Measurement of the cosmological constant

P. Antilogus [a]

[a]IPN Lyon , France

The type Ia Supernovae (SN Ia) provided the first direct indication of a non zero cosmological constant (Λ). After an introduction of the scientific context, the status of the cosmological constant measurement will be reviewed. The usage of SN Ia to probe the vacuum energy and more generally to study the dark energy seems quite promising. In a close future SN Ia should provide precise and well controlled measurements. The program "nearby SuperNova Factory" (SNFactory), centered on detailed studies of ∼400 nearby SN Ia, and the proposal "SuperNova Accelerating Probe satellite" (SNAP), which should be a break through in the study of the acceleration of the Universe expension, will be introduced.

1. Introduction

The concept behind the expression "cosmological constant" changed quite a lot since its introduction in general relativity. Today, following the point of view of S.Weinberg, the low value of the cosmological constant appears as "the bone in our throat" not only for cosmology but also for elementary particle theory. The reason for such point of view will be briefly explained in the first part of this note.

The type Ia supernovae (SN Ia) will be the core of the second part of this document. SN Ia appear today as the most promising probe to study the cosmological constant/acceleration of the universe expansion. Ground based measurements after their first success can pretend to reach a precision of $\sim 10\%$ on the measurement of Λ. To investigate further the enigma of its value, not only work on the statistic will be needed but specific work on the systematic will be required. Two projects introduced here, the nearby SNFactory program and the SNAP project, will in a close future pursue these objectives. Before the end of the decade, space observation using the SNAP satellite, let us expect a break through in the understanding of the dark energy, energy at the source of the observed acceleration of the universe expansion.

2. From the cosmological constant to the dark energy

In the original version of the general relativity, published by A.Einstein in 1915, the universe happened to be dynamic : at large scale the speed of the objects are not small compared to the speed of light. At first A.Einstein did not accept the idea of a non static universe. He proposed in 1917 to weaken one of the original requirement of its theory which was to find back, in a weak field, the Newton gravitational law. Having this constrain satisfied only at small scale ($\sim$ at the scale of the solar system), he was able to introduce the cosmological constant Λ : the matter density, which push toward a gravitational collapse, can be balanced by an uniform density $-\Lambda/4\pi G$, allowing, if Λ has the right value, the universe to be static.

DeSitter in the following years proposed a static cosmological model with no matter at all. This was somehow unexpected from the point of view of Einstein which was considering that the mass distribution of the universe was setting the inertial frame.

The work of V.Slipher between 1910-24 ended up to the conclusion that spiral nebula (= today galaxies) can have a strong reddening $z = \Delta\lambda/\lambda$, up to 6% in his work, indicating than astronomical objects are not static. E.Hubble between 1920-30 with the Palomar telescope discovered galaxies and the universe expansion, $v = H_0 r$:

the universe is not static.

Quite before this final prove, in 1923, Einstein in a letter to Weyl withdrew the cosmological constant : "*If there is no quasi-static world, good bye cosmological constant* ". And in the 50's at the end of his life Einstein said: "*the cosmological constant is the biggest blunder of my life*".

So "exit" the cosmological constant? From a pure "general relativity" argument may be. But in the 60's with the development of the quantum field theory a new concept appeared to play a major role in physics : the vacuum energy.

This new energy density, as all sources of energy density, should be taken into account in general relativity. For the vacuum the energy density tensor has the following form :

$$< T_{\mu\nu} >= - < \rho_V > g_{\mu\nu}$$

which gives a term with the same propriety than the original Einstein cosmological constant term:

$$< \rho_V >= \rho_\Lambda = \frac{\Lambda}{8\pi G}$$

If this "new" cosmological constant seems impossible to avoid, the difference between its expected and observed value is today one of the major problem of the fundamental physics [1].

The present cosmological observations imply $|\rho_\Lambda| \leq 10^{-29}$ g/cm$^3 \sim \left(10^{-3} eV\right)^4 \sim 10^{-47} GeV^4$

In quantum field theory the fundamental mode/vacuum of any field ($\sim$ the "zero point" of an harmonic oscillator) "diverges". Considering that the physics is understood up to a given cut-off/scale k_{max} [1] , we get for the sum of all the normal modes of a field : $|\rho| \sim k_{max}^4/16\pi^2$.Taking k_{max} at the Planck scale, gives

$|\rho_\Lambda| \sim 10^{92}$ g/cm$^3 \sim \left(10^{19} GeV\right)^4 \sim 10^{74} GeV^4$

120 orders of magnitude bigger than what is observed. Taking the electroweak scale instead still gives a discrepancy of 55 orders of magnitude. Everything looks like if the cut-off which should be considered is only of the order of 0.001 eV. Something has to be completely wrong in the above discussion. Nevertheless the Casimir effect, which is sensitive to the energy difference between two "kinds" of vacuum, shows the reality of the zero point energy.

Since the 70's and the success of the electroweak theory, the situation becomes even more striking. On top of the "harmonic oscillator" contribution to the vacuum energy, any broken symmetry, through the potential energy difference between the broken-unbroken symmetry, will generate a contribution to the vacuum energy. For the broken symmetry in the Standard Model, we expect a contribution of the order : $|\rho_\Lambda| \sim 10^{27} g/cm^3 \sim (200 GeV)^4$ ending to an extra 56 orders of magnitude of discrepancy with what is observed.

Today the concept of Dark Energy has been introduced to generalize further the idea of cosmological constant : it corresponds to any energy density, ρ, related to its associated pressure, p, by an equation of state $p = w\rho$ with $-1 \leq w < -\frac{1}{3}$. Such energy density, from the general relativity point of view, will contribute at some point to accelerate the universe expansion. The cosmological constant (or vacuum energy) corresponds to the simple case w =-1.

Recent theoretical developments consider a possible variation/"dynamic" of the cosmological constant/w, like in quintessence model where a scalar field goes slowly with time to its minimum.

3. The measurement of Λ

3.1. Results overview

In the 90's big progresses have been made in cosmological observations to measure the matter and the vacuum energy densities [2]

- DASI/BOOMERANG/MAXIMA...: $3^o K$-Cosmic Microwave Background, $\Omega_{tot} = \Omega_{\rm M} + \Omega_\Lambda = 1.^{+.06}_{-.05}$
- Dark matter: galaxies cluster + other, $\Omega_{\rm M} = 0.4 \pm 0.1$
- SCP (1998) : supernovae at high z, $\Omega_\Lambda \neq 0$ à 99 % cl.

[1] An "optimistic" choice for this cut off is the Planck scale $\sim 10^{19} GeV$. Nevertheless, the Electroweak scale $\sim 100 GeV$ well understood today seems the lower value than could be considered for this cut-off.

[2] $\Omega_{\rm M}$ and Ω_Λ are respectively the matter and the vacuum energy density divided by the critical density $\frac{3H_0^2}{8\pi G}$

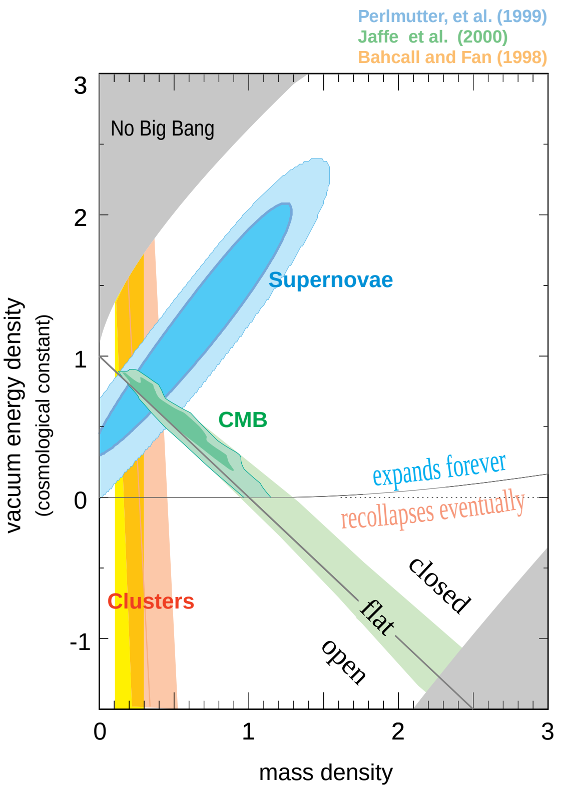

Figure 1. *Constrains in the $\Omega_{\rm M}/\ \Omega_\Lambda$ plane from the available observations. It can be noticed than the constrains from the CMB and the SN Ia are complementary as they gives "orthogonal" contour : the CMB is sensitive to $\Omega_{\rm M}+\Omega_\Lambda$ and the SN Ia, with the present observed range in z, to $\Omega_{\rm M}$-Ω_Λ.*

The universe is weighted with some good precision. Today the cosmology enter in the field of the measure (see figure 1). It will allow beyond the concepts of Cosmological Constant, $\Omega_{\rm M}$ and Ω_Λ to study in detail the "dark side" of the universe : the Dark Matter and the Dark Energy.

3.2. The measure with SN Ia

The apparent/observed luminosity f of an astrophysical object is related to its intrinsic luminosity $\mathcal{L}$ by $f = \mathcal{L}/4\pi d_L^2$, where d_L, the luminosity distance, is a function of the cosmological parameters H_0, $\Omega_{\rm M}$, Ω_Λ and the redshift z. Thus sources of known constant intrinsic luminosity, also called standard candle, can be used to measure relative distances. If at the same time red shift measurements are performed $\Omega_{\rm M}$ and Ω_Λ can be accessed. Only for the extraction of H_0 the value of the intrinsic luminosity itself is required. The SN Ia as explained in the next section are good standard candle. Since the first results presented in 1998-1999 (see figure 2), with the first indication of $\Omega_\Lambda > 0$, they emerged as the most powerful tool to measure the acceleration of the universe expansion.

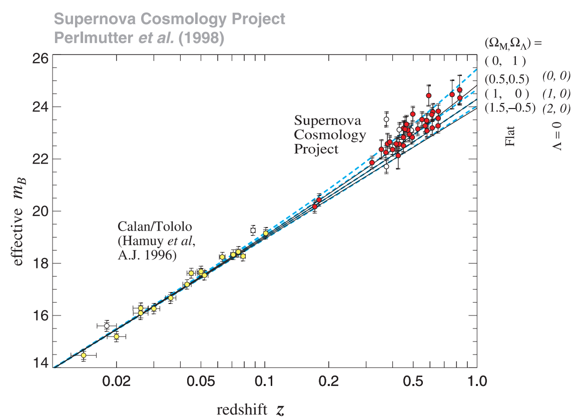

Figure 2. *Magnitude ($\sim \log d_L$) versus redshift for 4 kinds of flat universe ($\Omega_{\rm tot}$= 1) compared to the 42 high-z SN Ia of the SCP published sample [2]. The data are in favor of a positive value for Ω_Λ: for a flat universe Ω_Λ= 0 is excluded at 6 σ.*

3.3. The SN Ia

There is two distinct processes at the origin of supernovae explosion :

- the gravitational collapses of the core of a red giant (SN II) or of a super-giant star without hydrogen (SN Ib , SN Ic) into a neutron start.
- the nuclear explosion of a white dwarf.

The first case is the end of life expected for any stars of more than 8 $M_\odot$. SN II correspond to the release of $\sim$ 2-3 10^{53} ergs , 99% of this energy being taken away by the ν. The second case is at the origin of the SN Ia and will be described further in this section.

The favored model for the SN Ia explosion, which provides the best agreement with the observation, is the following :

- The initial star is a white dwarf, composed of carbon and oxygen, orbiting in a binary system (50% of the stars)
- This white dwarf goes through a long cool down and increases its mass by accretion of matter from the companion star.
- When the degenerate core (Fermi gas) reach ~ 1.4 $M_\odot$, there is a collapse/explosion. As the mass of the core get close to the Chandrasekhar limit of a gravitational collapse, the C and O at high density and temperature can undergo nuclear reactions. The pressure in the degenerate core (due to electrons) is decoupled from the increasing temperature (due to the nuclear reactions) : nuclear reactions can run away.
- The nuclear reactions produce 0.6-0.7 $M_\odot$ of ^{56}Ni.
- The energy released, higher than the white dwarf binding energy, blows up the star : 10^{51} ergs of kinetic energy are taken away by the ashes (2/3 of the produced energy).

The source of the SN luminosity comes from the nuclear decay chain of the ^{56}Ni, the ash of the initial nuclear reactions :
$^{56}Ni \rightarrow^{56} Co$, $\tau = 8.8$ days
followed by
$^{56}Co \rightarrow^{56} Fe$, $\tau = 110$ days
There is three phases in the SN Ia light curve. During the first 15 days the increase of the transparency end up to a fast increase of the luminosity. Then as the amount ^{56}Ni fuel decreases the luminosity starts to reduce. $\sim$ 40 days after the maximum a slower luminosity decrease is observed corresponding to the long lifetime of the ^{56}Co.

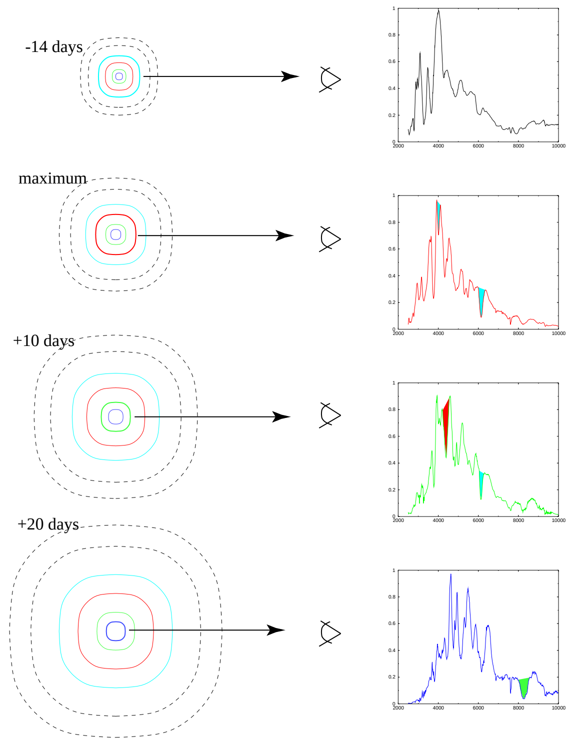

Figure 3. *As the ashes of the SN Ia explosion expand with time, the light collected is sensitive to the composition (spectral features) and the speed (width of the spectral features) of deeper and deeper layers of the SN Ia. By observing such time series the SNFactory project will improve our understanding of the SN Ia explosion.*

The interest of the SN Ia for the observational cosmology is then clear :

- As they are events with close initial condition, all have almost the same intrinsic luminosity : they are good standard candle.
- At its maximum the SN Ia luminosity is of the same order than a full galaxy ($\sim 10^9\odot$), they can be observed at high z (up to $z \sim$ 1.2 from the ground) .
- Due to their specific origin compared to the other kind of supernovae, the SN Ia explo-

sion can be easily identified by their spectral features.

Even more important for the usage of this probe, many observables associated to the SN Ia explosion like light curve shape or spectral features (see figure 3) are related to the energy released. They allow to identify small differences in the intrinsic luminosity of different SN Ia and further improve their status of standard candle.

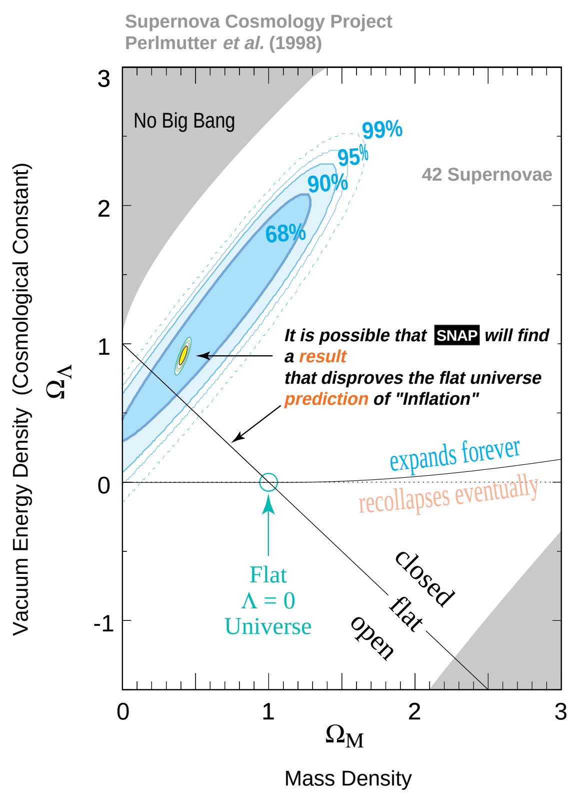

Figure 4. *The expected errors on* Ω_M *and* Ω_Λ *with 1 year of SNAP data compared to the present results. It should be noticed than SNAP is designed to study the dark energy and will be able to test many theoretical propositions as subjected on this plot.*

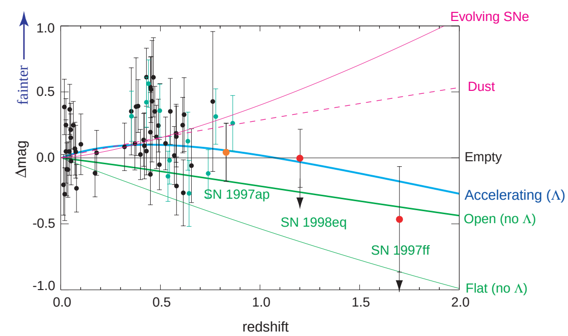

Figure 5. *The SN Ia at the highest z observed today are compatible with an accelerating (Λ) universe. In such model, as shown on this plot, above z ∼1 when the mass density was dominating the universe evolution, the universe undergo a clear deceleration, before the today observed acceleration. Effects like "evolving SN Ia" (SN Ia in a young universe may have a different chemical composition / energy release than in an old universe) or "grey dust" (extra-galactic dust which could dim the light over the full spectra for objects far away) mimic an accelerating universe at all z.*

4. The SNFactory and SNAP projects

To study the dark energy with SN Ia, different projects are going on or are planned. They will improve the statistical precision of the results and will provide a control of the systematics at the needed level.

The main improvements on the statistics will come from :

- The ground based measurements at $z < 1-1.2$, which are in progress today (SCP [4], High-Z Team [5], Megacam/SNLS [6])
- Space measurements at high z $(0.1 < z < 1.7)$ and high statistic (2 000 SN Ia/year). This is the goal of SuperNova Accelerating Probe satellite (SNAP [8]) for ∼ 2008.

To fulfill its objectives the SNAP satellite will be composed of

- ∼ 2m mirror

- a large field of view of $1^\circ \times 1^\circ$ equipped of 10^9 pixels (144 CCD and 36 HgCdTe)
- a spectroscopy facility : an Integral Field Unit 0.35-1.7 μm , $\lambda/\Delta\lambda$=80-600

SNAP data will be $\sim$ 6000$\times$ the biggest "HST deep survey".

Before SNAP, which plans to do cosmology at the "%" level with a strong emphasis on the systematic control, the two main questions raised by the present measurements and already under investigation are :

- does an extra-galactic grey dust makes SN Ia fainter at high z?
- does SN Ia are really good standard candle?

The recent discovery of the SN Ia SN 1997ff at $z = 1.755$ using the Hubble telescope [3] and the last SN Ia at high z discovered from the ground, as shown figure 5, give a good indication than the accelerating universe is a reality and than we are probably not dominated in the present results by effects associated to the previous two questions.

If the present understanding of the SN Ia is sufficient to do cosmological measurements at the 50% scale, improved studies of these objects will be needed to be able to go down to a better precision. If SN Ia are naturally good standard candle, they still present variation ($\sigma_{flux} \sim 50\%$) in their intrinsic luminosity. Empirical correction, estimated on small sample of nearby supernovae, have been proposed and used to reduce this dispersion ($\sigma_{effective\ flux} \sim 15\%$), taking advantage of correlation between the luminosity at maximum and the width of the light curve. A program, nearby SuperNova Factory (SNFactory) [7], will investigate further the SN Ia properties. It will :

- collect a big SN Ia sample ($\sim$ 400 $\sim$ 20 times the available statistic) between 2003-2006
- perform a detailed study of the SN Ia spectro-photometric evolution (10 spectra per SN Ia over 60-100 days).

The goal of this program, on top of providing a better understanding of the SN Ia, will be to reduce the luminosity dispersion for sub-classes of SN Ia and to estimate the systematics on the luminosity associated to each SN Ia in such sub-classes.

5. Conclusion

After a cosmology with uncertainties at the 50 % scale which end up to the unexpected $\Omega_\Lambda > 0$, measures at the 10% scale of Ω_Λ and $\Omega_{\rm M}$ are in progress today. The % level physics will be reached this decade (planned CMB satellites target, SNAP proposal).

More than the measurement of the cosmological constant itself, the goal of the observational cosmology with SN Ia is the study of the Dark Energy, energy at the source of the acceleration of the Universe expansion. With the expected precise SN Ia cosmological measurements, a break through in this objective is just around the corner.

REFERENCES

1. S. Weinberg, Rev. Mod. Phys. 61 (1989) 1.
2. S. Perlmutter et al. , Astrophys. J. 517 (1999) 565.
3. A.Riess et al. , Astrophys. J. in press (astro-ph/0104455)
4. Supernova Cosmology Project, S. Perlmutter et al. , cf *http://panisse.lbl.gov:80/public/*
5. High-Z Supernovae Team, B. Schmidt et al. , cf *http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html*
6. SuperNova Legacy Survey, cf *http://snls.in2p3.fr/*
7. nearby SuperNova Factory, cf *http://snfactory.in2p3.fr/*
8. SuperNova Accelerating Probe satellite, cf *http://snap.lbl.gov/*