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For over 50 years astronomers have been taking a careful inventory of matter in the universe. Comparing the visible mass with the amount inferred from dynamical estimators reveals that we do not know the nature of at least 90% of the material in the universe. Even then, the total mass is well below that required to halt the universe from expanding forever. Theoretical arguments compel us to search for dark matter in the form of regular matter as well as non-baryonic particles created in the aftermath of the Big Bang. We do know that this material is very dark and that it dominates the internal kinematics, clustering properties and motions of galactic systems. It plays a crucial role in the formation and evolution of structure in the universe and it is unlikely that galaxies could have formed without its presence. Determining the nature of dark matter is recognized as one of the most fundamental unsolved problems in modern cosmology; revealing its nature would allow us to construct the history of the universe and also to predict its fate.

Keywords: cosmology; dark matter; halo formation; haloes; clusters; galaxy

To do justice to the theoretical, experimental and observational work dedicated to uncovering the nature of dark matter would fill this entire issue. This article presents some of the latest observational evidence, several recent research highlights and future prospects for determining the nature of dark matter.

1. The evidence for dark matter

The concept of dark matter was initiated by Zwicky (1933), who was puzzled by the large velocities of individual galaxies in the Coma Berenices cluster. Zwicky argued that the entire system would disperse on a short time-scale, unless there was a considerable amount of dark material present to increase the depth of the gravitational potential well. Evidence that galaxies contained more mass than could be accounted for in the visible component began accumulating at the same time as Zwicky's findings (see Trimble (1994) for a historical review). However, it wasn't until the 1970s that it became generally accepted that galaxies contain a substantial component of mass in some unknown form (see, for example, Einasto *et al*. 1974; Rubin 1979), and that this missing mass in galaxies was somehow related to the missing mass in galaxy clusters.

Since the review by Ashman (1992), a host of observational data has accumulated, from the internal structure of galaxies to their large-scale clustering properties. We have seen new controversial results, such as the galactic microlensing studies (the interpretation of which are being debated) and the resolution of old controversies

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such as the rejection of possible dissipationless dark matter in the galactic disc. Theoretical modelling and interpretation of observational data has also improved, in part due to the high quality of the numerical studies of the formation of structure in different cosmological models.

(a) Dark matter in galactic haloes

The first compelling argument for dark matter associated with individual galaxies was made by Kahn & Waljter (1959) using the dynamics of the Local Group. The Andromeda nebulae is on a collision course with our own galaxy, moving at $120\,\mathrm{km\,s^{-1}}$ towards us. The relative motion has been generated by the mutual gravitational attraction of the two galaxies over a time-scale equal to the age of the universe, approximately 15 billion years. Solving the equation of motion for the system, assuming a radial orbit, gives a total mass of the Local Group of $4 \times 10^{12} M_{\odot}$. Dominated by the stellar component, the total mass of stars, gas, planets, black holes, brown dwarfs and other known baryonic constituents of the Local Group adds up to just 1% of the total mass.

Most of the galaxies in the universe are spirals, like our own Milky Way, wherein the stars and gas move on circular orbits confined to a thin disc-like plane. Observing the rotational velocity at a given position gives a direct estimate of the internal mass (e.g. figure 1). The contribution of the baryonic component (predominantly stars and gas) is insufficient to account for the observations, revealing the need for an additional dark component of matter. At the edge of the visible disc the dark to baryonic mass ratios are of order 10:1, although the total mass of the dark component is unknown since the stars or gas become too faint or diffuse to observe. The total extent of the dark matter surrounding galaxies is one of the key questions that future observations will help solve.

One of the key observational facts that we have learnt about the dark matter haloes of many galaxies is that they have a unique structure, with a density profile that is close to $\rho(r) \propto (r + r_{\mathrm{c}})^{-2}$ (see, for example, Moore 1994; Burkert 1995; Bosma 1999). The inner region has close to constant density (indicated by the linearly rising rotation curve) and the transition to an isothermal density structure (flat rotation curve) occurs at a scale length r_{c} of several kpc. This characteristic scale is roughly proportional to the circular velocity of the halo. These properties are fundamental and must be reproduced by any prospective cosmological model for structure formation.

The key question to be answered is, just how much dark matter is associated with galactic haloes? We shall see later that the most successful model for structure formation predicts that the dark matter extends to beyond 300 kpc for a galaxy like the Milky Way (see, for example, Navarro 1999). Confirming this prediction is extremely difficult since the visible disc component only probes the central few percent of the halo structure. The low surface brightness galaxy UGC 128 in figure 1 is remarkable since it traces the inner 25% of its dark matter halo.

The standard method used to measure masses is to balance the kinetic and potential energies using the virial theorem.† Unfortunately, galaxy haloes contain very few

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† A 'virialized' system is in equilibrium if (kinetic energy + kinetic energy)/2 = 0; therefore, its total mass can be found using $M = f\langle\sigma^2\rangle/\bar{r}$, where σ is the velocity dispersion of a tracer population at mean radius $\bar{r}$. f is a constant related to the three-dimensional orbital parameters of the tracer population.

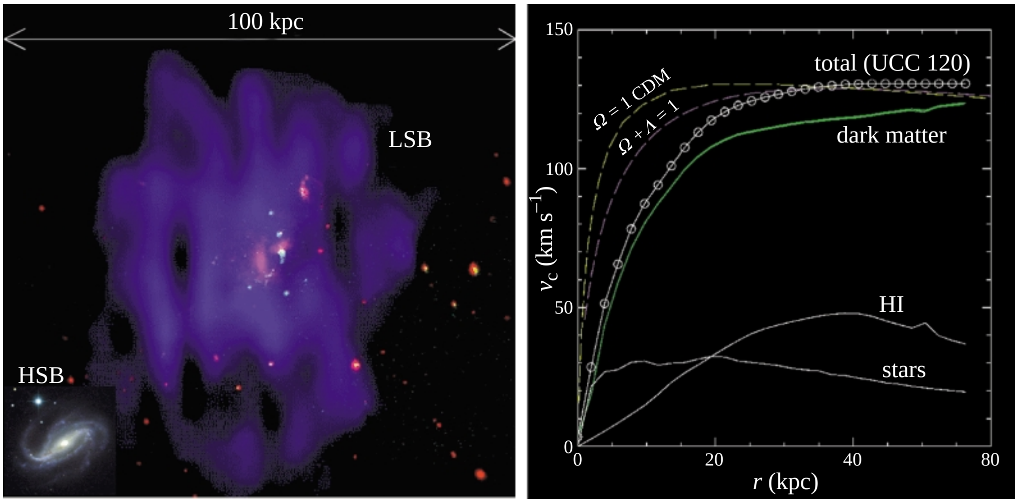

Figure 1. The left-hand panel shows an example of a low surface brightness galaxy (f5631, courtesy of E. de Blok). The diffuse blue light indicates the neutral hydrogen distribution observed in 21 cm emission and extends to *ca.* 50 kpc. The brighter star forming regions are plotted in red. For comparison, the lower left corner of this image contains a typical high surface brightness galaxy (n0613). Spiral galaxies maintain their flattened shapes by rapidly rotating. Measuring the velocity field across the galaxy yields the average rotation speed and therefore the internal mass ($M \propto \sqrt{(v_c^2/r)}$) as a function of radius, which is plotted in the right-hand panel for the LSB galaxy UGC 128 (de Blok & McGaugh 1997). The flat outer rotation curve indicates that the total mass is increasing with radius. The small contribution to the rotation curve from the stars and gas shows that a substantial dark component of mass is necessary to explain its high rotational velocity. Just how much dark matter is associated with galaxies is unknown, but it may extend well beyond the region where we can make observations with 21 cm emission.

visible objects that can be used to measure these quantities; just 12 satellite galaxies surround the Milky Way, and the mass may extend much further than is traced by the satellites. Co-adding the satellite distributions of a large sample of bright spirals is one way of improving the statistics and allows the structure of the 'average halo' to be quantified (Zaritsky *et al.* 1997). This work has provided compelling evidence that dark matter does extend beyond 100 kpc; however, the same data have also yielded some very puzzling results that have yet to be explained. Intriguingly, galactic satellites appear to avoid orbiting within the global plane defined by the primary's disc. A second puzzle is that the mass of dark matter associated with spiral galaxies appears to be independent of its luminosity.

There is a promising new technique that may unravel some of these mysteries. Massive objects act as giant gravitational lenses that deflect light, causing detectable image distortions and magnification. The basic effect was predicted by general relativity and confirmed by observations in 1919 (see Mellier (1999) and Wambsganss (1998) for reviews of gravitational lensing and its applications to cosmology). The amount of image distortion can be used to measure the mass of the lensing object. This technique has been successfully applied to individual galaxy clusters by observing the orientations of large numbers of very distant background galaxies whose light passes though the massive gravitational potential (e.g. figure 3). The effect is much

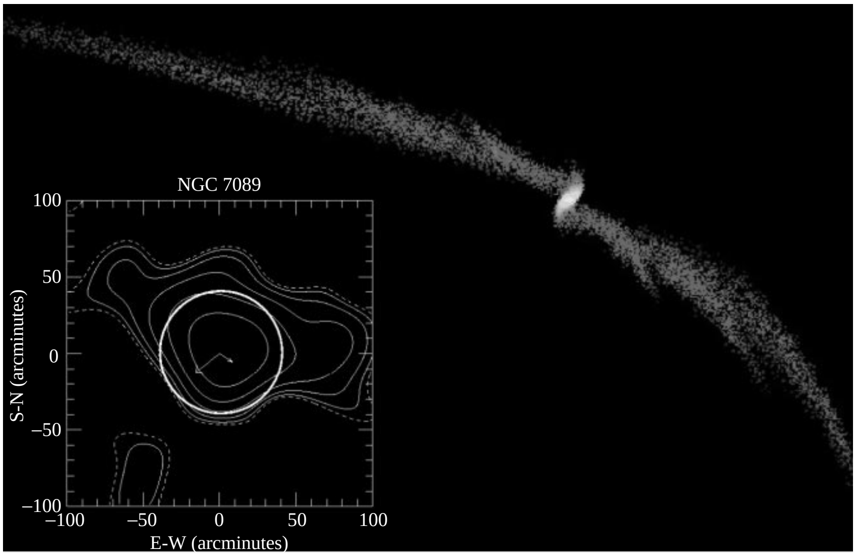

Figure 2. A numerical simulation of a globular cluster orbiting within the dark matter halo of the Galaxy. The equipotential surface is distorted perpendicular to the direction of the centre of the Galaxy and loosely bound stars can escape via the extremities of the distorted stellar system. These stars form symmetrical tidal tails that lead and trail the globular cluster in its orbit around the Galaxy. The inset contour diagram shows data taken from photographic plates for the globular cluster NGC 7089 (Grillmair *et al.* 1995). If this star cluster contained even a small amount of dark matter then these stars would remain bound to the cluster.

weaker for galaxy haloes which distort the images of background galaxies by $\lesssim 1\%$; therefore, the properties of any given halo cannot be inferred. Nevertheless, co-adding the data for a large number of similar galaxies allows the projected mass distribution of the foreground galaxies to be measured. Using CCD data for about 5000 galaxies, Brainerd *et al.* (1996) found further evidence for giant extended dark matter haloes, consistent with quasi-isothermal structures extending beyond 100 kpc.

Although observational data are still being accumulated, the total extent and structure of the dark matter haloes that encompass galaxies are poorly understood. Gravitational lensing surveys will help resolve this problem and we await data of sufficient quality such as will be obtained by the Next Generation Space Telescope (NGST).

(*b*) *Dwarf spheroidals and globular clusters*

The dynamics of small stellar systems within the Local Group provides some fascinating insights into the nature of the missing mass. The smallest galaxies that contain large amounts of dark matter are the dwarf spheroidals. These tiny galaxies have a similar luminosity to globular clusters with about 10^6 stars, but scale lengths of a few hundred parsecs, far larger than the compact star clusters. Several exist orbiting our Galaxy and it is possible to measure the velocities of their individual stars. The first results were obtained by Aaronson & Olszewski (1986), who found that the stars in the Draco dwarf galaxy were moving at $10\ \text{km s}^{-1}$; an order of magnitude larger than the expected velocity given the observed mass of stars.

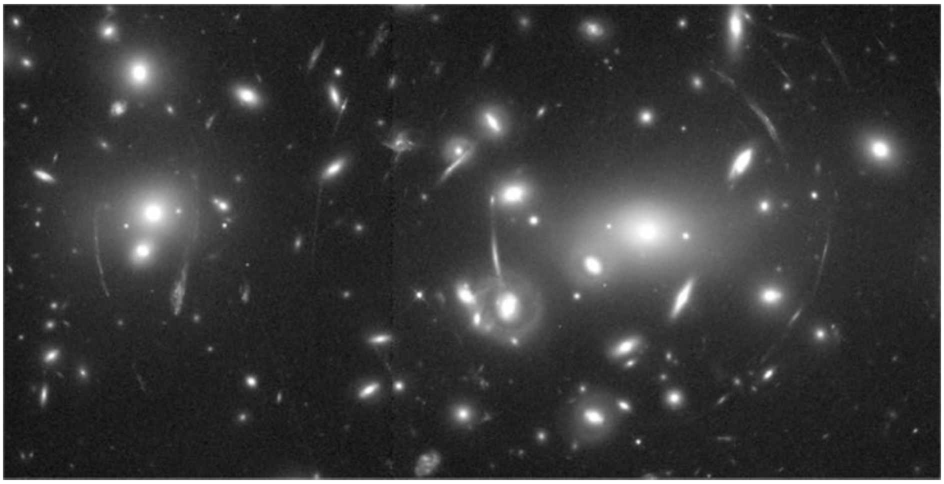

Figure 3. The spectacular cluster of galaxies Abell 2218 deforms the fabric of space and acts as a giant gravitational lens. This image, taken with the Hubble Space Telescope by W. Couch, shows many giant arcs of light from distant galaxies, which have been distorted and magnified by the massive gravitational potential of the cluster. The spectacular arcs occur when distant galaxies happen to lie behind caustics in space that form at the 'Einstein radius' of the cluster. The positions and appearance of these images can be used to recover the projected mass distribution of the cluster.

Collecting spectra is much easier today with large multi-optic fibre systems on modern telescopes that can measure the velocities of many stars simultaneously. We now know that dwarf spheroidals are completely dominated by dark matter at all radii (see Mateo (1999) for a review). These galaxies have the highest dark matter content of any known galactic system and are also the smallest objects within which dark matter has been detected. Globular clusters have similar numbers of stars but are 10–100 times smaller and do not appear to contain any dark matter. Tidal streams of stars can be observed escaping from these systems, torn away by the larger gravitational field of the Milky Way, which removes the most loosely bound stars (Grillmair *et al*. 1995). A numerical simulation of this effect is shown in figure 2. If globular clusters contained dark matter or had extended haloes of dark matter, then the stars would remain bound and we would not observe stellar tidal tails (Moore 1996).

(*c*) *Clusters of galaxies*

Clusters of galaxies are the most massive structures in gravitational equilibrium that exist; there has simply not been enough time since the Big Bang for larger systems of super-clusters to collapse and come to dynamical equilibrium. Most of the mass of a galaxy cluster resides in a relatively smooth dark matter component that has been stripped from the individual haloes of the galaxies.

Clusters are extremely useful systems for measuring the composition of the matter in the universe. They have formed from such a large region of space that they contain a fair and representative sample of matter (White *et al*. 1993). (Dissipative or feedback processes may have altered the baryonic content of individual galaxies.) Moreover, there are several independent methods for measuring their mass distribu-

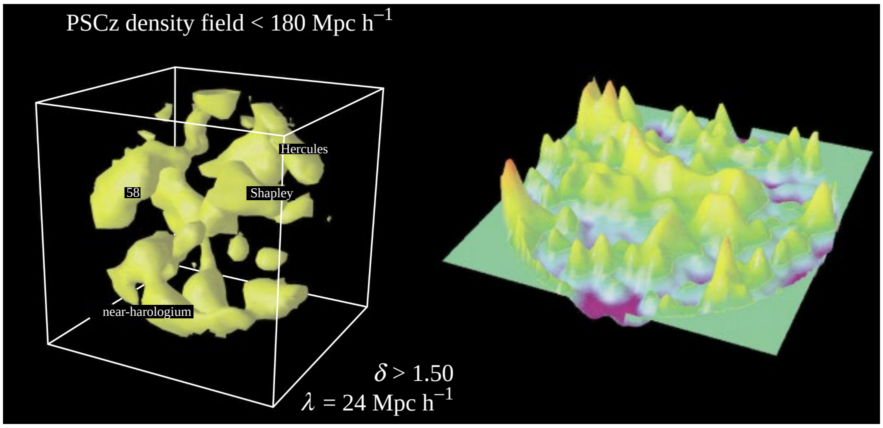

Figure 4. The left-hand image is a three-dimensional representation of the smoothed distribution of galaxies constructed using a large redshift survey of infrared selected galaxies. The surfaces enclose regions that have several times the mean galactic density; the Local Group is at the centre of the box and the survey extends to 180 Mpc. The right-hand image shows a slice of the universe with the Local Group at its centre, known as the Super-Galactic plane. The peak heights correspond to the local galaxy density; the key goal is to determine the relationship between the distribution of the galaxies and the distribution of the mass (images courtesy of L. Teodoro). Measuring the underlying mass distribution requires additional information such as the peculiar velocities of galaxies.

tions; standard virial estimators that use the galaxies as tracers, hydrodynamics of the X-ray emitting gas and gravitational lensing (see, for example, Wu *et al*. 1998). Figure 3 clearly shows the lensing effect produced by the cluster Abell 2218. In general, these methods give similar results and support Zwicky's original notion that clusters must be filled with large amounts of dark matter.

For these reasons, clusters of galaxies are the systems of choice for constraining the mass density in the universe and there are two separate ways in which to accomplish this. The standard method is to compare the 'mass-to-light' ratio of clusters with the value required for a critical density universe.† The latest results from the CNOC survey suggest that $\Omega_{\mathrm{m}} = 0.2 \pm 0.05$ (Carlberg *et al*. 1996). A second independent method is to compare the 'mass-to-baryon' fraction inside clusters with the *theoretical* universal baryon density calculated from the thermal history of the early universe. This technique gives slightly larger estimates of Ω_{m}, but still well below unity (White *et al*. 1993). Any biases in measuring cluster masses will be overcome by future instrumentation capable of measuring the velocities of planetary nebulae that orbit in clusters. These stars have been gravitationally stripped from cluster galaxies and provide many thousands of kinematical tracers that can be used to measure the cluster potential to very large radii.

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† The standard way of expressing the mass density Ω_{m}, is as a fraction of the critical density required for a flat universe, $\rho_{\mathrm{crit}} = 3H_0^2/8\pi G \sim 5 \times 10^{-29}$ g cm^{-3}, where the Hubble constant, $H_0 = 65 \pm 15$ km s^{-1} Mpc^{-1} and G is the gravitational constant. A flat or closed universe will have $\Omega = 1$. The mass is typically measured within a small region of the universe. If the galaxies ('light') are an unbiased tracer of the mass, then the mass-to-light ratio in a representative region can be compared with the mass-to-light ratio necessary for a universe with a critical density *ca.* $1000 M_{\odot}/L_{\odot}$.

(*d*) *The mass distribution on very large scales*

What is the largest scale on which dark matter is present? Is there a smooth component of mass that is clustered beyond the regions that can be probed by virialized galaxy clusters (cf. figure 4)? If this is the case then its properties or even its presence may be very difficult to detect. One possible candidate is a component of 'hot dark matter', particles that move so fast that they stream out of even the largest cluster potentials (cf. § 2 *b*).

Large mass inhomogeneities cause the motions of galaxies to deviate from a pure Hubble expansion. The so-called 'peculiar motion' of galaxies can be measured and related to the underlying mass in a well-defined way. Unfortunately, the relationship is only simple if galaxies are an unbiased tracer of the mass distribution, which is probably not the case. Nevertheless, these analyses provide additional evidence that $\Omega_{\mathrm{m}} \gtrsim 0.2$ on scales *ca.* 100 Mpc^3 (see, for example, Willick & Strauss 1998).

Current evidence is pointing towards a low value of the mass density, even when averaged over large scales. It is clear that if Ω is large, then galaxies should have much higher peculiar velocities. One radical solution is to invoke a dark matter candidate that interacts strongly with itself (cf. Carlson *et al*. 1992). The cosmic drag or 'ram-pressure' that occurs from halo–halo or halo–group interactions would significantly reduce the relative peculiar motions of galaxies.

Yet again we turn to the prospects of using gravitational lensing to probe the distribution of mass. The weakly nonlinear structures in the universe distort the images of background galaxies in the same way as galaxy clusters or galactic haloes. In the case of large-scale structure, the distortions will be even weaker but the area that can be surveyed is considerably larger.

2. Theoretical motivation

The detection of the cosmic microwave background (CMB) radiation firmly established the hot Big Bang model as the framework within which to construct detailed cosmogonic models. Observed today at 2.7277 ± 0.0001 K, this is the current temperature of the relic radiation from the epoch of creation after 15 billion years of cosmological expansion. The universe has evolved from a dense and extremely smooth 'hot fireball', into the complex distribution of stars and galaxies that we observe today. The tiny fluctuations that have recently been observed imprinted onto the microwave background reflect real fluctuations in the mass distribution at very early epochs (Smoot *et al*. 1992). It is thought that galaxies have grown from fluctuations with a much smaller scale than these, imprinted in the cosmic mass distribution by some, as yet unknown, random quantum effect.

The CMB contains a wealth of information on the fundamental parameters that have shaped the universe. Two planned space-based experiments, MAP and Planck, will make precise temperature maps of the background radiation at much higher angular resolutions than COBE. Various physical mechanisms leave characteristic imprints on the CMB fluctuations that can be used to measure combinations of the mean mass density, cosmological constant, baryonic density and the Hubble constant (see, for example, Hu *et al*. 1999). By the year 2010 the CMB may have provided most of the fundamental parameters that govern the evolution of the universe with unprecedented accuracy.

The second ingredient that must be added to this model is the dark matter component. The nature and amount of dark matter governs the way in which structures form within the expanding universe. Although the dark matter may be ordinary atomic material, or something far more exotic, the thermal history of the universe during the first few minutes can be used to predict the total amount of baryonic matter in the universe. Certain isotopes, such as deuterium, were only created during the Big Bang, and their present day abundance can be used to measure the amount of baryons (protons, neutrons, etc.) in the universe. 'Primordial nucleosynthesis' predicts that the total baryon density $\Omega_{\mathrm{B}} = 0.05 \pm 0.01\Omega_{\mathrm{crit}}$ (see, for example, Copi *et al*. 1995). Unfortunately, astronomers have only managed to locate about one-fifth of the expected density, leading to a second dark matter problem and a search for hidden baryonic material (Persic & Salucci 1997).

(*a*) *Baryonic dark matter*

Could all the dark matter be provided by regular baryonic material but be locked into some form that does not emit light? Many candidates have been considered, from dark stars to frozen crystals of hydrogen (see Carr (1994) for a review). However, a host of observational and dynamical constraints have been used to eliminate practically every possible means of hiding a closure density of dark baryons. Depending on just how much dark matter in baryons we are willing to accept, the most likely remaining possibilities are diffuse warm gas, cold and very dense clouds of molecular hydrogen or old stellar remnants of white dwarfs (Combes & Arnaboldi 1996; Alcock *et al*. 1993).

Recent developments in X-ray astronomy have lead to the discovery that a large component of the dark mass in groups and clusters of galaxies is hot gas (Mulchaey *et al*. 1993). The first X-ray satellites that could map out ionized hydrogen were sensitive only to the highest-energy photons and the hottest gas. Lower-temperature gas, such as shown in the NGC 2300 group and the extended gas distribution in the Coma cluster (see figure 5), was not detected until mapped by the ROSAT satellite.

The dynamical evidence shows that the total mass-to-*light* ratio in groups and clusters is typically as high as 300 times that of the Sun. However, once the diffuse gas is considered, then the mass-to-*baryon* ratio falls to approximately 30, closer to the universal value predicted by nucleo-synthesis. It is difficult to envisage a scenario in which the baryonic dark matter associated with isolated galaxies is not gaseous. It is not plausible that the missing baryonic dark matter could be low mass stars, or MACHOS, in the Milky Way and remain as diffuse gas in clusters. Clusters and groups form via the mergers of isolated galaxies like the Milky Way, therefore the gas must already be present and subsequently shock heated to the virial temperature in the denser environments. Evidence for this component may be found in the absorption spectra of quasars, or perhaps more locally as the high velocity clouds (Blitz *et al*. 1999), or warm ionized gas in the outer regions of galactic haloes and the Local Group.

The theory of 'inflation' predicts that we live in a flat universe which slowly grinds to a halt from its current rapid expansion (see, for example, Peebles (1990) and references within). Inflation does not allow for a universe that re-collapses under its mutual gravitational attraction, thus resolving some of the need for a special cosmic creation. However, the total sum of everything we can observe, including the

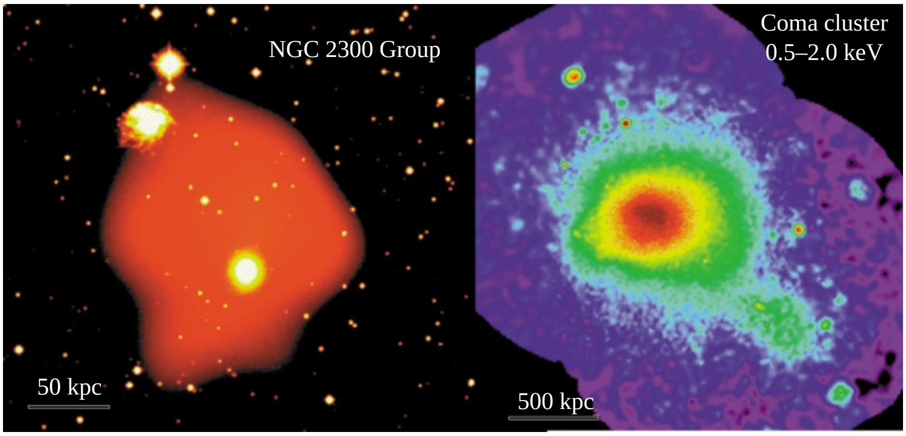

Figure 5. A combined X-ray and optical image of the NGC 2300 group of galaxies (Mulchaey *et al*. 1993) (left panel) and an X-ray map of the Coma cluster of galaxies (right panel). The false colours show the distribution of hot ionized gas observed by the ROSAT satellite. The Coma cluster is about 100 times more massive than the group and contains thousands of individual galaxies. The hot gas amounts to a factor of 10 larger than the visible mass of stars and can account for all the baryons predicted by nucleo-synthesis. Ionized or warm gas has not been detected surrounding galaxies, although it would be puzzling if the dark matter was stellar in galactic haloes and gaseous in clusters. How would the baryons 'know' to remain gaseous in the regions that hierarchically merge to form clusters?

dark mass associated with galaxies and clusters, adds up to *ca.* 20% of the required mass. The cosmic inventory leads to the conclusion that the universe will expand forever, slowly fading away until all the mass becomes 'dark matter'. One can reconcile inflation theory with observations only if the bulk of the dark matter is uniformly distributed over scales larger than a few megaparsecs, evading detection within galaxies and clusters.

The recent detection of tiny fluctuations at the level of 1 part in 10^5 in the cosmic background radiation has compounded the idea that structure forms hierarchically in a universe dominated by non-baryonic dark matter. If the universe contained just baryonic material, fluctuations this small could never have grown into objects as large as galaxies, let alone galaxy clusters (Peebles 1990). Whether we like it or not, both theory and data point towards an additional component of mass that is in some other form to the baryons we are made from (cf. Turner 1999). The most popular solution to accelerate the growth of fluctuations is to appeal to a large density of matter in the form of 'exotic' particles created during the early universe.

(*b*) *Exotic particle dark matter*

Non-baryonic dark matter candidates can be catagorized according to their velocities when they form in the early universe. 'Hot' dark matter is the best motivated candidate because the neutrino is known to exist and have mass (Fukada *et al*. 1998). Unfortunately, its relativistic velocity is so high that the small fluctuations that could form galaxies are washed out (White *et al*. 1983). Warm dark matter (perhaps heavy neutrinos) remains a viable candidate, but it is difficult to theoretically motivate a significant cosmological density of such particles (Schaeffer & Silk

1988). Cold dark matter has proven to be the most popular candidate, stemming in part from its apparent lack of free parameters in its first conception, motivation from particle physics, and its success at reproducing a host of observational results (Davis *et al*. 1985).

The only convincing way of demonstrating that most of the material in the universe is composed of exotic particles is to detect them in a laboratory. Two candidates remain as contenders for CDM, which are both promoted by theoretical particle physics models that attempt to unify the forces of nature. The axion, with a mass of just 10^{-5} eV (similar to the electron mass), and the neutralino with mass *ca.* 100 GeV (one proton is equivalent to 1 GeV). Given that we live *ca.* 10 kpc from the centre of a typical spiral galaxy, we can estimate the expected dark matter density at the position of the Sun using observations or numerical simulations. The expected density of dark matter at the Earth's position in the galaxy is equivalent to one proton per cubic metre. Therefore at the Earth's velocity of *ca.* 200 $\mathrm{km\,s^{-1}}$ through the halo, we expect about 1000 neutralinos passing through our body every second! Although 'lighter' than hot dark matter, axions are moving at non-relativistic velocities since they do not originate via a thermal mechanism in the very early universe. Axions can be detected in a laboratory by stimulating their conversion to photons using a very strong magnetic field. Experiments are underway that will probe the entire allowed parameter space within the next decade.

If neutralinos are to provide all of the dark matter, then they must have a small interaction cross-section of *ca.* $10^{-38}\ \mathrm{cm}^2$. Roughly once per day, a neutralino will collide with a nucleus in our body, raising our temperature by an immeasurable amount. Such a small energy release is only detectable in a super-cooled and highly pure material. Several research groups are using germanium crystals to detect temperature increases from individual collisions with nuclei and neutralinos. One way to discriminate from noise and spurious events is to search for a yearly modulation in the signal that results from the motion of the Earth around the Sun. A modest but controversial claim for such a signal has already been made by the Italian DAMA collaboration (Bernabei *et al*. 1998). If independent experiments with better statistics and longer baselines verify this detection, then the implications will have a similar impact to that of the discovery of the microwave background.

Current and planned direct detection experiments assume the dark matter in the galactic halo has a smooth distribution in phase space. Numerical simulations have demonstrated that this assumption is incorrect (see figure 8); the phase space structure of galactic haloes is remarkably complex. The dark matter may be clumped on extremely small scales (even below the mass of the Earth), such that a smooth component does not exist, which would leave laboratory experiments in the dark.

(*c*) *Vacuum energy and the cosmological constant*

The cosmological constant in Einstein's equations acts like a dark matter component that fills space uniformly. This component leaves a visible signature by causing an accelerated or decelerated expansion detectable in the cosmic microwave background fluctuations or as deviations in the redshift–magnitude diagram. If the distances to high-redshift objects are measured accurately enough then it is possible to measure the deceleration (or acceleration) of the universe. A positive cosmological constant would manifest itself as distant objects appearing to be accelerating away from each other. The most recent results using 50 supernovae observed to redshifts $z = 1$ suggest that Ω_Λ is at least twice as large Ω_m (Perlmutter *et al*. 1999).

The physical nature of this energy is as yet undetermined, as is the reason why it should make a non-negligible contribution to the energy density of the universe. The cosmological constant was invented by Einstein to make a static model for the universe. It has also been invoked to reconcile observational evidence that the universe was older than allowed from theoretical models, as well as the abundance of high redshift quasars. It may be a real component that corresponds to the energy of the virtual particles associated with the vacuum. We should learn from the history of its misuse and be careful before accepting a non-zero value.

3. Computational cosmology

The main goals of the first structure-formation models were to explain the origin of galaxies and their large-scale clustering properties. Unfortunately, linear theory and its extensions cannot follow the highly nonlinear processes that lead to galaxy formation. It was not until the advent of powerful computers, and efficient algorithms for simulating the formation of structure, that different cosmological models could easily be compared with observational data. Numerical simulations have played a key role in the interpretation of observational data since computers first became available for research. Some of the most influential work of the 1970s was Toomre's (1964) simulations of merging spiral galaxies. Cosmological simulation began in earnest in the 1980s with the initial investigations of cold and hot dark matter hierarchical models.

Direct simulation is a powerful tool for following the motions of dynamical systems as they evolve under their mutual gravitational potential. The mass distribution is represented by a system of particles (representing dark matter, stars, galaxies, etc.) that are continuously moved according to the gravitational force acting at each point. The exact solution is an N^2 problem, where N is the number of particles, but using techniques such as updating the forces from distant regions of space less frequently can reduce the computation to order $(0)N\ln(N)$.

As the numbers of particles in a simulation increases, then so do the density contrasts and the range of dynamical times ($\propto 1/\sqrt{\text{density}}$). If we weight the work done on the particles inversely with their natural time-steps, we find a potential gain of about 50, one of the last algorithmic areas where an order of magnitude improvement is still possible. From this point on we must rely on the continual increase in performance provided by faster processors to solve more complex problems. Computers have doubled in speed and memory capacity every 18 months; however, a significant increase in computing power has recently resulted from adapting the N-body codes to run on parallel computers.

Parallel computers have many hundreds of individual fast processors linked together with fast connections in an optimum topological configuration for maximizing interprocessor communication speed. The largest available systems for scientific research have as many as 1000 processors and memory capacities of 100 Gb. In several years' time we might expect a factor of 10 increase in size and a corresponding increase in individual processor power. Theoretical research now requires similar resources to observational astronomy, with large dedicated telescopes serving the community. By the year 2010 we should achieve one of the ultimate simulation

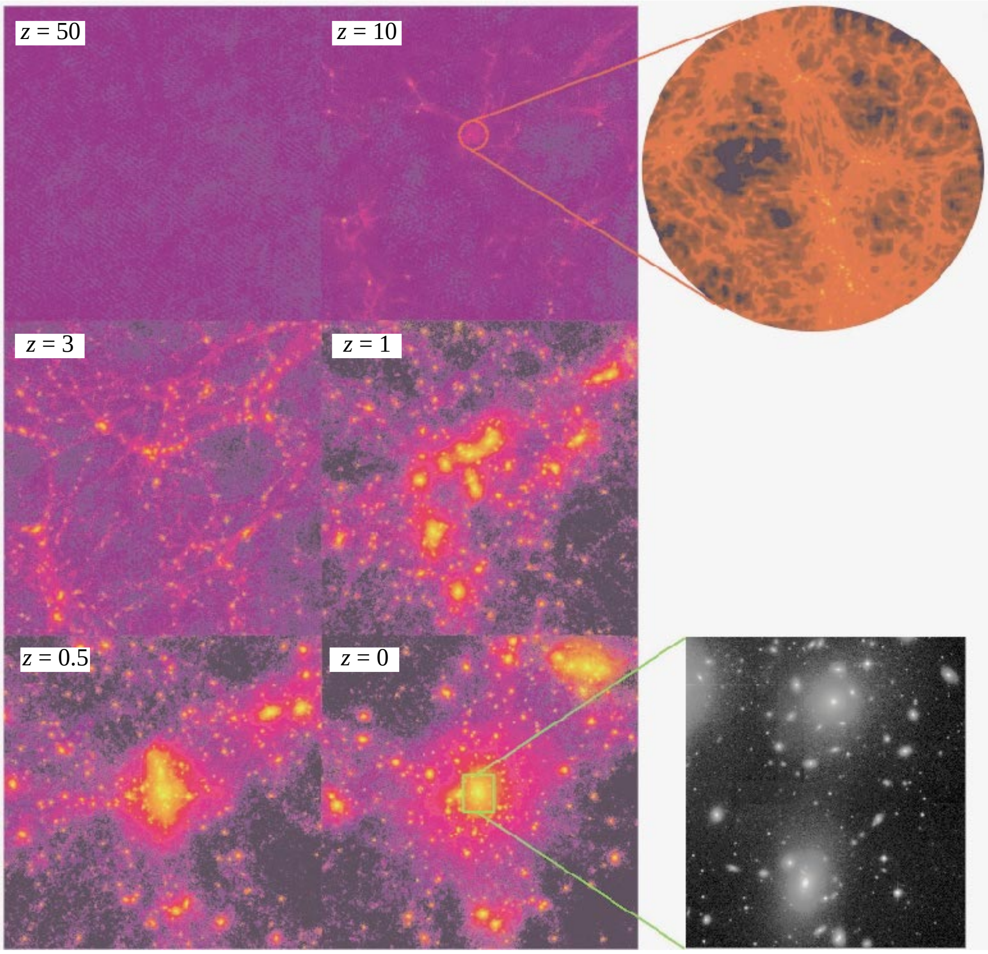

Figure 6. The hierarchical evolution of a galaxy cluster in a universe dominated by cold dark matter. Small fluctuations in the mass distribution are present but barely visible at early epochs. These grow by gravitational instability and accretion of mass, eventually collapsing into virialized quasi-spherical dark matter haloes. Gas can cool very efficiently within these objects which eventually merge into the large galactic systems that we observe today. This plot shows a time sequence of six frames of a region of the universe that evolves into a cluster of galaxies. The colours represent the local density of dark matter plotted using a logarithmic colour scale. Linear over-densities are darker blue, whereas the nonlinear collapsed regions attain over-densities of a million times the mean background density and are plotted as yellow/white. The simulation begins at a redshift $z = 50$, at which time the universe has expanded to just 2% of its final size and 0.2% of the present age. (As is usual when plotting numerical simulations, the data are viewed in co-moving coordinates by dividing out the expansion factor, i.e. the amount by which the universe has expanded at that redshift. Each box is 10 million parsecs wide (cf. Ghigna *et al*. 1998).)

goals: to resolve the formation of individual galaxies within a cosmological volume, a task that requires sub-kpc resolution in both the dark matter and baryonic components.

(*a*) *The hierarchical evolution of galaxies and clusters*

Figure 6 shows the hierarchical evolution of a galaxy cluster in a universe dominated by cold dark matter (CDM). This simulation took many months of dedicated time on a large parallel computer and is the most intensive ever carried out for astronomical research. More than 10^{15} operations were required to follow the evolution of the dark matter from the early universe to the present day.

Initially, there is no apparent structure in the mass distribution, although tiny fluctuations are present with an amplitude that is specified by the CMB observations. The second snapshot in figure 6 shows the universe at a redshift $z = 10$, when it was just 300 million years old. The mass distribution has a spectacular filamentary appearance, although a close-up view shows that the filaments are made up of many small dark matter haloes. At this time the first stars and quasars would be lighting up and re-ionizing the universe. Evidence for this activity may be found by searching for high redshift supernova with NGST. The amount of structure at this epoch is very sensitive to the amount of small-scale power, if the dark matter is 'warm', then NGST will detect nothing at these high redshifts.

Larger more massive structures, such as galaxy haloes, are rarer and collapse at later times, although they can be seen forming at the intersection of the filamentary structures. The topology of the mass distribution is complex and in this particular model it is almost scale free, small structures appear as scaled versions of larger structures. Between redshifts $z = 5$ to $z = 2$, galaxy-sized dark matter haloes have formed and the proto-cluster is clearly visible. At a redshift $z = 0.5$ the universe was almost a half of its present age (close to the epoch at which the Earth formed from recycled stellar debris from supernovae), the cluster has almost formed and most of the mass and galactic haloes are in place. This system undergoes a further five billion years of internal dynamical evolution before it reaches the present epoch at $z = 0$.

(*b*) *Successes and failures of the cold dark matter model*

High-density regions such as galaxy clusters are the hardest regions to simulate because of the short dynamical time-scales and strong gravitational forces. Only recently has it been possible to achieve sufficient numerical resolution to resolve the internal structure of virialized haloes. One of the most remarkable success of hierarchical clustering models is the natural formation of cluster of galaxies. Starting from the spectrum of tiny mass fluctuations observed in the CMB, structures evolve by gravity alone to form massive dark matter potentials that contain hundreds of individual dark matter haloes (see figure 7).

Can cold dark matter provide the dark matter within galactic haloes? This is the most fundamental test of any dark matter candidate and unfortunately, the cold dark matter model appears to fail this test. In figure 1 we plotted the rotation curve of a typical low surface brightness galaxy that is dominated by dark matter. The slowly rising rotation curve indicates a constant mass density in the central region. The density profiles of cold dark matter haloes are much steeper than this, rising as $\rho(r) \propto r^{-1.5}$. This produces the dashed curves in figure 1, which would give rise to much higher rotational velocities than observed.

A second 'feature' of the CDM model is the amount of substructure that is predicted to orbit within galactic haloes (Moore *et al*. 1999; Klypin *et al*. 1999). Figure 7 shows a comparison between the known distribution of satellites that surround the

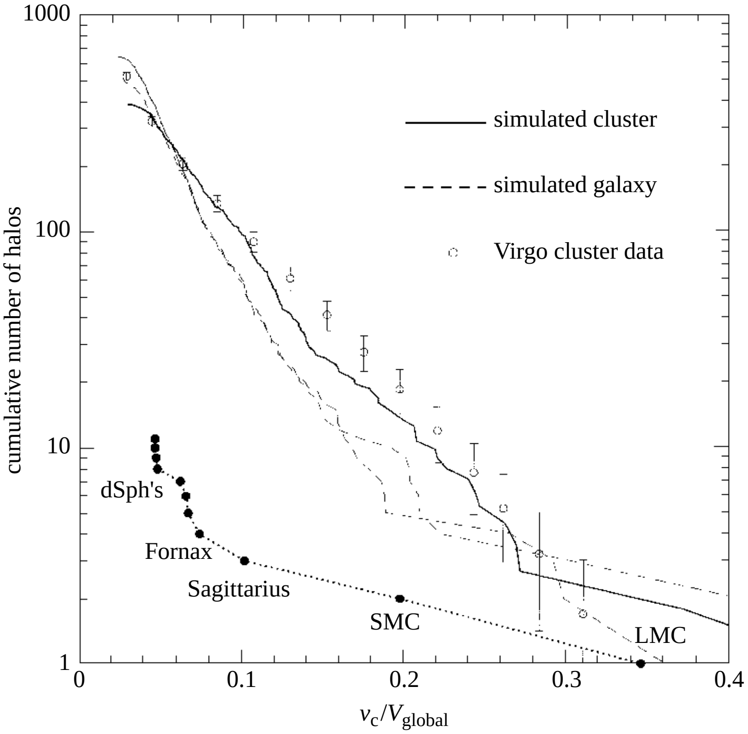

Figure 7. The mass function of cosmic substructure. The cumulative number of Virgo cluster galaxies with rotation speeds larger than a fraction of the global value, 1100 km s^{-1} (open symbols). The solid curve gives the prediction from the simulation of a hierarchical universe shown in figure 6. For comparison we show the circular velocities of observed substructure within the Milky Way's halo (dotted curve) above a fraction of the global value, 200 km s^{-1}. The dashed curves show predictions from the CDM model for galactic mass haloes. Clearly, the 'visible' mass function is not scale free and varies strongly from high to low mass systems, whereas the mass function of haloes in the hierarchical model is nearly independent of mass; galaxy clusters appear as scaled versions of individual galaxies (Moore *et al*. 1999).

Galaxy and the predictions of the CDM model. Just 12 satellite galaxies orbit the Milky Way, about a factor of 100 fewer than expected. If the expected amount of substructure is present, but very dark because of suppressed star formation, then it may only be detectable via its gravitational effect on spiral discs.

The velocity dispersion of disc stars correlate with their age (Wielen 1974). The older stars that have been present for the past 10 billion years are moving considerably faster than the stars that formed more recently. A physical heating mechanism for producing this correlation has been sought after without great success. Dark matter substructure provides an efficient mechanism for heating stellar discs and could explain the observed age–velocity dispersion relation. The only problem is that the thousands of high velocity encounters between CDM substructure and the disc may provide too much disc heating and erase the thin disc component (see figure 8).

A large part of the success of the CDM model stems from the fact that this model provides a picture of the universe that is fairly close to reality. Its failures on small scales that are just being uncovered indicate just how much effort has gone into testing this model against data. Many of its past problems have been overcome by the introduction of new concepts and additional free parameters that detract from the simplicity of the standard model. Crucial to the success of CDM are the controversial concepts of biasing and feedback. The latter was initially invoked to resolve the conflict between the low observed peculiar velocities with simulation results, while supernovae feedback is necessary to darken galaxies and reproduce the flat luminosity functions observed in galaxies, groups and the field. Perhaps it is time to devote more effort to investigating new models and new dark matter candidates.

4. Summary

The evidence suggests that the visible universe forms hierarchically, with small structures collapsing at high redshift which merge and accrete into the galaxies, clusters and super-clusters that we observe today. Currently, there is no viable alternative scenario. If observations turned up massive objects already in existence at high redshifts, then we could question this model.

The growth of structure is governed by the nature of the dark matter and the fundamental cosmological parameters. A universe dominated by a critical density of cold dark matter was the first cosmological model that had real predictive power and could withstand scrutiny against observations. The standard version of this model, with its well-motivated parameters, provides a picture that is remarkably close to reality. If this model is correct, then a comparison with observational data and theory compels us to believe that

$$\Omega_{B,\mathrm{observed}} \approx \Omega_{B,\mathrm{nucleosynthesis}}/5 \approx \Omega_{\mathrm{CDM}}/25 \approx \Omega_{\mathrm{crit}}/125.$$

We have seen that a universe dominated by cold dark matter can give rise to structures that resemble galaxies and galaxy clusters. This model can also reproduce the observed evolution of galactic systems and the large-scale clustering pattern. Although there is some degree of failure on small scales, whether or not this is fatal for the CDM model will only be established after further observational and theoretical investigation.

The cosmic inventory reveals that the universe contains about one-quarter of the mass necessary to halt its rapid expansion. Recent observational data suggest that a vacuum energy density may actually be larger than the mass density. Although this reconciles the standard inflation theory of a critical universe, it raises the question as to why the cosmological constant has a measurable value; the natural expectation was that it was either zero or incredibly large. Is this added complexity just reflecting our ignorance of the nature of dark matter? Could an alternative dark matter candidate reconcile observations with our theoretical prejudice for a closed universe, without resorting to a cosmological constant?

Ultimately, gravitational lensing surveys, microwave background experiments and direct detection experiments will reveal the properties of dark matter and the parameters that are embodied within our cosmological world model. Although we search for a single candidate, nature may not be that kind and we may live in a universe that contains several species of dark matter. The recent discovery that the neutrino has mass implies that 'hot dark matter' contributes an equivalent mass density as all the visible stars in the universe! Particle physics and theory has motivated a

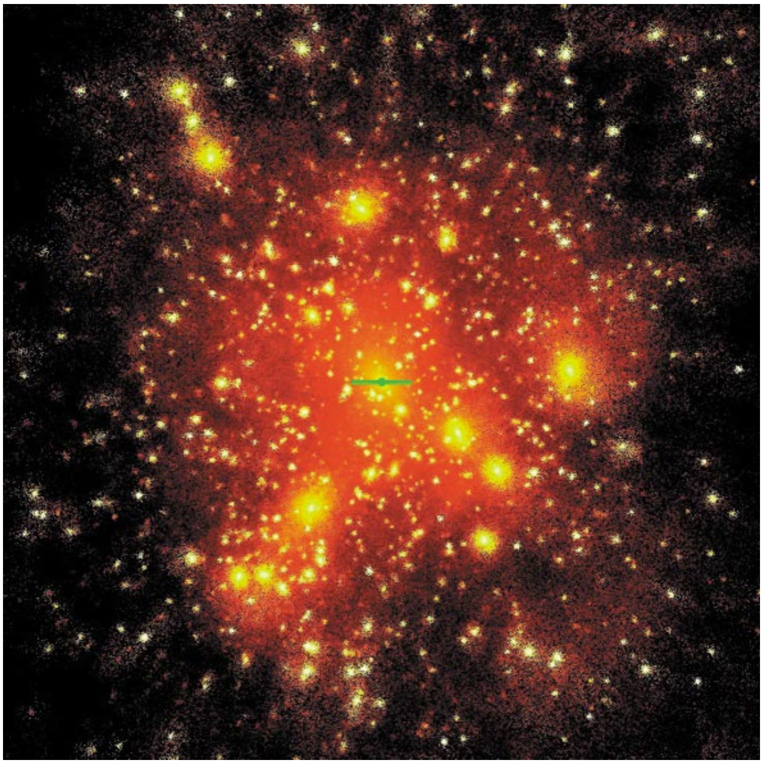

Figure 8. A massive dark matter halo of cold dark matter particles that may surround galaxies. This simulation is the most intensive computer calculation ever performed for cosmological research, requiring over 150 000 CPU hours on a large parallel supercomputer. The evolution of this dark matter halo proceeded in a nearly identical fashion to the cluster halo plotted in figure 6. However, the mass and length resolution is much higher, allowing us to accurately resolve the internal structure of a dark matter halo that forms within a hierarchical universe. The tiny green disc of stars at the centre illustrates the extent (*ca.* 20 kpc) of a spiral galaxy like the Milky Way. The expected clumpiness of dark matter within galactic haloes has only recently been predicted by high resolution numerical simulations such as this.

wealth of additional candidates, from topological defects to ghost universes. Hopefully, the identity of dark matter will be revealed within the next decade or so, by a combination of strategic observations and theoretical modelling.

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Ben Moore was born in Falstone, Northumberland, in 1966. He received a first class honours degree in astronomy and astrophysics from the University of Newcastle in 1988. After achieving his PhD from the University of Durham in 1991, he spent several years as a research associate at the University of California at Berkeley before moving to the University of Washington, Seattle. He returned to the UK in 1996 to take up a Royal Society Research Fellowship at Durham University. Aged 33, his scientific interests within the field of cosmology include galaxy formation and the origin of structure in the universe. His recreational activities include rock-climbing, mountaineering and snow-boarding.