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THE COSMIC MICROWAVE BACKGROUND DATA AND THEIR IMPLICATIONS FOR COSMOLOGY

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Abstract. Recently were published the results from three projects (BOOMERANG, DASI and MAXIMA) dealing with the observation of the temperature anisotropies of the cosmic microwave background (CMB). It was a real breakthrough for cosmology since these data established a new level in understanding the Universe. Here we present a review of the main results obtained by the projects mentioned above, emphasizing their significance to the nowadays status of cosmology. In this respect, we report on the increasing evidences for an inflationary period in the very early stages after the Big Bang, we discuss at large the values of the cosmological parameters and we acknowledge the picture of the Universe as it appears from the CMB data.
Key words: cosmic microwave background, cosmology

1. The Universe and the CMB

Conforming to the Big Bang theory, the nucleosynthesis took place at a redshift (z) around 10^9. Somewhere near the value z=1000, that is more or less 300 000 years later, the temperature of the Universe dropped to ~ 3000 K, permitting the formation of the neutral hydrogen. At a first glance this affirmation seams at least strange, knowing the fact that the ionization potential of hydrogen is 13.6 eV (10^5 K). However, at that epoch the number ratio between the photons and protons was 10^9 due to photons creation processes (i.e. Bremsstrahlung) hence a high-energy population of photons kept most of the hydrogen in an ionized state until lower temperatures. Because the scattering cross section of neutral hydrogen is smaller than the scattering cross section for free electrons (in this respect the protons are not important since the cross section is inverse proportional to the mass of the particle on which the photons are scattered off) there was a transition from an opaque Universe to a transparent one. This zone in the redshift space where the recombination (decoupling) happened is called the last scattering surface. Another significant moment in the Universe's history, from the point of view of the CMB physics, is the reionization of the matter at a roughly $z \approx 6$ ([1], [2]).

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If we assume that the expansion of the Universe is adiabatic, then an initial Planck spectrum will remain planckian ([3], [4]). The observed spectrum of the CMB is of a blackbody type, therefore as far as in the early stages the spectrum of the radiation was planckian (even there is a difference, namely a thermal spectrum becomes a blackbody one only for optically thick media, we will use both terms as having the same significance).

It can be shown that for redshifts greater than few times 10^4, Compton scattering ($\gamma e^- \rightarrow \gamma e^-$) can ensure kinetic equilibrium between radiation and matter. In this case the Bose-Einstein statistics is valid :

$$\eta = \left(e^{\frac{h\nu}{kT}+\mu} - 1 \right)^{-1} \quad (1)$$

where η is the occupation number and μ the chemical potential (providing a measure of the spectrum's distortion).

In order to have thermal equilibrium one needs processes that can create photons. It turns out that for $z>10^6$, double Compton scattering ($\gamma e^- \rightarrow \gamma e^- \gamma$) and bremsstrahlung ($e^- X \rightarrow e^- X\gamma$; X - nucleus) can generate thermal equilibrium. The Planck spectrum, actually a Bose -Einstein spectrum with null chemical potential, can be expressed by the Planck function :

$$B_\nu(T) = \frac{2h\nu^3 c^{-2}}{e^{\frac{h\nu}{kT}} - 1} \quad (2)$$

The "purity" of the CMB thermal spectrum is far greater than any laboratory experiment is capable of. In Table 1 is the temperature inferred from the COBE satellite data.

Table 1
The CMB temperature from the Planck spectrum

T(K)	***References***
2.735 ± 0.060	[5]
2.726 ± 0.010	[6]
2.728 ± 0.004	[7]

2. The temperature fluctuations of the CMB

The CMB manifests anisotropy : its temperature is not the same in every direction on the sky; the differences are of the order of μK. Basically, is possible to divide these fluctuations in two distinctive groups : primary fluctuations, which existed before the recombination, and secondary fluctuations, generated between the decoupling and the present time.

a) Primary fluctuations

Intrinsic fluctuations : initial perturbations in the density distribution of matter in the early stages of the Universe. Within the framework of the inflationary models, they are quantum fluctuations, with a Gaussian distribution, amplified to cosmic scales by the expansion of the Universe ([8]).

Sachs-Wolfe effect : overdensity regions form potential wells. The photons have to climb out of the gravitational potential, so they lose energy ([9]).

Doppler effect : the photons scattered by the matter falling in the potential wells undergo Doppler shifts ([3]).

b) Secondary fluctuations (selection)

Rees-Sciama effect : it takes place when photons cross a gravitational potential well that varies with time. In this way they can gain or lose energy.

Gravitational lensing : this effect is responsible for variations of the photons' trajectories in the transverse plan of the line of sight.

Sunyaev-Zeldovich effect : if photons traverse a hot intra-cluster gaseous medium, they are inverse Compton scattered on the free electrons.

It is conventional to expand the temperature fluctuations in spherical harmonics ([8], [10], [11], [12], [13]) :

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi) \qquad ; \quad l = \overline{0,\infty} \quad m = \overline{-l,l} \tag{3}$$

It's possible to define the so called correlation function, which depends only on the angle θ (not the same with the one used in eq. 3) between two directions on the sky (here after, the brackets <...> are ensemble averages) :

$$C(\theta) \equiv \left\langle \frac{\delta T}{T}(\overrightarrow{n_1}) \frac{\delta T}{T}(\overrightarrow{n_2}) \right\rangle \qquad \overrightarrow{n_1} \cdot \overrightarrow{n_2} = \cos\theta \tag{4}$$

Using the addition theorem for spherical harmonics :

$$\sum_m Y^*_{lm}(\overrightarrow{n_1}) Y_{lm}(\overrightarrow{n_2}) = \frac{2l+1}{4\pi} P_l(\overrightarrow{n_1} \cdot \overrightarrow{n_2}) \tag{5}$$

we can rewrite the correlation function using the Legendre polynomials :

$$C(\theta) = \frac{1}{4\pi} \sum_l a_l^2 P_l(\cos\theta) \tag{6}$$

where

$$a_l^2 = \sum_m |a_{lm}|^2 \tag{7}$$

In the simple case of Gaussian fluctuations we have :

$$a_{lm} = \int \frac{\delta T}{T}(\vec{n})\, Y_{lm}^*(\vec{n})\, d\vec{n} \tag{8}$$

and the angular power spectrum coefficients are defined :

$$C_l = \left\langle |a_{lm}|^2 \right\rangle \tag{9}$$

From the orthonormality of the spherical harmonics :

$$\int Y_{lm}(\vec{n})\, Y_{l'm'}^*(\vec{n})\, d\Omega = \delta_{ll'}\delta_{mm'} \tag{10}$$

one obtains the expression of the power spectrum, still for Gaussian fluctuations :

$$\left\langle a_{lm}^* a_{l'm'} \right\rangle = C_l \delta_{ll'}\delta_{mm'} \tag{11}$$

The definition of the angular power spectrum coefficients takes into account the fact that we are dealing with only one realization of the statistical ensemble, that is the Universe we are observing. The uncertainty in estimating these coefficients it is named cosmic variance :

$$C_l = \frac{1}{2l+1} \sum_m a_{lm}^* a_{lm} \tag{12}$$

Finally, the correlation function reads :

$$C(\theta) = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\cos\theta) \tag{13}$$

On small sections of the sky (l>>1), where its curvature can be neglected, the analysis becomes ordinary Fourier analysis and the power spectrum is displayed in a simpler manner :

$$\left(\frac{\delta T}{T}\right)^2 = \frac{l(l+1)}{2\pi} C_l \tag{14}$$

The angular scale θ is inverse proportional to the multipole l just as the wavenumber k is to the wavelength λ in ondulatory physics. We will see that this analogy is very powerful, enabling a qualitative understanding of the complex processes in the early epochs of the Universe.

The observations of the CMB can be carried out at different resolutions (that is various θ angles), the changes being recorded in the power spectrum. It is useful to define a horizon scale for the last scattering surface, say θ", meaning the angle corresponding to the particle horizon size at the time of decoupling (recombination). Its value is around 1 degree, depending on the assumptions made for some cosmological parameters. Generally speaking the CMB spectrum is divided into three regions : the Sachs-Wolfe plateau, the peaks zone and the null zone. For superhorizon scales (θ > θ"), the physical processes acting at two directions on the sky separated by angle θ are causally disconnected because θ exceeds the particle horizon scale. In this region the Sachs-Wolfe effect is dominant. At subhorizon scales (θ < θ"), the temperature fluctuations are model dependent and represent a tool to discriminate between various models for the formation of large scale structures in Universe. The characteristic for this region of the power spectrum is the presence of peaks and dips. For angular scales smaller than the thickness of the last scattering surface, the primary fluctuations are damped out, hence the null zone.

3. The photon-baryon fluid

In order to understand the formation of peaks in the power spectrum, some basics of the photon-baryon fluid are useful.

Before recombination, free electrons acted as glue between photons and baryons through Thompson and Coulomb scattering, matter and radiation forming together a photo-baryonic plasma. Due to the continuous competition between the radiation pressure and the gravitational collapse, the fluid oscillates, resulting acoustic waves, by analogy to the phenomenon of a pressure disturbance traveling through air. In the Inflation Theory the structure of the Universe is seeded by random quantum fluctuations in the energy density. They imply fluctuations in the local gravitational potential, therefore regions of high density generate potential wells, while regions of low density generate potential hills (peaks). An intuitive picture of the photon-baryon fluid is a series of mechanical oscillators : the strings represent the radiation pressure and the balls are the masses. These oscillators follow the "form" of the gravitational field, and so, the analogue of the compression of a group of them in a potential well is the rarefaction of another group in a potential hill. Elementary thermodynamics states that compressing a gas will increase its temperature, similarly, expansion conducts to temperature decrease. A very important conclusion emerge from here : the "acoustic oscillations", a direct link to the quantum fluctuations from the early Universe, are implemented in the thermal map of the CMB generating the temperature anisotropies we observe.

At recombination, when the baryons release the photons, the oscillations freeze out. From the multitude of vibrational modes, there are some with special characteristics. The mode for which the fluid just had enough time to compress once before recombination, forms the first peak in the power spectrum. There is a mode for which the photon-baryon plasma had time not only for a compression, but also for a complete rarefaction, giving the second peak. If the wavenumber of the first peak is defined as :

$$k_1 = \frac{\pi}{s} \tag{15}$$

where s is the sound horizon (the distance sound can travel in the time before decoupling), then the superior peaks are multiple integers of this value.

4. Cosmological parameters

The most important cosmological parameters with respect to the CMB physics are summarized here.

H - the Hubble parameter; usually it is expressed with the adimensional parameter h.

$$H = 100h \qquad km\ s^{-1}\ Mpc^{-1} \tag{16}$$

ρ_{crit} - the critical density; it marks the boundary between an eternally expanding Universe and a recollapsing one; it is customary in cosmology to express the densities in units of this critical density.

$$\rho_{crit} = \frac{3H^2}{8\pi G} \tag{17}$$

Ω_b - the baryonic density.

$$\Omega_b = \rho_b \rho_{crit}^{-1} \tag{18}$$

sometimes the physical baryonic density is used : $\omega_b = h^2\Omega_b$.
Ω_{rel} - the density of relativistic matter : hot dark matter (HDM), neutrino, radiation.

$$\Omega_{rel} = \Omega_{HDM} + \Omega_\nu + \Omega_\gamma \tag{19}$$

Ω_{nonrel} - the density of non-relativistic matter : cold dark matter (CDM), baryons.

$$\Omega_{nonrel} = \Omega_{CDM} + \Omega_b \tag{20}$$

Ω_m - the total density of matter.

$$\Omega_m = \Omega_{rel} + \Omega_{nonrel} \tag{21}$$

Ω_Λ - the vacuum energy density.

$$\Omega_\Lambda = \rho_\Lambda \rho_{crit}^{-1} \tag{22}$$

Ω - the total density.

$$\Omega = \Omega_m + \Omega_\Lambda \tag{23}$$

n - the spectral index of the primary fluctuations.
τ - the optical depth at reionization.
C_{10} - the amplitude of the multipole l=10 in the power spectrum.
f_ν - it' s defined as follows $f_\nu = \Omega_\nu / (\Omega_{CDM} + \Omega_\nu)$.
r - the ratio between the tensorial and scalar amplitudes of the fluctuations.

For a total density less than 1, the Universe is open. An exact value of 1 means a flat Universe and this is the prediction of the Inflation Theory. Finally, for Ω > 1 the Universe is closed.

5. Statistical mathematics intermezzo

It is useful to present a short concentrated list of definitions involving terms highly used in the next sections ([14]).

Let x_i be a set of variables and k_i a set of arbitrary values with $k_i \in (-\infty, +\infty)$, where $i = \overline{1, n}$.

The distribution function is defined :

$$F(x_1, \ldots, x_n) = P(x_1 < k_1, \ldots, x_n < k_n) \tag{24}$$

having the meaning of the probability of simultaneously fulfillment of the conditions $x_i < k_i$, $i = \overline{1, n}$.

The total probability density is :

$$f(x_1, \ldots, x_n) = \frac{\partial^n F(x_1, \ldots, x_n)}{\partial x_1 \ldots \partial x_n} \tag{25}$$

Sometimes there is just one variable of interest in the set, accordingly, the marginal distribution is defined :

$$g(x_r) = \int_{-\infty}^{+\infty} \ldots \int_{-\infty}^{+\infty} f(x_1, \ldots, x_n)\, dx_1 \ldots dx_{r-1} dx_{r+1} \ldots dx_n \tag{26}$$

For multiple parameters of interest (say m, with m < n), by modifying eq. 26, the multiple marginal distribution is obtained :

$$g(x_1, \ldots, x_m) = \int_{-\infty}^{+\infty} \ldots \int_{-\infty}^{+\infty} f(x_1, \ldots, x_n)\, dx_{m+1} \ldots dx_n \tag{27}$$

The mean value of a variable is :

$$\overline{x_r} = \int_{-\infty}^{+\infty} \ldots \int_{-\infty}^{+\infty} x_r \;\; f(x_1, \ldots, x_n)\, dx_1 \ldots dx_n = \int_{-\infty}^{+\infty} x_r \;\; g(x_r)\; dx_r \tag{28}$$

The variance reads :

$$\sigma^2(x_r) = \int_{-\infty}^{+\infty} \dots \int_{-\infty}^{+\infty} \left(x_r - \overline{x_r}\right)^2 \; f\left(x_1, \dots, x_n\right) dx_1 \dots dx_n \tag{29}$$

The covariance is defined :

$$\operatorname{cov}(x_i, x_j) = \int_{-\infty}^{+\infty} \dots \int_{-\infty}^{+\infty} \left(x_i - \overline{x_i}\right)\left(x_j - \overline{x_j}\right) g(x_i) \; g(x_j) \; dx_1 \dots dx_n \tag{30}$$

In practice, a common situation is to address the problem of the probability for a parameter' s value to be constrained in a given interval $[\lambda_1,\lambda_2]$. The confidence level for the parameter λ can be written :

$$CL(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} L(\lambda)\, d\lambda}{\int_{-\infty}^{+\infty} L(\lambda)\, d\lambda} \tag{31}$$

where L(λ) is a probability function (the likelihood function).

In many cases, the interval $[\lambda_1,\lambda_2]$ is unknown and more or less arbitrary values are assigned a priori to CL. When L(λ) has a Gaussian form (this is almost always true in the CMB physics), the values taken into account for the confidence level correspond to a normal distribution with 1σ, 2σ, 3σ, that is 68.3%, 95.4%, 99.7%.

A fortunate situation is that in which external information enable to set constraints on the interval $[\lambda_1,\lambda_2]$. Such supplementary conditions (priors) are very valuable in breaking down the degeneracies that might characterize a set of variables.

6. The power spectrum analysis

In order to extract the cosmological parameters from the power spectrum of the CMB, the so called maximum likelihood method is used ([15], [16], [17], [18]).

For an easier manipulation eq. 3 is rewritten :

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} \; Y_{lm}(\theta,\phi) \equiv \Delta(\vec{n}) \tag{32}$$

The correlation function from eq. 13 is just an idealization because experimentally, the CMB temperature measurements cannot be carried out punctually on the sky, but, because of instrumental limitations, in a small region centered on the line of sight $\vec{n}$. So, there is an integration over the beam that must be accounted for :

$$\Delta_b(\overrightarrow{n_p}) = \int \Delta(\vec{n})\, B\left(\overrightarrow{n_p}, \vec{n}\right) d\Omega \tag{33}$$

where the function B is the beam profile, $\vec{n}$ is the direction to a point on the sky, $\overrightarrow{n_p}$ is the direction of the beam axis. If B depends only on the angle θ' between $\vec{n}$ and $\overrightarrow{n_p}$, then is possible to write a modified correlation function :

$$C_b(\theta) = \left\langle \Delta_b(\overrightarrow{n_1})\, \Delta_b(\overrightarrow{n_2}) \right\rangle = \frac{1}{4\pi} \sum_l (2l+1)\, C_l\, |B_l|^2\, P_l(\cos\theta) \tag{34}$$

where the coefficients B_l are given by the expression :

$$B(\theta') = \frac{1}{4\pi} \sum_l (2l+1)\, B_l\, P_l(\cos\theta') \qquad ; \quad \vec{n}\cdot\overrightarrow{n_p} = \cos\theta' \tag{35}$$

Now, having a set of observational data $d_i = \Delta_b(\overrightarrow{n_i})$ and a model represented by a vector $\vec{\Theta}$ containing the parameters of interest, the idea is to fit the data with the model. Having this in mind, the likelihood function is defined, that is the probability of obtaining the data given the model parameters :

$$L(\vec{\Theta}) = \mathrm{Prob}\left(\vec{d} \mid \vec{\Theta}\right) = \frac{e^{-\frac{1}{2}\vec{d}^t C^{-1} \vec{d}}}{(2\pi)^{\frac{N_{pix}}{2}} |C|^{\frac{1}{2}}} \tag{36}$$

N_{pix} is the number of data, C the covariance matrix with the elements :

$$C_{ij} = \left\langle d_i\, d_j \right\rangle = T_{ij} + N_{ij} \tag{37}$$

with the signal $T_{ij} = C_b(\theta_{ij})$ and the noise N_{ij}.

The parameters' values are obtained by the maximization of the likelihood function.

7. The projects BOOMERANG, DASI and MAXIMA

In 2001 were released, almost simultaneously, the results of the above mentioned groups regarding the temperature anisotropies of the CMB. These projects are briefly described in this section.

BOOMERANG - Balloon Observations of Millimetric Extragalactic Radiation and Geophysics was launched on December 29, 1998 from McMurdo Station, Antarctica and acquired 10 days of data from an altitude of 39 km.

DASI is the acronym for Degree Angular Scale Interferometer. The instrument is based at the Amundsen-Scott South Pole Station (Antarctica). The data gathered comprise 97 days of observations during the period 5 May-7 November 2000.

MAXIMA, a balloon, means Millimeter Anisotropy Experiment Imaging Array. The data in discussion here have been taken during the August 2, 1998 flight in Palestine, Texas at an altitude of 32 km.

Supplementary information can be found in [19] and [20], also on-line at the addresses :

http://www.physics.ucsb.edu/boomerang/

http:// cosmology.berkeley.edu/group/cmb/

http://astro.uchicago.edu/dasi/

8. RESULTS

In Fig.1, 2 and 3 are represented the power spectra extracted from MAXIMA ([21], [22], [23]), BOOMERANG ([24], [25], [26]) and DASI ([27]) data. Three peaks rise in each diagram at approximate the same multipoles : 200, 550 and 850 ([28], [22], [29], [26], [24]). From previous data, the presence of the second and third peaks was incert. The fact that independent projects identified them successfully is a strong evidence for their real existence, a systematical error being unlikely. Still, there are some open questions regarding the amplitudes of the second and third peak.

For almost two decades, two families of models have been considered challengers for describing the formation of large scale structures in Universe : inflation and topological defects. Now, after the analysis of the new CMB data, it seems clear that pure topological defects are excluded ([30], [31]), for the simple reason they predict just one peak in the power spectrum. Some novel models mix inflation and topological defects in order to explain the observations, but the Inflationary Theory is doing that in a simpler manner ([32], [33], [34], [35]).

In the following we will discuss to some extend the values of the cosmological parameters and their constraints as they appear from the data sets of the three projects mentioned above. Sometimes, these data are combined with the ones gathered by the Cosmic Background Explorer (COBE) satellite, launched in 1989, the original discoverer of the temperature anisotropies in the CMB.

The constraints in the matter density-vacuum energy density plane from the MAXIMA and COBE data appear in Fig. 4 ([36]). Shaded contours show confidence levels of 68.3% (light gray), 95.4% and 99.7% (dark gray); the contours have the same signification hereafter. Overlaid are the bounds obtained from high redshift supernovae data, and the confidence levels of the joint likelihood. The straight line is the inflationary prediction (total density equals one). Apparently, the data seem to favorise an open Universe, however this could be just an artifact of the priors used.

Fig. 5 ([24]) is a replica of Fig. 4 with BOOMERANG and COBE measurements and priors on h and the age of the Universe. Here, the situation is in some respect inverted than it was in the case of MAXIMA data, pointing to a closed Universe. As mentioned before, the external conditions play a major role and any interpretation should be done with care.

In Fig. 6 ([37]) are represented marginalized likelihood functions calculated using weak priors on h from different data set combinations. Also, the constraints in the matter density-vacuum energy density plane are reproduced. Slight tendencies to a closed Universe and a baryon density higher than the one predicted within the Big Bang Nucleosynthesis Theory (BBN), $\Omega_b h^2 = 0.02$, are evident. These discrepancies are misleading since the errors involved in the calculations are not obvious in the diagrams. A comparison of the parameter extractions from different data using different number of variables for the theoretical models will be made during this report.

In the BOOMERANG data ([26]) the baryonic density is very well constrained near the value obtained from the BBN. The total density seems to be consistent with a flat Universe. The spectral index is around unity.

Fig. 7 ([27]) shows marginalized likelihood distributions from DASI measurements, assuming weak priors on h and varying the prior on the optical depth due to reionization. The shaded region is the BBN prediction. There is a good constraint on the baryon and cold dark matter densities. The total density is poorly constrained, nevertheless is close to unity. Note that for a null optical depth, the baryonic density gets closer tot the BBN value. This is strange since evidences ([1], [2]) point to the existence of a reionization period in the history of the Universe, hence such a value for the optical depth is ruled out.

The most recent analysis of the combined BOOMERANG, DASI and MAXIMA data set was carried out in [38], using a more general model with 11 parameters (previous authors used 7). Fig. 8 represents one of the results. In the first two rows are the constraints obtained from the use of only CMB and large scale structure (LSS) information. In the next ones, a prior on h was added. There is a very well defined constraint on the baryonic density and the spectral index. Adding the prior on h, the curvature density is restricted to 0; also the vacuum energy density is constrained near 0.6.

Table 2 presents the parameter extraction from BOOMERANG data ([26]), with the LSS and supernovae priors. In Table 3, the values are from DASI data ([27]) with the priors : h > 0.45 and $0.0 \le \tau \le 0.4$. The cosmological parameters in the case of MAXIMA project are featured in Table 4 ([36]), where the external conditions are : $0.4 \le h \le 0.9$, $\Omega_m > 0.1$ and the age of the Universe greater than 10 Gyr. From all three tables is clear a tendency of the total density to unity. The agreement between the BBN and the CMB regarding the value of the baryon density is quite outstanding, having in mind that one method involves nuclear physics when the Universe was seconds old, and the other plasma physics more than 100 000 years later (however, see [37] for a slightly different result). The spectral index is near 1, in accordance with the inflationary prediction of adiabatic primary density perturbations. As a general remark, there are hard evidences for the reality of the dark matter and the vacuum energy.

9. CONCLUSIONS

One of the main realizations of the BOOMERANG, DASI and MAXIMA experiments was the clear detection of the second peak in the CMB angular power spectrum. It means that the fluctuations originating in pure topological defects (e.g. strings) are excluded by the data. Taking also into account the proximity of the spectral index to unity, the picture emerging is that the primary fluctuations in the density of matter are of quantum type, leading to the assertion that, at least for the moment, the Inflation describes best the Universe we are living in.

A very good agreement between theory (BBN) and observations are to be noted in the case of the baryonic density.

The CMB brings in new arguments for the existence of the mysterious dark matter, which moreover, dominates the normal matter in an approximate ratio of 6 to 1. Despite the number of candidates for dark matter, and the experiments designed to reveal them, basically, its constitution is unknown. Even the statement that the dark matter interacts only gravitationally with the baryonic matter is presently debated. Particles as WIMP (Weak Interacting Massive Particles) or objects like MACHO (Massive Astrophysical Compact Halo Object) are only hypothetical ([39]). Still, something is clear : massive neutrinos can account just for a small fraction of the dark matter content in the Universe.

The Universe seems to be flat (total density equals one), dominated by an exotic type of energy : the vacuum energy (around 60 % of the total density).

The future of CMB research appear to be very dynamic : satellites as MAP (Microwave Anisotropy Probe; http://map.gsfc.nasa.gov/) already on orbit, or PLANCK (http://astro.estec.esa.nl/Planck), planed to be launched in 2007, will gather, hopefully, precious information, milestones in understanding this complex system called the Universe.

Note. During the editing of the present report, new data were released (May 25, 2002) from the CBI (Cosmic Background Imager; http://www.astro.caltech.edu/~tjp/CBI/) project. There is a very good agreement with the results commented here. The novelty is an excess power in the angular spectrum for high-l (at 3σ confidence level), in a region beyond the rezolution capabilities of the previous projects. For details, see [40], [41], [42], [43].

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Table 2
Cosmological parameter extraction from BOOMERANG data ([26])

Ω	n	$\Omega_b h^2$	$\Omega_{CDM} h^2$	Ω_Λ	Ω_m
0.99 ± 0.04	1.03 ± 0.10	0.023 ± 0.003	0.14 ± 0.03	0.65 ± 0.06	0.34 ± 0.07

Table 3
Cosmological parameter extraction from DASI data ([27])

Ω	n	$\Omega_b h^2$	$\Omega_{CDM} h^2$	Ω_m	Ω_Λ
1.04 ± 0.06	1.01 ± 0.08	0.022 ± 0.004	0.14 ± 0.04	0.40 ± 0.15	0.60 ± 0.15

Table 4
Cosmological parameter extraction from MAXIMA data ([36])

Ω	$\Omega_b h^2$	C_{10}	$\Omega_{CDM} h^2$
0.90 ± 0.18	0.0325 ± 0.0125	690 ± 200	0.17 ± 0.16

Caption Fig.1 – The CMB power spectrum from MAXIMA data. Top : for l<335 a map with a resolution of 5' was used ([21]); for l>335 was used a map with the resolution of 3' ([22]); the curve is the best fit to the data corresponding to a inflationary Universe with (Ω_b, Ω_{CDM}, Ω_Λ, n, h)=(0.1, 0.6, 0.3, 1.08, 0.53). Bottom : a comparison between the power spectrum from [21] (open circle) and from [22] (square). From [22].

Caption Fig.2 - The CMB power spectrum from BOOMERANG data. B00 ([25]) represent only 7% from the data assigned as B01 ([26]). Also are showed the recalibrations of the original data due to an improved analysis method. From [24].

Caption Fig.3 - The CMB power spectrum from DASI data. The solid line is the best fit. The dashed line corresponds to a model with (Ω_b, Ω_{CDM}, Ω_Λ, τ, n, h)=(0.05, 0.35, 0.60, 0, 1.00, 0.65). From [27].

Caption Fig.4 – The constraints in the Ω_m - Ω_Λ plane from MAXIMA and COBE data. From [36].

Caption Fig.5 – The constraints in the Ω_m - Ω_Λ plane from BOOMERANG and COBE data, with the priors 0.45<h<0.85 and age of the Universe greater than 10 Gyr. From [24].

Caption Fig.6 – Top : marginalized likelihood functions with weak priors on h from COBE+MAXIMA (M-1), COBE+BOOMERANG (B98), COBE+BOOMERANG+MAXIMA (B98+M-1), COBE+BOOMERANG+MAXIMA+LSS (+LSS). Bottom : constraints in the Ω_m - Ω_Λ plane. From [37].

Caption Fig.7 – Marginalized likelihood distributions from DASI data with h>0.45. For the solid-dotted line $0.0<\tau<0.4$, while for solid line τ=0.0. From [27].

Caption Fig.8 – Marginalized likelihood functions from combined MAXIMA, BOOMERANG and DASI data. In the first two rows only the information from CMB and LSS is used. In the next rows a prior on h is added h=0.74. From [38].

Figure 1

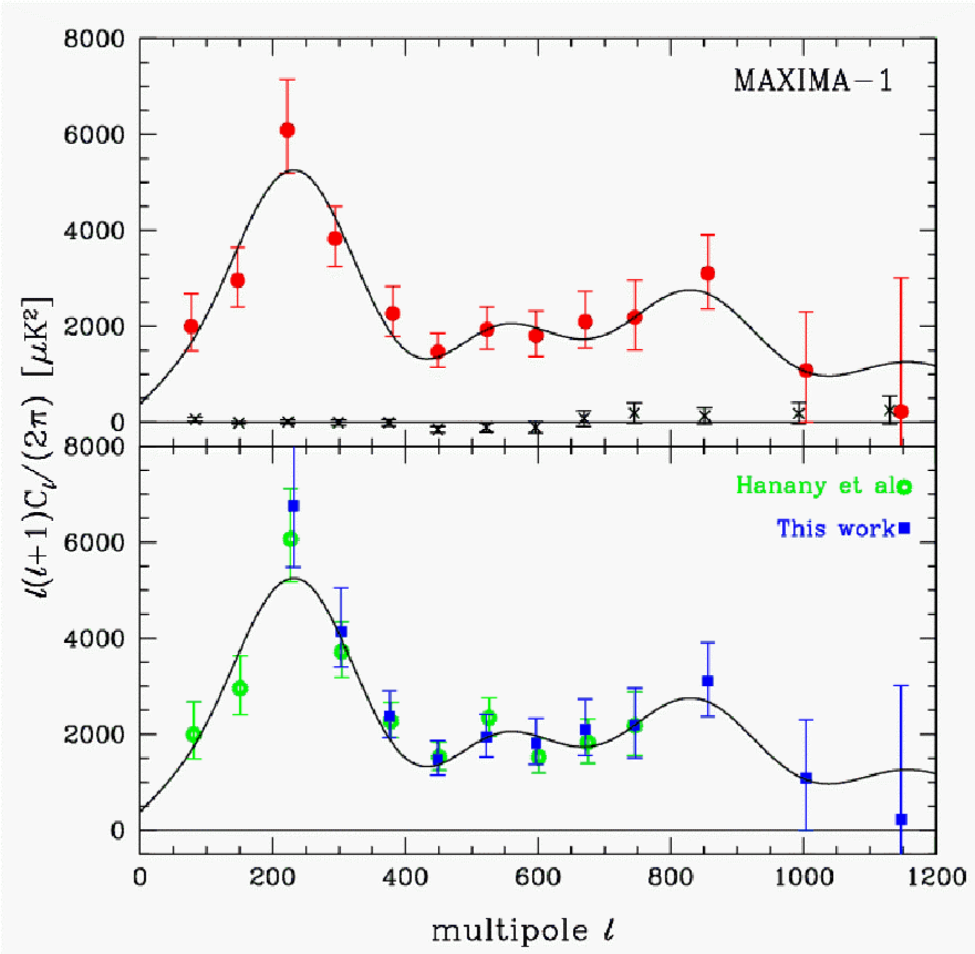
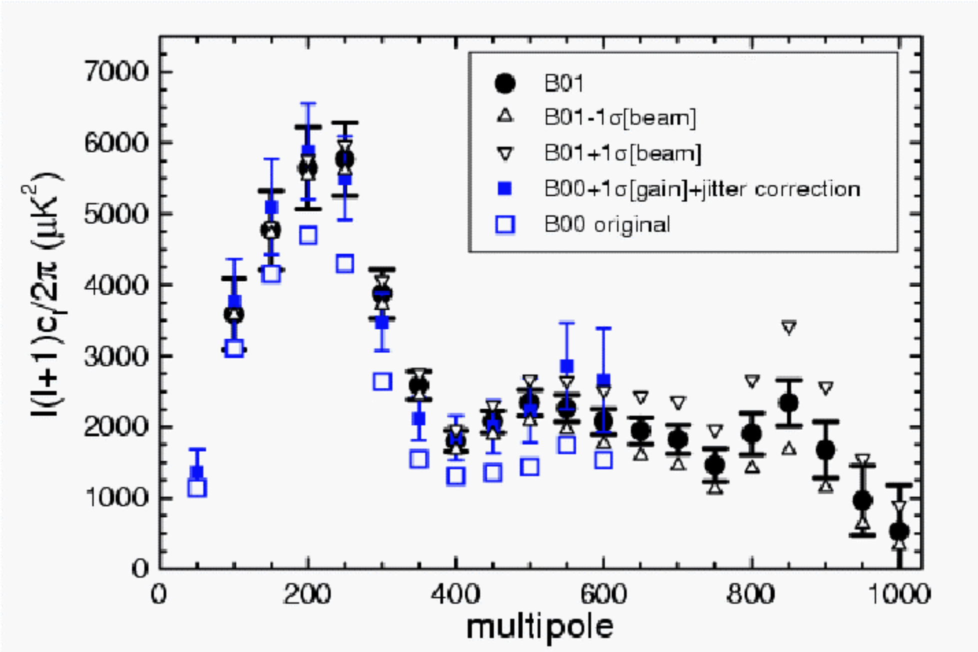

MAXIMA−1
Hanany et al
This work
multipole ℓ
ℓ(ℓ+1)Cℓ/(2π) [μK²]
8000
6000
4000
2000
0
0
200
400
600
800
1000
1200

Figure 2



B01
B01-1σ[beam]
B01+1σ[beam]
B00+1σ[gain]+jitter correction
B00 original
l(l+1)c_l/2π (μK^2)
multipole

Figure 3

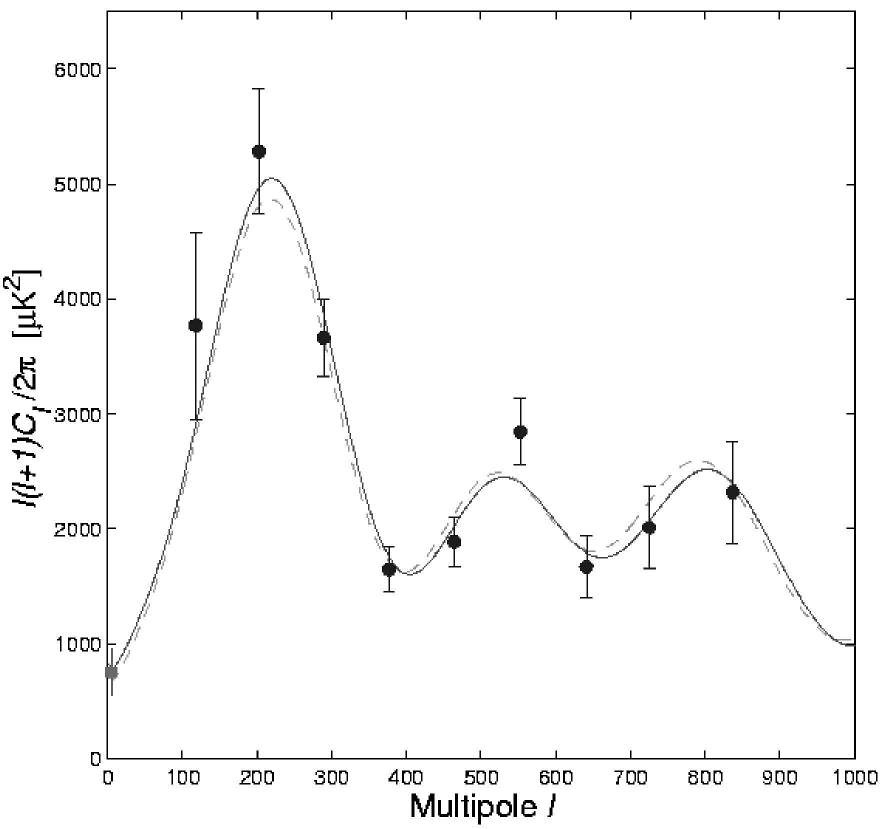

6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
700
800
900
1000
Multipole l
$l(l+1)C_l/2\pi$ [μK^2]

Figure 4

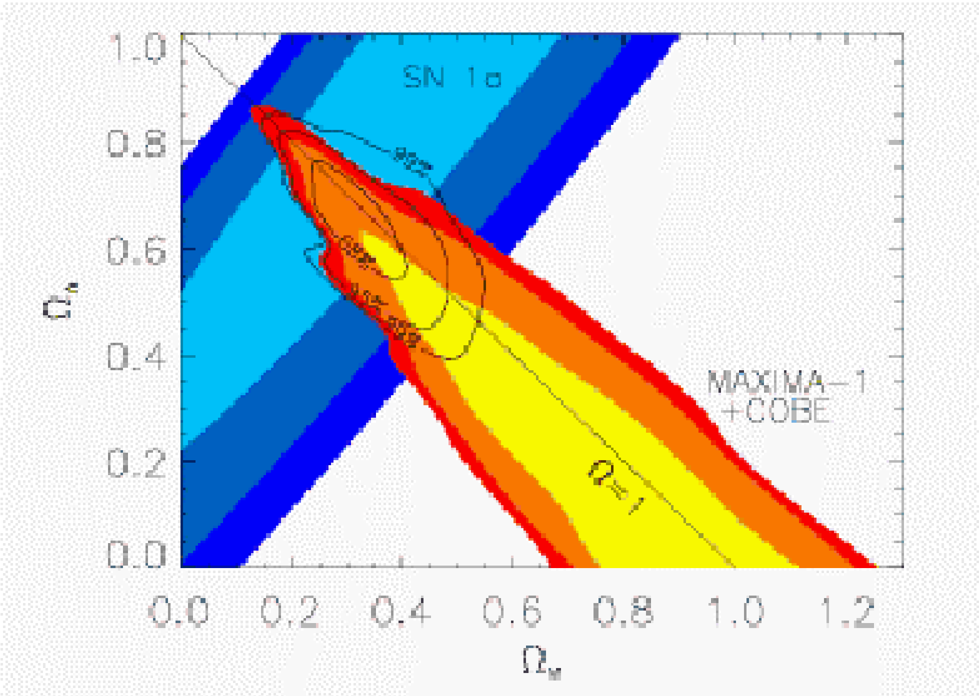


Figure 5

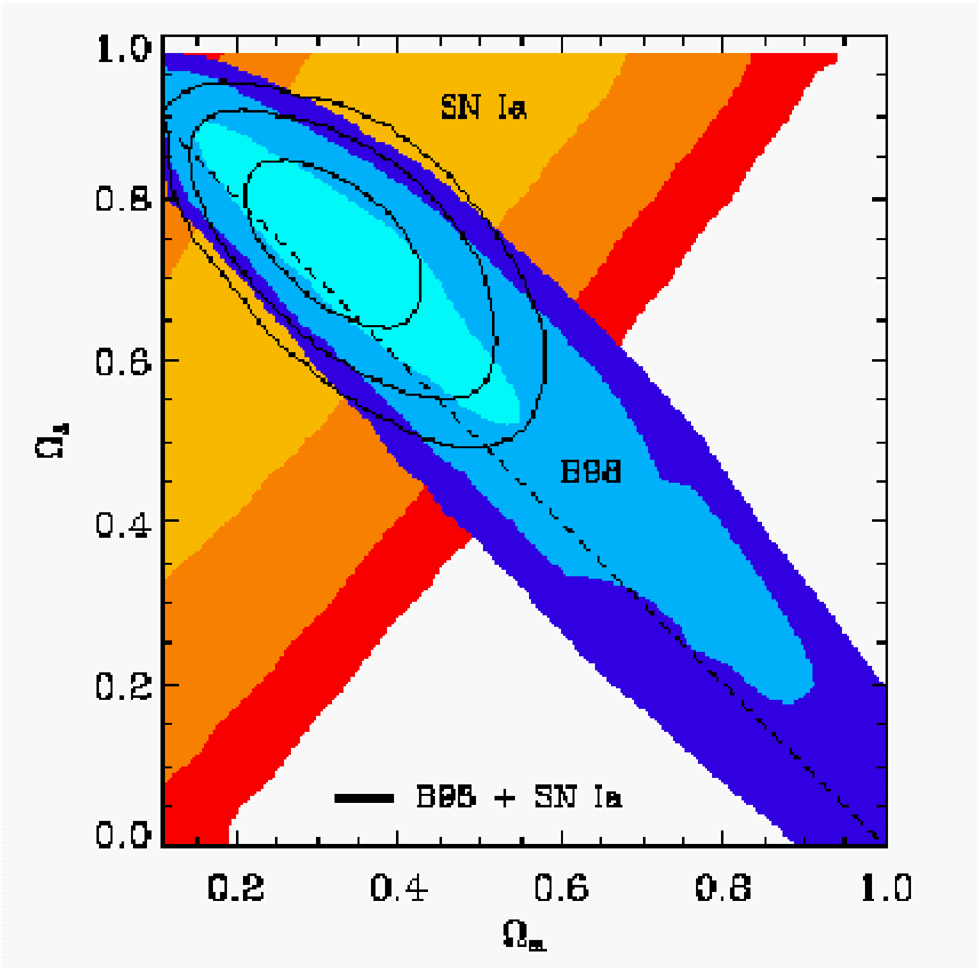


Figure 6

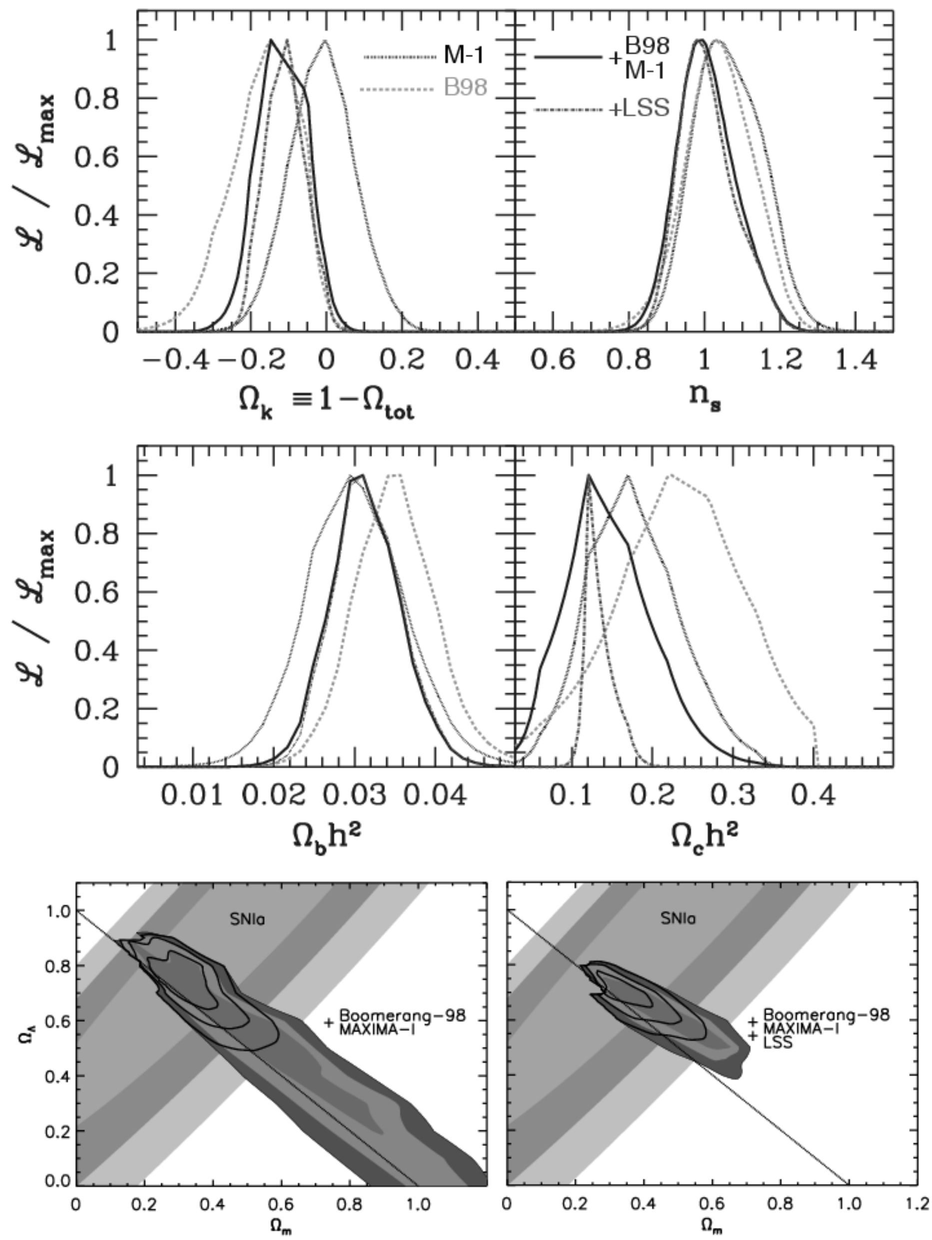

M-1
B98
+B98 M-1
+LSS
$\mathcal{L} / \mathcal{L}_{max}$
$\Omega_k \equiv 1-\Omega_{tot}$
n_s
$\Omega_b h^2$
$\Omega_c h^2$
SNIa
+ Boomerang-98 MAXIMA-I
+ Boomerang-98 + MAXIMA-I + LSS
Ω_Λ
Ω_m

Figure 7

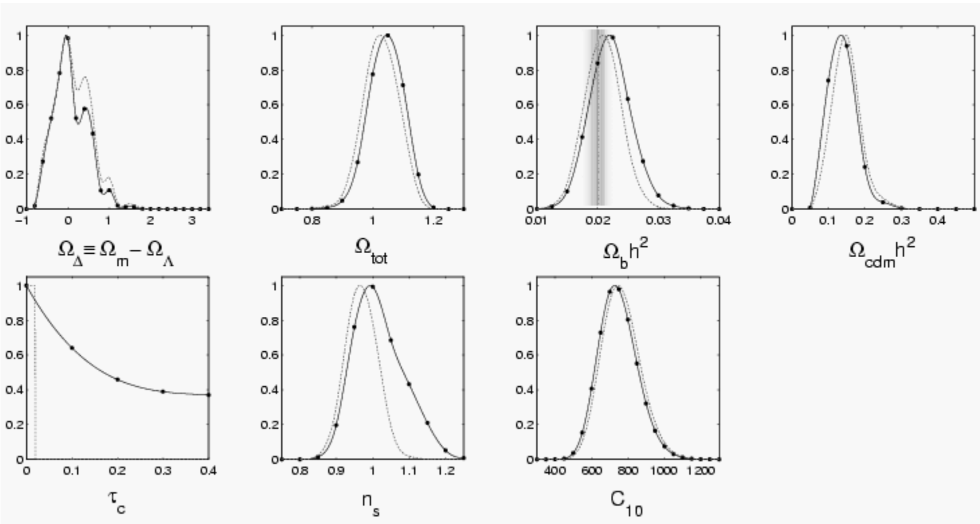
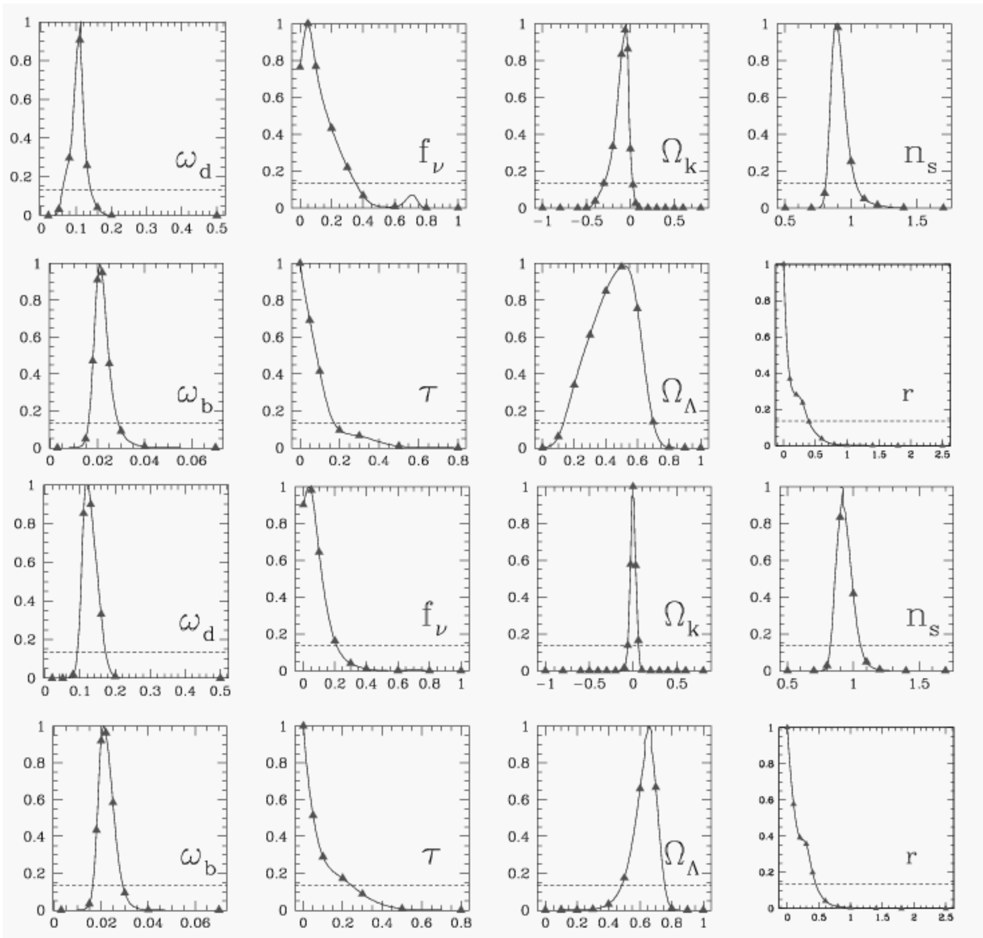


Figure 8


ω_d
f_ν
Ω_k
n_s
ω_b
τ
Ω_Λ
r
ω_d
f_ν
Ω_k
n_s
ω_b
τ
Ω_Λ
r

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