Snowmass2021 - Letter of Interest

Astrophysical signatures of the QCD axion and axion-like particles

Thematic Areas: (check all that apply ☐/■)

☐ (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
■ (Other) TF9

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Abstract:

We describe a program making use of astrophysical data sets to search for evidence of the Quantum Chromodynamics axion and axion-like particles. This LOI focuses on four related physical phenomena: (i) observable modifications to stellar cooling and core-collapse supernovae due to axions; (ii) hard X-ray spectra produced from evolved stars in the presence of axions from axion-photon conversion in astrophysical magnetic fields; (iii) spectral modulations induced by low-mass axions in X-ray and γ-ray data sets from astrophysical sources; (iv) nearly monochromatic radio lines produced by axion dark matter from either axion-photon conversion in NS magnetospheres or stimulated decay in the ambient Galaxy. Searches for the phenomena described above have already set some of the strongest constraints to-date on the axion across a wide range of possible masses and couplings, and we outline future theoretical and observational efforts needed to further improve sensitivity and possibly lead to a discovery.

The Quantum Chromodynamics (QCD) axion is a well-motivated extension to the Standard Model that may solve the strong-*CP* problem of the neutron electric dipole moment and also explain the observed dark matter (DM)[1–7]. The axion may arise naturally in String Theory constructions, which predict a large number of axion-like particles in the low-energy spectrum[8–10]. The QCD axion a is defined through its coupling to QCD: $\mathcal{L} = -(g^2/32\pi^2 f_a)aG\tilde{G}$, with f_a the axion decay constant, G the QCD field strength, and g the QCD coupling constant. Below the QCD confinement scale this operator generates a mass m_a for the axion: $m_a \approx 10\ \mu\text{eV}(10^{12}\ \text{GeV}/f_a)$. The axion couples also to photons and matter; in the infrared, these couplings can be described by

$$\mathcal{L} \supset \frac{C_{a\gamma\gamma}\alpha_{\text{EM}}}{2\pi f_a} \cdot \frac{1}{4} a F^{\mu\nu}\widetilde{F}_{\mu\nu} + \sum_f \frac{C_{af}}{2 f_a} \cdot (\partial_\mu a)\bar{f}\gamma^\mu\gamma_5 f\,, \tag{1}$$

with $C_{a\gamma\gamma}$ and C_{af} dimensionless coupling constants and f denoting the quark (or meson and baryon at low energies) and lepton fields. Note that it is common to define the axion-photon coupling $g_{a\gamma\gamma} \equiv C_{a\gamma\gamma} \cdot \alpha_{EM}/(2\pi f_a)$ and the dimensionless matter couplings $g_{aff} \equiv C_{af} m_f / f_a$, with m_f the fermion mass. Axion-like particles couple to photons and matter through the terms in (1) but do not (necessarily) couple to QCD; thus, their masses m_a do not need to have a simple relation to their couplings. Both the QCD axion and axion-like particles may make up the observed DM abundance over a wide range of possible masses and couplings through the mis-alignment mechanism and other non-thermal production mechanisms[11,12].

The axion parameter space is currently the subject of significant laboratory effort[13]. Some of the leading running and planned experiments are ADMX[14–16], HAYSTAC[17], CAPP[18,19], ABRACADABRA[20–22], DM Radio[23–26], CASPEr[27], MADMAX[28], CAST[29–32], IAXO[33], and ALPS-II[34]. However, indirect searches for axions with astrophysical observations play an important and complementary role to the laboratory searches. Here we discuss astrophysical observations that span a range of wavelengths and physical phenomena, including: signatures of axions in stellar cooling and core-collapse supernovae; X-ray searches for axion-photon conversion from axions produced in stars; X-ray and γ-ray signatures of axion-induced spectral modulations from astrophysical sources; and radio telescope searches for axion dark matter. The current constraints on the axion-photon coupling $g_{a\gamma\gamma}$ and the axion-electron coupling g_{aee} as functions of the axion mass m_a are summarized in Fig. 1. We note that the strongest constraints on these couplings and the other axion-matter couplings, across a broad range of possible masses, come from astrophysical observations. In this Letter of Interest (LOI) we argue that these search strategies are promising directions for future focus that could lead to the discovery of axions.

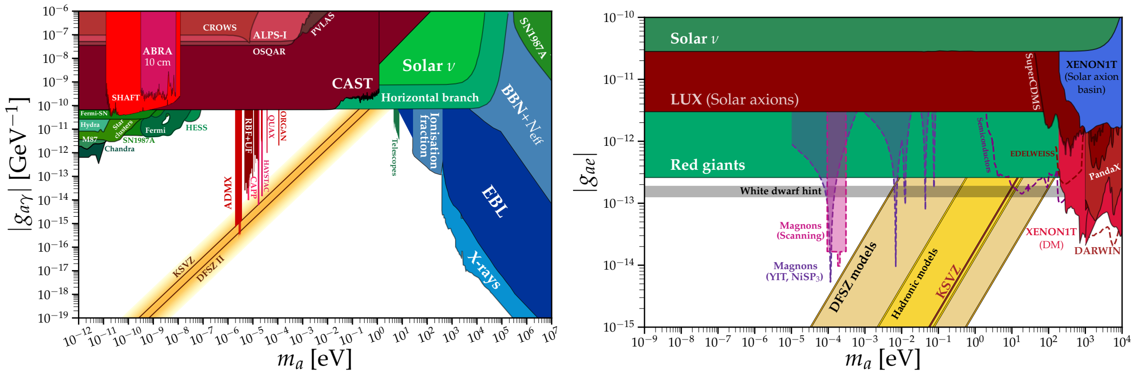

Figure 1: Current constraints on the axion-photon and axion-electron couplings (other axion-matter couplings not shown)[35]. The astrophysical searches discussed in this LOI are the most sensitive probes of axions over large regions the possible parameter space. Improving upon the sensitivity of these searches, through theoretical and observational developments, is crucial to maximize the chances of discovering axions.

Axion effects on stars and supernovae.—Axion production in stars has long been understood to provide a pathway by which stars may cool. Some of the strongest constraints on the axion-photon and the axion-matter couplings arise from stellar cooling observations, such as horizontal branch star, white dwarf (WD) star, neutron star (NS), and red giant star cooling (see Fig. 1)[36]. It is also known that axion emission from the core of a hot proto-NS might impact the observable supernova neutrino breakout burst and cooling phase[37–46]. Prospects for improving the constraints on axion emission in the course of a supernova explosion could allow for improvement in current limits[47] or could plausibly lead to a detection of new physics[48], and an analysis that takes into account upcoming experimental sensitivities of next-generation neutrino experiments[49] is important to pursue. Likewise, the study of the effects of axions on low-mass stellar populations have returned both positive and negative results[36,43,50–59], and investigating the effects of observational and modeling uncertainties on these inferences is a critical next step for understanding how axions impact stars. Finally, the implications of axion emission for other phases of stellar evolution and different stellar populations provide promising new signals, such as the impending detection of the black hole mass gap[60,61] in Advanced LIGO/Virgo.

X**-ray searches for stellar axions.—**Stellar axions may be directly observable as X-rays after they escape the stars and convert to photons in either the stellar or galactic magnetic fields[62–67]. Strong constraints on $g_{a\gamma\gamma}$ for low-mass axions have been set using NuSTAR data from Super Star Clusters[68] (see Fig. 1). Observations with *XMM-Newton* and *Chandra* towards nearby NSs[66] and WDs[65] have set the strongest constraints to-date on $g_{a\gamma\gamma} \times g_{an}$ (in addition to a possible detection[66]) and $g_{a\gamma\gamma} \times g_{ae}$, respectively, where g_{an} is the axion-neutron coupling. Significant progress across the X-ray axion searches could be made by future X-ray telescopes such as ATHENA, and better understanding the theoretical uncertainties both on the axion production in, *e.g.*, NSs and on the conversion probabilities in the stellar and galactic magnetic fields would also be fruitful.

X**-ray and** γ**-ray spectral modulations.—**The interconversion of photons and axions in astrophysical magnetic fields can lead to energy-dependent modulations in the spectra of γ- and X-ray sources. Searches for such an effect have been performed in γ-rays using data from, e.g., *Fermi*-LAT and H.E.S.S towards Galactic and extragalactic sources, such as Galactic pulsars[69], supernova remnants[70,71], and active galaxies[72–77], yielding a possible detection. X-ray modulation searches with *Chandra* towards *e.g.* NGC 1275[78] and M87[79] have set the strongest constraints on axion with masses below $\sim 10^{-12}$ eV (see Fig. 1), consistently with previous studies[80–83]. These analyses require modeling of the conversion in the intra-cluster, extragalactic and Galactic magnetic fields and are thus subject to uncertainties on these fields; better understanding these uncertainties is crucial for future progress. Next-generation instruments such as ATHENA and X-ray polarimeters are expected to further increase the sensitivity of these searches to axions[84,85].

Radio searches for axion dark matter.—Axion DM may fall into the gravitational potential wells of NSs and then resonantly convert to nearly monochromatic radio signatures in the strong magnetic fields in the magnetospheres[86–92]. NS magnetospheres give the photon an effective mass that increases monotonically as one approaches the surface; level crossing and resonant conversion occurs at the radius where the plasma mass matches the axion mass. Dedicated searches for the axion-induced radio signal were performed in[92–94]; no evidence for axions were found but strong constraints on $g_{a\gamma\gamma}$ were set for $m_a \sim 10\ \mu$eV. In recent years, the Breakthrough Listen project[95] on the Green Bank Telescope has made publicly available[96] a large set of target spectra in the 1-12 GHz range. This opens up the exciting possibility for model-independent stimulated axion decay searches[90,97,98] and NS searches across a wide range of masses. The projected reach of a dedicated search towards *e.g.* the GC with the planned Square Kilometer Array (SKA) is sufficient to cover larger regions of QCD axion DM parameter space for masses $m_a \sim 10\ \mu$eV[89,90]. More work is needed to (i) understand the theoretical uncertainties related to calculating the axion-induced radio flux, and (ii) developing search strategies for existing and future observatories.

References

[1] R. D. Peccei and H. R. Quinn, *Constraints Imposed by CP Conservation in the Presence of Instantons*, *Phys. Rev.* **D16** (1977) 1791–1797.

[2] R. D. Peccei and H. R. Quinn, *CP Conservation in the Presence of Instantons*, *Phys. Rev. Lett.* **38** (1977) 1440–1443.

[3] S. Weinberg, *A New Light Boson?*, *Phys.Rev.Lett.* **40** (1978) 223–226.

[4] F. Wilczek, *Problem of Strong P and T Invariance in the Presence of Instantons*, *Phys.Rev.Lett.* **40** (1978) 279–282.

[5] J. Preskill, M. B. Wise and F. Wilczek, *Cosmology of the Invisible Axion*, *Phys. Lett.* **B120** (1983) 127–132.

[6] L. F. Abbott and P. Sikivie, *A Cosmological Bound on the Invisible Axion*, *Phys. Lett.* **B120** (1983) 133–136.

[7] M. Dine and W. Fischler, *The Not So Harmless Axion*, *Phys. Lett.* **B120** (1983) 137–141.

[8] P. Svrcek and E. Witten, *Axions In String Theory*, *JHEP* **06** (2006) 051, [`hep-th/0605206`].

[9] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, *String Axiverse*, *Phys. Rev.* **D81** (2010) 123530, [`0905.4720`].

[10] J. Halverson, C. Long, B. Nelson and G. Salinas, *On String Theory Expectations for Photon Couplings to Axion-Like Particles*, `1909.05257`.

[11] L. D. Duffy and K. van Bibber, *Axions as Dark Matter Particles*, *New J. Phys.* **11** (2009) 105008, [`0904.3346`].

[12] S. Hoof, F. Kahlhoefer, P. Scott, C. Weniger and M. White, *Axion global fits with Peccei-Quinn symmetry breaking before inflation using GAMBIT*, `1810.07192`.

[13] I. G. Irastorza and J. Redondo, *New experimental approaches in the search for axion-like particles*, *Prog. Part. Nucl. Phys.* **102** (2018) 89–159, [`1801.08127`].

[14] S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz et al., *SQUID-Based Microwave Cavity Search for Dark-Matter Axions*, *Phys. Rev. Lett.* **104** (Jan, 2010) 041301.

[15] ADMX collaboration, N. Du et al., *A Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment*, *Phys. Rev. Lett.* **120** (2018) 151301, [`1804.05750`].

[16] ADMX collaboration, T. Braine et al., *Extended Search for the Invisible Axion with the Axion Dark Matter Experiment*, *Phys. Rev. Lett.* **124** (2020) 101303, [`1910.08638`].

[17] B. M. Brubaker, L. Zhong, S. K. Lamoreaux, K. W. Lehnert and K. A. van Bibber, *The HAYSTAC Axion Search Analysis Procedure*, `1706.08388`.

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

[19] J. Jeong, S. Youn, S. Bae, J. Kim, T. Seong, J. E. Kim et al., *Search for invisible axion dark matter with a multiple-cell haloscope*, `2008.10141`.

[20] 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`].

[21] 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.

[22] J. L. Ouellet et al., *"Design and Implementation of the ABRACADABRA-10 cm Axion Dark Matter Search"*, *Phys. Rev. D* **99** (2019) 052012.

[23] A. Phipps, S. Kuenstner, S. Chaudhuri, C. Dawson, B. Young, C. FitzGerald et al., *Exclusion limits on hidden-photon dark matter near 2 nev from a fixed-frequency superconducting lumped-element resonator*, in *Microwave Cavities and Detectors for Axion Research*, pp. 139–145. Springer, 2020.

[24] M. Silva-Feaver et al., *Design overview of dm radio pathfinder experiment*, *IEEE Transactions on Applied Superconductivity* **27** (2017) 1–4.

[25] S. Chaudhuri et al., *Radio for hidden-photon dark matter detection*, *Physical Review D* **92** (OCT 8, 2015) .

[26] S. Chaudhuri, K. D. Irwin, P. W. Graham and J. Mardon, *Optimal electromagnetic searches for axion and hidden-photon dark matter*, *arXiv preprint arXiv:1904.05806* (2019) .

[27] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran and A. Sushkov, *Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)*, *Phys. Rev.* **X4** (2014) 021030, [`1306.6089`].

[28] MADMAX WORKING GROUP collaboration, A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo et al., *Dielectric Haloscopes: A New Way to Detect Axion Dark Matter*, *Phys. Rev. Lett.* **118** (2017) 091801, [`1611.05865`].

[29] CAST collaboration, M. Arik et al., *Search for Solar Axions by the CERN Axion Solar Telescope with ^{3}He Buffer Gas: Closing the Hot Dark Matter Gap*, *Phys. Rev. Lett.* **112** (2014) 091302, [`1307.1985`].

[30] K. Barth et al., *CAST constraints on the axion-electron coupling*, *JCAP* **1305** (2013) 010, [`1302.6283`].

[31] CAST collaboration, M. Arik et al., *New solar axion search using the CERN Axion Solar Telescope with ^{4}He filling*, *Phys. Rev.* **D92** (2015) 021101, [`1503.00610`].

[32] CAST collaboration, V. Anastassopoulos et al., *New CAST Limit on the Axion-Photon Interaction*, *Nature Phys.* **13** (2017) 584–590, [`1705.02290`].

[33] IAXO collaboration, E. Armengaud et al., *Physics potential of the International Axion Observatory (IAXO)*, *JCAP* **1906** (2019) 047, [`1904.09155`].

[34] ALPS collaboration, A. Spector, *ALPS II technical overview and status report*, in *Proceedings, 12th Patras Workshop on Axions, WIMPs and WISPs (PATRAS 2016): Jeju Island, South Korea, June 20-24, 2016*, pp. 133–136, 2017. `1611.05863`. DOI.

[35] C. O'HARE, *cajohare/axionlimits: Axionlimits*, July, 2020. 10.5281/zenodo.3932430.

[36] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi and O. Straniero, *Revisiting the bound on axion-photon coupling from Globular Clusters*, *Phys. Rev. Lett.* **113** (2014) 191302, [`1406.6053`].

[37] R. P. Brinkmann and M. S. Turner, *Numerical Rates for Nucleon-Nucleon Axion Bremsstrahlung*, *Phys. Rev.* **D38** (1988) 2338.

[38] A. Burrows, M. S. Turner and R. P. Brinkmann, *Axions and SN 1987a*, *Phys. Rev.* **D39** (1989) 1020.

[39] A. Burrows, M. T. Ressell and M. S. Turner, *Axions and SN1987A: Axion trapping*, *Phys. Rev.* **D42** (1990) 3297–3309.

[40] J. Engel, D. Seckel and A. C. Hayes, *Emission and detectability of hadronic axions from SN1987A*, *Phys. Rev. Lett.* **65** (1990) 960–963.

[41] C. Hanhart, D. R. Phillips and S. Reddy, *Neutrino and axion emissivities of neutron stars from nucleon-nucleon scattering data*, *Phys. Lett.* **B499** (2001) 9–15, [`astro-ph/0003445`].

[42] W. Keil, H.-T. Janka, D. N. Schramm, G. Sigl, M. S. Turner and J. R. Ellis, *A Fresh look at axions and SN-1987A*, *Phys. Rev.* **D56** (1997) 2419–2432, [`astro-ph/9612222`].

[43] G. G. Raffelt, *Astrophysical axion bounds*, *Lect. Notes Phys.* **741** (2008) 51–71, [`hep-ph/0611350`].

[44] M. S. Turner, *Axions from SN 1987a*, *Phys. Rev. Lett.* **60** (1988) 1797.

[45] M. S. Turner, H.-S. Kang and G. Steigman, *Axions, SN 1987a and One Pion Exchange*, *Phys. Rev.* **D40** (1989) 299–308.

[46] J. H. Chang, R. Essig and S. D. McDermott, *Supernova 1987A Constraints on Sub-GeV Dark Sectors, Millicharged Particles, the QCD Axion, and an Axion-like Particle*, *JHEP* **09** (2018) 051, [`1803.00993`].

[47] T. Fischer, S. Chakraborty, M. Giannotti, A. Mirizzi, A. Payez and A. Ringwald, *Probing axions with the neutrino signal from the next galactic supernova*, *Phys. Rev. D* **94** (2016) 085012, [`1605.08780`].

[48] S.-F. Ge, K. Hamaguchi, K. Ichimura, K. Ishidoshiro, Y. Kanazawa, Y. Kishimoto et al., *Supernova-scope for the Direct Search of Supernova Axions*, `2008.03924`.

[49] S. W. Li, L. F. Roberts and J. F. Beacom, *Exciting Prospects for Detecting Late-Time Neutrinos from Core-Collapse Supernovae*, `2008.04340`.

[50] G. G. Raffelt, *ASTROPHYSICAL AXION BOUNDS DIMINISHED BY SCREENING EFFECTS*, *Phys. Rev. D* **33** (1986) 897.

[51] G. G. Raffelt, *Axion Constraints From White Dwarf Cooling Times*, *Phys. Lett. B* **166** (1986) 402–406.

[52] G. Raffelt and A. Weiss, *Red giant bound on the axion - electron coupling revisited*, *Phys. Rev. D* **51** (1995) 1495–1498, [`hep-ph/9410205`].

[53] H. Schlattl, A. Weiss and G. Raffelt, *Helioseismological constraint on solar axion emission*, *Astropart. Phys.* **10** (1999) 353–359, [`hep-ph/9807476`].

[54] P. Gondolo and G. G. Raffelt, *Solar neutrino limit on axions and keV-mass bosons*, *Phys. Rev. D* **79** (2009) 107301, [`0807.2926`].

[55] A. Friedland, M. Giannotti and M. Wise, *Constraining the Axion-Photon Coupling with Massive Stars*, *Phys. Rev. Lett.* **110** (2013) 061101, [`1210.1271`].

[56] A. Choplin, A. Coc, G. Meynet, K. A. Olive, J.-P. Uzan and E. Vangioni, *Effects of axions on Population III stars*, *Astron. Astrophys.* **605** (2017) A106, [`1707.01244`].

[57] P. Carenza, O. Straniero, B. Döbrich, M. Giannotti, G. Lucente and A. Mirizzi, *Constraints on the coupling with photons of heavy axion-like-particles from Globular Clusters*, `2004.08399`.

[58] L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia and E. Nardi, *Solar axions cannot explain the XENON1T excess*, `2006.12487`.

[59] F. Capozzi and G. Raffelt, *Axion and neutrino red-giant bounds updated with geometric distance determinations*, `2007.03694`.

[60] D. Croon, S. D. McDermott and J. Sakstein, *Missing in Axion: where are XENON1T's big black holes?*, `2007.00650`.

[61] D. Croon, S. D. McDermott and J. Sakstein, *Missing in Action: New Physics and the Black Hole Mass Gap*, `2007.07889`.

[62] E. D. Carlson, *Pseudoscalar conversion and X-rays from stars*, *Physics Letters B* **344** (Feb., 1995) 245–251.

[63] D. E. Morris, *Axion Mass Limits From Pulsar X-rays*, *Phys. Rev.* **D34** (1986) 843.

[64] G. Raffelt and L. Stodolsky, *Mixing of the Photon with Low Mass Particles*, *Phys. Rev.* **D37** (1988) 1237.

[65] C. Dessert, A. J. Long and B. R. Safdi, *X-ray signatures of axion conversion in magnetic white dwarf stars*, `1903.05088`.

[66] M. Buschmann, R. T. Co, C. Dessert and B. R. Safdi, *X-ray Search for Axions from Nearby Isolated Neutron Stars*, `1910.04164`.

[67] M. Giannotti, B. Grefenstette, A. Mirizzi, M. Nynka, K. Perez, B. Roach et al., "Constraints on light axions from a hard x-ray observation of betelgeuse.".

[68] C. Dessert, J. W. Foster and B. R. Safdi, *X-ray Searches for Axions from Super Star Clusters*, `2008.03305`.

[69] J. Majumdar, F. Calore and D. Horns, *Search for gamma-ray spectral modulations in Galactic pulsars*, *JCAP* **04** (2018) 048, [`1801.08813`].

[70] Z.-Q. Xia, C. Zhang, Y.-F. Liang, L. Feng, Q. Yuan, Y.-Z. Fan et al., *Searching for spectral oscillations due to photon-axionlike particle conversion using the Fermi-LAT observations of bright supernova remnants*, *Phys. Rev. D* **97** (2018) 063003, [`1801.01646`].

[71] G. A. Pallathadka, F. Calore, P. Carenza, M. Giannotti, D. Horns, J. Majumdar et al., *Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds*, `2008.08100`.

[72] FERMI-LAT collaboration, M. Ajello et al., *Search for Spectral Irregularities due to PhotonAxionlike-Particle Oscillations with the Fermi Large Area Telescope*, *Phys. Rev. Lett.* **116** (2016) 161101, [`1603.06978`].

[73] D. Malyshev, A. Neronov, D. Semikoz, A. Santangelo and J. Jochum, *Improved limit on axion-like particles from γ-ray data on Perseus cluster*, `1805.04388`.

[74] M. Libanov and S. Troitsky, *On the impact of magnetic-field models in galaxy clusters on constraints on axion-like particles from the lack of irregularities in high-energy spectra of astrophysical sources*, *Phys. Lett.* **B802** (2020) 135252, [`1908.03084`].

[75] H.E.S.S. collaboration, A. Abramowski et al., *Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155-304 energy spectrum*, *Phys. Rev.* **D88** (2013) 102003, [`1311.3148`].

[76] C. Zhang, Y.-F. Liang, S. Li, N.-H. Liao, L. Feng, Q. Yuan et al., *New bounds on axionlike particles from the Fermi Large Area Telescope observation of PKS 2155-304*, *Phys. Rev. D* **97** (2018) 063009, [`1802.08420`].

[77] J. Guo, H.-J. Li, X.-J. Bi, S.-J. Lin and P.-F. Yin, *The implications of the axion like particle from the Fermi-LAT and H.E.S.S. observations of PG 1553+113 and PKS 2155-304*, `2002.07571`.

[78] C. S. Reynolds, M. C. D. Marsh, H. R. Russell, A. C. Fabian, R. Smith, F. Tombesi et al., *Astrophysical limits on very light axion-like particles from Chandra grating spectroscopy of NGC 1275*, `1907.05475`.

[79] M. C. D. Marsh, H. R. Russell, A. C. Fabian, B. P. McNamara, P. Nulsen and C. S. Reynolds, *A New Bound on Axion-Like Particles*, *JCAP* **1712** (2017) 036, [`1703.07354`].

[80] D. Wouters and P. Brun, *Constraints on Axion-like Particles from X-Ray Observations of the Hydra Galaxy Cluster*, *Astrophys. J.* **772** (2013) 44, [`1304.0989`].

[81] M. Berg, J. P. Conlon, F. Day, N. Jennings, S. Krippendorf, A. J. Powell et al., *Constraints on Axion-Like Particles from X-ray Observations of NGC1275*, *Astrophys. J.* **847** (2017) 101, [`1605.01043`].

[82] J. P. Conlon, F. Day, N. Jennings, S. Krippendorf and M. Rummel, *Constraints on Axion-Like Particles from Non-Observation of Spectral Modulations for X-ray Point Sources*, *JCAP* **07** (2017) 005, [`1704.05256`].

[83] L. Chen and J. P. Conlon, *Constraints on massive axion-like particles from X-ray observations of NGC 1275*, *Mon. Not. Roy. Astron. Soc.* **479** (2018) 2243–2248, [`1712.08313`].

[84] J. P. Conlon, F. Day, N. Jennings, S. Krippendorf and F. Muia, *Projected bounds on ALPs from Athena*, *Mon. Not. Roy. Astron. Soc.* **473** (2018) 4932–4936, [`1707.00176`].

[85] F. Day and S. Krippendorf, *Searching for Axion-Like Particles with X-ray Polarimeters*, *Galaxies* **6** (2018) 45, [`1801.10557`].

[86] 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) 384–388, [`0711.1264`].

[87] 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`].

[88] 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. **D97** (2018) 123001, [`1803.08230`].

[89] B. R. Safdi, Z. Sun and A. Y. Chen, *Detecting Axion Dark Matter with Radio Lines from Neutron Star Populations*, `1811.01020`.

[90] R. A. Battye, B. Garbrecht, J. I. McDonald, F. Pace and S. Srinivasan, *Dark matter axion detection in the radio/mm-waveband*, *Phys. Rev. D* **102** (2020) 023504, [`1910.11907`].

[91] M. Leroy, M. Chianese, T. D. 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`].

[92] J. W. Foster, Y. Kahn, O. Macias, Z. Sun, R. P. Eatough, V. I. Kondratiev et al., *Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres*, `2004.00011`.

[93] J. Darling, *A Search for Axionic Dark Matter Using the Magnetar PSR J1745-2900*, `2008.01877`.

[94] J. Darling, *New Limits on Axionic Dark Matter from the Magnetar PSR J1745-2900*, `2008.11188`.

[95] M. Lebofsky, S. Croft, A. P. V. Siemion, D. C. Price, J. E. Enriquez, H. Isaacson et al., *The Breakthrough Listen Search for Intelligent Life: Public Data, Formats, Reduction, and Archiving*, **131** (Dec., 2019) 124505, [`1906.07391`].

[96] M. Lebofsky, S. Croft, A. P. V. Siemion, D. C. Price, J. E. Enriquez, H. Isaacson et al., *The Breakthrough Listen Search for Intelligent Life: Public Data, Formats, Reduction, and Archiving*, **131** (Dec., 2019) 124505, [`1906.07391`].

[97] A. Caputo, M. Regis, M. Taoso and S. J. Witte, *Detecting the Stimulated Decay of Axions at RadioFrequencies*, `1811.08436`.

[98] O. Ghosh, J. Salvado and J. Miralda-Escudé, *Axion Gegenschein: Probing Back-scattering of Astrophysical Radio Sources Induced by Dark Matter*, `2008.02729`.