On astrophysical explanations due to cosmological inhomogeneities for the observational acceleration

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§ 1. Introduction

Λ-dominated FLRW model with $(\Omega_M, \Omega_\Lambda) = (0.25, 0.75)$

SNIa (m, z) relation, CMB anisotropies,
cluster abubdance, BAO (RBAO), ISW :OK

→ concordant

Unresolved problems

cosmological-constant problem
incidence problem
low-l anomaly of CMB

Astrophysical explanations ?

Astrophysical explanations due to inhomogeneous models with $\Lambda = 0$. What inhomogeneity ?

(1) *Non-Copernican* inhomogeneity

A spherically symmetric underdense local inhomogeneity (local void)

(2) *Copernican* inhomogeneity

Uniform distribution of perturbations

a. Averaging and backreaction

b. Fitting

In 1999(Nov), Buchert and I talked on (2)a and (1) at the early stage, in the JGRG workshop (held in Hiroshima Univ, Japan).

Here I have a review of recent theoretical and observational works on these problems

§ 2. Local-void model and SN1a

Another possibility for the *non-Copernican* explanation of SNIa data (Riess et al., Perlmutter et al)

Celerier (2000) proposed independently A-A 353(00)63

qualitative discussions, general inhomogeneous solutions

Goodwin et al. (unpublished, similar epoch)

physical analyses, local to global Hubble const ratio

Tomita first model (2000) ApJ 529(00)26, 38

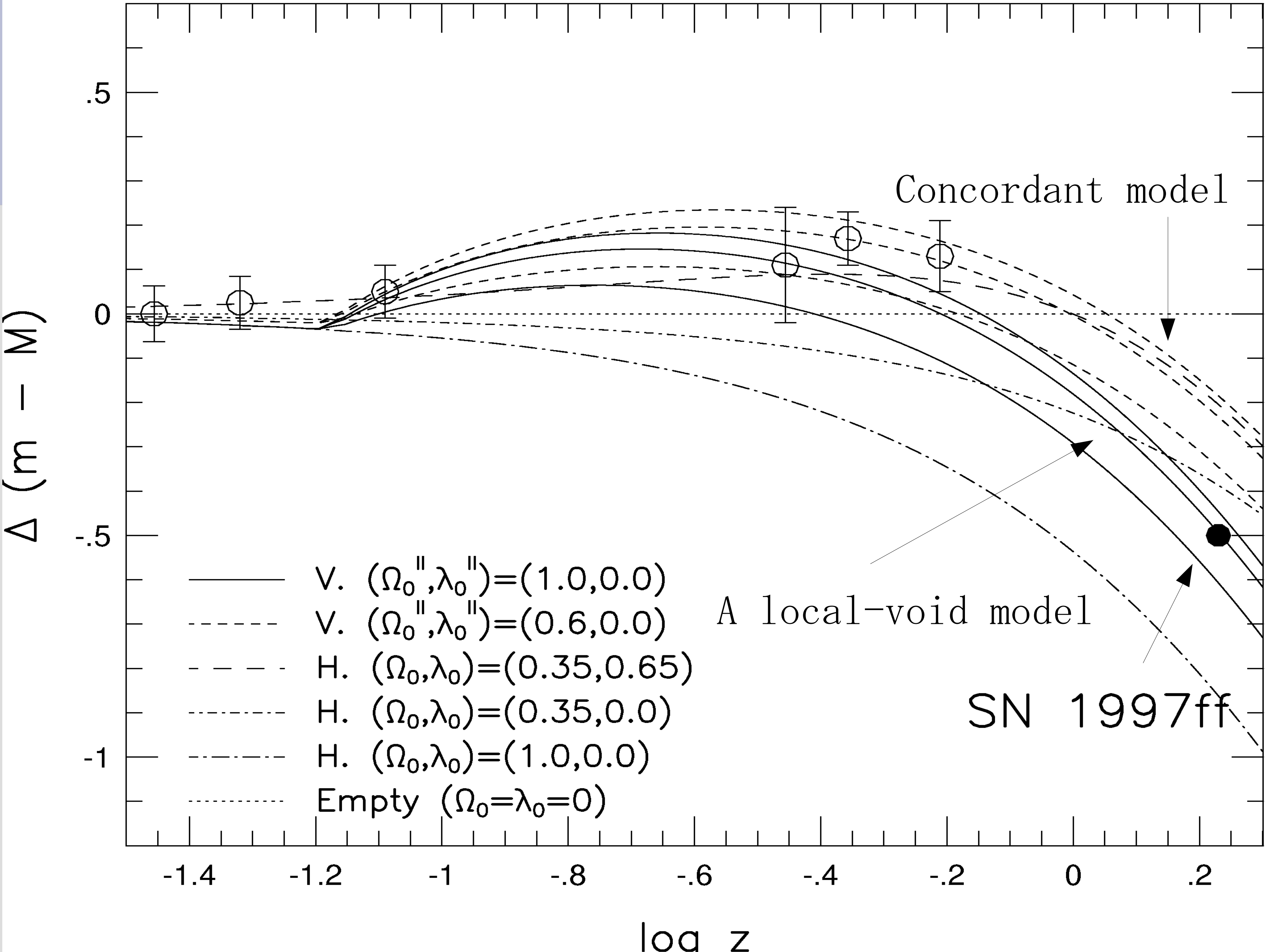
FRW sol (open, inner region)+ self-similar LTB sol (asymptotically flat, outer region) superhorizon version (1995)

Tomita second model (2001) MN 326(01)287, PTP 106(01)929

FRW sol (open, inner region) + discontinuous wall + FRW sol (flat, outer region)

Kasai (2007) PTP 117(07)1067

the observed data of SN1a can be divided into two groups ($z<0.2$, $z>0.3$) -> local structure ?



Concordant model
A local-void model
SN 1997ff
V. $(\Omega_0'', \lambda_0'')=(1.0,0.0)$
V. $(\Omega_0'', \lambda_0'')=(0.6,0.0)$
H. $(\Omega_0, \lambda_0)=(0.35,0.65)$
H. $(\Omega_0, \lambda_0)=(0.35,0.0)$
H. $(\Omega_0, \lambda_0)=(1.0,0.0)$
Empty $(\Omega_0=\lambda_0=0)$
Δ (m - M)
log z
.5
0
-.5
-1
-1.4
-1.2
-1
-.8
-.6
-.4
-.2
0
.2

For the (m, z) data of SN1a, the farthest one is "SN 197ff" , which deviates from the curve of the concotdant model. At present there is no data for z > 1.7, which are very important for the model selection. Will the data for z > 1.7 support the concordant model or the other model ?

The present situation of a probe for very high redshift supernovas is as follows:

SNAP - the SuperNova Acceleration Probe - is a proposed space observatory designed to measure the expansion of the Universe and to determine the nature of the mysterious Dark Energy that is accelerating this expansion. SNAP is being proposed as part of the Joint Dark Energy Mission (JDEM), which is a cooperative venture between NASA and the U.S. Department of Energy. If selected it will be launched before 2020.

(http://snap.lbl.gov/index.php)

Iguchi, Nakamura and Nakao (2002) PTP 108(02)809

more general LTB sol which reproduces the concordant (m-z) relation, a critical point appears ($z < 1.7$)

Vanderveld et al. (2006) PR D74(06)023506

geometrical structure of LTB solutions (include central weak singularity and critical point)

Yoo, Kai and Nakao (2008) arXiv:0807.0932

LTB model without critical pont which reproduces the concordant (m-z) relation and has the uniform big-bang time

Clifton et al. (2008) arXiv:0807.0443

LTB model (Gpc) without central weak singularity

Alnes et al.(06,07), Mansouri(06), Moffat(05,06), Biswas et al.(07), Alexander et al.(08), ...

Other LTB models which reproduce the observed (m-z) relation

§ 3. Consistency of local-void models with the other observations

A. CMB temperature anisotropies

acoustic peaks in the $C_l - l$ diagram for l > 200

Alnes et al. first peak PR D73(06)083519
Alexander, Biswas, Notari & Vaid
first and second peaks
(the Minimum model) arXiv:0712.0370
Blanchard et al. A-A 412(03)35
Hund and Sarkar PR D76(07)123504; arXiv:0706.2443

off-center observer -> CMB dipole
the upper limit of distance r of the observer from the center : r < rmin (=15Mpc)
from the observed dipole

Tomita ApJ 584(03)580, Moffat JCAP 10(05)12,
Alnes et al. PR D74(06)103520

B. Baryon acoustic oscillation (BAO)

BAO scale

$$r_s(z_{rec}) = \int_{z_{rec}}^{\infty} dz\, c_s(z)/H(z)$$

$$r_s \approx 147(\Omega_M h^2/0.13)^{-0.5} \times (\Omega_b h^2/0.024)^{-0.08}\, Mpc$$

distance measure

$$d_V(z) = [(1+z)^2 (d_A)^2 cz/H(z)]^{1/3}$$

d_A : angular diameter distance

Percival et al. 's relation MN 381(07)1053

$r_s/d_V(0.2) = 0.1980$ $r_s/d_V(0.35) = 0.1094$

Can we reproduce these relations ?

Concordant model	95%	OK
Tomita model	80%	NO (rule out)
Minimum model	similar situation	

-> Gpc-size inhomogeneous models

local void : z(boundary) > 0.35

Clifton et al. (08),

Garcia-Bellido & Haugbolle JCAP 4(2008)3

Radial BAO (RBAO)　　severer constraints

Gaztnago et al. (08)　　arXiv:0808.1921

observational data at z = 0.24, 0.43,
concordant models are OK

Zibin, Moss and Scott (08)　　arXiv:0809.3761

two models : constrained model and unconstrained model
(recent SN and WMAP data are reproduced,
z(boundary) = about 1,
a constraint condition is imposed or not)

The result of RBAO consistency test

(1) unconstrained model : OK for RBAO, but Ho = 44
-> ruled out

(2) constrained model : nearly OK for RBAO and Ho = about 60

At present, this model is not ruled out,
but the consistency is not good as the concordant model

C. Kinematic Sunyaev-Zeldovich effect (kSZ)

SZ : scattering by ionized gas in the center of clusters
kSZ : case of moving clusters, relative to CMB rest frame

$$\frac{\delta T_{SZ}}{T_{CMB}} = \tau_e \frac{v_{pec}}{c}$$: temperature fluctuation

$$v_{pec} = \delta H \times r \qquad \delta H = H - H_{EdS} \qquad r = cz/H$$

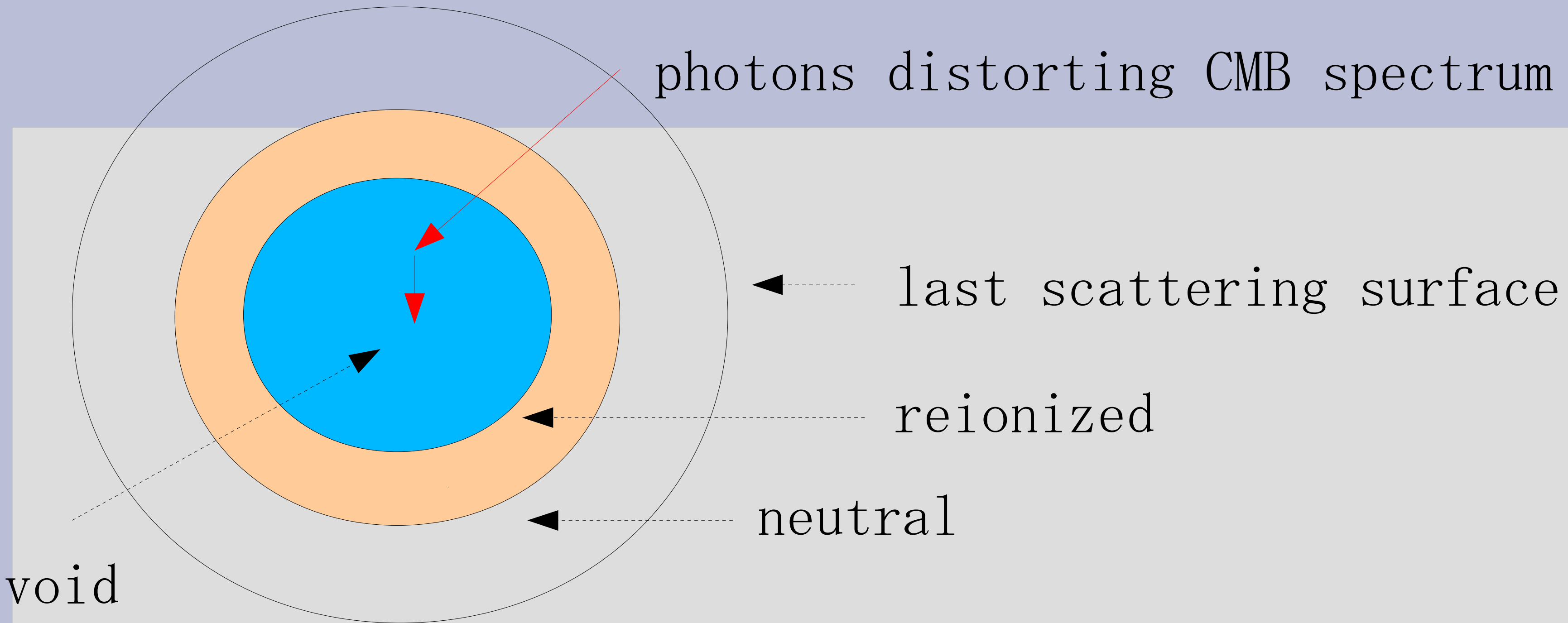
: peculiar velocity of clusters relative to CMB (in the EdS model)

observed upper limit of peculiar velocity gives the limit of $\delta H(z)$

Benson et al. (03) arXiv:astro-ph/0303510
Garcia-Bellido & Haugbolle (08) arXiv:0807.1326

local void with size >1.5Gpc : impossible

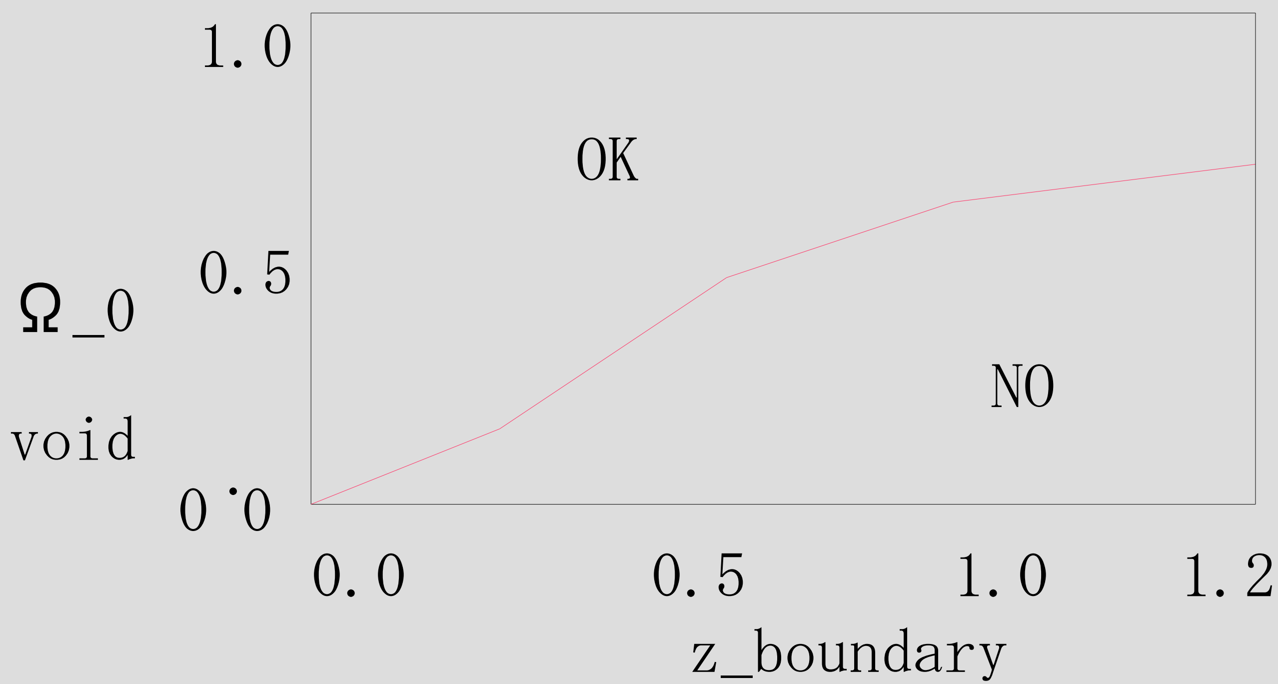
D. Spectral distortion of CMB at the reionized stage



The reionized universe serves as a mirror to reflect CMB photons and the photons within the void region distort the spectrum by the Doppler effect. The measurement of spectral distortion puts the limit to the void model.

Caldwell & Stebbin (07) arXiv:0711.3459

The allowed region on (the density in the void Ω_0 - Z_boundary) diagram is shown in the following Fig. It is found that large Gpc voids are not compatible with low density. For z_boundary = 0.5 (1.2 Gpc), we have $\Omega_0 > 0.5$.



§ 4. Uniform distribution of density perturbations (*Copernican* explanation)

A. Averaging and backreaction

Nambu(00-05), Kolb et al.(05-06), Kasai(92-95), Buchert(00-07), Zalaletdinov(92,93,08), Paranjape(08), ...

Buchert formalism in synchronous, comoving gauge

$$ds^2 = -dt^2 + q_{ij}(t, x^m)\, dx^i\, dx^j$$

averaging in the region D with volume V_D :

$$<\rho>_D = (1/V_D)\int_D \rho\, d\Sigma$$

and scale factor $a_D = (V_D)^{1/3}$

Einstein eqs

$$3(a''_D/a_D) = -\frac{1}{2}\kappa^2 <\rho>_D + Q_D, \qquad 3(a'_D/a_D)^2 = \kappa^2 <\rho>_D - \frac{1}{2} <R>_D - \frac{1}{2} Q_D$$

$$Q_D = \frac{2}{3}\left(<\theta^2>_D - <\theta>_D^2 \right) - \sigma_{ij}\sigma^{ij}$$

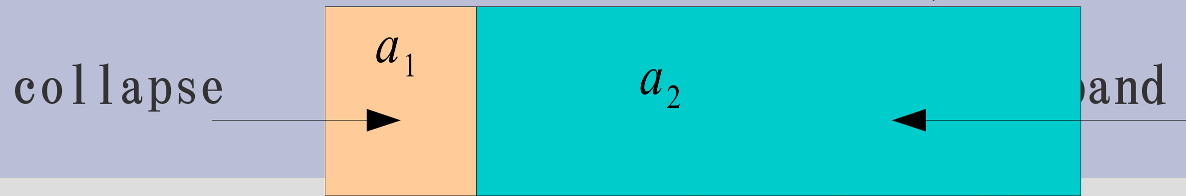
$$a''_D > 0 \longrightarrow Q_D > \frac{1}{2}\kappa^2 <\rho>_D .$$

Ishibashi & Wald (06) CQG 23(06)235

ambiguity with respect to time slicing and domain D

Nambu & Tanimoto gr-qc/0507027

Rasanen JCAP 11 (06) 003; Int. J. Mod. Phys. D15 (06) 2141



$$a^3=(a_1)^3+(a_3)^2$$

local cell structure

Paranjape & Singh JCAP 3 (08) 023: adjusted solution

LTB model for Rasanen's structure has no acceleration.

Newtonian gauge

$$ds^2=-(1+2\Psi)dt^2+a^2(t)(1-2\Psi)\gamma_{ij}dx^i dx^j$$

cosmological Poisson eq $$a^{-2}\Delta_3\Psi=\frac{1}{2}\kappa^2\delta\rho$$

$$\Psi\approx\frac{G\delta M}{c^2 r}\ll 1$$ for subhorizon structure like clusters, void and superclusters

cosmological Newtonian approximation has a long history

-> N-body simulation

Kasai, Asada & Futamase (06) arXiv:0807.1326

No-go theorem for subhorizon perturbations

$$\frac{a''}{a} = -4\pi\frac{G}{3}<\rho>.$$

-> the acceleration depends only on the average density, not on the local structure

Paranjape & Singh(08), Siegel & Fry(05) : negative results

Kolb, Matarrese, Notari & Riotto, Barausse et al.

treated averaging of super-horizon second-order perturbations

Mod.Phys.Lett. D74(06)023506, PR D71(05)063537

Flanagan: Are their perturbative analyses incomplete ? PR D71(05)103521

Geshnizjani et al. PR D72(05)023517

Kai, Kozaki, Nakao, Nambu & Yoo (08)

Averaged model due to LTB solutions (with Nambu & Tanimoto structure) can accelerate, if the size is comparable with or more than the horizon size arXiv:0807.1326

Wiltshire New J. Phys. 9(07)377; ApJ 672(08)L91; PR D78(08)084232

Difference of gravitational energy and clock in the different regions of average expansion, void and wall (finite infinity).

large difference of clock rates -> accelerated expansion

Definition of gravitational energy ? Why large ?
Is there any gauge ambiguity in the Ishibashi and Wald sense ?

B. Fitting

Vanderveld et al. (07) PR D76(07)083504

Comparison between inhomogeneous models (due to the post-Newtonian approximation) and FLRW models -> the effective Λ

$\Omega_\Lambda = 0.004 \ll 1$ for perturbations with CMB normalization

Marra et al. (07, 08) PR D76(07)123004; PR D77(08)023003

obtained the effective Λ necessary to reproduce accelerated expansion assuming nonlinear perturbations with lamplitudes much larger than CMB normalization. (using many arranged Swiss-Cheese models). But we do not know how these good perturbations can exist.

§ 5. Our recent works

Second-order Integrated Sachs-Wolfe effect

(1) Non-zero Λ case Tomita & Inoue, PRD **77**, 103521(2008)

ISW in concordant models

Discussions in Inoue's talk

$$\Delta T/T = (\Delta T/T)_1 + (\Delta T/T)_2 \qquad (\Delta T/T)_2 < 0$$

$<(\Delta T/T)_2> < 0$ average for all wavelengths

$(\delta T/T)_2 = (\Delta T/T)_2 - <(\Delta T/T)_2>$¿ observed second-order ISW

(2) zero Λ case

a simple toy model

inner region : open FRW model

outer region : EdS model

$$(\Delta T/T)_1 = 0$$

$(\delta T/T)_2 = (\Delta T/T)_2 - <(\Delta T/T)_2>$¿ observed (second-order) ISW

Analysis is OK for z(boundary) = 0.07,

but we are going to improve it to a Gps case

a LTB model

inner region : open FRW model

outer region : self-similar solution

ISW in self-similar spacetime ? Tomita, PRD **56**, 3341(1997)

§ 6. Concluding remarks

(1) Various inhomogeneous models with a local void were found to reproduce the (m-z) relation of SNIa without Λ. The geometrical structure of LTB solutions have been studied in details.
At present, on the other hand, there is no data for SNIa with z >1.7 which are important for the model selection.
From observations of BAO (RBAO), kSZ, spectral distortion at the reionized epoch, however, we found that many models with a local void is ruled out, and only models with a narrow range of parameters remain to be examined.
Practically ruled out or survive ?

(2) The averaging and backreaction of inhomogeneous models and the fitting with nonzero Λ models have been studied by many workers.

At present, however, it seems difficult to obtain the accelerated expansion or the expected effective Λ for the acceleration, unless we assume perturbations with amplitudes much larger than the values corresponding to CMB normalization, or gravitational energies with very high amplitudes. Can we have such high amplitudes of perturbations or gravitational energies ?

(3) In these analyses, we have assumed the models based on the Einstein gravitational theory and the existence of an inflationary early stage. If the models should be derived from the other theories, such as the superstring theory, the cosmological situation may be quite different, as we do not know what inflation we can have and whether the cosmological constant can exist or not, and then the inhomogeneous models with a local void may play some more role to explain the observed accelerating behavior.