Astro2020 Science White Paper
Gravitational probes of ultra-light axions

Primary thematic area: Cosmology and Fundamental Physics

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Abstract:
The axion is a hypothetical, well-motivated dark-matter particle whose existence would explain the lack of charge-parity violation in the strong interaction. In addition to this original motivation, an 'axiverse' of ultra-light axions (ULAs) with masses $10^{-33}\,\mathrm{eV} \lesssim m_\mathrm{a} \lesssim 10^{-10}\,\mathrm{eV}$ also emerges from string theory. Depending on the mass, such a ULA contributes to the dark-matter density, or alternatively, behaves like dark energy. At these masses, ULAs' classical wave-like properties are astronomically manifested, potentially mitigating observational tensions within the ΛCDM paradigm on local-group scales. ULAs also provide signatures on small scales such as suppression of structure, interference patterns and solitons to distinguish them from heavier dark matter candidates. Through their gravitational imprint, ULAs in the presently allowed parameter space furnish a host of observational tests to target in the next decade, altering standard predictions for microwave background anisotropies, galaxy clustering, Lyman-α absorption by neutral hydrogen along quasar sightlines, pulsar timing, and the black-hole mass spectrum.

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I. AXIONS: MOTIVATION & BACKGROUND

The nature of dark matter (DM) and dark energy (DE) that dominate the energy density of our universe remains a mystery. Axions are hypothetical particles proposed in the 1970s [1–3], and could constitute significant fractions of the DM and DE. They could resolve challenges to the Λ cold dark matter (CDM) cosmology on small scales and impact cosmological observables [4], like the CMB. Axions are characterized by a mass m_a measured in eV, and 'decay constant' f_a, which determines the importance of axion self-interactions. Beyond their original motivation to solve the charge-parity symmetry problem of Quantum Chromodynamics (QCD), axions also arise in many "beyond the standard model" (BSM) theories of particle physics, such as string theory [5–7]. There could be many (~ 200) axion species [8], and evidence for even one could hint at a larger "axiverse" [9–13].

For DM and DE to have the right abundances, the parameter ranges [10]

$$10^{-33} \text{ eV} \leq m_a \leq 10^{-2} \text{ eV}; \quad 10^7 \text{ GeV} \leq f_a \leq 10^{18} \text{ GeV}. \tag{1}$$

are of particular interest. In these ranges, axions are produced non-thermally, thus evading hot DM bounds.[1] Early on, when the Hubble parameter $H \lesssim mc^2/\hbar$, axions have equation-of-state parameter $w \simeq -1$ and their density scales as $\rho \approx$ constant [15, 16]. Afterwards, the axion field begins to rapidly oscillate, and on average, $w \simeq 0$, with $\rho \propto (1+z)^3$ [17, 18], where z is the cosmological redshift. Depending on when this transition occurs, axions can contribute to either the DM or DE of the universe. An axion with $m_a \lesssim 10^{-27}$ eV will behave as early DE, while one with $m_a \lesssim 10^{-33}$ eV behaves as standard DE and can drive cosmic acceleration today. Heavier axions behave as DM.

A variety of experimental and observational techniques could detect axions, such as radio-frequency resonance techniques [19, 20], nuclear magnetic resonance methods [21, 22], telescope searches [23], and others [24–28]. These rely on axion couplings to standard model (SM) particles, which scale as f_a^{-1} [10, 29]. Direct detection relies on a large cosmic density Ω_a and knowledge of the local DM density. Laboratory searches probe the ranges 10^{-17} eV $\lesssim m_a \lesssim 10^{-2}$ eV and 10^9 GeV $\lesssim f_a \lesssim 10^{16}$ GeV.

Axions would enhance stellar cooling [23, 30–34], affecting stellar populations and asteroseismology [23, 30, 35]. Axions can also be detected through their gravitational signatures if their Compton wavelength λ_C is astronomically relevant. If $m_a \simeq 10^{-10}$ eV, λ_C is comparable to the Schwarzschild radius of a stellar mass black hole (BH). Axions could then spin down BHs [9, 36]. If $m_a \simeq 10^{-33}$ eV, λ_C is comparable to the cosmic horizon, and axions could cause present-day cosmic acceleration. These scales bracket the *gravitational ultra-light axion (ULA) window*, where it is possible to search for axions using only their gravitational interactions, with no reliance on their (highly suppressed) couplings to the SM. Gravitational effects are entirely complementary to other signatures. We refer to all such particles as ULAs, noting the existence of other terms, like axion-like particles (ALPs) and weakly interacting slim particles (WISPs) [37]. We focus on real fields like the axion, but we note that complex scalar fields with $m_a \simeq 10^{-22}$ eV are also a DM candidate [38]. They behave as axions at early and late times, but redshift as $\rho \propto (1+z)^6$ and then $(1+z)^4$ at intermediate times, with distinct CMB and gravitational-wave signatures [38].

Cosmological observations are uniquely able to probe the ULA relic density, Ω_a (which is set by m_a, f_a, and dimensionless initial field value θ_i). If $f_a \sim 10^{16}$ GeV, the energy scale

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[1] There may also be a thermal sub-population, tested by measurements of N_{eff} [14].

of Grand Unified Theories or GUTs, and $\theta_i \approx 1$, ULA densities could be cosmologically relevant. For comparison's sake, we note that CMB and large-scale structure observations have established that the DE density is $\Omega_\Lambda = 0.685 \pm 0.007$, the DM density is $\Omega_c = 0.264 \pm 0.007$, and relic neutrinos must have $\Omega_\nu \leq 0.005$ [39]. For masses in the range 10^{-33} eV $\lesssim m_a \lesssim 10^{-16}$ eV the relic density is in the range $10^{-4} \lesssim \Omega_a \lesssim 1$, as shown in Fig. 1. Larger ULA densities correspond to even larger values of f_a, approaching the Planck scale, 2.4×10^{18} GeV. If some of the dark sector is composed of ULAs, then, the cosmological observables test low m_a and large f_a values, well beyond the reach of other techniques. The GUT prediction for Ω_a motivates exploration of the entire ULA mass window. We treat Ω_a and m_a as free parameters, keeping an open mind to a wide range of theoretical scenarios.

II.   AXIONS AND CHALLENGES TO ΛCDM

Let us not only ask what astrophysics can do for axions, but also what can axions do for astrophysics. ULAs could explain late-time cosmic acceleration, or compose some of the DM [4, 40–45]. They could cause an early DE epoch [46], thus mitigating tensions between CMB and local measurements of the Hubble constant H_0. ULAs recover the successes of pure ΛCDM on large scales but alleviate challenges to ΛCDM on small scales [4, 47]. Some dwarf galaxy DM halo profiles exhibit cores in their central density profiles, in contrast with naive ΛCDM predictions [47]. If ULAs exist and compose a significant fraction of DM, their macroscopic de Broglie wavelengths would cause galactic halo density profiles to have cores at $\sim 0.7 \, (m_a/10^{-22} \text{ eV})^{-1/2}$ kpc scales, possibly explaining observations of cores in Milky-Way dwarf Spheroidal galaxies [4, 48–55]. In particular, a dynamical analysis of Fornax and Sculptor yields 'hints' of a ULA solution to CDM small-scale problems with 0.3×10^{-22} eV $\lesssim m_a \lesssim 10^{-22}$ eV [51].

By suppressing the growth of cosmic structure on the smallest scales, ULAs in this mass range could address challenges to the ΛCDM paradigm, such as the paucity of Milky-Way satellite galaxies compared to expectations, by suppressing the number of low-mass subhalos around Milky-Way scale halos. ULAs in this window would also address the "too big to fail problem", the surprising depression of satellite galaxy masses in halos relative to ΛCDM expectations [10, 11, 50, 56]. The region of interest is shown as "ULA hints" in Fig. 1, where we also show current constraints and possibilities for new probes. The properties of the ultra-faint dwarf galaxy Eridanus II exclude most of the ULA mass window 0.8×10^{-21} eV $\lesssim m_a \lesssim 10^{-19}$ eV [57]. There are other tests of ULA DM using galactic dynamics [58–61].[2]

Axions may behave as a coherent macroscopic low-momentum state wave, referred to as Bose-Einstein condensate (BEC) dark matter [62–67]. Other ultra-light particles can display similar behavior, although the mass scale will determine the astrophysical phenomenology [68, 69]. If axions thermalize gravitationally, there could be galaxy-scale BECs [62], yielding caustic rings that are testable using galaxy rotation curves [68, 70–73]. The self-interaction of these particles is meaningful in determining the scale of stability of the BEC [65]. Axions have *attractive* self-interactions at leading order and thus fail one requirement for stable large-scale Bose condensation, the presence of *repulsive* self-interactions [65, 74–76]. This could lead to much-smaller coherence lengths, producing solitons or "axion stars" and "axteroids"[65, 77–83] (with mass $\sim 10^{-11} M_\odot$ for QCD axions). For ULAs, solitons are more massive, $\sim 10^6 \rightarrow 10^9 \, M_\odot$, and could constitute dwarf galaxy density cores [11, 84], with implications for halo structure and detection prospects. We explore the opportunities for astrophysical ULA detection in the next decade, starting with the CMB.

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[2] There are also baryonic explanations for these puzzles, and they will soon be critically tested.
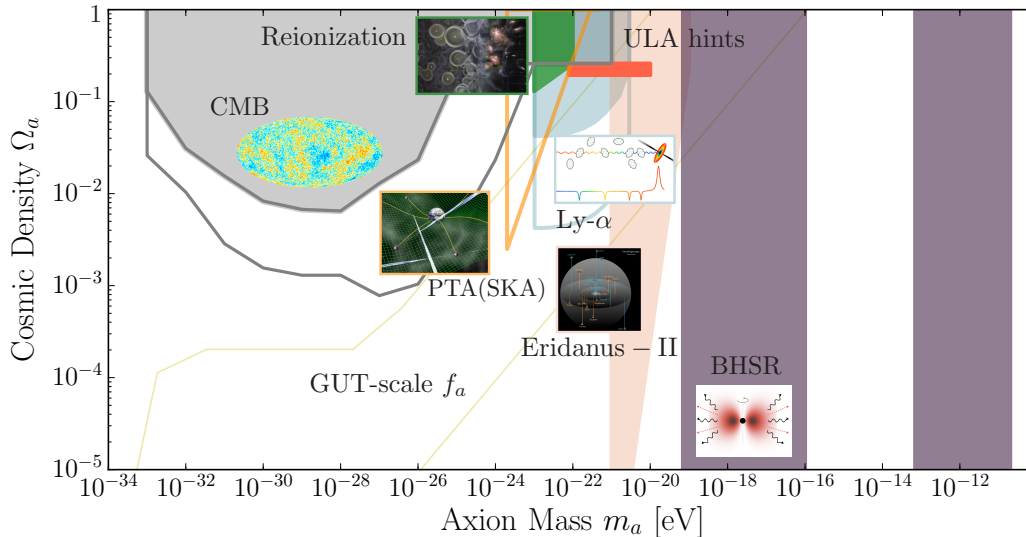
Figure 1. The cosmic window on ultralight axions, showing the reach of various astronomical probes. Shaded regions are currently excluded. Lines below them indicate the sensitivity of future experiments/surveys. ULA hints refers to the ULA mass scale suggested by MW-scale challenges. Local group schematic, *Credit: J. T. A. de Jong, Leiden University.* Planck CMB map, *Credit ESA, http://www.esa.int.* Black-hole super-radiance schematic [85] used with permission from American Physical Society, License RNP/19/MAR/012767. PTA Schematic *Image Credit: David Champion.* Lyman Alpha Schematic, *Image Credit: Ned Wright.* Reionization schematic used with permission from artist, J. F. Podevin, originally used in Ref. [86].

III. AXIONS AND THE CMB

In the DE-like mass window, ULAs roll slowly down their potential as a dark-energy component, shifting CMB acoustic peaks to smaller angular scales (higher ℓ), and increasing the largest scale anisotropies due to gravitational potential-well decay for $0 \lesssim z \lesssim 3300$ [15, 16, 87–90]. In the DM-like mass window, the imprint of ULAs on the Hubble expansion and perturbation growth alters peak heights measured in the temperature and E-mode polarization power spectra [44, 88, 89, 91, 92]. ULAs manifest wave-like properties on cosmological scales, suppressing density fluctuations the ULA comoving "Jeans scale" $\lambda \lesssim \lambda_{\rm J} \equiv 0.1$ Mpc $(m_{\rm a}/10^{-22}\,{\rm eV})^{-1/2}(1+z)^{1/4}$ [4, 10, 43, 44, 89, 92–98], affecting comoving wavenumbers $k > 2\pi/\lambda_{\rm J}$. This affects the strength and scale-dependence of gravitational lensing of the CMB [99–102].

In the window $10^{-32}\,{\rm eV} \lesssim m_{\rm a} \lesssim 10^{-26}\,{\rm eV}$, the imprint of these effects and *Planck* satellite data impose the constraint of $\Omega_{\rm a} \lesssim 10^{-2}$, as shown in Fig. 1 [98, 103]. Fig. 1 includes the effect of CMB lensing, which improves sensitivity by a factor of ~ 3 compared with the unlensed CMB or galaxy clustering. For $m_{\rm a} \lesssim 10^{-32}\,{\rm eV}$ (or $m_{\rm a} \gtrsim 10^{-25}\,{\rm eV}$), ULA effects on CMB/galaxy clustering signatures are indistinguishable from a cosmological constant (or DM) with current data, lifting these constraints [89].

In the next and coming decades, very sensitive experiments like the Simons Observatory (SO) [104], CMB Stage-4 (CMB-S4) [105], and PICO [106] (e.g., map noise levels of 6 μK-arcmin, 1 μK-arcmin, and 0.6 μK-arcmin, respectively) will achieve nearly cosmic-variance limited measurements of CMB primary anisotropies, and reduce lensing reconstruction noise

by a factor of ~ 20. CMB-S4 should improve ULA sensitivity to $\Omega_a \sim 10^{-3}$ at the most constrained m_a values and probe the range $m_a \sim 10^{-23}$ eV [96]. CMB lensing will drive future tests of BSM scenarios [96]. Additionally, electromagnetic couplings of ULAs will produce additional signatures from CMB anisotropies, including CMB spectral distortions [107–111].

Unique among DM candidates, axions with $f_a \gtrsim H_I$ imply the presence of a low-mass field during the inflationary era, exciting DM (isocurvature) fluctuations that are statistically independent from baryons, neutrinos, and radiation [112–118]. This would cause a phase shift and low-ℓ amplitude change in the CMB peaks [119]. The size of this ULA imprint would be controlled by H_I. H_I sets the amplitude of the inflationary gravitational-wave (GW) background, which is detectable through CMB B-mode polarization, parameterized by the tensor-to-scalar ratio r [120, 121]. In the mass window 10^{-25} eV $\lesssim m_a \lesssim 10^{-24}$ eV, current data allow a $\sim 10\%$ contribution of ULAs to the DM along with $\sim 1\%$ contributions of isocurvature and tensors to the CMB power spectrum [96].

Detecting primordial B-modes is a science driver for ground-based CMB observatories and future space missions (e.g. Spider [122], BICEP2-3/Keck Array [123, 124], CLASS [125], Simons Array [126], SO [127], CMB-S4 [105], LiteBIRD [128]), and PICO [106]). These efforts could probe values $r \sim 10^{-4} \rightarrow 10^{-3}$. Cosmological probes of Ω_a and the inflationary energy scale [88, 129–132] are thus complementary. For Ω_a saturating current bounds, the combined isocurvature and lensing sensitivity of CMB-S4 would probe values $H_I \gtrsim 10^{13.3}$ GeV [98, 105]. A detection of primordial B-modes at S4 sensitivity levels would test ULA contributions at the level of $\Omega_a \simeq 0.01$ [98, 105]. Foreground cleaning techniques may even allow measurements of the lensing power spectrum to multipoles of $L \sim 40,000$ [133]. The CMB could then distinguish between pure CDM and ULAs, in the preferred $\sim 10^{-22}$ eV window hinted at in the Milky Way [47, 50, 56]. This window will be tested by other structure formation probes.

IV.   OPTICAL & INFRARED SURVEYS

Another probe of axions is the clustering power spectrum $P_g(k)$ of galaxies, which has already imposed the limit $\Omega_a \sim 3 \times 10^{-2}$ at the most constrained m_a values, comparable to the unlensed CMB alone [89, 134]. The Large Synoptic Survey telescope (LSST) will produce surveys that improve error bars in $P_g(k)$ as well as weak lensing observables and thus sensitivity to Ω_a by an order of magnitude [135]. Additionally, future space missions like Euclid and WFIRST will improve sensitivity to the matter power-spectrum $P_\delta(k)$ by an order of magnitude [136–139]. Lyman-α (Lyα) absorption of quasar emission depends on the optical depth of neutral hydrogen, and is sensitive to DM densities at early times [140–145]. Depending on modeling details, the data impose a limit of $m_a \gtrsim 1 \rightarrow 40 \times 10^{-22}$ eV, if ULAs compose all of the DM.

Next-generation spectroscopic surveys like the Dark Energy Spectroscopic Instrument (DESI), Euclid and WFIRST will improve sensitivity to the matter power-spectrum $P_\delta(k)$ from Lyα measurements by an order of magnitude [146]. The small-scale power in ULA models relative to ΛCDM models scales as $(\lambda/\lambda_J)^8 \propto m_a^4$, and so these measurements could push the ULA mass limit as high as $m_a \gtrsim 4 \rightarrow 160 \times 10^{-22}$ eV. There are also prospects for Milky-Way scale effects. LSST's *complete* census of ultra-faint dwarf galaxies in the Milky Way will test extensions to standard ΛCDM, including ULAs [135]. An ultra-faint dwarf census can put an upper limit on M_{half}, the mass scale below which r.m.s density fluctuations fall to half their ΛCDM values [147]. LSST could test M_{half} values of $10^6 M_\odot$, probing values $m_a \gtrsim 10^{-19}$ eV [147].

The reionization of the universe occurred around redshift $z \sim 6$ and is tied to structure formation at early times and small scales. CMB constraints to the Thomson scattering optical depth from reionization and measurements of the galaxy luminosity function depend on the low mass galaxy population, and would be impacted by a significant fraction of ULA DM [148]. Current observations allow the range $m_a \geq 10^{-22}$ eV. Future James Webb Space Telescope (JWST) observations will constrain the UV galaxy luminosity function to rest-frame magnitudes of $M_{UV} = -16$, beyond the $M_{UV} = -17$ cutoff of 10^{-22} eV ULA DM, testing the ULA explanation for challenges to ΛCDM. Significant sensitivity will come from the non-linear regime [149], and so comparisons between N-body [150], fluid [151], Schrödinger [152–156] and Klein-Gordon approaches are essential, as is consideration of self-interactions [97, 103, 141, 145, 157].

V. BLACK HOLES AND GRAVITATIONAL WAVE ASTRONOMY

In the coming decade, pulsar timing arrays could detect a stochastic background of GWs down to $\sim 10^{-9}$ Hz or individual $\sim 10^9 M_\odot$ supermassive black hole (BH) binaries. If DM has a significant ULA component, the Milky Way gravitational potential will oscillate [on time scales $\delta t \simeq 20$ ns $(m_a/10^{-23}$ eV$)^{-3}(\Omega_a/0.3)$], within reach of pulsar timing efforts like NANOGrav and the Parkes Pulsar Timing Array (if $m_a \lesssim 10^{-23}$ eV) [158], and distinct from GW signals. The Square Kilometer Array (SKA) will improve sensitivity to Ω_a by an order of magnitude [158]. Reaching values $m_a \gtrsim 10^{-22}$ eV requires hundreds of new millisecond pulsars [158], though the detailed density profiles of ULAs [159] could improve sensitivity. Collisions and mergers of ultra-compact solitons could generate gravitational waves in addition to standard sources (BHs and neutron stars) [160–162].

Another powerful phenomenon is BH Superradiance (BHSR) [9, 10, 36, 85, 163]. If ULAs exist, they would form bound states near spinning BHs. An instability would lead to the spin down of BHs with Kerr radii comparable to their ULA Compton wavelengths, while transitions between bound states could lead to GW emission, enhanced in binary systems [164]. The existence of stellar and supermassive BH populations rules out ULAs with 6×10^{-13} eV $\lesssim m_a \lesssim 2 \times 10^{-11}$ eV and 10^{-18} eV $\lesssim m_a \lesssim 10^{-16}$ eV [85, 163]. Future measurements of the BH mass function by Advanced LIGO could push the lower limit of the stellar mass ULA window down to 1×10^{-13} eV. In the Advanced LIGO band, detections are possible in the $m_a \sim 10^{-10}$ eV range, while the LISA band is sensitive to values $m_a \sim 10^{-17}$ eV [36].

VI. CONCLUSIONS & RECOMMENDATIONS

Ultra-light axions could be an important component of the dark sector, as late-time dark energy, early dark energy, or dark matter, depending on the axion mass. This merits attention in the next decade, especially if searches for weakly interacting massive particles (WIMPs) yield null results [165]. We make the following recommendations:

- Support proposed CMB [105, 106, 127] and large-scale structure surveys [135–139].
- Support independent investigations in theory, simulations and data analysis, as well as comparisons of diverse methods via interaction between groups worldwide.
- Support development of novel probes, from ultra small-scale CMB experiments [133] to X-ray studies of neutron star cooling [166] and very large samples of pulsars [158], so that the window for all ultra-light axion dark matter 10^{-23} eV $\lesssim m_a \lesssim 10^{-19}$ eV is decisively probed via diverse methods, on the small scales where discovery potential is greatest.

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977), [,328(1977)].

[2] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[3] F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[4] W. Hu, R. Barkana, and A. Gruzinov, Phys. Rev. Lett. **85**, 1158 (2000), arXiv:astro-ph/0003365 [astro-ph].

[5] P. Svrcek and E. Witten, JHEP **06**, 051 (2006), arXiv:hep-th/0605206 [hep-th].

[6] B. S. Acharya, K. Bobkov, and P. Kumar, JHEP **11**, 105 (2010), arXiv:1004.5138 [hep-th].

[7] M. Cicoli, M. Goodsell, and A. Ringwald, JHEP **10**, 146 (2012), arXiv:1206.0819 [hep-th].

[8] M. Demirtas, C. Long, L. McAllister, and M. Stillman, (2018), arXiv:1808.01282 [hep-th].

[9] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, Phys. Rev. **D81**, 123530 (2010), arXiv:0905.4720 [hep-th].

[10] D. J. E. Marsh, Phys. Rept. **643**, 1 (2016), arXiv:1510.07633 [astro-ph.CO].

[11] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Phys. Rev. **D95**, 043541 (2017), arXiv:1610.08297 [astro-ph.CO].

[12] M. J. Stott, D. J. E. Marsh, C. Pongkitivanichkul, L. C. Price, and B. S. Acharya, Phys. Rev. **D96**, 083510 (2017), arXiv:1706.03236 [astro-ph.CO].

[13] L. Visinelli and S. Vagnozzi, (2018), arXiv:1809.06382 [hep-ph].

[14] D. Baumann, D. Green, and B. Wallisch, Phys. Rev. Lett. **117**, 171301 (2016), arXiv:1604.08614 [astro-ph.CO].

[15] J. A. Frieman, C. T. Hill, A. Stebbins, and I. Waga, Phys. Rev. Lett. **75**, 2077 (1995), arXiv:astro-ph/9505060 [astro-ph].

[16] D. J. E. Marsh and P. G. Ferreira, Phys. Rev. **D82**, 103528 (2010), arXiv:1009.3501 [hep-ph].

[17] L. F. Abbott and P. Sikivie, Phys. Lett. **B120**, 133 (1983), [,URL(1982)].

[18] M. S. Turner, Phys. Rev. D **28**, 1243 (1983).

[19] L. J. Rosenberg (ADMX), *Proceedings, International Conference on Axions 2010: Gainesville, Florida, January 15-17, 2010*, AIP Conf. Proc. **1274**, 109 (2010).

[20] S. M. Lewis (ADMX-HF), in *Proceedings, 12th Patras Workshop on Axions, WIMPs and WISPs (PATRAS 2016): Jeju Island, South Korea, June 20-24, 2016* (2017) pp. 86–89.

[21] P. W. Graham and S. Rajendran, Phys. Rev. **D88**, 035023 (2013), arXiv:1306.6088 [hep-ph].

[22] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran, and A. Sushkov, Phys. Rev. **X4**, 021030 (2014), arXiv:1306.6089 [hep-ph].

[23] G. G. Raffelt, *Axions: Theory, cosmology, and experimental searches. Proceedings, 1st Joint ILIAS-CERN-CAST axion training, Geneva, Switzerland, November 30-December 2, 2005*, Lect. Notes Phys. **741**, 51 (2008), [,51(2006)], arXiv:hep-ph/0611350 [hep-ph].

[24] J. K. Vogel *et al.*, in *8th Patras Workshop on Axions, WIMPs and WISPs (AXION-WIMP 2012) Chicago, Illinois, July 18-22, 2012* (2013) arXiv:1302.3273 [physics.ins-det].

[25] A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, and F. Steffen (MADMAX Working Group), Phys. Rev. Lett. **118**, 091801 (2017), arXiv:1611.05865 [physics.ins-det].

[26] N. Du *et al.* (ADMX), Phys. Rev. Lett. **120**, 151301 (2018), arXiv:1804.05750 [hep-ex].

[27] D. J. E. Marsh, K.-C. Fong, E. W. Lentz, L. Smejkal, and M. N. Ali, (2018), arXiv:1807.08810 [hep-ph].

[28] I. G. Irastorza and J. Redondo, Prog. Part. Nucl. Phys. **102**, 89 (2018), arXiv:1801.08127

[hep-ph].

[29] P. Sikivie, *Particle physics and cosmology: Dark matter*, Phys. Rev. Lett. **51**, 1415 (1983), [,321(1983)].

[30] D. Cadamuro, *Cosmological limits on axions and axion-like particles*, Ph.D. thesis, Munich U. (2012), arXiv:1210.3196 [hep-ph].

[31] A. Friedland, M. Giannotti, and M. Wise, Phys. Rev. Lett. **110**, 061101 (2013), arXiv:1210.1271 [hep-ph].

[32] R. Perna, W. Ho, L. Verde, M. van Adelsberg, and R. Jimenez, Astrophys. J. **748**, 116 (2012), arXiv:1201.5390 [astro-ph.HE].

[33] M. Giannotti, I. Irastorza, J. Redondo, and A. Ringwald, JCAP **1605**, 057 (2016), arXiv:1512.08108 [astro-ph.HE].

[34] M. Giannotti, I. G. Irastorza, J. Redondo, A. Ringwald, and K. Saikawa, JCAP **1710**, 010 (2017), arXiv:1708.02111 [hep-ph].

[35] J. Isern, E. Garcia-Berro, S. Torres, and S. Catalan, Astrophys. J. **682**, L109 (2008), arXiv:0806.2807 [astro-ph].

[36] N. Kitajima, J. Soda, and Y. Urakawa, JCAP **1810**, 008 (2018), arXiv:1807.07037 [astro-ph.CO].

[37] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, JCAP **1206**, 013 (2012), arXiv:1201.5902 [hep-ph].

[38] B. Li, P. R. Shapiro, and T. Rindler-Daller, Phys. Rev. **D96**, 063505 (2017), arXiv:1611.07961 [astro-ph.CO].

[39] N. Aghanim *et al.* (Planck), (2018), arXiv:1807.06209 [astro-ph.CO].

[40] T. Matos and J. A. Nieto, Rev. Mex. Fis. **39**, S81 (1993).

[41] T. Matos, F. S. Guzman, and L. A. Urena-Lopez, Class. Quant. Grav. **17**, 1707 (2000), arXiv:astro-ph/9908152 [astro-ph].

[42] A. Suarez and T. Matos, Mon. Not. Roy. Astron. Soc. **416**, 87 (2011), arXiv:1101.4039 [gr-qc].

[43] J.-c. Hwang and H. Noh, Phys. Lett. **B680**, 1 (2009), arXiv:0902.4738 [astro-ph.CO].

[44] C.-G. Park, J.-c. Hwang, and H. Noh, Phys. Rev. **D86**, 083535 (2012), arXiv:1207.3124 [astro-ph.CO].

[45] J. Magana, T. Matos, A. Suarez, and F. J. Sanchez-Salcedo, JCAP **1210**, 003 (2012), arXiv:1204.5255 [astro-ph.CO].

[46] V. Poulin, T. L. Smith, T. Karwal, and M. Kamionkowski, (2018), arXiv:1811.04083 [astro-ph.CO].

[47] J. S. Bullock and M. Boylan-Kolchin, Ann. Rev. Astron. Astrophys. **55**, 343 (2017), arXiv:1707.04256 [astro-ph.CO].

[48] C. H. Lee and S. J. Sin, J. Korean Phys. Soc. **28**, 16 (1995).

[49] A. Arbey, J. Lesgourgues, and P. Salati, Phys. Rev. **D68**, 023511 (2003), arXiv:astro-ph/0301533 [astro-ph].

[50] D. J. E. Marsh and J. Silk, Mon. Not. Roy. Astron. Soc. **437**, 2652 (2014), arXiv:1307.1705 [astro-ph.CO].

[51] D. J. E. Marsh and A.-R. Pop, Mon. Not. Roy. Astron. Soc. **451**, 2479 (2015), arXiv:1502.03456 [astro-ph.CO].

[52] A. X. González-Morales, D. J. E. Marsh, J. Peñarrubia, and L. A. Ureña López, Mon. Not. Roy. Astron. Soc. **472**, 1346 (2017), arXiv:1609.05856 [astro-ph.CO].

[53] T. Bernal, L. M. Fernández-Hernández, T. Matos, and M. A. Rodríguez-Meza, Mon. Not. Roy. Astron. Soc. **475**, 1447 (2018), arXiv:1701.00912 [astro-ph.GA].

[54] H. Deng, M. P. Hertzberg, M. H. Namjoo, and A. Masoumi, Phys. Rev. **D98**, 023513 (2018), arXiv:1804.05921 [astro-ph.CO].

[55] T. Broadhurst, I. de Martino, H. N. Luu, G. F. Smoot, and S. H. H. Tye, (2019), arXiv:1902.10488 [astro-ph.CO].

[56] D. J. E. Marsh, (2016), arXiv:1605.05973 [astro-ph.CO].

[57] D. J. E. Marsh and J. C. Niemeyer, (2018), arXiv:1810.08543 [astro-ph.CO].

[58] V. H. Robles, L. A. Martinez-Medina, and T. Matos, (2015), arXiv:1503.00799 [astro-ph.GA].

[59] L. A. Martinez-Medina, H. L. Bray, and T. Matos, JCAP **1512**, 025 (2015), arXiv:1505.07154 [astro-ph.GA].

[60] R. Emami, T. Broadhurst, G. Smoot, T. Chiueh, and L. H. Nhan, (2018), arXiv:1806.04518 [astro-ph.CO].

[61] X. Li, L. Hui, and G. L. Bryan, (2018), arXiv:1810.01915 [astro-ph.CO].

[62] P. Sikivie and Q. Yang, Phys. Rev. Lett. **103**, 111301 (2009), arXiv:0901.1106 [hep-ph].

[63] O. Erken, P. Sikivie, H. Tam, and Q. Yang, in *Proceedings, 7th Patras Workshop on Axions, WIMPs and WISPs (AXION-WIMP 2011): Mykonos, Greece, June 27-July 1, 2011* (2011) pp. 43–46, arXiv:1111.3976 [astro-ph.CO].

[64] K. Saikawa and M. Yamaguchi, Phys. Rev. **D87**, 085010 (2013), arXiv:1210.7080 [hep-ph].

[65] A. H. Guth, M. P. Hertzberg, and C. Prescod-Weinstein, Phys. Rev. **D92**, 103513 (2015), arXiv:1412.5930 [astro-ph.CO].

[66] N. Banik and P. Sikivie, arXiv e-prints , arXiv:1501.05913 (2015), arXiv:1501.05913 [astro-ph.CO].

[67] N. Banik, A. Christopherson, P. Sikivie, and E. M. Todarello, in *Proceedings, 11th Patras Workshop on Axions, WIMPs and WISPs (Axion-WIMP 2015): Zaragoza, Spain, June 22-26, 2015* (2015) pp. 134–139, arXiv:1509.02081 [astro-ph.CO].

[68] T. Rindler-Daller and P. R. Shapiro, Mod. Phys. Lett. **A29**, 1430002 (2014), arXiv:1312.1734 [astro-ph.CO].

[69] B. Li, T. Rindler-Daller, and P. R. Shapiro, Phys. Rev. **D89**, 083536 (2014), arXiv:1310.6061 [astro-ph.CO].

[70] A. Natarajan and P. Sikivie, Phys. Rev. **D73**, 023510 (2006), arXiv:astro-ph/0510743 [astro-ph].

[71] L. D. Duffy and P. Sikivie, Phys. Rev. **D78**, 063508 (2008), arXiv:0805.4556 [astro-ph].

[72] J. Dumas, H. J. Newberg, B. Niedzielski, A. Susser, J. M. Thompson, J. Weiss, and K. M. Lewis, Astrophys. J. **811**, 36 (2015), arXiv:1508.04494 [astro-ph.GA].

[73] S. S. Chakrabarty and P. Sikivie, Phys. Rev. **D98**, 103009 (2018), arXiv:1808.00027 [astro-ph.GA].

[74] P.-H. Chavanis, Phys. Rev. **D94**, 083007 (2016), arXiv:1604.05904 [astro-ph.CO].

[75] J. Berges, K. Boguslavski, A. Chatrchyan, and J. Jaeckel, Phys. Rev. **D96**, 076020 (2017), arXiv:1707.07696 [hep-ph].

[76] D. G. Levkov, A. G. Panin, and I. I. Tkachev, Phys. Rev. Lett. **121**, 151301 (2018), arXiv:1804.05857 [astro-ph.CO].

[77] P.-H. Chavanis and T. Harko, Phys. Rev. **D86**, 064011 (2012), arXiv:1108.3986 [astro-ph.SR].

[78] J. Eby, P. Suranyi, C. Vaz, and L. C. R. Wijewardhana, JHEP **03**, 080 (2015), [Erratum: JHEP11,134(2016)], arXiv:1412.3430 [hep-th].

[79] J. Eby, P. Suranyi, and L. C. R. Wijewardhana, Mod. Phys. Lett. **A31**, 1650090 (2016), arXiv:1512.01709 [hep-ph].

[80] J. Eby, M. Leembruggen, P. Suranyi, and L. C. R. Wijewardhana, JHEP **12**, 066 (2016), arXiv:1608.06911 [astro-ph.CO].

[81] L. Visinelli, S. Baum, J. Redondo, K. Freese, and F. Wilczek, Phys. Lett. **B777**, 64 (2018), arXiv:1710.08910 [astro-ph.CO].

[82] P.-H. Chavanis, Phys. Rev. **D98**, 023009 (2018), arXiv:1710.06268 [gr-qc].

[83] M. A. Amin and P. Mocz, (2019), arXiv:1902.07261 [astro-ph.CO].

[84] B. Schwabe, J. C. Niemeyer, and J. F. Engels, Phys. Rev. **D94**, 043513 (2016), arXiv:1606.05151 [astro-ph.CO].

[85] A. Arvanitaki and S. Dubovsky, Phys. Rev. **D83**, 044026 (2011), arXiv:1004.3558 [hep-th].

[86] A. Loeb, Scientific American **295** (2006).

[87] K. Coble, S. Dodelson, and J. A. Frieman, Phys. Rev. **D55**, 1851 (1997), arXiv:astro-ph/9608122 [astro-ph].

[88] D. J. E. Marsh, D. Grin, R. Hložek, and P. G. Ferreira, Phys. Rev. **D87**, 121701 (2013), arXiv:1303.3008 [astro-ph.CO].

[89] R. Hložek, D. Grin, D. J. E. Marsh, and P. G. Ferreira, Phys. Rev. **D91**, 103512 (2015), arXiv:1410.2896 [astro-ph.CO].

[90] R. Emami, D. Grin, J. Pradler, A. Raccanelli, and M. Kamionkowski, Phys. Rev. **D93**, 123005 (2016), arXiv:1603.04851 [astro-ph.CO].

[91] L. Amendola and R. Barbieri, Phys. Lett. **B642**, 192 (2006), arXiv:hep-ph/0509257 [hep-ph].

[92] L. A. Ureña López and A. X. Gonzalez-Morales, JCAP **1607**, 048 (2016), arXiv:1511.08195 [astro-ph.CO].

[93] M. Khlopov, B. A. Malomed, and I. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **215**, 575 (1985).

[94] P.-H. Chavanis, Astron. Astrophys. **537**, A127 (2012), arXiv:1103.2698 [astro-ph.CO].

[95] A. Suarez and P.-H. Chavanis, Phys. Rev. **D92**, 023510 (2015), arXiv:1503.07437 [gr-qc].

[96] R. Hložek, D. J. E. Marsh, D. Grin, R. Allison, J. Dunkley, and E. Calabrese, Phys. Rev. **D95**, 123511 (2017), arXiv:1607.08208 [astro-ph.CO].

[97] F. X. L. Cedeño, A. X. González-Morales, and L. A. Ureña L'opez, Phys. Rev. **D96**, 061301 (2017), arXiv:1703.10180 [gr-qc].

[98] R. Hložek, D. J. E. Marsh, and D. Grin, Mon. Not. Roy. Astron. Soc. **476**, 3063 (2018), arXiv:1708.05681 [astro-ph.CO].

[99] U. Seljak and M. Zaldarriaga, Phys. Rev. Lett. **82**, 2636 (1999), arXiv:astro-ph/9810092 [astro-ph].

[100] M. Zaldarriaga and U. Seljak, Phys. Rev. **D59**, 123507 (1999), arXiv:astro-ph/9810257 [astro-ph].

[101] T. Okamoto and W. Hu, Phys. Rev. **D67**, 083002 (2003), arXiv:astro-ph/0301031 [astro-ph].

[102] D. Hanson, A. Challinor, and A. Lewis, Gen. Rel. Grav. **42**, 2197 (2010), arXiv:0911.0612 [astro-ph.CO].

[103] V. Poulin, T. L. Smith, D. Grin, T. Karwal, and M. Kamionkowski, Phys. Rev. **D98**, 083525 (2018), arXiv:1806.10608 [astro-ph.CO].

[104] J. Aguirre *et al.* (Simons Observatory), JCAP **1902**, 056 (2019), arXiv:1808.07445 [astro-ph.CO].

[105] K. N. Abazajian *et al.* (CMB-S4), (2016), arXiv:1610.02743 [astro-ph.CO].

[106] S. Hanany *et al.* (NASA PICO), (2019), arXiv:1902.10541 [astro-ph.IM].

[107] S. Lee, G.-C. Liu, and K.-W. Ng, Phys. Lett. **B746**, 406 (2015), arXiv:1403.5585 [astro-ph.CO].

[108] G. Sigl and P. Trivedi, (2018), arXiv:1811.07873 [astro-ph.CO].

[109] S. Mukherjee, R. Khatri, and B. D. Wandelt, JCAP **1804**, 045 (2018), arXiv:1801.09701 [astro-ph.CO].

[110] S. Mukherjee, R. Khatri, and B. D. Wandelt, (2018), arXiv:1811.11177 [astro-ph.CO].

[111] M. A. Fedderke, P. W. Graham, and S. Rajendran, (2019), arXiv:1903.02666 [astro-ph.CO].

[112] M. Axenides, R. H. Brandenberger, and M. S. Turner, Phys. Lett. **126B**, 178 (1983).

[113] M. S. Turner, F. Wilczek, and A. Zee, Phys. Lett. **125B**, 35 (1983), [Erratum: Phys. Lett.125B,519(1983)].

[114] D. H. Lyth, Phys. Rev. **D45**, 3394 (1992).

[115] P. Fox, A. Pierce, and S. D. Thomas, (2004), arXiv:hep-th/0409059 [hep-th].

[116] M. P. Hertzberg, M. Tegmark, and F. Wilczek, Phys. Rev. **D78**, 083507 (2008), arXiv:0807.1726 [astro-ph].

[117] E. Komatsu *et al.* (WMAP), Astrophys. J. Suppl. **180**, 330 (2009), arXiv:0803.0547 [astro-ph].

[118] D. Langlois, Lect. Notes Phys. **800**, 1 (2010), arXiv:1001.5259 [astro-ph.CO].

[119] D. Baumann, D. Green, J. Meyers, and B. Wallisch, JCAP **1601**, 007 (2016), arXiv:1508.06342 [astro-ph.CO].

[120] U. Seljak and M. Zaldarriaga, Phys. Rev. Lett. **78**, 2054 (1997), arXiv:astro-ph/9609169 [astro-ph].

[121] M. Kamionkowski, A. Kosowsky, and A. Stebbins, Phys. Rev. **D55**, 7368 (1997), arXiv:astro-ph/9611125 [astro-ph].

[122] R. Gualtieri *et al.* (SPIDER), *17th International Workshop on Low Temperature Detectors (LTD 17) Kurume, Japan, July 17-21, 2017*, J. Low. Temp. Phys. **193**, 1112 (2018), arXiv:1711.10596 [astro-ph.CO].

[123] J. A. Grayson *et al.* (BICEP3), *Proceedings, SPIE Astronomical Telescopes + Instrumentation 2016 : Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII: Edinburgh, United Kingdom, June 28-July 1, 2016*, Proc. SPIE Int. Soc. Opt. Eng. **9914**, 99140S (2016), arXiv:1607.04668 [astro-ph.IM].

[124] P. A. R. Ade *et al.* (BICEP2, Keck Array), Phys. Rev. Lett. **121**, 221301 (2018), arXiv:1810.05216 [astro-ph.CO].

[125] T. Essinger-Hileman *et al.*, in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9153 (2014) p. 91531I, arXiv:1408.4788 [astro-ph.IM].

[126] B. Westbrook *et al.*, *17th International Workshop on Low Temperature Detectors (LTD 17) Kurume City, Japan, July 17-21, 2017*, J. Low. Temp. Phys. **193**, 758 (2018).

[127] N. Galitzki (2018) arXiv:1810.02465 [astro-ph.IM].

[128] A. Suzuki *et al.*, Journal of Low Temperature Physics **193**, 1048 (2018), arXiv:1801.06987 [astro-ph.IM].

[129] L. Visinelli and P. Gondolo, Phys. Rev. **D80**, 035024 (2009), arXiv:0903.4377 [astro-ph.CO].

[130] D. J. E. Marsh, D. Grin, R. Hložek, and P. G. Ferreira, Phys. Rev. Lett. **113**, 011801 (2014), arXiv:1403.4216 [astro-ph.CO].

[131] L. Visinelli and P. Gondolo, Phys. Rev. Lett. **113**, 011802 (2014), arXiv:1403.4594 [hep-ph].

[132] L. Visinelli, Phys. Rev. **D96**, 023013 (2017), arXiv:1703.08798 [astro-ph.CO].

[133] H. N. Nguyen, N. Sehgal, and M. Madhavacheril, (2017), arXiv:1710.03747 [astro-ph.CO].

[134] C. Blake *et al.*, Mon. Not. Roy. Astron. Soc. **406**, 803 (2010), arXiv:1003.5721 [astro-ph.CO].

[135] P. A. Abell *et al.* (LSST Science, LSST Project), (2009), arXiv:0912.0201 [astro-ph.IM].

[136] L. Amendola *et al.*, Living Rev. Rel. **21**, 2 (2018), arXiv:1606.00180 [astro-ph.CO].

[137] R. Thompson, J. Green, G. Rieke, D. Z. B. Robertson, G. Schneider, D. Stark, B. Jannuzi, D. Ebbets, M. Kaplan, and R. Gracey, (2013), arXiv:1312.4548 [astro-ph.IM].

[138] D. Spergel *et al.*, (2013), arXiv:1305.5425 [astro-ph.IM].

[139] O. Doré *et al.* (WFIRST), (2018), arXiv:1804.03628 [astro-ph.CO].

[140] E. Armengaud, N. Palanque-Delabrouille, C. Yèche, D. J. E. Marsh, and J. Baur, Mon. Not. Roy. Astron. Soc. **471**, 4606 (2017), arXiv:1703.09126 [astro-ph.CO].

[141] V. Desjacques, A. Kehagias, and A. Riotto, Phys. Rev. **D97**, 023529 (2018), arXiv:1709.07946 [astro-ph.CO].

[142] T. Kobayashi, R. Murgia, A. De Simone, V. Iršič, and M. Viel, Phys. Rev. **D96**, 123514 (2017), arXiv:1708.00015 [astro-ph.CO].

[143] V. Iršič, M. Viel, M. G. Haehnelt, J. S. Bolton, and G. D. Becker, Phys. Rev. Lett. **119**, 031302 (2017), arXiv:1703.04683 [astro-ph.CO].

[144] M. Nori, R. Murgia, V. Iršič, M. Baldi, and M. Viel, (2018), arXiv:1809.09619 [astro-ph.CO].

[145] K.-H. Leong, H.-Y. Schive, U.-H. Zhang, and T. Chiueh, (2018), arXiv:1810.05930 [astro-ph.CO].

[146] A. Aghamousa *et al.* (DESI), (2016), arXiv:1611.00036 [astro-ph.IM].

[147] A. Drlica-Wagner *et al.* (LSST Dark Matter Group), (2019), arXiv:1902.01055 [astro-ph.CO].

[148] B. Bozek, D. J. E. Marsh, J. Silk, and R. F. G. Wyse, Mon. Not. Roy. Astron. Soc. **450**, 209 (2015), arXiv:1409.3544 [astro-ph.CO].

[149] K. Markovic, S. Bridle, A. Slosar, and J. Weller, JCAP **1101**, 022 (2011), arXiv:1009.0218 [astro-ph.CO].

[150] J. Zhang, Y.-L. S. Tsai, J.-L. Kuo, K. Cheung, and M.-C. Chu, Astrophys. J. **853**, 51 (2018), arXiv:1611.00892 [astro-ph.CO].

[151] M. Nori and M. Baldi, Mon. Not. Roy. Astron. Soc. **478**, 3935 (2018), arXiv:1801.08144 [astro-ph.CO].

[152] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Nature Phys. **10**, 496 (2014), arXiv:1406.6586 [astro-ph.GA].

[153] H.-Y. Schive, M.-H. Liao, T.-P. Woo, S.-K. Wong, T. Chiueh, T. Broadhurst, and W. Y. P. Hwang, Phys. Rev. Lett. **113**, 261302 (2014), arXiv:1407.7762 [astro-ph.GA].

[154] P. Mocz, M. Vogelsberger, V. H. Robles, J. Zavala, M. Boylan-Kolchin, A. Fialkov, and L. Hernquist, Mon. Not. Roy. Astron. Soc. **471**, 4559 (2017), arXiv:1705.05845 [astro-ph.CO].

[155] X. Du, B. Schwabe, J. C. Niemeyer, and D. Büurger, Phys. Rev. **D97**, 063507 (2018), arXiv:1801.04864 [astro-ph.GA].

[156] J. Veltmaat, J. C. Niemeyer, and B. Schwabe, Phys. Rev. **D98**, 043509 (2018), arXiv:1804.09647 [astro-ph.CO].

[157] M. A. Amin, P. Zukin, and E. Bertschinger, Phys. Rev. **D85**, 103510 (2012), arXiv:1108.1793 [astro-ph.CO].

[158] N. K. Porayko *et al.*, (2018), arXiv:1810.03227 [astro-ph.CO].

[159] I. De Martino, T. Broadhurst, S. H. Henry Tye, T. Chiueh, H.-Y. Schive, and R. Lazkoz, Phys. Rev. Lett. **119**, 221103 (2017), arXiv:1705.04367 [astro-ph.CO].

[160] C. Palenzuela, P. Pani, M. Bezares, V. Cardoso, L. Lehner, and S. Liebling, Phys. Rev. **D96**, 104058 (2017), arXiv:1710.09432 [gr-qc].

[161] T. Helfer, E. A. Lim, M. A. G. Garcia, and M. A. Amin, Phys. Rev. **D99**, 044046 (2019), arXiv:1802.06733 [gr-qc].

[162] K. Clough, T. Dietrich, and J. C. Niemeyer, Phys. Rev. **D98**, 083020 (2018),

arXiv:1808.04668 [gr-qc].

[163] M. J. Stott and D. J. E. Marsh, Phys. Rev. **D98**, 083006 (2018), arXiv:1805.02016 [hep-ph].

[164] D. Baumann, H. S. Chia, and R. A. Porto, Phys. Rev. **D99**, 044001 (2019), arXiv:1804.03208 [gr-qc].

[165] G. Bertone and M. P. Tait, Tim, Nature **562**, 51 (2018), arXiv:1810.01668 [astro-ph.CO].

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