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ABSTRACT

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Contents

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Chapter 1

Dark Matter

For nearly a century, experimental evidence has suggested that a large portion of the universe is made up of a non-luminous type of matter. While this dark matter has only been detected indirectly via its interaction with normal matter through the gravitational force, recent experiments conclude that approximately 26% of the entire energy density of the universe is comprised by dark matter.

In this chapter, I will focus on the leading dark matter model, the experimental evidence for its existence, the different candidates for particle dark matter, and the current detection methods employed in the search for particle dark matter.

1.1 ΛCDM Model

One of the guiding principles of cosmology are the assumptions that the universe is both homogeneous and isotropic at large enoug scales (typically on the order 100 Mpc or 10^5 light years). Continuing with these principles and maintaining generality, we can arrive at the Robertson-Walker space-time metric

$$ds = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right) \tag{1.1}$$

Here, $a(t)$ is called the *scale factor*, an arbitrary function of time allowing for time dependent changes of the universe, and k is a constant modeling the curvature of the universe. For $k = -1$, the universe is considered open, for $k = 1$, the universe is considered close, and at $k = 0$ we are left with our Euclidean (flat) universe. Note that for $a(t) = 1$ and $k = 0$ the Robertson-Walker metric reduces to the Minkowski metric.

Using this metric in combination with Einstein's equation we can derive the equations for the Friedmann-Robertson-Walker universe described by the Friedmann equations.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \tag{1.2}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \tag{1.3}$$

We can define several useful (and commonplace) parameters to simplify the second Friedmann equation further.

Hubble Parameter: $H = \frac{\dot{a}}{a}$
Critical Density: $\rho_{crit} = \frac{3H^2}{8\pi G}$
Density Parameters: $\Omega_i = \frac{8\pi G}{3H^2}$, $\Omega_i = \frac{\rho_i}{\rho_{crit}}$

$$\Omega - 1 = \frac{k}{H^2 a^2}, \quad \Omega = \sum_i \Omega_i = \Omega_\Lambda + \Omega_{CDM} + \Omega_{Baryon} + \Omega_{Rad}\ldots \tag{1.4}$$

Here the critical density is defined such that the universe is flat ($k = 0$). One can think of $\frac{\Omega_i}{\Omega}$ as what part of the total matter and energy budget a particular component makes up. The main contributors to the density of the universe are dark energy and cold dark matter hence the ΛCDM Model. Measurements of the various density parameters and other ΛCDM parameters has been a very big area of research over the last two decades and will be discussed later in this chapter.

1.2 Evidence of Dark Matter

1.2.1 Dynamical Constraints from Clusters of Galaxies

The first evidence of dark matter came from Fritz Zwicky in 1933. Zwicky used a basic application of the virial theorem on galaxies in the Coma Cluster to estimate the mass of the cluster. He then estimated the total mass based on the brightness of the cluster and found significant disagreement between the results leading him to the conclusion that "if this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter." [1]

Figure 1.1: A composite image combining an X-ray data, courtesy of Chandra, and optical data, courtesy of the Sloan Digital Sky Survey. Image credit: X-ray - NASA/CXC/MPE/J.Sanders et al, Optical - SDSS

1.2.2 Dynamical Constraints from Galactic Rotation Curves

Nearly fourty years later, stronger evidence was provided for the existence of dark matter by Vera Rubin and Kent Ford in their 1970 paper looking at the rotation curve of the Andomeda Galaxy [3]. In this paper, Rubin used the Hα lines to determine the orbital velocities of different stars in the galaxy. Later measurements used the 21 cm hyperfine transition line to measure orbital velocities within other galaxies [2].

From simple Newtonian arguments, one gets the following description of the orbital velocity inside a galaxy:

$$v(r) = \sqrt{\frac{GM(r)}{r}} \tag{1.5}$$

In this equation, M(r) is the sum of the masses of all the gas and stars inside a given radius. Given that most of the mass from luminous matter is concentrated at the center, one would expect that at large distances from the center of the galaxy, the orbital velocity would fall off as $v \propto r^{-1/2}$.

However, what is seen differs from this simple approximation drastically. Fig. 1.2 is taken from Ref. [2] but the results are similar to what Rubin and Ford saw deecades earlier: the asymptotic behavior of the orbital velocity is constant and does not show any polynomial roll-off. By isolating the contributions from measurable mass densities (such as visible matter and gas), one can get an idea of the density distribution of dark matter in a galaxy. From the figure below, one could asymtotically estimate that $M(r) \propto r$ which would imply that $\rho(r) \propto r^{-2}$. One quickly realizes that this

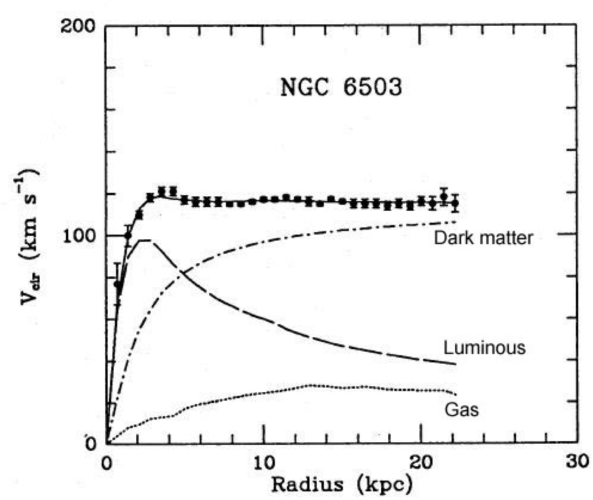

Figure 1.2: The rotation curve of the galaxy NGC 6503 broken down into individual components: visible matter (dashed), gas (dotted), and dark matter (dash dotted) [2].

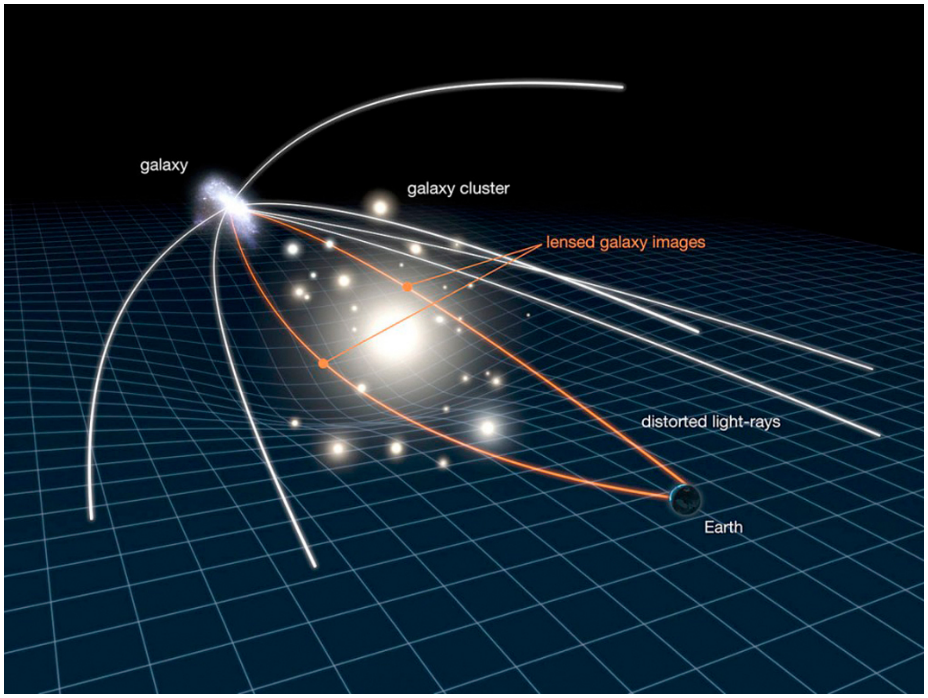

Figure 1.3: A cartoon showing the deflection of light due to the warping of spacetime caused by the presence of a massive galaxy cluster. Note that for very strong lensing, one expects multiple images of the source object and sometimes even an Einstein Ring around the lense. Image credit: NASA/ESA.

cannot be the true density since the mass of the galaxy diverges but approximates the density within an effective radius.

1.2.3 Evidence from Graviational Lensing

Gravitational lensing is the distortion of light coming from a source due to the warping of spacetime from the presence of large amounts of matter or energy. This effect is illustrated in Fig. 1.3 and actually captured in the form of an Einstein Cross in Fig. 1.4. In a gravitational lensing system, if we know the redshift (distance) of the source and the lense, we can estimate the gravitational field of the lensing system and hence its mass.

Mass estimation via gravitational lensing in itself is very useful for finding large discrepancies in mass from known sources and true mass (the discrepancy being attributed to dark matter). However, when combined with x-ray measurements, as

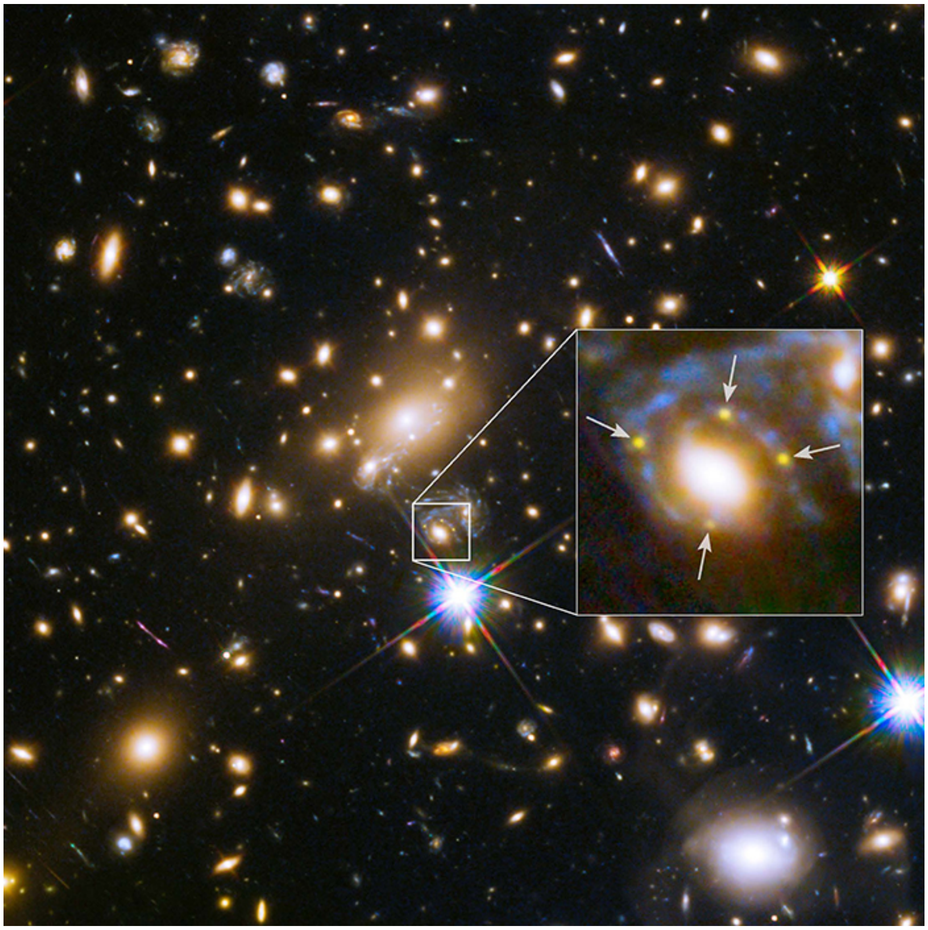

Figure 1.4: In this optical image you see the massive MACS J1149.6+2223 cluster. In the zoomed portion, you can actually see the same supernova, SN Refsdal, in four smaller images around a large galaxy within the cluster. Image credit: HST.

seen in Fig. 1.5, one gets even more interesting results. Shown in Fig. 1.5 is the Bullet Cluster (1E0657-558) which actually consists of two colliding sub-clusters. In the image on the left, one can see the infrared image from Magellan that is used, along with optical images from Hubble, to estimate the mass distribution of each galaxy cluster through graviational lensing. In the right image, one can see the X-ray map of the Bullet Cluster from the Chandra X-ray observatory with the same mass contours: one can see that the plasma from the clusters interacts giving the cone shapes in the center. However, the mass contours largely remained centered on the individual clusters (as seen in the optical image) implying that the majority of the matter interacted minimally during the collision [4]. This implies that the majority

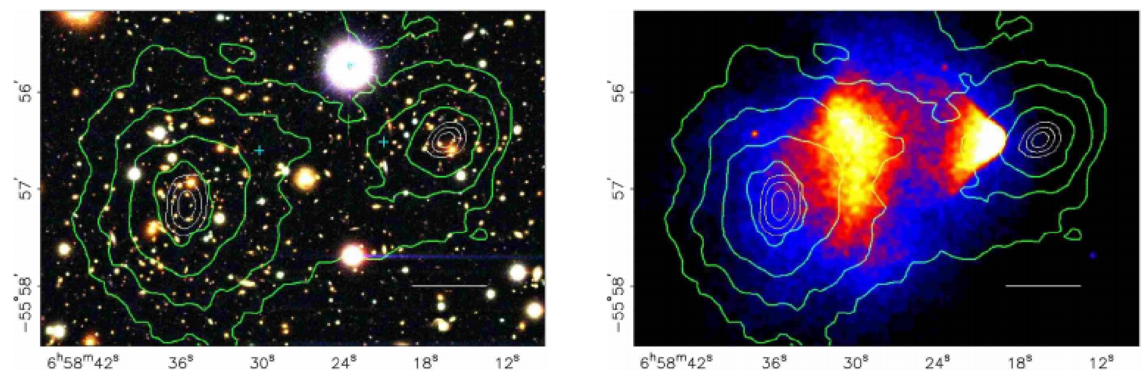

Figure 1.5: Infrared (left) and X-ray (right) maps of the Bullet Cluster (1E0657-558). While the plasma in the clusters interacts during the collision of the two individual clusters, as is seen by the shockwave in the center, the majority of the mass passes right through [4].

of the matter in these clusters at least does not interact electromagnetically.

1.2.4 Evidence from the Cosmic Microwave Background

The Cosmic Microwave Background (CMB) has proved to be one of the richest discoveries in all of cosmology. Accidentally discovered in 1964 by Penzias and Wilson [5], the radiation from the CMB is almost perfectly isotropic and described by a blackbody spectrum at 2.725 K [6]. The isotropy in the CMB provides the strongest evidence to date of the Big Bang Hypothesis and helped to formulate our current picture of the early universe down to the recombination epoch, where the universe was sufficiently cool such that hydrogen could form from the free electrons and protons in turn allowing photons to travel freely through the universe.

As the CMB has been studied in more detail, cosmologists began to see that there are in fact very small temperature fluctuations on the order of $\lesssim 100\mu K$ [7–9]. These temperature fluctuations, as seen in the 2015 measurement of the CMB by Planck satellite, are shown in Fig. 1.6. To characterize the temperature fluctuations of the entire sky, we use the spherical harmonics, $Y_{lm}(\theta, \phi)$.

$$T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi) \tag{1.6}$$

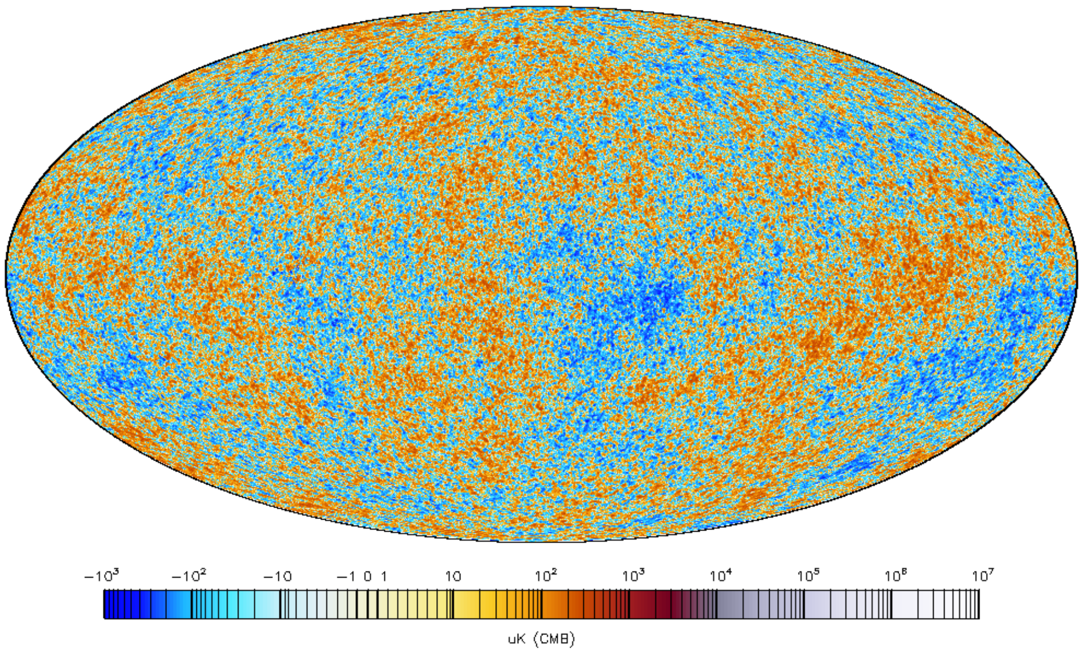

Figure 1.6: The Planck 2015 measurement of the temperature anisotropy of the CMB. Note that the largest deviations from the mean are on the order of $200\mu K$ from the 2.725 K mean (roughly 1 in 10^4). Image credit: IRSA, [7].

We assume that the distribution of a_{lm} should be described by a Gaussian distribution, as predicted by inflation, with a mean of 2.725 K for any given multipole moment l. Therefore, the only piece missing to completely describe these a_{lm} for each multiple moment is the variance of this distribution so we define $C_l \equiv \langle |a_{lm}|^2 \rangle$. These C_l form the power spectrum of the CMB and can be used to test various formation models of the universe. Planck tested the ΛCDM model described in Sec. 1.1 against their power spectrum (Fig. 1.7) and found remarkable agreement between prediction and data while constraining some of the universal constants including H_0, Ω_Λ, Ω_{CDM}, Ω_{Baryon}, and Ω_{Rad}. It is from this fit that we find that our universe has a curvature very close to zero and therefore is flat and that our universe is comprised of roughly 68.3% dark energy, 26.8% dark matter, and 4.9% ordinary matter [7].

The ΛCDM model has been tested since its inception using N-body simulations to propagate the formation of large scale structure in the universe. While small discrepancies between simulation and observation have been found, it is clear from

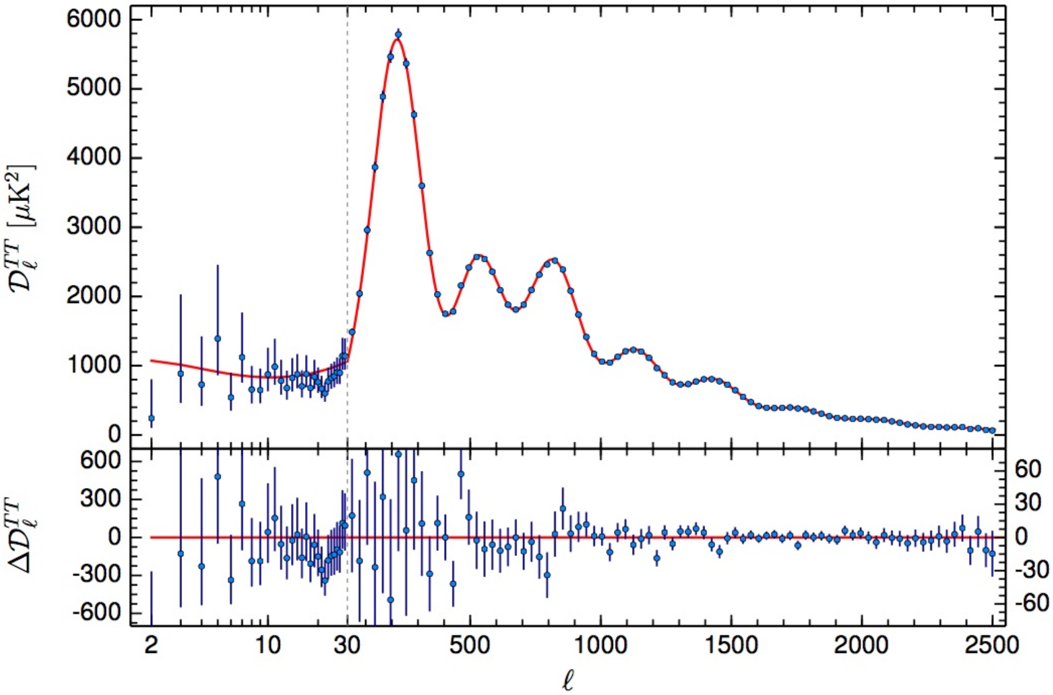

Figure 1.7: The power spectrum of the temperature anisotropies measured by Planck along with the best fit prediction from the ΛCDM model. $\mathcal{D}_l^{TT}$ is a proxy for C_i and is defined $\mathcal{D}_l^{TT} \equiv l(l+1)C_l/2\pi$ [7].

these simulations that without cold dark matter it is extremely difficult to explain the large scale structure we see in the universe given the anisotropies of the CMB [10–12].

1.3 Dark Matter Candidates

While there is an abundance of evidence to suggest that dark matter exists, we have little evidence to suggest what this cold dark matter actually is. In this section, we will discuss three of the most popular candidates for dark matter and their physical motivations. It should be noted that the candidates discussed do not form an exhaustive list but do satisfy the most basic requirements of a dark matter candidate:

- The lifetime of the particle is much greater than the lifetime of the universe (or is stable)

- The particle must be electrically neutral and very weakly interacting with ordinary matter
- The particle must be able to provide the correct relic density of cold dark matter as predicted by the CMB

1.3.1 Axions

Axions are hypothetical standard model particles that are introduced via the Peccei-Quinn mechanism as a solution to the strong-CP problem, one of the largest remaining deficiencies in the standard model [14]. CP (charge and parity) symmetry violation is required to explain the imbalance of matter and antimatter in the universe (why more matter exists) and has been observed in electroweak theory in a wide variety of measurements [15–19]. CP violation has never been observed in quantum chromodynamics even though there are natural terms in the QCD Lagrangian that would allow it. Therefore, this term in the Lagrangian, must be fine-tuned to exactly zero, hence the strong-CP problem. The axion introduced by Peccei-Quinn theory replaces this term with a field and gives the Lagrangian natural CP symmetry.

While the discovery of the axion would solve one of the largest problems of standard model, it also has the potential to solve one of the largest open mysteries of cosmology by making up at least a part of the cold dark matter density of the universe. Even though the axion is expected to have a very small mass ($10^{-6} - 10^{-2} eV$) it could still be produced cosmologically such that the large scale structure that we observe in the universe today is explained and we arrive at the CDM density estimated by Planck [20].

There are a number of experiments that can provide information about axions, both directly and indirectly. The mass range of axions, is essentially restricted from cosmological evidence from the CMB and stellar evolution. Simultaneously, cavity microwave experiments such as ADMX [13] and NMR based searches such as CASPeR [21] try to directly detect these low mass CDM candidates.

1.3.2 WIMPs

Weakly interacting massive particles (WIMPs), which will be the focus of the remainder of this work after this section, have proven to be the most popular dark matter candidate historically. WIMPs not only satisfy the basic criteria listed at the beginning of this section but additionally they have what is referred to as the "WIMP Miracle" in their favor. In the early stages of the universe, the temperature and density were so large that all particles were in a state of chemical equilibrium. A dark matter particle could annihilate by colliding with its anti-partner to form any type of particle vice versa. As time passed, however, the universe expanded and cooled making it more unlikely for these dark matter particles to be created or destroyed. Using this thermal equilibrium model alongside the ΛCDM model, one can infer that the CDM density in the universe today is approximately given by [22, 23]

$$\Omega_{CDM}h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{ann}v\rangle} \tag{1.7}$$

Several WIMP-like particles naturally fall out from the extensions of the standard model, such as supersymmetry, that

1.3.3 superWIMPs

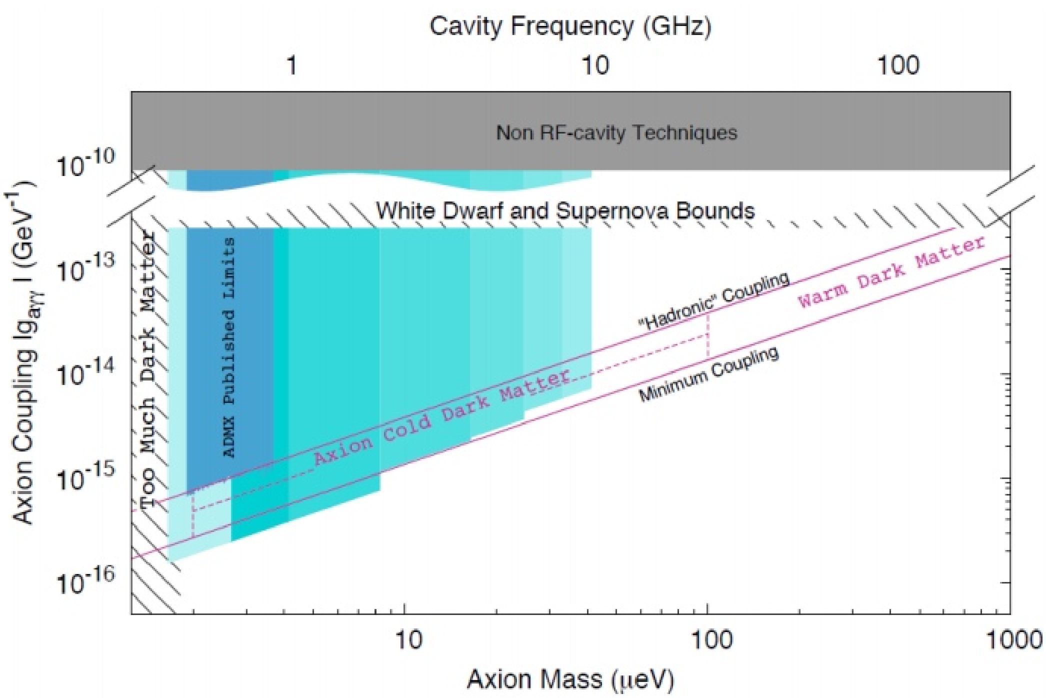

Figure 1.8: The projected sensitivity of the ADMX Generation 2 axion search. Note that strong cosmological constraints are placed on the mass range and the axion coupling is also constrained by the mass. The ADMX collaboration predicts that the searches shown will be completed by 2022 [13].

Chapter 2

Title of Chapter 2

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Bibliography

[1] F. Zwicky, "The redshift of extragalactic nebulae," *Helv. Phys. Acta*, vol. 6, p. 110, 1933.

[2] K. Begeman, A. Broeils, and R. Sanders, "Extended rotation curves of spiral galaxies: dark haloes and modified dynamics," *Monthly Notices of the Royal Astronomical Society*, vol. 249, no. 3, pp. 523–537, 1991.

[3] V. C. Rubin and W. K. Ford Jr, "Rotation of the andromeda nebula from a spectroscopic survey of emission regions," *The Astrophysical Journal*, vol. 159, p. 379, 1970.

[4] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, "A direct empirical proof of the existence of dark matter," *The Astrophysical Journal Letters*, vol. 648, no. 2, p. L109, 2006.

[5] A. A. Penzias and R. W. Wilson, "A measurement of excess antenna temperature at 4080 mc/s.," *The Astrophysical Journal*, vol. 142, pp. 419–421, 1965.

[6] D. Fixsen, E. Cheng, J. Gales, J. C. Mather, R. Shafer, and E. Wright, "The cosmic microwave background spectrum from the full cobe* firas data set," *The Astrophysical Journal*, vol. 473, no. 2, p. 576, 1996.

[7] P. A. Ade, V Salvatelli, V Stolyarov, F. Desert, J Knoche, M Giard, X Dupac, M Liguori, S Matarrese, Z Huang, *et al.*, "Planck 2015 results. xiii. cosmological parameters," *Astron. Astrophys.*, vol. 594, no. arXiv: 1502.01589, A13, 2015.

[8] C. L. Bennett, A. J. Banday, K. M. Górski, G Hinshaw, P Jackson, P Keegstra, A Kogut, G. F. Smoot, D. T. Wilkinson, and E. L. Wright, "Four-year cobe* dmr cosmic microwave background observations: maps and basic results," *The Astrophysical Journal Letters*, vol. 464, no. 1, p. L1, 1996.

[9] E. Komatsu, K. Smith, J Dunkley, C. Bennett, B Gold, G Hinshaw, N Jarosik, D Larson, M. Nolta, L Page, *et al.*, "Seven-year wilkinson microwave anisotropy probe (wmap*) observations: cosmological interpretation," *The Astrophysical Journal Supplement Series*, vol. 192, no. 2, p. 18, 2011.

[10] J. F. Navarro, "The structure of cold dark matter halos," in *Symposium-international astronomical union*, Cambridge University Press, vol. 171, 1996, pp. 255–258.

[11] V. Springel, C. S. Frenk, and S. D. White, "The large-scale structure of the universe," *arXiv preprint astro-ph/0604561*, 2006.

[12] M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, D. Nelson, and L. Hernquist, "Introducing the illustris project: simulating the coevolution of dark and visible matter in the universe," *Monthly Notices of the Royal Astronomical Society*, pp. 1518–1547, 2014.

[13] I. Stern, "Admx status," *arXiv preprint arXiv:1612.08296*, 2016.

[14] R. D. Peccei and H. R. Quinn, "Cp conservation in the presence of pseudoparticles," *Physical Review Letters*, vol. 38, no. 25, p. 1440, 1977.

[15] A Alavi-Harati, I. Albuquerque, T Alexopoulos, M Arenton, K Arisaka, S Averitte, A. Barker, L. Bellantoni, A Bellavance, J Belz, *et al.*, "Observation of direct CP violation in $K_{S,L} \to \pi\pi$ decays," *Physical Review Letters*, vol. 83, no. 1, p. 22, 1999.

[16] V Fanti, A Lai, D Marras, L Musa, A. Bevan, T. Gershon, B Hay, R. Moore, K. Moore, D. Munday, *et al.*, "A new measurement of direct CP violation in two pion decays of the neutral kaon," *Physics Letters B*, vol. 465, no. 1, pp. 335–348, 1999.

[17] B. Aubert, D Boutigny, I De Bonis, J.-M. Gaillard, A Jeremie, Y Karyotakis, J. Lees, P Robbe, V Tisserand, A Palano, *et al.*, "Measurement of CP-violating asymmetries in B^0 decays to CP eigenstates," *Physical Review Letters*, vol. 86, no. 12, p. 2515, 2001.

[18] K. Abe, R Abe, I Adachi, B. S. Ahn, H Aihara, M Akatsu, G Alimonti, K Asai, M Asai, Y Asano, *et al.*, "Observation of large CP violation in the neutral B meson system," *Physical Review Letters*, vol. 87, no. 9, p. 091 802, 2001.

[19] R Aaij, C. A. Beteta, B Adeva, M Adinolfi, C Adrover, A Affolder, Z Ajaltouni, J Albrecht, F Alessio, M Alexander, *et al.*, "First observation of CP violation in the decays of B_s^0 mesons," *Physical review letters*, vol. 110, no. 22, p. 221 601, 2013.

[20] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner, and K. A. van Bibber, "Experimental searches for the axion and axion-like particles," *Annual Review of Nuclear and Particle Science*, vol. 65, pp. 485–514, 2015.

[21] A. Garcon, D. Aybas, J. W. Blanchard, G. Centers, N. L. Figueroa, P. Graham, D. F. J. Kimball, S. Rajendran, M. G. Sendra, A. O. Sushkov, *et al.*, "Searching for dark matter with nuclear magnetic resonance: the cosmic axion spin precession experiment," *arXiv preprint arXiv:1707.05312*, 2017.

[22] G. Jungman, M. Kamionkowski, and K. Griest, "Supersymmetric dark matter," *Physics Reports*, vol. 267, no. 5-6, pp. 195–373, 1996.

[23] G. Bertone, *Particle dark matter: Observations, models and searches.* Cambridge University Press, 2010.