Dark Energy ?
Backreaction ?
Inhomogeneous viewpoint !

Masumi KASAI (Hirosaki University)

2008.12.9@KEK Cosmophysics Workshop
Is our Universe really undergoing an accelerated expansion ?
Dec. 8 - 12, 2008

Observed SNe Ia m-z relations seem to require Dark Energy (Λ).

Evidences of Cosmic Acceleration

- Type Ia SNe
- CMB by WMAP
- etc.

Evidences of Cosmic Acceleration

- Type Ia SNe
- CMB by WMAP
- etc.

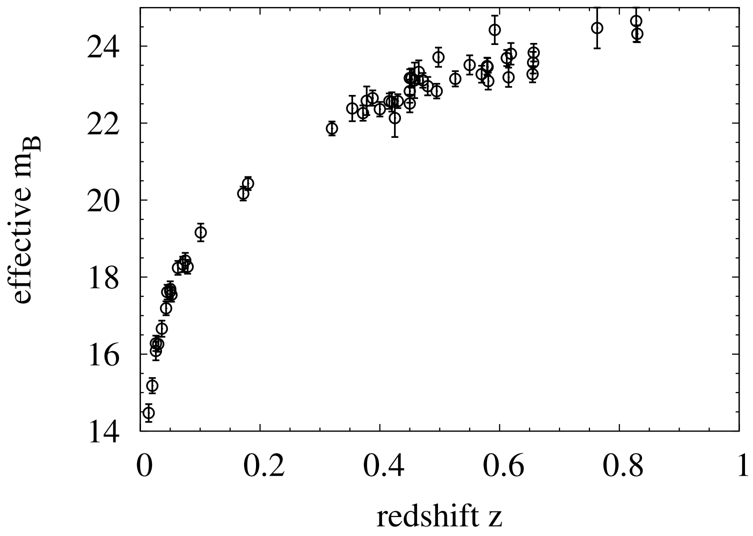
THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

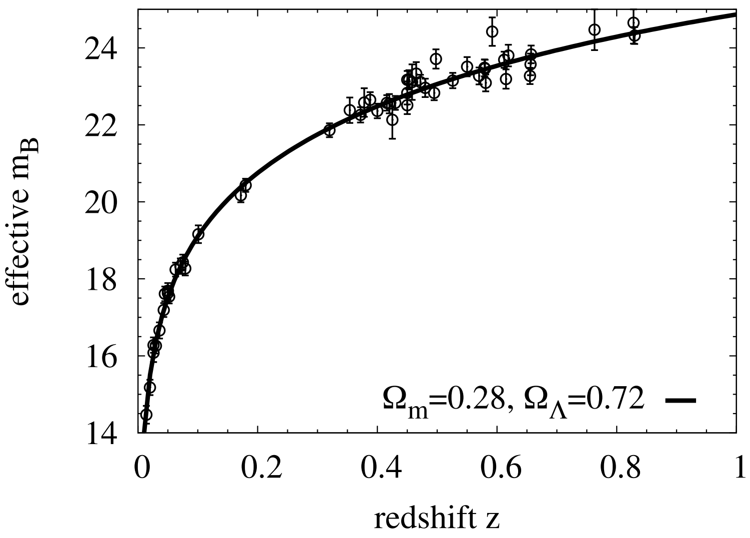
S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3] A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3] C. R. PENNYPACKER,[8] AND R. QUIMBY
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720
C. LIDMAN
European Southern Observatory, La Silla, Chile
R. S. ELLIS, M. IRWIN, AND R. G. MCMAHON
Institute of Astronomy, Cambridge, England, UK
P. RUIZ-LAPUENTE
Department of Astronomy, University of Barcelona, Barcelona, Spain
N. WALTON
Isaac Newton Group, La Palma, Spain
B. SCHAEFER
Department of Astronomy, Yale University, New Haven, CT
B. J. BOYLE
Anglo-Australian Observatory, Sydney, Australia
A. V FILIPPENKO AND T. MATHESON
Department of Astronomy, University of California, Berkeley, CA
A. S. FRUCHTER AND N. PANAGIA[9]
Space Telescope Science Institute, Baltimore, MD
H. J. M. NEWBERG
Fermi National Laboratory, Batavia, IL
AND
W. J. COUCH

The Supernova Cosmology Project

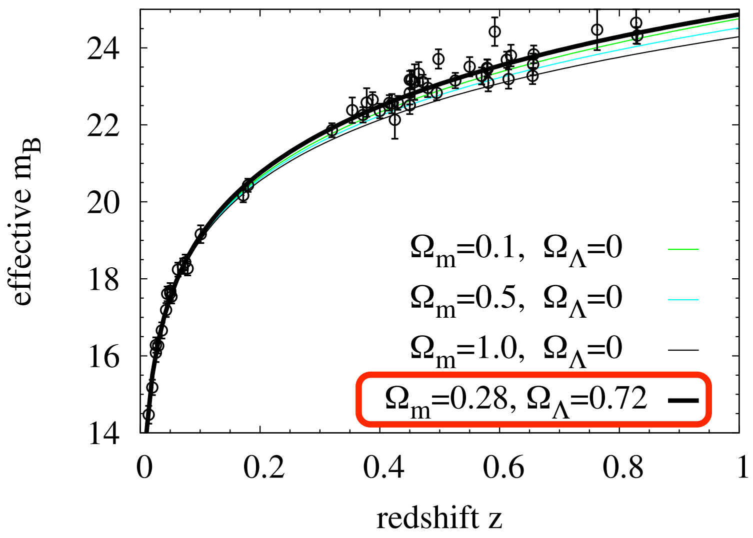
Perlmutter et al. (1999) Primary fit C data set



Perlmutter et al. (1999) Primary fit C data set



Perlmutter et al. (1999) Primary fit C data set



THE ASTROPHYSICAL JOURNAL, 607:665–687, 2004 June 1

TYPE Ia SUPERNOVA DISCOVERIES AT $z > 1$ FROM THE *HUBBLE SPACE TELESCOPE*: EVIDENCE FOR PAST DECELERATION AND CONSTRAINTS ON DARK ENERGY EVOLUTION[1]

ADAM G. RIESS,[2] LOUIS-GREGORY STROLGER,[2] JOHN TONRY,[3] STEFANO CASERTANO,[2] HENRY C. FERGUSON,[2] BAHRAM MOBASHER,[2] PETER CHALLIS,[4] ALEXEI V. FILIPPENKO,[5] SAURABH JHA,[5] WEIDONG LI,[5] RYAN CHORNOCK,[5] ROBERT P. KIRSHNER,[4] BRUNO LEIBUNDGUT,[6] MARK DICKINSON,[2] MARIO LIVIO,[2] MAURO GIAVALISCO,[2] CHARLES C. STEIDEL,[7] TXITXO BENÍTEZ,[8] AND ZLATAN TSVETANOV[8]

The Supernova Gold data set

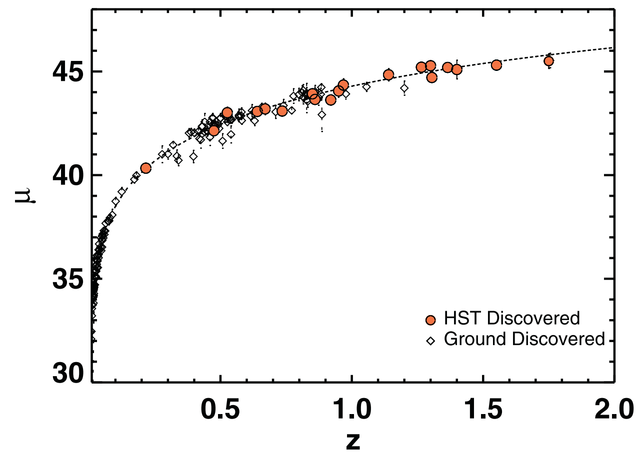


FIG. 4.—MLCS2k2 SN Ia Hubble diagram. SNe Ia from ground-based discoveries in the gold sample are shown as diamonds; *HST*-discovered SNe Ia are shown as filled symbols. Overplotted is the best fit for a flat cosmology: $\Omega_M = 0.29$, $\Omega_\Lambda = 0.71$.

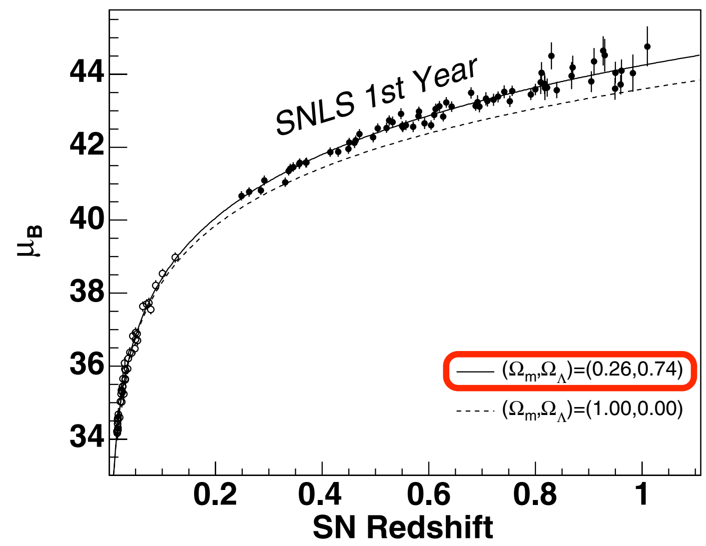
A&A 447, 31–48 (2006)
DOI: 10.1051/0004-6361:20054185

Astronomy & Astrophysics

The Supernova Legacy Survey: measurement of Ω_M, Ω_Λ and w from the first year data set[⋆,⋆⋆]

P. Astier[1], J. Guy[1], N. Regnault[1], R. Pain[1], E. Aubourg[2,3], D. Balam[4], S. Basa[5], R. G. Carlberg[6], S. Fabbro[7], D. Fouchez[8], I. M. Hook[9], D. A. Howell[6], H. Lafoux[3], J. D. Neill[4], N. Palanque-Delabrouille[3], K. Perrett[6], C. J. Pritchet[4], J. Rich[3], M. Sullivan[6], R. Taillet[1,10], G. Aldering[11], P. Antilogus[1], V. Arsenijevic[7], C. Balland[1,2], S. Baumont[1,12], J. Bronder[9], H. Courtois[13], R. S. Ellis[14], M. Filiol[5], A. C. Gonçalves[15], A. Goobar[16], D. Guide[1], D. Hardin[1], V. Lusset[3], C. Lidman[12], R. McMahon[17], M. Mouchet[15,2], A. Mourao[7], S. Perlmutter[11,18], P. Ripoche[8], C. Tao[8], and N. Walton[17]

The Supernova Legacy Survey



Cosmic Acceleration and Dark Energy

Dark Energy

a hypothetical energy that accelerates the cosmic expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

$$w \equiv \frac{P}{\rho} < -\frac{1}{3} \quad \Rightarrow \quad \frac{\ddot{a}}{a} > 0$$

Difficulties in Λ, DE

- No natural explanation for Λ of such size
- No natural candidate for Dark Energy

Then...

Explanation of Apparent Acceleration without Dark Energy

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Inhomogeneous approach

- **Tomita** (2000a, 2000b, 2001, ...)
  local void model, m-z relation
- **Iguchi, Nakamura, Nakao** (2002)
  Lemaitre-Tolman-Bondi (LTB), m-z
- **Alnes et al.** (2006)
  LTB, m-z & CMB

18

Observational indication of local void

19

THE ASTROPHYSICAL JOURNAL, 503:483–491, 1998 August 20

A LOCAL HUBBLE BUBBLE FROM TYPE Ia SUPERNOVAE?

IDIT ZEHAVI,[1] ADAM G. RIESS,[2] ROBERT P. KIRSHNER,[3] AND AVISHAI DEKEL[1,4]

Received 1997 September 16; accepted 1998 April 1

1. INTRODUCTION

Large-scale redshift surveys of galaxies show underdense regions of typical extent $\sim 50\ h^{-1}$ Mpc. These "voids" appear to be bordered by dense "walls" (Kirshner et al. 1981; Huchra et al. 1983 [CfA]; Broadhurst et al. 1990; Shectman et al. 1996 [Las Campanas Redshift Survey (LCRS)]). In particular, maps of our cosmological neighborhood display the Great Wall of Coma and the Southern Wall, which appear to connect into a shell-like structure of radius 70–80 h^{-1} Mpc about the Local Group (Geller & Huchra 1989 [CfA2]; da Costa et al. 1994 [Southern Sky Redshift Survey 2 (SSRS2)]). The volume encompassed by this structure appears to be of lower density.

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Mon. Not. R. Astron. Soc. **326,** 287–292 (2001)

A local void and the accelerating Universe

K. Tomita★
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8502, Japan

ABSTRACT

Corresponding to the recent observational claims that we are in a local void (an underdense region) on scales of 200–300 Mpc, the magnitude–redshift relation in a cosmological model with a local void is investigated. It is already evident that the accelerating behaviour of high-z supernovae can be explained in this model, because the local void plays a role similar to the positive cosmological constant. In this paper the dependence of the behaviour on the gaps of cosmological parameters in the inner (low-density) region and the outer (high-density) region, the radius of the local void, and the clumpiness parameter is studied and its implications are discussed.

Tomita model

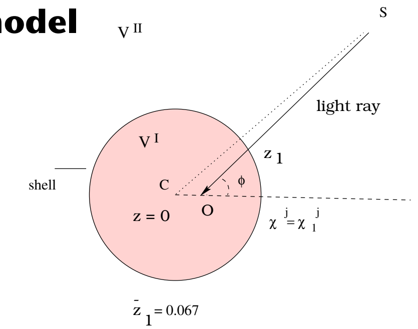


Figure 1. Model with a spherical single shell. Redshifts for observers at O and C are z and $\bar{z}$.

inner low-density Friedmann

Tomita model

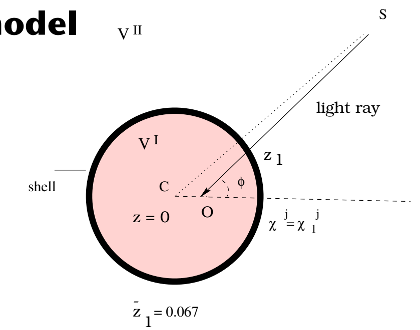


Figure 1. Model with a spherical single shell. Redshifts for observers at O and C are z and $\bar{z}$.

inner low-density Friedmann
+
singular mass shell (junction condition)

Tomita model

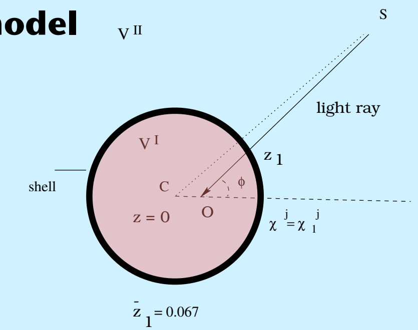


Figure 1. Model with a spherical single shell. Redshifts for observers at O and C are z and $\bar{z}$.

inner low-density Friedmann
+
singular mass shell (junction condition)
+
outer high-density Friedmann

Tomita's result for $d_L(z)$

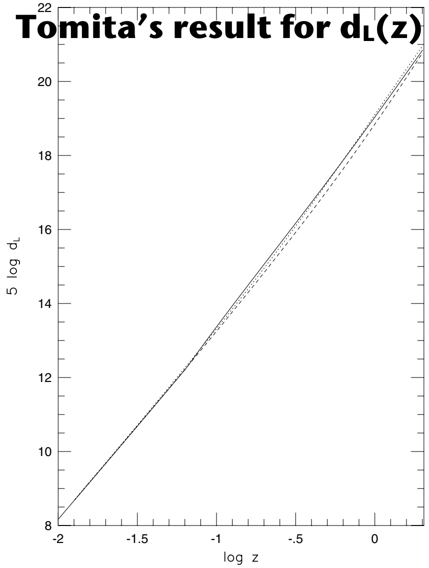


Figure 2. The $[m, z]$ relation in cosmological models with a local void. The solid line denotes the case with a standard parameter set given in equation (12). The dotted and dashed lines stand for homogeneous models with $(\Omega_0, \lambda_0) = (0.3, 0.7)$ and (0.3, 0.0), respectively, for comparison.

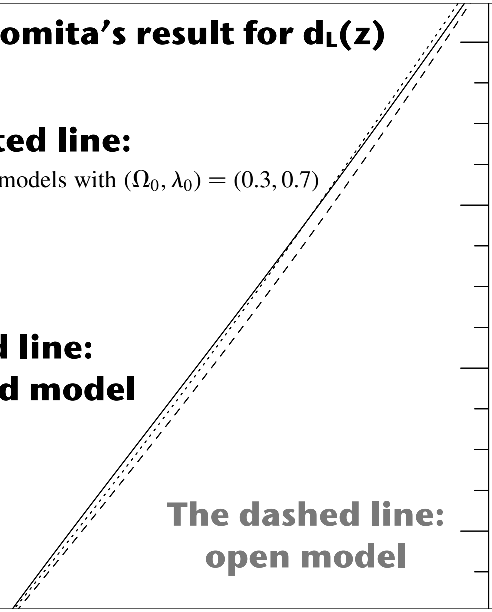
Tomita's result for $d_L(z)$

The dotted line:

homogeneous models with $(\Omega_0, \lambda_0) = (0.3, 0.7)$

The solid line:
local void model

The dashed line:
open model



Essential points have already been done by K. Tomita

Different values of H_0, Ω_m here and there

Tomita's local void model with singular mass shell might be a bit unrealistic...

Progress of Theoretical Physics, Vol. 108, No. 5, November 2002

Is Dark Energy the Only Solution to the Apparent Acceleration of the Present Universe?

Hideo IGUCHI,[1] Takashi NAKAMURA[2,*)] and Ken-ichi NAKAO[3]

[1]*Department of Physics, Tokyo Institute of Technology, Tokyo 152-8550, Japan*
[2]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[3]*Department of Physics, Osaka City University, Osaka 558-8585, Japan*

(Received August 2, 2002)

Even for the observed luminosity distance $D_L(z)$, which suggests the existence of dark energy, we show that an inhomogeneous dust universe solution without dark energy is possible in general. Future observation of $D_L(z)$ for $1 \lesssim z < 1.7$ may confirm or refute this possibility.

Progress of Theoretical Physics, Vol. 108, No. 5, November 2002

Is Dark Energy the Only Solution to the Apparent Acceleration of the Present Universe?

The luminosity distance $D_L(z)$ in the LTB model (as a more realistic model) can be consistent with observed SNe Ia data

PHYSICAL REVIEW D **73,** 083519 (2006)

Inhomogeneous alternative to dark energy?

Håvard Alnes,[1,*] Morad Amarzguioui,[2,†] and Øyvind Grøn[1,3,‡]

[1]*Department of Physics, University of Oslo, P.O. Box 1048 Blindern, 0316 Oslo, Norway*
[2]*Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, 0315 Oslo, Norway*
[3]*Oslo College, Faculty of Engineering, Cort Adelersgate 30, 0254 Oslo, Norway*

(Received 5 December 2005; published 17 April 2006)

Recently, there have been suggestions that the apparent accelerated expansion of the universe is not caused by repulsive gravitation due to dark energy, but is rather a result of inhomogeneities in the distribution of matter. In this work, we investigate the behavior of a dust-dominated inhomogeneous Lemaître-Tolman-Bondi universe model, and confront it with various astrophysical observations. We find that such a model can easily explain the observed luminosity distance-redshift relation of supernovae without the need for dark energy, when the inhomogeneity is in the form of an underdense bubble centered near the observer. With the additional assumption that the universe outside the bubble is approximately described by a homogeneous Einstein-de Sitter model, we find that the position of the first peak in the cosmic microwave background (CMB) power spectrum can be made to match the WMAP observations. Whether or not it is possible to reproduce the entire CMB angular power spectrum in an inhomogeneous model without dark energy is still an open question.

PHYSICAL REVIEW D **73,** 083519 (2006)

Inhomogeneous alternative to dark energy?

Håvard Alnes,[1,*] Morad Amarzguioui,[2,†] and Øyvind Grøn[1,3,‡]

Without the need for Dark Energy, LTB model can explain not only $D_L(z)$ of SNe Ia but also CMB

But...

Previous works depend on simplified toy models.

Psychological barrier

Such toy models can really describe our real world?

How to describe the effects of inhomogeneity without depending specific toy models?

37

Note:

nonlinear Backreaction of inhomogeneities?

38

No!

Note:

nonlinear Backreaction of inhomogeneities?

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Prog. Theor. Phys. Vol. 115, No. 4, April 2006, Letters

Toward a No-Go Theorem for an Accelerating Universe through a Nonlinear Backreaction

Masumi KASAI,[1,*)] Hideki ASADA[1,**)] and Toshifumi FUTAMASE[2,***)]

[1] *Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan*
[2] *Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*

Although our work does not give a complete proof, it strongly suggests the following no-go theorem: No cosmic acceleration occurs as a result of the nonlinear backreaction via averaging.

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Menu

I. Averaging

II. Backreaction

III. Inhomogeneous viewpoint

Menu

I. Averaging

II. Backreaction

III. Inhomogeneous viewpoint

Once upon a time, there were active discussions about...

cosmic acceleration by nonlinear backreaction ?

Papers

with positive conclusions for the backreaction (2005 ~)

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for physicists | Fermilab now | events | publications | Fermilab at work | jobs | press pass | help

05-08

PRESS RELEASE

March 16, 2005

Italian, US cosmologists present alternate explanation for accelerating expansion of the universe: Was Einstein right when he said he was wrong?

Why is the universe expanding at an accelerating rate, spreading its contents over ever greater dimensions of space? An original solution to this puzzle, certainly the most fascinating question in modern cosmology, was put forward by four theoretical physicists, Edward W. Kolb of the U.S. Department of Energy's Fermi National

Primordial inflation explains why the universe is accelerating today

Edward W. Kolb*
Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA and Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637-1433 USA

Sabino Matarrese†
Dipartimento di Fisica "G. Galilei," Università di Padova, and INFN, Sezione di Padova, via Marzolo 8, Padova I-35131, Italy

Alessio Notari‡
Physics Department, McGill University, 3600 University Road, Montréal, QC, H3A 2T8, Canada

Antonio Riotto§
INFN, Sezione di Padova, via Marzolo 8, I-35131, Italy

(Dated: March 3, 2006)

We propose an explanation for the present accelerated expansion of the universe that does not invoke dark energy or a modification of gravity and is firmly rooted in inflationary cosmology.

arXiv:hep-th/0503117 v1 14 Mar 2005

On cosmic acceleration without dark energy

Edward W. Kolb*
Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA and Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637-1433 USA

Sabino Matarrese†
Dipartimento di Fisica "G. Galilei" Università di Padova, INFN Sezione di Padova, via Marzolo 8, Padova I-35131, Italy

Antonio Riotto‡
INFN Sezione di Padova, via Marzolo 8, I-35131, Italy

arXiv:astro-ph/0506534 v1

Abstract

We elaborate on the proposal that the observed acceleration of the Universe is the result of the backreaction of cosmological perturbations, rather than the effect of a negative-pressure dark-energy fluid or a modification of general relativity. Through the effective Friedmann equations describing an inhomogeneous Universe after smoothing, we demonstrate that acceleration in our

PHYSICAL REVIEW D **71,** 063537 (2005)

Effect of inhomogeneities on the luminosity distance-redshift relation: Is dark energy necessary in a perturbed universe?

Enrico Barausse*

Dipartimento di Fisica "G. Galilei," Università di Padova, via Marzolo 8, Padova I-35131, Italy, and SISSA/ISAS, via Beirut 4, I-34014 Trieste, Italy

Sabino Matarrese†

Dipartimento di Fisica "G. Galilei," Università di Padova, via Marzolo 8, Padova I-35131, Italy, and INFN, Sezione di Padova, via Marzolo 8, Padova I-35131, Italy

Antonio Riotto‡

INFN, Sezione di Padova, via Marzolo 8, I-35131, Italy

(Received 12 January 2005; published 31 March 2005)

The luminosity distance-redshift relation is one of the fundamental tools of modern cosmology. We compute the luminosity distance-redshift relation in a perturbed flat matter-dominated Universe, taking into account the presence of cosmological inhomogeneities up to second order in perturbation theory. Cosmological observations implementing the luminosity distance-redshift relation tell us that the Universe is presently undergoing a phase of accelerated expansion. This seems to call for a mysterious Dark Energy component with negative pressure. Our findings suggest that the need of a Dark Energy fluid may be challenged once a realistic inhomogeneous Universe is considered and that an accelerated expansion may be consistent with a matter-dominated Universe.

Accelerating Universe via Spatial Averaging

Yasusada Nambu* and Masayuki Tanimoto†

Department of Physics, Graduate School of Science, Nagoya University, Chikusa, Nagoya 464-8602, Japan

(Dated: June 14, 2005)

We present a model of an inhomogeneous universe that leads to accelerated expansion after taking spatial averaging. The model universe is the Tolman-Bondi solution of the Einstein equation and contains both a region with positive spatial curvature and a region with negative spatial curvature. We find that after the region with positive spatial curvature begins to re-collapse, the deceleration parameter of the spatially averaged universe becomes negative and the averaged universe starts accelerated expansion. We also discuss the generality of the condition for accelerated expansion of the spatially averaged universe.

arXiv:gr-qc/0507057

Papers

with negative conclusions

(2005 ∼)

Can superhorizon cosmological perturbations explain the acceleration of the universe?

arXiv:astro-ph/0503582 v1 27 Mar 2005

Christopher M. Hirata[1,*] and Uroš Seljak[1,2]

[1]*Department of Physics, Jadwin Hall, Princeton University, Princeton, New Jersey 08544, USA*

[2]*International Center for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy*

(Dated: March 27, 2005)

We investigate the recent suggestions by Barausse et al. (astro-ph/0501152) and Kolb et al. (hep-th/0503117) that the acceleration of the universe could be explained by large superhorizon fluctuations generated by inflation. We show that no acceleration can be produced by this mechanism. We begin by showing how the application of Raychaudhuri equation to inhomogeneous cosmologies results in several "no go" theorems for accelerated expansion. Next we derive an exact solution for a specific case of initial perturbations, for which application of the Kolb et al. expressions leads to an acceleration, while the exact solution reveals that no acceleration is present. We show that the discrepancy can be traced to higher order terms that were dropped in the Kolb et al. analysis. We proceed with the analysis of initial value formulation of general relativity to argue that causality severely limits what observable effects can be derived from superhorizon perturbations. By constructing a Riemann normal coordinate system on initial slice we show that no infrared divergence terms arise in this coordinate system. Thus any divergences found previously can be eliminated by a local rescaling of coordinates and are unobservable. We perform an explicit analysis of the variance of the deceleration parameter for the case of single field inflation using usual coordinates and show that the infrared divergent terms found by Barausse et al. and Kolb et al. cancel against several additional terms not considered in their analysis. Finally, we argue that introducing isocurvature perturbations does not alter our conclusion that the accelerating expansion of the universe cannot be explained by superhorizon modes.

er M. Hirata[1,*] and Uros Seljak[1,2]

Iall, Princeton University, Princeton, New Jersey

eoretical Physics, Strada Costiera 11, 34014 Trie

(Dated: March 27, 2005)

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be traced to higher order terms that were droppe

the analysis of initial value formulation of genera

what observable effects can be derived from sup

53

Can the Acceleration of Our Universe Be Explained by the Effects of Inhomogeneities?

arXiv:gr-qc/0509108 v3

Akihiro Ishibashi[†] and Robert M. Wald[†‡]

Enrico Fermi Institute[†] and Department of Physics[‡]
The University of Chicago, Chicago, IL 60637, USA

November 14, 2005

Abstract

No. It is simply not plausible that cosmic acceleration could arise within the context of general relativity from a back-reaction effect of inhomogeneities in our universe, without the presence of a cosmological constant or "dark energy." We point out that our universe appears to be

54

Novembe

Abst

No. It is simply not plausible

within the context of general relativ

homogeneities in our universe, withou

stant or "dark energy." We point

55

Which is true?
Backreaction
accelerates? or not?

We shall clear up
the confusion!

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Basic Idea of the standard cosmology

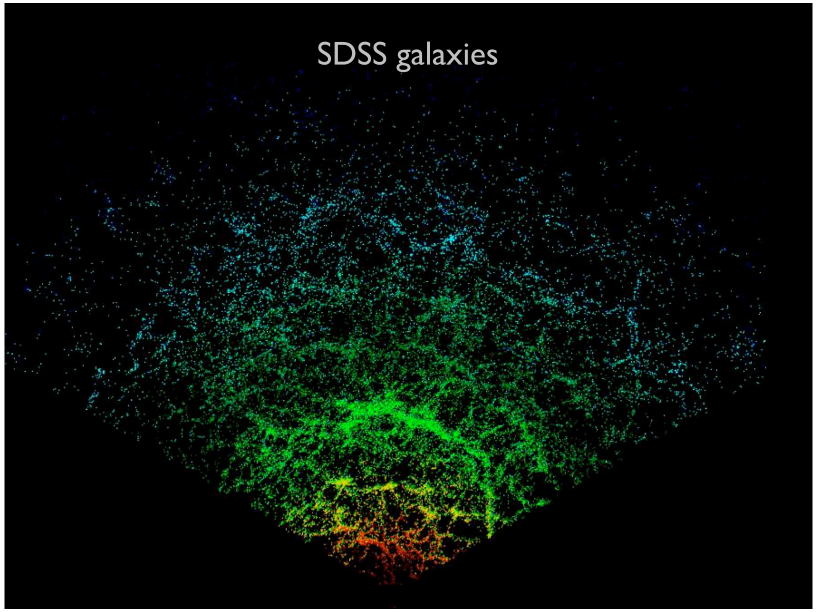
The Cosmological Principle

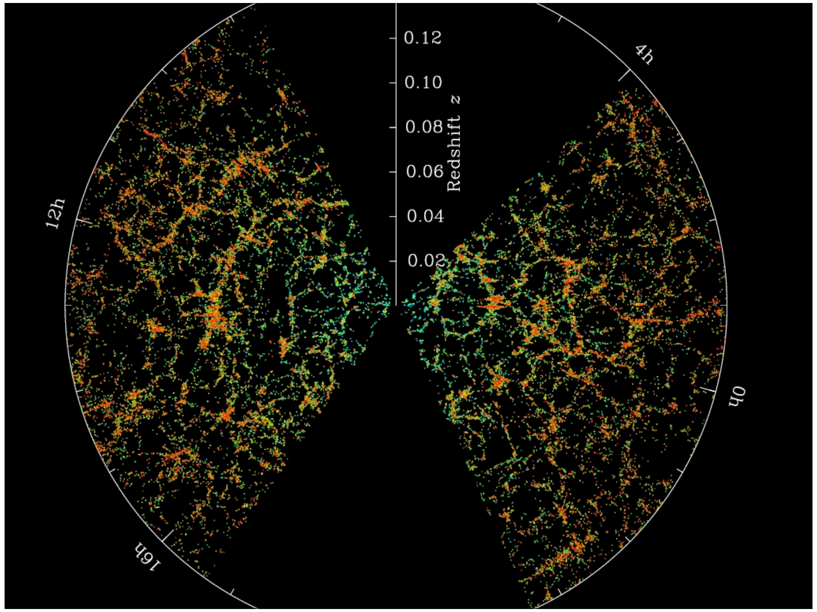
- The universe is spatially homogeneous and isotropic
- Matter distribution is smooth and homogeneous

i.e., the Friedmann model

However,

The actual universe is highly inhomogeneous.





Why
the universe is
believed to be
homogeneous and
isotropic?

an implicit
agreement
is...

OK, the universe is locally inhomogeneous,

but

the averaged behavior is described by the Friedmann model.

OK, the universe is locally inhomogeneous,

but

the averaged behavior is described by the Friedmann model.

What is Friedmann on average?

average density

$$\rho_b \equiv \langle \rho \rangle$$

scale factor

$$\frac{\dot{a}}{a} \equiv \frac{1}{3}\frac{\dot{V}}{V}$$

averaging the Einstein eq.

$$\langle G_{\mu\nu} \rangle = 8\pi G \langle T_{\mu\nu} \rangle$$

$$\Downarrow$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho_b + \Delta_x$$

If $\Delta_x = 0$, then

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho_b$$

a is driven merely by the mean density, collectively by the clumps of matter.

In general, however, due to the nonlinearity of the Einstein eq. ...

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho_b \boxed{+\Delta_x}$$

another source driving the cosmic expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho_b \boxed{+\Delta_x}$$

Δ_x is

the nonlinear backreaction

of inhomogeneities

Menu

I. Averaging

II. Backreaction

III. Inhomogeneous viewpoint

The backreaction
accelerates
the universe?

Pioneering works
on
the backreaction
(in 1990s and before)

Futamase's scheme

T. Futamase, Phys. Rev. Lett. D 61, 2175 (1988)
T. Futamase, Phys. Rev. D 53, 681 (1996)

The metric:

$$ds^2 = -\left(1+2\phi(x)\right) dt^2 + a^2(t)\left(1-2\phi(x)\right)\delta_{ij}\, dx^i dx^j$$

The averaging procedure:

$$\langle\!\langle \rho \rangle\!\rangle := \frac{1}{V}\int_D \rho\ d^3x$$

$$V := \int_D d^3x$$

The averaged Einstein eq.:

$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\left(\langle\!\langle \rho \rangle\!\rangle + \langle\!\langle \rho a^2 v^2 \rangle\!\rangle\right) + \frac{5}{3a^2}\langle\!\langle \phi^{,i}\phi_{,i} \rangle\!\rangle$$

$$> \frac{8\pi G}{3}\langle\!\langle \rho \rangle\!\rangle$$

speed up!

In the comoving synchronous gauge...

M. Kasai, Phys. Rev. D 52, 5605 (1995)

The metric:

$$ds^2 = -dt^2 + a^2(t)\left[\left(1 + \frac{20}{9}\Psi(x)\right)\delta_{ij} + 2a(t)\Psi_{,ij}\right] dx^i dx^j$$

The averaging procedure:

$$\langle\rho\rangle := \frac{1}{V_D}\int_D \rho\,\sqrt{{}^{(3)}g}\;d^3x$$

$$V_D := \int_D \sqrt{{}^{(3)}g}\;d^3x$$

$$\frac{\dot a_D}{a_D} := \frac{1}{3}\frac{\dot V_D}{V_D}$$

The averaged Einstein eq.:

$$\left(\frac{\dot a_D}{a_D}\right)^2 = \frac{8\pi G}{3}\langle\rho\rangle - \frac{1}{3a_D^2}\left\langle\frac{100}{81}\Psi^{,i}\Psi_{,i}\right\rangle$$

$$< \frac{8\pi G}{3}\langle\rho\rangle$$

speed down

In the previous works, the effects were already controversial (?)

- **positive? negative?**
- **gauge dependence?**
- **averaging procedure ambiguity?**

Note on the achievements in 1990s

Both agree with the followings:

- **the backreaction does not act as Λ.**
- **the backreaction behaves as a curvature term, $\propto a^{-2}$.**

Both agree with the followings:

- **the backreaction does not act as Λ.**
- **the backreaction behaves as a curvature term, $\propto a^{-2}$.**

One disagreement in 1990s is:

- **positive/negative contribution to $\dot{a}^2$**

The backreaction comes again in the 21st century.

But, people often writes...

an example: arXiv:astro-ph/0601699 v1 30 Jan 2006

terious dark energy to mimic Q. Of course, the averaging process is neither trivial nor unambiguous, but it is the art of physics to master it. Fortunately, there is an averaging formalism, developed mainly by Thomas Buchert[16, 17, 18, 19], which can easily be adapted to our LTB patch, having the same mass as the the FRW sphere cut out of it. In this formalism the space-average of any function $f(t,r)$ is defined by

$$\langle f \rangle \equiv \frac{1}{V_D}\int_D dV\, f, \qquad (7)$$

where dV is the proper volume element of the 3-dimensional domain D of the patch we are considering and V_D is its volume. It has been shown[16, 20] that in

Prof. T. Futamase

"an averaging formalism,

developed mainly by

Thomas Buchert? Hm?"

another example: arXiv:0809.1183v3 [gr-qc] 24 Oct 2008

B. Buchert averaging

Buchert's averaging scheme [17] is based on the starting point that, in the case of an energy–momentum tensor for irrotational dust particles in the presence of inhomogeneities, one can choose Gaussian normal coordinates

Prof. T. Futamase

"Buchert averaging? Hm?"

"Who's the pioneer?

We should write a definitive paper."

Prog. Theor. Phys. Vol. 115, No. 4, April 2006, Letters

Toward a No-Go Theorem for an Accelerating Universe through a Nonlinear Backreaction

Masumi KASAI,[1,*)] Hideki ASADA[1,**)] and Toshifumi FUTAMASE[2,***)]

[1] *Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan*
[2] *Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*

(Received January 6, 2006)

The backreaction of nonlinear inhomogeneities to the cosmic expansion is re-analyzed in the framework of general relativity. Apparent discrepancies regarding the effect of the nonlinear backreaction, which exist among the results of previous works in different gauges, are resolved. By defining the spatially averaged matter energy density as a conserved quantity in the large comoving volume, it is shown that the nonlinear backreaction neither accelerates nor decelerates the cosmic expansion in a matter-dominated universe. The present result in the Newtonian gauge is consistent with the previous results obtained in the comoving synchronous gauge. Although our work does not give a complete proof, it strongly suggests the following no-go theorem: No cosmic acceleration occurs as a result of the nonlinear backreaction via averaging.

So we wrote a paper.

Averaging is a delicate procedure.

VOLUME 61, NUMBER 19 PHYSICAL REVIEW LETTERS 7 NOVEMBER 1988

Approximation Scheme for Constructing a Clumpy Universe in General Relativity

Toshifumi Futamase
Department of Physics, Faculty of Sciences, Hirosaki University, Hirosaki, 036, Japan,[a] *and*

(background) 3-space average

The spatial average over a volume V is defined as usual,

$$\langle Q\rangle = V^{-1}\int_V Q\,dV\,, \tag{7}$$

where dV is the invariant volume element in the back-ground space.

Since the spatial average of the line element takes the following form,

$$\langle ds^2\rangle = a^2\{-d\eta^2 + (\delta_{ij}+\langle\bar{h}_{ij}\rangle)dx^i dx^j\}\,, \tag{12}$$

average of tensors

PHYSICAL REVIEW D VOLUME 53, NUMBER 2 15 JANUARY 1996

Averaging of a locally inhomogeneous realistic universe

Toshifumi Futamase
Astronomical Institute, Tohoku University, Sendai, 980-77, Japan
(Received 7 June 1995)

Isaacson averaging version

IV. DERIVATION OF FRW GEOMETRY BY AVERAGING

In the previous section we obtained our basic equations as perturbed equations around the background FRW model. The perturbed quantities are classified as scalar, vector, and tensor with respect to the background spatial geometry. Thus is would be natural to introduce the following averaging over the background spatial hypersurface according to Isaacson [10]:

$$\langle Q_{ij}(x)\rangle = \int g_i^{k'}(x,x')g_k^{l'}(x,x')Q_{k'l'}(x')f(x,x')d^3x'\,, \tag{36}$$

VOLUME 69, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1992

Construction of Inhomogeneous Universes Which Are Friedmann-Lemaître-Robertson-Walker on Average

Masumi Kasai
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 8046 Garching bei München, Germany and Department of Physics, Faculty of Science, Hirosaki University, 3 Bunkyo-cho, Hirosaki, 036 Japan[a]
(Received 29 May 1992)

The understanding of our Universe is based on the working hypothesis that the homogeneous and isotropic models give a successful description on a very large scale, despite the nonlinear inhomogeneity of the matter distribution in the present Universe. We consider the compatibility problem between the overall homogeneity and isotropy and the local inhomogeneity. A scheme to construct inhomogeneous irrotational dust universes which are homogeneous and isotropic on average is shown in the framework of general relativity; they represent "relativistic pancake solutions" analogous to those in Newtonian cosmology.

$$\rho_b = \langle\rho\rangle \equiv \lim_{V\to\Sigma_t}\frac{1}{\int_V[\det(g_{ij})]^{1/2}d^3x}\int_V \rho[\det(g_{ij})]^{1/2}d^3x\,,\quad V\subset\Sigma_t\,. \tag{6}$$

3-invariant spatial averaging of the 3-scalar has been introduced.

PHYSICAL REVIEW D VOLUME 56, NUMBER 4 15 AUGUST 1997

Age of the universe: Influence of the inhomogeneities on the global expansion factor

Heinz Russ,[1] Michael H. Soffel,[2] Masumi Kasai,[3,4] and Gerhard Börner[4]
[1]*Institut für Astronomie und Astrophysik, Universität Tübingen, Auf der Morgenstelle 10, D-72076 Tübingen, Germany*

spatial averaging, time derivative, and commutation rule in General Relativity

We introduce the averaging procedure [22]

$$\langle A \rangle = \frac{1}{V}\int_V A\sqrt{g}\,d^3x, \qquad (2.10)$$

APPENDIX A: COMMUTATION RULE

The time derivative of an averaged quantity reads

$$\frac{d}{dt}\langle A \rangle = -\frac{\dot{V}}{V}\langle A \rangle + \frac{1}{V}\int_V (\dot{A}\sqrt{g} + A\dot{\sqrt{g}})\,d^3x. \qquad (A1)$$

This leads to the commutation rule [22,16,17]

$$\frac{d}{dt}\langle A \rangle - \langle \dot{A} \rangle = -\langle \theta \rangle \langle A \rangle + \langle A\theta \rangle, \qquad (A2)$$

Averaging formalism, developed mainly by Thomas Buchert?

Anyway, Let us clear up the confusion.

General Setup

The metric

$$ds^2 = -(Ndt)^2 + \gamma_{ij}dx^i dx^j$$

(gauge not yet fixed)

The extrinsic curvature

$$K^i{}_j = \frac{1}{2N}\gamma^{ik}\dot{\gamma}_{kj}$$

(represents the 3-dim. deformation)

General Setup

3-dim. volume V

$$V = \int_D \sqrt{\det(\gamma_{ij})}\, d^3x$$

(D: a compact domain on t=*const.* slice)

the scale factor $a(t)$

$$3\frac{\dot{a}}{a} \equiv \frac{\dot{V}}{V}$$

(defined from the volume expansion rate)

General Setup

The averaging procedure

$$\langle A \rangle \equiv \frac{1}{V}\int_D A\,\sqrt{\gamma}\, d^3x$$

$$\Downarrow$$

$$3\frac{\dot{a}}{a} = \langle N K^i{}_i \rangle$$

The deviation from a uniform Hubble flow

$$V^i{}_j \equiv N K^i{}_j - \frac{\dot{a}}{a}\delta^i{}_j$$

General Setup

The averaged Einstein eq.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\langle T_{00} \rangle - \frac{1}{6}\langle N^2\, {}^{(3)}\!R \rangle - \frac{1}{6}\langle (V^i{}_i)^2 - V^i{}_j V^j{}_i \rangle$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\langle T_{00} + N^2 T_{ii} \rangle + \frac{1}{3}\langle (V^i{}_i)^2 - V^i{}_j V^j{}_i \rangle + \frac{1}{3}\langle N N^{|i}{}_{|i} + \dot{N} K^i{}_i \rangle$$

Up to this point,
the treatment is fully general.
(Gauge is not yet fixed.
cf. "Buchert formalism")

How to evaluate it?

Solving by iteration

Putting the linearized solution (in the Newtonian gauge)

$$ds^2 = -\big(1 + 2\phi(x)\big)dt^2 + a^2\big(1 - 2\phi(x)\big)\delta_{ij}\, dx^i dx^j$$

into the R.H.S. ... ⇓

$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\langle T_{00}\rangle + \frac{1}{a^2}\langle \phi_{,i}\phi_{,i}\rangle$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\langle T_{00} + \rho_b a^2 v^2\rangle - \frac{1}{3a^2}\langle \phi_{,i}\phi_{,i}\rangle$$

$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\langle T_{00}\rangle + \frac{1}{a^2}\langle \phi_{,i}\phi_{,i}\rangle > \frac{8\pi G}{3}\langle T_{00}\rangle$$

The backreaction

increases

the expansion rate?

No.

Not necessarily.

Check the average density $\bar\rho$ should obey

$\bar\rho\, a^3$ **= const.**

(Otherwise, the averaged spacetime it not compatible with Friedmann.)

Clearly, $\langle T_{00}\rangle \neq \bar\rho$

In order to guarantee

$$\dot{\bar{\rho}} + 3\frac{\dot{a}}{a}\bar{\rho} = 0,$$

it is uniquely determined

$$\bar{\rho} \equiv \langle T_{00} + \rho_b a^2 v^2 \rangle + \frac{1}{4\pi G a^2}\langle \phi_{,i}\phi_{,i} \rangle$$

The averaged Einstein equation should be written in terms of

$$\cdots = \bar{\rho} + \boxed{\text{addtional contributions}}$$

"the backreaction"

Summary

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{1}{9a^2}\langle \phi_{,i}\phi_{,i} \rangle$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\bar{\rho}$$

- The backreaction does not change the acceleration $\ddot{a}$.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{1}{9a^2}\langle\phi_{,i}\phi_{,i}\rangle < \frac{8\pi G}{3}\bar{\rho}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\bar{\rho}$$

- **The backreaction decreases $\dot{a}/a$.**

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{1}{9a^2}\langle\phi_{,i}\phi_{,i}\rangle$$

- **The backreaction term behaves as a (small) positive curvature term.**

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_b - \frac{k}{a^2}$$

(cf. Friedmann equation)

Furthermore, the results are

- **consistent with other (comoving) gauge calculations.**
- **not dependent on the definition of the averaging.**

No Go Theorem

Assumption 1:

The universe after decoupling was slightly perturbed Friedmann. (Supported by CMB obs.)

Assumption 2:

Perturbation theory well describes the inhomogeneous metric. (Even for $\delta>1$)

cf. Futamase's approximation scheme,
the relativistic Zeldovich approximation (Kasai), etc.

Then...

Nonlinear backreaction neither accelerate nor decelerate the cosmic expansion.

arXiv.org > astro-ph > astro-ph/0602506

Search for (Help | Adva

All pape

Astrophysics, abstract astro-ph/0602506

From: Masumi Kasai [view email]
Date: Thu, 23 Feb 2006 07:51:14 GMT (31kb)

Toward a No-go Theorem for Accelerating Universe by Nonlinear Backreaction

Authors: Masumi Kasai, Hideki Asada, Toshifumi Futamase
Comments: 6 pages (PTPTeX); accepted for publication in Prog. Theor. Phys

One more thing about averaging

Light feels local metric, not the averaged one.

Average of light propagation in inhomogeneous spacetime

is not equal to

light propagation in the averaged spacetime.

Attempt to explain apparent acceleration without Dark Energy

Inhomogeneous approach

- **Tomita** (2000a, 2000b, 2001, ...)
  local void model
- **Iguchi, Nakamura, Nakao** (2002)
  Lemaitre-Tolman-Bondi
- **Alnes et al.** (2006)
  Lemaitre-Tolman-Bondi

Simplified toy models to represent the actual universe.

Enough about toy models

What's
the observed data
telling us about
inhomogeneity?

The standard analysis
in the Friedmann model

Summary
of
SNe Ia m-z relation
by Perlmutter et al. (1999)

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

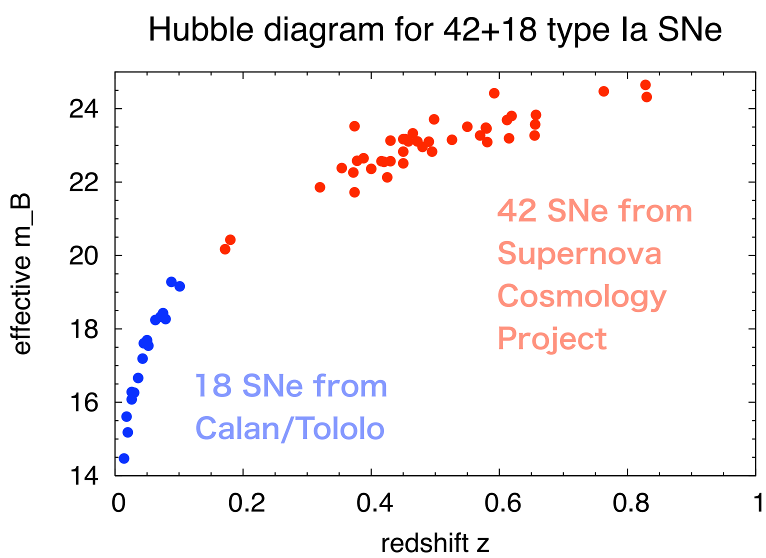
MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3] A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3] C. R. PENNYPACKER,[8] AND R. QUIMBY
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest

Observational data



data taken from Perlmutter et al. (1999)

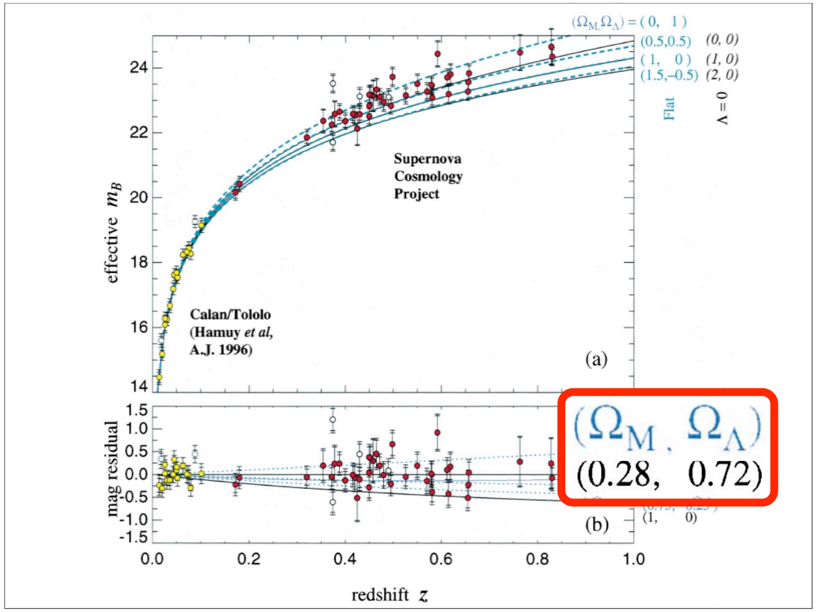
m-z relation to fit the data

$$m = M - 5 + 5\log_{10} D_L(z)$$

luminosity distance $D_L(z)$

$$D_L(z) = \frac{c\,(1+z)}{H_0\sqrt{1-\Omega_m-\Omega_\Lambda}} \times \sinh\left(\sqrt{1-\Omega_m-\Omega_\Lambda}\int_0^z \frac{dz'}{\sqrt{(1+\Omega_m z')(1+z')^3 - z'(2+z')\,\Omega_\Lambda}}\right)$$

$D_L(z)$ is a (bit complicated) function of z with the constant parameters H_0, Ω_m, Ω_Λ.



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Fit Results of Perlmutter et al. (1999)

TABLE 3
FIT RESULTS

Fit	N	χ^2	DOF	Ω_M^{flat}	$P(\Omega_\Lambda > 0)$	Best Fit $(\Omega_M, \Omega_\Lambda)$	Fit Description
Inclusive Fits:							
A	60	98	56	$0.29^{+0.09}_{-0.08}$	0.9984	0.83, 1.42	All supernovae
B	56	60	52	$0.26^{+0.09}_{-0.08}$	0.9992	0.85, 1.54	Fit A, but excluding two residual outliers and two stretch outliers
Primary fit:							
C	**54**	**56**	**50**	$\mathbf{0.28^{+0.09}_{-0.08}}$	**0.9979**	**0.73, 1.32**	**Fit B, but also excluding two likely reddened**
Comparison Analysis Techniques:							
D	54	53	51	$0.25^{+0.10}_{-0.09}$	0.9972	0.76, 1.48	No stretch correction[a]
E	53	62	49	$0.29^{+0.12}_{-0.10}$	0.9894	0.35, 0.76	Bayesian one-sided extinction corrected[b]
Effect of Reddest Supernovae:							
F	51	59	47	$0.26^{+0.09}_{-0.08}$	0.9991	0.85, 1.54	Fit B supernovae with colors measured
G	49	56	45	$0.28^{+0.09}_{-0.08}$	0.9974	0.73, 1.32	Fit C supernovae with colors measured
H	40	33	36	$0.31^{+0.11}_{-0.09}$	0.9857	0.16, 0.50	Fit G, but excluding seven next reddest and two next faintest high-redshift supernovae
Systematic Uncertainty Limits:							
I	54	56	50	$0.24^{+0.09}_{-0.08}$	0.9994	0.80, 1.52	Fit C with +0.03 mag systematic offset
J	54	57	50	$0.33^{+0.10}_{-0.09}$	0.9912	0.72, 1.20	Fit C with −0.04 mag systematic offset
Clumped Matter Metrics:							
K	54	57	50	$0.35^{+0.12}_{-0.10}$	0.9984	2.90, 2.64	Empty beam metric[c]
L	54	56	50	$0.34^{+0.10}_{-0.09}$	0.9974	0.94, 1.46	Partially filled beam metric

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TABLE 3
FIT RESULTS

Ω_M^{flat}	$P(\Omega_\Lambda > 0)$	Best Fit $(\Omega_M, \Omega_\Lambda)$	
$0.29^{+0.09}_{-0.08}$	0.9984	0.83, 1.42	All supernovae
$0.26^{+0.09}_{-0.08}$	0.9992	0.85, 1.54	Fit A, but excluding two
$\mathbf{0.28^{+0.09}_{-0.08}}$	**0.9979**	**0.73, 1.32**	**Fit B, but also excluding**

$\Omega_m = 0.28, \Omega_\Lambda = 0.72$ **is Not the Best Fit...**

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Cosmic Acceleration and Dark Energy

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Results of Perlmutter et al. (1999)

$\Omega_m = 0.28, \ \Omega_\Lambda = 0.72$

(Best Fit: $\Omega_m = 0.73, \ \Omega_\Lambda = 1.32$)

$$\Downarrow$$

$$\left.\frac{\ddot{a}}{a}\right|_{t_0} = H_0^2\left(-\frac{1}{2}\Omega_m + \Omega_\Lambda\right)$$

Menu

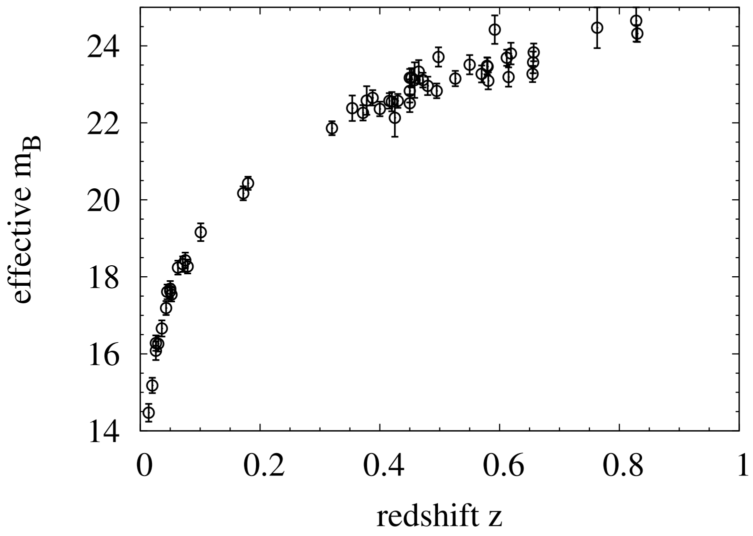
I. Averaging

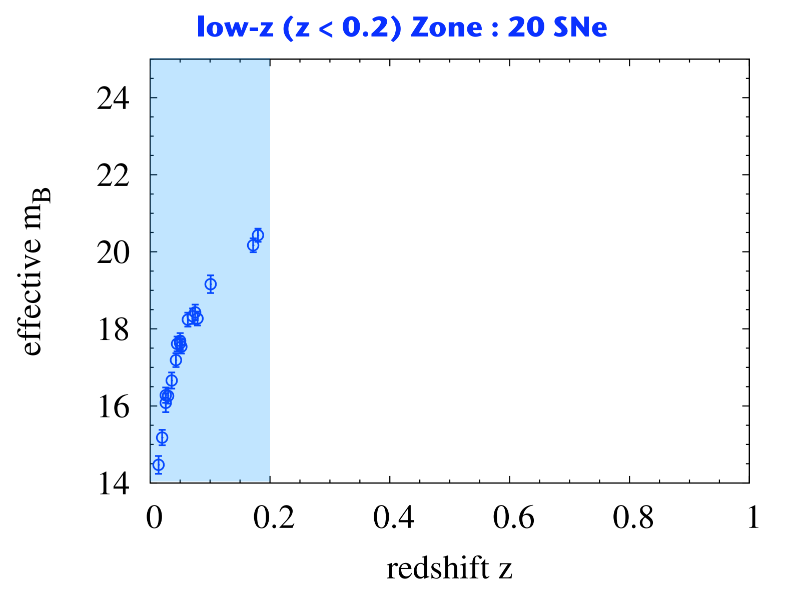
II. Backreaction

III. Inhomogeneous viewpoint

Re-analysis by two-zone model

Primary fit C data set : totally 54 SNe





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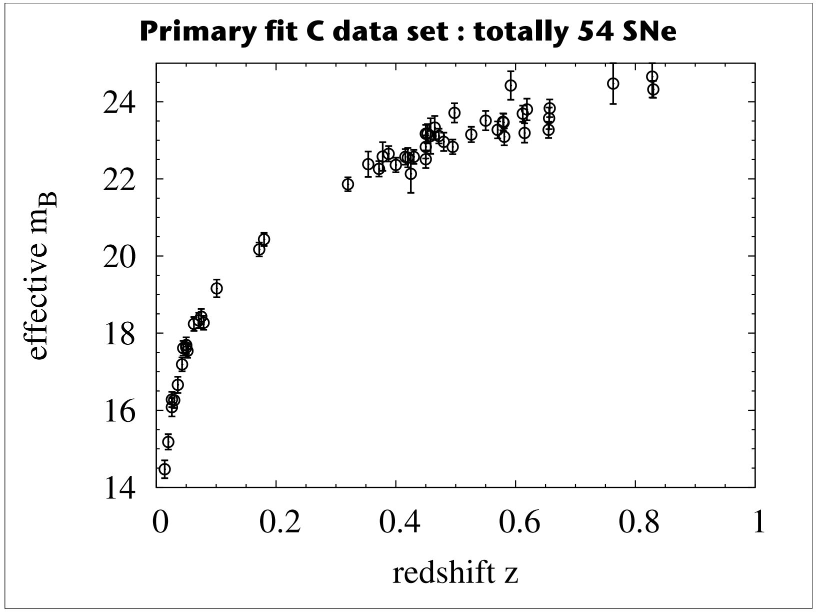

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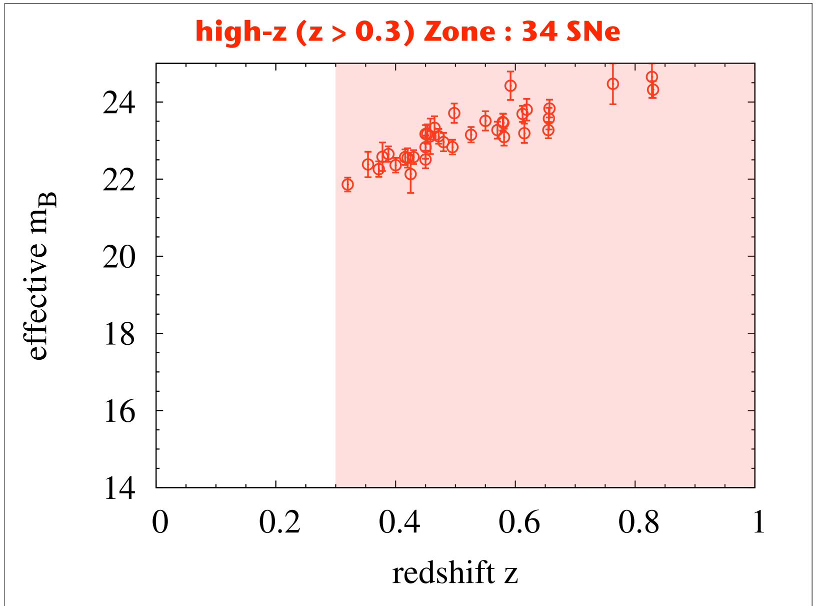

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The m-z relation to fit the data

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$$D_L(z) \equiv \frac{c}{H_0} d(z)$$

$$m = M_{\rm abs} - 5 + 5\log_{10} D_L(z)$$
$$= \mathcal{M} + 5\log_{10} d(z)$$

$$\mathcal{M} \equiv M - 5 + 5\log_{10}\frac{c}{H_0}$$

$\mathcal{M}$: "the magnitude zero-point" or

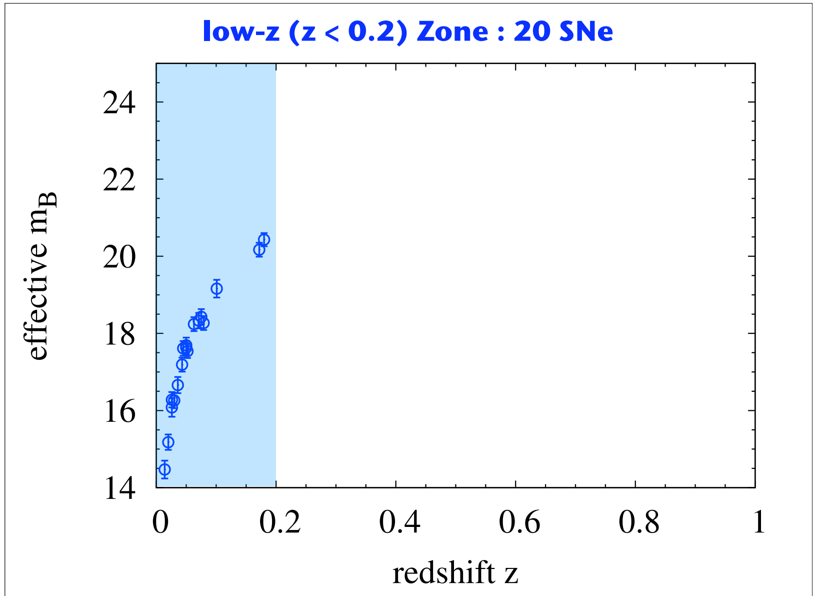
"H_0-free absolute magnitude"

The *m*-*z* relation

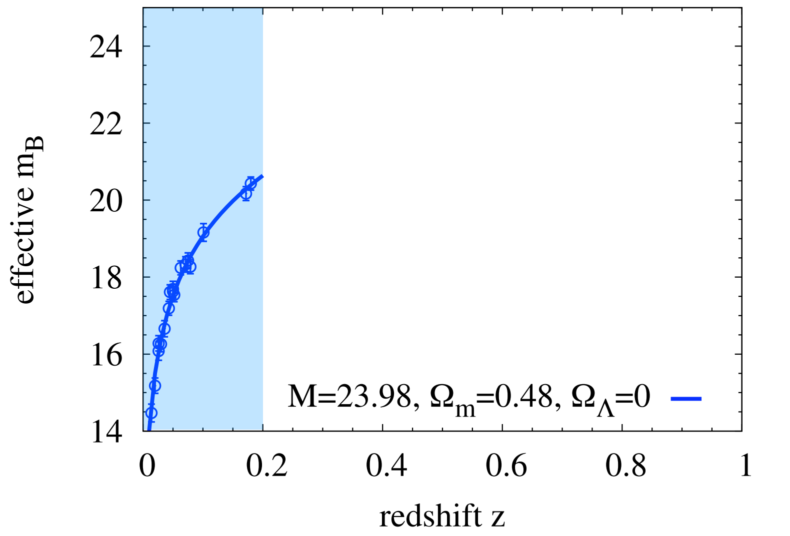
$$m = \mathcal{M} + 5\log_{10} d(z, \Omega_m)$$

fitting parameters are $\mathcal{M}$, Ω_m

low-z (z < 0.2)
zone fitting
without Λ

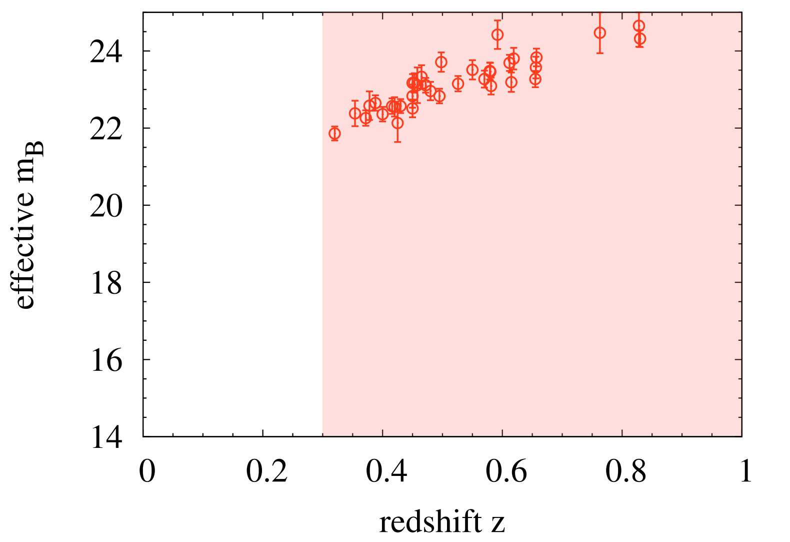


low-z (z < 0.2) Zone : 20 SNe

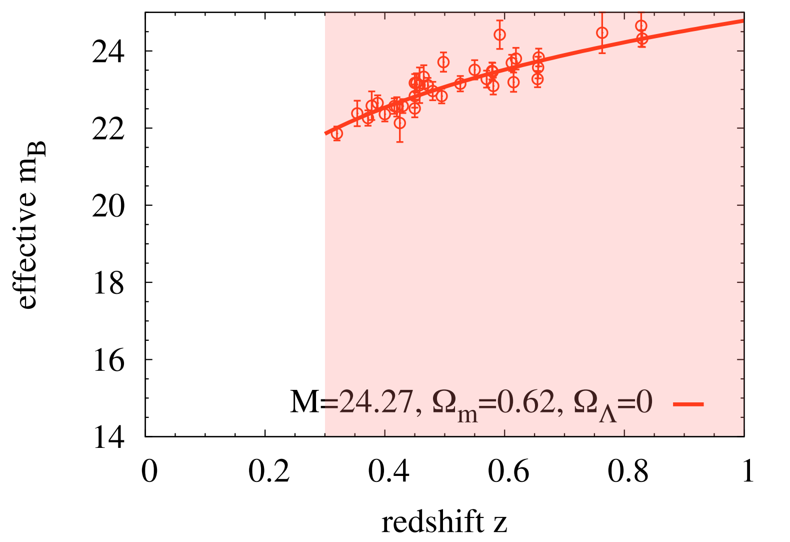


high-z (z > 0.3) zone fitting without Λ

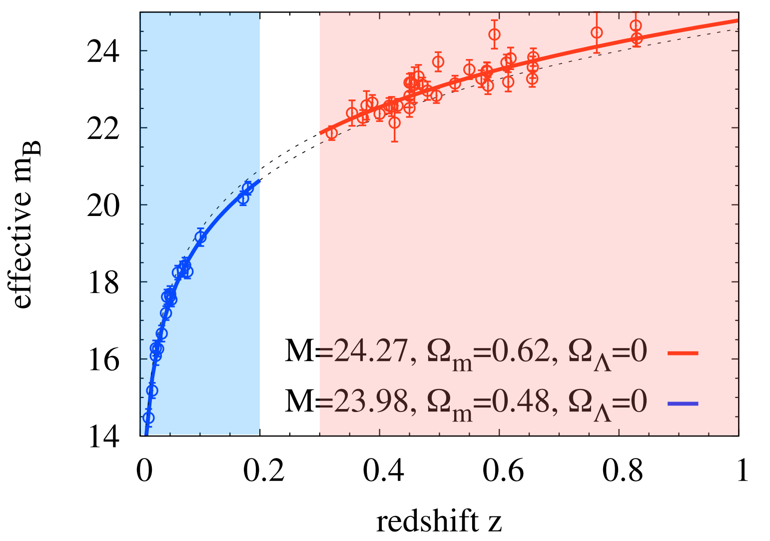
high-z (z > 0.3) Zone : 34 SNe

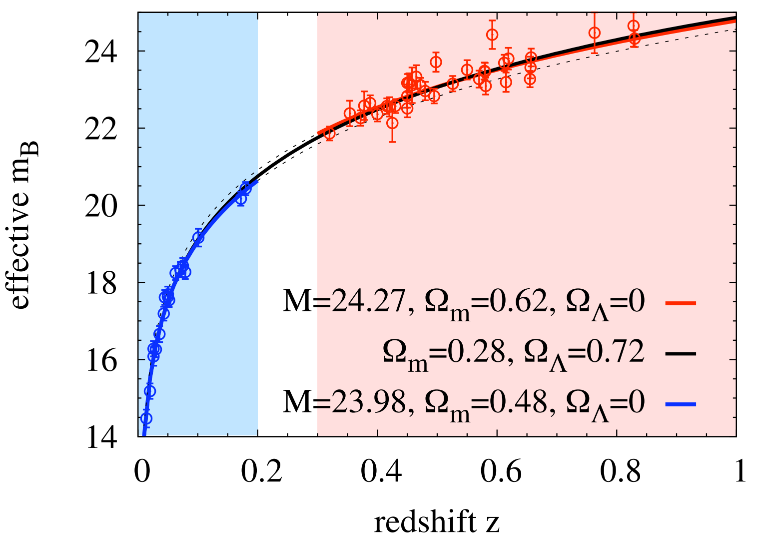


high-z (z > 0.3) Zone : 34 SNe

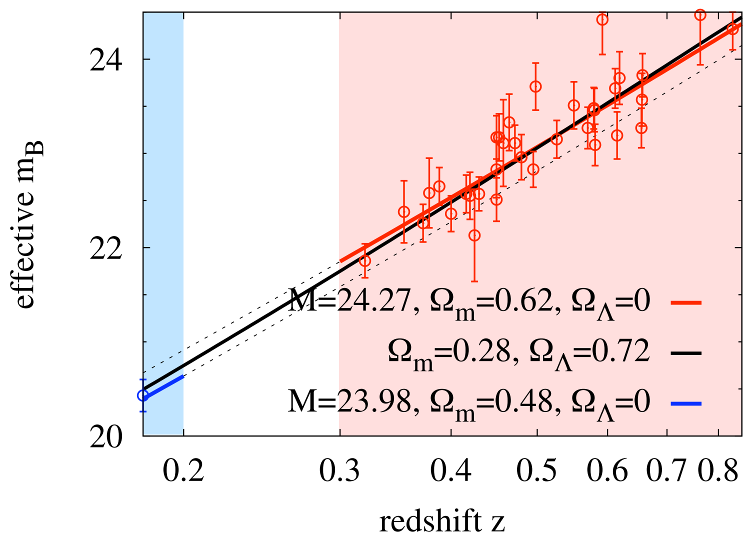


Plot all fittings...





Close up...



Determination of the cosmological parameters from the data fitting

Determination of the cosmological parameters from the data fitting

- $\mathcal{M}$ (hence H_0) is mainly from low-z data fitting

Determination of the cosmological parameters from the data fitting

- $\mathcal{M}$ (hence H_0) is mainly from low-z data fitting
- Assuming the $\mathcal{M}$ is constant,
  and fitting high-z data, Ω_Λ may be necessary

Determination of the cosmological parameters from the data fitting

- $\mathcal{M}$ (hence H_0) is mainly from low-z data fitting
- Assuming the $\mathcal{M}$ is constant, and fitting high-z data, Ω_Λ may be necessary
- **If the constancy of $\mathcal{M}$ are relaxed, we don't need Ω_Λ**

Inhomogeneous Interpretation?

$\mathcal{M}$(low-z) ≠ $\mathcal{M}$(high-z) ... Implication?

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

$\mathcal{M}$(low-z) ≠ $\mathcal{M}$(high-z) ... Implication?

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

1. the absolute luminosity M is different

$\mathcal{M}$(low-z) ≠ $\mathcal{M}$(high-z) ... Implication?

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

1. the absolute luminosity M is different

2. the speed of light c is different

$\mathcal{M}$(low-z) ≠ $\mathcal{M}$(high-z) ... Implication?

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

1. the absolute luminosity M is different

2. the speed of light c is different

3. H_0 is different

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

1. the absolute luminosity M is different

- Astronomically likely...
- Calibration done only for nearby SNe
- Difficulty in estimating M of high-z (different environment) SNe

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

2. the speed of light c is different

- modified gravity theories...

$$\mathcal{M} = M - 5 + 5\log_{10}\frac{c}{H_0}$$

In low-z and high-z regions,

3. H_0 is different

- **Inhomogeneous viewpoint**
- **effects of large-scale inhomgeneities**

SNe m-z relation implies

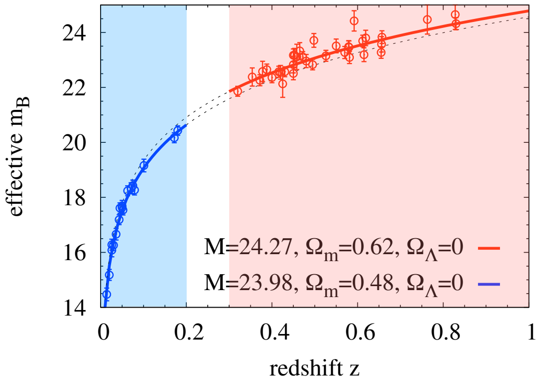
the existence of Λ,

The meaning: inhomogeneities in H_0 and Ω_m

The meaning: our universe is inhomogeneous

How large is the inhomogeneity in H_0 ?

$$\mathcal{M}(\text{low-}z) - \mathcal{M}(\text{high-}z) = 5\log_{10}\frac{H_0(\text{high-}z)}{H_0(\text{low-}z)}$$



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How large is the inhomogeneity in H_0 ?

$$23.98 - 24.27 = 5\log_{10}\frac{H_0(\text{high-}z)}{H_0(\text{low-}z)}$$

$$\Downarrow$$

$$\frac{H_0(\text{high-}z)}{H_0(\text{low-}z)} = 0.87$$

13% smaller H_0(high-z) can explain the data without Dark Energy

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Plausible?

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χ^2 test of Two-Zone model fitting

model	χ^2	# of param.	reduced χ^2
Flat Perlmutter (1999)	57.71	Ω_m, M	1.11

180

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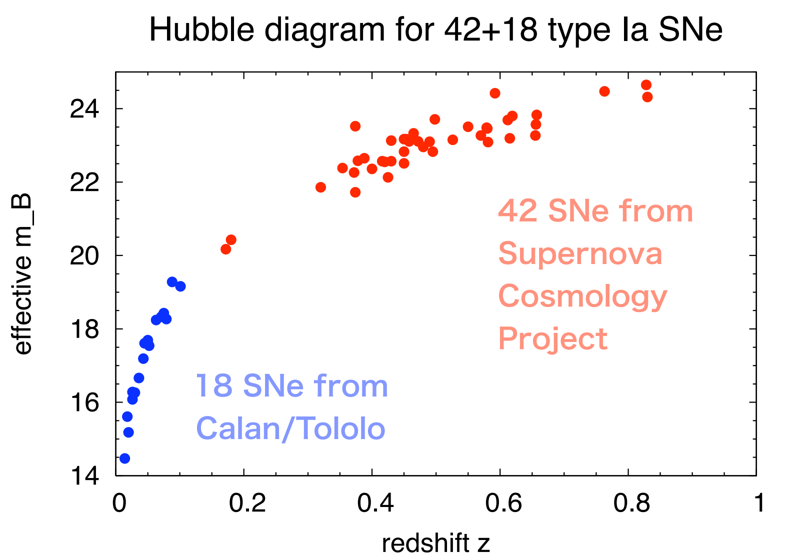
Flat Perlmutter (1999)	57.71	Ω_m, M	1.11
Two-Zone	55.93	$\Omega_m^{low}, \Omega_m^{high}$ M^{low}, M^{high}	1.12
One-Ω_m Two-Zone	55.95	Ω_m M^{low}, M^{high}	1.10

How to incorporate the post-Friedmannian effects of inhomogeneity into $D_L(z)$?

an illustration for z < 1 case



data taken from Perlmutter et al. (1999)

$$m = M - 5 + 5\log_{10} D_L(z)$$

luminosity distance $D_L(z)$

$$D_L(z) = \frac{c\,(1+z)}{H_0\sqrt{1-\Omega_m-\Omega_\Lambda}} \times \sinh\left(\sqrt{1-\Omega_m-\Omega_\Lambda}\int_0^z \frac{dz'}{\sqrt{(1+\Omega_m z')(1+z')^3 - z'\,(2+z')\,\Omega_\Lambda}}\right)$$

$D_L(z)$ is a (bit complicated) function of z with the constant parameters H_0, Ω_m, Ω_Λ.

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Yes, I know. But...

All SNe in the data are $z < 1$, therefore...

the Taylor expansion works.

The Taylor expansion of $D_L(z)$

$$D_L(z) = \frac{c}{H_0}\left(z + d_2\,z^2 + d_3\,z^3 + \cdots\right)$$

$$d_2 = \frac{1}{4}\,(2 - \Omega_m + 2\,\Omega_\Lambda)$$

$$d_3 = \frac{1}{8}\left(\Omega_m{}^2 + 4\,\Omega_\Lambda{}^2 - 4\,\Omega_m\,\Omega_\Lambda - 2\,\Omega_m - 4\,\Omega_\Lambda\right)$$

$$D_L(z) = \frac{c}{H_0}\left(z + d_2\, z^2 + d_3\, z^3 + \cdots\right)$$

$$m = M - 5 + 5\log_{10} D_L(z)$$

m-z relation for $z < 1$ SNe Ia

$$m = \mathcal{M} + 5\log_{10} z$$
$$+ 5\log_{10}\left\{1 + d_2\, z + d_3\, z^2 + \cdots\right\}$$

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- Fitting parameters are d_2, d_3, $\mathcal{M}$ (not H_0 itself)
- For $z \ll 1$,

$$m \simeq \mathcal{M} + 5\log_{10} z \quad \Rightarrow \mathcal{M} \text{ is obtained}$$

- Once d_2, d_3 are otained,

$$\Omega_m = 2(1 - d_2)(1 - 2\,d_2) - 2\,d_3$$

$$\Omega_\Lambda = d_2\,(2\,d_2 - 1) - d_3$$

determine Ω_m, Ω_Λ

In the homogeneous (Friedmann) model,

$$H_0 \equiv \frac{1}{3}\,\theta(t_0 \quad) \quad \text{(Volume expansion)}$$

$$\Omega_m \equiv \frac{8\pi G\,\rho(t_0 \quad)}{3\,{H_0}^2}$$

In the inhomogeneous universe,
H_0 and Ω_m generally become z-dependent,
due to the inhomogeneity in $\theta(t, x^i)$ and $\rho(t, x^i)$.

$$H_0(z) = \bar{H}_0\left(1 + h_1\, z + h_2\, z^2 + \cdots\right)$$

$$\Omega_m(z) = \bar{\Omega}_m\left(1 + \omega_1\, z + \omega_2\, z^2 + \cdots\right)$$

$h_1, h_2, \omega_1, \omega_2, \cdots$ are
the post-Friedmannian corrections.

Any model which has the Friedmann limit
(including LTB model)
can be expressed in this way

$$H_0(z) = \bar{H}_0\left(1 + h_1\, z + h_2\, z^2 + \cdots\right)$$

$$\Omega_m(z) = \bar{\Omega}_m\left(1 + \omega_1\, z + \omega_2\, z^2 + \cdots\right)$$

in the region $z < 1$

The luminosity distance with the post-Friedmannian corrections

$$D_L(z) = \frac{c}{\bar{H}_0}\left(z + \tilde{d}_2\, z^2 + \tilde{d}_3\, z^3 + \cdots\right)$$

$$\tilde{d}_2 = \frac{1}{4}\left(2 - \bar{\Omega}_m + 2\,\Omega_\Lambda - 4\, h_1\right)$$

$$\tilde{d}_3 = \frac{1}{8}\left(\bar{\Omega}_m^2 + 4\,\Omega_\Lambda{}^2 - 4\,\bar{\Omega}_m\,\Omega_\Lambda - 2\,\bar{\Omega}_m - 4\,\Omega_\Lambda\right)$$

$+$(terms with h_1, h_2, ω_1)

From $\tilde{d}_2$, $\tilde{d}_3$ obtained by the data fitting, assuming the Friedmannian $D_L(z)$, calculate the cosmological parameters...

$$\Omega_\Lambda^{\rm eff} \equiv \tilde{d}_2\,\left(2\,\tilde{d}_2 - 1\right) - \tilde{d}_3$$

From $\tilde{d}_2$, $\tilde{d}_3$ obtained by the data fitting, assuming the Friedmannian $D_L(z)$, calculate the cosmological parameters... even if the "bare" value is $\Omega_\Lambda = 0$,

$$\Omega_\Lambda^{\rm eff} \equiv \tilde{d}_2\,\left(2\,\tilde{d}_2 - 1\right) - \tilde{d}_3$$
$$= \frac{1}{8}\left\{6h_1\bar{\Omega}_m + \frac{4}{3}\omega_1\bar{\Omega}_m - 4h_1 + 8\,(h_1)^2 + 8h_2\right\}$$

$$H_0(z) = \bar{H}_0\left(1 + h_1\, z + h_2\, z^2 + \cdots\right)$$

$$\Omega_m(z) = \bar{\Omega}_m\left(1 + \omega_1\, z + \omega_2\, z^2 + \cdots\right)$$

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The post-Friedmannian corrections behave as Ω_Λ!

Ω_m is also dressed in the inhomogeneous corrections

$$\Omega_m^{\text{eff}} \equiv 2\left(1-\tilde{d}_2\right)\left(1-2\,\tilde{d}_2\right)-2\,\tilde{d}_3$$
$$=\left(1+\frac{3}{2}h_1+\frac{1}{3}\omega_1\right)\bar{\Omega}_m+3h_1+2(h_1)^2+2h_2.$$

$$\bar{\Omega}_m = \Omega_m(z=0)$$

$$H_0(z)=\bar{H}_0\left(1+h_1\,z+h_2\,z^2+\cdots\right)$$

$$\Omega_m(z)=\bar{\Omega}_m\left(1+\omega_1\,z+\omega_2\,z^2+\cdots\right)$$

So far, the data is Perlmutter et al. (1999) The Supernova Cosmology Project

What about the new data in the 21st century?

Supernova Legacy Survey (2006)

A&A 447, 31–48 (2006)
DOI: 10.1051/0004-6361:20054185

Astronomy & Astrophysics

The Supernova Legacy Survey: measurement of Ω_M, Ω_Λ and w from the first year data set⋆,⋆⋆

P. Astier[1], J. Guy[1], N. Regnault[1], R. Pain[1], E. Aubourg[2,3], D. Balam[4], S. Basa[5], R. G. Carlberg[6], S. Fabbro[7], D. Fouchez[8], I. M. Hook[9], D. A. Howell[6], H. Lafoux[3], J. D. Neill[4], N. Palanque-Delabrouille[3], K. Perrett[6], C. J. Pritchet[4], J. Rich[3], M. Sullivan[6], R. Taillet[1,10], G. Aldering[11], P. Antilogus[1], V. Arsenijevic[7], C. Balland[1,2], S. Baumont[1,12], J. Bronder[9], H. Courtois[13], R. S. Ellis[14], M. Filiol[5], A. C. Gonçalves[15], A. Goobar[16], D. Guide[1], D. Hardin[1], V. Lusset[3], C. Lidman[12], R. McMahon[17], M. Mouchet[15,2], A. Mourao[7], S. Perlmutter[11,18], P. Ripoche[8], C. Tao[8], and N. Walton[17]

(Affiliations can be found after the references)

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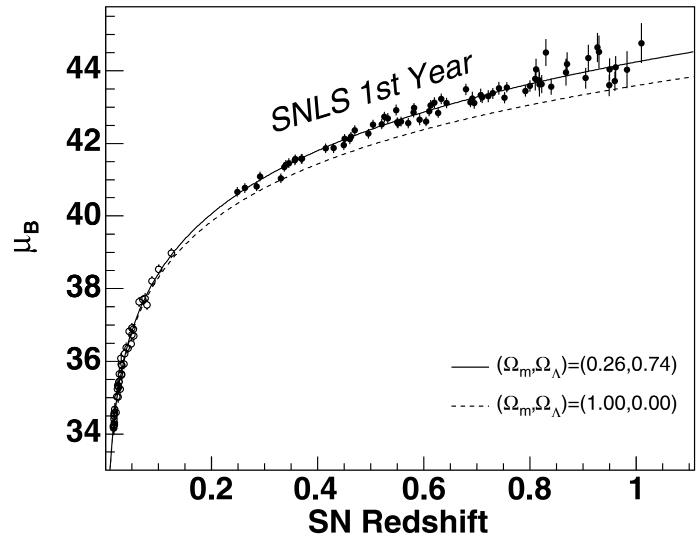
ABSTRACT

We present distance measurements to 71 high redshift type Ia supernovae discovered during the first year of the 5-year Supernova Legacy Survey (SNLS). These events were detected and their multi-color light-curves measured using the MegaPrime/MegaCam instrument at the Canada-France-Hawaii Telescope (CFHT), by repeatedly imaging four one-square degree fields in four bands, as part of the CFHT Legacy Survey (CFHTLS). Follow-up spectroscopy was performed at the VLT, Gemini and Keck telescopes to confirm the nature of the supernovae and to measure their redshift. With this data set, we have built a Hubble diagram extending to $z = 1$, with all distance measurements involving at least two bands. Systematic uncertainties are evaluated making use of the multi-band photometry obtained at CFHT. Cosmological fits to this first year SNLS Hubble diagram give the following results: $\Omega_M = 0.263 \pm 0.042$ (*stat*) ± 0.032 (*sys*) for a flat ΛCDM model; and $w = -1.023 \pm 0.090$ (*stat*) ± 0.054 (*sys*) for a flat cosmology with constant equation of state w when combined with the constraint from the recent Sloan Digital Sky Survey measurement of baryon acoustic oscillations.



Preliminary results

- zone-fittings converge only in the range: $z < 0.1$, $0.5 < z$
- multi-zone inhomogeneity?
- transient zone?
- z-dependence of H_0, Ω_m explicitly shown?

Our results give constraints on the inhomogeneous models.

Any models which (try to) explain SN m-z relation without Dark Energy, shoud have the following properties:

1\.
shoud have
Friedmann limit

2\.
behaves as if
Friedmann
in low-z region
($z < 0.1 \sim 0.2$)

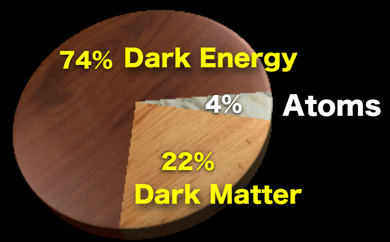
3\.
behaves as if
Friedmann
in high-z region
($0.3 \sim 0.5 < z$)

4.
mild
inhomogeneity
in H_0, Ω_m

$\Delta H_0 \sim -13\%$, $\Delta\Omega_m \sim 29\%$

Still you prefer
homogeneity?

If you stick to
the homogeneity,



you also need
the **Dark Side** of Energy.

Vader was seduced
by the dark side of
the Force...

Don’t be seduced by the Dark Side of energy!

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May the Force be with the inhomogeneous cosmologists.

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May the Force be with us.

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kasai@phys.hirosaki-u.ac.jp

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