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Dark matter in the universe: where, what, and why?

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ABSTRACT. The universe is pervaded by non-luminous matter. Observations at many wavelengths, and on many length scales, yield a reasonably good picture of the amount of dark matter and its distribution. In very broad terms, the larger the scale we survey, the larger the fraction of gravitating mass that does not emit its fair share of light. The range is from about 50% in the solar neighbourhood (the nearest few hundred parsecs†) to 99% or more in the largest clusters and superclusters of galaxies (ten million or more parsecs across). Observations do not, so far, tell us what that dark matter is made of, or even whether it is all the same kind of thing. Candidates that cannot currently be ruled out include tiny stars, stellar remnants, some kinds of black holes, neutrinos with rest masses 10^{-5} to 10^{-4} of the electron mass, and still more exotic kinds of particles (photinos, gravitinos, axions, majorons, Higgsinos...) that interact at most weakly with normal matter.

1. The concept

Dark matter is not very new in astronomy, either as an idea or as a phrase. Neptune remained unseen for less than a year after John Couch Adams and Urbain Leverrier provided accurate predictions of its position. But Sirius and Procyon had 'invisible' companions for 18 and 41 years respectively following Bessell's 1844 deduction of their existence.

In each case, it was the gravitational effect of the less luminous body on more luminous ones that revealed its presence. Most of the modern data for widespread dark matter are of the same form—motions of stars and galaxies which imply the presence of more gravitating mass than we see in the stars and galaxies themselves. This is, of course, no guarantee that the resolution will prove to be the same. Twentieth-century dark matter need not necessarily turn out to consist of fainter examples of previously known classes of objects.

The phrase is also older than the average reader of *Contemporary Physics*. Kapteyn (1922) remarked that stellar velocity distributions gave us 'the means of estimating the mass of dark matter in the universe', (though his 'universe' is our 'galaxy'). Jeans (1922) concurred. Ten years later, the increase in number of measured star velocities allowed Oort (1932) to attempt a determination not only of 'the amount of dark matter' but also of 'the distribution of dark matter' (in and out of a galactic disc much like our modern picture of the Milky Way). Each found a local mass density exceeding that provided by visible stars by roughly a factor of two, close to a popular modern value (Bachall 1984). Soon after, Zwicky (1933) analysed velocities of galaxies in the Coma cluster (galaxies like Andromeda and clusters like Coma and Virgo are often named for the constellation we have to look through to see them). He concluded 'dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materia', which means just what you

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† Astronomers normally express large distance in parsecs (pc), where one parsec is the distance at which the Earth–Sun distance (Astronomical Unit) subtends an angle of one arc second. It is also roughly the average distance between stars near us. The multiples kpc and Mpc are useful because we are about 10 kpc from the centre of our own galaxy and 10 Mpc from the nearest rich cluster of galaxies, Virgo.

think it might, if your German is no better than mine. Zwicky's cluster dark matter outweighed the luminous by almost 100:1, again close to modern values (Merritt 1987).

These pioneers suggested several candidates for their dark matter, including faint (low-mass) stars, planets or asteroids, and cold gas. With modern techniques of radio and X-ray astronomy, gas is no longer invisible at any temperature, and we know that it contributes on both scales under discussion—but only about 10% in the solar neighbourhood and a factor of two or so in rich clusters. Earth-like planets and asteroids must be even less important. Because hydrogen and helium will not remain solid long at the present 3 K temperature of interstellar space, only heavier elements can be locked in such configurations, and these contribute only 1–2% of the hydrogen mass.

Sufficiently faint stars remain among the contenders. A contracting gas cloud of less than 0·08 $M_\odot$ ($M_\odot$ = the mass of our sun = 2×10^{33} g) will become degenerate at its centre before heating up to the 10^7 K required for ignition of stellar nuclear reactions (normally the fusion of hydrogen to helium). These failed stars have only their contraction energy to radiate away and so are, on average, only one-thousandth as bright as true stars. The issue of what they should be called has generated more heat than the objects themselves. 'Brown dwarfs' seems to be winning at the moment. Jupiter at 0·001 $M_\odot$ is close to the dividing line between these and true (solid-force-dominated) planets.

Dark matter did not disappear for the next 40 years, but it was not regarded as a major topic of astrophysical research until about 1974. That year, two papers (Einasto *et al.* 1974, Ostriker *et al.* 1974) tabulated existing determinations of galaxy masses as a function of radius within which the mass was measured. The masses increased monotonically, and approximately linearly, with radius from 10^{11} $M_\odot$ for luminous cores, to 10^{12} $M_\odot$ at 100 kpc. Non-luminous matter, it became widely accepted, dominates astronomical dynamics, at least on large scales, and by at least an order of magnitude.

This acceptance has had some of the properties of a paradigm shift, and today it is the occasional non-believer in ubiquitous dark matter who finds himself† out of step and sometimes out of print. Historians may (or may not) want to note that the shift occurred, not so much as a result of new data, but as a product of the re-examining and compiling of previously disjoint existing data.

Since 1974, the astronomy, physics, and astrophysics literature pertinent to dark matter has become enormous. A recent longer review (Trimble (1987), referred to hereafter in totally unconvincing false modesty as T87) was confined to about 650 references only under dire threats from the editor, and an incomplete search in connection with the present discussion uncovered 92 new ones. In the sections that follow, many active workers in the field (and even some ideas) will be unjustifiably neglected. More detailed documentation can be found in T87, earlier reviews cited therein, and the semi-annual volumes of *Astronomy and Astrophysics Abstracts*, which have included 'dark matter' as an index entry since 1983.

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† Several colleagues have criticized my use of sexist language in this context. For some time it was possible to take refuge in the observation that the dissenters were all men. This no longer quite seems to be the case (Mineva 1987).

2. The clues

Dark matter of dynamical importance has been suggested by somebody on every scale from the 0·01 pc solar system (Nemesis!)† to the $\gtrsim 3000$ Mpc visible universe as a whole. From close objects to distant ones seems to be the natural order in which to approach the issues, though we will see that the evidence is clearest and most persuasive on the intermediate scales of individual galaxies and first-order clusters of them.

Units. A few words about astronomical conventions and objects are needed as a background. Masses are normally measured in $M_\odot$ and luminosities in $L_\odot$ ($3{\cdot}9 \times 10^{33}$ erg s^{-1}) or in $L_\odot$ within a particular wavelength band (blue and visual are common in addition to bolometric). The prevalence of dark matter is then expressed as a mass-to-light ratio in units $M_\odot/L_\odot$. The ratio for the Sun is one, to very high precision. For a population of stars, the expected M/L follows from (i) the known mass-luminosity relationship (L scales as M^3 to $M^{4\cdot5}$), (ii) the numbers of stars formed as a function of mass ($N \propto M^{-2}$ is typical), (iii) the lifetimes of stars (which scale as $M^{-2\pm1}$), and (iv) the range of common stellar masses over which these relationships apply (e.g. 0·3–30 $M_\odot$). One predicts $M/L = 1$ to 3. Such values are, in fact, observed for bound clusters of stars.

Larger values mean the presence of dark matter in suitable proportions (gas being invariably a small contributor). We are entitled to be surprised by a particular M/L ratio only the first time it appears in our journey from the local to the universal. For instance, once it is accepted that large galaxies have $M/L = 20 \pm 10$, then clusters of such galaxies must have M/L at least as large.

The distance scale. For objects outside the Local Group (the small cluster of galaxies to which our Milky Way belongs), measured quantities depend on the bitterly-debated choice of distance scale. The contenders are parametrized by the value of the universal expansion rate, Hubble's constant, $H_0 = 50$ or 100 km s^{-1} Mpc^{-1} (that is, expansion time scales of 6 or 3×10^{17} s $= 20$ or 10×10^9 yr). Distances enter linearly into most mass determinations and quadratically into luminosities, thus immediately providing an opportunity for factor-of-two arguments about M/L. A reasonably amicable way around this is the parameter $h = H/100$. Thus a representative galaxy might be described as having $M = 5 \times 10^{11}\, h^{-1}\, M_\odot$, $L = 5 \times 10^{10}\, h^{-2}\, L_\odot$, and $M/L = 10\,h$, all within a radius of 20 h^{-1} kpc. Several other aspects of normalization for masses and luminosities have also sometimes led to disagreements more apparent than real (Felten 1986).

The average density provided by a given class of objects scales as mass over distance cubed, hence as h^2. Luckily, the density of matter needed to halt universal expansion, $\rho = 3\, H_0^2/8\pi G$, also has an h^2 in it. Thus, estimates of the fraction of critical density provided by galaxies, large clusters, X-ray gas, or whatever, are independent of H_0 (though of course they may be wrong for other reasons!).

Converting velocities and positions to masses. The ages of galaxies and smaller units are large compared to their rotation periods or crossing times. We thus feel confident that the velocities in them are responding to a stationary gravitational potential, and that standard equations associated with the names Poisson, collisionless Boltzman and virial apply. Then a system with velocity dispersion $(\Delta V)^2$ and characteristic size R will have a mass $M \approx (\Delta V)^2 R/G$. For larger systems, especially the outskirts of clusters of

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† Nemesis is the name given to a hypothetical brown-dwarf companion to the Sun, supposedly responsible for periodic disturbances of the Oort comet cloud and so for periodic waves of extinction of terrestrial organisms.

galaxies, the age may be comparable with the crossing time. Thus, the gravitational potential and velocity distribution may be changing and out of equilibrium. Computer simulations of the appropriate *n*-body problems are now widely used to analyse such systems, leading to the conclusion that masses derived by assuming virial equilibrium are wrong, but typically by factors of only two or three.

2.1. *The solar neighbourhood*

Think of the bright part of our galaxy as a thin, flat disc, with the Sun only 10–20 pc from the median plane, but 7–10 kpc from the centre. Choose a class of stars that can be reliably identified to distances of one kpc or so. Now, measure their local velocity distributions and the decline of their number density away from the plane. Clearly, if there is little mass in the plane, a given set of velocities will carry the stars further away than if there is a great deal. Thus, following the trail blazed by Kapteyn, Jeans, and Oort, we can estimate the local mass density as $0{\cdot}12 \pm 0{\cdot}03\ M_\odot\ \mathrm{pc}^{-3}$ (Bahcall 1984, Bienaymé *et al.* 1987, T87). The luminosity density provided by known local stars is rather less, but also has sizable error bars. As a result, estimates of the proportion of non-luminous material range from one-tenth to two-thirds, corresponding to $M/L_v = 3$–8 or so.

Although evidence of this sort was the first indicator of dark matter in the galaxy, it may not represent a distinct component. There is independent evidence for a spheroidal component of dark matter (§ 2.2) which must pass through the disc and must have been somewhat concentrated there by the process of disc formation (T87), and this may also be what we are seeing in the disc (Binney *et al.* 1987).

2.2. *Single galaxies*

Galaxies differ in kinematics, as well as in the morphology that causes them to be classified as spiral, elliptical, and irregular, and so different techniques must be used to measure their masses. Of the numerous subtypes, the dwarf irregulars and dwarf ellipticals (the smallest and most diffuse of which are also called dwarf spheroidals) are most relevant to the nature of dark matter because they demonstrate how condensed and compact it can be.

2.2.1. *Spiral galaxies*

The spirals, including our own Milky Way, consist of (at least) two components—a bright, flat disc dominated by rotation of stars and gas on nearly circular orbits, and a less-luminous, slowly- or non-rotating spheroidal halo, whose light comes from old stars, including globular clusters with ages exceeding 10 Gyr. For spirals seen edge on, optical and radio emission lines from the gas enable us to trace out circular velocity as a function of radius (the graph is called a rotation curve), and so to measure mass interior to radius R as (to within factors like $\pi/2$) $M = V^2R/G$.

We would like also to use halo objects as probes, both because they extend out further than the visible disc and because they might tell us whether the mass distribution is flat (like the light) or spheroidal. The difficulties are the relative faintness and sparsity of halo stars and clusters, and uncertainty in halo kinematics. Not knowing whether the orbits are largely radial, largely circular (though randomly oriented), or isotropically distributed (the usual assumption), puts a factor between 1 and 10 in front of the averaged value of $\langle V^2R\rangle/G = M$, where V is the measured (one-dimensional) velocity.

Our own Milky Way galaxy has yielded the widest range of data, its mass being determinable from the local escape velocity and the sizes of satellite galaxies (set by tidal forces) as well as from rotation of the disc and the velocity dispersion of halo stars and clusters. There is general agreement (T87) that $M(R)$ roughly doubles from about $10^{11}\,M_{\odot}$ at solar R (9 ± 2 kpc), to $2 \times 10^{11}\,M_{\odot}$ at twice solar R. The corresponding M/L_B is then at least 10 for $L_B = 2 \times 10^{10}\,L_{\odot}$ (van den Bergh *et al.* 1987).

Out beyond $2R_0$, measurements necessarily rely on only a few objects, and there is less agreement. Total masses (for $R = 50$–100 kpc) ranging from 2·5 to $10 \times 10^{11}\,M_{\odot}$ have been found (T87, Little and Tremaine 1987, Sandage and Fouts 1987, Ninkovič 1987), corresponding to $M/L_B = 12$–30 (not 50, because the largest masses come from analyses using parameters that imply a galactic luminosity of 3–$4 \times 10^{10}\,L_{\odot}$). For the low end of this range (e.g. Little and Tremaine's analysis of globular cluster velocities), one must necessarily postulate additional dark matter belonging to the Local Group collectively to account for its binding and the escape velocity here of at least 450–500 km s^{-1}.

It is also generally agreed that most of the outlying mass is distributed spherically. The arguments for this (many of which apply also to other spiral galaxies) include flaring and warping of HI (neutral hydrogen) disc outskirts and the kinds of instabilities (producing bars and arms) that occur in thin discs as a function of the depth of spherical potential in which they reside (T87, Athanassoula *et al.* 1987).

For spiral galaxies other than our own, the most important information comes from rotation curves, either optical (Rubin *et al.* 1978) or radio (Roberts and Whitehurst 1975). The present concensus is that most spiral rotation curves can be matched by the same components we see in the Milky Way: a flat disc with $M/L_B = 5$–10, which dominates the inner portions, and a spheroidal halo whose importance increases with R, leading to total M to L_B ratios of 10–30 h (T87, Kent 1987). It is at least possible that the spheroidal distribution of dark matter is not evolutionarily associated with the visible halo objects that act as its tracers.

Several special cases yield additional information. Van der Kruit and Freeman (1984) have mapped gas velocities in six face-on spirals, thereby approximating Oort's analysis of the solar neighbourhood. Their results imply disc M/L_B values of 6 ± 2 and so $50 \pm 20\%$ dark matter, just as in the Milky Way. A few otherwise gas-deficient spirals have gaseous rings, orbiting perpendicular to the main stellar plane. These allow us to obtain rotation curves outside the main plane, which turn out to look just like the disc ones, implying spherical mass distributions (Whitmore *et al.* 1987) as expected. One might have hoped that gravitational lensing (or the lack of it) of distant galaxies and quasars by nearer ones would yield interesting mass values for the lenses (T87), but the limits set in fact tell us nothing new (Kovner and Milgrom 1987). Finally, some companion galaxies and others showing signs of close interactions have rotation curves that turn down at large radii. We conclude that tidal forces have removed the outer haloes (Zasov and Kyazumov 1983).

2.2.2. *Elliptical galaxies*

Elliptical galaxies present the same kinematic problem as haloes of spirals—we do not know whether the one-dimensional velocities we see are projections of radial, circular, or random orbits, and the uncertainty translates into a factor of three or so in $M/L = 7$–20 in the visible parts of most normal elliptical galaxies (Tonry 1983, T87). The same sort of uncertainty for the same reason applies to the value $M/L_B = 150\,h$ (out to radius $18\,h^{-1}$ kpc) found by Huchra and Brodie (1987) from the velocities of globular clusters around M87 (the galaxy at the centre of the Virgo cluster).

Luckily, we have a completely independent line of evidence. Many elliptical galaxies have retained some of the gas shed by their evolving stars and heated it to equilibrium with the stellar velocities of several hundred $\mathrm{km\,s^{-1}}$. The resulting temperatures. $T \sim m_p V^2 k^{-1}$, are 10^6–10^8 K and the gas, therefore, emits keV X-rays at detectable levels. The temperature of the gas (hence the X-ray spectrum) is a direct measure of the (three-dimensional) gravitational potential confining it, independent of stellar orbit shapes. The potential wells are typically deep, corresponding to masses of $10^{12-13}\,M_\odot$ for the larger elliptical galaxies. Thus $M/L_B = 50$–$150\,h$ (Forman *et al.* 1985, T87), where the range undoubtedly reflects real differences among galaxies. The error bars get broader (Trinchieri *et al.* 1986) if our assumptions about how gas temperature varies through the volume of a typical galaxy are wrong. Realistic cases do, however, always seem to lead to large values of M/L (Sarazin 1986).

Notice that elliptical masses and M/L values, are rather larger than spiral ones. There are two contributing factors. First, the biggest brightest galaxies (that is, the ones with the most mass in stars) are indeed elliptical and are often the ones found in rich clusters. Second, because bright star formation (virtually) ceased 10^{10} yr ago in elliptical galaxies, but continues today in spirals, the ellipticals are relatively faint for the amount of star-matter they contain. Thus the data are consistent with the two types having the same ratio of mass in stars and gas to dark mass.

2.2.3. *Dwarf galaxies*

We worry about these smallest visible galaxies because they ought to help us to address questions fundamental to galaxy formation and the nature of dark matter, questions like: (1) how compact can dark matter be?, (2) are there concentrations of luminous matter with no dark haloes?, (3) is the ratio of luminous to dark matter a function of galaxy mass?, and (4) could there be dark halos with no luminous matter at all, or with only tenuous gas that is not self-gravitating and so does not form stars? The very tentative answers seem to be (1) quite (Kormendy (1987) on the galaxy DDO 127 with a core radius only 2·3 kpc), (2) maybe, (3) probably, and (4) very probably (and we are quite possibly seeing them in the form of a forest of narrow Lyman-α absorption lines in the spectra of distant quasars; Rees (1988)). Some of the evidence follows.

The situation is rather different for the dwarf irregulars and dwarf spheroidals (or ellipticals). The dwarf irregulars, and related small spirals, contain gas from which we can obtain rotation curves, or at least line velocity widths pertaining to the galaxy as a whole. Where the gas extends out beyond the main stellar component, its velocity usually implies significant dark matter (T87, Carignan *et al.* 1988). Typically the halo-to-disc mass ratio is about one in the luminous regions and larger outside, much as for normal spiral galaxies. The case of the very compact DDO 127 (Kormendy 1987) implies that dark matter in the form of fermions must have particles' masses in excess of 100 eV (ruling out certain classes of neutrinos).

The dwarf spheroidals are the faintest known galaxies, so much so that we have seen only the ten or so that are close companions to the Milky Way and the Andromeda galaxy. These have luminosities of only $10^{5-7}\,L_\odot$, comparable with the larger globular clusters. But they are much more diffuse, having core radii of 100–500 pc, rather than 1–10 pc.

Dwarf spheroidals contain no gas to provide emission lines, and their stars are so far apart that only one at a time will fall on the slit of your spectrograph (unlike the case of globular clusters and normal ellipticals, for which we can get in one bite spectra representing the sum of hundreds or thousands of stars). Thus, painfully, one star at a time, the late Marc Aaronson and his colleagues (Aaronson 1987, T87) accumulated velocity dispersions for five dwarf spheroidals. The values obtained (from 5–10 stars per galaxy) lie in the range 6–7 km s^{-1}, implying M/L_B of only 1·4 in the brightest dwarf spheroidal (Fornax), but 150–200 in the faintest (Ursa Minoris). Doubt has recently been cast on these data with the recognition that, although several observers have found the same sorts of dispersions for the Carina dwarf spheroidal ($M/L_B = 7{\cdot}8$), they have found different velocities for particular stars (Godwin and Lynden-Bell 1987). The implication is that measured velocities are less accurate than hoped, or (perhaps more likely) that many of the stars are long-period, low-amplitude binaries. In either case, the velocity dispersion and implied mass drop by factors of 2–5.

The only independent check on these numbers arises from the expectation that the sizes of the dwarf spheroidals will be set by tidal forces from the Milky Way they orbit. Crudely, the derived M and M/L ratio scale linearly with the mass you take for the Milky Way. This, as we saw in § 2.2.1., has been measured at $2{\cdot}5\text{–}10 \times 10^{11}\,M_\odot$ by different investigators, and the derived masses for the dwarf spheroidals thus just nicely cover the same range found from the velocity dispersions of 6–7 *versus* 1·1–3·2 km s^{-1}.

The case for dark matter exceeding the luminous in these smallest galaxies must, therefore, be regarded as unproven, although many models of galaxy formation would imply that M/L ought to increase at small L, in the way we would find if the larger velocity dispersions are correct.

2.3. *Pairs, groups, and clusters of galaxies*

By looking at how galaxies move around each other, we can probe mass and M/L outside the ~20 kpc extent of detectable stars and gas. The caveats are many, including worries: (a) that apparent groupings may be optical projections or chance encounters rather than gravitationally bound systems, (b) that we do not know (as for stars in haloes) whether orbits are circular, radial or in between, and (c) that large systems, especially, even when they look smooth and regular, may not have had time to become dynamically relaxed enough for simple concepts like the virial theorem to apply. For these and other reasons (addressed in T87), numerical values should be construed as having at least factor-of-two uncertainties attached to them, unless all the assumptions are clearly listed; and two authors who claim without further qualification that typical galaxy pairs have $M/L_B = 20\,h$ and $(60 \pm 20)h$ respectively are quite possibly not in real disagreement.

The critical point is that very nearly all investigations of systems of galaxies find larger masses than would be obtained by adding up the individual (e.g. rotation curve) masses of the separate member galaxies.

2.3.1. *Binary galaxies and small groups*

Our Local Group can be looked at either as a dominant pair of galaxies, separated by about 700 000 pc and currently approaching each other at 100 km s^{-1} (hence almost certainly bound, since the universe as a whole is expanding; Kahh and Woltjer (1956)), or as a unit affecting the motions of the galaxies around it (Giraud 1986, Sandage 1987). Both approaches have been attempted a number of times (T87), with results of varying size and quality, but a range of masses $1\text{–}5 \times 10^{12}\,M_\odot$, and hence $M/L_B = 20\text{–}100$ seems to overlap all of the recent, carefully described results. Since authors who get small values for the total mass tend also to get small values for the individual galaxy masses, the Local Group really does seem to have some communal dark matter, over and above that probed by rotation curves, globular cluster velocities and so on.

Other binary galaxies must be treated statistically, since we cannot know their individual projection angles onto the plane of the sky, or where we are catching them in their orbits. Analyses are fairly numerous (T87), and two recent, careful studies disagree, at least at the 1-σ level, about whether the average M/L_V for spiral pairs is about 20 h (van Moorsel 1987) or about 40 h (Schweizer 1987), and about whether or not treating even wide pairs as consisting of point masses is an adequate approximation. They do agree that the pair masses exceed the sums of the individual galaxy masses by a factor of three, and Schweizer also finds that elliptical pairs have M/L ratios which are larger than those of spirals by a factor of nearly two (presumably because, as for single galaxies, elliptical galaxies lack young, bright stars). Most earlier investigations also concur on these two points.

One independent (and worrisome!) sample, analysed by a Soviet group, has persisted for some years in yielding the same average M/L_V value (≈ 7) both for the individual galaxies and for the pairs (Karachentsev 1985, Mineva 1987). I do not know precisely what to make of this, except that the process of selecting to guarantee bound pairs has picked out mostly rather small separations, and many of the pairs may be orbiting inside most of their common haloes.

Small groups, containing from three to tens of bright galaxies, have been recognized for more than 25 years (Burbridge and Burbridge 1961) as requiring masses near $10^{13} M_\odot$ and $M/L \sim 100$ if they are to be gravitationally bound. More recent studies (T87, Tully 1987) yield similar numbers. As with the binaries, there is one dissenting sample (Karachentsev and Karachentsev 1982) and some remaining reservations about whether the groups with the largest velocity spreads are actually bound systems (Valtonen and Byrd 1986).

Another subset of groups, in which the galaxies are separated by not much more than their own diameters, present the opposite problem of being so strongly bound that the members will merge in a few gigayears, and the groups in their present form cannot have ages much more than 10% of the age of the universe (Mamon 1987, Sulentic 1987, Malykh and Orlov 1986), whether or not the galaxies move within a common dark halo. Consistently, rotation curves turn down at the optical edges of these galaxies (Rubin 1986, private communication), indicating the absence of individual dark haloes. These compact groups count as an astronomical problem to which dark matter is not a solution!

Because members of small groups constitute the majority of galaxies in the universe, $M/L \sim 100$ is perhaps the best estimate of the amount of gravitating matter that we really know must be closely associated with normal galaxies made of stars and gas.

2.3.2. *Clusters of galaxies*

The rich clusters contain hundreds to thousands of galaxies each (mostly ellipticals, at least in their centres). Thus, if you have the patience to measure enough velocities, you can analyse the clusters one at a time (rather than collectively), using the virial theorem, or some more sophisticated relationship, to derive mass from the positions and motions of the galaxies. The problem of circular, radial or intermediate orbit shapes remains, and most data sets turn out to be explicable by a range of dynamical models with a range of total masses.

Applying the virial theorem to these rich clusters, in the way Zwicky (1933) originally did for the Coma cluster, has yielded $M/L_V = 100\text{–}300\, h$ many times for many clusters, once different assumptions were sorted out (T87, Dickens 1987, Nothenius and White 1987), Disagreement persists about whether virial theorem masses in incompletely relaxed clusters are likely, on average, to be too large (Tanaka 1985, Fitchett and Webster 1987) or too small (Evrard 1987, Navarro *et al.* 1987), in either case by a factor of two to three. There is, on the other hand, general agreement that galaxy velocities alone cannot distinguish a dynamical structure with circular orbits in cluster outskirts and $M/L_B \approx 100\,h$, from one with radial orbits there and $M/L_B \approx 300\,h$ (Merritt 1986, The and White 1987). We have some independent information on the point: the curvature of the radio sources associated with a few of the galaxies moving in the outer parts of clusters suggests a preponderance of circular orbits (O'Dea *et al.* 1987).

X-ray emitting gas provides separate evidence for dark matter in rich clusters, as it did for elliptical galaxies. As for the single galaxies, the confining gravitational potential wells are deep and so provide evidence for appreciable dark matter. For most clusters however, existing X-ray data do not tell us how gas temperature varies with position. If the gas is isothermal, then it implies the higher values for M/L associated with radial orbits (Sarazin 1986), while temperature gradients would permit the somewhat lower M/L values associated with circular orbits (The and White 1987, Cowie *et al.* 1987). In the latter case, the X-ray gas itself contributes significantly ($\sim$20–30%) to the necessary total mass, but probably still does not account for all of it (Hughes *et al.* 1987 a, b).

The amount of dark matter per galaxy in these dense environments is thus at least as large as that in less crowded regions. The galaxies no longer carry their shares in the form of separate 100 kpc haloes, both because these would overlap in cluster cores and because the large individual masses would produce more developed mass segregation than we see evidence for (T87).

2.4. *Superclusters and beyond*

Structure in the universe on scales larger than the few Mpc diameters of rich clusters has been recognized for some time (de Vaucouleurs 1953), though we are still not always certain whether the clusters of clusters represent dynamically-evolved bound-systems, relics of the initial conditions of galaxy formation, or both. On the largest scales, the use of the M/L ratio is generally replaced by the use of Ω, the ratio of the density we think we measure in a particular form to the density needed for gravity to win out over the present universal expansion and cause eventual contraction. This latter, critical, density is given by $\rho_c = 3H_0^2/8\pi G = 2\times 10^{-29}\,h^2\,\mathrm{g\,cm^{-3}}$.

Our best estimate of the luminosity density of the universe (Felten 1986) is such that, rather conveniently, $\Omega = (M/L)h/1000\,h$. Thus groups and clusters of galaxies have so far told us that $\Omega > 0{\cdot}1$. The superclusters that are generally regarded as statistically significant groupings (including the Virgo supercluster to the outer reaches of which our Local Group belongs) require $M/L = 100$–300 for binding (Abell 1961, T87, Ciardullo 1987), or $\Omega = 0{\cdot}2 \pm 0{\cdot}1$. Most have diameters of 10–30 h^{-1} Mpc.

Quite recently, systematic surveys of galaxy velocities and distances (Rubin *et al.* 1976, Dressler *et al.* 1987, Davies *et al.* 1987, James *et al.* 1987, Tully 1987 a, Kirshner *et al.* 1987, Zhou *et al.* 1986) have found evidence for mass concentrations and voids and for deviations from smooth universal expansion on still larger scales $\gtrsim 50$–$100\,h^{-1}$ Mpc. Member galaxies cannot have crossed these large structures even once in the age of the universe, and we are by no means sure whether the density fluctuations have produced fluctuations in the velocity fields, conversely, both, or neither. Attempts to understand the situation, via *n*-body simulations of dynamical evolution in an expanding substrate, constitute a very active branch of astrophysics. The very large scale structure and streaming, with its catchy vocabulary (cosmic voids, great attractors) may or may not, therefore, have anything directly to do with dark matter. There is, however, an important indirect connection through the problem of how, when, and from what galaxies formed (§ 2·5).

The universe as a whole must have an average density (unless it is infinite in extent and hierarchical on all scales). Thus, inevitably, we ask for indicators of whether that average is larger or smaller than ρ_c. Direct astronomical evidence—motions of galaxies and clusters, ages of the oldest stars, considerations of nucleosynthesis in the early universe, and so on—has long seemed to favour $\Omega < 1$ and an ever-expanding, infinite universe (Gott *et al.* 1974). But received opinion, especially among those who might describe themselves as astrophysicists rather than astronomers, has lately swung around to $\Omega = 1$. The space distribution of a set of galaxies seen by the Infrared Astronomy Satellite may indeed imply a high-density universe (T87, Villumson and Strauss 1987), but the primary pushers of the swing are three theoretical developments.

Understanding the physics and astrophysics of the very early universe is a formidable task, and is far from complete. Several long-standing problems (having to do with causality, large scale homogeneity, the near-Euclidean nature of the geometry, and the origin of density perturbations) are, however, simultaneously resolved by a scheme called *inflation* (Linde 1987). The inflationary scenario postulates that the universe passed through an epoch of exponential expansion, followed by reheating, nucleosynthesis, and galaxy formation. The form of Einstein's equations guarantees that such an epoch will leave the universe with a density exceedingly close to ρ_c. This is one strong motivation for considering $\Omega = 1$.

A second motivation comes from developments in efforts to unify the nuclear, and eventually gravitational, forces with the electroweak force. Many of the Grand and Supersymmetric Unified Theories (GUTs, SUSY, and so on for short) require the existence of new kinds of particles. These could contribute the rest of the density up to $\Omega = 1$ without otherwise making themselves conspicuous (Turner 1987), implying a close link between fundamental physics and cosmology and lots of interesting problems and jobs for practitioners of both. It is also widely hoped and expected that when we have got the particle physics right, we will also understand the cause of the inflationary epoch just mentioned. Some of the hypothetical new particles carry names indicating their relationships to known entities (photinos, gravitinos, sneutrinos), while others are less obvious (axions, Perry poles). The former category inspires the collective nickname inos and their expected physical properties the description weakly interacting massive particles (or WIMPs).

2.5. *Dark matter and the problem of galaxy formation*

The third main reason for considering a critical-density universe arises from the difficulties of forming galaxies and larger structures if $\Omega < 1$, without simultaneously introducing larger inhomogeneities into the 3 K microwave background radiation than are permitted by present upper limits, $\Delta T/T =$ a few $\times 10^{-5}$, on the angular scales (a few arcmin) that correspond to galaxies at the epoch when matter and radiation stopped interacting (i.e. when $T =$ ionization temperature of hydrogen, and redshift $Z \approx 10^3$).

Qualitatively, to make $\Delta\rho/\rho \sim 1$ now requires $\Delta\rho/\rho$ of about 10^{-3} then, since lumps can grow at most linearly with $1/(1+Z)$ in an expanding universe. This, in turn, imposes fluctuations of $\Delta T/T = (1/3)(\Delta\rho/\rho)$, which we will still see if the universe has remained optically thin. The predicted temperature variations are on the ragged edge of present upper limits even for $\Omega = 1$ in the form of ordinary matter (Efstathiou and Bond 1987, Gouda *et al.* 1987, Xiong 1987, Peacock *et al.* 1987). The situation is much worse if $\Omega < 1$, so that the galaxies and such like that we see correspond to $\Delta\rho/\rho \gg 1$.

Two different ways to save the phenomenon are under consideration. First, some copious source of ultraviolet photons could have re-ionized remaining intergalactic hydrogen, after galaxy formation was well underway, and smoothed out the photon background (Peebles 1987, Naselskii *et al.* 1986, Dorosheva and Naselskii 1987). The price one has to pay in ionization energy is very, perhaps intolerably, high and the photon scattering itself introduces new temperature fluctuations on smaller angular scales that are already perilously close to undetectability (Vishniac 1987).

A second, more interesting solution is the assumption that the average universal density has a contribution $\Omega = 0{\cdot}2 \pm 0{\cdot}1$ in ordinary baryonic matter and the rest, and $\Omega = 0{\cdot}8 \pm 0{\cdot}1$ in the form of weakly interacting particles of non-zero rest mass. These WIMPs will cease to interact with the radiation at temperatures of 10^9 K or more. Thus, small perturbations in their density can start growing much earlier than perturbations in ordinary matter and can reach $\Delta\rho/\rho \sim 1$ without producing corresponding temperature fluctuations.

Once ordinary matter cools and ceases to be ionized, it can flow into the gravitational potential wells established by the WIMPs (or whatever). The baryonic matter then forms the gas and stars we see inside larger dark haloes consisting of non-baryonic dark matter. This basic scenario has two major embodiments, depending upon whether the hypothetical particles have rest masses <100 eV (and so are relativistic at hydrogen recombination: hot dark matter = HDM), or rest masses considerably larger, up to 10^{16-19} GeV for some candidates (and so are non-relativistic at decoupling: cold dark matter = CDM). Other things being equal, HDM promotes structure on large scales and CDM on small scales.

Very many analytic and numerical calculations of both HDM-dominated and CDM-dominated universes have been carried out in the past half-dozen years (T87, Ikeuchi and Norman 1987, Doroshkevich *et al.* 1986, Dekel and Piran 1987, Shellard *et al.* 1987, Kofman *et al.* 1987, Vittorio and Turner 1987, Silk and Vittorio 1987, Hoffman 1987, Melott and Scherrer 1987, Bardeen *et al.* 1987, Suto 1987, Daly 1987, Turner *et al.* 1987; White *et al.* 1987, Brandenberger *et al.* 1987, Melott 1987, Batuski *et al.* 1987, Bertschinger 1988, Zurek 1988, Ikeuchi *et al.* 1988). Neither of the points of general agreement is terribly comforting. Firstly, it does not seem possible to get the kind of structure we see on all scales from galaxies to superclusters without invoking more than one non-baryonic entity. This can be HDM + CDM; two epochs of inflation; dark matter plus cosmic strings; dark matter that decays away; dark matter plus a cosmological constant; or dark matter plus something to bias galaxy formation very strongly in favour of only the highest density fluctuations. Secondly, producing the largest-scale structures and, especially, deviations from uniform Hubble flow of $\gtrsim 600\,\mathrm{km\,s^{-1}}$ over $\gtrsim 50$ Mpc is exceedingly difficult, or impossible, in all the models that have been fully worked out.

It is fair to say that, despite much effort, we do not now properly understand galaxy formation. Dark matter is almost universally regarded as being part of the solution, though there are days when I think it may be part of the problem!

3. The candidates

Observational evidence, summarized in table 1, leaves us reasonably confident that appreciable dark matter exists on many scales, but does not, so far, answer the question, what is it made of? The pioneers had in mind several forms dark matter might take.

Table 1. Amounts of mass on various scales implied by typical observational studies.

Scale	M/L	Ω
Visible stars and clusters	1–3	0·001
Visible parts of galaxies	10	0·01
Binary galaxies and groups	10–100	0·01–0·1
Rich clusters and superclusters	100–300	$0{\cdot}2 \pm 0{\cdot}1$
Largest coherent structures	700 ± 150?	0·5–1·0
Inflation	$1000\,h$	1·0

Jeans (1922) talked of dark stars (in a ratio of about 3 : 1 to luminous ones). Oort (1932) mentioned planets, asteroids, and comets and made specific allowance for stars fainter than the completeness limits of his counts, including a couple of white dwarfs. Zwicky (1933), looking at clusters of galaxies, thought primarily of intergalactic gas, left from an inefficient formation process. Advances in observational techniques (from radio to X-ray) have limited or ruled out some of these, while advances in theory have suggested a very large number of others. Current candidates can be categorized as baryonic or non-baryonic in nature (and the polite reader will not mention that the two categories bear a certain resemblance to Aristotle's probable impossible and improbable possible respectively).

3.1. *Baryonic dark matter: the nucleosynthesis problem*

The chief, long-standing objection to closing the universe with ordinary matter is that nuclear reactions early on, at $T = 1$–10 MeV, produce the light isotopes H^1, H^2, He^3, He^4 and Li^7 in very closely the abundances observed (where stars have not modified them too much)—but only if the baryonic matter density is $0{\cdot}015$–$0{\cdot}15\ \rho_c$ (Boesgaard and Steigman 1985, T87). Higher densities yield more He^4 than the $24 \pm 1\%$ we see (Ferland 1986), and, especially, less H^2 than the observed ratio $H^2/H^1 = 1$–2×10^{-5} (Blitz and Heiles 1987, Murthy *et al.* 1987). This constraint has generally been taken very seriously by the physics side of the community.

But there are several ways out, one or two of which may fit in with other things we think we know. Lowering Hubble's constant to $\lesssim 25\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, non-zero lepton number (T87), and nucleosynthesis in the presence of anti-matter (Dominguez-Teneiro and Yepes 1987) probably all work, but are all slightly *ad hoc*. Another possibility that deserves further study is nucleosynthesis in the presence of decaying dark matter (Vainer and Shchekinov 1986, Dimopoulos *et al.* 1988), which reheats the baryons relatively late and induces a second epoch of nuclear reactions. In this picture, non-baryonic dark matter dominates initially, but decays away, leaving us with $\Omega = 1$ in normal material today.

A final very promising line of investigation is nucleosynthesis in a universe where the phase transition from quark soup (or whatever) to hadrons leaves large density fluctuations on rather small scales, and a magnetic field sufficient to allow only the neutrons to leak into the low-density regions. The mix of products from the two zones (Alcock *et al.* 1987, Applegate *et al.* 1986) then yields light isotopes in the proper ratios (especially if some of the dense zone material collapses into black holes) apart from an excess of Li^7. This excess can, in turn, be wiped out by neutrons diffusing back across zone boundaries a bit later, though at the price of also reducing the deuterium abundance to the low side of the admissible range (Malaney and Fowler 1987).

I will adopt here the fence-sitting view that, even if none of these new scenarios quite works, there is enough available phase space that $\Omega = 1$ in baryons cannot be ruled out *a priori*.

3.2. *Baryonic dark matter candidates*

The chief charm of baryons is that we know they exist. A second point in their favour is that they both heat up and dissipate energy fairly easily and so can clump, or diffuse, over the full range of densities and length scales at which we seem to need dark matter. They are probably unique in this respect. The chief disadvantage of baryons (apart from the nucleosynthesis problem) is that they are rather hard to hide.

Section 1 noted that gas can now be seen and, with terrestrial planets, comets and asteroids, be severely limited as a dark matter contributor. In addition, true stars, even the faintest, would radiate more infrared than we see from, for example, the haloes of nearby spiral galaxies. Neutron stars and stellar-mass black holes, on the other hand, would produce too many X-rays because they accrete gas from their surroundings (T87).

What is left? Three main classes of objects—brown dwarfs (§ 1); old, cool, faint white dwarfs; and rather massive black holes, singly or in clusters, might be important. Brown dwarfs have been most widely discussed (Kafatos *et al.* 1986, Liebert and Probst 1987, T87). Many intensive searches have found none, and we currently have only one promising candidate, an infrared-emitting companion to the white dwarf G29-38 (Zuckerman and Becklin 1988). The probable implication is that dynamically important brown dwarfs must constitute a separate population, rather than being a monotonic continuation of the known distribution of stellar masses (Reid 1987) or being primarily companions to normal stars. Such a separate population could well be produced either before galaxies acquire their identities (Kashlinsky and Rees 1983) or during the early collapse phase of galaxy formation, when gas is cooling and flowing inward (Fabian *et al.* 1986).

White dwarfs as dark matter, at least on local and galactic scales, have been advocated particularly by Larson (1986). The idea is that early star formation probably produced a different distribution of stellar masses from the present one, and may have favoured stars with masses of two to eight $M_\odot$ that leave rather massive white dwarfs as their remnants. Past star formation of this sort provides a good fit to the colours of radio-emitting elliptical galaxies at moderate redshifts (hence seen as they were several billion years ago; Wyse and Silk (1987)). White dwarfs left from this early epoch should be very much fainter than the coolest, oldest ($\sim 8 \times 10^9$ yr; Winget *et al.* (1987)) ones presently known in the galactic disc.

Black holes, with masses anywhere from 10 to $10^6 M_\odot$, are possible relics of the pregalactic era (Carr 1985, Carr and Lacey 1987). If these are a dominant part of the dark matter in galactic haloes, then we can expect in due course to detect them through their effects on stellar dynamics and paths of light rays passing nearby (T87). In addition, accretion onto such black holes can be an efficient ($\gtrsim 0{\cdot}1\, mc^2$) extractor of energy. Just possibly, one can produce the 3 K background radiation this way and/or the helium, deuterium, and other light isotopes we see (Layser and Hively 1973, Carr 1985, Vainer 1986, T87, Hawkins and Wright 1988). Under these circumstances, the big bang could have been cold or warm rather than hot, and all nucleosynthetic constraints on baryonic dark matter disappear.

3.3. *Non-baryonic dark matter: primordial black holes, gravitational radiation, and unconventional gravitation theories*

These candidates have absolutely nothing in common except that they do not fit into either the preceding or the following sections! Black holes of less than stellar mass can be formed only in the very early universe. They therefore take their constituent baryons out of the equations before nucleosynthesis and are not subject to its constraints. They are also remarkably difficult to observe, or limit in any other way and could be the dark matter in galaxies or clusters or the universe as a whole (depending on their velocity dispersion), though probably not on all scales simultaneously (MacGibbon 1987).

A large energy density in gravitational radiation could also only arise from processes when the universe was both dense and chaotic. $\Omega=1$ at wavelengths of light days to years would jiggle pulsars around more than the stability of their observed periods allows (Romani and Taylor 1983), while wavelengths longer than the sizes of clusters of galaxies would distort the microwave background radiation. Limits are much less stringent at other wavelengths, but in any case, gravitational radiation can contribute only to the average density of the universe and not to the condensed dark matter of galaxies and clusters.

A non-zero value of Einstein's cosmological constant, Λ, can give the universe the geometry and some other properties that normally go with $\Omega=1$, including some assistance with the problems of galaxy formation. The value required is comparable with H_0^2 or $10^{-35}\,\mathrm{s}^{-2}$, but can be made to sound so small that logic requires it to be zero by expressing it in Planckian units as 10^{-120}. The vacuum energy of certain quantum fields (Zeldovich 1968) enters Einstein's equations in the form of a Λ, so that a small non-zero value need not be *ad hoc*.

Finally, the idea of gravitation (or the acceleration caused by it) being stronger than we expect at large distances has a long history (Finzi 1963, Milgrom 1986). The effect, clearly, will be to make us think we are seeing more gravitating mass than is really there on large scales. The details are sufficiently subtle that I have been instructed by one of the proponents not to attempt further discussion (Milgrom 1987), but see Kent (1987) for one observational test.

3.4. *Non-baryonic dark matter: hot (HDM)*

Hot dark matter, consisting of particles that are still fast-moving when hydrogen recombines, is particularly useful in creating large-scale structure (superclusters and perhaps beyond; Melott (1987)). It should be kept in mind, however, that there are other models in which such structure arises from gas dynamical processes rather than from the growth of density perturbations (Doroshkevich *et al.* 1967, Ikeuchi and Ostriker 1986, Kazhdan 1986, Couchman 1987, Saarinen *et al.* 1987) and that there are a number of other factors that also complicate extrapolation back from the distribution of luminous baryons to the underlying dark matter (T87).

The lightest stable one of the supersymmetric WIMPs and inos (table 2) may fall into this category, but the leading candidates are ordinary neutrinos (electron, muon and tau, plus their antiparticles) with non-zero rest mass. They can be considered in rather concrete fashion because we are reasonably confident (a) that they exist, (b) that many theories predict non-zero rest mass for them (Turner 1987), and (c) that we can calculate the number present (analogous to the 3 K photon sea) well enough to say that closing the universe requires masses of 10–100 eV (presumably ranked in the same order as the associated leptons—electron neutrino lightest and tau neutrino heaviest).

A preponderance of the laboratory (T87) and astrophysical (Bachall and Glashow 1987) evidence sets only upper limits, just above 10 eV, to the rest mass of the electron neutrino. This is a a little too small to work for the dark matter in individual galaxy haloes (Chau and Stone 1987), especially dwarfs (Kormendy 1987), but the three sorts of neutrino might well contribute on three different scales.

3.5. *Non-baryonic dark matter candidates: cold (CDM)*

Weakly-interacting particles that become non-relativistic well above 10^4 K favour formation of small-scale structures ($10^{6-8} M_\odot$). Larger things then arise from gravitational interactions and from some effect, called biasing, that allows protogalaxies to form only at peaks larger than 3σ in the mass distribution (White *et al.* 1987 a, Bardeen *et al.* 1987, Rees 1987, T87). The issue of whether the observed galaxy distribution actually matches the predictions of the biased CDM scenario is currently under debate (Phillips and Shanks 1987, Saslaw 1987, Brown and Peebles 1987, Shaeffer 1987, Maurogordar and Lachieze-Ray 1987, Thuan *et al.* 1987).

Meanwhile, the number of candidate particles in the CDM category is very large (table 2). Several names appear more than once because theory does not yet tell us the identity, or mass, of the lightest of the many expected supersymmetric partner particles (these are the ones, such as photino, gravitino whose names sound like familiar entities).

It is possible to imagine a wide variety of ways in which either astrophysical or laboratory results could definitely establish, or rule out (at least over particular mass ranges), the existence of these particles (T87). If there should be a positive laboratory detection between the writing and the reading of these words, I promise that you will have heard about it! In the interim, a good deal of effort is focused on ruling out zones of parameter space (particle mass, lifetime, interaction cross-section, etc.) that would interfere with nuclear reactions in stars or the early universe and other things that we think we understand (Renzini 1987, Salati *et al.* 1987, Dominguez-Teneiro 1987, Ruffini and Song 1987).

The recalcitrant problems of galaxy formation, dark matter candidates and the interface between particle physics and cosmology are being battered at so vigorously, by so many people, that the literature tends to lag behind by at least two or three revolutionary(?) ideas at any given time. The best strategy for keeping on top of the field is probably to start with a couple of the conference proceedings mentioned at the beginning of the reference section and then to haunt the preprint section of the nearest large astrophysics library.

4. Some conclusions

With varying degrees of confidence, we can attempt to answer the questions in the title of this article. Where is there dark matter? Undoubtedly in the haloes of individual galaxies and between them in groups and clusters (§§ 2.2. and 2.3.). On these scales, bodies with $M/L \gg 1$ outweigh bodies with $M/L \approx 1$ by an order of magnitude or more. There is, perhaps, a separate component associated with galactic discs (§ 2.1.), though the evidence for this has grown weaker with time (Gilmore (1987), Kuijken (1988), concerning an unpublished data sample), and I would not defend it strongly, despite its honourable history (Jeans 1922, Oort 1932).

The arguments for more than 99% dark matter, so that $\Omega = 1$ (§§ 2.4. and 2.5.) are still largely theoretical. This can, however, be expected to change. Efforts are currently under way on two complementary projects, (a) to map the velocity field out to more than 100 Mpc around us and use it to predict the density distribution responsible

Table 2. Non-baryonic dark-matter candidates and their properties.

Candidate/particle	Approximate mass	Predicted by	Astrophysical effects
G(R)	—	Non-Newtonian gravitation	Mimics DM on large scales
Λ (cosmological constant)	—	General relativity	Provides $\Omega = 1$ without DM
Axion, majoron, Goldstone boson	10^{-5} eV	QCD; PQ symmetry breaking	Cold DM
Ordinary neutrino	10–100 eV	GUTs	Hot DM
† Light higgsino, photino, gravitino, axino, sneutrino	10–100 eV	SUSY/SUGR	Hot DM
Para-photon	20–400 eV	Modified QED	Hot/warm DM
Right-handed neutrino	500 eV	Superweak interaction	Warm DM
† Gravitino etc.	500 eV	SUSY/SUGR	Warm DM
† Photino, gravitino, axino, mirror-particle, simpson neutrino	keV	SUSY/SUGR	Warm/cold DM
† Photino, sneutrino, higgsino, gluino, heavy neutrino	MeV	SUSY/SUGR	Cold DM
Shadow matter	MeV	SUSY/SUGR	Hot/cold (like baryons)
Preon	20–200 TeV	Composite models	Cold DM
Monopoles	10^{16} GeV	GUTs	Cold DM
Pyrgon, maximon, Perry pole, newtorites, Schwarzschild	10^{19} GeV	Higher-dimension theories	Cold DM
Supersymmetric strings	10^{19} GeV	SUSY/SUGR	Cold DM
Quark nuggets, nuclearites	10^{15} g	QCD, GUTs	Cold DM
Primordial (mini) black holes	10^{15-30} g	General relativity	Cold DM
Cosmic strings, domain walls	10^{8-10} M	GUTs	Promote galaxy formation, though small contributor to Ω.

† Of these various supersymmetric partners predicted by assorted versions of SUSY/SUGR, only one, the lightest, can be stable and contribute to Ω, but the theories do not at present tell us which one it will be or the mass to be expected.

QCD = quantum chromodynamics; PQ = Peccei–Quinn; GUTs = Grand Unified Theories; SUSY = supersymmetry; SUGR = supergravity; QED = quantum electrodynamics.

(Dressler *et al.* 1987) and (b) to map the distribution of IRAS galaxies on a similar scale (Yahil 1987) and use it to predict the expected velocity field. Unless the universe is unexpectedly perverse, these two approaches will eventually meet somewhere (Dressler 1988) and tell us the large-scale dynamical density. Meanwhile, those of us who are not directly involved in the fray can only suppose that the universe is open ($\Omega < 1$) on Wednesday, Friday, and Sunday and closed ($\Omega > 1$) on Thursday, Saturday, and Monday. (Tuesday is choir practice.)

What is the dark matter? I am something of a baryon chauvinist and inclined to bet at least evens on Ω (total) $= \Omega$ (baryon) and, if Ω (total $= 1$, on the limits associated with big-bang nucleosynthesis and other objections to baryonic dark matter (§§ 3.1. and 3.2.) being somehow surmountable. If I am wrong, then the range of available alternative candidates is enormous (§§ 3.3.–3.5.). There are currently no strong reasons to decide firmly for any one of these. For some (primordial mini black holes and non-standard theories of gravity for instance), the consequences have yet to be fully worked out.

The main-stream candidates, HDM and CDM, on the other hand, have been thought about at great length, especially in connection with galaxy formation, without producing general agreement in favour of one or the other. We seem to need some properties of each (though Ω (HDM) $= \Omega$ (CDM) $= 0{\cdot}5$ does not necessarily produce the right mix either). I do not see any very immediate prospects for convergence on a single, most likely non-baryonic type of dark matter. One of the planned laboratory searches for photinos and the like may see something, but agreement on just what is being seen will probably take at least as long as it has in the still-undecided case of neutrino oscillations as evidence for their finite rest mass (T87).

Why is dark matter? The answer to this depends very much on what you think it is. If 90% of Ω is in the form of WIMPs, then there is a new fine-tuning problem (comparable to that of getting Ω (baryon) $= \Omega$ (total) $= 0{\cdot}1$ rather than 1 or 0 in an open universe). Presumably the solution must come from the heights of modern theoretical physics (supergravity, string theory, or very possibly a peak not yet on our maps). It needs to tell us why $\rho_{(b)}/\rho_{(dark)} = 0{\cdot}1$ rather than 0 or ∞.

If, on the other hand, the dark matter is baryonic, then the question of how the baryons parcelled themselves out between brown dwarfs, VMOs or whatever and proper stars belongs to the discipline of stellar structure, formation, and evolution, on which we astronomers have been slogging away for generations. There are, in other words, plenty of questions and problems to go around. Anyone who is interested in dark matter and the universe, with skills in instrument building, observational astronomy, computer or analytic modelling, or abstract theory, can make a useful contribution. Please do!

References

For the reader interested in delving into the jungle that follows, here are some possible places to start. The International Astronomical Union Symposium edited by Kormendy and Knapp (1987) deals specifically with dark matter, as does the review by Trimble (1987: called T87 above). Problems connected with galaxies and their formation, are discussed in the proceedings edited by Faber (1987) and Kaiser and Lasenby (1988). Finally, the interface between particle physics and cosmology has been the subject of many conferences, including a series jointly sponsored by ESO and CERN. The second of these was edited by Setti and van Hove (1986). The third took place during May 1988, and its proceedings can be expected some time in 1989.

Aaronson, M., 1987, in Faber (1987).
Abell, G. O., 1961, *Astron. J.*, **66,** 607.
Alcock, C. A., *et al.* 1987, *Astrophys. J.*, **320**, 439.
Applegate, J. H., Hogan, C. J., and Scherrer, R. T., 1986, *Phys. Rev.* D, **35,** 1151.
Athanassoula, E., *et al.* 1987, *Astron. Astrophys.*, **179,** 23.
Bahcall, J. N., 1984, *Astrophys. J.*, **276,** 169; *ibid.*, **287,** 926.
Bachall, J. N., and Glashow, S., 1987, *Nature, Lond.*, **326,** 476.
Bardeen, J., *et al.*, 1987, *Astrophys. J.*, **321,** 28.
Batuski, D. J., *et al.*, 1987, *Astrophys. J.*, **322,** 48.
Bergh, S., van den, McClure, R. D., and Evans, R., 1987, *Astrophys. J.*, **323,** 44.
Bertschinger, E., 1988, *Astrophys. J.*, **324,** 5.
Bienayme, O., *et al.*, 1987, *Astron. Astrophys.*, **180,** 94.
Binney, J., *et al.*, 1987, *Mon. Not. R. astron. Soc.*, **226,** 149.
Blitz, L., and Heiles, C., 1987, *Astrophys. J. Lett.*, **313,** 95.
Boesgaard, A. M., and Steigman, G., 1985, *Ann. Rev. Astron. Astrophys.*, **23,** 319.
Brown, M. E., and Peebles, P. J. E., 1987, *Astrophys. J.*, **317,** 588.
Brandenberger, R., *et al.*, 1987, *Phys. Rev. Lett.*, **59,** 2369.
Burbidge, E. M., and Burbidge, G. R., 1961, *Astron. J.*, **66,** 541.
Carignan, N., *et al.*, 1988, *Astron. J.*, **95,** 37.
Carr, B. J., 1985, *Observational and Theoretical Aspects of Relativistic Astrophysics and Cosmology*, edited by J. L. Sanz and L. J. Goicoechs (Singapore: World Scientific), p. 1.
Carr, B. J., and Lacey, C. G., 1987, *Astrophys. J.*, **316,** 23.
Chau, W. Y., and Stone, J., 1987, *Astrophys. Space Sci.*, **137,** 195.
Ciardullo, R., 1987, *Astrophys. J.*, **321,** 607.
Couchman, H. M. P., 1987, *Mon. Not. R. astron. Soc.*, **225,** 795.
Cowie, L., Henriksen, M., and Mushotzky, R., 1987, *Astrophys. J.*, **317,** 593.
Daly, R., 1987, *Astrophys. J.*, **322,** 30.
Davies, R. L., *et al.*, 1987, *Astrophys. J. Suppl.*, **64,** 586.
Dekel, A., and Piran, T., 1987, *Astrophys. J Lett.*, **315,** 83.
Dickens, R. J., *et al.*, 1987, *Mon. Not. R. astron. Soc.*, **220,** 679.
Dimopoulos, S., *et al.*, 1988, *Phys. Rev. Lett.*, **60,** 7.
Dominguez-Teneiro, R., 1987, *Astrophys. J.*, **313,** 523.
Dominguez-Teneiro, R., and Yepes, G., 1987, *Astrophys. J. Lett.*, **317,** 1.
Dorosheva, E. I., and Naselskii, P. D., 1987, *Soviet Astron. AJ*, **31,** 1.
Doroshkevich, A. G., Zeldovich, Ya. B., and Novikov, I. D., 1967, *Soviet Astron. AJ*, **11,** 233.
Doroshkevich, A. G., *et al.*, 1986, *Soviet Astron. AJ*, **30,** 251.
Dressler, A., *et al.*, 1987, *Astrophys. J. Lett.*, **313,** 37.
Efstathiou, G., and Bond, J. R., 1987, *Mon. Not. R. astron. Soc.*, **227,** 33p.
Einasto, J., Kraasik, A., and Saar, E., 1974, *Nature, Lond.*, **250,** 309.
Evrard, A. E., 1987, *Astrophys. J.*, **316,** 36.
Faber, S. M. (editor), 1987, *Nearly Normal Galaxies* (New York: Springer-Verlag).
Fabian, A. C., *et al.*, 1986, *Astrophys. J.*, **305,** 9.
Felten, J. E., 1986, *Comments Astrophys.*, **11,** 53.
Ferland, G., 1986, *Astrophys. J. Lett.*, **310,** 67.
Finzi, A., 1963, *Mon. Not. R. astron. Soc.*, **127,** 21.
Fitchett, M., and Webster, R., 1987, *Astrophys. J.*, **317,** 653.
Forman, W., Jones, C., and Tucker, W., 1985, *Astrophys. J.*, **293,** 102.
Giraud, E., 1986, *Astron. Astrophys.*, **170,** 1.
Godwin, P. J., and Lynden-Bell, D., 1987, *Mon. Not. R. astron. Soc.*, **223,** 7p.
Gott, J. R., Gunn, J. E., Schramm, D. N., and Tinsley, B. M., 1974, *Astrophys. J.*, **194,** 543.
Gouda, N., *et al.*, 1987, *Astrophys. J. Lett.*, **321,** 1.
Hawkins, I., and Wright, E. L., 1988, *Astrophys. J.*, **324,** 66.
Hoffman, Y., 1987, *Astrophys. J.*, **318,** L7.
Huchra, J., and Brodie, J., 1987, *Astron. J.*, **93,** 779.
Hughes, J. P., *et al.*, 1988 a, *Astrophys. J.*, **327**, 615; 1988 b, *Astrophys. J.*, **329** (1 June).
Ikeuchi, S., and Norman, C. A., 1987, *Astrophys. J.*, **312,** 485.
Ikeuchi, S., and Ostriker, J. P., 1988, *Astrophys. J.*, **301,** 522.
Ikeuchi, S., Norman, C. A., and Zhan, Y., 1988, *Astrophys. J.*, **324,** 35.

James, P. A., *et al.*, 1987, *Mon. Not. R. astron. Soc.*, **229**, 53.
Jeans, J., 1922, *Mon. Not. R. astron. Soc.*, **82,** 122.
Kafatos, M., Harrington, R. S., and Maran, S. P. (editors), 1986, *Astrophysics of Brown Dwarfs* (Cambridge University Press).
Kahn, F., and Woltjer, L., and 1956, *Astrophys. J.*, **130,** 105.
Kaiser, N., and Lasenby, A. (editors), 1988, *The Post-Recombination Universe* (Dordrecht: Reidel).
Kapteyn, J. C., 1922, *Astrophys. J.*, **55,** 302.
Karachentsev, I. D., 1985, *Soviet Astron. AJ*, **29,** 243.
Karachentsev, V. T., and Karachentsev, I. D., 1982, *Astrofiz.*, **18,** 1.
Kashlinsky, A., and Rees, M. J., 1983, *Mon. Not. R. astron. Soc.*, **205,** 955.
Kazhdan, Ya. M., 1986, *Soviet Astron. AJ*, **30,** 261.
Kent, S. M., 1987, *Astron. J.*, **93,** 816.
Kirshner, R. P., *et al.*, 1987, *Astrophys. J.*, **314,** 492.
Kofman, L. A., *et al.*, 1986, *Soviet AJ Lett.*, **12,** 175.
Kormendy, J., 1987, in Kormendy and Knapp, 1987, p. 139.
Kormendy, J., and Knapp, G. R. (editors), 1987, *IAU Symp.* 117. *Dark Matter in the Universe* (Dordrecht: Reidel).
Kovner, I., and Milgrom, M., 1987, *Astrophys. J. Lett.*, **321,** 113.
Kruit, P. van der, and Freeman, K. C., 1984, *Astrophys. J.*, **278,** 81.
Larson, R. B., 1986, *Comments on Astrophys.*, **11,** 273.
Layser, D., and Hively, R., 1973, *Astrophys. J.*, **179**, 361.
Liebert, J., and Probst, R., 1987, *Ann. Rev. Astron. Astrophys.*, **25,** 473.
Linde, A., 1987, *Phys. Today*, **40,** No. 9, 61.
Little, B., and Tremaine, S. D., 1987, *Astrophys. J.*, **320,** 493.
MacGibbon, J. H., 1987, *Nature, Lond.*, **329,** 308.
Malaney, R. A., and Fowler, W. A., 1987, Orange Aid Preprint No. 682 (Caltech).
Malykh, S. A., and Orlov, V. V., 1986, *Astrofiz.*, **24,** 254.
Mamon, G. A., 1987, *Astrophys. J.*, **321,** 622.
Maurogordar, S., and Lachieze-Ray, M., 1987, *Astrophys. J.*, **319,** 13.
Melott, A., 1987, *Mon. Not. R. astron. Soc.*, **228,** 1001.
Melott, A., and Scherer, R. J., 1987, *Nature, Lond.*, **328,** 691.
Merritt, D., 1987, *Astrophys. J.*, **313,** 121.
Milgrom, M., 1986, *Astrophys. J.*, **306,** 9.
Mineva, V. A., 1987, *Astrofiz.*, **26,** 203.
Moorsel, G. A. van, 1987, *Astron. Astrophys.*, **176,** 13.
Murthy, J., *et al.*, 1987, *Astrophys. J.*, **315,** 675.
Naselskii, P. D., *et al.*, 1986, *Soviet Astron. AJ*, **30,** 625.
Navarro, J. F., *et al.*, 1987, *Astrophys. Space Sci.*, **133,** 241.
Ninković, S., 1987, *Astrophys. Space Sci.*, **136,** 299.
Nothenius, R., and White, S. D. M., 1987, *Mon. Not. R. astron. Soc.*, **225,** 505.
O'Dea, C., *et al.*, 1987, *Astrophys. J.*, **316,** 113.
Oort, J. H., 1932, *Bull. astr. Inst. Neth.*, **6,** 249.
Ostriker, J. P., Peebles, P. J. E., and Yahil, A., 1974, *Astrophys. J. Lett.*, **193,** 1.
Peacock, J. A., *et al.*, 1987, *Mon. Not. R. astron. Soc.*, **229,** 469.
Peebles, P. J. E., 1987, *Astrophys. J. Lett.*, **315,** 73.
Phillips, S., and Shanks, T., 1987, *Mon. Not. R. astron. Soc.*, **229,** 621.
Reid, N., 1987, *Mon. Not. R. astron. Soc.*, **225,** 873.
Renzini, A., 1987, *Astron. Astrophys.*, **171,** 121.
Roberts, M. S., and Whitehurst, R. N., 1975, *Astrophys. J.*, **201,** 327.
Romani, R., and Taylor, J. H., 1983, *Astrophys. J. Lett.*, **265,** 35.
Rubin, V. C., *et al.*, 1976, *Astron. J.*, **81,** 687, and 719.
Rubin, V. C., Ford, W. F., and Thonnard, N., 1978, *Astrophys. J. Lett.*, **225,** 107.
Ruffini, R., and Song, D. J., 1987, *Astron. Astrophys.*, **179,** 3.
Saarinen, S., Dekel, A., and Carr, B. J., 1987, *Nature, Lond.*, **325,** 598.
Salati, P., *et al.*, 1987, *Astron. Astrophys.*, **173,** 1.
Sandage, A. R., 1987, *Astrophys. J.*, **317,** 557.
Sandage, A. R., and Fouts, G., 1987, *Astron. J.*, **93,** 74.

SARAZIN, C., 1986, *Rev. mod. Phys.*, **58,** 1.
SASLAW, W. C., 1987, *Astrophys. J.*, **315,** L1.
SCHWEIZER, L., 1987, *Astrophys. J. Suppl.*, **63,** 411, 417, and 427.
SETTI, G., and HOVE, L. VAN (editors), 1986, *2nd ESO/CERN Symposium: Astronomy, Fundamental Physics, and Cosmology* (Munich: ESO).
SHAEFFER, R., 1987, *Astron. Astrophys.* L, **180,** 5.
SHELLARD, E. P. S., *et al.*, 1987, *Nature, Lond.*, **326,** 672.
SILK, J., and VITTORIO, N., 1987, *Astrophys. J.*, **317,** 564.
SULENTIC, J., 1987, *Astrophys. J.*, **322,** 605.
SUTO, Y., 1987, *Astrophys. J.*, **321,** 36.
TANAKA, K., 1985, *Publ. astron. Soc. Japan*, **37,** 481.
THE, L. S., and WHITE, S. D. M., 1988, *Astron. J.*, **95,** 15.
THUAN, T. X., *et al.*, 1987, *Astrophys. J.*, **315,** L93.
TONRY, J., 1983, *Astrophys. J.*, **266,** 58.
TRIMBLE, V., 1987, *Ann. Rev. Astron. Astrophys.*, **25,** 425.
TRINCHIERI, G., FABBIANO, G., and CANIZARES, C., 1986, *Astrophys. J.*, **310,** 637.
TULLY, R. B., 1987 a, *Astrophys. J.*, **323,** 1; 1987 b, *Astrophys. J.*, **321,** 280.
TURNER, M. S., 1987, in Kormendy and Knapp 1987, p. 445.
TURNER, M. S., *et al.*, 1987, *Astrophys. J.*, **323,** 423.
VAINER, B. V., 1986, *Soviet AJ Lett.*, **12,** 319.
VAINER, B. V., and SHCHEKINOV, YU. A., 1986, *Soviet Astron. AJ*, **30,** 480.
VALTONEN, M. J., and BYRD, G. G., 1986, *Astrophys. J.*, **303,** 523.
VAUCOULEURS, G. DE, 1953, *Astron. J.*, **58,** 30.
VILLUMSEN, J. V., and STRAUSS, M. A., 1987, *Astrophys. J.*, **322,** 37.
VISHNIAC, E. T., 1987, *Astrophys. J.*, **322,** 597.
VITTORIO, N., and TURNER, M. S., 1987, *Astrophys. J.*, **316,** 475.
WHITE, S. D. M., *et al.*, 1987, *Nature, Lond.*, **330,** 451.
WHITE, S. D. M., *et al.*, 1987 a, *Astrophys. J.*, **313,** 505.
WHITMORE, B. D., MCELROY, D. B., and SCHWEIZER, F., 1987, *Astrophys. J.*, **314,** 439.
WINGET, D. E., *et al.*, 1987, *Astrophys. J.*, **315,** L77.
WYSE, R. F. G., and SILK, J., 1987, *Astrophys. J. Lett.*, **319,** 1.
XIONG, S.-P., 1987, *Astrophys. Space Sci.*, **135,** 75.
YAHIL, A., 1987, in Faber 1987.
ZASOV, A. V., and KYAZUMOV, G. A., 1983, *Soviet Astron. AJ*, **27,** 384.
ZELDOVICH, YA. B., 1968, *Soviet Phys. Usp.*, **11,** 381.
ZHOU, Y.-Y. *et al.*, 1986, *Astrophys. J.*, **311,** 598.
ZUCKERMAN, B. M., and BECKLIN, E. E., 1988, *Science, N.Y.*, **239,** 23.
ZUREK, W. H., 1988, *Astrophys. J.*, **324,** 19.
ZWICKY, F., 1933, *Helv. phys. Acta*, **6,** 110.