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Part I

Dark matter in cosmology

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Particle dark matter

Gianfranco Bertone and Joseph Silk

1.1 Introduction

Dark matter is surely at the heart of modern cosmology. It undoubtedly pervades the Universe, unless we are being completely misled by diverse data sets, yet it has not been detected. The possible connection with proposed extensions of the Standard Model of particle physics, currently being searched for at accelerators, makes the identification of dark matter one of the highest priority goals in cosmology and particle physics. In this chapter we provide an introduction to the dark matter situation and an overview of the material presented in this book.

Dark matter has a venerable history (see e.g. ref. [742] for an historical account). One could even cite Solar System arguments for dark matter, including anomalies in the orbit of Uranus and the advance of Mercury's perihelion. One led to the discovery of a previously dark planet, Neptune, the other to a new theory of gravitation. Similar parallels may be drawn today. There are advocates of new theories of gravitation (see Chapter 6), who seek to dispense with dark matter, and there are observations of large-scale structure, such as gravitational lensing, the cosmic web and the cosmic microwave background acoustic fluctuations, that are notoriously difficult to reproduce in the absence of a dominant component of cold dark matter (CDM) particles (we refer the interested reader to Chapter 4, which includes an introduction to gravitational lensing in the context of the CDM paradigm, and its potential to discriminate CDM from modified-gravity theories). A strong case for the dominance of dark matter in galaxy clusters was made as long ago as 1933 [1977]. It is remarkable that our understanding of its nature has not advanced since then. Of course, modern observations have

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led to an increasingly sophisticated exploration of the distribution of dark matter, now confirmed to be a dominant component relative to baryonic matter over scales ranging from those of galaxy haloes to that of the particle horizon.

1.2 The baryon budget

It is useful to begin our overview by noting that diffuse baryons cannot account for the dark matter. There are three methods for determining the baryon fraction in the high-redshift Universe. The traditional approach is via primordial nucleosynthesis of ^{4}He, ^{2}H and ^{7}Li, and it provides a unique value of $\Omega_\mathrm{b} = 0.04 \pm 0.02$ which is generally consistent with recent data. There are, however, some potential difficulties, such as the tension between ^{2}H and ^{4}He, on the one hand, which in principle are the most sensitive baryometers, and ^{7}Li, whose abundance in metal-poor stars may or may not be depleted by stellar convection [498] (see Chapter 28). An independent probe of Ω_b comes from measuring the relative heights of the peaks in the acoustic temperature fluctuations of the cosmic microwave background. With conventional priors, the data yields excellent agreement between the baryon abundance at redshift $z \approx 1000$ and that inferred from nucleosynthesis at $z \approx 10^9$. A third independent measure of Ω_b, this time at $z \approx 3$, comes from modelling the Lyman alpha forest of the intergalactic medium (IGM). This depends on the square root of the ionizing photon flux, which in this redshift range is due predominantly to quasars and is measured. These are high-z measurements. At $z \sim 0$, cold intergalactic gas at the current epoch is sparser, and its detection ideally requires a far ultraviolet telescope such as FUSE. However, the IGM is found to dominate the known baryon fraction today, and amounts to about 30% of the total baryon fraction.

The most reliable present-epoch measure of the primordial baryon fraction comes from galaxy clusters, which are usually considered to be laboratories that have retained their primordial baryon fraction. The observed baryon fraction in massive clusters is about 15%, which is consistent with $\Omega_\mathrm{b} = 0.04$ for $\Omega_\mathrm{M} = 0.26$, the WMAP5-preferred value being $\Omega_\mathrm{b} h^2 = 0.02273 \pm 0.00062$ with Hubble parameter $h = 0.719 \pm 0.027$. However, there is a shortfall: the hot diffuse gas in clusters only accounts for 90% of the baryons expected from primordial nucleosynthesis considerations [987]. There are indications, motivated as much by theory as by observations, that the remaining baryons are in the warm-hot intergalactic medium (WHIM) at a temperature of 10^5–10^7 K [502]. According to the simulations, in fact, 30% or more of the baryons are actually heated by a combination of gravitational clustering and galactic outflows by the present epoch and remain diffuse. Observations seem to confirm the existence of some WHIM, which may contain as much as 50% of all the baryons in the Universe, in particular via detection of redshifted rest-frame UV OVI absorption towards quasars, extended soft X-ray emission near clusters, and OVII/OVIII X-ray absorption along lines of sight to active galactic nuclei (AGN) [1508], although the statistical significance of this detection is still controversial [1628]. Although too few lines of sight have so far been probed to confirm the expected WHIM mass fraction, the baryons are in plausible environments with plausible heating sources, and with every expectation of being present at the anticipated level.

1.3 The case for cold dark matter: good news and bad news

There are some noteworthy success stories for CDM. First and foremost is its success in predicting the initial candidates for structure formation, which culminated in the discovery of the temperature fluctuations in the cosmic microwave background (CMB). The amplitude of the Sachs–Wolfe effect was predicted to within a factor of 2, under the assumption, inspired qualitatively by inflation but quantitatively by the theory of structure formation via gravitational instability in the expanding Universe, of adiabatic scale-invariant initial density fluctuations. The first direct test of this theory came with the detection and mapping of the acoustic peaks. These are the hallmarks of galaxy formation, first predicted some three decades previously, and demonstrate the imprint of the density fluctuation initial conditions on the last scattering surface of the CMB at $z \approx 1000$. The first six peaks have been measured at high resolution by the ACBAR experiment [1635], and fit precisely onto the best-fit WMAP5 power spectrum [729]. This is a remarkable confirmation of the essential correctness of the hypothesis that approximately scale-invariant primordial adiabatic density fluctuations are the origin of structure in the Universe. It is also worth mentioning that the fluctuations seen in the CMB can be extrapolated to the present, to predict the peculiar velocities that distort redshift-space clustering. This extrapolation has been found to be in agreement with direct observations from galaxy surveys, thus providing a remarkable test of the CDM model [1550].

Another dramatic demonstration of the essential validity of CDM has come from the simulations of the large-scale structure of the Universe (see Chapter 2). Once the initial conditions, including gaussianity, are specified, growth occurs by gravitational instability, and the sole requirements on dark matter are that it be weakly interacting and cold. Thus was born CDM, and the CDM scenario works so well that we cannot easily distinguish the artificial universe from the actual Universe mapped by means of redshift surveys [1791]. More to the point, perhaps, is that the simulations are used to generate mock galaxy catalogues and maps that yield the observed correlations and clustering of galaxies, and precise values of the cosmological parameters, in combination with the CMB maps and the other cosmological probes.

Dark-matter-dominated haloes of galaxies are another generic success of CDM, as mapped out by rotation curves. However, the detailed predicted properties of haloes do not seem to be well matched to observations in the inner regions of many disk galaxies [1672]. Dark matter cusps (density $\rho \propto r^{-\alpha}$ with $1 < \alpha < 1.5$) are a robust CDM prediction [1504] and are not found in most low surface brightness dwarfs observed at high resolution [1863] (see Chapter 5 for a discussion of DM distribution at the centre of galaxies). Observational issues, however, can complicate the modelling of the data in well-studied examples [1887]. Nor is the predicted dark matter concentration ($C \equiv r_{200}/r_{\rm s} \approx 5-10$, where r_{200} is the radius at density contrast 200 and $r_{\rm s}$ is the halo scale length) consistent with the dark matter distribution in barred disk galaxies, possibly including our own Galaxy. Another issue is the predicted number of satellites as well as the frequency of massive galaxies both at present and in the past, cf. [1388]. There might be excess numbers of predicted satellites and too many massive galaxies predicted today, and maybe the converse is the case at $z \approx 2$–3 (see Chapter 3 for an exhaustive discussion). On the baryonic front, an unresolved challenge for theorists is the excessive loss of angular momentum by the contracting and cooling baryons in the dark halo. The resulting spheroids are too massive, and continuing minor mergers make the final disks too thick. Finely tuned merging models, with late gas infall forming a cold disk, may be able to reproduce late-type galaxies with small bulges [1000], although we cannot yet explain the observed frequency of thin disk-dominated galaxies or the distribution of angular momentum. The essential problem is that one simultaneously has to explain disk galaxies as well as account for the dark matter concentrations and the galaxy luminosity function. Hitherto, solving any one of these problems has generally aggravated the other contact points with data.

It is difficult, however, to be definitive about any possible contradiction between theory and observation. For example, reformation of bars by gas infall can avoid the problem of bar spin-down by dynamical friction [1722], gas bulk flows can dynamically soften the dark matter cusps of dwarf galaxies [1395] as well as massive galaxies [1164], and astrophysical processes, including supernova-driven winds, can render the dwarf satellites optically invisible. Many extremely faint dwarfs are indeed being discovered in our halo that could plausibly be identified with the expected faded relics. The observed numbers are within a factor of ∼4 of accounting for the missing satellite problem [1763]. At high redshift ($z \gtrsim 4$), the galaxy luminosity function slope is steep at the low luminosity end with $\alpha \approx 1.7$ [420], almost in accord with CDM expectations. Numerical simulations at high resolution of the subhalo mass function yield $\alpha \approx 1.9$ [1790]. Massive galaxies undergo strong AGN feedback that prevents excessive growth at late epochs, and also terminates but possibly accelerates early star formation. Hence astrophysical processes should be able to reconcile CDM reasonably well with the data.

This certainly is the conservative viewpoint, while a more radical view is that the tension between CDM and data motivates a more radical overhaul of the theory of dark matter, or even gravitational theory. For example, changing the weakly interacting nature of the dark matter by increasing the scattering cross-section helps to alleviate several problems, such as cuspiness and clumpiness. However, the resulting dark haloes are found to be too spherical [615]. CDM simulations are in excellent agreement with the data, predicting massive galaxy halo shapes with mean flattenings of 1:2 [64], whereas gravitational weak lensing studies find ellipticities of around 0.3 [1546] for all types and slightly larger values (∼0.4) for early types. Another approach modifies the law of gravity to the extent that one may be able to dispense entirely with dark matter. In particular, the MOND scheme or paradigm of Milgrom [1434; 1435; 1436] is singularly successful in explaining empirical facts such as the detailed shapes of rotation curves of galaxies, as well as the so-called Tully–Fisher relation, according to which the total mass in visible stars and gas (baryonic mass) in a disk galaxy is proportional to the fourth power of the asymptotic rotational velocity. Bekenstein has subsequently proposed a tensor–vector scalar theory, or TeVeS [254; 255; 258], which represents an embodiment of MOND into a full relativistic theory. Weak lensing observations currently pose the strongest challenge to these models, since they show that the source of the gravitational potential does not track baryonic matter [96; 433; 562; 827], thus pointing towards the need for DM. The successes and challenges of modified theories of gravity are thoroughly discussed in Chapter 6.

1.4 Portrait of a suspect

Baryons are not the dark matter. Nor are neutrinos. We are then left with the necessity of postulating new particles, arising in theories Beyond the Standard Model (BSM) of particle physics. In fact, the possible connection with BSM physics has prompted an enormous proliferation of dark

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matter candidates, which are currently being sought in an impressive array of accelerator, direct and indirect detection experiments. However, as our understanding of particle physics and astrophysics improves, we are accumulating information that progressively reduces the allowed regions in the parameter space of DM particles. In practice, a particle can be considered a good DM candidate only if a positive answer can be given to all of the following questions [1839]:

(i) Does it match the appropriate relic density?
(ii) Is it cold?
(iii) Is it neutral?
(iv) Is it consistent with Big Bang nucleosynthesis (BBN)?
(v) Does it leave stellar evolution unchanged?
(vi) Is it compatible with constraints on self-interactions?
(vii) Is it consistent with direct DM searches?
(viii) Is it compatible with gamma-ray constraints?
(ix) Is it compatible with other astrophysical bounds?
(x) Can it be probed experimentally?

The particle physics aspects of the DM problem are discussed in detail in Part II. In particular, the production mechanisms of DM in the early Universe are discussed in Chapter 7. The first and most studied mechanism is thermal production, positing that DM particles were in chemical and thermodynamical equilibrium with ordinary matter in the early Universe, until the DM annihilation rate dropped below the expansion rate of the Universe. The fact that the annihilation cross-section at the electroweak scale naturally leads to the appropriate relic abundance has made Weakly Interacting Massive Particles an excellent dark matter candidate, as already noticed in the late 1970s [657; 1144; 1317; 1692; 1911]. Among the most important physical processes that can modify the simplest version of thermal freeze-out, we mention co-annihilations with near-degenerate particles [355; 735; 1020]. Examples and references to this scenario, and to alternatives such as models in which the DM is produced gravitationally or through the decay of heavier particles, and scenarios with a non-standard expansion rate of the Universe, are discussed in detail in Chapter 7.

The most widely discussed extension of the Standard Model of particle physics is Supersymmetry (SUSY), and the most widely discussed DM candidate is the supersymmetric neutralino, although other candidates, such as the gravitino, naturally arise in SUSY scenarios (see Chapter 8 for a discussion of SUSY DM). SUSY is aesthetically appealing, and it has been built on a solid theoretical ground, with the aim of addressing some of the most important problems of the Standard Model of particle physics. In fact, SUSY has been used as a benchmark theory by both the ATLAS and CMS collaborations [144; 145; 237], part of the Large Hadron Collider, which started operation at CERN in 2009. Furthermore, numerical codes have been developed to scan the supersymmetric parameter space automatically, determine the properties of the neutralino (such as mass and couplings) and study the consequences for accelerator, direct and indirect searches (see Chapter 16).

The different steps involved in the hypothetical discovery and measurement of supersymmetry at the LHC, and the strategies for constraining the soft breaking parameters, are reviewed in Chapter 13, while a detailed discussion of the reconstruction of the DM properties, with particular attention to the relic density, starting from collider measurements is presented in Chapter 14. It is interesting to stress that there is a large portion of the parameter space where upcoming accelerator measurements cannot constrain the underlying SUSY scenario sufficiently to prove that newly discovered particles are actually *the* DM in the Universe. It is therefore important to perform direct and indirect DM searches that would provide complementary information, as we shall see later.

Despite the good theoretical motivation, there is no experimental evidence for SUSY. Many alternative theories have been proposed, usually abandoning the ambitious attempt to cure the Standard Model, and trying instead to address the DM problem in a phenomenological way. A review of alternative candidates at the electroweak scale can be found in Chapter 9, where the motivations for and properties of Kaluza–Klein, Little Higgs, technicolour, minimal and mirror DM candidates are discussed in detail. Kaluza–Klein DM is particularly appealing, and there are many efforts being made to understand how to discriminate the signatures of theories with (universal) extra dimensions from SUSY signatures with collider experiments (Chapter 15).

It is also possible that the DM is not a WIMP. For instance, we mentioned above the case of the gravitino, which is representative of a class of superweakly interacting particles, or superWIMPs, that also include Kaluza–Klein gravitons, axinos, quintessinos and others; furthermore, the mass scale may not be in the range 100 GeV to 1 TeV, as in the so-called WIMP-less scenarios (see Chapter 10 for a detailed discussion).

Axions provide another example of perfectly viable non-WIMP DM candidates. The theoretical motivation and possible production mechanism are discussed in Chapter 11. Finally, sterile neutrinos also provide an interesting alternative, as discussed in Chapter 12.

1.5 Observing cold dark matter

As we have seen, accelerator measurements will be invaluable to establish the theoretical framework chosen by nature. The discovery of new particles would be per se an extraordinary discovery, but it might not allow a straightforward identification with a successful DM candidate. In this case, progress will only be achieved by observing cold dark matter directly or indirectly.

Direct detection experiments aim at detecting the fraction of WIMPs, constantly flowing through the Earth with a flux $10^5(100\,\mathrm{GeV}/m_\chi)\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, that elastically scatter off nuclei in underground detectors, through the measurement of nuclear recoils [988]. The rate, R, and energies, E_R, of nuclear recoils can then be used to reconstruct the properties of the DM particle (see Chapter 17 for a review of the theoretical aspects of direct DM detection).

The total cross-section for the scattering of WIMPs off target nuclei can be separated into a spin-independent and a spin-dependent part: the spin-independent part arises from scalar and vector couplings to quarks, whereas the spin-dependent one originates from axial-vector couplings. This is important because different target nuclei are required to probe these two quantities. There are many uncertainties associated with the reconstruction of the WIMP properties from direct detection experiments, including particle physics uncertainties in the determination of scattering cross-section, and especially astrophysical uncertainties, such as the local density and velocity distribution of WIMPs. The prospects for detecting specific DM candidates, and for reconstructing their properties starting from direct detection data, are discussed in Chapter 17.

Scattering of WIMP particles leads to nuclear recoils that can be measured by at least three different techniques, namely applications of scintillation, phonons and ionization. The DAMA/LIBRA experiment, which makes use of NaI (Tl) (i.e. sodium iodide doped with thallium) scintillators (see Chapters 18 and 19) is the only experiment claiming the detection of a signal consistent with a DM interpretation, i.e. an annual modulation of the event rate, possibly due to the effect of the motion of the Earth around the Sun, that was predicted long ago as a peculiar signature of halo WIMPs [719; 881]. The evidence for the signal is strong, but an actual interpretation in terms of existing candidates and standard assumptions for the astrophysical properties of DM has to face the fact that no other experiments have observed a signal. It is however true that a comparison between different experiments can only be performed under specific assumptions, perhaps affected by theoretical prejudices. Possible ways to reconcile the DAMA/Libra signal with other experiments are discussed in Chapter 19.

Cryogenic detectors, i.e. solid state or superfluid ^{3}He detectors operated at temperatures lower than 77 K, encompass a large category of DM experiments, such as CDMS, CRESST, EDELWEISS and ROSEBUD (see Chapter 20). Historically, the first detectors of this type aimed to detect particles in a crystal by measuring the increase of temperature induced by the energy deposition. However, in order to reject the overwhelming background induced by gamma-rays and X-rays from radioactive contaminants, 'double parameter measurement' bolometers have been built, which are able to measure charge and phonon signals in ionization detectors, and light and phonon signals in scintillating bolometers (Chapter 20).

Noble liquid gases such as xenon, argon and neon appear today as extraordinarily promising targets for direct DM detection. They are in fact excellent scintillators (and, for Xe and Ar, also very good ionizers), and they can be scaled up to a large mass thanks to their modest cost. In practice, these experiments consist of time projection chambers (TPCs) with two phases, liquid and gas, of noble elements (liquid xenon for XENON, ZEPLIN and LUX, and liquid argon for ArDM and WArP), or a single phase of noble elements (XMASS and DEAP/CLEAN). For two-phased TPCs, ionization electrons and prompt scintillation photons produced by scattering events are simultaneously detected, and the ionization electrons are extracted from the liquid to the gas where they emit proportional scintillation photons. Photomultiplier tubes are then used to detect the prompt and delayed scintillation signals, thus providing information that allows one to separate WIMP-like events from electron recoil events produced by background beta- and gamma-rays. A complete discussion of liquid noble gas experiments is presented in Chapter 21.

Complementary information on the nature of DM may come from indirect detection searches, based on the search for secondary products (photons, neutrinos or antimatter) produced in the annihilation or decay of DM particles [1759].

Among these secondary products, gamma-rays appear particularly interesting, since they travel in straight lines and are practically unabsorbed in the local Universe. The observational strategies are different for the cases of annihilation and decay. In fact, while in the first case the galactic centre (central source, or surrounding diffuse emission) and possibly a few bright substructures represent the optimal targets, in the latter it is best to focus on the diffuse emission at high galactic latitudes, where the astrophysical backgrounds are less intense. The great success of the new generation of air Cherenkov telescopes, and the excitement about the upcoming data from the Fermi satellite, make this field very lively, as discussed in Chapter 24.