Evaluating WIMP Dark Matter Candidacy with Distant Astrophysical Phenomena

Matter is composed of subatomic particles which serve as the fundamental building blocks of our universe. The collective of all fundamental particles experimentally observed and encompassed by the current model for particle physics equations is classified as the Standard Model (SM) (*The Standard Model*, n.d.). As technological bounds are overcome and more particles are discovered, this model continues to evolve. Many scientists query the existence of particles outside of the SM which may govern important phenomena within the universe. Numerous theories propose that dark matter sources may belong to this group of particles.

The concept of dark matter was initially proposed by Lord Kelvin in 1884 following the observed discrepancy between his estimation of the mass of the Milky Way and the mass of visible stars within the galaxy. He suggested the presence of 'dark' objects which contribute to irregular gravitational field measurements (Kelvin, 1904). Measurements indicate that the presence of this extra force significantly affects the creation and matter distribution of galaxies, and thus learning more about the evolution of the universe and the fundamental force of gravity is intrinsically tied to the understanding of dark matter (Arbey & Mahmoudi, 2021).

Recent measurements from NASA's Planck mission highlight the influence of dark matter on the structure of the universe, indicating that dark matter constitutes approximately 27% of the observable universe, while visible matter constitutes 5%; dark matter particles outnumber known matter by 5:1. However, other than its gravitational effect on surrounding particles, dark matter negligibly interacts with normal matter, making it incredibly difficult to detect. Despite its significant influence on the cosmological macrostructure, the true nature of dark matter remains one of the universe's most substantial open questions; the contributor (or contributors) to the force generated by dark matter remains unknown. By leveraging quantum mechanics, computer simulations, supercollider data, and satellite images, scientists have proposed several candidates for the potential identity of dark matter.

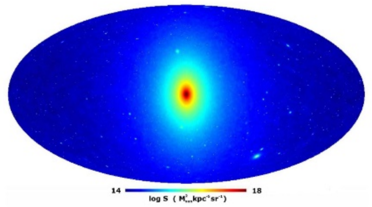

Figure 1: Simulated model of γ-ray emission from WIMP annihilation within a galactic halo (Vitale & Morselli, 2009).

Of the proposed theoretical dark matter candidates, those that are most intensely studied include: Massive Compact Astrophysical Objects (MACHOs), which are small stars or black holes in which little to no light reaches the area surrounding Earth; axions, particles generated by the collapse of strings (as suggested by String Theory) as well as early universe phase transitions; and Weakly Interacting Massive Particles (WIMPs) (Griest, 2002; Spergel, 1998). Of these, WIMPs have been widely considered the most promising candidate for dark matter and are the focus of this study.

WIMPs

WIMPs are a set of theoretical particles existing beyond the current SM. These heavy particles have a low interaction rate with SM particles and other WIMPs to a lesser extent (Baker & Thamm, 2018). As these particles do not emit, nor react with electromagnetic radiation, they are considered ‘dark’. A primary example of a weakly interacting particle is the neutrino, which does not interact with photons and requires massive underground detector chambers for identification. Many different types of particles, including those which are affiliated with String Theory and related models are considered to serve as dark matter sources. WIMP dark matter candidates are theorized to be Dirac (act as its own antiparticle). Consequently, a collision between two WIMPs results in the process of annihilation, where both particles cease to exist (Funk 2015).

Simulations have given insight into the origin of dark matter during the early universe. Thermal generation (spontaneous creation in the presence of extreme heat) during the period immediately following the Big Bang acts as the widely-accepted origin for WIMPs (Griest, 2002). Due to their high density during this period of the universe’s evolution, WIMP particles experienced frequent collisions, and the subsequent annihilations reduced particle density. As the universe cooled, WIMP thermal generation decreased at an exponential rate while annihilation continued (Arbey & Mahmoudi, 2021). Consequently, WIMP DM density decreased until the probability of a particle colliding with another particle was low enough that subsequent annihilations were unable to significantly affect overall density. This resulted in a remaining quantity of WIMP particles known as a relic abundance (Baker et al., 2020), whose average universal annihilation cross section has been mapped to $3*10^{-26}$ cm^{3}*s^{-1} (Funk, 2014). The gravitational effects caused by the WIMP relic abundance are likely a primary or sole contributor to the observable effects of dark matter.

Additionally, once a collision between two WIMP particles does occur, the law of conservation of energy dictates that new particles must be formed. The creation of specific product particles is referenced as an annihilation channel, which is dependent on the characteristics of the WIMP annihilation, particularly particle mass (Vitale & Morselli, 2009). Through the observation of these secondary particles, constraints on WIMP mass and interaction rate can be extrapolated.

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Efforts to detect WIMP particles are divided into three primary methods: accelerator-based detection, which leverages the LHC and other particle accelerators to probe for dark matter at specific energy ranges, direct, which utilizes large detectors and colliders to observe these particles, and indirect detection (Funk, 2014), using both space and ground-based high-energy telescopes to look for WIMP annihilation channel products. This study uses indirect detection and exammines of regions of space to look for WIMP annihilation relics.

Indirect Detection of WIMPS

To analyze dark matter properties within a region of space, scientists have focused on the measurement of a particular particle—a γ-ray—which is consistently a product of WIMP annihilation, either through direct production or through the decay of other particles. Typically, γ-ray telescopes such as the Fermi LAT, H.E.S.S, VERITAS, and other ground and orbit-based telescopes are used to observe the γ-ray flux in a specific region of space. (Arbey, 2021). Through the differentiation of WIMP and non-WIMP γ-rays, the annihilation cross section of WIMP dark matter can be approximated. Typically, the extrapolated parameter of choice is the upper bound of the 95% confidence interval of the annihilation cross section to consider uncertainties within the data, as well as the inclusion of other, lower-energy dark matter candidates. Regions of interest for these indirect detection methods include galaxy clusters and galactic centers—both of which are locations of significant DM mass—and dwarf spheroidals—small galaxies orbiting the Milky Way and larger galaxies—due to their lack of γ-rays caused by visible matter (Conrad, 2015).

While successful—along with pure DM and DM-baryon simulations—in establishing widely regarded limits for dark matter mass and density, the indirect nor direct detection of WIMPS have provided significant analysis of these theoretical particles to encompass the WIMPs into our physics model. Additionally, collider experiments conducted with the LHC have been unable to significantly constrain proposed WIMP DM energy values. As a result of this standstill, questions regarding the overall DM candidacy of WIMPs are now being raised (Baker & Thamm, 2018).

Dark Matter Halo Distribution

Within the realm of indirect detection, the computation of the dark matter annihilation cross-section depends upon the assumed dark matter density distribution throughout the given source. This DM distribution (often referred to as halo) lacks accurate experimental observation. As seen in Figure 1, simulations have illustrated the general shape of this halo, as well as possible dark matter substructures within the galaxy. Different equations modeling the form of the halo as a function of radius have been constructed based on various observations.

However, these profile equations differ from one another up to a factor of 10^4. While one function—the Navarro-Frank-White profile—is considered to be the best description of the halo shape, different sources are more-precisely modeled given each different profile (Vitale & Morselli, 2009).

This study focused on the observation of distant galaxies—a largely unobserved candidate for indirect WIMP DM surveys. As a result of this lack of observation, the dark matter interaction rate can be heavily constrained. Twelve galaxies were observed using photon data from the Fermi LAT, and a likelihood analysis was used to extrapolate the 95% upper confidence interval of the dark matter annihilation cross-section for particle masses between 10 GeV and 5 TeV. Additionally, radial partitioning of the data was utilized to determine the best dark matter halo profile equation for use in the gamma-ray flux extrapolation. We find that the dark matter annihilation cross lies XXX Akermann et al.'s 2014 dwarf spheroidal survey, heavily constraining masses XXX to XXX. Future studies regarding these sources must be conducted to further constrain WIMP mass and interaction rate. Within these sources.