Introduction

In the Relativistic Field Theory (RFT) program, version 9.7 aims to unify quantum coherence, entropy, and twistor geometry into a single framework. Here we focus on the adaptive scalaron field – a scalar field that can act as dark matter and self-gravitates – and show how its quantum decoherence, entropy production, and twistor-space topology are all facets of the same irreversible process. In essence, as a scalaron halo or soliton loses quantum coherence, it gains entropy and undergoes a topological change in its twistor representation that encodes an arrow of time. We will: (1) define a scalaron entropy functional $S(t)$ that grows as coherence is lost; (2) argue that gravitational collapse or halo decoherence induces an irreversible change in the scalaron’s twistor cohomology class (from $H^1(PT,\mathcal{O}(-2))$ to a distinct $H'^1$); and (3) propose a new geometric invariant in twistor space that monotonically increases, making the second law of thermodynamics manifest as a topological constraint. Together, these pieces form a geometric narrative of entropy and time’s arrow in RFT 9.7, paving the way for a fully unified RFT 10.0.

1. Scalaron Entropy and Self-Gravitational Decoherence

Defining the Entropy Functional: We introduce an entropy measure $S(t)$ for the scalaron field that depends on its quantum coherence. Let $F\_c(x,t)$ be the coherence fraction – a local measure of how much the scalaron’s state at position $x$ remains in a pure coherent state. (For example, $F\_c=1$ for a perfectly coherent condensate, and $F\_c\to 0$ for a completely incoherent mixture​

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x, which is analogous to an entropy density integral. This scalaron entropy $S(t)$ increases as coherence is lost (since $F\_c \to 0$ in parts of the field makes $-\ln F\_c$ large). Intuitively, $S$ quantifies the information loss of the scalaron’s quantum phase: a perfectly coherent field (all in one quantum state) has minimal $S$, whereas a fully decoherent field (random phases) has high $S$. This construction parallels entropy measures in quantum information – the coherence fraction serves to quantify purity​

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, and $S(t)$ resembles an entropic functional of that purity. Self-Gravity as a Decoherence Driver: Crucially, the scalaron’s own gravity can induce decoherence without any external observer. As the scalaron field evolves, gravitational self-interactions cause different parts of the wavefunction to acquire phase divergences and entangle with the gravitational field. This internal interaction acts like an “environment” that decoheres the field’s quantum state. In other words, gravity itself performs a measurement-like role, driving $F\_c$ downward and $S$ upward. This idea is consistent with the hypothesis of gravitational decoherence, proposed by Károlyházy, Diósi, Penrose and others, that gravity can cause quantum wavefunctions to collapse or lose coherence​

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. In fact, some have argued that gravitational decoherence underlies the very arrow of time​

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. Here we adopt that view: as a scalaron clumps under gravity, it spontaneously decoheres – no classical observer needed – and its entropy unavoidably rises. Interpretation via von Neumann Entropy: An equivalent formulation is to consider the scalaron’s one-particle density matrix $\hat{\rho}\_1(t)$ (obtained by tracing out all but one quantum of the field). Initially, if the field is in a pure Bose–Einstein condensate state, $\hat{\rho}\_1$ has rank 1 (all particles occupy one mode) and thus zero von Neumann entropy. But as the field decoheres into multiple modes, $\hat{\rho}1$ becomes mixed. We can quantify entropy as $S{\mathrm{vN}}(t) = -\mathrm{Tr}[\hat{\rho}\_1 \ln \hat{\rho}1]$. This $S{\mathrm{vN}}$ will increase in time, reflecting the growing mixture of modes. Indeed, calculations in analogous systems show that the one-particle entropy grows after perturbations (e.g. after a quench, the one-particle density matrix entropy increases logarithmically in time​

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). This supports our $S(t)$: in regions where $F\_c$ drops (indicating multiple modes locally), $\hat{\rho}\_1$ gains entropy. In summary, decoherence = entropy increase at both local and global levels​

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. Scalaron Collapse and Entropy Production: Consider a concrete scenario: a halo of scalaron dark matter initially has a large coherent core (a solitonic BEC) with $F\_c\approx1$ in the center. Over time, as the halo grows and experiences perturbations, the core might undergo density oscillations and interactions with the surrounding “granular” halo. The previously coherent core’s wavefunction begins to dephase relative to the halo – effectively, the core decoheres (its phase gets entangled with halo degrees of freedom). The coherence fraction $F\_c$ in the core drops from near 1 to some lower value. Accordingly, $S(t)$ increases. If the core eventually collapses (for instance, acquiring enough mass to overwhelm quantum pressure), the process is dramatic: the scalaron field in the core falls into a high-density state, potentially even forming a black hole or dense object. That collapse represents a huge increase in entropy – not only in the usual thermodynamic sense (a black hole has enormous entropy), but also in our scalaron entropy $S(t)$ because the field’s pure state is utterly scrambled. This is an irreversible process; once the scalaron has collapsed and decohered into a complex configuration, $S(t)$ has grown and cannot return to its original low value (short of a fine-tuned reversal of all dynamics). Thus, the self-gravity of the scalaron drives $S(t)$ upward, establishing a time-asymmetric evolution. This is perfectly in line with the second law of thermodynamics: the entropy of an isolated system (here the self-gravitating scalaron) tends to increase. In our case, the second law emerges from quantum dynamics: as gravity entangles the field with itself, microscopic entropy rises​

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, giving rise to macroscopic irreversibility. Notably, this perspective doesn’t require any external measurement or classical environment – gravity within the scalaron field causes “measurements” continuously. Penrose famously suggested that a quantum superposition of two different mass distributions has a finite lifetime, collapsing on a timescale $\sim \hbar/E\_G$ (with $E\_G$ the gravitational self-energy difference of the configurations)​

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. Here, instead of a single yes/no collapse event, we have a continuous entropy flow: the scalaron’s wavefunction gradually loses phase coherence and $S(t)$ rises steadily. This provides a microscopic arrow of time: time is the direction in which the scalaron’s entropy increases. Next, we show how this arrow is imprinted in the twistor geometry of the field.

2. Twistor Space and Irreversible Topology of the Scalaron

Twistor Representation of the Scalaron: Twistor theory provides a way to encode fields in spacetime as geometric objects in a complex projective space. In Penrose’s classic twistor correspondence, solutions of massless field equations correspond to cohomology classes of certain sheaves on projective twistor space ($PT$)​

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. For example, a free massless scalar field in 4D Minkowski space can be represented by an element of $H^1(PT,\mathcal{O}(-2))$ – a first cohomology class of the structure sheaf twisted by $\mathcal{O}(-2)$​

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. (Here $\mathcal{O}(-2)$ is a line bundle indicating homogeneity degree -2 on twistor space, as typical for scalar fields in Penrose transform theory.) In simple terms, any sufficiently nice (analytic) scalar field configuration corresponds to some holomorphic data on twistor space – often given by patching functions on overlapping regions of $PT$. The scalaron field, being (in the early universe or low-density limit) a light, coherent scalar, can be treated in this paradigm. Initially, when the scalaron is in a pure coherent state, its twistor description is correspondingly simple: one can imagine it corresponds to a single global cohomology class $[\alpha] \in H^1(PT,\mathcal{O}(-2))$ defined by a tidy holomorphic function (or a set of functions that glue consistently) on twistor space. Decoherence as Twistor Cohomology Change: Now consider what happens in twistor space when the scalaron decoheres or collapses. Quantum decoherence in spacetime means the field’s phase relationships break down across regions – effectively the field can no longer be described by one single wavefunction everywhere, but perhaps by a superposition or mixture of states localized in different regions. In twistor terms, this suggests that the original cohomology class $[\alpha]$ – which was a unified object – may fragment or become more complicated. Technically, the field configuration after decoherence might correspond to a different cohomology class $[\alpha']$. We propose that extreme processes like soliton collapse or halo-wide decoherence drive an irreversible transition $H^1(PT,\mathcal{O}(-2)) ;\to; H'^1(PT,\mathcal{O}(-2))$, where $H'^1$ represents a cohomology class that is topologically inequivalent to the original. In less formal terms, the twistor “fingerprint” of the scalaron field changes permanently. Why would the class change, rather than just the representative? The key is that decoherence is not a holomorphic, gentle deformation – it’s a violent process that introduces non-analytic features in the field. For instance, a perfectly coherent scalaron soliton might correspond to a nice meromorphic function on twistor space with a small number of poles (singularities). But once the soliton collapses, the field might radiate or develop fluctuations that correspond to a proliferation of poles or branch cuts in twistor space. The new field configuration cannot be described by the old twistor function without adding new singularities. In twistor cohomology language, what has happened is that the Čech 1-cocycle representing the field has changed by a 1-cocycle that is not a coboundary – i.e. you can’t just gauge it away or deform it back to the old one. It represents a genuinely different cohomology class. This is a topological change: cohomology classes are discrete labels (much like winding numbers or homotopy classes), and moving from one to another requires crossing a sort of barrier. One way to see the irreversibility is through obstruction theory. If one tries to continuously deform the decohered twistor data $[\alpha']$ back to the original $[\alpha]$, one encounters an obstruction – essentially, the new singularities in twistor space cannot be removed by any smooth deformation without encountering a singular limit. In physical terms, to restore the original class, the scalaron field would have to recohere – requiring an improbably precise cancellation of phases or even a violation of causality. The “gluing” interpretation is illustrative: before decoherence, one could cover twistor space with (say) two patches such that on their overlap the scalaron’s twistor function satisfies a simple gluing relation (defining the class $[\alpha]$). After decoherence, attempting the same patching results in a mismatch on overlaps – the would-be gluing function now has extra terms (from new poles) that cannot be reconciled. This failure to glue signals that no single cohomology class $[\alpha]$ on the original covering can represent the field; instead, the field is described by a different element $[\alpha']$ (one might need an enlarged Čech cover or higher-rank description). In short, the twistor sheaf encoding the scalaron has fragmented: what was one coherent sheaf section is now torn into pieces that do not fit together in the same way, so the topological class is new. Irreversibility and “No Smooth Return”: The transition $[\alpha]\to[\alpha']$ in cohomology is one-way. To reverse it, one would have to remove those additional twistor singularities or perfectly realign phases – essentially requiring the scalaron field to cool and reconverge into a single coherent wavefunction. But such re-coherence is thermodynamically forbidden (or at least fantastically unlikely) because it would mean a decrease of entropy. In practical terms, once a soliton has collapsed and shed its coherence, the twistor function has, say, dozens of poles scattered across $PT$; there is no continuous, low-energy process that will cause all those poles to magically coalesce back into the few original singularities. This is analogous to how one cannot unscramble an egg: the topological state of the system has changed. In many physical systems, a change in a topological invariant indicates a phase transition that cannot be reversed without going through a singular condition. Here, that singular condition was the moment of collapse or maximal decoherence – essentially a “phase transition” in the space of solutions, where the twistor description had to acquire a new singular structure. Thus, the cohomology class change is permanent under normal dynamics. The only way to get back would be to impose highly non-generic, time-reversed dynamics (violating the second law). To make this more concrete, consider a specific example: a scalaron soliton in a halo corresponds (schematically) to a simple pole in the twistor function at some location (related to the soliton’s momentum and position). As the halo decoheres, small density fluctuations in the halo can be thought of as the superposition of many wave modes – in twistor space, these are represented by many poles (each pole corresponds to a plane wave mode in space–time). Initially, those modes may have been coherent enough to effectively act like a single collective mode (one pole dominating). After decoherence, they act independently – the twistor pole splits into many. You can’t recombine them without interference. From the twistor point of view, the field’s holomorphic curve has broken apart. This is reminiscent of a holomorphic curve degenerating into several pieces, which in algebraic geometry is a singular limit that changes the genus or the class of the curve. No smooth deformation can glue the pieces back without leaving twistor space (since you’d have to pass through a configuration where the curve was singular or not holomorphic). All of this formal reasoning underlines: the twistor cohomology class after collapse/decoherence is topologically distinct and cannot be undone by any smooth, unitary evolution. The arrow of time is thus built into the geometry: the past configuration and the future configuration live in different sectors of twistor space. It is worth noting an extreme case: if the scalaron collapses into a black hole, the spacetime itself changes topology (an event horizon forms, and the twistor description – which typically assumes asymptotic flatness – might no longer even be applicable inside the horizon). In that case, certainly the twistor class as originally defined is no longer relevant; effectively information has been lost behind a horizon. While our focus is on the twistor class outside such extremes, the lesson is general: gravity-driven processes carry an inherent asymmetry. As Carroll and others emphasize, gravitational clumping (e.g. forming black holes) takes one from a low-entropy, symmetric state to a high-entropy, asymmetric one​

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– an irreversible step. We have translated that into twistor language: the “clumping” corresponds to a more complex twistor class that you can’t unclump without violating topology. In the next section, we introduce a measurable geometric index to quantify this increasing complexity.

3. Geometric Arrow of Time: Monotonic Twistor Invariants

To quantify the arrow of time in twistor space, we seek a geometric measure that only increases as the scalaron decoheres and collapses. In thermodynamics, entropy itself is the monotonic quantity. In our twistor-geometric context, we propose an invariant that plays a similar role – call it the twistor entropy index. While the precise definition can vary, the idea is to capture the complexity of the scalaron’s twistor cohomology data in a single number or set of numbers that never decrease in an isolated system. Candidate Invariant – Pole Complexity: One intuitive choice is to use the number of essential singularities (such as poles) needed to describe the scalaron’s twistor function. For a simple coherent field, the twistor function might be something like a rational function with a small number of poles. As time progresses and the field fragments, the twistor function will generally require more poles (or branch cuts, etc.) to represent it. We can define the pole count $N\_{\text{poles}}(t)$ as the count of poles (perhaps above some small residue threshold) in the twistor representation of the scalaron at time $t$. We expect $N\_{\text{poles}}(t)$ to increase or stay the same with time, but not decrease. For example, if initially $N\_{\text{poles}}=1$ (one dominant pole representing a single momentum mode), after decoherence one might have $N\_{\text{poles}}=10$ as the field’s wavefunction now has 10 significant components. Those poles might move or merge in minor ways, but unless coherence is restored (which is implausible), they won’t drop back to 1. Thus $N\_{\text{poles}}$ serves as a kind of arrow-of-time index. We can extend this idea to a more refined measure. Instead of a simple count, consider the distribution of pole strengths or other invariants of the twistor cohomology class. One could define an entropy-like quantity in twistor space: for instance, if pole $i$ carries a “weight” $w\_i$ (perhaps proportional to its residue or contribution to the solution’s energy), one could define

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, where $\tilde{p}i = w\_i/\sum\_j w\_j$ is the normalized weight of pole $i$. This $S{\text{twistor}}$ would be low if one pole dominates (all weight in one mode gives $\tilde{p}\approx1, S\_{\text{twistor}}\approx0$) and higher if the weight is spread among many poles (giving a higher entropy). $S\_{\text{twistor}}$ would thus monotonically increase as the scalaron’s wavefunction spreads out in twistor space. In essence, this is measuring how fragmented the twistor sheaf has become – analogous to how our original $S(t)$ measured how mixed the quantum state has become. We expect $S\_{\text{twistor}}(t)$ to correlate with the physical entropy $S(t)$. In fact, one can conjecture that $S\_{\text{twistor}}$ and $S$ are proportional in some regime, since both capture the number of independent degrees of freedom (modes or patches) that the field has split into. Another related invariant could be defined via the sheaf cohomology structure itself. For instance, one might define an index as the minimal number of charts needed to cover twistor space such that the scalaron’s data is analytic on each chart. A fully coherent field might require only 2 patches (like the North and South hemi-spheres of $\mathbb{CP}^1$ in the classic twistor construction). A decohered field might require many patches (or one patch with many singularities). The number of patches (or the rank of the sheaf) could serve as an invariant. Yet another possibility is to track the order of an obstruction in higher cohomology: if decoherence introduces a nonzero element in $H^2$ (an obstruction to gluing, as discussed), the norm of that element could be an indicator of irreversibility. The specifics can be formal, but the central point is that we can always find a property of the twistor representation that only moves one way. Chamblin (2004) provides a nice analogy in a different context: he showed that increasing entropy flux through a region corresponds to an increasing volume in twistor space​

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. In that holographic context, twistor space geometry literally expands with entropy. In our case, the “size” (or complexity) of the twistor data grows with entropy. We can say the twistor entropy index $I\_{\text{tw}}(t)$ satisfies $dI\_{\text{tw}}/dt \ge 0$. This is the geometric incarnation of the second law. If one attempted to decrease $I\_{\text{tw}}$, it would mean simplifying the twistor configuration – essentially erasing poles or shrinking volumes in twistor space – which is forbidden by the cosmic accountability of information. The only way to decrease it would be to externally impose coherence (like deliberately phase-aligning the field with some intervention), but in a closed system that’s as impossible as gas molecules spontaneously unmixing. Time’s Arrow as a Twistor Constraint: We can now reframe the second law of thermodynamics as a constraint on twistor-space evolution. The allowed transformations of the scalaron’s twistor cohomology are those that do not decrease the complexity of the twistor data. Time’s arrow is built in: one direction of evolution leads to finer analytic structure (more fragmented sheaves, higher pole count, greater twistor volume), while the reverse direction is not physically realized. In practical terms, any twistor-space trajectory that would lower the entropy index is suppressed (of measure zero in solution space). This provides a new angle on the arrow of time: it is not just statistical, but geometric. The geometry of twistor space – through which the scalaron’s state moves – has a kind of “directed acyclic” character: you can move to higher-complexity regions of twistor space, but not go back to simpler ones without leaving the physical solution manifold. To summarize this section, we introduced a monotonic geometric invariant (pole count, twistor entropy, or similar) that tracks the irreversible growth of complexity in the scalaron’s twistor representation. This invariant increases in tandem with the usual thermodynamic entropy $S(t)$. We thus identify the arrow of time with a direction in twistor space: the direction in which this invariant increases. The concept of an “allowable twistor transformation” can be thought of like a one-way street – consistent with the second law. In a very real sense, the arrow of time is the arrow of increasing twistor cohomology complexity.

Conclusion and Synthesis

We have developed a unified geometric framework in RFT 9.7 that links quantum coherence, entropy flow, and twistor topology in the behavior of the scalaron field. First, we defined a scalaron entropy $S(t) = -\int \rho,\ln F\_c,d^3x$ that quantifies loss of coherence and increases as the self-gravitating scalaron decoheres, in agreement with von Neumann entropy of the one-particle density matrix and the idea of gravitationally induced decoherence​

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. Next, we showed that this entropy increase corresponds to a topological change in twistor space: the scalaron’s twistor cohomology class $H^1(PT,\mathcal{O}(-2))$ irreversibly transitions to a new class $H'^1$ when a soliton collapses or a halo decoheres. This change is protected by a topological obstruction – it cannot be undone by smooth deformation, symbolizing the irreversibility of the process. Finally, we introduced the concept of a twistor entropy index (such as pole count or sheaf fragmentation measure) that increases monotonically with the scalaron’s decoherence and collapse. This index provides a concrete handle on the arrow of time: it is a geometric quantity that grows alongside physical entropy, encoding the second law as a restriction on the evolution of the scalaron’s twistor configuration​

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. In this synthesis, time’s arrow emerges as a geometric feature of the scalaron’s evolution. The universe, through the scalaron field, “chooses” trajectories in which the twistor-space representation becomes more intricate and information-rich (in the sense of complexity), never the opposite. The once purely quantum concept of decoherence is thus married to a global geometric invariant. This closes the conceptual loop between quantum field coherence, entropy production, and complex geometry. Such a unified picture is not only elegant but also potentially predictive. For instance, it suggests that observing a scalaron (fuzzy dark matter) halo’s decoherence could be linked to counting an increase in effective modes (perhaps observable via fluctuations​

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), or that a failed attempt to reverse a collapse would correspond to a missing cancellation in twistor terms. These are hypotheses that could be tested in simulations or perhaps even astrophysical observations (e.g. detecting irreversibly broadened interference patterns in scalaron wave dark matter). Looking ahead to RFT 10.0, this framework sets the stage for a deeper theory where quantum gravity and thermodynamics meet. If a single scalar field’s evolution can be tracked consistently from quantum coherence to classical entropy via twistor geometry, we move closer to a falsifiable theory of quantum gravity’s emergent phenomena. One could, for example, attempt to calculate the twistor entropy index for a given scalaron collapse in a simulation and see if it indeed only increases. Additionally, this approach may shed light on the fate of information in gravitational collapse (a twistor-space view of Hawking radiation entropy flow)​

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. In summary, RFT 9.7 has woven a narrative where entropy and time’s arrow are written in the language of geometry. This unified perspective strengthens the plausibility that we are capturing a fundamental aspect of nature – one where quantum coherence, gravity, and topology conspire to produce the temporal order of our universe. Sources:

Penrose, R. et al. – Twistor theory background​

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