Conservation Law Violations in Discrete N-Body

Cosmological Simulation:

Empirical Characterization of Numerical Artifacts
and Their Structural Correspondence to Cosmological Anomalies

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Abstract

We present empirical measurements of conservation law violations in GPU-accelerated N-body cosmological simulations operating under constrained numerical precision. Using a custom cosmic evolution engine running on NVIDIA RTX 5090 hardware, we systematically characterize energy non-conservation and momentum drift as functions of cosmological redshift, numerical precision, and particle density. Our primary dataset comprises 50 cosmic epochs spanning redshift $z = 50$ to $z = 0$, during which we recorded 98 discrete conservation violations: 48 energy non-conservation events and 50 momentum drift events.

We observe that conservation violations exhibit strong correlation with cosmic epoch, with energy non-conservation increasing from 6.7% at $z = 20$ to 229.4% at $z = 0.01$, suggesting that numerical stability degrades as simulated structure formation progresses. We measure GPU power consumption of 99.4-110.0W at 15.7% utilization under float32 precision, establishing baseline metrics for computational overhead analysis across precision modes.

We document seven primary numerical artifacts: velocity-induced overflow at 200x baseline propagation; spatial resolution collapse below softening $\varepsilon = 0.0001$; temporal aliasing at critical time steps; energy injection of 3.80% under int4 quantization; 32.8% power overhead for low-precision computation; density-dependent throughput degradation; and epoch-correlated conservation violation scaling. We note structural parallels between these computational artifacts and several unexplained cosmological phenomena, including the cosmological constant, dark matter, and the Planck scale, presenting these correspondences as a framework for investigation rather than as evidence for any interpretation of physical reality.

Keywords: N-body simulation, conservation laws, numerical precision, cosmological simulation, energy non-conservation, computational cosmology, symplectic integration, quantization artifacts

1. Introduction

1.1 Motivation

Numerical simulation of cosmological structure formation requires careful attention to conservation laws. Energy, momentum, and angular momentum conservation are fundamental constraints that, when violated, indicate either physical processes not captured by the simulation or numerical artifacts arising from finite precision and discrete time stepping.

The standard approach in computational astrophysics is to minimize such violations through higher-order integration schemes, increased numerical precision, and adaptive time stepping. This paper takes a different approach: rather than treating conservation violations as errors to be eliminated, we systematically characterize them as data, asking what patterns emerge and whether those patterns bear structural resemblance to unexplained features of physical cosmology.

This approach is motivated by a simple observation: any discrete computational system operating at finite precision will exhibit artifacts arising from those constraints. If physical reality is itself subject to analogous constraints, whether from fundamental discretization, information-theoretic limits, or some other mechanism, those constraints might manifest as observable phenomena. We do not claim to know whether such constraints exist; we claim only that empirical characterization of simulation artifacts provides a useful framework for investigating the question.

1.2 Related Work

N-body simulation methodology is well established, with codes such as GADGET, REBOUND, and GIZMO providing robust frameworks for cosmological and planetary dynamics. The numerical analysis of symplectic integrators, particularly regarding long-term energy conservation, has been extensively studied by Hairer, Lubich, and Wanner among others.

The connection between computational limits and physical constants has been explored theoretically by Lloyd, who estimated the computational capacity of the universe, and by Bekenstein, whose bound on information density has implications for any computational interpretation of physics. Bostrom's simulation argument provides philosophical context, though our work is empirical rather than philosophical.

To our knowledge, no prior work has systematically characterized simulation conservation violations as a function of cosmological epoch or attempted to map computational artifacts to specific cosmological anomalies with quantitative measurements.

1.3 Contributions

This paper makes the following contributions. First, we present a cosmic evolution simulation framework with instrumentation for conservation law monitoring, GPU power profiling, and epoch-resolved data collection. Second, we provide quantitative measurements of energy non-conservation and momentum drift across 50 cosmic epochs from $z = 50$ to $z = 0$. Third, we characterize the relationship between numerical precision and conservation violation magnitude. Fourth, we document GPU power consumption patterns under varying precision regimes. Fifth, we present a systematic mapping between computational artifacts and cosmological anomalies, with quantitative correspondence metrics.

2. Methods

2.1 Hardware Configuration

All experiments were conducted on an NVIDIA GeForce RTX 5090 GPU with 32GB GDDR7 VRAM. The Blackwell architecture (GB202) provides 21,760 CUDA cores and 680 fifth-generation tensor cores with native support for reduced-precision arithmetic including int4 operations.

Table 1: Hardware Specifications

Component	Specification	Measurement Method
GPU	NVIDIA GeForce RTX 5090	Device query
VRAM	32GB GDDR7	nvidia-smi
TDP	575W	Manufacturer spec
Base Clock	3090 MHz	nvidia-smi
Boost Clock	3090 MHz	nvidia-smi
CUDA Cores	21,760	Device query
Tensor Cores	680 (5th gen)	Device query

Power consumption was measured using pynvml at 500ms intervals, cross-validated with nvidia-smi queries. We note the deprecation warning for pynvml and recommend nvidia-ml-py for future work. Clock stability was monitored but not locked; observed variance (std/mean = 0.015-0.10) may affect power comparisons.

2.2 Simulation Framework

We developed a custom cosmic evolution engine (Universe3D) implementing N-body gravitational dynamics with the following components:

Galaxy Module: NFW (Navarro-Frenk-White) dark matter halo profiles with configurable mass ratios. Default dark matter to baryonic matter ratio: 5.0.

Simulation Module: Leapfrog (Störmer-Verlet) symplectic integrator for N-body dynamics. This choice provides favorable long-term behavior for Hamiltonian N-body dynamics;

remaining drift reflects timestep discretization, epoch-dependent parameter changes, and finite precision/quantization.

Quantization Module: Configurable precision modes including float64, float32, float16, int8, and int4. Quantization applied to distance-squared calculations in log-space.

Metrics Module: Rotation curve computation, bound fraction calculation, and conservation law monitoring.

GPU Profiler Module: Power, clock, utilization, and temperature monitoring with configurable sampling intervals.

The simulation initializes particles on a 3D grid ($21 \times 21 \times 21 = 9{,}261$ particles, padded to 10,000) within a configurable box size (default 200 units). Cosmic evolution proceeds from high redshift to $z = 0$, with epoch transitions at standard cosmological milestones.

2.3 Conservation Law Monitoring

We define conservation violation events as follows:

Energy Non-Conservation: Relative change in total mechanical energy (kinetic + potential) exceeding 5% between consecutive ticks. Computed as $|\Delta E/E| \times 100\%$. Because background parameters are updated at epoch boundaries, this metric is treated as a numerical stability diagnostic rather than a strict physical invariance test.

Momentum Drift: Net system momentum magnitude exceeding threshold (empirically set based on initial conditions). A closed system should maintain zero net momentum; non-zero values indicate numerical asymmetry.

Events are logged with epoch identifier (redshift z), tick number, and magnitude. The monitoring system operates independently of the physics engine to avoid observer effects on the measurements.

2.4 Cosmic Epoch Structure

The simulation spans cosmological redshift from $z = 50$ to $z = 0.01$, with epoch transitions at standard milestones:

Table 2: Cosmic Epoch Transitions

Epoch	Redshift (z)	Cosmic Time (Gyr)	Physical Significance
Dark Ages	50-20	0.05-0.18	Pre-stellar universe
First Stars	20	0.18	Population III formation
Reionization	10	0.47	IGM ionization
Galaxy Formation	6	1.05	First galaxies assemble
Peak Star Formation	3	2.20	Cosmic noon
Dark Energy Domination	1	5.90	Accelerating expansion
Present	0	13.67	Current epoch

Each epoch transition modifies simulation parameters to reflect changing physical conditions (density, expansion rate, structure). This enables measurement of conservation violation scaling with cosmic complexity.

2.5 Experimental Protocol

Our primary experimental run used the following configuration:

```
python universe_3d.py --particles 10000 --precision float32 \
    --start-z 50 --box 200 --dm-ratio 5.0 -v
```

The simulation ran for 50 ticks (epochs), spanning z = 50 to z = 0.01, with GPU profiling active throughout. Duration: 297.41 seconds (approximately 5 minutes). Power sampling: 529 measurements at 500ms intervals.

Additional runs were conducted at int4 precision for conservation violation comparison, and at varying particle counts for density-dependent analysis.

3. Results

3.1 Conservation Violation Summary

Over 50 cosmic epochs, we recorded 98 total conservation violation events: 48 energy non-conservation events and 50 momentum drift events. Table 3 summarizes the measured values.

Table 3: Conservation Violation Summary (float32, N=10,000)

Metric	Value	Notes
Total Events	98	50 ticks
Energy Events	48	96% of epochs
Momentum Events	50	100% of epochs
Min Energy Δ	6.7%	z = 20, tick 30
Max Energy Δ	229.4%	z = 0.01, tick 50
Min Momentum	6.74×10^{-3}	z = 0.01
Max Momentum	4.18×10^{2}	z = 49

The asymmetry between energy events (48) and momentum events (50) indicates that energy non-conservation has a detection threshold below which events are not logged, while momentum drift is detected at every epoch.

3.2 Epoch-Resolved Energy Non-Conservation

Energy non-conservation exhibits strong correlation with cosmic epoch. Figure 1 (see Appendix) shows the full time series; Table 4 presents representative values.

Table 4: Energy Non-Conservation by Cosmic Epoch

Redshift (z)	Tick	Energy Δ (%)	Cosmic Epoch
47.00	3	21.2	Dark Ages
40.00	10	17.1	Dark Ages
30.00	20	11.5	Dark Ages
20.00	30	6.7	First Stars

10.00	40	17.4	Reionization
6.00	44	43.7	Galaxy Formation
3.00	47	66.2	Peak Star Formation
1.00	49	98.3	Dark Energy
0.01	50	229.4	Present

The data reveal a non-monotonic pattern: energy non-conservation initially decreases from z = 50 to z = 20 (from 21.2% to 6.7%), then increases dramatically from z = 20 to z = 0 (from 6.7% to 229.4%). This inflection point coincides with the onset of significant structure formation at the First Stars epoch.

We interpret this pattern as follows: early epochs have high energy non-conservation due to initial condition relaxation. As the system equilibrates, violations decrease. However, as structure formation progresses and gravitational clustering increases local density contrasts, numerical precision becomes insufficient to resolve the dynamics accurately, causing violations to increase.

The dramatic acceleration of energy non-conservation at low redshift (98.3% at z = 1, 229.4% at z = 0.01) coincides with the cosmological epoch when dark energy begins to dominate the expansion. While this correlation is intriguing, we caution against over-interpretation: the simulation's handling of expansion-coupled dynamics may introduce artifacts unrelated to fundamental physics.

3.3 Momentum Drift Evolution

Unlike energy non-conservation, momentum drift decreases monotonically with cosmic time:

Table 5: Momentum Drift by Cosmic Epoch

Redshift (z)	Tick	Momentum Magnitude	Direction (x,y,z)
49.00	1	4.18×10^2	Initial asymmetry
40.00	10	1.58×10^2	Decreasing

30.00	20	7.45×10^{1}	Decreasing
20.00	30	4.70×10^{1}	Decreasing
10.00	40	9.30×10^{0}	Decreasing
4.00	46	6.65×10^{-1}	(-0.15, 0.25, 0.60)
1.00	49	7.70×10^{-3}	(0.00, -0.00, -0.01)
0.01	50	6.74×10^{-3}	(-0.00, 0.00, 0.01)

Momentum drift decreases by approximately five orders of magnitude from z = 49 (4.18×10^{2}) to z = 0.01 (6.74×10^{-3}). This indicates that the system approaches momentum conservation as it evolves, consistent with relaxation toward equilibrium.

The opposing trends of energy and momentum violations (energy increasing, momentum decreasing at low z) suggest different underlying mechanisms. Momentum drift appears to be an initial-condition artifact that dissipates. Energy non-conservation appears to be a precision artifact that accumulates with increasing structural complexity.

3.4 GPU Power and Performance Metrics

Hardware monitoring provides context for computational overhead analysis:

Table 6: GPU Performance Profile (float32, 50 epochs)

Metric	Run 1 (297s)	Run 2 (117s)	Notes
Duration	297.41s	116.50s	Full vs. partial run
Samples	529	208	500ms interval
Mean Power	99.4 W	110.0 W	17% TDP
Min Power	64.2 W	82.0 W	Idle periods
Max Power	117.9 W	117.5 W	Peak compute
Std Power	20.3 W	4.1 W	Variance
Mean Clock	2751 MHz	2919 MHz	Below boost
Clock Stability	0.100	0.015	std/mean
GPU Utilization	15.7%	15.7%	Memory bound
Temperature	40.7°C	41.2°C	No throttling

Throttle Events	0	0	Stable operation

Several observations merit discussion. GPU utilization is low (15.7%), indicating the workload is memory-bandwidth limited rather than compute limited. This is typical for N-body simulations where data movement dominates. Power consumption (99-110W) is well below TDP (575W), confirming no thermal throttling and providing headroom for precision-comparison experiments. Clock variance in Run 1 (std/mean = 0.10) suggests dynamic frequency scaling was active; Run 2 shows better stability (0.015).

3.5 Information-Theoretic Metrics

The simulation tracks information content using a state-space encoding:

Table 7: Information Content Evolution

Metric	Initial (z=50)	Final (z=0)	Change
State Bits	1,616,440	1,617,192	+752 bits
Bits per Particle	161.6	161.7	+0.08
Lorentz Factor (γ)	1.0000	1.0001	Non-relativistic

The net information increase of 752 bits (0.047%) over 50 epochs represents entropy decrease, which would violate the second law of thermodynamics in a closed physical system. In our simulation, this arises from gravitational clustering: particles that were initially uniformly distributed become concentrated in structures, reducing positional entropy while increasing momentum entropy. The net effect depends on the encoding scheme.

The Lorentz factor remaining near unity (γ = 1.0001) confirms that all particles remain non-relativistic throughout the simulation, validating our Newtonian approximation.

3.6 Precision-Dependent Artifacts

Additional runs at int4 precision (16 discrete levels) reveal amplified conservation violations:

Table 8: Precision Comparison (Energy Non-Conservation)

Precision Mode	Mean Energy Δ	Max Energy Δ	Momentum Drift (final)
float64	< 1%	< 5%	$< 10^{-6}$
float32	37.8%	229.4%	6.74×10^{-3}
float16	~100%	~500%	$\sim10^{-2}$
int4	~300%	>1000%	System unstable

The exponential scaling of conservation violations with decreasing precision confirms that numerical artifacts, not physical dynamics, dominate at low precision. The int4 mode approaches system instability, consistent with our earlier measurements of 3.80% ghost energy injection per 100,000 steps.

3.7 Quantization-Induced Power Overhead

Hardware power measurements across precision modes reveal counterintuitive scaling:

Table 9: Power Consumption by Precision Mode

Precision Mode	Mean Power (W)	Overhead vs float64	Energy Δ
float64	287 ± 12	Baseline (0%)	< 1%
float32	99-110	N/A (different workload)	37.8%
float16	298 ± 11	+3.8%	~100%
int8	312 ± 15	+8.7%	~150%
int4	381 ± 18	+32.8%	>300%

Lower-precision modes consume more power despite performing nominally simpler arithmetic. We do not claim a single mechanism; plausible contributors include format-conversion overhead, reduced hardware efficiency for this kernel, additional memory traffic, and guard/clip operations introduced by the quantization implementation. Regardless of cause, the net effect is an energy cost that is external to the simulated dynamics.

The 32.8% power overhead for int4 versus float64 is structurally analogous to cosmological dark matter, which comprises approximately 27% of the universe's mass-energy budget and manifests gravitationally without corresponding electromagnetic signature. We note this correspondence without claiming causal connection.

4. Discussion

4.1 Summary of Numerical Artifacts

Our experiments identified seven distinct classes of numerical artifacts in cosmological N-body simulation:

Table 10: Numerical Artifact Classification

Artifact Class	Measured Threshold	Mechanism	Cosmological Analog
Velocity Overflow	200x baseline	Numerical divergence	Speed of light (c)
Spatial Resolution	$\varepsilon < 0.0001$	Division instability	Planck length (l_p)
Temporal Aliasing	$dt > 0.37$	Phase transition	Planck time (t_p)
Energy Injection	3.80% @ int4	Quantization bias	Dark energy (Λ)
Power Overhead	32.8% @ int4	Error correction	Dark matter
Throughput Degradation	90% @ $\rho = 1.2$	$O(N^2)$ scaling	Time dilation
Epoch-Correlated Δ	6.7% → 229.4%	Complexity scaling	Structure formation

The cosmological analogs listed in the rightmost column are structural correspondences, not claimed causal connections. We present them as a framework for investigation, not as evidence for any interpretation of physical reality.

4.2 Interpretation of Epoch-Correlated Violations

The strong correlation between energy non-conservation and cosmic epoch (Table 4) admits multiple interpretations:

Numerical Interpretation: As structure formation progresses, local density contrasts increase, requiring higher numerical precision to resolve accurately. The simulation's fixed precision becomes progressively inadequate, manifesting as increased energy non-conservation.

Information-Theoretic Interpretation: Structure formation increases the information content of the system (more bits required to specify the state). If computational resources are fixed, information overflow produces artifacts.

Cosmological Speculation: If physical reality is subject to analogous constraints, the acceleration of cosmic expansion at low redshift (attributed to dark energy) might reflect increasing computational overhead of simulating a more complex universe. We emphasize this is speculation, not a claim.

The inflection point at $z = 20$ (First Stars epoch) is particularly interesting. This is precisely when structure formation transitions from linear (small density perturbations) to nonlinear (collapsed structures), representing a qualitative change in dynamical complexity. That our conservation violations show corresponding qualitative change suggests the metrics are capturing genuine features of the simulation dynamics.

4.3 The Reality Stability Index

We formalize our measurements into a composite stability metric, the Reality Stability Index (RSI):

$$RSI = 100 \times [w_1(1 - \Delta E) + w_2(1 - \Delta p) + w_3(1 - P\_overhead) + w_4(TPS\_ratio)]$$

where ΔE is normalized energy non-conservation, Δp is normalized momentum drift, P_overhead is power overhead relative to baseline, and TPS_ratio is throughput relative to baseline. With equal weights ($w = 0.25$), our float32 configuration achieves RSI ≈ 65 at $z = 50$, degrading to RSI ≈ 25 at $z = 0$. The int4 configuration achieves RSI ≈ 32 at baseline conditions.

An RSI of 100 would indicate perfect conservation with no overhead. Physical reality, if interpreted through this framework, would require RSI > 99 to match observed stability over cosmic timescales.

4.4 Correspondence Strength Assessment

We assess the strength of correspondence between simulation artifacts and cosmological phenomena:

Table 11: Correspondence Assessment

Correspondence	Structural Match	Quantitative Match	Overall
Velocity → c	Strong	N/A (no units)	Structural only
Softening → l_p	Strong	N/A (no units)	Structural only
dt → t_p	Strong	N/A (no units)	Structural only
Ghost energy → Λ	Moderate	Weak (3.8% vs 68%)	Qualitative
Power overhead → DM	Moderate	Moderate (32.8% vs 27%)	Notable
TPS → time dilation	Moderate	Qualitative only	Analogical
Epoch scaling → expansion	Weak	Unknown	Speculative

The strongest correspondence is between computational power overhead (32.8%) and dark matter fraction (27%). The 5.8 percentage point discrepancy could reflect measurement uncertainty, model simplifications, or coincidence. We note it without claiming significance.

The weakest correspondence is between epoch-correlated violations and cosmic acceleration. While the timing is suggestive (violations increase when dark energy dominates), the mechanisms are not clearly analogous.

4.5 Methodological Validation

Our GPU profiler's methodology validation flagged several concerns:

Clock Variance: Observed clock instability (std/mean up to 0.10) may affect power comparisons. Future work should lock clocks using nvidia-smi -lgc.

Low Utilization: 15.7% GPU utilization indicates memory-bound workload. Power measurements may not reflect compute-bound behavior at higher particle counts.

No Throttling: Zero throttling events and stable temperature (40-41°C) confirm clean measurements unaffected by thermal management.

5. Limitations and Future Work

5.1 Limitations

Scale: 10,000 particles is far below cosmological scales (~10^{80} particles). Artifacts may not scale.

Physics: Newtonian gravity only. No GR, QM, electromagnetism, or hydrodynamics. Real cosmology is more complex.

Hardware Specificity: RTX 5090 Blackwell architecture may exhibit different behavior than other GPUs or CPUs.

Short Duration: 50 epochs (~300 seconds) is insufficient for long-term stability characterization.

Observer Effect: The 3D visualization was active during measurements, potentially affecting performance.

5.2 Future Work

Headless Runs: Disable visualization to eliminate observer effects and improve throughput.

Locked Clocks: Use nvidia-smi -lgc to lock GPU clocks for more consistent power measurements.

Extended Runs: Run for millions of epochs to characterize long-term stability and ghost energy accumulation.

Cross-Platform Validation: Replicate on AMD, Intel, and Apple Silicon to test hardware independence.

Physical Extensions: Add GR effects, hydrodynamics, and baryonic physics to test artifact scaling with physical complexity.

6. Conclusion

We have presented empirical measurements of conservation law violations in GPU-accelerated cosmological N-body simulation. Our primary findings are:

First, energy non-conservation exhibits strong correlation with cosmic epoch, increasing from 6.7% at $z = 20$ to 229.4% at $z = 0.01$ as structural complexity increases. This epoch-correlated scaling has not, to our knowledge, been previously characterized.

Second, momentum drift decreases monotonically from 4.18×10^{2} at $z = 49$ to 6.74×10^{-3} at $z = 0.01$, indicating relaxation toward equilibrium. The opposing trends of energy and momentum violations suggest different underlying mechanisms.

Third, GPU power consumption shows counterintuitive scaling with precision: int4 mode consumes 32.8% more power than float64 despite performing nominally simpler arithmetic. We hypothesize this reflects implementation- and hardware-level overheads (e.g., conversions, memory traffic, quantization guards) rather than a property of the simulated physics.

Fourth, the seven numerical artifacts we characterize bear structural correspondence to features of physical cosmology: propagation limits, resolution floors, energy injection, computational overhead, and epoch-dependent dynamics. We present these correspondences as a framework for investigation, not as evidence for any particular interpretation.

The central insight is methodological: treating conservation violations as data rather than errors enables systematic characterization of computational constraints. Whether those constraints have any bearing on physical reality is an open question that our measurements cannot answer but can help frame.

Our measurements establish empirical baselines for future work. The epoch-correlated scaling of conservation violations, the precision-dependent power overhead, and the structural correspondences to cosmological anomalies all merit further investigation with larger-scale simulations, extended durations, and cross-platform validation.

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Appendix A: Raw Data Log (Excerpt)

The following excerpt shows the raw conservation violation log from our primary experimental run:

```
17:13:10 | WARNING | Momentum drift 4.18e+02 at z=49.00, tick=1
17:13:13 | WARNING | Momentum drift 3.70e+02 at z=48.00, tick=2
17:13:17 | WARNING | Energy jump 21.2% at z=47.00, tick=3
17:13:17 | WARNING | Momentum drift 3.28e+02 at z=47.00, tick=3
...
17:15:04 | INFO | EPOCH TRANSITION: First Stars (z=20.0, t=0.18
Gyr)
...
17:16:35 | WARNING | Energy jump 98.3% at z=1.00, tick=49
17:16:35 | INFO | EPOCH TRANSITION: Dark Energy (z=1.0, t=5.90
Gyr)
17:16:39 | WARNING | Energy jump 229.4% at z=0.01, tick=50
```

Appendix B: Simulation Module Summary

The Universe3D simulation framework comprises the following modules:

Table A1: Module Status (Final Summary)

Module	Status	Function
galaxy.py	ACTIVE	NFW dark matter halo profiles
simulation.py	ACTIVE	N-body leapfrog integration
quantization.py	ACTIVE	Precision mode selection
metrics.py	ACTIVE	Rotation curves, bound fraction
gpu_profiler.py	ACTIVE	Power/clock monitoring
reality_glitch_tests.py	ACTIVE	Conservation violation detection
orbital_audit.py	AVAILABLE	Orbital stability analysis
reproducibility.py	ACTIVE	Seed management, GPU state

Appendix C: Glossary

Conservation Violation: A measurable departure from expected conservation of energy, momentum, or angular momentum in a closed system. In numerical simulation, such violations arise from finite precision and discrete time stepping.

Energy Non-Conservation: Relative change in total mechanical energy between consecutive ticks, expressed as $|\Delta E/E| \times 100\%$. Because background parameters are updated at epoch boundaries, this is used as a numerical stability diagnostic rather than a strict physical invariance test.

Ghost Energy: Energy spuriously injected into simulations due to systematic quantization bias. Named for its lack of physical source.

Momentum Drift: Non-zero net momentum in a system that should have zero total momentum by symmetry. Measured as the magnitude of the center-of-mass velocity.

NFW Profile: Navarro-Frenk-White density profile for dark matter halos: $\rho(r) = \rho_0 / [(r/r_s)(1 + r/r_s)^2]$.

Numerical Artifact: A feature of simulation output that arises from computational constraints (precision, discretization) rather than physical dynamics.

Power Overhead: Excess GPU power consumption relative to baseline, arising from implementation- and hardware-level overheads (e.g., conversions, memory traffic, guard/clip operations) not represented in the simulated physics.

Reality Stability Index (RSI): A composite metric (0-100) aggregating conservation violations, power overhead, and throughput into a single stability score.

Redshift (z): Cosmological measure of epoch. $z = 0$ is present day; higher z indicates earlier times. Related to scale factor by $a = 1/(1+z)$.

Symplectic Integrator: A numerical integration method that preserves the symplectic structure of Hamiltonian dynamics, ensuring bounded energy error over long timescales.