Vacuum Selection from Cosmology Using Networks of String Geometries

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January 30, 2018

Collaboration

Physics Collaboration at Northeastern

String Theory

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Graph Theory

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arXiv:1711.06685

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- 3-folds ($\mathbb{C}^3$) are triangulated 3-D reflexive polytopes (4319)

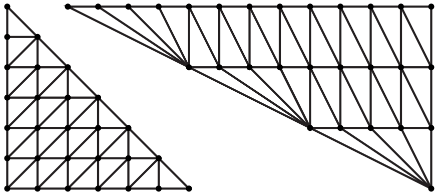

Image: Halverson et al. Phys. Rev. D 96, 126006 (2017).

The String Landscape

Landscape Problem: At least $1.96 \times \frac{4}{3} \times 10^{755}$ geometries

- Where is the Standard Model? (NP-Hard Search!)
- Are some vacua "special" compared to others? (Monte Carlo Random Walk)
- What are transition rates?
- What other information do we need to add?
- How do we characterize such a large system statistically?
- **Does a selection mechanism exist, and does it choose our universe? With what probability?**

Vacuum Selection

What does "vacuum selection" really mean?

- Every universe is a false vacuum
- Consider the model of eternal inflation in multiverse cosmology
- Vacuum bubbles nucleate, merge, and decay
- Contributors: Coleman, de Luccia, Steinhardt, Vilenkin, Guth
- Goal is to avoid the anthropic principle

Vacuum selection: the distribution of vacua at $t \to \infty$

“Simple” Topological Transitions

Two 3-folds are related by a **blowup**; # **cones** $+= 2$

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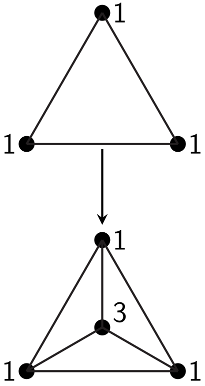
Face Blowup



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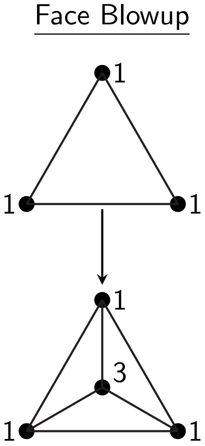

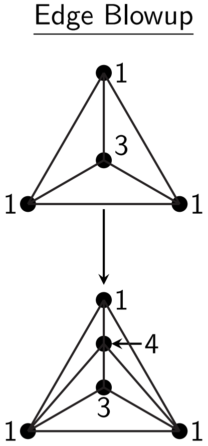

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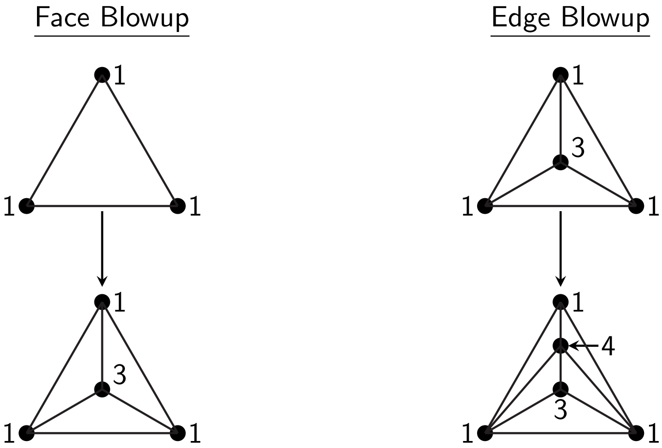

Height Restriction: $H \leq 6$

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- Transitions make sense when we think about bubble cosmology in eternal inflation

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Bubble Cosmology

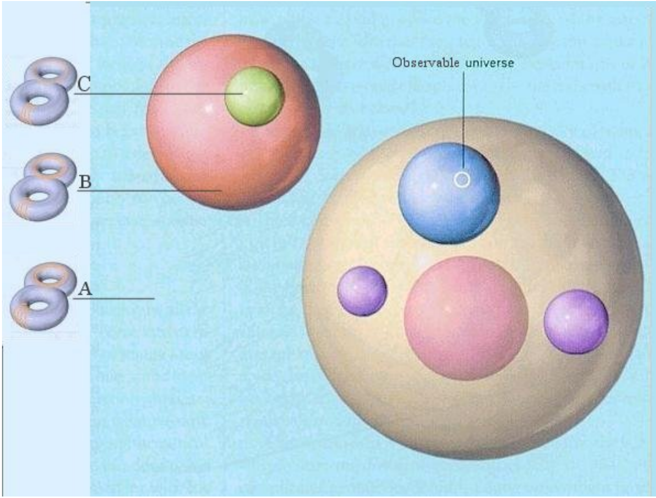

Image: universe-review.ca

Modeling Bubble Nucleation

Question: What is the distribution of vacua at $t \to \infty$?

Nucleation Rate: $\frac{d\mathbf{N}}{dt} = \mathbf{\Gamma N}$

Solution: $\mathbf{N} = e^{\mathbf{\Gamma} t}\mathbf{N}_0 = \sum_p a_p e^{\gamma_p t}\mathbf{v}_p$

Late-Time Solution: $\mathbf{N} \to a_0 e^{\gamma_0 t}\mathbf{v}_0$ Normalize: $\mathbf{p} = \mathbf{N}/|\mathbf{N}|$

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But to use **A** would require ~210 TB memory...

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Optimized algorithms: *W. Cunningham & D. Krioukov, arXiv:1709.03013 (2017).*

Data Analysis

How to compute the eigenvector centrality?

- The adjacency matrix **A** is **sparse**, **symmetric**, and **real**
- We want the eigenvector associated with the largest eigenvalue
- We can use either FEAST (Intel MKL) or cuSOLVER (NVIDIA CUDA) to get eigenvectors
- In current work, **A** is **non-symmetric** – harder to solve
- Hardware: Xeon E5-2680v4 (56 cores) and Tesla K80m (4992 cores), MPI not needed right now

Runtime: 24 hours to construct graph, $\sim$1 minute to analyze

The Eigenvector Centrality

We compute the eigenvector centralities of the (sparse) graph

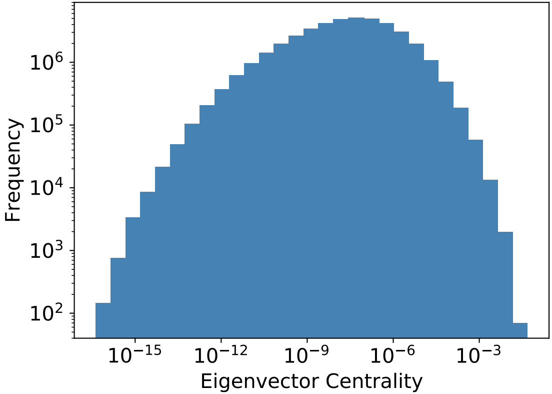
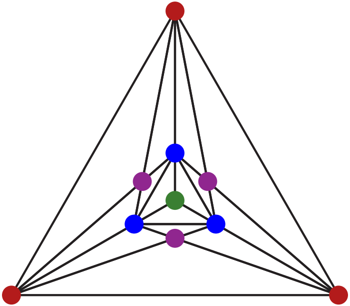


Image: Carifio, Cunningham, Halverson, Krioukov, Long & Nelson, arXiv:1711.06685 (2017).

The Selected Vacuum State



Selected Gauge Group: $E_8^3 \times G_2 \times SU(2)^3$

Full 10^{755} Network: $E_8^{37} \times F_4^{85} \times G_2^{220} \times SU(2)^{320}$

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- We also want to consider bubble collisions/decays
- We can use deep neural networks to search for the MSSM (Ruehle, Halverson & Nelson)

Conclusion

What did we learn?

1. The String Landscape problem is a graph theory problem
2. Toy models suggest evidence of a selection mechanism
3. This is the first combination of string theory, cosmology, and graph theory
4. We have a long way to go if we want *real physics* (predictive, testable)

Thank you for listening!