Cosmic microwave background constraint on a decaying cosmological constant

理論懇シンポジウム***@Rikkyo University***

Riou NAKAMURA (Kyushu University)

Masa-aki Hashimoto (Kyushu University)
Ichki Kiyotomo (University of Tokyo)

Introduction -時間変化する宇宙項-

- 宇宙項が存在する. (e.g. High-z SNIa, CMB)
  - 実体は不明。。。
- 様々な時間変化する宇宙項モデル (Overduin & Cooperstock 1998)
- 光子と couple する宇宙項モデル (DΛCDM)
  - Thermal evolution に影響あり (Kimura et al. 2001)
  - Molecular formation が $\Delta z \sim 10^3$ はやまる (Hashimoto et al. 2003).
  - First object formation at $z = 30$ from cooling diagram (Hashimoto et al. 2003).

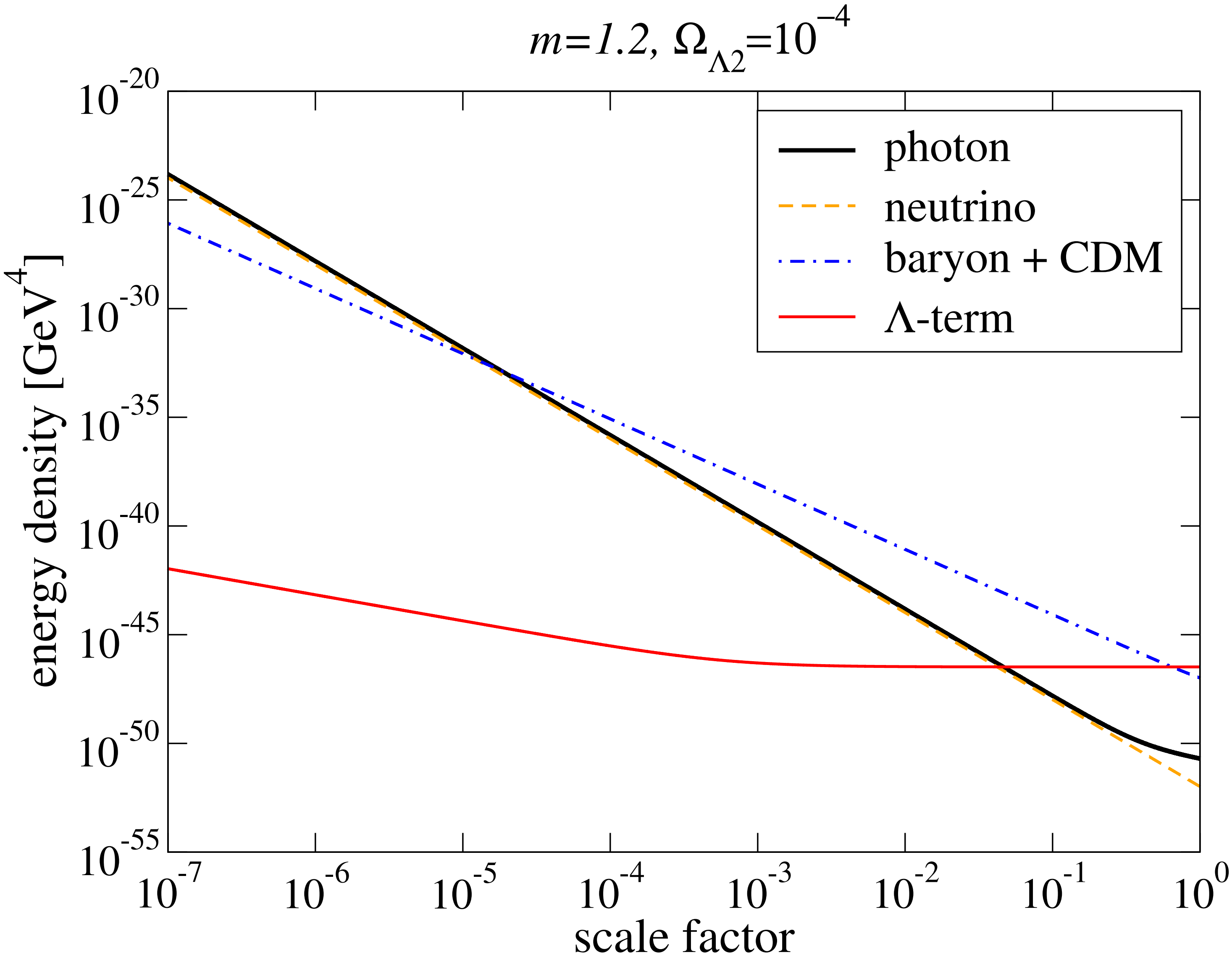
Our Purposes

- Effects of DΛCDM on thermal evolution in the universe.
- Constrains on DΛCDM from Cosmic microwave background

Field equation

- Friedmann eq.
  $$H^2 = H_0^2 \left[\frac{\Omega_{m0}}{a^3} + \Omega_\gamma(a) + \frac{\Omega_{\nu 0}}{a^4} + \Omega_\Lambda(a) + \frac{\Omega_{k0}}{a^2}\right]$$
  - $\Omega \equiv \frac{\rho}{\rho_{cr}}, \rho_{cr} \equiv \frac{3H_0^2}{8\pi G}, \Omega_k = -\frac{k}{3H_0^2}$
    - m : matter; γ : photon; ν : neutrino; k : 曲率
  - H_0: Hubble constant
    - 0 indicates present value.
- energy density of photon
  $$\frac{d\Omega_\gamma}{da} + 4\frac{\Omega_\gamma}{a} = -\frac{d\Omega_\Lambda}{da}$$
- Λ term (Matyjasek 1995; Kimura et al. 2001) $\Omega_\Lambda = \Omega_{\Lambda 1} + \Omega_{\Lambda 2} a^{-m}$

Evolution of energy densities



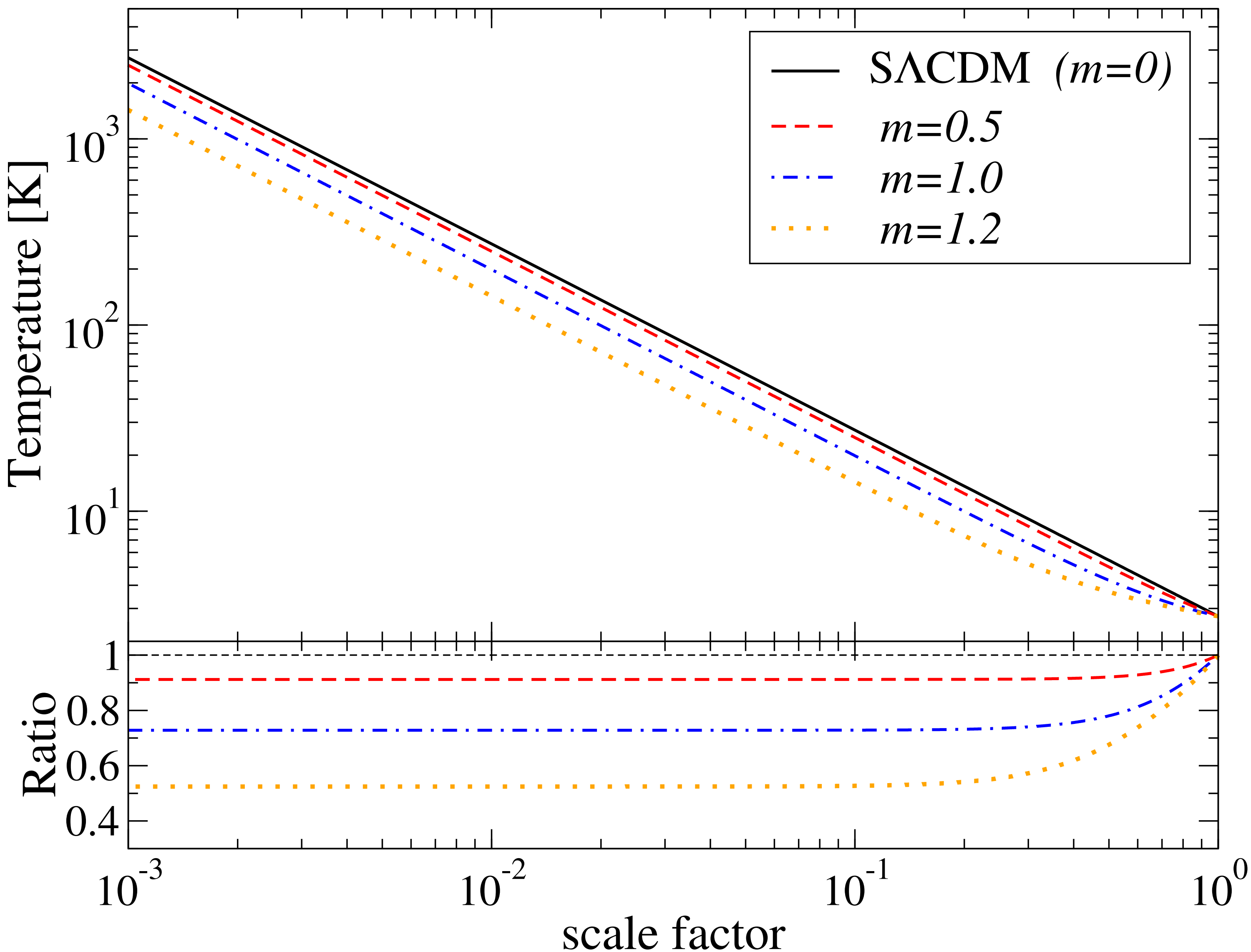
Effects of decaying-Λ on cosmic ev

- 過去に遡ると Λ が増加 $\longrightarrow$ Cosmic expansion rate at low-z
  - 影響はほとんど無し.
- Photon の振舞が a^{-4} からずれる
  - Photon temperature
  - Effects on CMB anisotropy

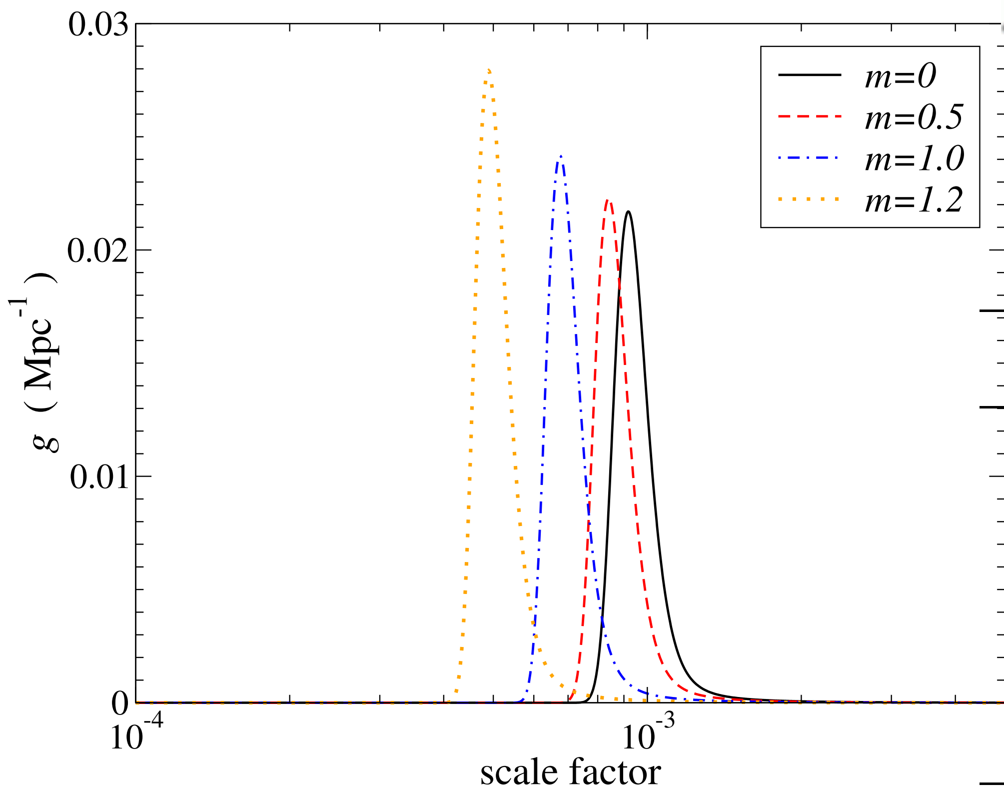
Temperature evolutions

- Radiation temperature T_γ: $\Omega_\gamma \propto T_\gamma^4$
  - $T_\gamma = \frac{T_{\gamma 0}}{a}\left(1 + \frac{\Omega_{\gamma\Lambda}}{\Omega_{\gamma 0}}\right)^{1/4}$
  - The decaying-Λ contribution: $\Omega_{\gamma\Lambda}$
    - $\Omega_{\gamma\Lambda} = \frac{m}{4-m}\Omega_{\Lambda 2}\left(a^{4-m} - 1\right)$
    - $\Omega_{\gamma\Lambda} = 4\Omega_{\Lambda 2}\ln a$
- If without Λ-decay, $T_\gamma \propto a^{-1}$

Temperature evolution



Effects on decoupling



- visibility function

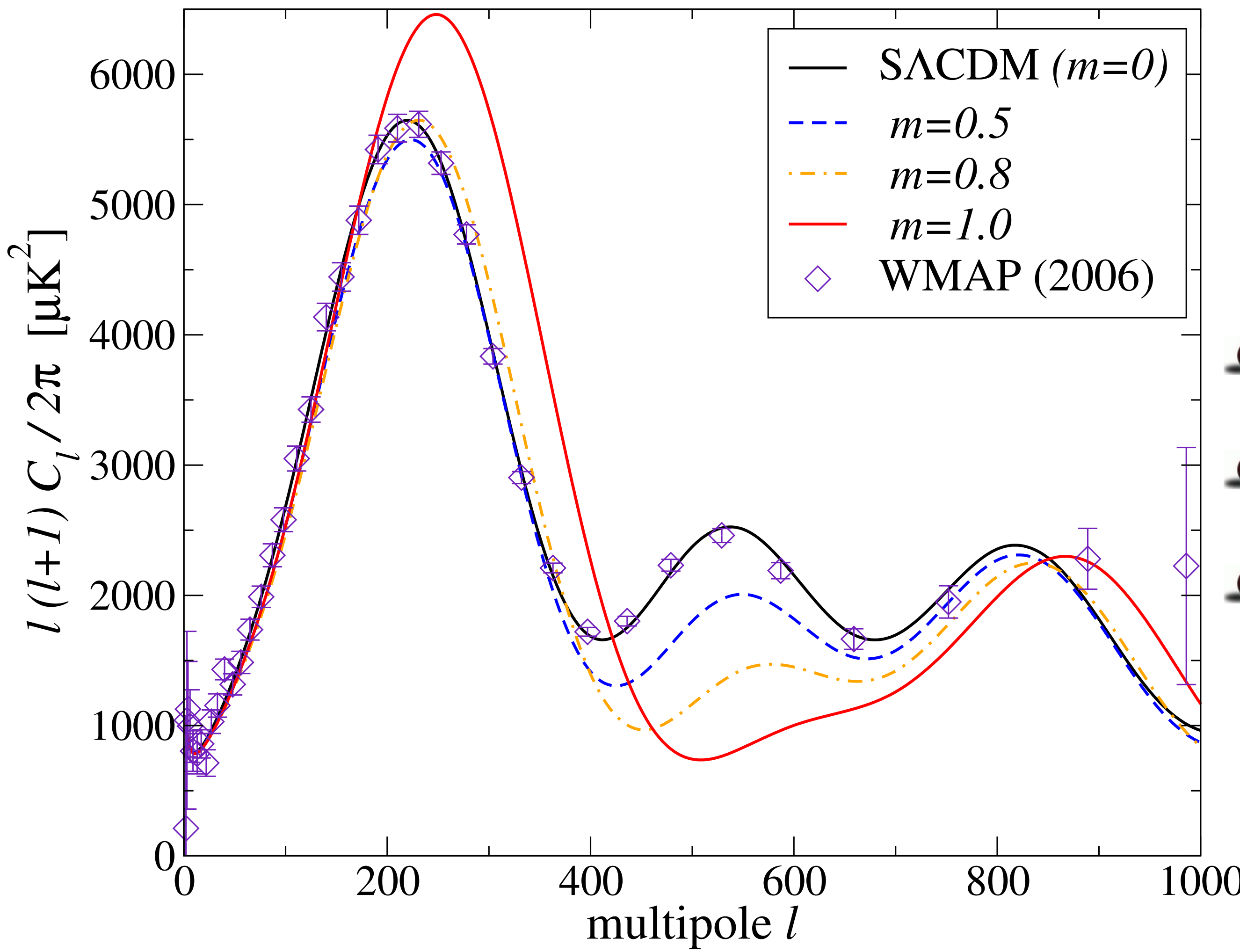
$$g(t) = -\dot{\kappa} e^{-\kappa},$$
$$\kappa = \sigma_T \int n_e dt$$

parameter	redshift z_{dec}	T_{dec} [K]
$m = 0.0$	1087	2965
$m = 0.5$	1188	2957
$m = 1.0$	1480	2939
$m = 1.2$	2043	2921

Boltzmann equation

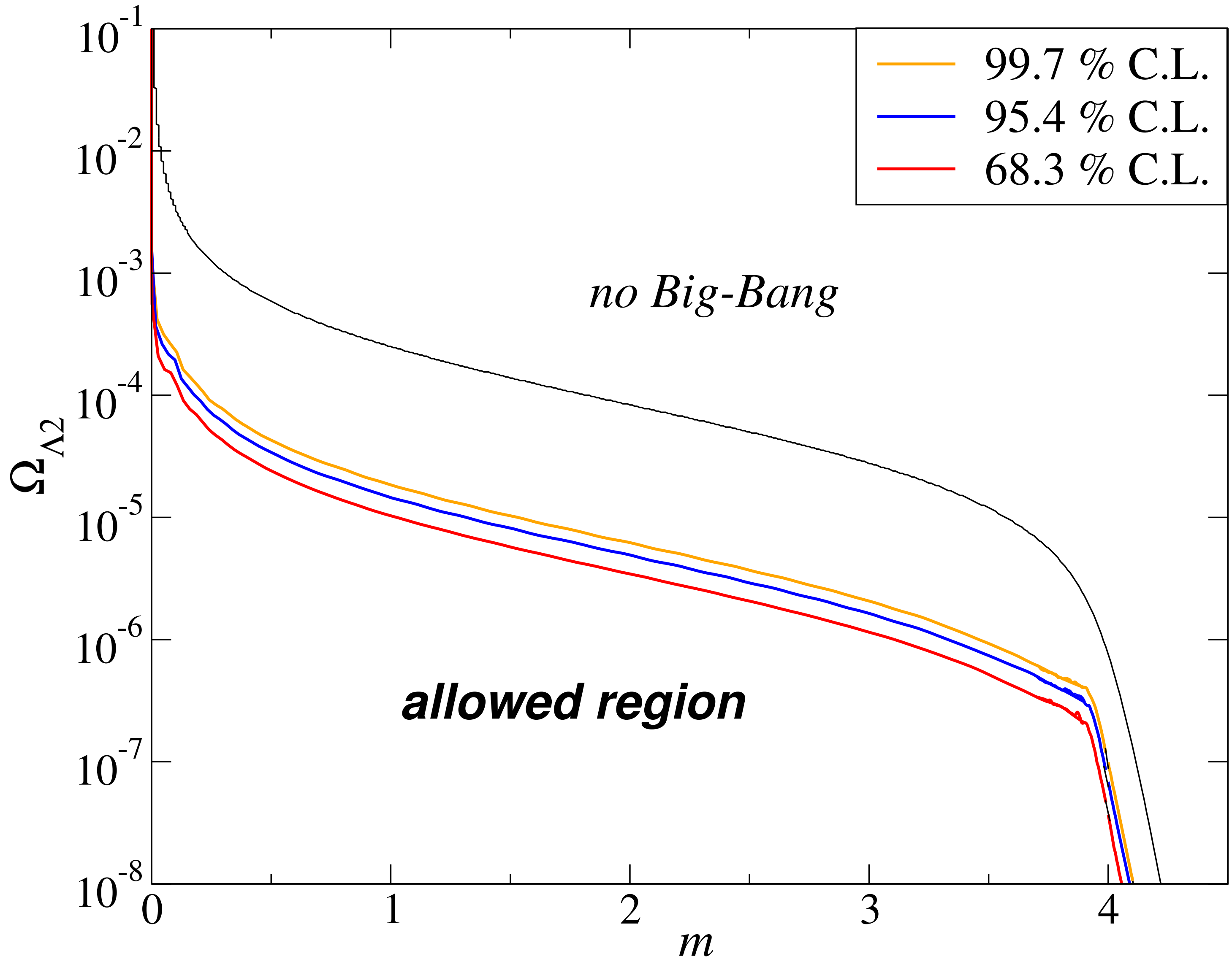
- When vacuum energy decay into photons, photon's distribution function is function of time (Lima 1996).
- The Boltzmann equation in $k-$space
  $$f_0\frac{\partial\Psi}{\partial\tau}+\Psi\frac{\partial f_0}{\partial\tau}+ik\mu f_0\Psi+q\frac{df_0}{dq}\left(\dot{\eta}+\frac{\dot{h}+6\dot{\eta}}{2}\mu^2\right)=\left(\frac{\partial f_0}{\partial\tau}\right)_{col}$$
- $\dot{F}_\gamma+ik\mu F_\gamma+\frac{4}{3}\left(\dot{h}+6\dot{\eta}\right)P_2+\frac{2}{3}\dot{h}-\frac{\dot{\rho}_\Lambda}{\bar{\rho}_\gamma}F_\gamma=\left(\frac{\partial F_\gamma}{\partial\tau}\right)_{col}$
  - $\dot{\delta}_\gamma=-\frac{4}{3}\delta_\gamma-\frac{2}{3}\dot{h}+\frac{\dot{\rho}_\Lambda}{\bar{\rho}_\gamma}\delta_\gamma$
  - $\dot{\theta}_\gamma=\frac{1}{4}k^2\delta_\gamma-k^2\sigma_\gamma+\frac{\dot{\rho}_\Lambda}{\bar{\rho}\gamma}\theta_\gamma-an_e\sigma_T\left(\theta_\gamma-\theta_b\right)$
  - $\dot{\sigma}_\gamma=\frac{4}{15}\theta_\gamma-\frac{3}{10}kF_{\gamma 3}+\frac{2}{15}\left(\dot{h}+6\dot{\eta}\right)+\frac{\dot{\rho}_\Lambda}{\bar{\rho}_\gamma}\sigma_\gamma-\frac{9}{10}\tau_C^{-1}\sigma_\gamma+\frac{1}{20}\tau_C^{-1}\left(G_{\gamma 0}+G_{\gamma 2}\right)$
  - $\dot{F}_{\gamma l}=\frac{k}{2l+1}\left(lF_{\gamma,l-1}-(l+1)F_{\gamma,l+1}\right)+\frac{\dot{\rho}_\Lambda}{\bar{\rho}_\gamma}F_{\gamma l}-\tau_C^{-1}F_{\gamma l}$

CMB anisotropy



- $Y_p = 0.24$
- $N_\nu = 3.04$
- $z_{re} = 0$

Constraint on $m - \Omega_{\Lambda 2}$



Half time

- Variable-Λ affect CMB temperature fluctuation significantly.
- Fixed cosmological parameters, we constrain on $m-\Omega_{\Lambda 2}$ plane from WMAP results.

$$\frac{m\Omega_{\Lambda,2}}{(4-m)} < 4.9\times 10^{-6}\ (2\sigma\ \mathtt{C.L.})$$

$\longrightarrow$ photon decoupling occur earlier by $\Delta z = 31$

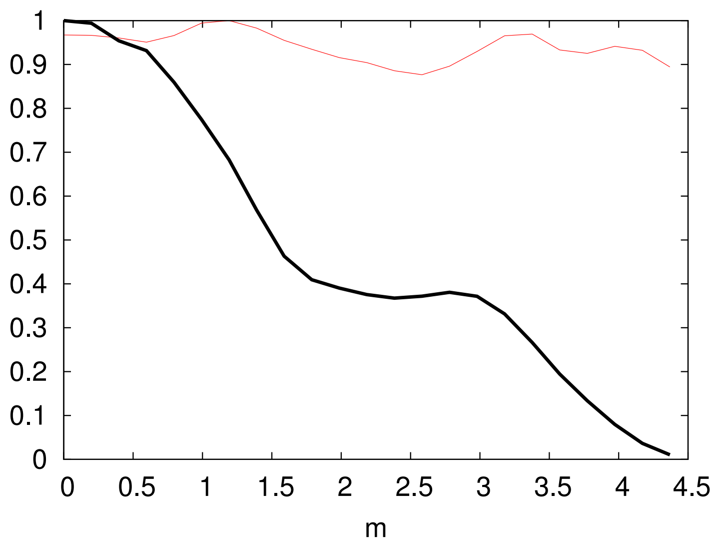
- CMB は他の宇宙論パラメータにも依存.
  - $\Omega_b, \Omega_{CDM}, H_0, \Omega_k$, reionization, etc...

Prior in our study

- $h = 0.72 \pm 0.08$ (Hubble Key Project prior)
- $\Omega_b h^2 = 0.02 \pm 0.002$ (BBN prior)
- $10 < t_0$ [Gyr] < 20
- $-0.3 < \Omega_k < 0.3$
- $0 < \Omega_\Lambda < 1,$
- $0 < m$
- $0 < \Omega_{\Lambda 2}$

Likelihood

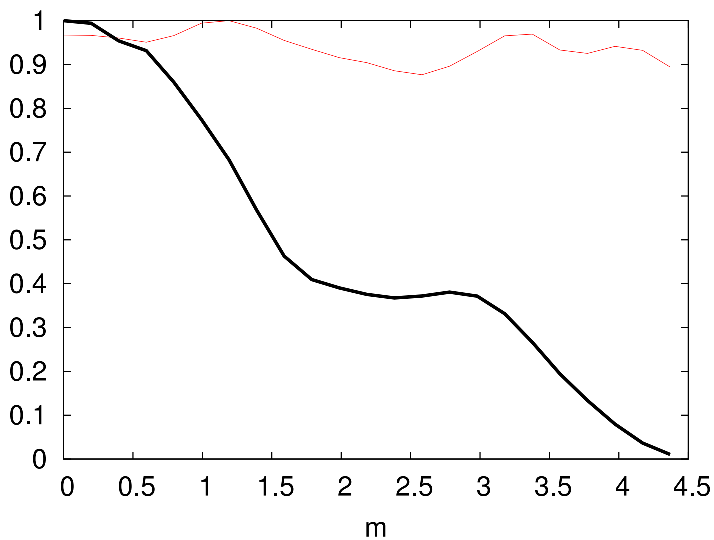
- $\Omega_\Lambda = \Omega_{\Lambda 1} + \Omega_{\Lambda 2} a^{-m}$

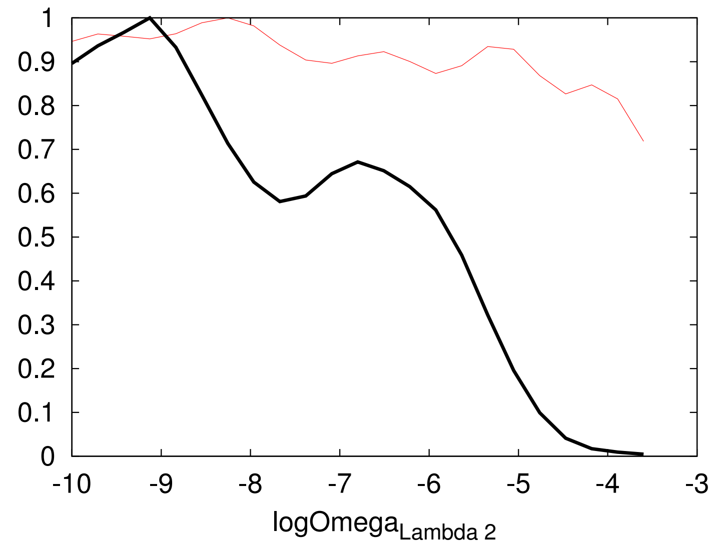


- $m < 4.2$ at 2σ C.L.
- 上限のみ決まる.

Likelihood

- $\Omega_\Lambda = \Omega_{\Lambda 1} + \Omega_{\Lambda 2} a^{-m}$

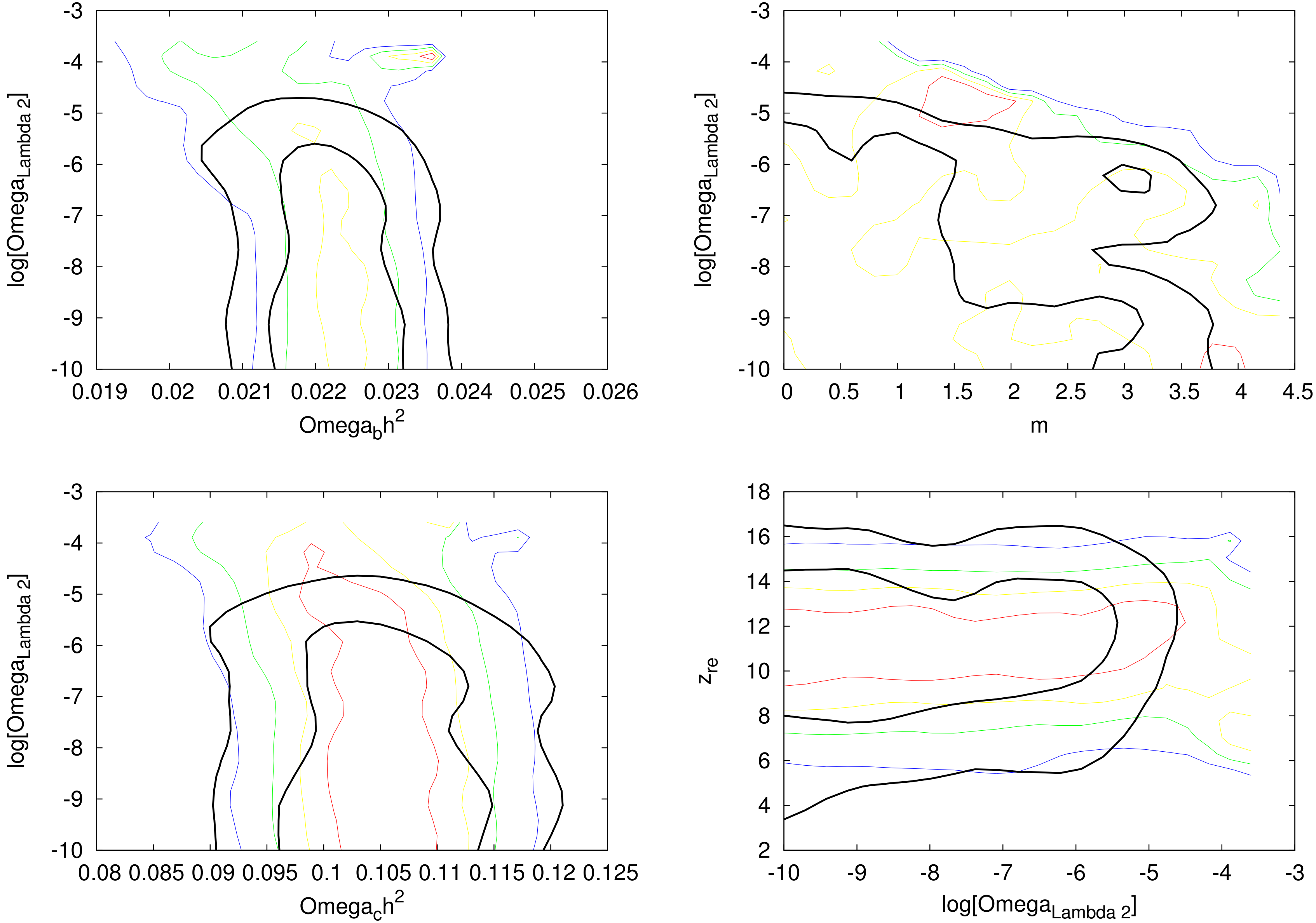




- $m < 4.2$ at 2σ C.L.
- 上限のみ決まる.

- $\log \Omega_{\Lambda 2} \leq -3.6$ at 2σ C.L.
- こちらも上限のみ.

contours


-3
-4
-5
-6
-7
-8
-9
-10
0.019 0.02 0.021 0.022 0.023 0.024 0.025 0.026
Omega$_b$h^2
log[Omega$_{Lambda\ 2}$]
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
m
0.08 0.085 0.09 0.095 0.1 0.105 0.11 0.115 0.12 0.125
Omega$_c$h^2
18
16
14
12
10
8
6
4
2
z$_{re}$
-10 -9 -8 -7 -6 -5 -4 -3

cosmological parameters

Parameter	DΛCDM	SΛCDM
$\Omega_{\Lambda 2}$	$< 1.9 \times 10^{-4}$	
m	< 4.2	
$\Omega_b h^2$	$0.0225^{+0.0027}_{-0.0038}$	$0.02230^{+0.00075}_{-0.00073}$
$\Omega_C h^2$	$0.104^{+0.054}_{-0.034}$	$0.109^{+0.017}_{-0.014}$
z_{re}	$11.7^{+8.3}_{-9.4}$	10.9 ± 2.6
n_s	$0.954^{+0.065}_{-0.064}$	0.951 ± 0.016
Ω_m	$0.26^{+0.18}_{-0.12}$	0.237 ± 0.034
Ω_Λ	$0.75^{+0.14}_{-0.18}$	0.763 ± 0.034

Results

- Decaying-Λ affects on CMB anisotropy significantly.
- We put constrains on cosmological parameters using MCMC method.
  - $m < 4.2, \Omega_{\Lambda 2} < 1.9 \times 10^{-4}$ at 2σ C.L.
  - There are no effects of a decaying-Λ on cosmological parameters
    - Flat universe & 70% Λ
  - Effects of a decayingΛ should be small.
  - Our results is suggested more early reionization.