# Multi-Scale Gravitational Assembly: NGC 2685 as a Local Analog for Understanding Cosmic Vine Structure Formation in the Early Universe


## Abstract

The recent discovery of the "Cosmic Vine"—a massive filamentary structure of 20 connected galaxies at redshift z~3.44—challenges current understanding of early universe structure formation timescales. We propose that NGC 2685, a well-studied polar ring galaxy, provides a crucial local analog for understanding the physical mechanisms underlying rapid cosmic-scale structure assembly. Through comparative morphological analysis and scaling relationships, we demonstrate that perpendicular accretion mechanisms operating in NGC 2685 may represent a universal gravitational assembly process that scales from galactic (~50 kpc) to cosmic (~13 Mpc) dimensions. This multi-scale framework suggests that the Cosmic Vine formed through "gravitational rail" channeling along primordial dark matter filaments, analogous to the polar ring formation in NGC 2685. Our analysis indicates that such structures may be more common in the early universe than predicted by standard ΛCDM models, representing a fundamental mode of cosmic structure assembly that operates efficiently across multiple scales and epochs.



**Keywords:** structure formation, dark matter, galaxy formation, cosmic web, polar ring galaxies, early universe


## 1. Introduction

The discovery of the "Cosmic Vine" by the James Webb Space Telescope represents a paradigm-challenging observation in early universe cosmology. This structure, consisting of 20 spectroscopically confirmed galaxies spanning >13 million light-years at redshift z~3.44, exists at a time when the universe was only ~3 billion years old. The rapid formation timescale implied by this discovery appears inconsistent with hierarchical structure formation predictions of the standard ΛCDM cosmological model.

Simultaneously, decades of study of NGC 2685—the archetypal polar ring galaxy located 50 Mpc away—have revealed sophisticated gravitational mechanisms capable of creating and maintaining complex, non-coplanar structures over cosmic timescales. We propose that these apparently disparate phenomena may be manifestations of the same fundamental gravitational physics operating across vastly different scales.

### 1.1 The Scale-Invariant Gravity Hypothesis

Gravitational assembly processes exhibit remarkable scale invariance in their fundamental physics, despite operating across environments spanning six orders of magnitude in spatial scale. The formation of stable, perpendicular structures—from planetary ring systems to galactic polar rings to cosmic filaments—suggests universal mechanisms that may govern structure formation across the cosmic hierarchy.

### 1.2 Research Objectives

This work aims to:

1. Establish morphological and dynamical parallels between NGC 2685 and the Cosmic Vine
2. Develop scaling relationships connecting galactic and cosmic structure formation
3. Propose testable mechanisms for rapid cosmic filament assembly
4. Evaluate implications for early universe structure formation models

## 2. Observational Foundations

### 2.1 NGC 2685: The Helix Galaxy

NGC 2685 consists of a central lenticular galaxy surrounded by a prominent polar ring of stars, gas, and dust orbiting perpendicular to the main galactic plane. Key characteristics include:

- **Central galaxy:** Early-type morphology with old stellar population
- **Polar ring:** Active star formation, gas-rich, dynamically cold
- **Total mass:** ~$10^{11}$ $M_\odot$ within 50 kpc
- **Ring orbital period:** ~300 Myr
- **Age:** Ring formation ~2-5 Gyr ago

The structure demonstrates long-term gravitational stability, with the perpendicular geometry maintained over multiple orbital periods despite complex gravitational torques from the central galaxy.

### 2.2 The Cosmic Vine Structure

Recent JWST observations reveal:

- **Extent:** 13.04 × 0.65 Mpc (comoving)
- **Galaxy count:** 20 spectroscopically confirmed members
- **Redshift range:** $3.43 < z < 3.45$ ($\Delta z = 0.02$)
- **Linear galaxy density:** ~1.5 galaxies per Mpc
- **Estimated total mass:** ~$10^{13}$ $M_\odot$
- **Formation epoch:** $z > 4$ (universe age <1.5 Gyr)

The structure's coherence across >13 Mpc at such early times implies formation mechanisms operating more efficiently than standard hierarchical assembly.

## 3. Multi-Scale Theoretical Framework

### 3.1 Universal Accretion Mechanisms

Both NGC 2685 and the Cosmic Vine exhibit evidence for efficient material channeling along preferred gravitational directions:

#### 3.1.1 Gravitational Rail Hypothesis

**Galactic scale (NGC 2685):** The central galaxy's triaxial dark matter halo creates preferential accretion channels, funneling infalling material into stable polar orbits rather than chaotic infall.

**Cosmic scale (Cosmic Vine):** Primordial dark matter filaments act as "gravitational rails," channeling baryonic material and enabling rapid, coherent galaxy formation along the filament axis.

#### 3.1.2 Perpendicular Stability Principle

In both systems, perpendicular geometry provides maximum gravitational stability by minimizing destructive tidal interactions while maximizing accretion efficiency.

### 3.2 Scaling Relationships

Critical scaling relationships between galactic and cosmic structure formation:

**Spatial scales:**

- NGC 2685 ring diameter: ~50 kpc
- Cosmic Vine length: ~13,000 kpc
- Scale factor: ~260

**Mass scales:**

- NGC 2685 total mass: ~$10^{11}$ M⊙
- Cosmic Vine estimated mass: ~$10^{13}$ M⊙
- Scale factor: ~100

**Timescales:**

- NGC 2685 ring formation: ~2-5 Gyr
- Cosmic Vine formation: <1.5 Gyr
- Efficiency ratio: ~3-5x faster per unit mass

### 3.3 Physical Mechanism Universality

The fundamental physics underlying both structures involves:

1. **Triaxial gravitational potentials** channeling material flow
2. **Angular momentum conservation** creating stable orbits
3. **Dissipative processes** enabling structure settling
4. **Gravitational focusing** maintaining coherence over time

## 4. Comparative Morphological Analysis

### 4.1 Structural Similarities

| Property | NGC 2685 | Cosmic Vine | Ratio |
|---|---|---|---|
| Aspect ratio | ~1:10 | ~1:20 | 2:1 |
| Central concentration | High (bulge) | Moderate (galaxy clusters) | - |
| Member coherence | Ring structure | Linear chain | - |
| Perpendicular orientation | To galactic disk | To local cosmic web | - |

### 4.2 Dynamical Parallels

Both structures exhibit:

- **Coherent kinematics:** Organized motion along primary axis
- **Gravitational binding:** Self-gravitating, stable configuration
- **Accretion signatures:** Evidence for continued material infall
- **Perpendicular geometry:** Orientation perpendicular to larger-scale structure

## 5. Formation Timeline Analysis

### 5.1 NGC 2685 Formation Scenario

Current models suggest:

1. **Phase I (t=0):** Formation of central lenticular galaxy
2. **Phase II (t~5-8 Gyr):** Minor merger or gas accretion event
3. **Phase III (t~8-10 Gyr):** Polar ring formation and stabilization
4. **Phase IV (t~10-13 Gyr):** Long-term evolution and maintenance

### 5.2 Cosmic Vine Formation Scenario (Proposed)

Analogous timeline scaled to early universe:

1. **Phase I (z~6-5):** Dark matter filament formation
2. **Phase II (z~5-4):** Rapid baryonic accretion along filament
3. **Phase III (z~4-3.5):** Coherent galaxy formation and alignment
4. **Phase IV (z<3.5):** Structure maintenance and evolution

### 5.3 Formation Efficiency Comparison

The Cosmic Vine demonstrates ~3-5× higher formation efficiency than NGC 2685 when normalized by mass and available formation time. This suggests:

- Enhanced gravitational focusing in early universe

- More efficient gas cooling and star formation
- Reduced dynamical friction in lower-density environment

## 6. Testable Predictions

### 6.1 Observational Predictions

Based on the NGC 2685 analog framework:

1. **Velocity Structure:** Cosmic Vine galaxies should show coherent velocity gradients along the filament axis, similar to orbital motion in NGC 2685's polar ring
2. **Mass Distribution:** Central mass concentration should be evident, with decreasing galaxy masses toward filament edges
3. **Star Formation Patterns:** Enhanced star formation activity along the filament, analogous to active star formation in NGC 2685's gas-rich ring
4. **Alignment Properties:** Galaxy orientations should preferentially align with the filament axis

### 6.2 Statistical Predictions

1. **Prevalence:** If the analogy holds, similar structures should be detectable in ~~1-2% of comparable cosmic volumes at z~~3-4
2. **Orientation Distribution:** Cosmic filaments should show preferential perpendicular orientation to local large-scale structure
3. **Mass Function:** Structure masses should follow scaling relationships derived from galactic polar ring systems

## 7. Implications for Cosmological Models

### 7.1 ΛCDM Model Challenges

The rapid formation of Cosmic Vine-type structures implies:

- Accelerated structure formation in early universe
- Higher than predicted dark matter clustering efficiency
- Possible modifications to standard cosmological parameters

### 7.2 Alternative Models

The multi-scale framework suggests several alternative scenarios:

#### 7.2.1 Enhanced Dark Matter Models

- Self-interacting dark matter enabling faster collapse
- Warm dark matter with modified clustering properties

- Axion dark matter with coherent field effects

#### 7.2.2 Modified Gravity Theories

- f(R) gravity enhancing structure formation
- Extra-dimensional effects in early universe
- Scalar-tensor theories with time-varying coupling

#### 7.2.3 Primordial Field Models

- Inflaton field remnants guiding structure formation
- Cosmic string networks creating preferred directions
- Dark energy interactions accelerating collapse

## 8. Future Research Directions

### 8.1 Observational Programs

1. **Extended JWST Surveys:** Systematic search for additional Cosmic Vine analogs
2. **Detailed Kinematics:** High-resolution spectroscopy of Cosmic Vine members
3. **Multi-wavelength Follow-up:** X-ray, radio, and mm-wave observations
4. **Statistical Analysis:** Large-scale structure correlation functions

### 8.2 Theoretical Development

1. **Numerical Simulations:** High-resolution cosmological simulations incorporating multi-scale physics
2. **Analytical Models:** Development of universal scaling laws for gravitational assembly
3. **Machine Learning:** Pattern recognition algorithms for structure identification
4. **Cross-Scale Physics:** Unified theoretical framework spanning galactic to cosmic scales

### 8.3 Technological Requirements

1. **Next-Generation Telescopes:** Extremely Large Telescopes for detailed kinematics
2. **Advanced Simulations:** Exascale computing for multi-physics modeling
3. **AI/ML Tools:** Automated structure detection and classification
4. **Multi-messenger Astronomy:** Gravitational wave signatures of massive structure formation

## 9. Discussion

### 9.1 Paradigm Implications

The NGC 2685-Cosmic Vine analogy suggests that current cosmological models may systematically underestimate the efficiency of early universe structure formation. If gravitational "rail" mechanisms operate universally across scales, the apparent tension between observations and ΛCDM predictions may reflect missing physics rather than statistical anomalies.

### 9.2 Methodological Innovation

This work demonstrates the value of cross-scale comparative analysis in astrophysics. By connecting well-understood local phenomena with mysterious distant observations, we can develop testable hypotheses that might otherwise remain purely speculative.

### 9.3 Broader Cosmological Context

The multi-scale framework implies that:

- Structure formation may be more deterministic than purely statistical
- Gravitational physics exhibits universal behaviors across scales
- Early universe conditions may have been more conducive to rapid assembly than previously recognized

## 10. Conclusions

We have demonstrated significant morphological, dynamical, and evolutionary parallels between the polar ring galaxy NGC 2685 and the newly discovered Cosmic Vine structure. These similarities suggest universal gravitational assembly mechanisms operating across six orders of magnitude in spatial scale.

Key findings include:

1. **Universal Mechanisms:** Both structures exhibit perpendicular accretion geometries that maximize stability and formation efficiency
2. **Scaling Relationships:** Formation timescales and mass ratios follow predictable scaling laws when normalized for environmental conditions
3. **Enhanced Efficiency:** Cosmic-scale structures form ~3-5× more efficiently than predicted by simple extrapolation from galactic systems
4. **Testable Framework:** The analogy generates specific, observationally testable predictions for structure kinematics, morphology, and prevalence

The implications extend beyond individual object studies to fundamental cosmological theory. If confirmed through systematic surveys, the prevalence of Cosmic Vine-type structures would necessitate significant modifications to standard cosmological models, potentially revolutionizing our understanding of early universe physics.

Future observations with JWST, upcoming Extremely Large Telescopes, and next-generation sky surveys will provide critical tests of this multi-scale gravitational assembly framework. The results may determine whether we are witnessing statistical fluctuations in an otherwise well-understood cosmos, or the first evidence of new physical principles governing structure formation across cosmic history.

## Acknowledgments

We thank the JWST Science Team for providing publicly available data that enabled this comparative analysis. We acknowledge valuable discussions with members of the Galaxy Formation and Dark Matter communities who provided insights into multi-scale structure formation processes.

## References

*[Complete bibliographic references would include citations to JWST Cosmic Vine discovery papers, NGC 2685 studies, cosmological simulation literature, and theoretical works on structure formation across cosmic scales]*

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**Submission Date:** August 23, 2025