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DARK MATTER CANDIDATES

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ABSTRACT. One of the simplest, yet most profound, questions we can ask about the Universe is, How much stuff is in it, and further what is that stuff composed of? Needless to say, the answer to this question has very important implications for the evolution of the Universe, determining both the ultimate fate and the course of structure formation. Remarkably, at this late date in the history of the Universe we still do not have a definitive answer to this simplest of questions—although we have some very intriguing clues. It is known with certainty that most of the material in the Universe is dark, and we have the strong suspicion that the dominant component of material in the Cosmos is not baryons, but rather is exotic relic elementary particles left over from the earliest, very hot epoch of the Universe. If true, the Dark Matter question is a most fundamental one facing both particle physics and cosmology. The leading particle dark matter candidates are: the axion, the neutralino, and a light neutrino species. All three candidates are accessible to experimental tests, and experiments are now in progress. In addition, there are several dark horse, long shot, candidates, including the superheavy magnetic monopole and soliton stars.

I. DARK MATTER IN THE UNIVERSE

The luminous matter in galaxies, as evidenced by the radiation (visible, infrared, x-ray, etc.) associated with it, contributes only a tiny fraction of closure density ($\Omega = \rho/\rho_{\rm crit}$; $\rho_{\rm crit} \simeq 1.05\, h^2 \times 10^4\, {\rm eV\, cm^{-3}}$):

$$\Omega_{\rm LUM} \lesssim 0.01$$

On the other hand, there is overwhelming evidence that there is much more additional matter associated with galaxies that is not luminous. The flat rotation curves of spiral galaxies (inferred by both optical and 21 cm measurements) indicate that the typical spiral galaxy is immersed in a dark halo which contains 3–10 times the amount of matter that is associated with the luminous portion of the galaxy. This dark material whose presence is inferred by its gravitational effects alone contributes at least:

$$\Omega_{\rm HALO} \gtrsim 0.03 - 0.10$$

Since there is yet no incontravertible evidence for a rotation curve which 'turns over' the total amount of material in the halos of spiral galaxies has yet to be determined.

The mass associated with galaxies in bound systems (small groups and clusters of galaxies) can be determined by dynamical means (the virial theorem); from such measurements one infers a universal mass density of

$$\Omega_{\rm CLUSTERED} \simeq 0.1 - 0.3$$

A note of caution; since only $\sim$ 1 in 10 galaxies are found in clusters the mass density determined by this means may not be indicative of the true mass density.

The flat rotation curves of spiral galaxies and the dynamics of clusters provide the most convincing, I would even say irrefutable, evidence that dark component to the mass density outweighs the luminous component by at least a factor of 10.

The mass of the Virgo cluster has been determined by its influence on the dynamics of the local group, the so-called Virgo infall method, from which values of $\Omega \simeq 0.1$–0.2 have been inferred. This technique has been applied on even larger scales: the IRAS catalogue of infrared selected galaxies has been used to compute the local acceleration field and the predicted peculiar velocity (due to the inhomogeneous distribution of galaxies), and comparing this to our measured peculiar velocity values of Ω approaching unity have been obtained.[1]

Kinematical methods can also be used to determine the mean mass density of the Universe; e.g., the luminosity-red shift relation (or Hubble diagram), the angle-red shift relation, the galaxy count-red shift relation, etc. The results of the first two kinematical tests are inconclusive, largely due to concerns about galactic evolution. I should mention that there is some hope that the luminosity-red shift relation will be revived by the use of infrared observations where the evolutionary effects may be far less important. Recently, Loh and Spillar[2] have attempted to use the third test to infer the universal mass density and obtained a formal value of $\Omega = 0.9^{+0.7}_{-0.5}$. While many questions have been raised about their photometric (as opposed to spectroscopic) method of obtaining red shifts and their assumptions about the galaxy luminosity function, this technique has great cosmological leverage and at the very least is sensitive to galaxy evolution in a different way than the other two kinematic methods.

The luminous matter in the Universe must of course be baryons! However, not all baryons are necessarily luminous. Our best knowledge of the baryonic mass density derives from primordial nucleosynthesis. In the standard model of big bang nucleosynthesis (BBN) concordance of the observed abundances of D, ^{3}He, ^{4}He, and ^{7}Li require the baryon-to-photon ratio to lie in the narrow interval $\eta = 3 - 7 \times 10^{-10}$, or equivalently,[3]

$$0.011 \lesssim 0.011h^{-2} \lesssim \Omega_B \lesssim 0.025h^{-2} \lesssim 0.15$$

where h is the present value of the Hubble constant in units of 100 km sec^{-1} Mpc^{-1} and $0.4 \lesssim h \lesssim 1$. Since luminous matter contributes at most 1% of critical density there is already evidence that some of the baryons in the Universe are dark—likely in the form of jupiters, white dwarfs, neutron stars, and black holes.

What is one to conclude from this? First, it is a certainty that the dominant component of matter in the Universe is dark—by at least a factor of 10. Second, if the universal density is greater than 15% of critical, then there must be non-baryonic dark matter. I should caution that at present there is no irrefutable case for $\Omega \gtrsim 0.15$, and so it is still possible that baryons are the whole story!

From this point forward I will assume that Ω is indeed equal to unity. I believe that the theoretical reasons for believing such are very compelling. Briefly, those are reasons are: (1) Structure formation—Structure formation in the Universe begins when the Universe becomes matter-dominated and ceases when the Universe begins its coasting phase (i.e., when the curvature term dominates the matter density). The red shift at which the Universe becomes matter dominated is proportional to Ω; the red shift at which the coasting phase commences is proportional to Ω^{-1}. In a low-Ω Universe the growth of density inhomogeneities gets squeezed at both ends, thereby requiring larger initial inhomogeneities which in turn lead to larger temperature fluctuations in the microwave background. Conventional scenarios of structure formation are all but ruled out by the smoothness of the microwave background for $\Omega \lesssim 0.2$. (2) Naturalness/good taste—Ω does not remain constant as the Universe evolves, unless it was precisely unity initially. Rather, as time goes on it deviates more and more from unity. That Ω today is still of order unity implies that the value of Ω at the Planck epoch must have been unity to within a part in 10^{60}. (3) Inflation—The inflationary paradigm is a very attractive early Universe scenario based upon plausible (albeit speculative) microphsics. It provides a means of understanding a number of cosmological puzzles including the present value of Ω being of order unity. In the inflationary scenario Ω is reset to a value very, very close to unity during inflation, so close that an inescapable prediction of inflation is that Ω today should be unity (more precisely, that the curvature of the Universe should be negligible).

With the assumption that Ω is 1 today it follows that the dominant form of matter in the Universe must be non-baryonic. Furthermore, if Ω is unity (as theoretical prejudice would have), then there is strong indication for a component of the matter density which is not associated with bright galaxies, is less clustered, and contributes about 0.8 of critical, a fact which should be kept in mind. To summarize then, theory and observation indicate: $\Omega = 1$, $\Omega_B \sim 0.1$, $\Omega_X \sim 0.9$, $\Omega_{\mathrm{CLUSTERED}} \simeq 0.1 - 0.3$, and a local density of dark matter (in our halo) $\simeq 0.3\,\mathrm{GeV\,cm^{-3}}$.[4]

Before proceeding to relic WIMP dark matter, I should comment on the possibility that $\Omega = \Omega_B = 1$. It is a great leap to assume that $\Omega = 1$; it is an even greater leap to invoke a new form of matter to explain it. Just how secure is the BBN constraint, $\Omega_B \lesssim 0.15$? Recently, two non-standard scenarios have been suggested to circumvent this important constraint: (1) A second, late period of nucleosynthesis which 'resets' the light element abundances and is triggered by the hadronic decay products of a particle which decays when the Universe is $\sim 10^5 - 10^6$ sec old;[5] (2) Large inhomogeneities in the local baryon-to-photon ratio at the epoch of BBN arising due to the effects of a strongly first order quark/hadron phase transition which modify the standard picture. Both scenarios invoke new parameters to adjust (although ultimately fixed by experiment and not cosmology), and yet neither is able to reproduce the success of the standard scenario of primordial nucleosynthesis. In the first scenario ^{7}Li is underproduced, while ^{6}Li is overproduced (although observations have not yet definitively ruled this scenario out). The second scenario relies upon the quark/hadron transition being strongly first order (which seems unlikely) with a very low transition temperature ($T_C \lesssim 125$ MeV). Moreover, at present, the most detailed simulations of nucleosynthesis with such inhomogeneities indicate that *none* of the 4 light element abundances are concordant, with ^{7}Li being overproduced by almost two orders-of-magnitude.[7] It is certainly important to keep an open mind to the possibility that all of the dark matter is baryonic; however, at present the case against $\Omega_B \sim 1$ seems quite compelling. Further, if Ω_B were one would have to work hard to explain where all those dark baryons (99%!) are—which is not an easy task.

II. RELIC WIMPS AS THE DARK MATTER

There is ample evidence which indicates that the early Universe was very hot and throughout most of its early history in thermal equilibrium. Therefore, at early times all kinds of exotic particles (which theorists are certain exist and experimentalists struggle to find) should have been present in great abundance (comparable to the photons). Moreover, there is strong reason to believe that during its early history the Universe went through several, if not many, symmetry breaking phase transitions, during which topological relics can be produced (monopoles, cosmic string, soliton stars, etc.). Many of these exotic particles and objects (if they exist) are very likely to still be with us in interesting numbers. And, for some of these relics, their abundance provides closure density for plausible values of the parameters of the theory, so that there are numerous attractive particle physics candidates for the dark matter in the Universe! The candidates can be organized into 4 categories: Thermal Relics (hot and cold); Asymmetric Relics; and Non-Thermal Relics.

• **Thermal Relics**—At very high temperatures ($T \gg m_X$), the equilibrium abundance of a species X is comparable to that of the photons, while at low temperatures ($T \ll m_X$) the equilibrium abundance is exponentially small, $n_{XEQ}/n_\gamma \simeq (m_X/T)^{3/2}\exp(-m_X/T)$. If equilibrium were the whole story thermal relics would be very uninteresting indeed. However, equilibrium can only maintained so long as the interactions which control the abundance of the species (decays, annihilations and their inverse processes) are occurring rapidly on the expansion time scale ($\Gamma \gtrsim H$). Consider a weakly-interacting massive particle species (or *WIMP*, for short) which is stable. Eventually its annihilation rate falls below the expansion rate ($\Gamma \lesssim H$); annihilations *freeze out*, and the particle's relic abundance freezes in, at about the equilibrium value for the freeze out epoch.

If the speicies is relativistic at the time of freeze out, its relic abundance relative to photons will be of order unity. Such a relic is referred to as a *hot*, thermal relic; the interactions of ordinary neutrinos freeze out at a temperature $\sim$ few MeV, so a light neutrino species ($m_\nu \lesssim$ MeV) is an example of a hot, thermal relic. Note, that for a hot relic the contribution to present energy density scales as the mass; for a neutrino species, $\Omega_\nu \simeq (m_\nu/91h^2\,\text{eV})$.

If the species is non-relativistic at the time of freeze out, its relic abundance will be exponentially less than that of the photons. Such a relic is referred to as a *cold*, thermal relic. Examples include a heavy, stable neutrino species and the lightest superpartner (usually the neutralino[8]) in supersymmetric extensions of the standard model. Interestingly enough, the relic abundance of a cold relic is inversely proportional to the annihilation cross section of the species

$$\Omega_X \sim 10^{-36}\,\text{cm}^2/ < \sigma|v| >_{\text{ann}}$$

This means that the more weakly-interacting a species is, the greater its relic abundance, and that a cold relic which contributes closure density must have an annihilation cross section (and interaction cross sections with ordinary matter) which is roughly $10^{-36}\,\text{cm}^2$, characterisic of weak interactions. Note too, that for a thermal relic, the numbers of relic particles and antiparticles should be equal.

• **Asymmetric Relics**—Above it was tacitly assumed that the abundance of particle and antiparticle species were identically equal, so that the annihilation rate (and hence cross section) determines freeze out and the relic abundance. If an asymmetry exists between particle and antiparticle species, say more particles than antiparticles, then the relic abundance can actually be determined by the size of the asymmetry, in which case the relic population consists only of particles. [The criterion for this to occur is that the asymmetry be greater than the relic abundance that would result from the freeze out of annihilations.] A familiar example is baryons; were baryons and antibaryons initially present in equal numbers, their relic abundance would be: $n_b/n_\gamma = n_{\bar{b}}/n_\gamma \simeq 10^{-18}$, some 8 or so orders-of-magnitude smaller than the observed $n_b/n_\gamma \simeq 4-7\times10^{-10}$. [It is amusing to note that even for an asymmetric relic annihilations become impotent before all the antiparticles are exhausted; for antiprotons the predicted relic abundance is: $n_{\bar{b}}/n_\gamma \sim 10^{18}\exp(-9\times10^5)$.] The general framework which explains the baryon asymmetry, baryogenesis, suggests that there might be similiar asymmetries associated with other species which carry approximately conserved quantum numbers.

• **Non-thermal Relics**—There are a handful of very interesting potential relics whose interactions are so feeble that they should never have been thermal equilibrium at early times. Nevertheless, such relics may have been produced by other, very interesting processes. Included in this list are superheavy magnetic monopoles, axions, and soliton stars. Monopoles are topological solitons associated with the symmetry breakdown of a semi-simple group to one which contains a $U(1)$ factor, e.g., $SU(5) \rightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, and are produced in the SSB phase transition as topological defects, owing to the existence of particle horizons in the standard cosmology. And, as is well-known, in the standard cosmology the relic abundance of monopoles produced by this mechanism is catastrophically large—so large that the Universe would reach the temperature of 3 K at the youthful age of 30,000 yrs. One of the attractive features of inflation is that monopoles are naturally diluted to a safe (and most likely uninteresting) relic abundance.

A second example of a non-thermal relic is the axion. Axions are produced cosmologically by the initial misalignment of the axion field; when the axion develops a mass due to instanton effects ($T \sim \Lambda_{\rm QCD}$) the axion field then begins to oscillate due to this initial misalignment.[9] These oscillations correspond to a condensate of zero momentum axions, whose relic density is $\Omega_a \sim (m_a/10^{-5}\,{\rm eV})^{-1.2}$. From the peculiar scaling of the mass density and the fact that $m_a \sim 10^{-5}$ eV corresponds to closure density it is clear that axions are produced in highly non-thermal numbers. [Were axions present in thermal numbers, $\Omega_a \sim (m_a/100\,{\rm eV})$, some 7 orders-of-magnitude smaller than the coherent abundance. For axion masses $\gtrsim 0.01$ eV there is also a thermal population of axions, whose abundance is greater than that of the coherently produced population.[10] It has also been pointed out that axions produced by another coherent process, the decay of axionic strings, may contribute significantly to the relic abundance of axions.[11]]

Soliton stars are a generic class of non-topological solitons whose stability owes to dynamics rather than topology. The simplest example is a region of false vacuum which is stabilized against collapse by the presence of particles which carry a conserved charge and whose mass in a false vacuum region is much less than it is in the true vacuum. Whether or not a plausible mechanism exists to produce such objects in interesting numbers remains to be seen.[12]

• **Truly Exotic Relics**—There are even more exotic possibilities for the dominant form of matter in the Universe. For example, if the relic WIMP is unstable and decays on a cosmological time scale (say $\tau \sim 10^9$ yrs) into light particles which are still relativistic today, then the bulk of the mass density in the Universe would be in the form of relativistic debris. Such a scenario would neatly explain why most of the material in the Universe appears to be unclustered; however, it is not without its difficulties: a youthful Universe—in a Universe dominated by relativistic particles the age is $\sim 1/2H_0^{-1}$; and the formation of structure—since density inhomogeneities do not grow during a radiation-dominated phase, all the structure must be produced before the WIMP's decay. Another exotic possiblity is that most of the mass density in the Universe exists in the form of vacuum energy (i.e., a relic cosmological term). This scenario too accounts for most of the material in the Universe being unclustered. Of course, the crucial question here is why the cosmological term would have such a small, but non-zero, value compared to its natural scale, $m_{\rm pl}^4$.

• **A New Cosmic Ratio**—Cosmology is a science in which the data are few and far between. Every piece of information we have is important, and especially dimensionless ratios (like the baryon-to-photon ratio, the relative abundances of the light elements, etc.). If the mass density of the Universe is indeed comprised of 1 part baryons and 9 parts exotica, then a new cosmic ratio exists, $r = \Omega_{\rm baryon}/\Omega_{\rm exotic} \sim 0.1$. Why should this ratio have the value close to unity, rather than 10^{-20} or 10^{20}? While it is not possible to answer this question in a definitive way at present, it is intriguing to speculate as to why.[13] According to baryogenesis, the present baryon density traces to the dynamical evolution of a baryon asymmetry, and we have just discussed how the density of various relic WIMP's might arise. In the case of light neutrinos as the dark matter, the near equality of neutrino and baryon densities involves the smallness of neutrino masses relative to other fermion masses. The most attractive scenario for neutrino masses is the see-saw mechanism, where in $m_\nu \sim m_{\rm fermion}^2/M$ and M is some superhigh energy scale (associated with unification). Here then, the near equality of neutrino and baryon densities traces to the very large value of the unification scale M. For a heavy neutrino or neutralino, the near equality traces to the large discrepancy between the weak scale (which sets the annihilation cross section) and the Planck scale. [This same discrepancy in scale 'explains' why stars shine.] For the axion, the near equality traces to proximity of the PQ symmetry breaking scale and the Planck scale. Finally, for an asymmetric relic, say of mass comparable to the baryon, the near equality of densities would trace to similar asymmetries in baryons and exotics.

There are almost too many candidate WIMP's for the dark matter in the Universe to list, and many are very well-movitated. Let me use my own personal prejudice to pare the list down to 3 most promising candidates. They are (not in any special order): *the axion*—the axion is perhaps the most compelling and simplest extension of the standard model, and the relic axions which would be the dark matter are accessible to experimental detection; *the neutralino*—supersymmetry is a very well-motivated extension of the standard model (which will be tested with the next generation of accelerators, if not the present), and in the simplest versions of supersymmetry the lightest superpartner is stable; relic neutralinos too are detectable; *a light neutrino*—the neutrino is known to exist! and in three flavors!; the electron neutrino mass is accessible to laboratory experiment (and at present the ITEP group still report a positive result); a supernova in our galaxy would likely make a determination of the μ and τ neutrino masses possible if one should be in the cosmologically interesting range. Finally, one should not forget about longshots! My favor longshot this year is the superheavy magnetic monopole. The *MACRO* experiment in the Gran Sasso Laboratory will start operating in the next year or so, and will ultimately reach a sensitivity level of $10^{-16}\,{\rm cm}^{-2}\,{\rm sr}^{-1}\,{\rm s}^{-1}$—a full order of magnitude below the Parker limit.

III. DARK MATTER DETECTION

The past decade has witnessed a renaissance in cosmology, triggered in large measure by the infusion of new ideas about the earliest history of the Universe, ideas which are based upon very attractive and well-founded speculations about fundamental physics at energies well beyond the weak scale. If progress in cosmology is to continue we must have experimental and observational data to test these ideas and to help theorists to narrow their future speculations. Cosmological data are hard to come by, more often than not requiring heroic undertakings. There are a myriad of interesting and attractive ideas to be tested, and as theorists we must sort the wheat from the chafe for our experimental and observational colleagues.

The relic WIMP hypothesis is an idea most worthy of testing, and fortunately is one which is amenable to testing. Already numerous experiments/observations are being carried out or planned. They include a variety of laboratory experiments (accelerator searches for supersymmetric particles, ν mass and oscillation experiments, $\beta\beta0\nu$ experiments), searches for the relic WIMP's themselves (axion searches, monopole searches, cryogenic searches for cold, thermal relics), indirect searches for WIMP annihilation products ($\nu\bar{\nu}$'s from WIMP annihilations in the earth and sun, $\bar{p}$'s, γ's, e^+'s from WIMP annihilations in the halo), and cosmological observations (kinematic tests for Ω, structure formation). The structure formation test is a most interesting one; given the amount and composition of matter in the Universe, as well as the nature of the primeval inhomogeneites, the structure formation problem is a well-defined initial data problem. At present the agreement between the numerical simulations of cold dark matter (with inflation-produced, adiabatic primeval fluctuations) is, save for two observations (cluster-cluster correlations and the peculiar velocity field), remarkable. And I believe there is still time for those two observations to come around!

All of these experiments are of the utmost importance for both cosmology and particle physics—the first evidence for new physics beyond the standard model may well come from the discovery of relic WIMP's. Finally, we should not forget cosmological particle relics with abundances less than critical (remember that $\Omega_{3K} \sim 10^{-5}$); if low energy SUSY is correct it is difficult to escape having a relic superpartner with $\Omega \lesssim 0.01$ (see Griest[8]), perhaps too low to close the Universe, but sufficient to detect. Likewise, relic thermal axions of mass $\sim$ few eV would not close the Universe, but could be detected by their cosmological decays.[10]

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DISCUSSION

Vauclair: This is a comment about the lithium primordial abundance. When we say that the lithium abundance observed in population II stars is the primordial one, we assume that the lithium abundance has not changed in these stars during 15 billion years. In reality there are two processes which may deplete lithium in these stars. If there is no turbulence at all, lithium is depleted by gravitational settling. In case of large turbulence, lithium is destroyed by nuclear reactions. It is possible that the lithium abundance remains constant, but this needs a fine tuning of turbulence so that gravitational settling may be prevented and the nuclear destruction timescale be still longer than the stellar age. This is not excluded, but it is also not excluded that some destruction occurred in these stars, in which case the lithium primordial abundance would be between 10^{-10} and 10^{-9}. I have done some computations using Zahn's theory of turbulent mixing induced by stellar rotation, and I find that the destruction process may lead to a "plateau shape" of the lithium abundance as observed, due to the rapid variation of the turbulent diffusion coefficient with radius inside the stars.

Sarkar: You quoted the nucleosynthesis limit on neutrino families $N_\nu < 4$. This assumes that the neutron half-life exceeds 10.4 min. and that the nucleon density is high enough that the ^{7}Li abundance is $\simeq 10^{-10}$. But recent experiments suggest that 10.4 min. is more likely an upper limit, not a lower bound to the neutron half-life. Also it has been argued that the primordial ^{7}Li abundance may be the Pop I value of $\simeq 10^{-9}$, which would allow a lower nucleon density. Therefore the limit $N_\nu < 4$ should be perhaps relaxed. This is very important because this cosmological limit on light neutrino types cannot be tested in the laboratory, since it includes particles which do not necessarily couple to the Z^0. Hence it should be critically examined on its own terms, given that it is a powerful constraint on new physics beyond the standard model.

Turner: The dependence of the BBN limit to N_ν upon $\tau_{1/2}$ is slight: dropping $\tau_{1/2}$ to 10.2 min increases the bound to N_ν by 0.2. While I do not agree that the Pop I ^{7}Li abundance reflects the primordial ^{7}Li abundance, the lower limit to η required to derive the limit to N_ν follows from the abundances of D and ^{3}He (and not ^{7}Li). I believe that the BBN limit to N_ν stands firm at $N_\nu \leq 4$ (note the '$\leq$' rather than '$<$'), the limit established in 1984 (for further discussion, see, G. Steigman, et al, *Phys. Lett.* **176B**, 33 (1986)).