International Journal of Research in Physics, Mathematics and Statistics (IJRPMS)

e-ISSN: Awaiting
Research Article
VOL: 1, Issue: 1, April-June 2026

Investigating the Role of Dark Matter in the Formation of Supermassive Black Holes in Early Universe Galaxies

***[1]K. Sai Krishna**

[*1]*Vivekananda Degree & PG College, Karimnagar, india*

ABSTRACT:

One of the greatest mysteries in cosmology is the formation of the supermassive black holes (SMBHs) in the early universe. The recent discoveries, especially through the James Webb Space Telescope, have identified SMBHs with a high mass at redshifts as large as $z \approx 10$ that are difficult to explain by conventional models, which only involve baryonic accretion. This is a review of the place of dark matter, in particular, cold dark matter (CDM) and self-interacting dark matter (SIDM) in the formation and rapid evolution of SMBHs. We explore the role that dark matter halos might have played in the collapse of gas clouds and black hole seed formation, which might have offered the conditions needed to form SMBHs at high redshifts. The review summarizes existing models and observational data and theoretical issues, pointing out the possible physical processes by which the dark matter might have accelerated SMBH growth during the early universe. In addition, we address the direction of future research and the observational techniques which are required in order to observe the imprint of dark matter during the early evolution of SMBHs.

Keywords: Supermassive Black Holes (SMBHs), Dark Matter, cold Dark Matter (CDM) Self-interacting Dark Matter (SIDM), Early Universe, Galaxy Formation, High-Redshift SMBHs, Dark Matter Halos, Baryonic Accretion, James Webb Space Telescope (JWST)

Received Date: 7 April-June 2026**; Accepted Date:** 17 April-June 2026**; Published Date:** 24 April-June 2026.

1. Introduction

1.1 Overview of Supermassive Black Holes (SMBHs)

Supermassive black holes are gigantic astronomical entities that are between 105 and 1010 solar masses and are located at the heart of most galaxies (Bambi, 2017, p. 7). These SMBHs are very important in the evolution of the galaxies and their properties usually have a very strong relationship with those of their host galaxies (Ferrarese and Ford, 2005, p. 525). The prevalence of SMBHs in big galaxies implies that they are not uncommon events and both the stellar dynamics and accretion studies have shown that they are common (Greene, 2012, p. 3).

It is now known that supermassive black holes, with masses of millions to billions of times the mass of the Sun, are ubiquitous in the center of most galaxies, are believed to be key drivers in the evolution of those galaxies (Volonteri, 2012, p. 544). The ubiquity of this and the tight correlations between mass and host galaxy characteristics, e.g., stellar mass and velocity dispersion, are strong indications of a fundamental co-evolutionary association between these cosmic phenomena and their host galaxies (Cattaneo et al., 2009, p. 213; Habouzit et al., 2021, p. 3016; Shank

1.2 Understanding Dark Matter

Modern cosmology is built on the existence of the dark matter, which is supported by extensive evidence of cosmic microwave background anisotropies, observations of large-scale structures, as well as by the Big Bang nucleosynthesis, which are all precise in constraining cosmological parameters (Borodatchenkova et al., 2006, p. 1). Nevertheless, in spite of this strong evidence of observation, the very essence of the dark matter is still a mystery, one of the greatest possible unresolved puzzles of not only astrophysics, but also particle physics (Feng, 2010, p. 497). The hypothesis is that it comprises non-baryonic particles, which are electrically neutral, uncolored and weakly interacting (A. & F., 2021, p. 103867). In fact, studies of cosmic microwave background anisotropies show that around 80% of the total matter content in the universe is made up of dark matter (Biondini et al., 2023, p. 2), which is by far greater than that of baryonic matter, 5.3 times the baryonic matter.

Although decades of experimental work have been focused on understanding what it constitutes, the exact elements of what form the dark matter have been elusive, and it has been mainly learned through the spectacles of cosmology and indirect astrophysical data but not through direct observation (Marques, 2025, p. 20). Although direct detection experiments have gained several orders of magnitude of sensitivity over the last ten years, no concrete evidence has been obtained yet that massive particles that may be weakly interacting, in particular, belong to the dark matter (Liu et al., 2017, p. 212). This lack of direct discovery though there have been huge improvements in detector technologies has prompted a re-assessment of the scientific community on the most promising dark matter candidates and methods of detection (Bertone and Tait, 2018, p. 51; Undagoitia and Rauch, 2015, p. 13001). In the present experimental studies, a broad spectrum of theoretical candidates is still being pursued and is no longer restricted to the conventional paradigm of the WIMP, including candidates over many orders of magnitude in mass (Razeto & Rossi, 2024, p. 1).

1.3 Purpose of the Review

It is this review that will specifically examine how the enigmatic attributes of the dark matter (and in this case, cold dark matter and self-interacting dark matter) might have contributed to the rapid growth of supermassive black holes in the early universe, given both direct and indirect formation pathways within the nascent galactic structures. The recent observation results of such facilities as the James Webb Space Telescope have revealed the unexpectedly early formation time of supermassive black holes, with some having masses of 4 × 107 M}}{ as early as z 10, which is a major challenge to the traditional models of baryonic accretion alone (Imai et al., 2025, p. 1; Roberts et al., 202 This inconsistency implies that non-baryonic processes, including those of the dark matter, could play a pivotal role in explaining the accelerated growth rates necessary to have these early-formed SMBHs (Roberts et al., 2024, p. 1).

2. Theoretical Background

2.1 Formation and Growth of SMBHs

The high-redshift quasars (z 7) have been found to form black holes that build up to $109 M o in a short period of time (around a billion years since the Big Bang) which poses a major challenge to the existing cosmological structure formation models (Whalen et al., 2012, p. 1). This rapid expansion requires unconventional physical processes, including super-Eddington accretion rates, collapse of supermassive stars, or very massive black hole seeds which have been formed in relativistic dark collapse (Sesana et al., 2021, p. 1338). The fact that these huge black holes existed already at such early times suggests that the original seed black holes must have been extremely huge, or their evolution must have occurred at an extremely high rate (Chon & Omukai, 2024, p. 1).

The high rate of supermassive black holes created at the high redshifts ($z > 6$) requires extremely effective growth processes of the existing seed black holes (Latif & Ferrara, 2016, p. 1). Such a quick increase is a serious issue because stellar-mass black holes do not accrete efficiently and cannot reach the masses they are observed to have during the cosmological time span (Kashlinsky et al., 2018, p. 19). As a result, astrophysical theories suggest several different mechanisms of the formation of these seed black holes, which are divided into the formation of light seeds (~100 MSTRU) and heavy seeds (>104 MSTRU) (Johnson et al., 2013). The light seeds (usually 10 to 100 solar masses) are believed to be the debris of the Population III stars (Burke et al., 2022, p. 1880; Izquierdo–Villalba et al., 2020, p. 4685).

2.2 Dark Matter and its Galaxy Formation

The dark matter, which is the largest constituent (26.8) of the total mass-energy content of the universe, has a strong gravitational effect that forms the base of hierarchical structure of cosmic structures (Övgün & Pantig, 2025, p. 1). The theorized non-baryonic component, which is abundant everywhere, is believed to have triggered the gravitational collapse of primordial density fluctuations, upon which the baryonic matter then condensed to form galaxies and black holes (Voit, 2005, p. 208; Volonteri, 2012, p. 544). It has been observed that the dark matter is about 90% of the total mass of a galaxy, which affects the galactic rotation curves, which are flatter than they should be due to visible matter only (Ahmed et al., 2025, p. 1; Uktamov et al., 2025, p. 1).

2.3 Evolution of the Universe and Galaxies

The current cosmological paradigm is that the earliest structures such as the first galaxies and the supermassive black holes are the gravitational collapse of primordial density fluctuations in a universe dominated by cold dark matter (Volonteri, 2012, p. 544). These oscillations were caused by quantum fluctuations in the pre-inflationary era, which resulted in regions of overdense matter which through gravitational forces pulled in baryonic matter, which was mostly hot hydrogen gas, into dark matter halos (Sellwood, 2014, p. 2; Srinivasan et al., 2023, p. 75). It is inside these halos that this baryonic gas cooled and condensed, which enabled the process of star formation, and eventually resulted in the formation of the first galaxies (Volonteri et al., 2021, p. 732).

3. Dark Matter and SMBH Formation: Hypotheses and Models

3.1 Dark Matter Influence on Galaxy Formation

These halos were important in the initial accretion of the baryonic matter which was directed to condense into the first structures due to its gravitational potential (Navarro et al., 1995, p. 56). The gravitational dominance of dark matter is the key driver in this process since it can collapse and virialize freely without effects of pressure and thus form the potential wells, which later trap baryonic matter (Barkana & Loeb, 2001, p. 152). The baryons, which were initially distributed on a near-uniform basis and followed the distribution of the dark matter up to a scale that is larger than the Jeans length, are then clumped in these deep potential wells, and this marks the beginning of the locations of galaxy formation (Benson, 2010, p. 38). According to this model of the formation of hierarchical structures, small dark matter halos are initially formed, then merging with each other and accreting diffuse matter, they form larger structures (Wang et al., 2017, p. 524; Wechsler et al., 2002, p. 52).

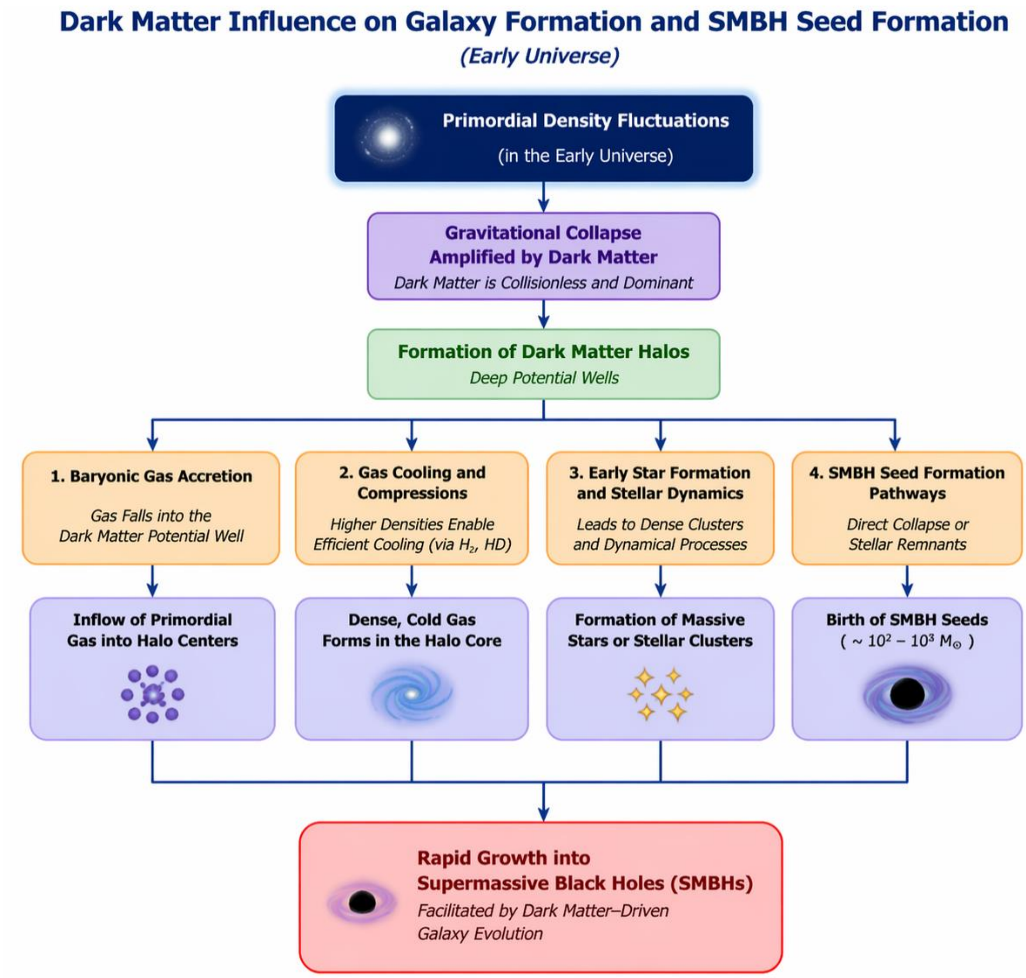

Figure 1: Dark Matter's Role in Galaxy Formation and Supermassive Black Hole Seed Creation

3.2 Theories of Dark Matter and SMBH formation

Existing astrophysical theories investigate the different ways in which the dark matter may directly or indirectly encourage the swift development of supermassive black holes in the early universe. Among the most notable issues such models help to tackle is the presence of a significant number of ~109 MSN SMBHs at high redshifts, which can hardly be formed in standard accretion-limited growth models in the age of the early universe (Choquette et al., 2019, p. 37; Wei-Xiang et al., 2021, p. 1). As an example, the fact that the James Webb Space Telescope has detected a 4 × 107 MSTRU SMBH at z ⁕ 10 suggests that it formed within 200400 Myr after photon decoupling, which is much too short to allow the growth of stellar-mass seeds by baryonic accretion (Imai et al., 2025, p.

3.3 Challenges and Uncertainties

The development and history of massive black holes in a cosmological framework requires us to consider the delicate connection between dark matter, baryonic matter and these mysterious entities (Volonteri, 2012, p. 548). Existing theories have a major obstacle to explaining the rapid growth of supermassive black holes, observed at high redshifts, and some of the discoveries of SMBHs have a supermassive black hole of 4 × 107 M Solar Mass as early as z = 10 (Imai et al., 2025, p. 1). These findings make the traditional growth processes questionable because the timeframes of baryonic accretion and mergers in the hierarchical structure formation models are usually not long enough to form such huge objects so early in the history of the universe (Sanchis-Gual et al., 2025, p. 1). Moreover, it is still unclear what exactly these SMBHs were made out of, what kind of seed black holes they may have grown out of, and thus even more research on the formation processes of these black holes at z > 10 is needed (Matteo et al., 2012, p. 1).

4. Observational Evidence

4.1 Observing Early Universe SMBHs

To examine how supermassive black holes may have formed in young galaxies, astronomers use numerous different methods of observation, such as gravitational wave detection, quasar observations, and so forth (Smith and Bromm, 2019, p. 114). Such techniques can be used to offer important clues on the demography of black holes in the center of the galaxies, hence explaining the overall galaxy formation process (Dallal and Azzam, 2019, p. 215). To take an example, the observations of high-redshift quasars tell us about the initial evolution of black holes and the co-evolution of black holes and galaxies (Li et al., 2023, p. 85). Laser Interferometer Space Antenna will detect gravitational waves of merging supermassive black holes at a wide range of masses (103 -107 M 1) to redshifts as large as z > 20, providing a unique probe of the assembly of black holes in the early universe (Bailes et al., 2021, p. 355; Haiman, 2012

4.2 Indirect Evidence of Dark Matter's Role

The fact that anomalous galactic rotation curves do not match the expectations of the models that rely on the presence of visible baryonic matter alone is evidence of the gravitational potential of large dark matter halo that surround galaxies (Gupta & Thareja, 2017, p. 35006; Qiao & Su, 2024, p. 1). This difference between the measured and the modeled rotational velocities leads to the assumption that there is a large portion of unobserved mass, usually estimated to make up about 90 percent of the total mass of a galaxy (Al-Badawi et al., 2024, p. 2; Uktamov et al., 2025, p. 1). Also, the presence of such large unseen parts of dark matter, in the outermost places of the spiral galaxies, is strongly supported by the fact that the velocity of the stars there remains constant despite the application of the Newtonian dynamics (Molla et al., 2023, p. 2, 2024, p. 3).

4.3 Case Studies

An interesting finding is that SMBHs with masses in the range of 109 solar masses are present at very high redshifts (z = 67) when the universe was just a tiny fraction of its present age, which is a challenge to the traditional baryonic accretion theoretic (Wei-Xiang et al., 2021, p. 1). This is problematic since the process of black holes growing up to such large sizes based on stellar-mass seeds is hard to attain using standard Eddington-limited accretion rates alone (Choquette et al., 2019, p. 37; Roberts et al., 2025, p. 4). The most recent discoveries of black holes with high redshifts by the James Webb Space Telescope only add to the importance of this dilemma, as it can either be assumed that heavy seeds have high seed masses or that black holes merge exceptionally quickly with light seeds (Ellis et al., 2025, p. 1).

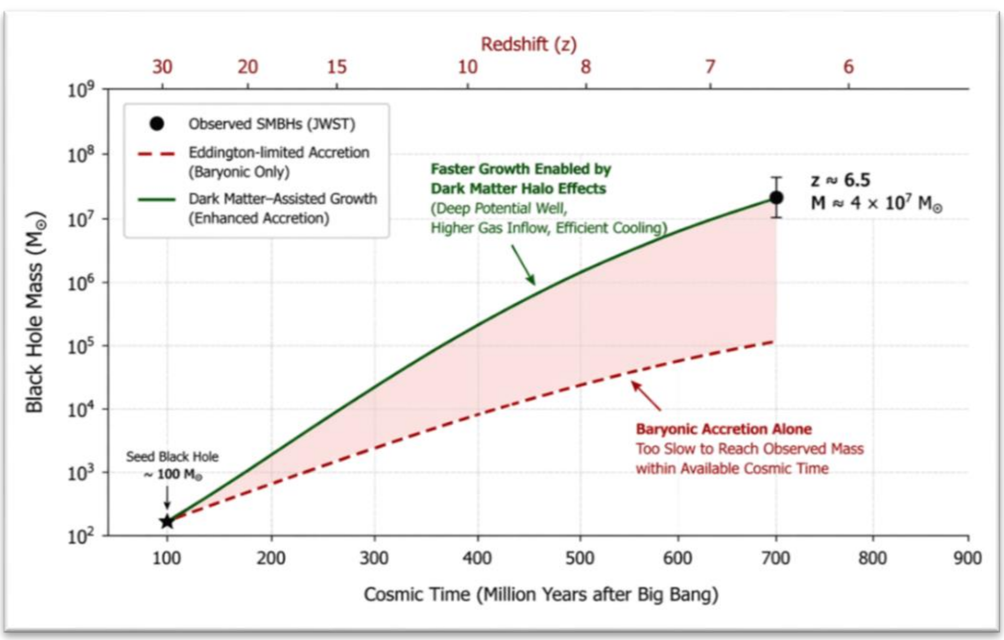

Figure 2: Rapid Growth of High-Redshift SMBHs – Baryonic Accretion vs Dark Matter–Assisted Growth

The existence of high masses of SMBHs in redshifts z 6-7 cannot be easily explained by conventional Eddington-limited accretion of stellar-mass seeds. SMBHs can be accelerated by dark matter halos via early gas inflow and super-Eddington accretion. This dark matter aided growth is how these SMBHs are able to attain masses that would not have been possible under the available cosmic time had it been only through baryonic accretion.

5. Implications and Future Directions

5.1 Implications for Galaxy Evolution

The detailed study of the effect of the dark matter on the primordial state and further development of supermassive black holes can provide new insights into the formation of galaxies in the early universe and the reionization epoch. In particular, the dark matter halos act as the gravitational potential wells where the baryonic matter is accreted and collapsed to become the first stars and galaxies, thus, initiating the process of the black hole seeding and growth (Volonteri, 2012, p. 544). This process is especially important in understanding the existence of supermassive black holes at large redshifts, which has been a problem to growth models based on accretion that has its seeds at stellar masses (Chuzhoy and Kolb, 2009, p. 21).

5.2 Improvements in Detection Methods

The longstanding null of direct detection experiments, even with the huge sensitivity enhancements, prompts the shift to considering other dark matter candidates and approaches to detection (Alonso-Álvarez and Curtin, 2024, p. 1). It involves examining other experimental methods in addition to Weakly Interacting Massive Particles to consider a more diverse set of theories and using astronomical surveys and the observations of gravitational waves (Bertone and Tait, 2018, p. 51). This extension includes the study of the feebly-interacting particles over a wide mass scale, and quantum measurement tools are becoming increasingly important in identifying the presence of waves of the dark matter (Antel et al., 2023, p. 92).

5.3 Open Questions and Future Research

Although much progress has been made, the relationship between dark matter and supermassive black holes formation at high redshifts is still a mystery that requires additional follow-up studies of how they are co-evolutionary (Kehrer and Fuller, 2024, p. 12). One of the key questions to investigate is how exactly massive black holes are correlated with the galaxy properties and not limited to classical correlations of luminosity and mass (Volonteri, 2012, p. 548). Besides, the possibility of dark matter halos to act as catalysts in the formation of supermassive black holes especially in different environments such as the dwarf and low surface brightness galaxies is another parameter space that is unexplored (Ferrarese and Ford, 2005, p. 620). Moreover, the presence of SMBHs at very high redshifts, some with mass of non-stellar seeds of approximately $10^{10} M_{odot}$ at about z 6, raises some fundamental questions on how they grow so fast, in particular, whether they have non-stellar seeds or super-Eddington accretion (Matthee et al., 2024, p. 2).

6. Conclusion

6.1 Summary of Key Findings

This part summarizes the main findings and theoretical models that transpire out of the comprehensive literature review with an accent on findings that are relevant to theory development and testing (Wong et al., 2013, p. 10). The systematic review of the literature helps to define the gaps in research and outline new methodological possibilities to make significant theoretical contributions (Riel & Snyder, 2024, p. 258). The overall synthesis of the different study results does not only reflect the underlying consistency of the major theoretical insights but also introduces a great opportunity to fold together complementary theoretical perspectives to fit the changing research environments (Achter et al., 2023, p. 105868; Heubeck, 2023, p. 32). Nevertheless, the synthesis process can be challenging because of the differences in contextual specifics of studies, so indicative summaries are more viable than complete synthesis (Sergeeva and Andreeva, 2015, p. 253).

6.2 Final Thoughts

The complex interaction between the phenomenon of the dark matter and the formation of the supermassive black holes poses an interesting frontier in astrophysics, especially with regard to the presence of the ultrarare SMBHs in the early universe (Davoudiasl et al., 2022). This relationship is important in improving cosmological models, as it is particularly surprising that the massive SMBHs formed very early as observed by the James Webb Space Telescope (Imai et al., 2025, p. 1). This premature emergence is problematic to the traditional baryonic growth models, which have difficulty to explain such accretion rates needed to reach those masses in the constrained cosmic time period (Roberts et al., 2025, p. 60). This has led to a search into other possible formation mechanisms, and primordial black holes are one of the dark matter candidates that may stimulate early black hole formation and subsequent evolution of high-redshift SMBHs and massive galaxies.

References:

1. A., A., & F., M. (2021). Dark matter and the early Universe: A review. *Progress in Particle and Nuclear Physics*, *119*, 103865. https://doi.org/10.1016/j.ppnp.2021.103865
2. Ahmed, F., Bouzenada, A., & Silva, E. O. (2025). AdS Black Hole Solution with a Dark Matter Halo Surrounded by a Cloud of Strings. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2509.10829
3. Al-Badawi, A., Shaymatov, S., & Sekhmani, Y. (2024). Schwarzschild Black Hole in Galaxies Surrounded by a Dark Matter Halo. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2411.01145
4. Alonso-Álvarez, G., & Curtin, D. (2024). Dark Astronomy with Dark Matter Detectors. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2412.06883
5. Antel, C., Battaglieri, M., Beacham, J. B., Bœhm, C., Buchmüller, O., Calore, F., Carenza, P., Chauhan, B., Cladé, P., Coloma, P., Crivelli, P., Dandoy, V., Darmé, L., Dey, B., Deppisch, F. F., Roeck, A. D., Drewes, M., Echenard, B., Flambaum, V. V., … Zurek, K. M. (2023). Feebly-interacting particles: FIPs 2022 Workshop Report. *The European Physical Journal C*, *83*(12). https://doi.org/10.1140/epjc/s10052-023-12168-5
6. Bailes, M., Berger, B. K., Brady, P. R., Branchesi, M., Danzmann, K., Evans, M., Holley-Bockelmann, K., Iyer, B. R., Kajita, T., Katsanevas, S., Krämer, M., Lazzarini, A., Lehner, L., Losurdo, G., Lück, H., McClelland, D. E., McLaughlin, M. A., Punturo, M., Ransom, S. M., … Vitale, S. (2021). Gravitational-wave physics and astronomy in the 2020s and 2030s [Review of *Gravitational-wave physics and astronomy in the 2020s and 2030s*]. *Nature Reviews Physics*, *3*(5), 344. Nature Portfolio. https://doi.org/10.1038/s42254-021-00303-8
7. Bambi, C. (2017). Testing black hole candidates with electromagnetic radiation. *Reviews of Modern Physics*, *89*(2). https://doi.org/10.1103/revmodphys.89.025001
8. Barkana, R., & Loeb, A. (2001). In the beginning: the first sources of light and the reionization of the universe. *Physics Reports*, *349*(2), 125. https://doi.org/10.1016/s0370-1573(01)00019-9
9. Benson, A. (2010). Galaxy formation theory. *Physics Reports*, *495*, 33. https://doi.org/10.1016/j.physrep.2010.06.001
10. Bertone, G., & Tait, T. M. P. (2018). A new era in the search for dark matter [Review of *A new era in the search for dark matter*]. *Nature*, *562*(7725), 51. Nature Portfolio. https://doi.org/10.1038/s41586-018-0542-z
11. Biondini, S., Brambilla, N., Qerimi, G., & Vairo, A. (2023). Effective field theories for dark matter pairs in the early universe: cross sections and widths. *Journal of High Energy Physics*, *2023*(7). https://doi.org/10.1007/jhep07(2023)006
12. Borodatchenkova, N., Choudhury, D., & Drees, M. (2006). Probing MeV Dark Matter at Low-Energye+e−Colliders. *Physical Review Letters*, *96*(14). https://doi.org/10.1103/physrevlett.96.141802
13. Burke, C. J., Shen, Y., Liu, X., Natarajan, P., Čaplar, N., Bellovary, J., & Wang, Z. F. (2022). Dwarf AGNs from variability for the origins of seeds (DAVOS): Intermediate-mass black hole

demographics from optical synoptic surveys. *Monthly Notices of the Royal Astronomical Society*, *518*(2), 1880. https://doi.org/10.1093/mnras/stac2478

14. Casanueva-Villarreal, C., Tissera, P. B., Padilla, N., Liu, B., Bromm, V., Pedrosa, S., Bignone, L., & Domínguez-Tenreiro, R. (2024). Impact of Primordial Black Hole Dark Matter on Gas Properties at Very High Redshift: A Semi-Analytical Model. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2405.02206
15. Cattaneo, A., Faber, S. M., Binney, J., Dekel, A., Kormendy, J., Mushotzky, R. F., Babul, A., Best, P. N., Brüggen, M., Fabian, A. C., Frenk, C. S., Khalatyan, A., Netzer, H., Mahdavi, A., Silk, J., Steinmetz, M., & Wisotzki, L. (2009). The role of black holes in galaxy formation and evolution. *Nature*, *460*(7252), 213. https://doi.org/10.1038/nature08135
16. Chon, S., & Omukai, K. (2024). Formation of supermassive stars and dense star clusters in metal-poor clouds exposed to strong FUV radiation. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2412.14900
17. Choquette, J., Cline, J. M., & Cornell, J. M. (2019). Early formation of supermassive black holes via dark matter self-interactions. *Journal of Cosmology and Astroparticle Physics*, *2019*(7), 36. https://doi.org/10.1088/1475-7516/2019/07/036
18. Chuzhoy, L., & Kolb, E. W. (2009). Reopening the window on charged dark matter. *Journal of Cosmology and Astroparticle Physics*, *2009*(7), 14. https://doi.org/10.1088/1475-7516/2009/07/014
19. Dallal, S. A., & Azzam, W. J. (2019). Formation of Galaxies in the Context of Gravitational Waves and Primordial Black Holes. *Journal of Modern Physics*, *10*(3), 214. https://doi.org/10.4236/jmp.2019.103016
20. Davoudiasl, H., Denton, P. B., & Gehrlein, J. (2022). Supermassive Black Holes, Ultralight Dark Matter, and Gravitational Waves from a First Order Phase Transition. *Physical Review Letters*, *128*(8), 81101. https://doi.org/10.1103/physrevlett.128.081101
21. Ellis, J., Fairbairn, M., Urrutia, J., & Vaskonen, V. (2025). Constraints on Dark Matter Models from Supermassive Black Hole Evolution. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2509.06955
22. Feng, J. L. (2010). Dark Matter Candidates from Particle Physics and Methods of Detection. *Annual Review of Astronomy and Astrophysics*, *48*(1), 495. https://doi.org/10.1146/annurev-astro-082708-101659
23. Ferrarese, L., & Ford, H. C. (2005). Supermassive Black Holes in Galactic Nuclei: Past, Present and Future Research. *Space Science Reviews*, *116*, 523. https://doi.org/10.1007/s11214-005-3947-6
24. Greene, J. E. (2012). Low-mass black holes as the remnants of primordial black hole formation. *Nature Communications*, *3*(1). https://doi.org/10.1038/ncomms2314
25. Gupta, P. D., & Thareja, E. (2017). Supermassive black holes from collapsing dark matter Bose–Einstein condensates. *Classical and Quantum Gravity*, *34*(3), 35006. https://doi.org/10.1088/1361-6382/aa51fc
26. Habouzit, M., Somerville, R. S., Li, Y., Genel, S., Aird, J., Anglés-Alcázar, D., Davé, R., Georgiev, I. Y., McAlpine, S., Rosas-Guevara, Y., Dubois, Y., Nelson, D., Bañados, E., Hernquist, L., Peirani, S., & Vogelsberger, M. (2021). Supermassive black holes in cosmological simulations – II: the AGN population and predictions for upcoming X-ray missions. *Monthly Notices of the Royal Astronomical Society*, *509*(2), 3015. https://doi.org/10.1093/mnras/stab3147
27. Haiman, Z. (2012). The Formation of the First Massive Black Holes. In *Astrophysics and space science library* (p. 293). Springer Nature (Netherlands). https://doi.org/10.1007/978-3-642-32362-1_6
28. Imai, A., Mathews, G. J., Tang, G., & Zhang, B. B. (2025). Dark Matter and the Early Formation of Supermassive Black Holes. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2508.11846

29. Izquierdo–Villalba, D., Bonoli, S., Dotti, M., Sesana, A., Rosas-Guevara, Y., & Spinoso, D. (2020). From galactic nuclei to the halo outskirts: tracing supermassive black holes across cosmic history and environments. *Monthly Notices of the Royal Astronomical Society*, *495*(4), 4681. https://doi.org/10.1093/mnras/staa1399
30. Johnson, J. L., Whalen, D. J., Li, H., & Holz, D. E. (2013). SUPERMASSIVE SEEDS FOR SUPERMASSIVE BLACK HOLES. *The Astrophysical Journal*, *771*(2), 116. https://doi.org/10.1088/0004-637x/771/2/116
31. Kashlinsky, A., Arendt, R. G., Atrio-Barandela, F., Cappelluti, N., Ferrara, A., & Hasinger, G. (2018). Looking at cosmic near-infrared background radiation anisotropies. *Reviews of Modern Physics*, *90*(2). https://doi.org/10.1103/revmodphys.90.025006
32. Kehrer, K. S., & Fuller, G. M. (2024). Dark Matter and General Relativistic Instability in Supermassive Stars. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2406.13887
33. Latif, M., & Ferrara, A. (2016). Formation of Supermassive Black Hole Seeds. *Publications of the Astronomical Society of Australia*, *33*. https://doi.org/10.1017/pasa.2016.41
34. Li, W., Inayoshi, K., Onoue, M., & Toyouchi, D. (2023). The Assembly of Black Hole Mass and Luminosity Functions of High-redshift Quasars via Multiple Accretion Episodes. *The Astrophysical Journal*, *950*(2), 85. https://doi.org/10.3847/1538-4357/accbbe
35. Liu, J., Chen, X., & Ji, X. (2017). Current status of direct dark matter detection experiments. *Nature Physics*, *13*(3), 212. https://doi.org/10.1038/nphys4039
36. Marques, D. J. G. (2025). 3D Tracking with the CYGNO/INITIUM experiment. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2509.10890
37. Matteo, T. D., Khandai, N., DeGraf, C., Feng, Y., Croft, R. A. C., López, J., & Springel, V. (2012). COLD FLOWS AND THE FIRST QUASARS. *The Astrophysical Journal Letters*, *745*(2). https://doi.org/10.1088/2041-8205/745/2/l29
38. Molla, N. U., Chaudhary, H., Mustafa, G., Atamurotov, F., Debnath, U., & Arora, D. (2024). Strong gravitational lensing by $$Sgr A^*$$ and $$M87^*$$ black holes embedded in dark matter halo exhibiting string cloud and quintessential field. *The European Physical Journal C*, *84*(6). https://doi.org/10.1140/epjc/s10052-024-12917-0
39. Navarro, J. F., Frenk, C. S., & White, S. D. M. (1995). The assembly of galaxies in a hierarchically clustering universe. *Monthly Notices of the Royal Astronomical Society*, *275*(1), 56. https://doi.org/10.1093/mnras/275.1.56
40. Övgün, A., & Pantig, R. C. (2025). Black hole in the Dekel-Zhao dark matter profile. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2501.12559
41. Qiao, C.-K., & Su, P. P. (2024). Time delay of light in the gravitational lensing of supermassive black holes in dark matter halos. *The European Physical Journal C*, *84*(10). https://doi.org/10.1140/epjc/s10052-024-13403-3
42. Razeto, A., & Rossi, N. (2024). Challenges for dark matter direct search with SiPMs. *Frontiers in Physics*, *11*. https://doi.org/10.3389/fphy.2023.1290449
43. Roberts, M. G., Braff, L. A., Garg, A., Profumo, S., Jeltema, T., & O'Donnell, J. H. (2025). Early formation of supermassive black holes from the collapse of strongly self-interacting dark matter. *Journal of Cosmology and Astroparticle Physics*, *2025*(1), 60. https://doi.org/10.1088/1475-7516/2025/01/060
44. Sanchis-Gual, N., Barranco, J., Degollado, J. C., & Núñez, D. (2025). Dark-to-black super accretion as a mechanism for early supermassive black hole growth. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2510.00644
45. Sellwood, J. A. (2014). Secular evolution in disk galaxies. *Reviews of Modern Physics*, *86*(1), 1. https://doi.org/10.1103/revmodphys.86.1
46. Sesana, A., Korsakova, N., Sedda, M. A., Baibhav, V., Barausse, E., Barke, S., Berti, E., Bonetti, M., Capelo, P. R., Caprini, C., García-

Bellido, J., Haiman, Z., Jani, K., Jennrich, O., Johansson, P. H., Khan, F. M., Korol, V., Lamberts, A., Lupi, A., … Zumalacárregui, M. (2021). Unveiling the gravitational universe at μ-Hz frequencies. *Experimental Astronomy*, *51*(3), 1333. https://doi.org/10.1007/s10686-021-09709-9

47. Shankar, F. (2009). The demography of supermassive black holes: Growing monsters at the heart of galaxies. *New Astronomy Reviews*, *53*, 57. https://doi.org/10.1016/j.newar.2009.07.006
48. Smith, A., & Bromm, V. (2019). Supermassive black holes in the early universe. *Contemporary Physics*, *60*(2), 111. https://doi.org/10.1080/00107514.2019.1615715
49. Srinivasan, R., Lamberts, A., Bizouard, M. A., Bruel, T., & Mastrogiovanni, S. (2023). Understanding the progenitor formation galaxies of merging binary black holes. *Monthly Notices of the Royal Astronomical Society*, *524*(1), 60. https://doi.org/10.1093/mnras/stad1825
50. Uktamov, U., Shaymatov, S., & Ahmedov, B. (2025). Static Black Hole Solution with a Dark Matter Halo. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2505.20031
51. Undagoitia, T. M., & Rauch, L. (2015). Dark matter direct-detection experiments. *Journal of Physics G Nuclear and Particle Physics*, *43*(1), 13001. https://doi.org/10.1088/0954-3899/43/1/013001
52. Voit, G. M. (2005). Tracing cosmic evolution with clusters of galaxies. *Reviews of Modern Physics*, *77*(1), 207. https://doi.org/10.1103/revmodphys.77.207
53. Volonteri, M. (2012). The Formation and Evolution of Massive Black Holes. *Science*, *337*(6094), 544. https://doi.org/10.1126/science.1220843
54. Wang, L., Chen, D., & Li, R. (2017). Baryon effects on the dark matter haloes constrained from strong gravitational lensing. *Monthly Notices of the Royal Astronomical Society*, *471*(1), 523. https://doi.org/10.1093/mnras/stx1617
55. Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. (2002). Concentrations of Dark Halos from Their Assembly Histories. *The Astrophysical Journal*, *568*(1), 52. https://doi.org/10.1086/338765
56. Wei-Xiang, F., Hai-Bo, Y., & Yi-Ming, Z. (2021). Seeding Supermassive Black Holes with Self-interacting Dark Matter: A Unified Scenario with Baryons. *The Astrophysical*
57. Whalen, D. J., Fryer, C. L., Whalen, D. J., & Fryer, C. L. (2012). THE FORMATION OF SUPERMASSIVE BLACK HOLES FROM LOW-MASS POP III SEEDS. *The Astrophysical Journal Letters*, *756*(1). https://doi.org/10.1088/2041-8205/756/1/l19
58. Xu, Z. (2025). “Cold” Freeze-out of Superheavy Dark Matter, Hubble Tension, and Ultra-high Energy Cosmic Rays (UHECRs) COSMO 25 CMU. *arXiv (Cornell University)*. https://doi.org/10.5281/zenodo.17393642
59. Zhang, S., Bromm, V., & Liu, B. (2024). How do Primordial Black Holes change the Halo Mass Function and Structure? *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2405.11381