Chapter 10
Observational Status of Dark Matter

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Abstract Identification of dark matter is one of the most urgent problems in cosmology. I describe the astrophysical case for dark matter, from both an observational and a theoretical perspective. I also review the current status of direct and indirect detection of dark matter, and review the prospects for future advances.

10.1 Introduction

Identification of dark matter is one of the most urgent problems in cosmology. It is most likely a weakly interacting particle that is yet to be discovered. One cannot eliminate exotic scalar fields as a model for dark matter or even alternative theories of gravity that dispense with dark matter. However theory favours a weakly interacting particle, to the extent that models such as SUSY provide a plethora of potential dark matter candidates. Moreover SUSY is highly motivated, so it behooves us to examine its predictions carefully. Of course should evidence for SUSY fail to emerge in the near future from the LHC one would have to reconsider a much wider range of dark matter models. These are not lacking. However because the SUSY LSP is such an appealing candidate on theoretical grounds, almost all dark matter searches are designed around the LSP. This overview will therefore focus on the observational motivations rather than the particle physics aspects of dark matter constraints on SUSY dark matter candidates such as the LSP, or NLSP, or even on non-SUSY candidates.

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10.2 The Observational Case

The first evidence for dark matter emerged from studies of galaxy clusters in the 1930s [1], on megaparsec scales. There is now overwhelming evidence for dark matter from kiloparsec scales to scales of hundreds of megaparsecs. Our best laboratories for dark matter are dwarf spheroidal galaxies. Most of these, a kiloparsec or less across, are almost pure dark matter. The ratio of dark matter to baryonic matter is an order of magnitude larger than the canonical value of 15 from the Big Bang. In the Milky Way, within say the orbit of the sun 8 kpc from the galactic center, there are approximately equal masses of ordinary matter and dark matter. Only on much larger scales does the dark matter to ordinary matter ratio approach the canonical value.

In fact this convergence to the primordial value is a function of the mass of the system. The Milky Way in its entirety, halo included, is deficient in ordinary matter by about a factor of 2. This is on a scale of 100 kpc. One has to go to galaxy groups and clusters, on a scale of order a Mpc, before the asymptotic value is attained, From here onto the horizon, the dark matter dominance amounts to a factor of 15. I conclude that dark matter is ubiquitous.

In addition, large-scale structure simulations demonstrate unambiguously that the dark matter is cold. Theory favours the idea that dark matter most likely is a weakly interacting massive particle (WIMP), with a favoured candidate being the LSP found in the theory of supersymmetry, in the mass range 0.001–10 TeV. The motivation for a WIMP arises from the so-called WIMP miracle: the relic abundance of dark matter arises naturally from production followed by thermal freeze-out of generic Majorana particle candidates with generically weak-like interactions if

$$1 \sim < n\sigma v > \sim \left(3 \times 10^{-26}\ \mathrm{cm^3/s}\right)(\Omega_\chi/0.3),$$

where σ is the self-annihilation cross-section. Of course there are numerous non-WIMP dark matter candidates ranging from very light particle such as axions (mass $\sim 10^{-6}$ eV) to GUT or even Planck-scale mass particles, as well as exotic scalar fields. However physicists are far from identifying the specific particle.

In this review I will focus on the astrophysics. I will describe the observational evidence for dark matter and illustrate how the field has evolved in recent years.

10.3 From Galaxies to Clusters

10.3.1 Galaxy Rotation Curves

Perhaps the best studied galaxy for dark matter is the Milky Way Galaxy. A new rotation curve model leads to estimates of the local dark matter density near the Sun at 8 kpc from the centre of the Galaxy of $0.235 \pm 0.030\ \mathrm{GeV\,cm^{-3}}$, and the total mass inside the Galaxy at 385 kpc, halfway to M31, of $(7.03 \pm 1.01) \times 10^{11} M_\odot$. This leads to a stellar baryon fraction of 0.072 ± 0.018, or about half of the primordial value [2].

Disk galaxies are generally dominated by dark matter. The dark matter problem assumed a central position in cosmology for two reasons. New developments in optical and in radio astronomy allowed dynamical measurements in the outer regions of individual spiral galaxies.

In the 1970s, Rubin and Roberts, among others, pioneered observations of extended flat rotation curves in the optical and 21 cm wave bands respectively. The first discussion of the need for unseen matter seems to be by Roberts and Rots (1973) [3] who argue that "The shapes of the rotation curves at large radii indicate a significant amount of matter at these distances and imply that spiral galaxies are larger than found from photometric measurements." Indeed an important paper that establishes the systematic flatness of rotation curves from optical data [4] builds on the earlier study led by Rubin [5]. They state that "Roberts and his collaborators deserve credit for first calling attention to flat rotation curves."

However uncertainty remained about the interpretation because of possible gradients in the disk mass-to-light (M/L) ratios (reviewed in [6] who state that "By the 1970s, flat rotation curves were routinely detected (Rogstad and Shostak 1972) [7] but worries about side bands still persisted, and a variation in M/L across the disk was a possible explanation."

At the same time there was new theoretical insight. This occurred in 1970. The first convincing dark matter inference was made by Freeman, [8] who modelled a self-gravitating exponential disk and demonstrated that the predicted decline of the rotation curve requires addition of dark matter to match the flat rotation curves known at the time. His transformational 1970 paper was the first indication from rotation curve analysis that the rotation curve is not determined by the mass distribution in the disk alone, but requires a contribution to its amplitude from an extended distribution of dark matter. This insight led to the concept of individual galaxies embedded in dark halos.

This was followed by a dynamical argument advanced by [9] that dark halos are required by global stability arguments in order to avoid non-axisymmetric instabilities and bar formation, A similar argument was given independently by [10]. This argument is now partly discounted because bulges stabilise and bars are virtually universal. Global stability requires a halo containing 60 % of the disk mass at the disk edge [11], but the presence of bulges may reduce this requirement. There does remain the issue of bulgeless galaxies however. Some massive galaxies are bulgeless and exceedingly flat [14], requiring a dark matter-dominated halo.

Freeman's argument was further refined by the notion of maximum disks, introduced in 1985 [12] because of the unknown disk M/L value. Maximum disks provide the maximum contribution of the disk mass to the rotation curve. Dark matter is required to account for 15 % of the rotation curve or 30 % of the mass within the scale of maximum rotation velocity [13], and dominates further out where the rotation curve flattens. Kinematical data demonstrates that most disks are indeed sub-maximal. Dark matter is universally accepted as required in disk galaxy halos, unless recourse is made to alternative theories of gravity such as MOND or TEVES, cf. [15].

Dwarf spheroidal galaxies are dark matter laboratories, dominated by dark matter. However the numbers defy interpretation. Feedback is readily adjusted to reduce the numbers of low mass dwarfs [16], but the most massive dwarfs predicted by LCDM simulations should be observed: they are not. Unorthodox feedback (AGN) may be a solution [17].

Most dwarfs have cores rather than cusps as predicted by CDM-only simulations. Supernova feedback may turn cusps into cores by gas sloshing [18]. Baryon feedback reconciles data with simulations that include baryon feedback and associated gas outflows [19].

The local dark matter density is poorly known. It is important for direct detection experiments. A disk component is predicted from dragging and disruption of satellites [20]. For an isothermal population of old tracers (A and F stars) [21], one find $\rho_{dm} = 0.003 \pm 0.008 M_\odot/\mathrm{pc}^3$ (90 per cent confidence level). However, the vertical dispersion profile of these tracers is poorly known. For a non-isothermal profile (similar to the blue disc stars from SDSS DR-7), the local density increases to $\rho_{dm} = 0.033 \pm 0.008 M_\odot/\mathrm{pc}^3$.

Galaxy clusters are a promising venue for testing dark matter predictions. The central dark matter cusp, if it exists, can be constrained by combining measurements of the stellar kinematics of the central galaxy with a strong lensing analysis of radial and tangential arcs near the cluster center (e.g., [22]). Outside the cluster core, the cluster mass profile can be measured through weak lensing (see [23]). The inferred cluster concentrations probe the cluster formation epoch. There is no consensus on whether the results are consistent with LCDM, or require additional large-scale power such as might be provided by non-gaussianity or by dynamical dark energy. X-ray studies of the hot intracluster medium (ICM) provide the gas pressure gradient. By assuming hydrostatic equilibrium, this yields the cluster mass (e.g., [24]). One can avoid assumptions about hydrostatic equilibrium via weak lensing, and also probe the ICM gas in a complementary fashion via the Sunyaev-Zeldovich effect on the cosmic microwave background (see, e.g., [25]).

Cluster counts are sensitive to the universal dark matter value, and in particular to the growth rate of density fluctuations. This is partially suppressed at recent epochs as dark energy dominates, and hence number counts of clusters are reduced [26].

10.4 Large-Scale Structure

10.4.1 Redshift Space Distortions

Galaxy redshift surveys have historically been the main probe of dark matter on large scales, those of clusters and of superclusters of galaxies. Redshift space distortions measure Ω_m. On smaller scales, these provide virial estimators [27] and are sensitive on quasilinear scales to the growth rate of density fluctuations. The new surveys (2DF, SDSS, WiggleZ) are able to probe the power spectrum of galaxies over $0.1 < z < 0.9$. Redshift-space distortions are measured on large scales, to over

$k < 0.3h/\text{Mpc}$. The growth rate is strongly dependent on Ω_m which is found to be 0.27 to about 5 % and is well probed over this redshift range [28].

10.4.2 Baryon Acoustic Oscillations

The acoustic imprint of the matter-radiation plasma prior to decoupling leaves baryon as well as radiation acoustic oscillations in the residual power spectra. The acoustic wavelength is a geometrical probe of the curvature of the universe. The baryon acoustic oscillations are especially powerful as a probe because one can slice the universe by redshift. Assuming the dark energy is a cosmological constant and allowing the spatial curvature to vary, recent studies of large galaxy samples find that this geometrical measurement of the curvature of universe yields $\Omega_k = 0.0035 \pm 0.0054$ [29, 30].

10.4.3 Cosmic Microwave Background

The radiation power spectrum has a high significance detection of the acoustic peaks. However projection onto the last scattering surface introduces additional degeneracies. These arise because the distance to last scatter (equivalently the age of the universe) is degenerate with respect to curvature. The spectral index adds further uncertainty. The situation has been improved with fine-scale measurements of the CMB anisotropies that probe the damping tail. Both the ACT and SPT experiments are able to measure the damping of the primordial primary CMB fluctuations and reconstruct the BAOs. To make progress one has to remove degeneracies that limit independent determinations of Ω_{DM}, Ω_b. For a Hubble constant prior ($h = 0.74$), one obtains $\Omega_b = 0.023 \pm 0.0012$, a more constraining result than obtained from primordial nucleosynthesis $\Omega_b = 0.022 \pm 0.002$ [31].

Other canonical parameters that have less than a few percent uncertainty are the scalar spectral index $n_s = 0.965$ and the normalisation to unit variance of galaxy count to mass fluctuations, $\sigma_8 = 0.8$, on mass scale $2.5 \times 10^{14} h^{-1} M_\odot$.

10.5 Future Prospects in Observation

Dark matter and dark energy surveys are complementary. The four leading methods in dark energy measurements are supernovae, BAO, weak lensing, and counts of clusters of galaxies. These measure various nearly orthogonal combinations of dark matter and dark energy, and are primarily being developed to constrain theories of cosmic acceleration. However improved dark matter diagnostics are an inevitable corollary. These methods are reviewed in [32]. The conclusions are that:

(a) Type Ia supernovae provide immense precision for measuring distances relative to local calibrators (i.e., distances in h^{-1} Mpc) at $z \sim 0.5$, with future surveys designed to achieve statistical errors of 0.01 mag or less (or ∼0.5 % in distance). However systematic uncertainties may be dominant, including imperfect photometric calibration, redshift evolution in the population of SNe, and the effects of dust extinction.

(b) The BAO method augments the SN method by measuring absolute distances (in Mpc), assuming a calibration of the sound horizon. Spectroscopic BAO measurements cover a greater comoving volume and measure $H(z)$ directly in addition to the distance-redshift relation. Cosmic variance-limited BAO surveys provide sensitivity to dark energy over the range $1 < z < 3$, independently of supernovae. However if the universe were more inhomogeneous than usually assumed over 100 Mpc scales, there would be considerable uncertainty in BAO approaches.

(c) Weak lensing measurements probe both the distance-redshift relation and the linear growth rate of structure. One challenge is to obtain an accurate PSF which affects galaxy images and must be determined to very high accuracy (∼0.001). Other major challenges are calibration of photometric redshift distributions to a similar level of accuracy, and correction for the intrinsic alignment of galaxies.

(d) Cluster abundance measurements measure the growth rate of structure and can thereby probe alternative gravity models. A major challenge is obtain the calibration of the cluster mass scale to better than 1 %. The combination of new x-ray and SZ surveys should help refine cluster mass determinations.

10.6 Future Prospects in Astrophysical Theory

Theory lacks adequate resolution and physics. Of course these issues are intricately connected. One needs to tackle baryon physics and the associated possibilities for feedback. At this point in time, the leading simulations, such as the ERIS cosmological simulation of the MWG, provide at best 10 pc resolution in a state of the art simulation with gas and star formation. The gas and star formation physics is included in an ad hoc way, because of the resolution limitation. For example, a star formation threshold in density is adopted. and varied to explore possible sensitivity of the results. However in reality it is the unresolved subgrid physics that determines the actual threshold, if one even exists. Mastery of the required subparsec-scale physics will take time, but there is no obvious reason why with orders of magnitude improvement in computing power we cannot achieve this goal.

For the moment, phenomenology drives all modelling. This is true especially for local star formation. A serious consequence is that physics honed on local star-forming regions, where one has high resolution probes of star-forming clouds and of ongoing feedback, may not necessarily apply in the more extreme conditions of the early universe.

One issue that arises frequently is whether the perceived challenges to LCDM justify a new theory of gravity. From MOND onwards, there are any number of alternative theories that are designed to explain certain observations. However none can explain all observations, as is often said to be the case for LCDM. But to the extent that any unexplained anomalies exist, these are invariably at no more than the 2-sigma level of significance. It seems to me that such "evidence" is not adequate motivation for abandoning Einstein-Newton gravity. While it is overwhelmingly clear that there are many potential discrepancies with LCDM, we have certainly not developed the optimal LCDM theory of galaxy formation. Current theory does not adequately include the baryons nor do we reliably understand star formation, let alone feedback.

Here is a summary of some of the key reasons that LCDM does not provide a robust explanation of the following observations: I list 10 examples.

- (a) Massive bulgeless galaxies with thin disks are reasonably common [14]. Simulations invariably make thick disks and bulges. Indeed the bulges are typically overly massive relative to the disks for all galaxies other than S0s. Massive thin disks are especially hard to simulate unless very fine-tuned feedback is applied. A consensus is that the feedback prescriptions are far from unique. One appealing solution involves supernova feedback. This drives a galactic fountain that feeds the bulge. A wind is driven from the bulge where star formation is largely suppressed for sufficiently high feedback [33]. Another proposal includes radiation pressure from massive stars as well as supernovae. The combined feedback helps expand the halo expansion, thereby limiting dynamical friction and bulge formation [34].
- (b) Dark matter cores are generally inferred in dwarf spheroidal galaxies, whereas LCDM theory predicts a cusp, the NFW profile. Strong supernova feedback can eject enough baryons from the innermost region to create a core [35].
- (c) The excessive predicted numbers of dwarf galaxies are one of the most cited problems with LCDM. The discrepancy amounts to orders of magnitude. The issue of dwarf visibility is addressed by feedback that ejects most of the baryons and thereby renders the dwarfs invisible, at least in the optical bands. There are three commonly discussed mechanisms for dwarf feedback: reionization of the universe at early epochs, supernovae and tidal stripping. AGN-driven outflows via intermediate mass black holes provide another alternative to which relatively little attention has been paid [36].

  Reionization only works for the lowest mass dwarfs. The ultrafaint dwarfs in the MWG may be fossils of these first galaxies [37]. It is argued that supernova feedback solves the problem for the more massive dwarfs [38]. However this conclusion is disputed by [17] for whom prediction in simulations of massive dwarfs is a problem. These authors argue that the relatively massive dwarfs should form stars, and we see no counterparts of these systems, apart possibly from rare massive dwarfs such as the Magellanic Clouds.

  One can also appeal to a lower star formation efficiency (SFE) in dwarfs, plausibly associated with low metallicities and hence low dust and H_2 content. Models based on metallicity-regulated star formation can account for the numbers and radial distribution of the dwarfs by a decreasing SFE [39]. This explanation is disputed by [40], who infer a range in SFEs for the dwarfs of some two orders of magnitude. A similar result appeals to the halo mass threshold below which star formation must be suppressed to account for the dwarf luminosity function, with the stellar masses of many observed dwarfs violating this condition [41]. Finally, tidal stripping may provide a solution [42], at least for the inner dwarfs.

- (d) Another long-standing problem relates to downsizing. Massive galaxies are in place before lower mass galaxies as measured by stellar mass assembly, and their star formation time-scales and chemical evolution time-scales at their formation/assembly epoch are shorter. It is possible to develop galaxy formation models with suitable degrees and modes of feedback that address these issues. However a major difficulty confronted by all semi-analytical models (SAMs) is that the evolution of the galaxy luminosity function contradicts the data, either at high or at low redshift. The SAMs that are normalised to low redshift and tuned to account for the properties of local galaxies fail at high redshift by generating too many red galaxies [43]. Too few blue galaxies are predicted at $z = 0.3$. This problem has been addressed by including AGB stars in the stellar populations. This fix results in a more rapid reddening time-scale by speeding up the evolution of the rest-frame near-infrared galaxy luminosity function [44]. There is a price to be paid however: now there are excess numbers of blue galaxies predicted at $z = 0.5$.
- (e) The luminosity function problem is most likely related to another unexplained property of high redshift galaxies.The SSFR evolution at high z is very different from that at low z. Essentially, it saturates. One finds an infrared main sequence of galactic star formation rates: SFR versus M_* [45].
- (f) Much has been made of nearby rotation curve wiggles that trace similar dips in the stellar surface density that seemingly reduce the significance of any dark matter contribution. Maximum disks optimise the contribution of stars to the rotation curve, and these wiggles are most likely associated with spiral density waves. A similar result may be true for low surface brightness gas-rich dwarf galaxies [46]. High mass-to-light ratios are sometimes required, but these are easily accommodated if the IMF is somewhat bottom-heavy. The case for IMF variations has been made for several data sets, primarily for early-type galaxies (e.g. [47]). The LSB dwarfs are plausible relics of the building blocks expected in hierarchical formation theories.
- (g) Spiral arms are seen in the HI distribution in the outer regions of some disks. This tells us that significant angular momentum transfer is helping feed in the optical inner disk. The baron self-gravity is large enough that one does not for example need to appeal to a flattened halo, which might otherwise be problematic for the DM model [48].
- (h) The slope and normalisation of the baryon Tully-Fisher relation does not agree with the simplest LCDM prediction. The observed slope is approximately 4, similar to what is found for MOND [49]. LCDM (without feedback) gives a slope of 3 [50], but fails to account for the observed dispersion and possible curvature.
- (i) The baryon fraction in galaxies is some 50 % of the primordial value predicted by light element nucleosynthesis. These baryons are not in hot gaseous halos [51]. Convergence to the universal value on cluster scales is controversial: convergence to the WMAP value is seen for x-ray clusters above a temperature of 5 keV [52],

but could be as large as 30 % even for massive clusters [53, 54]. If the latter discrepancy were to be confirmed, one would need significant bias of baryons relative to dark matter, presumably due to feedback, on unprecedentedly large scales.

- (j) Bulk flows are found over 100 Mpc scales that are up to several deviations larger than expected in LCDM [55]. The technique primarily uses Tully-Fisher and fundamental plane galaxy calibrators of the distance scale. An x-ray approach, calibrating via kSZ, claims the existence of a bulk flow out to 800 Mpc [56]. However the discrepancies with LCDM are controversial because of possible systematics.

10.7 Direct Detection

Many weakly interacting massive elementary particles, if dark matter, must pass through us every second, about $10^6\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$. Detection techniques involve large masses of some suitable material that is studied for weak signals from the rare WIMP interactions. The detectors are located deep underground or under mountains, to avoid spurious cosmic-ray induced events. The nuclear recoil signatures include ionisation, phonons and scintillation, and ideally require all of these effects.

Event detections have been reported by several experiments. These include CDMS2 (X kg germanium), CoGeNT and CRESST-II. However none of these have sufficient significance to be attributed to dark matter. The one exception is the NaI scintillation experiment, DAMA/LIBRA, now running for 14 years at Gran Sasso. This experiment uses solar modulation to enhance the direct detection signal and reports a 8.9 σ detection. The report of an almost 3 sigma detection of annual modulation in CoGeNT has produced considerable excitement, but tension remains with the other experiments in both amplitude of the modulation and scattering cross-section. The competing experiments rule out most explanations, including incoherent spin-independent scatterings. However windows remaining are via coherent spin-dependent scatterings by light WIMPs on protons, or via spin-dependent scatterings with isospin suppression of neutron scatterings. Alternatively, allowance for streams in the local dark matter density adds sufficient uncertainty to reduce these tensions [57]. The allowed WIMP mass range is 5–20 GeV. Discounting DAMA/LIBRA, the allowed window for neutralinos extends up to several TeV.

10.8 Indirect Detection

Halo Majorana fermion WIMPs occasionally annihilate today into energetic particles: $\nu, \gamma, \bar{p}, e^+$. They are also trapped by the sun and other stars. All of these lead to possible signals. Introduction of a primordial asymmetry reduces the annihilation signal relative to the direct detection signal, at the expense of increasing the annihilation rate for the subdominant symmetric component [58].

10.8.1 Helioseismology

WIMP scattering on protons modifies the solar temperature profile. Low mass ($m_\chi \gtrsim 5$ GeV) WIMPS are trapped and fill the solar core and modify $T(r)$. This leads to a detectable signal from solar physics-motivated experiments. Helioseismology has successfully studied p-modes from the outer regions of the sun. These measurements are sensitive to the temperature profile. The predicted signal probes solar structure. The revised solar opacities have thrown this field into disarray, since the totality of solar data, including solar neutrinos and helioseismology, can no longer be fit by the solar standard model. Addition of low mass WIMPs adds a new degree of freedom, and affects the helioseismology signal because of the modified solar temperature profile. The effect is especially strong for 5 GeV WIMPs that interact via spin-dependent scatterings. If their abundance is high enough, e.g. if annihilations are partially or totally suppressed, one can even eliminate them as a DM candidate. Annihilation suppression in favour of a built-in asymmetry is reasonably natural for WIMPs in the mass range 5–10 GeV. Asymmetric dark matter (aDM) provides a compelling explanation for the observed baryon fraction $\sim m_p/m_\chi$, admittedly at the price of losing the perhaps less "natural" SUSY LSP-motivated explanation for Ω_χ. Collider constraints on the large annihilation cross-sections required for the Majorana component require a light mediator particle that allows new annihilation channels that are weakly coupled to the standard model [59], although these limits are only restrictive for 10 GeV WIMPs if elliptical galaxy halo shapes are introduced as a constraint on the self-interaction dark matter cross-section.

10.8.2 High Energy Cosmic Rays

Rare particles in cosmic rays, most notably $\bar{p}$ and e^+, are a unique signature of dark matter annihilations. The search for high energy antiprotons has led to no surprises so far, although in principle because secondary $\bar{p}$ from cosmic ray spallations are Lorentz-boosted, there is a potential signal to be sought below 1 GeV. However solar modulation effects make this a difficult measurement.

Cosmic ray positrons have provided a far more productive target. Hints of a signal came with the HEAT balloon-borne experiment that detected a rise in the positron fraction $e^+/(e^+ + e^-)$ above $\sim$10 GeV. This result has been confirmed by the PAMELA satellite to $\sim$100 GeV, and most recently by FERMI to $\sim$200 GeV [60], and cannot easily be attributed to cosmic ray secondary production of e^+. Additional sources are needed. The associated cosmic ray electron flux has been measured by FERMI to $\sim$1 TeV , and to $\sim$3 TeV by HESS and most recently by MAGIC, [61] The spectrum shows a drop at a few TeV.

Possible explanations include nearby astrophysical positron sources, dark matter decays or dark matter annihilations. The most likely sources are nearby pair-wind pulsars by Milagro at a median gamma ray energy of 20 TeV. More distant pulsars will also contribute, but the nearest sources dominate in typical cosmic ray diffusion models. Supernova remnant acceleration models also present a viable option [62]. Such astrophysical solutions will be tested by the predicted anisotropy, which in the pulsar explanation already is close to the FERMI one-year upper limit [63].

The dark matter explanation of the positron excess requires a TeV particle. In the case of annihilations, considerable local substructure is required to give a boost to the annihilation rate. A halo dark matter clumpiness factor as large as 10^3 is usually invoked in order to boost the signal, since at a specified dark matter density (determined by the galactic rotation curve), the annihilation flux is inversely proportional to the square of the neutralino mass.

Theory struggles to generate such large clumpiness factors. One solution is via a Sommerfeld enhancement for ultracold dark matter. This might be expected for substructure in cold dense clumps (of order solar mass or below) in CDM. In this case, one achieves a local annihilation cross-section as required of order $10^{-23}\ \mathrm{cm^3\,s^{-1}}$. Production of excessive gamma rays from the inner galaxy is avoided if tidal destruction of substructure destroys most of the boost in the bulge region [64]. Extragalactic constraints are constraining but are unable to definitively eliminate the annihilation interpretation of the essentially local positron/electron fluxes. The strongest constraints include the effects of prolonging the decoupling of the CMB as well as diffuse gamma ray signals from dwarfs, but are insensitive for TeV WIMPs.

10.8.3 Gamma Rays

Recent data from the Fermi satellite has constrained dark matter models. The FERMI energy range spans 0.02–300 GeV, with angular resolution of 5 degrees to 5 arcmin, depending on the energy, and energy resolution of around 10 %. Theory of dark matter annihilations (and decays) predicts several gamma ray smoking guns. These include a harder spectrum than expected via π^0 decay channels, spectral bumps and lines, and inverse Compton gammas, as well as radio synchrotron photons from high energy electrons and positrons. The ideal laboratory for dark matter detection via annihilations is to look at dark matter laboratories such as gamma rays from nearby dark matter-dominated dwarf galaxies. Hitherto only upper limits have been set on gamma ray emission, with Fermi setting stronger limits at lower particle masses, and the ACT arrays at higher masses. For thermal decoupling, the neutralino mass must exceed $\sim$30 GeV from Fermi dwarf [65] and CMB [66] constraints.

10.8.4 The WMAP Microwave Haze

Dark matter annihilations in the galactic bulge lead to a possible radio synchrotron signal. The WMAP quasi-spherical haze residuals in the lowest frequency WMAP channels has been interpreted as such a signal [67], and led to the prediction that the same high energy electrons would lead to an inverse Compton gamma ray flux, produced by Compton scattering of e+e- on the interstellar radiation field. This leads to an expected Fermi haze, once known templates were subtracted [68]. Analysis of the diffuse gamma ray emission in the inner bulge, once known templates were subtracted, revealed the presence of enormous bubble-like features, north and south of the Galactic Center [69]. These clearly are not due to dark matter injection but rather arise from an immense explosion some tens of millions of years ago that requires local reacceleration over tens of degrees (at least a kpc) in order to account for the short electron lifetimes. The dark matter contribution has been recently revived. In addition to this large-scale diffuse emission, there is an unexplained spectral distortion within the central degree where part of the Fermi haze is unexplained by known sources or foregrounds. A second diffuse component seems to be required in addition to cosmic ray-induced gammas in the lower energy channels. A reasonable spectral and morphological fit is attained with neutralinos in the mass range 7–45 GeV for different annihilation channels with leptonic or hadronic final states [70]. The Fermi collaboration remains agnostic on these results, having produced significant unexplained residuals when all known sources are subtracted out in the GC region [71]. The origin of the possibly associated WMAP haze, also confirmed as a new CMB foreground component [72], still remains a mystery. Indeed the same electron component postulated for the Fermi spectral excess generates a synchrotron component that has been interpreted as contributing to the WMAP haze signal [73].

10.8.5 Decaying Dark Matter

Another dark matter option is via decays of massive neutralinos. The required decay time is $\sim 10^{26}$ sec [74]. The morphological differences between annihilating and decaying dark matter provides a distinguishable characteristic [75]. Decaying dark matter in galaxy clusters turns out to be the best probe since the nearest clusters just fill the Fermi beam and thereby give optimal sensitivity to a possible diffuse signal from the cluster. FERMI constraints effectively eliminate decaying dark matter as an option [76].

10.9 The Future

10.9.1 The Sun

As the sun orbits the galaxy, it traps massive neutralinos that scatter off protons. These accumulate in the solar core where they annihilate, producing energetic neutrinos that may induce signals via muon production in experiments under ice such as IceCube, or under water such as ANTARES. Future scaled-up experiments should be capable of imaging the sun if neutralinos indeed annihilate at masses up to a TeV.

If WIMPs do not self-annihilate, as would be the case for asymmetric WIMPs, the numbers build up in the sun and lead to another signal. At low masses, WIMPs fill the core of the sun and WIMP recoils redistribute the solar temperature profile. This effect is optimised at the lowest masses that do not evaporate from the sun ($\sim$5 GeV) but still gives a helioseismological signal for WIMPs below $\sim$20 GeV. This effect will be especially relevant once solar g-modes are detected [77]. There is also a potentially detectable solar neutrino signal [78] if WIMPs are allowed to accumulate and scatter via spin-dependent couplings where direct detection limits are weak.

10.9.2 Direct Detection

How low do we need to go in direct detection in order to eliminate SUSY-motivated WIMPs? Tonne-scale detectors are under construction [79] and should be able to go well beyond the LHC benchmark models in terms of sensitivity to dark matter.

10.9.3 Air Cerenkov Telescopes

Another technique that allows sensitive determinations of gamma rays measures atmospheric Cerenkov radiation from muon-poor air showers. These are induced by TeV gamma rays and have adequate resolution to resolve out identifiable discrete sources. An ultimate Cerenkov telescope array with 10 km^2 area can probe down to 10 GeV and achieve SUSY-model sensitivities comparable and complementary to those of ton-scale direct detection experiments [80]. ACTs provide the most promising avenue for complementing direct detection.

10.9.4 Strange Stars

A neutron star is a dark matter collector. If neutron matter is metastable, the energy from WIMP annihilations may trigger the conversion of a neutron star to a quark star [81]. The rest mass energy of the neutron star is liberated in high energy particles, neutrinos and photons. One might be able to observe such an event, in a region of high dark matter density, as a gamma ray burst of unusual characteristics. The explosion is intrinsically off-centre because of the thermal distribution of WIMPS that spans the inner part of the neutron star core. The resulting anisotropic ejection can provide a momentum kick to the surviving quark star.

10.9.5 The Galactic Centre

There is a black hole of mass $4 \times 10^6 M_\odot$ identified with the radio source SagA* at the Galactic Centre. Theoretical arguments suggest that when it formed it may have acquired a steep dark matter cusp that would yield an enhanced annihilation signal in gamma rays. The characteristic features of this spectrum are an exponential plus flat power-law, and no variability. HESS data confirms the exponential cut-off above a few TeV and no detectable variability [82], but the power-law is too steep for an annihilating particle with a unique mass. Addition of Fermi data confirms a complex inflected spectrum [83]. There are two possible interpretations: an astrophysical source, with novel spectral characteristics, or dark matter annihilations of a TeV particle together with a steep power-law contribution from an astrophysical source (and/or a lower mass annihilating particle).

10.9.6 LHC

The LHC reach overlaps with indirect dark matter detection experiments. The SUSY benchmark models for direct detection are accessible at the LHC and there is complementarity with indirect searches [84]. However the ultimate sensitivity to these models will come from combining direct detection with ACT array telescopes.

10.10 Summary

The case for dark matter is powerful. Alternative theories of gravity are far more complex than Einstein gravity. For example, both vector and tensor degrees of freedom are invoked in TEVES in addition to the usual scalar potential. And even with this extra freedom, a vigorous debate rages as to whether there remain observations that defy explanation. Motivation for exploring alternative gravity requires more than the need to test Einstein's theory, since there are a vast variety of alternatives waiting in the wings. Indeed Einstein gravity awaits its first major confrontation with the hopefully imminent detection of gravity waves. Rather, one needs a discrepancy of significance comparable to the precession of Mercury's perihelion advance that motivated Einstein to go beyond Newtonian gravity. The astronomical data show no such evidence. This is certainly true for galaxies and galaxy clusters. To reconcile with LCDM, there is a price to pay, namely that of astrophysical complexity. But this is hardly headline news. We do not invoke new physics to account for unusual weather patterns.

On the largest scales, there are intriguing hints of possible anomalies. These range from bulk flows to CMB features. However the data is too compromised by possible systematics to reach any robust conclusions. The greatest weakness in the dark matter saga is that we have not identified the nature of the dark matter itself.

This is a serious issue. But patience is counselled. We live at a moment when the new discipline of particle astrophysics is flourishing. Many experiments are underway or being planned to search for direct and indirect traces of dark matter, generally on the assumption that it is a weakly interacting elementary particle. The LHC is searching for hints of particle candidates for dark matter, motivated by supersymmetry. These arguments may be wrong. Theorists may be guilty of hubris. But as we finally approach the ability to probe large swathes of SUSY-motivated parameter space, the tantalizing claims of "discoveries" of dark matter signatures, hitherto unconfirmed, contribute to a feeling of growing excitement in the particle astrophysics community. We should revisit the situation in a decade. If by then we have not identified a dark matter particle candidate, I certainly will be more enthusiastic about exploring alternative gravity theories. Perhaps we will identify a theory that simultaneously accounts for dark matter and dark energy.

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