Abstract. Over the past decade, a consensus picture has emerged in which roughly a quarter of the universe consists of dark matter. The observational evidence for the existence of dark matter is reviewed: rotation curves of galaxies, weak lensing measurements, hot gas in clusters, primordial nucleosynthesis and microwave background experiments. In addition, a new line of research on Dark Stars is presented, which suggests that the first stars to exist in the universe were powered by dark matter heating rather than by fusion: the observational possibilities of discovering dark matter in this way are discussed.

1 Introduction

A standard model of cosmology is emerging (often dubbed the Concordance Model), in which the universe consists of 4% ordinary baryonic matter, ~23% dark matter, and ~73% dark energy, with a tiny abundance of relic neutrinos. The baryonic content is well-known, both from element abundances produced in primordial nucleosynthesis roughly 100 seconds after the Big Bang, and from measurements of anisotropies in the cosmic microwave background (CMB). The evidence for the existence of dark matter is overwhelming, and comes from a wide variety of astrophysical measurements.

2 Dark Matter in Galaxies and Clusters

The evidence that 95% of the mass of galaxies and clusters is made of some unknown component of Dark matter (DM) comes from (i) rotation curves (out to tens of kpc), (ii) gravitational lensing (out to 200 kpc), and (iii) hot gas in clusters.

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2.1 Rotation Curves

In the 1970s, Ford and Rubin [1970] discovered that rotation curves of galaxies are flat. The velocities of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the galactic centers as had been expected, remain constant out to very large radii. Similar observations of flat rotation curves have now been found for all galaxies studied, including our Milky Way. The simplest explanation is that galaxies contain far more mass than can be explained by the bright stellar objects residing in galactic disks. This mass provides the force to speed up the orbits. To explain the data, galaxies must have enormous dark halos made of unknown dark matter. Indeed, more than 95% of the mass of galaxies consists of dark matter. This is illustrated in Fig. 1, where the velocity profile of galaxy NGC 6503 is displayed as a function of radial distance from the galactic center. The baryonic matter which accounts for the gas and disk cannot alone explain the galactic rotation curve. However, adding a dark matter halo allows a good fit to data.

The limitations of rotation curves are that one can only look out as far as there is light or neutral hydrogen (21 cm), namely to distances of tens of kpc. Thus one can see the beginnings of DM haloes, but cannot trace where most of the DM is. The lensing experiments discussed in the next section go beyond these limitations.

2.2 Lensing

Einstein’s theory of General Relativity predicts that mass bends, or lenses, light. This effect can be used to gravitationally ascertain the existence of mass even when it emits no light. Lensing measurements confirm the existence of enormous quantities of dark matter both in galaxies and in clusters of galaxies.

Observations are made of distant bright objects such as galaxies or quasars. As the result of intervening matter, the light from these distant objects is bent towards the regions of large mass. Hence there may be multiple images of the distant objects, or, if these images cannot be individually resolved, the background object may appear brighter. Some of these images may be distorted or sheared. The Sloan Digital Sky Survey used weak lensing (statistical studies of lensed galaxies) to conclude that galaxies, including the Milky Way, are even larger and more massive than previously thought, and require even more dark matter out to great distances (Adelman-McCarthy et al. 2005). Again, the predominance of dark matter in galaxies is observed.

A beautiful example of a strong lens is shown in Figure 2. The panel on the right shows a computer reconstruction of a foreground cluster inferred by lensing observations made by Tyson et al. using the Hubble Space Telescope. This extremely rich cluster contains many galaxies, indicated by the peaks in the figure. In addition to these galaxies, there is clearly a smooth component, which is the dark matter contained in clusters in between the galaxies.

The key success of the lensing of DM to date is the evidence that DM is seen out
to much larger distances than could be probed by rotation curves: the DM is seen in galaxies out to 200 kpc from the centers of galaxies, in agreement with N-body simulations. On even larger Mpc scales, there is evidence for DM in filaments (the cosmic web).

2.3 Hot Gas in Clusters

Another piece of gravitational evidence for dark matter is the hot gas in clusters. Figure 3 illustrates the Coma Cluster. The left panel is in the optical, while the right panel is emission in the x-ray (observed by ROSAT) (Briel & Henry 1997). [Note that these two images are not on the same scale.] The X-ray image indicates the presence of hot gas. The existence of this gas in the cluster can only be explained by a large dark matter component that provides the potential well
Fig. 2. Left: The foreground cluster of galaxies gravitationally lenses the blue background galaxy into multiple images. Right: A computer reconstruction of the lens shows a smooth background component not accounted for by the mass of the luminous objects.

Fig. 3. COMA Cluster: without dark matter, the hot gas would evaporate. Left panel: optical image. Right panel: X-ray image from ROSAT satellite.

to hold on to the gas.
Fig. 4. A collision of galactic clusters (the bullet cluster) shows baryonic matter (pink) as separate from dark matter (blue), whose distribution is deduced from gravitational lensing.

2.4 Bullet Cluster

A recent image of the bullet cluster of galaxies (a cluster formed out of a collision of two smaller clusters) taken by the Chandra X-ray observatory shows in pink the baryonic matter; in blue is an image of the dark matter, deduced from gravitational lensing. In the process of the merging of the two smaller clusters, the dark matter has passed through the collision point, while the baryonic matter slowed due to friction and coalesced to a single region at the center of the new cluster. In modified gravity theories without dark matter, it is not likely that such a differentiation of these two components of the matter would take place.

In summary, the evidence is overwhelming for the existence of an unknown component of DM that comprises 95% of the mass in galaxies and clusters.

3 Cosmic Abundances

The cosmic abundances tell a consistent story in which the preponderance of the mass in the universe consists of an unknown DM component. The Cosmic Microwave Background provides the most powerful measurements of the cosmological parameters; primordial nucleosynthesis restricts the abundance of baryonic matter; Type IA supernovae provided powerful evidence for the acceleration of the universe, possibly explained by dark energy as the major constituent of the cosmic energy density.

3.1 The Cosmic Microwave Background

Further evidence for dark matter comes from measurements on cosmological scales of anisotropies in the CMB (WMAP Collaboration 2003, 2008). The CMB is the
remnant radiation from the hot early days of the universe. The photons underwent oscillations that froze in just before decoupling from the baryonic matter at a redshift of 1000. The angular scale and height of the peaks (and troughs) of these oscillations are powerful probes of cosmological parameters, including the total energy density, the baryonic fraction, and the dark matter component. The sound horizon at last scattering provides a ruler stick for the geometry of the universe: if the light travels in a straight line (as would be the case for a flat geometry), then the angular scale of the first Doppler peak was expected to be found at 1 degree; indeed this is found to be correct. Thus the geometry is flat, corresponding to an energy density of the universe of $\sim 10^{-29}$ gm/cm$^3$. The height of the second peak implies that 4% of the total is ordinary atoms, while matching all the peaks implies that 23% of the total is DM.

### 3.2 Primordial nucleosynthesis

When the universe was a few hundred seconds old, at a temperature of ten billion degrees, deuterium became stable: $p + n \rightarrow D + \gamma$. Once deuterium forms, helium and lithium form as well. The formation of heavier elements such as C, N, and O must wait a billion years until stars form, with densities high enough for triple interactions of three helium atoms into a single carbon atom. The predictions from the Big Bang are 25% Helium-4, $10^{-5}$ deuterium, and $10^{-10}$ Li-7 abundance by mass. These predictions exactly match the data as long as atoms are only 4% of the total constituents of the universe.

### 3.3 Dark Energy

Evidence for the 70% dark energy in the universe comes from observations of distant supernovae (Perlmutter et al. 1999, Riess et al. 1999, Riess et al. 2004). The supernovae are dimmer than expected, as is most easily explained by an accelerating universe. There are two different approaches to the dark energy: (i) a vacuum energy such as a cosmological constant or time-dependent vacuum (Freese et al. 1987) may be responsible, or (ii) it is possible that General Relativity is incomplete and that Einstein’s equations need to be modified (Freese & Lewis 2002, Freese 2005, 2005, Deffayet et al. 2002, Carroll et al. 2004). Note, however, that this dark energy does not resolve or contribute to the question of dark matter in galaxies, which remains as puzzling (if not more) than twenty years ago. We now have a concordance model of the universe, in which roughly a quarter of its content consists of dark matter.

### 4 Dark Matter Candidates

There is a plethora of dark matter candidates. MACHOs, or Massive Compact Halo Objects, are made of ordinary matter in the form of faint stars or stellar remnants; they could also be primordial black holes or mirror matter (Mohaptra & Teplitz 1999). However, there are not enough of these to completely resolve
the question. Of the nonbaryonic candidates, the most popular are the WIMPS (Weakly Interacting Massive Particles) and the axions, as these particles have been proposed for other reasons in particle physics. Ordinary massive neutrinos are too light to be cosmologically significant, though sterile neutrinos remain a possibility. Other candidates include primordial black holes, nonthermal WIMPzillas, and Kaluza-Klein particles which arise in higher dimensional theories.

4.1 MACHOs

MACHO candidates include faint stars, planetary objects (brown dwarfs), and stellar remnants (white dwarfs, neutron stars, and black holes). Microlensing experiments (the MACHO (Alcock et al. 2000) and EROS (Ansari et al. 2004) experiments) as well as a combination of other observational (HST) and theoretical results (Graff & Freese 1996) have shown that MACHOs less massive than 0.1 $M_\odot$ make an insignificant contribution to the energy density of the Galaxy. However, there is a detection (Alcock et al. 2000) of a roughly 20% halo fraction made of $\sim 0.5 M_\odot$ objects which might be made of stellar remnants such as white dwarfs. We found a number of constraints: the progenitors produce observable element abundances (C,N,He), they require an enormous mass budget, the initial mass function must be extremely sharply peaked, and, most important, the progenitors produce observable infrared radiation. Our conclusion from these constraints is that at most 20% of the Galactic Halo can be made of stellar remnants (Freese et al. 2000, Fields et al. 2000, Graff et al. 1999).

4.2 Axions

The good news is that cosmologists don’t need to “invent” new particles. Two candidates already exist in particle physics for other reasons: axions and WIMPs. Axions with masses in the range $10^{-207} (3^{-6})$ eV arise in the Peccei-Quinn solution to the strong-CP problem in the theory of strong interactions. Axion bounds (Asztalos et al. 2004) from the ADMX cavity experiment are approaching the remaining parameter range.

4.3 WIMPs (Weakly Interacting Massive Particles)

WIMPs are also natural dark matter candidates from particle physics. These particles, if present in thermal abundances in the early universe, annihilate with one another so that a predictable number of them remain today. The relic density of these particles comes out to be the right value:

$$\Omega_\chi h^2 = (3 \times 10^{-26} \text{cm}^3/\text{sec})/\langle\sigma v\rangle_{\text{ann}}$$  \hspace{1cm} (4.1)

where the annihilation cross section $\langle\sigma v\rangle_{\text{ann}}$ of weak interaction strength automatically gives the right answer. This coincidence is known as “the WIMP miracle” and is the reason why WIMPs are taken so seriously as DM candidates. The best WIMP candidate is motivated by Supersymmetry (SUSY): the lightest neutralino
in the Minimal Supersymmetric Standard Model. Supersymmetry in particle theory is designed to keep particle masses at the right value. As a consequence, each particle we know has a partner: the photino is the partner of the photon, the squark is the quark’s partner, and the selectron is the partner of the electron. The lightest supersymmetric partner is a good dark matter candidate (see the reviews by Jungman et al [1996], Lewin & Smith [1996], Primack et al [1988], Bertone et al [11]).

There are several ways to search for dark WIMPs. SUSY particles may be discovered at the LHC as missing energy in an event. In that case one knows that the particles live long enough to escape the detector, but it will still be unclear whether they are long-lived enough to be the dark matter. Thus complementary astrophysical experiments are needed. In direct detection experiments, the WIMP scatters off of a nucleus in the detector, and a number of experimental signatures of the interaction can be detected (Goodman & Witten [1985], Drukier et al [1986]). In indirect detection experiments, neutrinos are detected from the Sun or Earth that arise as annihilation products of captured WIMPs; the first papers suggesting this idea were by Silk et al [1985] in the Sun; and by Freese [1986] as well as Krauss, Srednicki and Wilczek in the Earth. Another way to detect WIMPs is to look for anomalous cosmic rays from the Galactic Halo: WIMPs in the Halo can annihilate with one another to give rise to antiprotons, positrons, or neutrinos (Ellis et al. [1985]). In addition, neutrinos, Gamma-rays, and radio waves may be detected as WIMP annihilation products from the Galactic Center (Gondolo & Silk [1999]). Many talks in this conference will discuss ongoing and planned DM searches.

5 Dark Stars

The first stars to form in the universe, at redshifts $z \sim 10 – 50$, may be powered by dark matter annihilation for a significant period of time (Spolyar, Freese, and Gondolo [2008]). We have dubbed these objects “Dark Stars.”

As discussed in the last section, WIMP dark matter annihilation in the early universe provides the right abundance today to explain the dark matter content of our universe. This same annihilation process will take place at later epochs in the universe wherever the dark matter density is sufficiently high to provide rapid annihilation. The first stars to form in the universe are a natural place to look for significant amounts of dark matter annihilation, because they form at the right place and the right time. They form at high redshifts, when the universe was still substantially denser than it is today, and at the high density centers of dark matter haloes.

The first stars form inside dark matter (DM) haloes of $10^6 M_\odot$ (for reviews see e.g. Ripamonti & Abel [2005], Barkana & Loeb [2001], and Bromm & Larson [2003]; see also Yoshida et al. [2006]). One star is thought to form inside one such DM halo. The first stars play an important role in reionization, in seeding supermassive black holes, and in beginning the process of production of heavy elements in later generations of stars. It was our idea to ask, what is the effect of the DM on these first stars? We studied the behavior of WIMPs in the first stars. As our canonical
values, we take $m_\chi = 100\text{GeV}$ for the WIMP mass and $\langle \sigma v \rangle_{\text{ann}} = 3\times 10^{-26}\text{cm}^3/\text{sec}$ for the annihilation cross section (motivated above). We find that the annihilation products of the dark matter inside the star can be trapped and deposit enough energy to heat the star and prevent it from further collapse. A new stellar phase results, a Dark Star, powered by DM annihilation as long as there is DM fuel.

5.1 Three Criteria for Dark Matter Heating

WIMP annihilation produces energy at a rate per unit volume

$$Q_{\text{ann}} = \langle \sigma v \rangle_{\text{ann}} \rho_\chi^2/m_\chi \simeq 10^{-29}\text{erg/cm}^3/\text{s} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\text{cm}^3/\text{s}}\right) \left(\frac{n}{\text{cm}^{-3}}\right)^{1.6} \left(\frac{100\text{GeV}}{m_\chi}\right),$$

(5.1)

where $\rho_\chi$ is the DM energy density inside the star and $n$ is the stellar hydrogen density. Paper I (Spolyar, Freese, & Gondolo 2008) outlined the three key ingredients for Dark Stars: 1) high dark matter densities, 2) the annihilation products get stuck inside the star, and 3) DM heating wins over other cooling or heating mechanisms. These same ingredients are required throughout the evolution of the dark stars, whether during the protostellar phase or during the main sequence phase.

**First criterion: High Dark Matter density inside the star.** Dark matter annihilation is a powerful energy source in these first stars because the dark matter density is high. To find the DM density profile, we started with an NFW (Navarro, Frenk & White 1996) profile for both DM and gas in the $10^6 M_\odot$ halo. Originally we used adiabatic contraction ($M(r) r$ = constant) (Blumenthal et al. 1985) and matched onto the baryon density profiles given by Abel, Bryan & Norman 2002 and Gao et al. 2007 to obtain DM profiles; see also Natarajan, Tan, & O'Shea 2008 for a recent discussion. Subsequent to our original work, we have done an exact calculation (which includes radial orbits) (Freese, Gondolo, Sellwood & Spolyar 2008) and found that our original results were remarkably accurate, to within a factor of two. At later stages, we also consider possible further enhancements due to capture of DM into the star (discussed below).

**Second Criterion: Dark Matter Annihilation Products get stuck inside the star.** In the early stages of Pop III star formation, when the gas density is low, most of the annihilation energy is radiated away (Ripamonti Mapelli & Ferrara 2006). However, as the gas collapses and its density increases, a substantial fraction $f_Q$ of the annihilation energy is deposited into the gas, heating it up at a rate $f_Q Q_{\text{ann}}$ per unit volume. While neutrinos escape from the cloud without depositing an appreciable amount of energy, electrons and photons can transmit energy to the core. We have computed estimates of this fraction $f_Q$ as the core becomes more dense. Once $n \sim 10^{13}\text{cm}^{-3}$ (for 100 GeV WIMPs), $e^-$ and photons are trapped and we can take $f_Q \sim 2/3$.

**Third Criterion: DM Heating is the dominant heating/cooling mechanism in the star.** We find that, for WIMP mass $m_\chi = 100\text{GeV}$ (1 GeV), a crucial transition takes place when the gas density reaches $n > 10^{13}\text{cm}^{-3}$
Fig. 5. Temperature (in degrees K) as a function of hydrogen density (in cm$^{-3}$) for the first protostars, with DM annihilation included, for two different DM particle masses (10 GeV and 100 GeV). Moving to the right in the figure corresponds to moving forward in time. Once the “dots” are reached, DM annihilation wins over H$_2$ cooling, and a Dark Star is created.

$(n > 10^9 \text{cm}^{-3})$. Above this density, DM heating dominates over all relevant cooling mechanisms, the most important being H$_2$ cooling (Hollenbach & McKee [1979]).

Figure 5 shows evolutionary tracks of the protostar in the temperature-density phase plane with DM heating included (Yoshida et al. [2008]), for two DM particle masses (10 GeV and 100 GeV). Moving to the right on this plot is equivalent to moving forward in time. Once the black dots are reached, DM heating dominates over cooling inside the star, and the Dark Star phase begins. The protostellar core is prevented from cooling and collapsing further. The size of the core at this point is $\sim 17$ A.U. and its mass is $\sim 0.6M_\odot$ for 100 GeV mass WIMPs. A new type of object is created, a Dark Star supported by DM annihilation rather than fusion.

5.2 Building up the Mass

We have found the stellar structure of the dark stars (hereafter DS) (Freese, Bodenheimer, Spolyar, & Gondolo [2008]). They accrete mass from the surrounding
Fig. 6. Evolution of a dark star ($n=1.5$) as mass is accreted onto the initial protostellar core of 3 $M_\odot$. The set of upper (lower) curves correspond to the baryonic (DM) density profile at different masses and times. Note that DM constitutes $<10^{-3}$ of the mass of the DS.

medium. In our paper we build up the DS mass as it grows from $\sim 1M_\odot$ to $\sim 1000M_\odot$. As the mass increases, the DS radius adjusts until the DM heating matches its radiated luminosity. We find polytropic solutions for dark stars in hydrostatic and thermal equilibrium. We build up the DS by accreting $1M_\odot$ at a time with an accretion rate of $2\times10^{-3}M_\odot/yr$, always finding equilibrium solutions. We find that initially the DS are in convective equilibrium; from $(100-400)M_\odot$ there is a transition to radiative; and heavier DS are radiative. As the DS grows, it pulls in more DM, which then annihilates. We continue this process until the DM fuel runs out at $M_{DS} \sim 800M_\odot$ (for 100 GeV WIMPs). Figure 6 shows the stellar structure. One can see “the power of darkness:” although the DM constitutes a tiny fraction ($<10^{-3}$) of the mass of the DS, it can power the star. The reason is that WIMP annihilation is a very efficient power source: 2/3 of the initial energy of the WIMPs is converted into useful energy for the star, whereas only 1% of baryonic rest mass energy is useful to a star via fusion.

5.3 Results and Predictions

Our final result (Freese, Bodenheimer, Spolyar, & Gondolo 2008), is very large first stars; e.g., for 100 GeV WIMPs, the first stars have $M_{DS} = 800M_\odot$. Once the DM fuel runs out inside the DS, the star contracts until it reaches $10^8K$ and fusion sets in. A possible end result of stellar evolution will be large black holes. The Pair Instability SN (Heger & Woosley 2002) that would be produced from 140-260 $M_\odot$ stars (and whose chemical imprint is not seen) would not be as abundant. Indeed this process may help to explain the supermassive black holes that have
been found at high redshift \( (10^9 M_\odot \text{BH at } z=6) \) and are, as yet, unexplained (Li et al. 2007; Pelupessy et al. 2007).

The stars are very bright, \(~ 10^6 L_\odot\), and relatively cool, \((6000-10,000) K\) (as opposed to standard Pop III stars whose surface temperatures exceed 30,000K). Reionization during this period is likely to be slowed down, as these stars can heat the surroundings but not ionize them. One can thus hope to find DS and differentiate them from standard Pop III stars.

5.4 Later stages: Capture

The dark stars will last as long as the DM fuel inside them persists. The original DM inside the stars runs out in about a million years. However, as discussed in the next paragraph, the DM may be replenished by capture, so that the DS can live indefinitely due to DS annihilation. We suspect that the DS will eventually leave their high density homes in the centers of DM haloes, especially once mergers of haloes with other objects takes place, and then the DM fuel will run out. The star will eventually be powered by fusion. Whenever it again encounters a high DM density region, the DS can capture more DM and be born again.

The new source of DM in the first stars is capture of DM particles from the ambient medium. Any DM particle that passes through the DS has some probability of interacting with a nucleus in the star and being captured. The new particle physics ingredient required here is a significant scattering cross section between the WIMPs and nuclei. Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a somewhat free parameter, set only by bounds from direct detection experiments. Two simultaneous papers (Freese, Spolyar, & Aguirre 2008; Iocco 2008) found the same basic idea: the DM luminosity from captured WIMPs can be larger than fusion for the DS. Two uncertainties exist here: the scattering cross section, and the amount of DM in the ambient medium to capture from. DS studies following the original papers that include capture have assumed (i) the maximal scattering cross sections allowed by experimental bounds and (ii) ambient DM densities that are never depleted. With these assumptions, DS evolution models with DM heating after the onset of fusion have now been studied in several papers (Iocco et al. 2008; Taoso et al. 2008; Yoon et al. 2008).

In short, the first stars to form in the universe may be Dark Stars powered by DM heating rather than by fusion. Our work indicates that they may be very large \((800 M_\odot \text{ for } 100 \text{ GeV mass WIMPs})\). Once DS are found, one can use them as a tool to study the properties of WIMPs.

6 Conclusion

95\% of the mass in galaxies and clusters of galaxies is in the form of an unknown type of dark matter. We know this from rotation curves, from gravitational lensing, and from hot gas in clusters. This assessment of the DM contribution to the global energy density of the universe is consistent with measurements of the
cosmic microwave background, primordial nucleosynthesis, supernova, and large scale structure. A consensus picture has emerged, in which the DM contributes 23% of the overall energy density of the universe. Its nature is still unknown. At most 1/5 of the DM in galaxies can be white dwarfs (or other MACHO candidates), but most is likely to be an exotic particle candidate. DM searches for the best motivated candidates, axions and WMPs are ongoing and promising over the next few years. One of the key properties of WIMP candidates is its annihilation cross section, yielding the proper relic density today. As a consequence of this annihilation, the first stars in the universe may provide another avenue to test the DM hypothesis. These stars may be powered by DM annihilation, and one can look for them in upcoming telescopes. The goal is to decipher this unknown dark matter over the next decade.

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