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Cosmology and the physics of our universe

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Abstract Cosmology is undertaking the character of a precision science. Our hope to understand the details of the cosmological evolution contends with larger and larger data amounts and more and more refined data analysis and theoretical techniques. An approach of thoroughly conscious ignorance is the prelude to every real advance of knowledge in this field.

Key words: Cosmology

1 THE UNIVERSE OVERALL

All of modern Cosmology relies on the basic assumption of the Cosmological Principle, a more general version of the Copernican Principle stating that the Earth is not at the center of the universe and that the universe must be homogeneous. The Cosmological Principle complements homogeneity with isotropy and states that nobody is at the center of the universe. We indeed know that at small scales the universe is neither homogeneous nor isotropic since cosmic structures, galaxies, stars, planets do exist around us. However, provided that we consider enough large scales, the universe looks approximately homogeneous and isotropic. The strongest evidence for this case is provided by the cosmic microwave background (CMB) radiation observed to be very smooth, at least in one part in 10^5 (Smoot et al. 1992). This fact has two immediate consequences. The first one is that the universe has a finite age. The second one is that there was a beginning of time.

The overall evolution of the universe is described by the Einstein field equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}\,, \tag{1}$$

where G is the Newton's gravitational constant, $G_{\mu\nu}$ is a complicated function of the space-time metric and $T_{\mu\nu}$ is the stress-energy tensor describing the energy-matter content of the universe. Written in the previous form, the Einstein's field equation is a set of 6 independent, non-linear partial differential equations of 10 functions (!) Symmetries are introduced to reduce the complexity of the problem and guide to an easier description of the overall structure of the universe. The Cosmological Principle, i.e., the assumption of homogeneity and isotropy, is the leading symmetry. Homogeneity and isotropy on large scales allow to model the contents of the universe as a perfect fluid with density ρ and pressure p, and allow to write the stress-energy tensor in a simple diagonal form (see, e.g., Kinney 2003). If matter in the universe is

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homogeneous and isotropic, then the metric tensor must also obey the symmetry. The most general line element which is consistent with this symmetry can be written in the form

$$ds^2 = dt^2 - R^2(t)\ dx^2 . \tag{2}$$

The vector dx^2 contains the space geometry and the scale factor $R(t)$ contains the cosmological dynamics describing the expansion (contraction) of space-time. With the metric in Eq. (2), the Einstein's field equations take on the Friedmann-Lemaitre (FL) form

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2} , \tag{3}$$

where $k = 0, \pm 1$ is a constant that describes the curvature of the space. The previous equation is coupled with the second-order equation

$$\left(\frac{\ddot{R}}{R}\right)^2 = \frac{4\pi G}{3}(\rho + 3p) . \tag{4}$$

To fully describe the evolution of the universe on large scales we have to complement these equations with the equation of state of the cosmic fluid

$$p = w\rho . \tag{5}$$

Note that an expanding universe is gradually accelerating (decelerating) for negative (positive) values of w.

1.1 Expansion of the universe

The main property of the universe is, in fact, its overall expansion. The notion of the cosmic expansion has been developed by a combination of converging facts, both from observations and from theory (Peebles 1993). During the 1920s and 1930s cosmologists began to realize that the universe is not static but is indeed expanding. The main evidence for such an expansion is provided by the Hubble's law, $v = H_0 \cdot D$, an empirical relation between the velocity v of a distant galaxy and its distance D set proportional by a factor H_0.[1] The expansion of the universe leads also to the concept of the expansion of space which is formally taken into account by writing the Hubble's law in terms of the time derivative of the scale factor R

$$v = \frac{\dot{R}}{R} \cdot D = H \cdot D \quad . \tag{6}$$

To probe the cosmic expansion we need to observe far enough regions of the universe so that the distance of the *candles* residing in these remote regions can be fair probes of their distance to us. Observation of distant SNe provide the best indication of cosmological distance up to now and probe quite well the validity of the Hubble's law (Perlmutter & Schmidt 2003). These observations also provide constraints on the rate of change of the cosmological expansion. Two independent teams, the SCP and the HZSNS teams, found evidence for an expanding universe which is undergoing an overall acceleration in the last ~ 7 Gyrs (Benitez, N. et al. 2002, see Fig.1). A driving force created by an energy field (vacuum energy or Dark Energy) permeating the whole universe should be responsible of such an acceleration. The presence of Dark Energy introduces an additional term to the density of the cosmic fluid in Eq. (3), $\rho = \rho_m + \rho_\Lambda$,

[1] The law is not exactly true since at smaller scale the universe is neither completely homogeneous nor isotropic and there is also the peculiar velocities from local gravitational forces. The law also breaks down at large distances when it is no longer a good approximation.

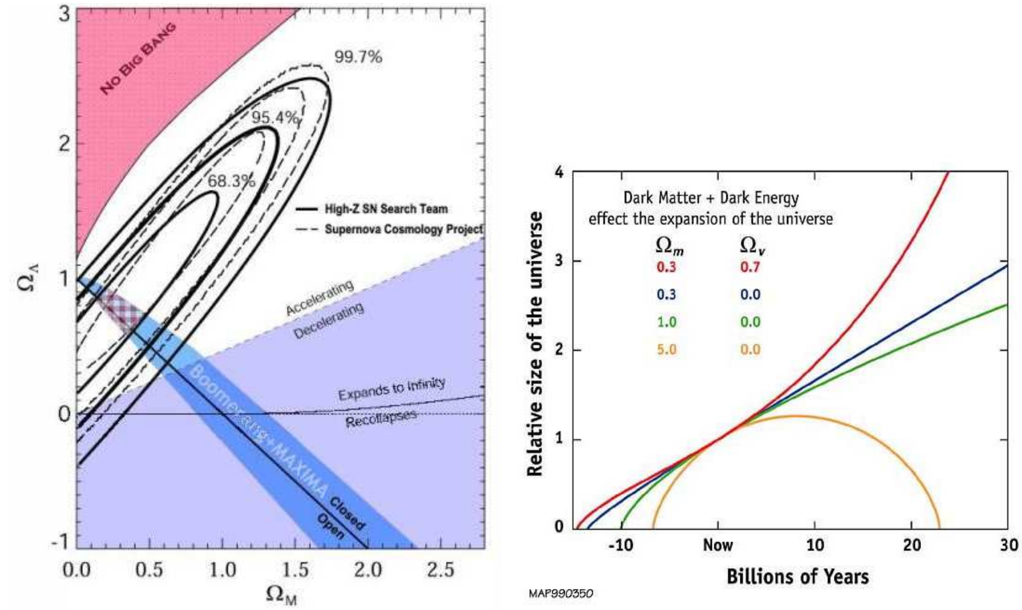

Fig. 1 **Left.** The constrains put from SNIa in the $\Omega_m - \Omega_\Lambda$ plane obtained by the SCP and by the HZSNS teams. The relative constraints put by CMB experiments are also shown here (from Perlmutter & Schmidt 2003). The recent WMAP result are consistent with the limits from this figure. **Right.** The dependence of the expansion factor of the universe from the combination of matter Ω_m and Dark Energy Ω_Λ densities (from the WMAP team).

whose entity might modify the cosmic expansion rate $\dot{R}/R$. The ultimate fate of the universe is therefore an answer which is hidden in the FL equation and it is basically provided by the balance among the three dominant terms Ω_m, Ω_Λ and Ω_k, as is evident from the alternative form of the FL equation

$$1 = \Omega_m + \Omega_\Lambda + \Omega_k \ , \tag{7}$$

once we write $\Omega_m = \frac{8\pi G\rho_m}{3H^2}$; $\Omega_k = -\frac{k}{(RH^2)}$; $\Omega_\Lambda = \frac{8\pi G\rho_\Lambda}{3H^2} = \frac{\Lambda}{(3H^2)}$. Thus the destiny of the universe is determined not only by its geometry (the term Ω_k) but also by the balance between the matter content and the dark energy/cosmological constant contributions to the total value of Ω. Thus, both the geometry and the matter/energy content of the universe determine its ultimate fate (see Eq. 7 and Fig.1). It is crucial, then, to understand the relative importance of the matter and Dark Energy fields in the universe.

2 FILLING THE UNIVERSE

The stress-energy tensor $T_{\mu\nu}$ in Eq. (1) contains information on the matter and energy content of the universe: the energy density associated with radiation (mainly the CMB) and to the Dark Energy and the matter density associated with the ordinary (baryonic) and Dark Matter.

The basic picture of the cosmic fluid in the expanding, cooling universe leads to a number of precise predictions: the formation of nuclei and the resulting primordial element abundances, and the later formation of neutral atoms and the consequent emergence of the CMB of photons. The (recombination) epoch, $z_{\rm rec}$, at which atoms form (when the universe was $\sim 3 \cdot 10^5$ years old and at temperature $\sim$ 3000 K) is described in terms of simple physics: at $T \gtrsim 3000$ K the universe consisted of a ionized plasma of mostly protons, electrons and photons with a few Helium nuclei and tiny traces of Lithium (Steigman 2002). This plasma was opaque to the background light, or more precisely the photon mean free path was much smaller than the horizon size. As the universe expanded and cooled, the plasma 'recombined' into neutral atoms, first the Helium and, a little later, the Hydrogen. The crucial parameter affecting the recombination process is the baryon-to-photon ratio, or the excess of baryons over anti-baryons in the universe, $\eta = (n_b - n_{\bar{b}})/n_\gamma = 2.68 \cdot 10^{-8}\ \Omega_b h^2$, where Ω_b is the baryon density and $h = (H_0/100)$ km s^{-1} Mpc^{-1}. Recombination happens quickly but not instantaneously. The universe goes from a completely ionized state to a neutral state over a redshift range $\Delta z \sim 200$.

Once the cosmic plasma was in a neutral state the photon mean free path increases to a size much larger than the horizon size and the CMB photons can freely propagate through the cosmic ambient preserving their blackbody distribution. At $z_{\rm rec}$ the CMB had a temperature $T \approx 3000$ K and, as the universe expands, the CMB photons redshift so that the CMB temperature drops like $T \sim R^{-1}(t)$. The CMB we observe today is a highly isotropic photon background with $T_0 \approx 2.73$ K. This allows us to determine the redshift (i.e., the distance) to the last scattering surface $1 + z_{\rm rec} = R(t_0)/R(t_{\rm rec}) = T_{\rm rec}/T_0 \approx 1100$. To the extent that recombination happens at the same time and in the same way everywhere, the CMB will be of precisely uniform temperature. In fact the CMB is observed to be uniform in temperature to about 1 part in 10^5.

The CMB is highly but not completely isotropic. The largest contribution to the CMB anisotropy is a local phenomena due to the Earth's motion relative to the 'comoving' cosmological reference frame. Such a dipole temperature anisotropy is $\delta T/T \approx 10^{-3}$ (Bennett et al. 1996) corresponding to a peculiar velocity of the Earth of ≈ 600 km s^{-1} in the direction of the constellation Leo. Intrinsic, primordial CMB anisotropies are nonetheless expected due to the fact that the last scattering surface was not completely uniform reflecting the existence of primordial fluctuations in the Dark Matter-baryon-photon fluid. The temperature and polarization fluctuations, reflecting fluctuations in the primordial density and velocity fields of the early universe, have the potential to provide the most precise constrains on the overall properties of the universe. The reasons are that *i*) the universe was quite simple at the epoch imaged by the CMB and is quite well described by a linear perturbation theory in a homogeneous and isotropic cosmological space-time; and *ii*) that the physical processes relevant at that epoch are sufficiently simple to be well understood.

The density fluctuations are of great physical interest, first because these are fluctuations which later collapsed to form all the structure in the universe. Second, the form of the primordial density fluctuations provides, within the paradigm of inflation, a powerful probe of the physics of the very early universe. Perturbations in the black body radiation filling a homogeneous and isotropic universe can be caused by three physical processes: *i*) a change in the intrinsic CMB temperature at a given point in space occurs if the radiation density increases via adiabatic compression, just as with the behaviour of an ideal gas; *ii*) a Doppler shift occurs if the radiation at a specific point is moving with respect to the observer. Any density perturbation found within the horizon scale is necessarily accompanied by a velocity perturbation. The induced CMB temperature fluctuation equals the peculiar velocity with motion towards the observer corresponding to a positive temperature fluctuation; *iii*) a difference in the gravitational potential between a specific point in space and the observer results in a temperature shift of the radiation propagating between the point and the observer due to a gravitational redshifting (the so called Sachs-Wolfe effect). A more formal description of all basic physical processes involved in the production of CMB fluctuations can be found in Hu & Dodelson (2002 and references therein).

The dominant peaks in the CMB spectrum are caused by the collapse of DM overdensities and the oscillation of photon-baryon fluid into and out of these fluctuations, and hence the

CMB power spectrum is sensitive to the combination of the main cosmological parameters: the curvature Ω_k, cosmological constant Ω_Λ, matter-radiation ratio ($\Omega_m h^2$), and baryon-photon ratio (baryon content $\Omega_b h^2$). Furthermore, consistency checks can be made with some model assumptions. It is the features of these peaks that provide us with an array of cosmological tests.

On April 30th 2001, at the same time, three different teams, BOOMERANG (Netterfield et al. 2001), DASI (Halverson et al. 2001) and MAXIMA (Lee et al. 2001) reported a detection of multiple features in the CMB angular power spectrum (see Fig.2).

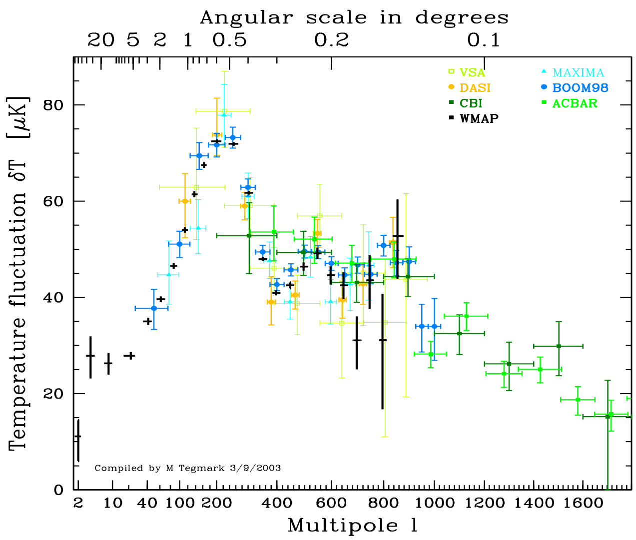

Fig. 2 The CMB power spectrum data from the most recent experiments as labelled (from http://www.hep.upenn.edu/ max/cmb/experiments.html).

The WMAP team confirmed these results and provided the best representation of the CMB power spectrum up to $\ell \sim 800$ and up to now. Data analysis from these experiments showed the main features of the CMB power spectrum: a dominant first acoustic peak at $\ell \sim 200$, a second peak at $\ell \sim 540$ and a third peak at $\ell \sim 840$. The position of the first peak $C_{\ell 1}$ measures the angular diameter distance to the last scattering surface and depends on the geometry of the universe: the available data (see Fig.2) indicate that the universe has a spatially flat geometry $\Omega_k \approx 0$. The second peak is thought to be an incontrovertible evidence of inflationary sound waves and the ratio $C_{\ell 2}/C_{\ell 1}$ is set by the physics at recombination and by the shape of the primordial spectrum $P(k)$. Higher ℓ peaks are sensitive to energy density ratio of DM to radiation and the third peak $C_{\ell 3}$ is specifically sensitive to the amount of Dark Matter. The WMAP data have been used to recover the fundamental cosmological parameters with an unprecedented precision (Spergel et al. 2003).

The CMB experiments results combined with other cosmological rulers like distant SNe, Large-Scale galaxy and galaxy clusters distribution lead to a concordance cosmological model of which we delineate here the gross features. Geometry and kinematics arguments tell us that we live in a flat, $\Omega_0 = 1$ universe which undergoes an acceleration of its expansion. The composition of our universe consists of Dark Energy $\Omega_\Lambda \sim 3/4$, Dark Matter with $\Omega_m \sim 1/4$ and normal atoms in a fraction $\Omega_b \sim 1/25$. The equation of state of the cosmic fluid Eq. (5) has $w \lesssim -0.7$. Microphysics tell us that inflation is working in the early universe and that density fluctuations (i.e., all cosmic structures) are produced from quantum fluctuations during inflation. The available data also tell us that our universe has an age of $t_0 \approx 13.7 \pm 0.2$ Gyr and that the Hubble constant is $H_0 \approx 71 \pm 3$ km s^{-1}Mpc^{-1} (see Spergel et al. 2003 for the complete of values of the cosmological parameters obtained from WMAP and other cosmological data sets).

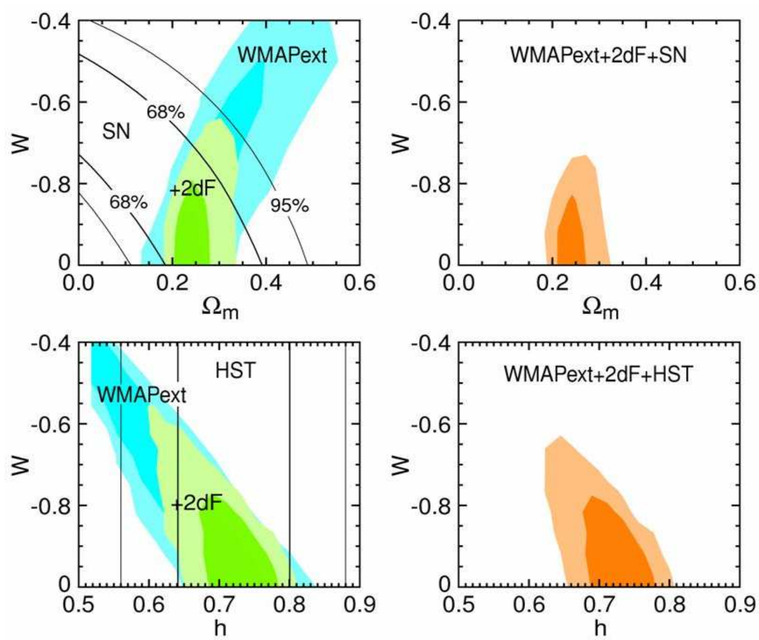

Fig. 3 The constraints on w, Ω_m and h as obtained from SNe, CMB and Large-Scale data are shown (from Spergel et al. 2003).

3 PRECISION COSMOLOGY ?

The recent cosmological data, and in particular the WMAP results, confirmed important aspects of the current cosmological model. Moreover, WMAP heralds a new age of precision cosmology with careful error analysis, tightly constraining many key parameters. Furthermore, WMAP's measurements of the CMB polarization power spectrum shows that the epoch of cosmic reionization - associated with the formation of the first stars - had already occurred when the universe was several hundred million years old.

At the same time we acknowledge these results, it is important to recognize that relevant issues still remain to be fully addressed. For example, Bridle et al. (2003) warned that it is not yet clear whether the CMB temperature spectrum is truly consistent with inflation. The spectrum is roughly scale-invariant, but there are hints of peculiarities and a key inflationary prediction - the presence of a gravitational wave background - has not yet observed. We also

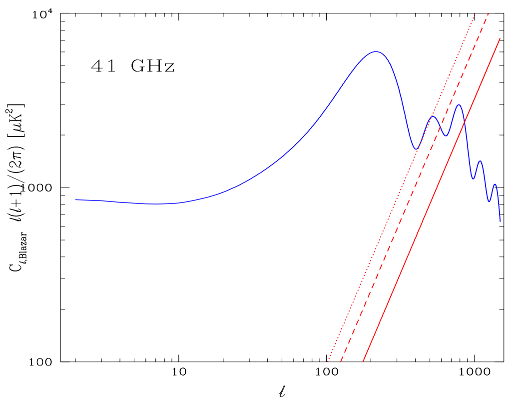

Fig. 4 The contribution of Blazars to the CMB fluctuation spectrum in the WMAP Q channel at 41 GHz (see Giommi & Colafrancesco 2004) is shown. A typical CMB power spectrum evaluated in a ΛCDM cosmology with $\Omega_m = 0.3, \Omega_\Lambda = 0.65, \Omega_b = 0.05$ which best fits the available data is shown for comparison. We report at http://www.asdc.asi.it/boomerang/ the list and spectral properties of Blazars found in the BOOMERANG map: 12 out of the 54 Blazars found in this map are also included in the WMAP source catalog.

do not know the nature of the Dark Energy and its relation with the vacuum energy (i.e., the cosmological constant). Dark Matter nature also remains mysterious: we do not know yet its nature, nor we are certain about its density or the amplitude of the initial ripples in its distribution. Moreover, beyond the cosmological constraints based on WMAP alone on the flatness of space, the near scale-invariance, adiabaticity and Gaussianity, some important issues can only be addressed by combining WMAP data with other cosmological measurements.

As an example of systematic uncertainty in the context of the analysis of CMB anisotropy maps, the issue of the role of the many foreground sources that may contaminate CMB maps at the working frequencies of CMB experiments still needs a definite assessment. In fact, Giommi & Colafrancesco (2004) have recently shown that Blazars heavily contaminate the CMB power spectrum at angular scales $\lesssim 0.3$ deg where the second and third acoustic peaks are observed (see Fig.4). The Poissonian spectrum of the Blazar population equals the CMB power spectrum at $\ell \approx 850$, and contaminates it at levels $\sim 30\%$ at $\ell \approx 500$ and $\sim 80\%$ at $\ell \approx 800$, thus rendering looser the determination of cosmological parameters.

On the other hand, also the cosmological constraints derived from distant SNe rely upon not yet completely understood issues concerning, e.g., k-corrections, extinction, selection effects, gravitational lensing and evolution. A similar situation also apply to the constraints derived by Large-Scale structure data.

4 THE UNIVERSE WE WOULD LIKE TO KNOW

The breakthroughs in technology and astronomical technique led to the assessment of today's concordance cosmological model. However, even after the historic WMAP breakthrough, there remain unresolved issues and several fundamental questions to be answered: *if $\Omega_0 = 1$, as predicted by inflation, what is the driving force of Inflation? What do we know about the physics of Inflation? What is the ultimate nature of Dark Energy? Do we really need Dark Energy? Which is the amount and ultimate nature of Dark Matter?*

The answer to these questions can be found in the realm of precision cosmology which will be at hand in the next coming decades. In the following, I will briefly present some recent working ideas which are on the discussion table of many cosmologists, astronomers and fundamental interaction physicists.

4.1 In the beginning

There are still many questions to be answered about inflation and mainly about its occurrence. Testing inflation involves testing its three most robust predictions: a spatially flat universe, a nearly scale-invariant, nearly power-law spectrum of Gaussian adiabatic density perturbations, and a spectrum of nearly scale-invariant gravitational waves. The first two predictions have now some robust indication but will be probed definitely over the next decade by CMB experiments like PLANCK: the value of Ω_0 should be determined to a precision better than $\sim 1\%$ and the spectral index n_S of the primordial density fluctuation spectrum should be measured to a $\sim \%$ accuracy. The CMB and the abundance of rare objects - such as galaxy clusters - will also allow the Gaussianity hypothesis to be tested. The detection of a gravitational wave background produced during inflation is also a "smokin' gun" test of the inflationary epoch. In fact, the amplitude of the primordial gravitational waves, $h_{\rm GW}$, is directly related to the scale of inflation, $h_{\rm GW} \sim H_{\rm inflation}/M_{\rm Planck}$. Combined measurements of $n_S - 1$ and $dn_S/d\ ln\ k$ can reveal much about the underlying scalar potential driving inflation (see, e.g., Turner 2002). The cosmological attraction of inflation is its ability to make the present state of the universe almost insensitive to its initial state. However, many cosmologists are also asking what happened before inflation. Progress in this field will depend on the theoretical developments of Quantum Gravity and or string theories (see, e.g., Linde 2001) as well as on the study of cosmological relics.

4.2 The destiny of the universe

Observations of distant SNIa have provided evidence that the universe is accelerating (see Fig.1). Since the matter energy density is diluted by the cosmic expansion as $\rho_m \sim R^{-3}$, the SNIa data imply that, to make the universe accelerate, the Dark Energy must slowly vary with time (roughly speaking, redshifting more slowly than R^{-2}) and space. A straightforward candidate for the Dark Energy component is the vacuum energy (see Carroll 2000) with $w = -1$. The idea that the Dark Energy is simply a constant term is in excellent agreement with the data (see Fig.3) but raises two main questions: *i*) why is the vacuum energy so small (the cosmological constant problem)? and *ii*) why are the matter and vacuum energy densities approximately equal today (the coincidence problem)? So, the simplest interpretation of the Dark Energy in terms of a cosmological constant is perhaps the hardest to analyze without a complete understanding of the cosmological constant problem: in this case, we are in the lowest energy state possible (or more properly that the particles we observe are excitation of such state) and that such energy does not vanish. Nonetheless, there is room to imagine that the Dark Energy is not perfectly constant, like a scalar field rolling slowly in a potential, sometimes known as quintessence. There are also other more exotic possibilities including tangled topological defects and variable-mass particles (Carroll 2001). One route to constrain the Dark Energy field is to characterize observationally its time evolution using a simple parametrization as in Eq. (5) which is able to characterize the Dark Energy evolution out to relatively nearby measurable redshifts. Distant SNe and distant galaxy clusters are among the best tools to probe the cosmic equation of state at intermediate redshifts $z \sim 1 - 3$. Blank-sky SZ surveys of galaxy clusters offer a very promising way to probe Dark Energy, in principle up to the formation redshift for these structures. In fact, since the SZ effect is redshift-independent, dedicated surveys can detect many distant clusters and strongly restrict the region of the $\Omega_m - w$ plane fitted by CMB, SNIa and cluster observations (Haiman et al. 2001).

4.3 The nature of the dark universe

The discovery of the nature of the Dark Energy may provide an invaluable clue to understand the nature and the dynamics of our universe. However, there is also $\sim 27\%$ of the matter content of the universe which is dark and still requires a detailed explanation.

Clusters of galaxies are the largest bound structures in the universe which can yield specific information on the presence and amount of Dark Matter from both the properties of the thermal Intra-Cluster medium (e.g., Sarazin 1988) and from the study of gravitational lensing of background object images distorted by the intervening cluster mass distribution (e.g., Bartelmann & Schneider 2001). These methods constitute standard astrophysical probes for the presence, amount and spatial distribution of DM in galaxy clusters, the fairest and most representative sample of DM concentrations in the universe. However, such methods are not able to yield constrains on the nature and physical composition of the DM particles.

Physical probes on the nature of the DM building up the large-scale structure gravitational potential field can be obtained, nonetheless, by studying the interaction of the DM particles (mainly their annihilation) through the relative signals of the interaction/annihilation in the galaxy (or galaxy cluster) atmospheres. These signals involve, in the case of a neutralino (χ) DM, the emission of gamma-ray, neutrinos, synchrotron and bremsstrahlung radiation together with the Compton scattering of the CMB photons by the secondary electrons produced in the DM annihilation process (see Colafrancesco 2004a for a review).

In this framework, Colafrancesco & Mele (2001, hereafter CM) suggested that the observational features of non-thermal phenomena in galaxy clusters (e.g., radio halos observed in many clusters and their gamma-ray emission which will be observable with the next generation gamma-ray telescopes, see Colafrancesco 2004a) can provide constraints on the mass and on the composition of the neutralinos χ, the lightest particle that is predicted in supersymmetric extensions of the Standard Model. In fact, CM have shown that - under the hypothesis that DM annihilation is responsible for most of the radio-halo emission via he associated secondary electrons - the highest observed frequency of the radio halo spectrum sets a lower limit to the neutralino mass $M_\chi \geq 70.5$ GeV $B_\mu^{-1/2}$ (here B_μ is the intra-cluster magnetic field in μG) which is independent of the χ composition. In the same framework, the slope of the radio halo spectrum could also give an indication on the neutralino physical composition. The radio halo spectrum of the two clusters considered here are well fitted by a model in which the neutralinos behave like pure gauginos, and annihilate mainly into fermions (see CM for details). Not only radio observations but also gamma-ray data can provide direct constrains on the neutralino physics. The next coming observations of nearby clusters in gamma-rays could, in fact, provide constraints on the neutralino mass from the observation of the cutoff in their gamma-ray spectra (see Colafrancesco 2004a). It has been recently proposed (Colafrancesco 2004b), in such a context, that the unavoidable Compton Scattering of CMB photons by the secondary electrons produced in $\chi\chi$ annihilation also provides an additional source of SZ effect, with specific spectral and spatial features that can limit the neutralino fundamental properties in the $M_\chi - \sigma_{\rm annihilation}$ plane (see discussion in Colafrancesco 2004b). It is reasonable, in conclusion, to expect - in the coming future - that the $M_\chi - \sigma_{\rm annihilation}$ plane will be further constrained from an appropriate combination of astrophysical and accelerator data. It is appealing, in these respects, to expect that some astrophysical features of galaxy clusters might give information on the fundamental properties of the DM particles.

5 EPILOGUE

The large amount of observational and theoretical results so far obtained testify that we are discerning the basic features of the universe. With the advent of precision cosmology we will be reasonably confident to say if those events that took place during the earliest stages of cosmic evolution have had a profound influence on the present state of the universe. There are impressive programs in place and in the coming future to test the inflationary period and the pre-inflationary stage of the cosmic history, the nature of the dark universe and of its main constituents: the Dark Energy and Dark Matter. The new uncertainties in our ultimate destiny will open an exciting door that may lead to a deeper understanding of our ultimate origin.

Even though there is a widespread belief that "this is already the dawning of the age of precision cosmology, when all the important cosmological parameters will be established to one significant figure or better", and that "in the age of accurate cosmology the model will be checked tightly enough to be established as a convincing approximation to reality", I am still prone to think that "a state of thoroughly conscious ignorance is the prelude to every real advance of knowledge (*James Clerk Maxwell*)".

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