Mg II, Al II, Fe II

$Z : 20 \sim 30$

$$\frac{\Delta\alpha}{\alpha} \sim -10^{-5} \quad 0.5 < z < 3.5$$

30 systems

Webb et al. (1999)

$0.5 < z < 1.6$

$\frac{\Delta\alpha}{\alpha} = (-1.1 \pm 0.4) \times 10^{-5}$

3σ

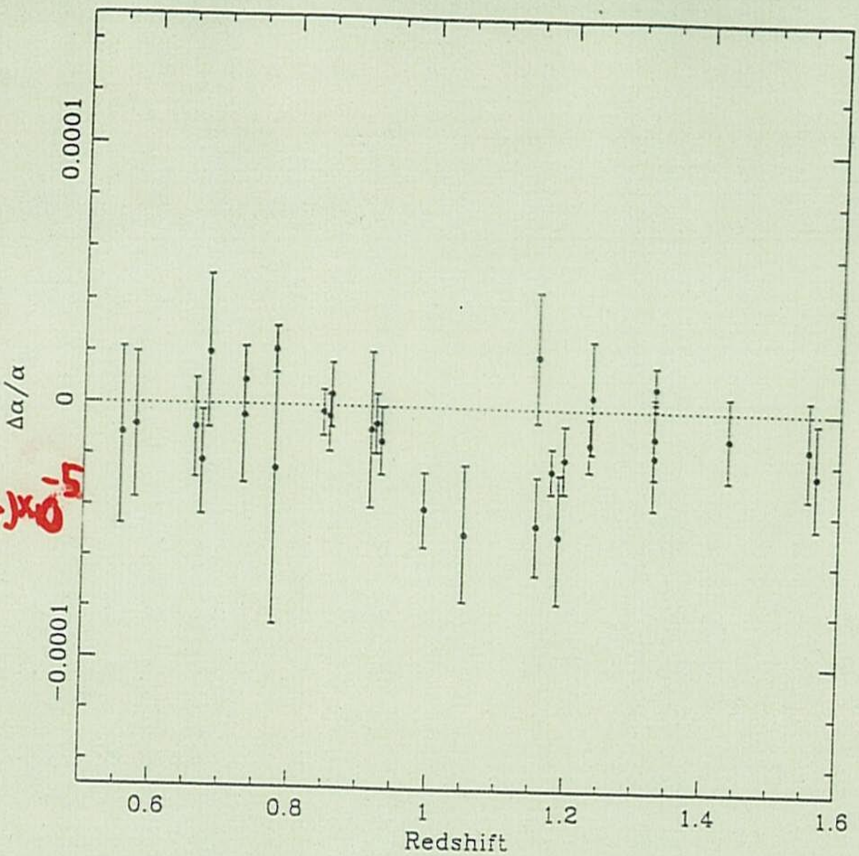


FIG. 1. Plot of $\Delta\alpha/\alpha$ vs z for 30 Fe II/Mg II absorption systems. All the transitions given in Eq. (3) were used, where available. Plotted error bars were determined from $\chi^2_{\min} \pm 1$ (but statistical results estimated using larger errors, as discussed in the text).

72 systems

Webb et al. (2000)

$0.5 < z < 3.5$

$\frac{\Delta\alpha}{\alpha} = (-0.72 \pm 0.18) \times 10^{-5}$

4σ

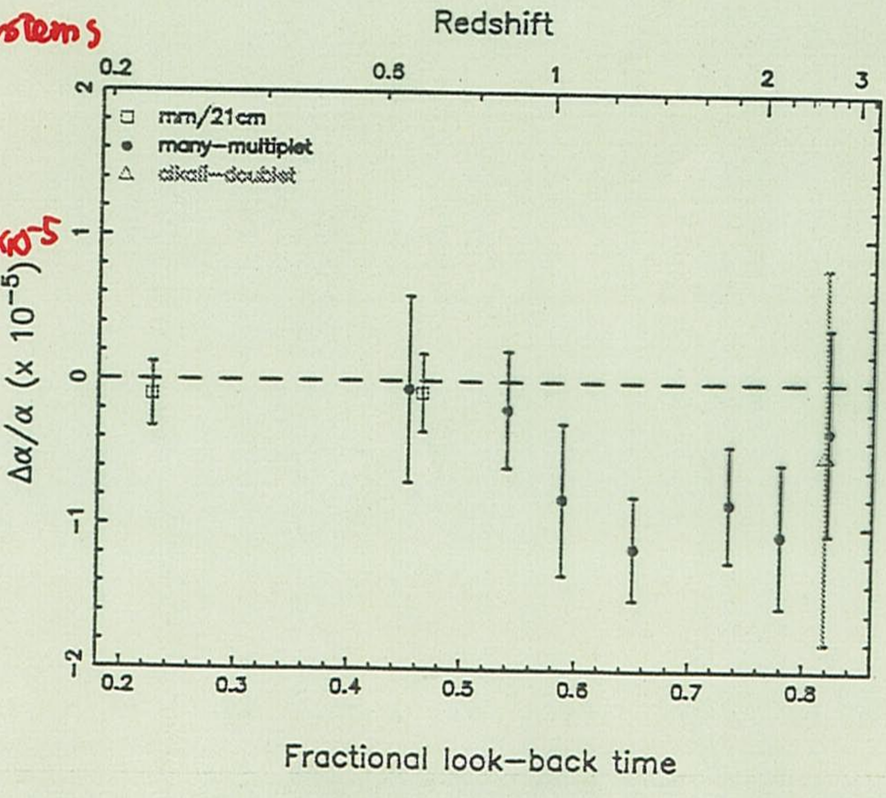


FIG. 1: $\Delta\alpha/\alpha$ vs. fractional look-back time to the Big Bang

128
systems

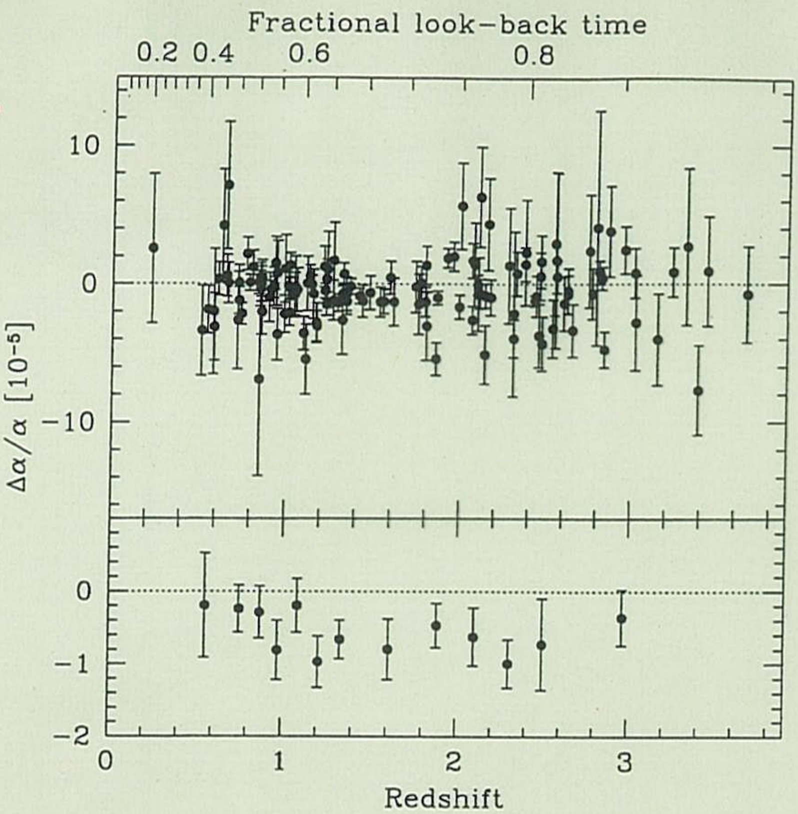
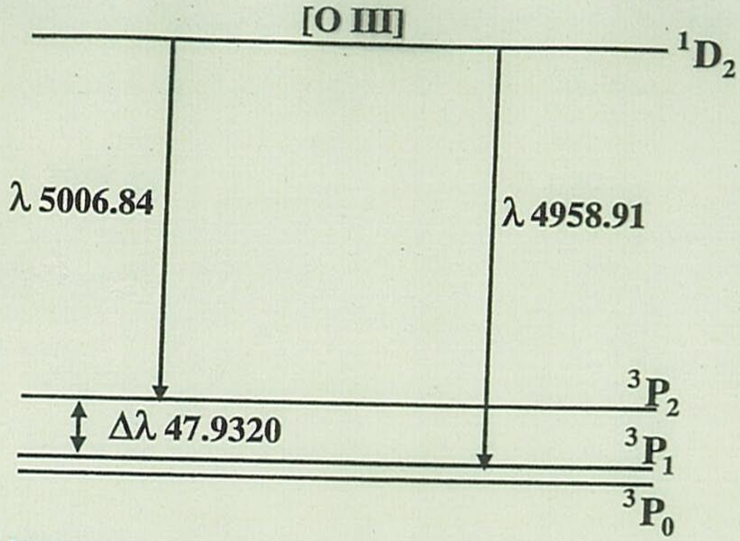


Figure 4: *Distribution of $\Delta\alpha/\alpha$ over absorption redshift. The upper panel shows $\Delta\alpha/\alpha$ for 128 absorption systems with 1σ errors. We bin $\Delta\alpha/\alpha$ in the lower panel, presenting the weighted mean $\Delta\alpha/\alpha$ and 1σ error at the mean redshift for each bin.*

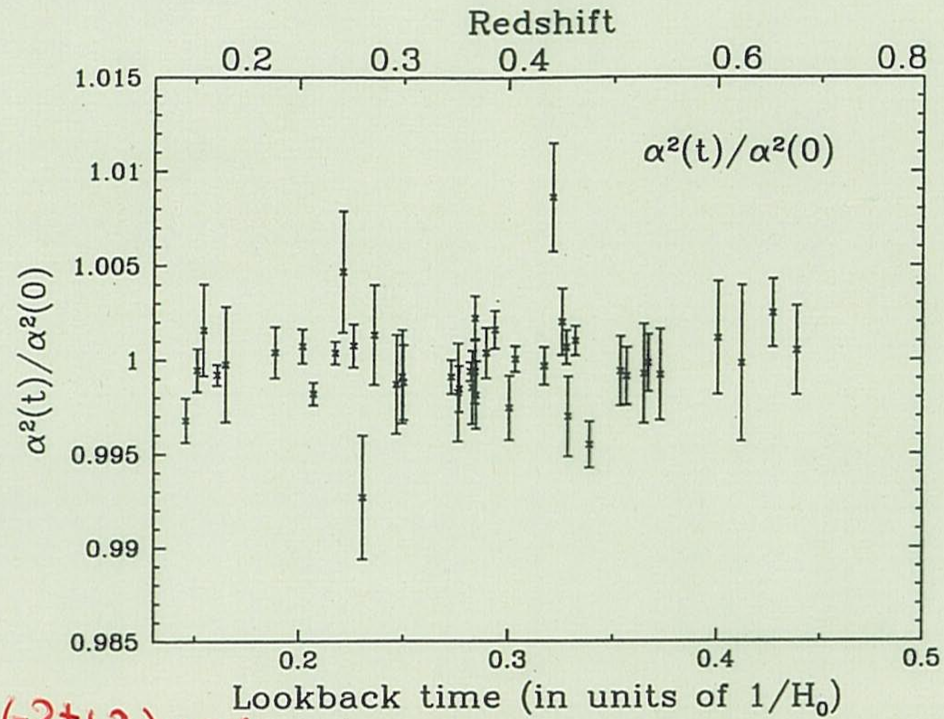
$$\frac{\Delta\alpha}{\alpha} = (-0.57 \pm 0.10) \times 10^{-5}$$

5σ

Webb et al. (2002)



Bahcall et al. (2003)



$\frac{\Delta\alpha}{\alpha} = (-2 \pm 1.2) \times 10^{-4}$ $0.16 < z < 0.80$

Table 3: Comparison of the O III and Many-Multiplet Methods.

	O III	Many-Multiplet
Number of ions	one	many; different Z, A
Transitions	one	many
Multiplets	one	many
Theory	simple	relativistic, many body
Wavelengths	relative	absolute
Sample precision	0.01 Å	0.0002 Å
Velocity profiles	identical	modeled; all ions same
Line strengths	strong	weak and strong
Misidentification (or blending)	no	a concern
Full disclosure	yes	extremely difficult

§ $\dot{\alpha}$

Oklo natural reactor

Site : Gabon, West Africa

20億年前 $(z \sim 0.1)$

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

中性子吸収の共鳴レベル : $E_r = 97.3$ meV

extremely low

⇐ 核子のポテンシャルの変化に敏感

(Shlyakhter 1976)

原子核のポテンシャル $V_0 \sim \mathrm{MeV} \propto \alpha$

(Coulomb energy)

$$\frac{\Delta V_0}{V_0} = \frac{\Delta E_r}{V_0} = \frac{\Delta \alpha}{\alpha}$$

$$\frac{\Delta \alpha}{\alpha} \simeq \frac{4 \pm 16\,\mathrm{meV}}{1\,\mathrm{MeV}} \approx (4 \pm 16) \times 10^{-9}$$

$$\Delta t = 2 \times 10^9\,\mathrm{yr} \quad \left|\frac{\dot{\alpha}}{\alpha}\right| < (2 \pm 8) \times 10^{-18}\,\mathrm{yr}^{-1}$$

σ_{149} vs. ΔE_r (Fujii et al. 2000)

別の核種の →
存在比から

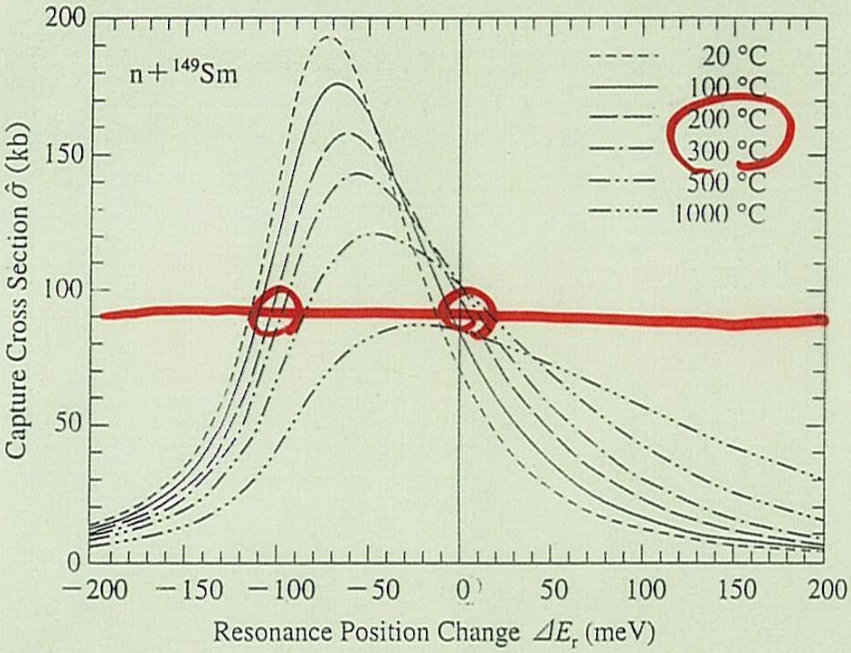


図2　n + ^{149}Sm → ^{150}Sm + γ 反応について，熱中性子分布を用いて平均化された断面積 $\hat{\sigma}_{149}$ を，共鳴エネルギー準位のずれ ΔE_r の関数として種々の温度 T について示したもの．（Y. Fujii, *et al.*: Nucl. Phys. B 573 (2000) 377 より転載.）

⇒ two allowed region

$$\Delta E_r = \underline{4 \pm 16 \text{ meV}} \quad \text{(null result)}$$

$$= -97 \pm 8 \text{ meV} \quad \leftarrow \text{excluded by Gd}$$

cf Damour-Dyson

$$-123 < \Delta E_r < 90$$

まとめ : $\dot{\alpha}$

		$\dot{\alpha}/\alpha$
QSO, Lab		$\lesssim 10^{-14}\ \mathrm{yr}^{-1}$
		$+\ 10^{-15}\ \mathrm{yr}^{-1}$ (?)
Oklo		$\lesssim 10^{-18}\ \mathrm{yr}^{-1}$
CMB	$\frac{\Delta\alpha}{\alpha} \sim 10^{-2} \sim 10^{-3}$	$\lesssim 10^{-12 \sim -13}\ \mathrm{yr}^{-1}$
BBN		$\lesssim 10^{-12 \sim -14}\ \mathrm{yr}^{-1}$

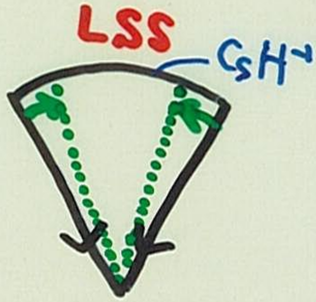
§ $\dot{G}$ CMB

$$G\nearrow \;\rightarrow\; H^{-1}\propto G^{-\frac{1}{2}}\searrow$$

(horizon)

$l_{peak}\nearrow$

(角度小)



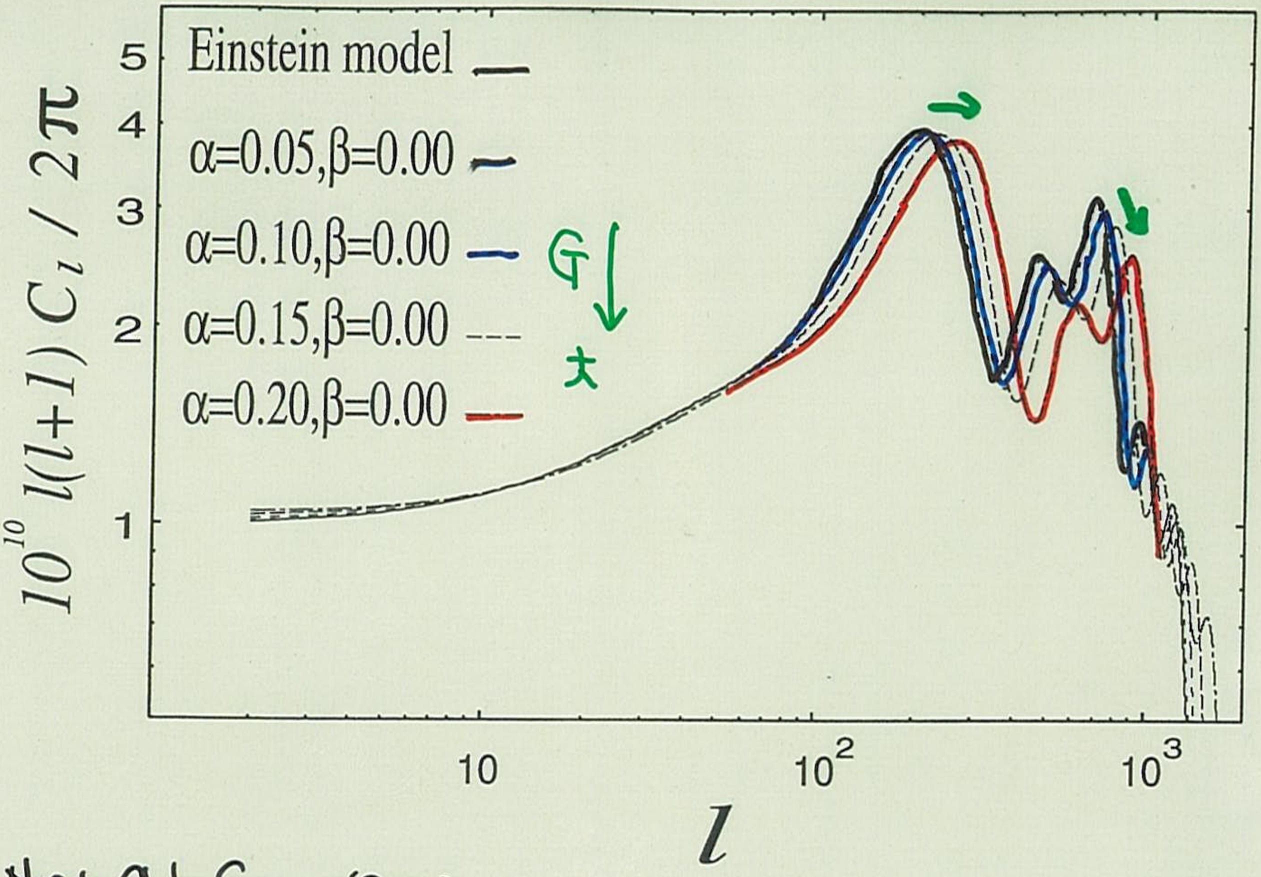
Diffusion damping

length $\quad k_D^{-2}=\left(\frac{H^{-1}}{n_e\sigma_T}\right)\searrow$

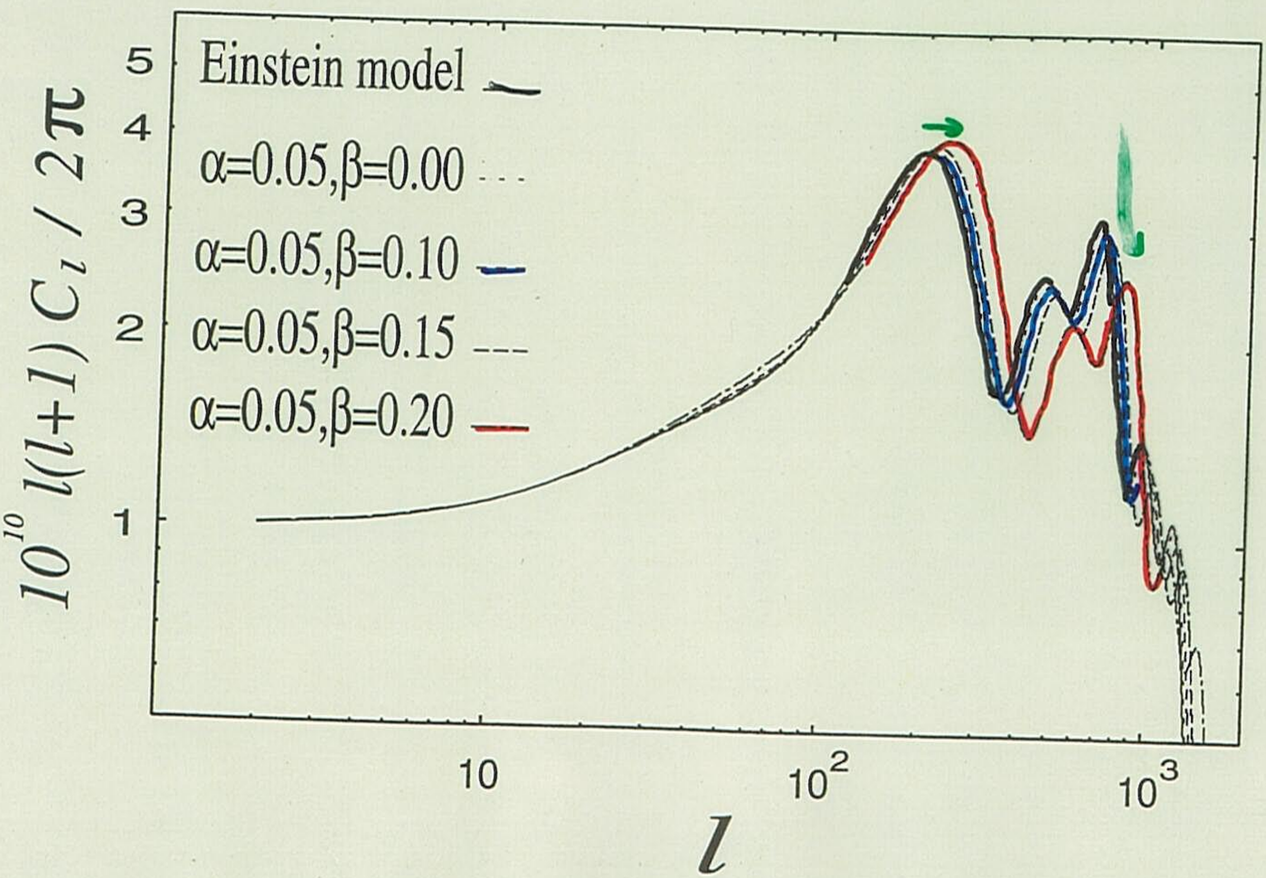
$$\frac{k}{k_D}\propto H^{\frac{1}{2}}\nearrow$$

damping factor
$$D=\int d\eta\,\dot{\tau}e^{-\tau}e^{-k^2/k_D^2}$$

$G\nearrow \;\rightarrow\; D\nearrow$ より減衰



Nagata Chiba Sugiyama (2002)



§ $\dot{G}$

$$G = G_0 + \dot{G}_0 (t - t_0)$$

$$\frac{d^2 x^i}{dt^2} = -\frac{G M x^i}{r^3} = -\frac{G_0 M x^i}{r^3} - \underline{\frac{\dot{G}_0}{G_0}\frac{G_0 M}{r}\frac{x^i (t-t_0)}{r^2}}$$

+ (post Newton)

惑星の運動から制限

- Viking (radar-ranging to Mars)
  (1976 ~ 1982)
- Luar-Laser-Ranging ← アポロ 11号
  (1969 ~)

Hellings et al. (1983) — $\dot{G}/G$

Viking, Mariner-9, LLR — $(2 \pm 4) \times 10^{-12}\ \mathrm{yr}^{-1}$

Müller et al. (1991)

LLR (1969 ~ 1990) — $(0.1 \pm 10.4) \times 10^{-12}\ \mathrm{yr}^{-1}$

Williams et al. (1996)

LLR (1970 - 1994) — $(1 \pm 8) \times 10^{-12}\ \mathrm{yr}^{-1}$

BBN

$G \nearrow \Rightarrow H_{BBN} \nearrow$

$\Rightarrow$ freeze-out earlier

$\Rightarrow n/p \nearrow$

$\Rightarrow {}^4He \nearrow$

(Walker et al. 1991)

$$Y_p \simeq 0.244 + 0.074\,(\xi^2 - 1)$$

$$\xi^2 = \left(\frac{H}{H_{SBBN}}\right)^2 = \frac{G}{G_0}$$

$$-0.32 \lesssim \frac{\Delta G}{G} \lesssim 0.08$$

$$\frac{\dot{G}}{G} \lesssim 10^{-11 \sim -12}\ \mathrm{yr}^{-1}$$

まとめ $\dot{G}$

	$\dot{G}/G$
太陽系の実験	$\lesssim 10^{-12}\ \mathrm{yr}^{-1}$
CMB	$(\lesssim 10^{-12}\ \mathrm{yr}^{-1})$
BBN	$\lesssim 10^{-11 \sim -12}\ \mathrm{yr}^{-1}$

Summary

- scenarios for $\frac{d}{dt}$(coupling const.) $\neq 0$

$$\underset{\text{constraint}}{\overset{\text{motivation}}{\rightleftarrows}} \quad \text{searching for } \frac{d}{dt}(\text{ `` }) \neq 0$$

- Constraints on $\dot{\alpha}$, $\dot{G}$ at various epoch are important

- any new methods should be welcome
  ← CMB is new comer
- possible detection of $\dot{\alpha} \neq 0$ by QSO should be checked independently.