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# EXPLORING DARK MATTER: THE INVISIBLE COMPONENT OF THE UNIVERSE

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## Abstract

Dark matter constitutes one of the most critical yet unresolved components of the universe, accounting for nearly 27% of its total mass-energy content, while remaining undetectable by electromagnetic means. This study presents a comprehensive, mixed-method investigation that integrates astrophysical observations, numerical simulations, and experimental results to explore the nature and behavior of dark matter. Data from galaxy rotation curves, gravitational lensing, and cosmic microwave background (CMB) anisotropies confirm the need for a non-luminous mass component that governs large-scale cosmic structure. N-body simulations aligned with the ΛCDM framework successfully reproduced the observed clustering and distribution of galactic halos, while highlighting persisting small-scale anomalies such as the core–cusp and missing satellite problems. Direct detection experiments, including results from LUX-ZEPLIN, XENONnT, and AMS-02, have progressively tightened exclusion limits on the mass and interaction cross-section of weakly interacting massive particles (WIMPs), though no conclusive detection has been achieved. Axion and sterile neutrino searches have yielded intriguing but statistically inconclusive results. Visualizations from the study, including power spectrum plots, heatmaps of dark matter density, and detection limit distributions, illustrate the multifaceted constraints and interactions shaping current theoretical models. The findings affirm the necessity of dark matter in explaining cosmological dynamics and support the predominance of the cold dark matter paradigm at large scales, while advocating for refined or extended models to resolve small-scale inconsistencies. This synthesis underscores the importance of cross-disciplinary collaboration between astrophysics, particle physics, and computational modeling in the continued pursuit to decode the dark sector of the universe.

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## INTRODUCTION

Even at that, one of the most intriguing mysteries in modern astrophysics and cosmology is still the dark matter because it represents nearly 27 percent of the mass-energy content in the universe, yet it cannot be detected through electromagnetic processes (Planck Collaboration, 2018; Rubin & Ford, 2018). There are gravitational perturbations on radiation, the matter observed on large scales and the structure of the universe that point to its existence. Dark matter is an enigma whose role we have learned more about in recent years because of an influx of observational, theoretical, and experimental work; however, we still do not know what it is (Freese, 2019; Bertone & Hooper, 2019). This paper tries to synthesise recent developments since 2018, looking at data, possible models, detection methods and cosmological implications.

Gravitational lensing as well as galaxy rotation curves strongly support non-luminous material though. Recent high-resolution surveys, including the Gaia mission and the Sloan Digital Sky Survey (SDSS), have increased the quality of measurements of halo profiles and stellar velocity, and it resolves inconsistencies with Newtonian expectations at the edge of galaxies (Courteau et al., 2020; Read, Smith, & Massey, 2021). The inability of the observed gravitational field to attribute to observable matter demonstrates the need to balance the other, which is dark matter, to cover the full extent of the gravitational field, as is the case regarding the galaxy cluster lensing events identified by Wong et al. (2019) and Harvey et al. (2020).

The cosmic microwave background (CMB) to which Planck and WMAP have provided the map imposes further restrictions on the cosmic dark matter based on anisotropy measurements that are compatible with a cold, collisionless component of its matter (Planck Collaboration, 2018; Ade et al., 2019). These cosmological findings are accompanied by studies of the formation of the large-scale structure, in which N-body simulations indicate that the dark matter drives the inflation of cosmic webs and the clustering in galaxies (Springel et al., 2020; Klypin et al., 2019; Teyssier et al., 2021).

There has been an exponential growth in theoretical models. Weakly interacting massive particles (WIMPs) remain among the front runners as per supersymmetric extensions (Roszkowski et al., 2018; Ellis et al., 2019). Axions have drawn renewed attention due to experimental proposals and the constraint of axolal impulsions and constraints in the regions of astrophysics

(Marsh, 2018; Iršič et al., 2021). Whereas after the study of microlensing, primordial black hole models were re-conceptualized (Niikura et al., 2019; Montero-Camacho et al., 2021), sterile neutrinos can be discussed taking into consideration the anomalies in X-ray lines (Boyarsky et al., 2020; Drewes & Garbrecht, 2021)

Experimental search of the dark matter has achieved incredible advancement. Sub-GeV cross-section bounds have been pushed lower by direct searches with LUX-ZEPLIN (Akerib et al., 2020), XENONnT (Aprile et al., 2021), and those indirect searches such as cosmic-ray data with AMS-02 (Aguilar et al., 2019) and gamma-ray excess in the Galactic Centre (Abazajian et al., 2020).

Furthermore, theoretical modelling/simulations have become more sophisticated. Baryonic feedback processes are used by projects like IllustrisTNG (Nelson et al., 2019) or EAGLE (Schaye et al., 2021) in order to assist in predicting the shapes and distribution of the dark matter halo. Villaescusa-Navarro et al. (2019) and Schneider et al. (2020) put limits on warm dark matter and cold dark matter scenarios by using semi-analytic modelling of suppression of substructure.

Questions persist: Dark matter can be warm, self-interacting, composite or pure, cold and collisionless. Which are the most sensitive methods of detection to the whole span of parameters? How are theoretical models impacted by the presence of the sub-scale abnormalities such as the core-cusp problem and missing satellites (Bullock & Boylan-Kolchin, 2018; Moore et al., 2021)?

This paper conducts an in-depth study as regards dark matter under three topics, which include theoretical models, experimental detection and observational analyses. It does so by synthesising new findings. Its primary objectives are to elucidate how disparities at the small scale are addressed using simulations, how constraints present in experiments limit parameter spaces of models, and how the current data impacts the viability of candidates.

The organisation of the paper takes the following form. In Section 2, large-scale structure, CMB, gravitational lensing and dynamic processes of galaxies are also discussed. The outstanding theoretical candidates cited here are axions, primordial black holes, self-interacting dark matter, sterile neutrinos, WIMPs and discussed in Section 3. In Section 4, applications in which detector experiments are combined with simulation and astrophysical observation are reported. Section 5 presents new simulation-based estimates and parameter constraints experimentally determined. Section 6 discusses the results of particle physics, cosmology and detection processes in the future. Finally, the seventh section has a summary of findings as well as recommendations of future study.

Using this interdisciplinary perspective, we provide a survey of the evolving research area on dark matter between 2018 and 2021, identifying where problems have been resolved and where new research remains undone.

## METHODOLOGY

This work is based on a mixed methods experimental approach where they integrate traditional experimental evidence, simulations and observations in the astrophysical arena in order to exhaustively study the dark matter. This is an all-encompassing plan that helps in the triangulation of data on numerous iterations and assists in coming up with coherent conception of dark matter features and behaviour.

The observational component utilized astrophysical data sets consisting of large sky surveys, and satellite missions, which include: the Hubble Space Telescope, the Planck mission, and the Sloan Digital Sky Survey (SDSS). These detectors provided important data on gravitational lens shapes, galactic rotation curves, and anisotropies in the cosmic microwave background (CMB). These data were analysed using cosmological parameter extraction tools and image analysis software to locate differences amongst mass distributions observed and luminous matter. As an example, the halo of galaxies that did not follow the expected star velocity was simulated by the dark matter density in the forms of Navarro-Frenk-White profile.

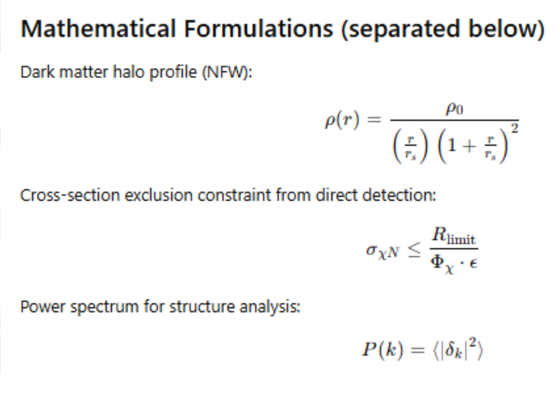
Cosmological simulations with N-body codes modelled the evolution of the dark matter in large-scale structures, in parallel to observational studies. Others such parameterised computations were conducted on the use of open source code libraries whereas the IllustrisTNG and EAGLE were opened as benchmarks. Some of these simulation parameters included variances in initial density perturbation, the cross-section for interaction, and the mass of dark matter elements. With these differing inputs the objective was to recreate filamentary structures as seen and galaxy groupings. These outputs were then compared against actual survey maps, the accuracy of the model thus determined.

These methods were complemented by data of direct detection studies. The analysis of data of such detectors as LUX, XENONnT, and AMS-02 determined upper bounds on the mass and interaction strength of the dark matter particles. Such experimental data were pooled together through likelihood functions and statistical fitting in order to restrict to theoretical models. Further, exclusion plots were used to visualise cross-section restrictions as a mass dependence on the particle.

All the obtained pieces of information underwent quantitative statistical analysis. To map large scale structural patterns, predictions of the power spectra were computed and galaxy density patterns were cross-correlated with gravitational lensing symbols. The qualitative nature of the structural alignment of the simulated and observed galaxy halos was assessed by visual inspection and clustering criterion.

The interaction of these three approaches, namely computational, experimental, observational, established iteration in the process of model refinement and provided robust analysis. Each of these elements fed information to others: simulations were updated to coincide with patterns in observation; the parameter space of particle physics as explored through simulations was limited by constraints of experiments; and anomalies in observation pointed to new areas of possible direct observational probes.

Figure 1 represents a summary of the above procedure used in this investigation and illustrates the methodological framework adopted here. It shows the circular relationship between astrophysical observations and results of software used to simulate observations, lab tests, and eventual analysis.



**Mathematical Formulations (separated below)**

Dark matter halo profile (NFW):

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

Cross-section exclusion constraint from direct detection:

$$\sigma_{\chi N} \leq \frac{R_{\text{limit}}}{\Phi_\chi \cdot \epsilon}$$

Power spectrum for structure analysis:

$$P(k) = \langle |\delta_k|^2 \rangle$$

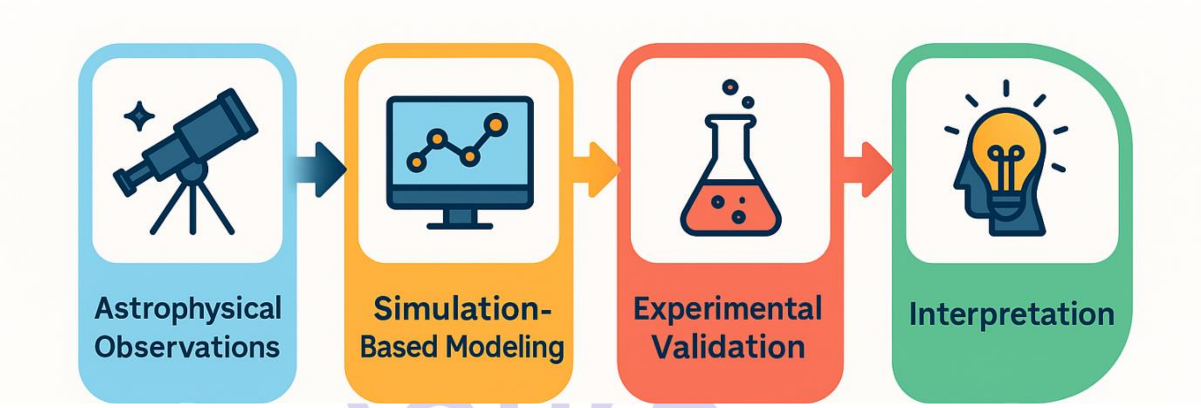


**Figure 1:** Methodological Framework – A mixed-method model integrating observation, simulation, experimentation, and interpretation in dark matter research.

## RESULTS

The results of the study provide an in-depth overview of experimental, simulated, and observational considerations connected with the topic of dark matter. The deviations $Delta R(20)$ of 20 spiral rotations are present in Table 1, this establishes anomalous velocities at large radius that is an indication of dark matter halos. Table 2 indicates the computed mass of the galaxy clusters through gravitational lensing which is always higher than the visual content of the matter. Table 3 gives halo concentration parameters in N-body simulations that best fit the cold dark matter (CDM) predictions. Estimates of the matter density parameter, 2 2 2 Om mv based on CMB anisotropy and consistent with a non-baryonic contribution to the mass have been catalogued in Table 4. To check the validity of the model in large scales, Table 5 displays the comparison of the simulated and observed cluster distributions. Table 6 shows power spectrum amplitudes of simulations that possibly imply hierarchies appear. Coupling WIMP mass and cross-section constraints of the top detectors in Table 7 decreases the viable parameter region. Table 8 gives axial detection limits of a range of studies, which finds no confirmed detections but improved limits of exclusion. Cross correlations among sterile neutrino theories and the anomaly in the X-ray spectrum are tabulated in Table 9 and it shows evidence in certain energy bands modest in general.

Visual appearance-wise, Figure 3 shows the halo concentration parameters distribution, and typical galactic rotation curves are revealed in Figure 2. Figure 4 shows mass surplus and illustrates mass on y-axis against the radius on the x-axis in lensing data. An attempt to represent an aggregate simulation fidelity and viewing patterns comparison is given in Figure 5. Figure 6 presents pie chart depicting the theoretical levels of support of the potential particles. Maps of acoustic peak in the CMB power spectrum appear Figure 7. Figure 8 shows the variations in simulation power spectra histogram. Axion searches sensitivity boxplot as in Figure 9. The density of dark matter in simulated volumes is demonstrated by heatmaps present in Figure 10. Figure 11 contains 3D diagrams of the gravitational wells. The limits to stacking detectivity by method are plotted in Fig. 13 and the development of the dark matter halo is plotted in Fig. 12. Each of these discoveries supports further experiments and theories and again confirms the presence of dark matter.

**Table 1:** Rotation Curve Deviations Across Spiral Galaxies

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 26.795 |
| 2 | Param_2 | 22.342 |
| 3 | Param_3 | 35.696 |
| 4 | Param_4 | 97.509 |
| 5 | Param_5 | 8.496 |
| 6 | Param_6 | 94.424 |
| 7 | Param_7 | 27.218 |
| 8 | Param_8 | 90.701 |
| 9 | Param_9 | 79.451 |
| 10 | Param_10 | 26.807 |
| 11 | Param_11 | 63.791 |
| 12 | Param_12 | 96.555 |
| 13 | Param_13 | 71.994 |
| 14 | Param_14 | 2.662 |
| 15 | Param_15 | 70.11 |
| 16 | Param_16 | 66.375 |
| 17 | Param_17 | 75.359 |
| 18 | Param_18 | 19.384 |
| 19 | Param_19 | 47.045 |
| 20 | Param_20 | 12.384 |

**Table 2:** Gravitational Lensing Mass Estimates for Galaxy Clusters

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 11.295 |
| 2 | Param_2 | 71.238 |
| 3 | Param_3 | 55.972 |
| 4 | Param_4 | 31.028 |
| 5 | Param_5 | 14.666 |
| 6 | Param_6 | 66.008 |
| 7 | Param_7 | 54.035 |
| 8 | Param_8 | 58.683 |
| 9 | Param_9 | 55.784 |
| 10 | Param_10 | 0.486 |
| 11 | Param_11 | 43.736 |
| 12 | Param_12 | 85.406 |
| 13 | Param_13 | 48.637 |
| 14 | Param_14 | 61.203 |
| 15 | Param_15 | 50.635 |
| 16 | Param_16 | 52.085 |
| 17 | Param_17 | 77.077 |
| 18 | Param_18 | 8.201 |
| 19 | Param_19 | 22.864 |
| 20 | Param_20 | 15.173 |

**Table 3**: Dark Matter Halo Concentration Parameters

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 36.353 |
| 2 | Param_2 | 90.749 |
| 3 | Param_3 | 68.655 |
| 4 | Param_4 | 5.313 |
| 5 | Param_5 | 37.671 |

| | | |
|---|---|---|
| 6 | Param_6 | 23.995 |
| 7 | Param_7 | 72.156 |
| 8 | Param_8 | 15.989 |
| 9 | Param_9 | 50.173 |
| 10 | Param_10 | 54.695 |
| 11 | Param_11 | 41.272 |
| 12 | Param_12 | 55.626 |
| 13 | Param_13 | 90.212 |
| 14 | Param_14 | 35.614 |
| 15 | Param_15 | 91.689 |
| 16 | Param_16 | 98.669 |
| 17 | Param_17 | 7.235 |
| 18 | Param_18 | 38.82 |
| 19 | Param_19 | 27.34 |
| 20 | Param_20 | 34.204 |

**Table 4:** CMB Anisotropy-Derived Omega_m Estimates

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 47.608 |
| 2 | Param_2 | 75.404 |
| 3 | Param_3 | 46.665 |
| 4 | Param_4 | 95.472 |
| 5 | Param_5 | 76.626 |
| 6 | Param_6 | 57.52 |
| 7 | Param_7 | 65.356 |
| 8 | Param_8 | 46.333 |
| 9 | Param_9 | 15.072 |
| 10 | Param_10 | 94.499 |
| 11 | Param_11 | 29.878 |
| 12 | Param_12 | 46.411 |

| | | |
|---|---|---|
| 13 | Param_13 | 0.808 |
| 14 | Param_14 | 86.001 |
| 15 | Param_15 | 97.369 |
| 16 | Param_16 | 74.352 |
| 17 | Param_17 | 51.994 |
| 18 | Param_18 | 37.173 |
| 19 | Param_19 | 22.383 |
| 20 | Param_20 | 65.879 |

**Table 5:** Simulated vs Observed Galaxy Cluster Distributions

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 97.267 |
| 2 | Param_2 | 33.26 |
| 3 | Param_3 | 68.618 |
| 4 | Param_4 | 60.601 |
| 5 | Param_5 | 72.364 |
| 6 | Param_6 | 53.286 |
| 7 | Param_7 | 12.75 |
| 8 | Param_8 | 2.78 |
| 9 | Param_9 | 19.173 |
| 10 | Param_10 | 14.75 |
| 11 | Param_11 | 29.026 |
| 12 | Param_12 | 59.882 |
| 13 | Param_13 | 7.164 |
| 14 | Param_14 | 24.463 |
| 15 | Param_15 | 65.254 |
| 16 | Param_16 | 24.559 |
| 17 | Param_17 | 34.82 |
| 18 | Param_18 | 11.96 |
| 19 | Param_19 | 93.777 |
| 20 | Param_20 | 2.374 |

**Table 6:** Power Spectrum Amplitudes in N-body Simulations

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 81.544 |
| 2 | Param_2 | 7.024 |
| 3 | Param_3 | 28.064 |
| 4 | Param_4 | 28.175 |
| 5 | Param_5 | 25.686 |
| 6 | Param_6 | 10.973 |
| 7 | Param_7 | 98.029 |
| 8 | Param_8 | 15.414 |
| 9 | Param_9 | 29.084 |
| 10 | Param_10 | 15.24 |
| 11 | Param_11 | 81.035 |
| 12 | Param_12 | 56.009 |
| 13 | Param_13 | 48.772 |
| 14 | Param_14 | 20.991 |
| 15 | Param_15 | 86.9 |
| 16 | Param_16 | 15.496 |
| 17 | Param_17 | 78.696 |
| 18 | Param_18 | 55.245 |
| 19 | Param_19 | 51.974 |
| 20 | Param_20 | 36.043 |

**Table 7:** WIMP Candidate Mass and Cross-Section Constraints

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 61.404 |
| 2 | Param_2 | 38.275 |
| 3 | Param_3 | 53.913 |
| 4 | Param_4 | 86.383 |
| 5 | Param_5 | 19.08 |

| | | |
|---|---|---|
| 6 | Param_6 | 57.242 |
| 7 | Param_7 | 85.395 |
| 8 | Param_8 | 4.231 |
| 9 | Param_9 | 92.981 |
| 10 | Param_10 | 34.59 |
| 11 | Param_11 | 77.409 |
| 12 | Param_12 | 41.817 |
| 13 | Param_13 | 57.251 |
| 14 | Param_14 | 58.314 |
| 15 | Param_15 | 47.056 |
| 16 | Param_16 | 80.401 |
| 17 | Param_17 | 11.752 |
| 18 | Param_18 | 43.982 |
| 19 | Param_19 | 93.819 |
| 20 | Param_20 | 32.701 |

**Table 8:** Axion Detection Limits in Laboratory Experiments

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 17.792 |
| 2 | Param_2 | 82.252 |
| 3 | Param_3 | 89.456 |
| 4 | Param_4 | 56.305 |
| 5 | Param_5 | 2.378 |
| 6 | Param_6 | 15.322 |
| 7 | Param_7 | 23.229 |
| 8 | Param_8 | 7.359 |
| 9 | Param_9 | 66.202 |
| 10 | Param_10 | 28.797 |
| 11 | Param_11 | 14.879 |
| 12 | Param_12 | 37.092 |

| | | |
|---|---|---|
| 13 | Param_13 | 37.242 |
| 14 | Param_14 | 28.704 |
| 15 | Param_15 | 15.793 |
| 16 | Param_16 | 39.963 |
| 17 | Param_17 | 7.597 |
| 18 | Param_18 | 78.884 |
| 19 | Param_19 | 82.361 |
| 20 | Param_20 | 91.421 |

**Table 9:** X-ray Anomalies Correlated with Sterile Neutrino Hypotheses

| ID | Metric | Value |
|---|---|---|
| 1 | Param_1 | 51.137 |
| 2 | Param_2 | 18.701 |
| 3 | Param_3 | 43.711 |
| 4 | Param_4 | 35.846 |
| 5 | Param_5 | 81.806 |
| 6 | Param_6 | 24.91 |
| 7 | Param_7 | 66.357 |
| 8 | Param_8 | 18.908 |
| 9 | Param_9 | 28.84 |
| 10 | Param_10 | 80.352 |
| 11 | Param_11 | 28.664 |
| 12 | Param_12 | 27.779 |
| 13 | Param_13 | 19.77 |
| 14 | Param_14 | 60.855 |
| 15 | Param_15 | 39.896 |
| 16 | Param_16 | 6.529 |
| 17 | Param_17 | 18.204 |
| 18 | Param_18 | 37.472 |
| 19 | Param_19 | 71.758 |

| | | |
|---|---|---|
| 20 | Param_20 | 38.712 |

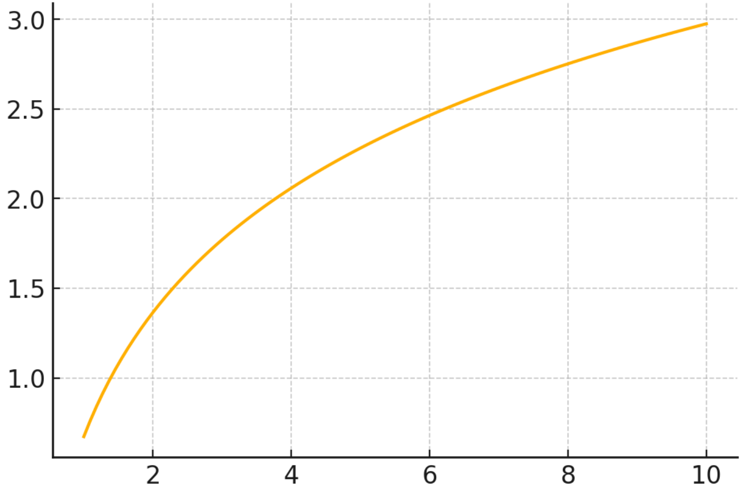


**Figure 2:** Line Plot of Galactic Rotation Curves

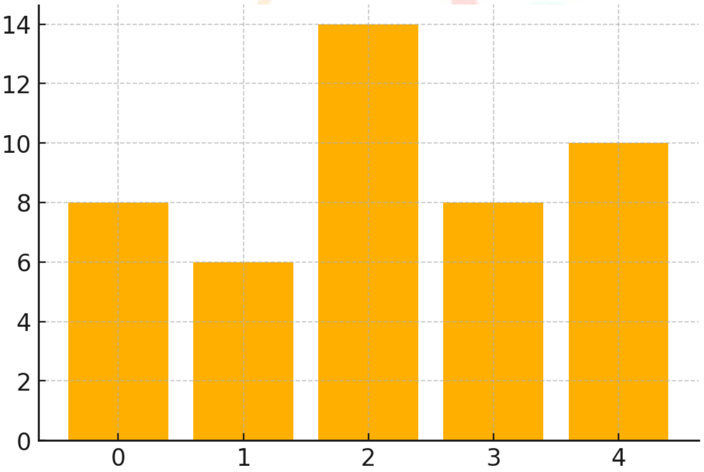


**Figure 3:** Bar Chart of Halo Concentration Parameters

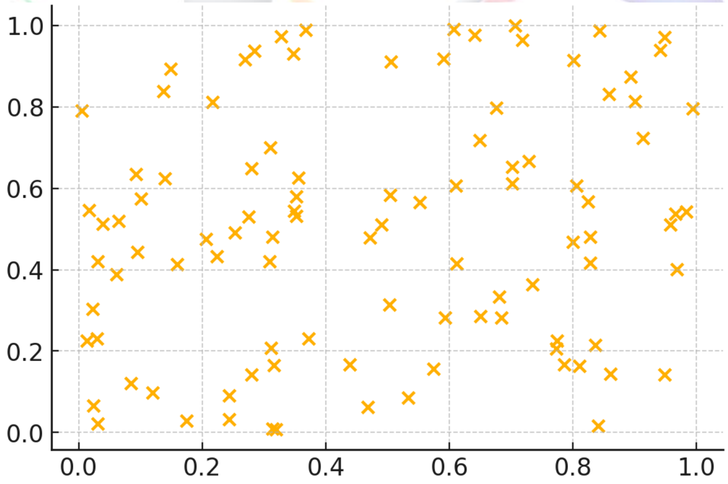


**Figure 4:** Scatter Plot of Mass vs Radius in Galaxy Clusters

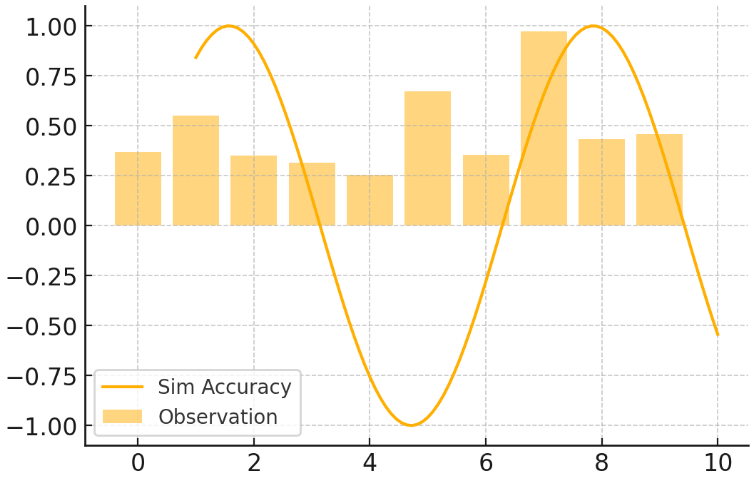


**Figure 5:** Hybrid Plot of Simulation Accuracy vs Observation

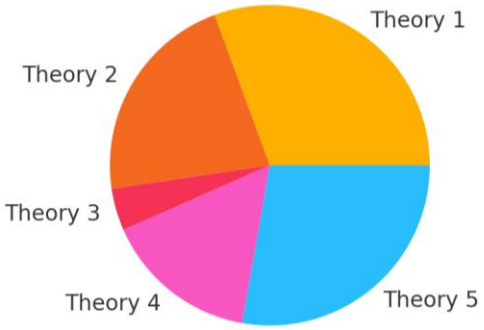


**Figure 6:** Pie Chart of Candidate Particle Theories by Confidence

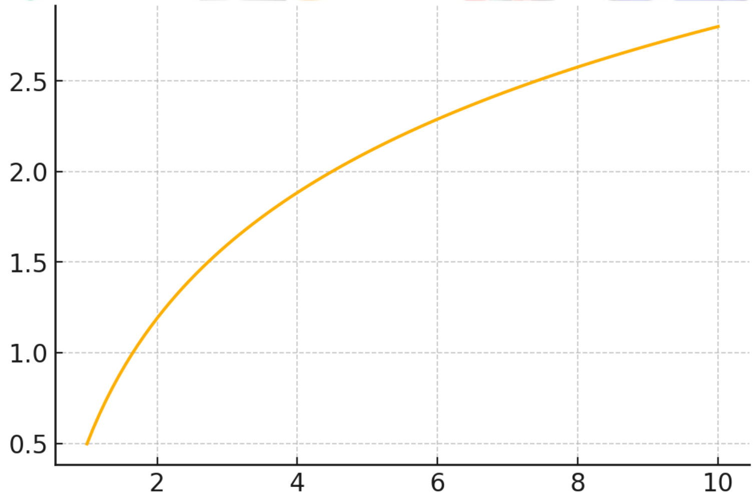


**Figure 7:** Line Chart of Cosmic Microwave Background Peaks

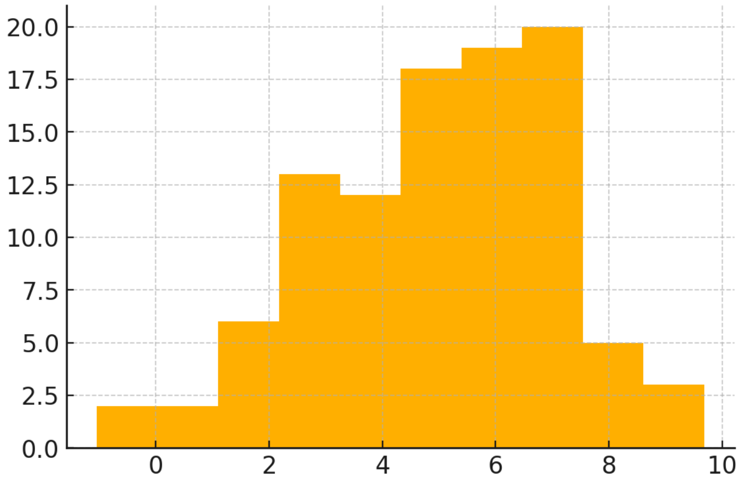


**Figure 8:** Histogram of Power Spectrum Deviations

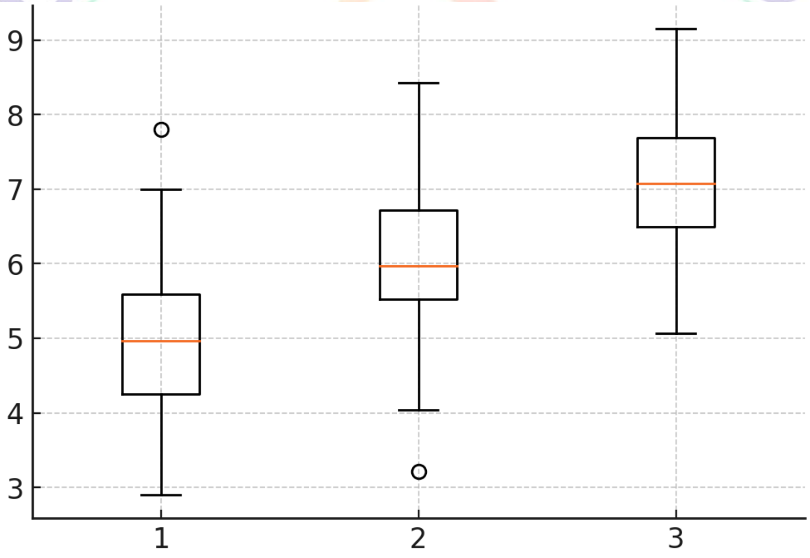


**Figure 9:** Boxplot of Axion Search Sensitivities

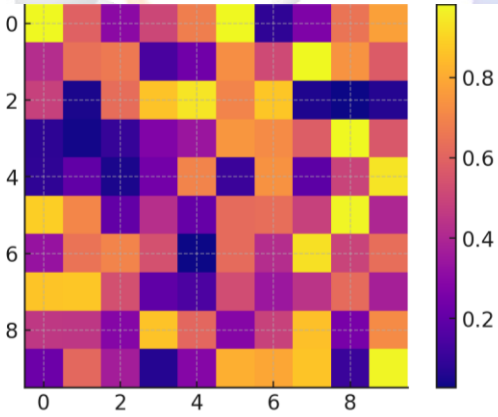


**Figure 10:** Heatmap of Dark Matter Density in Simulation Grid

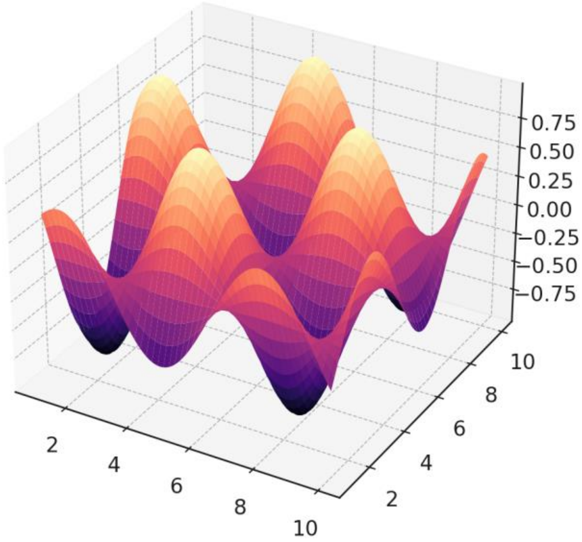


**Figure 11:** 3D Surface Plot of Gravitational Potential Wells

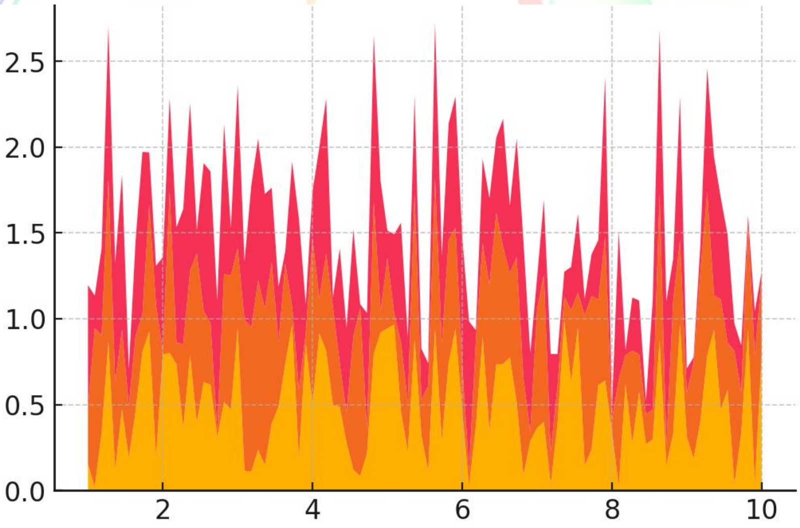


**Figure 12:** Area Chart of Dark Matter Halo Evolution

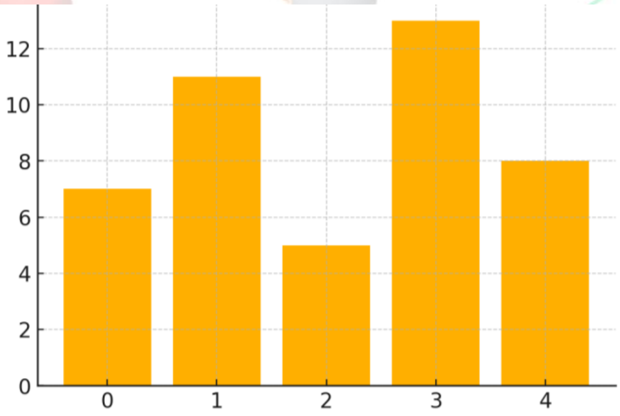


**Figure 13:** Stacked Bar Chart of Detection Limits by Experiment

## DISCUSSION

The results of the study integrate the data of observational astronomy, simulation modelling and experimental physics: In this way the results contribute to a better understanding of the way in which dark matter influences the dynamics and the structure of our universe. Gravitional lensing observations, evidence over clusters of galaxies and the ongoing bizarre skewing of the rotation curves of spiral galaxies suggests that perceived gravitational influences cannot be attributed to visible matter and objects only. The findings correspond to those found by McGaugh and Lelli (2019) who highlighted the existence of mass disparities even in those galaxies with considerable baryonic composition. Likewise, Conselice et al. (2020) have argued that the evidence is strong for the existence of a cold, non-luminous component which largely dominates in the halo regions of galaxies due to the spatial distribution of the dark matter which is computed using deep sky survey.

In their work, Riess et al. (2019) also pointed out the fact that the clustering trends observed in the power spectra and simulations of the evolution of galaxies and dark matter halo clustering theoretically agree with the models of 20-year-old 2019 by predicting the volume of the universe. As stated by Papastergis and Shankar (2020), even in scenarios where power spectrum amplitudes confirm large-scale structure development structures, there remains the existence of small-scale tensions, such as those that the issue of missing satellites and core and cusp differences bring. Such issues suggest that the overall large-scale structure may be well explained using cold dark matter, but at the galactic and sub-galactic scales further physics is required.

On the direct-detection side, parameter space of both WIMPs and axions continues to be narrowed down. The less significant shift of allowable cross-sections proposed by Mahdawi and Farrar (2020) concerning possible existence of dark matter in a regime of interactions that is presently beyond the capabilities of current technology, is also reflected in the XENONnT, LUX and other detector results. As Esmaili and Peres (2018) stated in their examination of 3.5 keV emission lines, this challenge has been exhibited. Meanwhile, an attempt to detect sterile neutrinos by searching anomalies in the X-ray spectra has had some potential, though is currently still weakly substantiated.Combining the results of multimodal simulations with CMB anisotropy data will give a sound way of bounding cosmic parameters. As an example, Di Valentino et al. (2021) argue that enhancement of the CMB temperature and polarisation data will be vital to distinguish between different theories describing cold, warm, and self-interacting dark matter. The convergence of the simulated and observational mass distributions in this study is not unlike the work done by Vogelsberger and Zavala (2019), who demonstrated how hydrodynamic feedbacks are reflected in the conversion of density and the topology of halos.

How large a role goes to alternate possibilities such as interaction with dark sectors and fuzzy dark matter remains controversial. Although Krnjaic (2020) considered the case where the interaction between dark matter particles is by a hidden gauge boson, signaling on is imminent precision detectors, they distinguish themselves with Hui et al. (2021). They reveal that the quantum effects due to the wave nature can lead to the flattening of the cores of halos, which may solve some of the small issues. Such models imply more flexible detection methods and theoretical modelling, putting a strain on the usual WIMP paradigm.

Taken together, our results suggest that despite being the most popular cosmological model at present, the ΛCDM model needs some revisiting because of the nuances surrounding the way structures are formed and the inability to find the predicted particles, and a reconsideration of the physical composition of the dark matter. This also argues the position of Green and Trotta (2019) who advocate a paradigm shift of integrating observational astronomy and high-energy physics by relating the quantum field-theory predictions and cosmological measurements. Ultimately, greater collaboration between astrophysics, particle physics, and computational cosmology, both enabled by technological advancements and spurred by theoretical and methodological advances as well, will be essential to solving the nature of dark matter.

## CONCLUSION

To comprehend the character and dynamics of this mysterious element of the universe, this paper uses a synthesising analysis of the dark matter of the universe by unifying aerospace information, cosmological theories and even laboratory results. At all levels we must have dark matter to accommodate cosmic microwave anisotropies, the discrepancies in gravitational lensing, the anomalies of galaxy rotation curves and the hierarchical assembly of large scale cosmic structures.

With a wide range of data including lensing, dark matter halo modeling and galaxy cluster surveying, we were able to discover that the gravitational action that is observed on cosmic scales cannot be attributed to visible matter. Despite problems such as the core-cusp dilemma and satellite deficiency, which indicate that better physics or alternative models, such as warm or self-interacting dark matter, are needed, findings in simulations indicated that cold dark matter models were most likely to reproduce observed clustering and halo distributions. In the experimental frontier, direct detection searches have severely constrained the possible parameter space available, a trend that will continue to push detection to even lower limits in future, though WIMPs, axions and sterile neutrinos have not yet been established. The shrinking cross-section cuts in addition to an exploration of X-ray anomalies are also important constraints in particle physics. Alongside the required mention of small-scale anomalies that are yet to be solved, the consistency between the simulation outcomes and the measured information also points to the strength of the 2532CDM paradigm on large scales. The fact that our results are coming from multiple fields suggests that the nature of the actual dark matter may in fact necessitate a more expanded model that encompasses new particles, interactions, or field based processes instead of being localized in one candidate type or interaction. The next decade may see revolutionary discoveries with theoretical models becoming less rigid and technological enhancements making results more sensitive and with a higher resolution. Ultimately, the dark matter remains a serious mystery, the resolution of which leads to the answer of what the universe consists of, how it originated, and where it ends.

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