Snowmass2021 - Letter of Interest

Ultralight Bosonic Dark Matter Theory

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

□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) Theory Frontier: Astroparticle Physics and Cosmology

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Abstract: With this letter of interest (LoI), we propose a Snowmass white paper which reviews and addresses outstanding questions in ultralight bosonic dark matter, or ultralight axion (ULA), theory. We outline next steps that will advance our theoretical understanding of ULAs outside of the regime of usual assumptions, which will pave the way for making sharper predictions for observational probes of realistic theories with ULAs. For the purposes of this LoI, we define ULAs to have masses around $\sim 10^{-20}$ eV. We choose this mass regime in particular because of novel astrophysical phenomena that could be a smoking gun signature for ULAs, including halo-scale solitons.

Introduction:

Axion-like particles (ALPs)[1–3], a generalized term that describe both the QCD axion and beyond-Standard-Model particles with potentials similar to the QCD axion, may comprise a substantial fraction of the dark matter (DM) and display exotic phenomenologies that are quite distinct from other particle DM candidates like weakly interacting massive particles (WIMPs)[4–6]. ALPs as DM candidates are increasingly compelling as targets of ongoing and planned experimental searches[7–10]. The classic QCD axion has been the biggest focus of ALP-related research, whether in the context of laboratory searches or more indirect astrophysical and cosmological approaches. More recently, ultralight ALPs (ULAs) with masses of order $\sim 10^{-22}$ eV have emerged as a way of dovetailing challenges in small-scale structure formation with string-inspired DM production mechanisms[11,12].

In considering the behavior of ULA DM in the context of astrophysical and cosmological settings, it is often assumed that ULAs interact primarily through gravity and that the ULA potentials can be neglected. In these simplistic models, critical physics such as self-interactions is often ignored because of analytical complexities associated with making them more realistic[13]. Moreover, much of the work on ULAs has primarily focused on $m \sim 10^{-22}$ eV mass ULAs comprising all of the DM, with the effects on small-scale structure in the nearby Universe in mind; however, several observational probes are converging to disfavor $m \lesssim$ few$\times 10^{-21}$ eV[14–23] if DM is entirely ULAs. In what follows, we outline some proposed topics of interest for the white paper and give examples of key questions for each topic. Note that there may be overlap between the topics and that the topics are meant to serve as broad categories.

Motivations:

We begin with the motivations for ULAs: what are the classes of theories which give rise to ULAs? What is the status of the QCD axion as a dark matter candidate? Ultralight bosons, particularly ALPs, are compelling DM candidates in the context of string theory, and their discovery could shed light on physics at extremely high energies (see *e.g.* [24]). We aim to summarize the theoretical motivations for ULAs and place them within the context of various UV theories.

Assumptions:

The theoretical work on ULAs often utilizes simplifying assumptions: what assumptions are made about ULA models? What is the regime of validity of these assumptions? For example, one simplifying assumption is to neglect the axion potential and to only consider the gravitational interactions of the axion with the Standard Model and with itself (as well as the effects of "quantum pressure" which arise due to the macroscopic de Broglie wavelength and not because of additional forces). However, axion fields obey a shift symmetry. Since shift-symmetric potentials generally have terms that are not quadratic in the axion field, the axion energy density does not necessarily redshift entirely as DM. We aim to enumerate the assumptions made in ULA theory and elaborate on the regime of validity of these assumptions and how they affect the formation, evolution, and constraints on ULAs.

Formation:

Given the motivations and assumptions about ULAs, how do we create a self-consistent formation history for ULAs? What are the early universe dynamics of ULAs? What are the initial conditions? What is considered the "natural" parameter space? For instance, ULAs with $m \sim 10^{-22}$ eV and decay constants of order Planck scale could be made in a way that is similar to the traditional misalignment mechanism for the QCD axion[12], which is somewhat reminiscent of the "WIMP miracle." Alternatively, a large misalignment angle, coupled with attractive self-interactions, can significantly enhance structure formation on small scales via a parametric resonance[25]. We aim to summarize these and other various production mechanisms of ULAs.

Cosmological Evolution:

Another key topic of interest is in the evolution of ULAs: what is the cosmological history of ULAs? What is the theory behind structure formation with ULAs? How do self-interactions affect the cosmological and astrophysical predictions of ULAs? The behavior of ULAs in the linear regime of clustering has been well studied, see e.g.[16]. Recent work has attempted to improve our understanding of structure formation with ULAs in the nonlinear regime with simulations and semi-analytic models[26–29], primarily focusing on the regime with $m \sim 10^{-22}$ eV ULAs comprising all DM and ignoring the axion potential.

We propose supporting an active research program with significant theoretical and numerical efforts dedicated to exploring ULA structure formation with a less restrictive set of assumptions. An (incomplete) list of such non-perturbative, nonlinear phenomena to be pursued that could reveal the underlying nature of ULAs include: non-perturbative, scale-dependent growth of linear perturbations in axions in the early (and late) universe[30,31] (including for example the effects of non-quadratic terms in the axion potential[32]), as well as the formation and dynamics of solitons (oscillons/oscillatons/axitons/axion-stars) and vortices in the early and present-day universe[14,33–36]. There are also interesting avenues to explore in the linear regime, where distinctions between fluid, field, Klein-Gordon/Schrödinger descriptions may have phenomenological consequences[31,37–40,40,41]. Moving beyond the non-interacting/weakly interacting limit, such phenomena should be investigated by including effects of strong self-interactions in axion-like fields[25,31,35,42], as well as potentially resonant interactions with other fields[43] and with the inclusion of sufficient baryonic physics in a realistic cosmological setting[26,27]. In some cases, these effects can enhance rather than suppress structure beyond the ULA Jeans scale.

Detection and Constraints:

Finally, how do we detect ULAs? How do the assumptions which go into ULA models affect the validity of the various constraints? For example, the earliest black hole superradiance constraints assumed negligible self-interactions[24,44,45]. More recent work has demonstrated that including self-interactions and other non-linear effects can dramatically alter the dynamics of black hole superradiance[44,46,47]. In addition, including the effects of dynamical friction in an ULA background may affect the predictions of ULA constraints[12,48,49]. Many structure formation constraints hinge on the ULA being a significant portion of the DM and only consider gravitational interactions[21,22,50]; more recent work has shown that going beyond these assumptions dramatically affect the phenomenology and constraints, for instance taking into account the axion potential. Current bounds from the Cosmic Microwave Background set an approximate limit on the axion decay constant, $f_a \gtrsim 10^{13}\mathrm{GeV}(10^{-20}\ \mathrm{eV}/m_a)$[32], independently of the axion production mechanism; even more stringent bounds can be derived if one assumes production through misalignment[51]. Furthermore, imprints on rotation curves in well-resolved, low surface-brightness disk galaxies mays be used to constrain the ULA mass from below, as analytic arguments and simulations suggest that ULAs form soliton cores in DM halos[52–55].

Outlook:

ULAs have a rich phenomenology in the context of astrophysics and cosmology, which has yet to be fully explored outside a regime of standard assumptions. These assumptions may not apply to well-motivated classes of theories. We advocate for more support for theoretical work in this area, focusing both on the extreme UV motivations and early Universe formation as well as the evolution and dynamics of ULAs at later times in the history of the Universe. In light of new theoretical developments, existing constraints may need reinterpretation or new observable predictions that may emerge; this program thus has the capability to engage theorists and observers alike across a broad range of sub-disciplines in astrophysics, cosmology, and particle physics.

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