On Observational Effects of Spherical Inhomogeneity

公募研究
「加速宇宙観測における等方な非一様性による系統誤差と宇宙原理の観測的検証」
の内容（一部）と進捗状況について

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Table

◎Non-Copernican universe model

- Spherical inhomogeneity around us
- Observational test of the cosmological principle

◎Observational constraints on LTB model without Λ

◎CMB constraints on ΛLTB(ongoing works)

- CMB power spectrum
- kinetic Sunyaev-Zeldovich(kSZ) effect

Test of Cosmological Principle

◎Isotropy around us can be directly observed

◎Direct observation of the homogeneity is impossible

- Communication w/ an observer separated by cosmological distance

◎Standard way

- Accept the Copernican principle
- Isotropy + Copernican principle
  → Homogeneity
  (Cosmological principle)

◎Non-standard way

- We are in the center of an isotropic universe
- How can you observationally rule out it?

◎Indirect observational tests of cosmological principle

Acceleration vs Inhomogeneity

◎Acceleration⇒small recession velocity in an earlier time

◎Cosmological observables on the past light cone

- Homogeneous universe:「past=far」
- Inhomogeneous case　:「past≠far」

⇒If expansion rate is smaller in a far region($\partial_r H < 0$),
apparent acceleration is possible

◎Distance-redshift relation for $\Lambda > 0$ FLRW can be realized
by the spherical inhomogeneous dust model(LTB) without Λ

[iguchi, Nakamura, Nakao,astro-ph/0112419]
[CY,Kai,Nakao,arXiv:0807.0932]

◎Spherical inhomogeneity may cause a systematic error
in estimation of Λ

(Λ)LTB model

◎Spherically symmetric dust solution of Einstein Eqs.

◎Two independent physical functional d.o.f of radial coord. r

$k(r)$ ：「curvature function」~ growing mode

$t_{\mathrm{B}}(r)$ ：「Bang time function」~ decaying mode

◎Here, we assume $t_{\mathrm{B}} = \mathrm{const.}$

・ Existence of the decaying mode spoils almost everything
→little prediction

◎Apparent acceleration is realized by a void structure

・ $\partial_r H < 0$ on a uniform density slice
⇒$\partial_r \rho > 0$ on a uniform Hubble slice

◎We focus on cosmological scale(~Gpc) void models

Constraints from CMB

◎Alnes, Amarzguioui, Gron[astro-ph/0512006]

- *"we find that the position of the first CMB peak can be made to match the WMAP observations."*
- It drove active discussion about non-Copernican universe

◎Recent analysis with CMB power spectrum

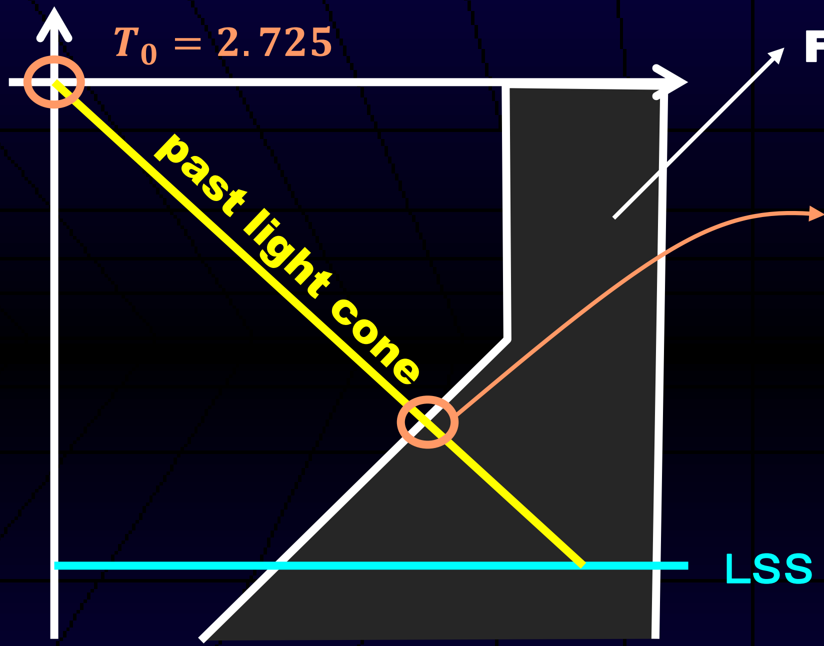
[e.g. Redlich et.al. arXiv:1408.1872]

- CMB power spectrum can be explained without Λ
- *"an extremely low expansion rate of* $h = 0.33 \pm 0.01$ *is favoured."* (h at the last scattering surface)

◎How to calculate the CMB power spectrum?

CMB in LTB

◎LTB with growing mode inhomogeneity



- Parametrize the LTB function $k(r)$
- Solving geodesic, we obtain the redshift~temperature ~radiation density
- Matter density is also known
- Others are free
- Temperature fluctuation for the corresponding FLRW model

◎Correction associated with difference of distance($\theta = \frac{\text{diameter}}{\text{distance}}$)

$$C_\ell = \sum_{\ell'} \frac{2\ell'+1}{2} C'_{\ell'} \int_0^\pi P_{\ell'}\left(\cos(\theta D_{\mathrm{A}}/\mathrm{D}'_A)\right) P_\ell(\cos\theta)\sin\theta d\theta$$

$$\xrightarrow[\text{flat sky approx.}(\ell \gg 1)]{} \quad C_\ell = (D'_{\mathrm{A}}/D_{\mathrm{A}}) C'_{D'_{\mathrm{A}}\ell/D_{\mathrm{A}}}$$

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- CMB power spectrum can be explained without Λ
- *"an extremely low expansion rate of* $h = 0.33 \pm 0.01$ *is favoured."* (h at the last scattering surface)
- Inhomogeneity inside LSS is not tightly constrained

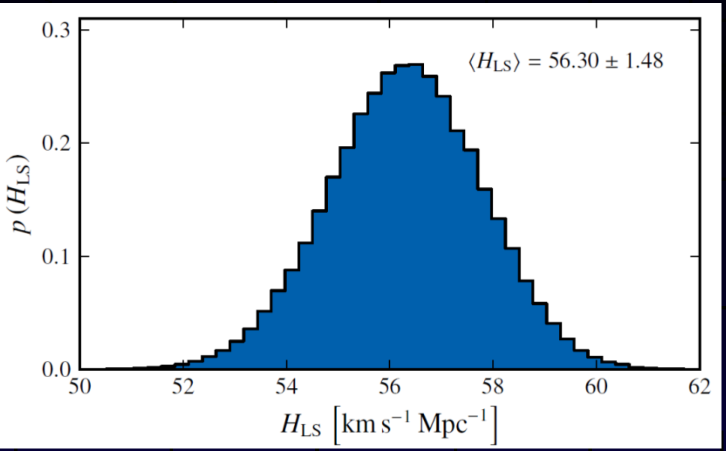
◎How to calculate the CMB power spectrum?

CMB+H_0+SNe

◎Including SNe, H_0 data

◎ Redlich et.al. [arXiv:1408.1872]

- *"The local Hubble rate still is much too low"*
  "the log likelihood value indicate that this model cannot compete with the FLRW model"



(for 3Gpc void model)

◎Note: the local H is higher than the asymptotic value

kSZ

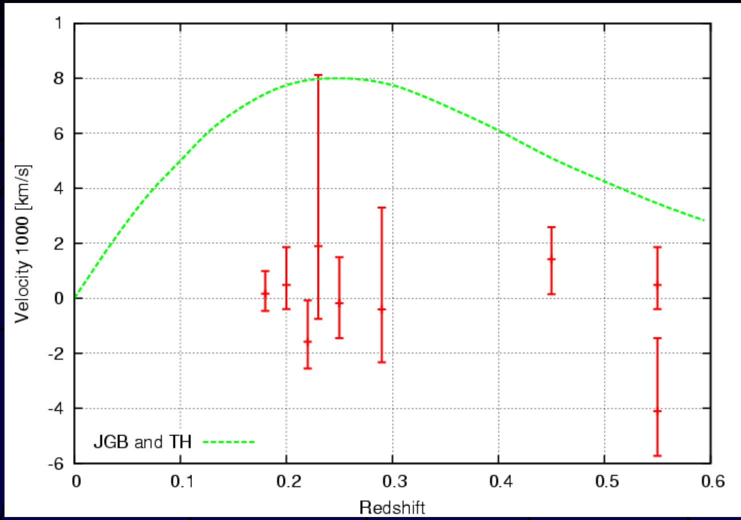
◎kinetic Sunyaev-Zeldovich effect（Homogeneous universe）

- Scattering due to a cluster with radial proper motion
  ⇒distortion of the thermal spectrum of CMB photons

- Origin: dipole anisotropy of CMB temperature from the cluster

◎Garcia-Bellido and Haugboelle[arXiv:0807.1326]

- *“current observations of only nine clusters with large error bars already rule out LTB models with void size greater than ～1.5Gpc”*



- Clusters are not at the center of the universe
  ⇒observes a dipole anisotropy
  ⇒effective kSZ effect

- Vanishing Λ is ruled out

Why not Λ!

◎Our motivation is not explaining observation without Λ

◎Observational constraints on spherical inhomogeneity?

◎How large systematic errors can be expected?

◎Local Hubble tension: Planck vs local measurements

- In moderate void models, local H_0 > asymptotic value of H_0
- Small σ_8 and fewer cluster

[Marra et.al, arXiv:1303.3121]
[Keenan et.al, arXiv:1304.2884]
[Lee, arXiv:1308.3869]
[Ichiki, CY, Oguri arXiv:1509.04342]

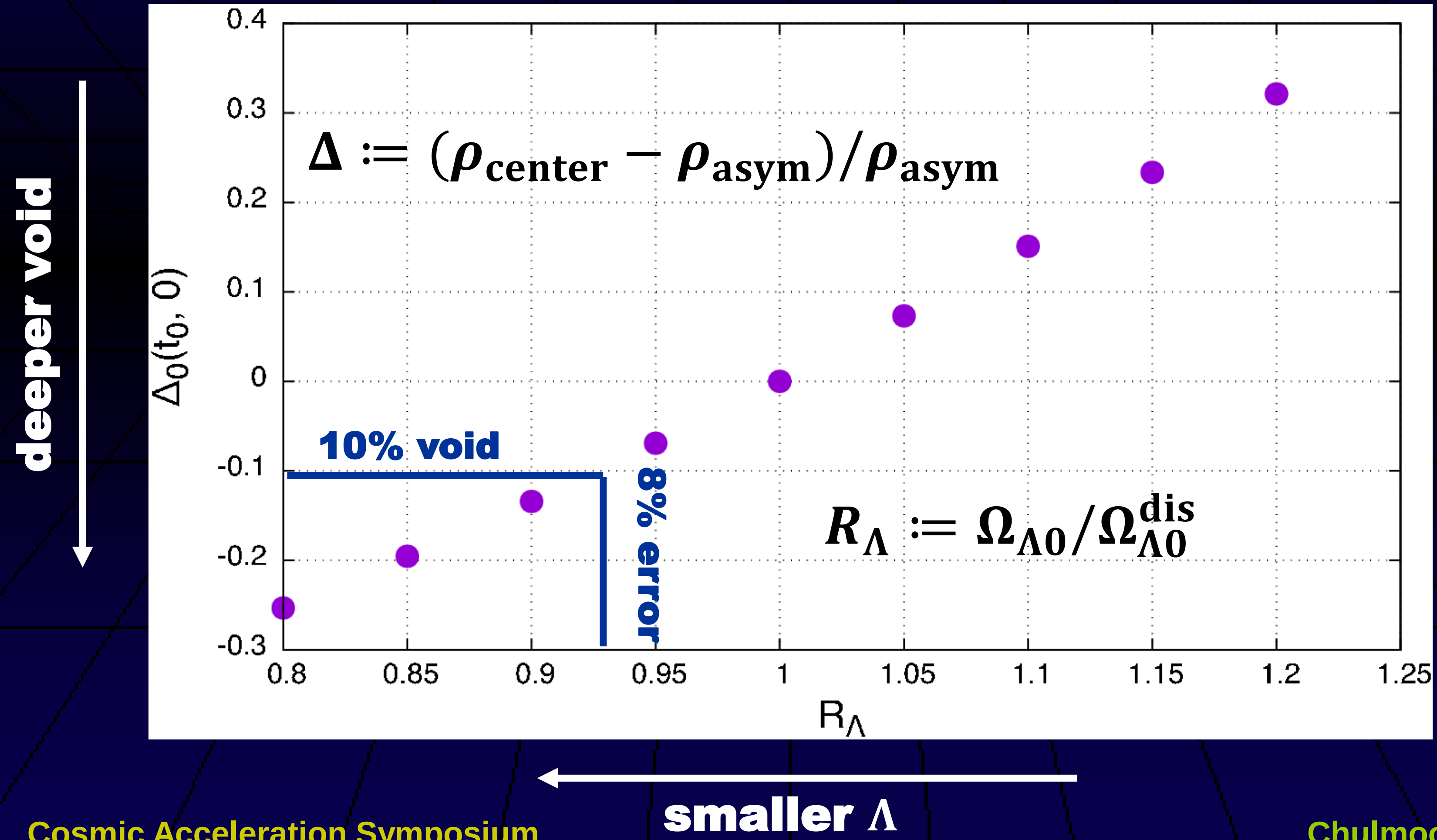
Λ and Void

◎Apparent value of Λ and void depth[Tokutake,CY arXiv:1603.01762]

- Distance-redshift relation: D_{FLRW} with $\Omega_{\Lambda 0}^{\rm dis}=0.7$ and $\Omega_{\rm m0}^{\rm dis}=0.3$
- Suppose these values are apparent values from observed distance
- Actual universe model is given by a ΛLTB model with $\Omega_{\Lambda 0}$
- The ΛLTB model is uniquely determined(no decaying mode)
- One void profile for each value of $R_\Lambda \coloneqq \Omega_{\Lambda 0}/\Omega_{\Lambda 0}^{\rm dis}$
- Void depth: $\Delta \coloneqq (\rho_{\rm center}-\rho_{\rm asym})/\rho_{\rm asym}$ (void for $\Delta<0$)

Λ and Void

◎**Error in Ω_Λ and void depth**[Tokutake,CY arXiv:1603.01762]
[Negishi et.al arXiv:1505.02472]



Λ and Void

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◎Parametrization of LTB

- Parameter set $(\Omega_{\Lambda 0}^{\mathrm{dis}}, \Omega_{\mathrm{m}0}^{\mathrm{dis}}, R_\Lambda)$ fixes the inhomogeneity

◎What about CMB constraints?

Setting for Power Spectrum

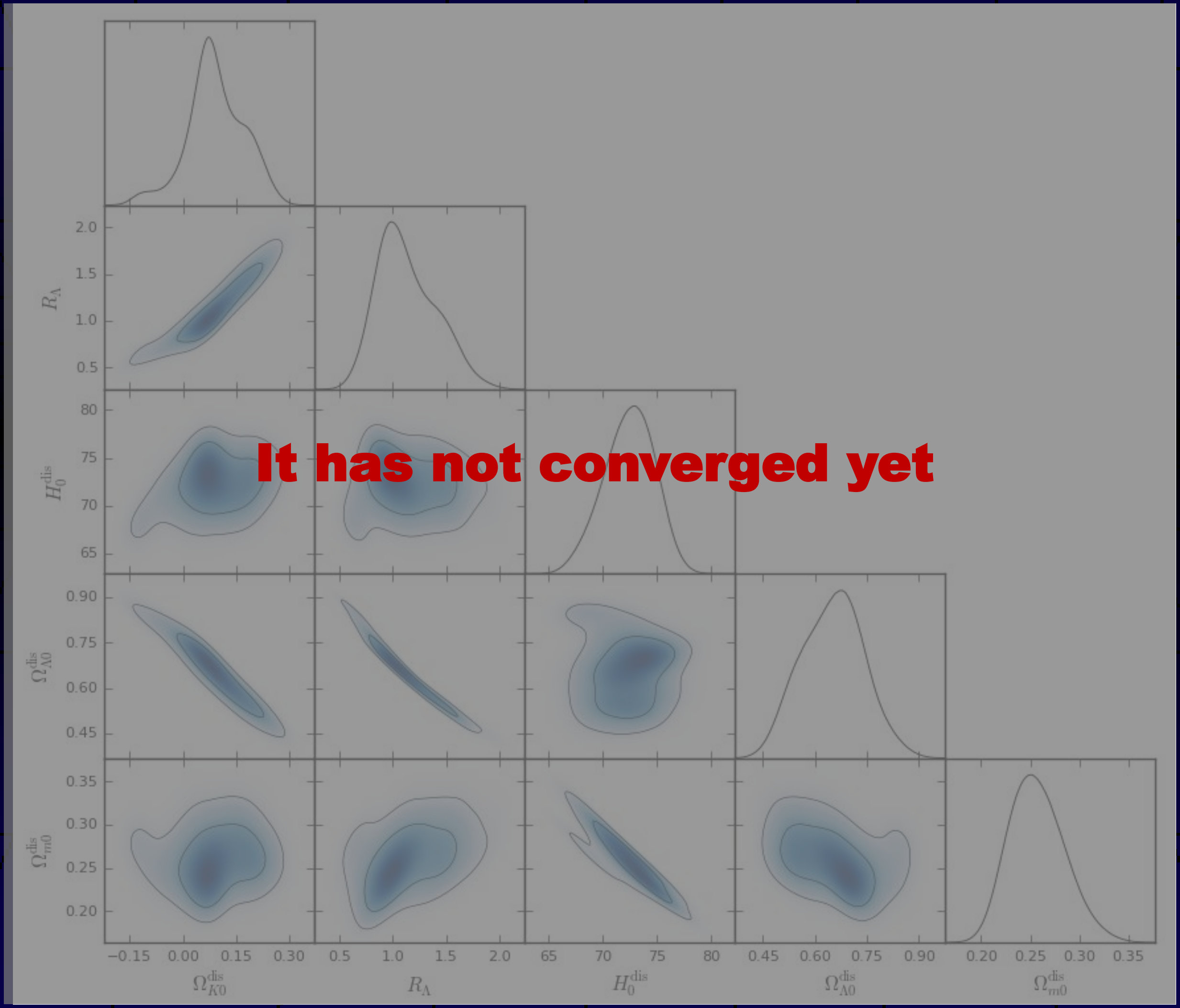
◎Data: Planck data ($\ell > 20$: flat sky approx)

◎Model parameters

- 3 LTB parameters ($\Omega_{\Lambda 0}^{\rm dis}$, $\Omega_{\rm m0}^{\rm dis}$, R_Λ)
- Optical depth τ is fixed as $\tau = 0.1$
- Other parameters (H_0, n_s, A, $\alpha \coloneqq \rm baryon/matter$)
- CosmoMC with 7 parameters
- Prior: $H_0 = 72.5 \pm 2.5[\rm km\ s^{-1}\ Mpc^{-1}]$ ⇒ Constraint on void depth

With Tokutake-kun and Ichiki-san

Calculating...



It has not converged yet

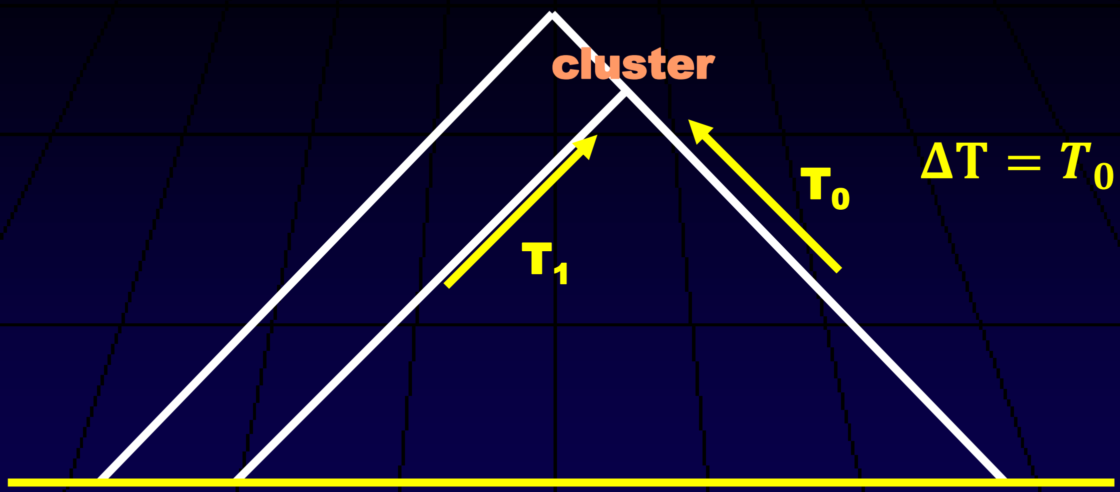
Expectation

◎Expectation

- Λ=0 will be ruled out but still significant void depth is possible

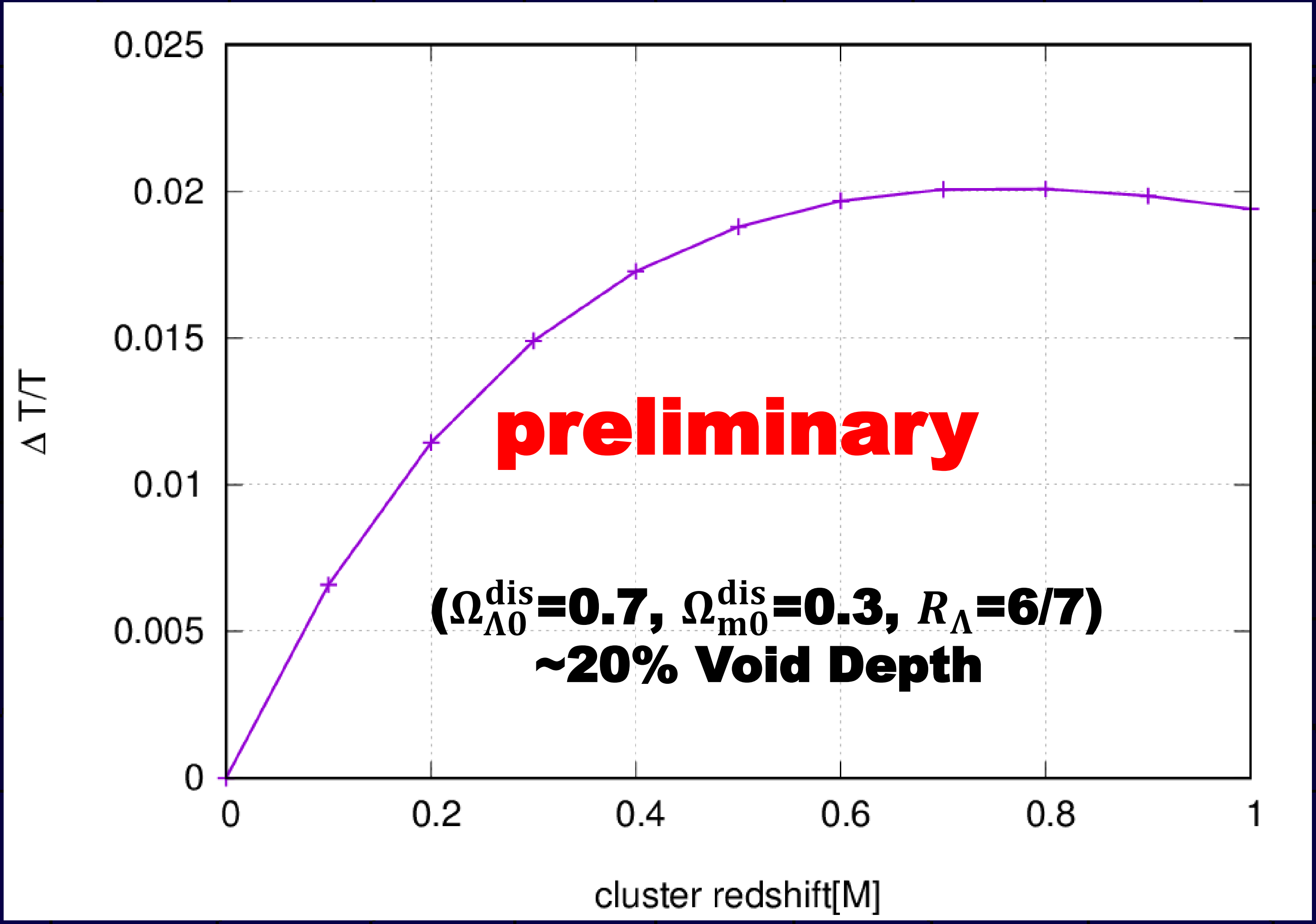
◎kSZ would be more effective to give a constraint

- Planck: $\Delta\mathrm{T}/\mathrm{T} \lesssim 6.4 \times 10^{-4}$ for $z < 1$
- Ongoing with Ichiki-san and Oguri-san



$\Delta\mathrm{T} = T_0 - T_1$

kSZ


0.025
0.02
0.015
0.01
0.005
0
Δ T/T
0
0.2
0.4
0.6
0.8
1
cluster redshift[M]
preliminary
$(\Omega_{\Lambda 0}^{\mathrm{dis}}=0.7,\ \Omega_{\mathrm{m}0}^{\mathrm{dis}}=0.3,\ R_\Lambda=6/7)$
~20% Void Depth

Expectation

◎Expectation

- Λ=0 will be ruled out but still significant void depth is possible

◎kSZ would be more effective to give a constraint

- Planck: $\Delta T/T \lesssim 6.4\times10^{-4}$ for $z<1$
- Ongoing with Ichiki-san and Oguri-san
- $R_\Lambda < 10^{-2}$… ?

◎Constraints from other observables related to "Cosmic Acceleration" are future works

Thank you

Cluster Number Count