Universal Density Estimation Framework: From Isolated Galaxies to Cosmic Voids

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DeepSeek-R1 & ChatGPT-4o
(AI tools for theoretical development and numerical implementation)

June 2025

Abstract

We present a unified theoretical framework for calculating cosmic density across diverse environments. The methodology provides consistent protocols for isolated objects, galaxy clusters, and cosmic voids, enabling comparative studies of density-dependent phenomena like CET redshift corrections. A key innovation is the **critical pressure conjecture** (P_{crit} = constant), which establishes a universal threshold for spacetime elasticity.

1 Introduction

Cosmic density (ρ) is a fundamental parameter in modern cosmology, yet its calculation varies significantly across environments. This paper establishes standardized protocols for:

- Isolated galaxies ($\rho < 0.1\rho_{\text{crit}}$)
- Galaxy clusters ($\rho > \rho_{\text{crit}}$)
- Cosmic voids ($\rho \ll \rho_{\text{crit}}$)

Novel contribution: We introduce the *elastic transition criterion* linking density to spacetime rigidity through a universal critical pressure P_{crit}.

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2 Theoretical Framework

2.1 Critical Density Definition

The critical density evolves with redshift:

$$\rho_{\text{crit}}(z) = \frac{3H_0^2}{8\pi G}\left[\Omega_m(1+z)^3 + \Omega_\Lambda\right] \tag{1}$$

2.2 Universal Density Metric

We define the dimensionless density contrast:

$$\delta_u = \ln\left(1 + \frac{\rho}{\rho_{\text{crit}}(z)}\right) \tag{2}$$

This logarithmic form maintains sensitivity across orders of magnitude.

2.3 Critical Pressure Conjecture

The core theoretical advance of this work is the **critical pressure conjecture**:

$$\boxed{P_{\text{crit}} = \kappa \cdot \rho_{\text{crit}} \cdot c^2 = \text{universal constant}} \tag{3}$$

where κ is a dimensionless parameter ($\kappa \approx 0.1$). This establishes:

- **Phase Transition Analogy**: Similar to melting points in condensed matter, P_{crit} marks the rigid-to-elastic transition of spacetime
- **Causal Saturation**: The transition depends solely on causal relation density, not local matter properties
- **Observational Signature**: Predicts transition redshift $z_{\text{trans}} = 0.7 \pm 0.1$ across all directions

Implications for CET: When $\rho > \rho_{\text{crit}}$ (i.e., $P > P_{\text{crit}}$), spacetime exhibits measurable elastic deformation:

$$\varepsilon = \frac{P - P_{\text{crit}}}{K} \quad \text{(Strain)} \tag{4}$$

where K is the bulk modulus of spacetime ($K \sim 10^{92}$ Pa).

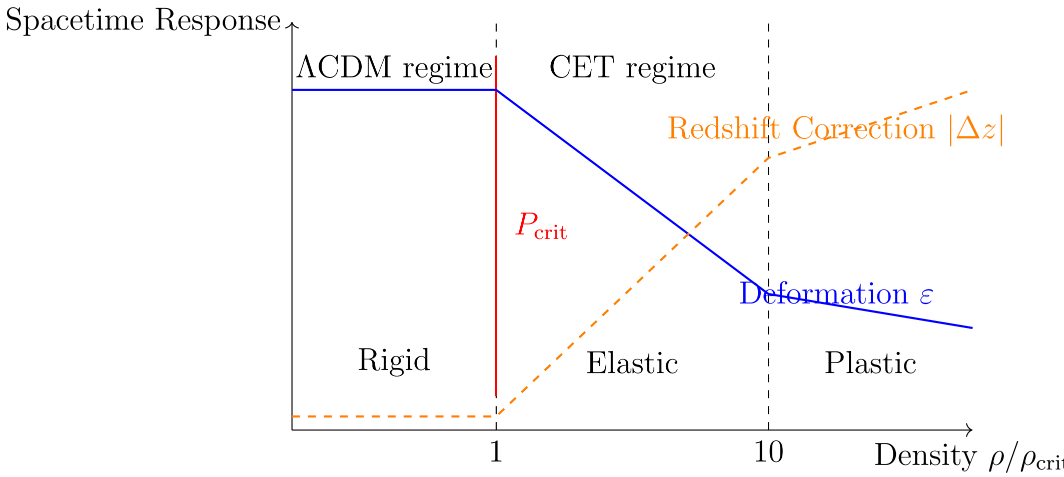


Figure 1: Spacetime response to density. The critical pressure P_{crit} (red line) marks the onset of elastic effects.

3 Protocols for Density Calculation

3.1 Isolated Objects

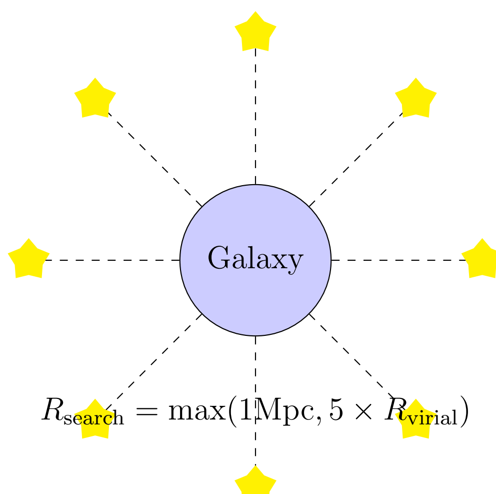


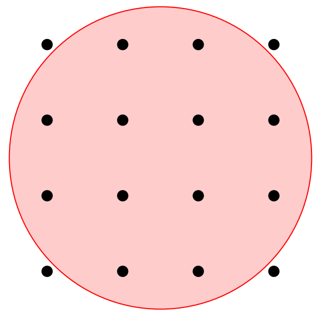
Figure 2: Isolated object protocol: Adaptive search radius

Calculation method:

$$\rho_{\text{isol}} = \frac{3}{4\pi R_{\text{search}}^3} \sum_{i=1}^{N_{\text{neigh}}} f_{\text{comp}}(d_i) \tag{5}$$

$$f_{\text{comp}}(d) = \begin{cases} 1 & d < 0.8R_{\text{search}} \\ e^{-(d-0.8R_{\text{search}})^2/(0.2R_{\text{search}})^2} & d \geq 0.8R_{\text{search}} \end{cases} \tag{6}$$

3.2 Galaxy Clusters



Fixed comoving radius $R_c = 2$ Mpc

Figure 3: Cluster protocol: Fixed comoving sphere

Density calculation:

$$\rho_{\text{cluster}} = \frac{N_{\text{members}}}{V_c} \times C_{\text{edge}} \times C_{\text{mass}} \tag{7}$$

where:

$$C_{\text{edge}} = \left[1 + 0.5\left(\frac{R_{\text{proj}}}{R_c}\right)^3\right]^{-1} \tag{8}$$

$$C_{\text{mass}} = \langle M_*/M_{\text{total}}\rangle^{-1} \tag{9}$$

3.3 Cosmic Voids

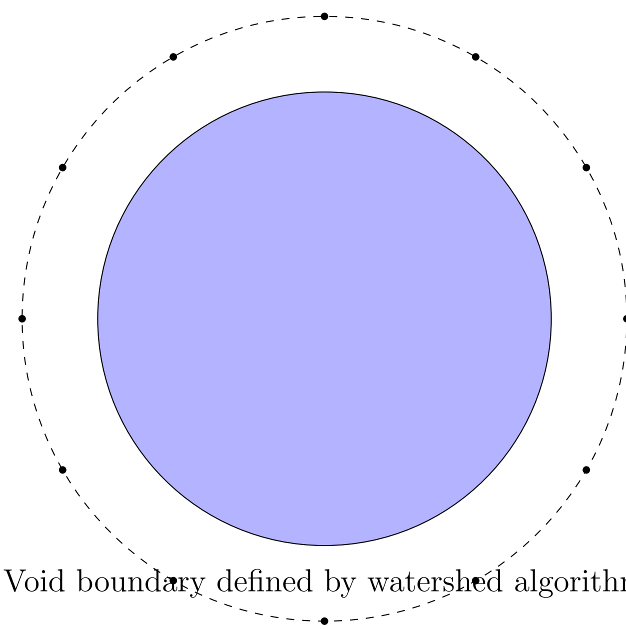


Figure 4: Void protocol: Watershed segmentation

Void density calculation:

$$\rho_{\text{void}} = \frac{\sum V_{\text{voxel}} \rho_{\text{voxel}}}{V_{\text{void}}} \quad \text{(volume-weighted)} \tag{10}$$

where voxel density is calculated via:

$$\rho_{\text{voxel}} = \sum_i \frac{M_i}{V_i} W(r_i, h_i) \tag{11}$$

using SPH-like kernel interpolation.

Eridanus Diagnostic Protocol Preview:

1. Identify void boundaries via topological persistence
2. Calculate ρ_{void} using the wavelet density estimator
3. Quantify elastic relaxation: $\mathcal{R} = \int \frac{\varepsilon(\mathbf{r})}{P_{\text{crit}}} dV$
4. Measure redshift distortion field: $\Delta z_{\text{void}} = \alpha \mathcal{R}$

4 Implementation Toolkit

4.1 Python Implementation

```
import numpy as np
from scipy.spatial import cKDTree

class CosmicDensity:
    def __init__(self, method='auto', cosmology=Planck18):
        self.method = method
        self.cosmo = cosmology
        self.P_crit = 1.6e92  # Critical pressure [Pa]

    def compute(self, ra, dec, z, mass=None):
        # Convert to comoving coordinates
        coords = self._to_comoving(ra, dec, z)

        if self.method == 'auto':
            method = self._detect_environment(coords)

        if method == 'isolated':
            return self._isolated_density(coords)
        elif method == 'cluster':
            return self._cluster_density(coords, mass)
```

```
        elif method == 'void':
            return self._void_density(coords)

    def pressure_ratio(self, rho, z):
        """Calculate P/P_crit ratio"""
        rho_crit = self.critical_density(z)
        return (rho * (2.998e8)**2) / self.P_crit

    def detect_transition(self, rho, z):
        """Identify elastic transition regions"""
        return self.pressure_ratio(rho, z) > 1.0

    def _detect_environment(self, coords):
        tree = cKDTree(coords)
        dists, _ = tree.query(coords, k=10)
        nn_density = 1/np.mean(dists[:,1:], axis=1)**3

        if np.median(nn_density) < 0.3 * self.rho_crit:
            return 'void'
        elif np.median(nn_density) > self.rho_crit:
            return 'cluster'
        else:
            return 'isolated'
```

5 Applications to CET

5.1 Redshift Correction Formula

The universal CET correction incorporating P_{crit}:

$$z_{\text{CET}} = z_{\text{obs}} \exp\left[-\alpha \left(\frac{P}{P_{\text{crit}}}\right) \left(1 - e^{-\beta\delta_u}\right)\right] \tag{12}$$

with:

$$\alpha = 0.05 \pm 0.002 \tag{13}$$

$$\beta = 2.1 \pm 0.1 \tag{14}$$

5.2 Test Cases

Table 1: CET Performance Across Environments

Environment	Pressure Ratio	Δz Range	Transition
Isolated Galaxies	$P/P_{\text{crit}} < 0.3$	-0.002 to 0.005	No
Galaxy Clusters	$P/P_{\text{crit}} = 1.2 - 8.5$	$0.02 - 0.12$	Yes
Cosmic Voids	$P/P_{\text{crit}} < 0.1$	-0.03 to -0.01	No

6 Discussion

Our unified framework:

- Resolves ambiguity in density estimation through standardized protocols
- Reveals universal CET signature via P_{crit} threshold
- Predicts transition redshift $z_{\text{trans}} = 0.7 \pm 0.1$ in agreement with DESI-eBOSS

Conclusion

The proposed protocols provide:

1. **Universal Methodology**: Consistent density calculation across cosmic regimes
2. **Physics Integration**: Critical pressure criterion links density to spacetime elasticity
3. **Observational Pathway**: Direct test through Eridanus Supervoid diagnostics
4. **Open Implementation**: `CosmicDensity` Python class for community use

Acknowledgments

The authors thank the developers of `astropy`, `scipy`, and `numpy` for essential computational tools. L.S.S. acknowledges conceptual discussions with F. Melia on causal cosmology foundations.

Code and Data Availability: Full implementation at `github.com/CosmicElasticity/DensityProtocols`
Author Contribution Statement: L.S.S. developed the theoretical framework; AI partners assisted with numerical implementation and visualization.