PERSPECTIVE

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Perspective

Perspective on the Cosmic Microwave Background

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Abstract – I give a view of Cosmic Microwave Background research, briefly describing its evolution and summarizing recent observations that include the *Planck* satellite and ground-based experiments. I describe some of the cosmological properties that the community has been able to extract from its rich information, and look to future goals for upcoming observations.

Introduction. – This year, 2015, marks the fiftieth anniversary of the discovery of the Cosmic Microwave Background (CMB) radiation. This is light reaching us from all directions in the sky, that started its journey just 380000 years after the Big Bang. The Universe has cooled as it expanded. At early times it was sufficiently hot that photons could ionize hydrogen and helium atoms, forming a tightly coupled plasma that co-existed with presumed dark matter particles. The photons scattered frequently off free electrons and were in thermal equilibrium. When the Universe had cooled to about 3000 K there were few enough photons with sufficient energy to ionize hydrogen atoms, so the light stopped scattering. These CMB photons could then travel freely through space with little distortion. By observing them today we see a picture of the Universe as it was at that time.

The CMB light was first detected by Arno Penzias and Robert Wilson in New Jersey, USA, using the Holmdel antenna [1]. They were using this large radio telescope to observe the Milky Way and picked up a faint signal even from apparently empty parts of the sky. Bob Dicke and his group at Princeton University interpreted it as the primordial CMB radiation that had been predicted years before [2,3]. The existence of the CMB provided compelling new evidence for the Big Bang, and laid to rest the opposing Steady State model of the Universe.

The CMB was later mapped over the whole sky by NASA's COBE satellite in 1990 [4,5], following a set of ground-, balloon-, and rocket-based experiments. The mean temperature was found to be a remarkably uniform 2.7 K in all directions, and the frequency distribution a near-perfect blackbody [4,6,7]. The COBE satellite also made the first detection of intrinsic anisotropies in the CMB temperature [8,9], variations of order one part in a hundred thousand. These tiny features trace the underlying density variations at the time of last scattering, with a large overdense region typically appearing as a cold spot due to the increased gravitational well from which the photons climb. The small size of the temperature variations imply that the Universe was rather featureless at these early times. The density variations were still vitally important though, as they provided the seeds of cosmic structure. Overdense regions grew gravitationally over millions of years to form the first stars and galaxies, and the CMB is our earliest view of this process.

The following decade saw numerous experiments designed to map the anisotropy with greater sensitivity and higher resolution. Around 2000, the BOOMERanG, MAXIMA, and TOCO experiments measured the peak of the CMB anisotropy at degree scale, determining the geometry of the Universe [10–12], and the CMB polarization was detected for the first time by DASI [13]. The temperature anisotropy was then mapped in greater detail over the whole sky by NASA's *WMAP* satellite, that was launched in 2001 and operated for nine years from the Lagrange point L2. *WMAP* mapped the microwave sky at five wavelengths with a fifth of a degree resolution, measuring polarization as well as temperature [14,15]. *WMAP* was followed by the European Space Agency's *Planck* satellite which mapped the sky from 2009 to 2012, also from L2 [16]. *Planck* had a low-frequency instrument with three wavelengths spanning 30–70 GHz, and a high-freqency instrument with six wavelengths spanning 100–857 GHz. *Planck* had a larger mirror than *WMAP*

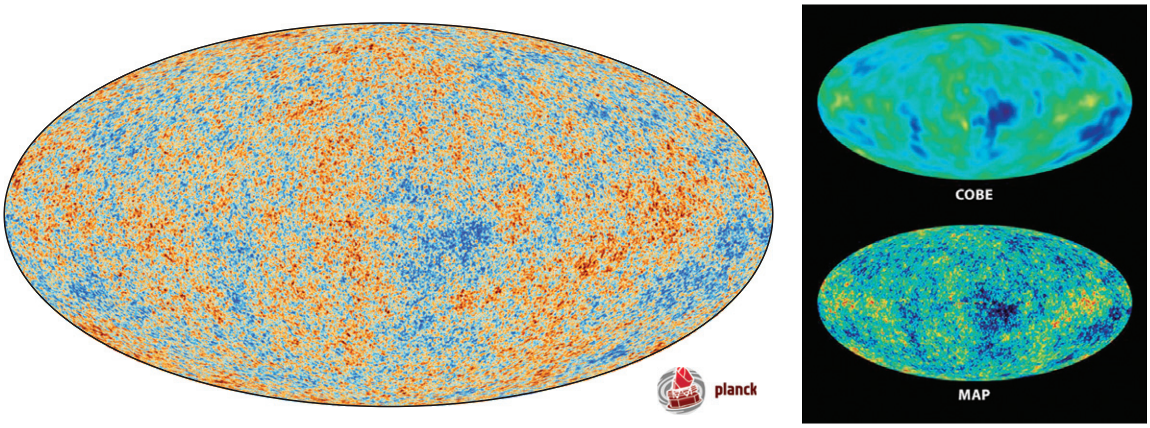

Fig. 1: (Colour on-line) The CMB temperature anisotropy measured by the *Planck* satellite (taken from [17]), compared to similar maps made by COBE in the 1990s and *WMAP* in the 2000s. At large scales the signal is common; increasingly smaller scales are revealed by *WMAP* and then *Planck*.

and used active coooling, increasing both the resolution and the sensitivity.

In parallel with *Planck*, there have been arcminute measurements made from the ground by the Atacama Cosmology Telescope and the South Pole Telescope, both with first-generation instruments from 2007–2010, and second-generation ones from 2012 to 2015 that include polarization [18–22]. New CMB polarization measurements have also been made by the BICEP2/Keck telescopes at the South Pole, and the POLARBEAR telescope in the Atacama [23,24]. Further experiments targeting improved polarization measurements include the BICEP3 experiment at the South Pole, the CLASS experiment in the Atacama, QUIJOTE in Tenerife, and the SPIDER balloon flown from Antarctica. Many more are planned or proposed for the coming decade.

Current measurements. –

Temperature anisotropy. The temperature anisotropy measured by *Planck* is shown in fig. 1, and compared to the equivalent COBE map made in the 1990s, and the *WMAP* map from the 2000s. The CMB has also been mapped at higher resolution by SPT and ACT over small regions of the sky. The same features are clearly visible in all the maps, although a different colour scale is used, and the increase in resolution is also apparent. To produce this map first requires maps be made at each of the observed wavelengths, which in itself requires converting the scanned data from many detectors into a single map. These multi-wavelength maps include both the CMB signal and "foreground" signals, *i.e.*, light from our Galaxy and other galaxies that lie between us and the CMB's last scattering surface.

The Galactic signal shows up most obviously as a hot region along the Galactic plane. Its behaviour varies with wavelength, as the emission arises from a combination of effects including synchrotron emission, Bremsstrahlung or free-free emission, and thermal emission from dust grains heated by starlight. The minimum Galactic signal is at about 100 GHz, where the CMB visibly dominates over most of the sky in intensity. The multi-wavelength maps are then combined to estimate the pure blackbody CMB signal (*e.g.*, [25]).

Polarization anisotropy. In the past, most of the information in the CMB has been contained in the temperature anisotropy. That is no longer true, as measurements of the smaller CMB polarization signal are improving rapidly. With *WMAP* and *Planck*, and with new ground-based experiments, we measure two linear polarizations of the CMB radiation, quantified by Q and U Stokes vectors, in addition to the intensity. Circular polarization is theoretically expected to be zero, and so is not generally measured. The polarization anisotropy provides an additional view of the features in the Universe at 380000 years (see, *e.g.*, [26]). Photons emerge polarized if they Thompson scatter off electrons with a quadrupole pattern of incident radiation. This pattern arises while photons free-stream during the recombination process, *i.e.* while atoms are beginning to form. The polarization then traces the motion of the coupled photon-baryon fluid, and so is expected to be correlated with the temperature.

The polarization signal is decomposed into two fields: a curl-free "E-mode" field that has purely radial or tangential patterns, and a divergence-free "B-mode" field [27]. Scalar fluctuations only generate E-mode–type polarization, but tensor fluctuations propagating as gravitational waves would generate both E and B modes.

The CMB Q and U Stokes vectors have been measured over the full sky by *WMAP* and *Planck* [15,17]. Polarization has also been mapped by ground-based experiments over smaller regions of the sky, with an example from the Atacama Cosmology Telescope polarimeter (ACTPol) shown in fig. 2 for a hundred square degree region [21]. The signal is clearly visible: the patterns in Q appear predominantly vertical and horizontal, and in U predominantly diagonal, which one expects from a dominant E-mode signal.

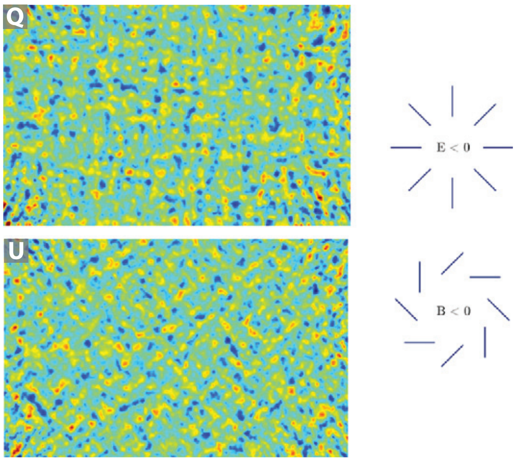

Fig. 2: (Colour on-line) The CMB polarization anisotropy measured over $100\,\mathrm{deg}^2$ by the Atacama Cosmology Telescope polarimeter, showing Q and U Stokes vectors (figure from [21]). The E-mode and B-mode patterns (right) are then estimated to compare with theory.

This pattern is also seen in the *Planck* data, as well as data from the POLARBEAR, BICEP2 and Keck, and South Pole Telescope experiments [22–24].

Gravitational lensing. In addition to the temperature and polarization anisotropy we now have a third map, of the gravitational lensing anisotropy. The CMB photons are gravitationally lensed on their journey to us due to the large-scale structure in the Universe, but the typical deflection is only 2 arcminutes. This means we have only recently been able to measure this effect, with the first direct detection made with the ACT telescope in 2011 [28]. The photons are coherently lensed by the large-scale structure, and this couples Fourier modes that are uncoupled in the unlensed CMB. The lensing potential can therefore be estimated using the correlation between modes: $\phi(L) \propto T(l)T(L-l)$ [29]. This signal is an integral of the total matter, including dark matter, along the line of sight, weighted with a distance factor that accounts for the distance to the lens planes. The signal peaks at degree scales, and has been measured over the full sky by *Planck* [30] and at higher resolution over smaller regions of the sky by ACT, SPT, and POLARBEAR [20,28,31–33].

Sunyaev Zel'dovich effects. The CMB photons are also distorted due to the thermal (tSZ) and kinetic (kSZ) Sunyaev-Zel'dovich effects [34]. The thermal effect arises due to hot electrons in galaxy clusters that inverse Compton scatter the CMB photons. This shifts the spectrum such that a cluster appears as a cold spot at frequencies below 220 GHz, and a hot spot above. The tSZ effect has recently been used to identify hundreds of clusters in the *Planck*, ACT and SPT maps [35,36]. It has been used to explore cluster astrophysics and also probes cosmology through measuring how the number of clusters has evolved. The kinetic effect arises due to the motion of electrons, and has recently been detected by ACT and *Planck* [37]. The momentum of galaxy clusters is determined by gravity on large scales, so the kSZ effect shows great promise for future tests of modified gravity.

Power spectra and the ΛCDM model. – With these maps of the temperature, polarization, and lensing anisotropies in hand, we can extract statistics to compare to theory, in order to answer questions about the geometry, contents and initial conditions of the Universe. The main statistic is the angular power spectrum which measures the size of the flucutations as a function of angular scale. For Gaussian fields, these two-point functions contain all of the information in the maps.

Figure 3 summarizes the temperature and E-mode angular power spectra currently measured by *Planck*, ACT, and SPT. The temperature power spectrum shows a rich pattern of oscillations, damped at the smallest scales and plateauing at the largest scales, that has been gradually revealed over the last twenty years. Remarkably, a model exists that can explain all of its features and provides an excellent fit to the data. It is known as "ΛCDM", and can be described by just a handful of parameters. In this model, primordial fluctuations are imprinted in the first fraction of a second, and their power spectrum can be described by a power law with an amplitude and scale dependence. They are Gaussian and adiabatic, implying that all fluids follow the same initial over- and under-densities. The most popular scenario for how those fluctuations could have been imprinted is cosmic inflation [38,39].

These linear fluctuations then evolved. At very large angular scales, where wavelengths are larger than the cosmic horizon, the fluctuations had not yet begun to evolve when the CMB formed, and they appear in the CMB temperature power spectrum as the Sachs-Wolfe plateau, with constant $\ell(\ell+1)C_\ell$ power [40]. As the Universe expanded, fluctuation modes entered the horizon. Dark matter overdensities tended to collapse, but baryons and photons were tightly coupled so overdensities set up sound waves in the photon-baryon plasma. We see these sound waves captured after 380000 years. At one-degree scales, $\ell \sim 200$, the first acoustic peak corresponds to the mode that has undergone half an oscillation between horizon entry and recombination, reaching maximal compression. The second acoustic peak corresponds to a mode that has undergone a compression and then a rarefaction. And so on. The multiple acoustic peaks are therefore a set of harmonics at regularly spaced angular intervals, but they are damped at increasingly small scales as photons have time to diffuse during recombination, as free electrons become rarer and scatterings become less frequent.

The angle at which we observe the CMB acoustic peaks depends on the distance to the surface of last scattering, which is a function of the matter density, the density in dark energy, or a cosmological constant, the curvature, and the expansion rate today. There is also an overall damping of the CMB when it scatters off reionized electrons that appeared when the first stars lit up the

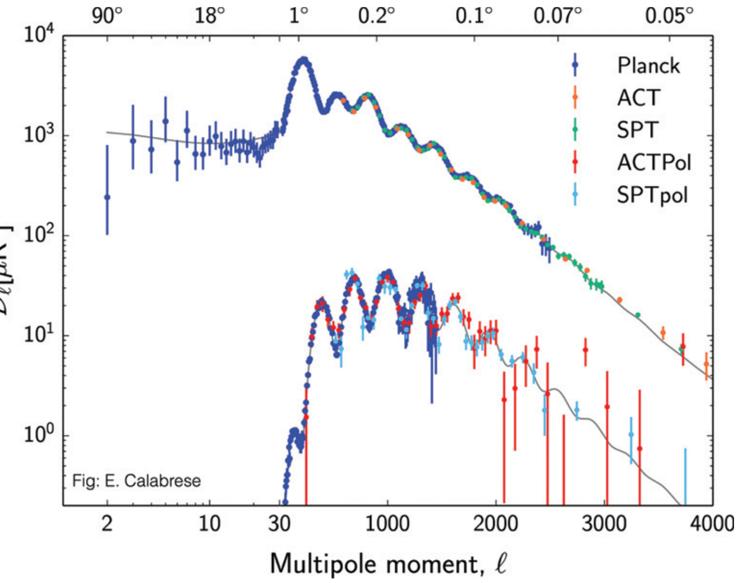

Fig. 3: (Colour on-line) The CMB temperature and polarization angular power spectra measured by the *Planck*, ACT, and SPT experiments (figure credit: E. Calabrese). The temperature spectrum has a plateau at the largest scales, which were super-horizon when the CMB formed. At degree and smaller scales, the damped acoustic peaks capture the evolution of sound waves in the photon-baryon fluid. The polarization peaks are offset from the temperature, as they trace the motion of the photon-baryon fluid. There is a smaller large-scale polarization signal not shown here.

Universe. In a flat universe, this ΛCDM model can be described by only six numbers: the amplitude and spectral index of the initial fluctuations; the baryon, cold dark matter, and cosmological constant densities, and the optical depth to reionization.

The LCDM model fits the data. Remarkably, this model fits the data from *WMAP* that reached to $\ell = 1000$ [41], and now also continues to fit the *Planck* data that significantly extends the scales probed [42]. This is shown in fig. 3. This goodness of fit was by no means a given, and is still surprising given that we do not yet know what the dark matter and dark energy components are, or exactly how the inititial fluctuations were seeded. Many alternative models with, for example, additional relativistic species, alternative descriptions of the initial fluctuations, or more unusual dark energy models, would modify the power spectrum.

The polarization data offer a powerful new handle, by measuring a different observable that probes the same underlying physics. In polarization there is no Sachs-Wolfe plateau, and the acoustic peaks follow the evolution of the velocity of the photon-baryon oscillations. The model also predicts a strong correlation between temperature and polarization, and the presence of super-horizon fluctuations. The 2015 measurement of the E-mode spectrum by *Planck*, shown together with polarization data from ACTPol and SPTPol, are shown in fig. 3. These data were not used to estimate the theory curve. Instead, the theory curve predicted from the temperature data appears highly consistent with the new data. Some systematic uncertainties are reported to remain at the few μK^2 level in the *Planck* data [42]. If those effects are confirmed to be small, the agreement between temperature and polarization greatly limits the vast zoo of alternatives to ΛCDM, including extra relativistic species, different initial fluctuations, extra contributions to the fluctuations including cosmic defects or magnetic fields, and extra dark matter energy injection [42]. The ground-based experiments are also extending the information to smaller scales and provide an alternative check at larger scales.

The CMB lensing map, and its associated power spectrum, is also powerful and is becoming increasingly more constraining. The lensing power spectrum is shown in fig. 4, where again the theory curve is not fit to the data but is the prediction of the ΛCDM model. This probe of the clustering of matter at late times, peaking at redshift $z = 1$–3, is powerful at distinguishing between models, and enables a 2% measurement of the curvature just from the CMB, and results in a strong upper limit on the sum of neutrino masses of $< 0.7\,\text{eV}$ at 95% confidence [42].

Implications for inflation. – A major question that the CMB hopes to answer is what happened at the start of the Universe's expansion. The favoured scenario is cosmic inflation, a period of exponential expansion driven by the potential of some scalar inflaton field. It was devised in the 1980s as a way to account for the apparent geometrical flatness of the Universe, and for the homogeneity of the CMB over the sky [38,39]. It also provides a mechanism for sourcing the initial perturbations: quantum fluctuations on microscopic scales are quickly expanded to superhorizon scales.

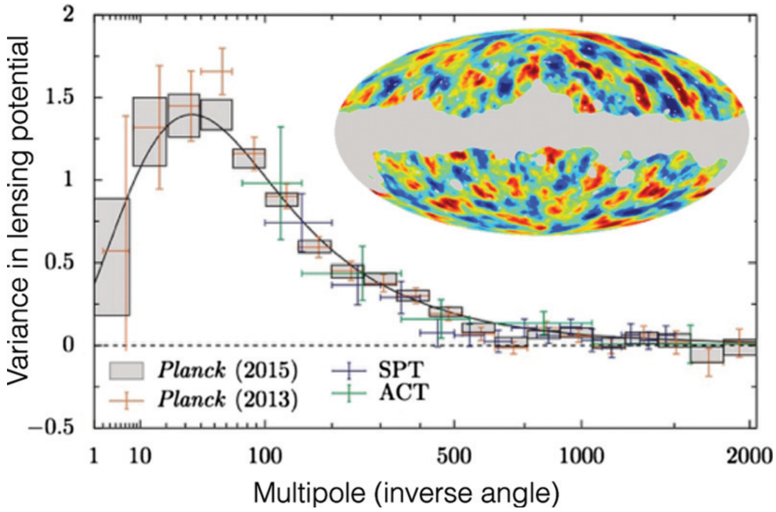

Fig. 4: (Colour on-line) The CMB gravitational lensing potential power spectrum measured by *Planck*, ACT, and SPT (*Planck* lensing potential map inset, both figures from [43]). Adding these data to the temperature anisotropy limits the curvature of the Universe to 2%, and the sum of neutrino masses to $\Sigma m_\nu < 0.7\,\mathrm{eV}$, both at 95% confidence [42].

So far, all of the CMB data are highly consistent with inflationary predictions, in particular when combined with other cosmological data. The geometry is measured to be flat to 0.5%, the fluctuations are observed to be super-horizon, they are Gaussian to high precision, and any non-adiabatic fluctuations are strongly limited [42]. The fluctuations are almost scale invariant as expected from inflation, characterized by the spectral index of the primordial power spectrum being close to unity. Before *Planck*, there was evidence at the 3σ level that the index was less than 1. With *Planck* this evidence has increased to 6σ, with $n = 0.966 \pm 0.006$ [42]. Many models for inflation predict $n < 1$, with slightly smaller fluctuations at scales that were imprinted later in the inflationary expansion. *Planck* has also placed significantly stronger limits on the non-Gaussianity of fluctuations [44].

Gravitational waves. A key inflationary prediction has not yet been seen. Inflation should imprint tensor fluctuations as well as scalar fluctuations, and these propagate as gravitational waves. The size of these tensor fluctuations, quantified by the tensor-to-scalar ratio r, depends on the energy scale of inflation. In many models they should be large enough to be seen in the next few years, with r typically larger than 0.01, but in others they would be too small to ever be detected [45].

Gravitational waves would polarize the CMB light during recombination with both an E-mode and a B-mode pattern. The expected B-mode pattern is a large-scale signal, peaking at scales of ∼90 degrees and a few degrees ($\ell \sim 80$), and damping at smaller scales. The other main mechanism for generating a B-mode pattern is the gravitational lensing of the E-mode into a partial B-mode signal. This is a well-characterized effect and peaks at smaller angular scales.

The search for the inflationary B-mode signal is now underway by a suite of ground and balloon-based

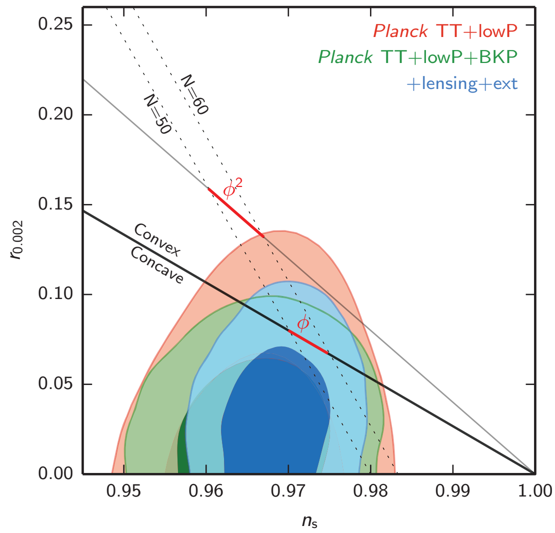

Fig. 5: (Colour on-line) The 95% confidence limits on the scalar spectral index, n_s, and the tensor-to-scalar ratio, r, measured by *Planck*, combined with information from B-mode polarization measured by the BICEP2/Keck experiment. Figure from [42].

experiments. There are a number of challenges to making such a detection, both technological and astrophysical. First, the signal is extremely small, at the nK level or below, so requires many highly sensitive detectors. Current experiments are fielding thousands of detectors, most commonly transition-edge-sensor (TES) bolometers, thermometers made from superconducting material whose resistance varies with temperature. Second, the foreground signals from the Galaxy are a significant challenge. The Galactic emission from synchrotron and thermal dust is overall more polarized than the CMB, so the foregrounds are more important in polarization and dominate the signal everywhere on the sky [46].

A number of ground-based experiments have now detected the B-mode lensing signal. A detection was made of a larger-scale B-mode signal in excess of the lensing signal by the BICEP2 experiment in 2014, but there is currently no evidence that this signal is primordial [23,47]. It was originally interpreted as such, but this was soon realised to be premature given the significant uncertainty in the size of the Galactic emission. The *Planck* data were then used to estimate the Galactic contamination from polarized thermal dust using a higher-frequency channel at 353 GHz. The outcome of a joint analysis was a new upper limit on the tensor amplitude, with $r < 0.09$ at 95% confidence, shown in fig. 5 [42,47]. This now disfavours a popular model for inflation, a slowly rolling single field with a quadratic potential.

Implications for the dark sector. – Two key parameters in the ΛCDM model quantify the current fractional energy density in dark matter and dark energy. These are now measured to percent level, with $\Omega_{\rm CDM} = 0.26 \pm 0.01$, and $\Omega_\Lambda = 0.69 \pm 0.01$ [42][1]. There is currently no evidence to suggest that the dark energy is not just a cosmological constant, but the tightest constraints on its evolution come from non-CMB observations [48]. There is also no evidence from the CMB that the dark matter is not a weakly interacting massive particle, although axions and massive sterile neutrinos are not excluded.

The CMB is rapidly providing new information about the hot dark matter sector, assumed to be the three active neutrino species. The number of relativistic species is now rather tightly constrained from the CMB, with $N_{\rm eff} = 3.13 \pm 0.32$ at 1σ [42]. The neutrinos' effects can be seen in the CMB, since increasing the number of relativistic species increases the amount of radiation that is not coupled to baryons. This affects both the expansion rate of the Universe, and the propagation of fluctuations.

The total mass of neutrinos is also strongly limited due to their effects both on the primordial CMB and on the clustering of matter seen via CMB lensing. Neutrinos suppress structure formation while relativistic at early times, but cluster like cold dark matter when non-relativistic at later times. This effect on the matter power spectrum enables the current CMB lensing measurements to limit the neutrino mass to < 0.7 eV at 95% confidence, and < 0.23 eV when combined with the acoustic oscillation scale measured through galaxy separations using the Sloan Digital Sky Survey (SDSS) [42,49]. It also has the potential to give a significant detection of non-zero neutrino mass in the next decade, given that the lower limit on the sum of masses is measured to be 0.06 eV from neutrino oscillation experiments. This will have interesting implications for lab-based direct-detection neutrino experiments.

Future directions. – There are a suite of ground- and balloon-based experiments currently mapping the sky, and many more planned or proposed. Key science targets of these new experiments include detecting and characterizing gravitational waves, or strongly limiting them, and measuring the neutrino mass sum and the number of relativistic species. Other important targets are to characterise dark energy and test gravity through cross-correlations of large-scale structure probes, and to understand how and when the Universe reionized. The main observable that needs to be better measured is the polarization anisotropy over a large fraction of the sky, both at large scales to target reionization and gravitational waves, and at smaller scales to better extract the CMB lensing signal for neutrino and dark sector physics. An improved measurement of the frequency spectrum of the CMB will also be valuable.

Upcoming experiments that are funded as of 2015 include the CLASS, Simons Array and Advanced ACT-Pol suite of experiments in the Atacama, that anticipate mapping half the sky with resolution reaching down to an arcminute. In Antarctica the BICEP3, SPT-3G and QUBIC experiments will map the sky more deeply over smaller areas, and from high-altitude balloons the PIPER, LSPE and second-generation SPIDER experiments are due to fly in the coming few years.

Looking beyond, we require large-area measurements reaching noise levels of 1 μK/arcmin or better, with sufficient frequency coverage to remove foregrounds, and control of systematic uncertainties. To this end, an ambitious ground-based project is planned, currently known as CMB-S4, that aims to bring together groups to field about 100000 detectors on multiple telescopes. Experiments from the ground can map much of the sky, but are limited to certain frequencies (typically 40, 90, 150, 220 GHz). Long-duration balloons will be well placed to complement these observations with higher-frequency observations. There are also a number of space missions proposed to the NASA, ESA, and JAXA space agencies, including the LiteBIRD satellite which would measure polarization at large angular scales, and the PIXIE satellite which would measure the CMB at hundreds of wavelengths using a spectrometer. A satellite might be the only route to measuring the largest-scale signals, but the path to new discoveries ahead is likely to involve a coordinated set of experiments using different platforms.

[1]Here, $\Omega_x = \rho_x/\rho_c$ is the dimensionless density parameter for component x with density ρ_x, defined relative to the critical density $\rho_c = 3H^2/8\pi G$.

REFERENCES

[1] Penzias A. A. and Wilson R. W., *Astrophys. J.*, **142** (1965) 419.

[2] Dicke R. H., Peebles P. J. E., Roll P. G. and Wilkinson D. T., *Astrophys. J.*, **142** (1965) 414.

[3] Peebles P. J. E., *Astrophys. J.*, **153** (1968) 1.

[4] Mather J. C., Cheng E. S., Eplee R. E. *et al.*, *Astrophys. J. Lett.*, **354** (1990) L37.

[5] Bennett C. L., Banday A. J., Górski K. M. *et al.*, *Astrophys. J. Lett.*, **464** (1996) L1.

[6] Gush H. P., Halpern M. and Wishnow E. H., *Phys. Rev. Lett.*, **65** (1990) 537.
[7] Mather J. C., Cheng E. S., Cottingham D. A. *et al.*, *Astrophys. J.*, **420** (1994) 439.
[8] Smoot G. F., Bennett C. L., Kogut A. *et al.*, *Astrophys. J. Lett.*, **371** (1991) L1.
[9] Smoot G. F., Bennett C. L., Kogut A., Wright E. L. *et al.*, *Astrophys. J. Lett.*, **396** (1992) L1.
[10] Miller A. D. *et al.*, *Astrophys. J. Lett.*, **524** (1999) L1.
[11] de Bernardis P., Ade P. A. R., Bock J. J., Bond J. R. *et al.*, *Nature*, **404** (2000) 955.
[12] Hanany S., Ade P., Balbi A., Bock J. *et al.*, *Astrophys. J. Lett.*, **545** (2000) L5.
[13] Kovac J. M., Leitch E. M., Pryke C., Carlstrom J. E., Halverson N. W. and Holzapfel W. L., *Nature*, **420** (2002) 772.
[14] Hinshaw G., Spergel D. N., Verde L., Hill R. S., Meyer S. S. *et al.*, *Astrophys. J. Suppl.*, **148** (2003) 135.
[15] Page L., Hinshaw G., Komatsu E., Nolta M. R., Spergel D. N. *et al.*, *Astrophys. J. Suppl.*, **170** (2007) 335.
[16] Planck Collaboration, *Astron. Astrophys.*, **571** (2014) 1.
[17] Planck Collaboration, submitted to *Astron. Astrophys.*, arXiv:1502.01582 (2015).
[18] Hincks A. D. *et al.*, *Astrophys. J.*, **191** (2009) 423.
[19] Story K. T., Reichardt C. L., Hou Z., Keisler R. *et al.*, *Astrophys. J.*, **779** (2013) 86.
[20] Das S., Louis T., Nolta M. R. *et al.*, *JCAP*, **4** (2014) 14.
[21] Naess S., Hasselfield M., McMahon J., Niemack M. D. *et al.*, *JCAP*, **10** (2014) 7.
[22] Keisler R., Hoover S., Harrington N., Henning J. W. *et al.*, *Astrophys. J.*, **807** (2015) 151.
[23] Bicep2 Collaboration, *Phys. Rev. Lett.*, **112** (2014) 241101.
[24] Polarbear Collaboration, *Astrophys. J.*, **794** (2014) 171.
[25] Gold B. *et al.*, *Astrophys. J. Suppl.*, **180** (2009) 265.
[26] Kamionkowski M., Kosowsky A. and Stebbins A., *Phys. Rev. D*, **55** (1997) 7368.
[27] Kosowsky A., *Ann. Phys.*, **246** (1996) 49.
[28] Das S., Marriage T. A., Ade P. *et al.*, *Astrophys. J.*, **729** (2011) 62.
[29] Hu W. and Okamoto T., *Astrophys. J.*, **574** (2002) 566.
[30] Planck Collaboration, *Astron. Astrophys.*, **571** (2014) 17.
[31] van Engelen A., Keisler R., Zahn O. *et al.*, *Astrophys. J.*, **756** (2012) 142.
[32] Polarbear Collaboration, *Phys. Rev. Lett.*, **112** (2014) 131302.
[33] Story K. T., Hanson D. *et al.*, arXiv:1412.4760 (2014).
[34] Sunyaev R. A. and Zel'dovich Y. B., *Astrophys. Space Sci.*, **7** (1970) 3.
[35] Marriage T. A., Baptiste Juin J., Lin Y.-T., Marsden D., Nolta M. R., Partridge B. *et al.*, *Astrophys. J.*, **731** (2011) 100.
[36] Bleem L. E., Stalder B., de Haan T. *et al.*, *Astrophys. J. Suppl.*, **216** (2015) 27.
[37] Hand N., Addison G. E., Aubourg E., Battaglia N. *et al.*, *Phys. Rev. Lett.*, **109** (2012) 041101.
[38] Guth A. H., *Phys. Rev. D*, **23** (1981) 347.
[39] Linde A. D., *Phys. Lett. B*, **108** (1982) 389.
[40] Sachs R. K. and Wolfe A. M., *Astrophys. J.*, **147** (1967) 73.
[41] Hinshaw G., Larson D., Komatsu E., Spergel D. N. *et al.*, *Astrophys. J. Suppl.*, **208** (2013) 19.
[42] Planck Collaboration, submitted to *Astron. Astrophys.*, arXiv:1502.01589 (2015).
[43] Planck Collaboration, submitted to *Astron. Astrophys.*, arXiv:1502.01591 (2015).
[44] Planck Collaboration, submitted to *Astron. Astrophys.*, arXiv:1502.01592 (2015).
[45] Baumann D., Jackson M. G. *et al.*, *Probing Inflation with CMB Polarization*, presented at *American Institute of Physics Conference Series* (2009).
[46] Planck Collaboration, to be published in *Astron. Astrophys.*, arXiv:1409.5738 (2014).
[47] BICEP2/Keck and Planck Collaborations, *Phys. Rev. Lett.*, **114** (2015) 101301.
[48] Betoule M., Kessler R., Guy J. *et al.*, *Astron. Astrophys.*, **568** (2014) A22.
[49] Anderson L., Aubourg É., Bailey S., Beutler F. *et al.*, *Mon. Not. R. Astron. Soc.*, **441** (2014) 24.