Snowmass2021 - Letter of Interest

Cosmic probes of ultra-light axion dark matter

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

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics and cosmology

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Abstract: Ultra-light axions are a compelling dark matter candidate, motivated by the string axiverse, the strong CP problem in QCD, and possible tensions in the CDM model. They are hard to probe experimentally, and so cosmological/astrophysical observations are very sensitive to the distinctive gravitational phenomena of ULA dark matter. There is the prospect of probing fifteen orders of magnitude in mass, often down to sub-percent contributions to the DM in the next ten to twenty years. The promise of exploring this parameter space motivates an extensive program of future theoretical, computational, and observational work.

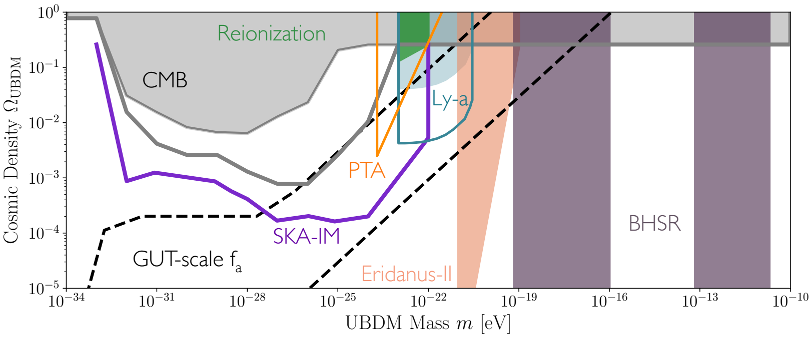

Figure 1: Current and projected exclusions on ULA DM[5].

The axion is a well-motivated dark matter (DM) candidate that solves the “strong CP problem”[1–3]. Ultra-light axions (ULAs) are axion-like particles with very small masses ($m_{\mathrm{a}} \lesssim 10^{-10}\,\mathrm{eV}$), generically present in string theories, which predict the existence of many different axions . Ultra-light axions are sufficiently light that wave-like behavior would manifest on astrophysical scales [$\sim$ kpc to Mpc]. This could explain possible tensions between observations and simulations of the standard cold dark matter (CDM) model on galactic scales. The very lightest ULAs ($m_{\mathrm{a}} \lesssim 10^{-29}\,\mathrm{eV}$) behave like dark energy at late times[4]. ULAs would alter cosmic expansion and perturbation growth[4,6–19], allowing *Planck* data to impose the constraint $\Omega_{\mathrm{a}} \lesssim 10^{-2}$ in the window $10^{-32}\,\mathrm{eV} \lesssim m_{\mathrm{a}} \lesssim 10^{-26}\,\mathrm{eV}$ (see Fig. 1)[19,20]. Future experiments like the Simons Observatory (SO)[21] and CMB Stage-4 (CMB-S4)[22] (e.g., map noise levels of 6 $\mu\mathrm{K\text{-}arcmin}$ and 1 $\mu\mathrm{K\text{-}arcmin}$) will achieve sensitive measurements of primary anisotropies, and reduce CMB lensing noise by a factor of ~ 20. CMB-S4 should improve ULA sensitivity to $\Omega_{\mathrm{a}} \sim 10^{-3}$ at the most constrained m_{a} values and probe the range $m_{\mathrm{a}} \sim 10^{-23}\,\mathrm{eV}$[17]. Electromagnetic ULA couplings will also yield CMB spectral-distortion signatures[23–27].

Axions would source isocurvature[28–34] with amplitude set by the inflationary Hubble parameter H_{I} and the axion decay constant f_a. H_I sets the amplitude of the inflationary gravitational-wave (GW) background, detectable through CMB B-mode polarization[35,36] (a driver for future experiments like SO[37], CMB-S4[22], LiteBIRD[38]), allowing sensitivity to $H_{\mathrm{I}} \gtrsim 10^{13.3}$ GeV and $\Omega_{\mathrm{a}} \simeq 0.01$ at S4 sensitivity levels[19,22]. Cosmological probes of Ω_{a} and the inflationary energy scale[12,39–42] are thus complementary. If 10^{-25} eV $\lesssim m_{\mathrm{a}} \lesssim 10^{-24}$ eV, current data allow a $\sim 10\%$ contribution of ULAs to the DM along with $\sim 1\%$ contributions of isocurvature and tensors[17]. Proposed small-scale experiments like CMB-HD[43] could measure the lensing power spectrum to $L \sim 40,000$, allowing the CMB to distinguish between pure CDM and ULAs in the $\sim 10^{-22}$ eV window relevant to Milky-Way (MW) scale challenges to ΛCDM[44–46].

The Lyman-α forest of neutral hydrogen absorption traces the underlying DM distribution at high redshift[47,48], probing the smallest scales ($\sim$ 500 kpc) accessible in the linear power spectrum[49]. As the wavenumber of the axion-induced power spectrum cut-off $k_{\frac{1}{2}} \propto m_{\mathrm{a}}^{4/9}$, accessing smaller scales gives sensitivity to heavier axions[50]. The challenge is to marginalize over the state of the IGM, leveraging recent advances in modeling the IGM and cosmic reionization[51–53], methods for statistical inference (e.g., optimized emulators)[54–57] and understanding of systematic effects in the data[58,59]. The strongest current bounds impose the bound $m_{\mathrm{a}} > 2 \times 10^{-20}$ eV at 95% credibility[60–63]. Independent measurements of IGM properties by eBOSS and DESI could break ULA/IGM degeneracies[64], allowing high-z measurements of the power spectrum to smaller scales ($\sim$ 100 kpc), thus probing larger axion masses ($m_{\mathrm{a}} \sim 10^{-19}$ eV).[65,66] We advocate for improved theoretical modeling and simulations of the impact of reionization on the IGM[67]. At higher z, intensity mapping of lines like the neutral hydrogen 21-cm transition by efforts like HIRAX and the SKA could detect a $\sim 10\%$ or smaller contribution of ULAs to DM for $m_{\rm a} \lesssim 10^{-22}$ eV.[68]

The effect of ULAs on the matter power spectrum will also manifest in the properties of individual galaxies and the large-scale galaxy distribution[13]. If ULAs constitute all or a significant fraction of the DM, the MW gravitational potential will oscillate on timescales $t \sim 20\,{\rm ns}\,(m_{\rm a}/10^{-23}\,{\rm eV})^{-3}(\Omega_{\rm a}/0.3)$. This is accessible with pulsar timing arrays (PTA), e.g., NanoGRAV, Parkes Pulsar Timing Array. The Square Kilometer Array (SKA) can improve sensitivity to $\Omega_{\rm a}$ by an order of magnitude. The Rubin Observatory Legacy Survey of Space and Time (LSST) will vastly improve upon current constraints with measurements of galaxy weak lensing. Future space-based missions, e.g., Euclid, WFIRST, will improve sensitivity to the matter power spectrum by an order of magnitude, improving sensitivity to ULA DM. By altering the growth of structure, ULAs would alter cosmic bulk flows (like neutrinos), altering the Compton-scattering imprint of galaxy clusters on the CMB (the kinetic Sunyaev Zel'dovich or kSZ effect)[69]. Work is needed to assess how well future CMB measurements and galaxy surveys could probe this signal[70].

ULAs suppress high-redshift galaxy formation and thus delay reionization. A combination of the *Hubble Space Telescope* Ultra Deep Field UV luminosity function at redshifts $6 < z < 10$ and the CMB optical depth to reionization[71,72] exclude ULAs being more than half of the DM with masses $m_{\rm a} \leq 10^{-23}$ eV, and similar future James Webb Space Telescope (JWST) measurements would probe the canonical fuzzy dark matter (FDM) mass of 10^{-22} eV.[73,74] The ULA suppression of the power spectrum also translates into a low-mass cutoff in the halo/subhalo abundance. MW satellite galaxies detected by the Dark Energy Survey and Pan-STARRS impose a lower limit on the ULA mass of $m_a > 2.9 \times 10^{-21}$ eV at 95% confidence[75], while subhalos inferred from strong lensing of quasars[76,77] and stellar stream perturbations observed by *Gaia* and Pan-STARRS[78–80] translate to a similar lower limit of $m_a > 2.1 \times 10^{-21}$ eV.[81] Future surveys are expected to discover hundreds of new MW satellites, thousands of new strong lenses, and to deliver precise stellar stream measurements, improving ULA mass sensitivity to $\sim 10^{-19}$ eV.[82] Analytic arguments and simulations suggest that ULAs form soliton cores in DM halos, with imprints on galactic rotation curves[83–86]. Well-resolved, low surface-brightness disk galaxies may thus be used to constrain the ULA mass from below and evade concerns about baryonic feedback. Cored density profiles of faint dwarf galaxies have been interpreted as signatures of ULAs[87], although it is unclear if the ULA masses that solve the "core–cusp problem" are compatible with other constraints[75,88,89].

Ultralight bosons can trigger a superradiant instability in the presence of a spinning black hole (BH), depleting the rotational energy of the BHs[90]. BHe superradiance has two implications: monochromatic gravitational radiation, and gaps at large spin in the BH spin-mass distribution.[91–95] The stochastic background of gravitational radiation implies the LIGO/Virgo experiment is sensitive to $m_s \in \left[2 \times 10^{-13} - 10^{-12}\right]$eV and LISA will be sensitive to $m_s \in \left[5 \times 10^{-19} - 5 \times 10^{-16}\right]$eV.[95]

To realize the potential of these probes, analysis pipelines and resources of many observational efforts need to include ULA DM as a science driver and ambitious observations (e.g. CMB-HD) are needed. Theoretical modeling must also be expanded, and current techniques subjected to critical tests. Predictions for linear-theory observables should be reexamined to clarify the relationship between ULA field and fluid descriptions[14,15,15,96–99]. Simulation codes for ULA DM[100–103] provide a tool to run numerical experiments to compare competing DM models. Simulations can refine analytic theory, higlight model features (e.g. non-linear structure-formation channels[104]), and aid in interpreting observations in current and upcoming space-based missions, ultimately setting new constraints on the DM particle mass and interactions. There is the need to develop and validate multiple implementations, particularly with regard to the coupling of dark matter with hydrodynamics governing gas physics and star formation and the detailed treatment of interference effects. Careful modeling of the ULA subhalo mass function is a key systematic uncertainty in the small-scale structure and kSZ analyses described above, and the impact of ULA self-interactions on cosmological subhalos is largely unexplored.

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