Supernoves i Cosmologia

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$$\boxed{\Lambda \sim 4 \cdot 10^{-84} GeV^2}$$

The magnitude which is governing the fate of the universe is that with the known smallest value in nature. Besides, variations on it imply very different history universes:

(The content of matter is $\Omega_M = 0.3$)

$\Lambda(10^{-84} GeV^2)$	$GEOMETRY$	$FATE$	q
~ -2	open	collapses	> 0
~ 0	open	collapses	> 0
~ 1	open	expands	> 0
~ 2	open	expands	< 0
~ 4	flat	expands	< 0
~ 6	closed	expands	< 0

SNe Ia try to distinguish these posibilites!!
(when the CC model is taken into account)

HOW?!

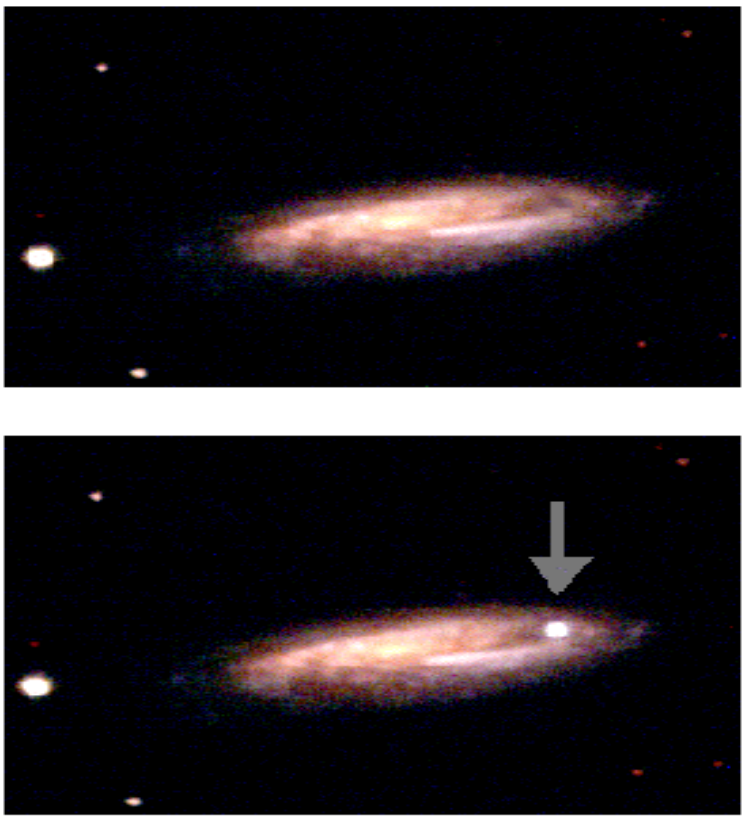
SUMMARY

- Introduction
- Determination of the cosmological parameters with SNe Ia
- Current state of research
- Dark energy
- Projects
- Conclusions

INTRODUCTION

Supernovae

A Supernova is an explosion of a star that makes its brightness grow till a value even grater than that of the entire galaxy.



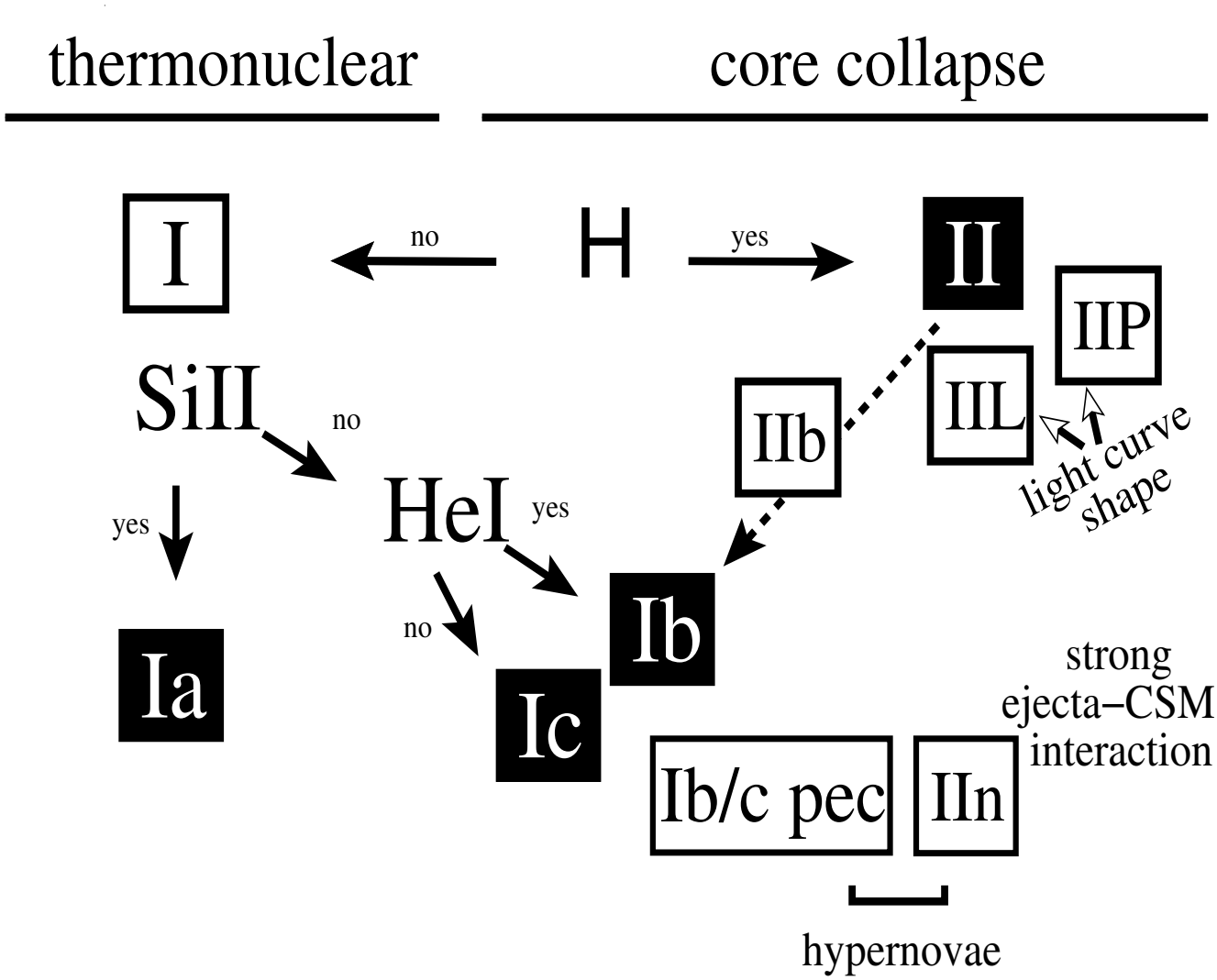
SN1998dh before and after the explosion

Classification

The first division was made by Minkowsky in 1941. It was purely observational.

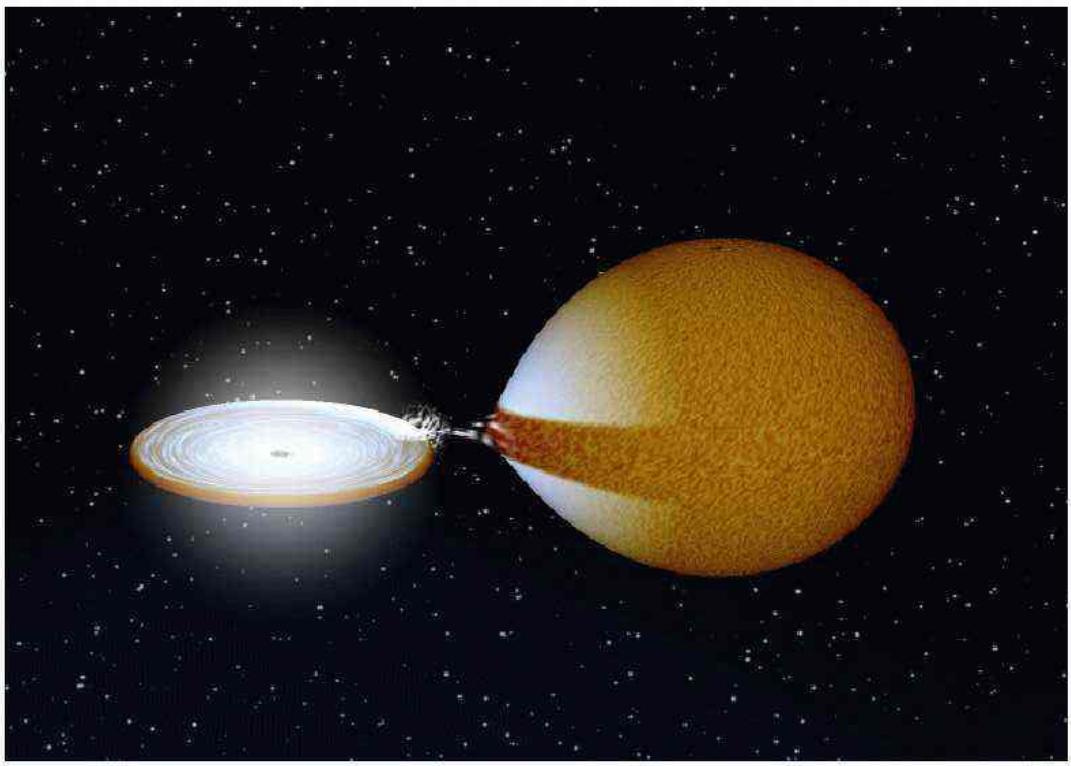
SNe	
Type I without H	Type II with H
SNe Ia (Si ∨)	SNe II-P
SNe Ib (He ∨)	SNe II-L
SNe Ic (Si X, He X)	SNe II-n
	SNe II-b

Actually, there are seven groups. The most accepted classification depends on the light curves and the spectra.



Massimo Turatto (astro-ph/0301107)

Physics of SNe Ia



Thermonuclear explosion of the degenerate core of a white darf of Carbon and Oxigen in a binary system. This mechanism makes the explosion brighter than those coming from a core colapse, so they will be favored respect the other types of SNe in high-z searches.

COSMOLOGY WITH SNe Ia

SNe Ia as standard candles. Light curves

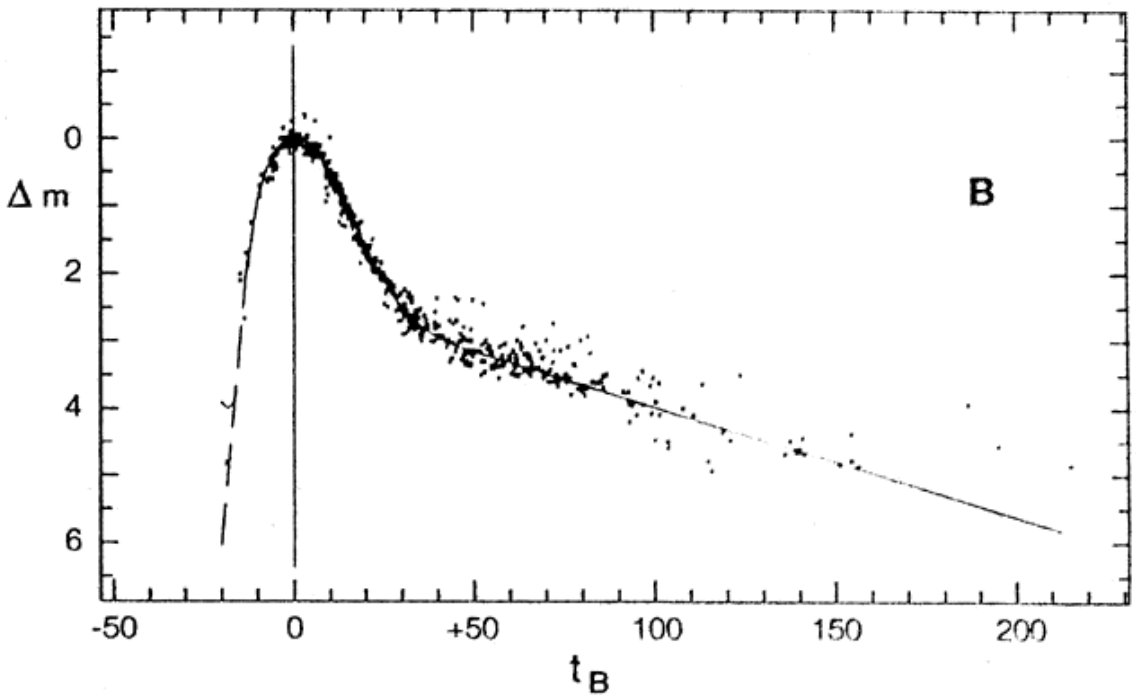
- Standard candles are objects whose absolute luminosity is exactly the same for the whole class. This fact allows to determine its luminosity distance once the aparent magnitude is known.

- In nature there are no standard candles at large distances, but if we are able to calibrate the absolute magnitude of a class of objects the result will be the same.

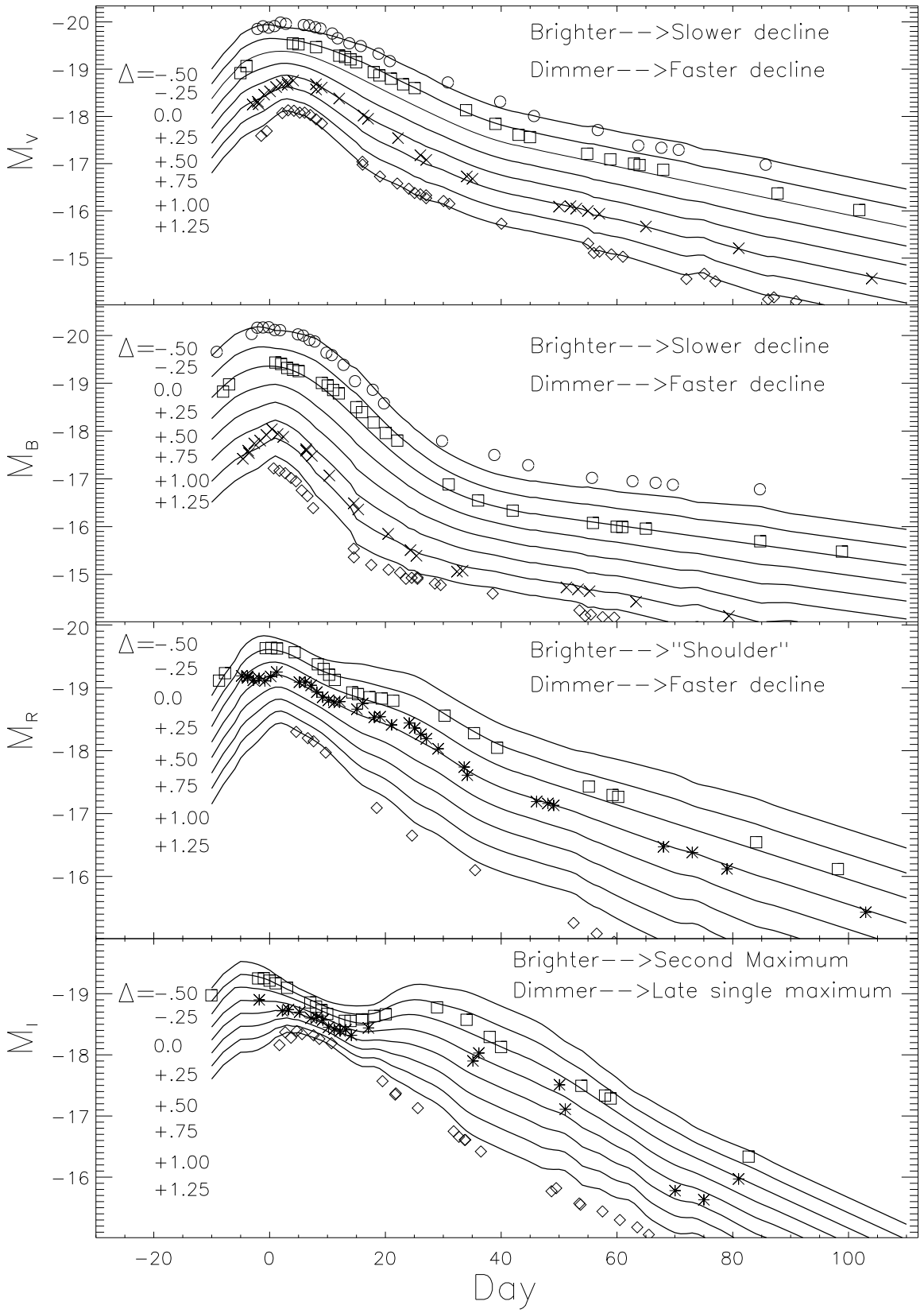
- Since 1912 when Henrietta Leavitt discovered the periodicity of the Cepheids diferent objects have been used as candles: Cepheids, RR Lyrae and SNe Ia.

- For SNe Ia, the dispersion in M_B^{peak} is less than 0.3mag (before corrections!):

Cadonau 1987 (Based on observations of 22 SNe Ia.)



The typical form of a light curve starts with a fast ascent of luminosity (the opacity descends as the matter expands) from the day of the explosion till its maximum. Then starts the decline (the radioactive energy diminishes), first with an strong slope (the decay of ^{56}Ni dominates) and then with a lighter one (the decay of ^{56}Co dominates).


Brighter−−>Slower decline
Dimmer−−>Faster decline
Δ=−.50
−.25
0.0
+.25
+.50
+.75
+1.00
+1.25
M_V
Brighter−−>Slower decline
Dimmer−−>Faster decline
M_B
Brighter−−>"Shoulder"
Dimmer−−>Faster decline
M_R
Brighter−−>Second Maximum
Dimmer−−>Late single maximum
M_I
−20
−19
−18
−17
−16
−15
−20
0
20
40
60
80
100
Day

Template-fitting methods

- Phillips relation (Δm_{15})
  It is an empirical linear relation between the absolute magnitude in the B band and the decay in magnitude of the light curve 15 days after the maximum.

  $m_{B,corr} = m_B + \Delta^{\{1.1\}}_{B,corr} = m_B + (-0.86 \pm 0.21)(\Delta m_{15} - 1.1)$

- Stretch factor (s)
  This method "stretches" the time axis from the light curve a factor $w = s(1+z)$ so that all the curves fit to a same "compound curve".

  $$m_{B,corr} = m_B + \alpha(s-1)$$

- Multicolor Light Curve Shape (Δ)
  Uses all the available color curves to fit the light curve together. The basic parameter (Δ) represents the number of magnitudes that the SN is brighter/fainter than some fiducial object.

  $$m_{B,corr} = m_B + \Delta$$

Note:

A fiducial object would have $\Delta m_{15} = 1.1$, $s = 1$ and $\Delta = 0$.

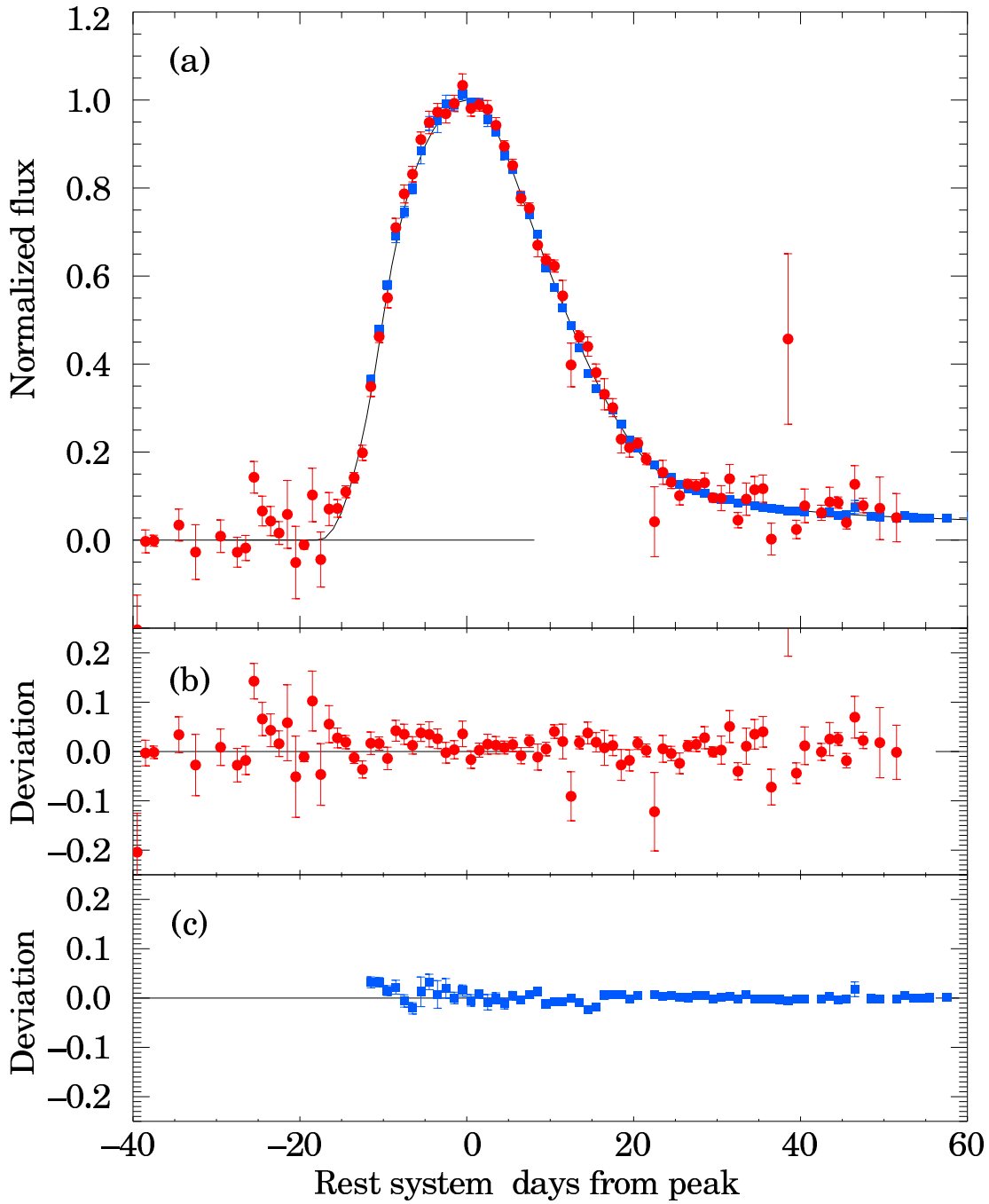


Figure 4: (a) The composite light curve and template for 35 SCP SNe (solid circles) and 18 (Calán/Tololo) SNe (solid squares). Here each point (i) from each of the SNe has been divided by $1 + z_i$ and by the stretch factor s_i. The data points shown have been averaged over all the SNe for each day relative to maximum light for the two data sets. (b) Residuals for the SCP photometry fits to a template, see reference 10. The epoch, between -40 and -20 days, has no SN signal. The large scatter observed comes from the reference images which have shorter exposures and hence larger errors. (c) Residuals for the Calán/Tololo photometry fits to the template.

Observational data and corrections

Observationaly we can get the magnitude of the SN at the peak of the light curve for an specific filter, but this value must be corrected so as it can be used:

$$\mathrm{m}_B^{eff}(\alpha) = m^{peak}{}_X + \alpha(s-1) - K_{BX} - A_X$$

Observed band,
Stretch factor correction,
Correction due to the change of band,
Galactic extinction.

With these corrections we are not considering neither extinction due to dust nor an evolution in the SN. Is this important?
(Answer: SN 1997ff)

Magnitude-redshift relation

$$\mathrm{m}^{th}(z,\Omega_M,\Omega_\Lambda) = M + 5log(H_0 d_L(z,\Omega_M,\Omega_\Lambda)) - 5logH_0 + 25 \equiv \mathcal{M} + 5log(D_L(z,\Omega_M,\Omega_\Lambda))$$

$$\mathrm{d}_L(z,\Omega_M,\Omega_\Lambda) = \frac{c(1+z)}{H_0\sqrt{\Omega_k}}\Psi\left(\sqrt{\Omega_k}\int_0^z \frac{dz\prime}{H(z\prime,\Omega_M,\Omega_\Lambda)}\right)$$

where,

$$\mathrm{H}(z,\Omega_M,\Omega_\Lambda) = \sqrt{\rho_M(z)+\rho_\Lambda(z)+\rho_k(z)} = \sqrt{\Omega_M(1+z)^3+\Omega_k(1+z)^2+\Omega_X(1+z)^{3(1+w)}}$$

$$\Psi(x) = \begin{cases} sin(x), & \Omega_k = 1-\Omega_M-\Omega_\Lambda & if \quad \Omega_M+\Omega_\Lambda > 1 \\ sinh(x), & \Omega_k = 1-\Omega_M-\Omega_\Lambda & if \quad \Omega_M+\Omega_\Lambda < 1 \\ x, & \Omega_k = 1 & if \quad \Omega_M+\Omega_\Lambda = 1 \end{cases}$$

$$\mathrm{p} = \mathrm{w}\ \rho$$

$w = -1 \Rightarrow Cosmological \quad constant,$

w=-1/3 $\Rightarrow strings,$

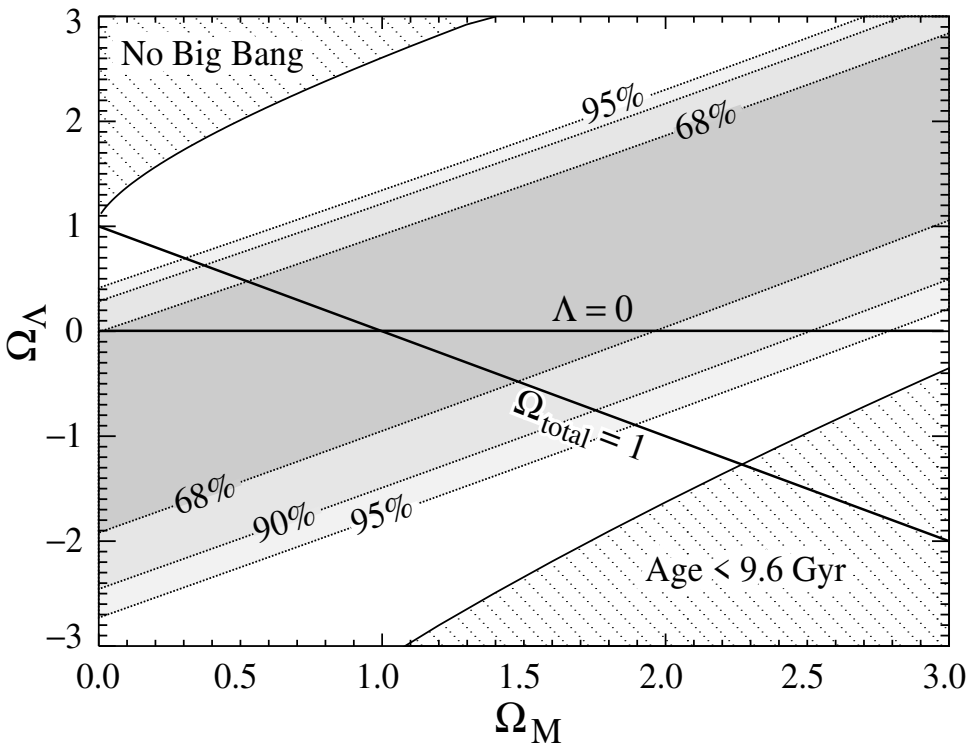
w=-1/3 $\Rightarrow textures,$

w=-2/3 $\Rightarrow walls.$

First results (1996)

Seven SNe Ia at $z > 0.3$

(Supernova Cosmology Project)



$$\chi^2(\alpha, \mathcal{M}, \Omega_M, \Omega_\Lambda) = \sum_i \frac{\left(m_i^{th}(\mathcal{M}, \Omega_M, \Omega_\Lambda) - m_i^{eff}(\alpha)\right)^2}{\sigma_i^2}$$

$$\Downarrow$$

$\mathcal{M}$, α : fitting with low-z SNe oder marginalizating

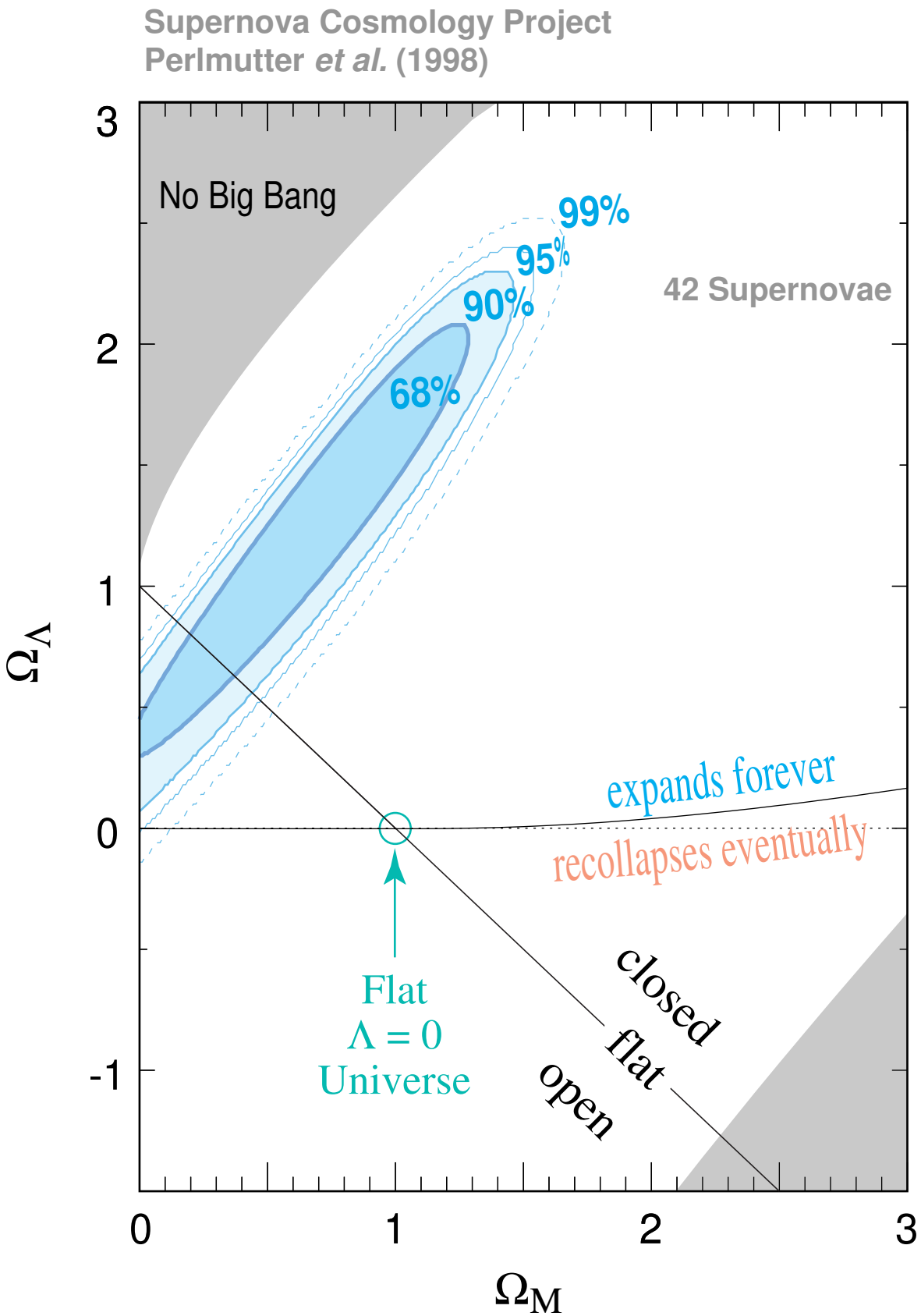
$$\chi^2(\Omega_M, \Omega_\Lambda) = \sum_i \frac{\left(\tilde{m}_i^{th}(\Omega_M, \Omega_\Lambda) - \tilde{m}_i^{eff}\right)^2}{\sigma_i^2}$$

Results from 1998-1999: The universe accelerates!

- Two groups (Supernova Cosmology Project and High-z Supernova Search Team) announced independently in 1998 the first conclusions from a considerable number of high-z SNe.

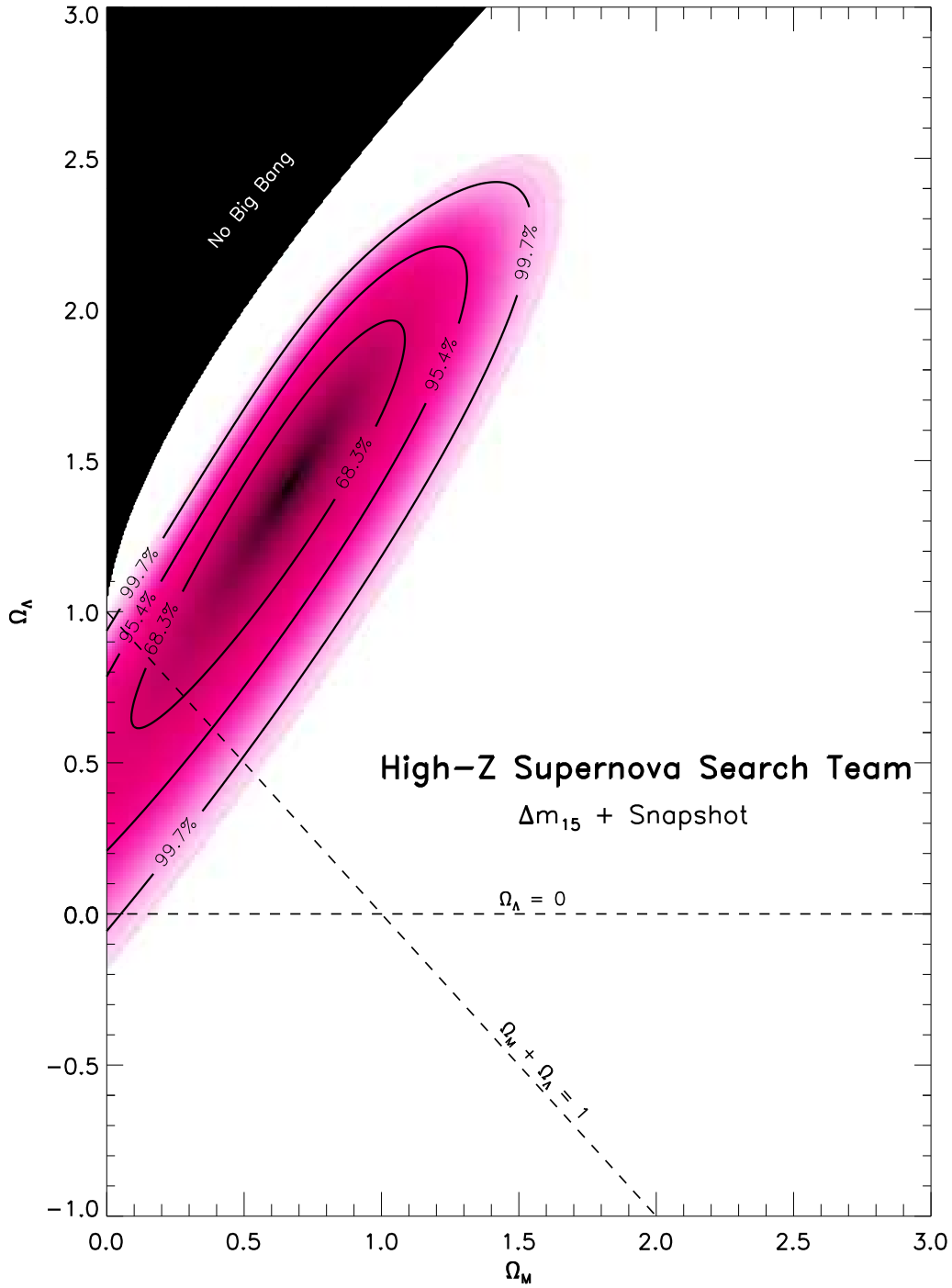
- Both of them use the 29 low-z SNe from the Calán–Tololo but the high-z SNe were discovered with own methods. As the processing of the data is also different, the results are independent.

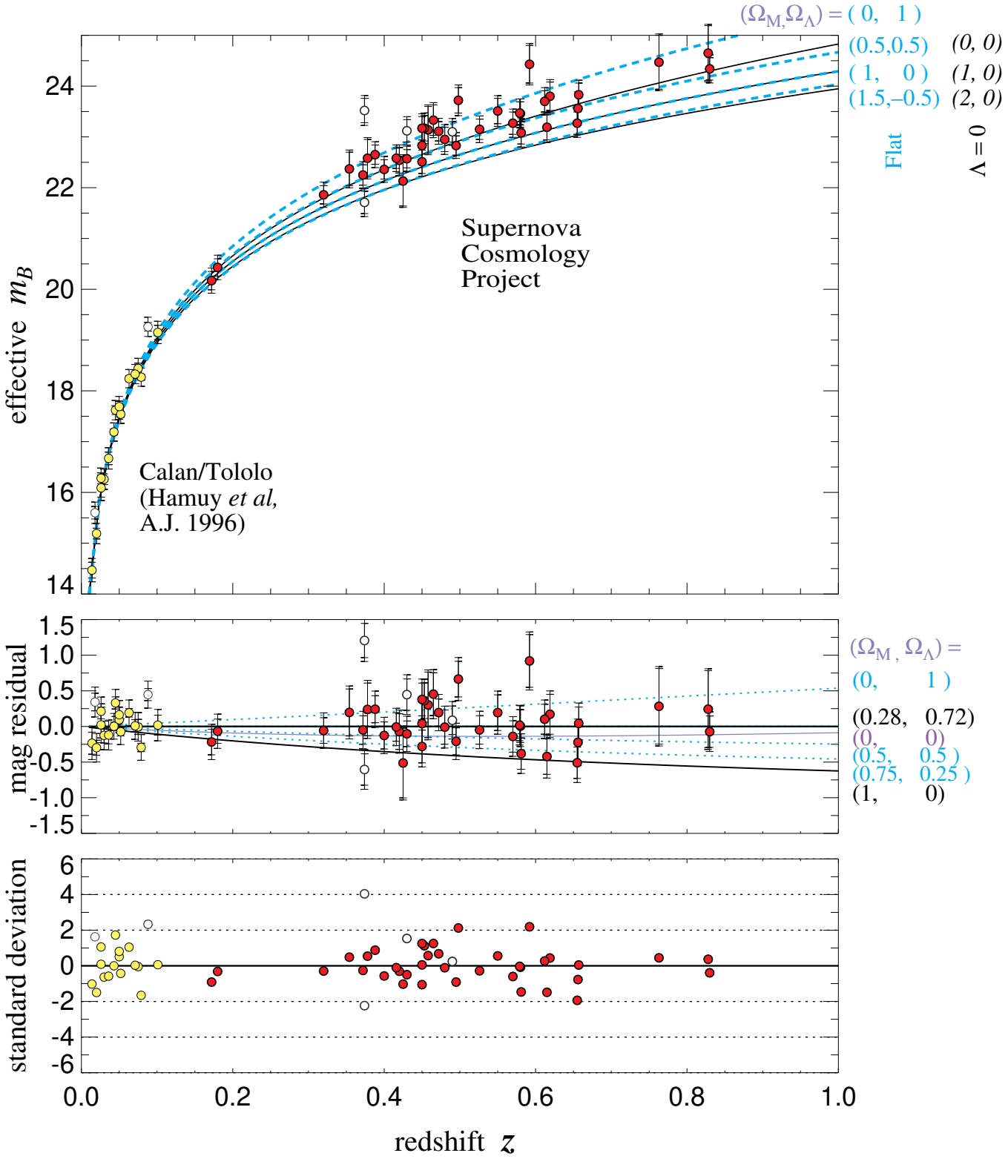
- In spite of this, the results are similar: the universe is now dominated by an energy component with negative presure which makes the expansion being accelerated at the present epoch. This kind of energy is called dark energy.


Supernova Cosmology Project
Perlmutter *et al.* (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
3
2
1
0
-1
0
1
2
3
Ω_Λ
Ω_M

High-Z Supernova Search Team

Riess *et al.* *(1998)*





Perlmutter, *et al.* (1998)

The cosmological constant

What are saying SNe about the cosmological constant? Let's take the results from SCP and consider $h_0 = 0.65$:

Best fit:

$$\Omega_M = 0.73, \quad \Omega_\Lambda = 1.32$$

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \quad \Longrightarrow \quad \Lambda \sim 8 \cdot 10^{-84} GeV^2$$

Best fit for a flat universe:

$$\Omega_M = 0.28, \quad \Omega_\Lambda = 0.72$$

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \quad \Longrightarrow \quad \Lambda \sim 4 \cdot 10^{-84} GeV^2$$

CURRENT STATE OF RESEARCH

Systematic errors

Basically four systematic error sources were analyzed by the two groups mentioned before:

- Extincion due to the host galaxies or inter-galactic medium.
- Evolution in redshift from SNe.
- Selection bias as effect of flux-limited surveys.
- Sample contamination at high-z where the the most distinctive features in spectra are redshifted out of the observed band.

The last two were considered to be insignificant, and although colour curves do not favor the first two, more work is being done on this.

Gray dust

Since the principal effect that suggest a positive cosmological constant is that we see SNe dimmer than expected, could that be caused by dust?

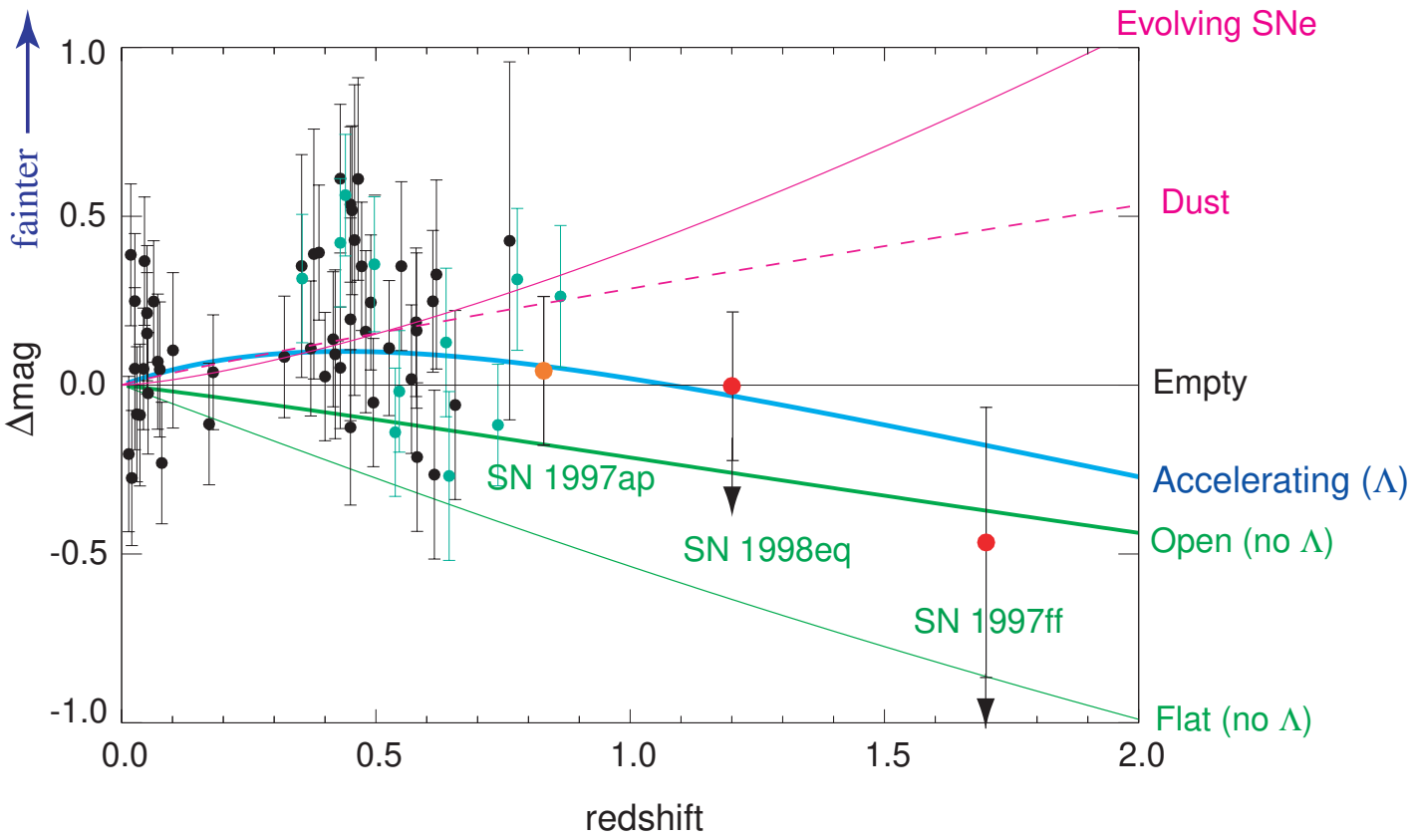
- Ordinary dust is descarted because it only absorbs the bluer parts of the spectra and that's contrary to observations.

- It has been proposed the existence of a gray dust responsable of an homogeneous absorption.

SNe Ia at $z > 1$ can test this hypothesis: in case there has been a change in the sign of the deceleration parameter, SNe which exploded in the deceleration era would be brighter.

The observed magnitude of SN1997ap ($z \simeq 0.8$), SN1998eq ($z \simeq 1.2$) and definitively SN1997ff ($z \simeq 1.7$) discarded the presence of this kind of dust and other alternatives as evolution at 3σ level.

Supernovae probing
the *deceleration* era
in the near-IR

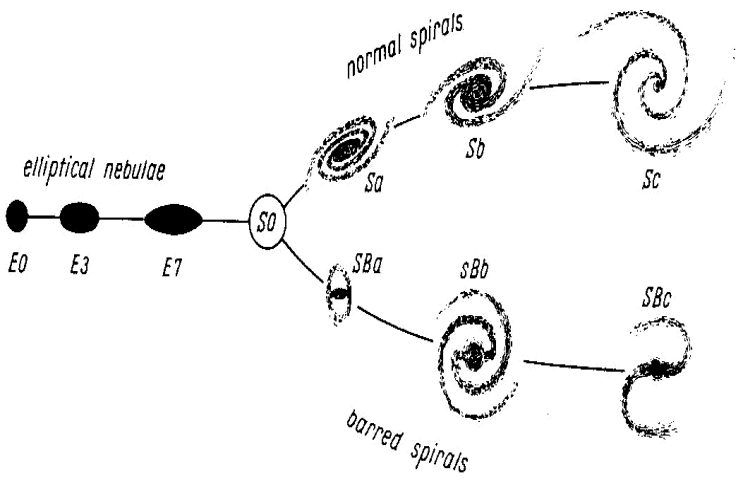


Morphologic analysis

M.Sullivan *et al.* *(astro-ph/0211444)*

In order to quantify the host galaxy extinction the fits have been done segregating the distant SNe Ia according to the types of host galaxy:

- E/S0. Spheroidal galaxies.
- Early. Early type spiral (from Sa to Sbc in the Hubble classification).
- Late & Irr. Late type spiral (from Sbc to irregulars in the Hubble classification).



$\longrightarrow$

- dust
+ age

+ dust
- age

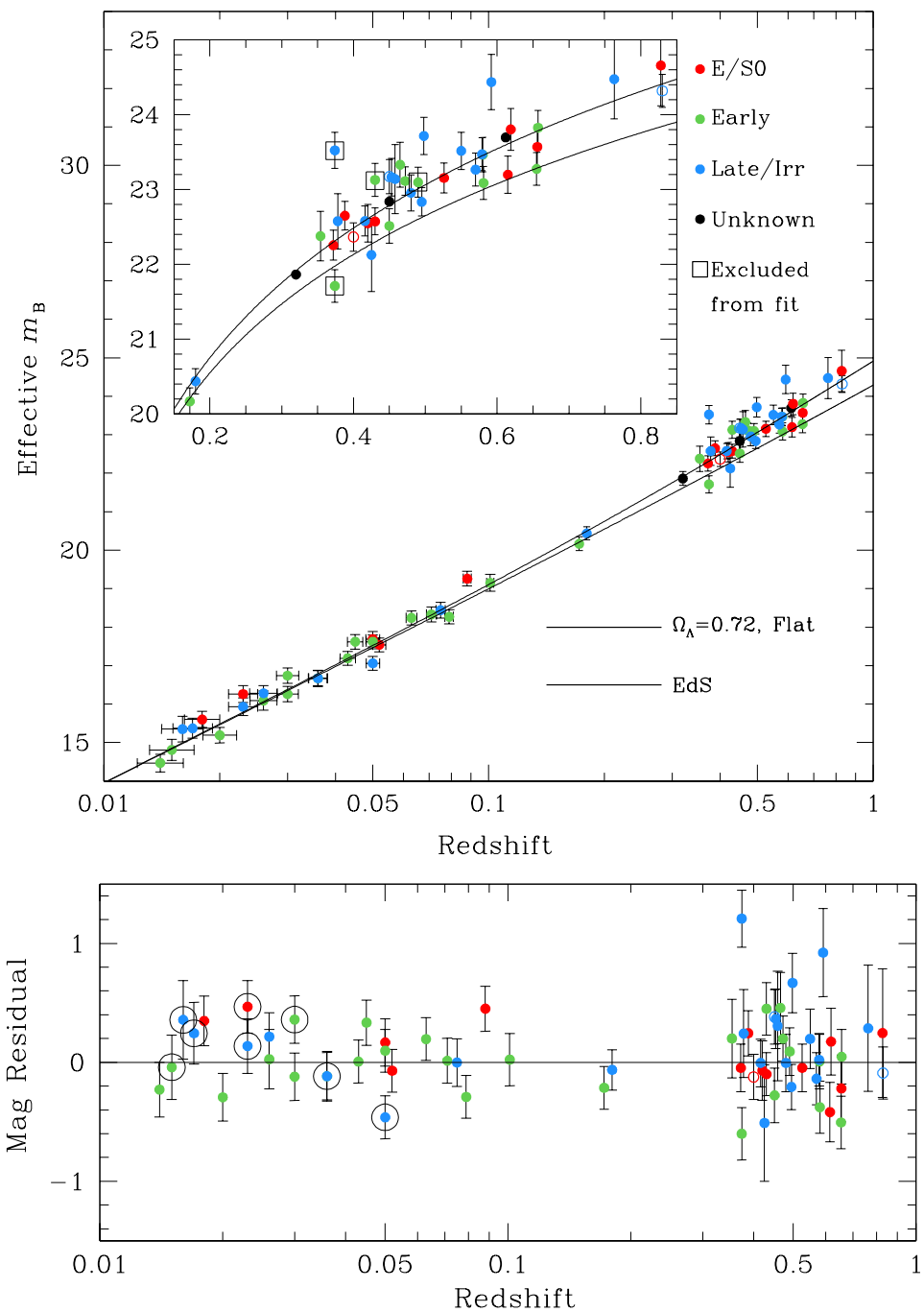


Figure 4. UPPER PANEL: The stretch-corrected SNe Ia Hubble diagram plotted according to the class of the host galaxy. The inset shows the high-redshift SNe, the main panel the Hubble diagram for the entire sample. Boxed points show SNe excluded from the P99 solution. **LOWER PANEL:** The residuals from the adopted cosmology ('fit-C' of P99) for both high and low-redshift SNe.Dotted-circled points discriminate between CfA SNe and C-T SNe. In both panels unfilled circles denote galaxies with a less secure type-classification.

Results

- Spheroidal galaxies are those with less dispersion. It is attributed to the lack of dust.

- Spiral galaxies host redder and fainter SNe. There, the extinction must be greater.

- Studying the location of the SNe in the host galaxy it is seen that SNe far away from the core show less dispersion. Once again, it is atributed to dust. Albeit, this segregation is less clear than the previous one.

- Although all the sub-samples favor a positive cosmological constant, the most "standard candles SNe Ia" (those in spheroidal galaxies) discard at 5σ level a zero cosmological constant in a flat universe (otherwise almost 3σ).

New high-z Sne Ia data

R.Knop *et al. (in preparation)*

- The Hubble Space Telescope (HST) observed 11 new SNe Ia with $0.36 < z < 0.86$.

- These data confirm the previous results:

  - Low-z + HST SNe: Similar results as the main fit in Perlmutter 99 in spite of using independent methods. The confidence regions are a bit wider due to the smaller number of SNe.

  - Low-z + High-z P99 + HST SNe: Similar results with narrower regions and best fit closer to the flat case.

- The results from CMB are still necessary to say something about the geometry of the univese.

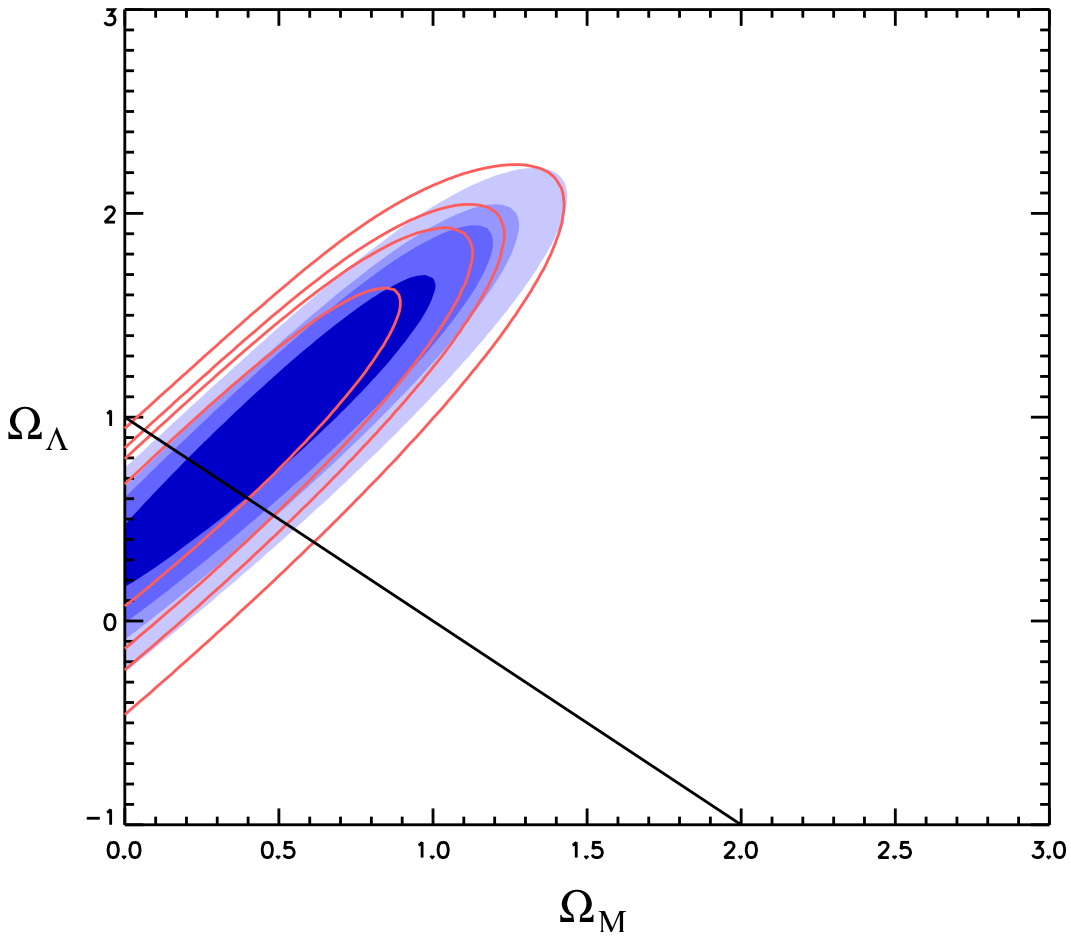


Fig. 3.— 68%, 90%, 95%, and 99% confidence regions in the Ω_M/Ω_Λ for fits (b) and (f) of Figure 2 and Table 4. Fit (b) is shown in solid contours; this fit included 8 of the HST supernovae from this paper in addition to the "Case C" supernovae of Perlmutter *et al.* (1999). Host galaxy extinction was handled by omitting supernovae with significant reddening; see Section 3. Fit (f) is shown in solid lines; this fit explicitly applied E(B-V) corrections from measured R-I colors and uncertainties, using the U-enhanced template to provide expected R-I colors for each supernova. These fits provide the strongest constraints on cosmology from SN Ia data available to date.

DARK ENERGY

Testing different theories

Equation of state. Quintessence

The equation of state of most candidates to dark enegy is described by the parameter w,

$$p = w\rho$$

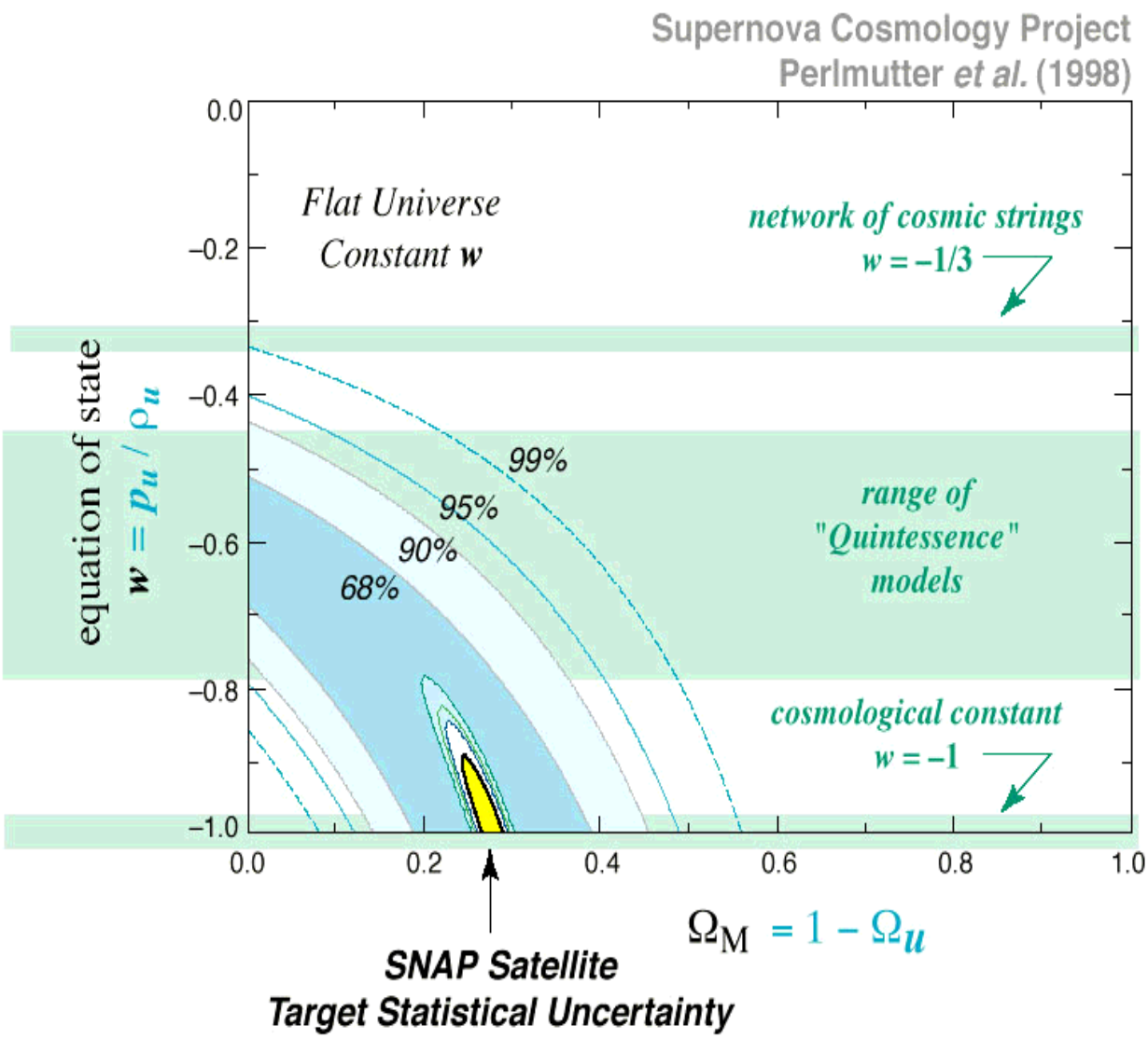
There are alternatives to this equation. For the Chaplygin gas the equation of state reads, $p = \frac{\tilde{w}}{\rho}$.

The magnitude-redshift relation can be written as a function of w, this way, w is considered a new parameter to determine, and it is the one that best describes 'what' is the dark energy. But w is not necessary constant, in fact, an expansion to first order of,

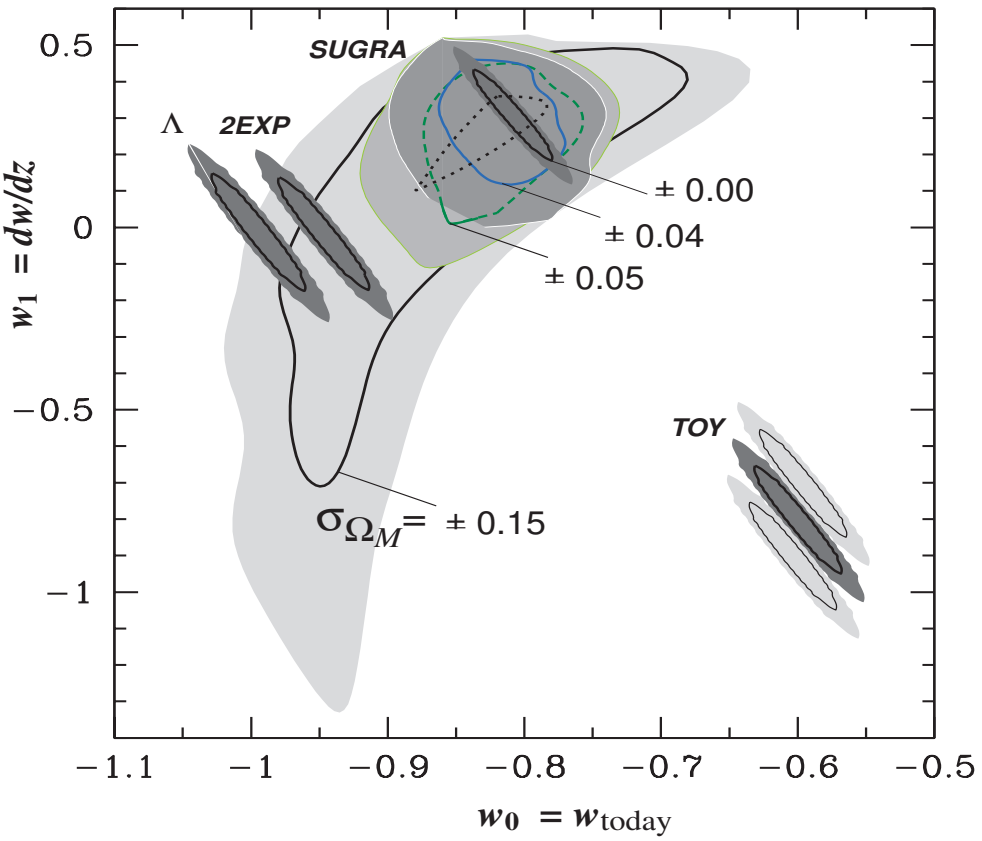
$$w = \sum w_i (1+z)^i$$

$$i.e., \qquad w = w_0 + w_1(1+z), \qquad w_1 = \frac{dw}{dz},$$

is an habitual form to test the nature of dark energy.


Supernova Cosmology Project
Perlmutter et al. (1998)
Flat Universe
Constant w
network of cosmic strings
w = –1/3
range of
"Quintessence"
models
cosmological constant
w = –1
99%
95%
90%
68%
equation of state
w = p_u / ρ_u
0.0
–0.2
–0.4
–0.6
–0.8
–1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ω_M = 1 – Ω_u
SNAP Satellite
Target Statistical Uncertainty

J.Weller and A.Albrecht (2001)



$$TOY : w_0 = -0.6, w_1 = -0.8$$

$$\Lambda : w_0 = -1, w_1 = 0$$

$$SUGRA : V(Q) = \frac{\Lambda^{4+\alpha}}{Q^{\alpha}} e^{\frac{\kappa}{2}Q^2}$$

$$2EXP : V(Q) = {M_{\text{Pl}}}^4 (e^{\alpha(Q-A)} + e^{\beta(Q-B)})$$

(Kaluza-Klein compactification in string theory)

Other models can not and will not be able to be distinguished neither with current nor with future data.

Testing brane theories
An example: Brane-induced gravity models

The universe where we live is a 4D brane embedded into a bulk space-time (5D in this case).

This kind of models have a crossover scale:

$$r_c \equiv \frac{M_{Pl}^2}{2M_{(5)}^3}$$

$$r < r_c \Longrightarrow F \sim \frac{1}{r^2} \quad 4Dgravity$$

$$r > r_c \Longrightarrow F \sim \frac{1}{r^3} \quad 5Dgravity$$

r_c must be of order H_0^{-1} so that it agrees with cosmology observations (BBN, CMB, SNe Ia). This requirement implies $M_{(5)} \sim 10 - 100 MeV$.

(taking $M_{(5)} \sim TeV$ $r_c \sim 10^{15} cm$ - the size of the solar system- but to this scale the gravitational effects are not observed.)

In order to test the model with SNe Ia the equivalent "Friedmann equation" must be given:

$$\mathrm{H}^2 + \frac{k}{a^2} = \left(\sqrt{\frac{\rho}{3M_{Pl}^2} + \frac{1}{4r_c^2}} + \frac{1}{2r_c} \right)^2$$

and when the energy-momentum conservation is taken into account:

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

where Ω_k and Ω_α are defined as usually and

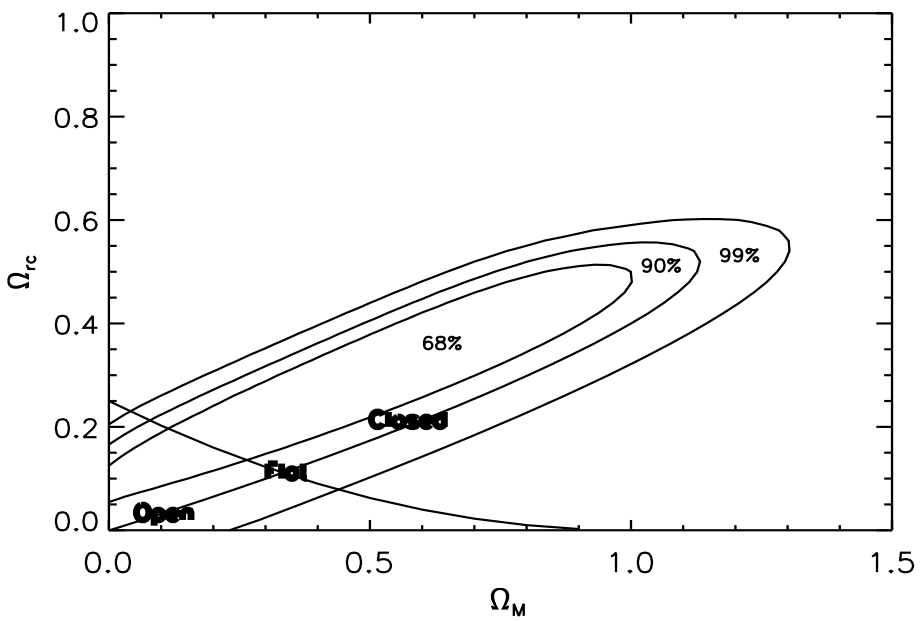
$$\Omega_{r_c} \equiv \frac{1}{4r_c^2 H_0^2}.$$

The constrain is now:

$$\Omega_k + \left(\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \sum \Omega_\alpha} \right)^2 = 1$$

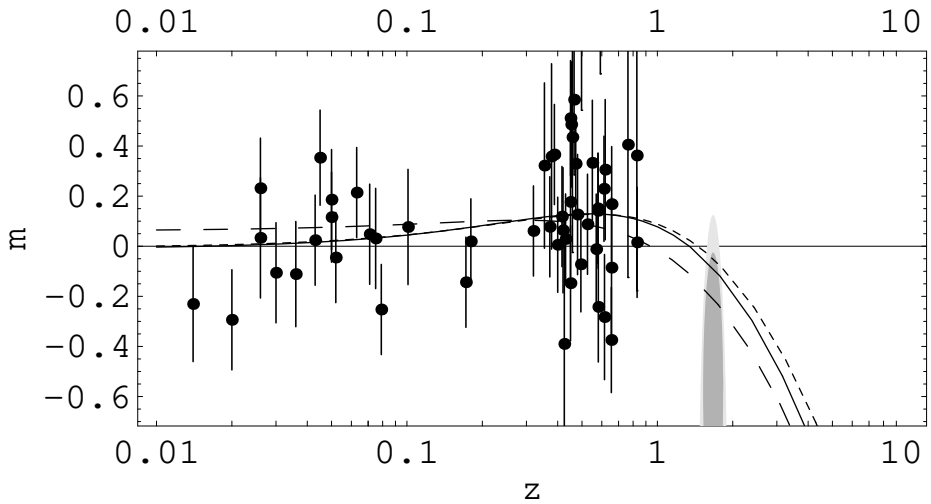
Note that for the flat case with only matter:

$$\Omega_{r_c} = \left(\frac{1-\Omega_M}{2} \right)^2$$



flat universe: $(\chi^2/dof = 1.12)$

$\Omega_M = 0.18,\ \Omega_{r_c} = 1.17,\ H_0 r_c \sim 1.2$



Brane I ($\Omega_M = 0.18$) dotted line, and brane II ($\Omega_M = 0.3$) dashed line. Solid line: usual $\Omega_M = 0.28$.

Running of the cosmological constant

Aproach: Consider the CC as a running parameter in a semiclassical formulation of the gravitational field equations with quantum effects computed via the Renormalization Group Method.

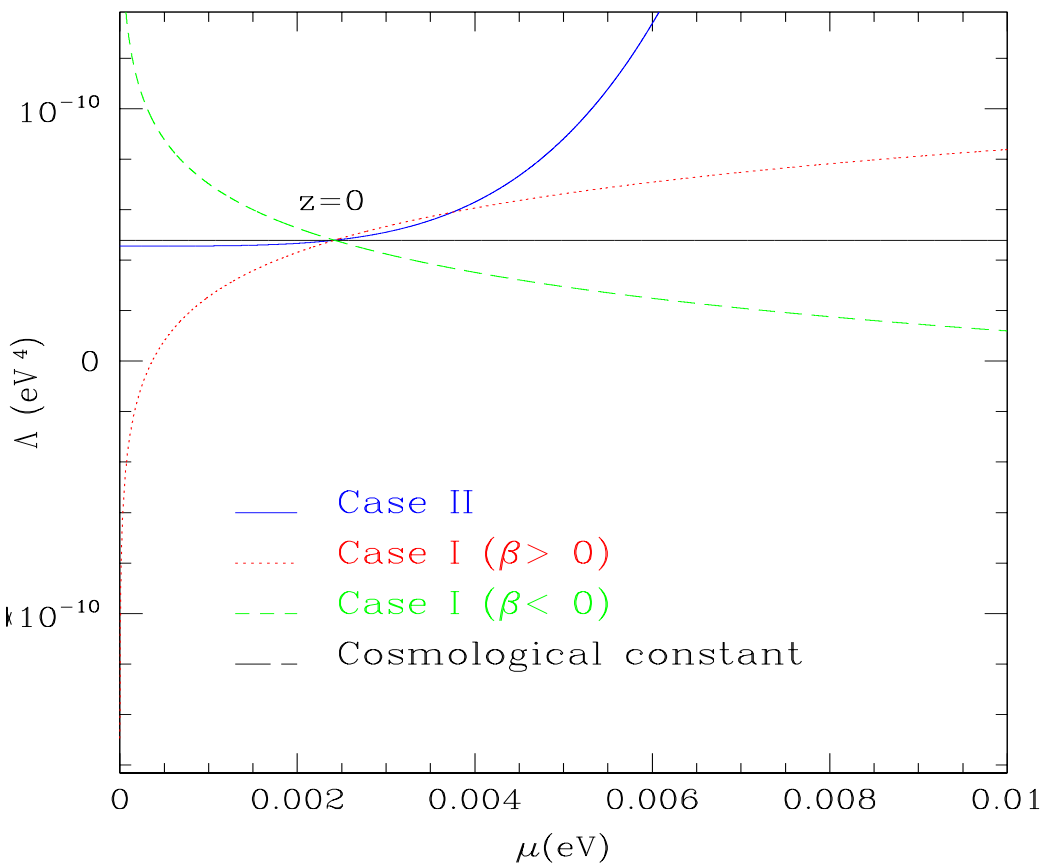
- Case I (I.Shapiro and J.Solà)
  RGE with SM's fields. In the aproximation at low energies only the particles with $m < \mu$ contribute:

$$(4\pi)^2 \frac{d\Lambda_{ph}}{dln(\mu)} = \beta_\Lambda = \frac{1}{2} m_S^4 - 4 \sum m_i^4$$

- Case II (A.Babić et al.)
  RGE with SM's fields. In the aproximation at low energies particles with $m > \mu$ have a larger contribution than those with $m < \mu$:

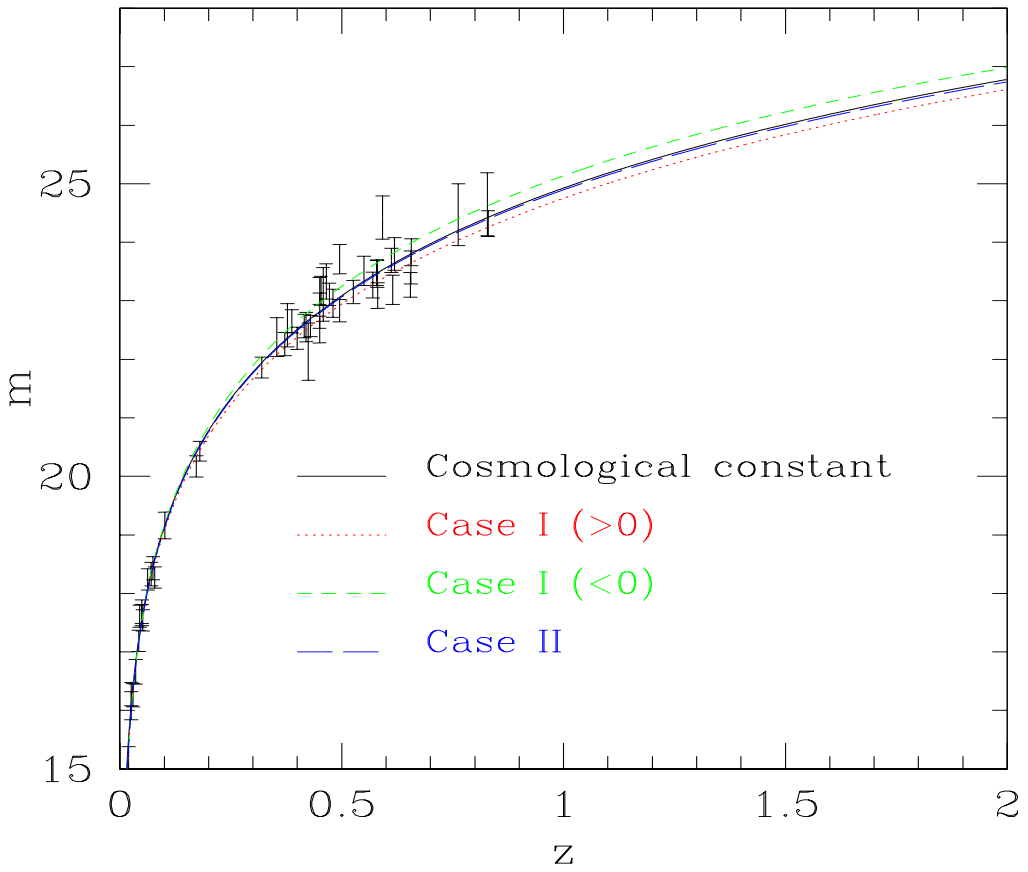
$$(4\pi)^2 \frac{d\Lambda_{ph}}{d\mu} = \beta_\Lambda = 4 \left[\frac{1}{2} \sum N_i - \frac{5}{4} \right] \mu^3$$

With these evolutions any possible fate of the universe is covered. Once again, SNe data will help to discard options.



Note that models differ significantly one from each other from $\mu \sim 0.004eV$ on. For ρ as energy scale this means $z > 2$.

After choosing an energy scale, the corresponding RGE can be written as a function of redshift, and now, with the only change of $\Lambda \Rightarrow \Lambda(z)$ the "new" Friedmann equation is obtained.



(Models showed here are NOT the best fits, they are only representative cases.)

Some results:

↪ Case I

- The existence of a scalar field is not discarded (not even at 1σ level) although a very small value of it or its absence are favored.

- If this scalar field is not considered one can fit the neutrino mass. Then $m_\nu \sim 0.005eV$ is found.

↪ Case II

- The only parameters to fit in this model are the usual Ω_M and Ω_Λ. Very close results to the CC case are obtained with a comparable χ^2.

- Artificial fits on $\sum N$ allows to think in a favored supersymmetric model.

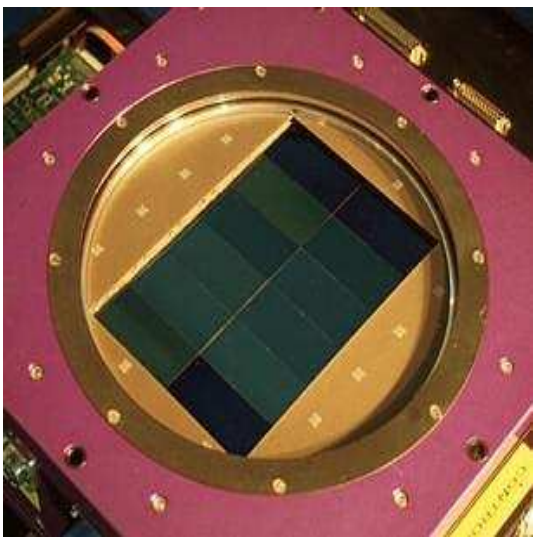
PROJECTS

Nearby Supernova Factory

Start:	Already operating
Results:	300 SNe Ia at low-z
Objective:	Physics of SNe Ia
Methode:	SNe are discovered using asteroid search images from the NEAT project.
Improvements:	New spectrograph SNIFS (Supernova Integral Field Spectrograph). It will simultaneously obtain 225 spectra of the SN, galaxy host and near field.

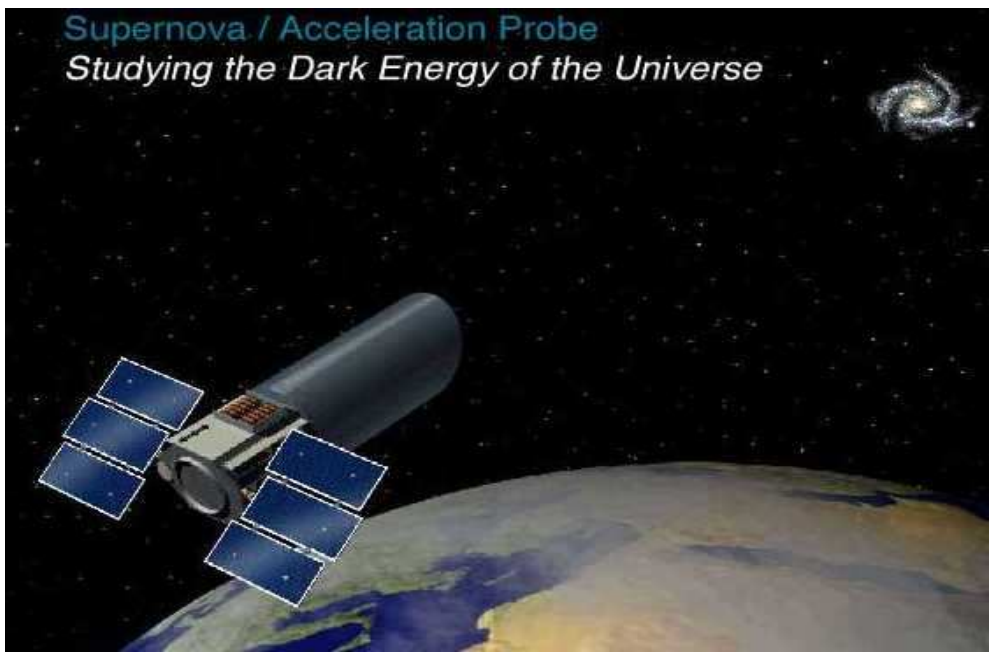
CFHT Legacy Survey

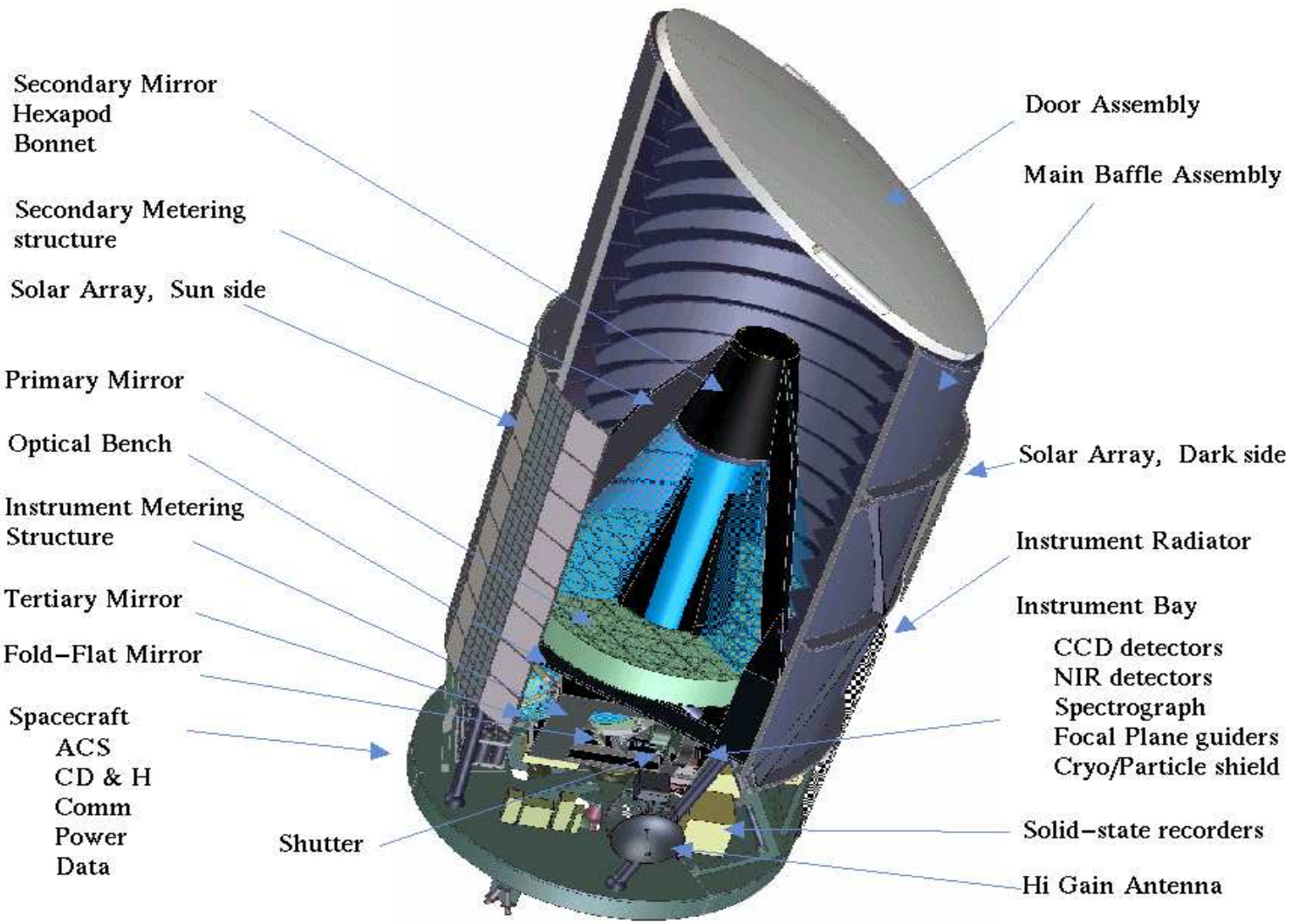
Start:	2003
Periode:	5 years
Results:	700 SNe Ia at $0.3 < z < 0.9$ in the deep survey
Objective:	Mesure w_x ($\sigma_w \sim 0.1$) $\sigma_m \sim 0.03$

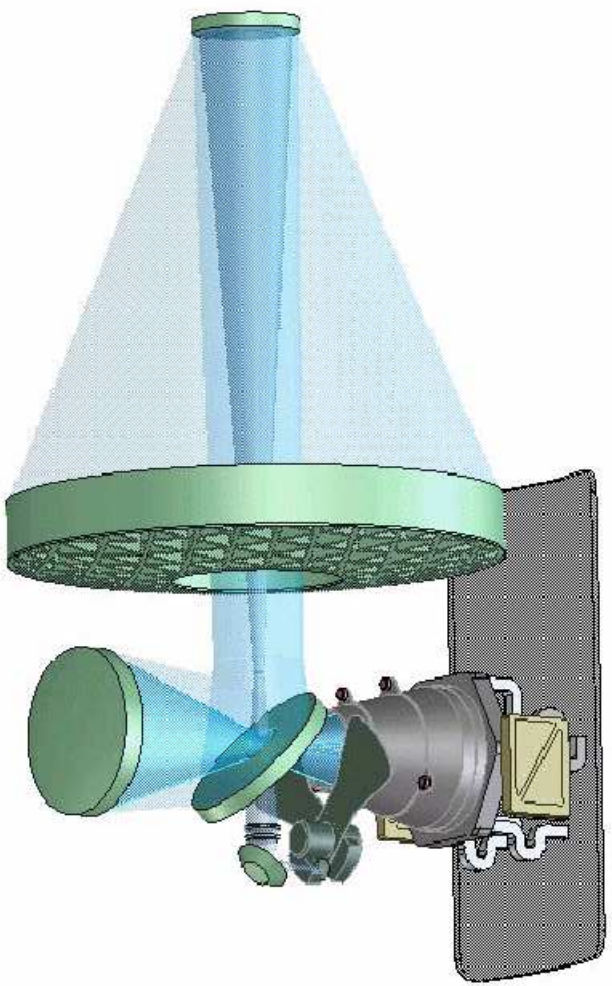


SNAP

Start:	2009
Periode:	3 years
Results:	2000 SNe Ia at $0.1 < z < 1.7$ per year
Objective:	Mesure w_1 $\sigma_m, \sigma_\Lambda < 0.02$




Secondary Mirror
Hexapod
Bonnet
Secondary Metering
structure
Solar Array, Sun side
Primary Mirror
Optical Bench
Instrument Metering
Structure
Tertiary Mirror
Fold-Flat Mirror
Spacecraft
ACS
CD & H
Comm
Power
Data
Shutter
Door Assembly
Main Baffle Assembly
Solar Array, Dark side
Instrument Radiator
Instrument Bay
CCD detectors
NIR detectors
Spectrograph
Focal Plane guiders
Cryo/Particle shield
Solid-state recorders
Hi Gain Antenna



Telescope is a three-mirror anastigmat

- 2.0 meter aperture
- 1.37 square degree field

Lightweight primary mirror

Low-expansion materials

Optics kept near 290K

Transverse rear axis

Side Gigacam location

- passive detector cooling
- combines Si & HgCdTe detectors

Spectrometers share Gigacam focal plane

Few moving parts in payload

- two-blade shutter for Gigacam
- focussers/adjusters at secondary & tertiary

CONCLUSIONS

- Dust in host galaxies can redden SNe. To avoid this we should use SNe Ia in spheroidal galaxies for cosmological purposes, although not discriminating them does not alter the conclusions significantly.

- Once we have a sample of standard candles, we can obtain the first results: our universe is being accelerated due to the presence of a kind of dark energy with a negative pressure. But Sne Ia by itself do not favor any universe geometry. We will have to wait till SNAP data is available to have an independent result to contrast with CMB.

- There are some alternative models to a pure CC which are consistent with SNe Ia data but still not favored by them. Others can be refused by this analysis.