Dark Matter and Relic Particles

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1. A general inventory of the universe

For the first time, we have a believable inventory of the contents of the universe. First, we have compelling evidence that the universe is flat (or at least very nearly so), consistent with the prediction of inflation. Measurements of the first acoustic peak in the angular power spectrum of the Cosmic Microwave Background (CMB) by Boomerang Netterfield et al. [2001], MAXIMA Hanany et al. [2000], and DASI Pryke et al. [2001] indicate that the total energy density of the universe is near the critical density, $\Omega_{\rm tot} \equiv \rho/\rho_{\rm crit} = 1.0 \pm 0.04$. Furthermore, independent observations give us a good idea how this total is distributed among its constituent parts Turner [2001].

- The shape of the matter power spectrum constrains the total matter density $\Omega_{\rm M} h = 0.20 \pm 0.03$, and the baryon/dark matter ratio $\Omega_{\rm b}/\Omega_{\rm M} = 0.15 \pm 0.07$.

- Cosmic Microwave Background measurements, in particular the position of the second acoustic peak, constrain $\Omega_{\rm M} h^2 = 0.16 \pm 0.04$, $\Omega_{\rm b} h^2 = 0.022^{+0.004}_{-0.003}$. This result is in addition to the constraint from the *first* acoustic peak on the total density of the universe.

- Big Bang Nucleosynthesis, combined with new observations of the ratio of deuterium to hydrogen from the Lyman-alpha forest, constrains $\Omega_{\rm b} h^2 = 0.020 \pm 0.001$. This result is in stunning agreement with the independent constraint on the baryon density from the CMB measurements.

- X-ray observations of galaxy clusters constrain the ratio of baryons to total matter by way of the "fair sample" hypothesis. That is, applying the assumption that the baryon/total matter ratio in objects as large as a galaxy cluster mirrors that of the larger universe gives a constraint of $\Omega_{\rm b}/\Omega_{\rm M} = (0.07 \pm 0.007) h^{-3/2}$.

- Direct measurement of the Hubble constant (in particular the HST Key Project) constrains $h = 0.72 \pm 0.07$.

These independent constraints give us a consistent "inventory" of the contents of the universe:

- Baryon density: $\Omega_{\rm b} = 0.04 \pm 0.008$.

- Matter density: $\Omega_{\rm M} = 0.33 \pm 0.035$.

- Dark Energy: $\Omega_\Lambda = 1.0 \pm 0.04 - \Omega_{\rm M} = 0.67 \pm 0.06$.

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Several features of the current observational situation are remarkable: First, a wide variety of independent, complementary observations provide a consistent picture of the makeup of the universe (the agreement is further strengthened by results from observations of distant supernovae Perlmutter et al. [1999]). Second, despite this agreement, the precise nature of these cosmological building blocks remains a mystery. The only component to have been directly identified is the baryonic component, which is not fully characterized. The exact identities of the non-baryonic dark matter and the dark energy remain unknown. The task, then, for the next generation of observation, experiment, and theory is to populate this inventory with fully realized physics. Particle physics will play a central role in this effort.

2. Dark Matter and Cosmology

Observations on both large and galactic scales constrain the properties of the Dark Matter. Structure on large scales, as quantified by the galaxy correlation function, power spectrum, and number density, is in good agreement with predictions if the dominant dark matter is cold, *i.e.* has negligible thermal velocities Primack [2000].

Observations of galactic rotation curves of low-surface-brightness galaxies (which should be dominated by dark matter) indicate a possible discrepancy between expectations and observations. The measured velocities indicate that some of the galaxies have less dark matter near their centers than is predicted by numerical simulations, which predict a so-called density "cusp." In many cases, the discrepancy may be due to inadequate resolution of the velocity very near the galactic center van den Bosch et al. [2000], but some cases apparently have sufficient resolution de Blok et al. [2001]. These cases suggest that the physics describing the galactic center is more complicated than believed, perhaps simply because some astrophysics effect (not yet understood) decreases the central density of the galaxies, or possibly because the spectrum of primordial density fluctuations is "tilted" to suppress small-scale fluctuations Alam et al. [2001].

The alternative is that the effect may be due to the particle-physics interactions of the dark matter. Theories of self-interacting dark matter Spergel and Steinhardt [2000], annihilating dark matter Kaplinghat et al. [2000], and warm dark matter Haiman et al. [2001] have been concocted primarily in an effort to make the central galactic core less dense. Although the mere possibility of learning about particle physics from such astronomical observations and simulations is exciting, the resulting particle physics theories themselves appear uncompelling. Furthermore, agreement with all observations is not so good under many of the new theories, either Primack [2000].

Simulations of cold dark matter also predict that there would be more low-velocity subhalos than the corresponding observed low-velocity galaxies in the local group Klypin et al. [1999]. However, this discrepancy may well be due to a suppression of the probability that small subhalos become observable galaxies; subhalos that collapse after the epoch of reionization should be unable to accrete gas and hence should remain wholly dark Bullock et al. [2000].

The distribution of dark matter in the Galaxy also has implications on the possibility of its detection. Models of hierarchical structure formation Stiff et al. [2001], as well as detailed N-body simulations Moore et al. [2001], indicate that most of the dark matter resides in streaming clumps, each of which has a relatively small velocity dispersion. Many clumps may overlap in the solar neighborhood, potentially producing an effectively smooth component of the dark matter. Alternatively, the possibility exists that much or most of the local dark matter belongs to a single streaming clump, such as would occur if we happen to lie close to a caustic. Caustics are concentrations of dark matter in physical space associated with folds of the flows in phase-space. Already there are hints of evidence for caustics in the halos of the Milky Way and other galaxies in the response of baryonic matter to their gravitational fields Sikivie [2001], Kinney and Sikivie [2000]. The small velocity dispersion of these clumps or caustic rings would provide a strong experimental signature particularly for axion searches, but also for WIMP searches Stiff et al. [2001], Moore et al. [2001], Baltz et al. [2001], Bergström et al. [1999, 2001], Freese et al. [2001].

Over the next decade, improved treatments of the complicated astrophysics associated with the details of structure formation, together with better observational data, will better constrain the properties of the dark matter. These constraints should be particularly fruitful if dark matter candidates described below are detected.

3. Baryons

Baryons make up around four percent of the total energy budget of the universe, but they are by far the best studied component of the cosmological matter. Surprisingly, however, the majority of baryons in the universe remain unidentified, or "dark." Tallying the baryons identified in our immediate neighborhood reveals that only a small fraction of the expected baryonic component is seen:

- Stars: $\Omega_{\rm stars} \simeq 0.0035$.
- Gas in galaxies: $\Omega_{\rm gas} \simeq 0.0006$.
- Gas in clusters: $\Omega_{\rm clustergas} \simeq 0.0025$.
- Total identified: $\Omega_{\rm identified} \simeq 0.007$.

Observations at higher redshift provide clear indications of a much larger density of baryons than is directly observed in local objects. Observations of the Lyman-alpha forest at redshifts $z \sim 2 - 4$ indicate that the baryon density is $\Omega_{\rm b} \geq 0.034$. Observations of the Cosmic Microwave Background (at redshift $z = 1100$) give $\Omega_{\rm b} = 0.04$. Physics at very high redshift, *i.e.*, Big Bang nucleosynthesis, also indicates $\Omega_{\rm b} = 0.04$. The question is: where are all the baryons today? Candidates include:

- Faint stars (ruled out by HST observations).
- Neutral hydrogen gas (ruled out by 21cm radio observations).
- Cold molecular hydrogen gas (most likely ruled out, but could still be possible if the gas is specially configured).
- Hot ionized gas (ruled out by X-ray observations).
- Brown dwarfs
- White dwarfs.
- Black holes.
- Neutron stars.

The last four of these fall into the category of MAssive Compact Halo Objects, or MACHOS, which have possibly been detected via gravitational microlensing. When a dark object passes directly between an observer and a distant star, gravitational lensing by the dark object amplifies the light from the star on a timescale related to the dark object's mass. The MACHO Collaboration Alcock et al. [2000] monitored 1.2 million stars in 30 fields toward the Large Magellenic Cloud, accumulating 5.7 years of data. Depending on cuts, between 13 (tight cuts) and 17 (loose cuts) microlensing events were observed. The fact that no events were seen with a timescale $t < 20$ days results in strong limits on MACHOS in the 10^{-7} to 0.1 solar mass range (see figure 1). A significant fraction of the halo in "brown dwarfs" or planet-sized objects is ruled out. Similarly, the lack of long-timescale events significantly limits the fraction of the halo in objects of $\sim 1 - 10$ solar masses. The observation of 13-17 events with $34 < t < 230$ days indicates the presence of at least some compact objects in the halo with masses on the order of half a solar mass.

The basic conclusions of gravitational microlensing surveys are then: (1) An all-MACHO halo is ruled out, bolstering support for weakly interacting massive particles (WIMPs) or axions as dark matter candidates. (2) Between 13 and 17 microlensing events were observed, and remain unexplained. While no compelling candidate yet exists to explain the observed microlensing events, possibilities include white dwarfs, primordial black holes, Q-balls, neutron stars, and black holes from stellar collapse. Most of these candidates, however, have serious difficulties with forming the correct population of dark objects without, for example, overproduction of heavy elements in galaxies or production of a cosmic infrared background. It is also possible that all of the observed microlensing events are due to lensing from stars, for instance self-lensing of the LMC disk or lensing from stars in an intervening dwarf galaxy. To resolve the identity of the microlensing sources, new studies using parallax techniques to determine the distance to the

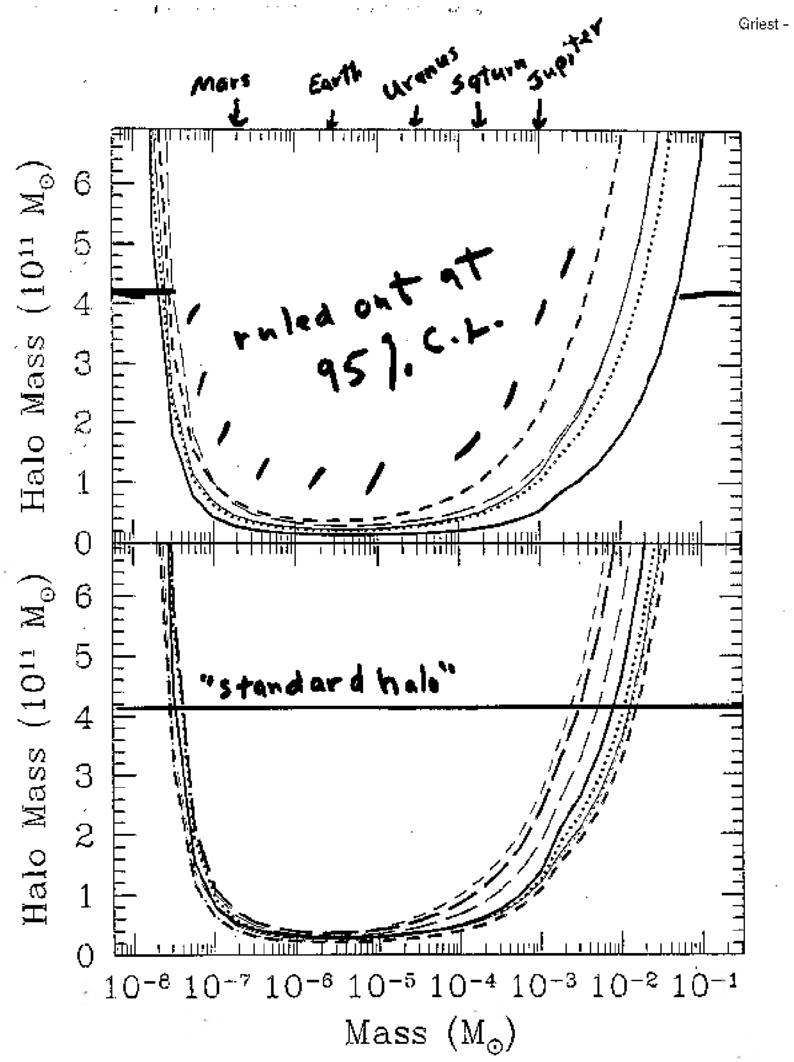

Figure 1: Exclusion plot of halo mass vs. MACHO mass for two different halo models. Note that a large range of MACHO masses are ruled out as a significant component of the halo.Alcock et al. [2000]

lensing sources are required. In addition, halo objects could potentially be directly identified, as in the case for halo white dwarfs searches Oppenheimer et al. [2001] In all, up to 20% of the dark matter could be in compact objects. Important questions remain unresolved:

- Where are the baryons today?
- What is the identity of the objects responsible for microlensing?
- What are the relative densities in galactic halos of baryonic and non-baryonic dark matter?
- What is the nature of the non-baryonic dark matter?

Particle physics and astrophysics will play complementary roles in resolving these questions in the next decade.

4. Neutrino dark matter

The discovery of neutrino oscillations at Super-Kamiokande tells us that at least one neutrino has a mass larger than about 0.07 eV. Neutrinos therefore contribute at least $\Omega_\nu \sim 0.0008$ to the energy budget of the universe. On the other side, primordial nucleosynthesis, the CMB power spectrum, the Lyman-α forest, and other structure formation considerations (see Abazajian et al. [2001], Gelmini [2000], Duda et al. [2001a] and references therein) place upper limits on the fraction of energy density in neutrinos, which can be as large as $\Omega_\nu < 0.05$ Wang et al. [2001]. There is therefore ample room for neutrinos as hot (and even warm or cold) dark matter, and possibilities that enhance the neutrino density, like for example sterile neutrinos or a cosmic lepton asymmetry, are currently being pursued Abazajian et al. [2001], Duda et al. [2001a].

5. Axions

5.1. The Strong CP Problem

Axion dark matter has its origins in the "Strong-CP" problem. The non-Abelian gauge theory describing the strong interactions, though successful, is not without loose ends. One of these is the prediction of non-trivial structure to the Quantum Chromodynamics (QCD) vacuum, which should lead ultimately to observable CP violation. No experiment to date (most notably the ongoing searches for a neutron electric dipole moment Altarev et al. [1992], Smith et al. [1990]) has detected any such violation. This implies that CP symmetry is conserved to a high degree. By contrast, CP symmetry is observed to be violated in the weak sector of the theory, *e.g.*, in the mixing of the B and $\bar{B}$ mesons. One would expect CP violation from the weak sector to feed into the strong sector through the intermediary of the QCD θ-angle.

A solution to this “Strong CP Problem” was proposed by Peccei and Quinn Peccei and Quinn [1977a,b] and involves the spontaneous breaking of a global $U_{PQ}(1)$ symmetry and the concomitant appearance of a quasi-Nambu-Goldstone particle - the axion Weinberg [1978], Wilczek [1978]. The axion solution to the Strong CP Problem is rich in experimental, observational and cosmological implications. If its mass is of order 10^{-5} eV, the axion is also a good candidate for the dark matter of the Universe.

The existence of an axion is the signature of the PQ solution to the Strong CP Problem. The axion mass is given in terms of f_a by

$$m_a \simeq 6\ \mu\text{eV}\ \frac{10^{12}\text{GeV}}{f_a}\,. \tag{1}$$

All the axion couplings are inversely proportional to f_a.

Several detailed reviews of the theory of the axion and its cosmological and astrophysical implications are found in ref. Kim [1987], Cheng [1988], Peccei [1989], Turner [1990], Raffelt [1990]. Experimental searches are described in the E6 Working Group summaries of this report.

5.2. Axion Production in the Early Universe

As temperatures in the early universe approach f_a, a phase transition occurs in which the $U_{PQ}(1)$ symmetry becomes spontaneously broken. At these temperatures the axion is massless and all values of $\langle a(x)\rangle$ are equally likely. Axion strings also appear as topological defects. In the subsequent evolution of the universe one must distinguish between two cases: 1) inflation occurs with a reheat temperature less than the PQ transition temperature. In this case the axion field gets homogenized by inflation and the axion strings are diluted away. In case 2) inflation occurring with reheat temperature higher than the PQ transition temperature (equivalently, for our purposes, inflation does not occur at all). Axion strings are present from the PQ transition to the QCD epoch.

When the temperature approaches the QCD scale, the potential associated with the spontaneous symmetry breaking $V(\bar{\theta})$ turns on and the axion acquires mass. At some well-defined time t_1 the axion field starts to oscillate in response to the axion mass turn-on. In case 1, where the axion field has been homogenized by inflation, the initial amplitude of this oscillation depends on how far from zero the axion field is at t_1. Since the axion field oscillations do not dissipate into other forms of energy they contribute to the cosmological energy density today. This contribution, called ‘vacuum realignment’, is the only contribution in case 1 Preskill et al. [1983], Abbott and Sikivie [1983], Dine and Fischler [1983], Ipser and Sikivie

[1983]. In case 2 the axion strings radiate axions from the time of the PQ transition until oscillations begin and each string becomes the boundary of N domain walls Harari and Sikivie [1985], Davis [1985a,b]. There are three contributions to the axion cosmological energy density in case 2. One contribution is from vacuum realignment, however, now the vacuum realignment contribution cannot be accidentally suppressed because it is an average over many horizon volumes at QCD time, each with a causally independent value of the initial misalignment angle. A second contribution is from axions that were produced in the decay of walls bounded by strings after t_1 Hagmann and Sikivie [1991], Lyth [1992], Nagasawa and Kawasaki [1994], Chang et al. [1999]. A third contribution Harari and Sikivie [1985], Davis [1985a,b], Hagmann and Sikivie [1991], Yamaguchi et al. [1999], Battye and Shellard [1994a,b, 1996], Hagmann et al. [1999, 2001] is from axions that were radiated by axion strings before t_1. Although some controversy exists about the exact magnitude of each contribution in case 2, with reasonable assumptions they can be made consistent with one another. A more thorough analysis reveals that the case 1 favors somewhat lighter axions for closure density.

5.3. Implications for Search Experiments

Independent of the exact details of their production, axions are a cosmologically interesting dark matter candidate only if they are light. However, light axions couple weakly to matter, making their detection a challenge. Although a variety of techniques have been employed in the search for axions, only the electromagnetic cavity conversion approach possesses the requisite sensitivity to detect light axions. Germane to these searches is the axion coupling to two photons:

$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a(x)}{f_a} \vec{E} \cdot \vec{B} \tag{2}$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, α is the fine structure constant, and g_γ is a model-dependent coefficient of order one. In the DFSZ model $g_\gamma = 0.36$ Dine et al. [1981], Zhitnitskii [1980], whereas $g_\gamma = -0.97$ in the KSVZ model Kim [1979], Shifman et al. [1980]. *A priori* the value of f_a, and hence that of m_a, is arbitrary.

From the point of view of experiment design, one must be prepared to search from the lowest estimated overclosure bound ($\sim 10^{-6}$ eV) to the upper bound set by astrophysical arguments ($\sim 10^{-3}$ eV). In any of the cosmological scenarios described above, Ω_a increases as m_a decreases, which motivates a search beginning from the lowest possible mass and proceeding upwards. Fortuitously, amplifier and cavity technology is sufficiently well advanced in the microwave region to search for axions at KSVZ coupling at a rate of ~ 1 MHZ/day. The signal ($\sim 10^{-23}$ W) is assumed to approximate a thermalized Maxwellian shape as a result of repeated random interactions with the gravitational potential of the galaxy. The resultant bandwidth ($\sim 10^{-6}\Delta E/E$) corresponds to a physical width of ~ 1 kHz.

5.4. Recent Axion Infall into the Halo

Besides the broad thermalized component, it is expected that there exist narrow peaks ($\sim 10^{-17}\Delta E/E$) in the axion signal due to recent infall onto the Galaxy. Each of the flows typically contains a few percent of the local halo density Sikivie et al. [1995, 1997]. This fine structure provides an opportunity to significantly improve the detection prospects because of the enhanced signal to noise ratio of the narrow peaks. Observation of this component would allow a time-ordered history of galaxy formation to be constructed.

6. Weakly interacting massive particles

Weakly interacting massive particles (WIMPs) remain a strong candidate for non-baryonic dark matter, despite the troubles that they may face if the dark matter density near the centers of galaxies would be as high as that predicted in current numerical simulations of galaxy formation. Indeed, even if WIMPs would constitute only a small fraction of the cold dark matter due to their large annihilation cross section in the early universe, their detection rates in direct searches would not be suppressed Bottino et al. [2001a], Duda et al. [2001b].

Most of the research on WIMPs focuses on the lightest supersymmetric particle, in particular the neutralino in the minimal supersymmetric standard model. Two philosophical views on the choice of models have made their way: the supergravity framework where unification of the strong and electroweak forces is incorporated in the theory and the electroweak symmetry breaking is achieved through radiative corrections to the Higgs boson masses, and the general parametric framework where the supersymmetric parameters are taken as given at the electroweak scale without assuming their origin in a more complete theory. The two frameworks differ in the number of relations satisfied by the supersymmetric parameters at the electroweak scale. The supergravity framework is more predictive and testable than the general framework, whereas the general framework's wider range of expected detection signals often borders or exceeds current limits.

The detectability of neutralino dark matter has been a topic of research for almost 20 years. New accelerator constraints on supersymmetry have been routinely added to the analysis. The most recent one comes from the Brookhaven measurement of the muon anomalous magnetic moment at 2.6σ above the standard model value. Explaining the excess with supersymmetry results into high detection rates of neutralino dark matter in direct searches, high enough to be accessible to next-generation detectors currently being built Baltz and Gondolo [2001], Chattopadhyay and Nath [2001]. Figure 2 compares the theoretical expectations with the current and projected experimental sensitivities of direct detection experiments.

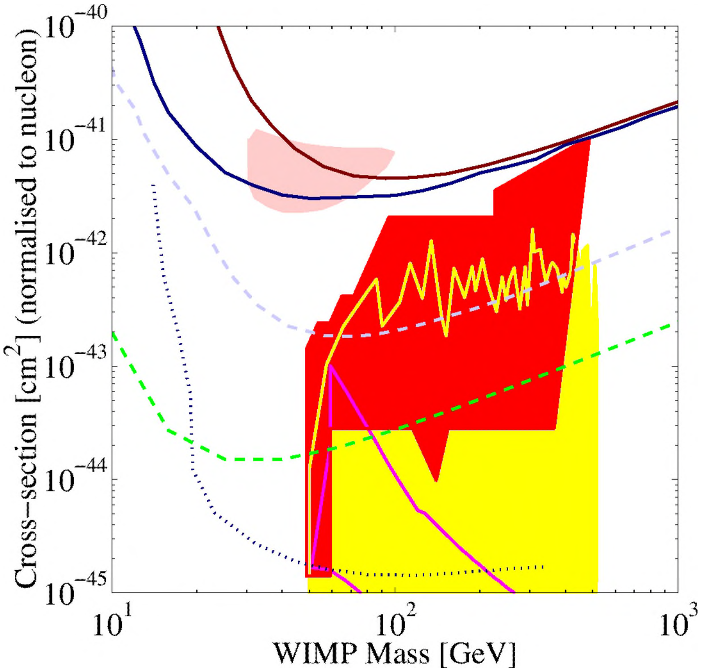

Figure 2: Comparison of theoretical expectations and experimental sensitivities for direct detection of neutralino dark matter. Plotted are the neutralino-nucleon spin-independent cross section vs the neutralino mass. Solid lines (from top to bottom: Edelweiss Benoit et al. [2001], CDMS Abusaidi et al. [2000]) are current experimental limits, and dotted and dashed lines are projected experimental sensitivities (from top to bottom: CRESST, CDMS-Soudan, Genius; solid region at upper left is the DAMA annual modulation region Bernadei et al. [2000]; the remaining regions are theoretical expectations (from top to bottom: MSSM with muon $g-2$ constraint Baltz and Gondolo [2001], MSSM Ellis et al. [2000a], and CMSSM Ellis et al. [2000b]). Figure generated with the Dark Matter Plotter Gaitskell and Mandic [2001].

What can be learned about particle physics with WIMP dark matter searches? From the observation of a signal in direct and indirect searches, one could determine the WIMP mass, the WIMP-nucleon cross section, and possibly the low-temperature WIMP annihilation cross section (although with some additional assumptions about the spin dependence of the interaction and the dark matter density in the halo). However, the WIMP relic density does not in general follow directly from these quantities; either it depends on the high-temperature annihilation cross section in the early universe, or it may be completely uncorrelated in the case of non-thermal WIMP production. So we are left with the basic question on what fraction of the dark matter, if any, the experiments would have detected Brhlik et al. [2001]. Even more difficult would be to find the values of the supersymmetric parameters on the basis of a dark matter detection. An example of the difficulties that arise is provided by the various conclusions reached in the analyses of the DAMA annual modulation signal in terms of WIMPs Bottino et al. [2001b], Ullio et al. [2001a], Smith and Weiner [2001]. The general conclusion we can draw is that we need accelerators to measure the values of the supersymmetric parameters, and that dark matter searches are useful as a guide.

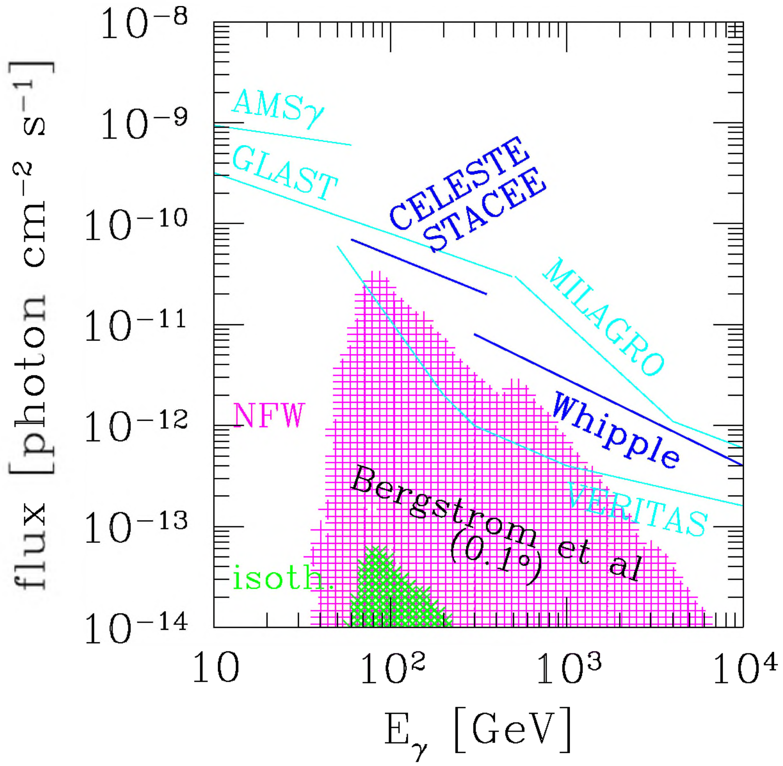

Figure 3: Gamma-ray line flux expected from neutralino annihilations in the galactic halo from the direction of the galactic center compared with experimental sensitivities. The region marked “NFW” is for a cuspy halo, and the region marked “isoth.” is for a standard halo. Theoretical models from Bergström et al. [1998]. Figure from Gondolo [2000a].

WIMP searches may provide information on the structure of dark halos. As described above, the clumpiness of dark matter in the Galaxy is currently under debate. Indirect signals from WIMP annihilation in the halo, such as positrons, antiprotons, and gamma-rays, are sensitive to the amount of clumpiness Moore et al. [2001], Baltz et al. [2001], Baltz and Edsjö [1999], and so could be used as a probe of the structure of the dark halo. Similarly, next-generation gamma-ray experiments could detect a WIMP annihilation signal from the Galactic center only if the dark matter density increases as a power law towards the Galactic center Bergström et al. [1998] (figure 3 from Gondolo [2000a] illustrates the expected gamma-ray line intensities from the direction of the galactic center together with experimental sensitivities and compares the expectations for cuspy and non-cuspy halos). Already, WIMPs are incompatible with a possible strong concentration of dark matter around the black hole at the galactic center, as WIMP annihilation would produce synchrotron emission well in excess of the observations Gondolo and Silk [1999], Gondolo [2000b]. This problem and suggestions to solve it by eliminating the WIMP concentration around the central black hole Ullio et al. [2001b], Milosavljević et al. [2001] were actively discussed at Snowmass. If WIMP signals are discovered, they will provide our most direct probe of the structure of the dark matter halo.

7. Conclusions

The past decade has been witness to a complete revision of our understanding of the universe. Older notions of an open, expanding universe have been supplanted with a more dynamic picture: that of a flat, albeit accelerating one. Importantly, a flat universe completely vindicates inflationary models. The accounting of visible matter in the universe falls dramatically short of what is needed for flatness: the burden of flatness thus falls on the existence of dark matter. Persistent observation should allow us to identify the baryonic component, and measuring its local density will be important for determining the local non-baryonic halo density and perhaps even help reveal its identity. Particle theories cast in a hot, expanding universe are rife with potential non-baryonic candidates, including WIMPS, axions and even more exotic entities. Experimental evidence for non-baryonic dark matter has kept up with the demand for its existence. Determining its precise nature will be a major challenge for the next decade.

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