PROCEEDINGS OF SCIENCE

Cosmology from type Ia supernovae

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Several experiments use the observations of type Ia supernovae to probe the expansion history of the history, in order to pin down the properties of dark energy. In this lecture, I will explain how this is done, discuss some of the problems encountered in this field, and present some of the perspectives for the next decade.

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[*] Speaker.

Foreword

The following notes correspond to a 90 minutes lecture, aimed at students who are not familiar with the field. They are *not* intended to be a review, but instead to present some of the problems encountered when one tries to use supernovae to do cosmology. There is a lot of personal bias in these notes, and other researchers in the field would probably have made different choices. In order to follow more closely the spirit of a lecture, the bibliographic references have been included as hyperlinks in the pdf version. Just click.

1. Introduction

1.1 Experimental tests of cosmology

Cosmology describes the expansion of a homogeneous and isotropic Universe (this hypothesis is called the Cosmological Principle), on which density and curvature inhomogeneities can form and grow, to form galaxies and clusters. The validity of this approach can be discussed (e.g. see [astro-ph/0605632], but we will stick to it in these lectures, as most people usually do in this field.

1.1.1 Observables in cosmology

A homogeneous and isotropic Universe is described by the Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = c^2dt^2 - R^2(t)\left[dr^2 + S_k^2(r)d\Omega^2\right] \tag{1.1}$$

where the expression of S_k depends on curvature ($k = 0$, -1 ou 1),

$$S_k(r) = \begin{cases} \sin r \\ r \\ \sinh r \end{cases} \tag{1.2}$$

The r, t and Ω coordinates are not identical to the usual coordinates of special relativity, and the cosmological frame is not an inertial frame. From there, one must find quantities that can be measured with meter sticks and clocks, on Earth. For instance, the frequency ν and the energy flux of the radiation we receive from a distant source, or the angle between two light rays received from an observer. One usually uses the **redshift** z, the luminosity distance d_L and the angular distance d_A.

The redshift is defined as

$$1 + z \equiv \frac{\nu_0}{\nu} \tag{1.3}$$

where ν_0 stands for the frequency measured in the restframe of the emitter, which is well defined for a given spectral line, for instance. The luminosity distance and the angular distance are defined as

$$d_A \equiv \frac{1}{1+z}R_0S_k(r) \quad \text{and} \quad d_L \equiv (1+z)R_0S_k(r) \tag{1.4}$$

The interpretation of the luminosity distance – we will not talk about angular distance anymore – is very clear: the bolometric flux received from an object located at fixed comobile coordinate r (an objet *at rest*) reads

$$\mathscr{F} = \frac{L}{4\pi d_L^2(z)} \tag{1.5}$$

This expression involves the coordinate r and the redshift z, which are not independent. They are related through

$$R_0\,dr = \frac{c}{H(z)}\,dz \tag{1.6}$$

Thus, using Eq. 1.4 and 1.6 one may directly infer $H(z)$, i.e. the history of the cosmological expansion, from measurements of $d_L(z)$.

It turns out that this quantity $H(z)$ is very important, as it is determined by the content of the Universe, through Friedmann equations

$$\left(\frac{\dot R}{R}\right)^2 = \frac{8\pi G\rho}{3}\rho + \frac{k}{R^2} \quad \text{and} \quad \frac{\ddot R}{R} = -\frac{4\pi G}{3}\left(\rho c^2 + 3p\right) \tag{1.7}$$

In this equation, ρ and p evolve in time. We can separate different contributions, from matter, radiation, cosmological constante, and so on. For each species, pressure p and density ρ are related by an equation of state, denoted $\alpha \equiv p/\rho$. By applying the first principle of thermodynamics[1] to an expanding volume V, we find that

$$d(\rho V) = -p\,dV \tag{1.8}$$

When α is constant during the expansion, one has

$$\rho = \rho_0(1+z)^{3+3\alpha} \tag{1.9}$$

Let focus on several particular cases:

- For nonrelativistic matter, $\alpha = 0$, so that $\rho \propto R^{-3}$, as naively expected: during expansion, the number of particles contained within the volume $V = R^2$ is conserved;
- For radiation (or ultrarelativistic matter), $\alpha = 1/3$, so that $\rho \propto R^{-4}$. The redshift contributes to another factor of $1+z \propto 1/R$ to the dilution of energy density;
- For a cosmological constant, density is constant by definition so that $\alpha = -1$. The corresponding equation of state reads $p = -\rho$.

In this last case, equation 1.7 shows that $\ddot R > 0$, expansion is accelerated. This is true for any equation of state for which $\alpha < -1/3$. It turns out that this acceleration is actually observed today in the Universe. One way to account for it is to suppose the existence of a component with an equation of state having $\alpha < -1/3$. This component is called **dark energy**, and the parameter α is traditionnally denoted as w. The nature of this dark energy is unknown. One of the goals of observational cosmology is to test this hypothesis and to provide as much information about this dark energy as possible, in order to guide or to constrain the different theoretical models supporting it.

When the parameter w is constant, the relation between r and z reads

$$R_0\,dr = \frac{c}{H(z)}\,dz = \frac{c}{H_0}\left[(1-\Omega)(1+z)^2 + \Omega_v(1+z)^{3+3w} + \Omega_m(1+z)^3 + \Omega_r(1+z)^4\right]^{-1/2} dz \tag{1.10}$$

However, note that w may depend on z: the relation $p = w\rho$ does not imply that p depends linearly on ρ. One should instead consider that w is defined as $w(z) \equiv p(z)/\rho(z)$.

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[1] This simple demonstration relies on nonrelativistic arguments and is a bit too naive to be rigourous. The results are correct, though.

1.1.2 Some words about negative pressure

Dark energy is defined by an equation of state involving a negative pressure. This may sound weird, but this situation is not uncommon in physics. When pressure is viewed as a force per unit area acting on a vessel wall, a negative pressure corresponds to the situation where the walls are attracted inwards. This happens to ordinary fluids in particular conditions (e.g. during a change of state). For instance, one may pull water with a piston closing a vessel containing only liquid water. If one pulls hard enough to exert a pressure overbalancing atmospheric pressure, the water will be in a negative pressure state. Very high negative pressure can be obtained this way. For water, this state is metastable and can undergo a phase transition to a state of positive pressure containing bubbles of gas, but there is nothing fundamental about this unstability, and one can very well imagine a stable state with negative pressure.

It may also be worth saying a few words about the role of pressure in the cosmological expansion. Naively, one associates positive pressure with a force acting outwards and expanding a system (indeed, a gas pushes outwards the walls of the vessel it is contained in). However, the Universe has no wall to push, and the effect of positive pressure is actually to lower $\ddot{R}$, i.e. to slow down the expansion. To explain this, consider the case of an ideal gas. According to the kinetic theory of gases, pressure is proportional to the momentum P of the particles and to their velocity v, $p \propto Pv$. General Relativity tells us that momentum generates gravitational fields: the field due to a moving mass is different from the field due to a mass at rest. For this reason, the gravitational influence of a gas on the expansion is greater when the particles have higher momenta, i.e. when the pressure is high.

1.2 Redshift-luminosity relation and standard candles

By measuring the flux observed from objects at different z, for which the luminosity L is known, one can determine the $d_L(z)$ relation from Eq. 1.5. In principle, one could then deduce $H(z)$, the evolution of the Hubble parameter, and then find the cosmological parameters Ω_i and w. These objects are called **standard candles**.

If we only consider nearby objects, the contribution Ω_r from radiation can be neglected, so that

$$R_0 S_k(r) = \frac{c}{H_0}\left(z - \frac{1+q_0}{2} z^2\right) \tag{1.11}$$

where the deceleration parameter $q_0 \equiv \Omega_m/2 - \Omega_v$ has been introduced. If instead one observes a bunch of distant objects located at a mean redshift z_0, the luminosity distance is sensitive to the combination

$$\frac{2(1+z_0)(1-\Omega) + 3\Omega_m(1+z_0)^2}{(1-\Omega)(1+z_0)^2 + \Omega_v + \Omega_m(1+z_0)^3} \tag{1.12}$$

obtained by expanding 1.10 around $z = z_0$. Figures 1 and 2 display the lines in the (Ω_m, Ω_v) plane for which the quantity 1.12 is constant. The actual degeneracy is better seen when plotting the apparent luminosity of objects located at a given redshift, as a function of Ω_m and Ω_v).

Actually, even when L is not known, $d_L(z)$ can be determined up to a normalisation factor, as long as all the objects have the same L, using

$$\frac{\mathscr{F}}{\mathscr{F}_0} = \left(\frac{d_L(z_0)}{d_L(z)}\right)^2 \tag{1.13}$$

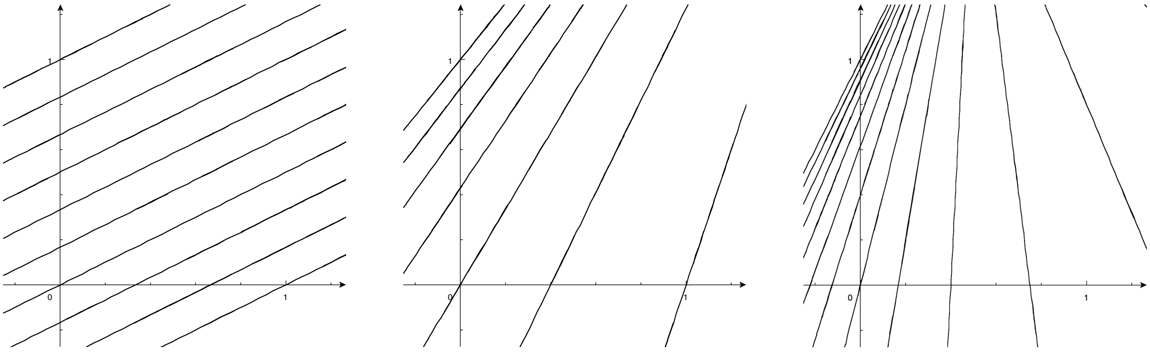

Figure 1: The curves along which the quantity (1.12) is constant, for $z_0 = 0$, 0.5 and 1. x-axis is for Ω_m and y-axis for Ω_v.

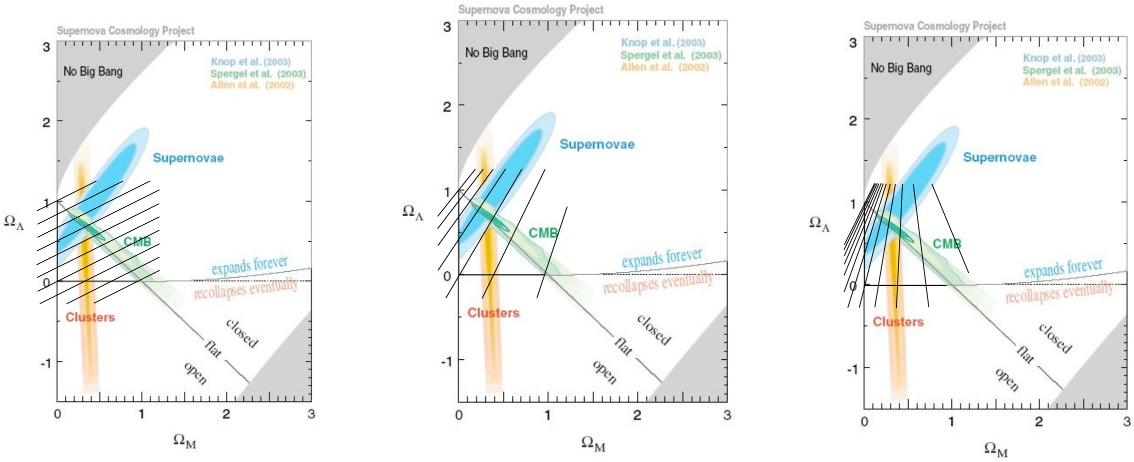

Figure 2: Same as previous curves, superimposed on constraints obtained by several cosmological probes.

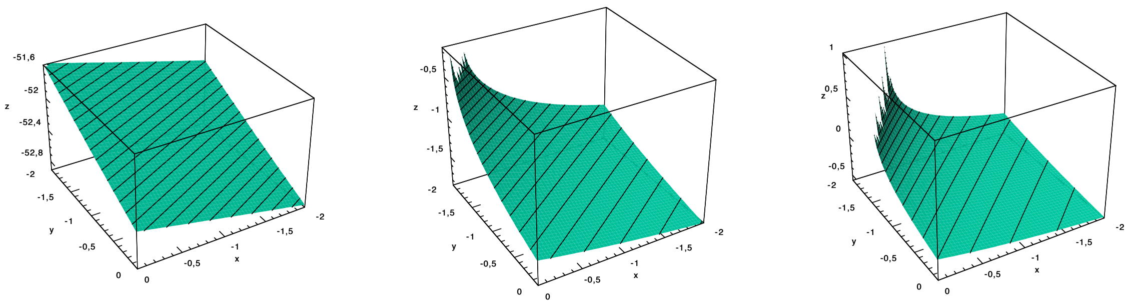

Figure 3: Surfaces showing the dependence of luminosity distance given in Eq. 1.4 on cosmological parameters, for the same values of z as the previous figures. x-axis is for Ω_m and y-axis for Ω_v.

where the 0 index refers to quantities relative to a nearby object ($z_0 \ll 1$). What is needed is one very well observed nearby object and a sample of distant objects.

Finally, event when L varies from one object to another, one can still use them to build the redshift-luminosity curve, if L is strongly correlated with another observable, *throughout the hole sample*. This is exactly why Cepheids are useful in cosmology: their absolute luminosity is strongly correlated with their period, which can be measured quite easily.

1.2.1 Supernovae are not standard candles

Supernovae fit well into this program. They are very bright transient stellar events, lasting for a few months. They can can be observed at high z. They have been observed as early as 2000 years ago, at least. After the Middle Age, Tycho Brahe observes one in 1572, and then Galileo another one in 1604. They are unable to measure any parallax, which proved they are very distant from us. This was one of the scientific events which changed our vision of the Universe, as the Heavens were proved to be subject of changes. Several centuries later (1998), the supernovae played a similar role, making the astrophysical community revise their vision of the Universe.

Astronomers and astrophysicists have different classifications for supernovae. Astronomers rely on the features visible in the spectra:

- when no hydrogen line is present in the spectrum, the supernova is called type I; a finer classification is introduced, but they are not so interesting here.
- in the other case, it is called a type II supernovae.

This classification should reflect the composition of the external shells of the object.

Astrophysicists prefer to classify them according to the physical process responsible for the collapse:

- some supernovae result from the collapse of an accreting white dwarf, once it reaches a mass greater than the Chandrasekhar limit. These are type Ia supernovae
- other result from the collapse of a massive star reaching a late stage of stellar evolution, when the nuclear reactions in the core become unable to hold the star against gravitational forces. These are type II, and probably also type Ib and Ic, supernovae.

The type Ia supernovae are very interesting in the context of cosmology, as the collapse is due to a process involving a threshold. One expects that these objects should have reached quite similar states when the explosion occurs, and should have similar, if not equal, absolute luminosity L (see below for caveats).

1.2.2 Type Ia supernovae

By monitoring the time variation of the luminosity of an object, one obtains a sampled lightcurve. For a supernova, it consists of a peak, which rise lasts for a few days and which fall lasts for several months. Supernovellists[2] use the word *phase* to refer to the number of days elapsed since the maximum of the light curve (premaximum days have negative phase).

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[2] well, it's shorter than *people studying supernovae*...

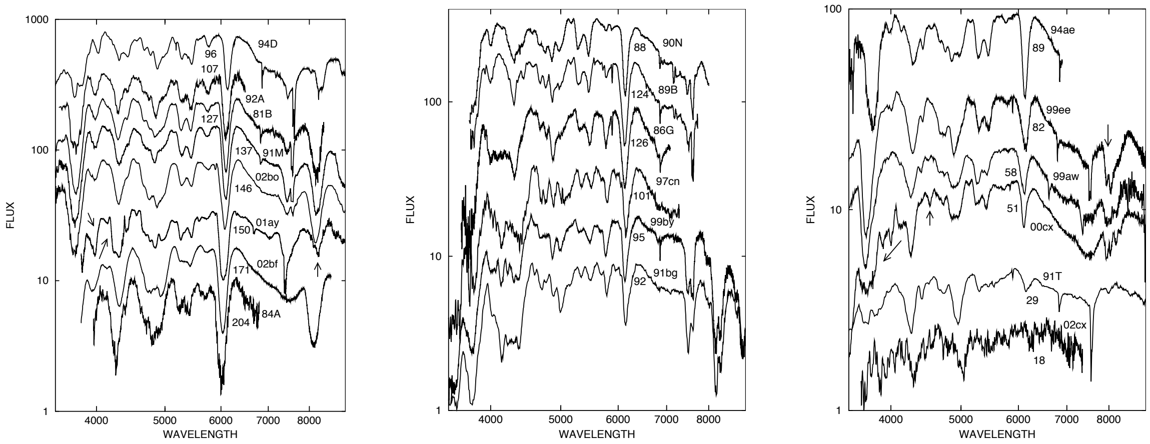

Figure 4: Spectra of supernovae, near the luminosity maximum.

We can also measure the spectrum of the light received at each phase (actually, it becomes more and more challenging after the maximum, when the total amount of luminosity fades out). This spectrum evolves strongly with phase. It is highly non thermal, with a lot of absorption lines. Their identification yields the redshift, and can sometimes help estimate the phase of the supernova, in particular before the maximum of brightness has occured. Sometimes, the spectrum of the host galaxy can also provide the redshift.

The costs of these two kinds of measurements – lightcurves and spectra – are very very different, in particular for very distant objects. A single spectrum may require several hours of observation with a very large (10 m) telescope. This means that it is out of question to take many of them. This is currently a strong limitation to the number of supernovae one can use for cosmology.

The more we observe type Ia supernovae, the more we find that they show peculiarities. These could have several physical origins. For instance:

- the composition of the initial white dwarf and of the accreted matter could vary from one case to the other, which could affect the Chandrasekhar mass;
- the explosion is certainly non spherical, and the observed properties could depend on our orientation relative to the object.
- the deflagration could start at different spots inside the collapsing dwarf, affecting the whole explosion process.

Some extreme SNIa are called peculiar, but it is not clear yet whether they constitue a separate subclass of objects (they are currently classified as such, for instance 91t or 91bg supernovae), or if they are only extreme cases in a large continuum of properties. Some objects are even believed to collapse at masses greater than the Chandrasekhar mass (they are called super-Chandrasekhar).

1.2.3 The lightcurve stretch

In the 1990, it was found that although different from one another, the lightcurves of nearby type Ia supernovae could be described as a one-parameter family, one lightcurve being deduced

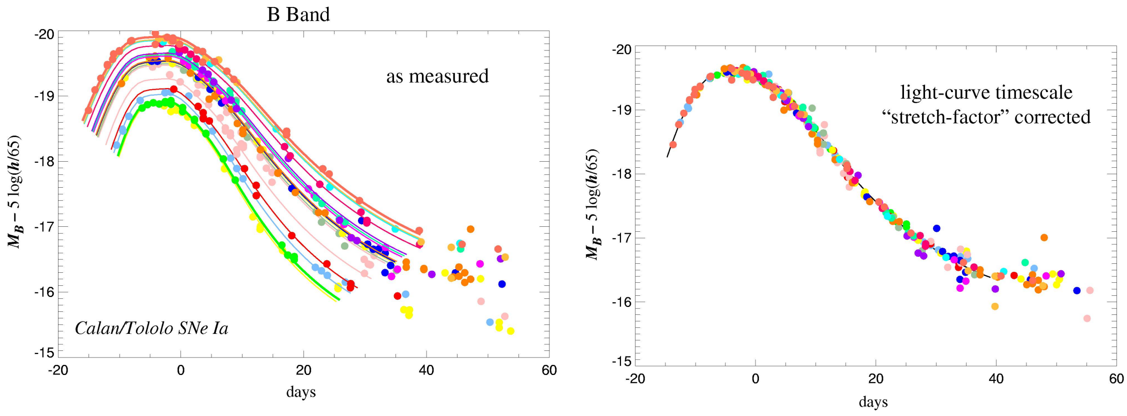

Figure 5: Left: lightcurves of type Ia supernovae. Right: same lightcurves after rescaling by the stretch factor, as described in the texte.

from a template lightcurve by a stretch by $(1+s)$ of the time axis and a simple scaling of the luminosity given by s (see Fig. 5). Assuming this property is also valid for distant supernovae, one can use it to build a standardized lightcurve, following this idealized procedure:

- the lightcurve is measured (and K-corrected, see below);
- the width of this lightcurve is measured;
- the stretch s corresponding to this width is determined from the nearby sample;
- the observed lightcurve is stretched accordingly and the resulting luminosity at maximum is compared to the luminosity of the corresponding nearby SN;
- the d_L value is plotted against z in the Hubble diagram.

The situation is actually more complex, for several reasons. At this stage, the important factor we have not talked about is the fact that the light we receive from the supernovae is redshifted, so that the bandwith in which we observe them does not match the same restframe bandwiths. Observations in the visible V band can correspond to light emitted in the blue band for a moderate z SN, or even to UV light for a high z SN. To perform the comparison with the nearby sample, one must have a way to convert the observed bands into restframes bands. This is called K-correction.

1.2.4 K-correction

From the flux observed in a given band, the flux that would have been observed in another band can be computed, provided one knows the transmission fonction of the filter and the spectrum of the object. Usually, the spectra are not observed and even when they are, the intercalibration is not good enough throughout the whole spectrum to be used that way. What is done is rather to use the lightcurves in several bandwidth and to interpolate between them as cleverly as we can.

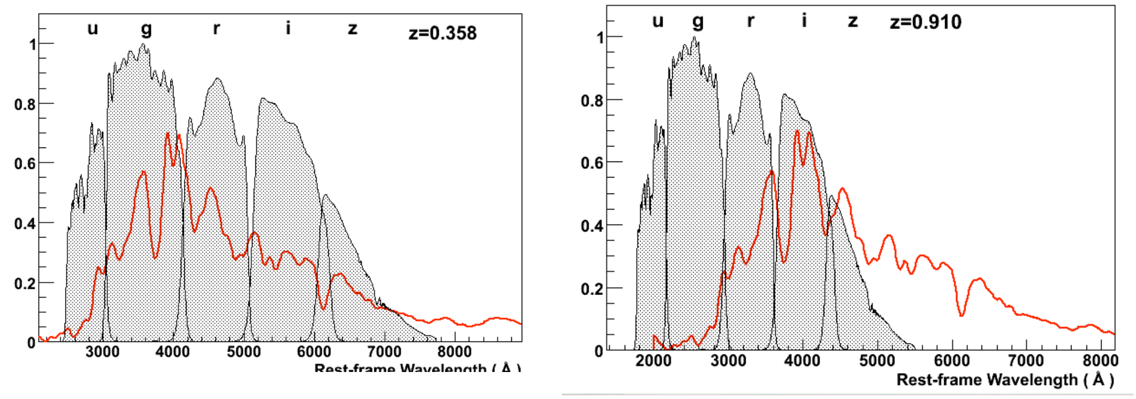

Figure 6: Relative positions of the observational filters for a given supernova and for two different values of *z*.

1.2.5 The brighter-slower and brighter-bluer relations

As the sample of well observed nearby supernovae grew larger, it was realized that the lightcurve family is much better described by two parameters, the stretch s we just introduced, and another parameter c relate to the instrinsic colour of the object. Brighter supernovae tend to be slower (larger stretch) and bluer.

The origin of these correlations is not very well understood yet, but it is not really a problem as they are very well established and constitute a robust scientific fact. The same way one can use a mercury thermometer without a fundamental understanding of the origin of dilatation in metals, one can use the brighter-bluer and brighter-slower correlations to do precision measurements of the expansion rate of the Universe.

Other parameterizations of lightcurves are also used. For instance, the timescale can be described by Δm_{15}, defined as the magnitude drop 15 days after maximum.

These parameterizations are implemented in several computer codes, in particular MLCS (Multi LightCurve Shapes) and SALT (Spectral Adaptive Lightcurve Template). So far, they are found to give consistent results when applied to the same data sets. By gathering spectra and lightcurves of a large number of supernovae, these codes aneable to describe the family of supernovae in a continous way and to determine the parameters c and s associated to a given observed supernova.

2. Experiments

Let us begin our story at the end of the 90's, when things really got started. At this time, the High-Z Supernova Search Team led by B. Schmidt[3] (Riess et al. 1998 [get]) and the Supernova Cosmology Project led by S. Perlmutter[4] (Perlmutter et al. 1999 [get]), announced the discovery of the acceleration of cosmological expansion, based on the luminosity-distance diagram built from 10+6 and 42 supernovae, respectively. From this time on, dark energy became a part of the standard

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[3] with a astronomer-like background

[4] with a particle physicist-like background

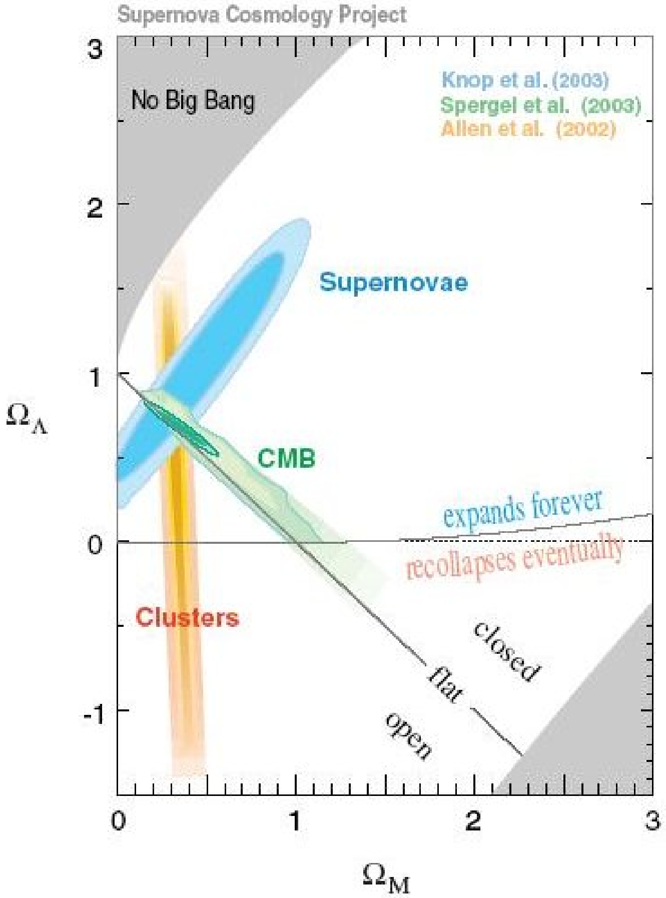

Figure 7: Summary of the constraints on the cosmological parameters obtained from different cosmological probes, assuming w is constant.

model of cosmology. These results have been confirmed by other independent probes, as the X-ray emission of clusters of galaxies (Allen 2002, [get]), the CMB (Spergel 2003, [get]), and the baryon acoustic peak (Eisenstein 2005, [get]). See Fig. 7 for the resulting constraints on Ω_Λ.

Several teams are now using supernovae to determine the cosmological parameters. Part of the HZT is now using the Hubble Space Telescope to detect and study supernovae with very high redshift ($z > 1$, up to $z \sim 1.6$). The two collaborations SNLS et ESSENCE currently have the greater number of supernovae, and have studied very carefully the systematics associated with the scientific results. I will focus on SNLS, which I know better.

SNLS is an acronym for *Supernova Legacy Survey*. This experiment/collaboration is part of the CFTHLS program of the CFHT, associated with a french-canadian 3.6 m telescope installed in Hawaii. A significant part of the observation time is dedicated to the search and observation of distant supernovae, with the large field camera MegaCam.

In a typical experiment of the kind described above, one would like to:

- measure the characteristics of many distant supernovae;
- determine the corresponding s and c values;

- compare their flux with the nearby sample;
- put them on the redshift-distance diagram.

To achieve this, we observe several fields in the sky, as often as possible, in several bandwidths, and we detect the objects which luminosity has changed. Their lightcurves are measured in these bandwidths, and those looking like promosing type Ia supernovae candidates are selected (on the basis of their lightcurve and of their colours), and their spectrum is observed with a (usually very large and expensive) telescope, in order to confirm they actually are type Ia.

2.1 Difficulties of principle

The first difficulty is that we do not directly measure the flux from the supernovae, but rather a quantity related to the luminous signal

$$s(t) = \int_0^\infty \frac{S[t/(1+z),\lambda/(1+z)]}{4\pi d_L^2(z)} T_{\rm obs}(\lambda) T_{\rm prop}(\lambda) T_{\rm host}[\lambda/(1+z)]\, d\lambda \tag{2.1}$$

where $T_{\rm host}$ denotes the transmission function in the host galaxy, accounting e.g. for absorption, $T_{\rm prop}$ accounts for whatever can happen to the light during propagation (absorption, diffusion, magnification by lensing, ...), $T_{\rm obs}$ is the transmission function of the atmosphere plus instruments, S is the source spectrum, and time dilatation has been taken into account through the $(1+z)$ term. Some of these factors may be poorly known, affecting the cosmological results (see below). The redshift z is relatively easy to measure from the spectrum of the supernova or the host galaxy, if it is bright enough. This is true only provided that this spectrum is actually available (this may become a problem when two many supernovae are detected).

The second difficulty is that type Ia supernovae are not really standard candles. The strong correlation between their colour and their luminosity turns out to be very helpful to use them in cosmology, as explained above, but the properties of the SN could also depend on redshift, which would be a problem as the entire method relies on a comparison between the properties of distant and nearby objects.

Finally, supernovae are observed in fixed spectral bands. Because of redshift, this correspond to different restframe bands for each supernova. In order to compare the properties of different supernovae, one has to correct for this effect (this is called K-correction), which is only possible if we know the spectrum of each object (this is not the case, and some modelling is necessary).

This can be an even bigger problem, as for very distant supernovae, the spectrum can be so much redshifted that some of the bands in which we observe can correspond to extreme restframe bands (in the UV), for which we have virtually no observation in the nearby sample. In the SNLS experiment, this problem occurs for supernovae more distant than $z \approx 0.8$.

2.2 Practical difficulties

As in every experiment, there are also a lot of technical challenges, or simply pratical difficulties. For instance,

- One has to detect a supernova *before* it reaches maximum brightness, to be able to select them for spectroscopy. The **rolling search** observation strategy is quite efficient for that:

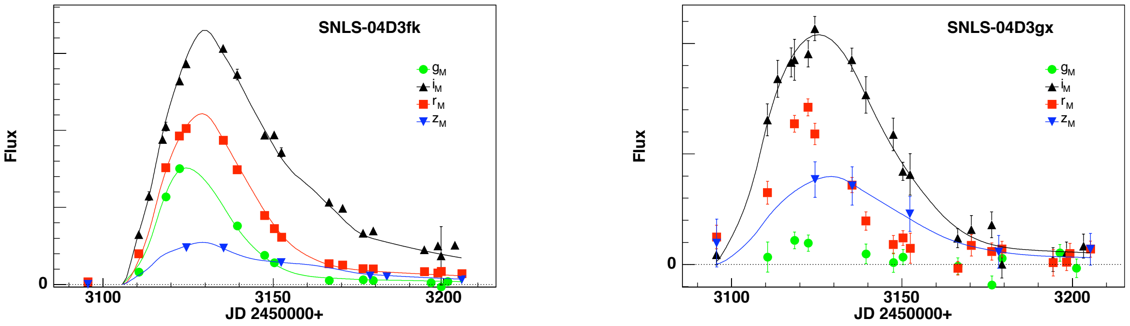

Figure 8: Left, a modestly distant SN, at $z = 0,358$. Right, a SN at $z = 0,91$ is so distant that some observation bands correspond to a restframe bands in which we have no information. One can not compare them to the nearby sample.

one observes the same fields again and again, these observations being used for detection of new candidates as well as for the flux measurements of objects already detected;

- One has to select the type Ia candidates before the brightness maximum, without spectroscopy. This is becoming easier and easier as more and more supernovae are observed, relying on some features in the time evolution of brightness and colour, for instance;
- The lightcurves are not evenly sampled, because of the Moon, bad weather, telescope or camera failures, other nasty astronomers wanting to share telescope time. The ligthcurve fitting being an important step in the determination of distance luminosity, undersampling has a direct impact on the determination of cosmological parameters.
- The conversion of the CCD signals into luminous fluxes is much more delicate than it may appear. There are a lot of systematics involved, which also translate into uncertainties in the cosmological parameters.

2.3 Results

The data taken during the first year of SNLS have been analysed and the resulting constraints on cosmology are summarized in Figs. 9 and 10. For the details, see astro-ph/0510447[5]

2.4 Intrinsic limitations of the method

As in every experiment, the determination of cosmological parameters with type Ia supernovae is subject to some errors, some of them related to the number of supernovae (statistical errors) and some of them not (systematic errors). When the number of observations grows larger, one usually expects that the systematic errors become dominant, so that it is very important to understand them to determine the ultimate precision reachable by the experiment.

2.5 Summary of systematics

Systematic errors can be summarized as follows. They are due to errors in

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[5] Astier el al., A& A 447 (2006) 31–48.

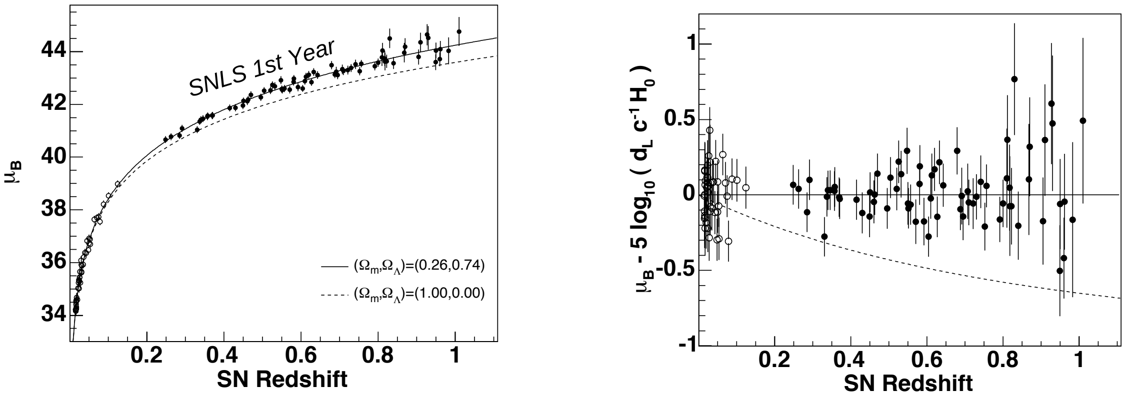

Figure 9: Left: Hubble diagram showing the luminosity distance vs redhift, for the first year SNLS dataset. Right: residues to the the best fit, showing the dispersion of data around the model providing the berst description. The study of these residues is crucial, as they should be rando: their correlation with any physical quantity would be the sign that the nalysis missed some important physics.

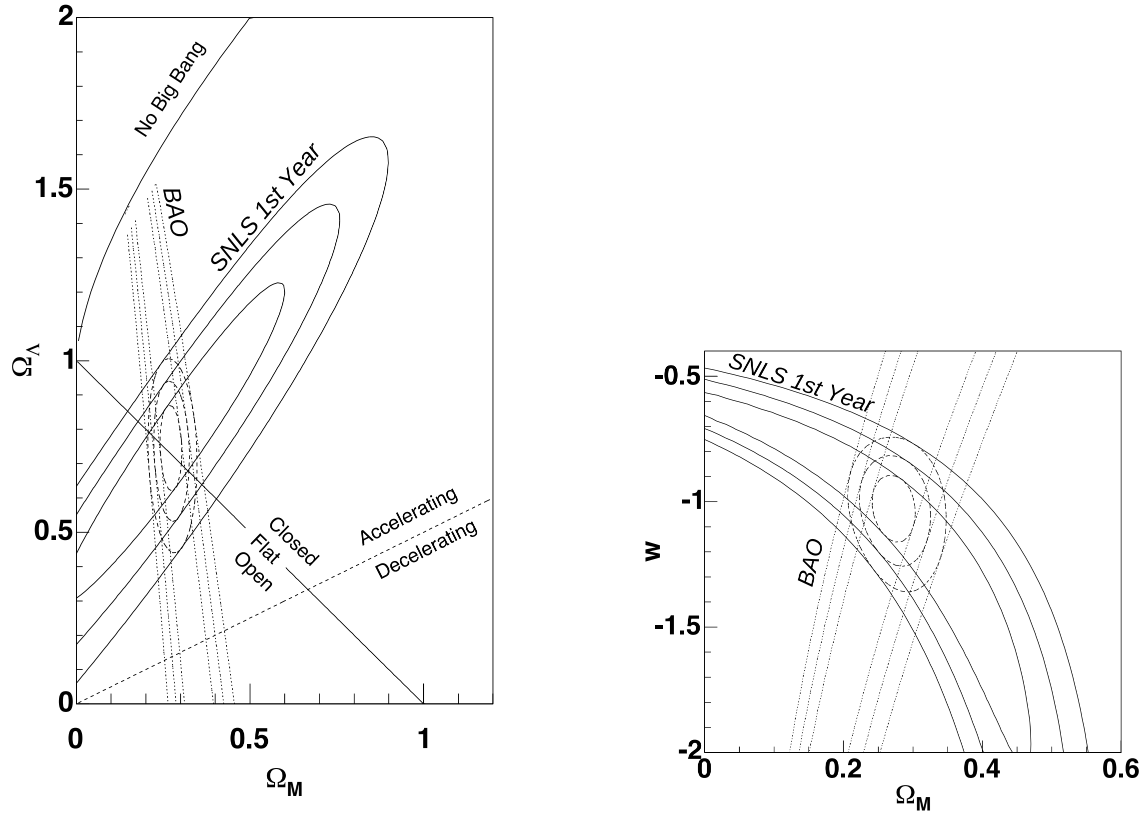

Figure 10: Contours of significance in the $(\Omega_m, \Omega_\Lambda)$ plane (left) when w is set to 1, and in the (Ω_m, w) plane when the Universe is supposed to be flat ($\Omega_m + \Omega_\Lambda = 1$).

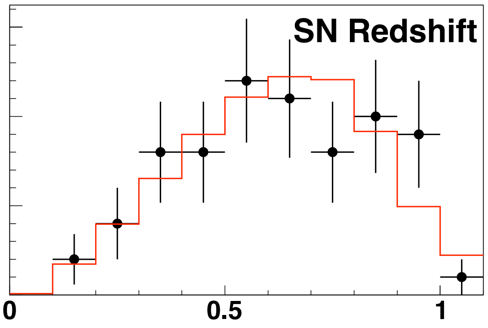

Figure 11: Histogram showing the distribution of redshifts in the SNLS first year sample. The actual distribution (points) is compared to, and found to be consistent with, what is expected from the characteristics of the experiments (line).

- photometry;
- calibration (convert electronic signal in CCD to a luminous flux in photons $\cdot\,\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$);
- identification of SN Ia;
- K-corrections;
- selection bias;
- instrinsic variation of the physical properties of SN with z;
- absorption;
- gravitational lensing (magnifying some SN in the observed sample);

Some of these sources of errors will actually decrease when more supernovae are observed, because our understanding of supernovae will be improved.

2.5.1 The problem of calibration

Calibration is a very crucial step towards obtaining the final Hubble diagram, and it is important to have thought about the following in order to understand how the experiments can be made more sensitive and accurate. The point is the following: light emitted from the supernova reaches the detector, where an electronic signal is measured. This signal must be converted into a luminous flux in a given spectral band. Calibration is the set of techniques by which this conversion can be performed. The relation between the flux and the magnitude in a band B is given by

$$m_B = m_B^0 - 2,5\log_{10}\left\{\frac{\int_0^\infty \phi(\lambda)T_B(\lambda)\,d\lambda}{\int_0^\infty \phi^0(\lambda)T_B(\lambda)\,d\lambda}\right\} \tag{2.2}$$

where $\phi^0(\lambda)$ is the spectrum of the reference object that defines the system of magnitudes, for instance the Vega star, and T_B is the transmission function of the filter defining the spectral band.

For the calibration, we use a set of well observed standard stars, which magnitude in several bands is known precisely. In principle, the conversion factor could be obtained by observing these stars with the same instrument as the one used to observe supernovae. This is not possible in practice, for several reasons:

- These reference stars are usually not in the science field used in the supernova science program.
- Even when they are, they are much too bright to be observed in the same conditions as the supernovae. One can use secondary standard stars. They are less bright stars which magnitude has been measured by comparison to the primary standards. For instance, SNLS use the so-called Landolt stars. As they are fainter, their magnitude is know with a greater uncertainty.
- the relation between luminous flux and magnitude also introduces an uncertainty, due for instance to the system of magnitude itself. For instance, variations of the spectrum of Vega introduce uncertainties in the definition of magnitudes!
- the spectrum of the standard stars is different from the spectrum of supernovae, which also affects the relation between flux and magnitude.
- the magnitude of standard stars are usually given for band filters which are not the ones used in the instrument.

For SNLS, the strategy is the following:

- go from the observations of Vega to a set of secondary standard (Landolt) stars, in the standard UBVRI filters;
- convert the UBVRI observations into Megacam $u^\star g^\star r^\star i^\star z^\star$ bands ;
- define tertiary standards in the SNLS fields, in the Megacam filters;
- compare the supernovae to the tertiary standards.

2.5.2 The importance of nearby supernovae

The lightcurve fitting process relies heavily on a sample of nearby supernovae. Their number is limited, which introduced a statistical error in the final result. As all the experiments currently use the same sample of nearby objects, the resulting errors are correlated.

Also note that if the properties of supernovae evolve on a cosmological timescale, the comparison to nearby objects induces a systematic error which could spoil the validity of the whole approach. Most experiments carefully address these questions by studying the evolution of supernovae properties with z.

2.6 Absorption

Absorption of light is a chromatic process which lowers the apparent luminosity and makes the spectra redder. If light is absorbed or diffused somewhere between the supernova and Earth,

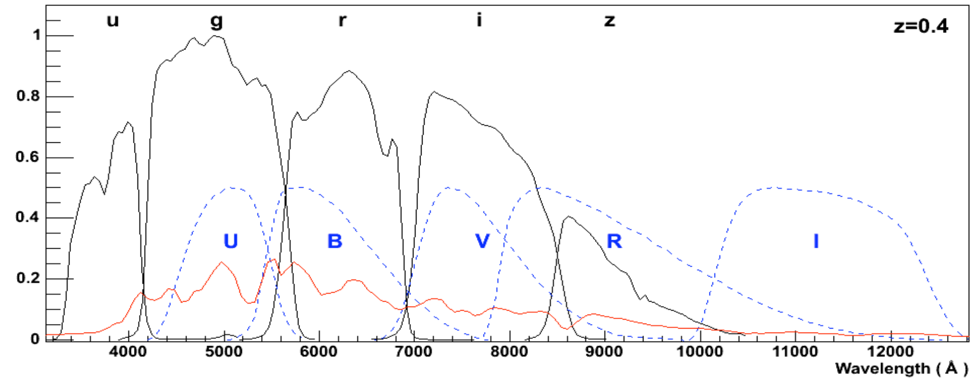

Figure 12: The Megacam filters and the corresponding UBVRI filters, in the rest frame of a supernova at $z = 0,4$.

the observed redshift-luminosity relation can not be used to determine the cosmological parameters, which is bad. Reddening can be detected and corrected for (or reddened supernovae can be discarded). However one can imagine physical processes that would lead to achromatic absorption (this is called **grey dust**). This would really be a problem as it would be impossible to detect in the observation of individual supernovae. The overall effect would be more and more important at higher redshift, and it would give the redshift-luminosity relation a shape that is different from what is observed. This phenomenon is basically excluded by the current studies of the redshift-luminosity relation, but there is still a very specific process, called **replenishing dust**, that could mimic an cosmic acceleration. It correspond to grey dust that would be permanently created in a way that exactly compensates for the dilution due to expansion.

This hypothesis is usually considered as far-fetched but there are several ways to test it:

- by using a very general relation between luminosity distance and angular distance,

  $$d_L(z) = (1+z)^2 d_A(z) \tag{2.3}$$

  which comes directly from the conservation of photon number in general relativity. Measurements of $d_L(z)$ and $d_A(z)$ are consistent with that relation, which constrain the processes that could change the number of photons, like absorption, but also more exotic phenomena like axion-photon conversion (e.g. see Kunz & Basset 2004).

- by using very high redshift data, for which the accelerating Universe hypothesis and the absorption hypothesis give very different predictions. For instance, the first hypothesis predicts a time dilatation of the supernovae lightcurves (see Riess 2004, with HST data).

2.7 Can we do better and how?

Some of the limitations mentionned above can be overcome by space missions (e.g. JDEM/SNAP and Dune, see below): observations can be made 24/7, with a lower background sky light, no cloud and no moonlight. From the ground, the use of a larger telescope with a larger camera is also being studied (e.g. LSST, see below).

Calibration can also be greatly improved by using artificial sources instead of standard stars, for instance a LED or a laser. This research field is closely related to military interests, see e.g. astro-ph/0604339, entitled *Telescope Spectrophotometric and Absolute Flux Calibration, and National Security Applications, Using a Tunable Laser on a Satellite*.

3. Projects

3.1 SNAP/JDEM

JDEM is an acronym for **Joint Dark Energy Mission**. It is a satellite that should be launched in 2014. It general goal is to study the properties of dark energy but the detailed specifications are not settled yet: a call for propositions was made several years ago, with the obligation for the projects to use at least two different observation techniques. Among the many projects that have been proposed, three have been selected to go on in the selection process (the JEDI project has not been selected):

- SNAP (supernovae and weak lensing), French project involving many labs, in Paris (DAPNIA-CEA, IAP, LPNHE), Marseille (LAM), Toulouse (CNES, EADS), Lyon (IPNL) ;
- Destiny (supernovae and infrared sky) ;
- ADEPT (supernovae and distribution of galaxies).

Regarding the SNAP proposal, it seems very natural to combine weak lensing and supernova searches, as these two techniques require large fields of observation and a large camera. This complementarity has been advertised a lot, and it may be useful to mention that there are some specific difficulties to combine these two probes on a same instrument. In particular, the constraints on the optical quality are very different. For weak lensing, an excellent control of the PSF is needed (good *geometrical* characteristic of the images) whereas for supernova, an excellent *photometric* control is wanted. For weak lensing, one would like to observe as many fields as possible whereas for supernovae, one wants to come back to the same fields as often as possible. The optimal strategy is difficult to find, and the final choices are as much the result of political fights as scientific discussions.

One should also be aware that the JDEM mission itself could be jeopardized. The *House Energy and Water Development Appropriations Bill* Committee Report wrote in 2007 that *NASA has failed to budget and program for launch services for JDEM. Unfortunately, in spite of best intentions, the multi-agency aspect of this initiative poses insurmountable problems that imperil its future*. Things will probably turn out right, but there is also a lot of political fight behind the scene...

This being said, the JDEM/SNAP mission, if accepted, should be able to observe 2000 SN up to a redshift $z \sim 1.7$, in two years. The projection of the scientific outcome is shown in figure 13.

3.2 Dune

Dune is an acronym for *Dark UNiverse Explorer*. It is a large field imager which should be launched around 2011 or 2012. It will be equipped with a 1.2 m telescope with a 0.5 deg^2 field of view and a resolution of 0.23 arcsec (see the official site). Here are its specifications

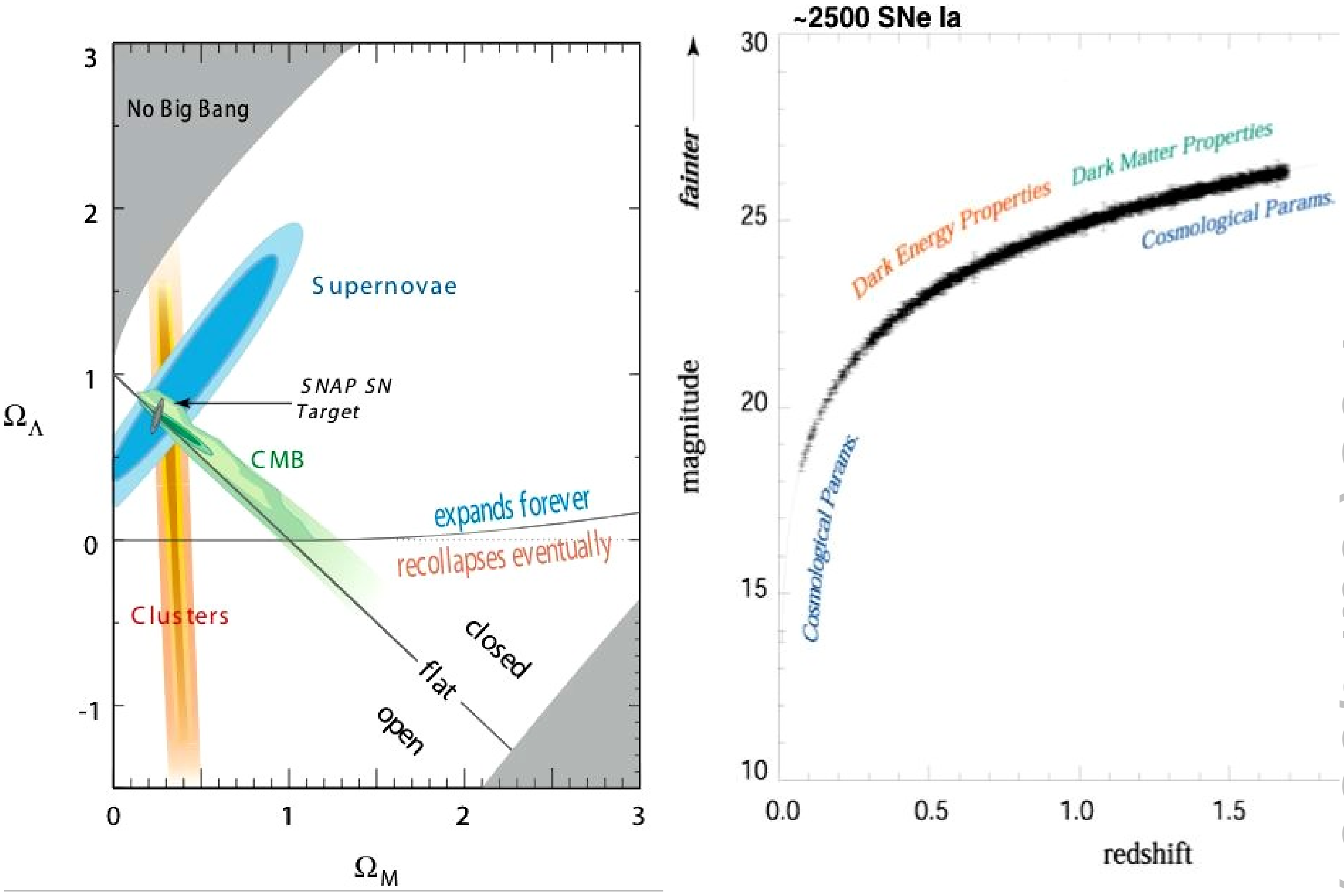

Figure 13: The expectations of JDEM/SNAP, in terms of cosmological parameters.

- diameter of the primary mirror : 1.2 ăm;
- annular field of view : $\sim$ 0,5 deg^2;
- camera : 470 Mpixels on a surface of $\sim$ 2000 cm^2;
- one image every 300 s;
- CCDs are read continuously, the charges on the CCDs being transferred as to follow the motion of the satellite. This is called time-delayed integration[6].

Dune was first supposed to be a satellite dedicated to the weak lensing effect, and the supernova program was added afterwards. As regards this program, it includes the observation of 2×60 deg^2 fields, each one being observed in 6 bands every 4 days for 9 months. This should provide 10,000 SN up to a redshift $z \sim 1$, for a 18 month total duration.

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[6] see e.q. astro-ph/0610062.

3.3 LSST

LSST [official site] is an acronym for *Large Synoptic*[7] *Survey Telescope*. It is a ground telescope, which should be intalled in the north of Chile on the same site as CTIO and should be running by 2014. Its specifications are the following:

- diameter of the primary mirror : 8.4 ăm;
- field of view : 10 deg^2;
- camera : 3,2 Gpixels on a surface $\sim$ 13,000 cm^2;
- one image every 30 s;
- pipeline : 18 Tb/night (about 1 CD per second).

A tunable laser will be used for calibration.

LSST will be make a huge step as far as scale is considered. It should discover about 10^6 supernovae per year (2700 per night), and to provide spectroscopic follow-up for about 10,000 per year, up to a redshift $z \sim 1,2$. A multifiber spectrograph will be used for nearby objects ($z \lesssim 0.3$), wheras photometric redshifts will be used for the distant ones (see below).

Such a sample will allow to study the diversity of type Ia supernovae and to understand some of the present systematics. There should also be between 0.1% and 1% of lensed supernovae, which could yield a new method for mesuring the Hubble constant.

3.4 Final remarks

For all these projects, it will be crucial to be able to determine the redshift of supernovae without relying on spectra (they are two expensive in terms of observation time). This is called **photometric redshift**, and many studies are currently investigating the precision and the reliability of this technique. The shear size of the samples will also allow, or even demand, elaborate specific statistical tools (astro-ph/0611004).

3.5 What else can we do with all this

There's a lot of science that could be done with a large sample of good quality observations of type Ia supernovae. For instance, one could

- measure the expansion rate of the Universe $H(z)$ (cf Riess 2006);
- constrain cosmological parameters(Ω_m, Ω_Λ, $w(z)$) ;
- test the absorption effects
- study the cosmological evolution of supernovae properties, study the correlation with the host galaxy properties;
- test the isotropy of expansion, measure the space correlation properties of supernovae;

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[7] Synoptic means something which gives a general view of a subject at a given time.

- mesure the local velocity field (astro-ph/0705.0979).
- ...