CMB constraints on varying G

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- introduction
- varying G
- CMB and G

varying constants?

- softening of physics?

  spacetime $\eta_{\mu\nu} \rightarrow g_{\mu\nu}$ (general relativity)

  physics laws $\alpha \rightarrow \alpha(\phi)$ (string theory)

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

(One of) Null tests

- Inverse square law
- Equivalence Principle
- (cosmological constant)

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!

varying G

scalar-tensor gravity

- gravity theory alternative to GR

$$S=\int d^4x\sqrt{-g}\,\frac{1}{16\pi G}\left(\phi R-\frac{\omega(\phi)}{\phi}(\nabla\phi)^2\right)+S_m(g_{\mu\nu},\psi)$$

ϕ : Brans-Dicke scalar (or dilaton)

$\leftarrow$ string theory (dilaton)

higher dimensional gravity (moduli)

ω : coupling function(Brans-Dicke function)

($\omega \to \infty$: GR)

effective gravitational constant: $G=\frac{2\omega+4}{2\omega+3}\frac{1}{\phi}$

- action

$$S=\int d^4x\sqrt{-g}\,\frac{1}{16\pi G}\left(\phi R-\frac{\omega(\phi)}{\phi}(\nabla\phi)^2\right)+S_m(g_{\mu\nu},\psi)$$

- via conformal transformation

$$g_{\mu\nu}=\frac{1}{\phi}\bar{g}_{\mu\nu}\equiv e^{2a(\varphi)}\bar{g}_{\mu\nu}$$

action becomes

$$S=\int d^4x\sqrt{-\bar{g}}\,\frac{1}{16\pi G}\left(\bar{R}-\left(\omega+\frac{3}{2}\right)\frac{(\bar{\nabla}\phi)^2}{\phi^2}\right)+S_m(e^{2a(\varphi)}\bar{g}_{\mu\nu},\psi)$$

- introducing φ by

$$\left(\omega+\frac{3}{2}\right)\frac{(\bar{\nabla}\phi)^2}{\phi^2}=2(\bar{\nabla}\varphi)^2$$

then the conformal factor is related to ω

$$\left(\frac{da}{d\varphi}\right)^2=\frac{1}{2\omega+3}$$

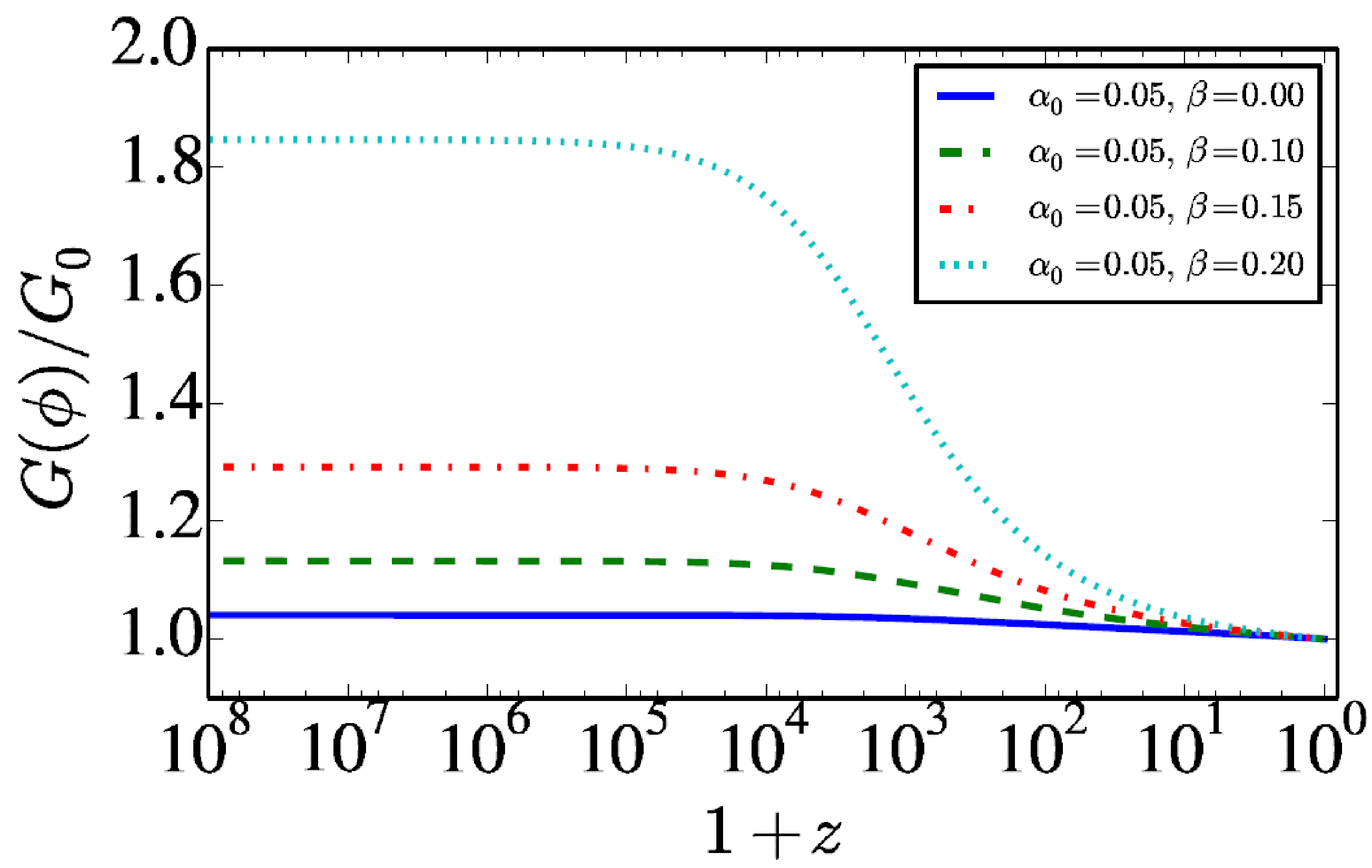
- harmonic attractor model:

$$\frac{1}{\phi} = \exp[2a(\varphi)] = \exp[2\alpha_0\varphi + \beta(\varphi - \varphi_0)^2]$$

$$\sim G$$

the slope of the potential (α_0) is related to the Brans-Dicke parameter: $\alpha_0^2 = 1/(2\omega+3)$

evolution of G



constraints on dG/dt

$z=0$ (solar system test: LRR)

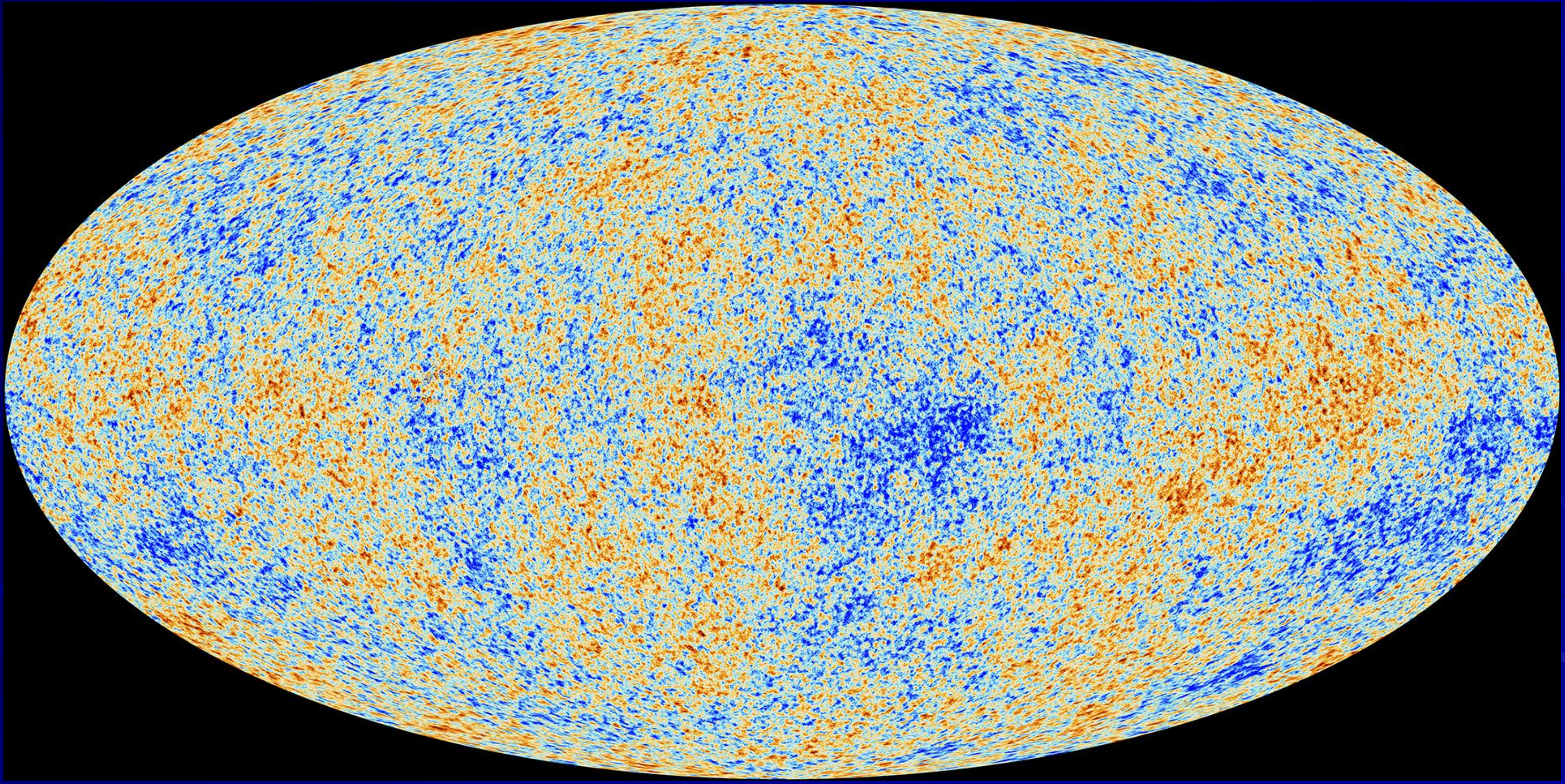
$dG/dt/G=(0.7\pm3.8)\ x10^{-13}\ yr^{-1}$

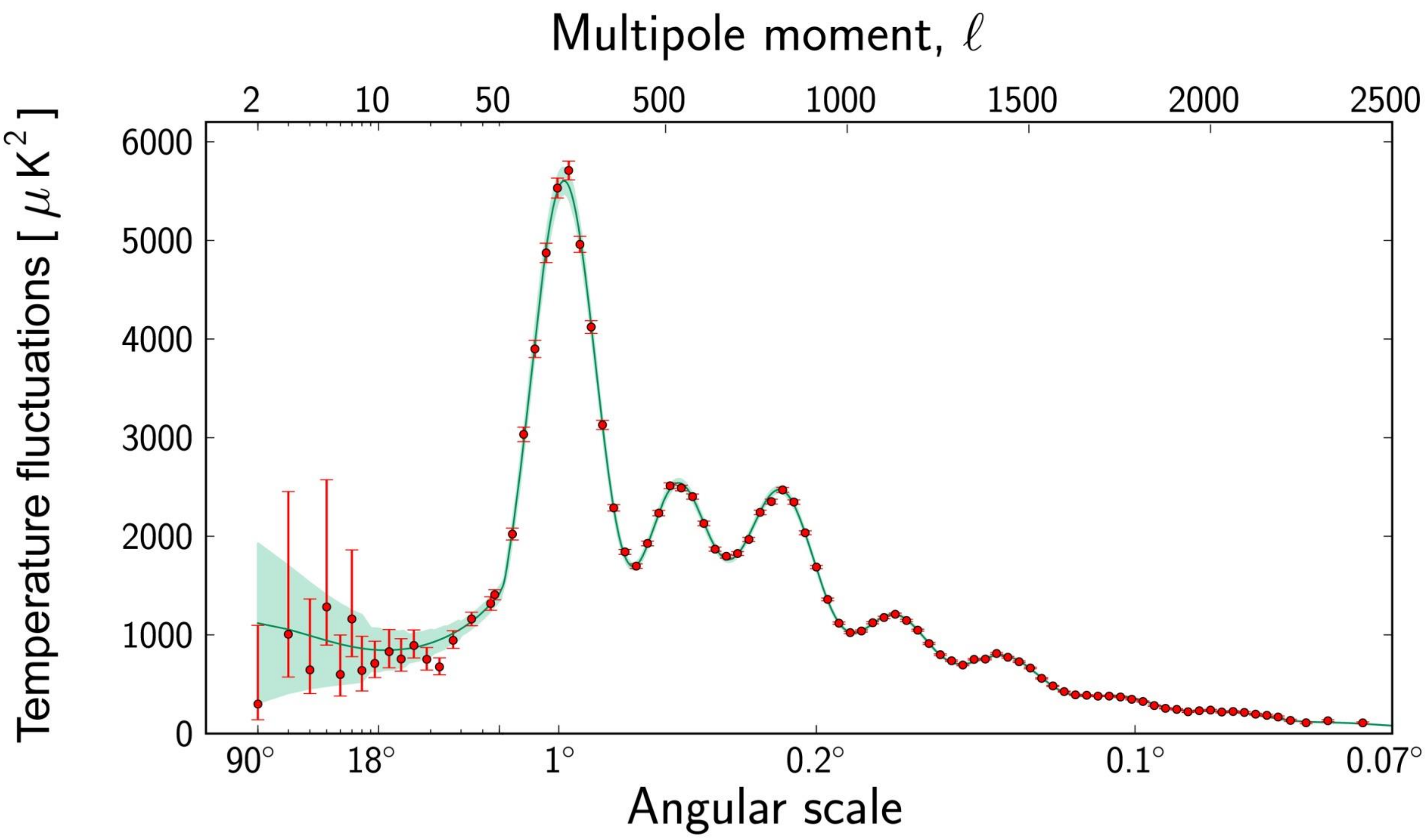
$z=1100$ (CMB) $(G_{recom}-G_0)/G_0<0.05$

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

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

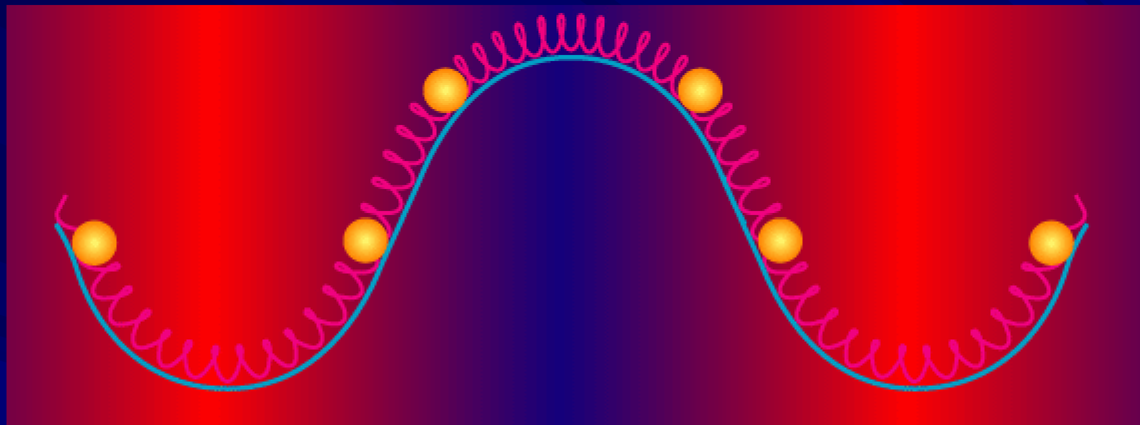
CMB and G



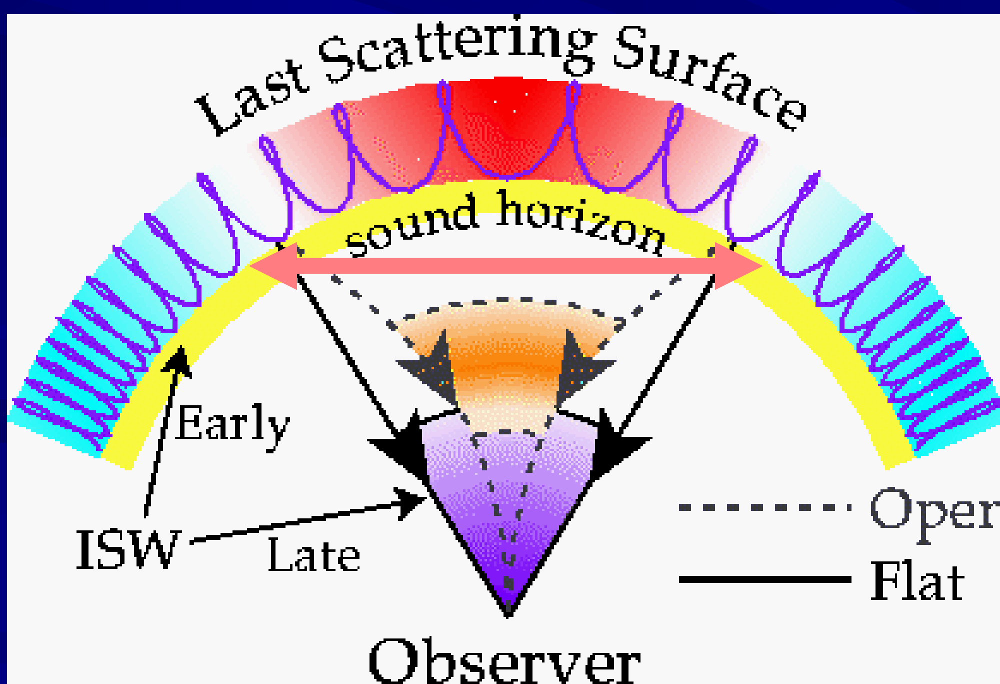


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

CMB at large angles ($\theta \sim 1^0$): acoustic oscillation

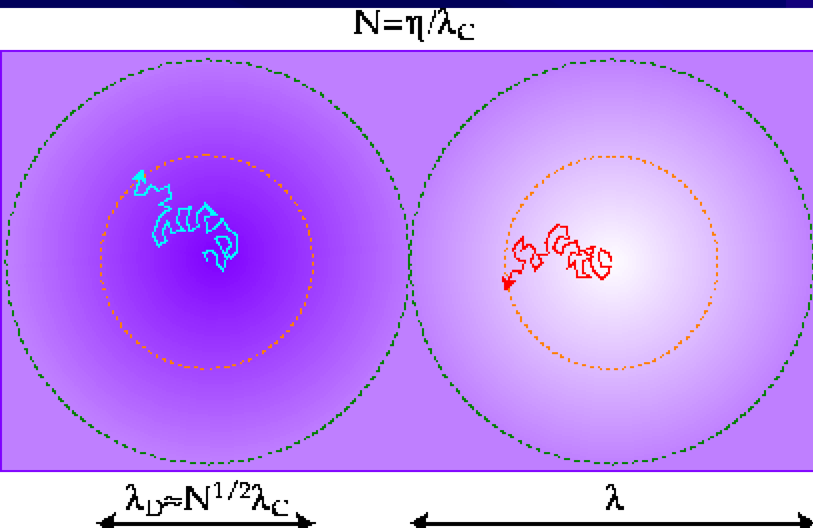


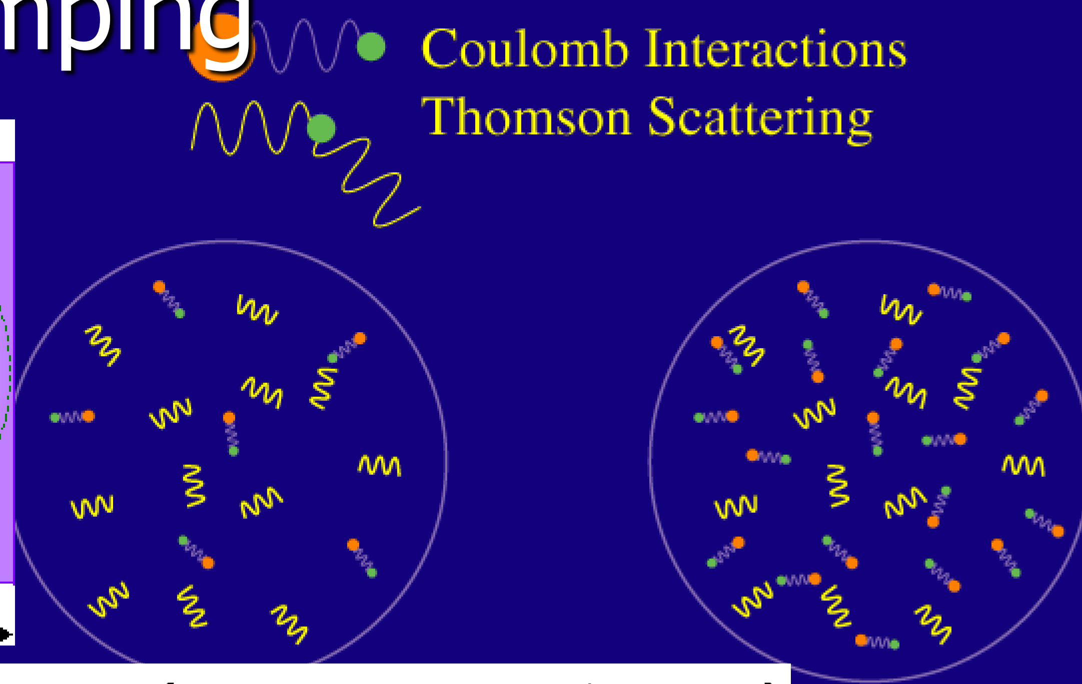
red (low T)
blue (high T)



$c_s H^{-1}$

CMB at small angles ($\theta \sim 0.1^0$): diffusion damping

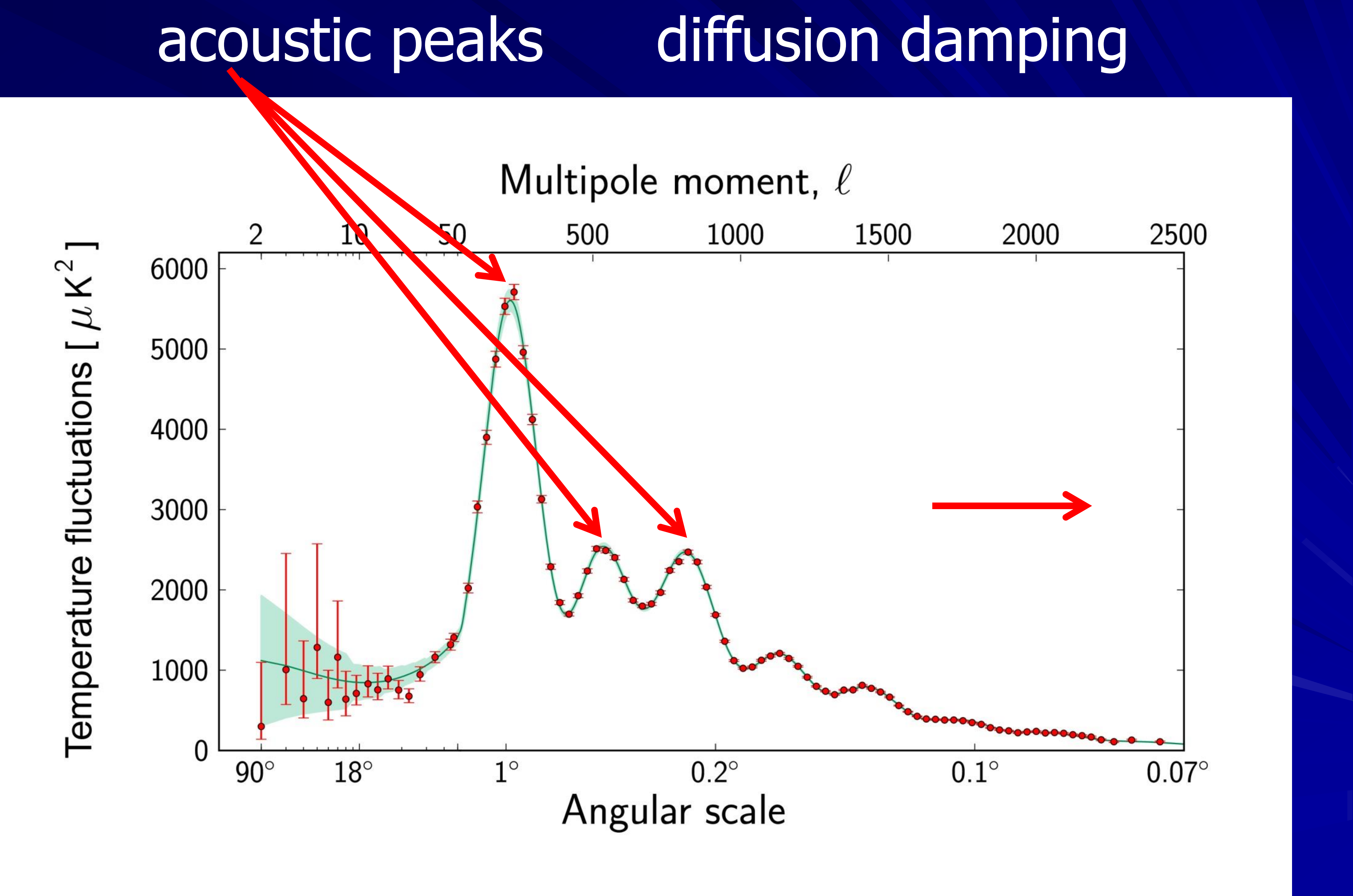




$$\lambda_D = \sqrt{N}\ell_{mfp} \quad (\ell_{mfp} = 1/n\sigma_T)$$

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

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


acoustic peaks
diffusion damping
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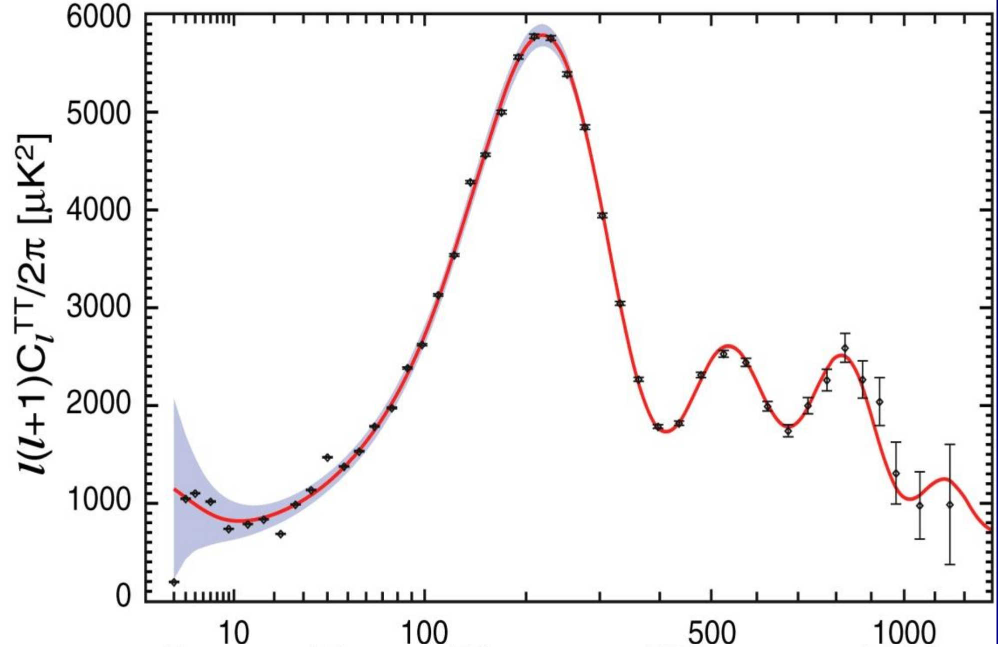
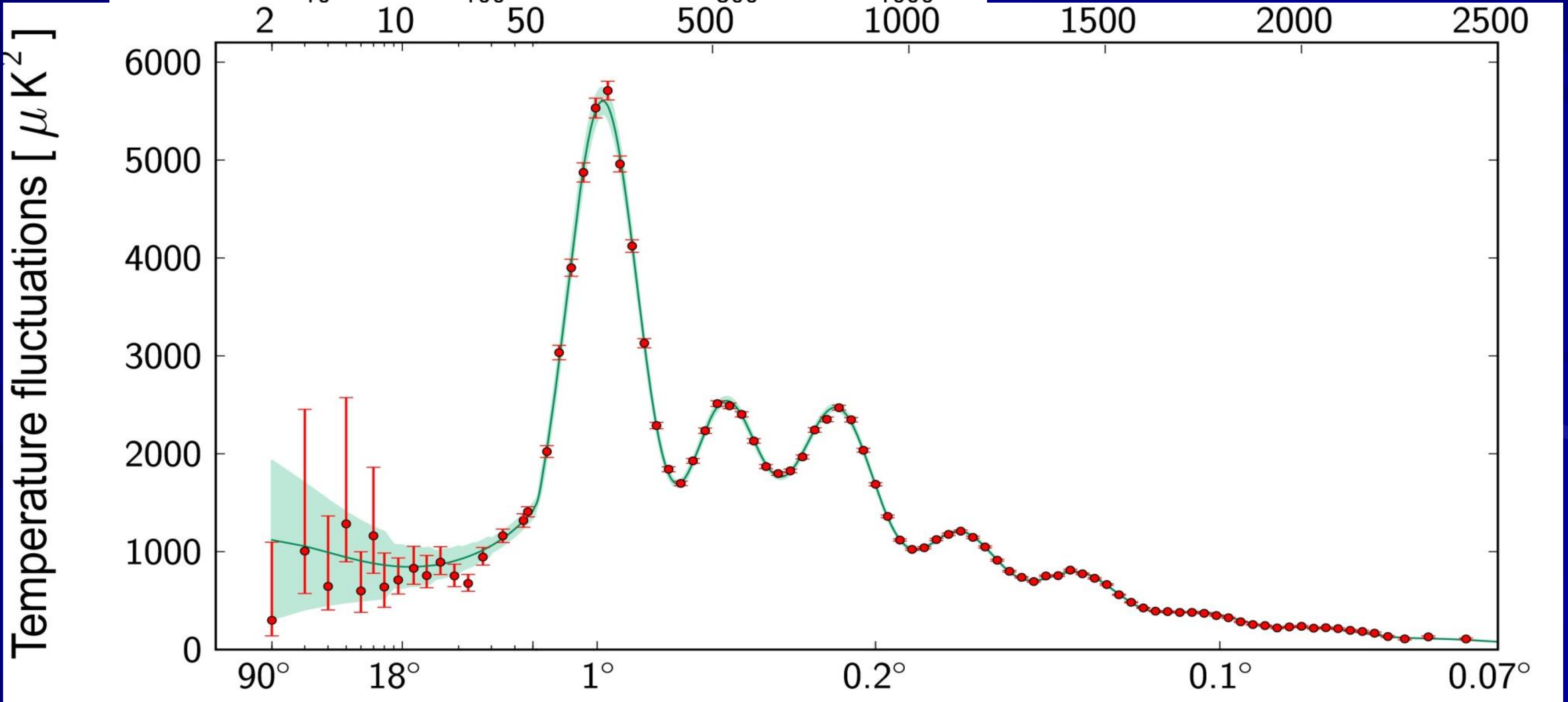


Planck vs. WMAP



effects of changing G on CMB

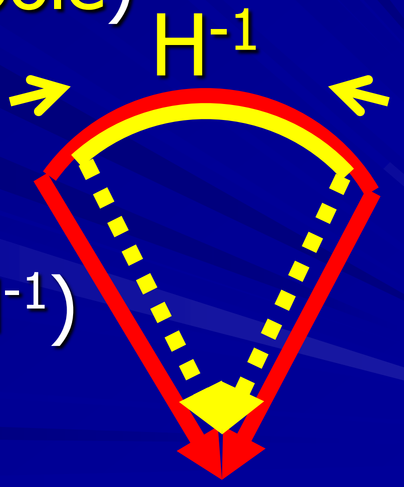
- Larger G shortens the horizon radius $H^{-1} \downarrow$

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

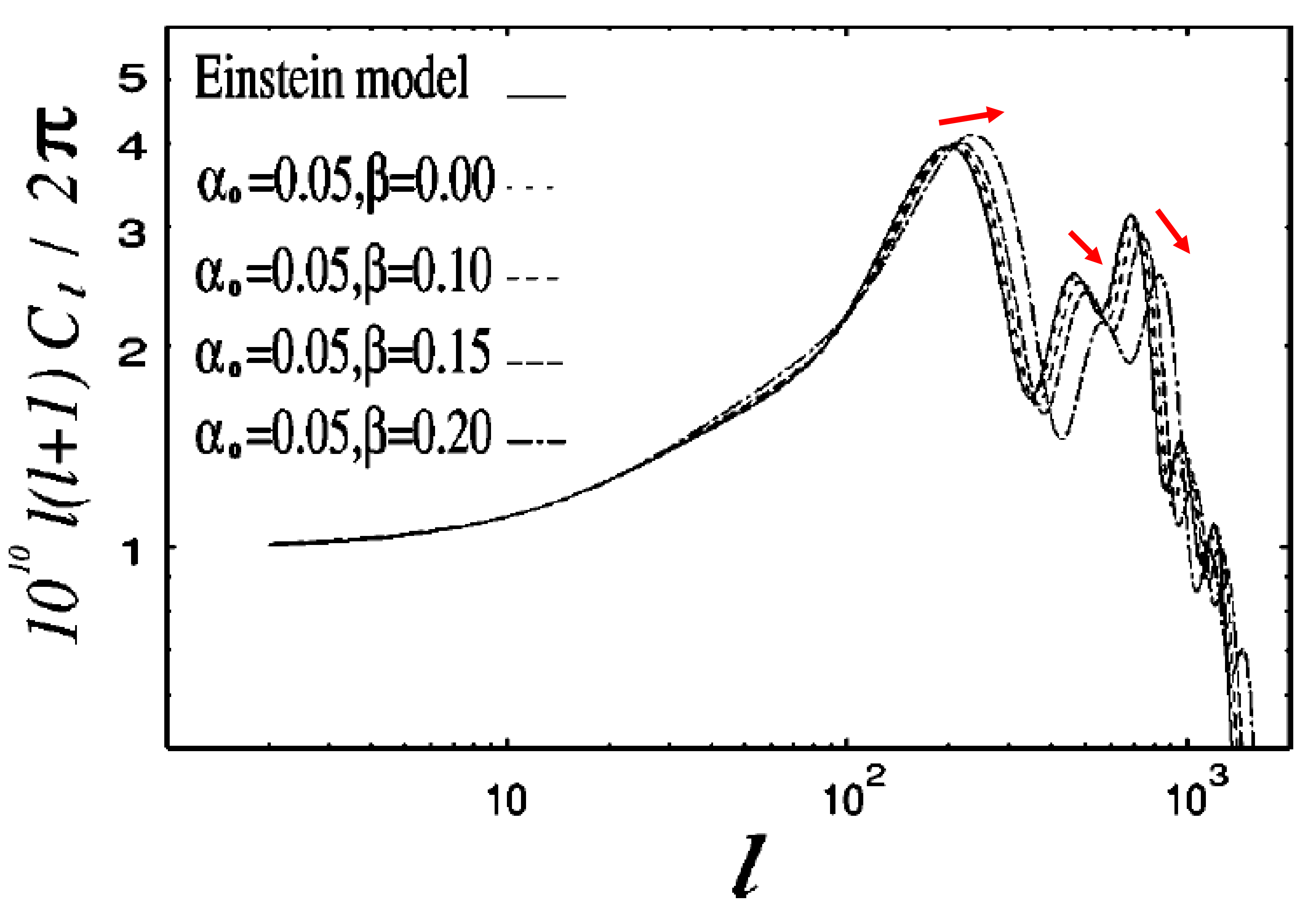
- Diffusion damping($\lambda_D \sim \sqrt{\ H^{-1} \ell_{mfp}} \downarrow$):

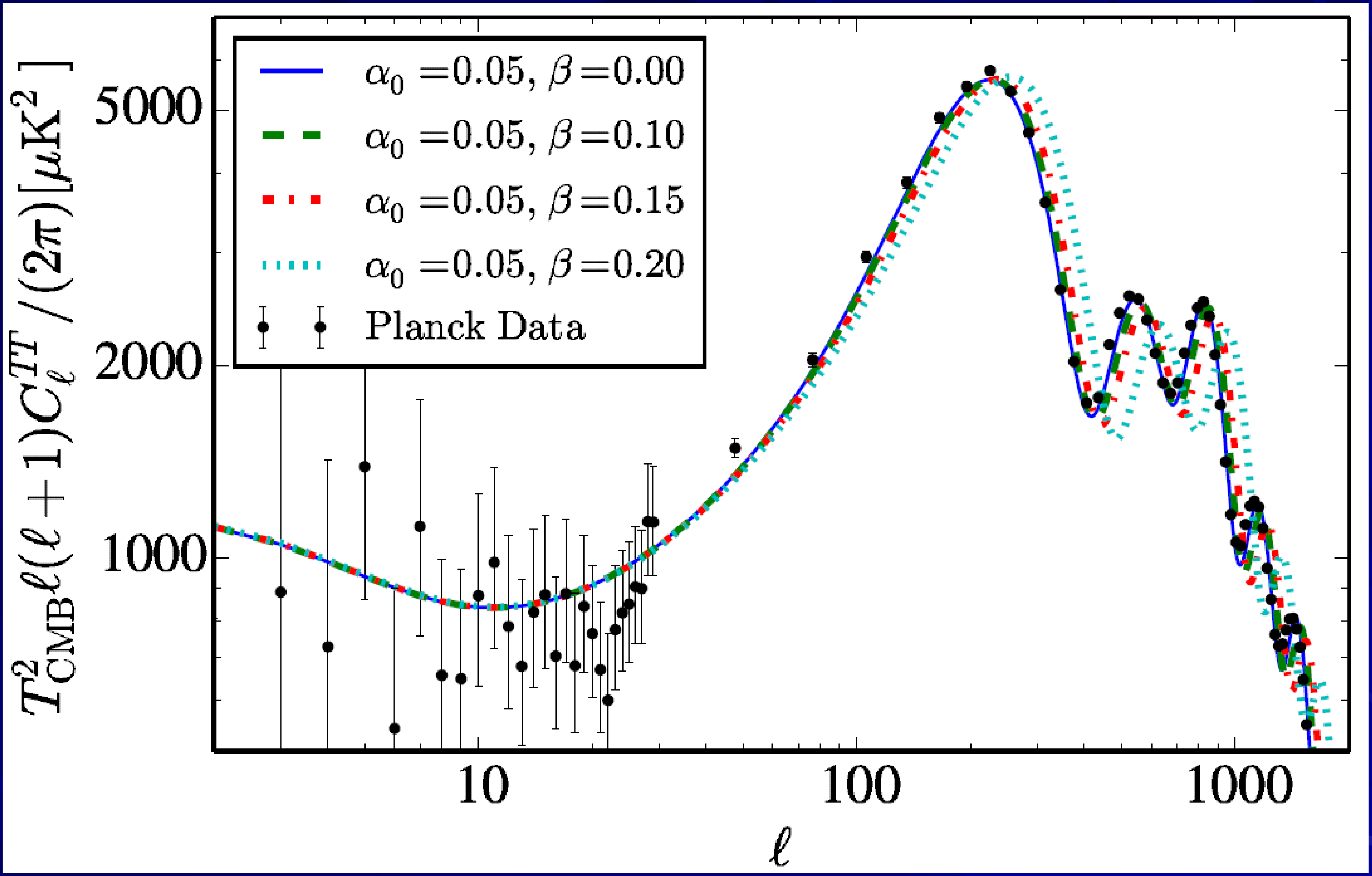
  damping factor at *m* th peaks ($\lambda \propto m\, H^{-1}$)

  $\exp(-\ \lambda_D^2 / \ \lambda^2) \downarrow \ \rightarrow$ damped more



Nagata-TC-Sugiyama(2002)





$(G_{recom}-G_0)/G_0<0.05$ (2σ) (WMAP1,Nagata,TC,Sugiyama,2004)

$(G_{recom}-G_0)/G_0<0.0048$ (2σ) (Planck, Oba,Ichiki,TC,Sugiyama, 1602.00809)

summary

- Precision measurements of CMB anisotropies enable us to put tighter constraints on the possible time variation of physical constants:
- G: $\Delta G/G < 4.8\mathrm{x}10^{-3}$
- α : $\Delta\alpha/\alpha = (-3.6 \pm 3.7)\mathrm{x}10^{-3}$

- order of magnitude improvement over the WMAP constraints

(G: $\Delta G/G < 5\mathrm{x}10^{-2}$ α : $\Delta\alpha/\alpha = (-2.5 \pm 3.5)\mathrm{x}10^{-2}$)

constraints on α_0 and β

$$\frac{1}{\phi} = \exp[2a(\varphi)] = \exp[2\alpha_0\varphi + \beta(\varphi-\varphi_0)^2]$$

$$\sim G$$

- CMB:

$\alpha_0^2 < 1.5 \times 10^{-4} \times 10^{-4-20\beta^2}$

- solar system (time delay):

$\omega > 43000$ or

$\alpha_0^2 < 1.2 \times 10^{-3}$