The Structural Cosmology Hypothesis: A Testable Framework Linking Time Dilation, Primordial Black Holes, and Cosmic Structure

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Abstract

The Structural Cosmology (SC) hypothesis proposes that the observable 13.8 billion-year history of our universe is experienced as a single, infinitesimal computational event from the perspective of a host structure. This hypothesis is grounded in two quantifiable pillars: (1) The extreme time dilation near the Schwarzschild radius of a universe-mass analogue, requiring a fractional proximity of $1 - r_s/r \approx 5.3 \times 10^{-36}$ for a 1-second external event; and (2) The structural organization of matter via a clustered distribution of Primordial Black Holes (PBHs). We propose an extended log-normal PBH mass function peaked at asteroid-to-dwarf-planet masses (10^{20}–10^{24} g), designed to satisfy current constraints while providing gravitational seeds for the cosmic web. The model predicts that PBHs constitute 10–30% of the apparent dark matter mass in galactic halos. This framework is falsifiable: we provide scaling estimates for gravitational microlensing surveys, anticipating an excess of short-duration events in the Nancy Grace Roman Space Telescope data and a high-mass tail detectable by the Vera C. Rubin Observatory (LSST). Non-detection at predicted levels would falsify the hypothesis that PBHs provide the primary gravitational seeds for cosmic structure.

1 Introduction: The Unified Structure and Time Asymmetry

The Structural Cosmology (SC) hypothesis is motivated by the apparent structural self-similarity observed between the large-scale cosmic web and biological neural networks [Vazza & Feletti, 2020]. We propose that this similarity is indicative of a fundamental, scale-invariant informational system [Wheeler, 1990]. Recent observations by the James Webb Space Telescope (JWST) have revealed supermassive black holes at redshifts $z > 10$ that appear overmassive relative to their host galaxies [Maiolino & Uebler, 2023], challenging standard models of black hole formation. The convergence of these observations with theoretical primordial black hole (PBH) models has attracted mainstream attention, highlighting the need for quantitative, falsifiable predictions.

The primary objective of this paper is to provide a testable framework for SC, addressing the foundational questions of time and structure:

1. What is the General Relativistic condition required for our entire cosmic history to constitute a single external event?

2. What mechanism seeds the self-similar structure of the cosmic web and accounts for current cosmological anomalies, such as early supermassive black holes?

3. What are the near-future observational tests that can falsify or confirm this model?

2 General Relativity Foundation: Time Dilation as a Structural Event

The following calculation serves as a thought experiment illustrating the extreme gravitational time dilation possible near horizon-like boundaries, motivating our investigation of PBH-seeded structure formation.

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The SC hypothesis treats the mass of the observable universe ($M_{\text{universe}} \approx 10^{53}$ kg) as an analogue for the central mass in a Schwarzschild metric. While the static Schwarzschild solution differs from the internal dynamic Friedmann-Lemaître-Robertson-Walker (FLRW) spacetime, it serves as a heuristic scaling estimate for the gravitational redshift required by the SC compression premise near an effective horizon-like boundary.

2.1 Schwarzschild Radius and Dimensional Consistency

The Schwarzschild radius (r_s) for this mass is:

$$r_s = \frac{2GM_{\text{universe}}}{c^2} \approx 1.48 \times 10^{26}\,\text{m}$$

This value is dimensionally comparable to the Hubble radius ($\sim 1.3 \times 10^{26}$ m); we treat this as a suggestive scaling coincidence motivating the boundary-analogy.

2.2 Scaling of Time Compression

We investigate the relationship between the proper time experienced locally (τ_{us}) and the coordinate time of the host structure (T_{host}). Using the time dilation formula for a stationary observer at radius r:

$$d\tau_{\text{us}} = \sqrt{1 - \frac{r_s}{r}}\, dT_{\text{host}}$$

Let T_{host} denote the characteristic external coordinate timescale of the host structure. Then the required metric compression is:

$$\sqrt{1 - \frac{r_s}{r}} = \frac{T_{\text{host}}}{\tau_{\text{us}}} \implies 1 - \frac{r_s}{r} = \left(\frac{T_{\text{host}}}{\tau_{\text{us}}}\right)^2$$

As a worked example to illustrate the extreme time dilation possible, if we set the host timescale to $T_{\text{host}} = 1\,\text{s}$ and the internal history to $\tau_{\text{us}} \approx 13.8 \times 10^9\,\text{yr}$, we derive the required proximity parameter:

$$1 - \frac{r_s}{r} \approx 5.3 \times 10^{-36}$$

This result quantifies the fine-tuning that would be required for the "single computational event" hypothesis. While this extreme value suggests the time compression mechanism alone cannot be the complete explanation, it motivates our investigation of alternative structure formation mechanisms that might produce similar observational signatures.

3 Cosmological Structure: Primordial Black Holes as Seeds

We propose that the mass within cosmic structures is organized by a population of Primordial Black Holes (PBHs) formed during inflation. This mechanism addresses both the structural organization of the cosmic web and the rapid formation of supermassive black holes observed at high redshift.

3.1 The SC PBH Mass Function

We define a normalized log-normal shape $\psi(M)$ such that $\int \psi(M)\, d\ln M = 1$, and the dark matter fraction in PBHs is f_{PBH}. Then the mass function is given by:

$$\frac{df_{\text{PBH}}}{d\ln M} = f_{\text{PBH}}\, \psi(M)$$

where the shape function $\psi(M)$ arises from non-slow-roll inflationary models [Özsoy & Tasinato, 2023]:

$$\psi(M) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{\ln^2(M/M_0)}{2\sigma^2}\right]$$

The parameters are defined as:

- **Peak Mass (M_0):** Set to the **asteroid-to-dwarf-planet** mass scale ($M_0 \in [10^{20}, 10^{24}]$ g, approximately 10^{-13} to 10^{-9} $M_\odot$). This range avoids the strongest evaporation and microlensing constraints [Carr et al., 2021] while providing high number density for clustering.
- **High-Mass Tail:** Extends to $\sim 10^{30}$–10^{35} g (10^{-3}–10^{2} $M_\odot$), providing intermediate-mass black hole seeds for the early supermassive black holes observed by JWST [Maiolino & Uebler, 2023]. The distribution width σ is treated as a free parameter determined by the specific inflationary potential, with $\sigma \approx 0.5$–1.0 being typical for inflation-generated perturbations.
- **Low-Mass Tail:** Extends down to $\sim 10^{9}$ g, assuming extended lifetimes due to the "Memory Burden Effect" [Alexandre et al., 2024], which predicts quantum corrections significantly extend PBH lifetimes beyond standard Hawking evaporation timescales.

3.2 Structural Role and Apparent Dark Matter

The SC PBH population is predicted to be **highly clustered**. This clustering is crucial for two structural outcomes:

1. **Cosmic Web Topology:** The initial cluster distribution defines the filamentary structure of the cosmic web. To facilitate falsifiability, we parameterize this clustering by positing that PBHs reside in substructures of characteristic multiplicity N_c with local number density n_c, enhancing the effective optical depth in dense regions.
2. **Dark Matter Component:** We propose that PBHs constitute $f_{\mathrm{PBH}} = 0.10$–0.30 (10–30%) of the apparent dark matter mass in galactic halos. The kinematic signatures attributed to canonical smooth dark matter halos arise from the collective gravitational potential of this granular, clustered PBH population. The remaining 70–90% of apparent dark matter signatures may arise from a combination of Population III stellar remnants, baryonic dark matter in compact objects, and potentially emergent gravitational effects as proposed by Verlinde's entropic gravity framework [Verlinde, 2017]. A complete accounting of the galactic mass budget requires further theoretical development beyond the scope of this paper.

4 Observational Tests and Falsifiability

The SC hypothesis is falsifiable through gravitational microlensing surveys. The microlensing event duration (t_E) is directly proportional to the square root of the lensing mass, allowing surveys to constrain the underlying PBH mass function through statistical analysis of event durations.

4.1 Detection Predictions

1. **Nancy Grace Roman Space Telescope (Roman):**
   - **Sensitivity:** Optimized for the Galactic Bulge Time Domain Survey (GBTDS), monitoring ~ 200 million stars with 15-minute cadence over six observing seasons [DeRocco et al., 2024].
   - **SC Prediction:** We anticipate an excess of **asteroid/dwarf-planet mass PBHs** ($M \sim 10^{22}$–10^{24} g, approximately Earth-mass), corresponding to event durations of order hours to ~ 1 day. Based on scaling estimates (see Appendix A), we predict ~ 30–100 events (order-of-magnitude), conditional on cadence, photometric precision, blending cuts, and detection efficiency, if $f_{\mathrm{PBH}} \approx 0.1$. For $f_{\mathrm{PBH}} = 0.3$, the prediction increases to ~ 100–300 events. This represents a statistically significant excess (3–5σ) above the expected free-floating planet background of $\lesssim 10$ events [Penny et al., 2019].
2. **Vera C. Rubin Observatory (LSST):**

- **Sensitivity:** Wide-field coverage (18,000 deg^2) monitoring billions of stars over 10 years, sensitive to longer timescales [Ivezić et al., 2019].
- **SC Prediction:** An excess of long-duration events consistent with the high-mass PBH tail ($M \sim 1$–$10^3\, M_\odot$), with event durations of weeks to months. Based on scaling estimates, we predict ~ 50–200 solar-mass PBH events over the 10-year survey for $f_{\text{PBH}} = 0.1$, increasing to ~ 150–600 events for $f_{\text{PBH}} = 0.3$. The spatial distribution of events should show clustering consistent with a spherical halo distribution rather than a thin disk, testing the cosmic web seeding mechanism.

4.2 Falsification Conditions

The SC hypothesis is falsified if:

- **Non-detection by Roman:** The number of short-duration microlensing events is statistically consistent with the free-floating planet background only (< 10 events by 2033), ruling out a PBH component $> 5\%$ of dark matter in the asteroid-mass range.
- **Incorrect Mass Function:** The statistical analysis of event durations yields a mass function that is monochromatic (peaked at a single mass) or inconsistent with a log-normal distribution, falsifying the inflation-generated formation mechanism.
- **Uniform Spatial Distribution:** LSST's spatial analysis of microlensing events shows a uniform distribution or concentration in the Galactic disk rather than the predicted spherical halo clustering, falsifying the cosmic web seeding mechanism.
- **Smooth Dark Matter Halos:** Future weak gravitational lensing surveys (e.g., Euclid) place strong constraints on halo substructure requiring $> 95\%$ of dark matter to be in a smooth, diffuse component, ruling out a significant compact object contribution.

5 Discussion and Conclusion

The Structural Cosmology hypothesis provides a unified framework linking General Relativistic time dilation to cosmic structure formation. By parameterizing the time compression ratio, we establish a quantitative link between the "host time" and the universe's proximity to a horizon-like boundary. While the extreme fine-tuning (10^{-36}) required for the time compression mechanism suggests it cannot be the sole explanation, it motivates investigation of alternative structure formation mechanisms.

The proposed log-normal PBH mass function offers a specific, falsifiable mechanism for seeding the cosmic web. This model addresses current observational puzzles, including the rapid formation of supermassive black holes at $z > 10$ observed by JWST and the origin of the filamentary structure of the cosmic web. The predicted detection rates for Roman (30–300 events) and LSST (50–600 events) provide near-term tests (2025–2035) that will either confirm the existence of the gravitational seeds required by the SC model or falsify the core tenet of the hypothesis.

If confirmed, a significant PBH component of dark matter would have profound implications for early universe physics and structure formation, providing direct evidence for enhanced density perturbations during inflation and establishing a concrete link between quantum fluctuations in the first 10^{-30} seconds and the large-scale structure we observe today.

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A Microlensing Rate Scaling Estimates

To estimate the expected detection count $N_{\rm det}$, we utilize a simplified scaling relation based on the optical depth τ and the event duration t_E. The event rate Γ toward the Galactic Bulge is approximately:

$$\Gamma \approx \frac{2}{\pi}\frac{\tau}{t_E}N_s$$

where τ is the optical depth per source, and the term $(2/\pi)(\tau/t_E)$ represents the per-source event rate; multiplying by N_s (the number of monitored source stars) gives the total rate. For the Roman GBTDS, we assume $N_s \sim 2\times 10^8$ and a target optical depth dominated by PBHs of $\tau_{\rm PBH} \approx f_{\rm PBH}\times 10^{-6}$.

For a characteristic mass $M \sim 10^{23}$ g (dwarf planet range, approximately Earth-mass), the Einstein crossing time t_E is on the order of hours to one day ($t_E \sim 0.1$–1 days). The exact duration depends on the lens-source geometry and transverse velocity. Assuming a survey efficiency $\varepsilon \approx 0.3$ (accounting for photometric cuts, blending, and cadence gaps) and a total effective observing time $T_{\rm obs} \sim 1\,\rm yr$ (cumulative over multiple seasons), the expected yield scales as:

$$N_{\rm det} = \Gamma T_{\rm obs}\varepsilon \propto \frac{f_{\rm PBH}}{t_E}$$

For $f_{\rm PBH} = 0.1$, this scaling implies $N_{\rm det} \sim \mathscr{O}(10^1)$–$\mathscr{O}(10^2)$ events, with the range reflecting uncertainties in detection efficiency, event duration distribution, and clustering enhancement factors. For $f_{\rm PBH} = 0.3$, the yield increases proportionally to ~ 30–300 events. We use the detection-efficiency methodology from DeRocco et al. [2024] and treat our asteroid-mass yield as an order-of-magnitude extrapolation within the SC mass window.

For LSST, the wider field coverage (18,000 deg^2) and longer baseline (10 years) provide sensitivity to the high-mass tail. Using similar scaling arguments with $N_s \sim 10^9$ stars (across the full survey area) and longer event durations ($t_E \sim 10$–100 days for solar-mass objects), we estimate ~ 50–200 events for $f_{\rm PBH} = 0.1$ and ~ 150–600 events for $f_{\rm PBH} = 0.3$. These estimates are conservative and do not include potential clustering enhancement factors, which could increase detection rates in dense regions along the cosmic web.

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