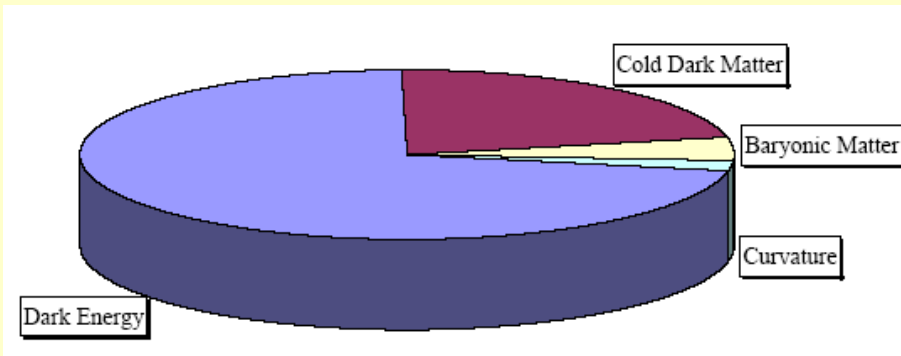


Cosmology overview

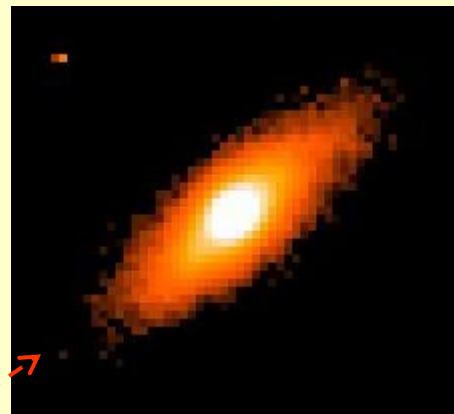
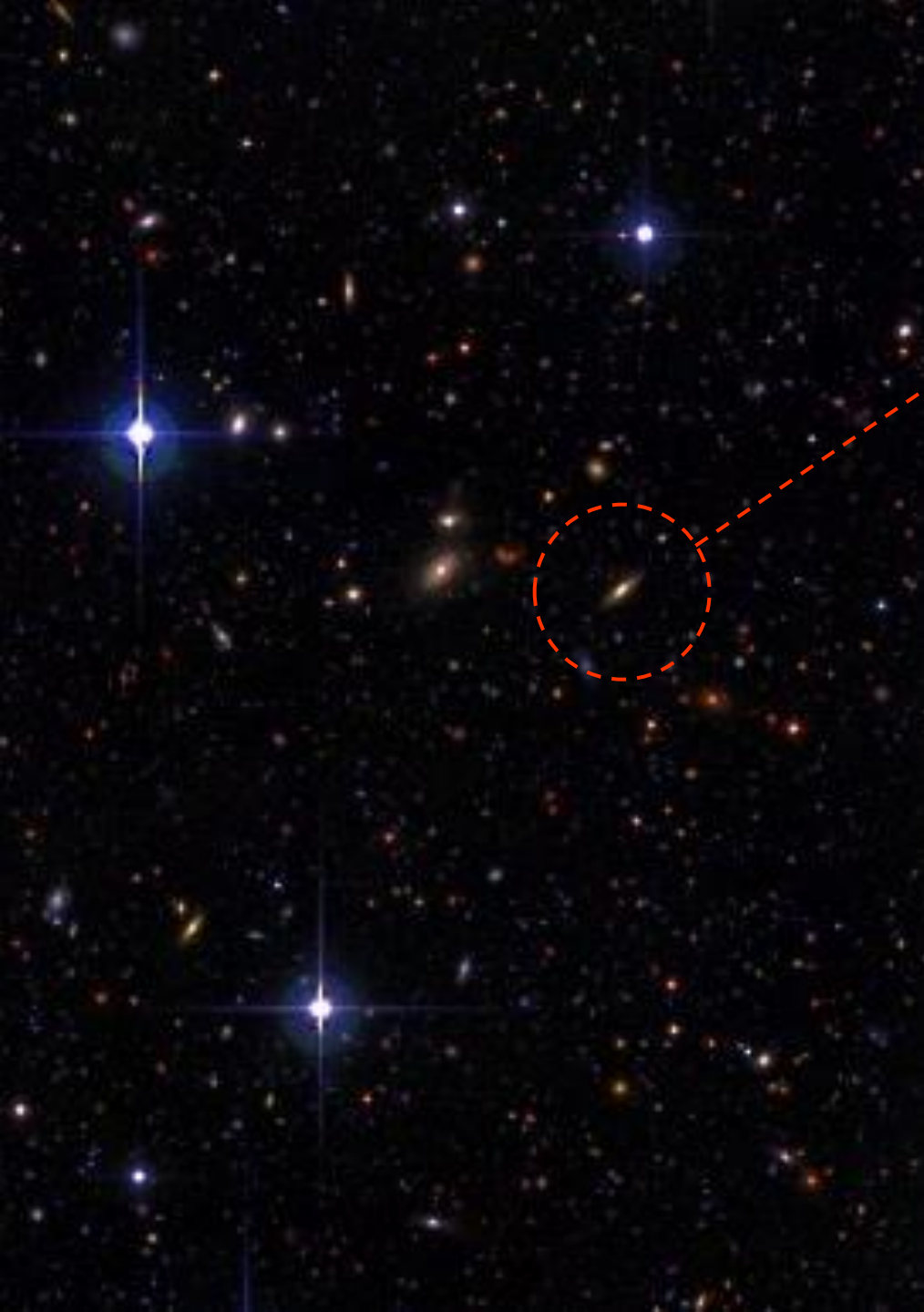
V.Ruhlmann-Kleider
CEA/Irfu/SPP - Saclay



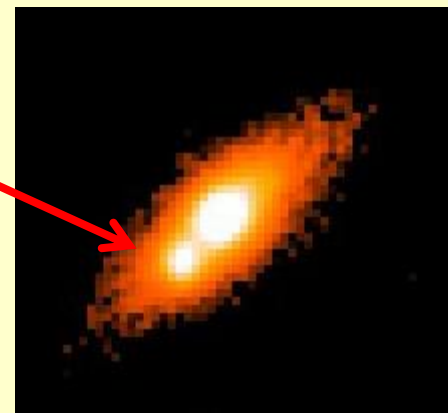
$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$

1. Cosmology with Type Ia SNe
2. Other cosmological probes
3. What is behind dark energy ?

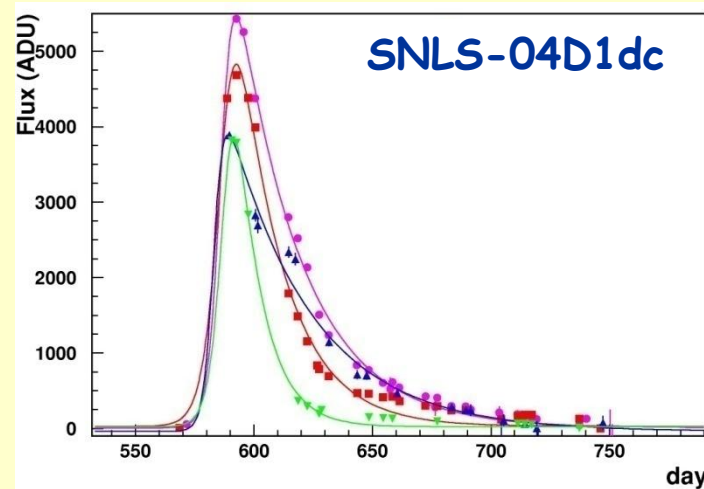




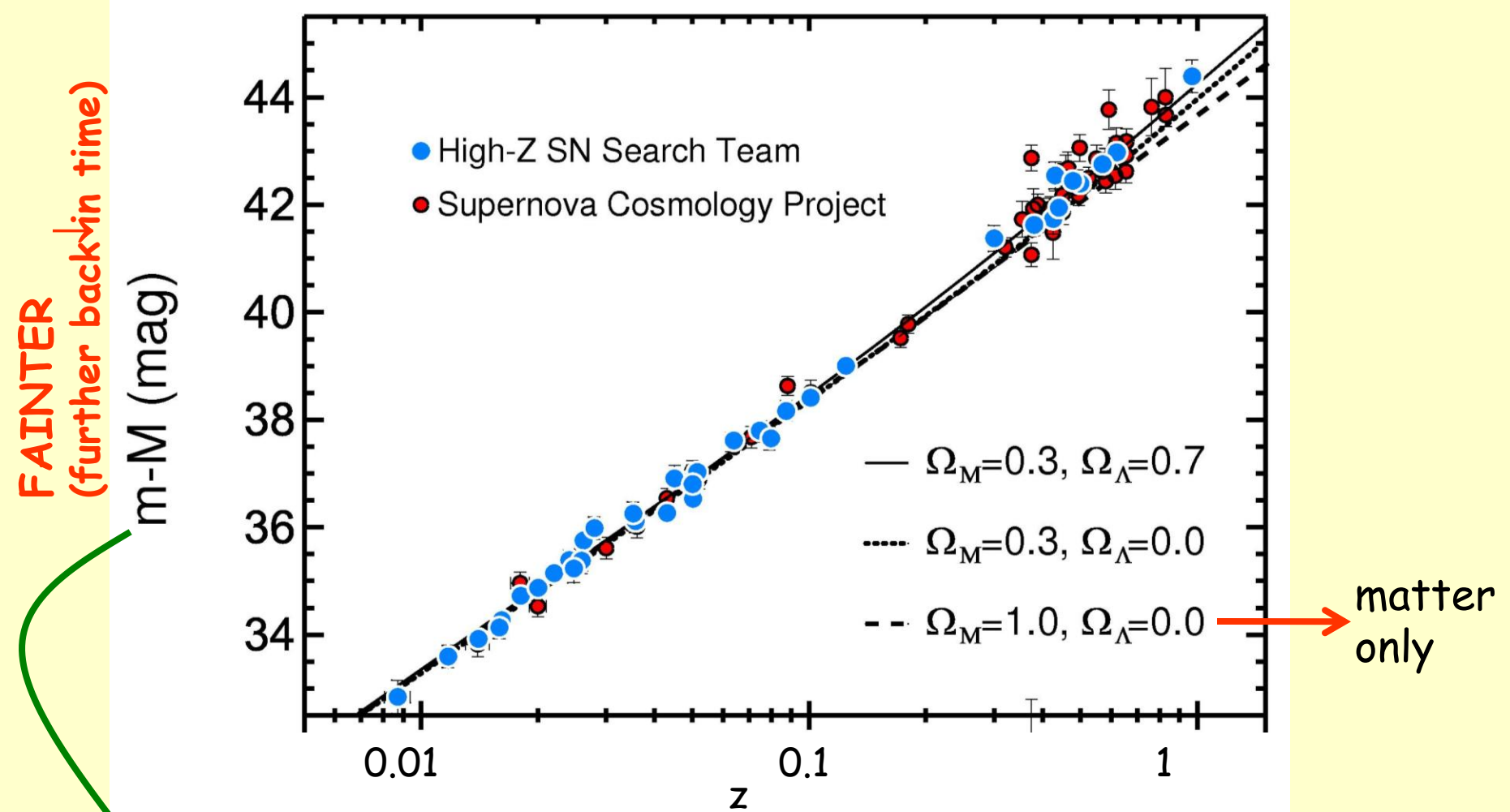
before
explosion



SN light curve



Accelerated expansion : Type Ia SNe, 1998

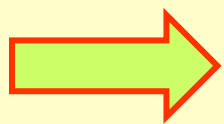


\sim apparent magnitude
 $= -2.5 \log_{10}(\mathcal{L} / 4\pi d_L^2)$

MORE REDSHIFT →
 (more expansion since explosion)

Cosmology with Type Ia SNe

- 1995/99: first experiments with distant SNe Ia:
 - lack of photometric precision
 - low statistics $\sim O(50)$
 - no way to test if SNe Ia are really standard candles
- 2003/10: second-generation experiments
 - dedicated experiments with optimised detection and follow-up strategies and improved photometric precision
 - larger statistics $\sim O(500)$
 - test "standard candle" hypothesis

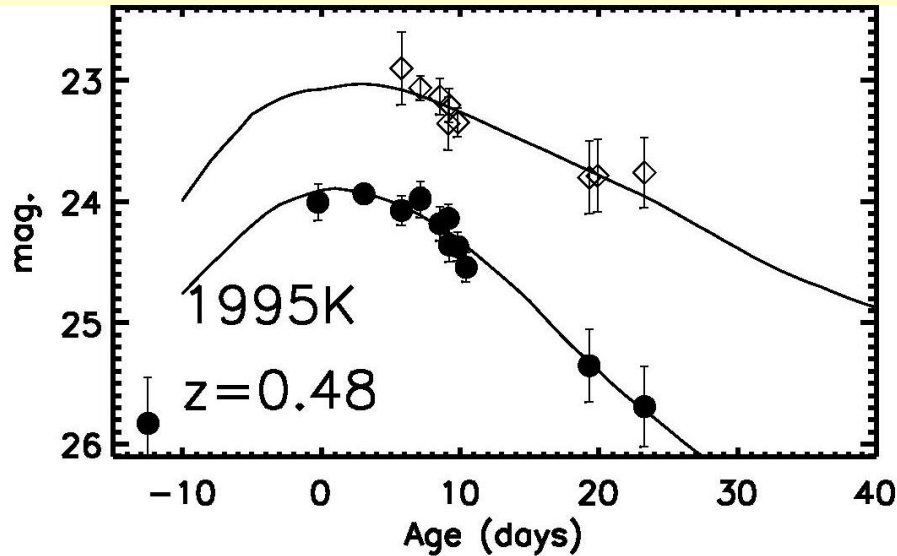


distant SNe: SNLS, ESSENCE, CSP, HST...

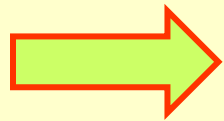
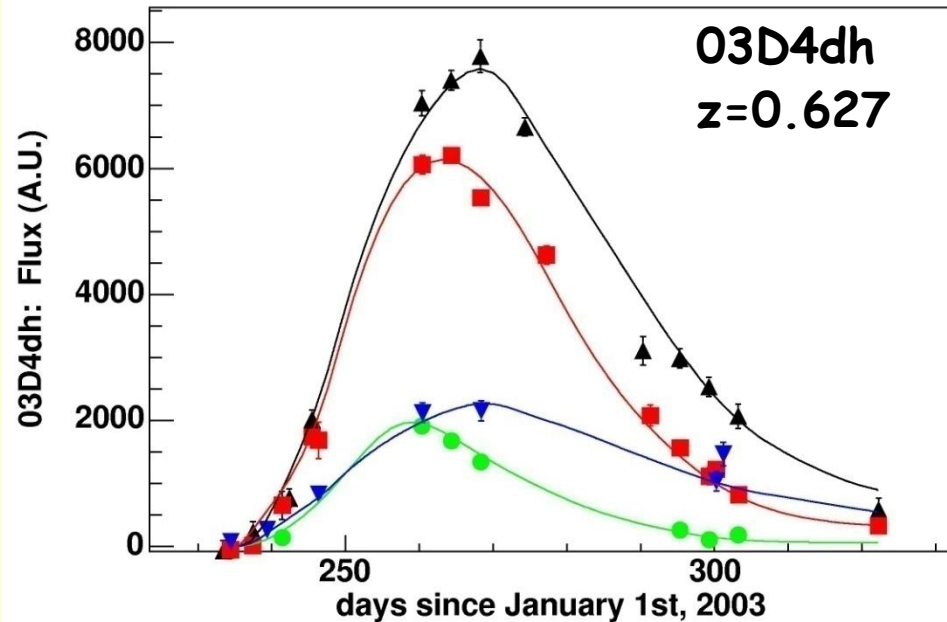
nearby SNe: CfA, CSP, SDSS, SNFactory...

From 1st to 2nd generation SN experiments

High-z SN search team

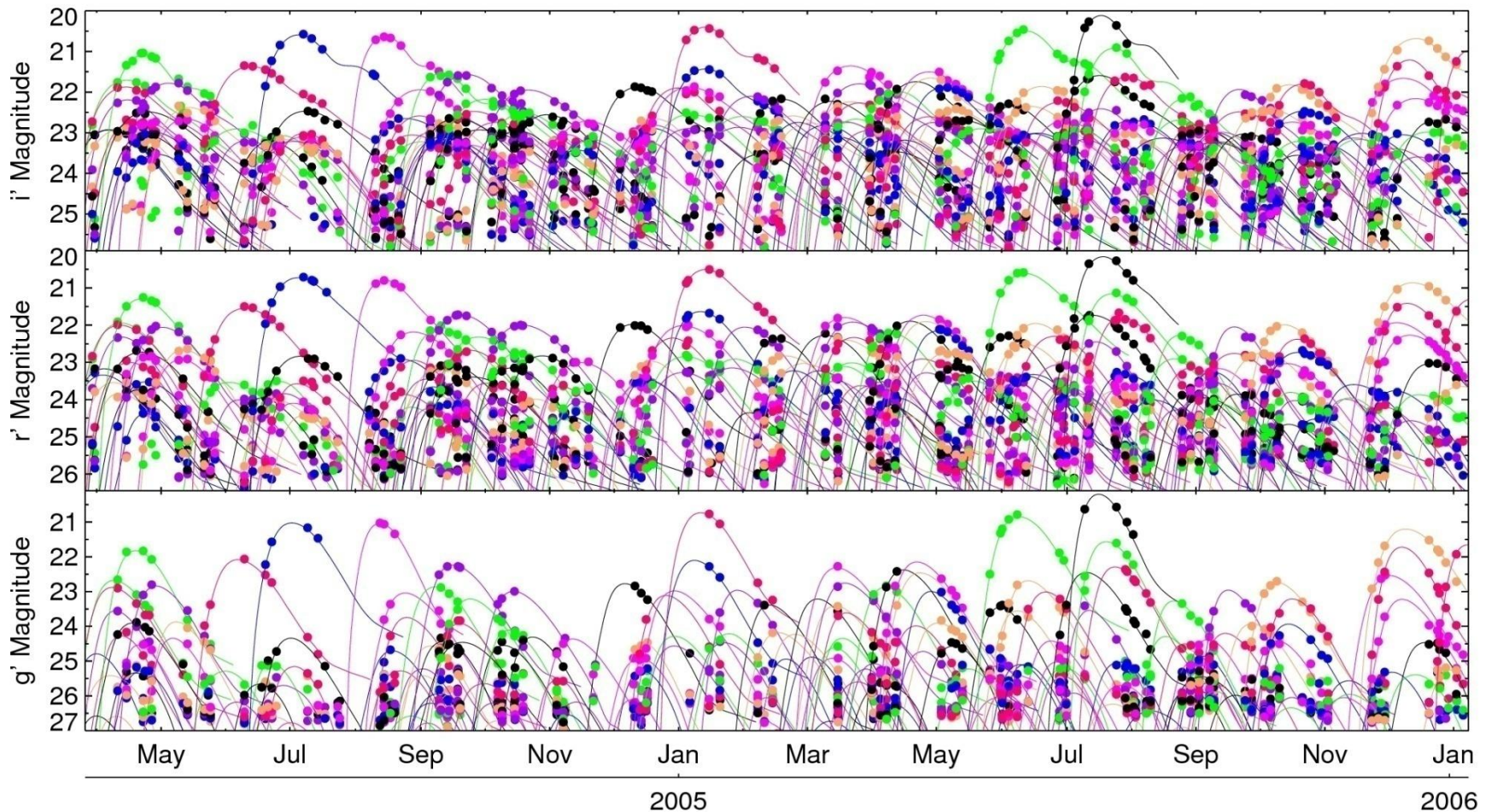


SNLS



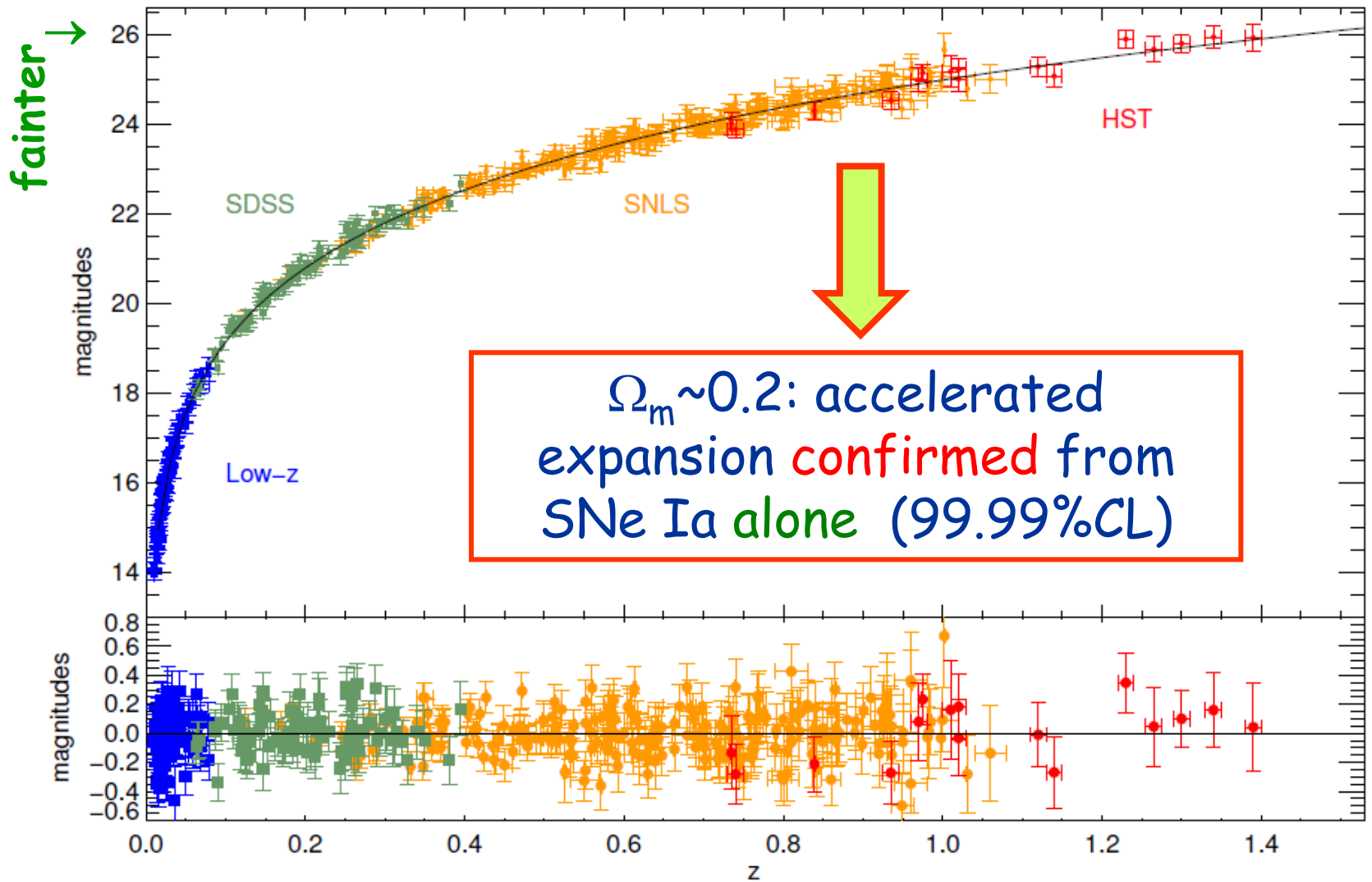
early detection
better temporal sampling
more filters
more precise photometry
larger data sample

SNLS "rolling search"



large and homogeneous sample of high-z spectroscopically confirmed SNe Ia, measured with good photometric accuracy

Latest results, summer 2010:



A. Conley et al., submitted to ApJ High quality data for 472 SNe Ia

Generic cosmology models

- Λ CDM: dark matter, curved Universe, cosmological constant
 $\rightarrow \Omega_m, \Omega_\Lambda$ (or Ω_k)

- w CDM: dark matter, flat Universe, dark energy with constant equation of state $\rightarrow \Omega_m, w$

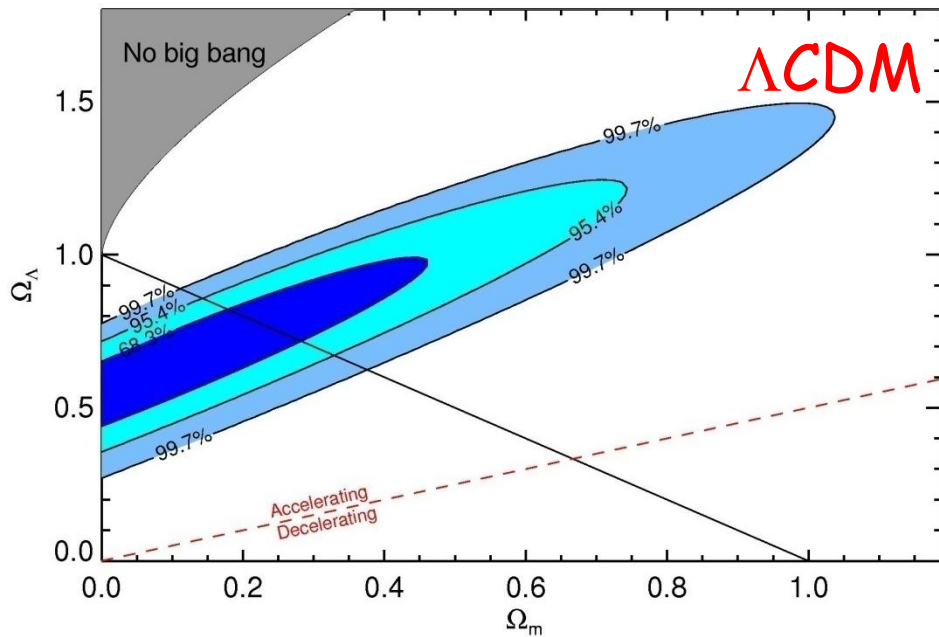
$$w = \frac{p_{de}}{\rho_{de}} \quad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1+w) \quad w=-1 \Leftrightarrow \Lambda$$

- ow CDM: similar to w CDM with curvature allowed $\rightarrow \Omega_m, \Omega_k, w$

- $w(z)$ CDM or $ow(z)$ CDM: similar to w CDM/ ow CDM but with time-dependent dark energy equation of state, e.g.

$$w(z) = w_0 + w_a \frac{z}{1+z} \quad \text{excellent approximation to a wide variety of dark energy models (scalar fields...)}$$

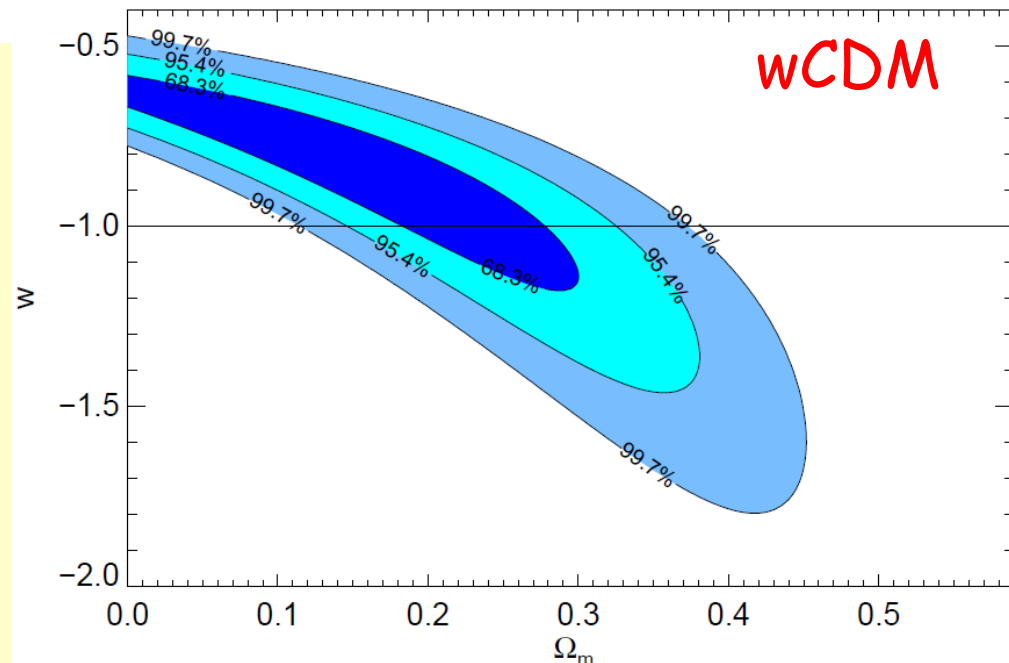
Cosmological fits from SNe Ia alone



δ_{stat} and δ_{sys} combined
(correlations accounted for)

better control of systematics
(photometric calibration, SNIa modeling)

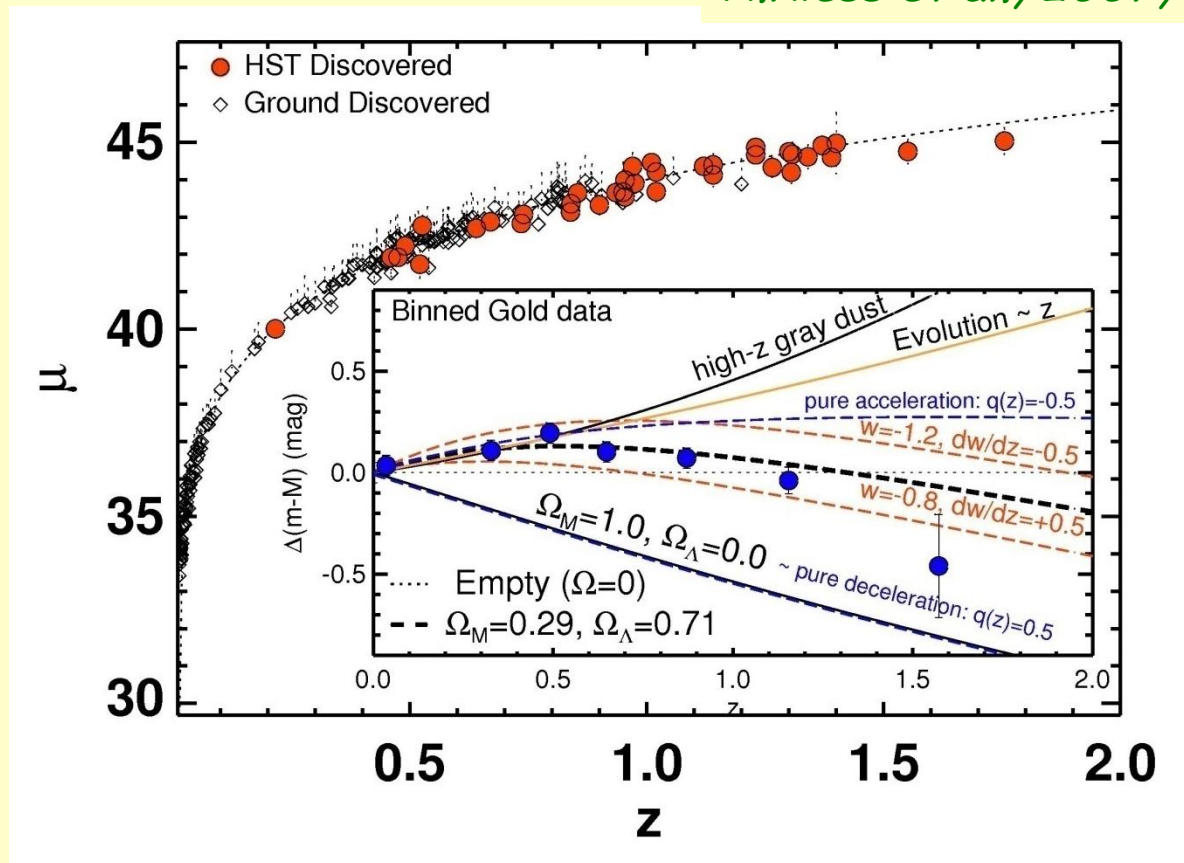
$$\Omega_m = 0.183^{+0.096}_{-0.102}$$
$$w = -0.91^{+0.17}_{-0.24}$$



A. Conley et al., submitted to ApJ

Reliability of SNe Ia as cosmological probes

A. Riess et al., 2007, ApJ, 659, 98



SNIa dimming of astrophysical origin ?

Simplest models of extinction by intergalactic dust or SNIa evolution ruled out by high-z SNIa data.

Dust scenarios also limited by other astrophysical data.

- o SNe Ia are (assumed to be) **standard candles** :

reproducible luminosity

$$m_{B^*} \text{ from } \Phi_{B^*} \cong \mathcal{L}(c, s) / 4\pi d_L^2 \quad \text{with} \quad d_L(z, H_0, \Omega_M, \Omega_\Lambda, w, \dots)$$

- o Distance estimator :

$$\mu_B = m_{B^*} - M_B + \alpha(s-1) - \beta c$$

apparent rest-frame
peak magnitude

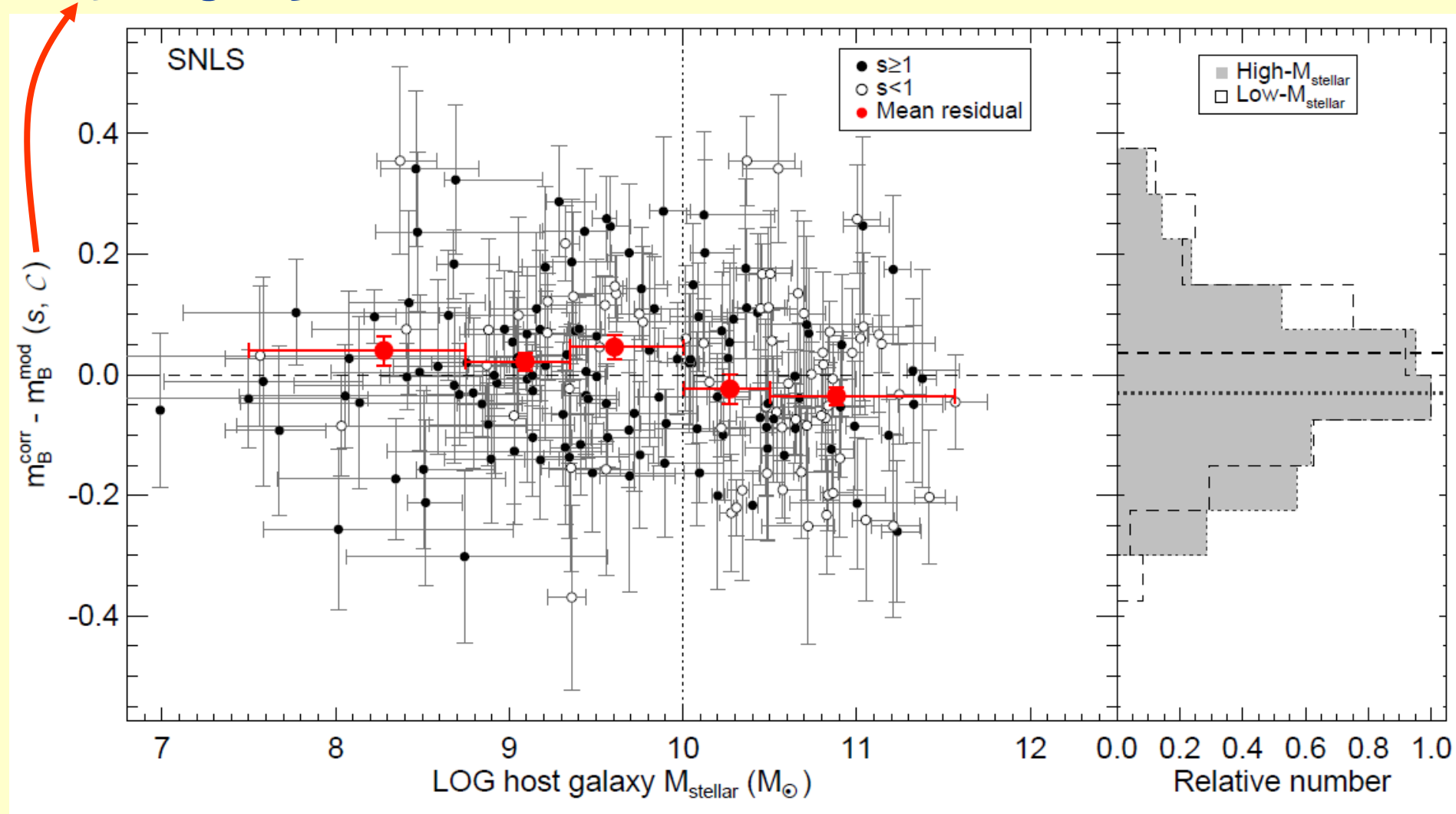
absolute B-band
magnitude

light curve **shape**
variability

(B-V) colour variability
(intrinsic variation and
extinction)

M_B, α, β assumed to be **z-independent**. Is that so ?
 \Rightarrow compare properties of SN sub-samples split by
 redshift, host activity...

$$\mu_B - 5 \log_{10} d_L$$



Corrected SNIa luminosities depend on host galaxy mass:
SNe Ia in massive galaxies appear brighter than those in
less massive galaxies ($>3\sigma$)

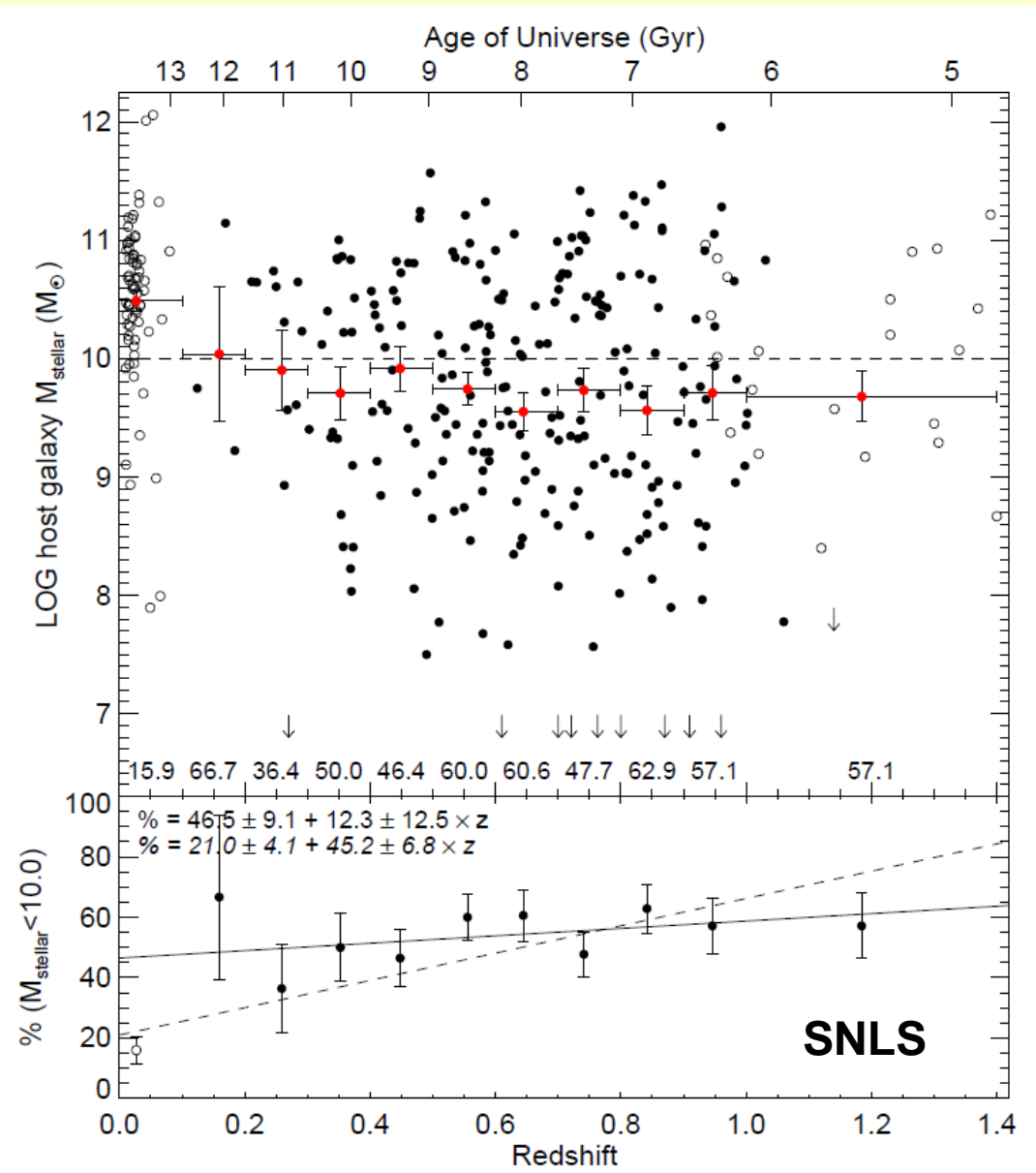
Mix of SNe Ia from
different hosts changes
with redshift
SN demographic shifts



to avoid bias in
cosmological results

Allow for a
host specific term
in cosmological fits:

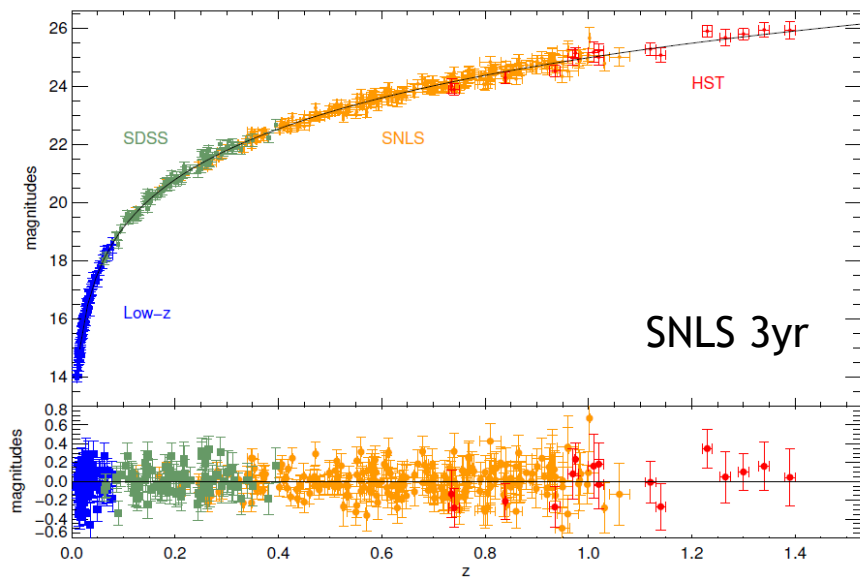
$M_B(\text{host})$ in μ_B



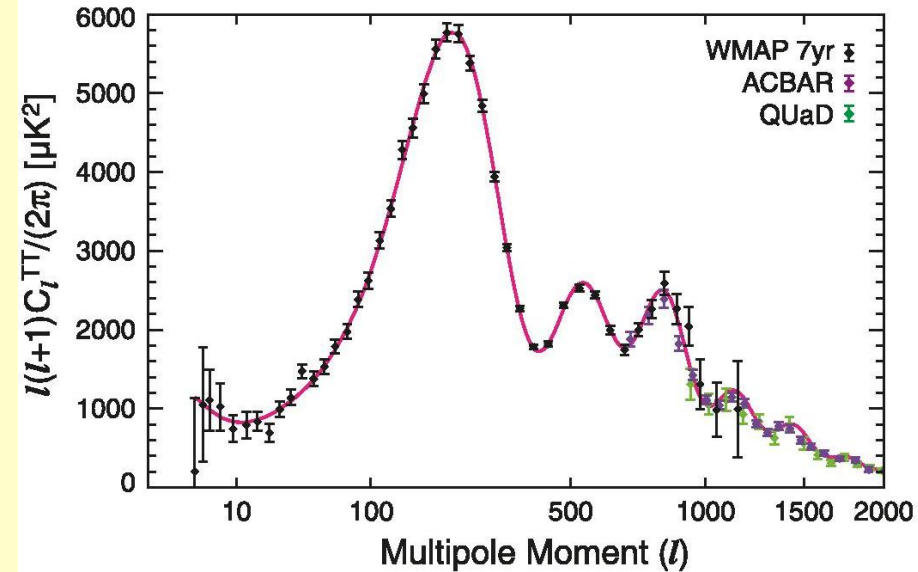
M. Sullivan et al., 2010, MNRAS 406, 782

Combined constraints

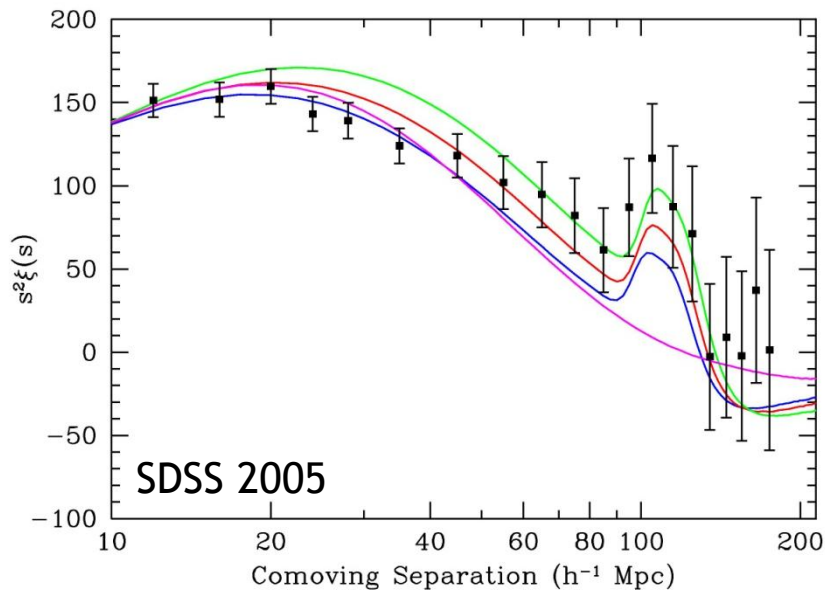
SN Ia distances for $z \leq 1.5$



CMB spectrum: distance to last scattering surface ($z=1089$)

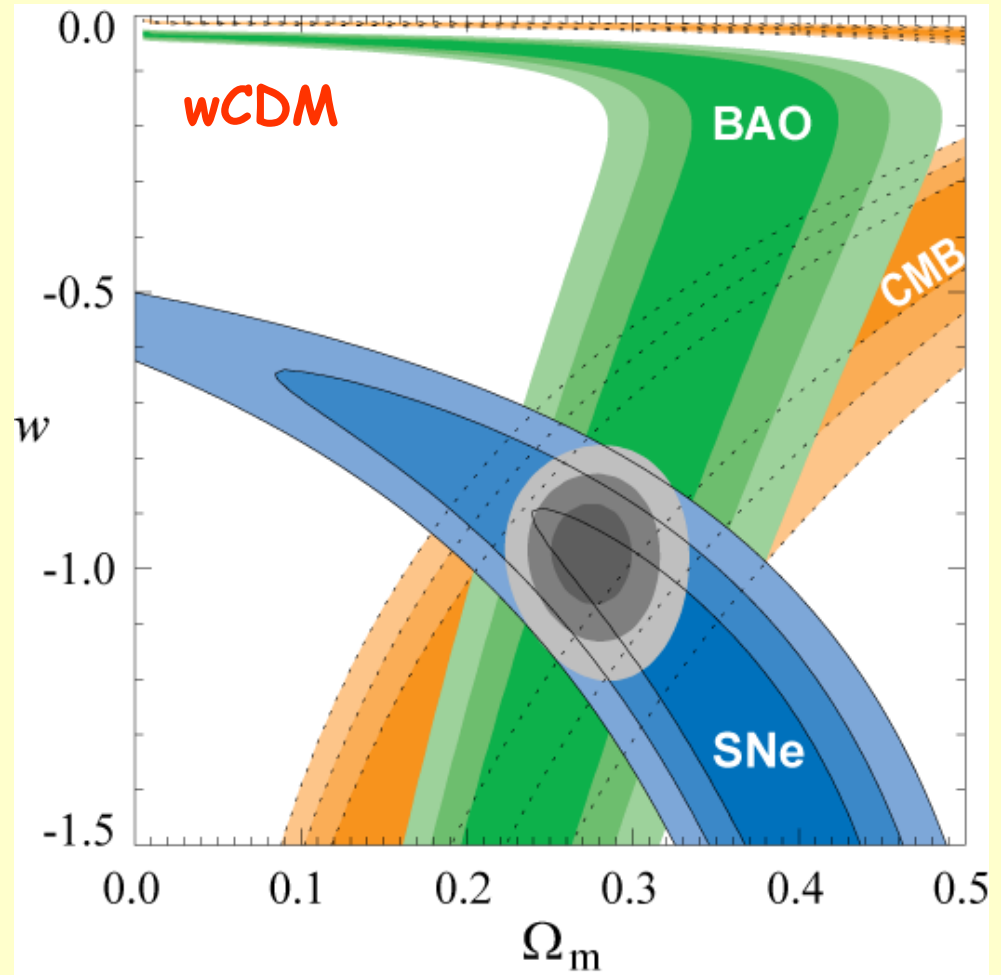
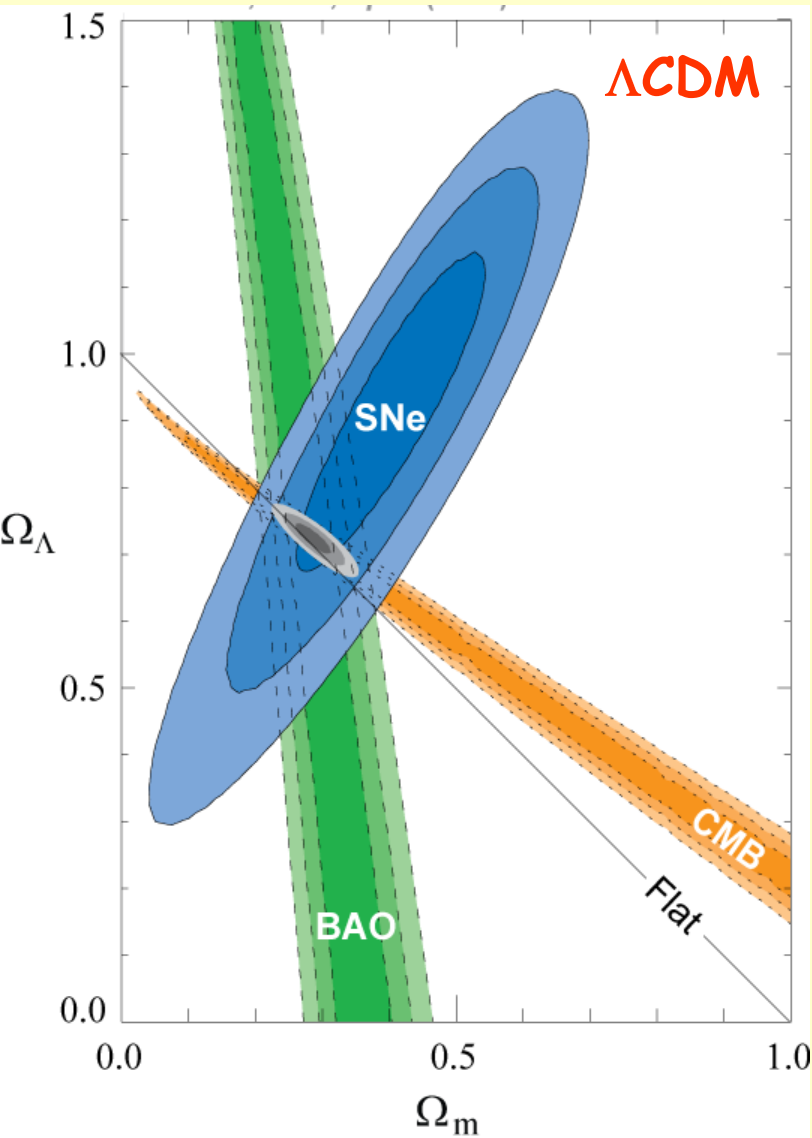


BAO: location of comoving galaxy separation at $z=0.2, 0.35$



Constraints from Union '08 SN set

M. Kowalski et al., 2008, ApJ, 686, 749

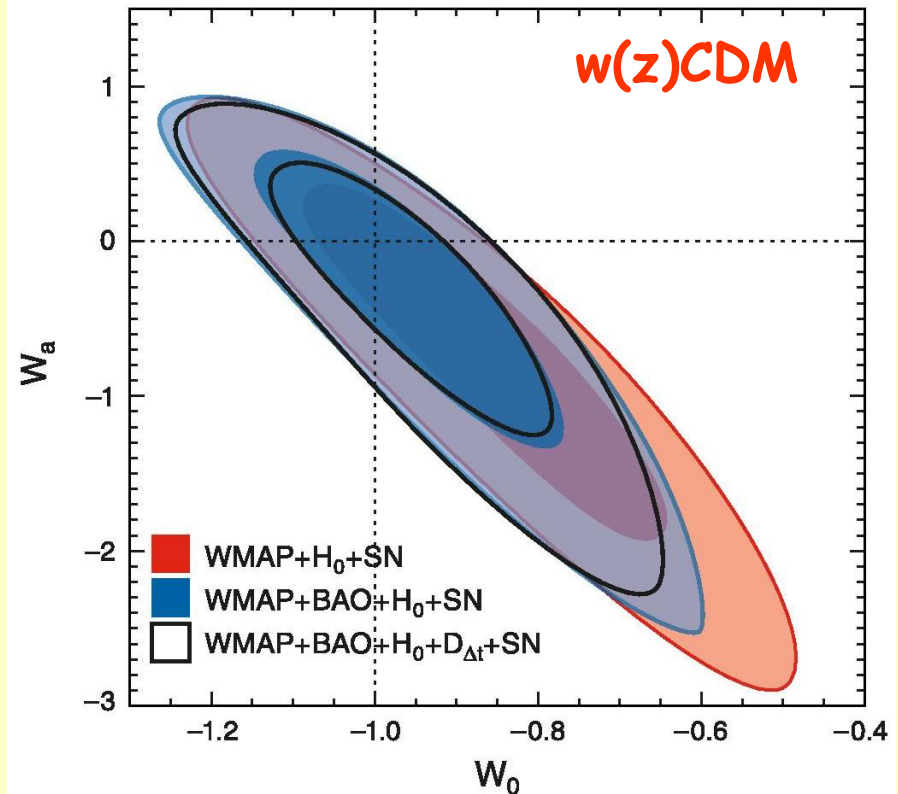
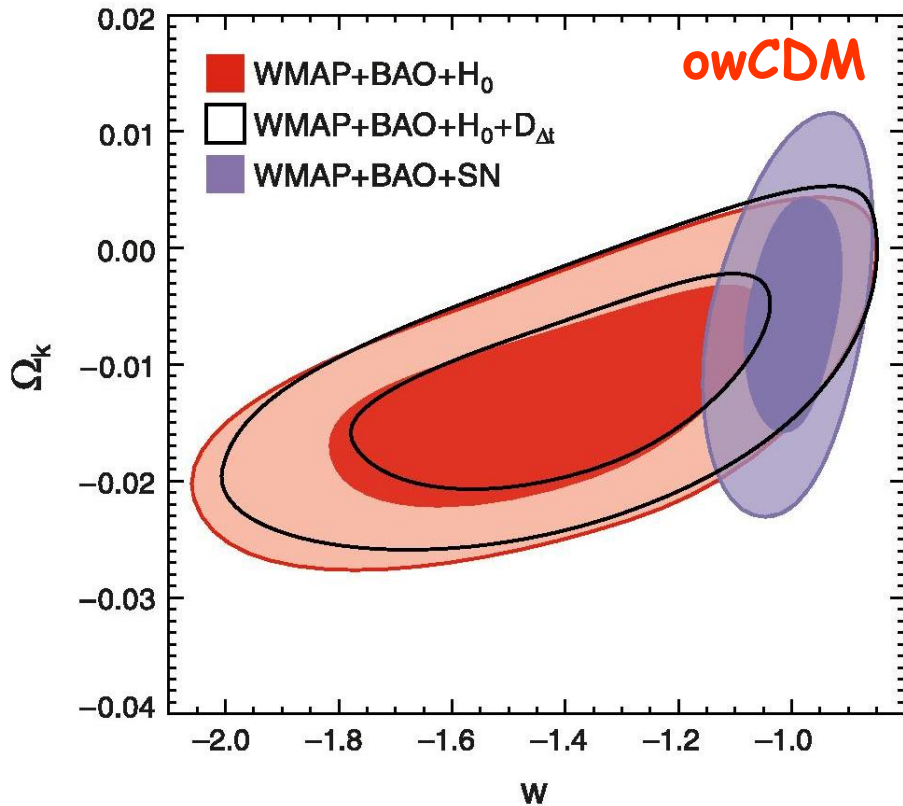


$$w = -0.969^{+0.059+0.063}_{-0.063-0.066}$$

SN=Union set '08, CMB=WMAP-5, BAO=SDSS'05

Constraints from WMAP-7

E. Komatsu et al., arXiv:1001.4538, submitted to ApJS



$wCDM$: $w = -0.980 \pm 0.053$ (stat)

$owCDM$: $w = -0.999^{+0.057}_{-0.056}$ (stat)

$w_0 = -0.93 \pm 0.12$ (stat)

$w_a = -0.38^{+0.66}_{-0.65}$ (stat)

Constraints beyond generic models

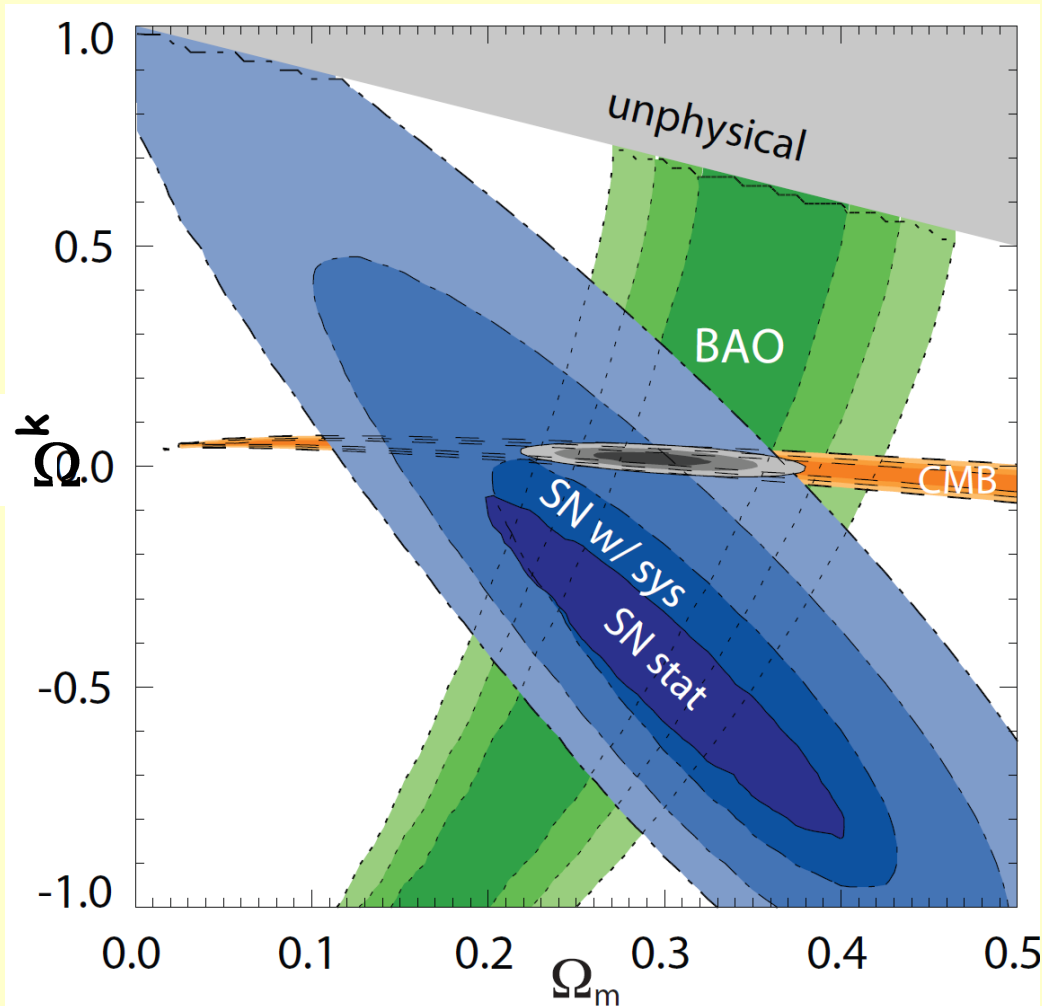
D. Rubin et al., 2009, ApJ, 695, 391

- Data sample:
 - **SNe Ia**: Union'08 compilation
 - **CMB**: WMAP-5year
 - **BAO**: SDSS 2005
 - A wide variety of DE models explored (extra dimensions, scalar fields, geometric dark energy...).
- Two examples:
- DGP braneworld gravity
 - Geometric dark energy

DGP Braneworld gravity

two-parameters: Ω_m and Ω_k

$$w(\mathbf{z}) = -\frac{1 - \Omega_k(\mathbf{z})}{1 + \Omega_m(\mathbf{z}) - \Omega_k(\mathbf{z})}$$

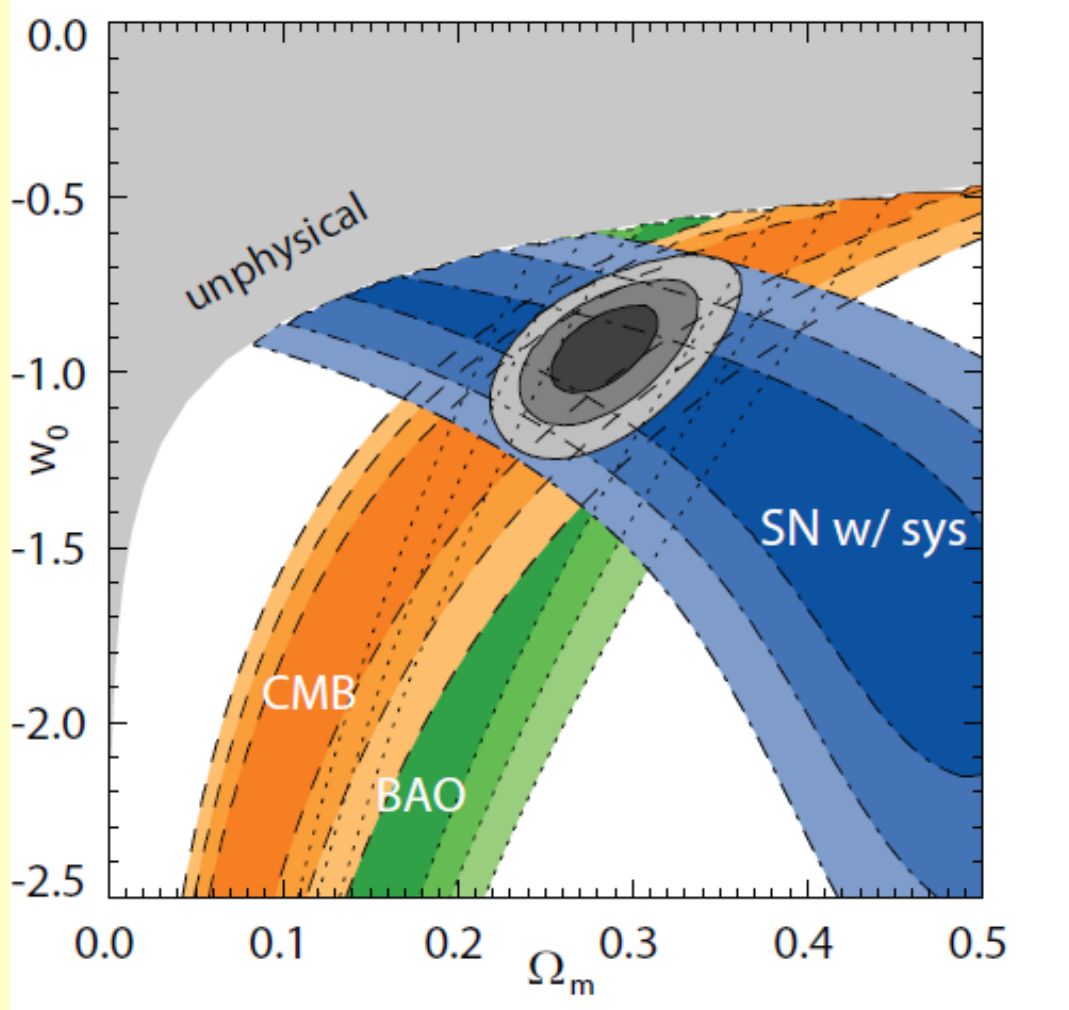


Poor fit to combined data (wrt Λ CDM fit)

Geometric dark energy R_{low}

two-parameters: Ω_m and w_0

$$w_0 = \frac{1 - 4r_0}{3(1 - \Omega_m)}$$



Good fit to combined data

$w_0 = -1$ favored but **distinct** physics from Λ CDM

CMB and BAO constraints
~close: SNe play a valuable role

Conclusions

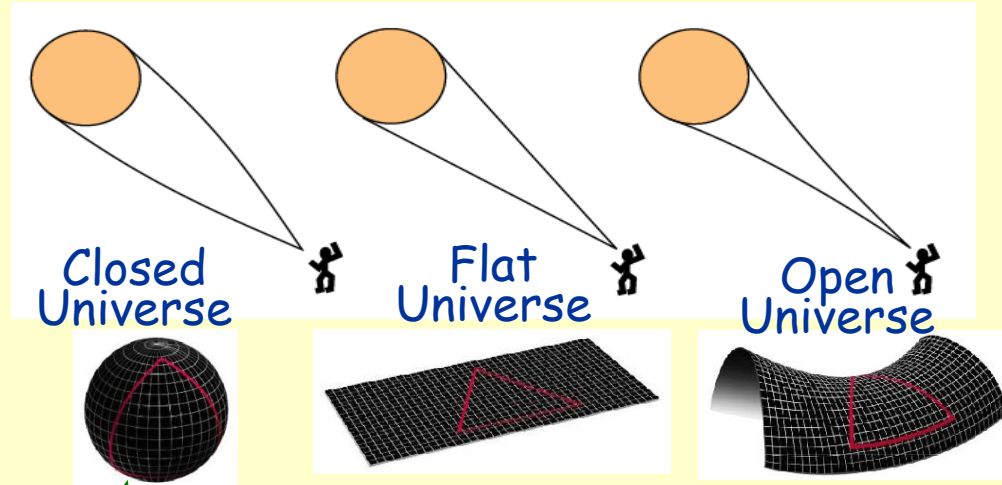
- Type Ia SNe: precision **much improved** recently (larger sample of **high quality** data, better control of **systematics**)
- Current data (SN+BAO+CMB) are consistent with Λ CDM **and with a wide diversity of dark energy models**: static dark energy is not necessarily the true answer
- To explain the nature of dark energy, need for next generation observations/probes **sensitive to $w(z)$**

Back up slides

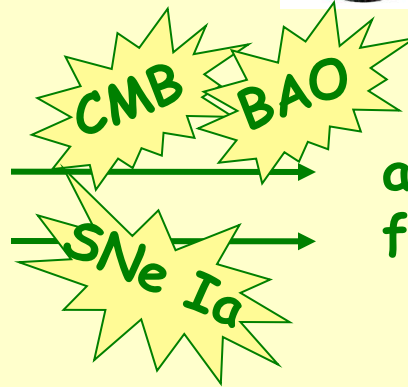
The energy balance of the Universe

$$\Omega_M + \Omega_\Lambda = 1 - \Omega_k$$

o measuring the geometry of the Universe



AT A GIVEN DISTANCE
Known physical size
Known luminosity



angle depends on geometry
flux depends on geometry

o measuring the energy content of the Universe

→ cluster distributions
→ DM distribution

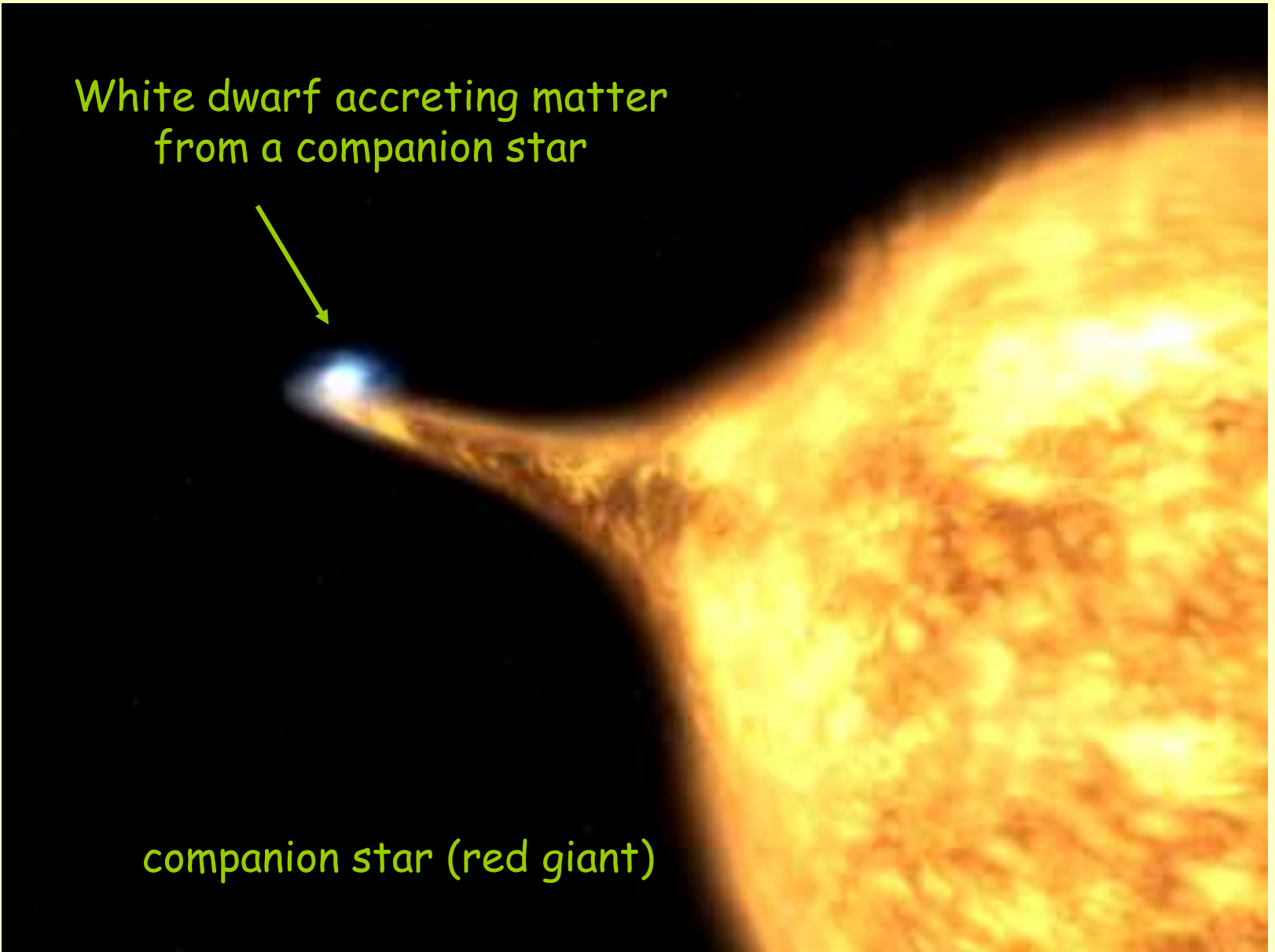


The standard SNIa scenario

White dwarf accreting matter
from a companion star

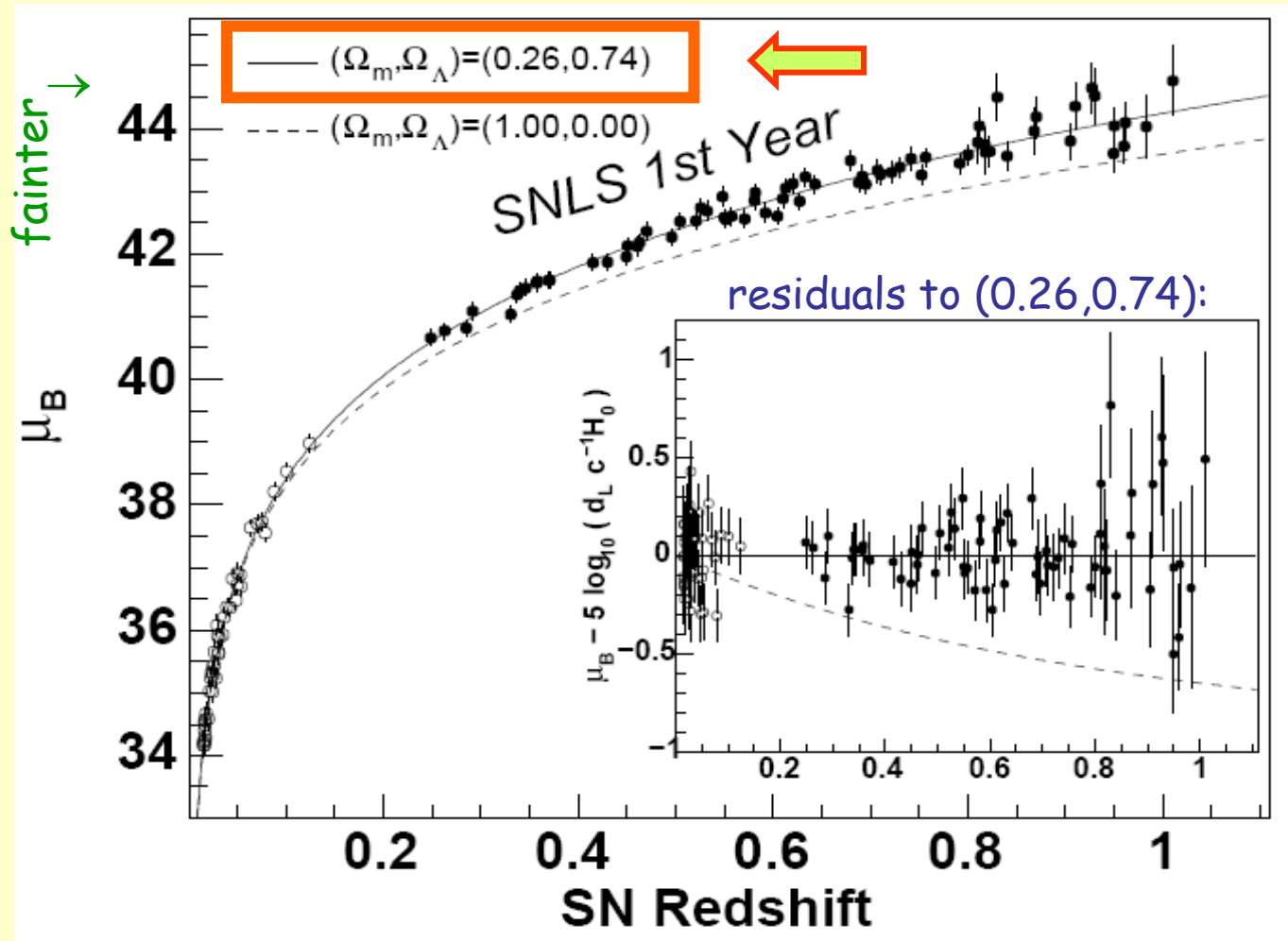


companion star (red giant)



1st year SNLS results

P.Astier et al., 2006, A&A, 447, 31

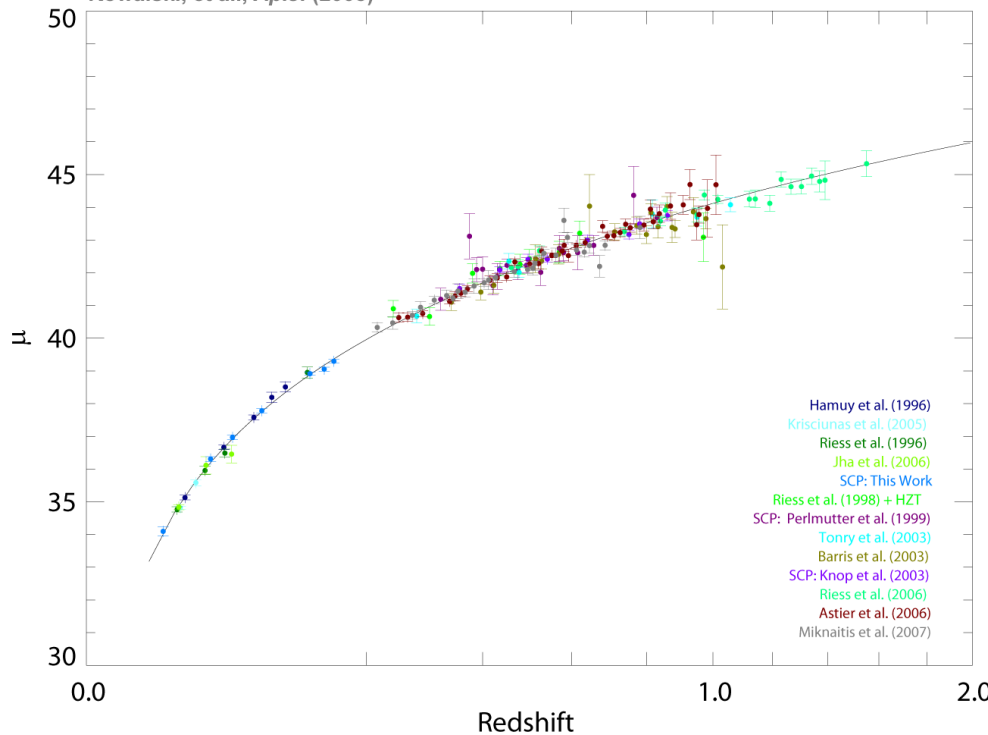


Accelerated expansion of the Universe : confirmed (71 SNe)

Union compilation, 2008

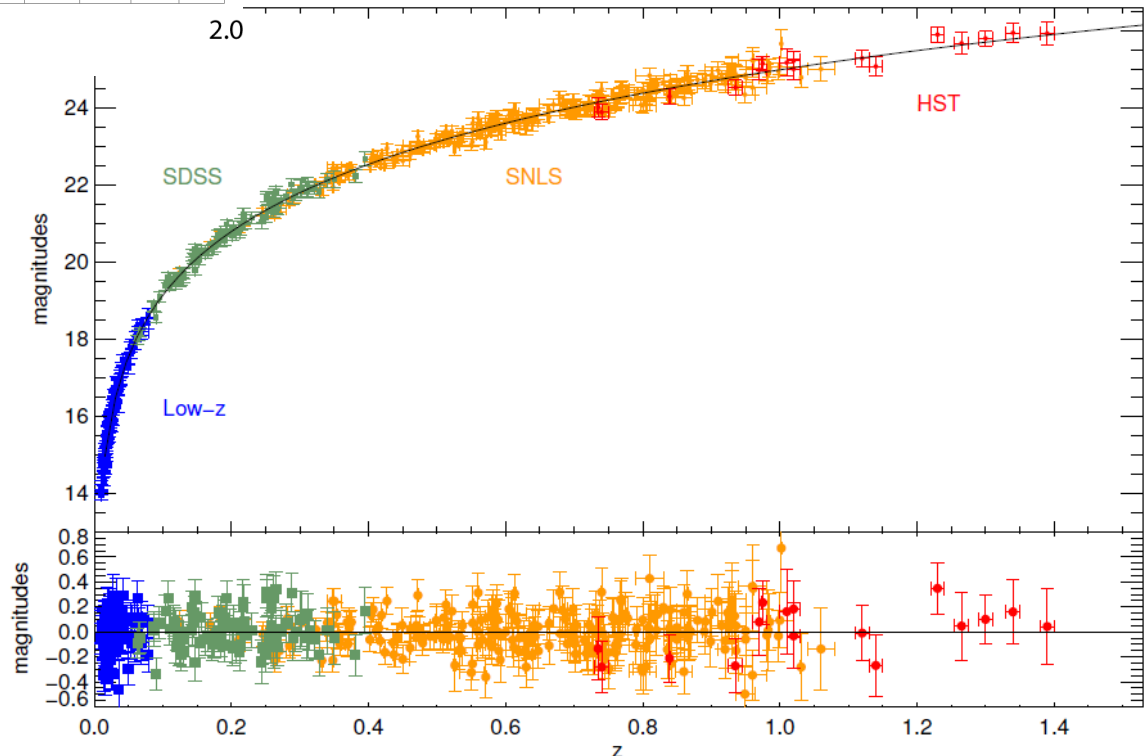
414 published SNe Ia
307 after selection cuts

M. Kowalski et al., 2008, ApJ, 686, 749



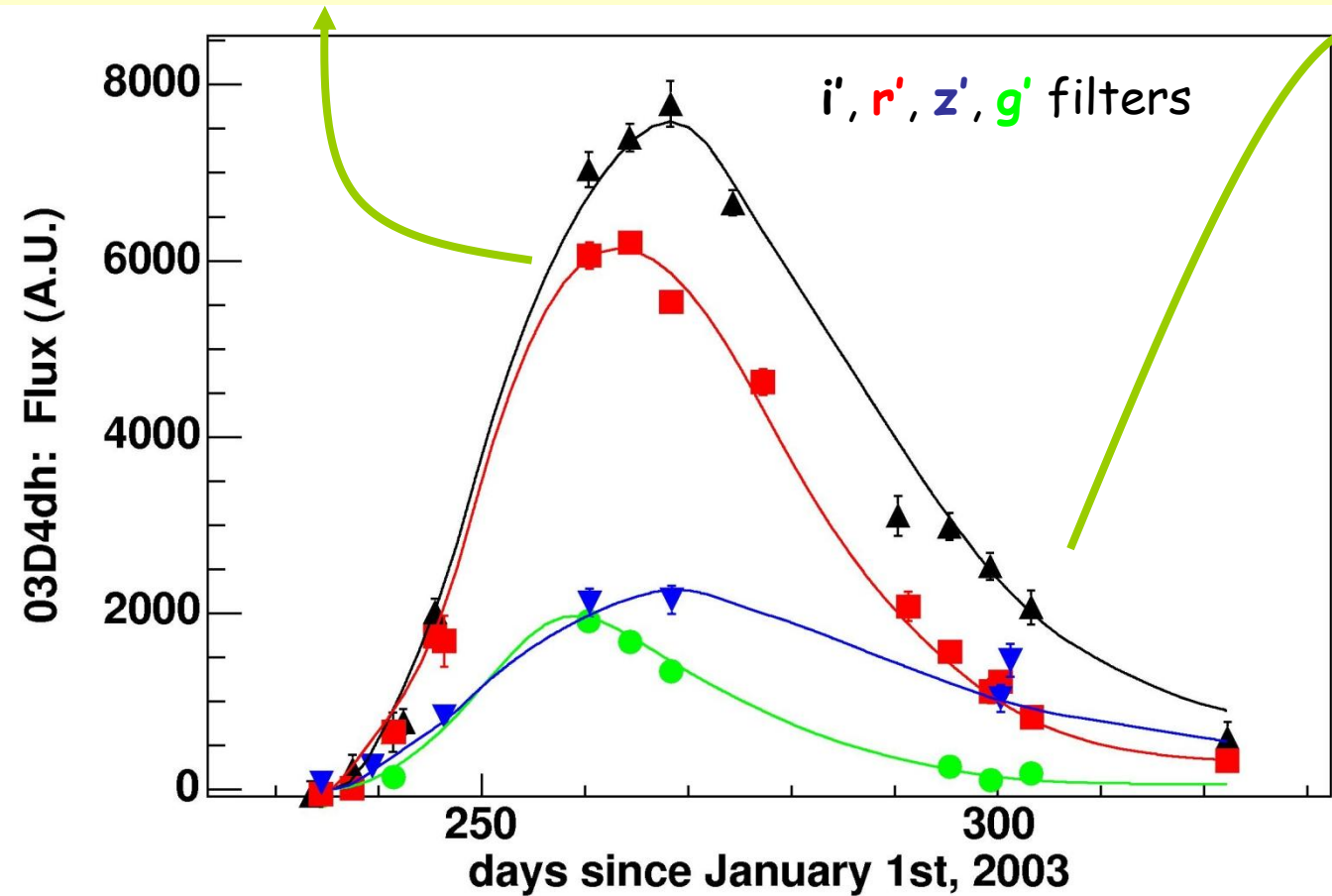
SNLS 3yr analysis:
- 285 high-z SNe Ia
- 242 good quality SNLS
evts combined with 230
good quality low-z, SDSS,
HST SNe

A. Conley et al., submitted



Cosmology with SNe Ia

spectroscopy triggered \Rightarrow type Ia confirmed, $z=0.627$

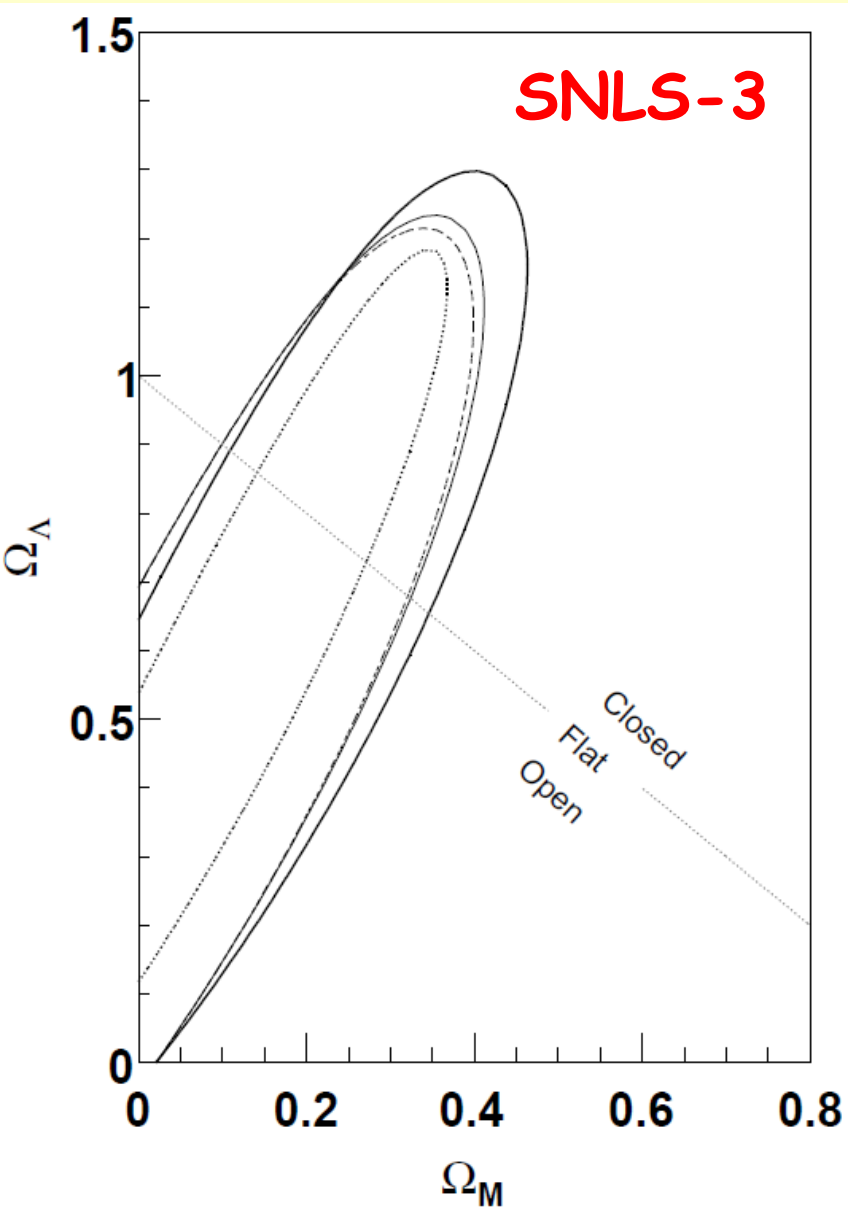


multi-band LC's :

test compatibility
with **SNIa model**
(trained on SNIa
lightcurves and
spectra)

apparent B magnitude : m_B^* , (B-V) colour C and stretch s

J.Guy et al., 2007, A&A, 466, 11



Flat Λ CDM fits from SN data
 $(\Omega_M + \Omega_\Lambda = 1, w = -1)$:

- SNLS-3yr data **alone**:
 $\Omega_M = 0.211 \pm 0.034 \pm 0.069$
- Better control of systematics:
 - empirical LC model 0.026
 - model training stat 0.034
 - **photometric calibration 0.048**
 - potential β evolution 0.022
 - residual scatter 0.010
 - Malmquist bias corr 0.004
 - SN-host correlation 0.003

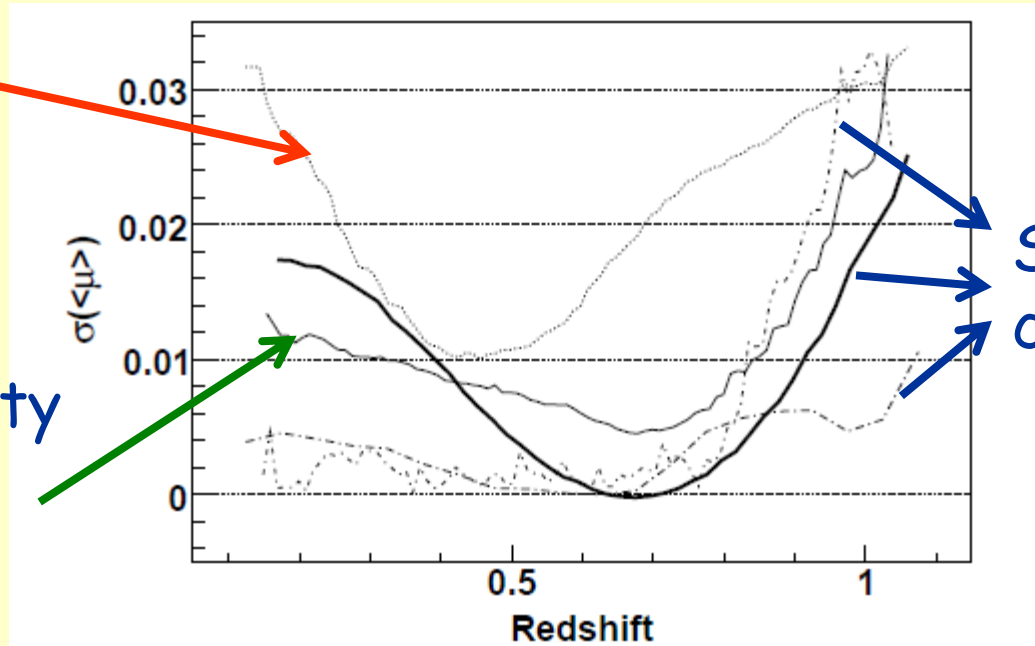
J. Guy et al., 2010, accepted by A&A

δ_{sys} on distance modulus measurements in SNLS-3yr data

$\sigma(\mu)=0.04$ 0.02 0.06

photometric calibration

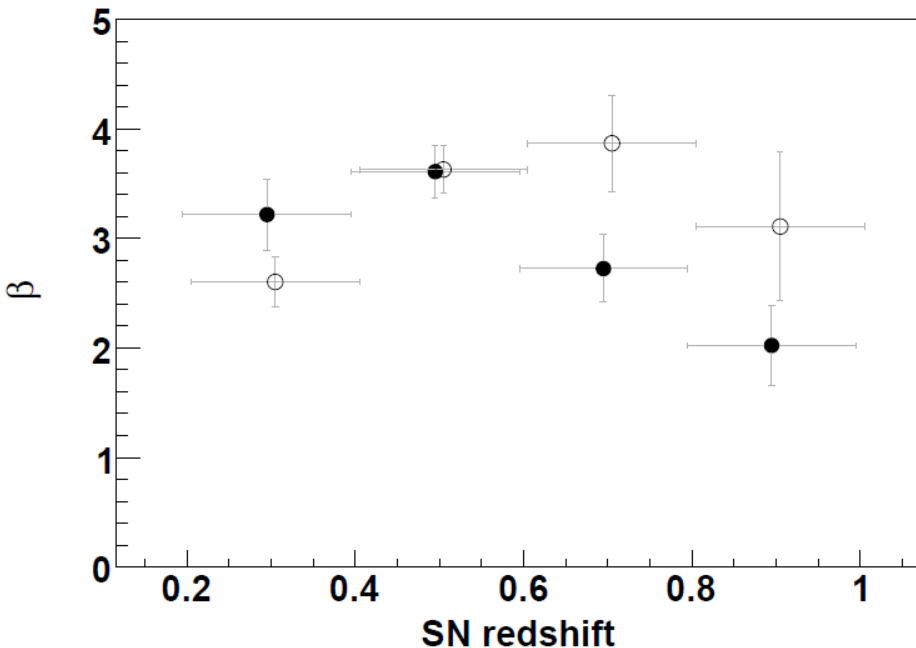
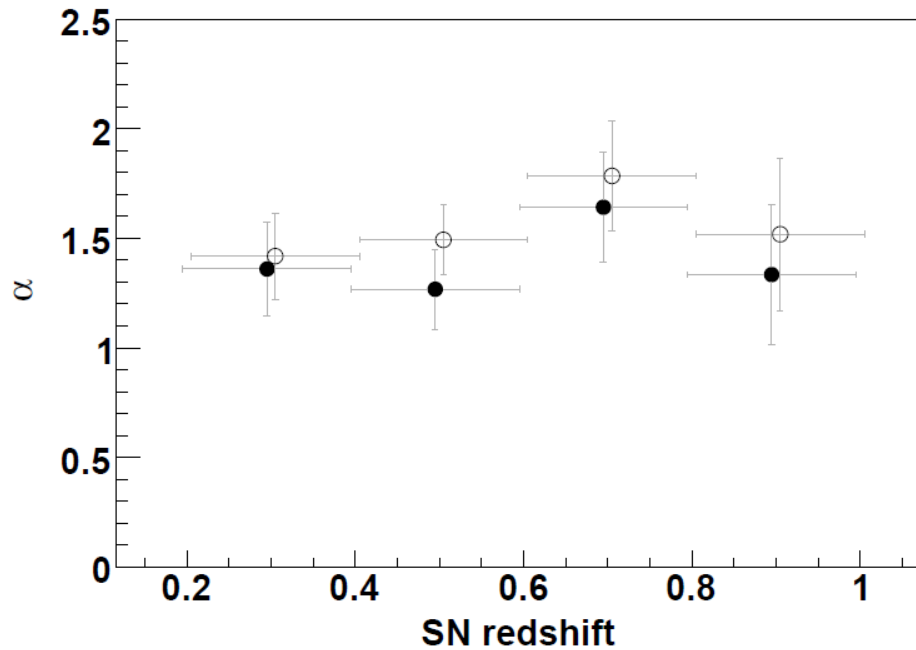
stat. uncertainty of SNIa light curve model training



SNIa light curve model

Fig. 16 Uncertainties on the average distance modulus μ in redshift bins of 0.2: impact of the statistical uncertainty of the training (for SALT2, thin solid curve), calibration uncertainties (dotted curve), residual scatter model (dotted short dashed curve), systematic uncertainty due to SALT2 regularisation (dotted long dashed curve) and differences between results obtained with the two light curve fitters (thick solid curve). Values of α and β that minimise residuals from the Hubble diagram were used.

J. Guy et al., 2010, accepted by A&A



From the SNLS-3 sample

- No evolution in α
(luminosity-shape relation)

- Possible evolution in β
(luminosity-colour relation)
→ accounted for in SN systematics

● SALT2 LC fitter

○ SiFTO LC fitter

J. Guy et al., 2010, accepted by A&A

Combined constraints on Λ CDM

- **SNe Ia:** SN distances $d_L(z)$ for $z \leq 2$

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{dz'}{H(z')}$$

- **CMB:** amplitude and location of acoustic peaks in CMB spectrum \rightarrow distance to the surface of last scattering at $z=1089$

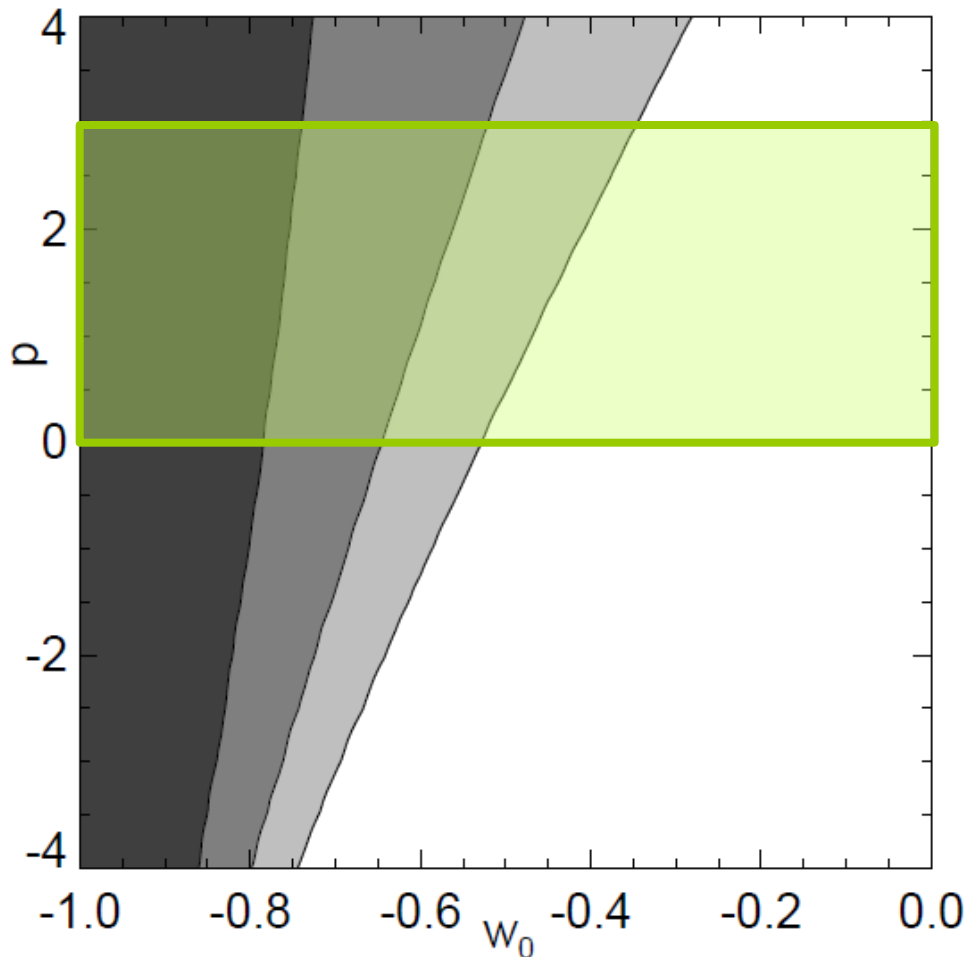
$$R \propto \sqrt{\Omega_m H_0^2} \int_0^{1089} \frac{dz'}{H(z')}$$

- **BAO:** location of comoving galaxy separation at $z=0.2, 0.35$

$$A(z) \propto \sqrt{\Omega_m H_0^2} H(z)^{-1/3} z^{-2/3} \left[\int_0^z \frac{dz'}{H(z')} \right]^{2/3}$$

Algebraic thawing model

three-parameters: Ω_m, w_0, p $1 + w(a) = (1 + w_0) a^p \left(\frac{1 + 0.3}{1 + 0.3 a^{-3}} \right)^{1-p/3}$



Good fit to combined data

$p \in [0, 3]$ $w_0 < -0.57$ (95%CL)

Models difficult to distinguish from Λ CDM

Require probes sensitive to w_0 and w_a