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STATUS OF OBSERVATIONAL COSMOLOGY AND INFLATION

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ABSTRACT

We review the latest developments in the determination of the cosmological parameters from the measurement of the Cosmic Microwave Background Radiation (CMBR) anisotropies and of the Large Scale Structure (LSS) of the Universe. We comment finally on the implications for the primordial spectrum and the consequences for inflationary models.

1 Introduction

It now more than apparent that we are in the era of precision cosmology: during the last year we had an impressive progress, the first detection of the polarization of the CMBR by DASI and the precise determination of the CMBR anisotropies and confirmation of the DASI result by the satellite experiment WMAP. Since the space at my disposal is limited, I will concentrate in these proceedings on the latest results and try to convey the status of observational cosmology after WMAP; I apologize in advance if I will appear to disregard all previous efforts, but they are covered for example in the proceedings of the past editions of the PIC conference series.

This conference is mainly attended by particle physicists not always familiar with the cosmological "jargon", so I will start with a short review of Standard Cosmology and then follow up with the latest observational highlights and the consequences of such measurements for the cosmological parameters. The last section will be devoted instead to inflation and the attempt to relate the initial power spectrum with the one predicted by a single-field inflationary model.

2 Standard Cosmology

The key assumption of our Standard Cosmological model is the fact that the Universe is homogeneous and isotropic on the very large scale. Thanks to this simplification we can write the background metric as a function of very few parameters, in the Friedmann-Robertson-Walker (FRW) form [1]:

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega\right] \tag{1}$$

where $R(t)$ is the *scale factor* of the universe and the constant k determines the spatial geometry ($k = +1, 0, -1$ for open, flat and closed universe respectively).

The evolution of the scale factor depends on the energy content and geometry of the universe and is given by the Friedmann equation,

$$H^2 = \left[\frac{\dot{R}(t)}{R(t)}\right]^2 = \frac{8\pi}{3M_{Pl}^2}\rho - \frac{k}{R^2} + \Lambda. \tag{2}$$

Here M_{Pl} is the Planck mass, the energy density ρ includes all the radiation and matter of the universe (i.e. relativistic and non-relativistic particles), while Λ is the cosmological constant or "vacuum energy". $H(t)$ is the Hubble parameter and its present value H_0 is called the Hubble constant; it is usually expressed via the adimensional quantity h, which is H_0 in units of 100 km/s Mpc^{-1}.

Table 1: *Equation of state, energy density as a function of R and time dependence of R and H for different types of energy.*

Type	w	$\rho(R)$	$R(t)$	$H(t)$
Generic	w	$\propto R^{-3(1+w)}$	$\propto t^{2/(3(1+w))}$	$2(1+w)/(3t)$
Radiation	$1/3$	$\propto R^{-4}$	$\propto t^{1/2}$	$1/(2t)$
Matter	0	$\propto R^{-3}$	$\propto t^{2/3}$	$2/(3t)$
Λ	-1	const.	e^{Ht}	$\sqrt{\Lambda}$

In order to solve for the evolution of the scale factor, it is also necessary to know the equation of state of the different types of energy, defined as the ratio of pressure over density and use the first law of thermodynamics:

$$w = \frac{P}{\rho} \qquad \frac{d\rho}{dt} = -3H\,(\rho + P) = -3H\rho\,(1+w). \tag{3}$$

In Table 1 are given the solutions for the energy density and the scale factor and Hubble parameter for different equations of state. Note that the dependence of H on time allows to distinguish between different types of energy.

Dividing by H^2, the Friedmann equation can be recast in the simple form

$$1 = \Omega_M + \Omega_k + \Omega_\Lambda \tag{4}$$

where $\Omega_M = \rho/\rho_c$, with $\rho_c = \frac{3M_{Pl}}{8\pi}H^2$ being the critical density, while $\Omega_k = -k/(H^2R^2)$ and $\Omega_\Lambda = \Lambda/H^2$. Cosmologists therefore usually measure densities in terms of the critical density as $\Omega_i h^2$, which is just the density in units of $\rho_c/h^2 = 1.879\times10^{-29}$ g/cm^3 $= 1.054\times10^4$ eV/cm^3. Also distances and time are measured by the redshift due to the cosmological expansion: $1+z = \lambda_{obs}/\lambda_{em} = R_0/R(t_{em}) \geq 1$, where λ_{em}, t_{em} are the wavelength and time at emission and λ_{obs}, R_0 the observed wavelength and the present scale factor respectively.

2.1 Structure formation

We have seen that the evolution of our universe is determined by its energy content, but we have not yet explained how an isotropic and homogeneous state evolves into stars, galaxies, cluster of galaxies. The Universe does not appear at all homogeneous on the small scale and this is due to the gravitational attraction: once a small over-density appears, gravity causes it to grow and finally collapse into a bounded system. So the basic ingredient for structure formation is the presence of initial fluctuations in the density, that can in later time act as seeds for the gravitational collapse [2].

Assuming that the initial fluctuations were gaussian, their properties can be completely described in term of their power spectrum

$$\mathcal{P}(k) \simeq |\delta\tilde{\rho}(k)|^2 \tag{5}$$

where $\delta\tilde{\rho}(k)$ is the Fourier transform of the density contrast $\delta\rho(x) = \rho(x) - \bar{\rho}$. The dependence of the power spectrum from the scale k is very often parameterized by the power-law k^{n-1}, with $n = 1$ corresponding to the scale-invariant case.

Since the fluctuations are very small (of the order of 10^{-5}), we can consider them as perturbations of the FRW metric and use perturbation theory to describe their dynamics. Their evolution depends only on the cosmological parameters h, Ω_{tot}, Ω_M, Ω_B, the nature of Dark Matter and the equation of state of the dominant component of the energy density. Clearly the density fluctuations cannot grow as long as the pressure of the plasma counteracts the gravitational force and therefore during radiation domination the system is still in the linear regime and only oscillations in the plasma (the acoustic peaks !) take place. Later, when matter dominates, the pressure drops to zero and the fluctuations can grow: structures start to form and we enter the complicated non linear regime.

So any cosmological observation of the density contrast (at present or at recombination epoch) contains in principle information on two class of quantities: the cosmological parameters describing the energy content of the universe and governing the evolution of the background metric and the initial conditions for the fluctuations, also known as the primordial spectrum. It is not always easy to disentangle between the two and it is important to beware of degeneracies and correlations between the different parameters.

3 Cosmic Microwave Background Radiation

The CMBR brings us information about the state of the universe at the recombination epoch at about $z \simeq 1000$, when the electrons were captured by the nuclei to form neutral atoms and radiation decoupled. The photons that reach us now had their last scattering at that time. Density fluctuation in the plasma in thermal equilibrium gave rise to temperature fluctuations, since the denser regions were hotter. So the temperature anisotropies in the CMBR bring us direct evidence of the density contrast at recombination.

It is traditional to express the temperature anisotropies into spherical harmonics functions [3]:

$$\Delta T(\theta, \phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi) \tag{6}$$

and obtain the temperature anisotropies as a function of the multi-pole number

$$C_\ell \equiv \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2. \tag{7}$$

Note that the multi-pole number ℓ corresponds to a particular length $\lambda = k^{-1} \propto \ell^{-1}$ on the last scattering surface. Since at this epoch we are still in the linear regime, the equation of motion for the single scales are independent and can be solved, e.g. using numerical codes like CMBFAST [4]. In very broad terms three different behaviours are present, depending on the wavelength: large scales (i.e. small multi-poles) do not oscillate, but feel the presence of the gravitational potential; scales equal or smaller than the sound horizon oscillate and the first acoustic peak corresponds to the scale of the horizon who has just completed one compression before recombination, while even peaks are instead rarefaction peaks; finally the very small scale (large multi-poles) oscillations are damped. For a detailed description of the physics of the CMBR see [3, 5].

3.1 Polarization

Another interesting property of the CMBR, which has been firstly measured in the last year, is that it is partially linearly polarized. Such polarization is due to the fact that Thomson scattering tends to produce preferentially a final photon polarized in the same direction as the initial photon [6, 5]. It is clear then that if the plasma would be completely isotropic, no net polarization would arise. But due to the density fluctuations, the local velocity field of the photons (i.e. the flux) in the rest system of the electrons is not homogeneous. Then the polarization reflects the local quadrupole in the velocity field, which is anti-correlated with the temperature anisotropies (the velocity is zero at maximal compression or rarefaction). The polarization can in general be decomposed into two different modes, the curl-free mode E and the curl mode B. Since the B mode is a pseudo-vector quantity, its cross correlations with T and E (which are a scalar and a vector) vanish. The cross correlation between the temperature anisotropies and the E mode of polarization is instead non-vanishing. We can therefore describe completely the CMBR temperature and polarization anisotropies via four independent correlations, the $< TT >$ correlation which corresponds to C_l introduced in the previous subsection, the mixed correlation between temperature and $E-$mode polarization anisotropies $< TE >$, and finally the pure $E-$ and $B-$mode correlations $< EE >$ and $< BB >$.

It is important to say that scalar density fluctuations excite predominantly E-mode polarization, while tensor fluctuations (as expected from gravity waves)

excite the E- and B-modes at the same level. Once both polarization modes will be detected, it will be clear how large is the contribution of the tensor fluctuations.

3.2 DASI

DASI (Degree Angular Scale Interferometer) is an interferometer experiment located at the South Pole, who first detected the CMBR polarization. The measurement was announced last year during the COSMO-02 conference (you can see the announcement live on the web-site [7]). For the detailed results and plots, I refer to the DASI web-site [8] and their publications [9]; the experiment measured all the four correlation in the multi-pole range between 200 and 800 and obtained evidence for a non-zero E-mode at 4.9σ. Their signal is in agreement with the expected E-mode polarization produced by scalar density fluctuations and with the measured temperature anisotropies. The $B-$mode instead is consistent with zero.

3.3 WMAP

WMAP (Wilkinson Microwave Anisotropy Probe) is a satellite experiment launched by NASA in 2001 (for the details of the mission, please look at their very exhaustive web-page [10]). The satellite completed the first full sky observation in April '02 and the first data release based on that sky map took place this year, in February. The data and pictures are publicly available on the web-portal LAMBDA [11]. WMAP is continuing to take data and so there is more to come in the future.

The WMAP team is measuring the intensity of radiation in 5 different bands and then the five maps (subtracting the dipole component and the Milky Way) are combined to obtain the full sky map of the temperature anisotropies. WMAP also measures the cross correlation between temperature and E-mode polarization anisotropies [12].

The WMAP data can reach the multi-pole $\ell \simeq 900$, up to the third acoustic peak; to extend to the higher multi-poles, to $\ell \simeq 1700$, the WMAP team included in their analysis the data of other two CMBR ground-based experiments, ACBAR (Arcminute Cosmology Bolometer Array Receiver) [13] and CBI (Cosmic Background Imager) [14].

4 Large Scale Structure (LSS)

Information on the density contrast can also be obtained from the distribution of galaxies in our universe. The main assumption in this case is that the visible matter follows the distribution of the invisible Dark Matter. The unknown difference

between the two distribution is usually parameterized by the bias parameter. Also it is necessary to correct for the non-linearity in the evolution of the small scale perturbations to extract the present linear spectrum, which allows to access directly the primordial one.

Present surveys include the 2 degree Field Galaxy Redshift Survey (2dF GRS) just completed, which released recently data about 270.000 galaxies [15]. An even larger survey is ongoing, the Sloan Digital Sky Survey (SDSS), which aims at 1 million of galaxies in one quarter of the sky [16]. From the distribution of the galaxies in the sky one can obtain the two point correlation function and the density contrast power spectrum.

Other ways to measure the density contrast rely on using photons of distant objects as a probe of the intervening matter or gas densities. Lyman α forest data measure the absorption lines in the spectra of distant quasars caused by intergalactic hydrogen and estimate the cosmic gas distribution out to large distances [17]. This method makes possible to access also the power spectrum at the very small scales, but its systematics are still under debate, since the power spectrum estimation relies on modeling and must be corrected for non-linearities [18]. Yet another way of accessing the matter distribution is weak gravitational lensing, which measures the shear (distortion) in the images of distant objects due to the gravitational potential of the intervening matter [19]. Weak lensing is sensitive to the total matter distribution along the line of sight, without any bias. Other methods to obtain informations on the matter distribution and the power spectrum are X-rays measurements [20] and peculiar velocities [1].

One recent development about measurements of the matter power spectrum is the fact that the results from CMBR determinations and from the different LSS methods are now overlapping with each other and cover continously all the scales between the horizon size, about $10^4\ h^{-1}$ Mpc, and $1\ h^{-1}$ Mpc (see e.g. [21] for a compilation of data on the power spectrum just before WMAP).

5 The cosmological parameters from WMAP and LSS

5.1 Total energy density and matter density

As discussed previously, the position of the first peak in the CMBR power spectrum corresponds to a wavelength equal to the sound horizon at the surface of last scattering. Since the sound horizon for a relativistic plasma is known, the angular position of the first peak measures directly the geometry of the universe, i.e. Ω_k. It is usual to express such a measure in terms of the the total energy density $\Omega_{tot} = 1 - \Omega_k$.

From a global fit including LSS data and a prior on the value of H_0, WMAP obtains $\Omega_{tot} = 1.02 \pm 0.02$[1] [22], completely in agreement with the previous result of Boomerang [23] and MAXIMA [24].

The dependence of the temperature anisotropies on the matter density is more involved and the quantity determined from the global fit is $\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$ [25]. Using the best fit value for the Hubble constant $h = 0.71^{+0.04}_{-0.03}$, this gives $\Omega_M = 0.27 \pm 0.04$ [25]. Together with the measurement of the total energy density, we obtain then $\Omega_\Lambda \simeq 0.7$, as measured independently from Supernova IA (SN IA) data [26, 27].

5.2 Baryon density

The baryon matter present in the plasma at recombination changes the dynamics of the oscillations, enhancing the compressions and suppressing the rarefactions. Therefore a very precise measurement of the baryon density comes from the comparison between odd and even CMBR peak heights. The WMAP collaboration obtains $\Omega_b h^2 = 0.0224 \pm 0.0009$ [25]. This values is much more precise and fully consistent with the one computed from the observed Deuterium abundance with standard Big Bang Nucleosynthesis (BBN). Still the ^4He and ^7Li abundances are not so concordant, as discussed in detail in [28]. It is still open if such discrepancies are due to systematics, non standard BBN or else.

5.3 Hot Dark Matter and neutrinos

Light particles with mass of the order of eV, which remain relativistic down to late times, constitute what is called Hot Dark Matter (HDM). Their main characteristic for what regards structure formation is the fact that they have a relatively large free-streaming length: for a massive non-interacting particle the free-streaming length is given by $\lambda_{FS} \simeq 1200/m_{\rm eV}$ Mpc, where $m_{\rm eV}$ is the mass of the particle in eV. The presence of such free streaming suppresses the formation of bound systems of sizes smaller than λ_{FS}, i.e. it suppresses the power spectrum of the small scales. This effect is absent for Cold Dark Matter, which has practically zero free-streaming length. For this reason the HDM density can be estimated from the power spectrum at small scales, which is measured by LSS data, in particular Lyman α data. The CMBR measurements are less sensitive to HDM since they sample larger scales than λ_{FS}, but they are useful for setting the other parameters in the game.

[1] All errors are 1σ if it is not explicitely stated otherwise.

Combining CMBR, 2dF GRS and Lyman α data, the WMAP collaboration obtains at 98% CL the bound $\Omega_\nu h^2 \leq 0.0076$ [25], which for 3 degenerate neutrinos with thermal distribution can be translated into $m_\nu \leq 0.23\,\mathrm{eV}$ at 98% CL. Note that the limit strongly depends on the cosmological parameters, the number of sterile neutrinos and their thermalization, as discussed by [29]. There a more conservative, but qualitatively not much different bound is obtained as: $\sum m_\nu \leq 1.01\ (1.38)$ eV for $N_\nu = 3\ (4)$. Not surprisingly, the bound is driven mostly by the Lyman α data, which sample the smaller scales; substituting those with X-rays data, [30] finds instead evidence for a non zero neutrino mass, $\sum m_\nu = 0.56^{+0.30}_{-0.26}$ eV. Further analysis and data are needed to clarify the issue.

Note anyway that the effect by HDM of suppressing the power spectrum at small scales could be partially mimicked by the "running" of the spectral index of the primordial spectrum or by the presence of quintessence at early times [31].

5.4 Equation of state of the Dark Energy

The WMAP team also performed a global fit for the equation of state of the Dark Energy combining CMBR data with the 2dF GRS and SN IA data and obtained the bound $w \leq -0.78$ at 95% CL [25] using a constant $w \leq 1$.

5.5 Reionization

A surprising result of the WMAP polarization data is the high signal at low multipoles $\ell < 10$. Such polarization on very large scales cannot be generated at recombination, but is instead due to Thomson scattering at a much later epoch, when the universe was re-ionized. The epoch of reionization took place after the gravitational collapse, when the light of the first stars ionized the hydrogen clouds. The effect of the presence of ionized gas on the temperature anisotropies is to reduce the spectrum by a factor $e^{-2\tau}$, where τ is the optical depth for a photon traveling in the ionized medium from the epoch of reionization to today. Until the WMAP result, the optical depth τ was thought to be very near to zero, consistent with the models which describe the formation of the early stars at $z \simeq 6$. The polarization data instead give $\tau = 0.17 \pm 0.06$, hinting at reionization happening at much earlier times, $z \simeq 20$ [12]. This independent determination of reionization via the polarization is very important because it breaks the degeneracy between the spectral index n and τ present in the temperature anisotropies.

6 Inflationary predictions

Inflation is a period of exponential expansion, which is usually introduced before the Standard Cosmology and solves some of its problems about initial conditions [32]. The exponential expansion is driven by the effective cosmological constant due to the displacement of a scalar field from the minimum of its potential. In order for the potential energy to give this effect, the scalar field must have negligible kinetic energy and descend very slowly towards the minimum, i.e. the inflaton potential V has to satisfy the slow roll conditions:

$$\epsilon = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad |\eta| = M_{Pl}^2\left|\frac{V''}{V}\right| \ll 1, \tag{8}$$

where the primes denote first and second derivative w.r.t. the inflaton field. Inflation ends when the scalar field starts to roll faster and finally to oscillate around the minimum; then it decays producing radiation and reheating the universe.

Many different models of inflation have been proposed and studied [33], all involving physics beyond the Standard Model, and one important question is to confront them with the data and try to gain insight on the new physics.

6.1 Comparison with the data

The CMBR observations agree very well with the general inflationary predictions for single field models [2], as we will discuss in detail.

- Inflation produces in general a spatially flat universe, i.e. $\Omega_{tot} = 1$, in perfect agreement with the WMAP measure of $\Omega_{tot} = 1.02 \pm 0.02$ [25].

- The primordial fluctuations are generated by the quantum fluctuation of the inflaton field, which is practically massless and non-interacting, and therefore they are gaussian and adiabatic; the measured power spectrum is consistent with gaussianity [34] and adiabaticity (the fraction of isocurvature perturbations $f_{iso} \leq 0.33$ at 95% CL) [35].

- The slow roll approximation predicts a nearly scale-invariant spectrum of the scalar primordial perturbations related to the inflaton potential as following:

$$\mathcal{P}(k) = \left.\frac{1}{12\pi^2 M_{Pl}^6}\frac{V^3}{(V')^2}\right|_{k=HR} \tag{9}$$

  where the l.h.s. is evaluated at the inflaton value corresponding to the time when the physical scale R/k was equal to the horizon H^{-1}. Due to the slow

roll of the inflaton field, the dependence from k is expected to be weak. In fact the spectral index is at lowest order in slow roll:

$$n(k) - 1 = \left. \frac{d\log(\mathcal{P}_\mathcal{R})}{d\log(k)} \right|_{k=HR} = 2\eta - 6\epsilon \ , \tag{10}$$

so inflation predicts a very small deviation from the Harrison-Zeldovich scale invariant case $n = 1$. The WMAP data are actually consistent with a spectral index equal to one, $n = 0.99 \pm 0.4$ in [25]. A similar result comes also from other data analysis [36, 37, 38, 39].

- A surprising hint from WMAP is the preference of the data for a "running" of the spectral index n, which means a non trivial k dependence. Expanding n in a Taylor series around a reference scale k_0,

$$n(k) = n(k_0) + n'(k_0) \ln\left(\frac{k}{k_0}\right) + ... \tag{11}$$

and neglecting higher order terms, the WMAP team obtains the best fit value, $n'(k_0) = -0.055^{+0.028}_{-0.029}$ for $k_0 = 0.002\text{Mpc}^{-1}$ [35].

The central value for n' appears too large to be consistent with the single field inflationary prediction, which is

$$n'(k) = -\frac{2}{3}\left[(n-1)^2 - 4\eta^2\right] - 2\xi^2, \tag{12}$$

where ξ^2 is a second order slow roll parameter $\xi^2 = M_{Pl}^4 \frac{V'V'''}{V^2}$. In fact the only way to accommodate large running for small $(n-1)^2 \simeq 4\eta^2 \leq 0.02$ is to assume a strange potential with unnaturally large ξ^2 [40]. Of course the value for n' is consistent with zero at the 2σ level [35], or even less [36, 37, 38, 39], so further investigations and statistics are required to settle the question.

- Tensor perturbations (primordial gravity waves) have instead power spectrum:

$$\mathcal{P}_{grav}(k) = \left. \frac{1}{6\pi^2} \frac{V}{M_{Pl}^4} \right|_{k=HR} \tag{13}$$

and spectral index

$$n_{grav}(k) = \left. \frac{d\log(\mathcal{P}_{grav})}{d\log(k)} \right|_{k=HR} = -2\epsilon. \tag{14}$$

So if the scale of inflation potential is much lower than the Planck mass, the contribution of tensor perturbations can be negligible. At the moment the data show no evidence for tensor perturbation, and for $r = \mathcal{P}_{grav}/\mathcal{P}_\mathcal{R}$ one finds $r < 0.90$ at 95% CL [25].

7 Conclusions and outlook

The era of precision cosmology continues and in this year we have seen the "concordance" ΛCDM universe confirmed by the new WMAP data. The cosmological parameters are nowadays measured to the level of few per cent, unthinkable precision up to a couple of years ago. This and the overlap between CMBR and LSS data for the power spectrum allow to put better constraints on the models of structure formation, as demonstrated by the strong bound on the energy density in neutrinos.

The polarization of the CMBR has been for the first time detected in the past year and this result confirms beautifully our understanding of the physics of acoustic peaks and gives an independent measure of the reionization.

For what regard the primordial fluctuations, the simple single field inflationary paradigm with negligible tensor perturbation is at the moment sufficient to describe the data.

Some small discrepancies in the concordance picture are appearing, e.g. BBN, the running of the spectral index, reionization, etc..., and are the object of present studies. We are looking forward to the next year with more data to come !

8 Acknowledgments

I would like to thank the organizers for the invitation to speak and the exciting atmosphere at the Workshop.

The bibliography here includes basically reviews and papers published in the last year in order to highlight the recent developments, it is surely not exhaustive nor complete. I apologize for the absences and I point the interested readers to the references of the references, in particular [1, 2, 3, 6, 33]. In the case of on-going experiments, I decided to give the reference not only of the publications, but also of the collaboration web-sites, where frequently updated informations and the latest achievements can be found.

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