**Ultralight Axion and the Fuzzy Scalaron in RFT Cosmology**

**Introduction**

In modern cosmology, the nature of dark matter remains one of the most profound mysteries. While the prevailing **Cold Dark Matter (CDM)** paradigm successfully explains large-scale structure, it faces notable challenges on small galactic scales (the so-called “small-scale crisis”). Issues such as the *missing satellites problem*, the *cusp–core problem*, and the *too-big-to-fail problem* suggest CDM predicts overly dense or numerous subgalactic structures​

[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=small%20scales%2C%20known%20as%20the,and%20the)

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[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=structure%20by%20astrophysical%20processes%20,2000)

. Proposed solutions include baryonic feedback or alternative dark matter models like **Warm Dark Matter (WDM)**, **Decaying DM**, **Self-Interacting DM (SIDM)**, and **Fuzzy Dark Matter (FDM)**​

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. Among these, FDM – also known as **ultralight axion-like dark matter**, **wave dark matter**, or a **Bose–Einstein condensate (BEC) dark matter** – has gained significant interest for its distinct quantum nature and potential to resolve small-scale tensions​

[aanda.org](https://www.aanda.org/articles/aa/pdf/2020/09/aa36272-19.pdf#:~:text=A%20promising%20alternative%20to%20WIMPs,solve%20some%20of%20the%20discrepancies)

. FDM posits that dark matter is composed of extremely light bosonic particles (mass $m\_a \sim 10^{-22}$ eV) which have astronomically large de Broglie wavelengths (~kpc scale)​

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. This imprints a “fuzzy” granularity on small scales and naturally produces **cored halo density profiles** instead of cusps, thereby addressing several CDM problems​

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In this report, we **investigate an ultralight axion as the fundamental origin of the “fuzzy scalaron”** in a theoretical RFT cosmology framework. *Scalaron* here refers to a scalar degree of freedom (as appears, for example, in extended gravity theories like $f(R)$ models) that is extremely light and behaves as fuzzy dark matter. The term **RFT cosmology** alludes to a high-energy framework (possibly a “Scalaron in *f*(R,T) gravity” or other *Relativistic Field Theory*) wherein this scalaron arises. We hypothesize that this fuzzy scalaron is not an ad-hoc field but rather originates from a string-theoretic **axion** in the **“Axiverse”** – a plethora of light axion-like fields predicted by string compactifications​

[arxiv.org](https://arxiv.org/html/2502.02256v1#:~:text=The%20string%20axiverse%20emerges%20naturally,a%20viable%20dark%20matter%20candidate)

. Our goal is to link high-energy theory with cosmological phenomenology: **How can string theory produce an ultralight axion ($m\_a \sim 10^{-22}$–$10^{-20}$ eV) with appropriate couplings? How does this axion-driven scalaron influence structure formation (e.g. solitonic cores and interference patterns) and cosmological observables?** We will derive the expected mass, decay constant, and interactions of such an axion; describe simulations of its cosmological evolution; compare its predictions against astrophysical data (from JWST, Gaia, Vera Rubin Observatory); explore detection strategies (precision clocks, interferometers); and contrast this scenario with CDM, WDM, SIDM, and MOND paradigms. The aim is to formulate a coherent, testable framework for an ultralight axion scalaron as a fundamental component of the cosmos.

**String Theory Axiverse and the Origin of Ultralight Axions**

High-energy physics, especially string theory, provides a compelling origin for ultralight axions through the concept of the **Axiverse**​

[arxiv.org](https://arxiv.org/html/2502.02256v1#:~:text=The%20string%20axiverse%20emerges%20naturally,a%20viable%20dark%20matter%20candidate)

. In string compactifications (such as Type IIB on Calabi–Yau orientifolds or M-theory on $G\_2$ manifolds), numerous light pseudo-scalar fields (axions) naturally arise from the extra-dimensional form fields integrated over various cycles. These axions inherit a **shift symmetry** (a remnant of higher-dimensional gauge invariance) that keeps them massless at the perturbative level. However, nonperturbative effects like **Euclidean brane instantons** or **hidden gauge instantons** can break the continuous shift symmetry to a discrete one, generating a periodic axion potential. In Type IIB, for example, axions can descend from the Ramond–Ramond 2-form or 4-form, and Euclidean D3-branes wrapping four-cycles induce a potential $V(a)$​

[arxiv.org](https://arxiv.org/html/2502.02256v1#:~:text=In%20this%20setting%2C%20the%20continuous,and%20for%20the%20Pfaffians)

. The generic form of an instanton-induced axion potential is:

V(a)  ≈  Λ4[1−cos⁡ ⁣(afa)],V(a) \;\approx\; \Lambda^4 \left[1 - \cos\!\left(\frac{a}{f\_a}\right)\right],V(a)≈Λ4[1−cos(fa​a​)],

where $f\_a$ is the axion’s **decay constant** (related to the gauge coupling or string modulus decay constant) and $\Lambda$ is an energy scale tied to the instanton action $S$ via $\Lambda^4 \sim M^4 e^{-S}$ (with $M$ some UV scale like the string or Planck scale). For small oscillations, this yields a **tiny axion mass**:

ma  ≃  Λ2fa  ≈  M e−S/2fa .m\_a \;\simeq\; \frac{\Lambda^2}{f\_a} \;\approx\; M \, \frac{e^{-S/2}}{f\_a}\,. ma​≃fa​Λ2​≈Mfa​e−S/2​.

In the **String Axiverse** scenario, a *wide range* of axion masses is possible​

[arxiv.org](https://arxiv.org/html/2502.02256v1#:~:text=The%20string%20axiverse%20emerges%20naturally,a%20viable%20dark%20matter%20candidate)

. Notably, there is no strict lower bound – volumes of cycles can be large, or hidden sector dynamics very weak, producing exponentially small $\Lambda$ and hence extremely light axions (even as low as $10^{-33}$ eV in principle). An **ultralight axion of mass $\sim10^{-22}$–$10^{-21}$ eV** is therefore not exotic in string theory; it can emerge from, e.g., a large-volume cycle or an instanton with an exceptionally large action. The **decay constants** $f\_a$ for string axions typically range from GUT-scale up to near Planck-scale ($10^{16}$–$10^{18}$ GeV)​

[link.aps.org](https://link.aps.org/accepted/10.1103/PhysRevD.96.056025#:~:text=Dynamical%20mechanisms%20to%20generate%20an,times%20the%20square%20of%20the)

. Indeed, an ultralight axion DM candidate in this mass range was noted to likely have $f\_a$ in the $10^{16}$–$10^{18}$ GeV range​

[link.aps.org](https://link.aps.org/accepted/10.1103/PhysRevD.96.056025#:~:text=Dynamical%20mechanisms%20to%20generate%20an,times%20the%20square%20of%20the)

. Large $f\_a$ ensures the axion is very weakly coupled (only gravitationally or via higher-dimension operators to standard model fields), consistent with being “dark.”

**Symmetry-breaking and instanton effects:** The production of such an ultralight axion relies on an **approximate global U(1) symmetry** (e.g. a Peccei–Quinn-like symmetry) that is broken *only by nonperturbative effects*. In the early universe, the axion is “frozen” at some misalignment angle in its potential. When the Hubble parameter drops to order $m\_a$, the field begins to oscillate coherently, acting as cold dark matter (through the misalignment production mechanism). Achieving $m\_a \sim 10^{-22}$ eV typically requires an *extreme hierarchy*: for instance, if $f\_a \sim 10^{17}$ GeV, one needs $\Lambda \sim 10^{-12}$ GeV (on the order of meV) to obtain such a tiny mass. This corresponds to an instanton action $S \approx 2\ln(M/\Lambda) \sim 2\ln(10^{19} / 10^{-3}) \sim 2 \ln(10^{22}) \approx 2 \times 50.7 \approx 101.4$. In other words, **a nonperturbative effect with action $S \sim 100$–$300$** could generate the desired ultralight mass. Such large actions are possible in the extra-dimensional geometry: e.g. an Euclidean D-brane wrapping a large cycle (volume $V \gg 1$ in string units) yields $S = 2\pi V$. The **Large Volume Scenario (LVS)** in Type IIB string theory is an attractive setup to realize this hierarchy. LVS compactifications naturally have one very large modulus controlling the overall volume and smaller moduli for local structures; an axion associated with a large cycle can acquire a exponentially suppressed mass while other moduli are stabilized at higher scales. Indeed, studies have found that in a single-modulus KKLT stabilization it’s hard to get an ultralight axion without fine-tuning the electroweak scale extremely low, whereas **in an LVS multi-modulus setup the separation between the weak scale and an ultralight $10^{-22}$ eV axion scale can be achieved naturally**​

[link.aps.org](https://link.aps.org/accepted/10.1103/PhysRevD.96.056025#:~:text=scale%20and%20the%20weak%20scale,is%20discussed%20and%20it%20is)

. Thus, high-energy theory provides a plausible **origin story**: the fuzzy scalaron corresponds to a string-theoretic axion with a large decay constant and an instanton-generated potential so shallow that its mass is $\sim10^{-22}$ eV.

**Theoretical predictions – mass, $f\_a$, and couplings:** We take as a benchmark a *fuzzy axion* with $m\_a \approx 10^{-22}$ eV and $f\_a \sim 10^{17}$ GeV. Such a field has a Compton wavelength $\lambda\_C = h/(m\_a c) \sim 1$ kiloparsec, meaning on astrophysical scales it behaves as a coherent wave rather than individual particles. The axion’s coupling to gravity is universal (it contributes to stress-energy). Couplings to Standard Model particles depend on details: for example, axions can couple to photons via $\mathcal{L}*{a\gamma} = \frac{g*{a\gamma}}{4} a F\_{\mu\nu}\tilde F^{\mu\nu}$ or to fermions via derivative couplings (pseudoscalar Yukawa). In string models, $g\_{a\gamma}$ or other couplings are typically suppressed by $f\_a$ (so extremely small, $g\_{a\gamma}\sim 1/f\_a$). This means direct detection is challenging, but as we will explore, **precision measurements can seek tiny oscillatory signatures**. If the fuzzy axion plays the role of a “scalaron” in an extended gravity theory (like an $f(R)$ model), it would also couple to the Ricci scalar (scalaron mixes with gravity). However, because $f\_a$ is huge, any “fifth-force” mediated by this field is highly suppressed – avoiding conflicts with equivalence principle tests. In summary, string constructions (Type IIB, M-theory) provide a robust framework for ultralight axions, yielding a **predicted mass** in the $10^{-22}$–$10^{-20}$ eV range, a **decay constant** $f\_a$ of order $10^{16-18}$ GeV, and only **feeble couplings** to normal matter aside from gravity. This matches the requirements for a dark matter scalaron.

**Fuzzy Scalaron in RFT Cosmology and Field Equations**

If the ultralight axion is a fundamental field from high-energy theory, in the low-energy **RFT cosmology** (a relativistic field theory framework, which could be akin to a scalar-tensor or $f(R)$ theory), it appears as a **classical scalar field** pervading the universe. We refer to it as a “fuzzy scalaron” to emphasize its wave-like nature and its role as a scalar degree of freedom influencing the cosmology. This section outlines its dynamics.

**Field dynamics:** At cosmological scales, an ultralight bosonic field with negligible interactions is governed by the Klein–Gordon equation in an expanding universe. During matter-dominated eras, the field oscillates rapidly at frequency $m\_a$ and its oscillation envelope behaves like pressure-less dust (an effect of **adiabatic invariance**). On smaller (galactic) scales, however, quantum pressure (from the field gradients) cannot be neglected. A convenient description splits into two regimes:

* **Linear regime / free streaming:** Initially, perturbations in the scalaron grow like CDM on large scales. But below a characteristic **Jeans scale** (set by when quantum pressure halts collapse), perturbation growth is suppressed. For $m\_a\sim10^{-22}$ eV, the Jeans length at matter–radiation equality corresponds to roughly the scale of dwarf galaxy halos (a few $10^8 M\_\odot$ in mass or kpc radius)​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=e.g.%20ultra,redshift%20of%20the%20sample%20may)

. This creates a **cutoff in the matter power spectrum** at small scales, analogous to WDM with a warm particle of a few keV mass​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=spectral%20energy%20distribution%20,halo%20formation%20as%20the%20FDM)

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* **Nonlinear regime / wave dynamics:** Once structure formation proceeds, the fuzzy field inside halos must be treated as a **coupled Schrödinger–Poisson system**. The nonrelativistic limit of an ultralight scalar in a gravitational potential $V$ can be described by a wavefunction $\psi(\mathbf{x},t)$ related to the density as $\rho = | \psi |^2$ and obeying: iℏ ∂ψ∂t  =  −ℏ22ma∇2ψ  +  ma V(x,t) ψ,i\hbar\,\frac{\partial \psi}{\partial t} \;=\; -\frac{\hbar^2}{2m\_a}\nabla^2\psi \;+\; m\_a\,V(\mathbf{x},t)\,\psi,iℏ∂t∂ψ​=−2ma​ℏ2​∇2ψ+ma​V(x,t)ψ, ∇2V=4πG (∣ψ∣2+ρother) ,\nabla^2 V = 4\pi G\, (|\psi|^2 + \rho\_{\rm other})\,,∇2V=4πG(∣ψ∣2+ρother​), where $V$ is the Newtonian gravitational potential sourced by the fuzzy DM density and any other matter. This is equivalent to the **Madelung formulation**: a continuity equation for $\rho$ and an Euler-like equation with a quantum pressure term $Q \propto \hbar^2/(m\_a^2)\nabla^2\sqrt{\rho}/\sqrt{\rho}$​

[aanda.org](https://www.aanda.org/articles/aa/pdf/2020/09/aa36272-19.pdf#:~:text=simulations%20including%20both%20of%20these,equations%2C%20with%20an%20additional%20pressure)

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[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=alternative%20dark%20matter%20models%20like,2000)

. The quantum pressure (or equivalently the Heisenberg uncertainty principle) prevents arbitrarily small clumping of the scalaron, leading to **soliton core** solutions in virialized halos.

**Scalaron as $f(R)$ gravity field:** If we interpret the fuzzy scalaron in context of an extended gravity theory (for instance, in Starobinsky’s $f(R)$ gravity, a scalaron field $\phi$ emerges via $f(R)=R+\frac{1}{6m^2},R^2$ and $\phi$ has a mass $m$), there is an intriguing identification: perhaps the ultralight axion *is* this scalaron. Traditional $f(R)$ models require $m$ relatively large (e.g. to mediate short-range forces), but one could conceive an extreme $f(R)$ or scalar-tensor model tuned such that the scalaron is ultralight and thus cosmologically active. In such a case, the **RFT cosmology** would be a scalar-tensor theory where the “fuzzy” scalar degree is the axion. The field equations would then mix gravitational and scalar dynamics. However, for the scope of this work, we largely treat the scalaron as **free dark matter field minimally coupled to gravity** (any deviations in cosmic expansion or gravity due to it being an $f(R)$ scalaron are assumed small on large scales, given the need to match $\Lambda$CDM successes). The key is that the scalaron oscillates coherently and gravitates just like CDM on large scales, while on small scales its wave nature manifests.

In summary, the fuzzy scalaron obeys the **Schrödinger–Poisson (SP) equations** in structure formation, yielding stable solitonic cores and interference patterns, and effectively behaves as CDM with a small-scale cutoff in linear cosmology. With the groundwork of the field’s theoretical origin and equations laid out, we turn next to quantitative predictions and simulations of how such a scalaron shapes cosmic structure.

**Simulation of Scalaron Cosmological Evolution**

Simulating ultralight axion dark matter requires capturing **wave mechanics** on kiloparsec scales within cosmological volumes – a formidable computational challenge. Over the past few years, significant progress has been made by using tailored simulation codes (e.g. modified gravity solvers or hybrid N-body methods). Here we review the methodologies and key findings from simulations using tools like **RAMSES**, **AREPO**, and dedicated scalar field codes.

**Schrödinger–Poisson solvers:** One approach is to directly solve the Schrödinger–Poisson equations on a grid. For example, *Mina et al.* developed *SCALAR*, an Adaptive-Mesh-Refinement (AMR) code based on **RAMSES** that evolves the wavefunction on refined grids​

[aanda.org](https://www.aanda.org/articles/aa/pdf/2020/09/aa36272-19.pdf#:~:text=We%20present%20a%20new%20code%2C,to%20demonstrate%20how%20accurately%20it)

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[aanda.org](https://www.aanda.org/articles/aa/pdf/2020/09/aa36272-19.pdf#:~:text=Fisher%202007%29,small%20scales%20of%20structure%20formation)

. Such codes can simulate the formation of halos including wave interference and **soliton core formation** self-consistently. Another approach is the pseudo-spectral method employed in some **AREPO** integrations (e.g., Mocz et al.), where the wave equation is solved in Fourier space or a **hybrid algorithm** is used. A hybrid strategy is often necessary because evolving the entire cosmological volume at the tiny spatial resolution required for FDM is impractical. Instead, **zoom-in simulations** focus computational effort on a region of interest (like a single halo) while treating larger scales with conventional N-body. Schwabe et al. (2022) introduced such a hybrid zoom-in scheme: they first run an N-body simulation (which is valid on large scales since FDM effects only appear below the cutoff), then replace a chosen halo’s particles with a reconstructed wavefunction and evolve that with the Schrödinger–Poisson solver​

[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=Investigating%20these%20highly%20nonlinear%20wave,sized)

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[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=mass%20accretion%20onto%20pre,to%20simulations%20significantly%20closer%20to)

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**Key results from simulations:** These simulations consistently show that **interference and solitons are hallmark features** of fuzzy dark matter structure formation. As structure collapses, wave interference of different modes leads to a wildly fluctuating granular density field within halos and filaments​

[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=,wave%20phenomena%20requires%20the%20spatially)

. The interference pattern manifests as quasi-random, time-varying density “speckles” of size on the order of the de Broglie wavelength (hundreds of pc to kpc). Eventually, the innermost region of each halo settles into a long-lived **solitonic core** – a self-gravitating ground-state solution where quantum pressure balances gravity. Surrounding this core, the halo’s outer profile matches a CDM-like envelope (often approximated by an NFW profile at radii much larger than the core). High-resolution simulations find a definite **core–halo mass relation**: lower halo masses have proportionally larger, less massive cores. For instance, a $10^{11}M\_\odot$ halo might host a soliton core of $\sim10^8M\_\odot$ within a radius of a few hundred parsecs, whereas a $10^9M\_\odot$ halo might be mostly soliton. These relations emerge naturally from the scaling properties of the SP equations and were first noted in early simulations (e.g. Schive et al. 2014). Subsequent studies refined this and found some scatter but the trend remains: **heavier halos => smaller relative core**.

*Density slices zooming into a simulated fuzzy dark matter halo, from large scales (left) to the inner core (right). The panels reveal the characteristic interference fringes and granular density structure of FDM, as well as the smooth, high-density solitonic core (bright yellow in the rightmost panel) at the halo center. These results (from a simulation by Schwabe & Niemeyer) illustrate how interfering wave modes produce a fluctuating “fuzzy” halo, while gravity drives condensation into a stable core.*

In the example illustrated above, by employing a Gaussian-beam wavefunction reconstruction, researchers achieved an **effective spatial resolution of ~20 pc** in the innermost halo region​

[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=mass%20accretion%20onto%20pre,to%20simulations%20significantly%20closer%20to)

– sufficient to resolve the core and interference pattern in a $M\_{\rm vir}\sim1.7\times10^{11}M\_\odot$ halo for $m\_a=2.5\times10^{-22}$ eV​

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. The simulation (in a $60,h^{-1}$ Mpc box) demonstrates that even with a particle mass at the lower end of the allowed window, one can approach realistic galaxy halo scales in computation. It confirms that on **large scales, FDM mimics CDM** (the halo’s virial mass and outer density profile are similar to what a CDM simulation would yield, aside from the absence of sub-halos below the FDM Jeans mass). On **small scales, the differences are stark**: the center is a soliton (with a radius $\sim$ a few percent of the virial radius) and the halo density field undergoes oscillations as interference patterns drift and decohere over time. These granular density fluctuations have typical amplitude of order unity (i.e. density can momentarily dip or spike by factors of order 2 on kpc patches) but average out to a smooth profile.

**Structure formation and cosmic web:** Cosmologically, fuzzy axion models produce noticeably different **halo mass functions** and clustering on small scales. Power spectrum calculations and N-body or semi-analytic methods have shown that FDM with $m\_a\sim10^{-22}$ eV suppresses the formation of low-mass halos below $\sim10^8$–$10^9 M\_\odot$​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=e.g.%20ultra,redshift%20of%20the%20sample%20may)

. The cosmic web in such a universe has **thicker filaments** and more diffuse small-scale structure compared to CDM. Interestingly, recent work suggests interference *within filaments* may lead to unique signatures: for example, **extended periodic density ripples** along filaments caused by coherent waves​

[arxiv.org](https://arxiv.org/abs/2412.10829#:~:text=ultralight%20bosonic%20dark%20matter%20species%2C,up)

. These interference fringes in large-scale structure are a distinctive prediction that has no counterpart in WDM (which would produce smooth filaments)​

[arxiv.org](https://arxiv.org/abs/2412.10829#:~:text=,up)

. Verifying such features would require detailed mapping of matter in filaments (e.g. via weak gravitational lensing at high resolution).

In summary, simulations with RAMSES/Arepo-based and custom codes consistently support the picture that an ultralight axion scalaron produces:

* **Cored halos:** A dense, stable soliton core at each halo center instead of a cusp.
* **Suppressed substructure:** A dearth of halos below the Jeans mass cut-off (reducing dwarf galaxy counts, etc.).
* **Interference-induced granularity:** Fluctuating density “grains” throughout halos and filaments, a unique wave phenomenon​

[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=,wave%20phenomena%20requires%20the%20spatially)

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* **Delayed small-scale collapse:** Structure formation on small scales (dwarf galaxies, $z>10$ mini-halos) is delayed relative to CDM due to the initial power suppression.

We will next confront these predictions with **astrophysical observations** to see if the ultralight axion model is favored or constrained, and then discuss how one might **experimentally detect** such a scalar field oscillating in the universe.

**Confrontation with Astrophysical Observations**

A successful cosmological model must not only solve small-scale issues but also **match existing observations across all scales and epochs**. Here we examine how the ultralight axion (fuzzy scalaron) scenario compares with data from galaxies, cosmology, and recent surveys, highlighting potential discriminators.

**Large-scale structure and CMB:** On scales of galaxy clusters, BAO, and the cosmic microwave background (CMB), a $10^{-22}$–$10^{-21}$ eV axion behaves almost indistinguishably from CDM. The linear matter power spectrum is identical down to the wavenumber $k\_{\rm cut}\sim \frac{m\_a}{10^{-22}{\rm eV}},(10~{\rm kpc})^{-1}$ (roughly $k\sim10$–$20h$/Mpc for $m\_a=10^{-22}$ eV). Only for $k$ beyond this (small scales) does the FDM power spectrum drop precipitously​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=e.g.%20ultra,redshift%20of%20the%20sample%20may)

. This means current CMB and large-scale galaxy clustering observations (e.g. Planck, SDSS) are consistent with fuzzy DM for the masses considered; they mainly constrain the total dark matter abundance (which in our case is all in the axion scalaron). One area where differences could appear is in the formation of the first structures at high redshift.

**High-redshift galaxy counts (JWST):** The **James Webb Space Telescope (JWST)** has provided an unprecedented look at galaxies in the epoch $z\sim7$–13. Surprising early results indicate an abundance of massive galaxies at $z>7$ that is higher than some $\Lambda$CDM models predicted. One interpretation is that **star-formation efficiency** in early halos must be higher than expected. However, if star formation is too efficient, it would overproduce ionizing photons and conflict with the relatively low optical depth from reionization measured by Planck. Fuzzy dark matter offers a potential reconciliation: by suppressing the number of low-mass halos, it reduces the total ionizing photon budget even if each halo is efficient in forming stars. Indeed, recent work finds that an axion mass $m\_a \approx 5\times10^{-23}$ eV (within uncertainty range $\sim3\times10^{-23}$ to $1\times10^{-22}$ eV) can **effectively suppress small halo formation** such that one can simultaneously fit the JWST high-$z$ galaxy densities (with high star formation efficiency in the few halos that do form) and adhere to reionization constraints from CMB​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=e.g.%20ultra,redshift%20of%20the%20sample%20may)

. Specifically, the FDM cutoff means fewer dwarf-mass halos at $z=8$, so to match JWST’s observed stellar mass density at $z\sim8$, each halo must form many stars – which JWST implies they did. But because there are fewer halos in total, the overall reionization photon count remains consistent with observations​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=5%5Ctimes10%5E%7B,redshift%20of%20the%20sample%20may)

. This is an elegant success for FDM (or equivalently, *WDM with particle mass of order a few keV, which has a similar cutoff effect*​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=spectral%20energy%20distribution%20,halo%20formation%20as%20the%20FDM)

). At $z\sim10$, JWST’s counts are even higher and may still challenge the model, though uncertainties in photometric redshifts could alleviate this​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=optical%20depth%20of%20CMB%20scattering,halo%20formation%20as%20the%20FDM)

. As JWST gathers more data on early galaxies, the **halo mass function at high redshift** could confirm or refute the characteristic cutoff expected from an ultralight axion. If the number of low-mass galaxies at say $z=10$–12 is found to be sharply lower than CDM predicts, that would strongly favor FDM/WDM models.

**Galactic cores and rotation curves:** One longstanding problem in CDM is that many dwarf galaxies and low-surface-brightness galaxies have **flat, cored inner density profiles** (as inferred from their rotation curves or stellar velocity dispersions), whereas naive CDM N-body simulations give steep cusps. Fuzzy dark matter naturally produces core-like profiles due to the soliton. The predicted core sizes for a given halo mass can be compared to observations of dwarf spheroidal galaxies (dSphs) in the Local Group or rotation curves of tiny dwarfs. Current data show cores of order $\sim$ few hundred pc in some dwarfs. A $m\_a\sim10^{-22}$ eV axion yields core radii in that ballpark for halo mass $M\sim10^9$–$10^{10} M\_\odot$, making it a viable explanation. If $m\_a$ were larger (e.g. $10^{-20}$ eV), the core radius for a dwarf would be much smaller (tens of pc), approaching a CDM-like cusp; if $m\_a$ were too small ($<10^{-22}$ eV), cores would be very large and perhaps in tension with denser dwarfs or Lyman-$\alpha$ forest (see below). Thus, dwarf galaxy dynamics provide a window to pinpoint the axion mass. Future **precision 3D stellar kinematic data** (e.g. from Gaia and ground-based follow-up) for faint dwarfs could map the mass distribution in the innermost regions and see if it is consistent with an FDM soliton profile (which has a specific shape: $\rho(r)\propto [1+0.091(r/r\_c)^2]^{-8}$ approximately, where $r\_c$ is core radius). A detection of this soliton profile would be a smoking gun for the wave nature of DM.

**Lyman-$\alpha$ forest constraints:** The absorption spectra of distant quasars (the Lyman-$\alpha$ forest) probe matter fluctuations at small scales $k\sim 1$–$10h$/Mpc around $z\sim 5$–6. This has been a powerful probe of warm/fuzzy dark matter. The absence of a strong suppression in the observed flux power spectrum has put a **lower bound on $m\_a$**. Analyses in recent years suggest that if FDM constitutes *all* the dark matter, one needs $m\_a \gtrsim 2\times10^{-21}$ eV to not conflict with the high-$z$ forest data at 95% confidence. Masses around $10^{-22}$ eV – the classic “fuzzy” value – are somewhat disfavored by these results, though the constraints may have model-dependent nuances (e.g., the simple FDM thermal history vs. a more detailed one, or the assumption of a sharp cutoff). Some authors have argued that properly accounting for the finite-temperature effects (quantum pressure can delay collapse of small-scale structure in a way that isn’t captured by a linear transfer function alone) can slightly weaken the bounds. Nevertheless, **Lyman-$\alpha$ remains one of the strongest constraints**, pushing the allowed axion mass towards the upper end ($10^{-21}$ eV or higher) if FDM is the sole DM component. It’s worth noting that JWST’s hints of early massive galaxies (as discussed above) seemingly prefer a lower mass ~$5\times10^{-23}$–$10^{-22}$ eV​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=e.g.%20ultra,redshift%20of%20the%20sample%20may)

. This tension could mean either a nuanced mixed DM scenario or potential systematics in one of the observations. Upcoming high-resolution Lyman-$\alpha$ data (e.g. from the DESI survey or extremely large telescopes) will refine these limits. If no suppression is seen, the pure $10^{-22}$ eV axion DM scenario could be ruled out, or conversely, evidence of a cutoff would bolster the case.

**Milky Way and Local Group observations:** Our own galaxy and its satellites offer many ways to test DM models:

* **Satellite galaxy counts:** The Milky Way’s subhalo mass function would be truncated in FDM. Current surveys have found dozens of dwarf satellites; LSST (Vera Rubin Observatory) is expected to find hundreds. In CDM, a Milky Way–sized halo could host $\sim 1000$ subhalos of mass $>10^7 M\_\odot$, many of which would be too faint to see. In FDM with $m\_a \sim 10^{-22}$ eV, halos below $\sim10^8 M\_\odot$ might not form at all. If LSST finds significantly fewer satellites than CDM predicts (even accounting for completeness), it could indicate a small-scale cutoff. Conversely, if it finds a rich population down to very low masses, that might force $m\_a$ to be larger (so the cutoff moves to smaller scales, allowing more small halos). Thus, **satellite counts vs. mass function** is a critical test.
* **Stellar stream perturbations:** Long, cold stellar streams (like Pal 5 or GD–1 in the Milky Way halo) act as “delicate seismometers” for granularity in the gravitational potential. In CDM, streams can be perturbed by encounters with subhalos (creating gaps or wobbles). In FDM, there are far fewer bound subhalos, but the diffuse interference pattern itself can disturb streams. The effect is more continuous and oscillatory rather than a single impact. Preliminary studies suggest that FDM granules (which have characteristic mass scales of $\sim10^7$–$10^8 M\_\odot$ and fluctuate on dynamical timescales) could produce observable heating or gap-like structures in streams, albeit with differences from CDM subhalo encounters (e.g. more numerous, low-density perturbers rather than fewer dense ones). Gaia’s detailed mapping of streams plus future deep surveys could measure the power spectrum of perturbations on streams. A **stochastic pattern of small perturbations** might point to FDM, whereas distinct large gaps might favor CDM subhalos.
* **Galactic center dynamics:** If a solitonic core exists in the Milky Way, it would be on the order of a few kpc in size for $m\_a\sim10^{-22}$ eV (though the MW’s halo is quite massive, $\sim10^{12}M\_\odot$, so its core would actually be smaller, perhaps $\sim100$ pc scale and quite dense). This could influence the orbits of stars near the center or the motion of globular clusters. However, the MW also has a supermassive black hole and baryonic bulge, complicating matters. It’s likely that in such massive halos the soliton core is small enough that baryonic effects dominate the inner rotation curve, making it hard to isolate the DM core.

**Galaxy clusters and lensing:** On the largest mass scales (clusters, $M\sim10^{14-15} M\_\odot$), fuzzy DM behaves almost exactly as CDM. The de Broglie wavelength for $m\_a=10^{-22}$ eV in cluster conditions (velocity dispersion ~1000 km/s) is tiny (pc scale), so quantum effects are negligible. Thus cluster masses and profiles (measured via X-ray, lensing, dynamics) are basically unchanged. One possible difference: FDM predicts fewer galaxy-scale subhalos in clusters, which could be tested by gravitational lensing perturbations (strong lensing “flux anomalies” or perturbations of Einstein rings by subhalos). So far, lensing studies favor the existence of substructure consistent with CDM levels, which might be at odds with a very low $m\_a$ that wipes out essentially all subhalos in cluster halos. However, detailed lensing mass maps could also potentially reveal interference fringes as tiny ripples in the projected mass distribution (this is speculative and would require extremely precise lensing data).

In aggregate, the astrophysical data **does not yet definitively confirm or refute** the fuzzy axion DM model, but it is honing in on the interesting parameter space. JWST and dwarf galaxy observations show some tantalizing hints that align with FDM’s expectations (suppression of small halos, presence of cores), whereas Lyman-$\alpha$ forest and lensing push towards higher particle masses (more like $>10^{-21}$ eV). It is possible that the truth allows for a small fraction of DM to be fuzzy (thus alleviating the most stringent constraints while still having some effect on small scales), or that improvements in modeling will reconcile these tensions. Ongoing and future observations (Gaia’s phase-space mapping, Vera Rubin’s deep wide-field survey, JWST’s continuing frontier imaging, 21-cm cosmology probing even smaller scales at high $z$) will provide **critical tests** of whether the universe has the subtle fingerprints of a coherent axion field.

**Detection Strategies for Ultralight Scalar Fields**

Beyond astrophysical inference, a major frontier is the **direct or indirect detection of the ultralight axion field** through its feeble non-gravitational interactions or its imprints on precision measurements. Unlike WIMPs, these axions are extremely light and very weakly coupled, so traditional collider or scattering experiments are not applicable. Instead, one exploits the facts that: (1) The field is **coherent and oscillatory** (frequency $\nu = m\_a c^2/h \sim 2.4\times10^{-8}$ Hz for $10^{-22}$ eV, up to $2.4\times10^{-6}$ Hz for $10^{-20}$ eV, i.e. periods of years to days), and (2) Huge numbers of axions occupy this state (meaning it can act as a classical oscillating background). Detection approaches can be broadly categorized into precision **frequency metrology**, **mechanical resonance**, and **gravitational wave detectors**, all searching for tiny time-varying signals matching the DM field frequency.

**Atomic clocks and precision spectroscopy:** Ultralight scalar or axion fields can induce tiny oscillations in fundamental constants (depending on the coupling). For example, if the scalaron couples to the QCD gluon field or quark masses, it can lead to oscillations in the proton mass or binding energies; coupling to electromagnetism could make the fine-structure constant $\alpha$ oscillate periodically. **Atomic clocks** compare frequency standards with extreme precision and can detect relative drifts at the $10^{-18}$ level or better. An oscillating DM field could cause an atomic transition frequency to vary sinusoidally in time. By comparing two different types of clocks (with different atomic transitions) or an atomic clock to an optical cavity, one can search for a modulation in the frequency difference. Recent advances have indeed used networks of optical clocks and cavities to set limits on such couplings in the mass range $10^{-22}$–$10^{-20}$ eV​

[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=comparison%20of%20lasers%20stabilized%20to,alone%20in%20this%20mass%20range)

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[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=Interactions%20between%20dark%20scalar%20fields,27%20%2C%20%2026%2C%2029)

. For instance, comparing optical clock data over a year-long period can look for an oscillation at a frequency corresponding to an axion mass. No signal has yet been seen, but these studies place new limits on the coupling of a light scalar to electrons and gluons in our mass window​

[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=clocks%20on%20board%20the%20Global,alone%20in%20this%20mass%20range)

. Moreover, experiments like **GPS constellation clock analyses** and dedicated laboratory setups have searched for both **continuous oscillations and transient “glitches”** (the latter could occur if topological defects in a scalar field, like domain walls, sweep through Earth, though that’s a different scenario). The basic message is that **precision metrology has become sensitive to the oscillatory signature of ultralight dark matter**, exploiting the fact that the field acts as a ~year-period oscillation of certain constants​

[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=intriguing%20and%20well,4)

. As clock technology and measurement time increase, these limits will tighten, perhaps eventually reaching the level to detect a signal if the axion’s dimensionless coupling is around $10^{-16}$–$10^{-17}$ (a rough target from some theoretical benchmarks).

**Mechanical resonators and accelerometers:** If the scalaron (axion field) couples to normal matter, it can effectively produce a tiny time-periodic force or strain. For example, an oscillating Newtonian potential (from the coherent field) could cause distances to vary periodically. High-quality-factor resonant detectors – like torsion pendulums, optical cavities (for length changes), or even gravitational wave bar detectors – can be tuned to the frequency of interest. Projects using micro-mechanical resonators or torsion balances are being devised to search for sub-Hz oscillations that could be attributed to a coherent DM wave. One interesting idea is to use the fact that Earth is moving through the DM field, so there could be a **spatial gradient or wind** of the axion field that induces a pressure on objects. Precision accelerometers might detect a tiny oscillatory acceleration not explainable by tides or seismic activity.

**Gravitational wave detector data mining:** Although $10^{-22}$–$10^{-20}$ eV corresponds to very low frequencies (well below the LIGO band), advanced gravitational wave detectors can probe certain ultra-light scenarios. For instance, if the axion coupled in such a way to make the length of the LIGO arms oscillate at the DM frequency (through oscillations of fundamental constants or metric couplings), LIGO could pick it up if the frequency falls in its sensitive band (tens of Hz). As an example, searches have been done for scalar DM with $m \sim 10^{-13}$ eV causing 10 Hz oscillations of the laser cavity length, achieving the strongest limits to date on scalar coupling in that regime​

[nature.com](https://www.nature.com/articles/s41586-021-04031-y#:~:text=Scalar%20field%20dark%20matter%20would,oscillations%20of%20the%20size)

. For our much lower frequencies, LIGO isn’t the right tool, but **pulsar timing arrays** might be: an oscillating gravitational potential across the Solar System would cause pulsar arrival times to vary periodically (effectively a very low-frequency gravitational wave signal). Current pulsar timing experiments (NANOGrav, PPTA, etc.) search for nHz frequencies (periods of years to decades) – the upper range of our axion mass window (around $10^{-21}$ eV which is $\sim$months period) could potentially create a telltale effect in pulsar timing residuals. No dedicated pulsar analysis for DM signals has yet claimed a detection, but the concept is being explored. Another idea is to use space-based atom interferometers or clocks spread over large distances (e.g. the proposed *MAGIS* space mission or a network of satellite clocks): these could directly detect spatial variations in the phase of the DM field by comparing phases at separated locations​

[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=ultralight%20dark%20matter%20to%20standard,Our%20analysis%20results%20in)

. In essence, by having two identical sensors far apart, one can look for the signature of the Earth moving through spatial oscillations of the field (a “halo orbit oscillation” signal).

**Axion-specific searches:** If the ultralight scalaron is a true QCD-like axion or axion-like particle (ALP), it may couple to photons (though typically $f\_a$ is so large that $g\_{a\gamma}$ is tiny). Still, in some models, observable effects like vacuum birefringence (rotation of polarization of light from distant sources) could accumulate. Experiments like ABRACADABRA and DM-Radio aim to detect oscillating electromagnetic fields caused by axion dark matter converting in a B-field (primarily for masses around $10^{-6}$–$10^{-12}$ eV, but techniques might extend lower in frequency with resonant LC circuits). For our range, one could envision a large, low-frequency electromagnetic resonator that might pick up a slow oscillatory signal. Additionally, ultralight axions can induce a torque on spin-polarized masses (via the axial coupling generating an oscillating “axion wind” magnetic field). The NASDUCK and CASPEr experiments use nuclear magnetic resonance techniques to search for oscillating effects on nuclear spins for axion masses down to ~peV (much heavier than $10^{-20}$ eV), but conceptually similar techniques could be extended to lower frequencies if long coherence times can be managed.

In summary, **experimental searches for ultralight DM are rapidly advancing**. The mass range ~$10^{-22}$ to $10^{-20}$ eV presents challenges because of the very low frequencies, but creative approaches (like year-long observations on stable clocks, pulsar timing over decades, networks of sensors) are turning this regime from a purely theoretical idea into an empirically testable one. So far, these experiments have placed new bounds on how strongly a scalaron of this mass could couple to normal matter​

[arxiv.org](https://arxiv.org/html/2312.13723v2#:~:text=comparison%20of%20lasers%20stabilized%20to,alone%20in%20this%20mass%20range)

. A detection would likely appear as a **spectrally sharp oscillation** in some precision measurement – essentially finding an unexpected periodic signal with a frequency that matches the local Compton frequency of the dark matter (which we could infer from the known local DM density and the assumed field amplitude). Given the local dark matter density $\rho\_{\rm DM}\approx0.4$ GeV/cc, the amplitude of the scalar oscillation $\phi\_0$ satisfies $\frac{1}{2}m\_a^2 \phi\_0^2 = \rho\_{\rm DM}$, which for $m\_a=10^{-22}$ eV yields $\phi\_0 \sim 5\times10^{17}$ GeV (roughly on order $f\_a$, as expected). This extremely large field amplitude (in natural units) is what compensates the tiny mass to give the right energy density. It also means the field is classical and not readily prone to particle-like interactions. Therefore, only through these **ultra-sensitive, large-scale measurements** (essentially looking for effects of a coherent background field) can we hope to either discover or further constrain the fuzzy axion hypothesis.

**Comparison with Other Dark Matter and Gravity Paradigms**

It is instructive to contrast the ultralight axion scalaron model with alternative theories: standard CDM, warm DM, self-interacting DM, and MOdified Newtonian Dynamics (MOND). Each has distinct implications, so identifying unique signatures is crucial for experimental discrimination.

* **Versus Cold Dark Matter (CDM):** By construction, on large scales the axion scalaron behaves like CDM – that’s a point in its favor since CDM fits those observations well. The differences arise on small scales. **Structure suppression:** FDM has an inherent cutoff in the matter power spectrum, whereas CDM predicts a self-similar continuation of structures to very small scales (earth-mass microhalos, etc.). Observationally, if we find a lack of low-mass halos or a minimum scale for collapse, that would conflict with pure CDM but align with fuzzy DM. **Halo density profiles:** CDM N-body simulations produce centrally cusped halos (density $\rho \propto r^{-1}$ or steeper at small $r$) absent baryonic effects, whereas FDM yields flat-density cores due to wave pressure. High-resolution rotation curve data or stellar dispersion profiles in small systems can thus test cusp vs core. While baryon feedback in CDM can also flatten cores (through supernova outflows, etc.), the **mass dependence** may differ: FDM cores are more pronounced in smaller halos, whereas feedback cores typically require sufficient star formation (which might not happen in the tiniest dwarfs). If cores are observed even in very low-mass, dim dwarfs (where baryonic feedback is negligible), that would favor FDM over CDM. **Gravitational lensing substructure:** CDM predicts many subhalos that can perturb lensed images (observed as flux anomalies). FDM would erase most subhalos below the cutoff (~$10^8 M\_\odot$). Precise strong lensing measurements could count subhalos; a deficit of small subhalos would point to FDM. Lastly, **dynamical heating** of star clusters: The grainy potential of FDM can heat star clusters or induce motions differently than CDM’s clumpy subhalos. Some studies of the longevity of thin disks or delicate structures under a grainy halo potential can set bounds on FDM (if too grainy, it might puff up thin disks more than observed). Currently, these are not definitive, but future observations (like vertical heating of the Milky Way’s disk measured by Gaia over time) might reveal subtle differences.
* **Versus Warm Dark Matter (WDM):** WDM consists of ~keV mass sterile neutrino-like particles that free-stream out of small-scale density fluctuations, also producing a small-scale cutoff in structure formation. On linear scales, WDM and FDM can be quite similar if one matches the cutoff. Indeed, a 2 keV WDM particle has a free-streaming cutoff comparable to a $m\_a\sim 10^{-22}$ eV axion’s quantum pressure cutoff. Thus, current observations that simply see a suppression (like fewer satellites or high-$z$ halos) might not clearly distinguish whether it’s due to FDM or WDM​

[arxiv.org](https://arxiv.org/abs/2209.13757#:~:text=spectral%20energy%20distribution%20,halo%20formation%20as%20the%20FDM)

. The **key differences** lie in the *nonlinear regime*: WDM still behaves as classical particles, forming cuspy halos (albeit lower concentration due to late formation) and clumpy subhalos (just truncated in mass). FDM forms wave-supported solitonic cores and an interference “fog” instead of bound subhalos below the cutoff. So, if we can probe internal halo structures, we could distinguish them. For example, observing a shallow core in a dwarf galaxy would favor FDM over WDM (WDM would likely still produce an NFW-like cusp in a dwarf, since it’s basically collisionless matter). Additionally, **halo-to-halo diversity** might differ: WDM suppression is essentially a sharp cutoff in halo mass function, whereas FDM might have more subtle effects like oscillatory features in the power spectrum due to interference (some works show a slight excess just above the cutoff scale due to wave effects​

[arxiv.org](https://arxiv.org/abs/2412.10829#:~:text=provide%20a%20unique%20fingerprint%20of,space%20information.%20Ellipsoidal%20collapse)

). If filament interference or specific core-halo scaling relations are observed, those would be unique to FDM and not expected in WDM​

[arxiv.org](https://arxiv.org/abs/2412.10829#:~:text=,up)

. Conversely, if dwarf galaxies are found to have core profiles but no evidence of ongoing fluctuations, one might also consider SIDM as an alternative cause (since WDM alone wouldn’t core them). In summary, **FDM vs WDM** can be distinguished by looking at *halo inner structure* and any evidence of *dynamical wave effects* (fluctuations, mergers behaving differently, etc.). For example, when two FDM soliton cores merge, they can exhibit interference afterglows and eventually form a larger core, whereas WDM halo mergers just behave like in CDM.

* **Versus Self-Interacting Dark Matter (SIDM):** SIDM proposes particle dark matter with significant mutual scatterings (cross-section on the order of 1 cm$^2$/g) which thermalize the inner halo and produce cores. SIDM and FDM both can yield cored density profiles in galaxies, but the physics is very different. **Core scaling:** SIDM core size generally scales with halo mass and the interaction cross-section – in clusters, where collision velocities are high, the cross-section might be less effective (especially if velocity-dependent), so clusters remain cuspy while only dwarfs have cores. FDM, on the other hand, cores are larger in smaller halos (in absolute physical size, cluster cores from FDM are tiny because the de Broglie wavelength is small in massive halos). So if cluster galaxies show evidence of cores, that could lean towards SIDM (with a tuned cross-section) since FDM wouldn’t impact cluster-scale halos much. Another discriminator is **halo shape**: CDM halos are triaxial; SIDM collisions isotropize the inner halo, making cores more spherical. FDM cores are inherently spherical (being a ground state), but the outer halo shape in FDM could still be triaxial. If detailed gravitational lensing or stellar kinematics can measure halo shapes, a finding of very spherical cores might hint at SIDM or FDM, whereas flatter/triaxial inner densities might disfavor certain SIDM models. Also, **time variability**: SIDM cores are basically static once formed (aside from secular evolution). FDM cores can execute a slow “breathing” oscillation at frequency $2m\_a$ (since the soliton solution can have small oscillations) and the surrounding granules cause the core to jitter (execute a random walk)​

[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=%3E%20,even%20disrupt%20the%20star%20cluster)

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[theskysearchers.com](https://www.theskysearchers.com/viewtopic.php?t=25083#:~:text=and%20can%20be%20studied%20using,wave%20phenomena%20requires%20the%20spatially)

. If we could measure the motion of a halo’s center-of-mass or the fluctuations in its gravitational potential (e.g. via precise pulsar timing in the halo), we might catch this “core oscillation/jitter”. It’s subtle, but conceptually SIDM’s effects are stochastic (collisions) but not coherent oscillations, whereas FDM’s wave nature could produce coherent oscillatory phenomena. **Mergers**: In SIDM, when halos merge, cores can get kicked around or even form large cores via gravothermal collapse; in FDM, when two soliton cores merge, they produce interference fringes and eventually settle into a new core. Simulations of collisions in SIDM vs FDM might yield different transient behaviors – for instance, core oscillations after a merger might be a giveaway for FDM.

* **Versus MOND (Modified Gravity):** MOND and related theories (like TeVeS) dispense with dark matter altogether and modify gravity at low accelerations to explain galaxy rotation curves. The philosophy is entirely different: in MOND, cores and missing mass issues are resolved by altering dynamics, whereas in FDM they are resolved by the presence of an actual new component (the scalar field). Distinguishing MOND from dark matter empirically has been an ongoing debate. Generally, MOND excels at predicting galaxy rotation curve shapes given the baryon distribution, often more so than straightforward CDM models do without baryonic feedback fine-tuning. However, MOND struggles with larger scale phenomena (galaxy clusters still need dark matter, e.g. in form of undetected neutrinos; cosmology and CMB acoustic peaks require something equivalent to DM, etc.). For our context: **MOND vs FDM** differences: On cosmic scales, MOND cannot replace dark matter in explaining structure formation or the CMB, whereas FDM (axion) is still a form of dark matter and fits into the standard cosmological framework. So cosmologically, the evidence of early universe (CMB, structure at $z=1000$) strongly supports there being a DM component – a win for any DM model including FDM, and a challenge for MOND. On galaxy scales, MOND predicts a very specific relation (the Radial Acceleration Relation, or the baryonic Tully-Fisher relation) linking baryonic content to dynamics. FDM, being basically collisionless DM on those scales, wouldn’t *predict* that relation on its own (it might emerge or be mimicked if baryons and FDM interplay). If MOND’s predicted relations hold universally (including for dwarfs, etc.) in a way that cannot be mimicked by any DM distribution, that would favor MOND. Another clear discriminator: **Galaxy clusters and gravitational lensing:** MOND alone cannot explain the mass discrepancies in clusters (especially the Bullet Cluster, where the gravitating mass is clearly displaced from baryons, aligning with collisionless DM). FDM, like CDM, naturally accounts for that with dark mass. The Bullet Cluster – two colliding galaxy clusters where the gas (baryons) is separated from gravitational mass centers – is a very strong argument for particle dark matter (including FDM) and against MOND (unless MOND is supplemented by some dark matter as well, in which case it’s not a pure modification any more). In essence, if one day MOND is completely ruled out by such observations (one could argue it already is for many), then the competition is among dark matter models, and FDM stands as a very viable one. Conversely, if no dark matter particle is ever found and modified gravity gains ground by explaining even cosmological observations, that would be revolutionary and put into question the need for an ultralight axion at all.

In conclusion, the ultralight axion scalaron model has a unique combination of features: a small-scale suppression (like WDM), wave interference phenomena (unlike any traditional DM), and a well-motivated high-energy origin. By examining multiple observational axes – **halo profiles, substructure counts, dynamical motions, early-universe structure, and precision small-scale measurements** – we can tease apart these models. Table 1 (not shown here) would summarize these differences succinctly. The hope is that upcoming data will provide a coherent story: for instance, we might see cores in dwarfs (favoring FDM or SIDM over CDM), a cutoff in the halo mass function (favoring FDM/WDM over CDM), evidence of grainy structure (favor FDM), and alignment with string theory expectations (perhaps an independent sign of an axion field from a lab experiment).

**Conclusion and Outlook**

Our exploration spans from the high-energy birth of an ultralight axion in string theory to its late-universe role as a fuzzy scalaron dark matter, and the manifold ways we can test this idea. We conclude with a synthesis of the theoretical framework and the key testable predictions that emerge:

* **Theoretical framework:** We posit that a $\mathbf{10^{-22},eV}$-scale axion, arising naturally in the string Axiverse (e.g. from large-cycle compactifications in Type IIB or $G\_2$-manifolds in M-theory), constitutes the dark matter of the universe. This axion has a large decay constant $f\_a\sim10^{17}$ GeV, ensuring its couplings to standard model fields are extremely weak (hence it has evaded direct detection so far). Its mass is generated by nonperturbative effects (instantons), which also imply the field is absolutely stable (the instanton potential gives no significant decay channels as long as $m\_a \ll 2m\_e$ so it cannot decay into standard particles except perhaps $2\gamma$ at an undetectably slow rate). This axion can be identified with a “scalaron” in an extended gravitational sector, meaning it could also be seen as a new light degree of freedom mediating gravity on ultra-large scales – however, due to its high $f\_a$, any deviations from GR are negligible in practice, and it mainly manifests via its clustering as dark matter. The framework thus smoothly connects high-energy theory with cosmology: the **string axion becomes a fuzzy dark matter particle**, providing a unifying explanation for both a particle physics and a cosmological puzzle.
* **Solitons and structure:** The model robustly predicts that every virialized halo will contain a **solitonic core** – a gravitationally self-bound Bose–Einstein condensate state. The properties of these cores (mass, radius) are calculable functions of the halo mass and the axion mass. A core in a dwarf galaxy might be $\sim$1 kpc in size with density $\sim10^2 M\_\odot/\text{pc}^3$, while in a Milky-Way halo it might be $\sim$50 pc with much higher density, and clusters effectively have no noticeable core. These solitons and their surrounding interference fringes are a clear-cut signature. We encourage observers to search for signs of such cores: for example, high-resolution rotation curves of dwarf galaxies should exhibit an almost uniform-density central region (which could be distinguished from, say, a cusp smoothed by feedback). Gravitational lensing at high resolutions (like JWST imaging of lensed galaxies) could potentially detect the smoother core lensing profile as opposed to a cusp. Furthermore, the phase coherence of the axion field in solitons might lead to phenomena like diffractive lensing (whereby light passing through the fuzzy core experiences phase shifts – this is speculative but a potential area to explore theoretically).
* **Time-domain signals:** A particularly novel prediction is the possibility of detecting the *oscillatory nature* of the scalaron. For instance, an optical cavity experiment might one day see its length oscillating with a period of one year (for $m\_a\approx10^{-22}$ eV) – effectively listening to the “hum” of the universe’s dark matter field. Similarly, an analysis of pulsar timing data might reveal a common periodic fluctuation across many lines of sight, which could be matched to a dark matter wave. These would be direct detections of the axion field, not unlike how LIGO directly detected gravitational waves. Achieving this will require pushing technology (stable references, long-term monitoring, separating signal from noise) to its limits, but it’s a well-defined target. The **signal characteristics** are well predicted: frequency (or period) tied to the particle mass, spatial coherence length about the de Broglie scale (~kpc), and amplitude related to local DM density and coupling strength. This means experiments can be **tuned** (e.g., if a particular mass is of interest from astrophysics, one can apply narrow-band searches in that frequency range).
* **Astrophysical discriminators:** We emphasize that *no single observation* will be enough to confirm the fuzzy axion model; rather, it’s the **convergence of multiple lines of evidence** that will build a compelling case. For example, if LSST finds a cutoff in the subhalo mass function *and* JWST high-$z$ galaxies fit an FDM power spectrum *and* dwarf galaxy cores are observed consistent with solitons *and* an atomic clock signal at the corresponding frequency is detected, then we have an overwhelmingly convincing story. Conversely, if upcoming observations show, say, an abundance of tiny halos (disfavoring any cutoff) or central cusps persist in the smallest galaxies (hard for FDM to explain unless baryons somehow did it), then the fuzzy axion model could be tightly constrained or ruled out as the dominant DM component. Already, if one takes the Lyman-$\alpha$ forest bounds seriously, a pure $10^{-22}$ eV axion DM is borderline – so one testable tweak of the framework is a **mixed dark matter scenario**: perhaps the axion scalaron is ~50% of DM and the rest is something like CDM. This could alleviate tension with Lyman-$\alpha$ while retaining benefits in galaxies. Such a scenario would still be testable (e.g. the degree of core formation would be reduced). The framework allows for that flexibility since string theory usually gives *multiple* axions; a heavier axion could make up the remainder of DM.
* **Gravitational vs non-gravitational effects:** An interesting aspect of the axion scalaron is that, unlike WIMPs, it is both a source of gravity and potentially a mediator of new forces (if viewed as a scalar-tensor field). However, because $f\_a$ is huge, fifth-force effects are highly suppressed – which is good, because no deviation in gravitational inverse-square law or variation of constants has been seen at relevant scales. Thus, the framework is consistent with gravity tests. One prediction though is that the presence of the scalar field could very slightly alter cosmological expansion in the early universe (as an extra degree of freedom it behaves like an additional matter component or early dark energy if not fully matter-like yet). Careful analysis of the CMB and Big Bang Nucleosynthesis with an ultralight field included shows it behaves just like an extra matter component (if it begins oscillating before CMB era) or extra radiation (if it hasn’t started oscillating by then). In our case, $m\_a=10^{-22}$ eV starts oscillating around matter-radiation equality, so it would act like an early dark matter component – detailed fits show these models can fit CMB data while allowing a fraction of DM to be ultralight, with slight shifts in parameters that future CMB-S4 experiments could detect. So another test: improved measurements of the CMB damping tail or lensing might detect the perturbation signature of ultra-light DM (though current data is fine with ~all DM being such an axion, as long as $m\_a>10^{-24}$ eV or so).

In closing, we have assembled a comprehensive picture that **either confirms or will soon rigorously constrain** the ultralight axion scalaron model as a fundamental component of our universe. The synergy of theoretical high-energy reasoning and multi-faceted observational scrutiny exemplifies how modern cosmology proceeds. If the model is confirmed, it not only solves small-scale cosmological issues but also provides a deep connection to string theory – implying that we have glimpsed new fundamental physics. If it is instead constrained away, we significantly narrow the Axiverse, pushing such axions (if they exist) to play at most a sub-dominant role. In either outcome, valuable lessons will be learned. The next decade promises to be extremely exciting: with JWST mapping the first galaxies, Rubin Observatory cataloguing the low-mass universe, precision labs listening for the soft whisper of waves in the dark, and possibly new surprises (e.g. a sudden anomalous signal that could be the first hint of the axion). The **ultralight axion as fuzzy scalaron** is a grand unifying idea – tying together string theory, astrophysics, and precision measurement – and it stands now at the cusp of either triumphant validation or transformative refutation by experiments. We have laid out the roadmap and are optimistic that definitive answers are within reach.

**References:** (The answer incorporates information and direct excerpts from a variety of sources, e.g., Refs.【4】,【8】,【10】,【14】,【16】,【20】,【25】,【32】, etc., as indicated in the text by the respective citation markers.)