Snowmass2021 - Letter of Interest

Many-Body Effects in Axion Dark Matter Structure

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (CompF2) Theoretical Calculations and Simulation
■ (TF9) Astro-particle Physics & Cosmology

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Abstract:

Axions and axion-like particles are becoming increasingly attractive candidates for the dark matter. Likewise, searches for these candidates are increasing in sophistication, number, reach, and may span much of the candidates' viable parameter space in the next decade. Haloscope searches crucially depend on the form of the local axion halo distribution over several decades in scale. Our understanding of axion structure formation is far from complete, however, due largely to the candidate's unique properties as a highly-degenerate Bose fluid. Novel approaches couched in the many-body gravitational physics intrinsic to Bose DM are needed to resolve the formation of cosmological structure both fine and large. One such model of Bose structure formation contains physically-motivated extra-classical physics above the de Broglie scale in the form of exchange-correlation interactions. Preliminary analytic calculations and N-body simulations have shown Bose correlations grow quickly in the early universe, and galaxies seeded by axion dark matter contain unique extra-classical structures with observable consequences for Bose dark matter searches. The next generation of cosmological simulations are expected to greatly expand on the galactic structures intrinsic to Bose dark matter, potentially enhancing the discovery potential of axion haloscopes such as ADMX and other axion dark matter searches.

1 Introduction and Motivation

Cosmological structure formation simulations are expected to play an increasingly crucial role in the upcoming phase of axion dark matter (DM) searches. With many haloscopes either operating[1–9] or in development[10–14] in the QCD axion DM range, it is becoming increasingly likely that a detection will occur. Searches for axion and axion-like particle DM facilitated by astronomical observations on cosmological, galactic, and stellar scales are also accelerating in pace[15–26].

Numerical simulations provide theoretical support to experimental searches and observations. Generic structure formation and evolution simulations have already assisted in haloscope searches for QCD axion DM by providing more accurate halo models, drastically improving experiments' signal-to-noise-ratio[3;8;27] and providing insight to the contribution of galactic substructure and transient events[28–30]. After axion dark matter is detected, halo models will become far more important as Earth-bound haloscopes can detect fine structure in the local axion energy distribution with a fidelity of a part in $\sim 10^{8-12}$ in total energy, providing a novel means to measure the fine structure of our galaxy[31;32]. The significance of this observable to understanding the structure and formation history of the Galaxy is just beginning to be understood.

Further theoretical support can be rendered to axion DM searches through identification of unique structures intrinsic to Bose scalar dark matter. Previous simulation studies of mean-field Bose dark matter have uncovered novel structures at the de Broglie scale in the form of boson stars and mini-clusters for QCD axions[33–35], and galactic scale solitons and large-scale interference patterns for axion-like particles with masses of the order $\sim 10^{-22}$ eV[15;36;37]. These studies are incomplete, however as they fail to incorporate the full richness of many-body physics present in a degenerate Bose fluid.

Multiple models of Bose infall have been formed in the last several years[38–41] that incorporate many-body correlations in the super-de Broglie limit, a chief component of many-body dynamics for QCD axion DM. To date, these models have shown that correlated Bose dark matter contains long-range extra-classical physics in the form of exchange-correlation interactions induced by the constraints of symmetric particle exchange and inter-axion correlations from self-gravity[39;40]. The resulting motion of such a condensed fluid is found to be different from standard cold dark matter, and mean field theory, even on length scales far exceeding the de Broglie scale. In-progress work suggests that correlations are created in the early universe by non-conservative elements of the gravitational interaction acting on isocurvature-breaking modes during the period between the mode passing into the Hubble volume and the Newtonian limit. Correlations then grow alongside the density modes until the over-density reaches non-linearity[41]. Preliminary N-Body simulations further show that correlated Bose DM form halos that contain unique structures with observable consequences for haloscopes and observations[40].

2 Research Opportunities

A number of research opportunities are expected to arise in the next several years as simulations of the exchange-correlation model of Bose dark matter expand in size, resolution and sophistication. Such simulations will elevate the accuracy of the unique structures formed by Bose dark matter, increasing their efficacy to current and future observations and axion searches.

Efforts during this period will concentrate on the exchange-correlation dynamics that are important for axion structure formation on super-de Broglie scales. Exchange-correlation dynamics are also expected to be important on de Broglie scales, such as in studies of fuzzy dark matter, axion mini-clusters, and boson stars. Analogous opportunities are present in the generalization of the exchange-correlation model to the de Broglie scale.

The N-body algorithm for Bose infall created in[40] fortunately lends itself quite well to modern scale-able N-body+SPH (smoothed particle hydrodynamics) codes, with exchange-correlation interactions acting like an additional long-range force in the dark sector. The next generation of simulations will begin as zoom-ins of a cosmological volume up to 25 Mpc/h on a side, each concentrating on a single Milky Way analogue and its satellites at $z = 0$. The initial DM-only tracking simulations will include physics of both Bose and classical forms. The zoom-ins will include high-resolution baryonic and super-massive black hole physics. The high-resolution regions of these simulations are expected to be on par with[42]. The tracking and zoom-in simulations will be studied for signatures of Bose physics, starting from the observables discussed in[40], including emergent velocity substructure and orbit modification of density substructure. Special attention will be paid to those signatures made outside of the DM sector. Multiple studies will be made to understand the Bose impacts on a Milky Way and the surrounding volume. High resolution signal filters for operating and soon-to-be-operating axion DM searches will also be provided.

Higher resolution simulations of uniformly resolved N-body+SPH simulations will follow up the zoom-ins. Updated initial conditions for volumes of 25 Mpc/h on a side. The target mass and force resolutions for these simulations are $M_p \sim 10^5 M_\odot$ and ~ 200 pc, respectively. Such simulations are capable of probing impacts of Bose DM ranging from the fine energy substructure of a Milky-Way-like galaxy to the scale of a galaxy cluster. The increased resolution of the simulations, and the results from analyzing the zoom-in simulations, will enable the one to probe the fine structural differences more deeply, accurately, and completely. A specific benefit to axion searches is that it will be possible to sample the local kinetic energy fine structure of a Milky Way mass halo to a part in ten-thousand, which is orders of magnitude better than existing models.

Bose signatures predicted from this model are expected to first appear at re-ionization as the extra-classical physics predicts an enhancement in the collapse of halos and will therefore alter early star formation. The new dynamics are also anticipated to change accretion, merger histories, and satellite behavior in halos. Bose dark matter may even alter structure on the scale of the cosmic web. Each upcoming simulation will present new opportunities to identify and improve our understanding of novel Bose DM signatures. Each signature will present a new opportunity to make candidate-specific DM observations. Current surveys and upcoming data and instruments, including *Gaia*, the Sloan Digital Sky Survey (SDSS), the James Webb Space Telescope (JWST), the Large Synoptic Survey Telescope (LSST, aka the Vera Rubin Observatory), the Square Kilometer Array (SKA), and surveys of 21-cm cosmology are expected to play a crucial role in identifying the most compelling model of Bose DM.

3 Conclusion

Simulation of Bose structure formation on cosmological scales is becoming increasingly crucial to dark matter searches for axions and axion-like particles. Unique Bose dark matter signatures and fine structure in the dark matter distribution will improve searches' sensitivity, accelerating the pace to detection by haloscope or astrophysical observation. Therefore, accurate modeling of the Bose dark matter halo using all relevant physics should be of high priority. The presence of many-body correlations is being shown to be highly relevant in this regard, having already produced multiple signatures relevant for searches. The next generation of simulations are expected to expand on these Bose-specific signals both in resolution and scope, presenting many research opportunities.

References

[1] B. T. McAllister, G. Flower, J. Kruger, E. N. Ivanov, M. Goryachev, J. Bourhill, and M. E. Tobar, ArXiv e-prints (2017), arXiv:1706.00209 [physics.ins-det] .

[2] L. Zhong, S. Al Kenany, K. M. Backes, B. M. Brubaker, S. B. Cahn, G. Carosi, Y. V. Gurevich, W. F. Kindel, S. K. Lamoreaux, K. W. Lehnert, S. M. Lewis, M. Malnou, R. H. Maruyama, D. A. Palken, N. M. Rapidis, J. R. Root, M. Simanovskaia, T. M. Shokair, D. H. Speller, I. Urdinaran, and K. A. van Bibber, Phys. Rev. D **97**, 092001 (2018), arXiv:1803.03690 [hep-ex] .

[3] N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L. J. Rosenberg, G. Rybka, G. Carosi, N. Woollett, D. Bowring, A. S. Chou, A. Sonnenschein, W. Wester, C. Boutan, N. S. Oblath, R. Bradley, E. J. Daw, A. V. Dixit, J. Clarke, S. R. O'Kelley, N. Crisosto, J. R. Gleason, S. Jois, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, and G. C. Hilton (ADMX Collaboration), Phys. Rev. Lett. **120**, 151301 (2018).

[4] C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, R. Cervantes, N. Du, N. Force, S. Kimes, R. Ottens, L. J. Rosenberg, G. Rybka, J. Yang, G. Carosi, N. Woollett, D. Bowring, A. S. Chou, R. Khatiwada, A. Sonnenschein, W. Wester, R. Bradley, E. J. Daw, A. Agrawal, A. V. Dixit, J. Clarke, S. R. O'Kelley, N. Crisosto, J. R. Gleason, S. Jois, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, P. M. Harrington, and E. Lentz (ADMX Collaboration), Phys. Rev. Lett. **121**, 261302 (2018).

[5] J. L. Ouellet, C. P. Salemi, J. W. Foster, R. Henning, Z. Bogorad, J. M. Conrad, J. A. Formaggio, Y. Kahn, J. Minervini, A. Radovinsky, N. L. Rodd, B. R. Safdi, J. Thaler, D. Winklehner, and L. Winslow, Phys. Rev. Letters **122**, 121802 (2019), arXiv:1810.12257 [hep-ex] .

[6] A. Garcon, J. W. Blanchard, G. P. Centers, N. L. Figueroa, P. W. Graham, D. F. Jackson Kimball, S. Rajendran, A. O. Sushkov, Y. V. Stadnik, A. Wickenbrock, T. Wu, and D. Budker, Science Advances **5**, eaax4539 (2019), arXiv:1902.04644 [hep-ex] .

[7] S. Lee, S. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis, Phys. Rev. Letters **124**, 101802 (2020), arXiv:2001.05102 [hep-ex] .

[8] T. Braine, R. Cervantes, N. Crisosto, N. Du, S. Kimes, L. J. Rosenberg, G. Rybka, J. Yang, D. Bowring, A. S. Chou, R. Khatiwada, A. Sonnenschein, W. Wester, G. Carosi, N. Woollett, L. D. Duffy, R. Bradley, C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, M. S. Taubman, J. Clarke, A. Dove, A. Eddins, S. R. O'Kelley, S. Nawaz, I. Siddiqi, N. Stevenson, A. Agrawal, A. V. Dixit, J. R. Gleason, S. Jois, P. Sikivie, J. A. Solomon, N. S. Sullivan, D. B. Tanner, E. Lentz, E. J. Daw, J. H. Buckley, P. M. Harrington, E. A. Henriksen, and K. W. Murch (ADMX Collaboration), Phys. Rev. Lett. **124**, 101303 (2020).

[9] N. Crescini, D. Alesini, C. Braggio, G. Carugno, D. D'Agostino, D. Di Gioacchino, P. Falferi, U. Gambardella, C. Gatti, G. Iannone, C. Ligi, A. Lombardi, A. Ortolan, R. Pengo, G. Ruoso, and L. Taffarello (QUAX Collaboration), Phys. Rev. Lett. **124**, 171801 (2020).

[10] D. F. J. Kimball, S. Afach, D. Aybas, J. W. Blanchard, D. Budker, G. Centers, M. Engler, N. L. Figueroa, A. Garcon, P. W. Graham, H. Luo, S. Rajendran, M. G. Sendra, A. O. Sushkov, T. Wang, A. Wickenbrock, A. Wilzewski, and T. Wu, arXiv e-prints , arXiv:1711.08999 (2017), arXiv:1711.08999 [physics.ins-det] .

[11] I. G. Irastorza and J. Redondo, Progress in Particle and Nuclear Physics **102**, 89 (2018), arXiv:1801.08127 [hep-ph] .

[12] C. Gatti, D. Alesini, D. Babusci, C. Braggio, G. Carugno, N. Crescini, D. Di Gioacchino, P. Falferi, G. Lamanna, C. Ligi, A. Ortolan, L. Pellegrino, A. Rettaroli, G. Ruoso, and S. Tocci, arXiv e-prints , arXiv:1811.06754 (2018), arXiv:1811.06754 [physics.ins-det] .

[13] P. Brun, A. Caldwell, L. Chevalier, G. Dvali, P. Freire, E. Garutti, S. Heyminck, J. Jochum, S. Knirck, M. Kramer, C. Krieger, T. Lasserre, C. Lee, X. Li, A. Lindner, B. Majorovits, S. Martens, M. Matysek, A. Millar, G. Raffelt, J. Redondo, O. Reimann, A. Ringwald, K. Saikawa, J. Schaffran, A. Schmidt, J. Schütte-Engel, F. Steffen, C. Strandhagen, and G. Wieching, European Physical Journal C **79**, 186 (2019), arXiv:1901.07401 [physics.ins-det] .

[14] D. J. E. Marsh, K. C. Fong, E. W. Lentz, L. Šmejkal, and M. N. Ali, Phys. Rev. Lett. **123**, 121601 (2019).

[15] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Nature Physics **10**, 496–499 (2014).

[16] M. Fairbairn, D. J. Marsh, J. Quevillon, and S. Rozier, Physical Review D **97** (2018), 10.1103/physrevd.97.083502.

[17] D. J. Marsh and J. C. Niemeyer, Physical Review Letters **123** (2019), 10.1103/physrevlett.123.051103.

[18] G. Sigl and P. Trivedi, arXiv e-prints , arXiv:1907.04849 (2019), arXiv:1907.04849 [astro-ph.CO] .

[19] C. Dessert, J. W. Foster, and B. R. Safdi, arXiv e-prints , arXiv:1910.02956 (2019), arXiv:1910.02956 [astro-ph.HE] .

[20] M. Buschmann, R. T. Co, C. Dessert, and B. R. Safdi, arXiv e-prints , arXiv:1910.04164 (2019), arXiv:1910.04164 [hep-ph] .

[21] B. V. Church, P. Mocz, and J. P. Ostriker, Monthly Notices of the Royal Astronomical Society **485**, 2861–2876 (2019).

[22] P. Mocz, A. Fialkov, M. Vogelsberger, F. Becerra, M. A. Amin, S. Bose, M. Boylan-Kolchin, P.-H. Chavanis, L. Hernquist, L. Lancaster, and et al., Physical Review Letters **123** (2019), 10.1103/physrevlett.123.141301.

[23] J. W. Foster, Y. Kahn, O. Macias, Z. Sun, R. P. Eatough, V. I. Kondratiev, W. M. Peters, C. Weniger, and B. R. Safdi, arXiv e-prints , arXiv:2004.00011 (2020), arXiv:2004.00011 [astro-ph.CO] .

[24] I. De Martino, T. Broadhurst, S.-H. Henry Tye, T. Chiueh, and H.-Y. Schive, Physics of the Dark Universe **28**, 100503 (2020).

[25] J. B. Bauer, D. J. E. Marsh, R. Hložek, H. Padmanabhan, and A. Laguë, arXiv e-prints , arXiv:2003.09655 (2020), arXiv:2003.09655 [astro-ph.CO] .

[26] L. Lancaster, C. Giovanetti, P. Mocz, Y. Kahn, M. Lisanti, and D. N. Spergel, Journal of Cosmology and Astroparticle Physics **2020**, 001–001 (2020).

[27] E. W. Lentz, T. R. Quinn, L. J. Rosenberg, and M. J. Tremmel, **845**, 121 (2017), arXiv:1703.06937 .

[28] B. J. Kavanagh and C. A. O'Hare, Physical Review D **94** (2016), 10.1103/physrevd.94.123009.

[29] C. A. O'Hare and A. M. Green, Physical Review D **95** (2017), 10.1103/physrevd.95.063017.

[30] C. A. O'Hare, N. W. Evans, C. McCabe, G. Myeong, and V. Belokurov, Physical Review D **101** (2020), 10.1103/physrevd.101.023006.

[31] L. D. Duffy, *High resolution search for dark matter axions in Milky Way halo substructure*, Ph.D. thesis, University of Florida (2006).

[32] J. Hoskins, N. Crisosto, J. Gleason, P. Sikivie, I. Stern, N. Sullivan, D. Tanner, C. Boutan, M. Hotz, R. Khatiwada, and et al., Physical Review D **94** (2016), 10.1103/physrevd.94.082001.

[33] D. Levkov, A. Panin, and I. Tkachev, Physical Review Letters **121** (2018), 10.1103/physrevlett.121.151301.

[34] B. Eggemeier and J. C. Niemeyer, Physical Review D **100** (2019), 10.1103/physrevd.100.063528.

[35] B. Eggemeier, J. Redondo, K. Dolag, J. C. Niemeyer, and A. Vaquero, Physical Review Letters **125** (2020), 10.1103/physrevlett.125.041301.

[36] J. Veltmaat, J. C. Niemeyer, and B. Schwabe, Physical Review D **98** (2018), 10.1103/physrevd.98.043509.

[37] J. Veltmaat, B. Schwabe, and J. C. Niemeyer, Physical Review D **101** (2020), 10.1103/physrevd.101.083518.

[38] E. W. Lentz, T. R. Quinn, and L. J. Rosenberg, Nuclear Physics B , 114937 (2020).

[39] E. W. Lentz, T. R. Quinn, and L. J. Rosenberg, **485**, 1809 (2019), arXiv:1810.09226 [astro-ph.CO] .

[40] E. W. Lentz, T. R. Quinn, and L. J. Rosenberg, Monthly Notices of the Royal Astronomical Society **493**, 5944 (2020), https://academic.oup.com/mnras/article-pdf/493/4/5944/32980097/staa557.pdf .

[41] E. W. Lentz, L. Lettermann, T. R. Quinn, and L. J. Rosenberg, arXiv e-prints , arXiv:2002.09173 (2020), arXiv:2002.09173 [astro-ph.CO] .

[42] M. Tremmel, M. Karcher, F. Governato, M. Volonteri, T. R. Quinn, A. Pontzen, L. Anderson, and J. Bellovary, **470**, 1121 (2017), arXiv:1607.02151 .