**The Fuzzy Scalaron: Toward a Fundamental Origin**

**Introduction**

In relativistic field theory (RFT) cosmology, **the “fuzzy scalaron” is a hypothetical scalar field postulated to account for dark matter–like effects**. This scalar field is “fuzzy” in the sense that its quanta are ultralight (extremely low mass) and have kiloparsec-scale de Broglie wavelengths, causing wave-like behavior on galactic scales​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=,The%20transition%20between%20soliton%20and)

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. Such a field can naturally form **stable, halo-sized wave solitons** (standing wave cores) and reproduces many large-scale successes of cold dark matter (CDM) while potentially resolving CDM’s small-scale problems (such as galaxy cores and missing satellites)​

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. The scalaron is treated phenomenologically – inserted “by hand” into cosmological models to mimic dark matter – yet **its fundamental nature remains unknown**​

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. We lack a clear derivation of why such a field should exist and how it fits into fundamental physics. This report undertakes a **cross-disciplinary investigation** to identify a strong theoretical hypothesis for the origin of the fuzzy scalaron as a fundamental entity, drawing on ideas from quantum gravity, emergent gravity, analogies to condensed matter, modified gravity, cosmological field theory, and unified physics frameworks.

Key challenges include explaining how a scalar field with an ultralight mass (~10^<sup>-22</sup> eV or similar) could arise naturally, why it remains stable and non-interacting except gravitationally, and how it **integrates with established theory**. Below, we survey multiple theoretical pathways, compare their merits, and then develop one promising framework in detail. The goal is to move beyond a mere phenomenological **“fix” for dark matter** and toward a *fundamental derivation* of the scalaron within a broader physical theory.

**Theoretical Pathways for the Scalaron’s Origin**

A number of diverse theoretical ideas could potentially explain the origin of an ultralight scalar field with dark matter behavior. We summarize several leading possibilities across different disciplines:

* **Quantum Gravity (String Theory – Axion “Axiverse”):** Modern string theories predict a plenitude of scalar fields, especially *axion-like* fields, arising from the compact extra dimensions. In the so-called *“string axiverse,”* one expects **many ultralight axions** with masses spanning a huge range – possibly **down to 10^<sup>-33</sup> eV**​

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. These axions are pseudo-Goldstone bosons of broken symmetries, and a shift symmetry protects them from acquiring large masses. *Fundamentally, a fuzzy scalaron could be one of these string-theoretic axions*, with a mass around 10^<sup>-22</sup> eV. Such an identification is compelling because it situates the scalaron in a well-motivated high-energy framework: **string theory naturally provides candidates** for ultralight, stable scalar fields​

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. This idea also connects to particle physics – e.g. axions resemble the QCD axion (proposed for the strong-CP problem), but with a much smaller mass and larger decay constant. In fact, **particle-physics arguments motivate fuzzy dark matter** as a viable scenario​

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, and an ultralight axion is a prime example. We will explore this axion hypothesis in depth in later sections.

* **Emergent Gravity and Entropic Forces:** An alternate view is that dark matter phenomena do **not require a new particle**, but emerge from modifications of gravity or spacetime microstructure. For example, Erik Verlinde’s *entropic gravity* proposal suggests that gravity and spacetime emerge from quantum information (entanglement entropy), and that **an extra “dark gravity” effect** arises from entropy displacement by baryonic matter​

[arxiv.org](https://arxiv.org/abs/1611.02269#:~:text=displacement%20caused%20by%20matter,currently%20attributed%20to%20dark%20matter)

. In this framework, the additional gravity mimics dark matter in galaxies and clusters without a physical scalar field​

[arxiv.org](https://arxiv.org/abs/1611.02269#:~:text=displacement%20caused%20by%20matter,currently%20attributed%20to%20dark%20matter)

. Similar ideas in AdS/CFT (holography) also hint that what we perceive as dark matter might be the holographic dual of some strongly-coupled sector, or a result of gravity’s emergent elasticity. However, these approaches **do not posit a fundamental scalaron field at all** – instead, dark matter effects are an *emergent phenomenon*. While elegant in avoiding new particles, they leave **no actual “scalaron” to derive**, and thus fall outside our goal of identifying the scalaron as a concrete entity. (They are mentioned for completeness, as a contrasting paradigm.)

* **Condensed Matter Analogies – Cosmic BECs/Superfluids:** There is a striking analogy between ultralight dark matter and Bose–Einstein condensates (BECs). In fact, a fuzzy scalar field in a halo can form a giant coherent condensate. **Recent studies have shown that the central halo region – the solitonic core – behaves like a cosmological-scale BEC**​

[ncl.ac.uk](https://www.ncl.ac.uk/press/articles/latest/2023/06/fuzzydarkmatter/#:~:text=Image%3A%20he%20centre%20of%20a,over%20thousands%20of%20light%20years)

. This has led to ideas that perhaps the scalaron emerges from some condensate mechanism in the early Universe or is itself a condensate of more fundamental constituents. For example, could the vacuum of space undergo a phase transition, condensing into a scalar field? Or could dark matter axions thermalize into a BEC state at cosmological scales? Some researchers have proposed a **“superfluid dark matter”** model where dark matter particles form a superfluid in galaxies, whose phonon excitations give rise to modified gravity behavior in galactic interiors​

[ncl.ac.uk](https://www.ncl.ac.uk/press/articles/latest/2023/06/fuzzydarkmatter/#:~:text=,new%20and%20exciting%20model%20observationally)

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. These condensed-matter inspired frameworks highlight that **the fuzzy scalaron might be an emergent state of many particles** rather than a fundamental field – or, conversely, that a fundamental scalar field can exhibit BEC phenomena on large scales. While these analogies deepen our understanding (e.g. explaining core formation as a ground-state condensate effect), they still require an underlying particle (or field) to condense. Thus, by themselves they shift the question: *what is the particle that forms the BEC?* – pointing us back to candidates like axions or other bosons.

* **Modified Gravity & Scalar–Tensor Theories:** In extended theories of gravity, extra scalar degrees of freedom often appear. Notably, *f(R) gravity* – a generalization of General Relativity where the Lagrangian is a function of curvature R – introduces a scalar degree of freedom commonly dubbed the **“scalaron.”** In Starobinsky’s $f(R)=R+\alpha R^2$ model this scalaron drove inflation, but in other $f(R)$ models the scalaron can be light and long-lived. Some authors have proposed that **a light $f(R)$ scalaron could play the role of dark matter**​

[arxiv.org](https://arxiv.org/abs/2105.02662#:~:text=,values%20would%20be%20required%20in)

. For example, in *chameleon $f(R)$ models* (e.g. Hu–Sawicki gravity), the scalaron’s effective mass is environment-dependent: it becomes heavy in high-density regions (suppressing local fifth forces) but remains ultralight in cosmic vacuum​

[worldscientific.com](https://www.worldscientific.com/doi/10.1142/S0217732321502655?srsltid=AfmBOopgrbSyTBv3S88KjzoJ7_o9gOT3xYdnPxBKsxWSgVRmX5FC56i_#:~:text=,light%20in%20the%20low)

. In cosmic voids and halos, such a scalaron would be virtually free and could **cluster akin to dark matter**, while in the Solar System it’s too massive to mediate detectable forces​

[worldscientific.com](https://www.worldscientific.com/doi/10.1142/S0217732321502655?srsltid=AfmBOopgrbSyTBv3S88KjzoJ7_o9gOT3xYdnPxBKsxWSgVRmX5FC56i_#:~:text=,light%20in%20the%20low)

. This offers a *modified gravity alternative* to a new particle, interpreting dark matter as an aspect of gravity itself. However, one can also **reinterpret this scenario in the Einstein frame** as an actual scalar field (with some potential) coupled to matter – effectively making it a physical field. The fundamental origin question then shifts to *why does gravity have an $f(R)$ form?* One idea is that quantum corrections to gravity or quantum gravity (like asymptotic safety or loop quantum gravity) might generate an $f(R)$ effective action, thus yielding a scalaron. Another creative proposal links the scalaron to the Higgs field: in a *mixed Higgs–scalaron scenario*, the scalaron was frozen until the electroweak phase transition, when the changing Higgs vacuum expectation triggered the scalaron to oscillate and become dark matter​

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. This kind of coupling to known physics can **give the scalaron a more concrete origin** (tied to electroweak symmetry breaking), but in the example studied the required mass was $m \sim 4\times10^{-3}$ eV​

[arxiv.org](https://arxiv.org/abs/2105.02662#:~:text=crossover%2C%20the%20oscillating%20scalaron%20can,values%20would%20be%20required%20in)

– much heavier than fuzzy dark matter, and thus it behaves more like standard cold dark matter rather than exhibiting “fuzzy” quantum effects.

* **Cosmological Field Theory Mechanisms:** In classical cosmology, scalar fields are ubiquitous (inflaton, quintessence, etc.), so one might ask if the fuzzy scalaron could be a **relic field from the early Universe**. For instance, an initially misaligned scalar field will begin oscillating when the Hubble expansion rate $H$ drops below its mass $m$; these coherent oscillations are pressureless and act like cold dark matter​

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. This is the well-known **misalignment production** mechanism, often discussed for axion dark matter (the axion field, initially almost constant, later oscillates and its energy behaves as matter)​

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. The fuzzy scalaron could originate as a field that was frozen during inflation (or radiation era) and then started oscillating, its relic density set by its initial displacement from the potential minimum. Additionally, **nonlinear processes** could play a role: a scalar field with self-interactions can fragment into clumps or solitons shortly after inflation or during reheating. For example, an axion-like potential can lead to parametric resonance that “shatters” the homogeneous field into localized lumps (sometimes called axion miniclusters or Bose stars). Such **fragmentation or soliton formation** phenomena might explain why the scalaron field ended up in discrete halo-like lumps. These ideas operate *within standard QFT and cosmology*, assuming the field exists; they help explain *how* the scalaron comes to behave as dark matter (production and structure), though not *why it exists* in the first place. Still, they demonstrate that a scalaron consistent with cosmology (e.g. one that oscillates as matter and clusters gravitationally) is quite plausible if a light field is present.

* **Unified Physics (GUTs, Supersymmetry, Hidden Sectors):** In grand unified theories or other extensions of the Standard Model, it’s common to have additional scalar fields. For instance, **supersymmetry** introduces scalar superpartners and gauge singlet fields (which could be light moduli or hidden sector scalars). A fuzzy scalaron might be a scalar from a hidden sector that luckily has the right properties (ultralight, stable, feebly coupled). Some GUT models predict axion-like particles (ALPs) as byproducts of symmetry breaking, and if one of these ALPs has a very high decay constant, it would be ultralight. **Entanglement-driven emergence** is another futuristic idea: some researchers speculate that quantum entanglement on cosmological scales could manifest as an effective field or influence that behaves like dark matter. While intriguing, such proposals are highly theoretical and not yet developed into concrete field-based models. **Among unified frameworks, the axion/axion-like particle remains the most concrete candidate** – it appears in string theory, SUSY (as the partner of the axino/saxion), and in hidden-sector dark matter models. In summary, unified physics often *permits* light scalars, but identifying one that exactly matches the fuzzy scalaron’s required properties is the challenge.

**Comparative Analysis of Proposed Origins**

Each of the above approaches sheds light on aspects of the fuzzy scalaron, but not all give a **satisfying fundamental explanation**. Emergent gravity ideas (entropic force, holography) are radical and avoid introducing a scalaron entity at all – they **explain away** dark matter effects via modified gravity​

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. This is elegant, but if we insist on the scalaron being a *real field*, such models are not directly useful (though if they succeeded, the “scalaron” would simply not exist as a fundamental particle). Modified gravity ($f(R)$, scalar-tensor theories) does introduce a field (the scalaron as a part of gravity), and interestingly shows that *gravity itself could house a dark component*. However, $f(R)$ models often require careful tuning or environmental dependence (chameleon mechanism) to satisfy local tests, and the link to fundamental theory is tentative – one might ask *why* that $f(R)$ form arises. **Condensed-matter analogies** beautifully illustrate *how* a scalar field can behave (forming a condensate, superfluid phases, etc.), but they do not by themselves provide *what the particle is*. Ultimately, the **axion-like particle hypothesis stands out** as a robust and well-motivated answer: it is firmly rooted in high-energy theory (axions arise from symmetries and are theoretically expected​

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), it naturally gives an ultralight, stable scalar, and it has been extensively studied in the context of dark matter. Indeed, the ultralight axion solution (often dubbed “fuzzy dark matter”) has a rich literature of derived phenomenology that matches the “fuzzy scalaron” concept​

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. Crucially, an axion-like scalar has a **clear provenance**: it’s a remnant of the early Universe with a calculable relic density (via misalignment), protected from decay by topology or symmetry, and possibly tied to grand-unified or string theory frameworks.

After weighing these options, we identify the **ultralight axion scenario** as the most compelling fundamental hypothesis for the fuzzy scalaron. In the following section, we develop this framework in detail – showing how a high-energy axion field can emerge as a fuzzy scalaron, deriving its Lagrangian and potential, and exploring its cosmological behavior and distinctive predictions.

**Ultralight Axion Scalaron: A Unified Theoretical Framework**

**Hypothesis:** The fuzzy scalaron is an **ultralight axion-like particle** arising from a broken global symmetry in the early Universe (for example, a string-theoretic axion from compact extra dimensions). This “axion scalaron” has a tiny mass ($m \sim 10^{-22}$–$10^{-21}$ eV) and is **fundamentally a quantum of a field with a periodic potential**, analogous to the QCD axion but with different mass scales. Its origin is tied to high-energy physics: a prime example would be an axion associated with a hidden $U(1)$ gauge field in a GUT or string model, with a decay constant of order the GUT or Planck scale and a correspondingly tiny mass generated by instanton effects​

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. Such a field would be present in the primordial Universe, get produced (e.g. via misalignment), and then **oscillate as cold dark matter** when the time is right​

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. In what follows, we outline the theoretical underpinnings of this hypothesis and demonstrate its consistency with both fundamental theory and cosmological observations.

**Motivation and Connection to High-Energy Theory**

Why expect an ultralight axion at all? Remarkably, **string theory suggests the presence of many ultralight axions** – one (or more) for each hidden topological cycle in the extra dimensions​

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. Unlike typical particles, whose masses are set by Standard Model physics, axion masses are determined by non-perturbative effects (like instanton actions) and can be exponentially small. Axions are stable (or extremely long-lived) because they are protected by an approximate shift symmetry $\phi \to \phi + \text{const}$ (the symmetry is exact in the limit the mass goes to zero). This makes them ideal dark matter candidates: they **do not dissipate energy or decay** on cosmic timescales, and they interact only very weakly with normal matter. The classic QCD axion is one such field (expected mass $\sim 10^{-5}$–$10^{-4}$ eV if it makes up dark matter), but string theory extends the idea to a whole spectrum of axion-like fields, often termed the **axiverse**​

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. It is *plausible that one of the lightest axions in the axiverse has $m \sim 10^{-22}$ eV*, exactly in the fuzzy dark matter range​

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. In fact, the range $10^{-22}$–$10^{-20}$ eV for axion mass is theoretically attractive: it is light enough to address small-scale structure issues, yet heavy enough to avoid certain cosmological constraints (we’ll discuss those shortly).

From a **symmetry perspective**, the scalaron could originate as a *pseudo-Nambu–Goldstone boson* of a broken global symmetry (for instance, a Peccei-Quinn-like $U(1)$ symmetry). When this symmetry breaks at a high energy scale $f\_a$ (the axion decay constant), a light field $\phi$ remains. Its potential is exactly flat if the symmetry is exact; but non-perturbative physics (such as a hidden-sector gauge group that becomes strong) introduces a slight tilt in the potential, giving $\phi$ a small mass. The **magnitude of the mass** is typically $m \sim \frac{\Lambda^2}{f\_a}$, where $\Lambda$ is the scale of the nonperturbative effect. To obtain $m \sim 10^{-22}$ eV, one can have $f\_a$ extremely large (e.g. GUT or Planck scale $\sim10^{16}$–$10^{19}$ GeV) and $\Lambda$ rather low (e.g. an MeV to eV scale hidden interaction)​

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. Such numbers are not implausible in string/M-theory contexts – for instance, $f\_a \sim 10^{17}$ GeV and $\Lambda \sim 100$ eV would give $m \sim 10^{-22}$ eV​

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. This illustrates **a key virtue of the axion hypothesis: it provides a natural explanation for the tiny mass** (the small mass results from exponentially suppressed effects, rather than fine-tuning).

In summary, our axion scalaron is well-rooted in theory: it is a **fundamental field predicted by high-energy considerations** (axion from a hidden sector or extra dimensions), with a symmetry reason for its lightness and stability. It neatly ties into existing frameworks – borrowing the concept of axions from QCD and string theory – and thus does not feel ad hoc. Next, we formalize the field’s Lagrangian and potential, to see explicitly how it behaves.

**Lagrangian and Scalaron Potential**

We can write down a generic effective Lagrangian for the scalaron field $\phi(x)$ as follows:

L  =  12 ∂μϕ ∂μϕ  −  V(ϕ) ,\mathcal{L} \;=\; \frac{1}{2}\,\partial^\mu \phi\,\partial\_\mu \phi \;-\; V(\phi)\,,L=21​∂μϕ∂μ​ϕ−V(ϕ),

where $V(\phi)$ is the scalaron’s self-interaction potential. **Axion-like fields** have a characteristic periodic potential, often given by a cosine form. For example, a suitable potential is:

V(ϕ)  =  Λ4[ 1−cos⁡ ⁣(ϕfa)] ,V(\phi) \;=\; \Lambda^4 \Big[\,1 - \cos\!\Big(\frac{\phi}{f\_a}\Big)\Big]\,,V(ϕ)=Λ4[1−cos(fa​ϕ​)],

where $f\_a$ is the large decay constant and $\Lambda$ sets the scale of the potential (related to the mass). Expanding this potential for small oscillations ($\phi \ll f\_a$) yields:

V(ϕ)  ≈  12m2 ϕ2  −  124 Λ4fa2 ϕ4  +  ⋯ ,V(\phi) \;\approx\; \frac{1}{2}m^2\,\phi^2 \;-\; \frac{1}{24}\,\frac{\Lambda^4}{f\_a^2}\,\phi^4 \;+\; \cdots\,,V(ϕ)≈21​m2ϕ2−241​fa2​Λ4​ϕ4+⋯,

which is a light massive scalar with a very weak self-interaction. The mass is $m^2 = \frac{\Lambda^4}{f\_a^2}$, so as anticipated, a large $f\_a$ and moderate $\Lambda$ produce an extremely small $m$. For instance, plugging in $f\_a=10^{17}$ GeV and $\Lambda=100$ eV gives $m \sim 1\times10^{-22}$ eV. The quartic self-coupling in this case is $\lambda \sim \frac{\Lambda^4}{f\_a^4}$, an unimaginably tiny number $\sim10^{-92}$ – effectively zero for any practical purpose! This means the scalaron is essentially a **free, non-self-interacting Bose field** on cosmic scales (any self-coupling effects are negligible, which justifies treating it as fuzzy *cold* dark matter rather than a hot/scattering fluid).

We should note that the above potential form could arise from, say, a hidden $SU(2)$ gauge group that confines at the $\Lambda$ scale and a coupling of $\phi$ to its instanton density (just as the QCD axion potential comes from QCD instantons). The important point is that **the Lagrangian is simple and well-behaved** – a canonical kinetic term and a shallow potential well with a minimum (often taken at $\phi=0$ for convenience). The field equation that follows is the Klein-Gordon equation with a mass term: $\ddot{\phi} + 3H(t)\dot{\phi} - \frac{\nabla^2 \phi}{a^2} + m^2 \phi = 0$ in an expanding Universe (where $H$ is the Hubble rate and $a$ the scale factor).

Because $V(\phi)$ has a minimum (say at $\phi=0$) and $\phi$ is initially displaced from it, **the field will oscillate about the minimum** once the Hubble friction is low enough. A classic result by Turner (1983) and others is that a coherently oscillating scalar field in a quadratic potential behaves like pressureless matter (dust) on average​

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. Physically, the oscillation frequency is $m$, and for $m \gg H$ the field oscillates many times per Hubble time, so its pressure (which oscillates between positive and negative) averages to zero over long timescales – mimicking a dust equation of state. Thus, as soon as $H \lesssim m$ (which for $m\sim10^{-22}$ eV occurs around cosmic time $t \sim 10^7$–$10^8$ seconds, roughly around matter–radiation equality or a bit before), the scalaron begins to act as cold dark matter, with an energy density that dilutes as $a^{-3}$.

To summarize the key theoretical features at the Lagrangian level:

* **Field Type:** Real scalar, spin-0, with negligible self-interactions (effectively a free field of mass $m$).
* **Origin of Mass:** Small explicit symmetry breaking (instantons) giving a periodic potential; $m$ is technically natural (stable against radiative corrections) due to the shift symmetry.
* **Stability:** The only allowed decays (in a typical axion setup) would be into very light particles like photons, but those couplings are suppressed by $f\_a$ which is enormous. For our parameters, the scalaron’s lifetime is far greater than the age of the Universe – it is effectively stable. (In contrast, some $f(R)$ scalarons with $m$ in the meV range could decay to photons, but an ultralight axion with $f\_a\gg 10^{15}$ GeV decays extremely slowly.)

We have thus established a concrete Lagrangian picture of the scalaron. Now we turn to how this field evolves cosmologically and what sort of **structures and signatures** it produces, comparing them with standard CDM expectations.

**Cosmological Dynamics and Structure Formation**

Once the scalaron (axion field) starts oscillating, it behaves as pressureless dark matter on large scales. However, **its microscopic nature – being a quantum wave of very low mass – imprints distinctive features on structure formation**. In essence, fuzzy scalaron dark matter is like CDM on large scales, but on small scales its wave characteristics lead to deviations. Let us enumerate the main dynamical and structural properties predicted for a Universe dominated by this ultralight scalaron, and where possible, compare them to CDM:

*Illustration of the predicted structure of a fuzzy scalaron (fuzzy dark matter) halo.* The image depicts a simulated dark matter halo where the central region (labeled **coherent soliton core**) is a standing wave (BEC-like condensate) of the scalaron field, surrounded by a “transition” to an **incoherent interference region**. The color coding represents the quantum phase of the field, and the right inset zooms into the core. **Soliton cores** are a hallmark of fuzzy scalar field dark matter – a consequence of the Heisenberg uncertainty-like pressure that balances gravity in the halo center​

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. In the outer halo, the field forms a granular, fluctuating density distribution (like interference patterns), behaving chaotically but on average reproducing a **CDM-like $r^{-3}$ profile** at large radii​

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. This structure is physically analogous to a Bose–Einstein condensate (core) surrounded by excited states or phonon-like waves​

[ncl.ac.uk](https://www.ncl.ac.uk/press/articles/latest/2023/06/fuzzydarkmatter/#:~:text=Image%3A%20he%20centre%20of%20a,over%20thousands%20of%20light%20years)

, spanning scales of kiloparsecs.

* **Jeans Scale and Halo Suppression:** Because the scalaron has a finite de Broglie wavelength $\lambda\_\mathrm{dB} \sim \frac{2\pi\hbar}{mv}$, it cannot support structures much smaller than this scale. For $m \sim 10^{-22}$ eV, $\lambda\_\mathrm{dB}$ in a typical dwarf galaxy (with $v \sim 30$ km/s) is on order kpc. This leads to a **quantum Jeans length** (or “fuzzy” analog of free-streaming length) beneath which density fluctuations are suppressed. Analytical and simulation studies find that **halos below a certain mass simply do not form** in fuzzy DM cosmologies​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=motivate%20FDM%2C%20review%20previous%20work,The%20transition%20between%20soliton)

. For example, with $m = 10^{-22}$ eV, the minimum halo mass $M\_\mathrm{min}$ is around $10^7 M\_\odot$​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=motivate%20FDM%2C%20review%20previous%20work,The%20transition%20between%20soliton)

. If $m$ is slightly heavier, the cutoff shifts: generally $M\_\mathrm{min} \propto m^{-3/2}$ in many estimates​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=,The%20transition%20between%20soliton%20and)

. Furthermore, even halos somewhat larger than this cutoff are less abundant than in CDM – the **halo mass function is suppressed at the low-mass end**​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=motivate%20FDM%2C%20review%20previous%20work,The%20transition%20between%20soliton)

. In practical terms, this means the scenario can resolve the *“missing satellites problem”*: CDM predicts many more tiny subhalos than observed as dwarf galaxies, whereas a fuzzy scalaron naturally prevents the formation of too-small halos. It also affects cosmic reionization and high-redshift structure: fewer mini-halos means delayed star formation in small protogalaxies, which could lead to a distinctive signature in the 21-cm hydrogen line power spectrum​

[inspirehep.net](https://inspirehep.net/legacy/arxiv/2412.06213#:~:text=Ultralight%20axion%20or%20axion,due%20to%20ultralight%20axion)

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* **Solitonic Cores in Halos:** A striking prediction is that each virialized halo will contain a **dense, stationary soliton core** at its center​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=,The%20transition%20between%20soliton%20and)

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[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=substantially%20smaller%20in%20FDM%20than,a%20distinct%20signature%20in%20the)

. This soliton is essentially the ground-state solution of the Schrödinger–Poisson equations (or Einstein-Klein-Gordon in a weaker field limit) for the scalaron. It has an almost flat density profile in the inner region (sometimes described as a “quantum pressure supported” core). Simulations show the core has a well-defined radius and mass that correlate with the host halo’s mass – more massive halos end up with denser, smaller cores (since the velocity dispersion is higher, the de Broglie wavelength is shorter, yielding a smaller core)​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=astrophysical%20signatures%2C%20and%20analyze%20several,disk%20and%20bulge%20in%20the)

. For a Milky Way-sized halo, the core might be ~ a few pc in radius; for a dwarf galaxy, it could be a few hundred pc. These cores provide a potential explanation for the observed **cored density profiles** of many dwarf galaxies (as opposed to the steep cusps predicted by CDM-only simulations). Notably, the **shape of rotation curves** in fuzzy DM halos would show a characteristic signature: a slowly rising rotation speed in the core (due to the roughly constant density), possibly a slight dip beyond the core radius, then an eventual rise to the usual outer halo values​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=substantially%20smaller%20in%20FDM%20than,a%20distinct%20signature%20in%20the)

. This is in contrast to a pure NFW (cuspy) profile of CDM which rises more sharply near the center. Thus, finding such a core-induced feature in galaxy rotation curves or dispersion profiles would strongly favor a scalaron/axion DM model.

* **Core–Halo Structure and Dynamics:** The halo outside the soliton core is often referred to as the “incoherent” or NFW-like envelope. Interestingly, the **transition from the soliton core to the halo envelope** is governed by a form of gravitational dynamical relaxation unique to wave DM. Hui et al. (2017) showed that the halo behaves *as if* it were composed of particles of mass $m\_\text{eff} \sim \rho,\lambda^3$ (where $\rho$ is local density and $\lambda$ the de Broglie wavelength) undergoing a two-body relaxation-like process​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=astrophysical%20signatures%2C%20and%20analyze%20several,disk%20and%20bulge%20in%20the)

. This effectively sets the boundary between the core and halo: where the relaxation time becomes comparable to the halo age. The scalaron halo can undergo excitations: for instance, two soliton cores merging can cause the resulting core to “overshoot” in mass and then shed mass via interference outward (sometimes described as *soliton beating*). Over time, halos might settle into an equilibrium of one core + halo waves, but with ongoing small fluctuations. One consequence is that **subhalos (satellite halos) made purely of solitons can gradually evaporate** via quantum tunneling of their mass out of the tidal radius​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=in%20gravitating%20systems%2C%20which%20proceeds,dwarf%20galaxy%20is%20composed%20of)

. This sets a lower limit to how long a subhalo can live near a host – effectively reducing substructure in the inner regions of galaxies (another difference from CDM, which tends to retain clumps unless disrupted by baryonic feedback).

* **Large-Scale Structure and Voids:** On scales much larger than the de Broglie length (clusters of galaxies, hundreds of kpc and above), the fuzzy scalaron behaves almost indistinguishably from CDM. It still gravitates and clusters, so the cosmic web of filaments and voids will form in a similar hierarchical manner. However, subtle differences can arise in the fine details of the cosmic web. Recent simulations indicate that **voids are cleaner and more empty in fuzzy DM cosmologies** compared to CDM, and filaments are smoother​

[arxiv.org](https://arxiv.org/abs/2301.09762#:~:text=We%20show%20that%20in%20FDM,revealed%20by%20a%20strong)

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[ui.adsabs.harvard.edu](https://ui.adsabs.harvard.edu/abs/2023MNRAS.525..348D/abstract#:~:text=Cosmic%20web%20dissection%20in%20fuzzy,range%20peak%20in)

. Intuitively, the lack of small-mass halos means voids aren’t peppered with tiny clumps; void galaxies might also form later. These differences might be detectable statistically (e.g. in void size distributions or in weak lensing maps). The linear matter power spectrum is suppressed at high $k$ (small scales) for fuzzy DM, somewhat akin to a warm dark matter scenario, but with a characteristic *gradual* cutoff (from the quantum pressure effect) rather than a sharp free-streaming cutoff. This could be probed with Lyman-$\alpha$ forest data of intergalactic hydrogen. Current analyses of the Lyman-$\alpha$ forest have put pressure on the pure fuzzy DM scenario, suggesting that if *all* dark matter is an ultralight scalar, its mass must likely exceed $\sim 10^{-21}$ eV (otherwise too much small-scale power is erased)​

[link.aps.org](https://link.aps.org/pdf/10.1103/PhysRevLett.126.071302#:~:text=Strong%20Bound%20on%20Canonical%20Ultralight,string%20axiverse%20and%20solutions)

. There is still debate, and some models allow a mix of fuzzy and heavy dark matter, but it’s a critical test: a true fuzzy scalaron must be in a narrow mass window to satisfy all astrophysical constraints.

In sum, the cosmological behavior of a scalaron/axion with $m\sim10^{-22}$ eV is rich and distinctive. It naturally forms **solitonic cores** and **suppresses sub-galactic structure**, offering solutions to long-standing issues like cusp-vs-core and missing satellites​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=motivate%20FDM%2C%20review%20previous%20work,The%20transition%20between%20soliton)

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[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=substantially%20smaller%20in%20FDM%20than,a%20distinct%20signature%20in%20the)

. It also predicts new phenomena, such as interference patterns in halos and possibly transient vortices or fluctuations in the dark matter distribution (some simulations show the formation of wave vortices under certain conditions, though observationally these would be hard to see except via their gravitational effects).

**Unique Observational Predictions**

The ultimate viability of this scalaron theory rests on whether its predictions can be experimentally or observationally tested and distinguished from other models (like standard CDM or other dark matter alternatives). Here we highlight **unique signatures of the fuzzy scalaron (axion) hypothesis**:

* **Soliton Core Signatures:** Perhaps the most direct evidence would be finding the solitonic core profile in dark-matter dominated systems. Dwarf spheroidal galaxies, with high dark matter fractions and relatively small sizes, are prime targets. The theory predicts a core of radius on the order of a few hundred parsecs for a typical dwarf galaxy mass, with a quasi-uniform density that sharply transitions to a steep fall-off. If stellar kinematic data in dwarf galaxies (or cold gas kinematics in low-surface-brightness galaxies) map out a constant-density core with a specific size–mass relation (the heavier the halo, the smaller the core radius), it would strongly favor a fuzzy scalar field over, say, warm dark matter (WDM) or self-interacting dark matter, which also produce cores but with different scaling relations. One claimed observation consistent with this is in the dwarf galaxy Fornax: it has ancient globular clusters orbiting at radii $\sim1$ kpc. In CDM, a cuspy halo would cause dynamical friction to bring those clusters to the center within a few Gyr, which is inconsistent with their observed orbits. A cored halo (as from a fuzzy scalaron) greatly reduces dynamical friction, allowing the clusters to survive for a Hubble time​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=tunneling%20through%20the%20tidal%20radius,galaxy%20should%20have%20long%20ago)

. Detailed modeling of Fornax’s dark matter distribution indeed hints at a core, which could be a soliton remnant rather than a baryon-made core. Upcoming **JWST and Extremely Large Telescope observations** of dwarf galaxies’ stellar proper motions or resolved velocity dispersion profiles could measure these cores with new precision.

* **Subhalo Mass Function and Galaxy Counts:** Fuzzy scalaron cosmology predicts a **sharp cutoff in the halo mass function** below $M\_{\min}\sim10^7$–$10^8 M\_\odot$​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=motivate%20FDM%2C%20review%20previous%20work,The%20transition%20between%20soliton)

. This could be tested by searches for ultra-faint dwarf galaxies and satellite populations in e.g. the Local Group. The *ΛCDM* model, even with baryonic effects, generally expects some subhalos down to $10^6 M\_\odot$ or less (though many might be dark). If surveys (like the Vera Rubin Observatory’s LSST) find *no* new dwarf satellites below a certain mass threshold, it might hint that halos simply stop forming below that scale – consistent with a fuzzy scalaron. Gravitational **lensing** provides another handle: future strong lensing observations can detect tiny dark matter clumps via flux anomalies in lensed quasars or distortions in Einstein rings. A lack of small clumps or a lower-bound on clump masses would point toward a suppression of small-scale power, distinguishing fuzzy scalaron from CDM. In contrast, warm dark matter (WDM) also suppresses small halos, but fuzzy DM and WDM differ in the details of the cutoff shape and in the core properties (WDM behaves more like a hot gas and doesn’t form stable soliton cores, and WDM particles have a Fermi or phase-space floor that leads to different core sizes vs halo mass).

* **Wave Interference Effects:** If the dark matter halo is a coherent wave on kiloparsec scales, it might cause time-dependent gravitational potential fluctuations. One speculative idea is that these fluctuations could heat stellar disks (leading to increased velocity dispersion or thickening of thin disks over time)​

[arxiv.org](https://arxiv.org/abs/1610.08297#:~:text=in%20gravitating%20systems%2C%20which%20proceeds,dwarf%20galaxy%20is%20composed%20of)

. Hui et al. noted that relaxation (from wave interference) *might* affect galactic disks and bulges over billions of years​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=Poisson%20equation%2C%20sometimes%20called%20a,effect%20on%20disk%20thickening%20or)

. For our Milky Way, one can look at the orbital eccentricity distribution of stars or the presence of dynamical heating signatures to see if an unseen grainy medium is perturbing them. Preliminary studies suggest the effects at solar neighborhood are not extreme (and within current limits)​

[osti.gov](https://www.osti.gov/biblio/1536231#:~:text=relaxation%20in%20gravitating%20N,a%20midplane%20density%20less%20than)

, but future Gaia data might find subtle signs of perturbations consistent with a grainy halo (distinguishing it from a smooth CDM halo). Additionally, if $\phi$ couples very weakly to normal matter (as axions do via, say, a photon coupling $g\_{\phi\gamma}$), the oscillating field background could induce tiny oscillations in atomic energy levels, particle masses, or electromagnetic force strength. Experimental efforts like atomic clock comparisons, resonant mass detectors, or even LIGO have been repurposed to search for the **effects of an oscillating scalar dark matter field**​

[arxiv.org](https://arxiv.org/abs/2401.18076#:~:text=,the%20coupling%20of%20size%20oscillations)

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[arxiv.org](https://arxiv.org/abs/2303.13088#:~:text=,within%20the%20detectors%27%20sensitivity)

. For instance, an oscillating scalar could periodically alter the size of the LIGO arms (if it couples to electron masses or the fine-structure constant), producing a signal. Recent LIGO data have been used to set direct limits on scalar field dark matter in the mass range ~$10^{-13}$–$10^{-11}$ eV (higher than fuzzy regime)​

[arxiv.org](https://arxiv.org/abs/2303.13088#:~:text=,within%20the%20detectors%27%20sensitivity)

. While these have not yet detected anything, they pave the way for more sensitive searches. In the truly fuzzy regime ($10^{-22}$ eV corresponds to oscillation period of about 30 years), direct detection is extremely challenging – but if the scalaron mass were a bit higher (say $10^{-20}$ eV, period ~3 months), precision experiments might eventually see a periodic variation in fundamental constants.

* **21-cm Cosmology and Reionization:** One intriguing avenue is the global 21-cm signal from the Cosmic Dawn era (when the first stars formed). There is a tentative detection (EDGES experiment) of an unexpectedly deep 21-cm absorption at redshift ~17, which has prompted exotic explanations. One idea is that **an ultralight axion dark matter could have cooled the hydrogen gas** or altered the expansion at that era​

[inspirehep.net](https://inspirehep.net/legacy/arxiv/2412.06213#:~:text=Ultralight%20axion%20or%20axion,due%20to%20ultralight%20axion)

. While those models are speculative, generally fuzzy scalaron dark matter delays small-scale structure formation, which delays heating and reionization of the intergalactic gas. Upcoming 21-cm power spectrum observations (HERA, SKA) can compare the timing and amplitude of fluctuations to infer the small-scale matter power. If they find evidence that structure below a certain scale was missing or late-forming, it could favor a fuzzy scalaron over CDM. In contrast, if early, abundant minihalos (as expected in CDM) are confirmed to have hosted efficient star formation, that might challenge the scalaron scenario.

* **Distinguishing from Alternative Theories:** It’s worth contrasting the axion scalaron with two other popular ideas: WIMP-like cold dark matter and MOND (Modified Newtonian Dynamics). WIMP CDM at GeV-scale basically predicts no core (cuspy halos) and abundant substructure – so any evidence of a uniform core or lack of subhalos leans away from WIMPs and *toward* scalarons. MOND, on the other hand, explains galaxy rotation without dark matter by altering dynamics, but MOND doesn’t naturally explain galaxy clusters or cosmology (and it has no particulate dark matter, so no halo substructure at all). The fuzzy scalaron provides *actual mass* in clusters (solving the cluster mass issue that MOND has) and fits into the cosmological framework (MOND does not produce a normal cosmic web or CMB peak pattern without additional dark components). Moreover, the scalaron yields distinct predictions like interference effects and specific core sizes that MOND doesn’t predict. Another alternative, **self-interacting dark matter (SIDM)**, can create cores in galaxies by particle collisions. SIDM cores, however, typically occur in certain mass ranges and have different thermodynamic behavior (isothermal cores, etc.) and SIDM does not suppress small-scale power (so it doesn’t address missing satellites). Thus, a combination of observed traits – *a small-scale cutoff in the power spectrum + presence of constant-density cores + lack of self-interaction signatures in clusters* – would point uniquely to the fuzzy scalaron as the explanation.

In conclusion, the axion-origin fuzzy scalaron framework is not only theoretically well-grounded, it is also *predictive*. It has already spurred a wide range of astrophysical and experimental investigations. As data improve, we expect a **confluence of evidence** to either bolster this hypothesis or constrain it. If the fuzzy scalaron is correct, we might soon see a paradigm shift where dark matter is understood not as “mystery particles” but as a new state of ordinary fields – a cosmic Bose-Einstein condensate born of the earliest universe and rooted in high-energy physics.

**Conclusion**

After an extensive theoretical survey, we identified the **ultralight axion hypothesis** as the most compelling origin for the fuzzy scalaron. This hypothesis situates the scalaron as a fundamental field arising from high-energy physics – for example, as one of the many light axion-like fields predicted by string theory compactifications​

[indico.mitp.uni-mainz.de](https://indico.mitp.uni-mainz.de/event/159/contributions/760/attachments/610/648/Gustavo_Salinas_de_Souza.pdf#:~:text=Axions%20in%20string%20theory%20String,10%20%E2%88%92%20100%29%20in%20many)

. By positing the scalaron as a pseudo-Goldstone boson with a tiny mass, we obtain a **natural, symmetry-protected explanation** for its existence and longevity. We developed this framework by presenting its Lagrangian (a simple scalar field with a shallow periodic potential) and showing how, when coupled to cosmology, it leads to **dark matter behavior with distinctive “fuzzy” signatures**: stable solitonic cores in galaxies, suppressed small-scale structure, and wave interference phenomena on halo scales. This theory elegantly bridges **quantum gravity and cosmology** – the scalaron’s origin lies in fundamental physics (e.g. the string axiverse or GUT symmetry breaking) while its effects address key astrophysical observations (dark matter distribution and cosmic structure).

Crucially, the axion-scalaron framework makes clear, testable predictions that distinguish it from traditional cold dark matter and other alternatives. Upcoming observations in dwarf galaxy dynamics, substructure lensing, 21-cm cosmology, and even laboratory tests of ultralight fields will further probe this idea. If evidence continues to mount for a cutoff in the matter power spectrum and for cored halo profiles, it will strengthen the case that **the dark matter of our universe is a coherent scalar field** – an insight that could open a new window into unified physics. On the other hand, if observations eventually refute these predictions (for instance, if we discover many Earth-mass micro-halos or confirm cuspy cores in the smallest galaxies), then the fuzzy scalaron hypothesis would be challenged, pushing us toward other explanations (perhaps different mass ranges or entirely different mechanisms).

In summary, **the strongest theoretical hypothesis for the fuzzy scalaron’s nature is that it is an ultralight axion field from the high-energy “axiverse.”** This idea stands on solid theoretical ground (with motivation from quantum gravity) and connects to a broad base of existing knowledge (axion physics, BEC dynamics, cosmological scalar fields). It provides a concrete and rigorous foundation for the fuzzy scalaron, transforming it from a mere phenomenological fix into a *predicted consequence* of fundamental physics. As interdisciplinary research continues – blending cosmology, particle theory, and even quantum information insights – our understanding of such scalar fields will deepen. The coming years hold the exciting possibility that we might finally demystify dark matter’s character, revealing it to be the manifestation of a gentle, all-pervading scalar field – the fuzzy scalaron – born from the fabric of quantum gravity itself.

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