

WaveTree

*A history-conditioned geometric framework for
the Now, the dark sector, and the origin of inertia.*

Carl Downs · Independent researcher · carl_downs@yahoo.com

In collaboration with Anthropic's Claude (Opus 4.7 and Fable 5).

Version 1.0 · July 2026.

FOREWORD

• On the origin of this work, and how to read it

It all started with Einstein's elevator. A person in a sealed, accelerating elevator cannot tell — by any local experiment — whether they are being pressed to the floor by acceleration or by gravity. Einstein called the insight behind that thought experiment the happiest thought of his life, elevated it to a postulate, and built general relativity on it. But a postulate is a debt: it says *that* two things are identical without saying *why*. The author — a layperson with no physics training beyond college, returning to the elevator over a period of years — could not stop asking what the universe would have to be like for the equivalence to be not an assumption but a consequence. That question, pressed outward to cosmological scale and joined to a second stubborn one — *if something we believe to be impossible is in fact not, what would the universe have to be like for it to be possible?* — is where this essay began. It ends, whatever else the reader makes of it, by proposing an answer to the elevator (Section 7.2).

What emerged, over years of iteration and pondering the known conundrums of physics, was a geometric picture of the universe — a Wave, a Now, a Tree — under which a great many independent puzzles seemed to click into place at once. Dark energy and dark matter. Gravity itself — and why it feels identical to acceleration. The wave–particle nature of light. The observer effect. Entanglement. Antimatter. The felt stability of a universe whose present is being written at the speed of light. The dark sector and gravity are, on the author's reading, the two great blindspots of modern physics — the places where the standard picture says *that* without saying *why* — and they are where this framework spends its effort. This essay is the picture, offered on

its own merits. **The author is not asking for belief. He invites the reader to consider, test, and critique what a decades-long thought experiment has produced — and to carry away whatever proves useful, if only a single idea.**

A word on method. The author is a computer scientist by training, and a layperson to physics. The instruments he brought to the puzzle were the ones a computer scientist brings to any problem — observe what is happening, identify where the current model does not explain the observation, hypothesize a mechanism that would close the gap, work through what would follow if the mechanism were correct, and expose the hypothesis to the possibility of being wrong. This is engineering problem-solving in the computer-science tradition, whose native habit is to reason about *substrates* — layered systems in which a small number of primitives, correctly composed, produce the observed behavior of a much richer surface. Its close cousin in physics is the *thought experiment*, which Einstein famously named as his own instrument — imagining riding a beam of light and following it home to special relativity, exactly as the elevator of this foreword's opening was followed to general relativity. WaveTree is what emerged when a layperson with computer-science discipline applied that method of visualization pressed against observation to the gaps he could see in current cosmology. The reader will recognize the substrate reasoning in the essay's central move: reading matter, dark matter, and dark energy as three regimes of one underlying field rather than as three separate substances. That is a computer-science instinct pressed against a physics observation. The author claims neither Einstein's mathematics nor his stature — nor a physicist's or cosmologist's training — and asks the reader only to consider whether the resulting picture is coherent, and whether the single testable prediction it makes (Section 6) is worth running.

The *form* this essay takes is a collaboration. The author is a non-specialist; the vision is his. Working from accumulated notes, sketches, and prior drafts, an Anthropic model (Claude, Opus 4.7) acted as subject-matter editor and translator — locating the vision within the vocabulary and standards the foundations-of-physics community uses, and rendering it into the language of Cauchy hypersurfaces, causal-past functionals, effective stress-energy, and testable observational discriminants. The author supplied the vision and the questions; the model supplied the reader's dialect. Errors of physics remain the author's alone.

The essay is structured in four layers. Section i is the **Vision** — the framework's core assertions in plain language, each stated together with the observations that motivated it, so the reader can see what the argument is *about* before the argument is dressed in symbols. Section iii states the **strongest anticipated objections** the authors could construct against the framework — several of which land, and are conceded in print — together with the framework's explicit falsifiers; a skeptical reader's time is best spent there first. Sections 1–12 form the

Technical framing — the geometric picture put alongside general relativity, the Standard Model, and Λ CDM, with a single sharp novel prediction (Section 6). Section 13 collects **Speculative extensions**, clearly fenced; Sections 14–15 record open problems and the essay's claimed contributions, and a References section grounds the works and experiments cited throughout.

THE VISION · ASSERTIONS AND THE OBSERVATIONS BEHIND THEM

i The vision

A note on this section. *The Vision states the framework's core assertions in plain language, each preceded by the observations that motivated it and followed by what it would explain. It is the picture the essay is about; Sections 1 onward translate the same picture into the working language of the foundations community, and Section iii states the objections. Readers who prefer formalism first are welcome to skip ahead; the technical framing does not require the Vision.*

i.1 The Wave and the Now

The universe is a never-ending explosion. It began with the Big Bang and it has been expanding ever since. The founding visualization is that of a hypersphere expanding forever — a blast front spreading outward in every direction of spacetime. (The blast-front image is a deliberate visualization, not a physical claim of a center and an edge; the technical body replaces it with a foliation that has neither. What the image is *for* is the next assertion.)

The **Wave** is that blast front — the absolute outer edge of the explosion. And that edge is **the Now**: spacetime as we experience it — the active, frothing edge where events are becoming real. It is current time. The Now can be visualized as the skin of an expanding balloon: the surface we live on and experience as the present.

The observables. The most peculiar empirical fact in physics is the constancy of the speed of light. Turn on a flashlight in a moving car; the beam propagates outward from the bulb at exactly c . Do the same on the ground; same c . Do it aboard a starship travelling at 99% of c

toward a distant observer; the observer still measures c , not $1.99c$. Doppler effects change the color of the light — its wavelength — but they never change its speed. Every electromagnetic emission — visible light, radio, microwaves, gamma rays, all of it — radiates outward in vacuum in every direction from its source at exactly c , regardless of the source's motion and regardless of the observer's motion. Special relativity was built to accommodate this fact; it did not explain why the fact holds.

The postulate. The Now advances at the speed of light. WaveTree posits this as the substrate reason for what special relativity observed but did not explain. What moves at c is not light — it is the spacetime substrate that light is *made of*. Every electromagnetic emission is a ripple on the Now; every photon is a small patch of the Now propagating outward with it. The observed constancy of c across every frame follows without further assumption: no observer can travel faster than c because no observer can outrun the substrate they are embedded in, and every EM measurement everywhere gives the same c because every EM emission is simply the substrate expanding.

The consequence. This is why light appears as both a wave and a particle. When we do not measure, light behaves as a wave — because it is a wave; it is the substrate expanding. When we measure, we see a photon — a discrete point on the substrate where our measurement intersected it. Light is not something riding on the wave. **Light IS the wave.**

One more observable belongs here, because it removes any suspicion that "the universe is a wave" is merely poetry: **spacetime itself waves**. Gravitational waves — ripples in the fabric of spacetime — were, within living memory, considered beyond any conceivable measurement; then they were measured directly, with instruments of almost absurd delicacy, and their speed was found to be indistinguishable from c . That spacetime can ripple, and that its ripples travel at precisely the speed the Now advances, is the WaveTree picture in miniature — observed.

i.2 Why our reality appears to be stable — the Tree

If the Now is expanding at the speed of light, why do we experience such stability? The Earth is ancient. Mountains and seas have existed for billions of years. Our world of mass and energy appears very steady.

The answer is all in the past. As time moves forward, the mass and energy that existed five seconds ago still exists. The mass and energy of five billion years ago still exists. **Most importantly, all of that historical mass and energy influences the mass and energy of the Now.**

Our theory derives its name from a useful metaphor — the tree. When a sapling is born, it grows through the seasons year after year to maturity. Cut the trunk in half, and the stump reveals concentric rings — one for each year of life. As the tree grew, the rings from earlier years provided the strength it needed to grow further. The outermost bark is like the Wave of the Now. The rings are like historical spacetime — **the Tree**.

The Wave of the Now advances at the speed of light. The Tree of historical spacetime stabilizes it. **The stabilizing effect of historical spacetime is the source of the forces we perceive.** Why $F = ma$ works — why bodies resist acceleration at all — is a question the framework answers with historical spacetime (the inertia postulate, §1.5). Why the energy of a moving body grows without bound as it approaches c — Einstein's $E = \gamma m_0 c^2$ — is answered the same way. Everything we perceive in the present is a manifestation of historical branches of mass and energy interacting. *The observable effects create the Now.*

i.3 The dark energy & dark matter postulate

The observables. Cosmologists have been trying to make the books balance for a long time. Galaxies rotate too fast for their visible mass — they should be flying apart under centrifugal force, and they aren't. Something invisible is holding them together. That something is called **dark matter**. Meanwhile, the expansion of the universe is *accelerating*, not slowing under gravity as one would expect. Something is pushing everything apart at every scale. That something is called **dark energy**. Between them, dark matter and dark energy account for roughly 95% of the mass–energy budget of the universe. Ordinary matter — everything you can see, touch, put in a telescope, split in an accelerator, or eat for breakfast — is only about 5%. And in fifty years of searching, no experiment has ever detected a dark matter particle. No experiment has ever measured a dark energy field.

The engineering problem. If I were designing a system from scratch and 95% of my budget was going to "something we cannot detect and cannot describe," I would suspect the description was wrong. The three-substance model — baryons, dark matter, dark energy — has the shape of a book that doesn't balance. It postulates two invisible substances to make the numbers work, and then, for fifty years, has failed to catch either of them in a jar. When a model has been unable to detect its own load-bearing components for half a century, the honest engineering move is to question the model, not to keep looking harder for particles that may not exist.

The postulate. There is no dark sector. There is only the Tree — historical spacetime — at three different degrees of coherence.

- What we call **ordinary matter** is the Tree where it has been *written into stable records*: atoms, molecules, stars, planets, us. The coherent skin of historical spacetime where the moving Now is writing entries as it advances.
- What we call **dark matter** is the Tree where it *clumps and pulls* — where the correlations of the past shape the local gravitational profile — but has not yet been written into records. History pressing on the present in unstructured form.
- What we call **dark energy** is the Tree at its *smoothest and most uniform*: the ensemble mean of historical spacetime, the substrate's floor, pushing everything outward at once.

The consequence. There are no missing particles because there is nothing missing. What astronomers call "dark" is not dark — it is history, in one of two states of coherence: clumped or smooth. The reason we cannot detect a dark matter particle is that there is not one to detect. The reason we cannot describe dark energy as a field is that it is not one. The three components of the mass–energy budget are three degrees of processedness in one substrate. The dark sector is not dark. It is history.

One further consequence deserves its own statement, because it answers the question hiding inside the word "dark." Under this postulate, matter and energy — in the classical, record-bearing sense — exist only on the Now: emission, absorption, collision, every electromagnetic act is a surface act, because light is the sweep itself (§i.1). **The past cannot shine — not because it is far away, but because shining is something only the present can do.** What the past can do is gravitate: gravity is the drag of history against the sweep (§i.4), and the drag persists. So as the Now advances, each moment's configuration is swept into the Tree, where it goes dark by necessity — unable to emit, unable to reflect, still pulling. Nothing is converted; the objects themselves sail on at the luminous tip. What accumulates behind them is imprint. Dark, in this framework, is not a species. It is the optical status of history. And one thing alone crosses the other way: antimatter — history pulled briefly back onto the surface (§i.7) — the third state, and the exception that proves the rule.

A final image for this postulate. An ocean carries currents, eddies, whirlpools, tsunamis — a full catalog of named phenomena, each real, each with its own distinct behavior, some gentle and some violent. And at the end of the day, water is the substrate: every one of them is something water does. In WaveTree, the catalog is matter, dark matter, dark energy, gravity, light. **Historical spacetime is the water.**

i.4 The gravity postulate

The observables. Every mass in the universe is drawn to every other mass. Newton described the *what* of it in 1687; Einstein described the *how* in 1915: mass tells spacetime how to curve, and spacetime tells mass how to move. In Einstein's picture, mass creates a dimple in the fabric of spacetime, and other masses roll into the dimple. If you sit in a Tesla with it set to Ludicrous Mode and mash the accelerator, your body is pressed deep into the seat by a force that is not, in the usual reading, gravity — but the sensation is *exactly* the same as gravity. Einstein noticed this a hundred years ago and called it his happiest thought.

The engineering problem. The classic rubber-sheet illustration explains gravity by pointing at gravity. Mass creates a dimple; other mass rolls into the dimple; we call that rolling "attraction." But this isn't an explanation — it's a re-description. Why does mass create a dimple? Why does the felt sensation of standing on the ground equal the felt sensation of being pressed into the seat of an accelerating Tesla? Einstein's equations describe *that* these things are true and give us the mathematics to compute them. He did not — and explicitly did not attempt to — describe *why*.

The postulate. Gravity is a force balanced between two parties: the expanse of the Now wave, sweeping forward, and the drag of spacetime history — the tail all matter and energy is based on — resisting that sweep.

The Now is advancing at c (§i.1). Every mass has a historical spacetime tail extending behind it — its Tree column. As the Now sweeps forward, that tail is dragged with it, and the drag registers in the geometry: where a mass stands, the sweep is disturbed, and the geometry carries the imprint of that disturbance outward around the body. (Its magnitude is set by the body's invariant energy content — not by the length or richness of its history; Section 8.4 explains why that distinction is forced by experiment.) The dimple in the rubber sheet is the visible signature of the disturbance around a massive body; the felt pressure in the Tesla seat is the same physics in a body being forced to change its state of motion. Two names for one thing. In the technical body this becomes precise: matter disturbs the sweep directly where it stands, and the surrounding vacuum field is the *transmitted record* of that disturbance (Section 7).

The consequences.

1. **Two masses close enough fall into a dance.** When Earth and Moon are close enough, their dimples in spacetime overlap: each body's motion is steered by the recorded imprint of the other. They fall into a mutual dance around a common center. That is what an orbit is. It is not two objects held together by an invisible thread — it is two spacetime dimples interlocking and following each other.

2. **The equivalence principle is not a postulate but a consequence.** Einstein *assumed* that gravity and acceleration must feel identical and built general relativity on that assumption. WaveTree *derives* the identity: both sensations are the drag of the same tail against the same sweep. Gravity and acceleration feel identical because they *are* identical.
3. **Gravity is hard to isolate directly** because we have no external referent point for the expansion of spacetime. We can only measure time itself, and time is relative to where we are and how fast we are moving. That is the fingerprint of gravity being an artifact of the substrate, not an independent field acting on top of it.

i.5 The inertia postulate

The observables. Special relativity tells us three things about fast-moving bodies that are ironclad and experimentally verified beyond argument:

1. **Energy grows with speed without bound.** A body of rest mass m_0 at velocity v carries energy $E = \gamma m_0 c^2$; as v approaches c , γ grows without limit.
2. **Time dilates with speed.** As v approaches c , the moving clock ticks slower and slower as measured in the lab frame.
3. **No massive object can reach c .** The required energy grows without bound before it gets there.

Both effects are governed by the same factor — the Lorentz factor γ , which depends on velocity (not on acceleration as such: clocks in muon storage rings at accelerations of 10^{18} g tick exactly as their speed alone dictates). They are confirmed by muon lifetimes in the atmosphere, by particle-accelerator momenta, and by the GPS system, whose satellite clocks are corrected daily for the combined special-relativistic and (larger, opposite-signed) gravitational effects that relativity predicts. Special relativity describes *that* these things happen and gives the mathematics for computing them exactly. It does not describe *why*.

The engineering problem. If energy and clock rate both change through the same factor γ , arising from the same motion, there ought to be a single mechanism producing both. Special relativity treats them as two outputs of the Lorentz transformation. But the Lorentz transformation is a mathematical device — it takes coordinates in one frame and returns coordinates in another. It tells us the outputs must come out a certain way. It does not tell us what is *physically* going on to make them come out that way.

The postulate. Inertia is the resistance of the historical spacetime tail to being cut across the nominal expansion line of the Now.

Every body drags a tail — its own column of causal-past history. At rest with respect to the local sweep, the tail extends behind the body parallel to the sweep of the Now — no resistance. Under acceleration, the tail tilts and begins to *cut across* the nominal expansion line of the Now. The more the tail tilts, the more it drags. Two everyday images carry the intuition: a kite is stabilized in flight by its tail, and steering the kite means dragging the tail through the air behind it; a person on tall stilts must reckon with the stilts before the person can change direction. That drag — the cost of re-aiming a body's history — is what we experience as inertia. (What the drag depends on is disciplined by experiment: only the body's invariant energy content, never the length or richness of its history — Section 8.4.)

The consequences.

1. **Energy and time are two projections of one unchanged content.** The tilt does not add anything to the body's rest content; it re-aims it. What the observer reads as growing energy and what the observer reads as a slowing clock are the spatial and temporal projections of the same tilted tail — one thing seen twice. The invariant — the body's rest mass — never changes (Section 8.3 gives the exact form).
2. **Why no massive body reaches c .** Not because a wall of infinite energy stands in the way, but because the tilt has no final position: the tail can approach alignment with the null direction of the sweep without bound and can never coincide with it. The exchange has no endpoint to reach.
3. **Why photons live on c .** A photon has no rest-frame content to re-aim. It has nothing to trade. So it can only sit on the sweep's own reference line, which is c . It has no other option.

i.6 The quantum tie-in

Once the postulates above are on the table — the Now advancing at c , the substrate being the Tree, mass and gravity and inertia all drag effects of the tail against the sweep — several features of quantum mechanics that had seemed strange begin to look less strange.

The constancy of the speed of light is not a coincidence — it is **the expansion coefficient** of the Now. Light and the wave are the same thing. That is why light is both wave and particle: it is a wave because it *is* the wave; it appears as a particle only when we look — when we measure.

The classic double-slit experiment demonstrates this without any need to invoke strangeness. Treated as particles, photons produce a result the slots cannot explain — how can particles going through one slit or the other interfere with themselves? Under WaveTree, the

spacetime wave carries through the slots and impacts the back substrate. Photons are measured only at that impact. **The wave passes through; photons appear on measurement.** Perfectly consistent.

The sharpest form of the experiment makes the point unanswerable. Dim the source until photons are emitted one at a time — one photon in flight, then a dot on the screen; another photon, another dot. Each emission writes exactly one record. And yet, dot after accumulating dot, the interference stripes still emerge. For a particle picture this is baffling: what did the lone photon interfere with? Under WaveTree it is exactly what must happen: a single emitted photon is one disturbance of the spacetime wave, the wave spreads through *both* slits and touches the whole screen every time, and each emission writes one record somewhere on the wave's footprint — including places no straight-line particle path could reach. Repeat the emission a thousand times and the footprint is revealed, one record at a time.

The observer effect in quantum mechanics — the fact that observing a system changes its outcome — is a natural consequence of everything being expressed in the spacetime wave. Looking at something is not passive. It is an *active* perturbation of the wave propagation.

The wave function of quantum mechanics IS the spacetime wave — the Now itself. Quantum mechanics is predicting the dynamic, chaotic nature of how spacetime expands. (This identification is stated at full strength for a single particle; its known limit for many entangled particles is conceded and handled in Sections iii.5 and 9.3.)

Even entanglement becomes simple in WaveTree: two objects that appear to be entangled across great distances **are in fact the same object**. Spacetime expands but is so fluid that one object can appear to different observers at different locations, while being the same object underneath.

And at our own scale, the picture is arresting. Physics has long known that the felt solidity of the world is a construction — the atom is mostly empty space. WaveTree adds the four-dimensional version of the same observation: a human body extends a couple of metres in space but decades in time, and in spacetime's own units that is a worldline some 10^{16} kilometres long against a metre of width. **The vast majority of what we are is behind us.** In the honest bookkeeping, a person is a filament of history with a thin luminous tip — and the tip is the only part the brain reports.

i.7 Antimatter, and the slice we see

Antimatter is historic spacetime pulled forward to the Now. It is fragile because, in our matter-dominated universe, its counterpart is always waiting on the Now to annihilate it.

Add to all this a modest but important observation. What we can see is limited by our light cone. The perceivable universe, at the order of trillions of galaxies, is only a portion of the whole. *We are seeing a slice of the entire pie.* Whatever conclusions we draw, we draw from that slice.

i.8 Zero-point energy, and the Alcubierre question

The observables. Quantum field theory assigns to "empty" space an enormous formal energy — the zero-point energy of the vacuum — and this is not a bookkeeping fiction: the Casimir effect, in which two uncharged plates in vacuum are pushed together by apparently nothing at all, measures the vacuum's energy structure directly. Yet the energy is inaccessible: no known process extracts net work from the vacuum, and the accounting rules of thermodynamics and the quantum energy inequalities stand guard over every proposal that has tried.

The WaveTree reading. Under this framework, the vacuum's energy is not mysterious stuff residing in empty space. It is the energy of the substrate itself — the Now advancing at c , everywhere, at all times. "Empty" space is the sweep. On that reading, the zero-point inventory is real for exactly the reason it is inaccessible: every apparatus we can build is embedded in the sweep, riding it, with no purchase on it — the way a swimmer drifting with a current cannot feel the current. A mechanism that could *bias* the local sweep and latch onto the difference — the way a windsurfer's sail catches wind moving over the ocean's surface — could in principle tap it. No such mechanism is known, and the essay claims none.

The Alcubierre question. In 1994, Miguel Alcubierre showed that general relativity admits a "warp drive" geometry: contract spacetime ahead of a craft, expand it behind, and the craft rides a bubble at effectively superluminal speed while locally moving slower than light. The solution is mathematically valid and physically stranded — it requires astronomical quantities of negative energy, which the quantum energy inequalities forbid at macroscopic scale. WaveTree does not remove that obstruction. What it offers the Alcubierre question is a reframing of both of its unknowns at once. *What the drive would need to manipulate:* under this framework, an Alcubierre bubble is precisely a bounded region where the sweep of the Now is locally biased — contracted ahead, expanded behind. *Where the energy would have to come from:* the same hypothetical coupling that could bias the sweep is the coupling that could draw on it. If the framework is right, the warp question and the zero-point question are one question. These are horizons of the picture, not claims of the essay: the technical body stakes nothing on them, and the known obstructions are stated in full where the reaches are discussed (Section 13).

i.9 The reach

The author is not a mathematician, and the formalization offered in this essay is a collaboration, not a derivation. But the framework's ambition is stated plainly: **Newtonian physics, Einsteinian physics, and quantum mechanics should all be accommodatable within the WaveTree picture** — and the vibrating strings of string theory, if they describe anything, can be read as cross-sections of the wave.

Recall the observable that closed §i.1: gravitational waves were considered beyond any conceivable measurement — until they were measured. Something believed impossible was not. Perhaps other things believed impossible are also not. **It is all sitting right there.**

ABSTRACT

ii Abstract

WaveTree (WT) is presented as an interpretive geometric framework in the tradition of Ellis's evolving block universe. The observable present — the *Now* — is modeled as a spacelike Cauchy hypersurface whose advance is conditioned at the speed of light: the domain of events determined by the surface's data grows behind a causal envelope generated by null geodesics, and c is the characteristic speed at which each new slice is written from the last. The causal past of each point is encoded in a history functional $\mathcal{H}$ — the *Tree* — whose expectation and correlations enter present dynamics through an effective stress-energy $T^{\mathcal{H}}_{\mu\nu}$.

The essay's central claim, **STP dominance** (STP: *Spacetime-Past*), is that historical spacetime constitutes the overwhelming majority of what enters the right-hand side of Einstein's equations, and that what cosmology currently calls "ordinary matter," "dark matter," and "dark energy" are three regimes of one substrate $\mathcal{H}$ — distinguished by the degree to which $\mathcal{H}$ has been coherently written onto the advancing Now. The framework provides geometric readings of gravity (as the Ricci- and Weyl-mediated response of the null sweep to stress-energy), inertia (as the drag of a body's causal-past worldline against the sweep, with its magnitude fixed by invariant rest-energy content alone), the classical–quantum boundary (as tangential versus slab structure on the Now), entanglement (as apparent multi-location of a single sub-surface object),

and antimatter (as historic spacetime pulled forward to the Now). It is consistent, by construction, with general relativity, the Standard Model, and Λ CDM at all currently tested scales.

Its distinguishing exploratory content is a single, sharp prediction — **history-linked correlations in dark-sector residuals**: halo lensing residuals should correlate with proxies for the halo's causal-past history (stellar-population mean age, metallicity, merger history) *in excess of* the correlation Λ CDM itself predicts through halo assembly bias and baryonic feedback. Stating the prediction as a residual over the simulated Λ CDM expectation makes the test harder and the claim honest. A convincing null returns the framework to its conservative core. A front-matter section (iii) states the strongest objections the authors could construct — together with the framework's explicit falsifiers; a speculative extensions section (13) records where the picture's imagination reaches beyond what can currently be measured.

READ THIS FIRST IF YOU ARE SKEPTICAL

iii Anticipated objections, and what would falsify this

The strongest objections we could construct against the framework are stated here, up front, together with the framework's answers — and, where an objection lands, the concession. A skeptical reader's time is better spent checking these than discovering them independently.

iii.1 "A universal Now is an ether. Michelson–Morley disposed of that."

Local Lorentz invariance is exact in WaveTree: no local experiment distinguishes the foliation, and the Michelson–Morley null is preserved untouched. What WT elevates is the same globally distinguished frame that cosmology already uses daily — the comoving frame in which the CMB dipole vanishes and cosmic time is defined. Every FLRW analysis privileges that frame *de facto*; WT gives it dynamical significance at cosmological scales only, through the $\mathcal{H}$ functional, and adds no local frame-dependence whatsoever. *Concession attached*: if any local Lorentz-violation experiment ever ties a positive signal to the CMB frame, WaveTree is affected exactly as GR + Λ CDM would be — no more protected, no less.

iii.2 "The universe does not expand 'at the speed of light.' Expansion is a rate, not a velocity."

Correct, and the technical body agrees. The Vision's phrase is formalized in Section 3 as a statement about causal structure, not recession velocity: the domain of events determined by data on the Now grows behind a null envelope — the conditioning of each new slice by the previous one propagates at c . Recession speeds exceeding c at large comoving distance are the standard FLRW bookkeeping and are untouched.

iii.3 "If inertia is the drag of a body's history-tail, inertia should depend on the body's history. It does not — to one part in 10^{15} ."

The objection is correct as far as it goes, and the framework accepts it as a constraint. Eötvös-class experiments and the MICROSCOPE mission find inertial and gravitational mass independent of composition — and therefore of history — to roughly one part in 10^{15} ; a freshly pair-produced positron has exactly the electron mass despite a history microseconds long; and antihydrogen, which Section 11 reads as *extracted* rather than accumulated history, falls normally (ALPHA-g). Therefore, in WaveTree, the tail's drag is fixed entirely by invariant rest-energy content — history determines *that* there is a substrate, never *how much* a given body drags (Section 8.4).

Two precisions keep this from being a surrender to convention. First, what these experiments establish is a *bound*, not a metaphysical verdict: any *differential* history-dependence — one body dragging harder than another because its past differs — is smaller than one part in 10^{15} . "History has no effect" is a stronger conclusion than the data licenses. Second, and more important, differential tests are structurally blind to a *universal* coupling: an effect that acts identically on every body cancels out of every Eötvös-style comparison and is silently absorbed into the measured values of mass and time themselves. WaveTree's tail is exactly such a universal coupling — every body drags its history in identical proportion to its invariant content — so the framework passes these tests not by retreating from the tail picture but by being the kind of mechanism composition comparisons cannot see. History is not absent from inertia in WaveTree; it is present *identically in all inertia*. Only where $\mathcal{H}$ varies from place to place — the halo scale — does it become separately visible, which is precisely why Section 6's halo test is the framework's discriminant and why no laboratory inertia anomaly is predicted.

iii.4 "ΛCDM already predicts halo–history correlations — assembly bias. The 'novel' prediction is not novel."

Correct as far as it goes. Halo concentration correlates with formation epoch (Wechsler et al. 2002), and halo clustering depends on assembly history (Gao, Springel & White 2005). The essay's prediction is therefore stated as a *residual*: after the simulated ΛCDM expectation — assembly bias plus baryonic feedback, calibrated against N-body and hydrodynamic simulations — is subtracted, ΛCDM predicts zero remaining correlation with stellar-population history; WaveTree predicts a positive remainder. A harder test and an honest one. Appendix C specifies the subtraction.

iii.5 "The wave function of N entangled particles lives in 3N-dimensional configuration space, not in spacetime. 'The wave function is the spacetime wave' cannot be right."

Conceded for the N-particle amplitude. The identification is clean for single-excitation states, whose mode functions do live on spacetime, and for the field operator itself, which is defined on spacetime; the multi-particle amplitude is a functional on configuration space, and WaveTree's image applies to it only at the level of the decohered record written onto the Now. The Vision's phrasing is a single-particle intuition; Section 9.3 carries the concession in full.

iii.6 "Stellar age and metallicity set the stellar mass-to-light ratio. 'At fixed stellar mass' is circular."

Correct; stellar masses are themselves inferred through age- and metallicity-dependent M_*/L models, so a naive residual–age correlation is degenerate with M_*/L systematics. Appendix C therefore requires dynamical- or lensing-calibrated masses and an explicit forward model of the M_*/L systematic. The rotation-curve arm of the test is additionally constrained already by the tightness of the radial acceleration relation (McGaugh, Lelli & Schombert 2016), whose scatter leaves little room for history-correlated residuals — which is why stacked lensing is the primary arm.

iii.7 "This is interpretation, not physics. Nearly everything here is consistency with known results."

Six of the essay's eight numbered statements in Section 12 are consistency checks, and they are labeled as such — the essay does not count agreement with existing data as prediction. The empirical exposure is: the halo residual test (P3), an EDM falsification floor for the exploratory baryogenesis reading (P5), and a fenced remark on evolving dark energy (Section 12). If P3

returns a convincing null, the essay says what follows plainly: WaveTree reverts to an interpretive reading of GR + Λ CDM + SM with no independent empirical content. The reader who regards interpretive frameworks without surviving discriminants as worthless will, at that point, be entitled to discard it.

FALSIFIERS, COLLECTED

- A convincing null on the halo-residual test (P3) at DESI/Euclid/LSST stacked precision, after assembly-bias and M_*/L controls, removes the framework's exploratory content.
- Any deviation of antihydrogen free fall from ordinary free fall at improved ALPHA-g precision falsifies the conservative antimatter reading (AM-C).
- Null results at the target sensitivities of ACME III ($|d_e| \lesssim 10^{-30} \text{ e}\cdot\text{cm}$) and n2EDM ($|d_n| \lesssim 10^{-27} \text{ e}\cdot\text{cm}$) are adopted, by declared convention, as the falsification floor for the exploratory baryogenesis reading (AM-X).
- Any local Lorentz-violation signal tied to the CMB frame falsifies the foliation reading as physics.
- A laboratory-scale inertia or free-fall anomaly correlated with history or composition would contradict the framework's own §8.4 and falsify it outright.

CONTENTS

• Foreword	7 Gravity as observed expansion
i The vision	8 Inertia as the historical tail
ii Abstract	9 Surface and slab
iii Anticipated objections & falsifiers	10 Entanglement
1 Introduction and scope	11 Antimatter as historic spacetime pulled forward
2 Where physics aligns, intersects, diverges	12 Predictions, checks, falsifiers
3 The Now and the Tree — formalization	13 Speculative extensions
4 Local stability of bound systems	14 Open problems
5 STP dominance	15 What WaveTree contributes
6 History-linked halo correlations	R References

SECTION ONE

1 Introduction and scope

The picture given in the Vision proposes a geometric reading of a small number of well-established results in cosmology, quantum field theory, and gravitation. It introduces one new empirical claim and one reframing of the composition of the universe. The reading is chosen so that its conservative core reduces to physics that is already tested; its exploratory extensions are labeled explicitly and are surrendered whenever they collide with data.

The framework rests on two objects and one relation between them.

THE NOW — Σ_T

A spacelike Cauchy hypersurface in a globally hyperbolic spacetime $(\mathcal{M}, g)$. The surface itself evolves along its timelike normal (standard 3+1 evolution); what any point of the new surface can inherit from the old one is bounded by the null cones $C^+(p)$, so the domain of determined events grows behind a null envelope — at c (Section 3.1). The "growing skin" of the Vision is retained as visualization; there is no preferred center and no physical edge.

THE TREE — $\mathcal{H}$

A functional over the causal past $J^-(p)$ of each spacetime point p , decomposable as $\mathcal{H} = \langle \mathcal{H} \rangle + \delta \mathcal{H}$. The mean $\langle \mathcal{H} \rangle$ is smooth in space and slowly varying in cosmic time; the fluctuation $\delta \mathcal{H}$ encodes spatial and merger-history correlations. The functional enters observable dynamics through an effective stress-energy $T^{\mathcal{H}}_{\mu\nu}$ on the right-hand side of Einstein's equations.

The advance of Σ_t along null generators of $C^+(p)$ is the essay's shorthand for the process by which structures on and near the Now become records: what was $\mathcal{H}$ becomes on-surface content of Σ_{t+dt} . This is the sense in which the Now "moves at the speed of light" locally — the phrasing refers to the null character of the sweep, not to a motion through a background space.

The essay is a *perspectives* contribution. It contains no first-principles derivation of the parameters of $T^{\mathcal{H}}$, no proposal for a Lagrangian from which $\mathcal{H}$ follows as a variational solution, and no computed cosmological fit. What it does contain is a coherent geometric picture; a placement of that picture with respect to existing programs so a specialist can locate it; and a single testable discriminant sufficiently specific that a working observer could construct the analysis pipeline (Appendix C).

SECTION TWO

2 Where established physics aligns, intersects, or diverges from WaveTree

The Vision does not stand alone. Established and heterodox programs alike address pieces of the same terrain — the ontology of time, the status of the past, the origin of inertia, the nature of the dark sector, the identity of antimatter, the structure of the classical–quantum boundary. This section traces the points of contact from WaveTree outward. The reader who wants to know whether the author has done his homework should judge by this section; full citations are collected in the References.

2.1 The advancing Now — *aligns with the growing block and Ellis's evolving block universe*

The growing-block ontology — the past is real and accumulating, the future is not yet — originates with C. D. Broad (1923). George Ellis's evolving block universe (2006 onward) embeds it in relativistic cosmology: the past is fixed and available for causal reference, the future is not yet realized, and the present is where the block grows. WaveTree accepts this ontology and adds that the fixed past is not inert — it enters present dynamics as a source $\mathcal{H}$. Where Broad and Ellis sharpen the temporal ontology, WaveTree gives that ontology a dynamical role.

2.2 The null sweep — *intersects* the Bondi–Sachs formulation of GR

The Bondi–Sachs characteristic formulation of general relativity foliates spacetime by null hypersurfaces and studies the propagation of gravitational information along their generators. The null conditioning-envelope of the Now (Section 3) lives in the same geometric family, and the machinery of the Raychaudhuri equation for null congruences is directly available in the WaveTree language.

2.3 Inertia from elsewhere — *aligns* with Mach's principle, rotated in time

Mach's principle — inertia arises from a body's relation to the rest of the matter in the universe — is the most venerable "inertia needs an origin" proposal in physics; Einstein named it and tried to build general relativity to satisfy it, with partial success (frame dragging exists; empty-spacetime solutions with inertia also exist). WaveTree's inertia postulate is a *temporal* Mach: inertia arises from a body's relation to its own causal past rather than to distant contemporary matter. The explanatory target is identical — why does inertia exist, and what does a body resist *against* — with the reference class rotated from "matter elsewhere" to "history behind." The equivalence-principle constraint (Sections iii.3 and 8.4) disciplines WaveTree exactly as precision tests have disciplined every Machian proposal before it.

2.4 Law from accumulated history — *aligns* with Smolin's principle of precedence

Lee Smolin's principle of precedence (2012; developed in *Time Reborn*, 2013) proposes that quantum systems behave as they do because of the accumulated precedent of past instances — physical law as habit built from history rather than as timeless external rule. This is the closest published cousin of the Tree: both make accumulated history the source of present regularity. WaveTree differs in mechanism (a stress-energy functional over the causal past rather than a law-selection principle) and in observational target (the dark sector rather than quantum novelty), but a reader who finds precedence coherent will recognize the Tree at once.

2.5 The Tree functional $\mathcal{H}$ — *intersects* Deser–Woodard non-local gravity

Non-local modifications of the Einstein–Hilbert action of the form $f(\Box^{-1}R)$ explicitly source present gravitational dynamics from the causal past of each event, since $\Box^{-1}$ is a Green's-function integral over $J^-(p)$. The Tree functional $\mathcal{H}$ occupies the same conceptual slot;

where Deser–Woodard offer an action, WaveTree asks the observational question (Section 6) that Deser–Woodard does not.

2.6 Dark phenomena as substrate memory **— *intersects* Verlinde's emergent gravity**

Erik Verlinde's emergent gravity (2017) derives gravitation as an entropic, elastic response of an underlying information substrate, with "apparent dark matter" arising as a memory effect tied to de Sitter entanglement entropy rather than as a particle species. This is the closest published cousin of STP dominance's dark-sector claim, and it generated weak-lensing tests (Brouwer et al. 2017) structurally similar to the pipeline of Appendix C. WaveTree differs in substrate — a causal-past functional rather than holographic entanglement entropy — and in strategy: WT preserves Λ CDM phenomenology at baseline where Verlinde modifies the force law. But the family resemblance is direct: dark phenomena as the memory of an underlying substrate, not as new substance.

2.7 Rotation curves without dark matter — *constrained* by MOND and the radial acceleration relation

Milgrom's MOND (1983) reads the rotation-curve anomaly as modified dynamics rather than missing mass. Its sharpest empirical descendant is the radial acceleration relation (McGaugh, Lelli & Schombert 2016): the observed acceleration in disk galaxies is a remarkably tight function of the baryonic one, with scatter small enough to leave little room for halo-to-halo variation correlated with anything else. This does not support WaveTree — it *constrains* it: the rotation-curve arm of Section 6's test must live inside that scatter, which is why Appendix C treats stacked weak lensing as the primary arm and rotation curves as a bounded secondary. An essay proposing to use the SPARC compilation — the MOND community's own dataset — owes this literature explicit acknowledgment, and gives it here.

2.8 The wave–particle reading of light **— *aligns with* QFT in curved spacetime**

The Vision's statement that *light IS the wave* — with photon detection reflecting a measurement event — is compatible with quantum field theory in curved spacetime. It is an interpretive image; it introduces no new dynamical claim about electromagnetism. Its limits for multi-particle states are conceded in Sections iii.5 and 9.3.

2.9 Antimatter as historic spacetime pulled forward — *aligns with* Feynman–Stueckelberg

The Feynman–Stueckelberg interpretation reads an antiparticle as a particle propagating along a reversed proper-time direction in a Feynman diagram. WaveTree's antimatter reading (Section 11) is a geometric restatement of this identification.

2.10 Advanced and retarded structure — *intersects* Wheeler–Feynman and the transactional interpretation

Wheeler–Feynman absorber theory (1945) makes radiation a transaction between retarded and advanced solutions — the future absorber conditions the present emission — and Cramer's transactional interpretation (1986) generalizes the handshake to quantum events. WaveTree's slab (Section 9) and its history-reflected antimatter reading (Section 11) inhabit the same advanced/retarded conceptual space, with the asymmetry placed in $\mathcal{H}$ — a past-dominant substrate — rather than in time-symmetric boundary conditions. WaveTree does not adopt the action-at-a-distance dynamics.

2.11 The surface/slab picture — *intersects* decoherent histories and light-front quantization

The decoherent-histories interpretation (Griffiths, Gell-Mann–Hartle) reads classical records as coarse-grained histories whose interference terms are suppressed. The Now as a records-surface (Section 9) is a geometric image for exactly this. The kinship claimed with Dirac's front-form quantization is geometric — the null structures of the sweep — and not an adoption of front-form dynamics: WaveTree's Now is a spacelike (instant-form) surface, and the front-form comparison is an analogy of setting, stated as such.

2.12 Physics as substrate — *intersects* and *diverges from* Wolfram and 't Hooft

The computational-substrate programs — 't Hooft's cellular-automaton interpretation of quantum mechanics (2016), Wolfram's hypergraph project (2020) — share WaveTree's founding instinct, which the author (trained in computer science) acknowledges as his own native habit: observed physics as the surface of an underlying update process. WaveTree differs in two respects. It proposes no discrete microdynamics — $\mathcal{H}$ is a functional on continuum general relativity — and no additional dimensions: the framework is deliberately silent on higher-dimensional structure, requiring only the four dimensions that are measured. Where string theory purchases its unification with six or seven unobserved dimensions, and the

computational programs purchase theirs with a pre-geometric layer beneath spacetime, WaveTree's entire ontological purchase is a functional on the spacetime we already have. And it locates the substrate in the *past of the manifold itself* rather than in a pre-geometric computational layer: where Wolfram derives space from the substrate, WaveTree takes spacetime as given and makes its history the substrate.

2.13 STP dominance — *diverges from the* Λ CDM ontology of three separate substances

The standard reading of the Λ CDM mass–energy budget treats baryonic matter, dark matter, and dark energy as three distinct kinds of stuff. WaveTree diverges here: it reads the three components as three regimes of one substrate $\mathcal{H}$ (Section 5). Whether this divergence carries empirical consequences is the question Section 6 tries to answer.

2.14 Entanglement as a single sub-surface object — *diverges from the ontology of two separated systems*

The standard reading of entanglement takes two particles as distinct systems sharing a joint state. WaveTree offers a divergent interpretation (Section 10) in which the two apparent particles are one object viewed through the fluidity of the Now. This is an interpretation only; it reproduces the standard predictions (no-signaling, the Tsirelson bound at Born-rule level), does not commit to a specific geometric implementation such as ER=EPR, and its unresolved obligations — monogamy, cross-species entanglement, measurement-choice correlations — are stated in Section 10.

POSITIONING

None of the programs above requires WaveTree; WaveTree draws on all of them. The essay's contribution is the composition — plus the residual prediction of Section 6.

SECTION THREE

3 The Now and the Tree — geometric formalization

Let $(\mathcal{M}, g)$ be a globally hyperbolic spacetime and let Σ_t be a smooth spacelike Cauchy hypersurface labeled by a cosmic time coordinate t . On cosmological scales we identify t with the FLRW cosmic time and Σ_t with the standard constant- t slice; on local laboratory scales t is any smooth time function whose level sets are spacelike.

A PREFATORY REMINDER

The framework treats "space" and "time" as strictly inseparable throughout. Following Minkowski's 1908 lecture — *henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality* — WaveTree speaks always of *spacetime*, never of space alone or time alone. The Now is a slice of spacetime; the Tree is causal-past spacetime; the wave expands through spacetime.

3.1 The sweep of the Now

At each point $p \in \Sigma_t$, the future light cone $C^+(p)$ is generated by null geodesics with tangent vectors k^a satisfying

$$g_{ab} k^a k^b = 0, \quad k^a \nabla_a k^b = 0, \quad (3.1)$$

parameterized by an affine parameter λ . (Null curves accumulate no proper time — that is their defining property — so the affine parameter, not proper time, is the correct label along them.)

The advance of the Now is then formalized by two complementary statements — one timelike, one null — and it is the second that carries the Vision's claim.

The timelike statement. The slice itself evolves along its timelike unit normal n^a : this is the standard 3+1 (ADM) evolution of a Cauchy surface, with lapse and shift, and nothing about it is novel. A spacelike surface pushed along null directions would cease to be spacelike; the Now does not move "on the light cone."

The null statement. What advances at c is the **conditioning** of each new slice by the old one. The future domain of dependence $D^+(\Sigma_t)$ — the set of events whose physics is fully determined by data on Σ_t — is bounded by null geodesics, and the causal future $J^+(S)$ of any region $S \subset \Sigma_t$ grows behind a null envelope. The speed at which "what history has determined" spreads — the characteristic speed of record-conditioning, the fastest speed at which anything written on Σ_t can matter to Σ_{t+dt} — is c , by construction of the causal structure. WaveTree's claim is that this null conditioning-envelope is not merely kinematic bookkeeping but the physically operative structure: *each new slice is written from the old one at the speed of light*. That is the rigorous content of the Vision's "the Now advances at c ."

No observer needs to identify their frame with this sweep; the Now is a global foliation choice that any single observer projects onto, and standard relativity of simultaneity is preserved. The objection that this reintroduces an ether is answered in Section iii.1.

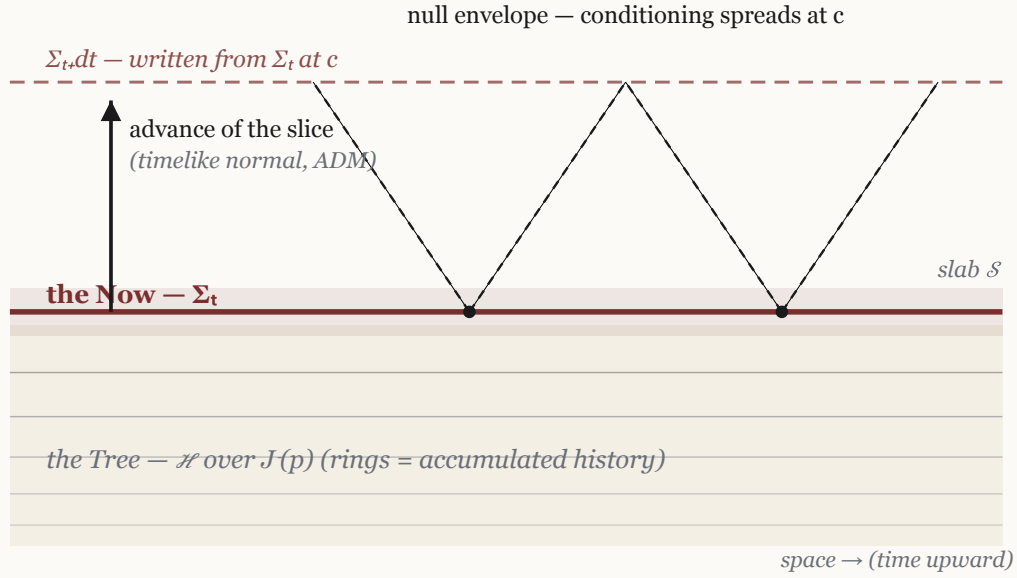


FIGURE 1. *The Now Σ_t as a spacelike surface (solid), the Tree as the accumulated causal past beneath it (rings), and the slab $\mathcal{S}_e$ straddling the surface. The slice advances along its timelike normal; what any point of the next slice Σ_{t+dt} can inherit from Σ_t is bounded by the null cones (dashed) — the conditioning of each new slice by the last spreads at c .*

3.2 The Tree as a causal-past functional

The Tree functional $\mathcal{H}$ associates to each spacetime point p a real value depending only on data on $J^-(p)$:

$$\mathcal{H}(p) = \mathcal{F}[g_{\mu\nu}, T^{\text{SM}}_{\mu\nu}, \rho, \dots; J^-(p)]. \quad (3.2)$$

The functional form $\mathcal{F}$ is not specified from first principles in this essay; the research program of Section 14 includes searching for an action from which $\mathcal{H}$ follows. What is specified is the decomposition

$$\mathcal{H} = \langle \mathcal{H} \rangle + \delta \mathcal{H}, \quad (3.3)$$

where $\langle \mathcal{H} \rangle$ is the ensemble mean over the causal past, taken as smooth in space and slowly varying in cosmic time, and $\delta \mathcal{H}$ is the spatially and temporally correlated fluctuation about that mean. These enter the essay's dynamics as sources of an effective stress-energy

$$T^{\mathcal{H}}_{\mu\nu} = T^{\mathcal{H},\text{smooth}}_{\mu\nu}[\langle \mathcal{H} \rangle] + T^{\mathcal{H},\text{clumping}}_{\mu\nu}[\delta \mathcal{H}]. \quad (3.4)$$

The right-hand side of Einstein's equations then reads

$$G_{\mu\nu} = 8\pi G (T^{\text{SM}}_{\mu\nu} + T^{\mathcal{H}}_{\mu\nu}), \quad (3.5)$$

with $T^{\text{SM}}_{\mu\nu}$ the standard-model matter and radiation content and $T^{\mathcal{H}}_{\mu\nu}$ the history-sourced contribution.

A REMARK ON NOTATION

The Tree functional is written $\mathcal{H}$ (script upper-case H) throughout, to avoid collision with the Hubble parameter $H(t)$. Where the essay refers to the Hubble parameter, it uses $H(t)$ or the dimensionless h .

3.3 Reduction to standard physics

For a laboratory observer at proper time τ and spatial extent $L \ll c/H$, the sweep of the Now over the laboratory reduces to standard local causal propagation, and $\mathcal{H}$ evaluated on $J^-(p)$ is approximately constant with fluctuations bounded by the smoothness of $\langle \mathcal{H} \rangle$. The Standard Model is recovered exactly at every currently accessible laboratory precision. Explicit bounds are collected in Section 12.

SECTION FOUR

4 Local stability of bound systems

A recurrent question in the WaveTree presentation is why bound systems — atoms, molecules, planets, galaxies — do not "fly apart" if the Now is advancing at the speed of light. The answer is standard cosmology and requires no new parameter.

FLRW cosmological expansion does not drag bound systems. A local system with characteristic size L and internal binding time scale $\tau_{\text{bind}} \ll H^{-1}$ decouples from the Hubble flow to leading order, and the leading correction is of order $(HL)^2$. Treatments by Cooperstock, Faraoni and Vollick (1998), Price and Romano (2005), and Carrera and Giulini (2010) show that cosmological expansion's influence on the classical Kepler problem is bounded by the ratio of the local dynamical time scale to the Hubble time, and is empirically negligible at every scale below galaxy-cluster scale.

In WaveTree language, the sweep of the Now over a bound system is diluted by the ratio of the system's dynamical rate to the Hubble rate; for an atom the relevant dimensionless correction $(HL/c)^2$ is suppressed by some seventy orders of magnitude, per the analyses cited above. The Vision's "the Tree stabilizes the Now" is the same statement in a different register: local binding is a fact laid down by the causal past, and it dominates the present at every scale where dominant means anything.

SECTION FIVE · THE CENTRAL THESIS

5 STP dominance

CENTRAL THESIS — STP (SPACETIME-PAST) DOMINANCE

Historical spacetime — the Spacetime-Past, STP — is the substrate of reality. What cosmology currently distinguishes as "ordinary matter," "dark matter," and "dark energy" are three regimes of one history field $\mathcal{H}$ — three degrees of coherence with which $\mathcal{H}$ has been written onto the advancing Now.

The Λ CDM cosmological model estimates a mass–energy budget in which approximately 5 percent of the universe is baryonic matter, 27 percent is dark matter, and 68 percent is dark energy. That partition is empirically robust and is not disturbed by WaveTree. What WaveTree offers is a reading: rather than three separate substances, the three components are three modes of one $\mathcal{H}$ substrate.

5.1 Three modes of $\mathcal{H}$

1. **Coherent-mode $\mathcal{H}$ (~5%) — "ordinary matter."** The regime in which $\mathcal{H}$ has been written into localized, coherent, record-making structures on Σ_t . Local $\mathcal{H}$ is highly non-Gaussian, spatially organized into stable field configurations that carry conserved quantum numbers, and interacts through the Standard Model.
2. **Textured-mode $\mathcal{H}$ (~27%) — "dark matter."** The regime in which $\mathcal{H}$ carries the correlations of the causal past — clumping, halo-forming, gravitationally active — but has not been coherently written into on-surface records. This regime sources $T^{\mathcal{H}, \text{clumping}}_{\mu\nu}$ with $w \approx 0$ and is observed through its gravitational effects only.
3. **Smooth-mode $\mathcal{H}$ (~68%) — "dark energy."** The regime in which $\mathcal{H}$ is at its ensemble mean $\langle \mathcal{H} \rangle$, spatially and temporally smooth, and sources $T^{\mathcal{H}, \text{smooth}}_{\mu\nu}$ with $w \approx -1$.

One honesty about this taxonomy, recorded here and listed among the open problems (Section 14): the criterion separating the regimes is currently descriptive, not derived. "Written into records" names the coherent regime by its Standard-Model couplings and conserved charges; "textured" names gravitationally active correlation without record structure; but the essay offers no principle that tells you, given a configuration of $\mathcal{H}$, which regime it occupies — and, in particular, no derivation of why textured-mode $\mathcal{H}$ fails to couple electromagnetically. As it stands, the three regimes are identified by the equations of state they were introduced to explain. Converting the taxonomy from description to derivation is the framework's most important theoretical debt.

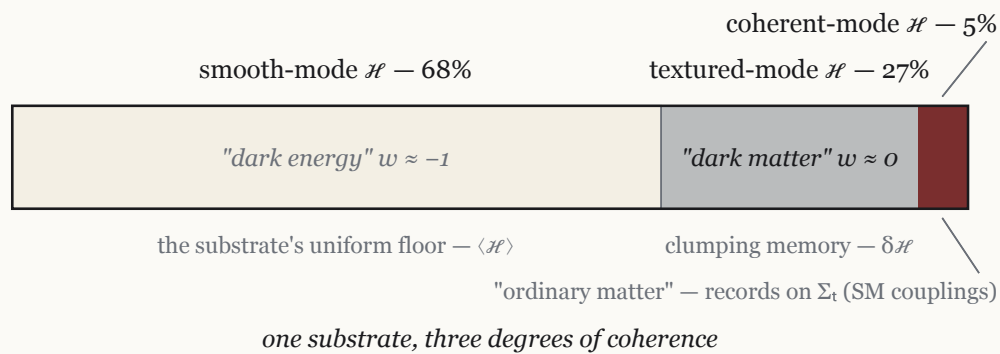


FIGURE 2. STP dominance: the empirically robust Λ CDM budget (68 / 27 / 5) re-read as three regimes of a single history substrate $\mathcal{H}$, distinguished by the degree to which $\mathcal{H}$ has been coherently written onto the Now — not by particle content.

5.2 Why STP dominance is more than relabeling

Identifying "the dark sector" with "components of an effective stress-energy" is what every dark-fluid model does; identifying it with a functional of the causal past is what Deser–Woodard non-local gravity does; and reading baryonic matter as the "coherent regime" of a deeper substrate is what many condensed-matter-inspired proposals do. The essay's claim to novelty rests on the composition: reading all three simultaneously as regimes of one causal-past functional, and asserting that $\mathcal{H}$ is the dominant term.

What follows from this composition — and what does not follow from any predecessor alone — is the empirical claim of Section 6. Because textured-mode $\mathcal{H}$ inherits the correlations of the causal past, its distribution at any point p must correlate with observable proxies for the causal-past history at p — *over and above* the correlation that Λ CDM itself already predicts. That qualification matters: Λ CDM's halos do remember their assembly history (concentration correlates with formation epoch — assembly bias; Section iii.4), so a bare halo–history correlation is not news. The WaveTree claim is that after the simulated Λ CDM expectation is subtracted, a positive residual correlation remains. Its detection or non-detection is the essay's proposed empirical discriminant.

5.3 Is $\langle \mathcal{H} \rangle$ constant? An exploratory note on evolving dark energy

A reader will ask why the ensemble mean of an ever-growing causal past should source a constant $w \approx -1$ rather than an evolving one. The essay is honest that it has two available readings and no derivation to choose between them. On the *saturating* reading, $\langle \mathcal{H} \rangle$ is a normalized mean over the causal past rather than an accumulating total, and approaches a constant at late times — recovering $w = -1$. On the *growth* reading, $\langle \mathcal{H} \rangle$ evolves slowly, and $w(z)$ drifts. The DESI baryon-acoustic-oscillation analyses (2024–2025) prefer evolving dark energy over a cosmological constant at modest significance in some data combinations; if that preference solidifies, it is circumstantial support for the growth reading. If instead $w = -1$ is confirmed to high precision at all accessible redshifts, WaveTree requires the saturating form — and says so. Either way the framework accommodates the data; the point of recording the fork now is that the two readings are distinguishable, and the data will choose.

There is a bookkeeping intuition behind this fork worth stating: if the dark sector is the imprint of accumulated history, the evolving budget fractions $\Omega_i(z)$ are the substrate's ledger — and "information is never lost" is the ledger's balancing rule. The measured growth of the smooth component's share, from negligible at recombination to dominant today, is consistent

with an accumulating ledger; the measured constancy of the dark-matter-to-baryon ratio over the same span is the hard constraint any accumulation reading must respect, and is why the textured mode's signature is a correlation (Section 6), not a growth in abundance.

STP DOMINANCE IN ONE SENTENCE

Matter, dark matter, and dark energy are not three substances but three depths of the same historical spacetime — the tip, the body, and the ocean floor of the same iceberg.

SECTION SIX · THE NOVEL DISCRIMINANT

6 History-linked halo correlations

PREDICTION P3 (NOVEL — STATED AS A RESIDUAL)

After the simulated Λ CDM expectation — halo assembly bias plus baryonic feedback, calibrated against N-body and hydrodynamic simulations — is subtracted, the remaining residuals of galaxy- and cluster-scale lensing profiles correlate positively with proxies for the causal-past history of the host halo: (i) the mean stellar-population age of the halo, (ii) its mean metallicity $[\text{Fe}/\text{H}]$, and (iii) its merger-history proxy — each proxy tested with the others controlled. Λ CDM predicts these post-subtraction residual correlations vanish; WaveTree predicts they do not. Testable at a precision achievable by DESI Y5, Euclid Wide, and LSST stacked analyses.

6.1 The mechanism, informally — and what Λ CDM already predicts

Textured-mode $\mathcal{H}$ is a functional of the causal past of each spacetime point. For a galaxy halo formed at redshift z_{form} and with a merger and star-formation history $H_{\text{SFR}}(z)$, the local textured-mode $\mathcal{H}$ integrates over that history. Two halos matched in present-epoch total mass and morphology but differing in their causal past — one older, more metal-rich; one younger, more pristine — are predicted to differ in the textured-mode $\mathcal{H}$ they carry, and therefore in their observed gravitational profiles.

Stated that baldly, however, the prediction is not yet distinguishable from standard cosmology. Λ CDM halos remember their assembly: halo concentration correlates with formation epoch (Wechsler et al. 2002), halo clustering depends on assembly history (Gao, Springel &

White 2005), and galaxy properties correlate with both. A bare correlation between halo profile and stellar age is therefore *expected* in Λ CDM. The WaveTree claim is sharper: take the full Λ CDM expectation — assembly bias and baryonic feedback, as realized in modern simulations — subtract it, and examine what remains. Λ CDM predicts the remainder carries no history correlation; WaveTree predicts a positive one, because $\mathcal{H}$ couples to history over and above what history does to halo assembly. This is a harder test than the naive version, and the honest one.

One further honesty about the proxies: they are not jointly monotonic. At fixed mass, mean stellar age and recent-merger richness frequently *anti*-correlate (mergers rejuvenate star formation), so the prediction is stated per proxy with the others controlled, not as a joint monotonic trend across all three.

6.2 What the observation would look like

A stacked weak-lensing analysis of galaxies in a spectroscopic sample (for example, DESI's Bright Galaxy Sample, or SDSS's main galaxy sample cross-matched to any standard stellar-population catalog) can bin galaxies at fixed mass by mean stellar age and by mean $[\text{Fe}/\text{H}]$, and compute the residual lensing signal $\Delta\kappa(\theta)$ in each bin after subtraction of the simulation-calibrated Λ CDM baseline. Two systematics must be controlled by design. First, the M_*/L degeneracy: stellar masses are themselves inferred through age- and metallicity-dependent mass-to-light models, so "fixed stellar mass" is partially circular; the analysis requires dynamical- or lensing-calibrated masses, or an explicit forward model of the M_*/L systematic. Second, assembly bias itself: the baseline must be conditioned on formation-history proxies as realized in simulations, not merely on mass.

A companion analysis on rotation curves — for instance the SPARC compilation — can run the same test, with an important caution recorded in Section 2.7: the tightness of the radial acceleration relation already bounds history-correlated rotation residuals severely, which is why the lensing arm is primary and the rotation arm is a bounded secondary. Appendix C sketches a pipeline.

6.3 Why this test is diagnostic

The essay's whole exploratory content stands on P3. A confirmed positive residual — surviving assembly-bias subtraction and M_*/L controls — would be a signature that Λ CDM does not predict. A convincing null result, at the precision reachable by Euclid + LSST + DESI stacked analyses in the second half of this decade, would return WaveTree to its conservative core — namely, a geometric interpretation of GR + Λ CDM + SM whose empirical content is exhausted by GR + Λ CDM + SM. Either way the test is worth running.

7 Gravity as observed expansion

The Vision proposes a reading of gravity in which the classic rubber-sheet dimple around a massive body is not a static well but a consequence of the differential response of the Now's advance to the body's presence. Where the standard general-relativistic reading interprets curvature as sourced by stress-energy through Einstein's equations, WaveTree offers a re-parameterization: the gravitational field is the observable disturbance of the null sweep — focused directly where stress-energy stands, and sheared everywhere the geometry carries that stress-energy's imprint outward. The two channels of this disturbance are made precise below.

7.1 Formal restatement

For a null congruence with tangent field k^a , the Raychaudhuri equation reads

$$k^a \nabla_a \theta = -(1/2) \theta^2 - \sigma_{ab} \sigma^{ab} + \omega_{ab} \omega^{ab} - R_{ab} k^a k^b, \quad (7.1)$$

where θ is the expansion of the congruence, σ_{ab} the shear, ω_{ab} the vorticity, and $R_{ab} k^a k^b$ the Ricci contraction along k^a — for null k^a , Einstein's equations give $R_{ab} k^a k^b = 8\pi G T_{ab} k^a k^b$, non-negative for matter satisfying the null energy condition. Two channels follow, and the distinction matters.

The Ricci channel (inside matter). Where stress-energy stands, $R_{ab} k^a k^b > 0$ focuses the congruence directly. This is the sweep being slowed *in* the source.

The Weyl channel (the vacuum exterior). Outside the source — where orbits, light-bending, and tides actually live — spacetime is Ricci-flat and the direct term vanishes. There the field is carried by the Weyl tensor C_{abcd} : the part of curvature that propagates through empty space. The Weyl tensor drives the evolution of the congruence's shear (schematically, $k^c \nabla_c \sigma_{ab} \sim -C_{acbd} k^c k^d + \dots$), and shear feeds back into focusing through the $-\sigma_{ab} \sigma^{ab}$ term of (7.1). The exterior gravitational field is, in this reading, literally *the transmitted record of the source*: matter focuses the sweep where it stands, and the geometry carries the imprint of that focusing outward as Weyl curvature, shearing — and thereby converging — the sweep around the mass.

This two-channel structure is welcome rather than awkward for WaveTree, because the Weyl tensor is precisely "curvature as memory of elsewhere and elsewhere" — the most history-native object in the formalism. The gravitational field of a star, in WaveTree language, is the

surrounding sweep responding not to the star directly but to the geometric record the star has already written. Gravitational waves are the propagating, purely-Weyl case of the same channel (Section 7.3). The reading offers no new prediction beyond general relativity; it offers a geometric image consistent with the Now-and-Tree framing, with the bookkeeping in the correct channel.

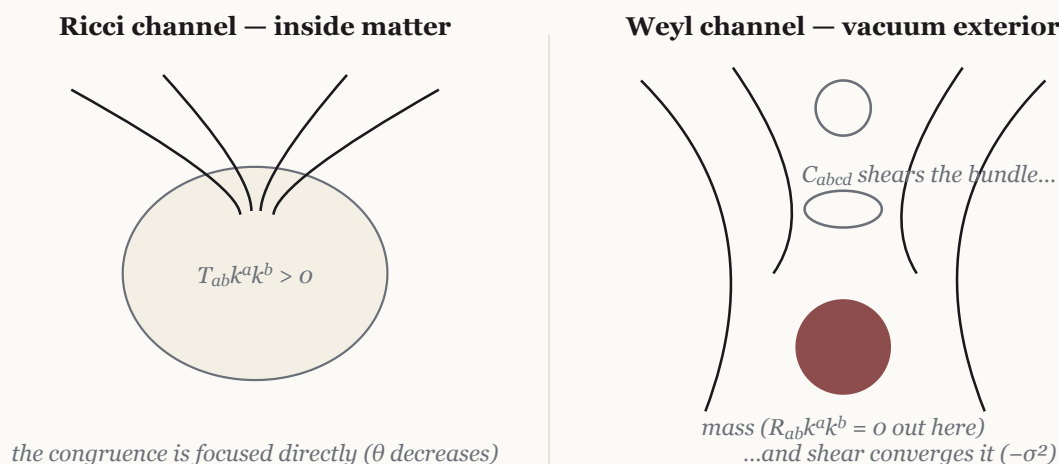


FIGURE 3. The two channels of equation (7.1). Inside matter, the Ricci term focuses the null congruence directly. In the vacuum exterior — where orbits and lensing live — the Ricci term vanishes; the field is carried by Weyl curvature, which shears the bundle (circle $\rightarrow$ ellipse), and shear feeds convergence. The exterior field is the transmitted record of the source.

THE GRAVITY-INERTIA SYNTHESIS, IN ONE LINE

It is the drag of spacetime history — the tail all matter and energy is based on — that IS gravity observed.

7.2 The equivalence principle as a consequence, not a postulate

General relativity takes the *equivalence principle* — that the felt effect of standing in a gravitational field is locally indistinguishable from the felt effect of being uniformly accelerated — as a foundational postulate, unexplained but assumed. WaveTree offers a reading in which the equivalence is not a postulate but a consequence of the substrate. Both sensations arise from the same physics: the drag of the accelerated or gravitationally situated body's causal-past tail

(Section 8) against the sweep of the Now. Gravitational drag (mass at rest in a $T^{\text{SM}} + T^{\mathcal{H}}$ region) and inertial drag (mass being accelerated) share a single geometric origin — the tilt of the body's proper-time axis relative to the local sweep direction. Einstein's happiest thought is, in this reading, the observation that gravity and acceleration must feel identical because they *are* identical.

7.3 Relation to gravitational waves

Gravitational waves are, in this reading, transient shears σ_{ab} of the null congruence generated by matter-motion sources. Their propagation speed matches the null-generator speed, which is c . Their strain patterns match the two tensor modes of general relativity. The GW170817 + GRB 170817A speed constraint $|v_{\text{GW}} - c|/c \lesssim 10^{-15}$ and the LIGO–Virgo–KAGRA polarization bounds are honored by construction.

SECTION EIGHT

8 Inertia as the historical tail

Special relativity predicts two experimentally confirmed effects of *velocity*, both governed by the same Lorentz factor $\gamma(v) = (1 - v^2/c^2)^{-1/2}$. First, **energy growth**: a body of rest mass m_0 moving at velocity v carries energy $E = \gamma m_0 c^2$ (the older phrase "relativistic mass increase" names the same physics in a convention modern usage has retired; the invariant rest mass never changes), so as $v \rightarrow c$, γ diverges and no finite energy suffices to reach c . Second, **time dilation**: a clock moving at velocity v ticks with proper time $d\tau = dt/\gamma$, so as $v \rightarrow c$ the clock's tick rate as measured in the lab frame slows without bound. Both effects share γ , and both depend on velocity alone — not on acceleration as such: the clock hypothesis, verified in muon storage rings at accelerations near 10^{18} g (Bailey et al. 1977), holds that acceleration per se does not affect clock rates. Both effects are extensively tested — the Ives–Stilwell experiment, atmospheric-muon lifetimes, particle-accelerator momenta, and the GPS system, whose satellite clocks are corrected by design for the combined effect of a special-relativistic slowing (about -7 $\mu\text{s/day}$) and a larger, opposite-signed gravitational blueshift (about $+45$ $\mu\text{s/day}$). Einstein's equations describe *that* these effects occur. WaveTree here proposes to describe *why*.

8.1 The mechanism — cutting across the nominal expansion line

For an observer at rest with respect to the local sweep of the Now, the tail — the object's column of causal-past history — extends behind the object along the nominal proper-time direction of the observer's frame. Tail and sweep are aligned. There is no resistance to talk about: the historical column and the advance of the Now are pointed the same way.

When the object accelerates, its proper-time axis tilts relative to the observer's. The tail, following the object's worldline, no longer extends parallel to the observer's sweep direction. It begins to **cut across the nominal expansion line of the Now**. As v approaches c , the angle of cut approaches the lightlike limit and the tail becomes maximally transverse to the observer's sweep.

8.2 Why cutting across produces both of Einstein's effects

Both ironclad SR effects are consequences of the same tilt geometry:

1. **Relativistic mass increase.** A tail aligned with the sweep is dragged with no additional resistance. A tail forced to cut across the sweep encounters progressively increasing drag as the tilt angle grows. This is the WaveTree reading of why the differential energy required for a unit velocity change scales as γ^3 , and why the divergence of the drag at the lightlike limit forbids acceleration to c .
2. **Time dilation.** The object's clock ticks are events on its own proper-time axis. As that axis tilts, the ticks project onto the observer's proper-time axis with a foreshortening set by the tilt angle. The clock, viewed from the lab, appears to slow. $d\tau = dt/\gamma$ is the projected foreshortening — a geometric consequence of the same cutting-across.

The two effects share a single geometric origin: the tilt of the accelerating body's proper-time axis, and the consequent cutting of its causal-past tail across the sweep of the Now. The kite and stilts analogies of the Vision speak to the mass side — a body carrying its history behind it has a steering cost that grows with tilt. Time dilation is the same geometry seen from the perspective of the tail's projection rather than the body's steering effort. WaveTree is offering a *why* underneath Einstein's *what*. Neither SR prediction is modified; every SR test is recovered exactly.

NOTE ON REGISTER

The mechanism above is a geometric interpretation, not a modification of special relativity. It sits inside the standard Minkowski-diagram picture: the "tilt of the proper-time axis" is exactly the rapidity ϕ with $\tanh(\phi) = v/c$ and $\gamma = \cosh(\phi)$. What WaveTree adds is the reading of that tilt as physical resistance of a causal-past tail dragged against the null sweep — a Vision-language image that connects mass, time, gravity (Section 7), and the dark sector (Section 5) under one substrate.

8.3 Mass and time as an exchange

A deeper reading of the same geometry is that energy and clock rate are not two independent consequences of γ but two projections of one fixed object. The tail has a fixed rest-frame content — the invariant rest mass m_0 — and a boost does not add to that content. It rotates it. A boost is a *hyperbolic rotation* (through the rapidity ϕ , with $\tanh \phi = v/c$): exactly as an ordinary rotation trades a rod's x-extent for y-extent while preserving the rod's length, a boost trades the four-momentum's temporal projection (energy, and with it the observed clock rate) against its spatial projection (momentum) while preserving the four-momentum's invariant length.

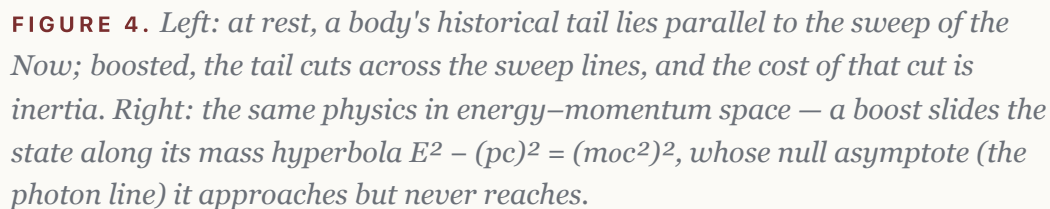
THE EXCHANGE

The four-momentum $p^\mu = (E/c, \mathbf{p})$ of a moving body satisfies the invariant relation $E^2 - (pc)^2 = (m_0 c^2)^2$. Under a boost, E and p both grow — but as projections of one four-vector whose invariant length never changes. **A boost does not create mass, and it does not steal time. It rotates the body's four-momentum, hyperbolically, trading temporal projection for spatial.**

The geometric picture: the body's state slides along its *mass hyperbola* — the curve $E^2 - (pc)^2 = (m_0 c^2)^2$ in the energy–momentum plane — as it accelerates. The hyperbola's asymptote is the null line $E = pc$. In WaveTree language: the exchange is the tilting tail trading its projections against the sweep, and the invariant is the tail's rest-frame content, conserved across the exchange.

Two consequences follow directly.

- ## the tail, at rest and tilted



8.4 What the tail cannot do — the history-independence of inertia

An honest framework states its own strongest constraint. If inertia were sensitive to the *detail* or *length* of a body's history — if a longer or richer tail dragged harder — then inertial mass would be history- and composition-dependent. It is not. Eötvös-class experiments and the MICROSCOPE mission (Touboul et al. 2022) find the equivalence of inertial and gravitational mass independent of composition to roughly one part in 10^{15} . A positron created in pair production a microsecond ago has exactly the electron mass, indistinguishable from that of any electron that has existed since the early universe. And antihydrogen — which Section 11 reads as history *extracted* onto the Now rather than accumulated behind it — falls under gravity like ordinary hydrogen (ALPHA-g), which on a naive tail reading it should not.

The framework therefore adopts, as a constraint and not as a choice, the following: **the tail's drag is fixed entirely by invariant rest-energy content.** History determines *that* there is a substrate; it never determines *how much* a given body drags. The rapidity-tilt mechanism of Sections 8.1–8.3 respects this automatically — the drag depends on the current tilt and the invariant m_0 , and on nothing else about the worldline behind the body.

The consequence is stated plainly, because it disciplines the whole essay: *history does no inertial work at laboratory scale.* $\mathcal{H}$ -texture can produce observable effects only where it varies — which is the halo scale and above. This is exactly why Section 6's halo test is the framework's empirical discriminant, and why WaveTree predicts no laboratory inertia anomaly of any kind. A laboratory anomaly correlated with history or composition would not confirm the framework; it would falsify it (Section iii, falsifiers).

8.5 STP dominance at the human scale

The picture has a striking consequence at the human scale that is worth noting, because it makes the framework's central thesis felt rather than merely stated.

The brain reports the world as solid. Physics has long known that it is not: baryonic matter is overwhelmingly empty space at the atomic scale — the volume fraction occupied by the nucleus of an atom is on the order of 10^{-15} . STP dominance adds a four-dimensional observation to that familiar three-dimensional one. Consider the honest bookkeeping of a human being as a spacetime object: a body extends a couple of metres in space, but decades in time — in geometric units, where one second is 300,000 kilometres, a human worldline is some 10^{16} kilometres long against a metre of width. Virtually all of any body's four-dimensional extent is its past. That —

not a borrowed cosmological percentage — is the precise form of the Vision's filament image (§i.6): in the spacetime bookkeeping, a person is a filament of history with a thin luminous tip, and the tip is the only part the brain reports. It is offered as an intuition, not a mechanism.

SECTION NINE

9 Surface and slab — the classical–quantum boundary

WaveTree reads the classical–quantum boundary as tangential-versus-slab structure on the Now. It is a geometric image compatible with quantum field theory in curved spacetime; it makes no operational prediction that departs from QFT.

9.1 The surface

The Now Σ_t carries classical, tangential observables: expectation values of fields, geodesic bundles, records made by measurement devices. On Σ_t , a record — an ionization track, a mark on a photograph, an entry in a memory register — has a definite value.

9.2 The slab

A slab $\mathcal{S}_\varepsilon$ of proper-time thickness ε straddling Σ_t carries the quantum-amplitude structure. Within $\mathcal{S}_\varepsilon$, coherent superpositions are physical; interference effects are computable through the standard machinery of QFT in curved spacetime. The parameter ε has no fundamental value; it is set by the decoherence time scale of the environment, in the sense of Zurek's einselection or the Gell-Mann–Hartle decoherence functional.

9.3 The wave function as spacetime wave — and where the identification stops

The Vision offers the identification *the wave function of quantum mechanics is the spacetime wave — the Now itself*. In technical register, this is an interpretive claim: the quantum-field amplitude structure inhabiting the slab $\mathcal{S}_\varepsilon$ — the object whose modulus squared gives on-surface Born-rule probabilities — is the same geometric object as the advancing Now surface, viewed on the scale of a coherence length. The identification is compatible with QFT and does not introduce new dynamics; it offers a geometric intuition for why the wave function has the propagation properties it does (they are the propagation properties of the Now).

The identification has a well-defined limit, and the essay states it rather than waiting for a referee to. For a single-excitation state, the mode function genuinely lives on spacetime, and the image is clean. For N entangled particles, the wave function is a functional on $3N$ -dimensional *configuration space* — not a field on spacetime — and no naive "wave in space" reading survives that fact; this is the classic objection to all such readings, from Schrödinger's day onward. What does live on spacetime, for any N , are the field operators and the decohered records; WaveTree's image applies to the multi-particle state only at that level. The Vision's phrasing is a single-particle intuition, and the framework claims nothing stronger (Section iii.5).

9.4 The double-slit experiment

The Vision's reading of the double-slit result — the wave carries through both slits and photons are recorded only at measurement — is the standard quantum-mechanical outcome expressed in Now/Tree language. The wave function inhabits the slab spanning both slits; the on-surface record is written at the moment of detection. No new prediction; a compatible image.

9.5 Quantum computation in this language

If the surface/slab picture earns its keep anywhere as a descriptive language, it is with the one working technology built directly on quantum amplitude structure. A quantum computer's entire state is a single wave function over its n qubits — a superposition of 2^n configurations, each carrying a complex amplitude — and a quantum algorithm is choreographed interference: unitary gates arranged so that amplitudes for wrong answers cancel destructively while amplitudes for right answers reinforce, with a measurement at the end that commits one classical outcome. Shor's factoring algorithm and its relatives are, in this exact sense, industrial applications of the physics of Section 9.4.

In WaveTree language the machine has an unusually clean description. **A quantum computer is a machine for holding a patch of the Now open.** Preparation writes a known record onto the surface — the initialized register. The computation then lifts the register into the slab — the not-yet-recorded — and holds it there by brute engineering: cryogenic isolation, shielding, error correction. All steering happens in the slab, where amplitudes are physical and interference does work. Readout forces a single record back onto the surface. The machine's one failure mode, decoherence, is in this language the environment *writing the record early*; quantum error correction is the engineering of postponement. Every practical difficulty of building a quantum computer is, on this reading, the difficulty of keeping a region of the world unrecorded on demand.

The computation is thereby the intersection of Tree and Now, and the framework's central division does real descriptive work in it. The boundary conditions — the initial state, the program — are records: history. Given them, the wave's evolution is *exactly* determined; unitarity is the operating form of "information is never lost," and it runs in both temporal directions. What is not determined is the record: the Tree fully determines the wave that presses against the Now, and does not determine which record the Now writes — only the Born-rule statistics of it. History extrapolates the amplitudes perfectly and the facts only probabilistically. The surface/slab split of this section is not decoration on quantum computing; it is a statement of the machine's operating principle.

There is a foundations point here worth making explicit. David Deutsch famously argued that quantum computation forces the many-worlds question: when Shor's algorithm factors a number by way of more intermediate amplitude structure than there are atoms in the visible universe, *where was the number factored?* His answer is: in parallel universes. WaveTree's answer is one world and one sentence: *in the slab* — the not-yet-recorded amplitude structure straddling the Now, conditioned by the Tree, resolved into a single record on readout. To be clear about what this does and does not accomplish: it does not refute Deutsch's argument, which is an argument about ontology and cannot be settled by a description; it offers a differently economical description of the same formalism, and the reader who prefers many worlds loses nothing by it. The two answers are empirically identical.

The concession of Section 9.3 applies here with full force, and is restated so no reader need raise it: an n -qubit register's state inhabits a 2^n -dimensional Hilbert space, not spacetime. The claim of this subsection is therefore not that the register's wave function *is* the spacetime wave; it is that the computation is *slab-resident* — conducted wholly in the not-yet-recorded regime, conditioned by records, and resolved into a record. No prediction differs from standard quantum mechanics, and quantum computers succeed identically under every interpretation of the formalism. The gain claimed is descriptive economy, nothing more — and nothing less.

SECTION TEN

10 Entanglement — one object at multiple apparent locations

The standard quantum-mechanical reading of entanglement takes two particles as distinct systems sharing a joint state; measurement outcomes are correlated across arbitrary spatial separation while no useful information is exchanged (no-signaling). WaveTree offers an interpretation: the two "particles" are one object of the Now that has, in the coordinate

description, taken multiple apparent locations. In this reading, apparent spatial separation on the surface does not entail separateness in the substrate: a single sub-surface object can be projected onto separated regions of Σ_t without being multiple objects.

This reading is observationally identical to standard QM. It reproduces:

- Born-rule correlations to within experimental precision;
- No-signaling — no useful information passes through the entangled channel, because there is only one object and its state is one state;
- The Tsirelson bound on Bell inequalities at the CHSH form.

The interpretation loosely aligns with the ER=EPR conjecture of Maldacena and Susskind — that entangled pairs may be connected by geometric structure — without committing to the wormhole implementation. In WaveTree, the geometric connection is the connectedness of the sub-surface substrate itself; the two apparent locations are surface projections of a single sub-surface object.

Three things this image does not do, stated plainly so the reader need not discover them. It does not explain the *monogamy* of entanglement — why maximal correlation with one partner excludes correlation with a third. It does not obviously extend to entanglement between different species (a photon and an atom: the same object?) or to systems entangled in one degree of freedom but not others. And it does not by itself account for how spacelike-separated *measurement choices* select the correlated outcomes — the standard mystery is relocated into the substrate, not dissolved. The image earns its keep as economy of ontology — one object rather than two-plus-mystery — and as an invitation to sharper formulation, not as a mechanism.

The interpretation offers no new prediction; a fenced speculation about environment-correlated tests lives in Section 13.3, where speculation belongs.

SECTION ELEVEN

11 Antimatter as historic spacetime pulled forward to the Now

The Vision offers the identification: *antimatter is historic spacetime pulled forward to the Now*. In technical register, an antiparticle mode is a segment of the causal-past-supported functional $\mathcal{H}$ that has been extracted from $J^-(p)$ and instantiated on Σ_t . Its opposite-charge quantum

numbers reflect the reversed proper-time direction of its origin (Feynman–Stueckelberg). Its fragility in ordinary settings is a consequence of the matter-dominant local $\mathcal{H}$ that immediately reclaims the extracted segment through annihilation.

11.1 Conservative reading (AM-C)

In the conservative reading, the identification is a geometric restatement of Feynman–Stueckelberg. CPT symmetry is preserved. Cross-sections, spectra, decay rates, and gravitational response are unchanged. All laboratory tests of antimatter — antihydrogen spectroscopy (ALPHA at CERN), antihydrogen free fall (ALPHA-g, 2023: a measured acceleration of about $0.75 \pm 0.13 \pm 0.16$ g, consistent with ordinary free fall at roughly 20–25% precision), CPT tests in meson systems, lepton $g - 2$ — are reproduced exactly. The free-fall result also disciplines the essay's own inertia section: antimatter read as *extracted* history falls normally, which is among the constraints that force the invariant-content reading of Section 8.4.

11.2 Exploratory reading (AM-X): history-biased baryogenesis

The exploratory reading asks a question that Feynman–Stueckelberg alone does not ask: if antiparticle modes are extracted from the causal past, and if the early-universe $\mathcal{H}$ was strongly spatially and temporally varying (as required for structure to form), could effective CP-violating phases — for instance the QCD θ parameter, the CKM phase δ , or higher-dimension operators — have been modulated by early-universe $\mathcal{H}$ gradients in a way that biases the Sakharov conditions and produces the observed baryon asymmetry?

This is a well-posed question in the sense that it can be tested — but the essay owes the reader precision about what "tested" means here, because a prediction of "EDMs near, but below, current bounds" is rubber: it survives every null result by retreating downward. Without a mechanism, AM-X fixes no EDM magnitude, and the essay does not pretend otherwise. It therefore adopts a falsification convention and declares it: **if ACME III (targeting $|\mathbf{d}_e| \lesssim 10^{-30}$ e·cm) and n2EDM at PSI (targeting $|\mathbf{d}_n| \lesssim 10^{-27}$ e·cm) both reach their design sensitivities with null results, AM-X is to be regarded as disfavored, and the essay's antimatter content reverts to the conservative reading AM-C alone.** A declared floor is weaker than a derived one, and the essay says so; it is also the difference between a falsifiable speculation and an unfalsifiable one.

11.3 Fragility of antimatter in ordinary settings

Because textured-mode $\mathcal{H}$ in our local causal past is matter-dominated (Section 5), antimatter modes extracted onto the Now encounter a matter-biased $\mathcal{H}$ on the surrounding surface. Their persistence is limited by the annihilation channels supplied by that matter-biased background. This is the standard fragility of antimatter in ordinary laboratory settings, seen through a geometric intuition.

SECTION TWELVE

12 Predictions, consistency checks, and falsifiers

The empirical content of the essay is summarized as eight numbered statements — and the essay refuses to inflate the count: **six of the eight are consistency checks**, statements that the framework agrees with existing data by construction, and they are labeled as such. Agreement with what is already measured is a precondition, not a prediction. The essay's genuine empirical exposure is P3 (a novel residual prediction), P5 (an exploratory prediction with a declared falsification floor), and the fenced evolving-dark-energy remark below.

- P1 Cosmological baseline.** (*consistency check*) All standard cosmological observables — CMB acoustic peaks and damping tail, baryon acoustic oscillations, Type Ia supernova distance–redshift relation, growth of structure $f\sigma_8$, weak-lensing convergence power spectrum — are reproduced at Planck / DESI / SDSS / Euclid precision by tuning of the $\mathcal{H}$ partition.
- P2 Gravitational-wave propagation.** (*consistency check*) Gravitational-wave speed $|v_{\text{GW}} - c| / c \lesssim 10^{-15}$, as constrained by GW170817 + GRB 170817A; polarization consistent with the two tensor modes of general relativity, as constrained by LIGO–Virgo–KAGRA. WaveTree respects these bounds by construction.
- P3 History-linked halo residuals.** (*novel prediction — the headline*) After subtraction of the simulated Λ CDM expectation (assembly bias + baryonic feedback), residual halo lensing profiles correlate positively with stellar-population age, metallicity [Fe/H], and merger-history proxies — each proxy tested with the others controlled, with M_*/L systematics forward-modeled. Λ CDM predicts these post-subtraction residuals vanish. Testable at DESI Y5, Euclid Wide, LSST stacked precision (Section 6, Appendix C).

- P4 Antimatter free fall.** (*consistency check*) Free-fall acceleration of antihydrogen equals that of hydrogen — consistent with the ALPHA-g 2023 result ($\approx 0.75 \pm 0.13 \pm 0.16$ g, consistent with 1g at $\sim 20\text{--}25\%$ precision). AM-C predicts continued agreement at improved precision; any deviation would falsify AM-C.
- P5 Electric dipole moments.** (*exploratory prediction, declared floor*) AM-X predicts residuals of early-epoch CP modulation appear as EDMs. By the convention declared in Section 11.2, double nulls at the design sensitivities of ACME III and n2EDM disfavor AM-X and revert the essay's antimatter content to AM-C. The conservative reading does not predict a positive signal; AM-X does.
- P6 Coupling constant drift.** (*consistency check*) Any environmental or cosmological drift in α , μ , or Λ_{QCD} lies below existing bounds from atomic clocks, Oklo, quasar absorption lines, BBN, and the CMB.
- P7 Local Lorentz invariance, no-signaling, and Bell.** (*consistency check*) All present tests of local Lorentz invariance, no-signaling, and the Tsirelson bound are respected. The entanglement reading of Section 10 makes no operational departure.
- P8 Special relativity and the equivalence principle.** (*consistency check*) All standard SR predictions — time dilation, length contraction, γ -factor of relativistic momenta — are recovered exactly, and inertia is history-independent per Section 8.4. The inertia interpretation of Section 8 is a reading of the invariant structure, not a modification of it.

A NOTE ON EVOLVING DARK ENERGY (EXPLORATORY)

Section 5.3 records a fork the data will decide: if the DESI-era preference for evolving dark energy solidifies, it is circumstantial support for the growing- $\langle \mathcal{H} \rangle$ reading of the smooth mode; if $w = -1$ is confirmed to high precision, WaveTree requires the saturating reading. The framework survives either outcome, but the two readings are distinguishable, and the essay commits to updating rather than reinterpreting after the fact.

THE ESSAY'S FATE HANGS ON P3

Statements P1, P2, P4, P6, P7, P8 are consistency checks — they can embarrass the framework only if the underlying tested physics is itself overturned. P5 is exploratory, with its falsification floor declared. P3 is the essay's headline and its genuine exposure. A convincing null on P3 at the precision reachable in the second half of this decade returns WaveTree to its conservative core: an interpretive reading with no independent empirical content, and the essay says so without hedging.

SECTION THIRTEEN · SPECULATIVE EXTENSIONS

13 Speculative extensions

Reader's note. *The material in this section is exploratory. It extends the geometric picture of the Vision beyond what the technical body of the essay stakes as claims, and beyond what any of the predictions in Section 12 rely on. It is included so that readers can see where the framework's imagination reaches. A reader who declines to engage with speculative extensions can skip this section without loss to the technical argument.*

The framework, at its exploratory limit, suggests two categories of technological implications worth naming so the reader can see where the picture extends.

13.1 Energy coupling to the null sweep (the "zero-point" question)

Quantum field theory attributes to the vacuum a formally divergent zero-point energy density that, in the standard reading, is renormalized away and is not accessible for macroscopic energy extraction. The dynamical Casimir effect, in which a moving boundary produces measurable photons from vacuum modes, is an experimentally verified example of localized vacuum energy conversion; it respects thermodynamic accounting.

The Vision proposes that the Now advances at c and that the vacuum's energy content is participating in that advance. In this reading, a hypothetical mechanism that couples to the local rate of null-generator expansion — a mechanism that could "bias" the sweep — could, in principle, tap the vacuum inventory. The framework offers no first-principles derivation of such a mechanism, and any energy extracted by such a mechanism must respect quantum energy inequalities (Ford–Roman bounds) and the second law of thermodynamics. It is included here as an exploratory implication of STP dominance, not a claim.

13.2 Local bias of the sweep and warp-bubble geometries

General relativity mathematically permits Alcubierre-like warp geometries in which a bounded region of spacetime is contracted ahead of a craft and expanded behind, producing effective superluminal transport with subluminal local frame. The macroscopic negative energy required for such a configuration is forbidden by quantum energy inequalities for macroscopic durations; no known mechanism produces the required stress-energy.

WaveTree offers no route around these bounds. The framework notes only that if the picture of Section 7 (gravity as observed rate of null-generator sweep) is taken at its exploratory limit, biasing the local sweep is the operational content of any warp mechanism. Whether such biasing is achievable by any physical process is an open question; the essay does not answer it and does not claim to.

13.3 Environment-correlated entanglement tests

If entanglement is the projection of a single sub-surface object at multiple locations (Section 10), one might speculate that extreme differential perturbations of the Now across the two projections — for instance, radically different gravitational environments — could induce minute environment-correlated deviations in Bell-type correlations. This speculation must be fenced with unusual care, because any such deviation would contradict quantum mechanics itself, not merely refine it: loophole-free Bell tests (2015 onward) reject local realism at high significance and agree fully with quantum predictions, and no mechanism or magnitude is offered here. The expectation is null. The speculation is recorded only because the interpretation of Section 10 naturally raises the question, and honest bookkeeping records questions with their expected answers — including "no."

ON WHAT THIS SECTION IS

This section is exploratory imagination in physics-community register. Nothing in it appears as a prediction in Section 12. It is included because the Vision reaches to it and because a reader is entitled to see the reach.

SECTION FOURTEEN

14 Open problems

The essay is a perspectives contribution. Its open problems are explicit and are proposed as a research program.

1. **No Lagrangian for $\mathcal{H}$.** The Tree functional is introduced by its causal-past support and by the decomposition (3.4) into smooth and clumping pieces. No action from which $\mathcal{H}$ follows as a variational solution is offered. A candidate research direction is to extend the Deser–Woodard non-local gravity action $f(\Box^{-1}R)$ with an explicit clumping sector.
2. **Sign and amplitude of the P3 residual.** The essay asserts a positive sign for the post-subtraction residual–history correlation as the natural reading of $\mathcal{H}$ accumulating with history; it does not derive the sign, and it does not compute the amplitude. Both require a specific parameterization of $T^{\mathcal{H},\text{clumping}}$, and the amplitude must be computed relative to the simulated Λ CDM assembly-bias baseline of Appendix C — a smaller target than the naive version of the prediction.
3. **No operational criterion for the $\mathcal{H}$ regimes.** As recorded in Section 5.1, the coherent/textured/smooth taxonomy is descriptive: no principle yet determines which regime a given $\mathcal{H}$ configuration occupies, or why textured-mode $\mathcal{H}$ carries no electromagnetic couplings. This is the framework's most important theoretical debt.
4. **Concrete mechanism for AM-X.** AM-X is a research question, not a mechanism. Its concrete realization — which CP phase is modulated by which functional of early-universe $\mathcal{H}$ — is unspecified. The falsifiers (EDMs) are well defined even without the mechanism.
5. **Mechanism for the exploratory extensions.** The energy-coupling and warp-bias implications of Section 13 are named as horizon points, not mechanisms. Whether any physical route to them exists is an open question the essay does not answer.

Three concrete follow-up items for interested readers:

1. A data-analysis pass on DESI + DES / KiDS weak-lensing stacks binned by stellar age at fixed stellar mass, testing P3 (Appendix C).
2. Theoretical work on a non-local gravity action of the form $f(\Box^{-1}R) + g(\delta \Box^{-1} \rho)$ with a clumping sector that reduces to Λ CDM at baseline while producing a positive P3 signature.
3. N-body cosmological simulations with a $\delta\mathcal{H}$ -sourced clumping perturbation, predicting the P3 signature amplitude as a function of the perturbation strength.

SECTION FIFTEEN

15 What WaveTree contributes

The essay's contribution, in three items.

1. A substrate reading of the Λ CDM mass–energy budget. Ordinary matter, dark matter, and dark energy read as three regimes of one history substrate $\mathcal{H}$, distinguished by the coherence with which $\mathcal{H}$ has been written onto the advancing Now. This is the STP-dominance thesis (Section 5).

2. One novel, specific, testable empirical prediction. History-linked correlations in dark-sector residuals, at the halo scale and larger, correlated with stellar-population history proxies. Diagnostic: a convincing null returns the framework to its conservative core.

3. A geometric composition of existing threads. The growing block of Broad and Ellis, the Bondi–Sachs characteristic formulation of GR, Mach's principle rotated into time, Smolin's precedence, Deser–Woodard non-local gravity, Verlinde's emergent-gravity reading of the dark sector, Feynman–Stueckelberg antimatter, Wheeler–Feynman advanced–retarded structure, decoherent histories, and the substrate instinct of the computational programs are stitched together under one geometric picture in which each is doing part of a larger job — and the picture is disciplined by MOND's radial acceleration relation and the equivalence-principle tests where they bite (Sections 2.7, 8.4). The composition is not derivational; it is compositional. Whether the composition is worth continuing is the question the essay poses to the reader.

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APPENDIX A

A Claim audit

A traffic-light audit of the framework's claims, ranked by their status against currently tested physics. **Green**: compatible with GR + SM + Λ CDM + data at all precisions currently achieved. **Yellow**: speculative but not excluded; testable at achievable precisions in this decade. **Red**: readings the framework itself excludes — retained in the table deliberately, because a framework that cannot name what it forbids cannot be tested.

CLAIM	STATUS	NOTES
Now Σ_t as spacelike Cauchy surface; advance conditioned at c via growth of $D^+(\Sigma_t)$	GREEN	Geometric restatement of standard causal structure (Section 3.1); no preferred frame, no edge, no proper time along null curves claimed.
Tree $\mathcal{H}$ as causal-past functional; $T^{\mathcal{H}}_{\mu\nu}$ on RHS of Einstein's equations	GREEN	Formal parallel to Deser–Woodard non-local gravity; parameterization degenerate with Λ CDM.
Local stability of bound systems from standard cosmology	GREEN	Cooperstock, Price–Romano, Carrera–Giulini; no new parameter required.
STP dominance: matter/DM/DE as three regimes of $\mathcal{H}$	YELLOW	Compositional reading of the mass–energy budget; taxonomy currently descriptive (Section 5.1); stands or falls with P3.
Prediction P3: history-linked halo residuals in excess of Λ CDM assembly bias	YELLOW	Novel, stated as a residual over the simulated Λ CDM expectation with M_*/L controls; testable at DESI / Euclid / LSST stacked precision.
Gravity as the two-channel (Ricci/Weyl) response of the sweep	GREEN	Reparameterization of GR via Raychaudhuri + Weyl-sourced shear (Section 7); no new prediction.
Inertia as tail drag, magnitude fixed by invariant content alone	GREEN	Interpretation of SR's invariant structure; all SR and EP tests recovered (Sections 8.3–8.4).

CLAIM	STATUS	NOTES
Surface/slab reading of classical–quantum boundary	GREEN	Geometric semantics for decoherent histories and einselection; no operational departure.
Wave function identified with the spacetime wave	YELLOW	Clean for single-excitation states; conceded for N-particle amplitudes (configuration space — Sections iii.5, 9.3); no operational departure from QFT.
Entanglement as one object at multiple apparent locations	GREEN	Interpretive; reproduces no-signaling and Tsirelson bound; unresolved obligations stated in Section 10.
Antimatter as historic spacetime pulled forward (AM-C)	GREEN	Geometric restatement of Feynman–Stueckelberg; CPT and lab results preserved; ALPHA-g quoted correctly at ~20–25% precision.
History-biased baryogenesis (AM-X)	YELLOW	Exploratory; falsification floor declared at ACME III + n2EDM design sensitivities (Section 11.2).
Evolving dark energy from growing $\langle \mathcal{H} \rangle$	YELLOW	Fenced fork (Section 5.3): DESI-era evolving-w preference would support the growth reading; confirmed $w = -1$ forces the saturating reading.
Energy coupling to the null sweep (Section 13.1)	YELLOW	Exploratory; no mechanism specified; bounded by QEIs and thermodynamics.
Warp-bubble geometries via sweep biasing (Section 13.2)	YELLOW	Exploratory; requires bypassing QEI bounds on macroscopic negative energy; no mechanism specified.
History- or composition-dependent inertial mass (naive tail reading)	RED — EXCLUDED	Ruled out by Eötvös/MICROSCOPE at $\sim 10^{-15}$ and by ALPHA-g; the framework forbids it (Section 8.4). A lab anomaly here would falsify WaveTree, not confirm it.

CLAIM	STATUS	NOTES
Environment-correlated Bell-inequality deviations	RED — EXCLUDED	Would contradict quantum mechanics itself; retained only as fenced speculation with expectation null (Section 13.3).
Macroscopic vacuum-energy extraction without a compensating ledger	RED — EXCLUDED	Forbidden by quantum energy inequalities and thermodynamics; Section 13.1 respects these bounds.

APPENDIX B

B Notation

- $(\mathcal{M}, g)$ — a smooth Lorentzian spacetime, assumed globally hyperbolic.
- Σ_t — a smooth spacelike Cauchy hypersurface labeled by a smooth time function t ; on cosmological scales identified with the FLRW constant-cosmic-time slice.
- $C^+(p), C^-(p)$ — the future and past light cones of the point $p \in \mathcal{M}$.
- $J^-(p)$ — the causal past of p , i.e. the union of all points $q \in \mathcal{M}$ from which a future-directed causal curve reaches p .
- k^a — a future-directed null tangent vector field to the null generators of $C^+(p)$.
- $\mathcal{H}$ — the Tree functional; a real functional over $J^-(p)$ with decomposition $\mathcal{H} = \langle \mathcal{H} \rangle + \delta \mathcal{H}$.
- STP — Spacetime-Past: the essay's name for historical spacetime as substrate; "STP dominance" is the central thesis of Section 5.
- $D^+(\Sigma_t)$ — the future domain of dependence of Σ_t : the set of events whose physics is fully determined by data on Σ_t .
- λ — an affine parameter along null geodesics (null curves accumulate no proper time; affine parameterization replaces it).
- C_{abcd} — the Weyl (conformal) tensor: the part of curvature that propagates through vacuum and carries tidal information (Section 7).
- $T^{\text{SM}}_{\mu\nu}$ — the Standard-Model matter and radiation stress-energy tensor.

- $T^{\mathcal{H}}_{\mu\nu}$ — the history-sourced effective stress-energy, with smooth and clumping components.
- $\mathcal{S}_\varepsilon$ — a slab of proper-time thickness ε straddling Σ_t .
- $H(t)$, h — the Hubble parameter and dimensionless Hubble rate. *Note:* not the Tree functional $\mathcal{H}$.
- P1...P8 — the essay's numbered predictions (Section 12).
- AM-C, AM-X — the conservative and exploratory readings of the antimatter mapping (Section 11).
- θ , σ_{ab} , ω_{ab} — expansion, shear, and vorticity of the null congruence with tangent k^a .

APPENDIX C

C Analysis sketch for the halo-correlation test

A minimal analysis pipeline for Prediction P3 is presented here in schematic form. It is written so that a working observational cosmologist can turn it into a specification without undertaking any of the framework's interpretive commitments.

C.1 Sample

- Primary sample: DESI Bright Galaxy Sample cross-matched with a stellar-population catalog (SDSS MPA-JHU, GAMA StellarMasses, or equivalent) providing mean stellar age $\langle \log \tau_* \rangle$, mean $[\text{Fe}/\text{H}]$, and stellar mass M_* .
- Lensing: DES Y6, KiDS-1000, or HSC three-year weak-lensing convergence maps, stacked around galaxy positions to construct $\Delta\kappa(\theta; \text{bin})$.
- Companion: SPARC compilation for the rotation-curve version of the test.

C.2 Binning and masses

- Primary bin variable: mean stellar age $\langle \log \tau_* \rangle$, in three or four quantile bins.
- Nuisance bin: mass — with the M_*/L degeneracy handled by design. Because stellar masses are inferred through age- and metallicity-dependent mass-to-light models, "fixed stellar mass" is partially circular with respect to the primary bin variable. The pipeline

therefore uses dynamical or lensing-calibrated masses where available, and elsewhere forward-models the M_*/L systematic explicitly, propagating it into the error budget.

- Secondary bin variables (independent per-proxy tests, each with the others controlled): mean $[\text{Fe}/\text{H}]$; merger-history proxy (e.g., major merger within $\tau < 3$ Gyr as inferred from morphology or a companion catalog). The proxies are not jointly monotonic (Section 6.1) and are not combined into a single score.

C.3 Baseline subtraction — including assembly bias

This is the step on which the test's integrity rests, because a naive baseline produces a false positive in a pure ΛCDM universe: ΛCDM halos at fixed mass differ in concentration according to their formation history (assembly bias), and old-population galaxies preferentially occupy earlier-forming, more concentrated halos — generating a residual–age correlation with no new physics. The baseline must therefore be conditioned on formation history, not merely on mass:

- Fit a ΛCDM -consistent halo occupation distribution to the aggregate stacked signal to establish $\Delta\kappa_{\text{baseline}}(\theta)$ at each mass.
- Condition the baseline on assembly bias using N-body and hydrodynamic simulations (e.g., IllustrisTNG, FLAMINGO): predict, within the simulation, the expected residual–age correlation from halo formation-time and concentration differences alone, and subtract it — or equivalently, match observed and simulated samples on concentration proxies before comparing.
- Include baryonic feedback in the baseline using an established parameterization (BAHAMAS, FLAMINGO).

The WaveTree signal is the residual after all three components: $\Delta_{\text{WT}}\kappa(\theta) = \Delta\kappa(\theta; \text{bin}) - \Delta\kappa_{\text{baseline+assembly+baryons}}(\theta; \text{mass, concentration})$.

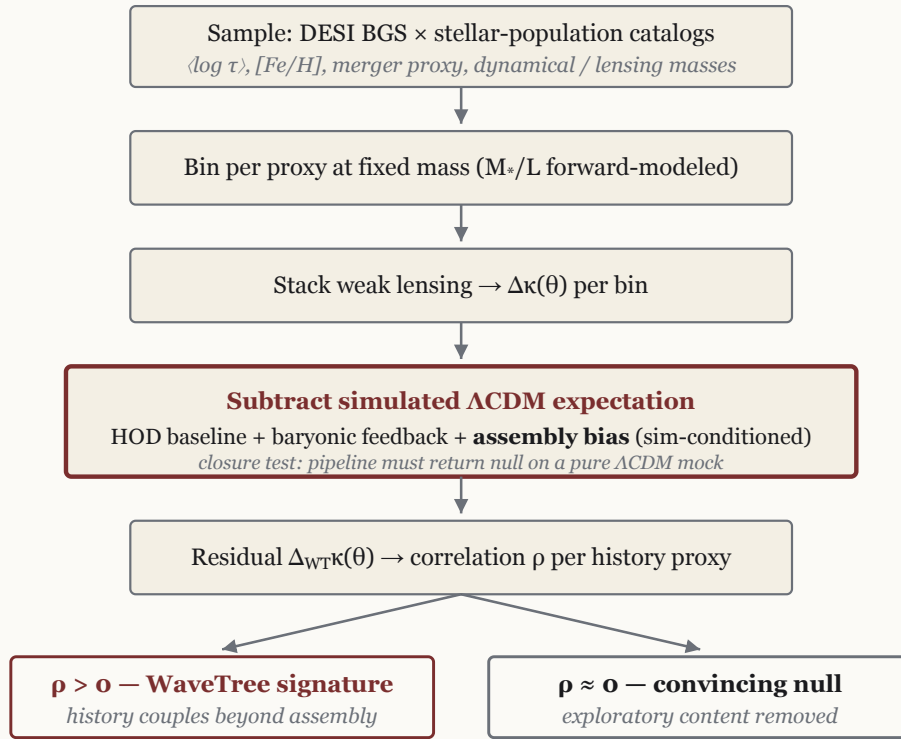


FIGURE 5. *The P3 pipeline. The integrity of the test rests on the highlighted step: the Λ CDM baseline must include the assembly-bias expectation from simulations, or the pipeline manufactures a false positive in a pure Λ CDM universe. Both outcomes of the fork are informative, and the essay accepts either.*

C.4 Estimator and prediction

The estimator is the correlation ρ between $\Delta_{\text{WT}}\kappa(\theta)$ at fixed θ and the primary bin variable, within mass bins, per proxy. Prediction P3 is $\rho > 0$ for each history proxy after the C.3 subtraction. (Illustrative scale only, pending a real power analysis: a stacked sample of order 10^6 galaxies, with a null defined as $|\rho|$ below the few-percent level at high confidence across the interesting mass range, is the regime DESI- and Euclid-era data make reachable.) A convincing null removes the exploratory content of the essay.

C.5 Controls

- Randomized bin labels: shuffling the stellar-age assignments should produce ρ consistent with zero within the estimator's error.
- Photometric vs spectroscopic age: the correlation, if detected, should be stable under a change of age proxy.

- M_*/L stress test: re-run the analysis under deliberately varied mass-to-light prescriptions; a real signal survives, an M_*/L artifact tracks the prescription.
- Simulation closure test: run the full pipeline on a pure Λ CDM mock (simulation output with no $\mathcal{H}$ physics); the pipeline must return null. Failure of this closure test invalidates the analysis, not the theory.
- Sample split by redshift: ρ should be stable in redshift bins, or evolve monotonically as $\mathcal{H}$ dominance would predict.
- Rotation-curve arm: any SPARC-based companion analysis must be benchmarked against the radial acceleration relation's measured scatter (Section 2.7), which already bounds the accessible signal in that arm.

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Correspondence — carl_downs@yahoo.com.

Prepared in collaboration with Anthropic's Claude (Opus 4.7).