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DARK MATTER: PAST, PRESENT, AND FUTURE

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Abstract The words "dark matter" are a shorthand for an enormous range of evidence indicating (a) that various astronomical mass-to-light (M/L) ratios are larger than can be accounted for by visible stars and gas at any temperature and (b) that M/L systematically increases as one measures it on larger and larger distance scales. The evidence is reviewed historically and attention given to the range of possible gravitating substances (collectively "dark matter candidates") that might make up all or part of the stuff. A handful are currently taken seriously, but the total inventory is at least several dozen. Dark energy comes at the end, but is also to be taken seriously.

1. INTRODUCTION

Both the concept of dark matter ("unenlightened stars" according to Edward Pigott (1) in 1805) and evidence for some forms of it (companions of Sirius and Procyon and outlying gas giants in the solar system, associated with the names of Bessell, Adams, and LeVerrier in the 1840s) are older than any reader of this paper. Jeans wrote of dark stars (outnumbering light stars 3:1) in 1922, and Kapteyn wrote of dark matter ("quantity not excessive") in the same year. The first observation generally mentioned in dark matter reviews is Fritz Zwicky's 1933 analysis of his own measurements of velocities of galaxies in the Coma cluster (2), which lead (via a virial theorem) to a ratio of mass to light near 100 in solar units, using a modern distance scale. He wrote of "dunkel materie" and supposed it to consist of gas and faint stars. The present author does not quite remember the era of Kapteyn and Jeans but knew Zwicky near the end of his career and the beginning of hers (1964-74).

Forty years later, measurements of masses of galaxies from rotation curves, binary pairs, cluster velocity dispersions, and other indicators had accumulated to the point where two brief 1974 reviews by an Estonian trio (3) and an American trio (4) tipped the consensus of the community in favor of

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large quantities of matter that neither emitted nor absorbed its fair share of light and that was much less concentrated toward the centers of galaxies than the luminous stars and gas. An extrapolation of their M/L vs. scale relations reached the density needed to close the universe at somewhere around the Hubble radius.

An expectation that the total density would be the closure one, but with only 5-10% of the matter luminous, also took hold, particularly in light of the predictions of inflation theory early in the 1980s that space should be flat. James Gunn, Richard Gott, David Schramm, and Beatrice Tinsley (5) in the same year made a strong case for the total density being only 20-30% of the critical value, setting up a sort of observers vs. theorists (yes, they counted as observers in this context!) confrontation which held for a couple of decades. Their arguments pertained partly to baryons and partly to any sort of matter, and, with a current value of the Hubble constant, their considerations of big bang nucleosynthesis, the age of the universe, and so forth still apply. Reconciliation of the two views has come through the (gradual) acceptance of a non-zero cosmological constant, or its variants, quintessence, dark energy, etc., which contribute to flattening space but not to velocity dispersions or to nuclear reactions. Not reaching the critical matter density can be associated with (but not attributed to) the lack of structures on distance scales large than 150-200 Mpc. The universe is not fractal beyond superclusters, filaments, and voids (6).

An early theoretical argument for dark matter was the need for massive spherical halos to suppress bar instabilities in disks (7). This has been re-evaluated from time to time, but in any case, modern opinion is far more swayed by the need for dark matter (and indeed dark energy) in order to arrive at a satisfactory scenario for the formation of galaxies and clusters from the very small density fluctuations present at the time of recombination. Crudely, the idea is that linear perturbations can grow only linearly with $(1+z)^{-1}$, so we would need something like 10^{-3} fluctuations in density at $z = 1000$ to grow to non-linear ones now, but the near-isotropy of the CMB (Cosmic Microwave Background) requires that the actual fluctuations be only parts in 10^5 not parts in 10^3. The literature of galaxy formation is simply enormous, and (8) is just a random recent paper to get you into the system.

The total topic of dark matter transcends enormity in its accumulated (and exponentially increasing) literature. I have provided earlier snapshots in 1987 (9), 1988 (10), 1993 (11), and 2002 (12) and more extensive historical material in 1990 (13) and 1995 (14). In addition, from 1997 onward, each of the reviews "Astrophysics in 1997" to "Astrophysics in 2003" (15) has had a section of dark matter candidates and cosmological models, including the momentary favorites (which have changed with time), new promising candidates (like self-interacting dark matter, which came and went very quickly), and some suggestions about which one can only say, "remarkable!". These secondary sources will be relied upon a good deal, lest the reference section of this discussion overflow the total page limits. They are abbreviated as Ap97 etc.

2. DATA THEN AND NOW

How early could someone have compiled the sort of M/L trends reported in (3) and (4) and shown in Table 1? In principle, shortly before the outbreak of World War II, using the work of Jeans and Kapteyn, or Oort a decade later for the solar neighborhood, Hubble's 1934 discussion of the inner parts of galaxies (16), a rotation curve for the outer parts of M31 that formed part of the PhD dissertation of the late Horace W. Babcock (17), the binary galaxies presented by Holmberg in 1937 (18), also part of his PhD dissertation, and a 1936 study of the Virgo cluster by Sinclair Smith (19), in case you happened not to like Fritz Zwicky, as indeed some of his contemporaries did not.

TABLE 1. MASS-TO-LIGHT RATIOS (SOLAR UNITS) AS A FUNCTION OF SIZE SCALE ON WHICH THEY ARE MEASURED AND CONTRIBUTIONS TO THE COSMIC DENSITY

LENGTH SCALE	TYPICAL, OBJECTS, TECHNIQUES, REFERENCES	M/L	CONTRIB. TO Ω_M
few - 100 pc	star clusters, solar neighborhood: star velocity dispersions (23, 50)	0.2-10	0.0002 - 0.01
1-10 kpc	optically bright parts of galaxies: stellar velocity dispersions, inner rotation curves (M/L systematically larger for Es than Ss) (24, 25)	few-20	0.003 - 0.02
10-100 kpc	whole galaxies: rotation curves, velocities of globular clusters & satellite galaxies, X-rays, strong lensing (24, 26)	10-50	0.01 - 0.05
0.3 - 3 Mpc	binary galaxies, Local Group, other small groups: Virial theorem, X-rays, velocity dispersions of outer satellites, pair-wise velocity differences, approach of M31 (27, 28, 29)	20 - 100	0.02 - 0.1
10 - 30 Mpc	groups, clusters: Virial theorem, X-rays, gravitational lensing (30)	100	0.1
100-300 Mpc	large clusters and superclusters of galaxies: weak gravitational lensing, X-ray temperatures, Virial theorem (31, 32, 33, 34)	100 - 300	0.1 - 0.3
Global	universe out to the Hubble radius and beyond: Type Ia supernovae, cosmic shear, largest structures, fluctuations in 3K background (35, 36, 37, 38)	270	0.27

Note that the conversion between the last two columns assumed a cosmic luminosity density of 1000 solar luminosities per cubic mega-parsec. Only for the last line (where the 0.27 is known to better than 10%) does the uncertainty on this matter to any of the numbers indicated.

How early did someone actually provide such a table? The first I've found came from Martin Schwarzschild in 1954 (20) and had the key numbers for inner galaxies, outer parts, and whole clusters. He also noted that elliptical galaxies nearly always have larger M/L's than spirals. We would now say that this is mostly because their bright young stars are gone, so that L is smaller, rather than M being bigger. Indeed ellipticals of various sorts include both the very smallest dwarf spheroidal galaxies of 10^6 solar masses and giants of up to 10^{13} solar masses. Schwarzschild suggested that old white dwarfs were an important part of dark matter, which would account for the differences between ellipticals and spirals.

In order to compare numbers across the decades, it is essential to allow for changes in the best estimate of the cosmic distance scale or the Hubble constant (H). In most cases, the L that you deduce for a galaxy (etc.) from its brightness will be proportional to the square of its distance, d, or to H^{-2}, and the mass you calculate, from some form of $M = V^2R/G$, will be proportional to d or H^{-1}. Thus M/L scales as d^{-1} or H, and a velocity dispersion for a cluster of galaxies plus its angular size on the sky that led to M/L = 1000 for H = 500 km/sec/Mpc now, with H = 70 km/sec/Mpc, corresponds to M/L = 140. When Schwarzschild produced his table, the community was just incorporating the first of the large drops in H, from about 500 to 250 km/sec/Mpc.

What did the numbers look like when I first reviewed the subject in 1987 (9)? Pretty much like Schwarzschild's, after allowance for the continued decline in H, and with a few additional data points for the Local Group, for galaxies and clusters with X-ray sizes and temperatures (hence independent Virial-type masses), and for large galaxies (including our own) from the dispersion of velocities of globular clusters and satellite galaxies.

Those numbers, in turn, apart from being given for H = 100 km/sec/Mpc, were very much like those of Table 1. The references indicated in the table are a very small subset of recent ones, not always the most comprehensive, but they provide a representative view of details of the determinations and the major potential sources of errors. Divergent views exist, and recent papers in the ApXX series (15) each include a few data sets for which a matter density close to the closure value (9.5×10^{-30} g-cm^{-3}) is a good a fit as, or better than, the consensus value of 27% of this. Some special mention must be made of Jan H. Oort, whose early papers (21, 22) drew attention to dark matter in our own and other galaxies, which he took to be very faint stars and/or gas at temperatures not then observable, and who continued to consider related issues, including black holes at galactic centers, for another half century.

3. THE CANDIDATES YOU COULD TAKE HOME TO MOTHER

You are going to meet a very large number of these, beginning with a summary of categories ordered chronologically. Then will come some discussion of those that have been taken seriously over a reasonable length of time. The next section will include a take-out menu of more recent suggestions, some to be taken seriously, others perhaps not.

Baryons were first, from the dark, eclipsing stars or planets of Edmund Pigott and John Goodricke (1) in the 1780s via the faint stars, gas, and faint galaxies of Oort (21) and Zwicky (2). As far as I can tell, we then skip 30 years to the possibility of deviations from Newtonian or Einsteinian gravity that will allow the luminous matter to bind galaxies and clusters, as put forward by Arigo Finzi (39). Candidates belonging to the realm of modern theoretical physics started slowly with neutrinos of non-zero rest mass from Gershtein and Zeldovich in 1966 (40) and primordial black holes the same year, also a Russian invention (41). And then the flood gates opened up on both sides of the iron curtain. I would not swear to absolute priority for these papers, but at any rate the indicated candidates were not lost again afterwards.

- Topological singularities from spontaneous symmetry breaking at phase transitions, according to Kirzhnits and Linde in 1972 (42).
- Primoridal gravitational radiation, Grischuk 1974 (43), associated with scenarios we would now call inflation, Starobinsky 1979 (44). And if you declare that inflation had not yet been invented, you will have the givers of several major prizes on your side.
- Non-topological solitons, Friedberg et al. 1976 (45), of which Q-balls, quark nuggets, and soliton stars are later variants.
- Axions arising from Peccei-Quinn symmetry (1977) as a cure for the strong CP violation problem (46).
- And, the name that eventually led all the rest, supersymmetric (and other symmetries) partners of the particles you know and love, put in initial order by Lee and Weinberg (47). The particles have been called inos (as in gravitino), spartners (as in sneutrinos), and WIMPs (weakly interacting massive particles).

Within the year, all the best people (48, 49) were including cold dark matter (CDM) in their models for galaxy formation. From then to now, speakers and writers of the CDM words generally mean WIMPs and their ilk, though axions and a few other candidates behave in much the same way during structure formation. "Bias," the idea that luminous baryons will be more tightly clustered than the CDM (presumably because they are dissipative) dates from the same period.

Now, what has become of all these?

Baryons still exist (for which we are grateful) and will continue to do so for at least the 10^{32} year (lower limit) half life of the proton. That they do not make up most of the dark matter is a joint and concordant conclusion from (a) data collected by the WMAP satellite (Wilkinson Microwave Anistropy Probe) and (b) comparisons of calculations with data for big bang nucleosynthesis (38, 51, 52). The official number is $\Omega_b = 0.044 \pm 0.004$. At large redshift, most of the baryons were in moderate-contrast structures responsible for producing assorted kinds of absorption features in QSO spectra. At present, about half are in visible stars and X-ray-emitting gas. The locus of the rest is generally thought on both observational and theoretical grounds to be a filamentary WHIM (warm-hot intergalactic medium, Ap02, Sect. 12.6.3). This has not kept colleagues from putting forward additional baryon collections (next section).

Electromagnetic radiation, closely allied with baryons, now contributes only 0.1% of the closure density, nearly all of it from the CMB (53), though of course radiation dominated all forms of matter at redshifts larger than about 1200.

Non-standard descriptions of gravity designed to avoid the need for dark matter now number half a dozen or so. None has had the full range of its consequences worked out for comparison with data (meaning the solar system tests, evolution of binary pulsars, time scales of QPOs in X-ray binaries, etc., as well as large scale gravitational lensing, structure formation, and so forth). MOND, (MOdified Newtonian Dynamics [54] and many earlier papers) comes closest. It continues to have supporters (who are younger than we and so should outlive us), but the tide is against it (55, 56). The general idea is a minimum allowed acceleration, below which gravity turns over to a 1/R force. The difficulties arise in making structure formation, reionization, and gravitational lensing all come out right with the same value of that minimum.

Neutrinos no longer count as "dark matter candidates" since they are known experimentally to oscillate among flavors and so to have non-zero rest masses. The implied masses are such that the ones we know and love contribute less than $\Omega_\nu = 0.01$ (Ap00, Sect. 12.4.2). Observed large scale structure and models for its formation are happiest with $\Omega_\nu = 0.006$ or thereabouts. (57)

Primordial black holes (PBH) cannot be entirely ruled out at present, provided that they formed early enough not to have been baryonic during nucleosynthesis. One can say that either the universe is not closed by black holes near 10^{15}g, or Hawking radiation doesn't happen, or both (Ap02, Sect. 12.7). Planet-to-star masses that would gravitationally lens stars behind them (called MACHOs for MAssive Compact Halo Objects) are excluded, and so are (a) blacks holes of 10^{5-6} solar masses, which would mess up galactic dynamics and (b) ones of 10^{6-11} solar masses, which would act as gravitational lenses of background QSOs and GRBs (Ap01, Sect. 12.5). A bit of phase space still remains (Ap00, 12.4.2, Ap03, 3.6, Ap99 Sect. 12.6).

Topological singularities or defects have had their good years and bad years. They come in all possible numbers of dimensions: zero (monopoles, and that these turned out to be the same as the Dirac magnetic monopole was a surprise) with mass near the decoupling scale, one (strings), two (domain walls), three (textures), and convoluted (vortons, hedge-hogs, etc). The finite-dimension ones can have masses at least as large as a small galaxy. That the universe was not entirely overrun with monopoles (limits on which can be set from the persistence of large scale magnetic fields) was one of the original motivations for inflation. Too many strings or domain walls would make recognizable patterns in the CMB. All act more or less like cold dark matter and can perhaps also arise without phase transitions (Ap00, 12.4.3). It does not seem possible to close the universe with such singularities, but they may have a role in seeding galaxy formation (Ap00) or in generating primordial magnetic fields (Ap01, Sect. 12.5).

Primordial gravitational radiation means the sort that comes from stuff sloshing around in the early universe. As with the case of PBHs, there are limits well below $\Omega_{gr} = 1$ in many regimes (wavelength rather than mass in this case, [58]), but also still some for which limits are not very tight, except in the generic sense that the universe acts like most of its positive pressure stuff is matter, with density proportional to $(1+z)^3$ rather than radiation with density proportional to $(1+z)^4$.

Non-topological solitons bring us to the first of the candidates about which one is left a little uncertain about which things belong to which class, given that, for instance, Q-balls turned up in another list of "non-topological extended objects that may or may not be supersymmetric and may or may not be stable," while quark nuggets also appeared as "super-heavy entities, produced by non-thermal processes in the early universe." They are, therefore, all relegated to the next section.

Axions come out of a sort of Bose-Einstein condensation in the early universe rather than from a state of thermal equilibrium, and so will be cold no matter how small their masses. Kolb and Turner in their 1990 duograph (59) gave them a whole chapter (chapter 10), and nothing seems to have happened since to make them a less serious candidate, though the masses must now be in the smaller of the two ranges then possible, near 10^{-5} eV, to keep decay products below detectability (Ap01, Sect. 12.5). Laboratory searches are in progress, and if they find something persuasive, you won't need me to tell you about it.

WIMPs are in the same condition, with searches in progress. Indeed there has been one positive report, but also contradictory evidence from other experiments (60), suggesting that the annual variation in flux reported may have arisen from something other than our annual change in velocity of motion relative to the galactic halo rest frame. Only one conventional WIMP can be truly stable, the lowest-mass sypersymmetric particle (LSP for short) which is quite likely to be a linear combination of Higgsino, photino, and Zino (for instance). Back in 1987, the LSP could have had any mass from 10-100 eV up to a TeV. The low end is now ruled out by the requirement that the stuff be cold during structure formation, and the laboratory limits have gradually squeezed in as well. Some very strange particle physics also begins to happen for dominant stuff above about half a TeV (60). Thus, current laboratory searches focus on masses of 100-400 GeV and cross sections smaller than 10^{-5} picobarns. Recall that "pico" = 10^{-12}, and a barn was what traditional nuclear physicists couldn't hit the broad side of (10^{-24} cm^2). A shed was smaller.

Some of the more popular variations on classical WIMPs do not require inventing any new words. These include (a) decaying CDM (61), admittedly the authors start with charged dark matter and end with something like a superWIMP or massive Kaluza-Klein graviton, but you get the idea, (b) annihilating dark matter (62), and (c) self-interacting dark matter. This last has some significant cross section for scattering its own particles, e.g. 4×10^{-25} cm^2/GeV, but much smaller, or zero, cross sections for annihilation or dissipation or other interactions with baryons. It was a surprise "princess" candidate (Ap00, 12.4.2) to which more and more objections were found over the next few years (Ap00-Ap03), the most serious perhaps that it didn't actually solve the problem for which it had been invented, that of turning a sharp density cusp of a simulated galaxy halo into the flat core of a typical observed galaxy halo.

4. CANDIDATES TO LEAVE BEHIND AT THE SINGLES BAR

Some of these are simply rather new (but promising), and there is no use distressing the family prematurely. Others you should perhaps not take home no matter how long you have known them. Will I always tell you which is which? No; why offend colleagues unnecessarily (but you could chase down the journals in which each originally appeared as an indicator). Alternative titles for this section might have been NIBY ("not in my back yard", like nuclear reactors) or NIH ("not invented here").

I begin with a handful of names that appeared in early lists (9, 10) but seem to have dropped from the recent literature. Some have probably changed names (in the way that shadow matter is now often called mirror matter); others may be indistinguishable for astrophysical purposes from better motivated candidates. And others may have been ruled out by non-astrophysical considerations.

- majoron and goldstone boson: 10^{-5} eV, like the axion, arising out of QCD
- paraphoton and right-handed neutrino, keV particles from modified QED and super-weak interaction theory
- cosmion, flatino, and magnino: MeV to GeV particles from SUSY and supergravity
- preons: multi-TeV particles from composite models
- pyrgons, maximons, perry poles, newtorites, and Schwarzchilds: Planck-mass particles in higher-dimensional theories

Baryonic candidates were traditionally brown dwarfs, old white dwarfs, neutron stars, and stellar mass black holes. Both they and the new ones are subject to the big bang nucleosynthesis constraint above; others might accrete matter, thus radiating, absorb at some wavelengths, or otherwise reveal themselves.

- solid hydrogen (Ap97, Sect. 12.2)
- dense, cold molecular gas clouds in galaxies (Ap97, 00, 01, 03), fairly firmly ruled out by absence of absorption (63)
- high velocity clouds of neutral hydrogen (Ap00 Sect. 12.4.1)
- white dwarfs supposedly detected in the MW halo (Ap00, 01)
- stellar mass black holes (or quark stars or boson stars) because early accretion on them would produce reionization too soon (Ap01 - this should perhaps be re-thought given the WMAP evidence for reionization beginning near z = 20)
- white dwarfs that were never luminous and never produced carbon (etc.) that was blown out (overcoming two of the objections to the usual ones, Ap99, 01)
- large numbers of halo BDs, WDs, or anything else (stellar mass quark nuggets?) that would contribute more MACHO events than seen (Ap03, Sect. 3.6)

Some non-standard theories of gravity have seen less play in the astrophysical literature than has MOND, perhaps only because fewer people have felt passionately that they want to disprove these theories.

- time dependent G (Ap97)
- conformal gravity (Ap97, 02)
- a vector-based theory of gravity (Ap97)
- quantized rotation curves for galaxies (Ap99)
- a scalar-tensor theory in which masses of PBHs grow with time (Ap00, Sect. 12.5.2)
- a second gravitational potential of the Yukawa form (64), i.e. a finite rest mass for the carrier. Secretly we have always rather liked this, as a modern-sounding version of Finzi's (39) idea, but have also always

suspected that, if you invoke one non-zero-rest-mass graviton or gravitino to strengthen gravity as you go from local to galactic scales, you will need additional ones to move outward to larger scales, ending with 10^{-63}g or less at 10 Mpc or more, a number we first heard from Fritz Zwicky in about 1965. He was, of course, in favor of dark matter, but against superclustering.

Additional neutrinos beyond the three you know and love would have to be sterile (that is, not get involved in big bang nucleosynthesis or in neutrino oscillations as currently observed). They could be massive enough to be warm, rather than hot, DM (Ap01 Sect. 12.5). One sort would be made cold from the regular neutrino flavors by MSW oscillation (Ap99, Sect. 12.6). Decaying neutrinos had a certain wild beauty when it seemed their masses might be just above 2 x 13.6 eV, so that the product photons could have contributed to (re)ionization in various contexts (65). Most combinations of properties that would make them interesting can now be ruled out (Ap97, 99, 01), because of their propensity to mess up the CMB early on and to yield detectable UV photons later.

A couple more "warm" candidates probably go about here, including mirror or shadow neutrinos or majorons (Ap01, Sect. 12.5). These must have masses in excess of 0.25 - 0.4 keV or something bad will come down the chimney (probably reionization that smears out the Lyman alpha forest clouds). A 40 eV neutrino popped up in Ap97 (Sect. 12.2), and it was not clear how to avoid having so many of these that the universe would fold up into Pauli's pocket. (See Ap02 for generic objections to warm DM of any sort.)

We haven't found any new sorts of PBHs or sources of gravitational radiation that seem less likely than those in Sect. 3, so here is the lightest gluino-containing baryon (73) to keep the paragraph from feeling unwanted. A couple of more items were published in mainstream journals by people at mainstream institutions, or you might otherwise have supposed that they should go at the screwy end of the paper (whichever that is). Three examples: Rydberg matter (Ap03), which means atoms in highly excited orbits like n = 109, not something at 13.6 eV; dust with charge = mass in the c = G = 1 units of general relativity (Ap97); and clusters of MACHOs with cluster mass around 4 x 10^4 solar masses, so as to evade the limits from both gravitational microlensing and from stellar dynamics (Ap97).

The topological and non-topological boxes both seem to have a few left-overs. Indeed they have left-overs in common, which would probably bother us less if we knew precisely what topological meant in this context. Imprecisely, those are the ones that also get described as singularities, while the non-topological also get described as solitons (standing waves, we think, in something, but not water or galactic gas). The T-box still holds decaying domain walls (Ap98 Sect. 11.4), which sweep the monopoles out of the way first, and several sorts of topological solitons, including instantons, Skyrmions, and 't Hooft-Polyakov monopoles (Ap02, Sect. 12.7).

The non-T box is perhaps the most crowded. Early ones live in chapter 7 of (59) and include soliton stars, Z-balls, non-topological cosmic strings, neutrino balls, and quark nuggets. The soliton stars and quark nuggets probably have masses in the MACHO range, and so are not the answer for the halo of the Milky Way and, by extension, other galaxies. "Moving right along" as speakers often say when they have already exceeded their allotted time by 15 minutes, we find Q balls still alive and well in Physical Review Letters (Ap02), while the B balls are decaying in the same journal (Ap99).

Axions need a big box by particle standards. Have you ever worried about a Heisenberg uncertainty size for something with a mass of 10^{-5} eV at T = 3K? We get 2.2 mm. And they have such a box, a big chunk of a Reviews of Modern Physics (66).

Most of the recent variants of WIMP-ish CDM (decaying, annihilating, self-interacting) live in the previous section, but here are LIMPS (which do their weak interacting only with leptons, (67), and have masses of 1 - 10 TeV); hot, low-mass WIMPs from the decay of scalar particles (Ap99); the CDM that comes from B-ball decay (Ap99); and axinos as the product of LSP decay (Ap99). Since no decaying or annihilating WIMPs have been seen in the lab, limits on their masses, cross-sections, and half-lives sometimes come from astrophysical constraints (Ap00, Ap03). Repulsive dark matter (meaning the shape of its potential, not any personal characteristics) popped up a couple of times (Ap00, Ap01) and may or may not belong in this section.

At this point, we could branch off in several directions and must (unlike Lord Ronald in Stephen Leacock's "Gertrude the Governess") resist the urge to jump on our horse and ride madly off in all of them. The territory galloped over can still be described as "respectable but new or less familiar," and we encounter:

- WIMPzillas (Ap03) of more than 10^{15} GeV, somewhere around the energy scale where the color force breaks loose from the electroweak force. These could (Ap99, Ap00) even be capable of nuclear and electromagnetic interactions, if the masses are large enough and the charges small enough. Somewhere nearby live the cryptons of D. V. Nanopoulos and the strange quark nuggets of E. Witten (Ap03).
- A generic scalar field will have an associated generic scalar boson, and with it you can do most of the things that dark matter is supposed to do (75), and some (like making 10^{10} solar mass stars) that it is not (Ap00). The fields and particles can be traced back to 1968 (68), which perhaps entitles them to Section 3 status.

Additional spatial dimensions beyond the three we move in (anywhere from one extra, as in traditional Kaluza-Klein theory, up to 11 or thereabouts) imply the possibility of extra symmetries, extra conserved quantities, and a lowest-mass particle that cannot decay without violating that conservation law and which is, therefore, a possible DM candidate. Some names we caught were:

- branons (Ap03), with masses of 10^2 - 10^4 GeV, the usual WIMP range and with cross sections less than 10^{-43} cm^2 at the low-mass end
- the lightest Kaluza-Klein gauge boson (Ap03), with potentially observable decay products (69, 70)
- the Kaluza-Klein gravitino (76) which might get trapped inside neutron stars

Mirror or shadow matter also belongs to the extra-dimension territory. The particles are just like ours (hadrons, leptons, and all), but can interact with us only gravitationally across a slightly extended fifth dimension of a particular sort of superstring theory. The standard early reference is (71), and a recent one, whose authors would like to use the stuff for supernovae is (72).

"Other" you might suppose would be a superfluous category after all the items above, but the following have also been swept up in the yearly overviews. They are ordered chronologically.

Ap97: Short-lived particles, created continuously from vacuum quantum fluctuations in the gravitational fields of galaxies; 10^{-34} eV mass, spin zero, neutral bosons with a time-dependent scalar field.

Ap99: Ether.

Ap00: PBHs that are also responsible for ball lightning, because the presence of the Earth catalyzes radiation emitted by gravitational tunneling. DAEMONS (DArk Electric Matter Objects) are particles for which thermodynamic time runs backwards, preventing electromagnetic interactions.

Ap01: A fluid with negative energy density (which would permit an oscillating universe without a singularity). Vacuum energy of a simple, quantized free scalar field of low mass.

Ap02: Stars made of WIMPs. Point-like particles of stellar mass with gas halos around them, so that the gravitational lensing events they produce are non-grey and so not recognized. Planck mass relics of the evaporation of PBHs.

At the transition to the next section, we find (1) naturally soft bosons that could also be responsible for cosmic acceleration (Ap00), and (2) a unified "dark sector" in which the energy density of a scalar field acts like a cosmological constant and the value of the field sets the DM particle masses via Yukawa coupling (77). Current data can be fit, but some of the predictions are different from those of standard CDM, including the long range future of the universe (though this is not a testable prediction for people my age). Two dark matter families are possible.

5. QUINTESSENCE, DARK ENERGY, AND ALL THAT?

For something that began life as an integration constant, "in order to obtain the most general expression with vanishing covariant derivative," (78), Λ has received some remarkable bad press over the years. "Einstein's infamous cosmological constant," "Einstein's greatest blunder," "whose desirability is otherwise itself controversial" (This last from Dennis W. Sciama, who was no stranger to controversy), and so forth.

Let us skip at once to 2004 and observe that the "consensus cosmology," in place at least since 1997 (the Kyoto General Assembly of the International Astronomical Union, for instance) has 70% or a bit more of the gravitating stuff in the universe (whose total adds up to the critical, flat density) present in the form of something with negative pressure. The simplest possible incarnation (consistent with all available data at present) is indeed constant in both time and space, and, like cold dark matter, has no new interactions or forces (79).

If you write the Friedman equation in one of several standard forms as

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \qquad (1)$$

then the consensus parameter set has k = 0 (flat space-time), and the other terms of roughly comparable size, with units of t^{-2} implied. Others tuck in a c^2 so that Λ has units of $(\text{length})^{-2}$. A universe in which it is the dominant term will expand exponentially with time, as in (a) the de Sitter solution, (b) steady state cosmology, and (c) an inflationary epoch.

It is generally said that Einstein kept the Λ term in his early papers to permit a static universe. Alexander Friedman showed in 1922-24 that it could also be part of an expanding (or contracting) universe. Many relativists through the 1930s held on to the constant, often because it permitted an age larger than H^{-1}, and that motivation has recurred more or less continuously (80, 81). It eased off a bit when estimates of the Hubble constant dropped from 1952 into the 1970s, and crept back when the oldest stars and radioactive elements began to push the age on past 10 Gyr. The worry that the Earth and stars might be older than the universe was one (of several) motivations also for the 1948 steady state universe.

There was a separate burst of enthusiasm for non-zero Λ in the late 1960s, arising from a seeming excess of QSOs with redshifts very close to 1.95, which could be interpreted as the coasting epoch of a universe dominated early on by matter of some sort, from which Λ had begun to take over. Notice that flat space, where $\Omega_M + \Omega_\Lambda = 1$ has only an inflection point in R(t), indeed somewhere around z = 2, not a coasting period. The excess of z = 1.95 redshifts has, in any case, been gradually erased by additional samples with different selection effects.

With a little effort, one could probably find at least one paper every five years, from 1917 to the present, in which a cosmological constant was taken reasonably seriously, so the idea has never really been lost. Until recently however, most textbooks set it equal to zero, at least from chapter 2 onward. Authors could claim various, Occamal, philosophical reasons for this. But, perhaps more important, if you keep it, the equations relating angular diameters, observed brightnesses, look back time, etc. to redshift become very much more complex and not always amenable to analytic solutions.

A separate objection came from the particle physicists when they began to take an interest in cosmology in the 1970s and to think of Λ as the zero-point energy of one or more fields. The natural value in the universe of Eq. (1) would be $(\tau_p)^{-2}$, where τ_p is the Planck time, about 10^{-43}s. Thus it would be bigger than the other terms in Eq. (1) by about 10^{120} (see 82), and theorists tended to feel that it would be easier to achieve exact cancellation and $\Lambda = 0$ than cancellation so nearly, but not quite, complete. Many astronomers, on the other hand, have remained content to say that zero, versus small but non-zero, was an observational issue. Gerard de Vaucouleurs was among them, and the number grew when it began to be clear that there were observations that could actually separate Λ from the other cosmological parameters (83). Some of these are still producing only upper limits, some of which hit hard against the consensus number (15, sect. 3.5), but there is now a positive result from the integrated Sachs-Wolfe effect (84), which is the expected correlation between relatively small angular scale fluctuations in the CMB and the distribution of gas in protoclusters that are still expanding, so that photons passing through come out blueshifted. It is there in a comparison of the Sloan Digital Sky Survey of galaxies and clusters with WMAP.

The observational camp being on top, at least for the time being, theoretical physicists have turned their attention to new candidates, and new names, for the negative pressure stuff. The inflaton was first. If inflation results from the behavior of a scalar field, someone was bound to call it an inflaton field and the associated scalar boson the inflaton. This was already common by 1990 (59), with one version regarding the present exponential expansion as just a leftover bit of inflation.

Ap97 was the first annual report to record a majority of papers favoring non-zero Λ. Ap98 registered both the word "quintessence" and the idea of a more general equation of state, with $P = -w\rho$, and w potentially a function of time (or something else). The stuff is also allowed to be clumpy (85), and to participate in structure formation. The case w = 1 is equivalent to the invariant Λ. [The name "quintessence" derives from the classical elements: earth, air, fire, and water for terrestrial objects/phenomena, and quintessence for celestial ones.] X-matter appeared the next year (Ap99) with roughly the same meaning as quintessence and fairly short half-life. An upper limit to -w near -0.6 came from the Type Ia supernova data as they then stood. That point has proven fairly robust. None of the assorted relevant data prefer $w \neq 1$, and the WMAP limit is 0.78 (38).

The term dark energy acquired majority status in Ap00, and theorists were working out the consequences of w being a function of time. For instance, if the dark energy melted away, our accelerating universe might yet contract back to high enough density that any surviving observers would cease to take an interest in whether a singularity would result. Some versions of the scalar field required for current dark energy were motivated by string theory, though this did not guarantee agreement with observations (86 and many slightly later papers).

The 0.7/0.3 ratio of dark energy to dark matter has fairly small error bars if you take all the observations seriously, so theorists began, in the new century (Ap01), to try to identify mechanisms that could lock in such a ratio (vs. zero or infinity) long enough for life to evolve and all. Some of the associated concepts are a Brans-Dicke (scalar-tensor) field, a false vacuum, a scalar field that locks onto negative pressure, and, of course, ideas connected with strings and branes. Up to this point, at least, most of the ideas first surfaced in Physical Review Letters, Physics Letters, and other reasonably respectable venues, in contrast to some of the more imaginative candidates for dark matter. This happy state of affairs probably won't last.

Observable consequences of the various candidates typically appear in the fine structure and polarization of the CMB, probably undetectable until the Planck Satellite Mission or beyond, though a more interesting one would be a bubble of negative potential energy expanding at the speed of light, which you would presumably notice (very briefly) as it overtook you. Some of the ideas are likely to send the reader scurrying back to textbooks. Let a holographic quantum contribution that should always keep Λ smaller than the dominant matter component (87) stand for many appearing in Ap02 and Ap03.

It would be rash indeed to be on the "dark flavor of the month" (except perhaps bitter chocolate). A unified dark sector proposal (77) was noted at the end of the previous section. Raman Sundrum (88) has given the graviton a finite size and urged that searches for deviations of the gravitational force from $1/R^2$ be continued down to the 20 μm scale. The difficulty with such experiments (89) is in getting the centers of two very large masses very close together. Samples of neutron star material would not help, since the gravitational potential confines the stuff only for masses larger than about 0.1 solar masses.

New darkness leaks continuously into the astronomical literature from the physics literature and astro-ph. The past year has seen a positive (or rather negative) spigot of Chaplygin gas (90, 91, 92). In light (or darkness) of my fruitless search for Prof. Cardass of Cardassian expansion (93), I was pleased to discover that Chaplygin (Sergei Alekseevich, 1869-1942), whose village of birth was renamed for him, was a real person, to be found in the Dictionary of Scientific Biography and other (mostly Russian) sources. Most of his work was in what would now be called fluid dynamics, and the crucial 1904 paper invoked a compressible fluid with an equation of state given by $P = -A/\rho$. for use in considering the lift of a rigid wing. His work in general has not ever been forgotten, with regular citations in SCI, but that particular equation of state had to be independently rediscovered several times, for instance by Theodore von Karman in 1941, also in an aeodynamical context. I mention von Karman of several rediscoverers because he is the anti-hero of a story of which the punchline is, "Mr. Bird, where is Maryland?"

Kamenshchik et al. (94) seem to have been the first to fill a universe with a Chaplygin gas. They also mention its connections with brane theory and supersymmetry, discovered by others. A generalized Chaplygin gas has $P = -A/\rho^{\alpha}$. where α can be a function of time, to carry the universe across from a pressure-free state to a negative pressure one.

The long range future of a universe with a dark energy sector (whatever you call it) is a lonely one (Ap02, Ap03). It is today already too late to send a message to a galaxy we see with redshift greater than 1.7-1.8 and have it ever arrive (unless the dark energy decays away), and we will never see a galaxy with $z = 5$ at any age large than 6 Gyr. Come back in a few Hubble times, and nothing will remain within our horizon (stationary at about 5 Gpc away) but the merged product of our own Local Group and its nearest neighbors.

The phrase "phantom energy" snuck into glossaries a couple of years ago to describe dark energy with $w > 1$. Observationally (Ap03, 9.5) it cannot be much larger, or $-w$ much smaller than -1, but even a few % will take Ω_Λ to infinity in finite time, tearing up clusters and galaxies, then the solar system and stars, the Earth (at half an hour before the end), and by then it hardly matters that atoms are going to vanish 10^{-19} seconds before the instant of doom!

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