Computational Architecture for a Covariant Static Universe: Adaptive Integration, State Orchestration, and Visualization

1. Architectural Foundations of a Speculative Cosmological Engine

The development of a computational physics engine to simulate a static, non-expanding universe over a 15-billion-year epoch represents a formidable challenge that operates at the intersection of theoretical physics, covariant mathematics, and advanced software architecture. Standard cosmological simulations generally rely on the ΛCDM framework, assuming an expanding pseudo-Riemannian manifold where fundamental constants—such as the speed of light in a vacuum (c), the gravitational constant (G), and the mass of elementary particles—remain strictly invariant over time. However, simulating highly speculative covariant paradigms, such as the Variable Speed of Light (VSL), Tired Light (TL), and Covarying Coupling Constants (CCC) theories, requires a fundamentally divergent architectural approach.[1]

In this computational framework, spacetime is not treated as a dynamic, expanding fabric governed by a mutable metric scale factor. Instead, space is redefined algorithmically as a static, Euclidean, non-physical void.[3] Within this absolute relational environment, the observed cosmological redshift—traditionally modeled as a Doppler-like effect of metric expansion—must be simulated programmatically as a kinematic decay of fundamental forces, a thermodynamic energy dissipation of massive photons, and the resulting mass-boom of baryonic matter.[3]

To achieve this without encountering floating-point arithmetic collapse or violating the fundamental laws of thermodynamics across billions of simulated years, the engine relies on rigorous Test-Driven Development (TDD) constraints, treating physical laws as a dynamically evolving codebase. Translating these non-standard cosmological models into a strictly typed, Object-Oriented TypeScript library requires isolating mathematical mutations into discrete, highly specialized modules. Furthermore, the continuous integration of covariant constants over astronomical time scales necessitates the abandonment of fixed-step numerical solvers in favor of dynamically adaptive algorithms.[5] Finally, the sheer volume of high-precision state data generated over these epochs mandates specialized memory management strategies and advanced downsampling algorithms for visual rendering.[6] This report exhaustively details the architectural, mathematical, and programmatic mechanics required to build, execute, and visualize this speculative cosmology engine.

2. Project Hierarchy and Test-Driven Thermodynamic Invariants

To maintain a clean separation of concerns across the varying speed of light (VSL) mechanics, tired light (TL) energy decay, and the underlying mathematical solvers, the TypeScript library is structured into a rigid information hierarchy. This ensures that physical state mutations do not introduce unhandled side effects into the global integration loop.

2.1 Object-Oriented Module Structure

The root of the engine is divided into discrete operational domains. The src/constants/ConstantsManager.ts module acts as the covariant coupling heart of the engine, continuously recalculating $c(t)$, $G(t)$, and system mass $m(t)$ while enforcing the strict invariance of dimensionless ratios.[1] The entities themselves are isolated: src/entities/PhotonEntity.ts manages continuous and discrete energy attenuation (tired light), while src/entities/ParticleEntity.ts enforces covariant mass scaling.[3]
The numerical heavy lifting is sequestered in the src/engine/ directory, where the CorePhysicsEngine.ts houses the adaptive integration loop and the MetricTensorSolver.ts calculates spatial propagation and Proca dispersion.[8] These modules are coordinated by src/orchestration/SimulationOrchestrator.ts, which manages the overarching 15-billion-year (timeGy) execution loop and raw data logging, before passing the memory buffers to src/visualization/VisualizationGrapher.ts for projection.[6]

2.2 Core TypeScript Interfaces and State Boundaries

The engine relies on strongly typed interfaces to guarantee memory shape and operational predictability during the millions of iterations required by the integration loop. The primary state container is the CosmicState interface, which defines the physical boundaries at any given tick of the cosmic clock:

```TypeScript
export interface CosmicState {
  timeGy: number;          // Cosmic time in Gigayears (-15.0 to 0)
  timeStepSec: number;     // Dynamically adapted integration time step
  c_t: number;             // Current localized speed of light
  G_t: number;             // Current Gravitational constant
  alpha: number;           // Fine structure constant (Strict Invariant)
  e_charge: number;        // Elementary charge (Covariant)
  h_bar: number;           // Reduced Planck constant (Covariant)
  massMultiplier: number;  // System rest mass multiplier
}
```

This state is initialized and modified based on the SimulationConfig parameters, allowing

researchers to toggle between distinct cosmological hypotheses, such as switching the vslModel between 'EXPONENTIAL' or 'FRACTAL', or alternating the tlModel between 'CONTINUOUS' exponential decay and discrete 'COMPTON_SCATTERING'.[3]

2.3 Test-Driven Cosmology: The "Red, Green, Refactor" Matrices

In classical software development, TDD ensures logic does not regress when the codebase changes. In this cosmological engine, TDD is repurposed to ensure the physical universe does not regress into thermodynamic paradoxes when fundamental constants are mutated. "Test-Driven Cosmology" treats physical laws as an algorithmic codebase that must pass observational tests without producing terminal logical exceptions.[3]

Using the Jest testing framework, the engine enforces strict invariant matrices. For example, the VSL_Kinematic_Decay test asserts that the initial speed of light at -15 Gyr aligns precisely with the chosen theoretical decay curve. More importantly, the Covariant_Mass_Conservation test targets the ParticleEntity, asserting that $m(t) \cdot c(t)^2$ remains a constant value.[3] If the engine slows the speed of light but fails to proportionally increase the system mass, the total energy of the universe would artificially decay, violating Noether's Theorem and continuous time translation symmetry.[3]

Similarly, the Dimensionless_Stability test ensures that the ConstantsManager accurately balances the elementary charge and Planck's constant so that the fine-structure constant (α) at -15 Gyr is floating-point identical to the present day, anchoring the simulation against chemical impossibility.[1]

3. The Covariant Constants Manager: Simulating VSL Frameworks

At the core of the engine's physics logic is the necessity to continuously recalculate the values of fundamental constants based on the elapsed cosmic time, t. The ConstantsManager supports several mutually exclusive Variable Speed of Light (VSL) frameworks, each possessing unique mathematical consequences for the evolution of the simulated universe.

3.1 The Pipino Kinematic Decay Model

The first model supported by the SimulationConfig state is the Pipino exponential decay model.[12] This hypothesis posits that observational anomalies, such as unexplained variations in high-energy physics, anomalous stellar rotational velocities, and atomic decay rates over vast temporal baselines, are the result of a speed of light that decays proportionally to the Hubble constant (H_0).[13] The foundational differential equation is formulated as:

$$\frac{dc}{dt} = -Hc$$

Integrated over cosmic time, the ConstantsManager calculates the speed of light at any given

epoch using the exponential decay function:

$$c(t) = c_0 e^{k \cdot H_0 t}$$

Where c_0 is the present-day speed of light ($299,792,458$ m/s), t is the cosmological time (where negative values represent the deep past, starting at -15 Gyr), and k is a dimensionless scaling factor utilized to fit the deceleration curve to observed galactic acceleration trends.[14] For example, this model provides a quantitative justification for the acceleration trend ($a_c = -Hc_e$) of stars in the Andromeda galaxy without invoking dark matter halos.[13] In the simulation state, at $t = -15$ Gyr, the initial speed of light is calculated to be significantly higher than the modern limit, establishing an ancient electromagnetic substrate operating at accelerated kinematic regimes.

3.2 The Alfonso-Faus Fractal Time and Mass-Boom Paradigm

Alternatively, the engine can be configured to instantiate the Alfonso-Faus model, which posits that the speed of light is inversely proportional to cosmological time, scaling strictly as $c(t) \propto 1/t$.[15] This model fundamentally links the evolution of the universe directly to the metric of time itself, operating on the assumption that any time interval δt is proportional to the total age t, thereby establishing a fractal dimensional scaling ($\delta t/t = \text{constant}$).[11]

Because the linear momentum of a system (mc) is postulated to remain strictly constant across all cosmological epochs in this framework, a linear decrease in the speed of light mathematically necessitates a linear increase in all localized masses.[11] This is computationally represented within the engine as the "Mass-Boom" effect.[4]

The ParticleEntity module enforces this covariant mass conservation to resolve thermodynamic paradoxes. If energy is defined as $E = m(t)c(t)^2$, and momentum $p = m(t)c(t)$ is conserved, the mass at any time t is recalculated dynamically by the engine as:

$$m(t) = m_0 \frac{c_0^2}{c(t)^2}$$

This mass-boom logic perfectly offsets the kinematic decay of $c(t)$, preventing the destruction of total system energy.[4] Within the simulation environment, as c decays towards the present day, the rest mass of all baryonic matter scales up proportionally. This framework allows the engine to output an entirely gravitational and variable-light-speed explanation for the anomalous acceleration of the Pioneer 10 and 11 spacecraft, rendering dark matter assumptions unnecessary for local solar system dynamics within this specific configuration.[4]

3.3 Dimensionless Stability and the CCC+TL Framework

A critical programmatic constraint of the engine is the absolute prevention of chemical impossibility. If the speed of light and mass vary wildly over 15 billion years, the fine-structure constant ($\alpha \approx 1/137.036$), which dictates the strength of electromagnetic interactions and atomic orbital stability, must remain utterly invariant.[1]
The Covarying Coupling Constants plus Tired Light (CCC+TL) framework, theorized by Rajendra Gupta, extends this principle. In the CCC+TL model, only quantities with explicit length dimensionality covary through a universal scaling function $f(z)$, while dimensionless constants and dimensionless ratios remain structurally intact.[1]

The engine's ConstantsManager executes a balancing algorithm to satisfy this. As $c(t)$ varies, covariant adjustments are forced onto the elementary charge (e) or the reduced Planck constant ($\hbar$) so that the equation $\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c}$ remains perfectly balanced across the entire temporal loop.[1] This ensures that Big Bang Nucleosynthesis (BBN) constraints and early-universe elemental abundances (as visualized on a Schramm plot) remain valid and aligned with Planck CMB values despite the radical shifts in the dimensional constants.[1]

Cosmological Model	c(t) Decay Mechanics	Mass Mechanics	Dimensionless Constants	Primary Observational Target
Pipino Exponential	$c(t) =$	Covariantly scaling	α strictly invariant	High-energy stellar rotation [13]
Alfonso-Faus Fractal	$c(t) \propto 1/t$	Mass-Boom ($m \propto$)	α strictly invariant	Pioneer anomaly, Redshift [4]
Gupta CCC+TL	Covaries via $f(z)$	Covaries via $f(z)$	Invariant (BBN Compliant)	Baryon Acoustic Oscillations [18]

4. Proca Electrodynamics and the Tired Light Condensate

To successfully simulate a static void, the PhotonEntity and MetricTensorSolver modules are responsible for integrating "Tired Light" (TL) mechanics. In a universe devoid of spatial expansion, cosmological redshift is treated algorithmically as a mechanical loss of energy by

photons traversing an immense, non-empty interstellar medium over billions of years.[3]

4.1 Proca Vacuum Dispersion and Massive Photons

To allow light to structurally degrade, the engine abandons classical Maxwellian electrodynamics (which assumes an exactly massless photon and absolute c invariance) and implements Proca electrodynamics. In this framework, the photon possesses an incredibly small but non-zero invariant rest mass (m_p), constrained by modern laboratory limits to roughly $\sim 10^{-50}$ grams or 10^{-18} eV.[3]

The inclusion of the μ^2 scalar and vector potential terms in the modified Gauss's Law ($\nabla \cdot E = \rho - \mu^2 \Phi$) and Ampere's Law ($\nabla \times B = J + \frac{\partial E}{\partial t} - \mu^2 A$) introduces a frequency-dependent dispersion of the velocity of light.[3] Because of this nonzero photon mass, higher-frequency photons travel marginally faster than lower-frequency photons. The MetricTensorSolver calculates the group velocity (v_g) of the wave packet as:

$$v_g \approx c\left(1 - \frac{\mu^2 \gamma c^2}{2\omega^2}\right)$$

where ω is the frequency and γ is the Lorentz factor.[20]

Over a 15-billion-year simulation, this minute velocity differential ($v_{\text{high}} > v_{\text{low}}$) accumulates significantly. The engine algorithmically causes the initial spectrum of an ancient supernova event to geometrically stretch as it propagates across the static void, synthetically spooling a pulse duration ($\Delta t_1 \to \Delta t_2$) that accurately mimics the time-dilation curves traditionally attributed to an expanding spacetime metric.[3]

4.2 Thermodynamic Phase Transition into Dark Matter

As the massive PhotonEntity propagates through the simulation, it undergoes attenuation. The engine applies continuous exponential energy decay ($E(t) = E_0 e^{-t/\tau}$) or discrete probabilistic Free Electron Compton (FEC) scattering collisions, bleeding kinetic energy into the ambient cosmic magnetic vector potential.[3]

A unique physical consequence modeled by the engine is the thermodynamic phase transition of these exhausted photons. As their frequency (ν) drops toward zero through progressive cosmological redshifting, they lose their active electromagnetic radiation characteristics.[3]

Stripped of kinetic energy but retaining their invariant rest mass (m_p), they transition into a cold, non-relativistic, sub-luminal condensate of stable bound states. The engine logs these entities as "graviballs" or slow quanta.[3] Over the simulated 15-billion-year epoch, this invisible condensate aggregates around galaxies, providing the localized Newtonian gravitational lensing

effects classically attributed to exotic Weakly Interacting Massive Particle (WIMP) dark matter.[2]

5. Electromagnetically Induced Transparency and Stationary Light Engine

As a sophisticated expansion of the simulation's scope, the engine is capable of simulating localized observer interactions within this static void—specifically, introducing the paradox of navigating a spacecraft through a universe filled with the "stationary" or severely decelerated light comprising the tired-light dark matter condensate.[3]

5.1 Quantum Interference and Group Velocity Reduction

The mechanical interaction between an observer and a massive photon field with a near-zero group velocity draws algorithmic parallels from quantum optics—specifically, Electromagnetically Induced Transparency (EIT).[3] EIT utilizes destructive interference in a Λ-type quantum system (consisting of two ground states $|1\rangle$, $|2\rangle$ and one excited state $|3\rangle$) to render a normally opaque medium transparent while drastically lowering the speed of light.[3] Within the CorePhysicsEngine, the Kramers-Kronig relations dictate that a sharp gradient in the real part of the refractive index reduces the group velocity (v_g) approximation to:

$$v_g \approx \frac{c}{1 + \frac{g^2 \mathcal{N}}{2\Omega_c^2}}$$

where g is the atom-field coupling constant, $\mathcal{N}$ is the atomic density of the medium, and Ω_c is the Rabi frequency of the control field.[3] By algorithmically driving the control field intensity to zero ($\Omega_c \to 0$), the group velocity halts completely.[3]

5.2 Dark-State Polaritons (DSPs) and Bragg Gratings

In this stopped state, the electromagnetic energy is not destroyed; instead, it is coherently mapped onto the atomic medium as a bosonic quasiparticle known as a Dark-State Polariton (DSP).[3] The state vector Ψ of the DSP is dynamically governed by a mixing angle θ, defined by $\tan^2\theta = g^2\mathcal{N}/\Omega_c^2$. As light stops ($\theta \to \pi/2$), the polariton becomes purely matter-like, transferring its electromagnetic flux into the internal potential energy of the atomic matter.[3] Furthermore, the simulation supports Stationary Light Pulses (SLPs), which trap the electromagnetic field using counter-propagating control beams (Ω_c^+ and Ω_c^-). These beams interfere to form a standing wave, writing a highly precise, dynamically controlled photonic Bragg grating directly into the coherent atomic medium. The induced Bragg scattering continually reflects the probe field back and forth over microscopic distances, forcing the net group velocity to exactly zero while retaining localized oscillating electromagnetic energy.[3]

6. Relativistic Macroscopic Drag and Kinematic

Asymmetry

When a simulated observer (a macroscopic spacecraft) moves at velocity v through this dense, non-relativistic background of tired light and matter-like polaritons, the engine must calculate massive kinematic resistance.

6.1 The Abraham-Minkowski Controversy and Momentum Transfer

The simulation strictly enforces momentum transfer according to the Minkowski formulation, which asserts that photon momentum inside a dispersive medium is proportional to the refractive index n (canonical momentum), rather than the Abraham formulation (kinetic momentum).[3] Because spatial translation symmetry strictly dictates momentum conservation via the Cauchy momentum equation, the kinetic momentum absorbed by the spacecraft from the static optical field generates an extreme radiation pressure and physical retarding force.[3] The effective spacetime geometry experienced by the spacecraft through this medium is computationally mapped using the Finslerian Gordon metric.[3]

6.2 Baryonic vs. Radiative Drag Scaling Equations

At high relativistic speeds ($\beta \approx 0.99$), the observer suffers catastrophic drag from both the baryonic medium (interstellar gas and dust) and the stationary radiative fields (the CMB and the tired-light condensate).[3] The physics engine calculates this drag continuously at each tick.
Due to Lorentz length contraction in the direction of travel, the ambient spatial volume compresses, boosting the apparent density of the ambient interstellar medium to γn_0.
Simultaneously, relativistic momentum inflation multiplies the force of each impacting particle by $\gamma m_p v$.[3] Integrating this particle flux over the cross-sectional area of the spacecraft's forward hemispherical hull (radius R) yields the precise baryonic gas drag formula executed by the engine:

$$F_{\text{gas}} = \gamma^2 \pi R^2 \rho_{\text{gas}} v^2$$

Dust drag scales identically, though the gas-to-dust mass ratio in standard models renders dust a minor ($\sim 1\%$) contributor.[3]
Concurrently, the engine evaluates the radiative drag. Stellar aberration forces the ambient photon density into a high-intensity forward beam. Assuming total inelastic absorption or scattering, the opposing drag generated by the cosmic radiation field is modeled as:

$$F_{\text{rad}} = \gamma^2 \pi R^2 u_{\text{rad}} \frac{v}{c}$$

The orchestration loop establishes a dynamic velocity crossover threshold ($v_c = \frac{u_{\text{rad}}}{\rho_{\text{gas}} c}$).[3]
Below this threshold, radiative drag from stationary/tired light dictates the kinetic profile; above

it, baryonic mass impacts dominate.
This dual-drag calculation proves a fundamental kinematic and thermodynamic asymmetry in the simulation: a spacecraft moving at c through a stationary field of tired light is subjected to lethal kinetic bombardment (over 200 MeV per impact), whereas a stationary spacecraft observing active light passing by at c remains at relational rest with the cosmic mass shell, requiring zero propulsive work and experiencing only standard electromagnetic irradiation.[3]

7. The Orchestration Layer: Adaptive RKF45 Numerical Integration

Simulating the differential equations governing VSL, TL, covariant mass scaling, and Proca dispersion over a 15-Gyr span is computationally volatile. Standard numerical integrators, such as Euler or classical 4th-Order Runge-Kutta (RK4), utilize a fixed time step (Δt). In models like the Alfonso-Faus fractal model ($c(t) \propto 1/t$), the derivative of the speed of light approaches near-infinite steepness in the deep past ($t \to 0$ in absolute terms of universe origin).[15] A fixed Δt large enough to complete a 15-Gyr simulation in a reasonable timeframe would cause floating-point arithmetic to catastrophically collapse during these high-gradient early epochs, violating thermodynamic conservation.
To circumvent this mathematical instability, the SimulationOrchestrator implements the Runge-Kutta-Fehlberg method (RKF45), an adaptive step-size control algorithm that dynamically shrinks or expands the cosmic time step based on continuous local truncation error estimates.[5]

7.1 Embedded Truncation Error Estimation

The RKF45 algorithm simultaneously computes a fourth-order estimate (y_{n+1}) and a fifth-order estimate (y^*_{n+1}) using the exact same six functional evaluation nodes (k_1 through k_6). The mathematical difference between these two estimates provides a highly accurate approximation of the local truncation error (Δ_1) without requiring independent, computationally expensive step-doubling.[5]

The general form to advance the function $f(t, y)$ from t_n to t_{n+1} via step size h is encoded in the engine as:

$$k_1 = hf(t_n, y_n)$$

$$k_2 = hf(t_n + a_2 h, y_n + b_{21} k_1)$$

$$\dots$$

$$k_6 = hf(t_n + a_6 h, y_n + b_{61}k_1 + \cdots + b_{65}k_5)$$

The fourth-order and fifth-order updates are evaluated as:

$$y_{n+1} = y_n + \sum_{i=1}^{6} c_i k_i + \mathcal{O}(h^5)$$

$$y^*_{n+1} = y_n + \sum_{i=1}^{6} c^*_i k_i + \mathcal{O}(h^6)$$

The truncation error is isolated as the difference between the weighted coefficients:

$$\Delta_1 = |y_{n+1} - y^*_{n+1}| = \sum_{i=1}^{6} (c_i - c^*_i) k_i$$

.[5]

7.2 Dynamic Step Size Adaptation Matrix

If Δ_1 exceeds a predefined accuracy tolerance threshold (Δ_0), the current step is immediately discarded by the orchestrator, and the variables are recalculated with a smaller, safer h. Conversely, if Δ_1 is safely below the threshold, the step is accepted, and h is aggressively increased for the next iteration to minimize CPU cycles over stable, low-gradient epochs (such as the linear stasis of the modern era).[5]

The optimal scaling factor for the new time step (h_{new}) is determined algorithmically:

$$h_{\text{new}} = h_{\text{old}} \times \left(\frac{\Delta_0}{\Delta_1} \right)^{0.2}$$

The exponent 0.2 ($1/5$) corresponds to the order of the error estimate scaling (h^5).[5]
To optimize execution speed and reduce overhead within the TypeScript CorePhysicsEngine, the Fehlberg coefficients ($\alpha_i, \beta_{ij}, c_i, c_i^*$) are hardcoded as static constants.[25]

Stage (i)	ai	ci (4th Order Weight)	ci∗ (5th Order Weight)	Truncation Difference (ci −ci∗)

1	0	25/216	16/135	1/360
2	1/4	0	0	0
3	3/8	1408/2565	6656/12825	-128/4275
4	12/13	2197/4104	28561/56430	-2197/75240
5	1	-1/5	-9/50	1/50
6	1/2	0	2/55	-2/55

By utilizing this adaptive mechanism, the orchestrator seamlessly shrinks Δt to fractions of a second during the intense curvature of the deep past, while expanding it to millions of years during the linear epochs, ensuring absolute thermodynamic parity without triggering execution timeouts.[5]

8. High-Performance Memory Architecture: Float64Array and Chunking

Simulating the universe over 15 billion years with adaptive micro-stepping generates a phenomenal computational data footprint. Storing each tick of the simulation in a standard Object-Oriented TypeScript array (e.g., Array<CosmicState>) introduces massive memory overhead. The Node.js V8 JavaScript engine utilizes a garbage collector and object structural wrappers that limit standard heap sizes. Attempting to push tens of millions of high-precision object insertions—representing the RKF45 integration state across billions of steps—will inevitably cause the V8 engine to exceed its heap limits and crash.

To bypass these language-level limitations, the architecture utilizes explicitly sized Typed Arrays—specifically Float64Array—which operate directly on underlying binary buffers.[7] A Float64Array allocates contiguous 64-bit floating-point numbers (8 bytes per element) directly in raw memory, matching the IEEE 754 double-precision standard. This precision is absolutely mandatory to prevent mathematical loss across the massive numerical gulfs separating variables like $G(t)$ (on the order of 10^{-11}) and $c(t)$ (on the order of 10^{8}).[7]

8.1 Chunked ArrayBuffers and Multithreading Integration

The simulation maps the core variables of the CosmicState (Time, $c(t)$, $G(t)$, α, e, $\hbar$, $m(t)$

, λ_{Proca} , v_{group} , Error Delta) to a flattened index architecture. Each tick of the RKF45 integrator requires exactly 80 bytes of memory ($10 \text{ variables} \times 8 \text{ bytes}$). A high-resolution simulation requiring 50 million adaptive steps therefore requires exactly 4.0 gigabytes of active memory.

To handle this gracefully without triggering OS-level contiguous memory allocation errors, the SimulationOrchestrator implements a Chunked Buffer Strategy.[7] Rather than attempting to allocate a monolithic 4GB block, the engine allocates a pool of 100-megabyte ArrayBuffer chunks.

As the RKF45 loop executes, a cursor writes directly into the Float64Array view mapping the current active buffer.[28] When the cursor hits the boundary length of the chunk, the engine seamlessly pushes the filled buffer to disk or transfers it to a Web Worker context. For real-time multi-threaded processing and visualization, a SharedArrayBuffer is utilized.[7] This allows a background worker thread to calculate the intensive RKF45 physics while the main UI thread simultaneously reads the resulting coordinates for visualization plotting, entirely bypassing the expensive memory-cloning overhead associated with standard postMessage serialization.[7]

9. Data Projection and Decimation: The Largest-Triangle-Three-Buckets Algorithm

Once the Float64Array buffers are filled with tens of millions of raw physics nodes, passing this massive dataset directly to the VisualizationGrapher (such as an HTML5 Canvas or WebGL plotting context) will instantly freeze the rendering engine. However, applying a standard moving-average downsampling algorithm inherently destroys the crucial visual anomalies of the data. Simple averaging smooths out the steep hyperbolic curve of the Alfonso-Faus model, erases the sharp exponential drop of the Pipino model at -15 Gyr, and destroys the high-frequency Proca dispersion noise across ancient epochs.[6]

To solve this data projection paradox, the visualization pipeline enforces the **Largest-Triangle-Three-Buckets (LTTB)** algorithm.[6] LTTB is a highly optimized downsampling algorithm that mathematically reduces an N -point dataset to a highly manageable M -point dataset (e.g., from 50,000,000 to 5,000 points) while rigidly maintaining the exact visual fidelity and geometric shape of the underlying physical signal.[6]

9.1 Algorithmic Mechanics of LTTB

LTTB makes a deliberate computational trade-off, discarding strict statistical accuracy (like mean moving averages) in favor of visual shape preservation by evaluating relative geometric extremity.[6]

The algorithm operates through a strict bucketed procedure:

1. **Boundary Preservation:** The first and last points of the raw time-series dataset are definitively kept to preserve the absolute temporal bounds.[6]
2. **Bucket Division:** The remaining $N - 2$ points are divided evenly into $M - 2$ sequential data buckets.[6]

3. **Triangle Area Maximization:** For every central bucket i, the algorithm must select exactly one representative point. It evaluates every point in bucket i to determine which one forms the largest geometric triangle with two surrounding reference nodes:
    - Point A: The permanently selected point from the previous bucket ($i-1$).
    - Point C: The mathematical average of all data points in the upcoming bucket ($i+1$).[6]
    - Point B: The candidate point currently being evaluated in bucket i.

The area of the triangle formed by these three points is calculated rapidly using the standard absolute coordinate formula:

$$\text{Area} = \frac{1}{2}|x_A(y_B - y_C) + x_B(y_C - y_A) + x_C(y_A - y_B)|$$

By selecting the point B that maximizes this area, the algorithm inherently zeroes in on local maxima, minima, and steep inflection points.[6] When mapping the Pipino Kinematic Decay, LTTB perfectly captures the aggressive exponential descent at the simulation's origin without rounding the curve off, ensuring the visual representation of the universe's origin remains mathematically faithful to the theoretical physics. The algorithm operates in $\mathcal{O}(n)$ linear time, making it exceptionally fast to execute directly in TypeScript on the underlying Float64Array buffers before shipping the decimated array to the charting renderer.[6]

10. Conclusion

The comprehensive computational architecture detailed in this report realizes an extraordinarily robust mechanism for exploring speculative, non-standard cosmological models. By replacing the geometric scaling of the ΛCDM expanding spacetime metric with the algorithmic scaling of covariant variables—such as the Alfonso-Faus mass-boom effect, the Pipino kinematic speed of light decay, and the Gupta CCC+TL invariant stabilization—the physics engine mathematically isolates and resolves the deep thermodynamic paradoxes historically inherent in static-universe frameworks.[1]

Through the programmatic implementation of Proca electrodynamic modifications, the engine natively simulates the frequency dispersion of massive photons, successfully mapping the progressive phase transition of exhausted "tired light" into the cold, sub-luminal condensate classically labeled as dark matter.[3] This transition sets the stage for deeply complex macroscopic observer mechanics, constrained by the Minkowski momentum controversy, EIT dark-state polaritons, and Gordon metric interactions.[3]

Crucially, the success of this 15-billion-year simulation relies entirely on the precise bridging of theoretical physics with cutting-edge software engineering paradigms. Without the highly specific Runge-Kutta-Fehlberg (RKF45) adaptive integration protocol, the steep derivatives of deep-past dimensional constants would result in catastrophic floating-point collapse.[5] Without

the implementation of contiguous 64-bit chunked memory ArrayBuffers and multithreaded sharing, the immense temporal depth of the simulation would induce immediate V8 heap overflow.[7] Finally, without the Largest-Triangle-Three-Buckets (LTTB) algorithm mathematically decimating the data, the subtle, high-frequency physical phenomena generated by the engine would either be lost to statistical averaging or freeze the computational visualizer entirely.[6] Together, these strict, Test-Driven computational components provide a flawless, structurally sound engine capable of modeling and visualizing the most radical, boundary-pushing fringes of theoretical cosmology.

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