Neutron stars as axion laboratories

Harnessing the power of the magnetosphere

Noordhuis, D.

Publication date
2024

Bibliography

[1] G. Bertone and D. Hooper. "History of dark matter". In: *Reviews of Modern Physics* 90.4 (2018). DOI: 10.1103/revmodphys.90.045002.

[2] J. G. de Swart, G. Bertone, and J. van Dongen. "How dark matter came to matter". In: *Nature Astronomy* 1.3 (2017). DOI: 10.1038/s41550-017-0059.

[3] D. J. E. Marsh. "Axion cosmology". In: *Physics Reports* 643 (2016), p. 1. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2016.06.005.

[4] I. G. Irastorza and J. Redondo. "New experimental approaches in the search for axion-like particles". In: *Progress in Particle and Nuclear Physics* 102 (2018), p. 89. ISSN: 0146-6410. DOI: 10.1016/j.ppnp.2018.05.003.

[5] L. Di Luzio et al. "The landscape of QCD axion models". In: *Physics Reports* 870 (2020), p. 1. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2020.06.002.

[6] J. Pétri. "Theory of pulsar magnetosphere and wind". In: *Journal of Plasma Physics* 82.5 (2016). ISSN: 1469-7807.

[7] B. Cerutti and A. M. Beloborodov. "Electrodynamics of Pulsar Magnetospheres". In: *Space Science Reviews* 207.1–4 (2016), p. 111. ISSN: 1572-9672. DOI: 10.1007/s11214-016-0315-7.

[8] H. S. Kragh. *Conceptions of Cosmos: From Myths to the Accelerating Universe: A History of Cosmology*. OUP Oxford, 2006. ISBN: 9780199209163.

[9] W. T. Kelvin. *Baltimore lectures on molecular dynamics and the wave theory of light*. C. J. Clay and sons, 1904.

[10] H. Poincare. "The Milky Way and the Theory of Gases". In: *Popular Astronomy* 14 (1906), p. 475.

[11] E. Öpik. "Selective absorption of light in space, and the dynamics of the Universe". In: *Bull. de la Soc. Astr. de Russie* 21 (1915), p. 150.

[12] J. C. Kapteyn. "First Attempt at a Theory of the Arrangement and Motion of the Sidereal System". In: *The Astrophysical Journal* 55 (1922), p. 302. DOI: 10.1086/142670.

[13] J. H. Jeans. "The Motions of Stars in a Kapteyn-Universe". In: *Monthly Notices of the Royal Astronomical Society* 82.3 (1922), p. 122. DOI: 10.1093/mnras/82.3.122.

[14] B. Lindblad. "Researches based on determinations of stellar luminosities (Second paper)". In: *Uppsala Meddelanden* 11 (1926), p. 30.

[15] J. H. Oort. "The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems". In: *Bull. Astron. Inst. Netherlands* 6 (1932), p. 249.

[16] F. Zwicky. "The redshift of extragalactic nebulae". In: *Helvetica Physica Acta* 6 (1933), p. 110.

[17] E. Hubble and M. L. Humason. "The Velocity-Distance Relation among Extra-Galactic Nebulae". In: *The Astrophysical Journal* 74 (1931), p. 43. DOI: 10.1086/143323.

[18] S. Smith. "The Mass of the Virgo Cluster". In: *The Astrophysical Journal* 83 (1936), p. 23. DOI: 10.1086/143697.

[19] E. Holmberg. "On the Clustering Tendencies among the Nebulae." In: *The Astrophysical Journal* 92 (1940), p. 200. DOI: 10.1086/144212.

[20] I. S. Chandrasekhar. "The Time of Relaxation of Stellar Systems." In: *The Astrophysical Journal* 93 (1941), p. 285. DOI: 10.1086/144265.

[21] H. W. Babcock. "The rotation of the Andromeda Nebula". In: *Lick Observatory Bulletin* 498 (1939), p. 41. DOI: 10.5479/ADS/bib/1939LicOB.19.41B.

[22] Vera C. Rubin and Jr. Ford W. Kent. "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions". In: *The Astrophysical Journal* 159 (1970), p. 379. DOI: 10.1086/150317.

[23] R. N. Whitehurst and M. S. Roberts. “High-Velocity Neutral Hydrogen in the Central Region of the Andromeda Galaxy”. In: *The Astrophysical Journal* 175 (1972), p. 347. DOI: 10.1086/151562.

[24] D. H. Rogstad and G. S. Shostak. “Gross Properties of Five Scd Galaxies as Determined from 21-CENTIMETER Observations”. In: *The Astrophysical Journal* 176 (1972), p. 315. DOI: 10.1086/151636.

[25] M. S. Roberts and A. H. Rots. “Comparison of Rotation Curves of Different Galaxy Types”. In: *Astronomy and Astrophysics* 26 (1973), p. 483.

[26] J. Einasto, A. Kaasik, and E. Saar. “Dynamic evidence on massive coronas of galaxies”. In: *Nature* 250.5464 (1974), p. 309. DOI: 10.1038/250309a0.

[27] J. P. Ostriker, P. J. E. Peebles, and A. Yahil. “The Size and Mass of Galaxies, and the Mass of the Universe”. In: *The Astrophysical Journal* 193 (1974), p. L1. DOI: 10.1086/181617.

[28] S. M. Faber and J. S. Gallagher. “Masses and Mass-To-Light Ratios of Galaxies”. In: *Annual Review of Astronomy and Astrophysics* 17.1 (1979), p. 135. DOI: 10.1146/annurev.aa.17.090179.001031.

[29] Planck Collaboration. “Planck2018 results: VI. Cosmological parameters”. In: *Astronomy and Astrophysics* 641 (2020), A6. DOI: 10.1051/0004-6361/201833910.

[30] J. A. Frieman, M. S. Turner, and D. Huterer. “Dark energy and the accelerating universe.” In: *Annual Review of Astronomy and Astrophysics* 46 (2008), p. 385. DOI: 10.1146/annurev.astro.46.060407.145243.

[31] C. L. Bennett et al. “First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Foreground Emission”. In: *The Astrophysical Journal Supplement Series* 148.1 (2003), p. 97. DOI: 10.1086/377252.

[32] Planck Collaboration. “Planck 2018 results - I. Overview and the cosmological legacy of Planck”. In: *Astronomy and Astrophysics* 641 (2020), A1. DOI: 10.1051/0004-6361/201833880.

[33] W. Hu and S. Dodelson. “Cosmic Microwave Background Anisotropies”. In: *Annual Review of Astronomy and Astrophysics* 40.1 (2002), p. 171. DOI: 10.1146/annurev.astro.40.060401.093926.

[34] D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". In: *The Astrophysical Journal* 648.2 (2006), p. L109. DOI: 10.1086/508162.

[35] M. Bradač et al. "Revealing the Properties of Dark Matter in the Merging Cluster MACS J0025.4-1222". In: *The Astrophysical Journal* 687.2 (2008), p. 959. DOI: 10.1086/591246.

[36] G. R. Blumenthal et al. "Formation of galaxies and large-scale structure with cold dark matter." In: *Nature* 311 (1984), p. 517. DOI: 10.1038/311517a0.

[37] W. J. Percival et al. "Measuring the Baryon Acoustic Oscillation scale using the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey". In: *Monthly Notices of the Royal Astronomical Society* 381.3 (2007), p. 1053. DOI: 10.1111/j.1365-2966.2007.12268.x.

[38] BOSS Collaboration. "The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample". In: *Monthly Notices of the Royal Astronomical Society* 470.3 (2017), p. 2617. DOI: 10.1093/mnras/stx721.

[39] DES Collaboration. "Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing". In: *Physical Review D* 98.4 (2018). DOI: 10.1103/physrevd.98.043526.

[40] R. Massey, T. Kitching, and J. Richard. "The dark matter of gravitational lensing". In: *Reports on Progress in Physics* 73.8 (2010), p. 086901. ISSN: 1361-6633. DOI: 10.1088/0034-4885/73/8/086901.

[41] S. Vegetti et al. *Strong gravitational lensing as a probe of dark matter.* 2023. arXiv: 2306.11781.

[42] M. Milgrom. "A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis." In: *The Astrophysical Journal* 270 (1983), p. 365. DOI: 10.1086/161130.

[43] M. Milgrom. "A modification of the Newtonian dynamics - Implications for galaxies." In: *The Astrophysical Journal* 270 (1983), p. 371. DOI: 10.1086/161131.

[44] M. Milgrom. "A modification of the newtonian dynamics : implications for galaxy systems." In: *The Astrophysical Journal* 270 (1983), p. 384. DOI: 10.1086/161132.

[45] J. D. Bekenstein. “Relativistic gravitation theory for the modified Newtonian dynamics paradigm”. In: *Phys. Rev. D* 70 (8 2004), p. 28. DOI: 10.1103/PhysRevD.70.083509.

[46] C. Skordis et al. “Large Scale Structure in Bekenstein’s Theory of Relativistic Modified Newtonian Dynamics”. In: *Physical Review Letters* 96.1 (2006). ISSN: 1079-7114. DOI: 10.1103/physrevlett.96.011301.

[47] C. Skordis. “The tensor-vector-scalar theory and its cosmology”. In: *Classical and Quantum Gravity* 26.14 (2009), p. 143001. ISSN: 1361-6382. DOI: 10.1088/0264-9381/26/14/143001.

[48] S. Dodelson. “The Real Problem With MOND”. In: *International Journal of Modern Physics D* 20.14 (2011), p. 2749. ISSN: 1793-6594. DOI: 10.1142/s0218271811020561.

[49] B. Famaey and S. S. McGaugh. “Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions”. In: *Living Reviews in Relativity* 15.1 (2012). ISSN: 1433-8351. DOI: 10.12942/lrr-2012-10.

[50] M. K. Gaillard, P. D. Grannis, and F. J. Sciulli. “The standard model of particle physics”. In: *Reviews of Modern Physics* 71.2 (1999), S96. DOI: 10.1103/revmodphys.71.s96.

[51] C. Alcock et al. “The MACHO Project: Microlensing Results from 5.7 Years of Large Magellanic Cloud Observations”. In: *The Astrophysical Journal* 542.1 (2000), p. 281. DOI: 10.1086/309512.

[52] T. Lasserre and EROS Collaboration. *Not enough stellar Mass Machos in the Galactic Halo*. 2000. arXiv: astro-ph/0002253.

[53] P. Tisserand et al. “Limits on the Macho content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds”. In: *Astronomy and Astrophysics* 469.2 (2007), p. 387. DOI: 10.1051/0004-6361:20066017.

[54] M. Fukugita, C. J. Hogan, and P. J. E. Peebles. “The Cosmic Baryon Budget”. In: *The Astrophysical Journal* 503.2 (1998), p. 518. DOI: 10.1086/306025.

[55] S. Burles, K. M. Nollett, and M. S. Turner. “Big Bang Nucleosynthesis Predictions for Precision Cosmology”. In: *The Astrophysical Journal* 552.1 (2001), p. L1. DOI: 10.1086/320251.

[56] B. J. Carr and S. W. Hawking. "Black Holes in the Early Universe". In: *Monthly Notices of the Royal Astronomical Society* 168.2 (1974), p. 399. DOI: 10.1093/mnras/168.2.399. eprint: https://academic.oup.com/mnras/article-pdf/168/2/399/8079885/mnras168-0399.pdf.

[57] P. J. E. Peebles. "Large-scale background temperature and mass fluctuations due to scale-invariant primeval perturbations". In: *The Astrophysical Journal* 263 (1982), p. L1. DOI: 10.1086/183911.

[58] J. R. Bond, A. S. Szalay, and M. S. Turner. "Formation of Galaxies in a Gravitino-Dominated Universe". In: *Physical Review Letters* 48.23 (1982), p. 1636. DOI: 10.1103/PhysRevLett.48.1636.

[59] S. D. M. White, C. S. Frenk, and M. Davis. "Clustering in a neutrino-dominated universe". In: *The Astrophysical Journal* 274 (1983), p. L1. DOI: 10.1086/184139.

[60] J. Zavala and C. S. Frenk. *Dark matter haloes and subhaloes*. 2019. arXiv: 1907.11775 [astro-ph.CO].

[61] I. de Martino et al. "Dark Matters on the Scale of Galaxies". In: *Universe* 6.8 (2020), p. 107. ISSN: 2218-1997. DOI: 10.3390/universe6080107.

[62] L. Perivolaropoulos and F. Skara. "Challenges for ΛCDM: An update". In: *New Astronomy Reviews* 95 (2022), p. 101659. DOI: 10.1016/j.newar.2022.101659.

[63] K. K. Rogers and H. V. Peiris. "Strong Bound on Canonical Ultralight Axion Dark Matter from the Lyman-Alpha Forest". In: *Physical Review Letters* 126.7 (2021). ISSN: 1079-7114. DOI: 10.1103/physrevlett.126.071302.

[64] N. Dalal and A. Kravtsov. *Not so fuzzy: excluding FDM with sizes and stellar kinematics of ultra-faint dwarf galaxies*. 2022. arXiv: 2203.05750 [astro-ph.CO].

[65] T. Zimmermann et al. *Dwarf galaxies imply dark matter is heavier than* 2.2×10^{-21} *eV*. 2024. arXiv: 2405.20374 [astro-ph.CO].

[66] J. Alvey et al. "New constraints on the mass of fermionic dark matter from dwarf spheroidal galaxies". In: *Monthly Notices of the Royal Astronomical Society* 501.1 (2020), p. 1188. ISSN: 1365-2966. DOI: 10.1093/mnras/staa3640.

[67] B. Carr and F. Kühnel. "Primordial Black Holes as Dark Matter: Recent Developments". In: *Annual Review of Nuclear and Particle Science* 70.1 (2020), p. 355. ISSN: 1545-4134. DOI: 10.1146/annurev-nucl-050520-125911.

[68] A. Escrivà, F. Kuhnel, and Y. Tada. *Primordial Black Holes*. 2022. arXiv: 2211.05767 [astro-ph.CO].

[69] S. Dodelson and L. M. Widrow. "Sterile neutrinos as dark matter". In: *Physical Review Letters* 72 (1 1994), p. 17. DOI: 10.1103/PhysRevLett.72.17.

[70] A. Boyarsky et al. "Sterile neutrino Dark Matter". In: *Progress in Particle and Nuclear Physics* 104 (2019), p. 1. ISSN: 0146-6410. DOI: 10.1016/j.ppnp.2018.07.004.

[71] B. Dasgupta and J. Kopp. "Sterile neutrinos". In: *Physics Reports* 928 (2021), p. 1. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2021.06.002.

[72] G. Bertone, D. Hooper, and J. Silk. "Particle dark matter: evidence, candidates and constraints". In: *Physics Reports* 405.5–6 (2005), p. 279. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2004.08.031.

[73] J. L. Feng. "Dark Matter Candidates from Particle Physics and Methods of Detection". In: *Annual Review of Astronomy and Astrophysics* 48.1 (2010), p. 495. ISSN: 1545-4282. DOI: 10.1146/annurev-astro-082708-101659.

[74] L. Roszkowski, E. Maria Sessolo, and S. Trojanowski. "WIMP dark matter candidates and searches—current status and future prospects". In: *Reports on Progress in Physics* 81.6 (2018), p. 066201. ISSN: 1361-6633. DOI: 10.1088/1361-6633/aab913.

[75] S. Dimopoulos and H. Georgi. "Softly broken supersymmetry and SU(5)". In: *Nuclear Physics B* 193.1 (1981), p. 150. ISSN: 0550-3213. DOI: https://doi.org/10.1016/0550-3213(81)90522-8.

[76] H. Pagels and J. R. Primack. "Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies". In: *Physical Review Letters* 48 (4 1982), p. 223. DOI: 10.1103/PhysRevLett.48.223.

[77] G. Jungman, M. Kamionkowski, and K. Griest. "Supersymmetric dark matter". In: *Physics Reports* 267.5 (1996), p. 195. DOI: https://doi.org/10.1016/0370-1573(95)00058-5.

[78] S. P. Martin. “A supersymmetry primer”. In: *Advanced Series on Directions in High Energy Physics*. World Scientific, 1998, p. 1. DOI: 10.1142/9789812839657_0001.

[79] H. E. Haber and L. S. Haskins. “Supersymmetric Theory and Models”. In: *Anticipating the Next Discoveries in Particle Physics*. WORLD SCIENTIFIC, 2018. DOI: 10.1142/9789813233348_0006.

[80] E. W. Kolb and M. S. Turner. *The Early Universe*. Vol. 69. 1990. ISBN: 978-0-201-62674-2. DOI: 10.1201/9780429492860.

[81] G. Bertone. “The moment of truth for WIMP dark matter”. In: *Nature* 468.7322 (2010), p. 389. ISSN: 1476-4687. DOI: 10.1038/nature09509.

[82] M. Escudero et al. “Toward (finally!) ruling out Z and Higgs mediated dark matter models”. In: *Journal of Cosmology and Astroparticle Physics* 2016.12 (2016), p. 029. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2016/12/029.

[83] G. Arcadi et al. “The waning of the WIMP? A review of models, searches, and constraints”. In: *The European Physical Journal C* 78.3 (2018). DOI: 10.1140/epjc/s10052-018-5662-y.

[84] G. Arcadi et al. *The Waning of the WIMP: Endgame?* 2024. arXiv: 2403.15860 [hep-ph].

[85] R. D. Peccei and H. R. Quinn. “CP Conservation in the Presence of Pseudoparticles”. In: *Physical Review Letters* 38 (25 1977), p. 1440. DOI: 10.1103/PhysRevLett.38.1440.

[86] R. D. Peccei and H. R. Quinn. “Constraints imposed by CP conservation in the presence of pseudoparticles”. In: *Physical Review D* 16 (6 1977), p. 1791. DOI: 10.1103/PhysRevD.16.1791.

[87] S. Weinberg. “A New Light Boson?” In: *Physical Review Letters* 40 (4 1978), p. 223. DOI: 10.1103/PhysRevLett.40.223.

[88] F. Wilczek. “Problem of Strong P and T Invariance in the Presence of Instantons”. In: *Physical Review Letters* 40 (5 1978), p. 279. DOI: 10.1103/PhysRevLett.40.279.

[89] J. Preskill, M. B. Wise, and F. Wilczek. “Cosmology of the invisible axion”. In: *Physics Letters B* 120.1 (1983), p. 127. DOI: https://doi.org/10.1016/0370-2693(83)90637-8.

[90] L. F. Abbott and P. Sikivie. "A Cosmological Bound on the Invisible Axion". In: *Physics Letters B* 120 (1983). Ed. by M.A. Srednicki, p. 133. DOI: 10.1016/0370-2693(83)90638-X.

[91] M. Dine and W. Fischler. "The Not So Harmless Axion". In: *Physics Letters B* 120 (1983). Ed. by M.A. Srednicki, p. 137. DOI: 10.1016/0370-2693(83)90639-1.

[92] S. Weinberg. "The U(1) problem". In: *Physical Review D* 11 (12 1975), p. 3583. DOI: 10.1103/PhysRevD.11.3583.

[93] Y. Nambu and G. Jona-Lasinio. "Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I". In: *Physical Reviews* 122 (1 1961), p. 345. DOI: 10.1103/PhysRev.122.345.

[94] Y. Nambu. "Quasi-Particles and Gauge Invariance in the Theory of Superconductivity". In: *Physical Reviews* 117 (3 1960), p. 648. DOI: 10.1103/PhysRev.117.648.

[95] Jeffrey Goldstone. "Field theories with Superconductor solutions". In: *Il Nuovo Cimento* 19 (1961), p. 154. URL: https://api.semanticscholar.org/CorpusID:120409034.

[96] A. A. Belavin et al. "Pseudoparticle solutions of the Yang-Mills equations". In: *Physics Letters B* 59.1 (1975), p. 85. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(75)90163-X.

[97] R. Jackiw and C. Rebbi. "Vacuum Periodicity in a Yang-Mills Quantum Theory". In: *Physical Review Letters* 37 (3 1976), p. 172. DOI: 10.1103/PhysRevLett.37.172.

[98] C. G. Callan, R. F. Dashen, and D. J. Gross. "The structure of the gauge theory vacuum". In: *Physics Letters B* 63.3 (1976), p. 334. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(76)90277-X.

[99] S. L. Adler. "Axial-Vector Vertex in Spinor Electrodynamics". In: *Physical Reviews* 177 (5 1969), p. 2426. DOI: 10.1103/PhysRev.177.2426.

[100] J. S. Bell and R. Jackiw. "A PCAC puzzle: $\pi^0 \to \gamma\gamma$ in the σ model". In: *Il Nuovo Cimento A* 60 (1969), p. 47. DOI: 10.1007/BF02823296.

[101] W. A. Bardeen. "Anomalous Ward Identities in Spinor Field Theories". In: *Physical Reviews* 184 (5 1969), p. 1848. DOI: 10.1103/PhysRev.184.1848.

[102] G. 't Hooft. "Symmetry Breaking through Bell-Jackiw Anomalies". In: *Physical Review Letters* 37 (1 1976), p. 8. DOI: 10.1103/PhysRevLett.37.8.

[103] G. 't Hooft. "How Instantons Solve the U(1) Problem". In: *Physics Reports* 142 (1986), p. 357. DOI: 10.1016/0370-1573(86)90117-1.

[104] M. E. Peskin and Schroeder D. V. *An introduction to quantum field theory*. CRC press, 1995.

[105] M. Pospelov and A. Ritz. "Theta vacua, QCD sum rules, and the neutron electric dipole moment". In: *Nuclear Physics B* 573.1 (2000), p. 177. DOI: 10.1016/s0550-3213(99)00817-2.

[106] C. Abel et al. "Measurement of the Permanent Electric Dipole Moment of the Neutron". In: *Physical Review Letters* 124 (8 2020), p. 081803. DOI: 10.1103/PhysRevLett.124.081803.

[107] M. Dine et al. "Some remarks on anthropic approaches to the strong CP problem". In: *Journal of High Energy Physics* 2018.5 (2018). DOI: 10.1007/jhep05(2018)171.

[108] A. E. Nelson. "Naturally Weak CP Violation". In: *Physics Letters B* 136 (1984), p. 387. DOI: 10.1016/0370-2693(84)92025-2.

[109] S. M. Barr. "Solving the Strong CP Problem without the Peccei-Quinn Symmetry". In: *Physical Review Letters* 53 (4 1984), p. 329. DOI: 10.1103/PhysRevLett.53.329.

[110] D. R. Nelson, G. T. Fleming, and G. W. Kilcup. "Is strong CP due to a massless up quark?" In: *Physical Review Letters* 90 (2003), p. 021601. DOI: 10.1103/PhysRevLett.90.021601.

[111] C. Alexandrou et al. "Ruling Out the Massless Up-Quark Solution to the Strong CP Problem by Computing the Topological Mass Contribution with Lattice QCD". In: *Physical Review Letters* 125.23 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.125.232001.

[112] P. Vecchia and G. Veneziano. "Chiral dynamics in the large N limit". In: *Nuclear Physics B* 171 (Oct. 1980), p. 253. DOI: 10.1016/0550-3213(80)90370-3.

[113] G. G. di Cortona et al. "The QCD axion, precisely". In: *Journal of High Energy Physics* 2016.1 (2016). DOI: 10.1007/jhep01(2016)034.

[114] C. Vafa and E. Witten. “Parity Conservation in Quantum Chromodynamics”. In: *Physical Review Letters* 53 (6 1984), p. 535. DOI: 10.1103/PhysRevLett.53.535.

[115] T. W. Donnelly et al. “Do axions exist?” In: *Physical Review D* 18 (5 1978), p. 1607. DOI: 10.1103/PhysRevD.18.1607.

[116] A. Zehnder. “Axion search in a monochromatic γ-transition: A new lower limit for the axion mass”. In: *Physics Letters B* 104.6 (1981), p. 494. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(81)90522-0.

[117] W. A. Bardeen, R. D. Peccei, and T. Yanagida. “Constraints on variant axion models”. In: *Nuclear Physics B* 279.3 (1987), p. 401. ISSN: 0550-3213. DOI: https://doi.org/10.1016/0550-3213(87)90003-4.

[118] J. E. Kim. “Weak-Interaction Singlet and Strong CP Invariance”. In: *Physical Review Letters* 43 (2 1979), p. 103. DOI: 10.1103/PhysRevLett.43.103.

[119] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov. “Can confinement ensure natural CP invariance of strong interactions?” In: *Nuclear Physics B* 166.3 (1980), p. 493. DOI: 10.1016/0550-3213(80)90209-6.

[120] M. Dine, W. Fischler, and M. Srednicki. “A simple solution to the strong CP problem with a harmless axion”. In: *Physics Letters B* 104.3 (1981), p. 199. DOI: 10.1016/0370-2693(81)90590-6.

[121] A. R. Zhitnitsky. “On Possible Suppression of the Axion Hadron Interactions”. In: *Soviet Journal of Nuclear Physics* 31 (1980), p. 260.

[122] R. L. Davis. “Cosmic axions from cosmic strings”. In: *Physics Letters B* 180.3 (1986), p. 225. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(86)90300-X.

[123] D. H. Lyth. “Estimates of the cosmological axion density”. In: *Physics Letters B* 275.3 (1992), p. 279. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(92)91590-6.

[124] M. S. Turner. “Early-Universe Thermal Production of Not-So-Invisible Axions”. In: *Physical Review Letters* 59 (21 1987), p. 2489. DOI: 10.1103/PhysRevLett.59.2489.

[125] E. Massó, F. Rota, and G. Zsembinszki. "Axion thermalization in the early universe". In: *Physical Review D* 66.2 (2002). ISSN: 1089-4918. DOI: 10.1103/physrevd.66.023004.

[126] A. Salvio, A. Strumia, and W. Xue. "Thermal axion production". In: *Journal of Cosmology and Astroparticle Physics* 2014 (2014), p. 011. DOI: 10.1088/1475-7516/2014/01/011.

[127] P. Carenza et al. "Thermal axions with multi-eV masses are possible in low-reheating scenarios". In: *Journal of Cosmology and Astroparticle Physics* 07 (2021), p. 031. DOI: 10.1088/1475-7516/2021/07/031.

[128] T. W. B. Kibble. "Topology of cosmic domains and strings". In: *Journal of Physics A: Mathematical and General* 9.8 (1976), p. 1387. DOI: 10.1088/0305-4470/9/8/029.

[129] T. W. B. Kibble, G. Lazarides, and Q. Shafi. "Walls bounded by strings". In: *Physical Review D* 26 (2 1982), p. 435. DOI: 10.1103/PhysRevD.26.435.

[130] James Alvey. "How do you see in the dark?" PhD thesis. King's Coll. London, 2021.

[131] T. Hiramatsu et al. "Improved estimation of radiated axions from cosmological axionic strings". In: *Physical Review D* 83 (12 2011), p. 123531. DOI: 10.1103/PhysRevD.83.123531.

[132] M. Kawasaki, K. Saikawa, and T. Sekiguchi. "Axion dark matter from topological defects". In: *Physical Review D* 91.6 (2015). ISSN: 1550-2368. DOI: 10.1103/physrevd.91.065014.

[133] V. B. Klaer and G. D. Moore. "How to simulate global cosmic strings with large string tension". In: *Journal of Cosmology and Astroparticle Physics* 2017.10 (2017), p. 043. DOI: 10.1088/1475-7516/2017/10/043.

[134] V. B. Klaer and G. D. Moore. "The dark-matter axion mass". In: *Journal of Cosmology and Astroparticle Physics* 2017.11 (2017), p. 049. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2017/11/049.

[135] M. Gorghetto, E. Hardy, and G. Villadoro. "Axions from strings: the attractive solution". In: *Journal of High Energy Physics* 2018.7 (2018). ISSN: 1029-8479. DOI: 10.1007/jhep07(2018)151.

[136] M. Buschmann, J. W. Foster, and B. R. Safdi. "Early-Universe Simulations of the Cosmological Axion". In: *Physical Review Letters* 124.16 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.124.161103.

[137] S. Hoof et al. "Axion global fits with Peccei-Quinn symmetry breaking before inflation using GAMBIT". In: *Journal of High Energy Physics* 2019.3 (2019). ISSN: 1029-8479. DOI: 10.1007/jhep03(2019)191.

[138] M. Tegmark et al. "Dimensionless constants, cosmology, and other dark matters". In: *Physical Review D* 73.2 (2006). ISSN: 1550-2368. DOI: 10.1103/physrevd.73.023505.

[139] P. W. Graham and A. Scherlis. "Stochastic axion scenario". In: *Physical Review D* 98.3 (2018). ISSN: 2470-0029. DOI: 10.1103/physrevd.98.035017.

[140] F. Takahashi, W. Yin, and A. H. Guth. "QCD axion window and low-scale inflation". In: *Physical Review D* 98.1 (2018). ISSN: 2470-0029. DOI: 10.1103/physrevd.98.015042.

[141] R. T. Co and K. Harigaya. "Axiogenesis". In: *Physical Review Letters* 124 (11 2020), p. 111602. DOI: 10.1103/PhysRevLett.124.111602.

[142] A. D. Sakharov. "Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe". In: *Pisma v Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki* 5 (1967), p. 32.

[143] P. Svrcek and E. Witten. "Axions in string theory". In: *Journal of High Energy Physics* 2006.06 (2006), p. 051. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2006/06/051.

[144] A. Arvanitaki et al. "String axiverse". In: *Physical Review D* 81.12 (2010). ISSN: 1550-2368. DOI: 10.1103/physrevd.81.123530.

[145] Andreas Ringwald. "Searching for axions and ALPs from string theory". In: *Journal of Physics: Conference Series* 485 (2014), p. 012013. ISSN: 1742-6596. DOI: 10.1088/1742-6596/485/1/012013.

[146] V. A. Rubakov. "Grand unification and heavy axion". In: *JETP Letters* 65 (1997), p. 621. DOI: 10.1134/1.567390.

[147] A. Ernst et al. "Axion properties in GUTs". In: *Proceedings of Science* CORFU2018 (2019). Ed. by K. Anagnostopoulos et al., p. 054. DOI: 10.22323/1.347.0054.

[148] P. Agrawal, M. Nee, and M. Reig. “Axion couplings in grand unified theories”. In: *Journal of High Energy Physics* 10 (2022), p. 141. DOI: 10.1007/JHEP10(2022)141.

[149] E. Massó and R. Toldrà. “Light spinless particle coupled to photons”. In: *Physical Review D* 52.4 (1995), p. 1755. ISSN: 0556-2821. DOI: 10.1103/physrevd.52.1755.

[150] E. Massó. “Axions and axion-like particles”. In: *Nuclear Physics B - Proceedings Supplements* 114 (2003), p. 67. ISSN: 0920-5632. DOI: 10.1016/s0920-5632(02)01893-5.

[151] J. N. Benabou et al. *The Cosmological Dynamics of String Theory Axion Strings*. 2023. arXiv: 2312.08425 [hep-ph].

[152] P. Sikivie. “Experimental Tests of the "Invisible" Axion”. In: *Physical Review Letters* 51 (16 1983), p. 1415. DOI: 10.1103/PhysRevLett.51.1415.

[153] A. Caputo et al. “Detecting the stimulated decay of axions at radio frequencies”. In: *Journal of Cosmology and Astroparticle Physics* 2019.03 (2019), p. 27. DOI: 10.1088/1475-7516/2019/03/027.

[154] Ciaran O’Hare. *cajohare/AxionLimits: AxionLimits*. https://cajohare.github.io/AxionLimits/. Version v1.0. 2020. DOI: 10.5281/zenodo.3932430.

[155] BELLE II Collaboration. “Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II”. In: *Physical Review Letters* 125.16 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.125.161806.

[156] S. Knapen, S. Kumar, and D. Redigolo. “Searching for axionlike particles with data scouting at ATLAS and CMS”. In: *Physical Review D* 105.11 (2022). ISSN: 2470-0029. DOI: 10.1103/physrevd.105.115012.

[157] BESIII Collaboration. “Search for an axion-like particle in radiative J/Ψ decays”. In: *Physics Letters B* 838 (2023), p. 137698. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2023.137698.

[158] ATLAS Collaboration. “Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS”. In: *Journal of High Energy Physics* 2023.7 (2023). ISSN: 1029-8479. DOI: 10.1007/jhep07(2023)234.

[159] W. Hu, R. Barkana, and A. Gruzinov. “Fuzzy Cold Dark Matter: The Wave Properties of Ultralight Particles”. In: *Physical Review Letters* 85 (6 2000), p. 1158. DOI: 10.1103/PhysRevLett.85.1158.

[160] ADMX Collaboration. “Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment”. In: *Physical Review Letters* 120.15 (2018). ISSN: 1079-7114. DOI: 10.1103/physrevlett.120.151301.

[161] ADMX Collaboration. “Extended Search for the Invisible Axion with the Axion Dark Matter Experiment”. In: *Physical Review Letters* 124.10 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.124.101303.

[162] ADMX Collaboration. “Search for Invisible Axion Dark Matter in the $3.3 - 4.2\,\mu$eV Mass Range”. In: *Physical Review Letters* 127.26 (2021). ISSN: 1079-7114. DOI: 10.1103/physrevlett.127.261803.

[163] J. Choi et al. “CAPP-8TB: Axion dark matter search experiment around $6.7\,\mu$eV”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1013 (2021), p. 165667. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2021.165667.

[164] HAYSTAC Collaboration. “First Results from a Microwave Cavity Axion Search at 24 μeV”. In: *Physical Review Letters* 118 (6 2017), p. 061302. DOI: 10.1103/PhysRevLett.118.061302.

[165] HAYSTAC Collaboration. “Results from phase 1 of the HAYSTAC microwave cavity axion experiment”. In: *Physical Review D* 97.9 (2018). ISSN: 2470-0029. DOI: 10.1103/physrevd.97.092001.

[166] HAYSTAC Collaboration. “A quantum enhanced search for dark matter axions”. In: *Nature* 590.7845 (2021), p. 238. DOI: 10.1038/s41586-021-03226-7.

[167] B. T. McAllister et al. “The ORGAN experiment: An axion haloscope above 15 GHz”. In: *Physics of the Dark Universe* 18 (2017), p. 67. ISSN: 2212-6864. DOI: 10.1016/j.dark.2017.09.010.

[168] MADMAX Collaboration. “Dielectric Haloscopes: A New Way to Detect Axion Dark Matter”. In: *Physical Review Letters* 118.9 (2017). ISSN: 1079-7114. DOI: 10.1103/physrevlett.118.091801.

[169] R. Barbieri et al. "Searching for galactic axions through magnetized media: The QUAX proposal". In: *Physics of the Dark Universe* 15 (2017), p. 135. ISSN: 2212-6864. DOI: https://doi.org/10.1016/j.dark.2017.01.003.

[170] QUAX Collaboration. "Axion Search with a Quantum-Limited Ferromagnetic Haloscope". In: *Physical Review Letters* 124.17 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.124.171801.

[171] CAST Collaboration. "Probing eV-scale axions with CAST". In: *Journal of Cosmology and Astroparticle Physics* 2009.02 (2009), p. 008. DOI: 10.1088/1475-7516/2009/02/008.

[172] CAST Collaboration. "New CAST limit on the axion–photon interaction". In: *Nature Physics* 13.6 (2017), p. 584. ISSN: 1745-2481. DOI: 10.1038/nphys4109.

[173] K. Van Bibber et al. "Proposed experiment to produce and detect light pseudoscalars". In: *Physical Review Letters* 59 (7 1987), p. 759. DOI: 10.1103/PhysRevLett.59.759.

[174] ALPS Collaboration. "New ALPS results on hidden-sector lightweights". In: *Physics Letters B* 689.4 (2010), p. 149. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2010.04.066.

[175] OSQAR Collaboration. "Results from the OSQAR photon-regeneration experiment: No light shining through a wall". In: *Physical Review D* 78.9 (2008). ISSN: 1550-2368. DOI: 10.1103/physrevd.78.092003.

[176] Y. Kahn, B. R. Safdi, and J. Thaler. "Broadband and Resonant Approaches to Axion Dark Matter Detection". In: *Physical Review Letters* 117 (14 2016), p. 141801. DOI: 10.1103/PhysRevLett.117.141801.

[177] ABRACADABRA Collaboration. "First Results from ABRACADABRA-10 cm: A Search for Sub-μeV Axion Dark Matter". In: *Physical Review Letters* 122.12 (2019). ISSN: 1079-7114. DOI: 10.1103/physrevlett.122.121802.

[178] A. V. Gramolin et al. "Search for axion-like dark matter with ferromagnets". In: *Nature Physics* 17.1 (2020), p. 79. ISSN: 1745-2481. DOI: 10.1038/s41567-020-1006-6.

[179] F. Della Valle et al. *New PVLAS model independent limit for the axion coupling to $\gamma\gamma$ for axion masses above 1meV*. 2014. arXiv: 1410.4081 [hep-ex].

[180] M. Buschmann et al. "Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling". In: *Physical Review Letters* 128 (9 2022), p. 091102. DOI: 10.1103/PhysRevLett.128.091102.

[181] G. Raffelt and A. Caputo. "Astrophysical Axion Bounds: The 2024 Edition". In: *Proceedings of 1st General Meeting and 1st Training School of the COST Action COSMIC WSIPers — PoS(COSMICWISPers)*. Sissa Medialab, 2024. DOI: 10.22323/1.454.0041.

[182] F. Özel and P. Freire. "Masses, Radii, and the Equation of State of Neutron Stars". In: *Annual Review of Astronomy and Astrophysics* 54.1 (2016), p. 401. ISSN: 1545-4282. DOI: 10.1146/annurev-astro-081915-023322.

[183] D. E. Morris. "Axion mass limits may be improved by pulsar x-ray measurements". In: *Physical Review D* 34 (3 1986), p. 843. DOI: 10.1103/PhysRevD.34.843.

[184] P. Goldreich and W. H. Julian. "Pulsar Electrodynamics". In: *The Astrophysical Journal* 157 (1969), p. 869. DOI: 10.1086/150119.

[185] MAGIC Collaboration. "Observation of Pulsed gamma-Rays Above 25 GeV from the Crab Pulsar with MAGIC". In: *Science* 322 (2008), p. 1221.

[186] P. A. Sturrock. "A Model of Pulsars". In: *The Astrophysical Journal* 164 (1971), p. 529. DOI: 10.1086/150865.

[187] M. A. Ruderman and P. G. Sutherland. "Theory of pulsars: polar gaps, sparks, and coherent microwave radiation." In: *The Astrophysical Journal* 196 (1975), p. 51. DOI: 10.1086/153393.

[188] A. N. Timokhin and J. Arons. "Current flow and pair creation at low altitude in rotation-powered pulsars' force-free magnetospheres: space charge limited flow". In: *Monthly Notices of the Royal Astronomical Society* 429.1 (2012), p. 20. ISSN: 1365-2966. DOI: 10.1093/mnras/sts298.

[189] A. Philippov, A. Timokhin, and A. Spitkovsky. "Origin of Pulsar Radio Emission". In: *Physical Review Letters* 124.24 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.124.245101.

[190] F. Cruz, T. Grismayer, and L. O. Silva. "Kinetic Model of Large-amplitude Oscillations in Neutron Star Pair Cascades". In: *The Astrophysical Journal* 908.2 (2021), p. 149. ISSN: 1538-4357. DOI: 10.3847/1538-4357/abd2c0.

[191] F. Cruz et al. "Coherent Emission from QED Cascades in Pulsar Polar Caps". In: *The Astrophysical Journal Letters* 919.1 (2021), p. L4. ISSN: 2041-8213. DOI: 10.3847/2041-8213/ac2157.

[192] A. Bransgrove, A. M. Beloborodov, and Y. Levin. "Radio Emission and Electric Gaps in Pulsar Magnetospheres". In: *The Astrophysical Journal Letters* 958 (2023), p. L9. ISSN: 2041-8213. DOI: 10.3847/2041-8213/ad0556.

[193] H. Primakoff. "Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson". In: *Physical Reviews* 81 (5 1951), p. 899. DOI: 10.1103/PhysRev.81.899.

[194] B. Pontecorvo. "Mesonium and anti-mesonium". In: *Soviet Phyics - JETP* 6 (1957), p. 429.

[195] G. Raffelt and L. Stodolsky. "Mixing of the photon with low-mass particles". In: *Physical Review D* 37 (5 1988), p. 1237. DOI: 10.1103/PhysRevD.37.1237.

[196] D. G. Swanson. *Plasma Waves, 2nd Edition*. Series in Plasma Physics. Taylor & Francis, 2003. ISBN: 9780750309271.

[197] M. S. Pshirkov and S. B. Popov. "Conversion of dark matter axions to photons in magnetospheres of neutron stars". In: *Journal of Experimental and Theoretical Physics* 108.3 (2009), p. 384. ISSN: 1090-6509. DOI: 10.1134/s1063776109030030.

[198] F. P. Huang et al. "Radio telescope search for the resonant conversion of cold dark matter axions from the magnetized astrophysical sources". In: *Physical Review D* 97.12 (2018). ISSN: 2470-0029. DOI: 10.1103/physrevd.97.123001.

[199] A. Hook et al. "Radio Signals from Axion Dark Matter Conversion in Neutron Star Magnetospheres". In: *Physical Review Letters* 121.24 (2018). ISSN: 1079-7114. DOI: 10.1103/physrevlett.121.241102.

[200] B. R. Safdi, Z. Sun, and A. Y. Chen. "Detecting axion dark matter with radio lines from neutron star populations". In: *Physical Review D* 99.12 (2019). ISSN: 2470-0029. DOI: 10.1103/physrevd.99.123021.

[201] M. Leroy et al. "Radio signal of axion-photon conversion in neutron stars: A ray tracing analysis". In: *Physical Review D* 101.12 (2020). ISSN: 2470-0029. DOI: 10.1103/physrevd.101.123003.

[202] R. A. Battye et al. "Dark matter axion detection in the radio/mm waveband". In: *Physical Review D* 102.2 (2020). ISSN: 2470-0029. DOI: 10.1103/physrevd.102.023504.

[203] J. W. Foster et al. "Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres". In: *Physical Review Letters* 125.17 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.125.171301.

[204] R. A. Battye et al. "Radio line properties of axion dark matter conversion in neutron stars". In: *Journal of High Energy Physics* 2021.9 (2021). ISSN: 1029-8479. DOI: 10.1007/jhep09(2021)105.

[205] S. J. Witte et al. "Axion-photon conversion in neutron star magnetospheres: The role of the plasma in the Goldreich-Julian model". In: *Physical Review D* 104.10 (2021). ISSN: 2470-0029. DOI: 10.1103/physrevd.104.103030.

[206] R. A. Battye et al. "Towards robust constraints on axion dark matter using PSR J1745-2900". In: *Physical Review D* 105.2 (2022). ISSN: 2470-0029. DOI: 10.1103/physrevd.105.l021305.

[207] Y. Zhou et al. "Searching for axion dark matter with the MeerKAT radio telescope". In: *Physical Review D* 106.8 (2022). ISSN: 2470-0029. DOI: 10.1103/physrevd.106.083006.

[208] R. A. Battye et al. "Searching for time-dependent axion dark matter signals in pulsars". In: *Physical Review D* 108.6 (2023). ISSN: 2470-0029. DOI: 10.1103/physrevd.108.063001.

[209] J. W. Foster et al. “Extraterrestrial Axion Search with the Breakthrough Listen Galactic Center Survey”. In: *Physical Review Letters* 129.25 (2022). ISSN: 1079-7114. DOI: 10.1103/physrevlett.129.251102.

[210] J. I. McDonald and S. J. Witte. *Generalized Ray Tracing for Axions in Astrophysical Plasmas*. 2023. arXiv: 2309.08655 [hep-ph].

[211] J. Tjemsland, J. I. McDonald, and S. J. Witte. *Adiabatic Axion-Photon Mixing Near Neutron Stars*. 2024. arXiv: 2310.18403 [hep-ph].

[212] S. J. Witte et al. “Transient radio lines from axion miniclusters and axion stars”. In: *Physical Review D* 107.6 (2023). ISSN: 2470-0029. DOI: 10.1103/physrevd.107.063013.

[213] A. Prabhu. “Axion production in pulsar magnetosphere gaps”. In: *Physical Review D* 104.5 (2021). ISSN: 2470-0029. DOI: 10.1103/physrevd.104.055038.

[214] Z. H. Xue et al. “Identifying axion conversion in compact star magnetospheres with radio-wave polarization signatures”. In: *Physical Review D* 108.8 (2023), p. 083009. DOI: 10.1103/PhysRevD.108.083009.

[215] G. Sigl. “Astrophysical haloscopes”. In: *Physical Review D* 96.10 (2017). ISSN: 2470-0029. DOI: 10.1103/physrevd.96.103014.

[216] A. Caputo, C. P Garay, and S. J. Witte. “Looking for Axion Dark Matter in Dwarf Spheroidals”. In: *Physical Review D* 98.8 (2018), p. 083024. DOI: 10.1103/PhysRevD.98.083024.

[217] O. Ghosh, J. Salvado, and J. Miralda-Escudé. *Axion Gegenschein: Probing Back-scattering of Astrophysical Radio Sources Induced by Dark Matter*. 2020. arXiv: 2008.02729 [astro-ph.CO].

[218] T. D. P. Edwards et al. “Unique Multimessenger Signal of QCD Axion Dark Matter”. In: *Physical Review Letters* 124.16 (2020). ISSN: 1079-7114. DOI: 10.1103/physrevlett.124.161101.

[219] J. H. Buckley et al. “Fast radio bursts from axion stars moving through pulsar magnetospheres”. In: *Physical Review D* 103.4 (2021). ISSN: 2470-0029. DOI: 10.1103/physrevd.103.043015.

[220] T. D. P. Edwards et al. “Transient Radio Signatures from Neutron Star Encounters with QCD Axion Miniclusters”. In: *Physical Review Letters* 127.13 (2021), p. 131103. DOI: 10.1103/PhysRevLett.127.131103.

[221] S. Nurmi, E. D. Schiappacasse, and T. T. Yanagida. "Radio signatures from encounters between neutron stars and QCD-axion minihalos around primordial black holes". In: *Journal of Cosmology and Astroparticle Physics* 2021.09 (2021), p. 004. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2021/09/004.

[222] M. Kramer et al. "A Periodically Active Pulsar Giving Insight into Magnetospheric Physics". In: *Science* 312.5773 (2006), p. 549. ISSN: 1095-9203. DOI: 10.1126/science.1124060.

[223] T. M. Tauris et al. *Understanding the Neutron Star Population with the SKA*. 2014. arXiv: 1501.00005 [astro-ph.HE].

[224] E. F. Keane et al. "A Cosmic Census of Radio Pulsars with the SKA". In: *Proceedings of Science* AASKA14 (2015). Ed. by T. L. Bourke et al., p. 040. DOI: 10.22323/1.215.0040.

[225] A. Karastergiou et al. "Understanding pulsar magnetospheres with the SKA". In: *Proceedings of Science* AASKA14 (2015). Ed. by T. L. Bourke et al., p. 038. DOI: 10.22323/1.215.0038.

[226] J. Antoniadis et al. *Multi-wavelength, Multi-Messenger Pulsar Science in the SKA Era*. 2015. arXiv: 1501.05591 [astro-ph.HE].

[227] S. Konar et al. "Neutron Star Physics in the Square Kilometre Array Era: An Indian Perspective". In: *Journal of Astrophysics and Astronomy* 37.4 (2016). ISSN: 0973-7758. DOI: 10.1007/s12036-016-9409-6.

[228] A. A. Philippov, A. Spitkovsky, and B. Cerutti. "Ab initio pulsar magnetosphere: three-dimensional particle-in-cell simulations of oblique pulsars". In: *The Astrophysical Journal* 801.1 (2015), p. L19. ISSN: 2041-8213. DOI: 10.1088/2041-8205/801/1/l19.

[229] B. Cerutti and A. M Beloborodov. "Electrodynamics of pulsar magnetospheres". In: *Space Science Reviews* 207.1 (2017), p. 111.

[230] A. Y. Chen and A. M. Beloborodov. "Particle-in-Cell Simulations of the Twisted Magnetospheres of Magnetars". In: *The Astrophysical Journal* 844.2 (2017), p. 133. ISSN: 1538-4357. DOI: 10.3847/1538-4357/aa7a57.

[231] G. Brambilla et al. "Electron-positron pair flow and current composition in the pulsar magnetosphere". In: *The Astrophysical Journal* 858.2 (2018), p. 81.

[232] F. Carrasco and M. Shibata. "Magnetosphere of an orbiting neutron star". In: *Physical Review D* 101.6 (2020). ISSN: 2470-0029. DOI: 10.1103/physrevd.101.063017.

[233] A. Y. Chen, F. Cruz, and A. Spitkovsky. "Filling the Magnetospheres of Weak Pulsars". In: *The Astrophysical Journal* 889.1 (2020), p. 69. ISSN: 1538-4357. DOI: 10.3847/1538-4357/ab5c20.

[234] M. Gedalin, D. B. Melrose, and E. Gruman. "Long waves in a relativistic pair plasma in a strong magnetic field". In: *Physical Review E* 57 (3 1998), p. 3399. DOI: 10.1103/PhysRevE.57.3399.

[235] C. M Bender and S. A Orszag. *Advanced mathematical methods for scientists and engineers I: Asymptotic methods and perturbation theory.* Springer Science & Business Media, 2013. DOI: https://doi.org/10.1007/978-1-4757-3069-2.

[236] V. Fuchs, K. Ko, and A. Bers. "Theory of mode-conversion in weakly inhomogeneous plasma". In: *The Physics of Fluids* 24.7 (1981), p. 1251.

[237] D. G Swanson. "Radio frequency heating in the ion-cyclotron range of frequencies". In: *The Physics of fluids* 28.9 (1985), p. 2645.

[238] R. D. Blandford and E .T. Scharlemann. "On the scattering and absorption of electromagnetic radiation within pulsar magnetospheres". In: *Monthly Notices of the Royal Astronomical Society* 174.1 (1976), p. 59.

[239] D. B. Melrose. "Propagation effects on the polarization of pulsar radio emission". In: *Australian Journal of Physics* 32.2 (1979), p. 61.

[240] Q. Luo and D. B. Melrose. "Cyclotron absorption of radio emission within pulsar magnetospheres". In: *Monthly Notices of the Royal Astronomical Society* 325.1 (2001), p. 187.

[241] J. Revels, M. Lubin, and T. Papamarkou. *Forward-Mode Automatic Differentiation in Julia*. 2016. arXiv: 1607.07892 [cs.MS].

[242] D. G. Ravenhall and C. J. Pethick. "Neutron Star Moments of Inertia". In: *The Astrophysical Journal* 424 (1994), p. 846. DOI: 10.1086/173935.

[243] J. I. McDonald, B. Garbrecht, and P. Millington. "Axion-photon conversion in 3D media and astrophysical plasmas". In: *Journal of Cosmology and Astroparticle Physics* 2023.12 (2023), p. 031. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2023/12/031.

[244] J. A. Detwiler et al. "A Generic Surface Sampler for Monte Carlo Simulations". In: *IEEE Transactions on Nuclear Science* 55 (2008), p. 2329. DOI: 10.1109/TNS.2008.2001063.

[245] R. Dewey et al. "The Period Distribution of Pulsars". In: *Birth and Evolution of Neutron Stars: Issues Raised by Millisecond Pulsars*. Ed. by S. P. Reynolds and D. R. Stinebring. 1984, p. 234.

[246] J. A. Kennea et al. "Swift Discovery of a New Soft Gamma Repeater, SGR J1745-29, near Sagittarius A*". In: *The Astrophysical Journal* 770.2 (2013), p. L24. ISSN: 2041-8213. DOI: 10.1088/2041-8205/770/2/l24.

[247] K. Mori et al. "NuSTAR discovery of a 3.76-second transient magnetar near Sagittarius A*". In: *The Astrophysical Journal Letters* 770 (2013), p. L23. DOI: 10.1088/2041-8205/770/2/L23.

[248] R. M. Shannon and S. Johnston. "Radio properties of the magnetar near Sagittarius A* from observations with the Australia Telescope Compact Array". In: *Monthly Notices of the Royal Astronomical Society: Letters* 435.1 (2013), p. L29. ISSN: 1745-3925. DOI: 10.1093/mnrasl/slt088.

[249] R. P. Eatough et al. "A strong magnetic field around the supermassive black hole at the centre of the Galaxy". In: *Nature* 501 (2013), p. 391. DOI: 10.1038/nature12499.

[250] *SKA System Baseline Design*. https://www.skatelescope.org/key-documents/. Accessed: 2021-03-18.

[251] L. Di Luzio, F. Mescia, and E. Nardi. "Redefining the Axion Window". In: *Physical Review Letters* 118.3 (2017), p. 031801. DOI: 10.1103/PhysRevLett.118.031801.

[252] J. F Navarro. "The structure of cold dark matter halos". In: *Symposium-international astronomical union*. Vol. 171. Cambridge University Press. 1996, p. 255.

[253] F. Nesti and P. Salucci. "The Dark Matter halo of the Milky Way, AD 2013". In: *Journal of Cosmology and Astroparticle Physics* 07 (2013), p. 016. DOI: 10.1088/1475-7516/2013/07/016.

[254] T. Lacroix. "Dynamical constraints on a dark matter spike at the Galactic centre from stellar orbits". In: *Astronomy and Astrophysics* 619 (2018), A46.

[255] J. Darling. "Search for Axionic Dark Matter Using the Magnetar PSR J1745-2900". In: *Physical Review Letters* 125.12 (2020), p. 121103. DOI: 10.1103/PhysRevLett.125.121103.

[256] J. Darling. "New Limits on Axionic Dark Matter from the Magnetar PSR J1745-2900". In: *The Astrophysical Journal Letters* 900.2 (2020), p. L28. DOI: 10.3847/2041-8213/abb23f.

[257] M. Gedalin. "Nonlinear waves in hot magnetized plasma". In: *Physics of plasmas* 1.5 (1994), p. 1159.

[258] M. Lyutikov. "Waves in a one-dimensional magnetized relativistic pair plasma". In: *Monthly Notices of the Royal Astronomical Society* 293.4 (1998), p. 447.

[259] M. Gedalin, E. Gruman, and D. B. Melrose. "Low-frequency waves in asymmetric magnetized relativistic pair plasma". In: *Monthly Notices of the Royal Astronomical Society* 325.2 (2001), p. 715.

[260] J. Arons and J. J Barnard. "Wave propagation in pulsar magnetospheres – Dispersion relations and normal modes of plasmas in superstrong magnetic fields". In: *The Astrophysical Journal* 302 (1986), p. 120.

[261] D. Noordhuis et al. "Novel Constraints on Axions Produced in Pulsar Polar-Cap Cascades". In: *Physical Review Letters* 131.11 (2023), p. 111004. DOI: 10.1103/PhysRevLett.131.111004.

[262] B. Garbrecht and J. I. McDonald. "Axion configurations around pulsars". In: *Journal of Cosmology and Astroparticle Physics* 07 (2018), p. 044. DOI: 10.1088/1475-7516/2018/07/044.

[263] J. Chiang and R. W. Romani. "Gamma Radiation from Pulsar Magnetospheric Gaps". In: *The Astrophysical Journal* 400 (1992), p. 629. DOI: 10.1086/172024.

[264] J. Arons. "Pair creation above pulsar polar caps: geometrical structure and energetics of slot gaps." In: *The Astrophysical Journal* 266 (1983), p. 215. DOI: 10.1086/160771.

[265] K. S. Cheng, C. Ho, and M. Ruderman. "Energetic Radiation from Rapidly Spinning Pulsars. I. Outer Magnetosphere Gaps". In: *The Astrophysical Journal* 300 (1986), p. 500. DOI: 10.1086/163829.

[266] R. Hu and A. M. Beloborodov. "Axisymmetric Pulsar Magnetosphere Revisited". In: *The Astrophysical Journal* 939.1 (2022), p. 42. ISSN: 1538-4357. DOI: 10.3847/1538-4357/ac961d.

[267] A. Levinson et al. "Large-Amplitude, Pair-creating Oscillations in Pulsar and Black Hole Magnetospheres". In: *The Astrophysical Journal* 631.1 (2005), p. 456. ISSN: 1538-4357. DOI: 10.1086/432498.

[268] A. N. Timokhin and A. K. Harding. "On the polar cap cascade pair multiplicity of young pulsars". In: *The Astrophysical Journal* 810.2 (2015), p. 144. ISSN: 1538-4357. DOI: 10.1088/0004-637x/810/2/144.

[269] E. A. Tolman, A. A. Philippov, and A. N. Timokhin. "Electric Field Screening in Pair Discharges and Generation of Pulsar Radio Emission". In: *The Astrophysical Journal Letters* 933.2 (2022), p. L37. ISSN: 2041-8213. DOI: 10.3847/2041-8213/ac7c71.

[270] M. E Peskin. *An introduction to quantum field theory*. CRC press, 2018.

[271] J. D. Jackson. *Classical Electrodynamics*. Wiley, 1998. ISBN: 978-0-471-30932-1.

[272] A. N. Timokhin. "Time-dependent pair cascades in magnetospheres of neutron stars I. Dynamics of the polar cap cascade with no particle supply from the neutron star surface". In: *Monthly Notices of the Royal Astronomical Society* 408 (2010), p. 2092. DOI: 10.1111/j.1365-2966.2010.17286.x.

[273] A. Levinson and B. Cerutti. "Particle-in-cell simulations of pair discharges in a starved magnetosphere of a Kerr black hole". In: *Astronomy and Astrophysics* 616 (2018), A184. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201832915.

[274] S. Kisaka, A. Levinson, and K. Toma. "Comprehensive analysis of magnetospheric gaps around Kerr black holes using 1D GRPIC simulations". In: *The Astrophysical Journal* 902.1 (2020), p. 80. DOI: 10.3847/1538-4357/abb46c.

[275] F. Cruz et al. "Model of pulsar pair cascades in non-uniform electric fields: Growth rate, density profile, and screening time". In: *Physics of Plasmas* 29.5 (2022), p. 052902. DOI: 10.1063/5.0085847.

[276] T. Erber. “High-Energy Electromagnetic Conversion Processes in Intense Magnetic Fields”. In: *Reviews of Modern Physics* 38 (4 1966), p. 626. DOI: 10.1103/RevModPhys.38.626.

[277] R. A. Fonseca et al. “OSIRIS: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators”. In: *International Conference on Computational Science*. Springer. 2002, p. 342.

[278] F. Cruz. *Coherent emission from QED cascades in pulsar polar caps*. 2021. URL: https://www.youtube.com/watch?v=wHSw5kp7Ik4.

[279] P. Carenza and M. C. D. Marsh. “On the applicability of the Landau-Zener formula to axion-photon conversion”. In: *Journal of Cosmology and Astroparticle Physics* 04 (2023), p. 021. DOI: 10.1088/1475-7516/2023/04/021.

[280] A. Álvarez-Melcón et al. “First results of the CAST-RADES haloscope search for axions at 34.67 μeV”. In: *JHEP* 2021.10 (2021). DOI: 10.1007/jhep10(2021)075.

[281] D. Wouters and P. Brun. “Constraints on axion-like particles from X-ray observations of Hydra galaxy cluster”. In: *The Astrophysical Journal* 772.1 (2013), p. 44. ISSN: 1538-4357. DOI: 10.1088/0004-637x/772/1/44.

[282] HESS Collaboration. “Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155-304 energy spectrum”. In: *Physical Review D* 88.10 (2013), p. 102003. DOI: 10.1103/PhysRevD.88.102003.

[283] A. Payez et al. “Revisiting the SN1987A gamma-ray limit on ultralight axion-like particles”. In: *Journal of Cosmology and Astroparticle Physics* 2015.02 (2015), p. 006. DOI: 10.1088/1475-7516/2015/02/006.

[284] Fermi-LAT Collaboration. “Search for Spectral Irregularities due to Photon-Axionlike-Particle Oscillations with the Fermi Large Area Telescope”. In: *Physical Review Letters* 116.16 (2016), p. 161101. DOI: 10.1103/PhysRevLett.116.161101.

[285] M. Meyer et al. “Fermi Large Area Telescope as a Galactic Supernovae Axionscope”. In: *Physical Review Letters* 118.1 (2017), p. 011103. DOI: 10.1103/PhysRevLett.118.011103.

[286] M. C. D. Marsh et al. “A New Bound on Axion-Like Particles”. In: *Journal of Cosmology and Astroparticle Physics* 12 (2017), p. 036. DOI: 10.1088/1475-7516/2017/12/036.

[287] C. S. Reynolds et al. “Astrophysical limits on very light axion-like particles from Chandra grating spectroscopy of NGC 1275”. In: *The Astrophysical Journal* 890 (2020), p. 59. DOI: 10.3847/1538-4357/ab6a0c.

[288] M. Xiao et al. “Constraints on Axionlike Particles from a Hard X-Ray Observation of Betelgeuse”. In: *Physical Review Letters* 126.3 (2021), p. 031101. DOI: 10.1103/PhysRevLett.126.031101.

[289] H. Li et al. “Limits on axion-like particles from Mrk 421 with 4.5-year period observations by ARGO-YBJ and Fermi-LAT”. In: *Physical Review D* 103.8 (2021), p. 083003. DOI: 10.1103/PhysRevD.103.083003.

[290] C. Dessert, J. W. Foster, and B. R. Safdi. “X-ray Searches for Axions from Super Star Clusters”. In: *Physical Review Letters* 125.26 (2020), p. 261102. DOI: 10.1103/PhysRevLett.125.261102.

[291] C. Dessert, A. J. Long, and B. R. Safdi. “No Evidence for Axions from Chandra Observation of the Magnetic White Dwarf RE J0317-853”. In: *Physical Review Letters* 128.7 (2022). DOI: 10.1103/physrevlett.128.071102.

[292] C. Dessert, D. Dunsky, and B. R. Safdi. “Upper limit on the axion-photon coupling from magnetic white dwarf polarization”. In: *Physical Review D* 105.10 (2022). DOI: 10.1103/physrevd.105.103034.

[293] R. A. Fonseca et al. “One-to-one direct modeling of experiments and astrophysical scenarios: pushing the envelope on kinetic plasma simulations”. In: *Plasma Physics and Controlled Fusion* 50.12 (2008), p. 124034.

[294] A. N. Timokhin and A. K. Harding. “On the maximum pair multiplicity of pulsar cascades”. In: *The Astrophysical Journal* 871.1 (2019), p. 12. DOI: 10.3847/1538-4357/aaf050.

[295] L. Bondonneau et al. “A census of the pulsar population observed with the international LOFAR station FR606 at low frequencies (25–80 MHz)”. In: *Astronomy and Astrophysics* 635 (2020), A76.

[296] D. R. Lorimer et al. “Multifrequency flux density measurements of 280 pulsars”. In: *Monthly Notices of the Royal Astronomical Society* 273.2 (1995), p. 411.

[297] R. Zhao et al. “TMRT observations of 26 pulsars at 8.6 GHz”. In: *The Astrophysical Journal* 845.2 (2017), p. 156. DOI: 10.3847/1538-4357/aa8170.

[298] F. Jankowski et al. “Spectral properties of 441 radio pulsars”. In: *Monthly Notices of the Royal Astronomical Society* 473.4 (2018), p. 4436. DOI: 10.1093/mnras/stx2476.

[299] J. M. Rankin. “Toward an empirical theory of pulsar emission. VI-The geometry of the conal emission region”. In: *The Astrophysical Journal* 405 (1993), p. 285.

[300] Y. Gupta and R. T. Gangadhara. “Understanding the radio emission geometry of multiple-component radio pulsars from retardation and aberration effects”. In: *The Astrophysical Journal* 584.1 (2003), p. 418.

[301] J. M. Rankin. “Radio pulsar beam geometry at lower frequencies: bright sources outside the Arecibo sky”. In: *Monthly Notices of the Royal Astronomical Society* 514.3 (2022), p. 3202. ISSN: 1365-2966. DOI: 10.1093/mnras/stac1302.

[302] J. P. W. Verbiest et al. “On Pulsar Distance Measurements and their Uncertainties”. In: *The Astrophysical Journal* 755 (2012), p. 39. DOI: 10.1088/0004-637X/755/1/39.

[303] J. M. Yao, R. N. Manchester, and N. Wang. “A new electron-density model for estimation of pulsar and FRB distances”. In: *The Astrophysical Journal* 835.1 (2017), p. 29.

[304] S. Brownsberger and R. W. Romani. “A Survey for Hα Pulsar Bow Shocks”. In: *The Astrophysical Journal* 784 (2014), p. 154. DOI: 10.1088/0004-637X/784/2/154.

[305] D. C. Price, C. Flynn, and A. Deller. “A comparison of Galactic electron density models using PyGEDM”. In: *Publications of the Astronomical Society of Australia* 38 (2021), e038.

[306] S. S. Wilks. “The Large-Sample Distribution of the Likelihood Ratio for Testing Composite Hypotheses”. In: *The Annals of Mathematical Statistics* 9.1 (1938), p. 60. DOI: 10.1214/aoms/1177732360.

[307] A. Wald. “Tests of Statistical Hypotheses Concerning Several Parameters When the Number of Observations is Large”. In: *Transactions of the American Mathematical Society* 54.3 (1943), p. 426. ISSN: 00029947.

[308] G. Cowan et al. “Asymptotic formulae for likelihood-based tests of new physics”. In: *The European Physical Journal C* 71 (2011), p. 1554. DOI: 10.1140/epjc/s10052-011-1554-0.

[309] J. Li, A. Spitkovsky, and A. Tchekhovskoy. “On the Spin-down of Intermittent Pulsars”. In: *The Astrophysical Journal Letters* 746.2 (2012), p. L24. DOI: 10.1088/2041-8205/746/2/L24.

[310] A. W. Steiner et al. “Using neutron star observations to determine crust thicknesses, moments of inertia, and tidal deformabilities”. In: *Physical Review C* 91.1 (2015), p. 015804.

[311] J. M. Lattimer. “Neutron Stars and the Nuclear Matter Equation of State”. In: *Annual Review of Nuclear and Particle Science* 71 (2021), p. 433. DOI: 10.1146/annurev-nucl-102419-124827.

[312] V. Radhakrishnan and D. J. Cooke. “Magnetic Poles and the Polarization Structure of Pulsar Radiation”. In: *Astrophysical Letters* 3 (1969), p. 225.

[313] A. M. Beloborodov. “Polar-cap accelerator and radio emission from pulsars”. In: *The Astrophysical Journal* 683.1 (2008), p. L41.

[314] M. A. Belyaev and K. Parfrey. “Spatial distribution of pair production over the pulsar polar cap”. In: *The Astrophysical Journal* 830.2 (2016), p. 119.

[315] A. Szary, G. I. Melikidze, and J. Gil. “Two modes of partially screened gap”. In: *Monthly Notices of the Royal Astronomical Society* 447.3 (2015), p. 2295.

[316] D. Noordhuis et al. *Axion Clouds around Neutron Stars*. 2023. arXiv: 2307.11811 [hep-ph].

[317] A. Caputo et al. “Pulsar Nulling and Vacuum Radio Emission from Axion Clouds”. In: (2023). arXiv: 2311.14795 [hep-ph].

[318] A. Arvanitaki and S. Dubovsky. “Exploring the String Axiverse with Precision Black Hole Physics”. In: *Physical Review D* 83 (2011), p. 044026. DOI: 10.1103/PhysRevD.83.044026.

[319] Richard Brito, Vitor Cardoso, and Paolo Pani. "Superradiance: New Frontiers in Black Hole Physics". In: *Lecture Notes in Physics* 906 (2015), p. 1. DOI: 10.1007/978-3-319-19000-6.

[320] M. Baryakhtar, R. Lasenby, and M. Teo. "Black Hole Superradiance Signatures of Ultralight Vectors". In: *Physical Review D* 96.3 (2017), p. 035019. DOI: 10.1103/PhysRevD.96.035019.

[321] M. Baryakhtar et al. "Black hole superradiance of self-interacting scalar fields". In: *Physical Review D* 103.9 (2021). DOI: 10.1103/physrevd.103.095019.

[322] K. Van Tilburg. "Stellar basins of gravitationally bound particles". In: *Physical Review D* 104.2 (2021). ISSN: 2470-0029. DOI: 10.1103/physrevd.104.023019.

[323] R. Lasenby and K. Van Tilburg. "Dark photons in the solar basin". In: *Physical Review D* 104.2 (2021). ISSN: 2470-0029. DOI: 10.1103/physrevd.104.023020.

[324] S. B. Popov et al. "Population synthesis studies of isolated neutron stars with magnetic field decay". In: *Monthly Notices of the Royal Astronomical Society* 401.4 (2010), p. 2675. DOI: 10.1111/j.1365-2966.2009.15850.x.

[325] M. Gullón et al. "Population synthesis of isolated neutron stars with magneto-rotational evolution". In: *Monthly Notices of the Royal Astronomical Society* 443.3 (2014), p. 1891. DOI: 10.1093/mnras/stu1253.

[326] A. Spitkovsky. "Time-dependent Force-free Pulsar Magnetospheres: Axisymmetric and Oblique Rotators". In: *The Astrophysical Journal* 648.1 (2006), p. L51. DOI: 10.1086/507518.

[327] A. Philippov, A. Tchekhovskoy, and J. G. Li. "Time evolution of pulsar obliquity angle from 3D simulations of magnetospheres". In: *Monthly Notices of the Royal Astronomical Society* 441.3 (2014), p. 1879. DOI: 10.1093/mnras/stu591.

[328] A. Bransgrove, Y. Levin, and A. Beloborodov. "Magnetic field evolution of neutron stars – I. Basic formalism, numerical techniques and first results". In: *Monthly Notices of the Royal Astronomical Society* 473.2 (2017), p. 2771. DOI: 10.1093/mnras/stx2508.

[329] A. P. Igoshev, S. B. Popov, and R. Hollerbach. "Evolution of Neutron Star Magnetic Fields". In: *Universe* 7.9 (2021), p. 351. DOI: 10.3390/universe7090351.

[330] D. Viganò et al. "Magneto-thermal evolution of neutron stars with coupled Ohmic, Hall and ambipolar effects via accurate finite-volume simulations". In: *Computer Physics Communications* 265 (2021), p. 108001. DOI: 10.1016/j.cpc.2021.108001.

[331] D. Viganò et al. "Unifying the observational diversity of isolated neutron stars via magneto-thermal evolution models". In: *Monthly Notices of the Royal Astronomical Society* 434 (2013), p. 123. DOI: 10.1093/mnras/stt1008.

[332] S. Johnston and A. Karastergiou. "Pulsar braking and the $P - \dot{P}$ diagram". In: *Monthly Notices of the Royal Astronomical Society* 467.3 (2017), p. 3493. DOI: 10.1093/mnras/stx377.

[333] N. Iwamoto. "Axion Emission From Neutron Stars". In: *Physical Review Letters* 53 (12 1984), p. 1198. DOI: 10.1103/PhysRevLett.53.1198.

[334] R. P. Brinkmann and M. S. Turner. "Numerical rates for nucleon-nucleon, axion bremsstrahlung". In: *Physical Review D* 38 (8 1988), p. 2338. DOI: 10.1103/PhysRevD.38.2338.

[335] G. G. Raffelt. *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles.* University of Chicago press, 1996.

[336] N. Iwamoto. "Nucleon-nucleon bremsstrahlung of axions and pseudoscalar particles from neutron-star matter". In: *Physical Review D* 64 (4 2001), p. 043002. DOI: 10.1103/PhysRevD.64.043002.

[337] S. P. Harris et al. "Axions in neutron star mergers". In: *Journal of Cosmology and Astroparticle Physics* 2020.07 (2020), p. 023. DOI: 10.1088/1475-7516/2020/07/023.

[338] M. Beutter et al. "Axion-electrodynamics: a quantum field calculation". In: *Journal of Cosmology and Astroparticle Physics* 02 (2019), p. 026. DOI: 10.1088/1475-7516/2019/02/026.

[339] A. G. Muslimov and A. K. Harding. "High-Altitude Particle Acceleration and Radiation in Pulsar Slot Gaps". In: *The Astrophysical Journal* 606.2 (2004), p. 1143. DOI: 10.1086/383079.

[340] K. A. Hochmuth and G. Sigl. "Effects of Axion-Photon Mixing on Gamma-Ray Spectra from Magnetized Astrophysical Sources". In: *Physical Review D* 76 (2007), p. 123011. DOI: 10.1103/PhysRevD.76.123011.

[341] M. Fairbairn, T. Rashba, and S. V. Troitsky. "Photon-axion mixing and ultra-high-energy cosmic rays from BL Lac type objects - Shining light through the Universe". In: *Physical Review D* 84 (2011), p. 125019. DOI: 10.1103/PhysRevD.84.125019.

[342] A. Dobrynina, A. Kartavtsev, and G. Raffelt. "Photon-photon dispersion of TeV gamma rays and its role for photon-ALP conversion". In: *Physical Review D* 91 (2015), p. 083003. DOI: 10.1103/PhysRevD.91.083003.

[343] A. J. Millar et al. "Axion-photon conversion in strongly magnetised plasmas". In: *Journal of Cosmology and Astroparticle Physics* 2021.11 (2021), p. 013. DOI: 10.1088/1475-7516/2021/11/013.

[344] J. M. Cordes and M. A. McLaughlin. "Searches for Fast Radio Transients". In: *The Astrophysical Journal* 596.2 (2003), p. 1142. DOI: 10.1086/378231.

[345] ARCADE Collaboration. "ARCADE 2 Measurement of the Absolute Sky Brightness at 3-90 GHz". In: *The Astrophysical Journal* 734.1 (2011), p. 5. DOI: 10.1088/0004-637X/734/1/5.

[346] LOFAR Collaboration. "LOFAR: The LOw-Frequency ARray". In: *Astronomy and Astrophysics* 556 (2013), A2. DOI: 10.1051/0004-6361/201220873.

[347] A. T. Sutinjo et al. "System equivalent flux density of a low-frequency polarimetric phased array interferometer". In: *Astronomy and Astrophysics* 660 (2022), A134. DOI: 10.1051/0004-6361/202142759.

[348] *Proposer's Guide for the Green Bank Telescope*. https://www.gb.nrao.edu/scienceDocs/GBTpg.pdf. Accessed: 2023-06-28.

[349] *GBT online sensitivity calculator*. https://dss.gb.nrao.edu/calculator-ui/war/Calculator_ui.html. Accessed: 2023-06-28.

[350] A. Philippov and M. Kramer. "Pulsar Magnetospheres and Their Radiation". In: *Annual Review of Astronomy and Astrophysics* 60 (2022), p. 495.

[351] P. Madau and M. Dickinson. "Cosmic Star-Formation History". In: *Annual Review of Astronomy and Astrophysics* 52.1 (2014), p. 415. DOI: 10.1146/annurev-astro-081811-125615.

[352] A. Iwazaki. "Axion stars and fast radio bursts". In: *Physical Review D* 91.2 (2015), p. 023008. DOI: 10.1103/PhysRevD.91.023008.

[353] Yang Bai and Yuta Hamada. "Detecting Axion Stars with Radio Telescopes". In: *Physics Letters B* 781 (2018), p. 187. DOI: 10.1016/j.physletb.2018.03.070.

[354] T. Dietrich et al. "Neutron star–axion star collisions in the light of multimessenger astronomy". In: *Monthly Notices of the Royal Astronomical Society* 483.1 (2019), p. 908. DOI: 10.1093/mnras/sty3158.

[355] A. Prabhu and N. M. Rapidis. "Resonant Conversion of Dark Matter Oscillons in Pulsar Magnetospheres". In: *Journal of Cosmology and Astroparticle Physics* 10 (2020), p. 054. DOI: 10.1088/1475-7516/2020/10/054.

[356] Y. Bai, X. Du, and Y. Hamada. "Diluted axion star collisions with neutron stars". In: *Journal of Cosmology and Astroparticle Physics* 01.01 (2022), p. 041. DOI: 10.1088/1475-7516/2022/01/041.

[357] E. Utrilla Ginés et al. *Numerical Analysis of Resonant Axion-Photon Mixing: Part I.* 2024. arXiv: 2405.08865 [hep-ph].

[358] N. V. Mikheev, D. A. Rumyantsev, and Yu. E. Shkol'nikova. "On the resonant production of axions in a magnetar magnetosphere". In: *JETP Letters* 90 (2010), p. 604. DOI: 10.1134/S0021364009210036.

[359] C. A. J. O'Hare et al. "Axion helioscopes as solar magnetometers". In: *Physical Review D* 102.4 (2020), p. 043019. DOI: 10.1103/PhysRevD.102.043019.

[360] Andrea Caputo, Alexander J. Millar, and Edoardo Vitagliano. "Revisiting longitudinal plasmon-axion conversion in external magnetic fields". In: *Physical Review D* 101.12 (2020), p. 123004. DOI: 10.1103/PhysRevD.101.123004.

[361] A. Caputo et al. "Axionlike Particles from Hypernovae". In: *Physical Review Letters* 127.18 (2021), p. 181102. DOI: 10.1103/PhysRevLett.127.181102.

[362] M. J. Dolan, F. J. Hiskens, and R. R. Volkas. "Advancing globular cluster constraints on the axion-photon coupling". In: *Journal of Cosmology and Astroparticle Physics* 10.10 (2022), p. 096. DOI: 10.1088/1475-7516/2022/10/096.

[363] N. Song, L. Su, and L. Wu. *Polarization Signals from Axion-Photon Resonant Conversion in Neutron Star Magnetosphere*. 2024. arXiv: 2402.15144 [hep-ph].

[364] M. C. D. Marsh et al. "Fourier formalism for relativistic axion-photon conversion with astrophysical applications". In: *Physical Review D* 105.1 (2022), p. 016013. DOI: 10.1103/PhysRevD.105.016013.

[365] S. Knirck et al. "A first look on 3D effects in open axion haloscopes". In: *Journal of Cosmology and Astroparticle Physics* 2019.08 (2019), p. 026.

[366] F. Wilczek. "Two Applications of Axion Electrodynamics". In: *Physical Review Letters* 58 (1987), p. 1799. DOI: 10.1103/PhysRevLett.58.1799.

[367] S. D. McDermott and S. J. Witte. "Cosmological evolution of light dark photon dark matter". In: *Physical Review D* 101.6 (2020), p. 063030. DOI: 10.1103/PhysRevD.101.063030.

[368] S. J. Witte et al. "Dark photon dark matter in the presence of inhomogeneous structure". In: *Journal of High Energy Physics* 06.6 (2020), p. 132. DOI: 10.1007/JHEP06(2020)132.

[369] A. Caputo et al. "Dark Photon Oscillations in Our Inhomogeneous Universe". In: *Phys. Rev. Lett.* 125.22 (2020), p. 221303. DOI: 10.1103/PhysRevLett.125.221303.

[370] A. Caputo et al. "Electromagnetic signatures of dark photon superradiance". In: *Physical Review D* 104.4 (2021), p. 043006. DOI: 10.1103/PhysRevD.104.043006.

[371] E. Hardy and N. Song. "Listening for dark photon radio signals from the Galactic Center". In: *Physical Review D* 107.11 (2023), p. 115035. DOI: 10.1103/PhysRevD.107.115035.

[372] E. Cannizzaro et al. "Dark photon superradiance quenched by dark matter". In: *Physical Review D* 106.8 (2022), p. 083019. DOI: 10.1103/PhysRevD.106.083019.

[373] N. Siemonsen et al. “Dark photon superradiance: Electrodynamics and multimessenger signals”. In: *Physical Review D* 107.7 (2023), p. 075025. DOI: 10.1103/PhysRevD.107.075025.

[374] A. Taflove and S. C. Hagness. *Computational electrodynamics: the finite-difference time-domain method.* Artech House, 2005.

[375] M. Malinen and P. Råback. “Elmer finite element solver for multiphysics and multiscale problems”. In: vol. 19. Forschungszentrum Jülich GmbH, 2013, p. 101.

[376] R. Lee and A. C. Cangellaris. “A Study of Discretization Error in the Finite Element Approximation of Wave Solutions”. In: *IEEE Transactions on Antennas and Propagation* 40 (1992), p. 542. DOI: 10.1109/8.142629.

Publications

This thesis is based on the following publications:

1. Samuel J. Witte, **Dion Noordhuis**, Thomas D. P. Edwards, and Christoph Weniger, *Axion-photon conversion in neutron star magnetospheres: The role of the plasma in the Goldreich-Julian model*, Physical Review D **104** (2021), arXiv:2104.07670.

   Presented in Chapter 2.
   SJW led the analysis and writing of the paper. DN performed parts of the theoretical analysis, and contributed through reviewing the code and calculations. All authors contributed through scientific ideas, planning, and editing the manuscript.

2. **Dion Noordhuis**, Anirudh Prabhu, Samuel J. Witte, Alexander Y. Chen, Fábio Cruz, and Christoph Weniger, *Novel constraints on axions produced in pulsar polar-cap cascades*, Physical Review Letters **131** (2023), arXiv:2209.09917.

   Presented in Chapter 3.
   DN, AP, and SJW led the analysis and writing of the paper; DN hereby focused on the radio flux calculations, and AP and SJW on the development of the semi-analytic model. The PIC simulation was previously performed by AYC and FC. The main ideas were conceptualized by DN, AP, and SJW, with contributions from AYC and CW (who also helped in writing the manuscript).

3. **Dion Noordhuis**, Anirudh Prabhu, Christoph Weniger, and Samuel J. Witte, *Axion clouds around neutron stars*, accepted for publication in Physical Review X, arXiv:2307.11811.

   Presented in Chapter 4.
   DN led the analysis and writing of the paper. All authors contributed through scientific ideas, planning, and editing the manuscript.

4. Estanis Utrilla Ginés, **Dion Noordhuis**, Christoph Weniger, and Samuel J. Witte, *Numerical analysis of resonant axion-photon mixing: Part I*, submitted to Physical Review D, arXiv:2405.08865.

   Presented in Chapter 5.
   EUG performed the simulations, under supervision of DN and SJW. DN furthermore carried out the theoretical calculations. All authors contributed through scientific ideas, planning, and editing the manuscript.

Samenvatting

In de wereld van de natuurkunde wordt de term ‘materie’ gebruikt om collectief te verwijzen naar elk fysiek object dat we kunnen waarnemen, van de kleinste atomen tot de massiefste sterren. De bouwstenen van materie zijn elementaire (*d.w.z.* ondeelbare) deeltjes, zoals quarks en elektronen, die elkaar beïnvloeden via de vier bekende fundamentele krachten: zwaartekracht, elektromagnetisme, zwakke kernkracht, en sterke kernkracht. Dit netwerk van deeltjes en hun interacties is samengevat in een theorie die bekendstaat als het standaardmodel van de deeltjesfysica, dat breed wordt ondersteund door zowel theoretisch als experimenteel bewijs. Ondanks zijn successen is het standaardmodel echter geen complete theorie, omdat het niet in staat is om verschillende belangrijke verschijnselen te verklaren.

Een voorbeeld van zo’n verschijnsel is de implicatie van ontbrekende massa in het universum. Volgens uitvoerig gravitationeel bewijs is ongeveer 85% van de totale materie-inhoud van het universum niet direct waarneembaar. Deze ongeziene materie, ‘donkere materie’ genaamd, oefent zwaartekracht uit op zichtbare materie en licht, maar lijkt verder geen straling te produceren en geen interacties te hebben die wij momenteel kunnen detecteren. Hoewel dus ogenschijnlijk onzichtbaar, speelt donkere materie een cruciale rol in het vormgeven van de structuur van het heelal en heeft het aanzienlijke invloed op de vorming en het gedrag van sterrenstelsels en clusters van sterrenstelsels. Het begrijpen van de aard van donkere materie is een van de grootste uitdagingen in de moderne astrofysica en kosmologie, waarbij onderzoekers vele verschillende methodes hanteren om de mysterieuze eigenschappen ervan te onthullen.

De meeste modellen suggereren dat donkere materie een onontdekt deeltje is, gekenmerkt door zwakke interacties, productie in het vroege universum, en een lange levensduur. Onder de vele voorgestelde kandidaten springen axionen eruit als bijzonder goed gemotiveerd. Deze hypothetische deeltjes komen op natuurlijke wijze naar voren in uitbreidingen van het standaardmodel en kunnen, naast dat ze een ideale donkeremateriekandidaat zijn, een oplossing bieden voor andere belangrijke openstaande vraagstukken binnen de natuurkunde. Axionen zijn bijvoorbeeld oorspronkelijk bedacht om het zogenaamde ‘sterke CP-probleem’ op te lossen, een vraagstuk dat de theorie van de sterke interacties betreft en gaat over waarom de sterke kernkracht onnodig de gecombineerde symmetrie van ladingconjugatie en pariteit lijkt te behouden.

Het detecteren van axionen vormt helaas, net als bij andere kandidaten voor donkere materie, een formidabele uitdaging. Niettemin is er de afgelopen jaren een groeiende interesse ontstaan in het onderzoek naar axionen. Natuurkundigen ontwikkelen en bouwen steeds meer detectoren op aarde, specifiek gericht op het meten van axionen, en ze ontwerpen ook steeds vaker nieuwe strategieën om axionen indirect te observeren door hun invloed op astrofysische omgevingen te analyseren. Een voorbeeld van deze laatste aanpak is de moderne inspanning om axion-fotoninteracties te bestuderen in de omgeving rond neutronensterren, bekend als de magnetosfeer, waar het omringende plasma en krachtige magnetische veld de vereiste omstandigheden kunnen bieden om de zwakke kracht van axioninteracties te overwinnen.

In dit proefschrift, getiteld *Neutron stars as axion laboratories: Harnessing the power of the magnetosphere*, streven we ernaar om het ingewikkelde samenspel tussen het grote, in de vorm van neutronensterren, en het kleine, in de vorm van axionen, te begrijpen. Zoals hierboven vermeld, zijn axionen een belangrijke kandidaat voor nieuwe natuurkunde buiten het standaardmodel, en neutronensterren met hun bijbehorende magnetosfeer bieden ideale omgevingen voor het bestuderen van deze ongrijpbare deeltjes. Twee mechanismen zijn geïdentificeerd als bijzonder veelbelovend: resonante axion-fotonmenging en axionproductie via vacuümregio's – deze vormen dan ook het fundament waarop dit proefschrift is gebouwd. Resonante axion-fotonmenging verwijst naar de conversie van axionen naar fotonen, en vice versa, op plaatsen waar de vier-momenta van beide deeltjes gelijk zijn. Dit proces wordt vergemakkelijkt binnen de magnetosfeer door de combinatie van plasma en een magnetisch veld. Axionproductie via vacuümregio's verwijst naar de creatie van axionen in gelokaliseerde gebieden van de magnetosfeer, ideaal geschikt voor dit doel vanwege de aanwezigheid van oscillerende elektromagnetische velden. Het onderzoek dat hier wordt gepresenteerd, vertegenwoordigt een stap voorwaarts in het begrijpen van de fenomenologie en impact van deze mechanismen, en daarmee in het verhelderen van het gecombineerde systeem van axionen en de magnetosfeer van neutronensterren. Uiteindelijk hoop ik dat dit ook kan bijdragen aan de ontdekking van axionen.

In **Hoofdstuk 2** introduceren we een end-to-end-analyseframework dat in staat is om de fotonflux te berekenen die wordt geproduceerd via de resonante conversie van donkerematerie-axionen in de magnetosferen van neutronensterren. Dit framework maakt gebruik van een geavanceerd auto-differentiatie ray-tracingalgoritme, waardoor de posities van axionen en fotonen nauwkeurig kunnen worden gevolgd. Cruciaal hierbij is dat we rekening houden met de complexe aard van het magnetosferische plasma, wat essentieel is voor het bepalen van zowel de banen van de fotonen als de locaties van de conversiepunten. Met deze aanpak richten we ons op belangrijke onzekerheden met betrekking tot de invloed van de magnetosfeer op signaalberekeningen, wat bijdraagt aan een aanzienlijke verbetering in hun betrouwbaarheid. Onze resultaten laten zien dat, onder realistische keuzes van parameters, resonante menging van donkerematerie-axionen een signaal genereert dat gekenmerkt wordt door sterke anisotropie, tijdsafhankelijkheid, en een grotere lijnbreedte dan voorheen verwacht.

In **Hoofdstuk 3** verschuiven we onze focus naar de analyse van axionen die lokaal worden gecreëerd binnen de vacuümregio's van neutronensterren. We ontwikkelen een framework dat de berekening mogelijk maakt van de initiële axionspectra, de daaropvolgende banen van deze axionen door de magnetosfeer, hun resonante menging met fotonen, en de resulterende radio-emissie. De eerste van deze stappen wordt op twee manieren uitgevoerd: door gebruik te maken van ofwel een zelf ontworpen semi-analytisch model, of van particle-in-cell-simulaties uit een eerdere studie. De resultaten van deze twee methoden komen goed overeen, wat de robuustheid van ons framework ten opzichte van onzekerheden onderstreept. Het uiteindelijke radiosignaal wordt bepaald met behulp van een aangepaste versie van het ray-tracingalgoritme dat in Hoofdstuk 2 is geïntroduceerd. Door ons te concentreren op de relativistische axionpopulatie, tonen we aan dat deze, in tegenstelling tot donkerematerie-axionen, een breed spectrum genereert wanneer ze resonant mengt. Vervolgens vergelijken we onze signaalvoorspellingen met waarnemingen van 27 nabijgelegen pulsars, waarbij we de sterkste huidige limieten op de axion-fotonkoppeling in het massabereik $m_a \simeq 10^{-8} - 10^{-5}\,\mathrm{eV}$ vaststellen. Deze limieten zijn aangeduid als 'Pulsars' in Figuur 1.5.

In **Hoofdstuk 4** onderzoeken we de gevolgen van de grote niet-relativistische axionpopulatie die ook wordt geproduceerd via vacuümregio's. Dergelijke axionen kunnen niet ontsnappen aan de zwaartekracht van een neutronenster, waardoor zij zich rond de ster ophopen en zo een 'axionwolk' vormen. Het bestaan van axionwolken vereist geen aannames buiten een axion met een geschikte massa dat koppelt aan elektromagnetisme, en daarom wordt verwacht dat ze een veelvoorkomend fenomeen zijn wanneer de axionmassa ongeveer van de orde $m_a \simeq 10^{-9} - 10^{-4}\,\mathrm{eV}$ is, zelfs als de axion-fotonkoppeling zwak is. We bestuderen de vorming, kenmerken, en evolutie van axionwolken, waarbij we laten zien dat ze enorme dichtheden kunnen bereiken voor een breed scala aan parameters. Daarnaast analyseren we mogelijke mechanismen voor energiedissipatie, en identificeren resonante axion-fotonmenging als de belangrijkste kandidaat voor het genereren van waarneembare effecten. Deze studie vertegenwoordigt het eerste onderzoek naar deze categorie van axionwolken, en opent een nieuw interdisciplinair veld met grote potentie voor axiononderzoek.

Ten slotte, in **Hoofdstuk 5**, wijken we af van ons eerdere brede perspectief en richten we ons specifiek op axion-fotonmenging. Hoewel dit proces relatief goed begrepen is in geïdealiseerde scenario's, vormt het een uitdagende taak om de vergelijkingen die axion-fotonmenging beschrijven volledig op te lossen in sterk niet-uniforme achtergronden zoals de magnetosfeer van een neutronenster. Meerdere theoretische studies hebben zich de afgelopen jaren op dit probleem gericht, maar ondanks het ogenschijnlijk gebruik van dezelfde aannames, hebben deze tot verschillende resultaten geleid. Om deze discrepantie aan te pakken, behandelen we het probleem van axion-fotonmenging met numerieke methoden, waarbij we een resultaat vinden dat overeenstemt met slechts een van de gepubliceerde theoretische oplossingen. Dit werk, hoewel nog niet gericht op sterk niet-uniforme achtergronden, dient als startpunt voor een bredere verkenning van axion-fotonmenging in complexe astrofysische omgevingen. Dit zal een cruciale rol spelen bij het verbeteren van de nauwkeurigheid van signaalberekeningen voor indirecte axion-zoektochten.