Supernovae and Dark Energy

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Supernovae and Dark Energy

- JDEM selected Beyond Einstein's programme by NASA/DOE
- Three missions: SNAP, DESTINY, ADEPT

Measure the equation of state of dark energy

Reduce systematic and statistical errors

Supernovae and Dark Energy

- The analysis w(z)

- Beyond two parameter analysis of w(z)

- The SN database: joint databases

  Wood-Vasey et al. 2007 (ESSENCE)

  Kowalski et al. 2008 (SCP)

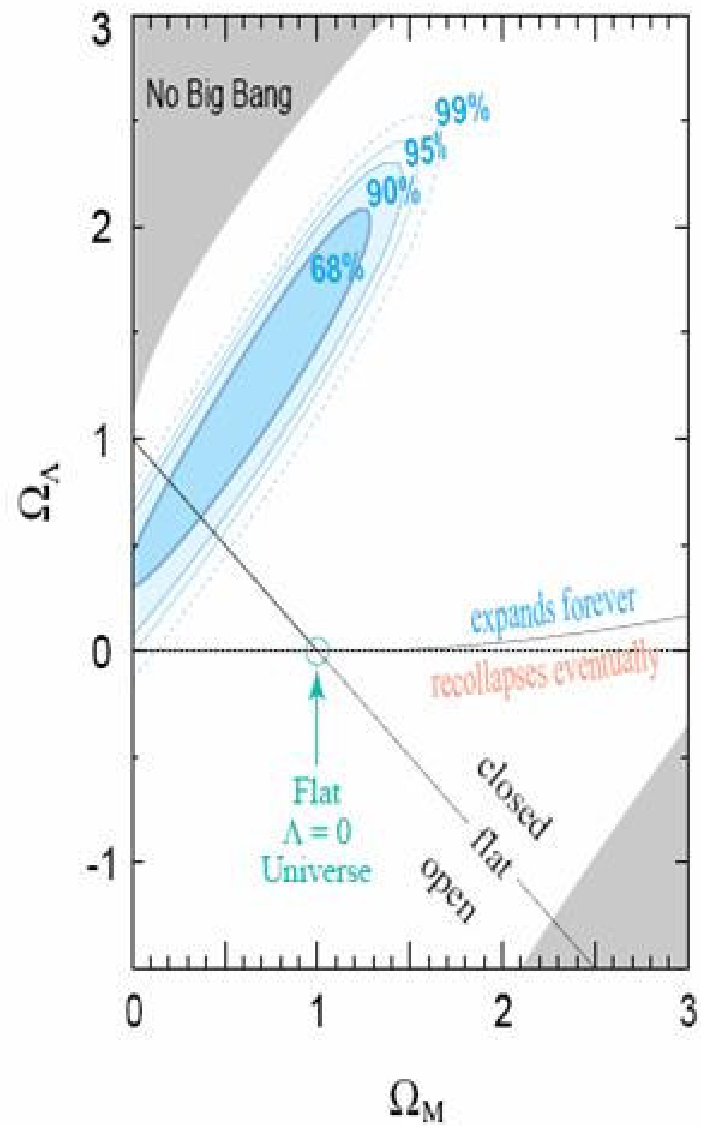
  307 SNe Ia

Evidence of acceleration of the expansion of the Universe in 1998

Cosmological constant or modified gravity?

Evidence Ω_M-Ω_Λ, using 42 SNeIa Perlmutter et al.: ApJ 517, 565 (1999)

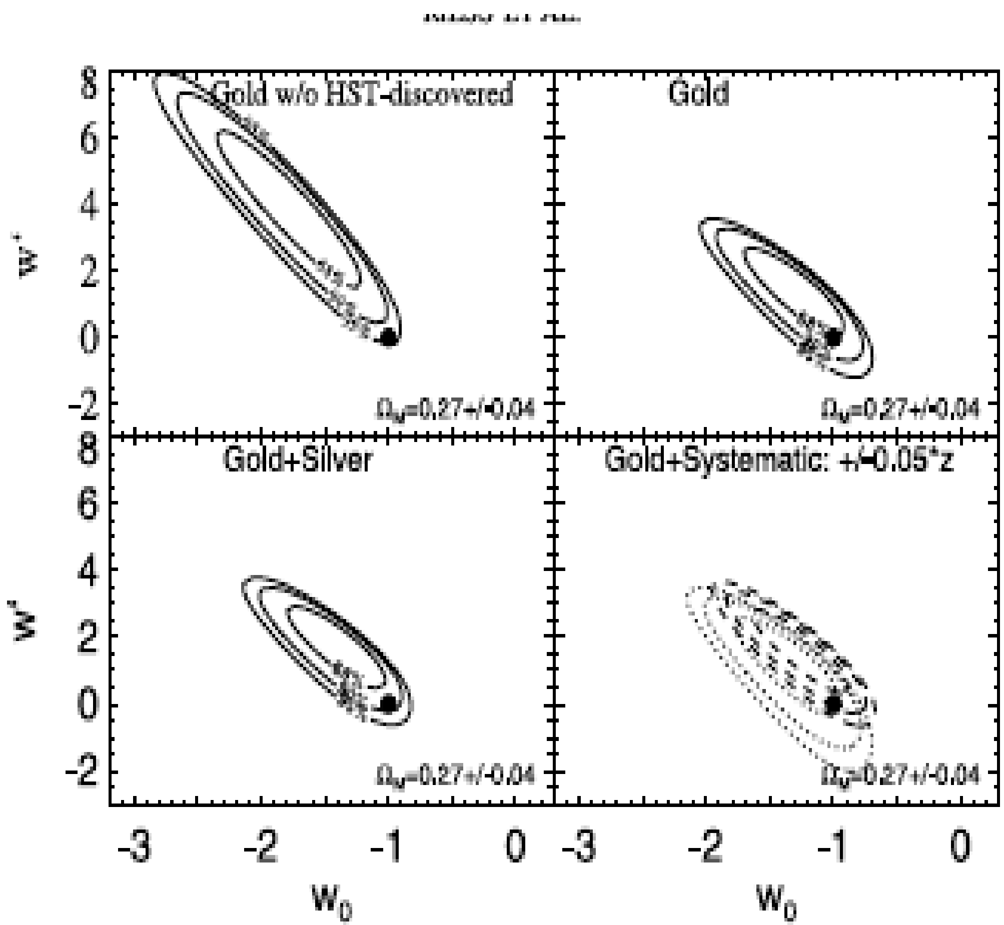
Riess et al.: AJ 116, 1009 (1998)

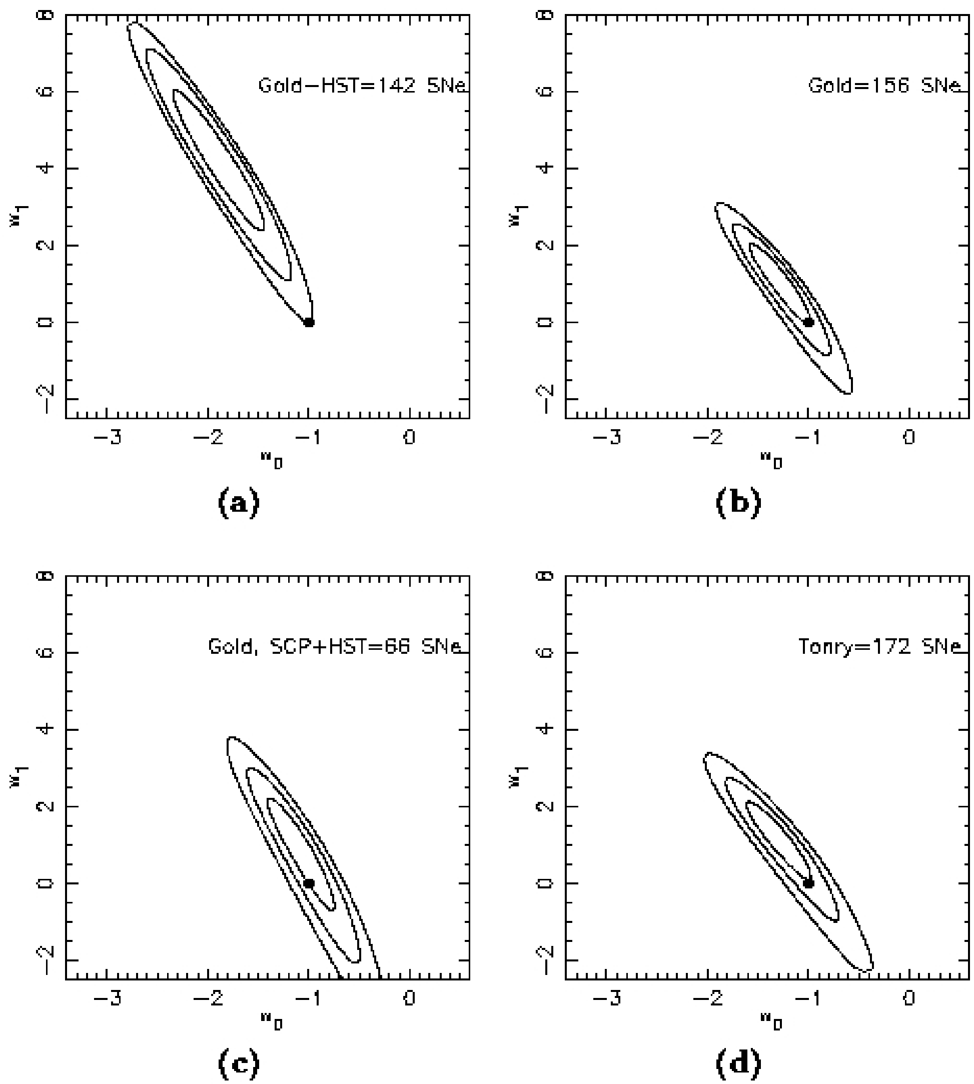


First constraints on w´

Confidence regions in the parameter space of w_0–w' of the equation of state of dark energy *$w(z) = w_0 + w'z$.*

Gold sample results using the *prior* $\Omega_M = 0.27 \pm 0.04$ (Riess et al.: ApJ 607, 665, 2004)





Riess(04)

gives $w_0 = -1.31^{+0.22}_{-0.28}$ $w' = 1.48 \pm^{0.81}_{0.90}$

Riess et al.: ApJ, 607, 665 (2004)

w(z)

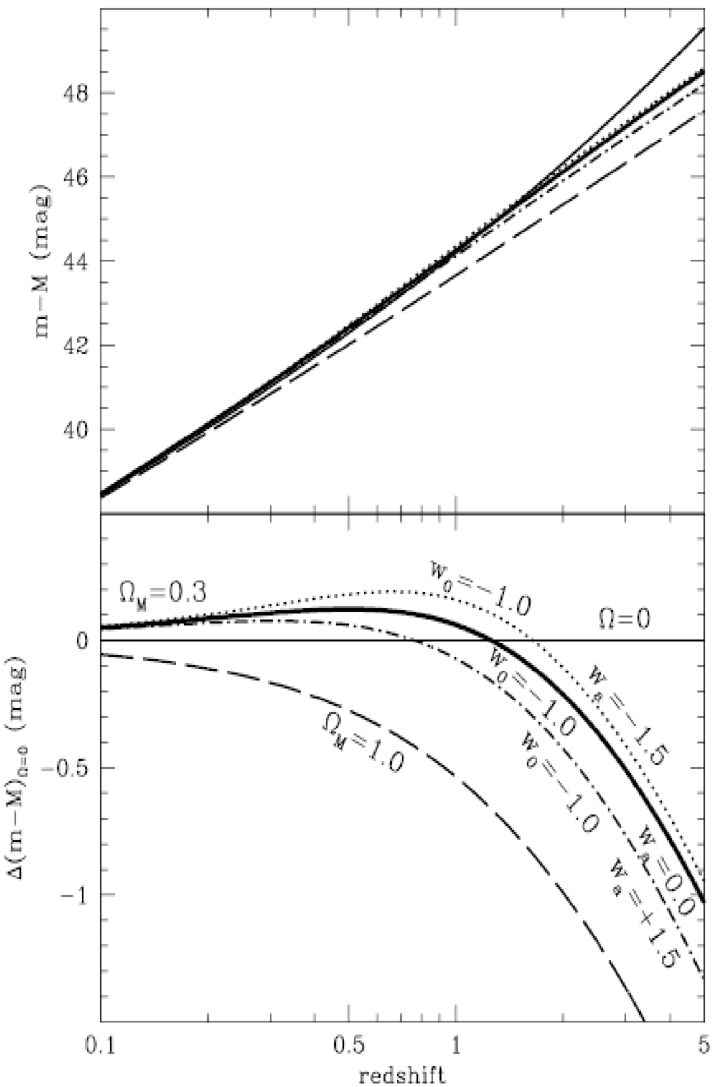
$$w(z) = w_0 + w_1 z \qquad w_1 = \left.\frac{dw}{dz}\right|_0$$

$$w(z) = w_0 + w_a(1 - a)$$

$$w(z) = w_0 + w_a \frac{z}{1+z} \qquad w_a = \left.\frac{dw}{da}\right|_0$$

Chevallier & Polarski: Int. J. Mod. Phys. D 10, 213 (2001)

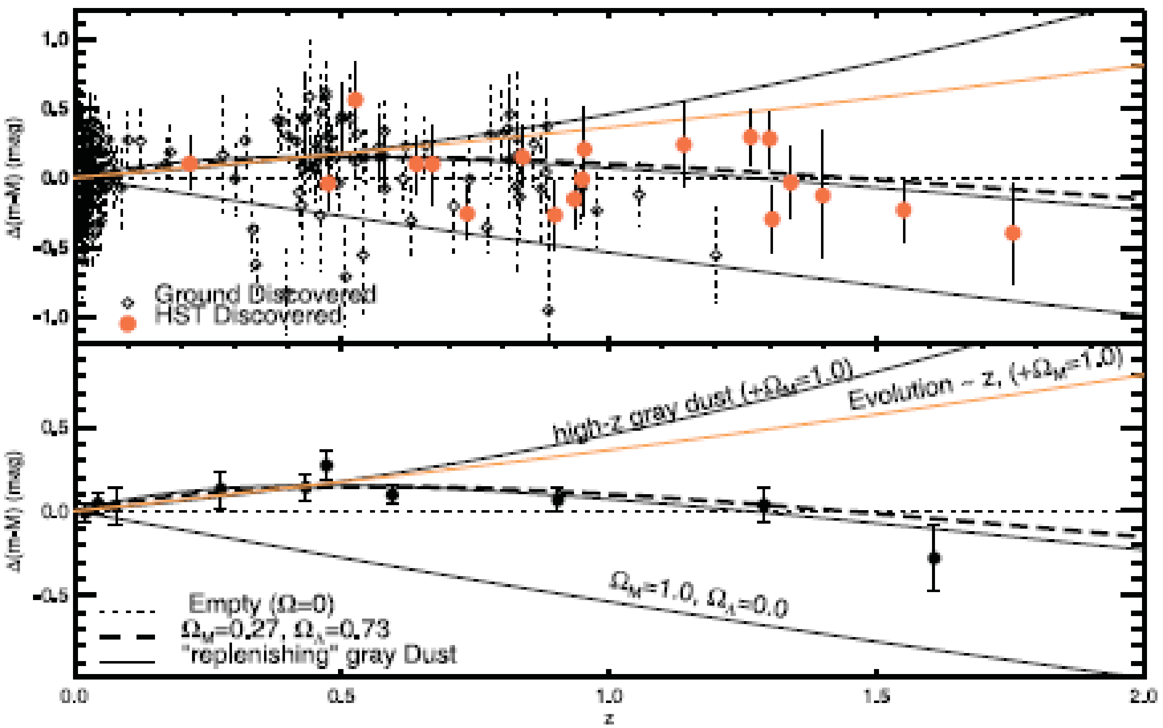
Linder: Phys. Rev. Lett. 90, 091301 (2003)



Ruiz-Lapuente: Class. Quantum Grav. 24, R91 (2007)

The Higher-Z Team

Targeting SNeIa at z > 1 with the HST
Riess et al.: ApJ 607, 665 (2004).



Empirical progress in $d_L(z)$ from supernovae

TABLE I

ERROR CONTRIBUTIONS TO HIGH SUPERNOVA DISTANCES in 1998

Systematic Uncertainties (1σ)	Magnitude	Statistical Uncertainties (1σ)	Magnitude
Photometric System Zero Point	0.05	Zero Points, S/N	0.17
Evolution	< 0.17	K-corrections	0.03
Evolution of Extinction Law	0.02	Extinction	0.10
Gravitational Lensing	0.02	Light curve sampling	0.15

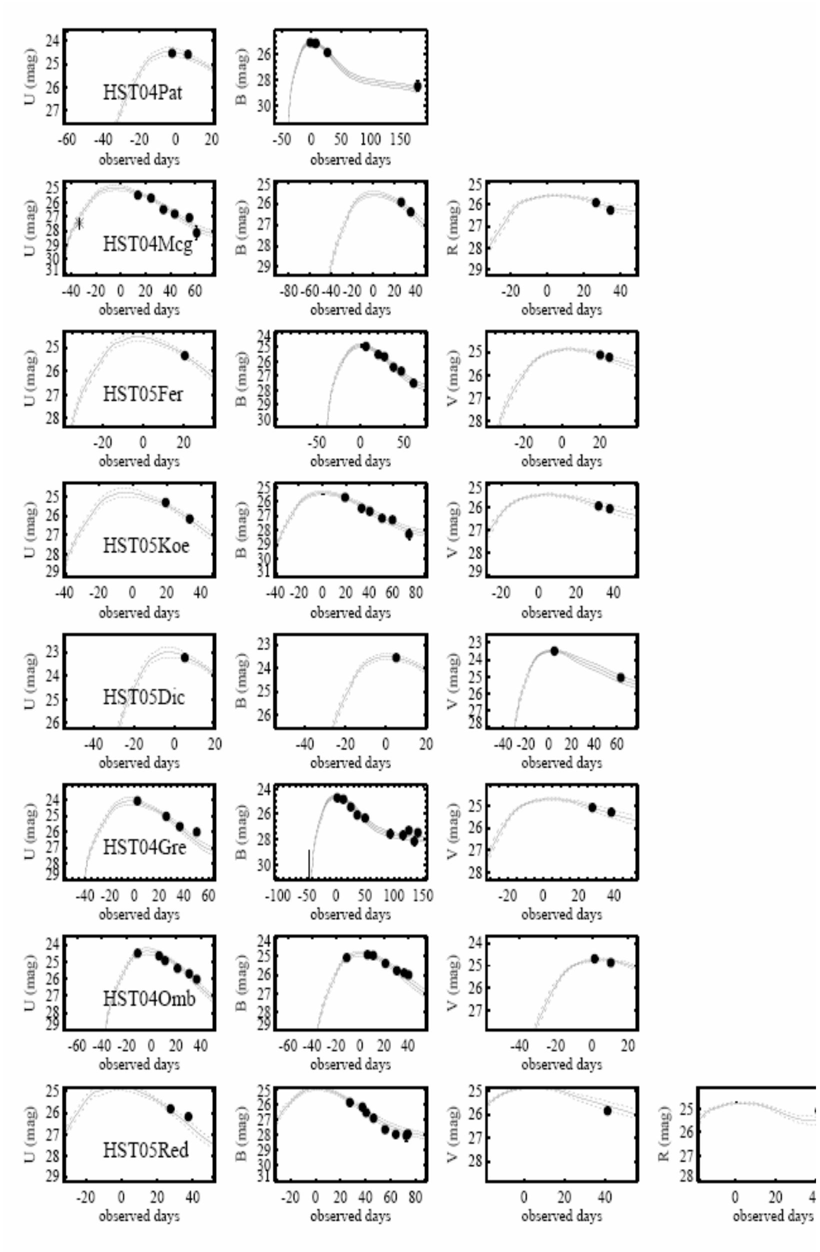
PROSPECTS TOWARDS 1% ERROR IN $d_L(z)$ in a space mission

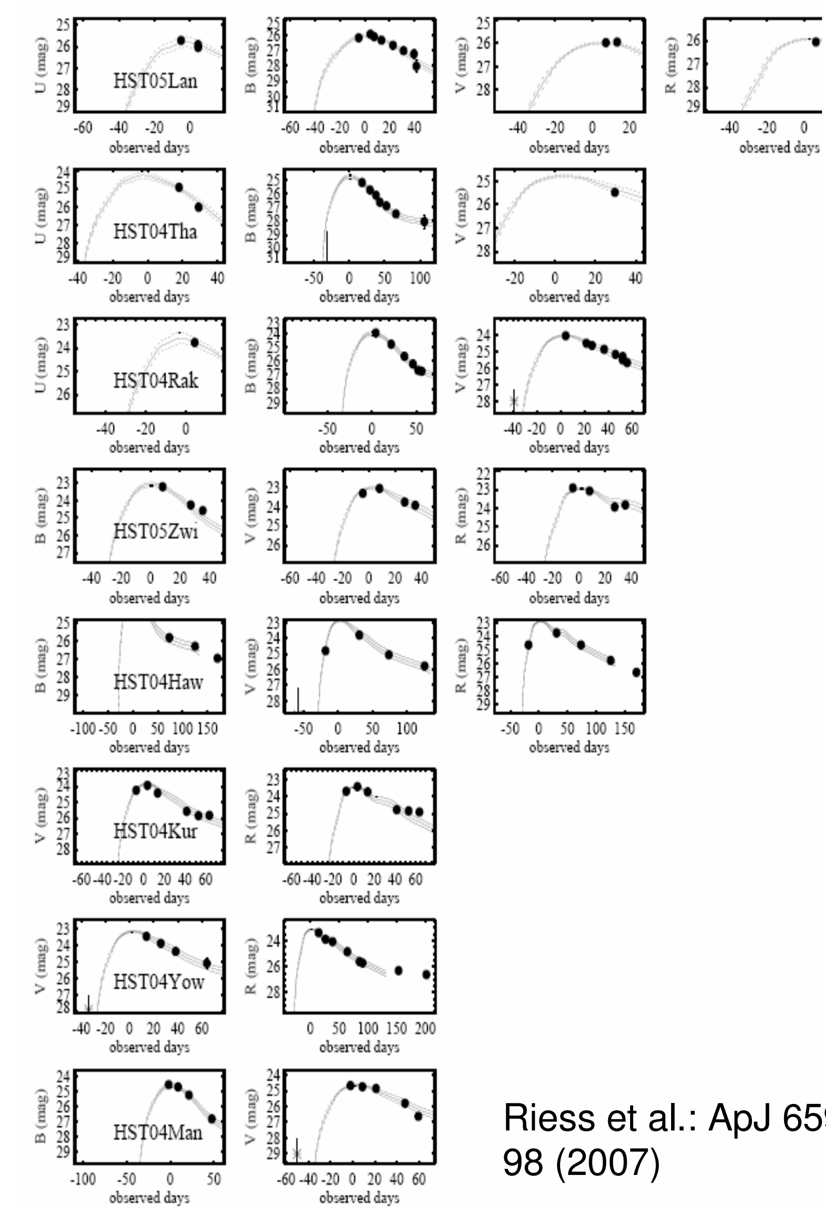
Systematic Uncertainties (1σ)	Magnitude	Statistical Uncertainties (1σ)	Magnitude
Photometric System Zero Point[a]	0.01	Zero Points, S/N	0.00*
Evolution	0.00*	K-corrections	0.00*
Evolution of Extinction Law	< 0.02	Extinction	0.00*
Gravitational Lensing	< 0.01	Light curve sampling	0.00*

[a] 0.00* means values of the order of 10^{-3}. The statistical errors are for the redshift bin.
[b] In the Table for prospects in a space mission, the statistical error from light curve sampling of SNe Ia is reduced due to the large number of SNe Ia data per redshift bin.

Ruiz-Lapuente: Class. Quantum Grav. R91 (2007)

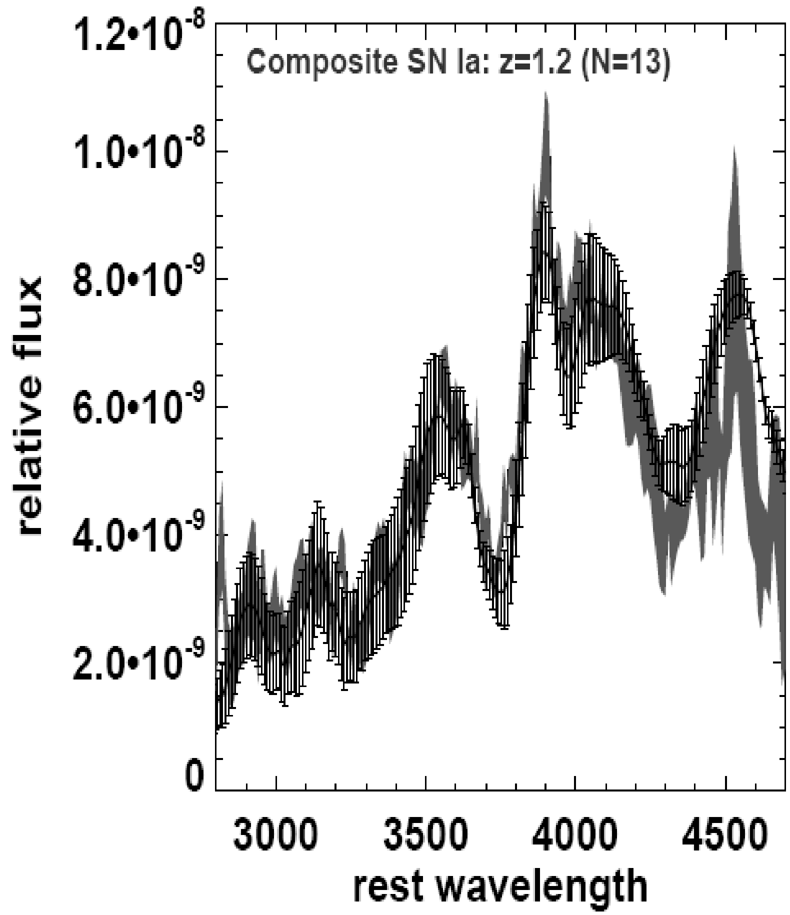
Gold Riess 2007 sample





Riess et al.: ApJ 659, 98 (2007)

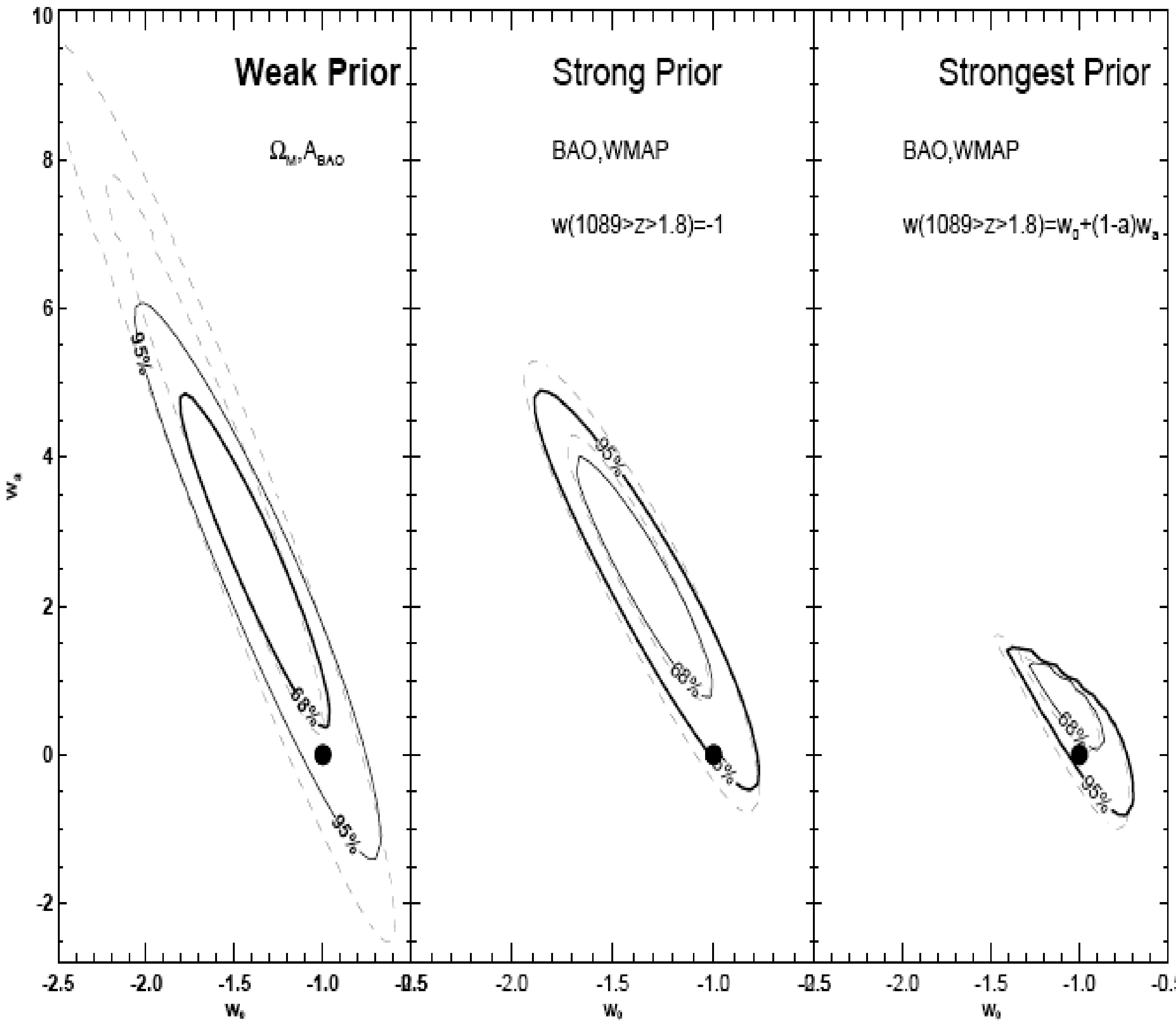
Composite spectrum



Riess et al.: ApJ 659, 98 (2007)

``Weak'' prior, ``Strong´´ prior

- ``Weak prior´´: No behavior in the range $1.8 < z < 1089$
- ``Strong prior´´: $w = -1$ at $z > 1.8$



Riess et al.: ApJ 659, 98 (2007)

w(z)

$$w(z) = w_0 + w_a z/(1+z)$$

$$w(z) = \sum_i^4 w_i(\ln(1+z))^i$$

Median in 4 z intervals

Riess et al.: ApJ 659, 98 (2007)

$$\mathcal{W}_i = \sum_j T_{ij} w_j$$

Principal Components Analysis

Riess et al.: ApJ 659, 98 (2007)

Table 5. Likelihood Regions For $\mathcal{W}_z$

w_z	peak	1 σ	2 σ
		Prior=Weak, Sample=All Gold	
$\mathcal{W}_{0.25}$	-1.05	-1.15 to -0.95	-1.26 to -0.85
$\mathcal{W}_{0.70}$	-0.45	-0.86 to -0.06	-1.49 to 0.32
$\mathcal{W}_{1.35}$	0.59	-2.62 to 3.03	-16.6 to 6.15
		Prior=Weak, Sample=Gold minus HST	
$\mathcal{W}_{0.25}$	-1.06	-1.16 to -0.95	-1.27 to -0.86
$\mathcal{W}_{0.70}$	0.11	-0.43 to 0.61	-1.17 to 1.17
$\mathcal{W}_{1.35}$	10.77	1.86 to 18.55	-20.1 to 27.92
		Prior=Strong, Sample=All Gold	
$\mathcal{W}_{0.25}$	-1.02	-1.12 to -0.93	-1.23 to -0.84
$\mathcal{W}_{0.70}$	-0.15	-0.57 to 0.131	-1.05 to 0.46
$\mathcal{W}_{1.35}$	-0.76	-1.78 to -0.16	-15.8 to 0.51
		Prior=Strong, Sample=Gold minus HST	
$\mathcal{W}_{0.25}$	-1.03	-1.14 to -0.94	-1.25 to -0.85
$\mathcal{W}_{0.70}$	0.151	-0.26 to 0.61	-0.80 to 1.00
$\mathcal{W}_{1.35}$	-1.95	-5.89 to -0.70	-17.8 to 0.35
		Prior=Strongest, Sample=All Gold	
$\mathcal{W}_{0.25}$	-1.02	-1.11 to -0.92	-1.21 to -0.83
$\mathcal{W}_{0.70}$	-0.13	-0.47 to 0.17	-0.88 to 0.48
$\mathcal{W}_{1.35}$	-0.85	-1.81 to -0.46	-17.0 to -0.30
		Prior=Strongest, Sample=Gold minus HST	
$\mathcal{W}_{0.25}$	-1.03	-1.13 to -0.94	-1.24 to -0.85
$\mathcal{W}_{0.70}$	0.24	-0.17 to 0.64	-0.70 to 1.06
$\mathcal{W}_{1.35}$	-1.89	-5.50 to -0.80	-18.0 to -0.34
		Prior=Strong, Sample=All Gold with MLCS2k2 Fits to SNLS SNe	
$\mathcal{W}_{0.25}$	-1.05	-1.14 to -0.94	-1.26 to -0.84
$\mathcal{W}_{0.70}$	-0.09	-0.45 to 0.23	-0.91 to 0.56
$\mathcal{W}_{1.35}$	-1.01	-2.23 to -0.26	-15.8 to 0.37

Riess et al.: ApJ 659, 98 2007

Supernova samples

Samples unified by

Riess et al.: ApJ 659, 98, 2007

Wood-Vasey et al.: ApJ 294 2007

Kowalski et al. 2008

Posible Tests of Dark Energy Models

With this enlarged that set it is possible to test several dark energy ideas

Extra dimensions

The expansión law departs from the usual Friedmann law (Deffayet, Dvali & Gavadadze: Phys. Rev. D 65, 044023, 2002). The 5-dimensional term in the Einstein-Hilbert action dominates over the 4-dimensional terms at large distances and gravity becomes weaker. The Hubble law is of the type:

$$H^2(z) = H_0^2 \left\{ \Omega_k (1+z)^2 + \left(\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \sum_\alpha \Omega_\alpha (1+z)^{3(1+w_\alpha)}} \right)^2 \right\}$$

with

$$\Omega_\alpha \equiv \frac{\rho_\alpha^0}{3{M_{\rm Pl}}^2 H_0^2 a_0^{3(1+w_\alpha)}} \qquad \Omega_{r_c} \equiv \frac{1}{4 r_c^2 H_0^2}$$

For a flat Universe, $\Omega_{rc} < 1$

Effective action at low energy in a model with an extra spatial dimension

$$S = \frac{M_{\rm Pl}^2}{r_c} \int d^4x\, dy \sqrt{g^{(5)}}\, \mathcal{R} + \int d^4x \sqrt{g}\, \left(M_{\rm Pl}^2 R + \mathcal{L}_{\rm SM} \right)$$

M_{Pl}^2 = 1/8πG; $g_{AB}^{(5)}$ is the 5D metric

y the addtional space coordinate

r_c crossover radius. Gravity behaves 5D beyond this crossover radius

The induced metric in the brane is:

$$g_{\mu\nu}(x) \equiv g_{\mu\nu}^{(5)}(x, y = 0)$$

There are accelerated solutions obtained for the 4-dimensional matter source $\boldsymbol{T_{\mu\nu}}$

$$\frac{1}{r_c}\mathcal{G}_{AB} + \delta(y)\, \delta_A^\mu \delta_B^\nu \left(G_{\mu\nu} - 8\pi G\, T_{\mu\nu} \right) = 0$$

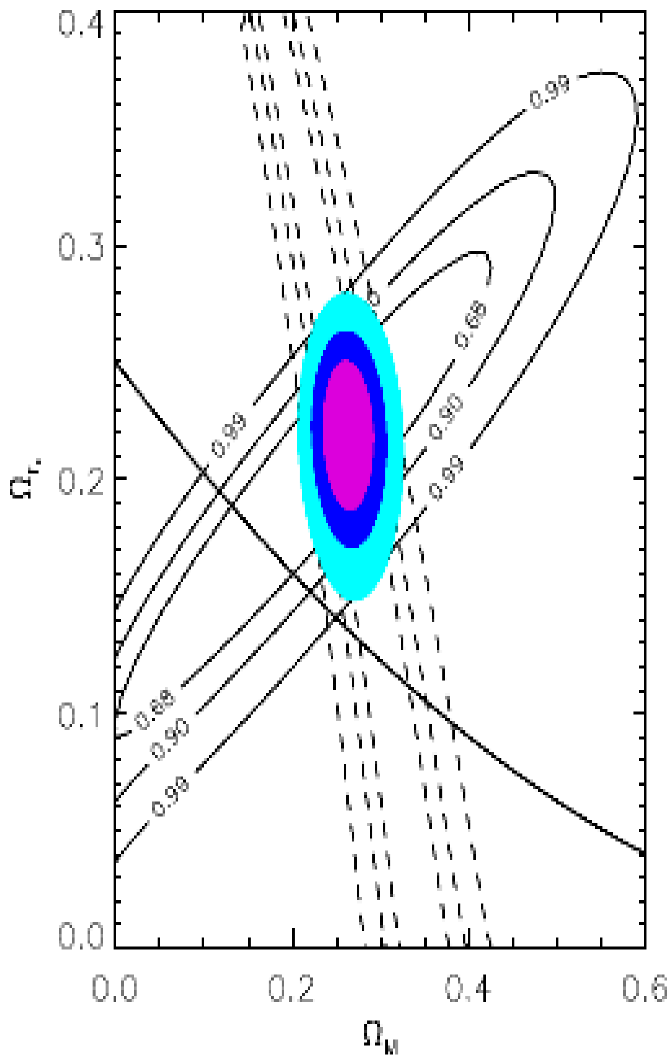
$$ds_5^2 = f(y, H) ds_4^2 - dy^2 \qquad \text{(ds FRW-like)}$$

The modified Friedmann equation

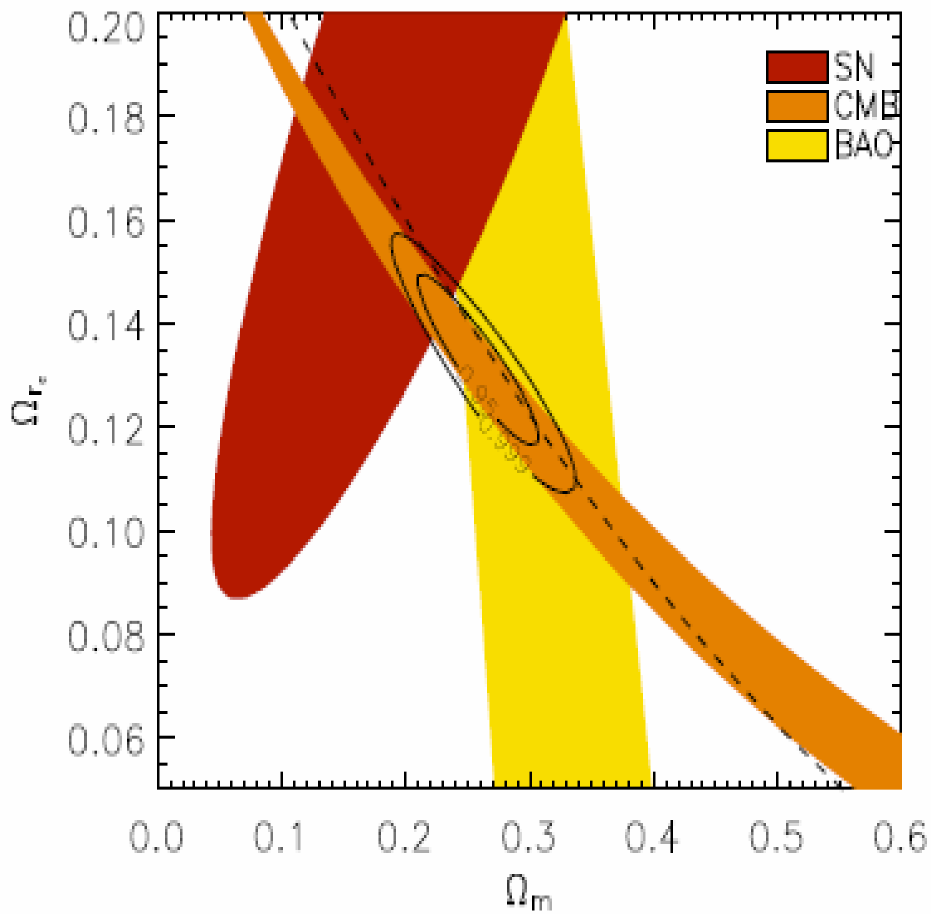
$$H^2 \pm \frac{H}{r_c} = \frac{8\pi G \rho_M}{3}$$

DGP model

Confidence regions 68, 90 , 99%, in the plane $\Omega_M - \Omega_{rc}$. BAO+ SNLS. Bold line is the flat Universe in this diagram. Is the DGP model incompatible with a flat Universe?



Fairbairn & Goobar: Phys. Lett. B 642, 432 (2005)



Davis et al.: ApJ 666, 716 (2007)

Other extra dimensional models

The Hubble law arising from gravity with extra dimensions can be expressed by adding H^α terms to the standard Friedmann equation:

$$H^2 - \frac{H^\alpha}{r_c^{2-\alpha}} = \frac{8\pi G \rho_M}{3}$$

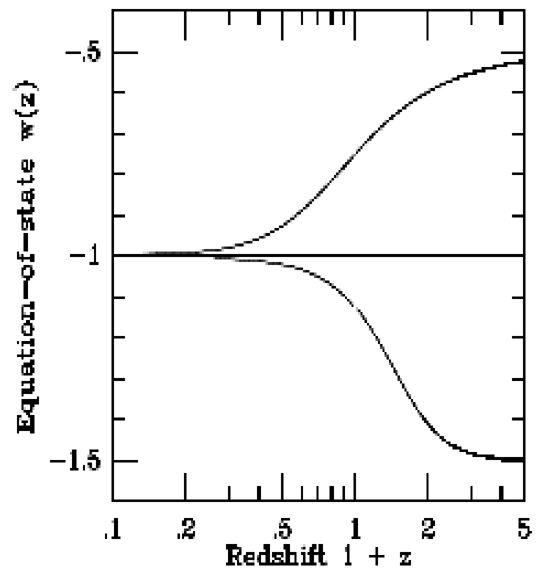
where r_c is the crossover radius, i.e. the transition radius from a regime to another in the gravity law, and α is the parameter to be empirically determined. From redshift $z = 0$ to $z = 2$, this Friedmann equation gives an effective index of the equation of state:

$$w_{\text{eff}} \approx -1 + 0.3\alpha$$

Dvali & Turner: astro-ph/0301510 (2003)

such effective equation of state evolves too fast to be compatible with current SNeIa data, unless α is small. Present data favor α close to 0.

Durrer: hep-th/0507066 (2005)



Dvali and Turner
approach

$$w_{\text{eff}} = -1 + \frac{\alpha}{2}$$

$$w_{\text{eff}} \approx -1 + 0.3\alpha$$

Dvali & Turner: astro-ph/0301510
(2003)

Scalar-tensor theories

We aim at retrieving the self-interaction potential of the scalar *V(Φ)* and the coupling function to matter and gravity *A(Φ)* in the matter term of the action:

$$S_{\mathrm{matter}}(\psi, A^2(\phi) g_{\mu\nu})$$

We expand *A(Φ)* in its derivatives α_0, β_0 and higher orders:

$$\ln A(\phi) \equiv \alpha_0(\phi - \phi_0) + \frac{1}{2}\beta_0(\phi - \phi_0)^2 + \mathcal{O}(\phi - \phi_0)^3$$

Solar system tests + binary pulsar tests give precise bounds to the first and second derivatives, while SNeIa should, in principle, allow to reconstruct the full shape of *A(Φ)*. Knowledge of the luminosity distance and the density fluctuations $\delta\rho/\rho$ as functions of *z* are sufficient to reconstruct the potential *V(Φ)* and the coupling function *A(Φ)*

Barrow & Cotsakis: Phys. Lett. B 214, 515 (1988)
Barrow & Maeda: Nucl. Phys. B 341, 290 (1990)
Amendola: MNRAS 312. 521 (2000)
Esposito-Farese & Polarski: Phys. Rev. D 63, 063504 (2001)
Esposito-Farese: gr-qc/0409081 (2004)

Identify the scalar

The scalar field responsible for dark energy can be identified by recovering its potential or, equivalently, its effective equation of state.The presence of a scalar field *Φ* would induce an action:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$$

The field contributes to the stress-energy momentum tensor with effective mass density and pressure:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

The effective value of the equation of state parameter depends on the form of the potential and it can evolve with time

$$w_{\rm eff} = \frac{p_\phi}{\rho_\phi}$$

Weiler & Albrecht: Phys. Rev. D 86, 1939 (2001)

Dark energy scalar field

Then the effective value of the equation of state parameter w_{eff} depends on te form of the potential $V(\Phi)$ and it can evolve with time

$$w_{\text{eff}} = \frac{p_\phi}{\rho_\phi}$$

A search for general properties of this potential leads, in analogy with the inflation potential, to suggest potentials with tracking behaviour. Different forms of the potential have been proposed from the original $V = \kappa/\phi^\alpha$

Ratra & Peebles: : Phys. Rev D 37, 3406 (1988)

Wetterich: Nucl. Phys. B 302, 668 (1988)

Steinhardt et al.: Phys. Rev. D 59, 123504 (1999)

Peebles & Ratra: Rev. Mod. Phys. 75, 559 (2003)

Copeland et al.: Int. J. Mod. Phys. B 15, 1753 (2006)

Reconstruction of the dark energy scalar-field potential

Techniques for reconstructing the scalar-field potential from SN distances.

The comoving radial distance (Cooray et al. 2007)

$$r(z) = \int_0^z dz'/H(z')$$

Can be expanded as a simple power-law:

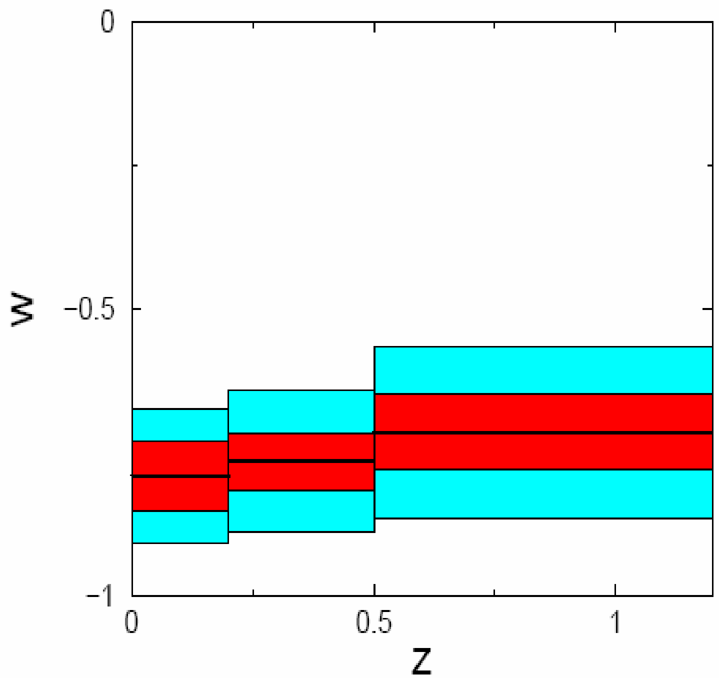
$$r(z) = z + a_2 z^2 + a_3 z^3 + a_4 z^4$$

Given the problems encountered when estimating the derivatives of *r(z)*, a Padé form can also be considered:

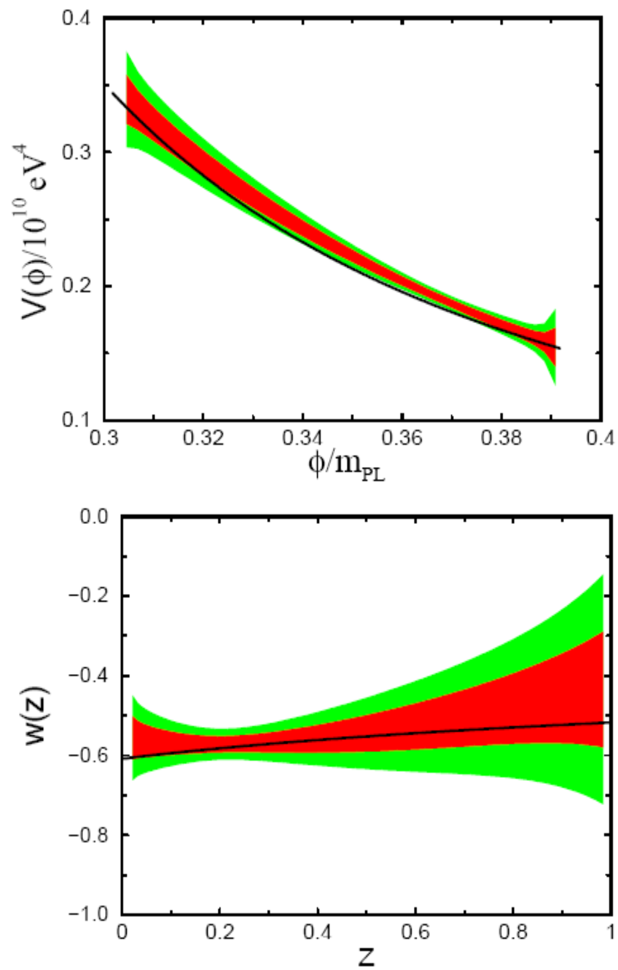
$$r(z) = 2\frac{z + c_1(1-\sqrt{1+z})}{c_2(1+z) + c_3\sqrt{1+z} + 2 - c_1 - c_2 - c_3}$$

such that as $z \to 0$, $r(z) \to z$. In this form, using $r(z \to \infty)$, one can additionally constrain the parameters with:

Reconstruction of the dark energy scalar-field potential



w(z) parameterized by constant values in redshift bins



Confidence regions based on Monte Carlo simulations of 2000 SNeIa with individual uncertainties of 0.15 mag

Huterer & Turner: Phys. Rev. D 71, 123527 (2001)

Reconstruction of the dark energy scalar-field potential

$$3\Omega_M \leq \frac{4c_2 + 2c_3 - c_1}{2 - c_1}$$

$$1 \leq \frac{1}{c_2} \leq \frac{1}{2}\int_1^{\infty} \frac{dx}{\sqrt{1 - \Omega_M + \Omega_M x^3}}$$

In addition to the two fitting forms for *r(z)*, it can be also determined through model parameterizations of *w(z)*, that including

$$w(z) = w_0 + (1 - a) w_a$$

and

$$w(z) = w_0 + \alpha \ln(1 + z)$$

In each of the two parametric descriptions of *r(z)* there are three free parameters. As for *w(z)*, there are two parameters plus Ω_M (assuming a flat universe). A prior on Ω_M is taken. In each case, to obtain the joint likelihood distribution of the parameters, given the data, a likelihood analysis is performed:

$$\chi^2(p_i) = \sum_{i=1}^{N} \frac{[\mu - \mu_B(z_i)]^2}{\sigma_{\mu_B}^2 + \sigma_{\rm int}^2}$$

Reconstruction of the dark energy scalar-field potential

For each of the distance curves $r_i(z)$, the scalar-field potential is obtained, in dimensionless units such that

$$\tilde{V}(\tilde{\phi}) = V(\phi)/\rho_{\rm crit} = V/(3H_0^2/8\pi G)$$

through

$$\tilde{V}(\tilde{\phi}) = \left[\frac{1}{(d\tilde{r}/dz)^2} + \frac{1+z}{3}\frac{d^2\tilde{r}/dz^2}{(d\tilde{r}/dz)^3}\right] - \frac{1}{2}\Omega_M(1+z)^3$$

where $\tilde{r} = H_0 r$ The mapping between z and Φ is given by:

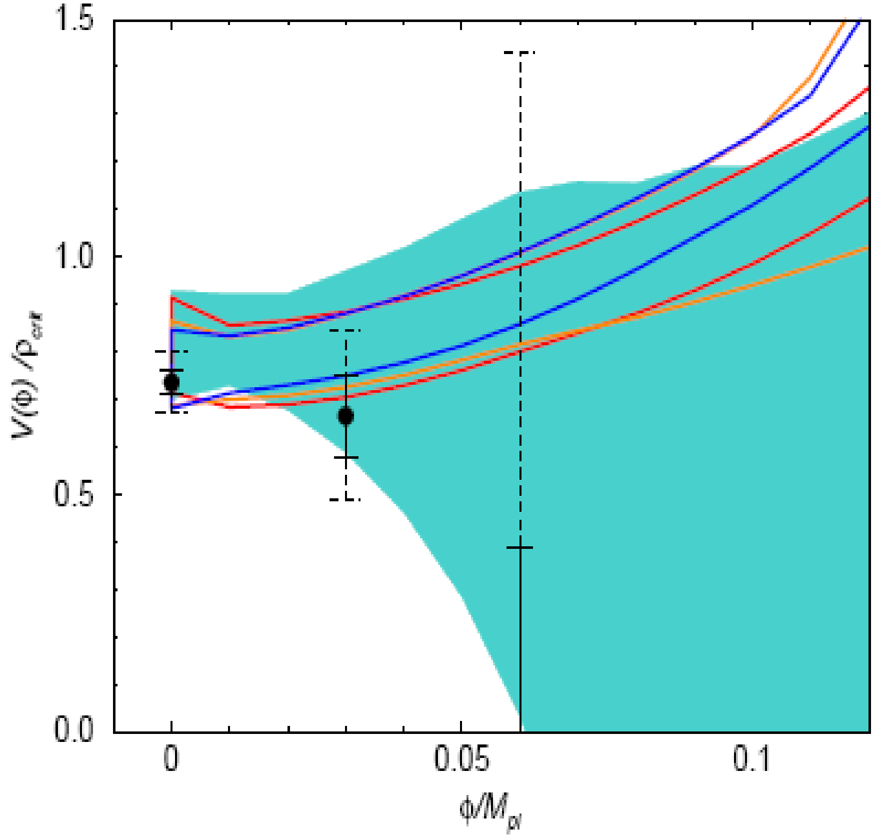
$$\frac{d\tilde{\phi}}{dz} = -\frac{d\tilde{r}/dz}{(1+z)} \times \left[-\frac{1}{4\pi}\frac{(1+z)d^2\tilde{r}/dz^2}{(d\tilde{r}/dz)^3} - \frac{3}{8\pi}\Omega_M(1+z)^3\right]^{1/2}$$

where $\tilde{\phi} = \phi/m_{\rm Pl}$ For models with the $r(z)$ parameterization:

$$w(z) = \frac{1+z}{3}\frac{3\Omega_m(1+z)^2 + 2(d^2r_i/dz^2)/(dr_i/dz)^3}{\Omega_m(1+z)^3 - (dr_i/dz)^{-2}} - 1$$

Reconstruction of the dark energy scalar-field potential

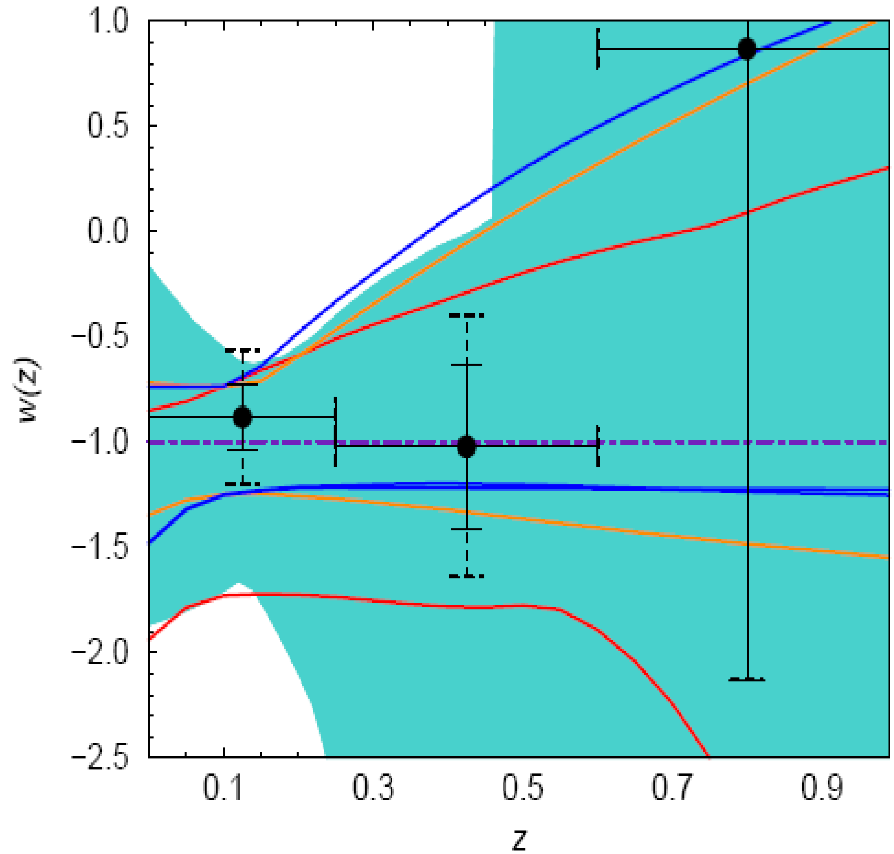
Potential reconstruction by all four different methods



Li, Holz & Cooray: Phys. Rev. D 75, 103503 (2007)

Reconstruction of the dark energy scalar-field potential

Reconstruction of the dark energy EOS



Li, Holz & Cooray: Phys. Rev. D 75, 103503 (2007)

Reconstruction of the dark energy scalar-field potential

Model-free estimates: binning *w(z)* in redshift

Potential as a function of the field, with constant gradients over binned intervals:

$$V(\phi) = V_0 + \sum_{i=1}^{N-1} (dV/d\phi)_i \Delta\phi + (\phi - (N-1)\Delta\phi)(dV/d\phi)_N$$

Earlier approach by Huterer & Turner: Phys Rev. D 71, 123527 (2001)

Other approaches: España-Bonet & Ruiz-Lapuente: hep-ph/0503210 (2005)

Extended curvature gravity

Actions with inverse functions of *R* :

$$S = \int d^4x \sqrt{-g}\,[R + f(R,P,Q)] + \int d^4x \sqrt{-g}\,\mathcal{L}_{\mathcal{M}}$$

where

$$f(R,P,Q) = \frac{\mu^{4n+2}}{(aR^2 + bP + cQ)^n}$$

and

$$P \equiv R_{\mu\nu}R^{\mu\nu}\ , \qquad Q \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

Chiba: Phys. Lett. B 575, 1 (2003)

Starobinsky: JETP Lett. 86, 157 (2007)

Action including a Gauss-Bonnet term R_{GB}

The Gauss-Bonnet term can be found in the effective low-energy string Lagrangian and in brane theories. The case of the simplest action containing the Gauss-Bonnet term can be written as:

$$S = \frac{1}{4\pi}\int \sqrt{-g}\left\{\frac{R}{4} - \frac{1}{2}(\partial_\mu \phi)^2\right\} - \int \sqrt{-g}\,W(\phi)(R^2_{\mu\nu\rho\sigma} - 4R^2_{\mu\nu} + R^2)$$
$$+ S_{\mathrm{matter}}[\mathrm{matter}\,;\, g_{\mu\nu}]$$

This Lagrangian includes the Gauss-Bonnet term coupled to a field $\Phi \equiv \sigma$, for instance the modulus field in Antoniadis et al. (1994), where $W(\sigma)$ is the coupling of the modulus field to the Gauss-Bonnet term R_{GB}:

$$R^2_{GB} \equiv R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$

For an action which includes the GB term, one can have an equation of state with $w_{\mathrm{eff}} < -1$ for a canonical scalar field (positive kinetic energy), avoiding the Big Rip

Langlois: Int. J. Mod Phys. A 1, 2701 (2004)

Antoniadis et al.: Nucl. Phys. B 415, 497 (1994)

Nojiri et al.: Phys. Rev. D 71, 123509 (2005)

Light Curve Fitting Methods

The distance moduli obtained by the various collaborations are calculated in slightly different ways. The *SCP* used

$$\mu_B = m_B - M + \alpha(s-1)$$

The method

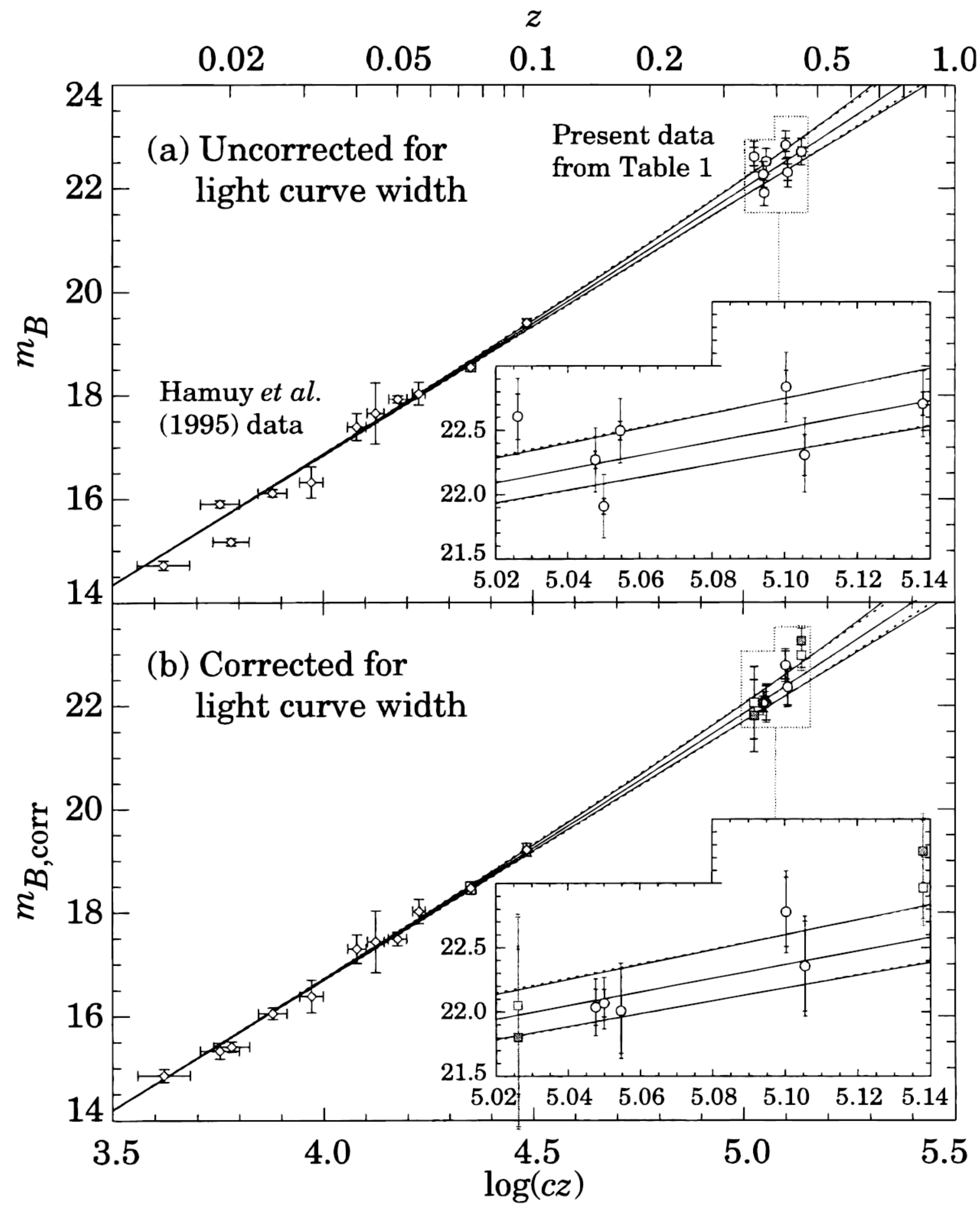
$$m_{eff} = m_B + \alpha(s-1) - A_B$$

The *SNLS* decided to introduce a color correction to the distance moduli

$$\mu_B = m_B - M + \alpha(s-1) - \beta c$$

The β parameter enters as a variable.

We take $A_B = R_B E(B-V)$ with $R_B = 4.1$ and $E(B-V)$ measured from the excess in the Phillips-Lira way compared with the standard excess for a given SN with stretch s



z
0.02
0.05
0.1
0.2
0.5
1.0
(a) Uncorrected for light curve width
Present data from Table 1
Hamuy et al. (1995) data
m_B
(b) Corrected for light curve width
$m_{B,corr}$
log(cz)

Stretch

Calibrated candles through the relation magnitude- rate of decline

Pskvoskii-Branch effect (known in the 80's)

Phillips: ApJ 413, L105 (1993)

Δm_{15}

Riess, Press and Kirshner: ApJ 438, L17 (1995)

MLCS

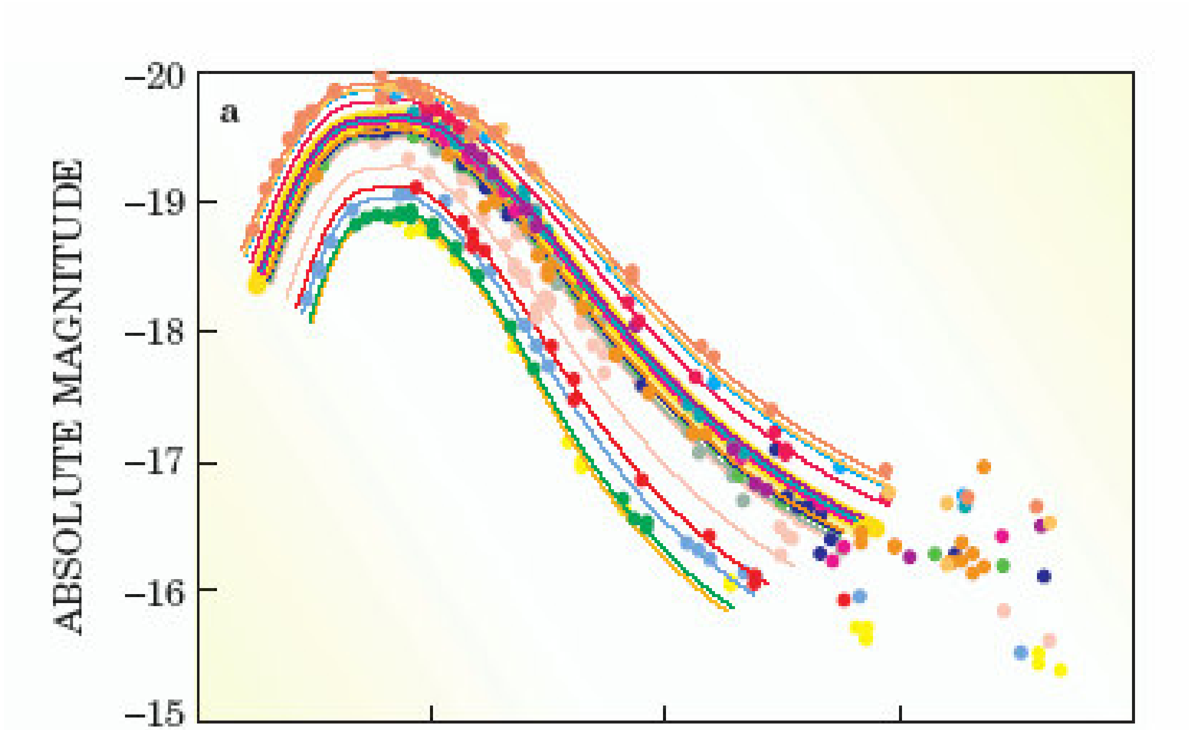
Perlmutter et al.: ApJ 483, 565 (1997):

stretch s

σ≈0.15 mag

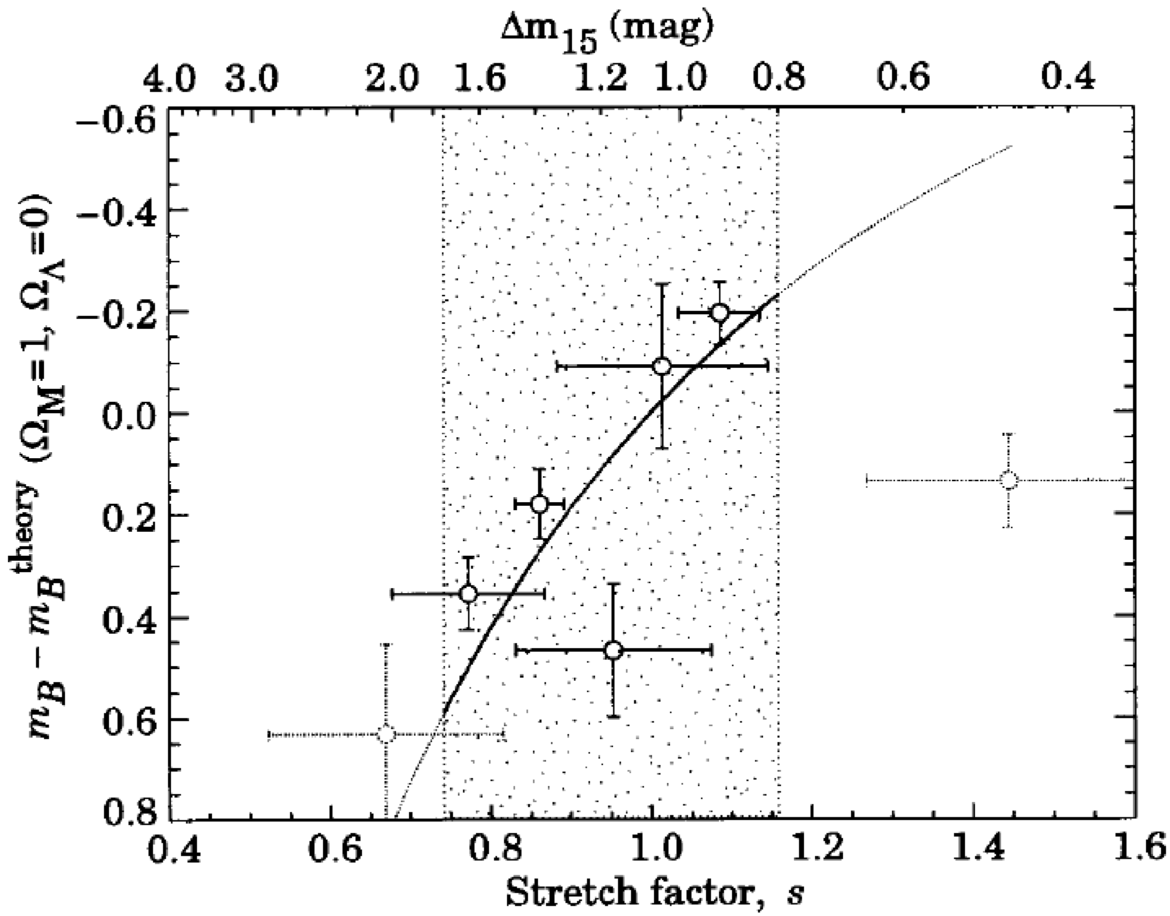
With color information

σ≈0.11 mag



Relation stretch and other methods

Most recent exploration by Jha et al. (2006)



Jha et al.: AJ 531, 527 (2006)

The *K*-corrections

Comparing objects with significant redshifts with nearby counterparts, it is necessary to account for the effect of wavelength shift of light on the luminosity distances. That is known as the *K-correction.* The *K*-correction K_i is defined such that an object of magnitude m_i in filter *i* as a function of redshift *z* is

$$m_i(z) = m_i(z = 0) + K_i(z)$$

An object with spectrum *F(λ)* observed with a filter with sensitivity function $S_i(\lambda)$ has

$$m_i(z = 0) = -2.5 \log \frac{\int S_i(\lambda) F(\lambda)\, d\lambda}{\int S_i(\lambda)\, d\lambda} + \mathscr{Z}_i$$

where $\mathscr{Z}_i$ is the zero point of the filter. It has been demonstrated that

$$K_i = 2.5 \log \left\{ (1 + z) \frac{\int F(\lambda) S_i(\lambda)\, d\lambda}{\int F[\lambda/(1 + z)] S_i(\lambda)\, d\lambda} \right\}$$

where K_i accounts for the (1 + *z*) shift of the photons in wavelength and the (1 + *z*) increase in the unit *dλ* they occupy

K-correction

The *K*-correction, which is necessary to calculate the apparent magnitude in a y filter band of a source observed in a x filter band at redshift z is given by

$$K_{xy} = 2.5log(1+z) + 2.5log\left(\frac{\int F(\lambda)S_x(\lambda)d\lambda}{\int F(\lambda/(1+z))S_y(\lambda)d\lambda}\right) + Z_y - Z_x$$

where $F(\lambda)$ is the source spectral energy distribution, and $S_x(\lambda)$ is the transmission of the filter x. The $Z_i - Z_x$ term accounts for the difference in zero points of the filters.
$K_{g'g'}$, $K_{r'r'}$, $K_{ii'}$ and $K_{g'B}$ have been computed for each SN, at the corresponding redshift, by means of Nugent's spectral templates. For a more accurate correction we recalibrated Nugent's templates, warping them in order to reproduce Hamuy's light curve template with $\Delta m_{15}(B)$ = 0.87, 0.94, 1.11, 1.47 and we computed the *K*-correction adopting the templates corresponding to the $\Delta m_{15}(B)$ closest to the value measured in a preliminary fit of the data. Since Hamuy's light curve templates are normalized to zero, they have previously been rescaled using the relation given by Phillips *et al.:* AJ 118, 1766 (1999):

$$B_{max} - V_{max} = -0.07(\pm 0.012) + 0.114(\pm 0.037)[\Delta m_{15}(B) - 1.1]$$

$$V_{max} - I_{max} = -0.323(\pm 0.017) + 0.250(\pm 0.056)[\Delta m_{15}(B) - 1.1]$$

Extinction correction uncertainty

- The magnitude correction for extinction by dust in the host galaxies of the SNe is the single dominant source of both statistical and systematic error for SNe distances and the derived cosmological parameters
- Dramatically so at $z > 1$ even with *HST*
- Typical color uncertainties:

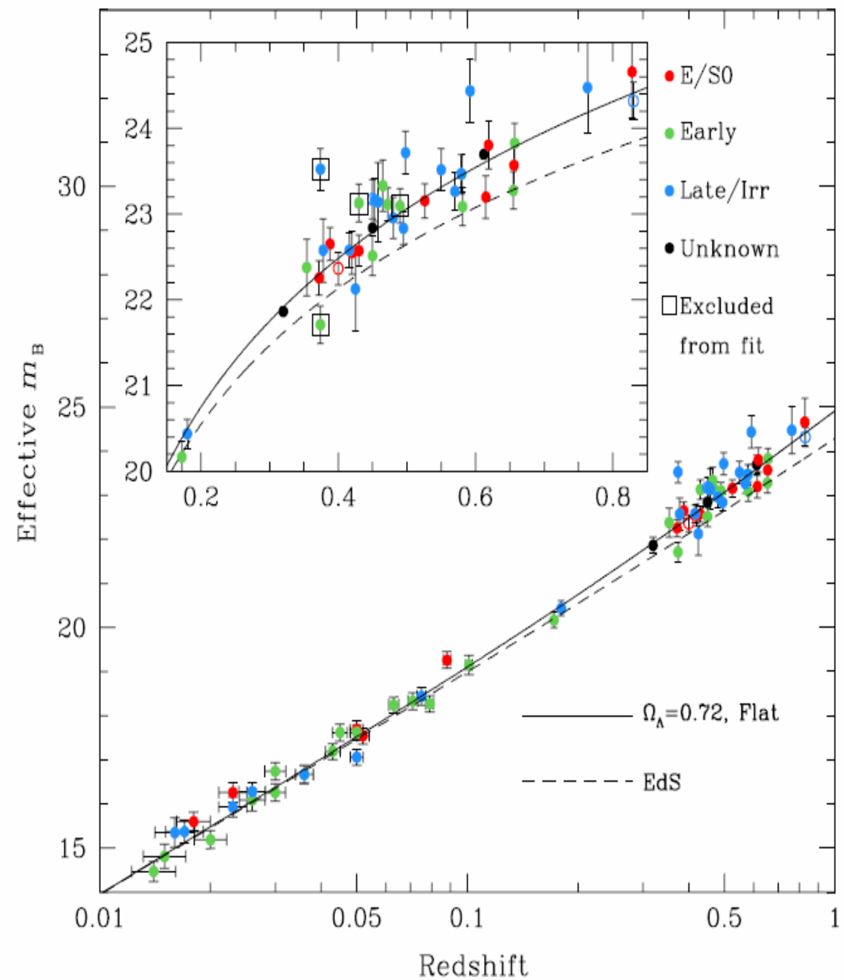
$$0.08 - 0.1 \text{ in } B - V \rightarrow \sigma > 0.4 \text{ mag in } EC$$

- Dispersion grows to $\sigma \approx 0.5$ when uncertainty on $R_B \equiv A_B/E(B-V)$ is taken into account ($R_B = 4.1 \pm 0.5$)
- That results in poor constraints on the dark energy equation of state parameter w and its time variation given by w_0 and w'
- The dispersion problem has been dealt with by applying a strong Bayesian prior to the distribution. Assumes knowledge of the dust and SN distribution in the $z > 1$ host galaxies. Being one-sided (no negative reddening), they introduce systematic biases when the error bars increase with z. Also, the mean value of R_B may drift from low to high z

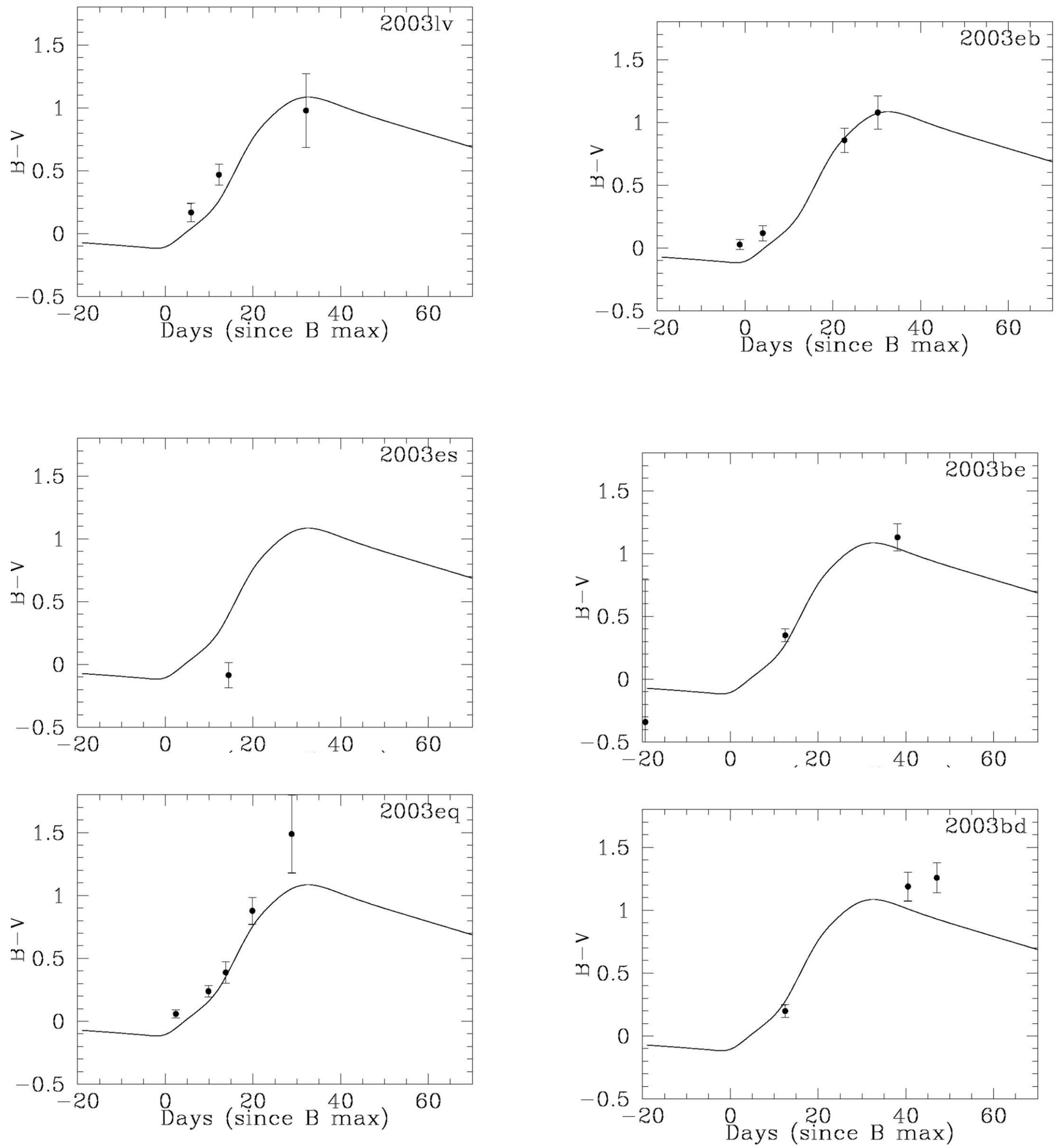
SNeIa: reducing systematics

Sullivan et al.: MNRAS 340, 10578 (2002) SCP

Dependencies of SN Ia properties on local environment disappear after stretch correction



Colors


2003lv
2003eb
2003es
2003be
2003eq
2003bd
B−V
Days (since B max)
1.5
1
0.5
0
−0.5
−20
0
20
40
60

Use of SNeIa in elliptical galaxies

- The dispersion about the Hubble diagram of for SNeIa in ellipticals is only $\sigma \approx 0.16$ mag (including ground-based measurement error). That is three times smaller than just the measurement uncertainty for extinction-corrected SNeIa at $z > 1$
- Due to the absence of dust
- Statistically each SNeIa is nine times worthier than a SNeIa in a spiral galaxy, and free of the systematics associated with extinction correction
- A sample of ~ 10 SNeIa at $z \geq 1$ in cluster elliptical host galaxies would yield the stronger constraints on w_0 *vs* w' without extinction prior systematics
- The $z = 0.9 – 1.6$ range provides key leverage on the cosmological model and especially on w'. Also, cluster potentials first begin responding to the acceleration due to dark energy

Dust in cluster ellipticals

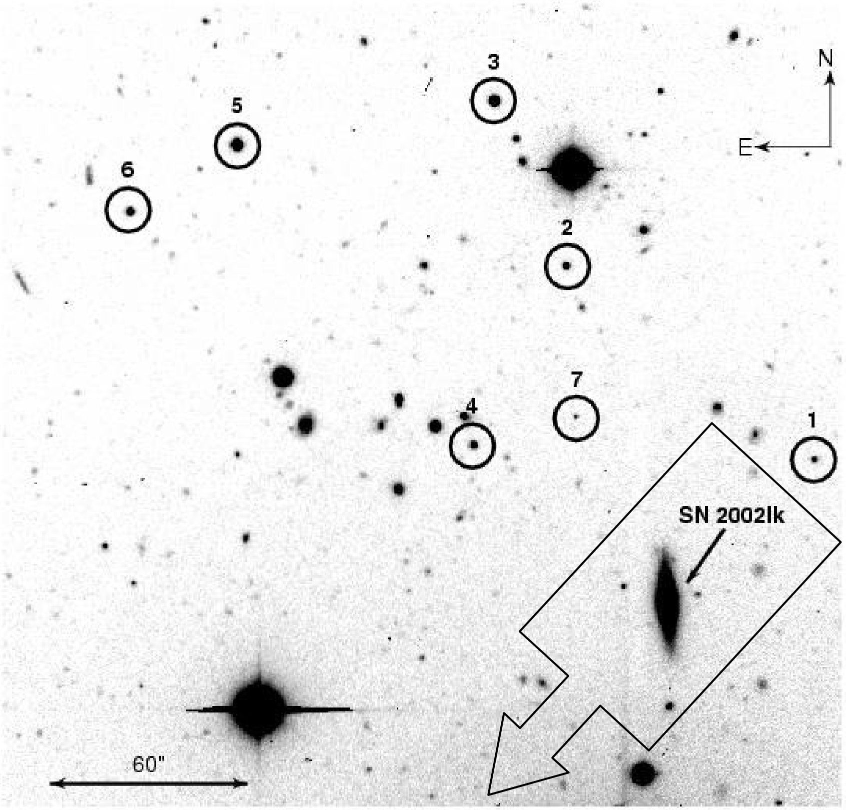
- How is it known that dust is not an issue in $z \geq 1$ cluster ellipticals?
- Although some dust is found in about half of nearby ellipticals, the quantity is generally very small and confined to a central disk with a very small cross-section
- Clearest evidence from the tightness of the color-magnitude relation, recently shown (Hogg *et al.: ApJ 624, 54,* 2005) to be universal for early type galaxies, both in clusters and in lower-density environments, based on huge sample from *SDSS*
- Recent results from *ACS* on *HST* show the same small dispersion in color extending to $z \geq 1$. Imaging at $z = 1.24$ finds intrinsic dispersion of $\sigma = 0.024 \pm 0.008$ mag for 30 ellipticals in rest-frame $U - B$. Since some intrinsic color variation due to that in the age and metallicity of stellar populations is likely, the dispersion due to dust should be smaller still
- Thus, the observed smaller scatter of SNeIa hosted in ellipticals at $z \sim 0.5$ to continue in $z \geq 1$ cluster ellipticals

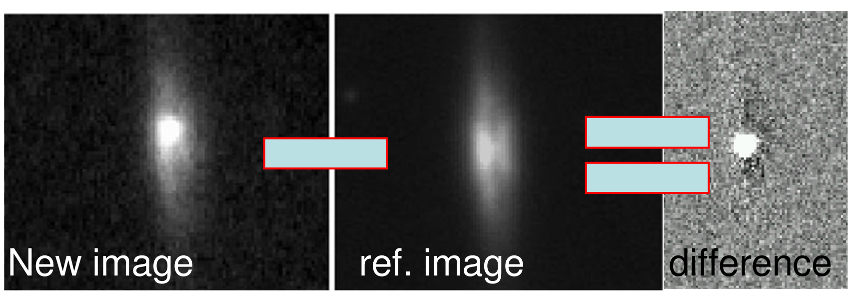
TESTING EVOLUTION

Intermediate z SNe Ia ITP 2002

PI: Ruiz-Lapuente

Supernovae a $0.07 \leq z \leq 0.327$

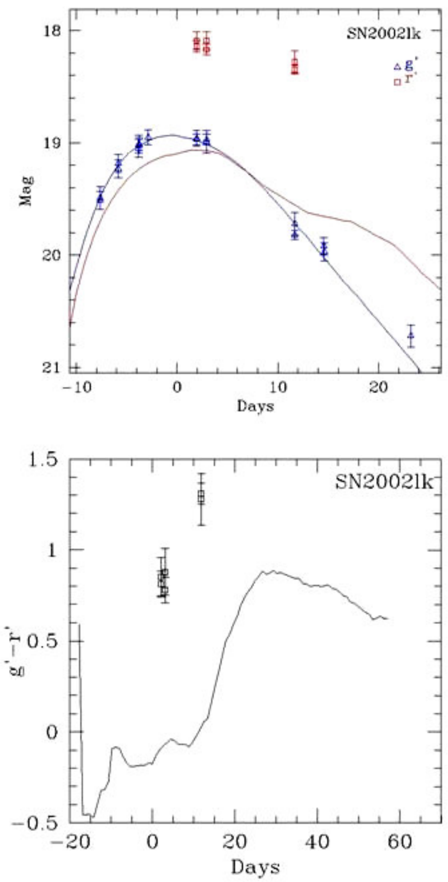




SN 2002lk.

ITP 2002

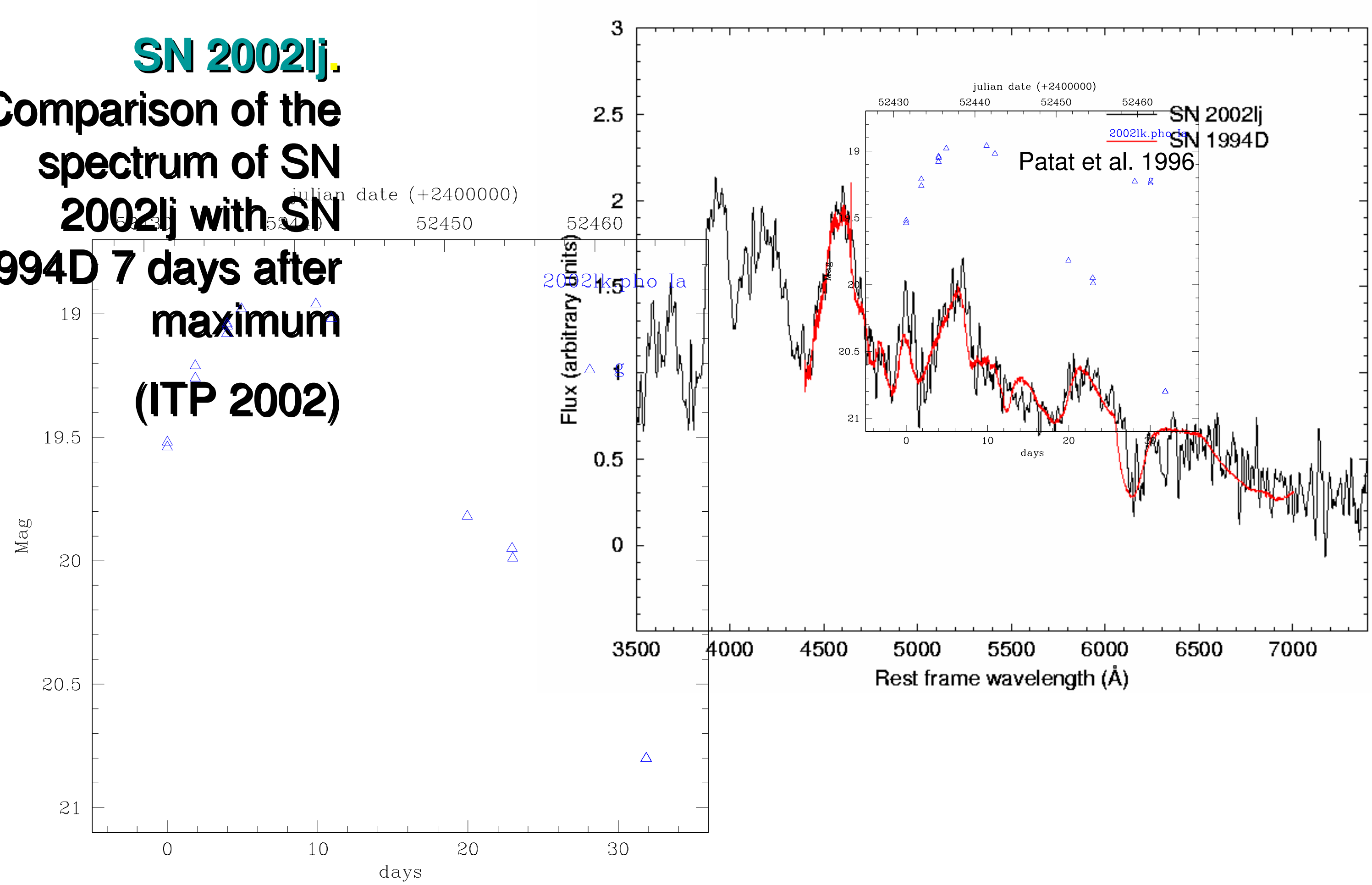
Ligt curve and color evolution of a SNeIa at intermediate *z*, obtained by the *European Supernova Cosmology Consortium* with *International Telescope Time* at ENO (2002)



ITP 2002

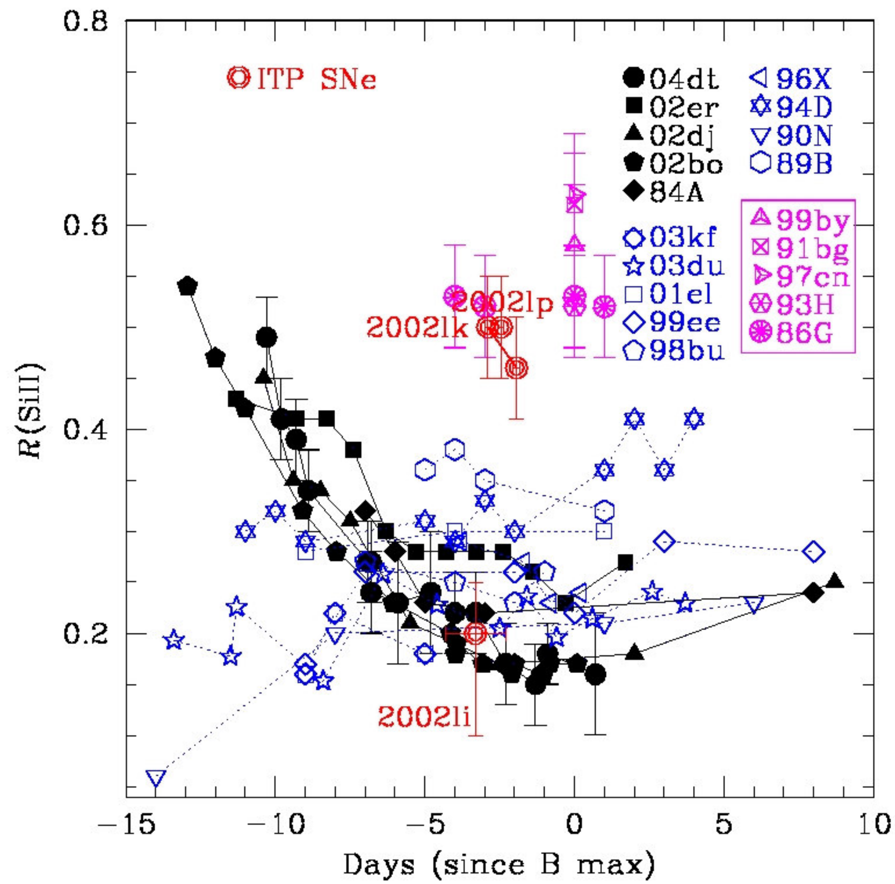
SN 2002lj. Comparison of the spectrum of SN 2002lj with SN 1994D 7 days after maximum

(ITP 2002)



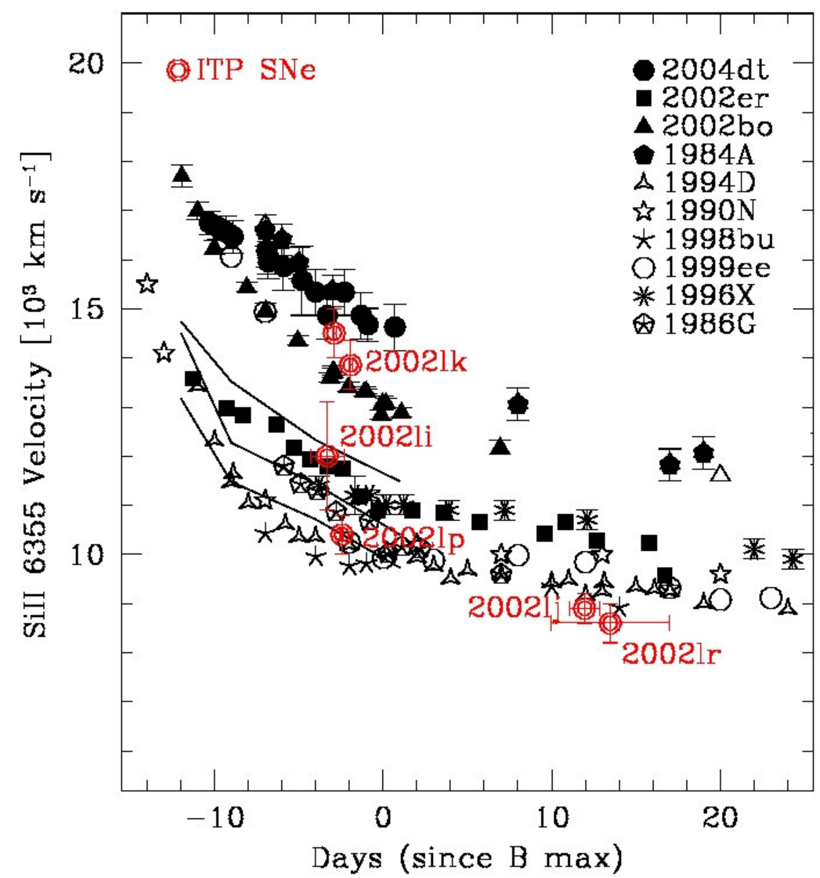
ITP 2002
(Altavilla, Ruiz-Lapuente, Balastegui, Mendez et al. 2006)

R(Si II) a key to the brightness and explosion mechanism
SNe Ia from ITP 2002 La Palma



The intermediate z sample

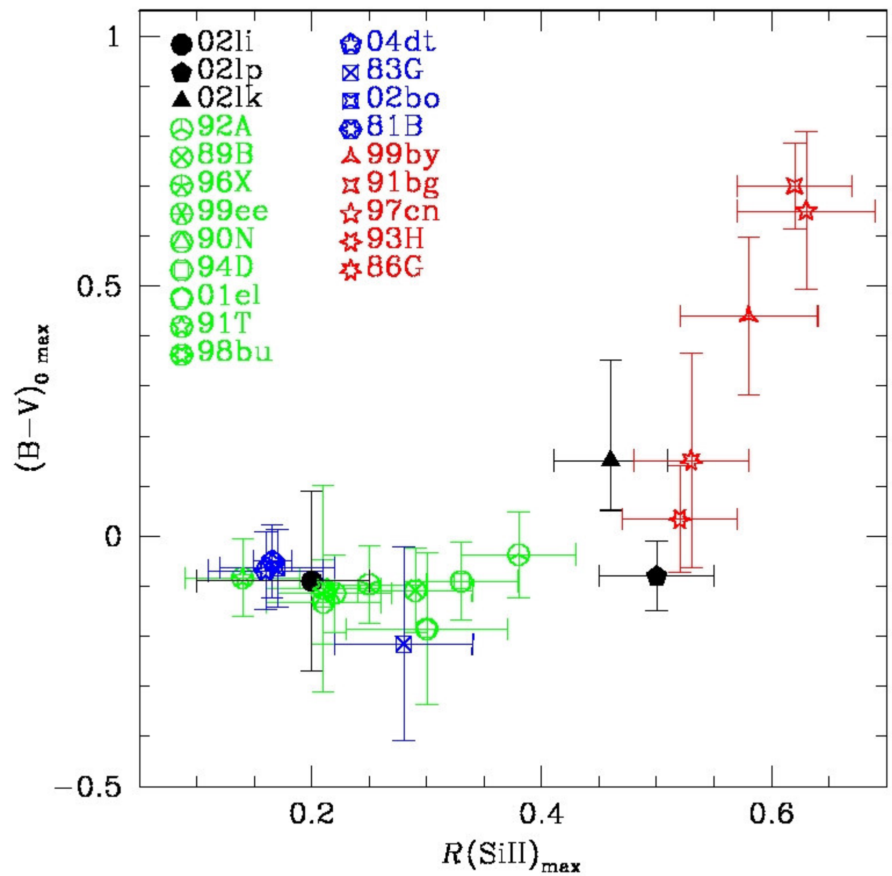
Expansion velocities are the same

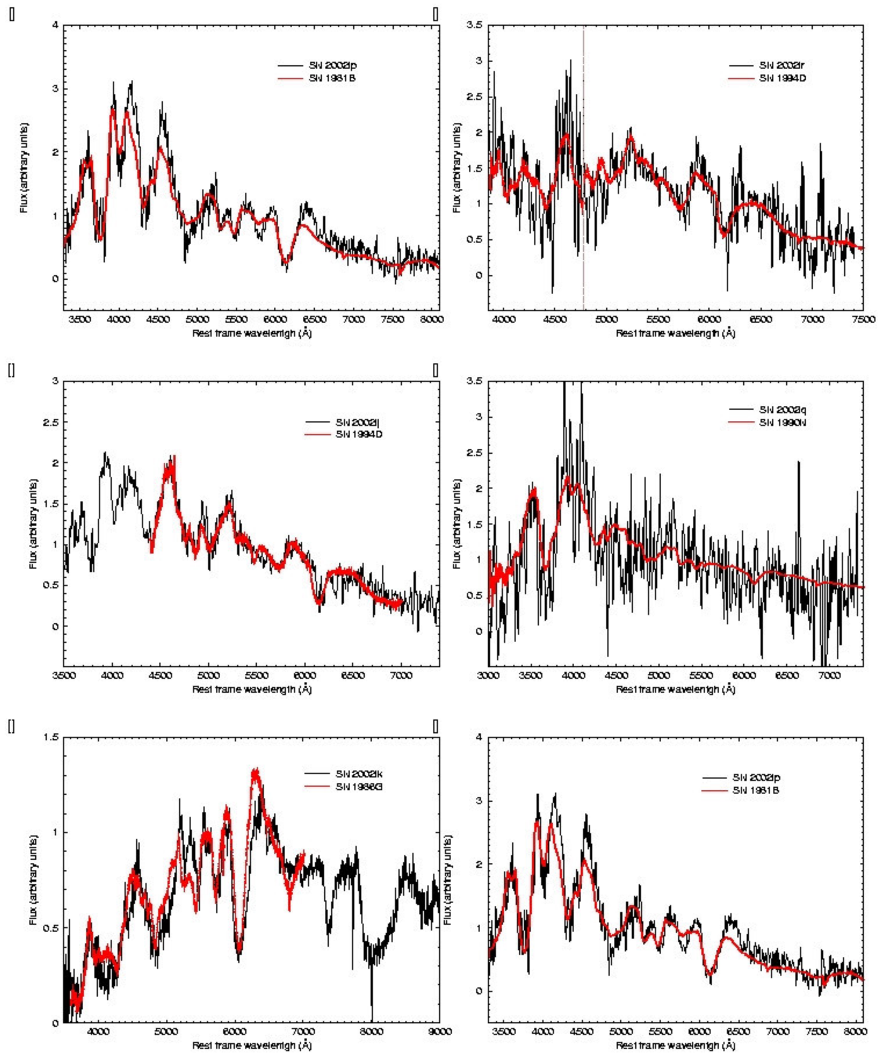


An idea to test intrinsic color versus reddening

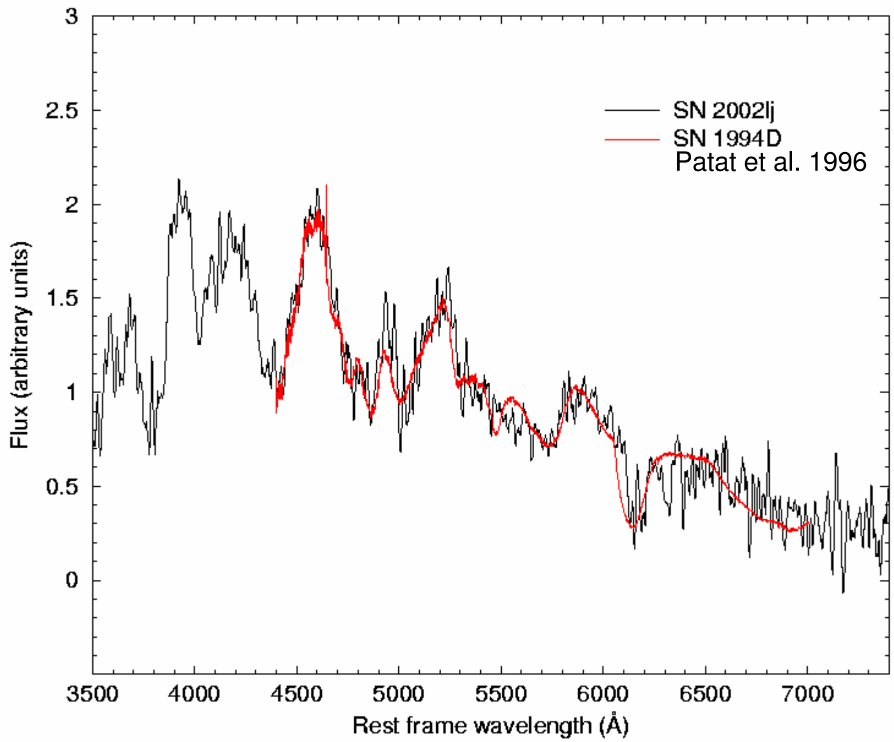
astro-ph/0610143 (2006)

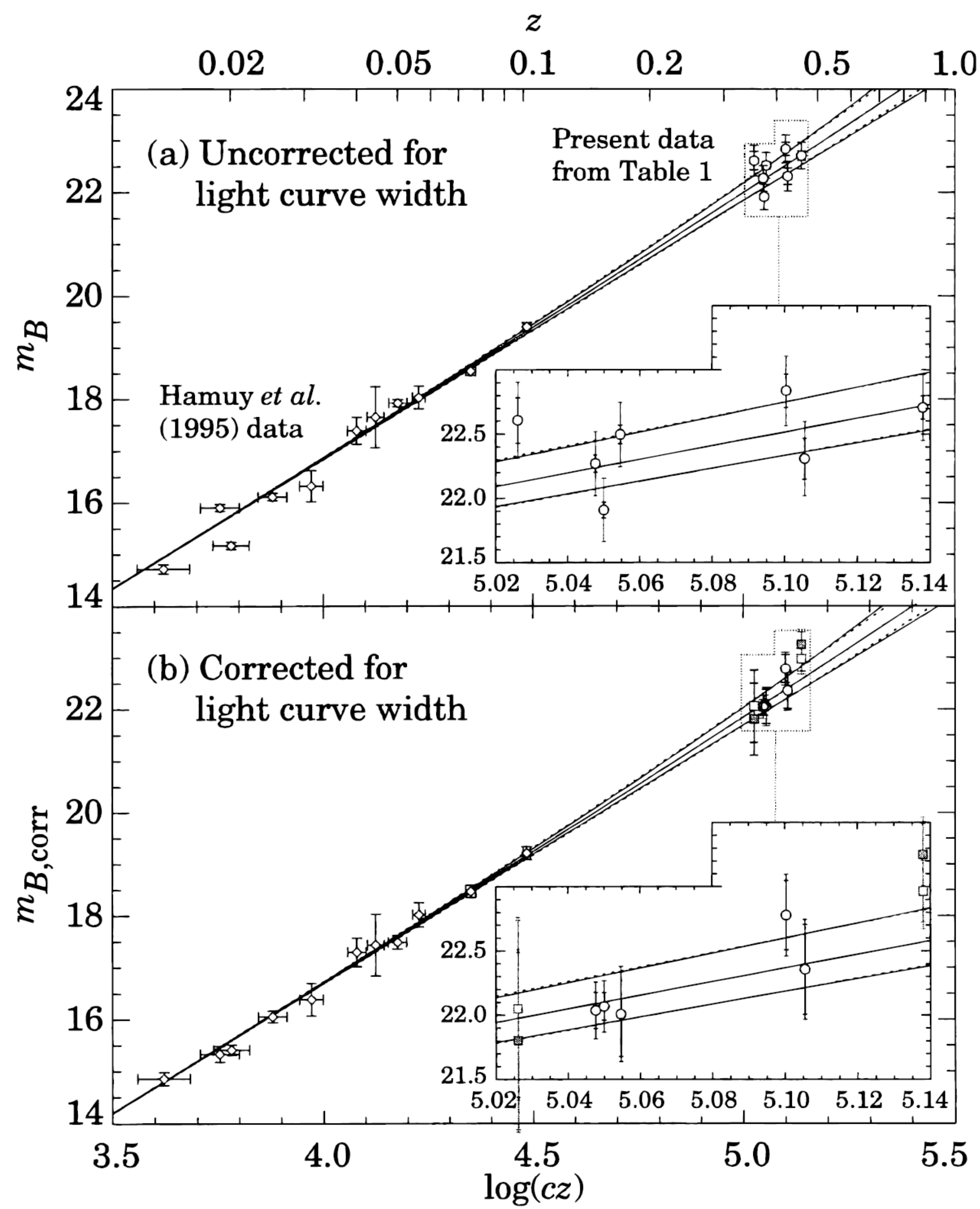
R(SiII)max




SN 2002bp
SN 1981B
Flux (arbitrary units)
Rest frame wavelength (Å)
SN 2002br
SN 1994D
SN 2002bj
SN 1994D
SN 2002bq
SN 1990N
SN 2002bk
SN 1986G
SN 2002bp
SN 1981B

SN 2002lj. Comparison of SN 2002lj smoothed spectrum with that of SN 1994D 7 days past maximum.





z
0.02
0.05
0.1
0.2
0.5
1.0
(a) Uncorrected for light curve width
Present data from Table 1
Hamuy et al. (1995) data
m_B
(b) Corrected for light curve width
$m_{B,corr}$
log(cz)

Reconstruction methods

Is there evolution in *w(z)*?

Parameters, Taylor series, Padé aproximants, polinomical fits, non parametric reconstruction of *w(z)*

Two parameter:

$$w(z) = w_0 + w_1 z \qquad w_1 = \left.\frac{dw}{dz}\right|_0$$

$$w(z) = w_0 + w_a(1-a)$$

$$w(z) = w_0 + w_a \frac{z}{1+z} \qquad w_a = \left.\frac{dw}{da}\right|_0$$

The relation mag-z in a flat Universe:

$$m^{th}(z,\Omega_M,w(z)) = \mathcal{M} + 5\log[D_L(z,\Omega_M,w(z))]$$

where

$$\mathcal{M} \equiv M - 5\log H_0 + 25$$

and D_L

$$D_L(z,\Omega_M,w(z)) = c(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_X(z')}}$$

$$\Omega_X(z) = \Omega_X \exp\left(3\int_0^z dz' \frac{1+w(z')}{1+z'}\right).$$

Reconstruction methods

Is there evolution *w(z)*?

Parameters, Taylor's series, Padé's approximants, polynomial fits, nonparametric reconstruction of *w(z)*

$$w(z) = w_0 + w_1 z \qquad\qquad w_1 = \left.\frac{dw}{dz}\right|_0$$

Incorporates badly the information at $z \sim 1$ and diverges at high z, giving nonphysical results at z_{CMB}

$$w(z) = w_0 + w_a(1-a)$$

$$w(z) = w_0 + w_a \frac{z}{1+z} \qquad\qquad w_a = \left.\frac{dw}{da}\right|_0$$

Testing the FRW metric

Large samples of SN will soon allow to test $d_L(z)$ in different directions and z bins. The direction-averaged d_L is:

$$d_L^{(0)}(z) = \frac{1}{4\pi}\int d\Omega_{\mathbf{n}} d_L(z,\mathbf{n}) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

The directional dependence $d_L(z, \mathbf{n})$ can test the isotropy assumption

The dispersion at each z interval and in every direction satisfies:

$$\frac{\sigma(d_L(z_{bin},\mathbf{n}))}{d_L(z_{bin},\mathbf{n})} = \frac{\ln(10)}{5}\sigma(m(z_{bin},\mathbf{n}))$$

The scaling solutions of the regionally averaged cosmologies can simulate a negative pressure component, but that would show in the dispersion of the Hubble diagram. From future experiments like *SNAP*, the total error in each z bin of width $\Delta z = 0.1$ is dominated by the systematics

$$\sigma_{bin} = \sqrt{\frac{\sum \sigma_{st}^2}{N_{bin}} + \sigma_{sys}^2}$$

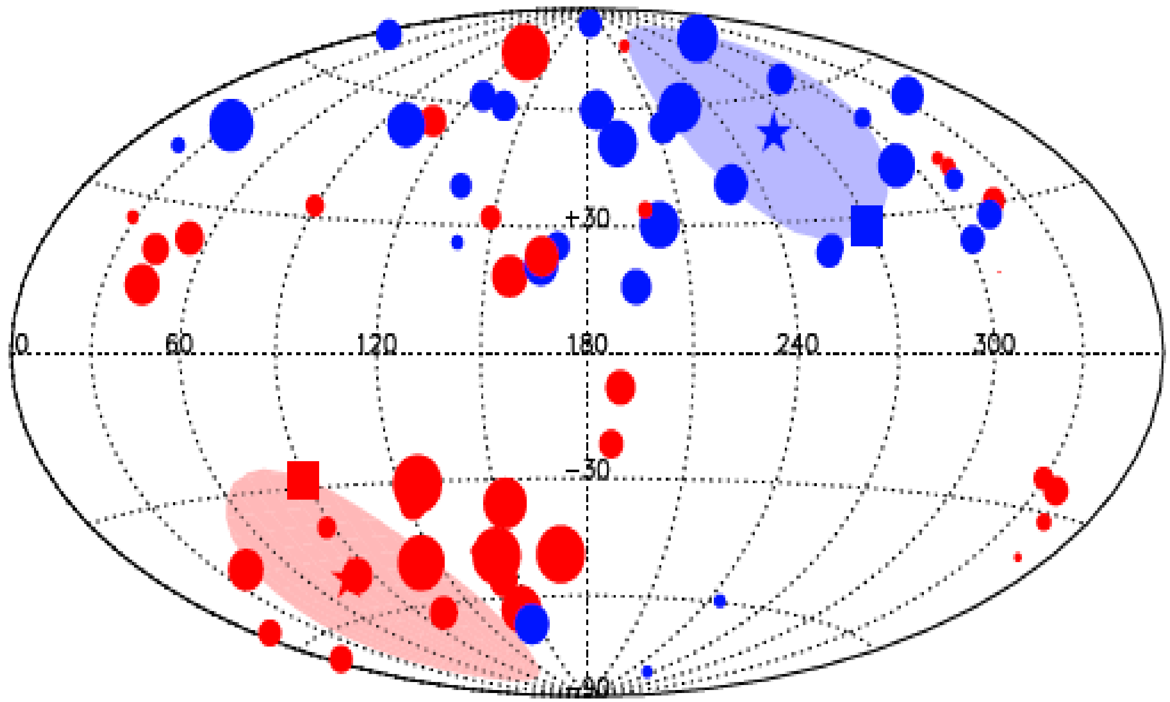
with expected systematic error

$$\sigma_{sys} = 0.02\ z/z_{max}$$

Buchert et al.: Class. Quant. Grav. 23, 6379 (2006)

Bonvin et al.: Phys. Rev. Lett. 96, 191302 (2006)

Buchert:: gr-qc/0612166 (2006)



MLCS2k2 69 SN Ia Local Group frame

$1500\ \mathrm{km\ s^{-1}} \leq H_0 d_{SN} \leq 7500\ \mathrm{km\ s^{-1}}$

Complementarity

The SNeIa test on *w(z)* benefits from independent information on Ω_M. Also, baryon acoustic oscillations measure distance along *z*, in this case angular distances $d_A(z)$. Generally, for any geometry one has:

$$A = \frac{\sqrt{\Omega_M}}{E(z)^{\frac{1}{3}}} \left[\frac{1}{z\sqrt{|\Omega_K|}} S\left(\sqrt{|\Omega_K|} \int_0^z \frac{dz'}{E(z')} \right) \right]^{\frac{2}{3}}$$

A measurement of d_A has been obtained

$$A = \frac{\sqrt{\Omega_M}}{E(z_1)^{1/3}} \left[\frac{1}{z_1} \int_0^{z_1} \frac{dz}{E(z)} \right]^{2/3} = 0.469 \pm 0.017$$

where z_1 = 0.35 is the redshift at whch the acoustic scale has been measured

Eisenstein et al.: ApJ 633, 560 (2005)

Summary

- Various methods give the same results

- Extinction correction issues

- Very high-z Sne Ia and new low z
  The SN union (largest union sample is about 300)

No evidence of significant departure from Lambda at low z

No information on dark energy at z > 1