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Understanding the Dark Universe

Dark matter: The astrophysical case

La matière noire : Le cas de l'astrophysique

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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.

RÉSUMÉ

L'identification de la matière noire est l'un des problèmes les plus urgents de l'astrophysique. Je décris l'aspect astrophysique du problème, dans une perspective observationnelle autant que théorique.

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 (Lightest SUSY Particle) 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 specific dark matter candidates. First, however, I summarise the astronomical evidence for dark matter.

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 centre, there are approximately

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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 1 GeV–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

$$H \sim \langle n\sigma v\rangle \sim \left(3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\right)(\Omega_\chi/0.3)$$

where σ is the self-annihilation cross-section and H is the Hubble parameter. Of course there are numerous non-WIMP dark matter candidates ranging from very light particle such as axions (mass $\sim 10^{-5}$ eV or less) to keV sterile neutrinos, which constitute “warm” dark matter [2], 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.

3. From galaxies to clusters

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 [3].

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) [4] 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 [5] builds on the earlier study led by Rubin [6]. 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 [7] who state that “By the 1970s, flat rotation curves were routinely detected (Rogstad and Shostak, 1972) [8] but worries about radio 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 [9], 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 [10] 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 [11]. 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 [12], but the presence of bulges may reduce this requirement. There does remain the issue of bulgeless galaxies however, which are often exceedingly flat [13], requiring a dark matter-dominated halo.

Freeman’s argument was further refined by the notion of maximum disks, introduced in 1985 [14] 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 [15], 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. [16].

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 [17], but the most massive dwarfs predicted by LCDM simulations should be observed: they are not. Unorthodox feedback (AGN) may be a solution [18].

Most dwarfs have cores rather than the cusps predicted by CDM-only simulations. Supernova feedback may turn cusps into cores by gas sloshing [19], more recently addressed in [20]. Baryon feedback reconciles data with simulations that include associated gas outflows [21].

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 [22]. For an isothermal population of old tracers (A and F stars) [23], one find $\rho_{dm} = 0.003 \pm 0.008\ \mathrm{M_\odot/pc^3}$ (90% 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 $\rho_{dm} = 0.033 \pm 0.008\ \mathrm{M_\odot/pc^3}$.

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 centre, e.g., [24]. Outside the cluster core, the cluster mass profile can be measured through weak lensing, see [25]. 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., [26]). 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., [27]).

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 [28].

4. Large-scale structure

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 [29] and are sensitive on quasilinear scales to the growth rate of density fluctuations. The new redshift 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 $k < 0.3h/\mathrm{Mpc}$. 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 [30].

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 $\Omega_k = 0.0035 \pm 0.0054$ [31,32].

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 [33] and SPT [34] 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 $\Omega_b = 0.022 \pm 0.002$ [33].

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 $2.5 \times 10^{14} h^{-1}\ \mathrm{M_\odot}$.

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 [35]. 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) (where $H_0 = 100h$ km/s/Mpc) at $z \sim 0.5$, with future surveys designed to achieve statistical errors of 0.01 mag or less (or $\sim 0.5\%$ in distance). However systematic uncertainties may be dominant, including imperfect photometric calibration, redshift evolution in the population of Type 1 supernovae, 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 point spread function 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 to obtain the calibration of the cluster mass scale to better than 1%. The combination of new X-ray and SZ surveys should help to refine cluster mass determinations.

6. Future prospects in astrophysical theory

Numerical simulations lack adequate resolution and, more importantly, any fundamental understanding lacks essential 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 Milky Way Galaxy, 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 the standard cold dark matter model (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 [13]. Simulations invariably make thick disks and bulges. Indeed the bulges are typically overly massive relative to the disks for all galaxies other than lenticular galaxies. 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 [36]. 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 [37]. Another proposal includes radiation pressure from massive stars as well as supernovae. The combined feedback helps expand the halo, thereby limiting dynamical friction and bulge formation [38].
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 [39,20].
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: reionisation 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 [40].
Reionisation only works for the lowest mass dwarfs. The ultrafaint dwarfs in the MWG may be fossils of these first galaxies [41]. It is argued that supernova feedback solves the problem for the more massive dwarfs [42]. However this conclusion is disputed by [18] 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 [43]. This explanation is disputed by Boylan-Kolchin et al. [44], who infer a range in SFEs for the dwarfs that span over 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 [45]. Tidal stripping may provide a solution [46], at least for the inner dwarfs. Finally, there is always warm dark matter. Sterile neutrinos of mass of a keV or so would, via free-streaming, reduce the dwarf number density and also soften dark matter cores. But the heavy price to pay is that the suppressed power delays the onset of galaxy formation, perhaps unacceptably [47].

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 [48]. 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 [49]. There is a price to be paid however: now there is an excessive number 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, in a plot of star formation rate versus stellar mass [50].
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 [51]. 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. [52]). 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 [53].
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 [54]. LCDM (without feedback) gives a slope of 3 [55], 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 [56]. 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 [57], but could be as large as 30% even for massive clusters [58,59]. 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 [60]. 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 [61]. However the discrepancies with LCDM are controversial because of possible systematics.

7. 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. I have not considered dark energy in this review. One can hardly avoid adding that dark energy provides an equally enormous challenge to known physics, and it might not come as too great a surprise were one to eventually find that they shared a common solution. But we are very far from such a paradigm.

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 beyond-the-standard model physics, including 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 tantalising 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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