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Indirect detection of the QCD axion

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The QCD axion, originally proposed to solve the strong CP problem in QCD, is a prominent candidate for dark matter (DM). In the presence of strong magnetic fields, such as those around neutron stars, axions can theoretically convert into photons, producing detectable electromagnetic signals. This axion-photon coupling provides a unique experimental pathway to probe axions within a specific mass range. We investigate a novel observational approach using the Green Bank Telescope (GBT) to search for radio transients that could arise from interactions between neutron stars and dense DM clumps known as axion miniclusters. By observing the core of Andromeda with the VErsatile GBT Astronomical Spectrometer (VEGAS) and the X-band receiver (8 to 10 GHz), we achieve sensitivity to axions with masses in the range of 33 - 42 μeV, with a mass resolution of 3.8×10^{-4} μeV. We detail our observational and analytical strategies developed to capture transient signals from axion-photon conversion, achieving an instrumental sensitivity of 2 mJy per spectral channel. Despite our sensitivity threshold, no candidate signals exceeding the 5σ level were identified. Future implementations will extend this search across additional spectral bands and refine the modeling used for the processes involved, strengthening the constraints on axion DM models. Based on Refs. [1–3] and ongoing work.

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1. Introduction

The strong-CP problem can be addressed by introducing a new global symmetry into the Standard Model (SM) of particle physics, as proposed by Peccei and Quinn (PQ) [4, 5]. This solution predicts the existence of the QCD axion, a pseudo-scalar particle [6, 7], which could serve as dark matter (DM) if produced through non-thermal processes that ensure the axion remains non-relativistic by the time of recombination [8–10]. An active search for the QCD axion and related axion-like particles is ongoing, see Refs. [11–14] for reviews, though detection is challenging due to the axion's weak interactions with SM particles. Most experimental efforts focus on the axion-photon coupling, $g_{a\gamma\gamma}$, which modifies Maxwell's equations in the presence of axions [15–21]. This coupling motivates various terrestrial experiments [22–41], searches in helioscopes [42–44], and astrophysical searches for axion-photon conversion in regions with strong magnetic fields, such as those surrounding neutron stars (NSs) [1, 45–49].

The QCD axion's production history is closely tied to the thermal evolution of the early Universe. If PQ symmetry breaking occurs after inflation has ended, random fluctuations in the initial field conditions lead to the formation of self-gravitating clumps of axions around matter-radiation equality, known as axion miniclusters (AMCs) [50–53]. Simulations suggest that a substantial fraction of cold axions may reside within these bound structures, parameterized by $f_{\rm AMC}$, which can range from 1% to nearly 100% [54, 55]. This fraction directly influences detection prospects: if most DM is bound in AMCs, Earth's encounters with these structures become rare, limiting direct detection sensitivity [56] (see Ref. [41] for a recent laboratory search). AMC-like structures are also expected within inflationary scenarios [57, 58]. As AMCs traverse the galactic halo, interactions with stars in the disk disrupt these structures. Repeated tidal stripping by stellar encounters gradually erodes miniclusters, altering their internal structure and spatial distribution over time [59, 60]. A framework to quantify these effects on the AMC population was presented in Ref. [3], using a Monte Carlo approach to simulate AMC-stellar interactions. The model assumes a steady Milky Way structure post-formation and a simplified stellar population. Despite these assumptions, this analysis establishes a framework to assess the AMC survival rates and spatial distribution, with the associated numerical pipeline available at github.com/bradkav/axion-miniclusters. See also subsequent work on the topic in Refs. [61–64]. Although this study focuses on miniclusters, AMCs may also host axion stars, another class of axionic objects formed through gravitational relaxation [65–68], with quantum pressure counteracting gravitational collapse (see, e.g., [69, 70]). Additionally, AMC encounters with neutron star populations could produce transient radio signals observable as short bursts, as discussed in the companion analysis of Ref. [2]. The results predict a wide range of expected fluxes, from microjansky to several jansky for bright, detectable signals.

In recent years, efforts have focused on searching for axion-photon conversion signals from AMC-NS encounters across different radio frequency windows. This search was conducted using the VErsatile GBT Astronomical Spectrometer (VEGAS) receiver of the Green Bank Telescope (GBT), accounting for the environmental and astrophysical conditions. The findings, summarized in Ref. [1], indicate that although individual encounters between AMCs and NSs are relatively rare, cumulative interactions across the NS population could produce detectable bursts of radio-frequency signals within a given time frame. These results align with earlier predictions [2] but suggest that the outcome is highly sensitive to the AMC distribution and tidal disruption effects. Several key parameters impacting detectability include the spatial distribution of AMCs, their internal density profiles, and unaccounted interactions between axion stars and compact stellar remnants. Regions within the galactic plane with a high density of axion stars were found to have a substantially higher probability of generating detectable signals compared to other parts of a galaxy. Notably, the presence of axion stars that survive tidal stripping could enhance detection prospects, as these remnants tend to cluster in localized regions. These aspects are discussed further below.

2. Searching for transient events

The axion field originates when the PQ symmetry spontaneously breaks. At much lower temperatures corresponding to the QCD phase transition, explicit symmetry breaking by QCD instantons drives the axion field to oscillate coherently around a CP-conserving minimum in a process known as vacuum realignment [8–10]. These oscillations store DM energy density within the axion condensate, determined by the initial misalignment angle θ_i. This density is related to the axion mass, which is fixed by matching the current axion energy density to the observed DM abundance. The QCD axion's production history is then directly linked to the thermal evolution of the early Universe [71]. If the PQ symmetry breaks before inflation, θ_i is effectively homogeneous across the observable universe. However, if it breaks after inflation, fluctuations in the axion density become decoupled from cosmological expansion, and overdense regions collapse gravitationally around matter-radiation equality, forming self-gravitating structures known as AMCs [50–53].

The AMC mass distribution follows an initial halo mass function that evolves as structure formation progresses, as shown in simulation results [72, 73]. The density within these gravitationally bound structures is determined by the initial overdensity, evaluated through numerical simulations [54, 55, 74]. The spatial distribution of AMCs within galaxies is typically modeled according to the DM density profile, such as the Navarro-Frenk-White (NFW) profile [75]. Tidal interactions with the mean galactic gravitational field and nearby stars further perturb both the AMC mass and spatial distribution, a process initially quantified in [60, 76] and later refined using more detailed Monte Carlo approaches [3, 61–64]. While a substantial portion of AMC mass may be stripped away, residual AMC cores are expected to persist, particularly in the outskirts of galaxies.

Ref. [2] explores potential radio signatures from axion-photon conversion during NS encounters with AMCs within the Milky Way. The study simulates a large sample of such encounters to predict distributions of fluxes, durations, and sky locations. Events are modeled by sampling key parameters: galactocentric radius, height above the Galactic plane, and azimuthal angle. The internal density profiles of AMCs are modeled with either a power-law or a NFW distribution. Radio emissions from AMC-NS encounters are characterized by narrow-band spectral profiles driven by axion velocity dispersion, with radio flux density estimated based on encounter distance and relevant physical parameters. The flux distribution, assuming isotropic emission and integrating over encounter durations, peaks in flux densities between $(10^{-6}–10^{2})\,\mu$Jy, with event durations typically spanning from days to several months. Notably, bright events exceeding the sensitivity threshold of radio telescopes like the Very Large Array are primarily produced by encounters with denser AMCs. For this analysis, a DM axion mass of $20\,\mu$eV is assumed, though this parameter could vary over a broad range. The sky distribution of AMC-NS encounters in the Milky Way

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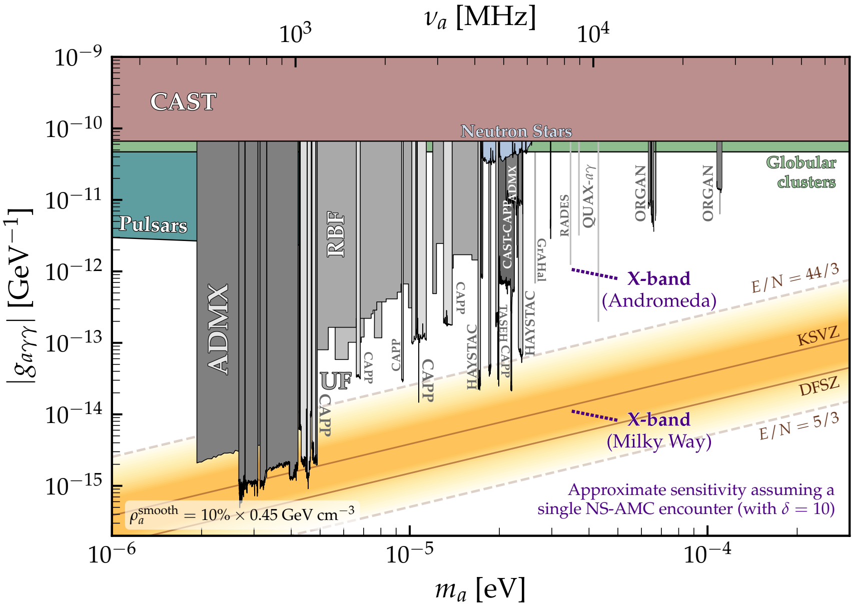

Figure 1: Estimated sensitivity to axion-photon couplings assuming the observation of a single AMC-NS encounter, compared with the QCD axion model band (yellow) and a number of existing constraints from haloscopes, helioscopes, and astrophysical searches. Details are given in Ref. [1]. Figure adapted from https://cajohare.github.io/AxionLimits/AxionLimits.

shows a concentration of events near the Galactic center, mirroring the NS spatial distribution. This spatial concentration could play a key role in detecting axion DM. The encounter rate is heavily influenced by the internal AMC density profile, with NFW profiles producing fewer bright events than power-law profiles, although the latter has a higher encounter rate. These results suggest that current and forthcoming radio telescope capabilities are well-suited to detect such transient signals, presenting a promising path toward identifying axion DM in the near future.

3. Results from GBT searches

In August 2021, a proposal was made to observe the center of the Andromeda galaxy (M31) using the GBT in the X band, representing the first dedicated effort to search for radio transients potentially caused by AMC-NS collisions. The initial search, conducted in 2022 (GBT22A-067), consisted of four two-hour observation sessions. During this campaign, seven candidate signals were identified above the 5σ detection threshold. However, none exhibited the characteristics expected of AMC-NS transients, leading to the conclusion that no detectable AMC-NS event occurred in M31 during the observation period [1]. Figure 1 illustrates the sensitivity reach for the axion-photon coupling parameter $g_{a\gamma\gamma}$ under specific assumptions regarding the overdensity parameters and the properties of the AMC involved.

Since the initial observations, theoretical modeling has advanced, now indicating a peak event rate near 3 GHz instead of the 10 GHz suggested in earlier studies [2, 77]. The updated model suggests that detectable events in the X-band are less frequent, requiring longer and broader observational windows to capture an AMC-NS collision. The event rate remains significant at particle masses below the expected range for cosmic axions that contribute to AMC formation [78, 79]. To investigate this, the search for AMC-NS collisions in M31 has continued, now focusing on the 3 GHz event-rate peak. In 2023, follow-up observations (GBT23A-245) were conducted using the GBT's C-band receiver, covering frequencies from 4.0 to 8.0 GHz (16 to 33 μeV axion mass range). Observing time was also awarded with the ultra-wideband receiver, which spans 0.7 to 4 GHz; however, technical issues prevented data collection. Currently, observations are underway with the L-band receiver on the Green Bank Observatory's 20-meter Telescope, covering 1.3 to 1.8 GHz (5.4 to 7.4 μeV axion mass range), with data analysis in progress. In addition to M31, preliminary observations of the nearby young neutron star RBS1223 began in 2023 using the ARO 12-meter Telescope. Observations were carried out using 2 and 3 mm receivers, targeting the 84 to 95 GHz and 140 to 158 GHz ranges, corresponding to higher axion mass ranges (350 to 650 μeV). These observations are set to continue, with plans to apply the same analysis pipeline used for X-band data across these higher-frequency bands.

4. Future goals

Identifying the DM particle remains one of the central objectives of astrophysical research, and its discovery would have profound implications for both particle physics and astrophysics. Simulations suggest that, while individual AMCs are sparse, the cumulative effect of multiple axion structures in the Milky Way could produce a steady stream of faint signals, potentially detectable by future axion search experiments equipped with advanced radio technology. To advance this search, the establishment of a dedicated observing facility is proposed to continue the search for AMC-NS collisions and to determine the DM axion mass. Given the rarity of these events, longer observation times are necessary to provide meaningful constraints on the axion parameter space, justifying the need for dedicated instrumentation. Should a candidate signal be detected, collaboration with laboratory experiments would be pursued to measure the axion-photon coupling constant $g_{a\gamma\gamma}$. Furthermore, both current and upcoming axion detection initiatives would benefit from a refined understanding of the distribution of overdensities, whose dynamics is critical to estimating the likelihood of observable events in laboratories.

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References

[1] L. Walters, J. E. Shroyer, M. Edenton, P. Agrawal, B. Johnson, B. J. Kavanagh et al., *Axions in Andromeda: Searching for minicluster-neutron star encounters with the Green Bank Telescope*, *Phys. Rev. D* **110** (2024) 123002 [2407.13060].

[2] T. D. P. Edwards, B. J. Kavanagh, L. Visinelli and C. Weniger, *Transient Radio Signatures from Neutron Star Encounters with QCD Axion Miniclusters*, *Phys. Rev. Lett.* **127** (2021) 131103 [2011.05378].

[3] B. J. Kavanagh, T. D. P. Edwards, L. Visinelli and C. Weniger, *Stellar disruption of axion miniclusters in the Milky Way*, *Phys. Rev. D* **104** (2021) 063038 [2011.05377].

[4] R. D. Peccei and H. R. Quinn, *CP Conservation in the Presence of Instantons*, *Phys. Rev. Lett.* **38** (1977) 1440.

[5] R. D. Peccei and H. R. Quinn, *Constraints Imposed by CP Conservation in the Presence of Instantons*, *Phys. Rev. D* **16** (1977) 1791.

[6] S. Weinberg, *A New Light Boson?*, *Phys. Rev. Lett.* **40** (1978) 223.

[7] F. Wilczek, *Problem of Strong P and T Invariance in the Presence of Instantons*, *Phys. Rev. Lett.* **40** (1978) 279.

[8] L. F. Abbott and P. Sikivie, *A Cosmological Bound on the Invisible Axion*, *Phys. Lett. B* **120** (1983) 133.

[9] M. Dine and W. Fischler, *The Not So Harmless Axion*, *Phys. Lett. B* **120** (1983) 137.

[10] J. Preskill, M. B. Wise and F. Wilczek, *Cosmology of the Invisible Axion*, *Phys. Lett. B* **120** (1983) 127.

[11] I. G. Irastorza and J. Redondo, *New experimental approaches in the search for axion-like particles*, *Prog. Part. Nucl. Phys.* **102** (2018) 89 [1801.08127].

[12] L. Di Luzio, M. Giannotti, E. Nardi and L. Visinelli, *The landscape of QCD axion models*, *Phys. Rept.* **870** (2020) 1 [2003.01100].

[13] F. Chadha-Day, J. Ellis and D. J. E. Marsh, *Axion dark matter: What is it and why now?*, *Sci. Adv.* **8** (2022) abj3618 [2105.01406].

[14] M. Giannotti, *Status and Perspectives on Axion Searches*, 12, 2024, 2412.08733.

[15] P. Sikivie, *Experimental Tests of the Invisible Axion*, *Phys. Rev. Lett.* **51** (1983) 1415.

[16] P. Sikivie, *Detection Rates for 'Invisible' Axion Searches*, *Phys. Rev. D* **32** (1985) 2988.

[17] F. Wilczek, *Two Applications of Axion Electrodynamics*, *Phys. Rev. Lett.* **58** (1987) 1799.

[18] S. V. Krasnikov, *New astrophysical constraints on the light pseudoscalar photon coupling*, *Phys. Rev. Lett.* **76** (1996) 2633.

[19] L. Visinelli, *Axion-Electromagnetic Waves*, *Mod. Phys. Lett. A* **28** (2013) 1350162 [1401.0709].

[20] H. Terças, J. D. Rodrigues and J. T. Mendonça, *Axion-plasmon polaritons in strongly magnetized plasmas*, *Phys. Rev. Lett.* **120** (2018) 181803 [1801.06254].

[21] L. Visinelli and H. Terças, *B-field induced mixing between Langmuir waves and axions*, *Phys. Rev. D* **105** (2022) 096024 [1807.06828].

[22] ADMX collaboration, *Results from a high sensitivity search for cosmic axions*, *Phys. Rev. Lett.* **80** (1998) 2043 [astro-ph/9801286].

[23] ADMX collaboration, *Large scale microwave cavity search for dark matter axions*, *Phys. Rev. D* **64** (2001) 092003.

[24] ADMX collaboration, *An Improved RF cavity search for halo axions*, *Phys. Rev. D* **69** (2004) 011101 [astro-ph/0310042].

[25] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner and K. A. van Bibber, *Experimental Searches for the Axion and Axion-Like Particles*, *Ann. Rev. Nucl. Part. Sci.* **65** (2015) 485 [1602.00039].

[26] ADMX collaboration, *Extended Search for the Invisible Axion with the Axion Dark Matter Experiment*, *Phys. Rev. Lett.* **124** (2020) 101303 [1910.08638].

[27] S. Al Kenany et al., *Design and operational experience of a microwave cavity axion detector for the 20–100 μeV range*, *Nucl. Instrum. Meth. A* **854** (2017) 11 [1611.07123].

[28] B. M. Brubaker et al., *First results from a microwave cavity axion search at 24 μeV*, *Phys. Rev. Lett.* **118** (2017) 061302 [1610.02580].

[29] MADMAX Working Group collaboration, *Dielectric Haloscopes: A New Way to Detect Axion Dark Matter*, *Phys. Rev. Lett.* **118** (2017) 091801 [1611.05865].

[30] MADMAX Working Group collaboration, *MADMAX: A new Dark Matter Axion Search using a Dielectric Haloscope*, in *12th Patras Workshop on Axions, WIMPs and WISPs*, 11, 2016, DOI [1611.04549].

[31] D. Alesini, D. Babusci, D. Di Gioacchino, C. Gatti, G. Lamanna and C. Ligi, *The KLASH Proposal*, 1707.06010.

[32] D. Alesini et al., *KLASH Conceptual Design Report*, 1911.02427.

[33] Y. Kahn, B. R. Safdi and J. Thaler, *Broadband and Resonant Approaches to Axion Dark Matter Detection*, *Phys. Rev. Lett.* **117** (2016) 141801 [1602.01086].

[34] J. L. Ouellet et al., *First Results from ABRACADABRA-10 cm: A Search for Sub-μeV Axion Dark Matter*, *Phys. Rev. Lett.* **122** (2019) 121802 [1810.12257].

[35] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran and A. Sushkov, *Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)*, *Phys. Rev. X* **4** (2014) 021030 [1306.6089].

[36] R. Barbieri, C. Braggio, G. Carugno, C. S. Gallo, A. Lombardi, A. Ortolan et al., *Searching for galactic axions through magnetized media: the QUAX proposal*, *Phys. Dark Univ.* **15** (2017) 135 [1606.02201].

[37] S. Lee, S. Ahn, J. Choi, B. R. Ko and Y. K. Semertzidis, *Axion Dark Matter Search around 6.7 μeV*, *Phys. Rev. Lett.* **124** (2020) 101802 [2001.05102].

[38] D. Alesini et al., *Search for Galactic axions with a high-Q dielectric cavity*, *Phys. Rev. D* **106** (2022) 052007 [2208.12670].

[39] D. Alesini et al., *The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories*, *Phys. Dark Univ.* **42** (2023) 101370 [2309.00351].

[40] C. Gatti, L. Visinelli and M. Zantedeschi, *Cavity detection of gravitational waves: Where do we stand?*, *Phys. Rev. D* **110** (2024) 023018 [2403.18610].

[41] ADMX collaboration, *Search for non-virialized axions with 3.3-4.2 μeV mass at selected resolving powers*, 2410.09203.

[42] T. O'Shea, M. Giannotti, I. G. Irastorza, L. M. Plasencia, J. Redondo, J. Ruz et al., *Prospects on the detection of solar dark photons by the International Axion Observatory*, *JCAP* **06** (2024) 070 [2312.10150].

[43] T. O'Shea, A.-C. Davis, M. Giannotti, S. Vagnozzi, L. Visinelli and J. K. Vogel, *Solar chameleons: Novel channels*, *Phys. Rev. D* **110** (2024) 063027 [2406.01691].

[44] J. Ruz et al., *NuSTAR as an Axion Helioscope*, 2407.03828.

[45] M. S. Pshirkov and S. B. Popov, *Conversion of Dark matter axions to photons in magnetospheres of neutron stars*, *J. Exp. Theor. Phys.* **108** (2009) 384 [0711.1264].

[46] F. P. Huang, K. Kadota, T. Sekiguchi and H. Tashiro, *Radio telescope search for the resonant conversion of cold dark matter axions from the magnetized astrophysical sources*, *Phys. Rev. D* **97** (2018) 123001 [1803.08230].

[47] A. Hook, Y. Kahn, B. R. Safdi and Z. Sun, *Radio Signals from Axion Dark Matter Conversion in Neutron Star Magnetospheres*, *Phys. Rev. Lett.* **121** (2018) 241102 [1804.03145].

[48] B. R. Safdi, Z. Sun and A. Y. Chen, *Detecting Axion Dark Matter with Radio Lines from Neutron Star Populations*, *Phys. Rev. D* **99** (2019) 123021 [1811.01020].

[49] M. Leroy, M. Chianese, T. D. P. Edwards and C. Weniger, *Radio Signal of Axion-Photon Conversion in Neutron Stars: A Ray Tracing Analysis*, *Phys. Rev. D* **101** (2020) 123003 [1912.08815].

[50] C. J. Hogan and M. J. Rees, *AXION MINICLUSTERS*, *Phys. Lett. B* **205** (1988) 228.

[51] E. W. Kolb and I. I. Tkachev, *Nonlinear axion dynamics and formation of cosmological pseudosolitons*, *Phys. Rev. D* **49** (1994) 5040 [astro-ph/9311037].

[52] E. W. Kolb and I. I. Tkachev, *Axion miniclusters and Bose stars*, *Phys. Rev. Lett.* **71** (1993) 3051 [hep-ph/9303313].

[53] K. M. Zurek, C. J. Hogan and T. R. Quinn, *Astrophysical Effects of Scalar Dark Matter Miniclusters*, *Phys. Rev. D* **75** (2007) 043511 [astro-ph/0607341].

[54] A. Vaquero, J. Redondo and J. Stadler, *Early seeds of axion miniclusters*, *JCAP* **04** (2019) 012 [1809.09241].

[55] M. Buschmann, J. W. Foster and B. R. Safdi, *Early-Universe Simulations of the Cosmological Axion*, *Phys. Rev. Lett.* **124** (2020) 161103 [1906.00967].

[56] P. Sikivie, *Axion Cosmology*, *Lect. Notes Phys.* **741** (2008) 19 [astro-ph/0610440].

[57] M. P. Hertzberg, E. D. Schiappacasse and T. T. Yanagida, *Axion Star Nucleation in Dark Minihalos around Primordial Black Holes*, *Phys. Rev. D* **102** (2020) 023013 [2001.07476].

[58] Z. Yin and L. Visinelli, *Axion star condensation around primordial black holes and microlensing limits*, *JCAP* **10** (2024) 013 [2404.10340].

[59] V. S. Berezinsky, V. I. Dokuchaev and Y. N. Eroshenko, *Formation and internal structure of superdense dark matter clumps and ultracompact minihaloes*, *JCAP* **11** (2013) 059 [1308.6742].

[60] P. Tinyakov, I. Tkachev and K. Zioutas, *Tidal streams from axion miniclusters and direct axion searches*, *JCAP* **01** (2016) 035 [1512.02884].

[61] V. Dandoy, T. Schwetz and E. Todarello, *A self-consistent wave description of axion miniclusters and their survival in the galaxy*, *JCAP* **09** (2022) 081 [2206.04619].

[62] X. Shen, H. Xiao, P. F. Hopkins and K. M. Zurek, *Disruption of Dark Matter Minihalos in the Milky Way Environment: Implications for Axion Miniclusters and Early Matter Domination*, *Astrophys. J.* **962** (2024) 9 [2207.11276].

[63] C. A. J. O'Hare, G. Pierobon and J. Redondo, *Axion Minicluster Streams in the Solar Neighborhood*, *Phys. Rev. Lett.* **133** (2024) 081001 [2311.17367].

[64] I. DSouza and C. Gordon, *Disruption of dark matter minihalos by successive stellar encounters*, *Phys. Rev. D* **109** (2024) 123035 [2402.03236].

[65] D. G. Levkov, A. G. Panin and I. I. Tkachev, *Gravitational Bose-Einstein condensation in the kinetic regime*, *Phys. Rev. Lett.* **121** (2018) 151301 [1804.05857].

[66] B. Eggemeier and J. C. Niemeyer, *Formation and mass growth of axion stars in axion miniclusters*, *Phys. Rev. D* **100** (2019) 063528 [1906.01348].

[67] J. Chen, X. Du, E. W. Lentz, D. J. E. Marsh and J. C. Niemeyer, *New insights into the formation and growth of boson stars in dark matter halos*, *Phys. Rev. D* **104** (2021) 083022 [2011.01333].

[68] A. S. Dmitriev, D. G. Levkov, A. G. Panin and I. I. Tkachev, *Self-Similar Growth of Bose Stars*, *Phys. Rev. Lett.* **132** (2024) 091001 [2305.01005].

[69] L. Visinelli, S. Baum, J. Redondo, K. Freese and F. Wilczek, *Dilute and dense axion stars*, *Phys. Lett. B* **777** (2018) 64 [1710.08910].

[70] E. D. Schiappacasse and M. P. Hertzberg, *Analysis of Dark Matter Axion Clumps with Spherical Symmetry*, *JCAP* **01** (2018) 037 [1710.04729].

[71] L. Visinelli and P. Gondolo, *Axion cold dark matter in non-standard cosmologies*, *Phys. Rev. D* **81** (2010) 063508 [0912.0015].

[72] B. Eggemeier, J. Redondo, K. Dolag, J. C. Niemeyer and A. Vaquero, *First Simulations of Axion Minicluster Halos*, *Phys. Rev. Lett.* **125** (2020) 041301 [1911.09417].

[73] B. Eggemeier, C. A. J. O'Hare, G. Pierobon, J. Redondo and Y. Y. Y. Wong, *Axion minivoids and implications for direct detection*, *Phys. Rev. D* **107** (2023) 083510 [2212.00560].

[74] M. Buschmann, J. W. Foster, A. Hook, A. Peterson, D. E. Willcox, W. Zhang et al., *Dark matter from axion strings with adaptive mesh refinement*, *Nature Commun.* **13** (2022) 1049 [2108.05368].

[75] J. F. Navarro, C. S. Frenk and S. D. M. White, *The Structure of cold dark matter halos*, *Astrophys. J.* **462** (1996) 563 [astro-ph/9508025].

[76] V. I. Dokuchaev, Y. N. Eroshenko and I. I. Tkachev, *Destruction of axion miniclusters in the Galaxy*, *J. Exp. Theor. Phys.* **125** (2017) 434 [1710.09586].

[77] S. J. Witte, D. Noordhuis, T. D. P. Edwards and C. Weniger, *Axion-photon conversion in neutron star magnetospheres: The role of the plasma in the Goldreich-Julian model*, *Phys. Rev. D* **104** (2021) 103030 [2104.07670].

[78] C. A. J. O'Hare, G. Pierobon, J. Redondo and Y. Y. Y. Wong, *Simulations of axionlike particles in the postinflationary scenario*, *Phys. Rev. D* **105** (2022) 055025 [2112.05117].

[79] M. Gorghetto and E. Hardy, *Post-inflationary axions: a minimal target for axion haloscopes*, *JHEP* **05** (2023) 030 [2212.13263].