加速膨張

ダークエネルギー？

非一様宇宙！

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加速膨張の観測的証拠

最近の

加速膨張ブーム

ダークエネルギーブーム

は

超新星観測による

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., Ω

宇宙定数がないとだめ!

constraint on mass der

consistent with $q_0 < 0$

confidence levels, for tw

0.2, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncer-

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

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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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

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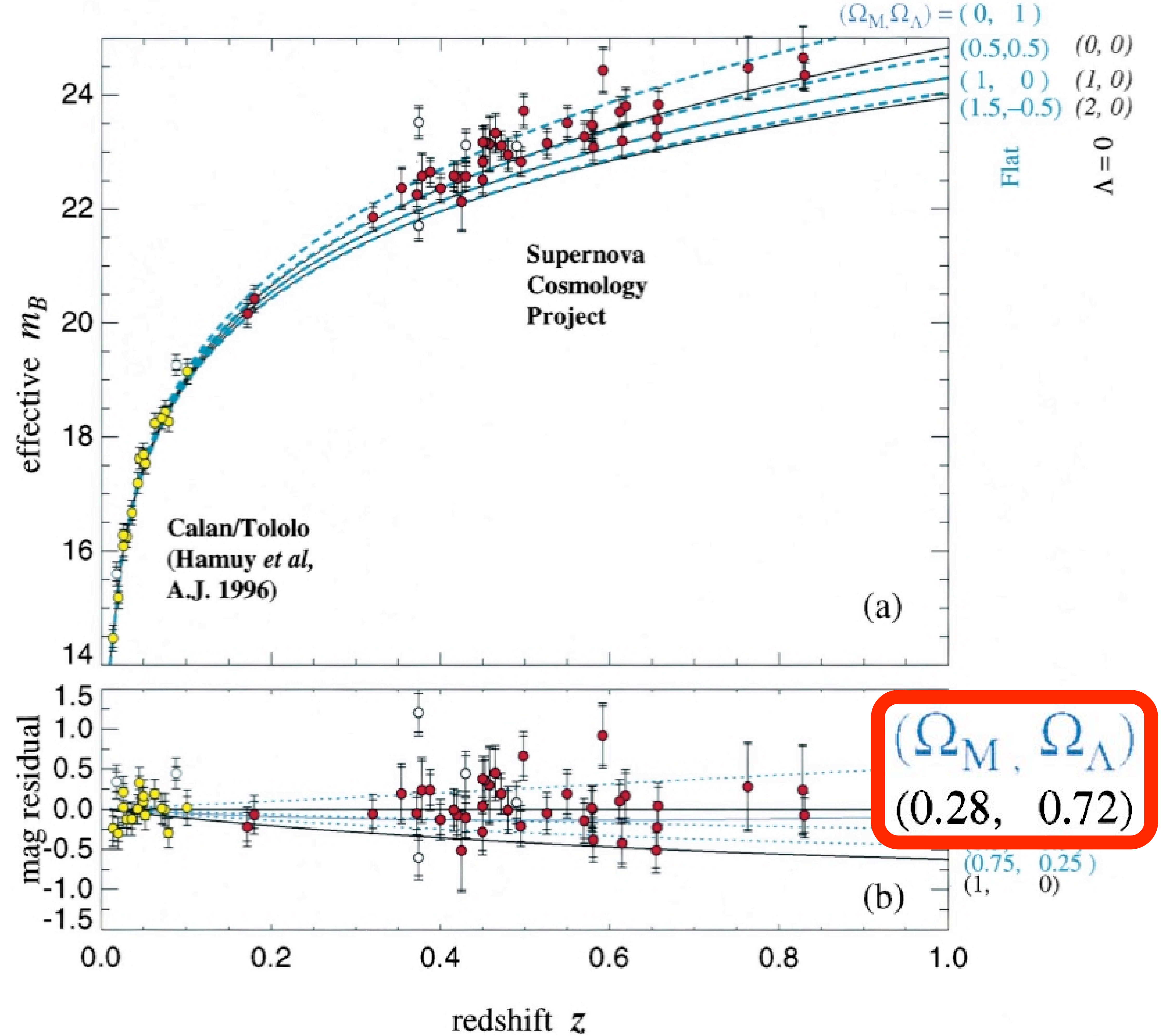

(ΩM, ΩΛ) = (0, 1)
(0.5,0.5)
(0, 0)
(1, 0)
(1, 0)
(1.5,–0.5)
(2, 0)
Flat
Λ = 0
Supernova
Cosmology
Project
Calan/Tololo
(Hamuy et al,
A.J. 1996)
(a)
effective mB
(ΩM , ΩΛ)
(0.28, 0.72)
(0.75, 0.25)
(1, 0)
(b)
mag residual
redshift z

（見かけの）加速膨張を
ダークエネルギー無しで
説明しようとする試み

ダークエネルギーが必要なのは

一様等方宇宙を仮定して得られた

m-z relation を使うから

現実の宇宙は非一様なんだから
非一様宇宙での光の伝播
解かなきゃ...

でも
一般的な非一様宇宙って
難しいから
まずは簡単な toy model で…

非一様宇宙の可能性

- **Tomita** (2000a, 2000b, 2001, ...)
  local void model
- **Iguchi, Nakamura, Nakao** (2002)
  Lemaitre-Tolman-Bondi (LTB) model
- **Alnes** et al. (2006)
  LTB modelでSNもCMBもOK!?

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

A local void and the accelerating Universe

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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.

local void は宇宙定数と似た振る舞いをする

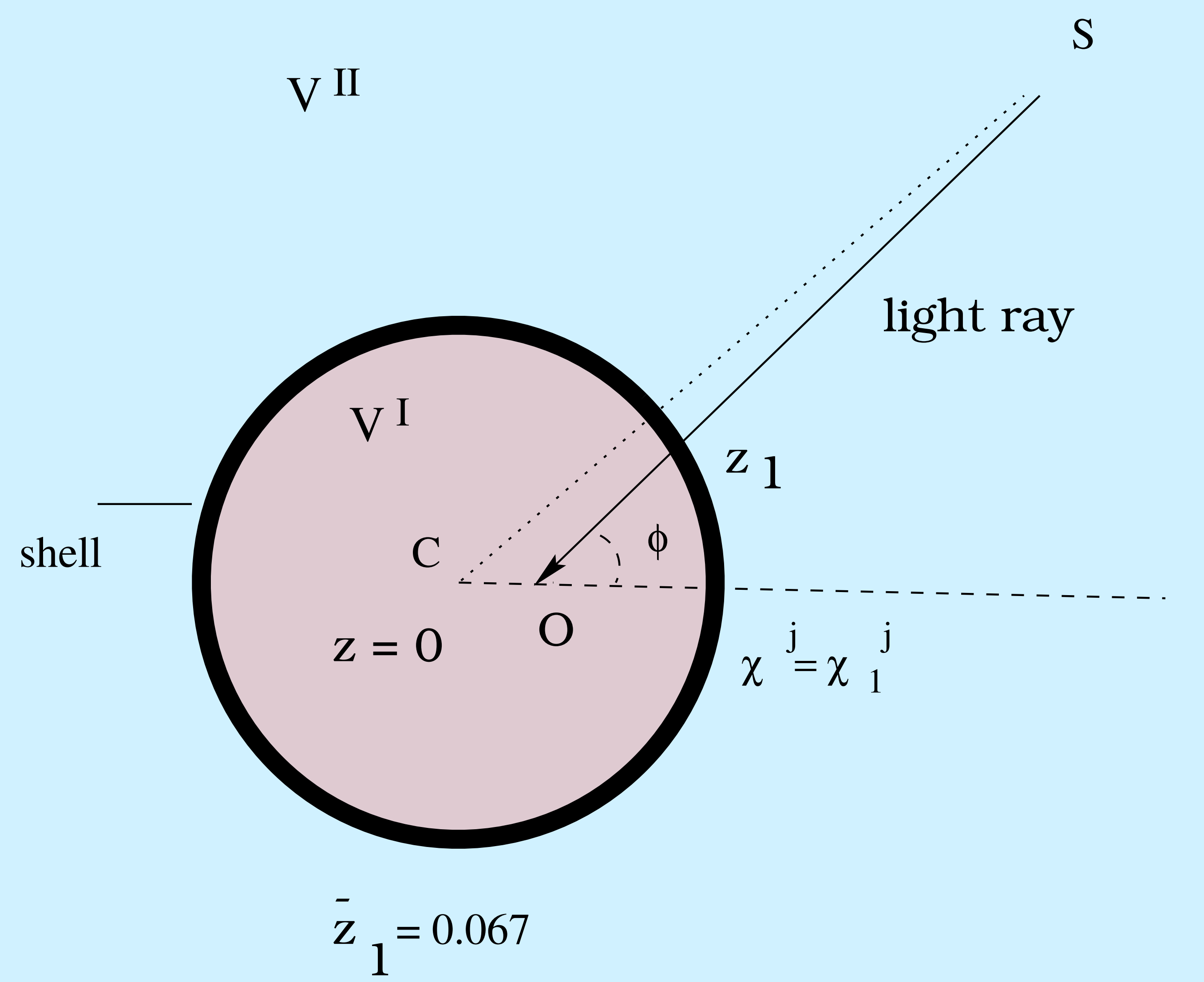


Figure 1. Model with a spherical single shell. Redshifts for observers at O and C are z and $\bar{z}$.

inner low-density Friedmann

+

singular mass shell (junction condition)

+

outer high-density Friedmann

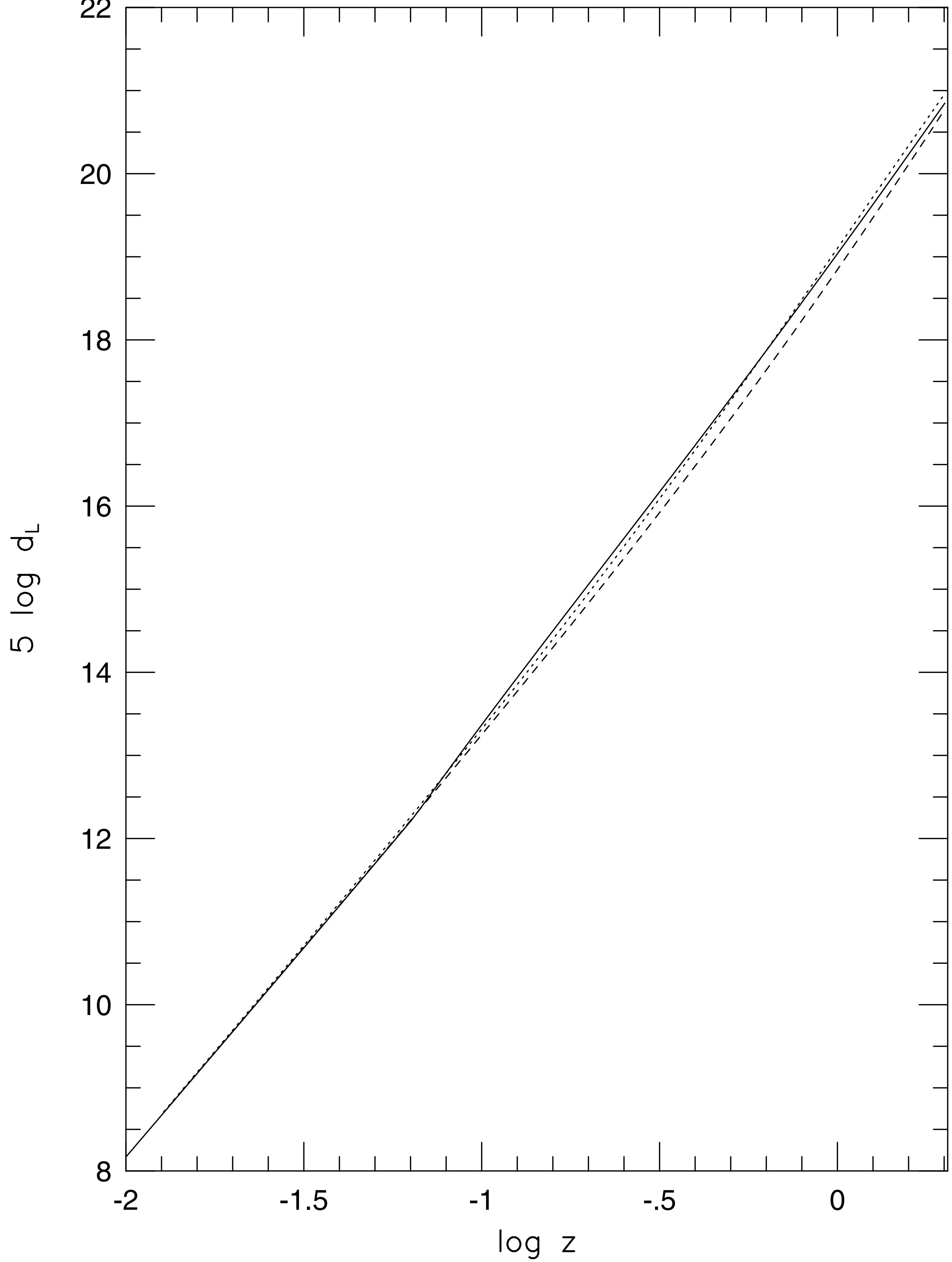


Figure 2. The $[m, z]$ relation in cosmological models with a local void. The solid line denotes the case with a standard parameter set given in equation (12). The dotted and dashed lines stand for homogeneous models with $(\Omega_0, \lambda_0) = (0.3, 0.7)$ and $(0.3, 0.0)$, respectively, for comparison.

essential なところは
一連の冨田論文で尽きている

しかし…

現実の我々の宇宙が
そんな toy model で
本当に記述されるのか？
という心理的バリア

そこで

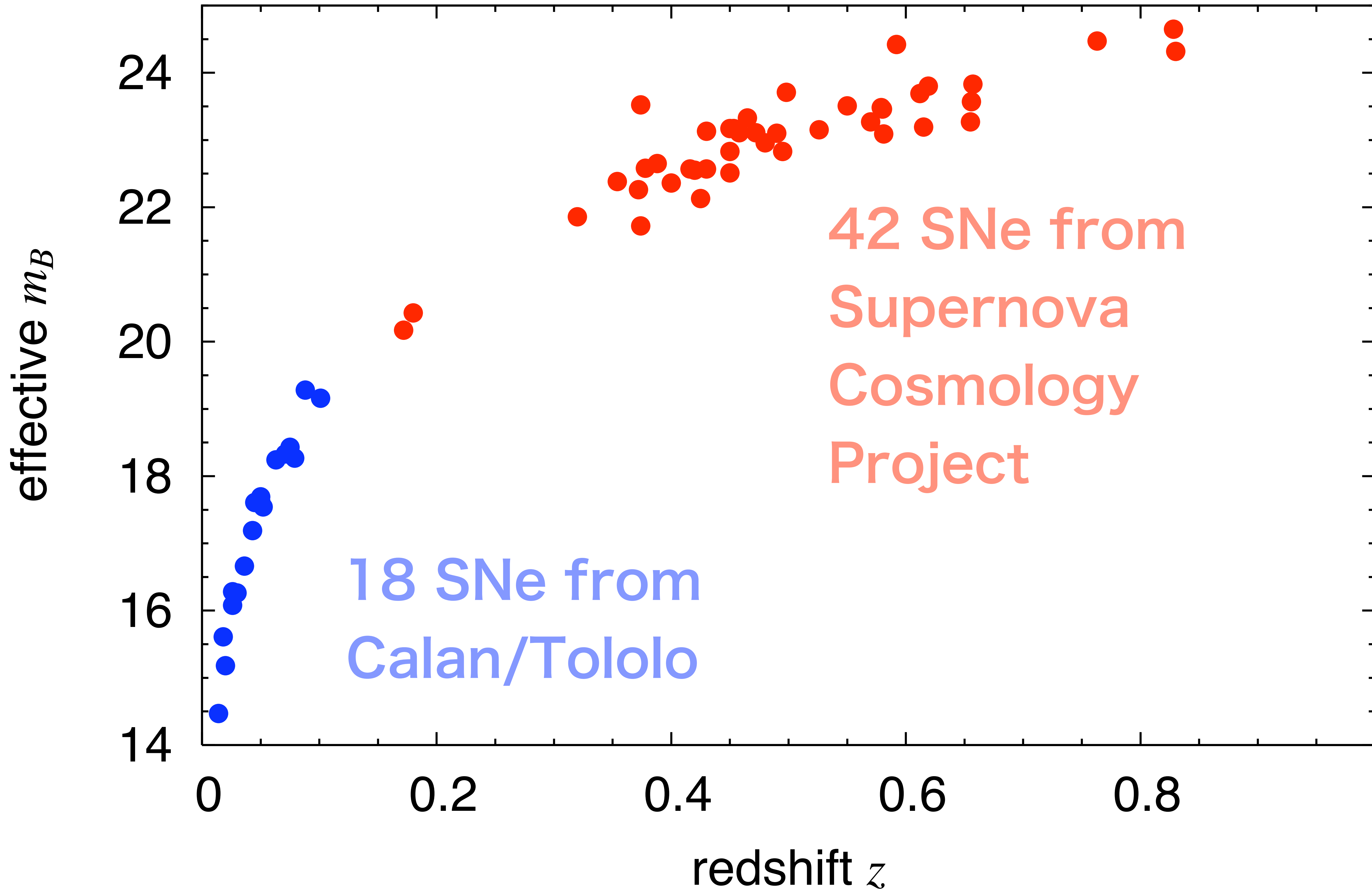
提案

特定の toy model に
依存せずに
非一様宇宙の効果を
記述する手法

超新星の
m-z relation
再吟味

対象とする
観測データは…

Hubble diagram for 42+18 type Ia SNe



data taken from Perlmutter et al. (1999)

観測データを
fitさせる
m-z relation

luminosity distance $D_L(z)$ は

3つの定数 H_0, Ω_m, Ω_Λ をパラメータに持つ

z の(複雑な)関数

だが...

対象とするSNデータが $z < 1$ なので

Taylor 展開した式で十分

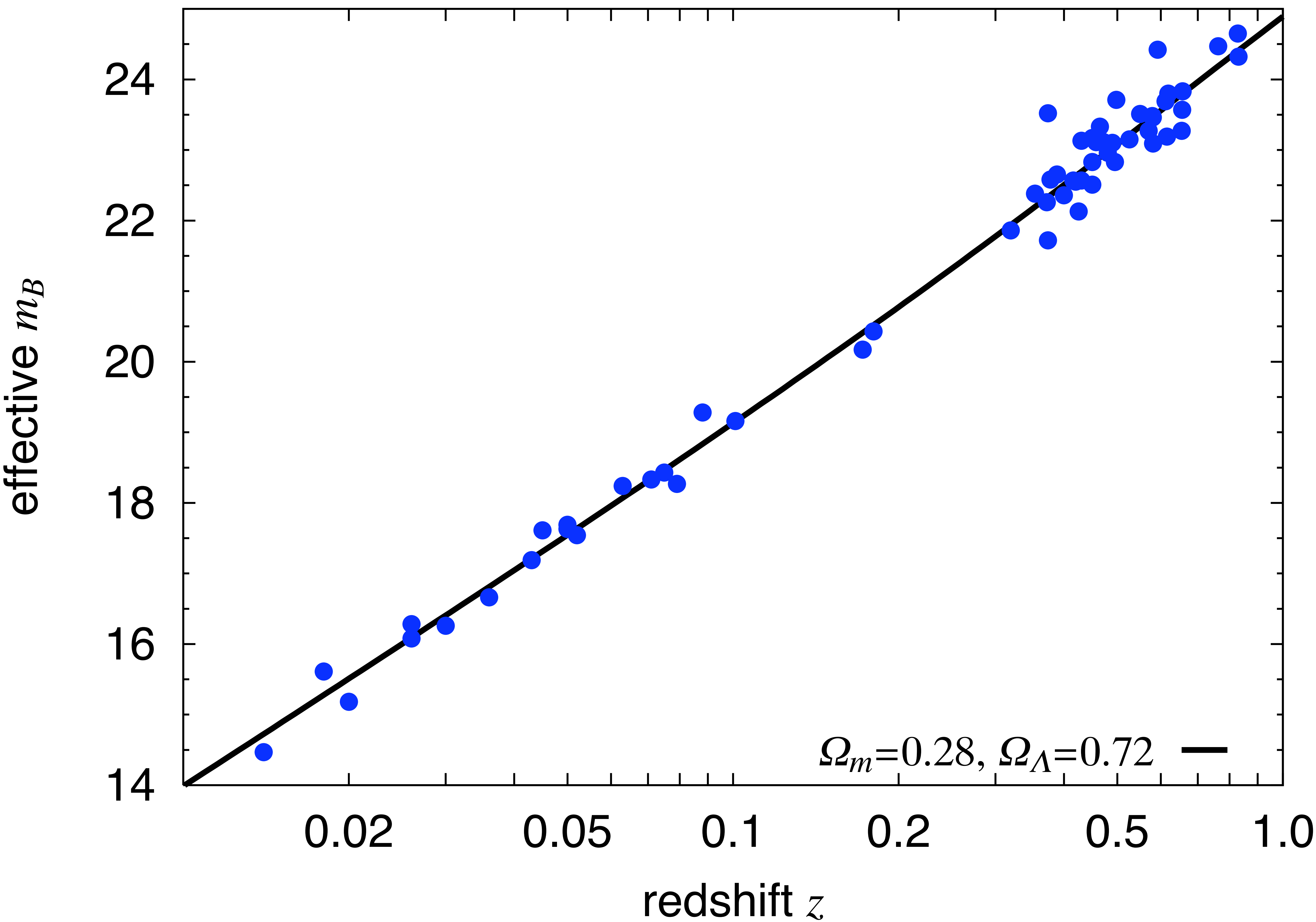
$$D_L(z) = \frac{c}{H_0}\left(z + d_2\, z^2 + d_3\, z^3\right)$$

$$\begin{aligned} m &= M - 5 + 5\log_{10} D_L(z) \\ &= \mathcal{M} + 5\log_{10}\left\{z + d_2\, z^2 + d_3\, z^3\right\} \end{aligned}$$

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

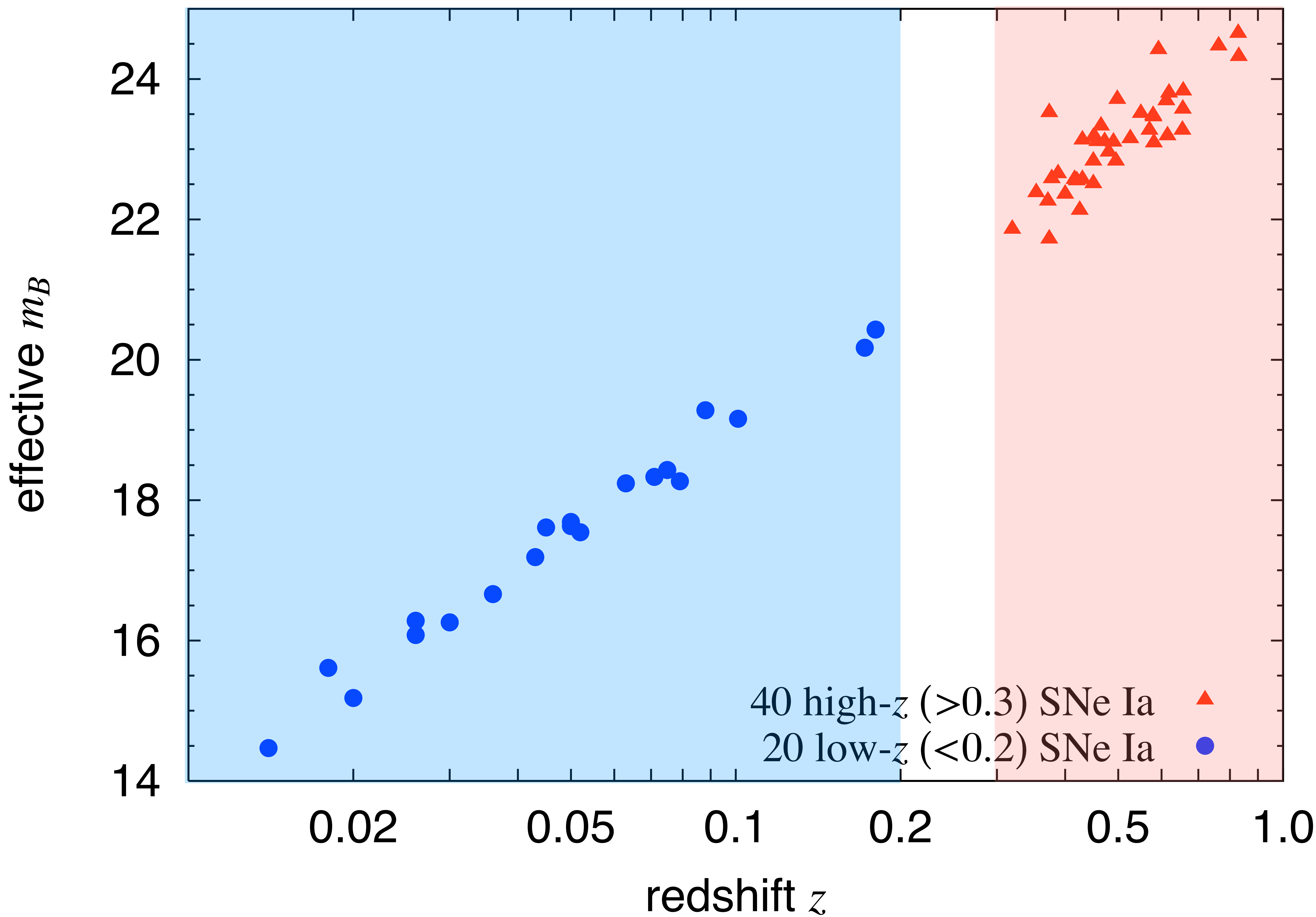
$\mathcal{M}$: "the magnitude zero-point" or

"H_0-free absolute magnitude"



effective m_B
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
Ω_m=0.28, Ω_Λ=0.72

ちょっと
遊んでみる



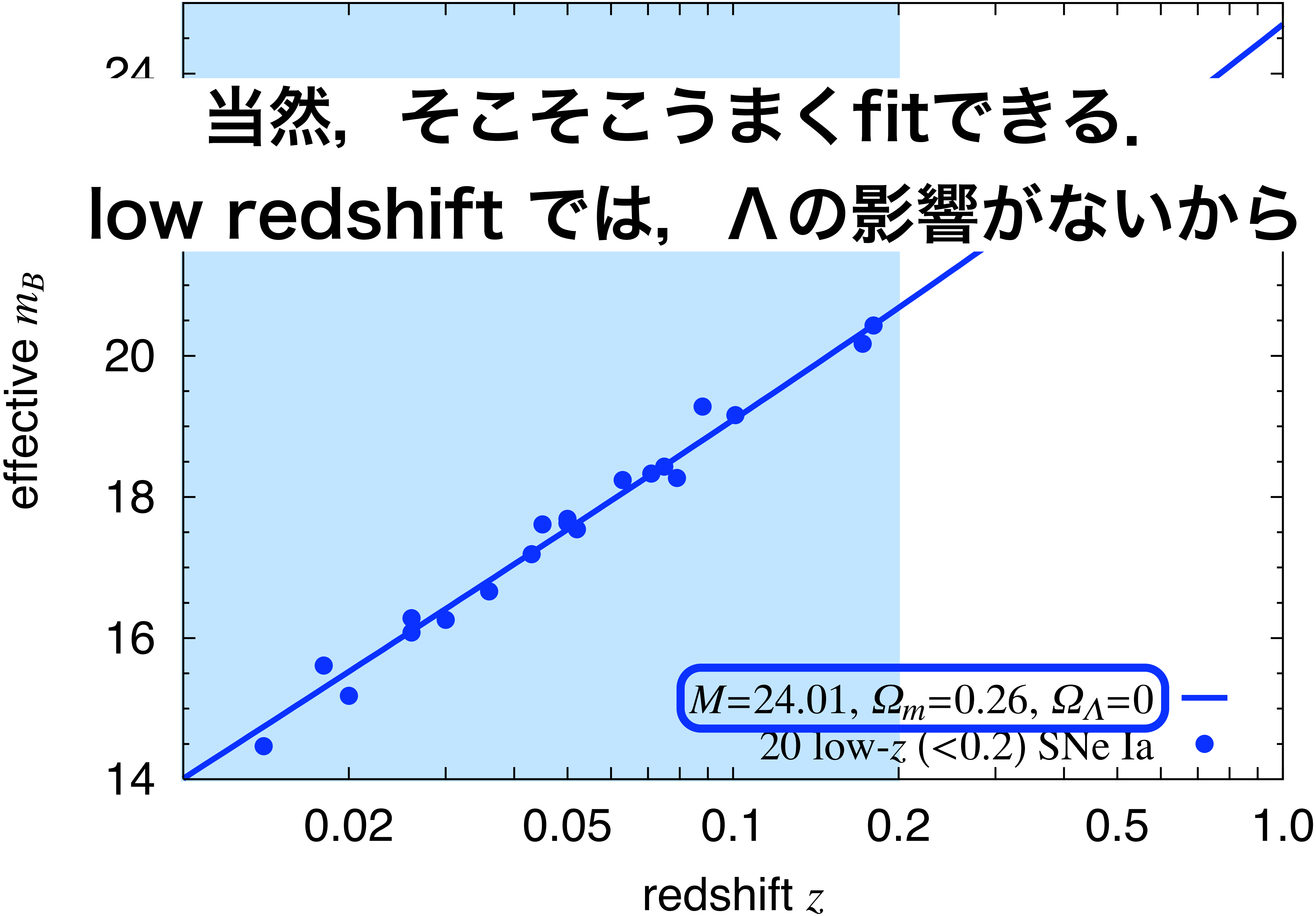
effective m_B
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
40 high-z (>0.3) SNe Ia
20 low-z (<0.2) SNe Ia

low redshift

z < 0.2 のみを

Λ なしで fit

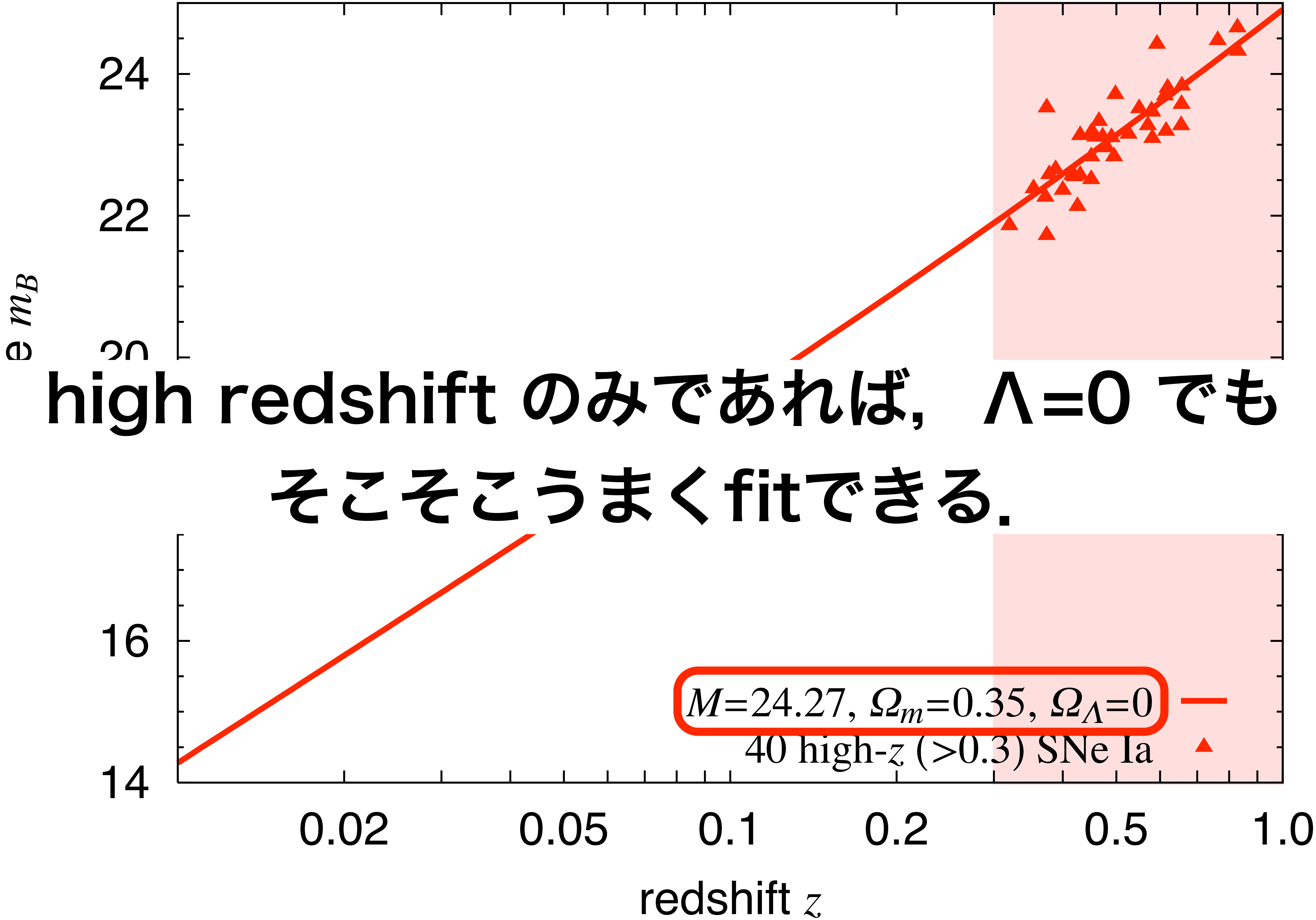
当然，そこそこうまくfitできる．
low redshift では，Λの影響がないから



high redshift

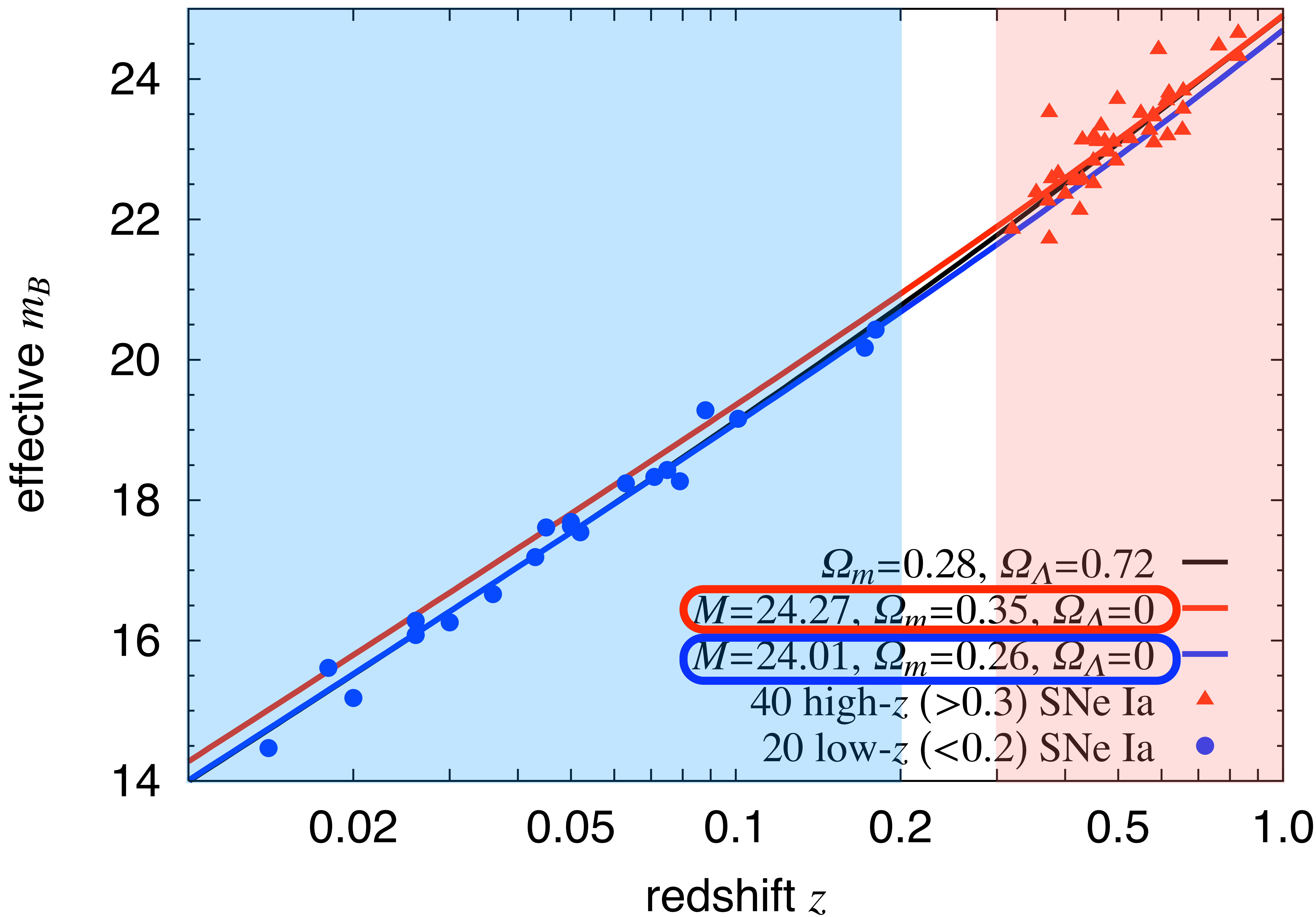
z > 0.3 のみを

Λ なしで fit



high redshift のみであれば，Λ=0 でも
そこそこうまくfitできる.

まとめて表示



effective m_B
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
Ω_m=0.28, Ω_Λ=0.72
M=24.27, Ω_m=0.35, Ω_Λ=0
M=24.01, Ω_m=0.26, Ω_Λ=0
40 high-z (>0.3) SNe Ia
20 low-z (<0.2) SNe Ia

宇宙論パラメータ決定のあらまし

- おもに low redshift データから
  $\mathcal{M}$ 従って H_0 が決まる.
- その値を一定として high redshift データも
  fit しようとすると, Ω_Λ が必要になる.
- low-z と high-z で異なる値の $\mathcal{M}$ を許せば,
  それぞれは Λ 無しでも fit できる.

low-z, high-z で違う $\mathcal{M}$. その解釈は?

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

low-z 領域と high-z 領域では...

1. 絶対等級 M が違う

2. 光速 c が違う

3. H_0 が違う

超新星の m-z relation が意味するのは,

Λ があることではなく,

H_0 や Ω_m が一定ではないこと!?

$\mathcal{M}$ の違いが H_0 の違いによる，とすると…

$$24.01 - 24.27 = 5\log_{10}\frac{H_0(\text{high-}z)}{H_0(\text{low-}z)}$$

$$\Downarrow$$

$$\frac{H_0(\text{high-}z)}{H_0(\text{low-}z)} = 0.89$$

high-z の H_0 が 11% 小さい，とすれば

Dark Energy なしで OK

非一様宇宙の
post-Friedmann的効果を
luminosity distance に
どのように取り込むか？

一様宇宙なら,

$$H_0 \equiv \frac{1}{3}\theta(t_0, x_i) \Rightarrow H(t_0) \quad (\text{定数})$$

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

非一様宇宙では,

$$H(t_0, x^i) = H\left(t_0, x^i(z)\right) \Rightarrow H_0(z)$$

$$\Omega_m(t_0, x^i) = \Omega_m\left(t_0, x^i(z)\right) \Rightarrow \Omega_m(z)$$

非一様宇宙では

expansion θ や density ρ の空間依存性に起因して H_0 や Ω_m は，一般に redshift z 依存性を持つだろう.

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

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

$h_1, h_2, \omega_1, \omega_2, \cdots$ が post-Friedmannian corrections

時空の非一様性に起因するpost-Friedmann的補正を考慮したluminosity distance

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

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

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

$$+(\text{terms with } h_1, h_2, \omega_1)$$

観測データとのfittingによって得られた$\tilde{d}_2$, $\tilde{d}_3$から
一様等方宇宙だと思い込んで
宇宙論パラメータを求めると
たとえ，$\Omega_\Lambda = 0$であっても

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

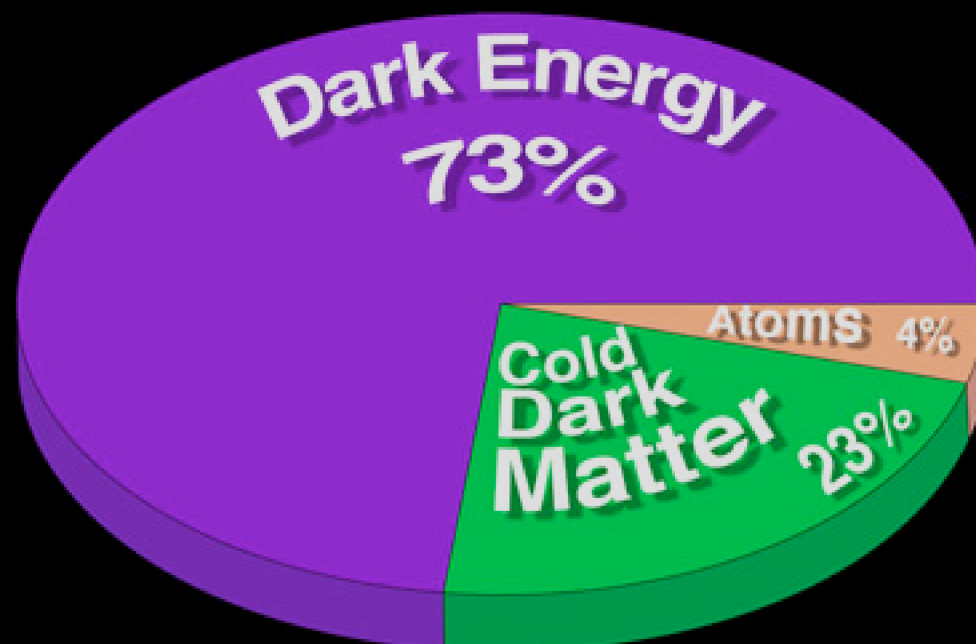
非一様宇宙の post-Friedmannian correctionが
Ω_Λとしてふるまう!

それでも

一様等方宇宙に

こだわる？

一様等方モデルにこわだる限り
「Dark Side」は必要...



正体不明の「Dark Side」の
導入は問題解決になる？

「Dark Side」

に

身をゆだねるな！

非一様宇宙論屋に
Forceの御加護が
　ありますように…

Apparent Acceleration through Large-scale Inhomogeneities --Post-Friedmannian Effects of Inhomogeneities on the Luminosity Distance--

Masumi Kasai

(Submitted on 13 Mar 2007 (v1), last revised 24 May 2007 (this version, v3))

We re-analyze the observed magnitude-redshift relation of type Ia supernovae (SNe Ia) and examine the possibility that the apparent acceleration of the cosmic expansion is not caused by dark energy but is instead a consequence of the large-scale inhomogeneities in the universe. We propose a method to phenomenologically describe the effects of the large-scale inhomogeneities without relying on the specific toy models of the inhomogeneous universe. This method clearly illustrates how the post-Friedmannian effects of inhomogeneities, i.e. the effects due to the deviation from a perfectly homogeneous and isotropic model, act as an effective cosmological constant in the magnitude-redshift relation of SNe Ia.