Dark Matter Possibilities

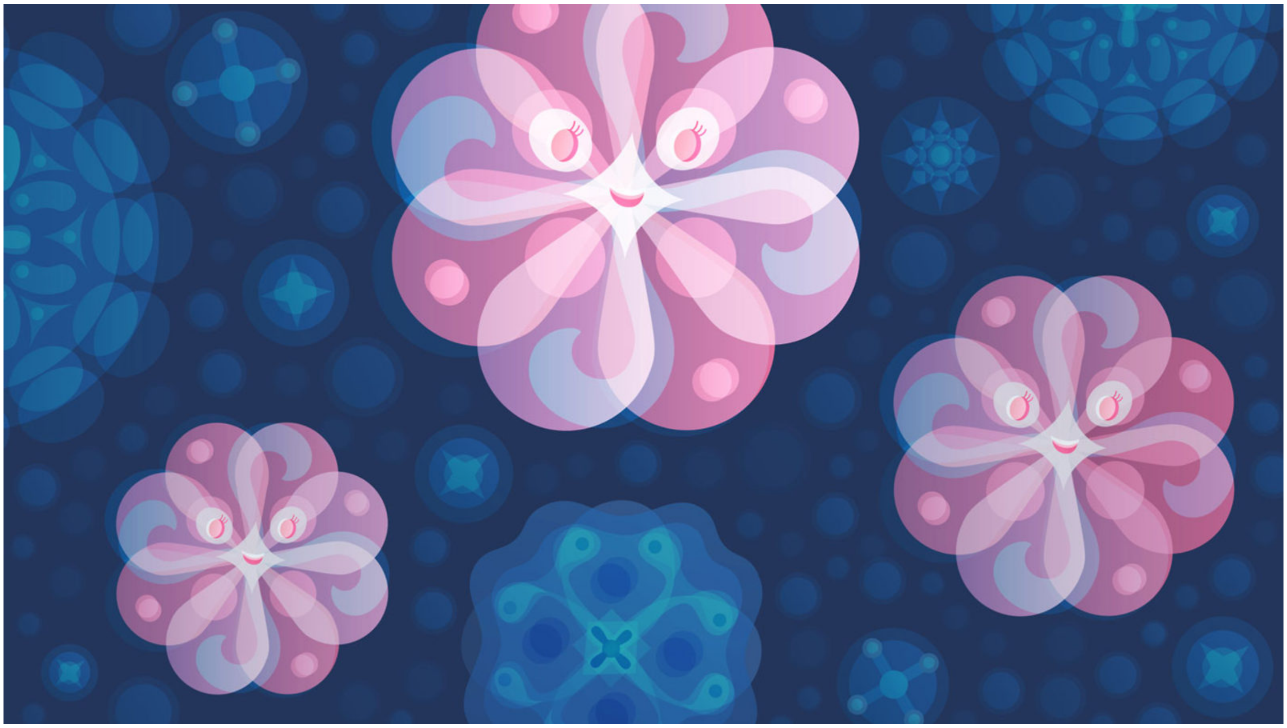
We now delve into possible explanations for this dark matter problem. Two readings on explanations for Dark Matter:

1. "Miraculous WIMPs", by Manuel Gnida, Symmetry Magazine, July 2015.

   https://www.symmetrymagazine.org/article/july-2015/miraculous-wimps

2. "Existence and Nature of Dark Matter in the Universe," Virginia Trimble, Ann. Rev. Astron. Astrophys. **25**, 452-72 (1987). Section 1 (pp. 425-7) and Sections 6 and 7 (pp. 452-62). The full article and references are on Quercus.

symmetry
dimensions of particle physics



Artwork by Sandbox Studio, Chicago with Ana Kova

Miraculous WIMPs

07/15/15 | By Manuel Gnida

What are WIMPs, and what makes them such popular dark matter candidates?

Invisible dark matter accounts for 85 percent of all matter in the universe, affecting the motion of galaxies, bending the path of light and influencing the structure of the entire cosmos. Yet we don't know much for certain about its nature.

Most dark matter experiments are searching for a type of particles called WIMPs, or weakly interacting massive particles.

“Weakly interacting” means that WIMPs barely ever “talk” to regular matter. They don’t often bump into other matter and also don’t emit light—properties that could explain why researchers haven’t been able to detect them yet.

Created in the early universe, they would be heavy (“massive”) and slow-moving enough to gravitationally clump together and form structures observed in today’s universe.

Scientists predict that dark matter is made of particles. But that assumption is based on what they know about the nature of regular matter, which makes up only about 4 percent of the universe.

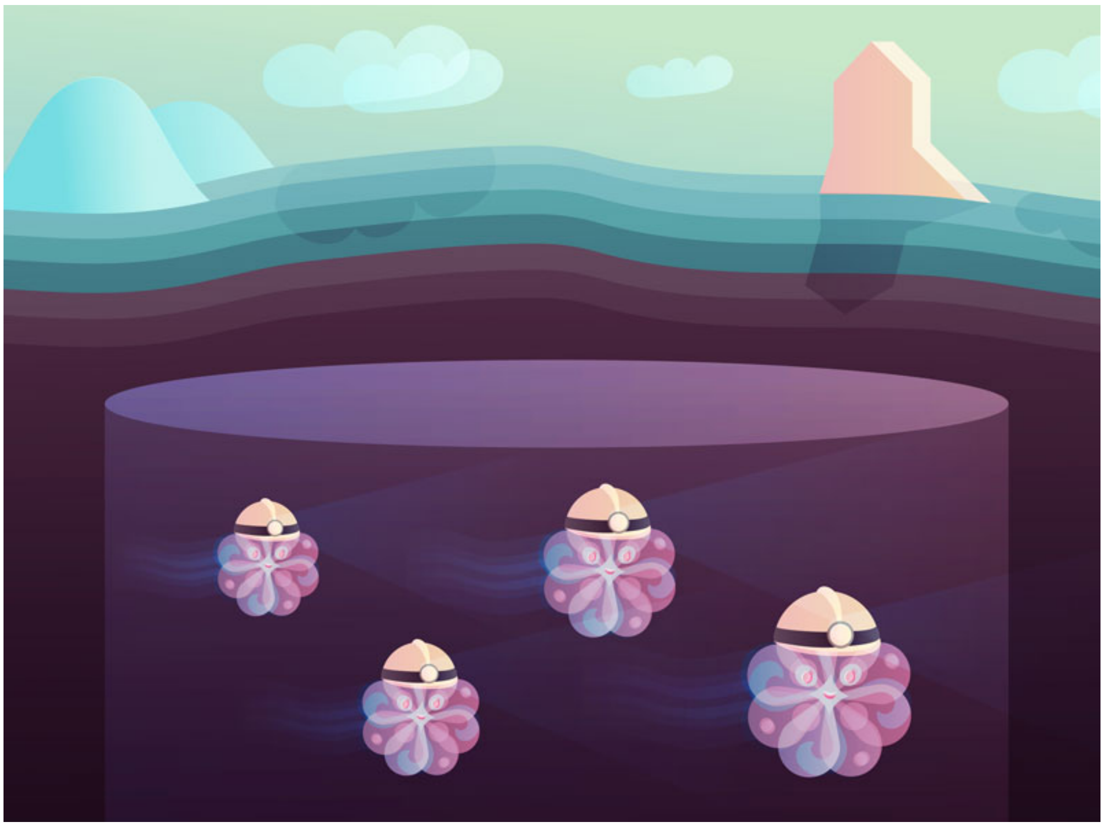
WIMPs advanced in popularity in the late 1970s and early 1980s when scientists realized that particles that naturally pop out in models of Supersymmetry could potentially explain the seemingly unrelated cosmic mystery of dark matter.

Supersymmetry, developed to fill gaps in our understanding of known particles and forces, postulates that each fundamental particle has a yet-to-be-discovered superpartner. It turns out that the lightest one of the bunch has properties that make it a top contender for dark matter.

“The lightest supersymmetric WIMP is stable and is not allowed to decay into other particles,” says theoretical physicist Tim Tait of the University of California, Irvine. “Once created in the big bang, many of these WIMPs would therefore still be around today and could have gone unnoticed because they rarely produce a detectable signal.”

When researchers use the properties of the lightest supersymmetric particle to calculate how many of them would still be around today, they end up with a number that matches closely the amount of dark matter experimentally observed—a link referred to as the “WIMP miracle.” Many researchers believe it could be more than coincidence.

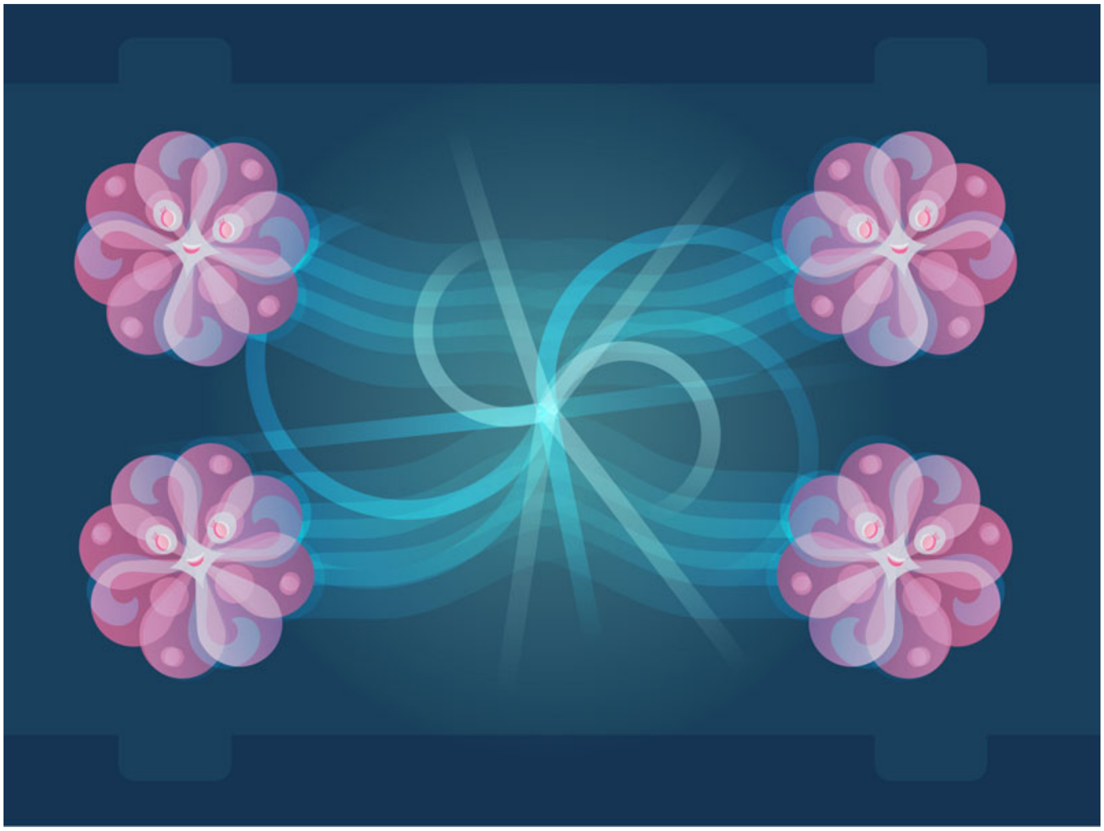
“But WIMPs are also popular because we know how to look for them,” says dark matter hunter Thomas Shutt of Stanford University and SLAC National Accelerator Laboratory. “After years of developments, we finally know how to build detectors that have a chance of catching a glimpse of them.”



(https://www.symmetrymagazine.org/sites/default/files/images/standard/WIMPsLUX.jpg)

Shutt is co-founder of the LUX experiment and one of the key figures in the development of the next-generation LUX-ZEPLIN experiment. He is one member of the group of scientists trying to detect WIMPs as they traverse large, underground detectors.

Other scientists hope to create them in powerful particle collisions at CERN’s Large Hadron Collider. “Most supersymmetric theories estimate the mass of the lightest WIMP to be somewhere above 100 gigaelectronvolts, which is well within LHC's energy regime," Tait says. "I myself and others are very excited about the recent LHC restart (http://www.symmetrymagazine.org/article/june-2015/lhc-arrives-at-the-next-energy-frontier). There is a lot of hope to create dark matter in the lab."



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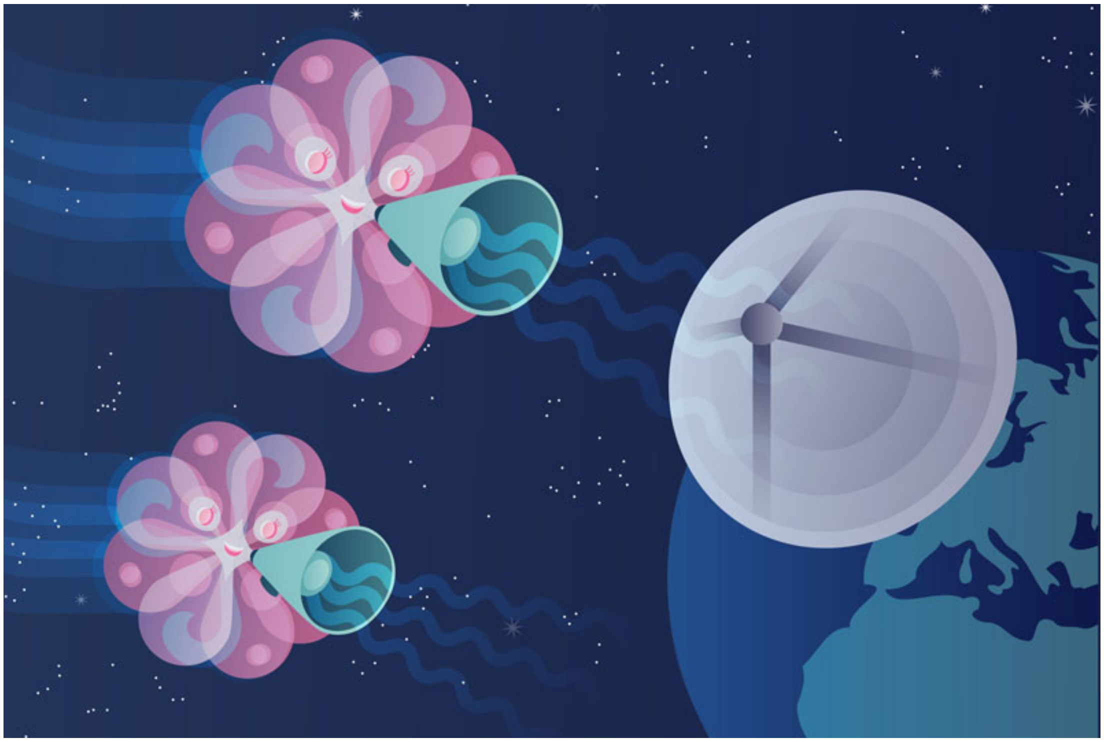
A third way of searching for WIMPs is to look for revealing signals reaching Earth from space. Although individual WIMPs are stable, they decay into other particles when two of them collide and annihilate each other. This process should leave behind detectable amounts of radiation. Researchers therefore point their instruments at astronomical objects rich in dark matter such as dwarf satellite galaxies orbiting our Milky Way or the center of the Milky Way itself.



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“Dark matter interacts with regular matter through gravitation, impacting structure formation in the universe,” says Risa Wechsler, a researcher at Stanford and SLAC. “If dark matter is made of WIMPs, our predictions of the distribution of dark matter based on this assumption must also match our observations.”

Wechsler and others calculate, for example, how many dwarf galaxies our Milky Way should have and participate in research efforts under way to determine if everything predicted can also be found experimentally.

So how would researchers know for sure that dark matter is made of WIMPs? “We would need to see conclusive evidence for WIMPs in more than one experiment, ideally using all three ways of detection,” Wechsler says.

In the light of today’s mature detection methods, dark matter hunters should be able to find WIMPs in the next five to 10 years, Shutt, Tait and Wechsler say. Time will tell if scientists have the right idea about the nature of dark matter.

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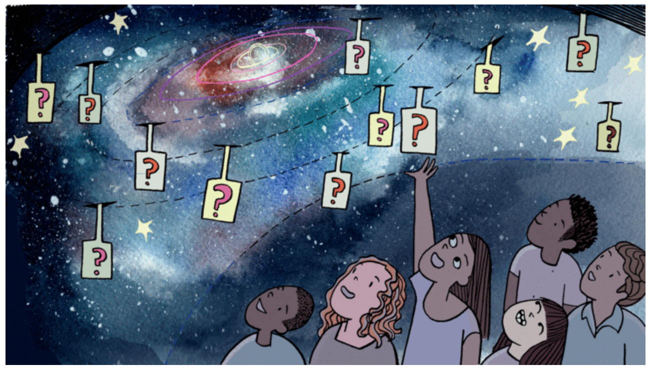

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EXISTENCE AND NATURE OF DARK MATTER IN THE UNIVERSE

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1. HISTORICAL INTRODUCTION AND THE SCOPE OF THE PROBLEM

The first detection of nonluminous matter from its gravitational effects occurred in 1844, when Friedrich Wilhelm Bessel announced that several decades of positional measurements of Sirius and Procyon implied that each was in orbit with an invisible companion of mass comparable to its own. The companions ceased to be invisible in 1862, when Alvan G. Clark turned his newly-ground $18\frac{1}{2}''$ objective toward Sirius and resolved the 10^{-4} of the photons from the system emitted by the white dwarf Sirius B. Studies of astrometric and single-line spectroscopic binaries are the modern descendants of Bessel's work.

A couple of generations later, data implying nonluminous matter on two very different scales surfaced almost simultaneously. First, Oort (498, 499) analyzed numbers and velocities of stars near the Sun and concluded that visible stars fell shy by 30–50% of adding up to the amount of gravitating matter implied by the velocities. Then, in 1933, Zwicky (777) concluded that the velocity dispersions in rich clusters of galaxies required 10 to 100 times more mass to keep them bound than could be accounted for by the luminous galaxies themselves. The former result was taken much more seriously than the latter by contemporary and succeeding astronomers (being dignified by the name "the Oort limit"), which is perhaps more a statement about the personalities of Oort and Zwicky than about anything else.

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The next decades were by no means devoid of relevant ideas and investigations (346, 484). The beginning of the modern era of dark-matter research can, however, be dated to 1974, when Ostriker, Yahil & Peebles (506) and Einasto, Kraasik & Saar (193) tabulated galaxy masses as a function of the radius to which they applied and found M increasing linearly with R out to at least 100 kpc and $10^{12}\ M_{\odot}$ for normal spirals and ellipticals.

Since then, a mainstream astronomer who seriously doubted that we are somehow not readily seeing 90% or more of the stuff in the Universe has found himself in the position of having to justify his discordant views. The low-mass torch, upheld for a time by Burbidge (109) and Woltjer (755), has recently been refueled by Valtonen (706–708).

Because dark matter has been invoked in many different objects and on many different scales, a very large fraction of astronomical research bears in some way on the issue. Necessarily, then, many aspects are given rather short shrift here.

First, nothing is said about the value of the Hubble constant, though it enters in powers from -2 to $+2$ into various determinations of mass and luminosity of distant objects and is arguably the largest single uncertainty in these determinations (268). Hodge's (301) 1981 conclusion that an impartial choice of value for H_0 would be both difficult and unprofitable remains regrettably correct. Besides, like Hodge, I have friends in both camps.

Next, several other relevant topics that have recently been reviewed in this series are somewhat neglected. These include evolution of galaxies in clusters (186), models of the Milky Way (36), the contribution of low-mass stars to the local mass density (415), constraints on dark matter in globular clusters (196), and properties of the Milky Way spheroid (229). In general, little is said about how calculations were done, except where methods have been substantially criticized. References cited for results generally explain how they were obtained, and, for the researcher desiring to acquire a thorough knowledge of methods, the standard starting place is Chandrasekhar's *Stellar Dynamics* (132). For many of the cases considered, $GM/R \sim V^2$ is all the physics needed.

Finally, the literature search approached completeness only for English-language journals received by University of California, Irvine, and/or University of Maryland between May 1984 and July 1986 and catalogued under Library of Congress designation QB (astronomy and astrophysics). Some relevant work appearing earlier, in books, and in non-English or nonastronomical journals has undoubtedly been missed. Much of the pre-1979 literature can be accessed through Faber & Gallagher's (200) fine review of masses of galaxies.

For the objects and systems discussed here, masses and luminosities will normally be given in solar units. That is, $M/L_B = 10$ means 10 solar masses of gravitating material for every one solar luminosity in the blue band. If no wavelength band is indicated, either bolometric luminosity is meant or the number has sufficiently large error bars that the wavelength makes no difference.

There exist a modest number of objects and systems where little or no dark matter can be present. These either have the dynamical mass equal to the luminous mass, or larger (but there exist more attractive explanations than dark matter), or seemingly smaller (so that some kind of energy input is needed to prevent collapse). The solar system, having been stable for some 4.5×10^9 yr, can be used to put rather stringent limits on nearest permitted approaches of black holes, substellar mass objects, and other hypothetical forms of dark matter (299, 325), including a possible substellar companion to the Sun (746).

Other objects under this heading include high-latitude molecular clouds (seemingly unbound, but perhaps confined magnetically or by hot coronal gas pressure; 366, 433), Galactic plane molecular clouds (which require nonthermal support or continuous energy input; 621, 638), and the radio-emitting lobes of extragalactic radio sources [for which gravitational confinement by a massive black hole has been proposed (108), but pressure confinement is now more widely accepted]. One intergalactic H I cloud that looks unbound (594) may be gravitationally attached to a pair of galaxies (593) or be a genuinely transient configuration (559, 734).

Star clusters, both open (440, 441, 747) and globular (158, 159, 196, 269, 524, 535), display dynamical properties fully explicable by the mass in visible stars and predictable stellar remnants. The very large proper motions, leading to $M = 10^8\ M_\odot$ for one cluster (486), need to be confirmed. Most measurements pertain only to brighter parts of clusters and would permit very extended, massive dark halos (520), but at least in M15, the velocity dispersion declines from 15 km s^{-1} in the core to less than 1 km s^{-1} in the outskirts [see work by P. Seitzer & K. C. Freeman reported in (231)], suggesting that the light edge is also the mass edge.

2. SINGLE GALAXIES

Mass estimates applying to individual galaxies can come from velocity dispersions or rotation curves of the stars and gas (including X-ray-emitting gas) making up the galaxy itself or from positions and velocities of test particles like globular clusters and satellite galaxies. Where several methods can be applied to the same part of the same galaxy, results are frequently, but not always, in reasonable agreement. In the conventional

$\Omega = 1$. The final section is devoted to a brief discussion of possible kinds of dark matter and observational constraints on them.

6. OBSERVATIONAL CONSTRAINTS ON THE NATURE OF DARK MATTER

If one accepts the evidence for nonluminous mass on many scales, the next obvious question is, what is it made of? A single candidate would be the most elegant solution, but it is asking a great deal of any one sort of thing that it be "cold" enough to settle down into the Milky Way disk and simultaneously "hot" enough to remain much less clustered than the superclusters over the age of the Universe.

Curiously ordinary, baryonic matter may come closest to meeting this stringent condition, since it is known to exist in both dense stars and very diffuse X-ray-emitting gas. The objection to $\Omega = 1$ in baryons derived from nucleosynthetic considerations and possible ways around it are addressed in Section 6.2. Other candidates currently under consideration include black holes, neutrinos, and a whole zoo of (mostly hypothetical) particles predicted by various branches of theoretical high-energy physics. Section 6.4 discusses these.

6.1 *The Nonstarters*

A few dark-matter candidates (stars and gas) would be so conspicuous that they can be ruled out easily, and a few others (gravitational radiation and primordial black holes) would be so inconspicuous that little can be said about them.

True stars, which derive most of their energy from nuclear reactions, extend down to 0.085 $M_\odot$ and $\lesssim 10^{-3}\, L_\odot$ (345). Dim though they are, they could be seen individually in our own Galaxy (161, 248) and collectively in other galaxies (626) if they were responsible even for the $M/L = 5$–10 implied by spiral rotation curves.

Gas is similarly well inventoried in all possible forms in the Milky Way and other galaxies. On intergalactic scales, a closure density of cold or warm gas would produce conspicuous emission and/or absorption lines which we do not see (515). Very hot gas would radiate X rays, and indeed we see a highly isotropic X-ray background well matched by 40 ± 5 keV thermal bremsstrahlung (439), which if produced by hot intergalactic gas would require something close to the closure density (266). There are two objections. First, heating the gas requires more than 10% of all available nuclear energy in the Universe, and there are no very obvious sources (220, 266). Second, after removing the contributions of galaxies, quasars, and clusters that are known X-ray sources, the remaining spectrum can no longer be fit by thermal radiation (244).

Gravitational radiation of many but not all possible wavelengths could close the Universe without having yet been detected (19, 556). Clearly it cannot be clustered or clumped, but it can mimic dark matter in clusters in some ways (543). Primordial black holes could also dominate Ω (126, 480), and the extent to which they might cluster depends upon their (unknown) velocities. Because PBHs must form very early, if at all, they do not count as baryonic matter in the context of nucleosynthesis and are not conspicuous in any other way either.

6.2 *Baryons: The Nucleosynthesis Problem*

The ability of the conventional hot big bang to account for about 25% helium in the matter expanding and cooling from it (284) is generally regarded as one of its great triumphs. Simultaneous minor reactions can also yield small amounts of H^2, He^3, and Li^7, consistent with the quantities observed (728). But the initial conditions must be chosen very carefully. If the baryon density is too high, or the number of neutrino species larger than three (or several other if's), then too much He and not enough H^2 come out.

The largest Ω(baryon) consistent with deuterium production depends on the present abundance [which varies at least from $D/H = 3 \times 10^{-6}$ to 2×10^{-5} (717)], on how much has been destroyed by passage through stars [perhaps as much as two thirds of the original supply (143)], and on a number of details of nuclear physics and cosmology (86). Given conventional physics, a standard hot big bang, and generous error bars, $0.015 \leq \Omega h^2 \leq 0.15$ (86, 170).

This nucleosynthesis limit overlaps the Ω determined from clusters and superclusters, which could, therefore, consist entirely of baryonic matter. It can also be stretched toward one in a variety of ways, most simply by lowering H_0 to $\lesssim 25$ km s^{-1} Mpc^{-1} (610), in which case clusters are bound by their X-ray gas. A second, more drastic modification is nonzero lepton number, which changes the equilibrium n/p ratio and can therefore either raise or lower H^2 and He production at a given baryon density (228, 703). Third, various inhomogeneities in density, temperature (569a), and n/p ratio can also push production up or down, possibly enough to permit $\Omega = 1$ in baryons. Variations in n/p arising because neutrons can drift out of dense regions in the presence of a magnetic field, but protons cannot, look particularly promising (20, 307). Finally, one might abandon big-bang nucleosynthesis completely and produce deuterium, helium, and perhaps the photon background elsewhere. Although early efforts at this were not terribly successful (549), considerably recent effort has focused on pregalactic stars, especially supermassive ones of $10^{6\pm2}\ M_{\odot}$ that have long since become black holes (90, 126, 359, 398, 540, 616).

In light of these possibilities, it may be premature to rule out baryonic dark matter, even at the level of $\Omega = 1$. Conversely, the idea that dark matter at least up to the scale of galaxies must be baryonic to account for the near-constancy of $\rho(\text{dark})/\rho(\text{luminous})$ (39) is subject to the reservation that formation of the luminous disks might have been directly controlled by the dark halos, or the halos by the disks (202, 209).

6.3 *Baryonic Dark Matter: The Candidates (Brown Dwarfs, White Dwarfs, Black Holes)*

It is not absolutely certain that we need baryonic dark matter even in the Galactic disk. The process of disk formation could draw inward enough of the hypothetical nondissipative matter of the halo to account for the Oort limit (54, 140). But baryons are clearly a possibility, at least up to $\Omega \sim 0.1$–0.2. How might they be assembled? Normal stars and gas were among the nonstarters in Section 6.1. In addition, even the Oort limit in neutron stars and stellar-remnant black holes can probably be ruled out. First, ongoing accretion of interstellar gas would result in the radiation of more X rays than we see. Second, the stellar evolution and demise that formed them would have scattered into the interstellar gas far more heavy elements than are present (288, 447). The additional upper limit of 2 $M_{\odot}$ on disk dark objects based on the long-term survival of wide binary systems (40) is probably a bit less stringent than the two already mentioned (733).

Brown dwarfs are substellar objects whose only energy source is contraction. It is not certain that any (apart from the Jovian planets) have ever been detected (627). A number of searches have identified no candidates (345). On the other hand, at least one survey (283) found interesting numbers of very red (presumably cool, faint) images, and at least one set of models for the evolution of low-mass stars and substars (163) implies that the known faint stars are part of a population whose number is still rising as $M^{-1.68}$ at 0.1 $M_{\odot}$. In addition, a separate population of objects $\lesssim 0.08\ M_{\odot}$ as old as the Galaxy could not yet have been seen in any way, and might be expected to arise from star formation in gas under pressure (205) or in pregalactic objects of $10^{6\text{-}8}\ M_{\odot}$ (359). The upturn of star numbers in M13 for star masses below 0.5 $M_{\odot}$ (427a) is interesting in connection with the possibility of a separate, low-mass population.

For other galaxies, we can say very little about the initial mass function of small stars (171a, 585), and it could continue to rise smoothly, putting large amounts of material into faint stars and substars. Brown dwarfs in sufficient numbers to be dynamically important might show up in deep exposures taken with the Wide Field/Planetary Camera of the Hubble

Space Telescope (640) or in the infrared flux from galaxies at moderate redshift (639).

White dwarfs are the normal remnants of $0.5–8 \pm 2\ M_\odot$ stars and can fade below detectability in less than the age of the Galaxy (163). Even so, the ones remaining from stars produced at constant initial mass function and formation rate over the history of the Galaxy contribute at most 0.007 $M_\odot\ pc^{-3}$ locally (163, 221), only about 5% of the Oort limit. One model of galactic chemical evolution does, however, posit an early generation of intermediate-mass stars whose white-dwarf remnants might account for the dynamical mass in the Milky Way disk and, probably, the halo as well (406, 493). This early generation would have had to be even more prominent to contribute significantly on the scale of clusters and superclusters. Since these very old degenerate dwarfs could be as cool as the hypothetical brown dwarfs and will surely be much smaller, they will be exceedingly difficult to detect or rule out.

Black holes of stellar masses have already been noted as nonstarters, and very small primordial ones are essentially unconstrainable. This leaves massive ones that might have formed in the early Universe (126, 127, 398). If these make up the halo dark matter, then, in addition to having contributed (perhaps) helium and photons in the past, they will now be stirring up the disk stars and contributing to the known increase of stellar velocity dispersion with age that is generally blamed on giant molecular clouds (393) or spiral arms (122). Black holes that are too massive will be too efficient at this, but a $10^{12}\ M_\odot$ halo consisting of $10^6\ M_\odot$ objects is just right (336, 350, 394). If similar black holes make up the dark matter in dwarf ellipticals, then they must be clustered toward the center, predicting an outward decrease of stellar velocity dispersion as a test of the model (394). In addition, $10^6\ M_\odot$ black holes in halos should reveal themselves by gravitationally lensing radiation from objects behind them (504, 509). Resolution of radio components may be possible with (VLBI), but optical observations will have to wait for the space optical interferometer.

By way of summary, baryonic matter definitely cannot be ruled out and even has some advantages at least up to the $\Omega \sim 0.15$ level, consistent with conventional nucleosynthesis. If one takes very seriously the nucleosynthetic lower limit on Ω_b or the need for dissipative material in galactic disks, then at least some of the nonluminous mass must be baryonic.

6.4 *Nonbaryonic Dark Matter*

One's first impression is that this category includes a countably infinite number of indistinguishable, hypothetical entities. There is some truth in this. But a count of words mentioned in three recent reviews of particle physics and cosmology (492, 532, 690) uncovered only 36 names, not quite all of which in fact designate physically distinct entities. These can be classified in terms of their predicted masses and the theories that predict them and by their astrophysical contribution as dark-matter mimics, hot dark matter (relativistic when galaxies form and so promoting large-scale structure), or cold dark matter [nonrelativistic when galaxies form and so promoting small-scale structure (89)].

Table 3 attempts such a classification. For most of the entities, the requirement that Ω(baryon)/Ω(dark) ~ 0.1 constitutes a new form of fine tuning, replacing that required to get Ω close to but not exactly one. The ratio may arise naturally for quark nuggets (753), but it must otherwise require a particular value of the energy scale of a symmetry breaking or some other process (690).

6.4.1 THE DARK MATTER MIMICS—$G(R)$ AND Λ A gravitational coupling constant that increases monotonically with separation or varies suitably with acceleration would mean that the amount of matter present in luminous galaxies and parts of galaxies could act like a larger amount of dynamical mass and suffice to account for flat rotation curves, large velocity dispersions, etc. (466, 576, 666). There are theoretical (245) and even experimental (482) indications that G may indeed vary, though probably on distance scales much smaller than those required to simulate dark matter. Although many details of such models remain to be worked out (216, 577), preliminary results are that they do not match observations as well as dark-matter models (188, 295). Their main virtue is that of producing the required effect over a range of distance scales.

A nonzero cosmological constant Λ, on the other hand, acts like the zero-point energy of a quantum field theory (771) and contributes homogeneously. It also permits the curvature of space k and the deceleration parameter q_0 to become independent parameters, so that most of the standard cosmological tests (apparent magnitude or angular diameter vs. redshift, source counts, etc.) do not really tell us Ω, but only some combination of Ω and Λ or k or q_0, even when authors (422) hope they are measuring Ω. To make $q_0 = 1/2$ or $k = 0$ with $\rho < \rho_c$ takes Λ of order $\pm 10^{-35}$ s^{-2}. This is also a sort of fine-tuning problem, at least in an inflationary universe, where Λ is briefly enormous (100). Astrophysicists have debated the likelihood of nonzero Λ for years (339, 446, 665) without reaching any definite conclusion. It shares with most "real" dark matter the virtue of making galaxy formation a bit easier (724), but cannot solve the dark-matter problem on all scales, being unable to cluster. This objection need not apply to the zero-point energy of a real field theory (J. Weber, personal communication, 1986).

Table 3 Summary of nonbaryonic dark matter candidates[a]

Candidate/particle	Approximate mass	Predicted by	Astrophysical effects
$G(R)$	[redacted]	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[b]	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.[b]	500 eV	SUSY/SUGR	Warm DM
Photino, gravitino, axino, mirror particle, simpson neutrino[b]	keV	SUSY/SUGR	Warm/cold DM
Photino, sneutrino, higgsino, gluino, heavy neutrino[b]	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 black holes	10^{15-30} g	General relativity	Cold DM
Cosmic strings, domain walls	$10^{8-10}\ M_{\odot}$	GUTs	Promote galaxy formation, but cannot contribute much to Ω

[a] Abbreviations: DM, dark matter; QCD, quantum chromodynamics; PQ, Peccei & Quinn; GUTs, grand unified theories; SUSY, supersymmetric theories; SUGR, supergravity; QED, quantum electrodynamics.

[b] Of these various supersymmetric particles predicted by assorted versions of supersymmetric theories and supergravity, 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.

6.4.2 HOT DARK MATTER AND GALAXY FORMATION All constraints derived from models of galaxy formation should be accepted with some caution, because a number of additional, unrelated parameters and processes undoubtedly contribute, and their effects are not always separable. Among these are (*a*) the spectrum of the initial perturbations; (*b*) the possibility that galaxies do not trace mass but form only at 2–3 σ peaks [biasing (50, 546, 623, 757)]; (*c*) gravitational clustering and relaxation after formation (155, 655), some kinds of which can mimic biasing (305); and (*d*) nongravitational mechanisms for galaxy formation including the selective shadowing of radiation pressure by dust (309) and gas-dynamical effects of exploding stars, supermassive objects, or active nuclei that pile up gas (330). All of these complicate the extrapolation back from observed galaxies to the nature of the underlying dark matter.

Nevertheless, the hot/cold distinction is an important one because in an expanding, cooling universe dominated by particles of mass m_i, the Jeans mass is

$$M_J = 3 \times 10^{18}\ M_{\odot}/m_i\ (\text{eV}) \qquad 2.$$

(92, 773). Thus, with a dominant particle of 10–100 eV (HDM), supercluster-sized structures will acquire their identity first and later fragment into galaxies, while masses of MeV, GeV, or more will lead to galaxies or smaller structures forming first and larger things being built up by gravitational clustering (CDM). Observations of amount of clustering as a function of redshift ought eventually to be able to tell us which happened (343) but have not yet done so.

Hot dark matter was the first to be considered and has several virtues. First, one sort is actually known to exist—the neutrinos and antineutrinos of electron, muon, and (presumably) tau flavors—which in most modern pictures of symmetry breaking should have some rest mass (690). Second, small extrapolations back in time of the hot big-bang conditions known from nucleosynthesis permit a fairly precise calculation of their number density at about 100 cm^{-3} for each species. Thus, the rest masses must be 10–100 eV if they are to add up to $\Omega = 1$ (154, 243). Other (hypothetical) particles in the same mass range do not share these virtues, but will behave in the same way during galaxy formation.

Three different experimental groups have reported evidencc for neutrino rest masses in the cosmologically interesting range (423, 550, 625). Each has in turn been firmly doubted (16, 64, 85, 164, 421), and the case must currently be regarded as not proven. One of the (many) suggested resolutions of the solar neutrino problem (70) invokes a rest mass that might also fall in the interesting range.

Simulations of galaxy formation in a universe dominated by HDM have been carried out by many groups, first enthusiastically (596), next with the realization that they make galaxies too late ($Z \lesssim 3$) and with velocity dispersions in the small-scale structure much larger than we see (135, 233, 740), and then in a spirit of "save the HDM" (455, 612). The current situation can probably be summarized by saying that hot dark matter is exceedingly useful in producing large-scale structure, including perhaps even the very large-scale streaming (153, 183, 234, 457, 700), and may have some part in scenarios with decaying dark matter or two "tooth fairies" (see Sections 6.4.4 and 6.4.5), but that it cannot be the only nonbaryonic component present at the time of galaxy formation.

6.4.3 COLD DARK MATTER A large fraction of the candidates listed in Table 3 come under this heading and are collectively called "ino's," WIMPs (weakly interacting massive particles), or just cold dark matter. Axions are formed cold (690) and so belong here despite their small masses.

It was recognized from the beginning that CDM scenarios would require something like biasing to provide correlations over large scales (270). If galaxies form only at several-sigma density peaks, then they will be more clustered than the underlying dark matter, because most of these peaks will be small fluctuations sitting atop larger scale, smaller amplitude ones. The biased cold dark matter program has now been explored in considerable detail and has achieved a number of successes in accounting for the observed properties of galaxies and clusters (50, 83, 84, 123, 169, 328, 539, 548, 570, 586, 634, 743, 765). There are minor disagreements about how best to do the calculations and interpret them (629), but the chief problem is in accounting for the largest scale voids and superclusters and, especially, for the very large-scale streaming motions (725, 726a, 739).

Because HDM gets into trouble with small-scale phenomena and CDM with large-scale ones, a natural thought is to try to combine their virtues in some way. This has been attempted through the assumption of massive particles that decay to relativistic ones (Section 6.4.4) and through the positing of two or more kinds of dark matter (Section 6.4.5).

6.4.4 DECAYING DARK MATTER The general idea here is that the Universe came out of its inflationary epoch with $\Omega = 1$ in some unstable WIMP that helped to make galaxies and then decayed away, leaving $\Omega = 1$ total in the decay products but only 0.2 in bound structures. There must be no photons in the decay products, thus the WIMPs cannot be photinos (495), but gravitinos and heavy neutrinos are possibilities. Calculations of this type are numerous (185, 240, 303, 326, 496, 583, 647, 691, 703a) and reasonably successful in making galaxies without disturbing the 3-K background. They require, however, fine tuning of the decay epoch, make the look-back age of the Universe uncomfortably short (since $R \propto t^{1/2}$ in a radiation-dominated universe), and must leave at least half the initial dark mass of a spiral galaxy in the halo in order to reproduce flat rotation curves (223). The advantages, therefore, probably do not outweigh the disadvantages.

6.4.5 SCENARIOS WITH TWO TOOTH FAIRIES By way of explanation, when an American child loses a milk (baby) tooth, he is supposed to put it under his pillow at bedtime. The tooth fairy comes during the night, takes away the tooth, and leaves a suitable coin in its place. The hope in these scenarios (595) is that we can put dark matter under our computers at quitting time and find that a good fairy has left galaxies by morning, except that in most of the schemes currently under investigation, it really takes two of them.

Biased CDM belongs to this category, unless the biasing comes automatically out of the way the perturbations grow (548). Percolation of explosive galaxy formation plus HDM is another possible combination (133). More popular, however, are the combination of (*a*) one hot and one cold entity, which together with the baryons add up to $\Omega = 1$ (9, 195, 211, 608, 699, 716), (*b*) one dark matter candidate plus nonzero cosmological constant (532), or (*c*) a dark matter background in which the seeds for galaxy formation are quark nuggets, primordial black holes, or cosmic strings (774). The strings, at least, automatically introduce large-scale correlations or biasing and are the 1986 "best-buy" model (12, 68, 255, 308, 547, 548, 643, 692, 718). It is, however, a safe bet that, by the time you read this in 1987 or later, some other combination will seem at least as likely to leave realistic galaxies under the computer.

6.4.6 DETECTION OF DARK MATTER CANDIDATES—ASTROPHYSICAL METHODS Existing or proposed observations can constrain, or possibly provide evidence for, the presence of several possible kinds of DM. Clearly the two are not entirely distinct; an effect attributable, for instance, to photino decay either proves the existence of photinos or sets an upper limit to them, depending on the likelihood of other causes of the same effect.

The excluded candidates are those with combinations of mass, lifetime, and cross section that would more than close the Universe, spoil nucleosynthesis, or produce a larger background of photons than we see in some waveband (86, 91, 268, 374, 590, 624, 649, 726). No whole class can be eliminated in this way.

Prospects for future detection include baryons (gas, faint galaxies, supermassive black holes, etc.) in voids whose presence would favor biasing and whose absence would favor strings as the mechanism for producing large-scale coherent structure. Gamma rays from WIMP decays or annihilations in the Milky Way halo should also eventually be measurable (565, 637).

Of the observations that could indicate detection of DM candidates has already occurred, some gravitational lenses and a feature near the center of our own Galaxy have been blamed on strings (141, 510), a possible 1667-Å feature in the ultraviolet radiation background has been attributed to light neutrino decay (644), and photons at higher energies attributed to decay or annihilation of more massive WIMPs (601–603). These could also be responsible for the unexpectedly high flux of low-energy cosmic-ray antiprotons (646); and sneutrinos might cool white dwarfs faster than conventional energy-transport mechanisms (472).

The most far-reaching of these "we may already have seen them" proposals is the simultaneous use of WIMPs to close the Universe, reduce the solar neutrino flux to the observed value, and adjust the frequencies of solar normal modes to match data (215, 241, 246, 532, 650). The particles must necessarily be trapped in cores of other stars as well and influence their structure and evolution, in ways that remain to be worked out but could be either good (J. Faulkner, personal communication, 1986) or bad (A. Renzini, personal communication, 1986) from the point of view of bringing theory and observation into accord.

6.4.7 DETECTION OF DARK MATTER CANDIDATES—LABORATORY METHODS

As in the astrophysical case, some volumes of parameter space can be ruled out on the basis of existing experiments (10, 177, 236a). All positive results so far reported—neutrino rest mass (550), axions (756), and monopoles (119)—have been questioned and need further work for their confirmation.

Future prospects include both the use of existing proton-decay apparatuses to look for high-energy neutrinos from WIMP decay (379) and the construction of new, dedicated apparatus. Some of these, like a proposed large, high-Q microwave cavity to detect axions through their propensity to convert to photons in the presence of a strong magnetic field (620), carry price tags in the modern high-energy physics range. Two others, germanium or silicon spectrometers (32, 732) and bolometers (115, 190, 232), that detect WIMPs through their propensity to interact with nuclei and deposit energy in superconducting grains, could register roughly one count per day with a 10-kg detector and a cost in the individual PI grant range. These are, of course, enormously exciting possibilities, although we confess that we have not yet started urging our friends and relations to build suitable detectors.

7. L'ENVOI

Is there a dark-matter problem? Not necessarily, though there clearly are a number of astrophysical problems to which different kinds of dark matter are among the possible solutions. There are also astrophysical problems [e.g. the Great Red Spot on Jupiter (19a)] to which dark matter is not a solution.

No one kind of dark matter, with the remotely possible exception of ordinary baryons, can solve all the problems at once. On the other hand, to invoke five or six different kinds to match the properties of spiral disks and halos, ellipticals, dwarf galaxies, clusters, superclusters, and galaxy formation is probably also the wrong strategy. How are we betting? At least evens on baryons on scales up to superclusters, and maybe one chance in four on baryons all the way (either closing the Universe or managing to exist in an open one). The remaining probability spreads rather uniformly over a very large number of candidates at the moment. Several different events (confirmation of neutrino oscillations, laboratory detection of 10-GeV photinos, or whatever) could collapse the wave function considerably.

Finally, there are well-defined, finite, observational, theoretical, and experimental programs that can be expected to improve our understanding of the amount, distribution, and nature of nonluminous mass. These range from studying the brightness of K giants as a function of metal abundance and looking for baryonic matter in cosmic voids to pursuing higher dimensional theories of particle physics and building superconducting microwave cavities. There is surely at least one task suitable for every scientist who is interested in the problem. Failing this, feel free to keep in mind this thought from James Russell Lowell ("A Fable for Critics"): "Nature fits all of her children with something to do. He who would write, but can't write, can surely review."

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