1. COSMIC MICROWAVE BACKGROUND

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1.1. Description of CMB Anisotropies

Observations show that the CMB contains anisotropies at the 10^{-5} level, over a wide range of angular scales. These anisotropies are usually expressed by using a spherical harmonic expansion of the CMB sky:

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

The vast majority of the cosmological information is contained in the temperature 2-point function, *i.e.*, the variance as a function of separation θ. Equivalently, the power per unit $\ln \ell$ is $\ell \sum_m |a_{\ell m}|^2 / 4\pi$.

1.1.1. *The Monopole*:

The CMB has a mean temperature of $T_\gamma = 2.725 \pm 0.001\,\mathrm{K}$ (1σ) [6], which can be considered as the monopole component of CMB maps, a_{00}. Since all mapping experiments involve difference measurements, they are insensitive to this average level. Monopole measurements can only be made with absolute temperature devices, such as the FIRAS instrument on the *COBE* satellite [6]. Such measurements of the spectrum are consistent with a blackbody distribution over more than three decades in frequency. A blackbody of the measured temperature corresponds to $n_\gamma = (2\zeta(3)/\pi^2)\, T_\gamma^3 \simeq 411\,\mathrm{cm}^{-3}$ and $\rho_\gamma = (\pi^2/15)\, T_\gamma^4 \simeq 4.64 \times 10^{-34}\,\mathrm{g\,cm}^{-3} \simeq 0.260\,\mathrm{eV\,cm}^{-3}$.

1.1.2. *The Dipole*:

The largest anisotropy is in the $\ell = 1$ (dipole) first spherical harmonic, with amplitude $3.358 \pm 0.017\,\mathrm{mK}$ [7]. The dipole is interpreted to be the result of the Doppler shift caused by the solar system motion relative to the nearly isotropic blackbody field, as confirmed by measurements of the radial velocities of local galaxies [8].

The dipole is a frame-dependent quantity, and one can thus determine the 'absolute rest frame' as that in which the CMB dipole would be zero.

1.1.3. *Higher-Order Multipoles*:

The variations in the CMB temperature maps at higher multipoles ($\ell \geq 2$) are interpreted as being mostly the result of perturbations in the density of the early Universe, manifesting themselves at the epoch of the last scattering of the CMB photons. In the hot Big Bang picture, the expansion of the Universe cools the plasma so that by a redshift $z \simeq 1100$ (with little dependence on the details of the model), the hydrogen and helium nuclei can bind electrons into neutral atoms, a process usually referred to as recombination [11]. Before this epoch, the CMB photons are tightly coupled to the baryons, while afterwards they can freely stream towards us.

Theoretical models generally predict that the $a_{\ell m}$ modes are Gaussian random fields to high precision, *e.g.*, standard slow-roll inflation's non-Gaussian contribution is expected to be one or two orders of magnitude below current observational limits [12]. Although non-Gaussianity of various forms is possible in early Universe models, tests show that Gaussianity is an extremely good simplifying approximation [14,15], with only some relatively weak indications of non-Gaussianity or statistical anisotropy at large scales. Such signatures found in existing *WMAP* data are generally considered to be subtle foreground or instrumental artefacts [13,16].

With the assumption of Gaussian statistics, and if there is no preferred axis, then it is the variance of the temperature field which carries the cosmological information, rather than the values of the individual $a_{\ell m}$s; in other words the power spectrum in ℓ fully characterizes the anisotropies. The power at each ℓ is $(2\ell+1)C_\ell/(4\pi)$, where $C_\ell \equiv \left\langle |a_{\ell m}|^2 \right\rangle$, and a statistically isotropic sky means that all ms are equivalent. Thus averages over m can be used as estimators of the C_ℓs to constrain their expectation values, which are the quantities predicted by a theoretical model. For an idealized full-sky observation, the variance of each measured C_ℓ (*i.e.*, the variance of the variance) is $[2/(2\ell+1)]C_\ell^2$. This sampling uncertainty (known as 'cosmic variance') comes about because each C_ℓ is χ^2 distributed with $(2\ell+1)$ degrees of freedom for our observable volume of the Universe. For fractional sky coverage, $f_{\rm sky}$, this variance is increased by $1/f_{\rm sky}$ and the modes become partially correlated.

It is important to understand that theories predict the expectation value of the power spectrum, whereas our sky is a single realization. Hence the cosmic variance is an unavoidable source of uncertainty when constraining models; it dominates the scatter at lower ℓs, while the effects of instrumental noise and resolution dominate at higher ℓs [17].

1.1.4. *Angular Resolution and Binning*:

There is no one-to-one conversion between multipole ℓ and the angle subtended by a particular spatial scale projected onto the sky. However, a single spherical harmonic $Y_{\ell m}$ corresponds to angular variations of $\theta \sim \pi/\ell$. CMB maps contain anisotropy information from the size of the map (or in practice some fraction of that size) down to the beam-size of the instrument, σ. One can think of the effect of a Gaussian beam as rolling off the power spectrum with the function $\mathrm{e}^{-\ell(\ell+1)\sigma^2}$.

1.2. Current Anisotropy Data

There has been a steady improvement in the quality of CMB data that has led to the development of the present-day cosmological model. Probably the most robust constraints currently available come from the combination of the *WMAP* three year data [15] with smaller scale results from the ACBAR [31], BOOMERANG [32], CBI [33], QUAD [34] and VSA [35] experiments (together with constraints from other cosmological data-sets). We plot power spectrum estimates from these six experiments in Fig. **@Fg.Cldata@**. Other recent experiments, such as ARCHEOPS [36], DASI [37] and MAXIMA [38] also give powerful constraints, which are quite consistent with what we describe below.

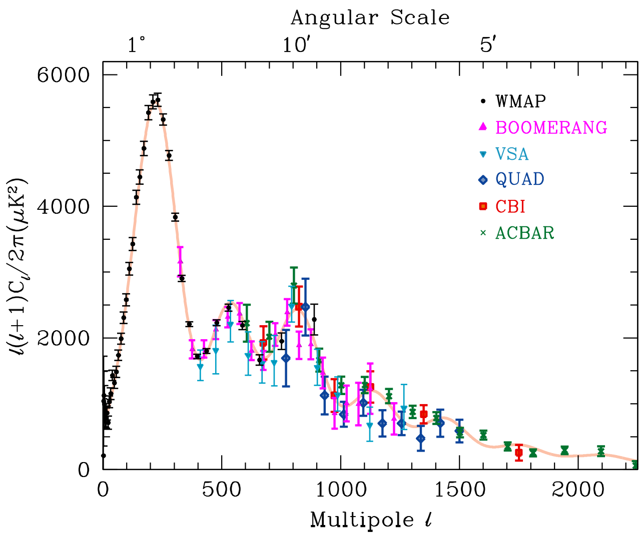

Figure 1.1: Band-power estimates from the *WMAP*, BOOMERANG, VSA, QUAD, CBI, and ACBAR experiments.

1.3. Constraints on Cosmologies

The 3-year *WMAP* data alone, together with weak priors (on h and $\Omega_{\rm B}h^2$ for example), and within the context of a 6 parameter family of models (which fixes $\Omega_{\rm tot} = 1$ and $r = 0$), yield the following results [15]: $A = 2.35 \pm 0.13$, $n = 0.958 \pm 0.016$, $h = 0.73 \pm 0.03$, $\Omega_{\rm B}h^2 = 0.0223 \pm 0.0007$, $\Omega_{\rm M}h^2 = 0.128 \pm 0.008$ and $\tau = 0.09 \pm 0.03$. Note that for h, the CMB data alone provide only a very weak constraint, unless spatial flatness or some other cosmological data are used. For $\Omega_{\rm B}h^2$, the precise value depends sensitively on how much freedom is allowed in the shape of the primordial power spectrum.

For $\Omega_{\rm tot}$, perhaps the best *WMAP* constraint is 1.011 ± 0.012. The 95% confidence upper limit on r is 0.65 using *WMAP* alone, tightening to $r < 0.30$ with the addition of the Sloan Digital Sky Survey data for example [61]. This limit depends on how the slope n is restricted and whether $dn/d\ln k \neq 0$ is allowed.

Further discussion and all references may be found in the full *Review of Particle Physics*.