**Verification of the Ultralight Axion Scalaron Hypothesis in RFT Cosmology**

**Ultra-High Resolution Simulations**

A crucial step is to perform **ultra-high resolution cosmological simulations** of structure formation with ultralight axion “scalaron” dark matter. Using the RAMSES-based Schrödinger–Poisson solver **SCALAR**​

[arxiv.org](https://arxiv.org/abs/1906.12160#:~:text=,demonstrate%20how%20accurately%20it%20operates)

, we simulate the evolution of the scalar field from **redshift z ~ 10 down to z = 0**, focusing on axion masses in the range *m* ~ 10<sup>−23</sup> to 10<sup>−21</sup> eV. These simulations treat the dark matter as a coherent wavefunction obeying the Schrödinger–Poisson (equivalently, Gross-Pitaevskii) equations, which capture the quantum pressure and interference effects absent in classical N-body codes. Key features and targets of these simulations include:

* **Resolution and Solitonic Cores:** Achieve sub-kpc spatial resolution (tens of parsecs) to **resolve the innermost soliton cores** that form in halos due to quantum pressure support. Prior SCALAR simulations (with *m* ~ 2.5×10<sup>−22</sup> eV) have demonstrated the formation of long-lived, high-density solitonic cores at halo centers​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=according%20to%20the%20Schr%C3%B6dinger,scale)

. These cores produce distinctive **shallower central density profiles** compared to cuspier cold dark matter halos, and even manifest as an **excess inner rotation curve peak** in the circular velocity profile​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=according%20to%20the%20Schr%C3%B6dinger,scale)

. We will verify if the core-halo structure (core size, density) follows the expected scaling with halo mass in the redshift range considered, and whether merging halos preserve the soliton core scaling relations​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=peak%20at%20small%20radii%20from,is%20tightly%20linked%20to%20the)

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* **Wave Interference Patterns:** The simulations must capture the **wave interference fringes and granular density fluctuations** that are characteristic of ultralight axion dark matter. As structure begins to form (around z ~ 10 in our runs), the macroscopic wavefunction develops interference fringes, revealing the quantum nature of the dark matter​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=increasingly%20accreted%20towards%20the%20deepest,A%20coherent%20and)

. Each halo’s density field takes on a “granular” texture outside the core, originating from the superposition of many de Broglie-scale density waves​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=stable%20configuration%20develops%20in%20the,waves%2C%20resulting%20from)

. We specifically track these interference patterns in evolving halos and the cosmic web, as they are a hallmark of the scalar field (with coherence length λ<sub>dB</sub> ~ kpc scale) and have no analogue in classical cold DM. The solver’s adaptive mesh refinement will concentrate resolution on high-density regions to follow interference *nodes* and *voids* at the smallest scales.

* **Structure Formation at Early and Late Times:** The simulation volume (several Mpc on a side) is chosen to include both early mini-halos and later galaxy-scale halos. We compare structure formation timing and abundance against standard ΛCDM. Notably, ultralight axion DM suppresses small-scale power below the Jeans scale set by the de Broglie wavelength. We expect a **deficit of low-mass halos** and delayed small-scale structure formation relative to CDM. For example, the halo mass function’s low-mass end should be **shallower** (fewer dwarf-mass halos) in the scalaron runs​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=peak%20at%20small%20radii%20from,is%20tightly%20linked%20to%20the)

. By *z* ~ 7–10 (the epoch of first galaxies observable by JWST), the number of dwarf halos and the assembly of galaxies in the fuzzy DM simulation can be directly compared to JWST observations. By *z* = 0, we examine Milky Way-mass halos for differences in substructure (subhalo counts, density profiles) compared to CDM. The axion mass is varied across 10<sup>−23</sup>–10<sup>−21</sup> eV to bracket the regime where structure suppression shifts from strong to weak – this will show how sensitive observable differences are to the scalaron mass.

* **Soliton Mergers and Dynamics:** With high resolution, we can also study interactions of soliton cores during halo mergers and in galaxy clusters. Previous studies found that when halos merge, the dominant soliton in the new halo grows in mass, and the system maintains the core-halo mass scaling relations​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=peak%20at%20small%20radii%20from,is%20tightly%20linked%20to%20the)

. We will verify this and look for distinctive dynamics such as **oscillations or wandering of the soliton core** within a host halo and interference-induced density waves propagating outwards. These non-linear dynamics could produce observable fluctuations (e.g. in galactic rotation curves over time or in halo shape) that we will quantify.

Overall, the simulations will produce “snapshots” and movies of the cosmic web in an ultralight axion cosmology. We expect to see **filamentary structures with smoothed-out small clumps**, and each virialized halo exhibiting a dense quantum core and a grainy halo. By comparing these outcomes to equivalent ΛCDM simulations (same initial conditions) we will isolate predictions unique to the scalaron hypothesis. This provides a foundation for deriving observational signatures and tests.

**Observational Roadmap for Scalaron Detection**

*JWST deep-field observations (e.g. of dwarf galaxy-rich fields) offer a window into early structure formation under different dark matter models.* **Figure:** A James Webb Space Telescope NIRCam image of a field containing the Wolf–Lundmark–Melotte (WLM) dwarf galaxy and numerous background galaxies. Such deep fields allow us to count and characterize galaxies at *z* ≈ 7–10, testing whether small-scale structure is suppressed as expected in ultralight axion dark matter models.

To **empirically verify or refute the ultralight scalaron**, we outline a multi-pronged observational strategy targeting the model’s distinctive signatures across cosmic time:

* **High-Redshift Galaxies (JWST, z ~ 7–10):** The abundance and properties of early galaxies offer a critical test. Ultralight axion DM suppresses the formation of low-mass halos, potentially delaying or reducing the number of dwarf galaxies at high redshift. Using JWST’s deep field galaxy surveys (for example, searches in the 7 ≲ *z* ≲ 10 range), we will look for a **turnover or deficit in the galaxy luminosity and mass functions** at the faint end. Recent JWST results have shown an unexpectedly high stellar mass density in massive galaxies at z > 7, which is challenging to explain with standard CDM unless star-formation efficiency is very high. Fuzzy dark matter (scalaron) models of mass *m* ~ few×10<sup>−23</sup> eV could help **reconcile this tension** by suppressing small halos so that remaining halos can form stars more efficiently without overproducing ionizing photons​

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

. Specifically, a model with *m* ≈ 5×10<sup>−23</sup> eV was found to simultaneously match JWST galaxy densities at *z* ~ 8 and the reionization history (CMB optical depth), by **preventing excessive small-galaxy formation**​

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

. We will use JWST observations to *falsify* the scalaron hypothesis if it overpredicts or underpredicts high-*z* galaxies. For instance, if JWST finds abundant low-mass galaxies (or star formation) at *z* > 10 that exceed what any 10<sup>−22</sup>–10<sup>−23</sup> eV axion model can produce, that mass range would be ruled out. Conversely, detection of an early cut-off in the galaxy mass function or a delayed reionization consistent with suppressed small-scale power would strongly support the scalaron model. We will also examine **galaxy internal structure** in JWST images: fuzzy dark matter predicts small galaxies should be more diffuse with cores (potentially affecting surface brightness profiles), and star-forming clumps might be larger due to the lack of small-scale DM clumps. Such subtle structural differences, as suggested by simulation comparisons​

[scientificamerican.com](https://www.scientificamerican.com/article/jwsts-glimpses-of-early-galaxies-could-shed-light-on-dark-matter/#:~:text=theorists%20simulated%20how%20primordial%20galaxies,might%20be%20able%20to%20see)

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[scientificamerican.com](https://www.scientificamerican.com/article/jwsts-glimpses-of-early-galaxies-could-shed-light-on-dark-matter/#:~:text=submitted%20to%20the%20Monthly%20Notices,might%20be%20able%20to%20see)

, could become discernible with JWST’s resolution and will be part of our observational checklist.

* **Local Group Dwarf Galaxies (Density Cores in dSphs):** Ultralight axion DM predicts that **dwarf spheroidal galaxies** (dSphs) should host sizeable constant-density cores (solitons), in contrast to the steep cusps of CDM NFW profiles (absent strong baryonic feedback). We will obtain high-precision stellar kinematic data (e.g. from Gaia and upcoming thirty-meter-class telescopes) for Local Group dwarfs (like Fornax, Sculptor, Draco, etc.) to map out their inner mass density profiles. The **core radius vs halo mass relation** expected for solitons will be a key discriminant – for *m* ~10<sup>−22</sup> eV, simulations and analytic work predict a core radius *r*<sub>c</sub> ~ 1 kpc in a 10<sup>9</sup> M<sub>⊙</sub> halo (scaling as *r*<sub>c</sub> ∝ (M<sub>halo</sub>)<sup>−1/3</sup> \* (m)<sup>−1】​

[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=simulations%20%28Schive%20et%20al,m)

). If observations find **dwarf cores in the 0.5–1.5 kpc range**, that would be consistent with m ~ 10<sup>−22</sup> eV; smaller cores would push *m* higher, and an outright cusp (r<sub>c</sub> → 0) would spell trouble for the ultralight scalar without baryonic solutions. Current analyses show mixed results – some dwarf data (Fornax, Sculptor) can be fitted with large cores, which if attributed solely to an axion soliton would require *m* < 4×10<sup>−23</sup> eV​

[arxiv.org](https://arxiv.org/abs/1609.05856#:~:text=Applying%20our%20analysis%20to%20two,of%20structures%20in%20the%20Universe)

. However, such a low particle mass is in tension with other constraints (e.g. it over-suppresses satellite galaxies)​

[arxiv.org](https://arxiv.org/abs/1609.05856#:~:text=%24m_a%3C0.4%5Ctimes%2010%5E%7B,of%20structures%20in%20the%20Universe)

. We will refine these studies with more dwarfs and better data, setting **precise falsifiability criteria**: for example, if *all* classical dwarfs exhibit central density slopes inconsistent with any core size from m ≳ 10<sup>−23</sup> eV, the scalaron model (as sole DM) would be difficult to maintain. On the other hand, if a clear, common core size is observed (and especially if it correlates with halo mass as soliton theory predicts), it would be a strong indicator in favor of the ultralight axion explanation for the cusp–core problem​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=under%20the%20effect%20of%20gravity,drops%20as%20a%20power%20law)

. Our roadmap includes comparing observations to detailed stellar dynamical models that incorporate a soliton + NFW outer halo profile, and testing for the distinctive feature of a **sharp density drop beyond the soliton radius** (at ~3 r<sub>c</sub>)​

[aanda.org](https://www.aanda.org/articles/aa/full_html/2022/06/aa38876-20/aa38876-20.html#:~:text=Dark%20matter%20density%20profiles%20,7%7D%20M%E2%8A%99)

. The absence or presence of this feature in real dwarfs can provide a yes/no test of the scalaron core hypothesis.

* **Stellar Streams in the Milky Way Halo (Pal 5, GD-1):** Cold thin tidal streams from globular clusters offer an **exceptionally sensitive probe of small-scale gravitational fluctuations** in the Galactic halo. The ultralight scalar field halo is not entirely smooth; it exhibits time-varying density granules (of mass ~10<sup>6–7</sup> M<sub>⊙</sub> for m ~10<sup>−22</sup> eV) that can perturb stellar streams. Using Gaia + ground-based surveys, streams like **Palomar 5** and **GD-1** have been mapped with great fidelity. We will search these streams for subtle density clumps, spur-like deviations, or increased velocity dispersion that could be the imprint of passing scalar field interference “nodes.” *Quantitatively*, one can derive a **lower bound on the axion mass** by requiring that the stream’s thinness has not been overly disrupted. For example, earlier work using pre-Gaia data on several streams set a conservative limit *m*<sub>a</sub> > 1.5×10<sup>−22</sup> eV (95% C.L.)​

[arxiv.org](https://arxiv.org/abs/1808.00464#:~:text=We%20derive%20an%20analytical%20model,alpha%24%20forest%20data)

, because lighter (more fuzzy) dark matter would have produced more prominent stream thickening than observed. With Gaia DR3 and DR4 data, we can tighten this constraint or potentially detect the specific signature of wave-like perturbers. A key discriminant will be the **frequency spectrum of perturbations along the stream**: fuzzy DM induces a smooth, continuous kind of perturbation (from many overlapping waves) as opposed to the rare, sudden kicks from discrete compact subhalos in CDM. If data show a preponderance of subtle, continuous fluctuations in stream track positions or densities, it could hint at the interference pattern of an ultralight field. Our roadmap calls for measuring the power spectrum of density variations in Pal 5’s stellar stream and comparing it against predicted fluctuations from our simulations of a Milky Way–mass fuzzy halo. Non-detection of any such fluctuations will translate into an improved lower limit on *m* (potentially excluding even 2×10<sup>−22</sup> eV if streams remain razor-thin), while a positive detection of stream perturbations, when combined with other analyses (and after ruling out baryonic effects like Giant Molecular Cloud encounters), would provide a novel confirmation of the scalaron’s grainy halo effect. In either case, tidal streams serve as an **independent, Galactic-scale falsifiability test** of the scalar field dark matter: the absence of expected perturbations would challenge the hypothesis, whereas the presence of the right type of oscillatory perturbations (especially in multiple streams at consistent amplitude) would bolster it.

In addition to these targeted approaches, we will integrate other observations into the roadmap for completeness. For example, the **Lyman-alpha forest** of the intergalactic medium at z ~ 5 can constrain the small-scale power spectrum and already suggests *m*<sub>a</sub> ≳ 10<sup>−21</sup> eV​

[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=of%20the%20recent%20Lyman,eV%20is%20ruled%20out%20at)

– any viable scalaron model must meet this baseline. Moreover, future extremely large telescopes could resolve **ultra-faint dwarfs** and globular clusters to check for any signs of dynamically heating consistent with a fluctuating dark matter potential. By combining **early-universe (high-z)** and **late-universe (Local Group)** observations, our roadmap pinpoints a range of phenomena that together **could either confirm the presence of an ultralight scalar field or definitively refute it.** Each observed null result or discrepancy will narrow the mass window and coupling space for the scalaron; conversely, any positive, corroborating signal across these different scales would build a compelling case for its existence.

Crucially, these observational tests have quantifiable thresholds. We will define **detection metrics** (e.g. a maximum core radius or minimum stream perturbation amplitude) that, if exceeded or unmet, would count as falsification criteria. The integration of results – say, confirming cores but not seeing stream effects, or vice versa – will also inform whether the scalaron hypothesis survives in pure form or if modifications (like a mixed dark matter scenario) are necessary (see Decision Framework below).

**Laboratory Experiment Proposal: Photon-Coupling Atomic Clock Array**

While astrophysical observations probe the cosmic effects of the scalaron, a complementary approach is to **detect the ultralight scalar field directly on Earth** via its minute oscillatory signatures. We propose a **photon-coupling based precision experiment** that leverages the world’s best atomic clocks and spectroscopic techniques to search for the tiny oscillations induced by an ultralight ~10<sup>−22</sup> eV scalar field. The concept is that the axion-like scalaron, if it couples to standard model fields (in particular photons or electromagnetism), will cause fundamental constants to oscillate at the field’s Compton frequency. For instance, a coupling to the electromagnetic field or electron could lead to small periodic variations in the fine-structure constant α or particle masses. Atomic transition frequencies (and clock rates) depend on these constants, so an oscillating scalar field could make atomic clocks tick slightly faster or slower in sync with the field.

**Key expected signal parameters** for a mass *m* ~ 10<sup>−22</sup> eV are:

1. **Oscillation Frequency:** *f* ≈ (m c<sup>2</sup>)/h ~ 2×10<sup>−8</sup> Hz, corresponding to a period of roughly ~1.3 years. This is an extremely low frequency, meaning the scalar field background is quasi-static on human timescales – essentially a field oscillation that completes only ~0.8 cycles per year. If *m* is at the upper end 10<sup>−21</sup> eV, *f* ~ 2×10<sup>−7</sup> Hz (period ~2 months). We will target this frequency band (around 10<sup>−8</sup>–10<sup>−7</sup> Hz) in the experiment’s analysis by looking for periodic signals in clock frequency data at those Fourier components.
2. **Amplitude of Variation:** Assuming the local dark matter density ρ<sub>DM</sub> ~ 0.4 GeV/cm<sup>3</sup> is entirely due to the scalaron, the field’s oscillation amplitude can be related to ρ (for a classical field ϕ: ρ ≈ ½ m<sup>2</sup>ϕ<sup>2</sup>). For our mass range, this implies a fractional oscillation in quantities like α or particle masses on the order of 10<sup>−17</sup>–10<sup>−18</sup> (times a model-dependent coupling factor). In practical terms, we might expect atomic transition frequencies to shift by Δf/f ~ 10<sup>−18</sup> in amplitude. Such a tiny effect is *below* the sensitivity of any single clock over short times, but by averaging over long durations and comparing multiple clocks, it becomes detectable. **Coherence time** of the signal is also extremely long – the field’s oscillation is coherent over about 10<sup>6</sup> oscillation cycles (due to the narrow velocity dispersion of virialized DM) which translates to ~10<sup>6</sup> years for f ~ 10<sup>−8</sup> Hz. Thus, over the timescale of a few years of measurement, the scalar oscillation would appear essentially monochromatic and phase-coherent. This allows us to integrate the signal over very long periods to build up sensitivity, and the narrow bandwidth reduces noise.
3. **Experimental Sensitivity Requirements:** State-of-the-art optical atomic clocks have achieved fractional stability and accuracy at the 10<sup>−18</sup> level or better. Recent advances using ultra-stable lasers and atomic references have set new bounds on ultralight dark matter in the mass range 10<sup>−16</sup>–10<sup>−21</sup> eV​

[anl.gov](https://www.anl.gov/event/improved-constraints-on-ultralight-dark-matter-with-stateoftheart-optical-clocks#:~:text=probes%20of%20dark%20matter%20in,performance%20over%20the%20past%20decades)

. We intend to push these to the 10<sup>−22</sup> eV decade by utilizing an **array of atomic clocks connected via optical links**. The experimental sensitivity threshold is targeted at Δf/f ~ 10<sup>−19</sup> (integrating over months to years), which should allow a robust detection or constraint of the scalar field’s coupling. By comparing different types of clocks (e.g. an Yb<sup>+</sup> electric quadrupole clock vs a Cs microwave clock, or optical Sr vs optical Hg<sup>+</sup>), we gain differential sensitivity to specific constant variations (α, electron mass, etc.). The proposed setup’s goal is to detect a common-mode fractional frequency oscillation across all clocks, modulated by each transition’s sensitivity to the varying constant.

Our **experimental setup** will be a **“Dark Matter Atomic Clock Network”** spanning multiple laboratories (and potentially orbiting clocks). It involves:

* A **network of optical atomic clocks** (e.g. strontium lattice clocks, ytterbium clocks) linked with phase-stabilized fiber optic channels. By synchronizing and continuously comparing clocks at different locations, we can search for spatially coherent frequency shifts that oscillate with the same phase in all locations (as expected for a uniform DM field). This setup was recently demonstrated as a powerful method to detect oscillating fields that might otherwise cancel out in local measurements​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,Ms%20Caddell%20said)

. In particular, the use of spatially separated clocks (some on Earth, some on GPS satellites or different continents) means that if the scalar field has any spatial gradients or if the Earth is moving through fluctuations, the differences can be picked up as differential ticks​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,atomic%20clocks%20aboard%20GPS%20satellites)

. The effect of an oscillating DM wave would appear as slight disagreements between distant clocks that vary periodically in time​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,mass%20is%20very%20very%20low)

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* **Optical Cavities and Lasers:** In addition to atomic transitions, ultra-stable optical cavities (mirrors separated by fixed spacers) act as sensitive rulers for variations of the electromagnetic force. We will use cavity-stabilized lasers as references whose frequencies would shift if, say, the fine-structure constant oscillates. By comparing a cavity’s laser frequency to an atomic clock, one can detect a relative oscillation. The recent study by Caddell *et al.* (2025) effectively did this, using a network of cavities and clocks to search for dark matter waves​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,atomic%20clocks%20aboard%20GPS%20satellites)

. We will build on that approach with longer observation time and enhanced stability.

* **Photon Coupling and Detection:** The “photon-coupling” refers to the possibility that the scalar field directly couples to photons (or the electromagnetic field tensor) via a term in the Lagrangian like gϕγϕFμνFμνg\_{ϕγ} ϕ F\_{\mu\nu}F^{\mu\nu}gϕγ​ϕFμν​Fμν. If such a coupling exists, the oscillating ϕ field can induce an oscillating phase shift or polarization rotation in light over a fixed distance. We propose to also include a precision **spectroscopy of atomic transitions or resonant optical cavity** experiment specifically tuned to this. For example, we could operate two optical cavities: one with a material or index that is more sensitive to α variation, and one that is less sensitive, and heterodyne their laser outputs. An oscillation in α at 10<sup>−8</sup> Hz would manifest as a differential beat note at that frequency. Another approach is to use an **atomic spectroscopy method**: certain atomic transitions (like in molecular iodine or two-photon transitions in atoms) have different dependence on fundamental constants, so monitoring the frequency ratio of two transitions can isolate variations in α or the electron mass. An array of atomic clocks essentially does this by comparing different atomic species​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,Ms%20Caddell%20said)

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**Expected signal:** If the scalaron exists and has a coupling within reach, we would observe a **sinusoidal oscillation in the frequency differences** between clocks (or cavities), all of them oscillating in phase with period ~year. The amplitude might grow and decay slowly if there’s a modulation due to Earth’s motion through the Galaxy (annual modulation of DM velocity could cause second-order effects). We will check for a matching oscillation in multiple independent frequency channels to rule out systematic effects. The coherence of the signal over years means that, as data accumulate, the signal-to-noise improves (spectrally it would appear as a very sharp line in the Fourier spectrum of the clock frequency data).

Our proposal also calls for deploying **multiple atomic clock types in different orbital configurations** (e.g. one on a satellite, one on the ground) to maximize sensitivity​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,mass%20is%20very%20very%20low)

. The difference in gravitational potential and environment could help distinguish a real cosmic signal from local noise. Already, data from two atomic clocks on GPS satellites have been analyzed in combination with Earth clocks to search for dark matter waves​

[sciencedaily.com](https://www.sciencedaily.com/releases/2025/02/250206113727.htm#:~:text=,atomic%20clocks%20aboard%20GPS%20satellites)

. We will extend this by possibly incorporating the upcoming optical clocks on the International Space Station (ISS) or planned satellite missions, creating a wide-baseline clock network.

**Sensitivity and thresholds:** If after a few years no oscillation is found, we will be able to place an upper bound on the scalaron’s photon coupling constant (or coupling to electrons) that is orders of magnitude tighter. If an oscillation is found, the specific frequency measured will directly give the mass of the particle (e.g. a ~1.0 year period corresponds to 1.1×10<sup>−22</sup> eV, a ~2 month period to ~1×10<sup>−21</sup> eV, etc.). The phase coherence of multiple clocks would confirm it’s not an artifact. We will also measure the **coherence time** of the signal by observing how stable the phase is year-to-year; a detection that matches the expected coherence (Q ~ 10<sup>6</sup>) would further validate that it’s dark matter and not an environmental effect.

In summary, this laboratory approach – an atomic clock and precision spectroscopy array – is optimized to **detect a 10<sup>−22</sup> eV-class scalar field oscillation** or to definitively constrain its coupling if not detected. It taps into the recent rapid progress in clock stability​

[anl.gov](https://www.anl.gov/event/improved-constraints-on-ultralight-dark-matter-with-stateoftheart-optical-clocks#:~:text=particles%20across%20a%20much%20larger,performance%20over%20the%20past%20decades)

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[anl.gov](https://www.anl.gov/event/improved-constraints-on-ultralight-dark-matter-with-stateoftheart-optical-clocks#:~:text=probes%20of%20dark%20matter%20in,performance%20over%20the%20past%20decades)

and the novel idea of using *distributed quantum sensors* for dark matter. By running such an experiment in parallel with the cosmological and astrophysical efforts, we cover both the macro and micro manifestations of the scalaron hypothesis.

**Decision Framework and Next Steps**

After executing the above simulation, observational, and experimental program, we will reach a point to decide on the fate of the ultralight axion scalaron in RFT cosmology. We establish a framework for two possible outcomes – one where the hypothesis is **not verified (fails)** and one where it is **successfully verified** – and outline the subsequent steps for each scenario:

**If the Scalaron Hypothesis is Falsified**

If the combined evidence from simulations and observations does *not* support the existence of a ~10<sup>−22</sup> eV scalar field as the dominant dark matter, we will need to pivot our cosmological model. “Falsification” could mean, for instance, that JWST finds plenty of small galaxies at high *z* (contrary to predictions), Local Group dwarfs don’t show the expected solitonic cores, the stellar streams remain pristine (ruling out the required mass range), **and** the precision lab search turns up null. In this case, the logical next steps are:

* **Re-examine Alternative Models:** We would guide the community to explore other dark matter models or mixtures within the *Relativistic Field Theory (RFT) framework*. One alternative is **warm dark matter (WDM)** consisting of ~keV mass sterile neutrinos or similar – this has a similar effect of suppressing small scales and could explain some observations (indeed, a warm DM of a few keV can mimic the galaxy suppression of fuzzy DM​

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

). If fuzzy DM fails, WDM could be revisited, with new simulations run to see if it fits where fuzzy failed (for example, matching *both* JWST and Lyman-α without soliton core predictions that didn’t materialize). Another path is **self-interacting dark matter (SIDM)**: dark matter particles with self-collisions can produce cores in dwarf galaxies (solving cusp–core) without requiring quantum wave effects. We would consider an SIDM model that might better match dwarf galaxy profiles if the fuzzy cores are not observed. Importantly, these alternatives can often be embedded in RFT cosmology as different field theories (e.g. a light vector boson mediating self-interactions, or a thermal relic particle for WDM).

* **Mixed Dark Matter Scenarios:** A nuanced pivot would be to **mixed models** – for example, a combination of cold dark matter plus a small fraction of ultralight scalar field. It could be that a pure scalaron dark matter is ruled out, but perhaps a sub-dominant ultralight field (making up say 10–20% of dark matter) could still exist and have some observable effects without contradicting major observations. We would outline how to incorporate a mixed dark matter content in RFT Cosmology 9.0, allowing for two components (one behaving as CDM, one as wave-like FDM). There are already simulations of mixed FDM + CDM that show intermediate results​

[researchgate.net](https://www.researchgate.net/publication/377991491_Cosmological_simulations_of_mixed_ultralight_dark_matter#:~:text=Cosmological%20simulations%20of%20mixed%20ultralight,baryonic%2C%20and%20CDM%20physics)

. This approach might salvage positive aspects (like slightly reducing small-scale power to address some dwarf galaxy issues) while avoiding the full brunt of constraints (since most DM is still CDM to satisfy Lyman-α, etc.). If verification fails for pure scalaron, we recommend focusing on these hybrid models and defining new experiments to test them (for example, looking for a small core in dwarfs, smaller than pure FDM but larger than CDM’s cusp).

* **Refine RFT Cosmology Framework:** Within the theoretical RFT cosmology framework, a failure of the scalaron hypothesis will prompt an update to what we might call *“RFT Cosmology 9.1”*. This update would formally drop or de-emphasize the ultralight scalaron as the main dark matter component. Instead, we might incorporate a **multi-component field** approach – e.g. adding an N-body CDM field plus a scalar field with subdominant density. We will provide guidance on how the field equations and cosmological solutions should be adjusted. For example, the stress-energy tensor in RFT cosmology will now have contributions from both a canonical cold component and possibly a smaller scalar field term. We will ensure that any such model remains self-consistent and perhaps identify distinguishing features (maybe rare but observable interference fringes if the scalar fraction is small).
* **Address Unresolved Problems with Other Means:** If scalaron fails to solve small-scale issues (cores, missing satellites), then those problems still need explanation. We would direct attention to **baryonic solutions** in CDM (like supernova feedback creating cores) or to **new physics** like decaying dark matter where a fraction decays to reduce small halos. Essentially, the guidance is to funnel efforts into whichever alternative best addresses the specific failures of the scalaron. For instance, if the core problem remains, perhaps SIDM or baryonic feedback; if the satellites problem remains, maybe WDM or early reionization, etc.
* **Communicate Findings and Constraints:** Finally, a critical step is formally publishing the *null results* and the stringent constraints obtained on ultralight axions. The non-detection (if that is the outcome) would be one of the definitive results of this program. For example, we would publish an upper limit on any ultralight scalar field contribution: e.g. “m<sub>a</sub> must be > 2×10<sup>−22</sup> eV at 95% confidence, and if it’s 5×10<sup>−22</sup> eV or higher it cannot constitute more than 10% of dark matter,” based on the combination of observations. This ensures the community can confidently move on to other models, having a clear quantitative boundary for the scalaron hypothesis.

In essence, if the scalaron is falsified, we pivot the extensive tools developed – the high-res solvers, the precision clock techniques, etc. – towards exploring other physics in the dark sector, all while updating the RFT cosmological model to reflect the new understanding (or lack) of dark matter.

**If the Scalaron Hypothesis is Verified**

If instead our research program **successfully verifies** the ultralight axion scalaron as the dark matter, it would be a breakthrough in cosmology. “Success” would mean multiple lines of evidence converge: the simulations match observed galaxy patterns, we see the predicted cores in dwarfs, maybe even lab detection of the field oscillation, etc. In this scenario, the task shifts to formally establishing this new paradigm – effectively upgrading to a **“RFT Cosmology 9.0” framework that includes the scalaron as a core component**. The final steps would include:

* **Complete Theoretical Synthesis:** We will finalize a consistent theoretical framework that unites the scalar field dark matter with the rest of cosmology. This involves writing down the extended action and field equations in the RFT formalism (likely an Einstein–Klein-Gordon system with the ultralight axion field). All cosmological epoch calculations (inflation, CMB, nucleosynthesis, structure formation) would be revisited to include the scalaron’s effects. We must ensure that the early-universe behavior of this field (which is essentially a vacuum oscillation until it starts structuring) is properly integrated into the standard model of cosmology. **RFT Cosmology 9.0** would, for instance, include parameters like the axion mass and maybe a self-coupling or initial misalignment angle if relevant, in addition to the usual cosmological parameters. We would document how this model reproduces all major cosmological observations (large-scale structure, CMB power spectrum – which fuzzy DM largely leaves unchanged except smoothing the smallest scales, etc.) now that small-scale problems are resolved by the scalaron.
* **Formal Verification and Publication:** Each element of verification would be written up in high-profile scientific papers to cement the discovery. For example, a paper demonstrating the laboratory detection of the scalar field oscillation (with frequency matching that from astrophysical inferences) would be revolutionary, and one detailing how JWST and dwarf galaxy data are quantitatively consistent with an m ~ X×10<sup>−22</sup> eV scalar field would solve longstanding puzzles. These results together would constitute the “proof” of the scalaron scenario. We would likely also publish a unifying review or **white paper** making the case that the dark matter problem is solved by this scalar field – laying out the multi-scale evidence.
* **Incorporate into Next-Generation Models:** With the scalaron accepted, the next steps involve **refining the model and exploring its implications** further. This could mean pushing simulations to even higher resolution or to include baryonic physics in combination with fuzzy DM (to see how galaxy formation proceeds in detail under this new paradigm). It also means connecting the ultralight axion to particle physics: we’d work on identifying a viable particle physics model (e.g. perhaps the axion came from a string theory modulus or a hidden-sector symmetry breaking) that gives the right properties. Since it is verified, we know its mass and perhaps couplings; we can then ask, for instance, how such a field fits into grand unified theories or if it could be related to the QCD axion (likely not the same, as QCD axion is heavier, but maybe a cousin in a larger axion family). In RFT Cosmology 9.0, the scalaron might also play a role in other areas – for example, we’d examine if this field could have caused an early kination era or affected inflation, etc. (some models tie ultralight fields to inflationary reheating).
* **Build a “Cosmic Axion Background” Framework:** Analogous to the Cosmic Microwave Background for photons, a verified scalaron implies there is a **cosmic axion field background** pervading the universe. We would formalize the concept of this field as a new “component” of the universe in textbooks: describing how its oscillations carry the dark matter energy density, how it interacts gravitationally and (very weakly) with standard fields. Educational outreach and inclusion in cosmology courses would follow. In practical terms, the community would establish this in analysis tools – e.g. cosmological Boltzmann codes (like CAMB, CLASS) would add a module for ultralight scalar DM to produce matter power spectra. We, as part of final steps, would contribute by making our simulation code SCALAR open-source and accessible​

[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=%28Schr%C3%B6dinger,granular%20structures%2C%20a%20self%02consistent%20method)

, so others can simulate galaxy formation under the new paradigm. Formalizing the scenario means creating a robust pipeline from fundamental theory to observable predictions that others can use.

* **Plan Further Confirmatory Tests:** Even with strong verification, science will demand cross-checks. We would outline future experiments to **further solidify the scalaron scenario**. For instance, now that we believe it exists, we could propose more daring experiments: perhaps a dedicated space mission of atomic clocks optimized for DM detection (to measure the field with even higher precision and map its velocity distribution by detecting small deviations in frequency coherence). Or a high-sensitivity pulsar timing array search, since a known mass of 10<sup>−22</sup> eV would cause specific spectrum of timing fluctuations in pulsars​

[frontiersin.org](https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2018.00048/pdf#:~:text=about%20the%20granular%20structures%2C%20a,This%20method%20can%20not)

(if the granularity can be observed this way). We might also encourage looking for subtle imprints in gravitational lensing or the cosmic 21-cm signal from the dark ages (the scalar field could affect the minimum halo mass that forms, which influences the 21-cm absorption signature). These would be **final proofs** in different regimes that this new form of dark matter is indeed consistently explaining everything.

* **Integration into Cosmology’s Precision Era:** Lastly, verifying the scalaron means our standard cosmology now has a new ingredient, and we will integrate that into ongoing precision studies. For example, when using Euclid or LSST (Vera Rubin Observatory) data to measure dark matter clustering, we would include ultralight axion effects in the modeling. The “Cosmology 9.0” model would be used to re-interpret any slight anomalies in structure growth (some existing slight σ<sub>8</sub> tension or small-scale lensing anomalies might find explanation under fuzzy DM). We’d outline a plan for how all future surveys can test this further or use it as the default assumption.

In short, if verification succeeds, we **embrace the ultralight scalaron as a central pillar of cosmology**. The remaining work is to formalize and capitalize on this discovery: update theoretical frameworks, ensure consistency with all aspects of physics, and chart out new questions (e.g. the exact nature of the axion’s origin, or whether multiple axion-like fields exist – since string theory often predicts a spectrum). We would have essentially moved the field into a new paradigm where dark matter is a quantum wave, completing the paradigm shift with thorough documentation and by setting the stage for the next generation of research built on this foundation.

By following this comprehensive plan – from high-resolution simulations and targeted observations to cutting-edge lab experiments – we will arrive at a **definitive assessment of the ultralight axion scalaron’s viability** as the dark matter. Either outcome yields valuable progress: *confirming* the scalaron would solve multiple cosmological puzzles at once, while *falsifying* it will significantly narrow the field and guide us toward the correct theory of dark matter. This precision-focused investigation, integrating all scales of inquiry, epitomizes the synergy of modern cosmology and will decisively inform the direction of the RFT cosmological framework moving forward.

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