The Big Bang Picture: a Remarkable Success of Modern Science

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Abstract. During the XXth century a scientific picture of the universe and its history has emerged on the basis of the "Primeval Atom", the original proposition of Georges Lemaître. Indeed, I will show during this review that modern cosmology is a scientific theory, and as such does not pretend to provide the "Truth", but a framework in which predictions are possible and can be confronted to observations for possible falsification in Popper sense. The last forty years have offered a remarkable list of observational verifications of the predictions of the standard picture, on the basis of well established physics. During the last twenty five years a more revolutionizing picture has emerged: essential pieces of information for fundamental physics are obtainable from cosmology: this picture specifies the existence of non-baryonic matter, of dark energy and the physics relevant at energies well above what is accessible to terrestrial laboratories. Although definitive conclusions are obviously more uncertain, this approach is still a fully scientific path which successes have been remarkable and allow to consider cosmology as a new and rich branch of modern physics.

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1. INTRODUCTION

The status of cosmology as a science has been quite often debated. My personal point of view is that the question of Cosmology, i.e. obtaining the description of the geography and the history of the universe, is one of the oldest question of mankind, and therefore the scientific approach was much more difficult than say in thermodynamics. Indeed speaking about the universe as a whole, of its history, of its possible origin have strong meaning for any human being and therefore the scientific approach, which pretends to access to some knowledge is subject to more impact on every one’s thought depending on his own prejudice. Clearly, the Big Bang picture, first defended by a priest, G. Lemaître could easily be interpreted as being close to the christian vision and be accepted ... or rejected on this basis, rather than on its scientific value. Cosmology is indeed perhaps the only field in science where the general public heard that the global picture may be wrong and that some scientists deny that its achievement could be regarded as robust or even as acceptable as scientific results (Bonnet-Bidaud, 2004). The conference held in Moncao is an example of this somehow special status. As I said, because I believe the reason for this skeptical point of view is essentially philosophical in its origin (Blanchard, 2004), I do not expect that it will disappear ever. However, I intend to show that modern cosmology works accordingly to the very general scheme of science as a mathematical representation of the world which is first built to reproduce existing data and then used to make predictions which are confronted to experiences. In this respect, there are no theory in science which can be qualified as being right, but only two classes of theories: those which are already rejected by observations... and theories which are not yet rejected by the observations. Therefore science should never be thought as telling us some definitive truth: we can only be sure about what is wrong. An other comment is that some questions, which are well defined and sounds perfectly scientific may not be solvable by science. A modern example of this is topology: we will never know what is the actual topology of the universe.

As I stated, modern cosmology has reached an incredible level of achievement: cosmologists pretend to figure out what was the history of the universe, including those of the structures it contains, from the very first instants (a sentence which exact meaning has to be explained) to the present state, fifteen billion years after, to know more or

1 For those who are surprised by this statement, I just mean that our observations can access only scales below the horizon... and that the actual universe may not even be connected!
less its geometry, and its composition. Furthermore, it is claimed that most of the universe is made of two unknown materials: dark matter, a non-baryonic component which dominates the gravitational mass of structures in the universe and the dark energy, an extremely strange stuff filling up 70% of the universe having negative pressure and a repulsive gravitational action on itself.

I will try to present the various evidences for these different claims. I will distinguish between what I call the classical Big Bang, the neo classical Big Bang, the inflationary Big Bang and the concordance Big Bang. Each one of these models can be regarded as an extension of the previous picture. However, I want to immediately stress that these extensions are not build to solve problems met previously. Each extension could be falsified by observations without diminishing the scientific merit of the previous level. For this reason, when an extension is validated by observations the whole construction obviously gains in strength, but falsification of an extension is by no mean a weakness of the starting theory (like failing to found a common extension of general relativity and quantum mechanics cannot be regarded as a weakness of these theories, it is rather a failure of the scientist who tried it...).

2. THE CLASSICAL BIG BANG

The classical Big Bang corresponds to what is commonly regarded as the classical cosmological tests: the expansion of the universe, the abundance of light elements and the existence and blackbody spectrum of the cosmic radiation. This is already a huge challenge to alternative views: to my knowledge there is no theory based on standard physics which accommodates these three observational facts simultaneously. Very often alternative views try to explain one of these facts, on the basis of a new non-standard process in physics (or which relevance is far from being obvious). And of course all these are “postdictions”, i.e. built to reproduce the basic fact as does the Big Bang picture. This immediately puts them in a much weaker situation.

2.1. The expansion of the Universe

In my opinion there is a lot of misconceptions about the early developments of cosmology before Hubble discovery. Let me give here my point of view. Immediately after Einstein’s first cosmological model based on general relativity, it is well known that de Sitter proposed his empty solution (De Sitter, 1917). What is remarkable is that this model leads to a shift of the frequency of light proportional to the traveled distance. At that time, it was not immediately understood that this shift is essentially (i.e. at short distance) due to Doppler shift because space inflates with time, as the solution was considered as static. But it was clear to some astronomers like Eddington that the large redshift observed in most galaxies, may be the observational counterpart of this prediction. Carl Wirtz is one of the first astronomer to have looked for the observational signature of the de Sitter model and to note a correlation between distance and redshift. Lemaître in 1925 noticed that the de Sitter solution could be regarded as an inflating space and this process was the source of redshift, but this was associated to the arbitrary choice of the coordinates system (because the solution does not content any matter). In 1927, he published a paper, making a crucial step, in which he argued that it was possible to find solutions in general relativity which allow a description of the observations (redshift and non zero matter content of the universe) and he clearly explicitied the “Hubble law”, i.e. distant objects flow away with a velocity proportional to their distance. From the historical point of view the situation is quite clear: cosmological models based on general relativity able to explain a shift of the light of distant galaxies predicted that this shift was proportional to their distance. This is exactly what Hubble found and although he did not emphasized on its interpretation, he mentioned the fact that this result could be related to the de Sitter cosmological model.

Since that time, a criticism which is often made is that Hubble observations do not prove that the universe is expanding. This comment is right... but irrelevant to the scientific merit of the Big Bang picture: the model did a clear prediction and the prediction was verified a posteriori, this is the very usual validation of scientific theory. The Big Bang picture provides a frame in which different predictions can be done, related to its expansion. A direct test of the expansion would be to have a measure of the distance at two different times and check that the distance varies accordingly to the expectations. Unfortunately this is probably beyond realistic possibilities. An other test, although less direct, is known as the Tolman test, based on the surface brightness dimming with redshift. This test has revealed to be extremely difficult to work out: Sandage and Perelmuter (1991) argued that they found a surface brightness variation consistent with the prediction of the Big Bang picture, but that the question of selecting an homogeneous sample was terribly difficult. Indeed, evolution is to be taken into account in the standard picture and makes the interpretation of...
this kind of tests problematic (Pahre et al., 1996).

An other example of a test which happens not to have led to clear conclusions is the age of the Universe: the Big Bang picture makes a very definite prediction, there should be no objects older than the age of the Universe! However, the theoretical age of universe depends of several parameters, including the value of the Hubble constant, which was not well known for decades. Furthermore there has been a variety of ages of object in the universe from 10 to 20 Gyr even in recent years. The final word on this issue comes from WMAP (Spergel et al., 2003)! Models consistent with WMAP data have an age of $14.0 \pm 0.5$ Gyr, oldest stars are believed to be $12.5 \pm 3$ Gyr (Cayrel et al., 2001), a good success but to which little attention is paid, given the significant changes in the preferred values over years.

However there is plenty of consequences of an expanding universe: the observed duration of any event should be delayed in the same way than light period. Again this is a natural and straightforward prediction which has been done long time ago. The large sample of distant SNIa available at different redshift is now giving credit to the expanding picture (see Foley et al. 2005 for a recent analysis of this question).

An other consequence of an expanding universe is that the temperature of the cosmic microwave sky should be different at higher redshift : $T(z) = T_0(1+z)$. It is in principle possible to measure the temperature at different redshift through absorption lines in suitable molecules. Such measurements have been available and are consistent with the expanding picture. The observed temperature is sometime higher, but this is not much surprising because excitation by other mechanisms is possible. However, even this limitation can be solved (Srianand et al. 2000). What would be seriously problematic would be that the temperature is measured lower than $T_0(1+z)$, which has never been the case. So again we have a very definite prediction (temperature should never be smaller than $T_0(1+z)$)! and observations are in very good agreement with this prediction.

Finally, let me mention two examples of specific predictions which were done within the standard model and which have been observed a posteriori: 1) the first one is the existence of multiple QSO’s, as a result of lensing configuration with time delay between images, has been predicted within the expanding universe, which were observed with characteristics in the range of expectation. 2) the second one is the location of the acoustic peak in the CMB angular fluctuations power spectrum. Although these predictions were done for other primary purpose, it should be realized that they were done within the expanding paradigm, and the observations were found to be in agreement with the predictions. They are therefore predictions which have been verified and are therefore to be put on the credit of the model.

Most criticisms of the expanding picture picked up one of the above observational fact, and try to find an alternative explanation for instance Narlikar and Arp (1997) and this is sometime presented as a weakness of the expanding picture. However, one should realize that it makes an huge difference to have on one side a model which makes clear predictions based on standard physics and by which the model has never been invalidated and on the other side to build an alternative explanation a posteriori based on unverified physics!

The conclusion of this first aspect of the description of standard model is that to my knowledge the expanding picture makes several well defined predictions, some of which could have led to major falsifications of the theory, but the observations were actually in agreement with it (even if none of these agreements can be regarded as a “proof” of the validity of the model, just because an observation cannot prove the validity of a model, it can only prove that the model was wrong...). To my knowledge no alternative theory accommodates these facts with established physics.

### 2.2. Abundance of light elements

The origin of light elements is fundamental in the standard picture in the sense that the hot Big Bang picture was built from the question of Helium 4. It might not be the most robust evidence in favor of the Big Bang picture, but it is still a very impressive achievement of modern cosmology. Again the power of the theory comes from its ability to produce predictions that were verified a posteriori. Furthermore, postdictions by alternative explanations are often obtained by postulating the existence of medium with similar properties than those existing in the early universe in the standard view. Alternatives are therefore often, from my point of view, pale imitations.

Helium 4 is known to be produced in the heart of stars and its production through nuclear reaction needs quite high densities and high temperatures. The fact that the universe is roughly made of 25% of Helium 4 is therefore possible from star production, but because normal stars produced a large amount of more heavy elements and remnants, it is extremely difficult to obtain the 25% of Helium 4 without unacceptable large polution of heavier elements. Of course some tentatives exist.
Let us examine the consequence of the Big Bang picture: most of Helium 4 being primordial very little difference should exist between stars, apart from the limited of He4 produced by stars themselves. Indeed, the abundances of He4 as measured in different environments, even with extremely low metallicity, are in the range 23–25% (reliable measurements with 1% precision being extraordinary difficult to achieve). This is already an important achievement: would some stars be found with a low He4, with no stellar explanation, the standard picture would be in serious trouble. In fact the situation is even better: He4 abundance increase slightly with metallicity of regions where measured. This is consistent with the model of an initial value slightly polluted latter by chemical evolution. More interestingly, there are clear predictions of nucleosynthesis: the abundances of primordial He3, Li7, D are predicted with a single free parameter. Identically, since the seventies it was clear that nucleosynthesis does not allow more than 5 neutrinos families (when laboratories experiments put limits of few thousands...).

The abundances of the light elements, He3, Li7, D are predicted by the theory and could be compared to the observed abundances. Without the primordial nucleosynthesis the origin of these elements which are not easily synthesized by stars would be rather unclear. D for instance is almost always destroyed during stellar evolution and never created. The rough observed abundances are in quite good agreement with the predictions. However, this agreement is not of very good quality: using observed abundances and their strict uncertainty could lead to too optimistic conclusions (Kernan and Kraus, 1994). The abundances quite often vary from object to object. This is often understandable in term of chemical evolution and stellar evolution, but renders difficult a meaningful comparison. Even at the present time, the role of chemical evolution is probably still not well understood. The way Li7 was used for nucleosynthesis is a good illustration: in early time the measured abundance in stars which was taken as being primordial was $10^{-9}$. However, Spite and Spite (1992) pointed out that using population II halo hot stars was likely to provide a measurement closer to the primordial value, and they found a value closer to $10^{-10}$. Vauclair (1988) emphasized that the internal structure of these stars may nevertheless lead to a depletion. Almost twenty years after the role of stellar depletion mechanisms remains unclear (Charbonnel and Primas, 2005; Boesgaard and Novicki, 2005).

A very central prediction of nucleosynthesis which was done since the beginning of the field is about the amount of baryons in the universe:

$$\rho_b \sim 5 \times 10^{-31} \text{g/cm}^2$$

(corresponding to $\Omega_\rho \sim 0.05$ in the standard picture). Actually, if one is looking for a weakness in the classical Big Bang here is one! The amount of baryonic material predicted by nucleosynthesis has not been seen yet by far. Most of the observed baryonic material lies in stars and these stars represents only $\Omega_\rho \sim 0.003$. The situation would be very problematic if dark baryons were a very unlikely possibility. However, it is relatively easy to imagine forms of dark baryons and as I will discuss latter, there is apparently much more matter than what is shining. A classical way to hide baryonic matter is within stellar remnants. This possibility is however severely constrained through the fact that stellar remnants are not detected neither by direct search nor by microlensing signature. There is however one natural form for dark baryons, that is in the form of an ionized gas. In clusters, the baryonic component is mainly in the form of a hot gas detected in x-ray. This gas represents roughly ten times the mass in stars (Roussel et al., 2000). If this ratio is universal the amount of baryons in the universe in roughly in agreement with the prediction of nucleosynthesis. A direct detection would however be more convincing anyway and may actually have been achieved recently (Soltan et al., 2005).

A recent success in this domain has come from a somewhat unexpected direction. The detection of the CMB fluctuations angular spectrum allows the determination of cosmological parameters including the baryonic content of the universe (Le Dour et al, 2000; Tegmark and Zaldarriaga, 2000). The WMAP data allow a precise determination of $\Omega_\rho$ actually more accurate than from nucleosynthesis and in good agreement with it (Spergel et al, 2003).

Of course the most famous prediction of primordial nucleosynthesis is the existence of a blackbody radiation with a temperature of few K (Alpher and Herman, 1948). Its discovery by Penzias and Wilson (1965) is the most important discovery in the foundation of modern cosmology.

### 2.3. The blackbody radiation

The existence and the properties of the blackbody radiation are central in the development of modern cosmology. Its intensity, its spectrum, its fluctuations were predicted before being observed and the observations were entirely consistent with the predictions. Furthermore, this is based again on elementary standard physics that is tough during first years at the university. Its existence is already difficult to explain in term of its energy content today: if nuclear energy to produce He4 from all known stars was transferred to microwave radiation, only one third of the CMB
FIGURE 1. Very accurate measurements of the CMB spectrum were obtained with FIRAS instrument on COBE, with more than 50 independent measurements, relative errors compared to a perfect blackbody are as small as 0.2%.

intensity would be produced. That’s not a definitive problem for a stellar origin of the CMB intensity but nevertheless needs the existence of a large amount of dark stellar remnants (greater than known stars). It is well known that a blackbody radiation is obtained if there is “enough” exchanges between matter (mainly electrons) and photons. In the standard model this is achieved only during the first 10 days of the history of the universe when the electron density was high enough. After this the blackbody spectrum is conserved even in the absence of thermal coupling. COBE has provided the most precise measurement of the spectrum of the cosmic microwave sky. No departure from a pure blackbody has been found over nearly fifty independent frequencies and no departure representing more than $10^{-4}$ in energy content would be acceptable. Thermalization by hypothetic dusts have never been shown to reproduce the blackbody spectrum to the COBE precision. In addition, thermalization at low redshift (Lerner, 1995) is forbidden by the fact that sources are detected at radio and millimeter wavelength at high redshift (Peebles et al., 1991; Carilli et al., 2004). To my knowledge, no alternative explanation exists able to just reproduce the basic observed properties properties of the CMB.
FIGURE 2. The presence of tiny fluctuations in the cosmic microwave sky which amplitude is related to present matter fluctuations has been predicted soon after the discovery of the microwave radiation by Penzias and Wilson (1965). The statistical properties of these fluctuations have been now measured with a high accuracy, providing around 1000 of independent points. The result expressed as the $C_l$ can be fitted with a six parameters CDM model. The best values of this fit match very well existing independent measurements of the same parameters including: Hubble constant, baryonic matter density, non-baryonic matter density, dark energy density, matter fluctuations amplitude. The last parameter, the index of primordial fluctuations matches the predictions of inflation. On this figure, each dot is a measurement, dispersion around the theoretical curve follows the expectations. Similar prediction exist for the polarized signal.

2.4. Conclusion about the classical Big Bang

The remarkable conclusion is that from known physics, the hot Big Bang picture emerged as a logical consequence of the starting hypothesis of an uniform medium. It has led to a large number of predictions which were verified. Alternative views or propositions have produced a limited number of postdictions and remain silent on many aspects which are easily described and predicted in the standard picture, furthermore they always involve physics in an ad hoc way, which has not be proven to apply in the relevant condition. Such constructions look like very much like the epicycle theory! Does this mean that alternative views are useless? Not entirely, the classical Big Bang pretends to offer a robust description of the universe from known physics from $t \sim 10^{-10}$s to the present time ($t \sim 5 \times 10^{17}$s). If one of the three aspects above could be convincingly reproduced from an alternative view using therefore very different assumptions but with clear different predictions, we would have a quite fascinating perspective to try to develop crucial tests and therefore spend more efforts in trying to falsify the standard picture, and either falsify it or reinforce its robustness. In the present time the classical picture seems so much above alternative propositions that tests of its foundations are not regarded as deserving strong observational efforts, a situation which is somewhat a pity.

3. THE NEOCLASSICAL BIG BANG

In 1933, several aspects were added to the cosmological field: Lemaître investigated the gravitational growth of structures in an expanding universe using exact spherical solution: the theory of structure formation by gravitational instability in an expanding universe was born, and F.Zwicky (1933) claimed that there was apparently more mass in the Coma cluster than seen in galaxies. Both propositions have gained in strength over years. Accordingly to standard theory of gravitation, rotation curves of galaxies, velocity dispersion of galaxies in clusters, temperature of the x-ray
gas in clusters, gravitational lensing, large scale flows of galaxies are all evidencing the presence of more mass than actually seen or even than mass associated to the central part of galaxies. The only alternative view is in the form of modified theory of gravity. The surprise for standard cosmologists has come from the fact that the amount of dark matter is so large that most of it should not be baryonic (otherwise the nucleosynthesis constraint would be violated). Actually many astronomers were reluctant to this idea. But again the scheme has been predictive: the cold dark matter (CDM) picture (Peebles, 1982) was a well defined framework in which the statistical properties of fluctuations were specified and could be worked out to make predictions. It is reasonable to say that again the theory was quite successful and that the general properties of large scale structure, the properties of galaxies, the distribution of matter on small scale were in good agreement with observations. It is also fair to say that there was not so much clear predictions which could be considered as verified a posteriori as we have seen in the classical Big Bang. On the other hand, the problem was clearly of a much higher level of difficulty because structures like galaxy clusters and galaxies are non linear objects and subject to complex astrophysical processes. Therefore, although it has been possible to develop a description which accounts for the properties of large scale structure, galaxy clusters, galaxies, Lyman α forest, as well as many aspects of the spatial distribution, the complexity of the astrophysical situations obscures the predictive power of the model. A good illustration of this situation is the debate on what is the exact predicted inner profile of dark matter in halos and whether it agrees with observations (Moore et al.; 1999). It is not yet clear whether the problem is real or not, but anyway a model for which problems are at this level of sophistication seems to me in very good health!

>From the epistemological point of view the situation is rather unusual however, and have made numerous scientists to feel uncomfortable: this model postulates that accordingly to the laws of physics a new type of matter should exist and should even be the dominant contribution to the matter density. This is somewhat an analogous of aether, which one can imagine that it will go away when a new formulation will be found. Modified theory of gravitation are in this respect an healthy alternative, but probably cannot claim to achieve the elegance of special relativity! However, this debate is somewhat philosophical and should not be regarded as a scientific argument. The only scientific approach (in the absence of a great new idea that revolutionizes our vision) is to develop the observational consequences of the various theories and to increase the amount of data to test them. For instance, there is a firm belief that the dark matter is made of particles that could be found in laboratory experiments. In this case the possibility to match the dark matter is limited (for instance neutrinos are now known to be massive... and not to be dominant in the mass budget of the Universe!). One should keep in mind however, that dark matter could be very different from what we first think of. This is somewhat unsatisfactory, because would no dark matter being found in laboratory experiments, it will by no way falsify the non-baryonic assumption!

However, a fundamental test of the above picture including the nature of dark matter is through the fluctuations of the CMB : within the theory it has been indeed possible to predict the properties of the fluctuations of the microwave sky. >From the assumptions that the initial fluctuations exist and are gaussian distributed with a power law spectrum, and allowing for non-baryonic dark matter, but not requesting it one can predict what the angular spectrum of the fluctuations, the $C_l$ curve, should be. The amplitude can be even determined in order to match galaxy clusters abundance or/and large scale weak lensing measurements. The power of this test is qualitative and quantitative: first in the standard picture the observed properties of the fluctuations are produced by physics when the universe was younger than 300 000 years, and the properties depend on many of the ingredients of standard cosmology: expansion rate, baryonic content, dark matter content, dark energy content, present day amplitude and shape of matter fluctuations. The simplest model contains six parameters. The observed WMAP data provide around one thousand of independent measurements and the precision could be as good as a few percents. The observed curve agrees with the expectation from models. The power of this test may not have yet been fully appreciated: a thousand of independent measurements are reproduced with a model having only six parameters! And the 5 best values for the cosmological parameters derived from the $C_l$ agree with the observed values for the parameters of the concordance model! The sixth parameter is the index of primordial fluctuations and is found extremely close to one. The addition of more parameters does not improve the fit. What can be added to this? In fact this is the killer of any alternative view: the data are so accurate that it seems impossible to produce an alternative description. Heroic tentative of this type few years ago when data were not that good are entirely ruled out by WMAP intensity data. Notice also that the model predicts a very distinct polarization signal which is an other prediction allowing to test the model further if anyone feels it still needs to be. No alternative model has been able to produce similar –successful– predictions. Some earlier postdictions have been severely ruled out by more recent measurements. A final comment about the fact that some properties seem to differ slightly from expectations: the shape of $C_l$ at low $l$, the value of the $\chi^2$, some privileged alignment, and the shape of the correlation function. These discordances are sometimes presented as severe weakness of the model, but none of these discordances has a very high degree of significance (in particle physics results below 5σ are not regarded as
The nature of the large scale distribution of galaxies. The statistical properties of the galaxies population on large scale is well reproduced within the standard model of an homogeneous universe to which fluctuations are added, which follow the CDM power spectrum and gaussian statistics. The high order statistics are well in agreement with the expected properties of gravitational instability. An alternative view has been proposed by Mandelbrot in the seventies (although early considerations exist back to the beginning of the XX th century by Charlier (1908)). This question was addressed again by Pietronero in 1987, despite the fact that scaling of angular correlation functions were apparently inconsistent with the fractal vision (Peebles, 1980). In the fractal picture, the classical (for cosmologists) correlation function $\xi$ is an incorrect quantity to look at and the relevant quantity is $1 + \xi$ which should behave as a power law. The SLOAN digital sky survey has delivered one of the largest sample well suited for measuring this quantity with a high accuracy (Eisenstein et al., 2005): the given precision is $\Delta \xi \approx 0.005$. The resulting quantity $1 + \xi$ is presented on figure 3. Several points are 200 $\sigma$ away from the fractal predictions.

4. THE INFLATIONARY BIG BANG

Inflation (Guth, 1981) is a great idea. But some wonder whether it is an actual scientific theory. Especially given the fact that numerous versions have appeared which seem to manage to accommodate any type of data (why the earlier versions made definitive predictions: flat geometry, gaussian scale invariant fluctuations). Nevertheless, any specific scenario of inflation could be at least in principle falsified by observations. Furthermore, the basic recent observations are consistent with a flat geometry and gaussian scale invariant fluctuations have been observed and measured. So the three basic predictions of the theory in its simplest form have been verified. It might of course well be that the theory will be invalidated and that something very different could produce the same observational conclusions like the topological defects scenario tried few years ago (I would be very surprised if this was the case, because the basics above predictions seem so natural to the theory, but I can imagine that a new theory will be to inflation what general relativity has been to Newtonian theory...).
5. THE CONCORDANCE BIG BANG

The introduction of a cosmological constant in the general theory of relativity is a possibility which is almost as old as the theory itself, being introduced by Einstein in 1917 just one year after the initial paper on his theory. Also its presence have been discussed several times in Cosmology, its introduction was regarded as inelegant from the theoretical point of view and not necessary from the strict point of view of the observational situation. This situation has changed with the first measurements of fluctuations on small scales in 1995, as flat models were favored (Lineweaver et al., 1997) while open (low density) universes were clearly excluded (Lineweaver and Barbosa, 1998). This conclusion has only been reinforced as the number of measurements increased. The additional discovery of an apparent acceleration of the universe through the Hubble diagram of distant supernovae (Schmidt et al., 1998; Perlmutter et al., 1999) has convinced a large fraction of the community of the reality of an acceleration phase of the present expansion rate. This represents one of the most extraordinary claim in modern cosmology: the classical Big Bang is build on well experimented physics without any exotic content, the neo classical Big Bang leads to the introduction of an unknown form of matter (the non baryonic component) but which follows usual law of physics and which might be detected in laboratory experiments, the inflationary Big Bang is more an application of speculative physics to the Big Bang (and contrary to a common mis understanding, falsifying inflation will absolutely not have any consequence for the validity of the classical Big Bang). These theories have led to the prediction of the $C_l$ which has provided the most remarkable success of modern cosmology. We are now confronted to a new challenge: are the astrophysical data convincing enough that our basic theory of gravity has to be revised? This is indeed a new change of perspective because if real the dark energy is the most astonishing component of the Universe: it dominates over normal matter, it has a negative pressure ($p \approx -\rho$) and its gravitational action is repulsive...

5.1. Is dark energy a new aether?

In order to make short a long story short, I will say that the evidence for dark energy until 2004 was real, but could be regarded as weak given the nature of the claim. Its introduction allowed a better fit to data, but hardly
FIGURE 5. The correlation function, expressed in a slightly different way than previously, show that Einstein de Sitter models (dot-dashed, blue line and solid, green line) fails to reproduce the observed shape of the correlation function, while its shape is in good agreement with a concordance model adjusted on the WMAP data (dotted, black line). This indicates that it seems not possible to reproduce both WMAP data and correlation function at large scales without dark energy (Blanchard et al., 2005).

lead to prediction that could be verified (the integrated Sachs-Wolfe signal is probably the only counter example but with a limited significance level below $3\sigma$. Indeed, the WMAP data and the large scale structure of galaxies could be reproduced without explicitly requesting the existence of dark energy (Blanchard et al., 2003). In addition the difference in magnitude between an Einstein de Sitter model and a concordance model is a linear function of time as illustrated by figure 4. It would be therefore quite possible that some astrophysical process like evolution or dust extinction produces the apparent dimming.

5.2. New evidence for dark energy

The measurement of the correlation function of the red galaxies in the Sloan digital sky survey (SDSS) has provided a distinct way to test the scenarios described in Blanchard et al. (2003). In this work we outlined that models with and without dark energy differ significantly on their large scale behavior. The comparison as shown in figure 5 unambiguously excluded the Einstein de Sitter cases. This is very likely to be a generic result: one cannot accommodate both the correlation function on large scales as measured by SLOAN and the CMB as measured by WMAP and other small scales experiments without introducing dark energy (Blanchard et al., 2005). This is a considerable success of the concordance model which reproduces quite well the observed correlation function including the so-called acoustic peak and has to be regarded as one of the most convincing direct evidence for the actual existence of dark energy (I used this term in a wide sense for any thing which would mimic a cosmological constant).

6. CONCLUSION: IS COSMOLOGY IN CRISIS?

At the present time and after the successes I have described, the standard picture can certainly not be regarded as in crisis in the sense of meeting more and more difficulties in reproducing observations. The situation is rather that of “golden age” that not only the foundations of the theory are getting stronger and stronger, but also bringing deep
implications for other sectors of fundamental physics (dark matter, dark energy, high energy physics). There exists no viable alternative which can accommodate even 50% of the facts that I have described above (unless an explanation is designed by hand for each observation), furthermore, and more important than anything no alternative view has been able to make a prediction clearly distinct from the standard model and which has been validated a posteriori. On the contrary tens of predictions of the standard model were neatly verified. In addition, there are still several predictions that wait for confirmation. Nevertheless Cosmology can be indeed regarded as confronted to a crisis similar to the one met some years ago in particle physics: there is a standard model, the concordance model, which has passed successfully the confrontation tests to observations. The agreement is so good that it seems already that it will be extremely difficult to find any new element to offer a new perspective. Most experiments which are designed are just proposing to achieve a better precision, to detect the non-baryonic dark matter in laboratory experiments, to establish the equation of state of the dark energy which is by now well represented by a simple cosmological constant. May be the perspective of B-mode detection in the polarized sky is the most important progress that we could hope in the future, which will provide some new clue toward new physics (although their non detection won’t – unfortunately – be a falsification of the framework).

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