

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Challenging the Standard Paradigm of Early Universe Cosmology

Robert Brandenberger, McGill University

PASCOS 2026, Sheffield, June 22 2026

Work in collaboration with S. Brahma, S. Laliberte and J.
Pasiecznik [arXiv:2107.11512](https://arxiv.org/abs/2107.11512),
[arXiv:2206.12468](https://arxiv.org/abs/2206.12468), [arXiv:2409.00254](https://arxiv.org/abs/2409.00254)

Outline

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology
- 6 Conclusions

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology
- 6 Conclusions

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative theory** of all four forces of Nature.

Candidate: matrix cosmology.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative** theory of all four forces of Nature.

Candidate: matrix cosmology.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative** theory of all four forces of Nature.

Candidate: matrix cosmology.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative theory** of all four forces of Nature.

Candidate: **matrix cosmology**.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative theory of all four forces of Nature**.

Candidate: matrix cosmology.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Standard Paradigm of Early Universe Cosmology: a period of **cosmological inflation** transiting to the radiation phase of Standard Big Bang cosmology via a **reheating transition**, analyzed using **effective field theory**.

Trans-Planckian Censorship Criterion → Standard paradigm

- violates unitarity
- violates the second law of thermodynamics

Lesson: Need a **new paradigm** based on **non-perturbative theory** of all four forces of Nature.

Candidate: **matrix cosmology**.

Anisotropies in the Cosmic Microwave Background (CMB)

Emergent

R. Brandenberger

Introduction

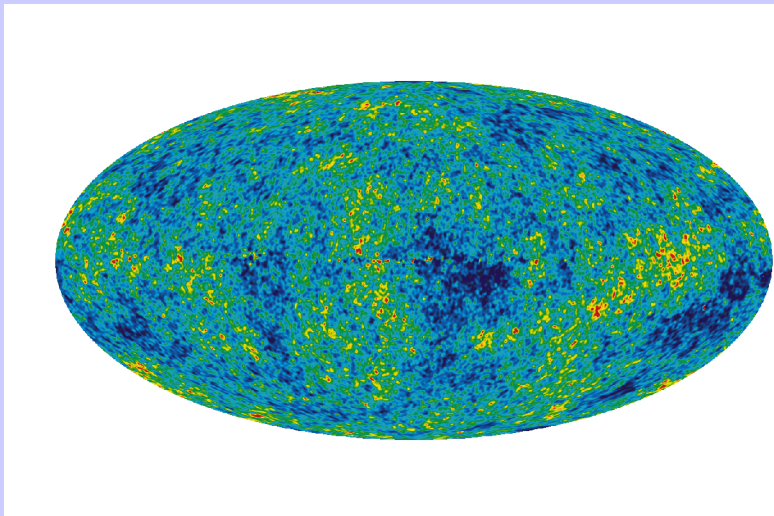
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Credit: NASA/WMAP Science Team

Angular Power Spectrum of CMB Anisotropies

Emergent

R. Brandenberger

Introduction

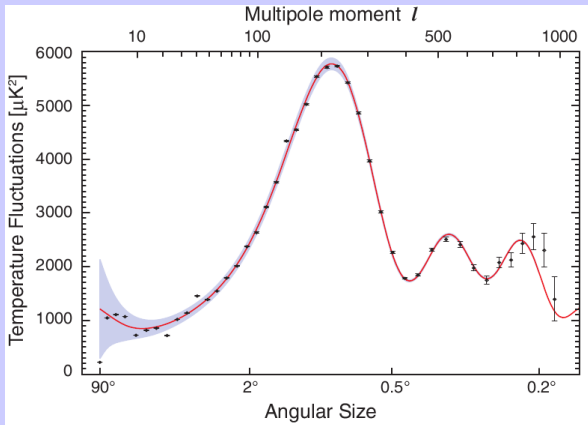
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Credit: NASA/WMAP Science Team

Predictions from 1970

R. Sunyaev and Y. Zel'dovich, *Astrophys. and Space Science* **7**, 3 (1970); P. Peebles and J. Yu, *Ap. J.* **162**, 815 (1970).

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Given a **scale-invariant power spectrum of adiabatic fluctuations** on "super-horizon" scales before t_{eq} , i.e. standing waves.
- → "correct" power spectrum of galaxies.
- → **acoustic oscillations in CMB angular power spectrum.**
- → **baryon acoustic oscillations in matter power spectrum.**

Criteria for a Successful Early Universe Scenario

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Horizon \gg Hubble radius** in order for the scenario to solve the “horizon problem” of Standard Big Bang Cosmology.
- Scales of cosmological interest today **originate inside the Hubble radius at early times** in order for a causal generation mechanism of fluctuations to be possible.
- Mechanism for producing a **scale-invariant spectrum of curvature fluctuations** on super-Hubble scales.

Inflation as a Solution

Emergent

R. Brandenberger

Introduction

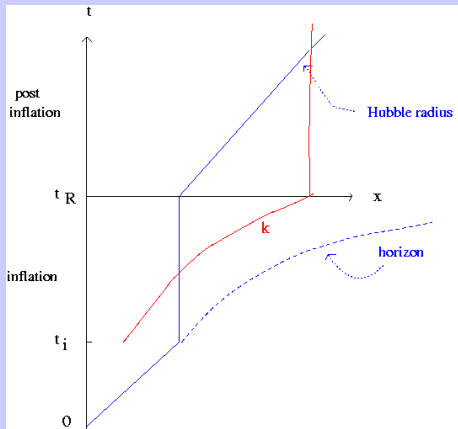
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Bouncing Cosmology as a Solution

F. Finelli and R.B., *Phys. Rev. D65, 103522 (2002)*, D. Wands, *Phys. Rev. D60 (1999)*

Emergent

R. Brandenberger

Introduction

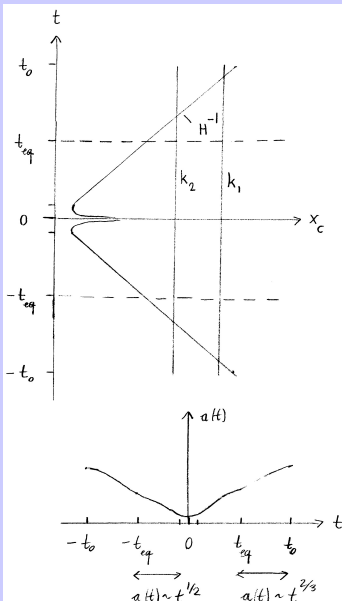
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Emergent Universe

R.B. and C. Vafa, *Nucl. Phys. B*316:391 (1989)

Emergent

R. Branden-
berger

Introduction

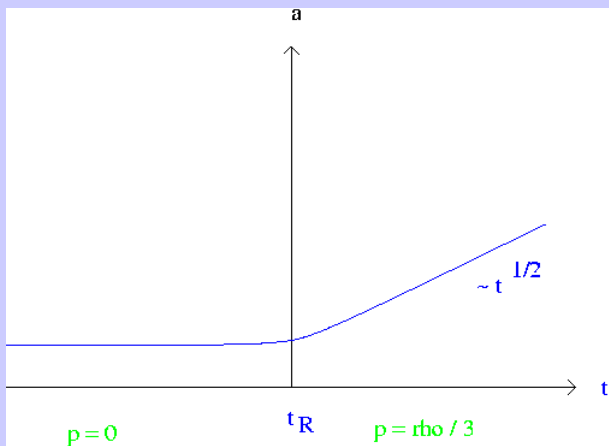
Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Emergent Universe as a Solution

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett.* 97:021302 (2006)

Emergent

R. Brandenberger

Introduction

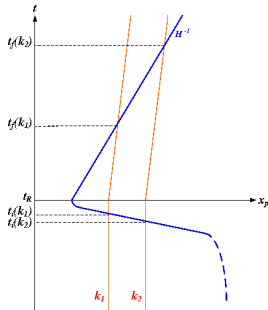
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Need to go beyond Effective Field Theory (EFT)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Bouncing Cosmology** requires going beyond EFT.
- **Emergent Cosmology** requires going beyond EFT.
- What about **inflation**? TCC → need to go beyond EFT.

Need to go beyond Effective Field Theory (EFT)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Bouncing Cosmology** requires going beyond EFT.
- **Emergent Cosmology** requires going beyond EFT.
- What about **inflation**? TCC → need to go beyond EFT.

Need to go beyond Effective Field Theory (EFT)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Bouncing Cosmology** requires going beyond EFT.
- **Emergent Cosmology** requires going beyond EFT.
- What about **inflation**? TCC → need to go beyond EFT.

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 **Trans-Planckian Censorship Criterion**
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology
- 6 Conclusions

Trans-Planckian Problem

J. Martin and R.B., *Phys. Rev. D63, 123501 (2002)*

Emergent

R. Branden-
berger

Introduction

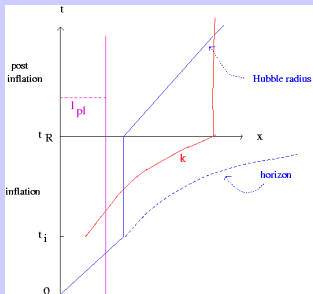
Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



- **Success of inflation:** At early times scales are inside the Hubble radius \rightarrow causal generation mechanism is possible.
- **Problem:** If time period of inflation is more than $70H^{-1}$, then $\lambda_p(t) < l_{pl}$ at the beginning of inflation.
- \rightarrow breakdown of effective field theory; new physics **MUST** be taken into account when computing observables from inflation.

Trans-Planckian Censorship Conjecture (TCC)

A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

EFT description breaks down if trans-Planckian modes can exit the Hubble horizon.

$$ds^2 = dt^2 - a(t)^2 dx^2$$

$$H(t) \equiv \frac{\dot{a}}{a}(t)$$

$$\frac{a(t_R)}{a(t_i)} \Big|_{pl} < H(t_R)^{-1}$$

Trans-Planckian Censorship Conjecture (TCC)

A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

EFT description breaks down if trans-Planckian modes can exit the Hubble horizon.

$$ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$$

$$H(t) \equiv \frac{\dot{a}}{a}(t)$$

$$\frac{a(t_R)}{a(t_i)} \Big|_{pl} < H(t_R)^{-1}$$

Justification 1: Analogy with Penrose's Cosmic Censorship Hypothesis

R.B. arXiv:1911.06056

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Effective field theory of General Relativity allows for solutions with **timelike singularities**: super-extremal black holes.
- → Cauchy problem not well defined for observer external to black holes.
- Evolution **non-unitary** for external observer.
- Conjecture: ultraviolet physics → **external observer** shielded from the **singularity** and **non-unitarity** by **horizon**.

Cosmological Version of the Censorship Conjecture

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Translation

- Position space \rightarrow momentum space.
- Singularity \rightarrow trans-Planckian modes.
- Black Hole horizon \rightarrow Hubble horizon.

Observer measuring super-Hubble horizon modes must be shielded from trans-Planckian modes.

Cosmological Version of the Censorship Conjecture

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Translation

- Position space \rightarrow momentum space.
- Singularity \rightarrow trans-Planckian modes.
- Black Hole horizon \rightarrow Hubble horizon.

Observer measuring super-Hubble horizon modes must be shielded from trans-Planckian modes.

Why Hubble Horizon?

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: Fluctuations only oscillate on sub-Hubble scales.
- Recall: Fluctuations freeze out, become **squeezed states** and **classicalize** on super-Hubble scales.
- **Demand:** classical region be insensitive to trans-Planckian region.
- → no trans-Planckian modes ever exit Hubble horizon.

Why Hubble Horizon?

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: Fluctuations only oscillate on sub-Hubble scales.
- Recall: Fluctuations freeze out, become **squeezed states** and **classicalize** on super-Hubble scales.
- **Demand: classical region be insensitive to trans-Planckian region.**
- → no trans-Planckian modes ever exit Hubble horizon.

Justification 2: Unitarity Problem

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: **non-unitarity** of **effective field theory** in an expanding universe (N. Weiss, Phys. Rev. D32, 3228 (1985); J. Cotler and A. Strominger, arXiv:2201.11658).
- \mathcal{H} is the product Hilbert space of harmonic oscillator Hilbert spaces for all **comoving** wave numbers k
- **UV cutoff: time dependent** $k_{max} : k_{max}(t)a(t)^{-1} = m_{pl}$
- Continuous mode creation \rightarrow **non-unitarity**.
- **Demand: classical region be insensitive to non-unitarity.**
- \rightarrow no trans-Planckian modes ever exit Hubble horizon.

Justification 2: Unitarity Problem

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: **non-unitarity** of **effective field theory** in an expanding universe (N. Weiss, Phys. Rev. D32, 3228 (1985); J. Cotler and A. Strominger, arXiv:2201.11658).
- \mathcal{H} is the product Hilbert space of harmonic oscillator Hilbert spaces for all **comoving** wave numbers k
- **UV cutoff: time dependent** $k_{max} : k_{max}(t)a(t)^{-1} = m_{pl}$
- Continuous mode creation \rightarrow **non-unitarity**.
- **Demand: classical region be insensitive to non-unitarity.**
- \rightarrow no trans-Planckian modes ever exit Hubble horizon.

Justification 2: Unitarity Problem

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: **non-unitarity** of **effective field theory** in an expanding universe (N. Weiss, Phys. Rev. D32, 3228 (1985); J. Cotler and A. Strominger, arXiv:2201.11658).
- \mathcal{H} is the product Hilbert space of harmonic oscillator Hilbert spaces for all **comoving** wave numbers k
- **UV cutoff: time dependent** $k_{max} : k_{max}(t)a(t)^{-1} = m_{pl}$
- Continuous mode creation \rightarrow **non-unitarity**.
- **Demand: classical region be insensitive to non-unitarity.**
- \rightarrow no trans-Planckian modes ever exit Hubble horizon.

Justification 2: Unitarity Problem

R.B. arXiv:1911.06056; A. Bedroya and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: **non-unitarity** of **effective field theory** in an expanding universe (N. Weiss, Phys. Rev. D32, 3228 (1985); J. Cotler and A. Strominger, arXiv:2201.11658).
- \mathcal{H} is the product Hilbert space of harmonic oscillator Hilbert spaces for all **comoving** wave numbers k
- **UV cutoff: time dependent** $k_{max} : k_{max}(t)a(t)^{-1} = m_{pl}$
- Continuous mode creation \rightarrow **non-unitarity**.
- **Demand: classical region be insensitive to non-unitarity.**
- \rightarrow no trans-Planckian modes ever exit Hubble horizon.

Justification 2: Unitarity Problem

R.B. arXiv:1911.06056; A. Bedroia and C. Vafa., arXiv:1909.11063

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Recall: **non-unitarity** of **effective field theory** in an expanding universe (N. Weiss, Phys. Rev. D32, 3228 (1985); J. Cotler and A. Strominger, arXiv:2201.11658).
- \mathcal{H} is the product Hilbert space of harmonic oscillator Hilbert spaces for all **comoving** wave numbers k
- **UV cutoff: time dependent** $k_{max} : k_{max}(t)a(t)^{-1} = m_{pl}$
- Continuous mode creation \rightarrow **non-unitarity**.
- **Demand: classical region be insensitive to non-unitarity.**
- \rightarrow no trans-Planckian modes ever exit Hubble horizon.

Justification 3: Application of the Second Law of Thermodynamics

S. Brahma, O. Alaryani and RB, arXiv:2005.09688

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Consider **entanglement entropy density** $s_E(t)$ between sub- and super-Hubble modes.
- Consider an **phase of inflationary expansion**.
- $s_E(t)$ increases in time since the phase space of super-Hubble modes grows.
- **Demand:** $s_E(t)$ remain smaller than the post-inflationary thermal entropy.
- → Duration of inflation is bounded from above, consistent with the TCC.

Effective Field Theory (EFT) and the CC Problem

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- EFT: expand **fields** in comoving Fourier space.
- Quantize each Fourier mode like a harmonic oscillator
→ ground state energy.
- Add up ground state energies → CC problem.
- The usual quantum view of the CC problem is an artefact of an EFT analysis!

Effective Field Theory (EFT) and the CC Problem

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- EFT: expand **fields** in comoving Fourier space.
- Quantize each Fourier mode like a harmonic oscillator
→ ground state energy.
- Add up ground state energies → CC problem.
- **The usual quantum view of the CC problem is an artefact of an EFT analysis!**

Implications for Dark Energy

R.B., arXiv:2503.17659

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Dark Energy cannot be a bare cosmological constant.
- Quintessence models of Dark Energy are constrained (L. Heisenberg et al. arXiv:2003.13283]

Trans-Planckian Censorship and Cosmological Scenarios

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- **Bouncing cosmologies** are **consistent** with the TCC provided that the energy scale at the bounce is lower than the Planck scale.
- **Emergent cosmologies** are **consistent** with the TCC provided that the energy scale of the emergence phase is lower than the Planck scale.
- **Inflationary cosmologies** are **inconsistent** with the TCC unless the energy scale of inflation is fine tuned.

All early universe scenarios require going beyond EFT.

Trans-Planckian Censorship and Cosmological Scenarios

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- **Bouncing cosmologies** are **consistent** with the TCC provided that the energy scale at the bounce is lower than the Planck scale.
- **Emergent cosmologies** are **consistent** with the TCC provided that the energy scale of the emergence phase is lower than the Planck scale.
- **Inflationary cosmologies** are **inconsistent** with the TCC unless the energy scale of inflation is fine tuned.

All early universe scenarios require going beyond EFT.

- Current early Universe models are based on **effective point particle quantum field theory (EFTs)**.
- **Conceptual problems** → breakdown of EFT.
- Require an approach **beyond EFT** consistent with a **unified description of all forces of Nature**.
- **Superstring theory**: best candidate for a **unified quantum theory of all forces**.
- **Question**: **What emerges from a non-perturbative approach to superstring theory**
- **Question**: **will a new early Universe scenario emerge?**

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Starting point: **BFSS matrix model**.
- Yields an emergent metric space-time.
- Yields an emergent early universe cosmology.
- Yields specific predictions for upcoming observations.

Preview

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Starting point: **BFSS** matrix model.
- Yields an **emergent metric space-time**.
- Yields an **emergent early universe cosmology**.
- Yields specific **predictions** for upcoming observations.

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model**
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology
- 6 Conclusions

Requirement: Nonperturbative Definition of Superstring Theory

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Point particle theory

- Step 1: classical mechanics of point particles.
- Step 2: quantum mechanical scattering of point particles (Feynman diagrams).
- Step 3: Nonperturbative approach: **point particles** \rightarrow **quantum fields**, **particles** are **point-like excitations** for the fields.

String theory

- Step 1: classical mechanics of strings (classical field theory)
- Step 2: quantum mechanical scattering of strings.
- Step 3: Nonperturbative approach: **strings** \rightarrow “**mystery object**”, **strings** are **linear excitations** of the “**mystery object**”.

Requirement: Nonperturbative Definition of Superstring Theory

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Point particle theory

- Step 1: classical mechanics of point particles.
- Step 2: quantum mechanical scattering of point particles (Feynman diagrams).
- Step 3: Nonperturbative approach: **point particles** \rightarrow **quantum fields**, **particles** are **point-like excitations** for the fields.

String theory

- Step 1: classical mechanics of strings (classical field theory)
- Step 2: quantum mechanical scattering of strings.
- Step 3: Nonperturbative approach: **strings** \rightarrow “**mystery object**”, **strings** are **linear excitations** of the “**mystery object**”.

Requirement: Nonperturbative Definition of Superstring Theory

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Point particle theory

- Step 1: classical mechanics of point particles.
- Step 2: quantum mechanical scattering of point particles (Feynman diagrams).
- Step 3: Nonperturbative approach: **point particles** \rightarrow **quantum fields**, **particles** are **point-like excitations** for the fields.

String theory

- Step 1: classical mechanics of strings (classical field theory)
- Step 2: quantum mechanical scattering of strings.
- Step 3: Nonperturbative approach: **strings** \rightarrow “**mystery object**”, **strings** are **linear excitations** of the “**mystery object**”.

Requirement: Nonperturbative Definition of Superstring Theory

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Point particle theory

- Step 1: classical mechanics of point particles.
- Step 2: quantum mechanical scattering of point particles (Feynman diagrams).
- Step 3: Nonperturbative approach: **point particles** \rightarrow **quantum fields**, **particles** are **point-like excitations** for the fields.

String theory

- Step 1: classical mechanics of strings (classical field theory)
- Step 2: quantum mechanical scattering of strings.
- Step 3: Nonperturbative approach: **strings** \rightarrow “**mystery object**”, **strings** are **linear excitations** of the “**mystery object**”.

Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2108.1152

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Starting point: “mystery object” is a quantum mechanical matrix model, the **BFSS matrix model**. → **no space**.

We consider the initial state to be a **thermal high temperature state**. → **no time**.

- BFSS model is a **quantum mechanical model** of $d + 1$ $N \times N$ Hermitean matrices.
- Note: no space!
- Note: no singularities!
- Note: BFSS matrix model is a proposed non-perturbative definition of M-theory: 10 dimensional superstring theory emerges in the $N \rightarrow \infty$ limit.

Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2108.1152

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Starting point: “mystery object” is a quantum mechanical matrix model, the **BFSS matrix model**. → **no space**.

We consider the initial state to be a **thermal high temperature state**. → **no time**.

- BFSS model is a **quantum mechanical model** of $d + 1$ $N \times N$ Hermitean matrices.
- Note: no space!
- Note: no singularities!
- Note: BFSS matrix model is a proposed non-perturbative definition of M-theory: 10 dimensional superstring theory emerges in the $N \rightarrow \infty$ limit.

Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2108.1152

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Starting point: “mystery object” is a quantum mechanical matrix model, the **BFSS matrix model**. → **no space**.

We consider the initial state to be a **thermal high temperature state**. → **no time**.

- BFSS model is a **quantum mechanical model** of $d + 1$ $N \times N$ Hermitean matrices.
- Note: no space!
- Note: no singularities!
- Note: BFSS matrix model is a proposed non-perturbative definition of M-theory: 10 dimensional superstring theory emerges in the $N \rightarrow \infty$ limit.

Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2108.1152

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Starting point: “mystery object” is a quantum mechanical matrix model, the **BFSS matrix model**. → **no space**.

We consider the initial state to be a **thermal high temperature state**. → **no time**.

- BFSS model is a **quantum mechanical model** of $d + 1$ $N \times N$ Hermitean matrices.
- Note: no space!
- Note: no singularities!
- Note: BFSS matrix model is a proposed non-perturbative definition of M-theory: 10 dimensional superstring theory emerges in the $N \rightarrow \infty$ limit.

Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2108.1152

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Starting point: “mystery object” is a quantum mechanical matrix model, the **BFSS matrix model**. → **no space**.

We consider the initial state to be a **thermal high temperature state**. → **no time**.

- BFSS model is a **quantum mechanical model** of $d + 1$ $N \times N$ Hermitean matrices.
- Note: no space!
- Note: no singularities!
- Note: BFSS matrix model is a proposed non-perturbative definition of M-theory: 10 dimensional superstring theory emerges in the $N \rightarrow \infty$ limit.

BFSS Model

T. Banks, W. Fischler, S. Shenker and L. Susskind, Phys. Rev. D **55**, 5112 (1997), B. de Wit, J. Hoppe and H. Nicolai, Nucl. Phys. **B305** (1988), 545.

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

$$L = \frac{1}{2g^2} [\text{Tr}(\frac{1}{2}(D_t X_i)^2 - \frac{1}{4}[X_i, X_j]^2)] + L_f$$

- $X_i, i = 1, \dots, d$ are $N \times N$ Hermitean matrices.
- D_t : gauge covariant derivative (contains a matrix A_0)

't Hooft limit: $N \rightarrow \infty$ with $\lambda \equiv g^2 N = g_s l_s^{-3} N$ fixed.

Note: It is precisely in $d = 9$ that both a supersymmetric extension is possible and a normalizable zero energy state exists (J. Froehlich, G-M. Graf, D. Hasler, J. Hoppe and S-T. Yau, hep-th/9904182).

BFSS Model

T. Banks, W. Fischler, S. Shenker and L. Susskind, Phys. Rev. D **55**, 5112 (1997), B. de Wit, J. Hoppe and H. Nicolai, Nucl. Phys. **B305** (1988), 545.

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

$$L = \frac{1}{2g^2} [\text{Tr}(\frac{1}{2}(D_t X_i)^2 - \frac{1}{4}[X_i, X_j]^2)] + L_f$$

- $X_i, i = 1, \dots, d$ are $N \times N$ Hermitean matrices.
- D_t : gauge covariant derivative (contains a matrix A_0)

't Hooft limit: $N \rightarrow \infty$ with $\lambda \equiv g^2 N = g_s l_s^{-3} N$ fixed.

Note: It is precisely in $d = 9$ that both a supersymmetric extension is possible and a normalizable zero energy state exists (J. Froehlich, G-M. Graf, D. Hasler, J. Hoppe and S-T. Yau, hep-th/9904182).

Thermal Initial State

N. Kawahara, J. Nishimura and S. Takeuchi, JHEP **12**, 103 (2007)

Emergent

R. Brandenberger

Introduction

Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Consider a high temperature state.
- Matsubara expansion:

$$X_i(t) = \sum_n X_i^n e^{2\pi i n t T}$$

- $S_{BFSS} = S_{IKKT} + \mathcal{O}(1/T)$
- S_{IKKT} : contribution of the $n = 0$ modes.
- At high temperatures, the bosonic sector of the (Euclidean) BFSS model is well approximated by the bosonic sector of the (Euclidean) **IKKT matrix model**.

$$A_i \equiv T^{-1/4} X_i^0$$

Thermal Initial State

N. Kawahara, J. Nishimura and S. Takeuchi, JHEP **12**, 103 (2007)

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- Consider a high temperature state.
- Matsubara expansion:

$$X_i(t) = \sum_n X_i^n e^{2\pi i T t}$$

- $S_{BFSS} = S_{IKKT} + \mathcal{O}(1/T)$
- S_{IKKT} : contribution of the $n = 0$ modes.
- At high temperatures, the bosonic sector of the (Euclidean) BFSS model is well approximated by the bosonic sector of the (Euclidean) **IKKT matrix model**.

$$A_i \equiv T^{-1/4} X_i^0$$

Thermal Initial State

N. Kawahara, J. Nishimura and S. Takeuchi, JHEP **12**, 103 (2007)

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- Consider a high temperature state.
- Matsubara expansion:

$$X_i(t) = \sum_n X_i^n e^{2\pi i T t}$$

- $S_{BFSS} = S_{IKKT} + \mathcal{O}(1/T)$
- S_{IKKT} : contribution of the $n = 0$ modes.
- At high temperatures, the bosonic sector of the (Euclidean) BFSS model is well approximated by the bosonic sector of the (Euclidean) **IKKT matrix model**.

$$A_i \equiv T^{-1/4} X_i^0$$

Thermal Initial State

N. Kawahara, J. Nishimura and S. Takeuchi, JHEP 12, 103 (2007)

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- Consider a high temperature state.
- Matsubara expansion:

$$X_i(t) = \sum_n X_i^n e^{2\pi i T t}$$

- $S_{BFSS} = S_{IKKT} + \mathcal{O}(1/T)$
- S_{IKKT} : contribution of the $n = 0$ modes.
- At high temperatures, the bosonic sector of the (Euclidean) BFSS model is well approximated by the bosonic sector of the (Euclidean) **IKKT matrix model**.

$$A_i \equiv T^{-1/4} X_i^0$$

Idea

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Space-time background** emerges from the Matsubara zero modes.
- Non-zero modes → **thermal fluctuations** which live on the background.

IKKT Matrix Model

N. Ishibashi, H. Kawai, Y. Kitazawa and A. Tsuchiya, Nucl. Phys. B **498**, 467 (1997).

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

Proposed as a non-perturbative definition of the IIB Superstring theory.

Action:

$$S_{IKKT} = -\frac{1}{g^2} \text{Tr} \left(\frac{1}{4} [A^a, A^b][A_a, A_b] + \frac{i}{2} \bar{\psi}_\alpha (C\Gamma^a)_{\alpha\beta} [A_a, \psi_\beta] \right),$$

Partition function:

$$Z = \int dA d\psi e^{iS}$$

Emergent Time from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**.
- Work in the basis in which A_0 is diagonal.
- Numerical studies: $\frac{1}{N} \langle \text{Tr} A_0^2 \rangle \sim \kappa N$
- $\rightarrow t_{max} \sim \sqrt{N}$
- $\rightarrow \Delta t \sim \frac{1}{\sqrt{N}}$
- \rightarrow infinite continuous time.

Emergent Time from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**.
- Work in the basis in which A_0 is diagonal.
- Numerical studies: $\frac{1}{N} \langle \text{Tr} A_0^2 \rangle \sim \kappa N$
- $\rightarrow t_{max} \sim \sqrt{N}$
- $\rightarrow \Delta t \sim \frac{1}{\sqrt{N}}$
- \rightarrow infinite continuous time.

Emergent Time from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**.
- Work in the basis in which A_0 is diagonal.
- Numerical studies: $\frac{1}{N} \langle \text{Tr} A_0^2 \rangle \sim \kappa N$
 - $\rightarrow t_{max} \sim \sqrt{N}$
 - $\rightarrow \Delta t \sim \frac{1}{\sqrt{N}}$
 - \rightarrow infinite continuous time.

Emergent Time from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**.
- Work in the basis in which A_0 is diagonal.
- Numerical studies: $\frac{1}{N} \langle \text{Tr} A_0^2 \rangle \sim \kappa N$
- $\rightarrow t_{max} \sim \sqrt{N}$
- $\rightarrow \Delta t \sim \frac{1}{\sqrt{N}}$
- \rightarrow infinite continuous time.

Emergent Space from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Note: work in Minkowski signature!

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: A_j matrices elements decay when going away from the diagonal.
 - $\sum_i \langle |A_i|_{ab}^2 \rangle$ decays when $|a - b| > n_c$
 - $n_c \sim \sqrt{N}$
 - $\sum_i \langle |A_i|_{ab}^2 \rangle \sim \text{constant}$ when $|a - b| < n_c$

Emergent Space from Matrix Theory

Y. Ito, J. Nishimura and A. Tsuchiya, arXiv:1506.04795

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Note: work in Minkowski signature!

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: A_i matrices elements decay when going away from the diagonal.
- $\sum_i \langle |A_i|_{ab}^2 \rangle$ decays when $|a - b| > n_c$
- $n_c \sim \sqrt{N}$
- $\sum_i \langle |A_i|_{ab}^2 \rangle \sim \text{constant}$ when $|a - b| < n_c$

Emergent Space from Matrix Theory

S. Kim, J. Nishimura and A. Tsuchiya, arXiv:1108.1540

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: A_i matrices elements decay when going away from the diagonal.
- Pick $n \times n$ blocks $\tilde{A}_i(t)$ about the diagonal ($n < n_c$)

Emergent

R. Brandenberger

Introduction

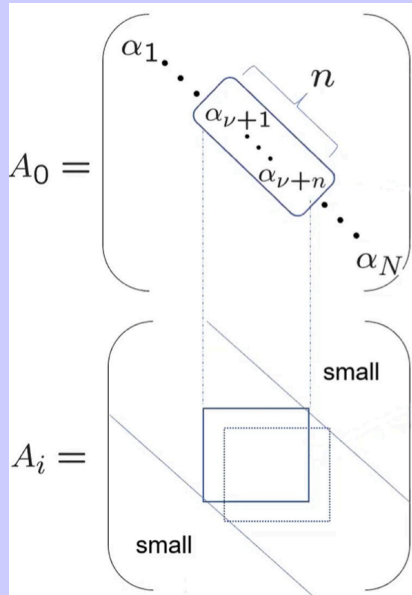
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Spontaneous Symmetry Breaking in Matrix Theory

J. Nishimura, PoS CORFU 2019, 178 (2020) [arXiv:2006.00768 [hep-lat]].

Emergent

- Eigenvalues of A_0 become emergent time, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal.
- Work in the basis in which A_0 is diagonal: A_i matrices become block diagonal.
- **Extent of space** in direction i

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

$$x_i(t)^2 \equiv \left\langle \frac{1}{n} \text{Tr}(\bar{A}_i(t))^2 \right\rangle,$$

- In a thermal state there is spontaneous symmetry breaking: $SO(9) \rightarrow SO(6) \times SO(3)$: three dimensions of space become larger, the others are confined.
[J. Nishimura and G. Vernizzi, JHEP 0004, 015 (2000);
]S.-W. Kim, J. Nishimura and A. Tsuchiya, Phys. Rev. Lett. 109, 011601 (2012)]

Spontaneous Symmetry Breaking in Matrix Theory

J. Nishimura, PoS CORFU 2019, 178 (2020) [arXiv:2006.00768 [hep-lat]].

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

- Eigenvalues of A_0 become emergent time, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal.
- Work in the basis in which A_0 is diagonal: A_i matrices become block diagonal.
- **Extent of space** in direction i

$$x_i(t)^2 \equiv \left\langle \frac{1}{n} \text{Tr}(\bar{A}_i(t))^2 \right\rangle,$$

- **In a thermal state there is spontaneous symmetry breaking: $SO(9) \rightarrow SO(6) \times SO(3)$:** three dimensions of space become larger, the others are confined.
[J. Nishimura and G. Vernizzi, JHEP **0004**, 015 (2000);
]S.-W. Kim, J. Nishimura and A. Tsuchiya, Phys. Rev. Lett. **109**, 011601 (2012)]

Emergent Metric from Matrix Theory

S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: pick n (**comoving spatial coordinate**) and consider the block matrix $\tilde{A}_i(t)$.
- **Physical distance** between $n_i = 0$ and n_i (**emergent space**):

$$l_{phys,i}^2(n_i, t) \equiv \left\langle \text{Tr}(\tilde{A}_i(t))^2 \right\rangle,$$

- $l_{phys,i}(n_i) \sim n_i$ (for $n_i < n_c$)
- **Emergent infinite and continuous space** in $N \rightarrow \infty$ limit.
- **Emergent metric** (S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468).

$$g_{ii}(n_i)^{1/2} = \frac{d}{dn_i} l_{phys,i}(n_i)$$

Emergent Metric from Matrix Theory

S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: pick n (**comoving spatial coordinate**) and consider the block matrix $\tilde{A}_i(t)$.
- **Physical distance** between $n_i = 0$ and n_i (**emergent space**):

$$l_{phys,i}^2(n_i, t) \equiv \left\langle \text{Tr}(\tilde{A}_i(t))^2 \right\rangle,$$

- $l_{phys,i}(n_i) \sim n_i$ (for $n_i < n_c$)
- **Emergent infinite and continuous space** in $N \rightarrow \infty$ limit.
- **Emergent metric** (S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468).

$$g_{ii}(n_i)^{1/2} = \frac{d}{dn_i} l_{phys,i}(n_i)$$

Emergent Metric from Matrix Theory

S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Eigenvalues of A_0 become **emergent time**, continuous in $N \rightarrow \infty$ limit.
- Work in the basis in which A_0 is diagonal: pick n (**comoving spatial coordinate**) and consider the block matrix $\tilde{A}_i(t)$.
- **Physical distance** between $n_i = 0$ and n_i (**emergent space**):

$$l_{phys,i}^2(n_i, t) \equiv \left\langle \text{Tr}(\tilde{A}_i(t))^2 \right\rangle,$$

- $l_{phys,i}(n_i) \sim n_i$ (for $n_i < n_c$)
- **Emergent infinite and continuous space** in $N \rightarrow \infty$ limit.
- **Emergent metric** (S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468).

$$g_{ii}(n_i)^{1/2} = \frac{d}{dn_i} l_{phys,i}(n_i)$$

No Flatness Problem in Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468

Emergent

Emergent metric:

$$g_{ii}(n_i)^{1/2} = \frac{d}{dn_i} l_{phys,i}(n_i)$$

Result:

$$g_{ii}(n_i, t) = \mathcal{A}(t)\delta_{ij} \quad i = 1, 2, 3$$

$SO(3)$ symmetry \rightarrow

$$g_{ij}(\mathbf{n}, t) = \mathcal{A}(t)\delta_{ij} \quad i = 1, 2, 3$$

\rightarrow spatially flat.

Note: Local Lorentz invariance emerges in $N \rightarrow \infty$ limit.

R. Brandenberger

Introduction

Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

No Flatness Problem in Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2206.12468

Emergent

Emergent metric:

$$g_{ii}(n_i)^{1/2} = \frac{d}{dn_i} I_{phys,i}(n_i)$$

Result:

$$g_{ii}(n_i, t) = \mathcal{A}(t)\delta_{ij} \quad i = 1, 2, 3$$

$SO(3)$ symmetry \rightarrow

$$g_{ij}(\mathbf{n}, t) = \mathcal{A}(t)\delta_{ij} \quad i = 1, 2, 3$$

\rightarrow **spatially flat.**

Note: Local Lorentz invariance emerges in $N \rightarrow \infty$ limit.

R. Brandenberger

Introduction

Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space**
- 5 Matrix Theory Cosmology
- 6 Conclusions

Physical Origin of the Emergence of Three Spatial Dimensions in IKKT Model

R.B. and J. Pasiecznik, arXiv:2409.00254

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Hypothesis:** winding D1-strings allow only three dimensions of space to become large.
- What are D1-strings in the IKKT matrix theory?
- D1-strings are solitonic matrix excitations.
- **Analogy:** particles are point-like excitations of fields in QFT.
- Thermal initial state contains all excitations of Type IIB string theory.

Physical Origin of the Emergence of Three Spatial Dimensions in IKKT Model

R.B. and J. Pasiecznik, arXiv:2409.00254

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Hypothesis:** winding D1-strings allow only three dimensions of space to become large.
- What are D1-strings in the IKKT matrix theory?
 - D1-strings are solitonic matrix excitations.
 - **Analogy:** particles are point-like excitations of fields in QFT.
 - Thermal initial state contains all excitations of Type IIB string theory.

Physical Origin of the Emergence of Three Spatial Dimensions in IKKT Model

R.B. and J. Pasiecznik, arXiv:2409.00254

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Hypothesis:** winding D1-strings allow only three dimensions of space to become large.
- What are D1-strings in the IKKT matrix theory?
- D1-strings are solitonic matrix excitations.
- **Analogy:** particles are point-like excitations of fields in QFT.
- Thermal initial state contains all excitations of Type IIB string theory.

Physical Origin of the Emergence of Three Spatial Dimensions in IKKT Model

R.B. and J. Pasiecznik, arXiv:2409.00254

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Hypothesis:** winding D1-strings allow only three dimensions of space to become large.
- What are D1-strings in the IKKT matrix theory?
- D1-strings are solitonic matrix excitations.
- **Analogy:** particles are point-like excitations of fields in QFT.
- Thermal initial state contains all excitations of Type IIB string theory.

Physical Origin of the Emergence of Three Spatial Dimensions in IKKT Model

R.B. and J. Pasiiecznik, arXiv:2409.00254

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **Free energy** consideration: a spatial dimension can only expand if winding D1 strings can annihilate.
- **In the supersymmetric IKKT model**, the **force between parallel D1-strings vanishes** (to leading order).
- → decay of winding strings requires crossing of world sheets.
- **Vanishing probability** in more than 3 large spatial dimensions.
- → **precisely three spatial dimensions become large.**

Note: This mechanism carries over to the BFSS matrix model (RB and JP, in preparation).

Some details

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Consider a **matrix background** (Note: breaks supersymmetry)

$$A_{\mu}^b = A_{\mu}^q + A_{\mu}^{D1},$$

where A_{μ}^{D1} is the classical matrix configuration for a pair of parallel D1-strings along the 1 axis separated by a distance b along the 2 axis.

Consider **fluctuations** about this background, insert into the expression for the **one loop effective action** W_{eff} .

Result: W_{eff} independent of $b \rightarrow$ **vanishing force between the parallel D1-strings.**

Note: supersymmetry of the IKKT matrix model is crucial.

Some details

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

Consider a **matrix background** (Note: breaks supersymmetry)

$$A_{\mu}^b = A_{\mu}^q + A_{\mu}^{D1},$$

where A_{μ}^{D1} is the classical matrix configuration for a pair of parallel D1-strings along the 1 axis separated by a distance b along the 2 axis.

Consider **fluctuations** about this background, insert into the expression for the **one loop effective action** W_{eff} .

Result: W_{eff} independent of $b \rightarrow$ vanishing force between the parallel D1-strings.

Note: supersymmetry of the IKKT matrix model is crucial.

Some details

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Consider a **matrix background** (Note: breaks supersymmetry)

$$A_{\mu}^b = A_{\mu}^q + A_{\mu}^{D1},$$

where A_{μ}^{D1} is the classical matrix configuration for a pair of parallel D1-strings along the 1 axis separated by a distance b along the 2 axis.

Consider **fluctuations** about this background, insert into the expression for the **one loop effective action** W_{eff} .

Result: W_{eff} independent of $b \rightarrow$ **vanishing force between the parallel D1-strings.**

Note: **supersymmetry of the IKKT matrix model is crucial.**

Some details

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

$$A_0^{D1} = \begin{bmatrix} \frac{T}{\sqrt{2\pi n}} q & 0 \\ 0 & \frac{T}{\sqrt{2\pi n}} q' \end{bmatrix}$$

$$A_1^{D1} = \begin{bmatrix} \frac{L}{\sqrt{2\pi n}} p & 0 \\ 0 & \frac{L}{\sqrt{2\pi n}} p' \end{bmatrix}$$

$$A_2^{D1} = \begin{bmatrix} b/2 & 0 \\ 0 & -b/2 \end{bmatrix}$$

$$[q, p] = i,$$

with eigenvalue distribution

$$0 \leq q, p \leq \sqrt{2\pi N}$$

Some details

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

$$A_0^{D1} = \begin{bmatrix} \frac{T}{\sqrt{2\pi n}} q & 0 \\ 0 & \frac{T}{\sqrt{2\pi n}} q' \end{bmatrix}$$

$$A_1^{D1} = \begin{bmatrix} \frac{L}{\sqrt{2\pi n}} p & 0 \\ 0 & \frac{L}{\sqrt{2\pi n}} p' \end{bmatrix}$$

$$A_2^{D1} = \begin{bmatrix} b/2 & 0 \\ 0 & -b/2 \end{bmatrix}$$

$$[q, p] = i,$$

with eigenvalue distribution

$$0 \leq q, p \leq \sqrt{2\pi N}$$

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

**Matrix Theory
Cosmology**

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology**
- 6 Conclusions

Late Time Dynamics

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Consider the expansion of the 3-d large space.
- Late time evolution given by the classical matrix equations of motion.

- Result:

$$\mathcal{A}(t) \sim t^{1/2}$$

- Note: no sign of a cosmological constant.

Late Time Dynamics

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Consider the expansion of the 3-d large space.
- Late time evolution given by the classical matrix equations of motion.

- Result:

$$\mathcal{A}(t) \sim t^{1/2}$$

- Note: no sign of a cosmological constant.

Emergent Universe as a Solution

Emergent

R. Brandenberger

Introduction

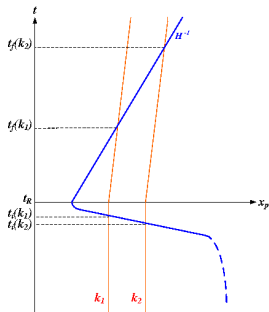
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Matrix Theory Cosmology

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

**Matrix Theory
Cosmology**

Conclusions

- **Thermal correlation functions** in the three large spatial dimensions calculated in the high temperature state of the BFSS model (following the formalism developed in String Gas Cosmology).
- → curvature fluctuations and gravitational waves.

Matrix Theory Cosmology: Thermal Fluctuations

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Start with the **BFSS partition function** .
- Note: $\frac{1}{T}$ correction terms in the BFSS action are crucial!
- Calculate matter correlation functions in the emergent phase.
- For fixed k , convert the matter fluctuations to metric fluctuations at Hubble radius crossing $t = t_i(k)$.
- Evolve the metric fluctuations for $t > t_i(k)$ using the usual theory of cosmological perturbations.

Note: the matter correlation functions are given by partial derivatives of the **finite temperature partition function** with respect to T (density fluctuations) or R (pressure perturbations).

Extracting the Metric Fluctuations

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^2 = a^2(\eta) \left((1 + 2\Phi) d\eta^2 - [(1 - 2\Phi)\delta_{ij} + h_{ij}] dx^i dx^j \right).$$

Inserting into the perturbed Einstein equations yields

$$\langle |\Phi(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0_0(k) \delta T^0_0(k) \rangle,$$

$$\langle |h(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i_j(k) \delta T^i_j(k) \rangle.$$

Note: We assume the validity of the semi-classical Einstein equations in the far IR.

Extracting the Metric Fluctuations

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^2 = a^2(\eta) \left((1 + 2\Phi) d\eta^2 - [(1 - 2\Phi)\delta_{ij} + h_{ij}] dx^i dx^j \right).$$

Inserting into the perturbed Einstein equations yields

$$\langle |\Phi(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0_0(k) \delta T^0_0(k) \rangle,$$

$$\langle |h(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i_j(k) \delta T^i_j(k) \rangle.$$

Note: We assume the validity of the semi-classical Einstein equations in the far IR.

Computation of Fluctuations

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

**Matrix Theory
Cosmology**

Conclusions

$$P(k) = k^3 (\delta\Phi(k))^2 = 16\pi^2 G^2 k^2 T^2 C_V(R)$$

$$C_V(R) = \frac{\partial}{\partial T} E(R)$$

$$E = -\frac{\partial}{\partial \beta} \ln Z(\beta)$$

Matrix Theory Cosmology: Results

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Thermal fluctuations in the emergent phase \rightarrow

- **Scale-invariant spectrum of curvature fluctuations**
- **With a Poisson contribution for UV scales.**
- **Scale-invariant spectrum of gravitational waves.**

Prediction: $n_t = 1 - n_s$

Matrix Theory Cosmology: Results

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Thermal fluctuations in the emergent phase \rightarrow

- **Scale-invariant spectrum of curvature fluctuations**
- **With a Poisson contribution for UV scales.**
- **Scale-invariant spectrum of gravitational waves.**

Prediction: $n_t = 1 - n_s$

Matrix Theory Cosmology: Results

S. Brahma, R.B. and S. Laliberte, arXiv:2107.11512

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Thermal fluctuations in the emergent phase \rightarrow

- **Scale-invariant spectrum of curvature fluctuations**
- With a Poisson contribution for UV scales.
- **Scale-invariant spectrum of gravitational waves.**

Prediction: $n_t = 1 - n_s$

Status of the Research Program on Matrix Cosmology

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

→ BFSS matrix model yields emergent infinite space, emergent infinite time, emergent spatially flat metric and an emergent early universe phase with thermal fluctuations leading to scale-invariant curvature fluctuations and gravitational waves.

Open Problems

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Include the effects of the fermionic sector for late time cosmology (Y. Lei, J. Paciesznik, RB; in progress)
- Understand **phase transition** to the expanding phase of Big Bang Cosmology (would allow the determination of n_s).
- Understand the emergence of a **low energy effective field theory**, and in particular the **emergence of GR**.
- Focus on localized excitations of matter.
- Connection with other approaches to the emergence of space.
- What about Dark Energy?

Open Problems

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Include the effects of the fermionic sector for late time cosmology (Y. Lei, J. Paciesznik, RB; in progress)
- Understand **phase transition** to the expanding phase of Big Bang Cosmology (would allow the determination of n_s).
- Understand the emergence of a **low energy effective field theory**, and in particular the **emergence of GR**.
- Focus on localized excitations of matter.
- Connection with other approaches to the emergence of space.
- What about Dark Energy?

Plan

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- 1 Introduction
- 2 Trans-Planckian Censorship Criterion
- 3 Emergent Metric Space-Time from the BFSS Matrix Model
- 4 Physical Origin for 3D Space
- 5 Matrix Theory Cosmology
- 6 **Conclusions**

Conclusions

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **BFSS matrix model** is a proposal for a non-perturbative definition of superstring theory. Consider a **high temperature state** of the BFSS model.
- → **emergent time, 3D space and metric**. Emergent space is **spatially flat** and infinite.
- **Thermal fluctuations** of the BFSS model → **scale-invariant spectra of cosmological perturbations and gravitational waves**.
- **Horizon problem, flatness problem and formation of structure problem** of Standard Big Bang Cosmology resolved **without requiring inflation**.
- Transition from an emergent phase to the radiation phase of expansion. **No inflation, no cosmological constant**.

Conclusions

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- **BFSS matrix model** is a proposal for a non-perturbative definition of superstring theory. Consider a **high temperature state** of the BFSS model.
- → **emergent time, 3D space and metric**. Emergent space is **spatially flat** and infinite.
- **Thermal fluctuations** of the BFSS model → **scale-invariant spectra of cosmological perturbations and gravitational waves**.
- **Horizon problem, flatness problem and formation of structure problem** of Standard Big Bang Cosmology resolved **without requiring inflation**.
- Transition from an emergent phase to the radiation phase of expansion. **No inflation, no cosmological constant**.

String Gas Cosmology

R.B. and C. Vafa, *Nucl. Phys. B*316:391 (1989)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Idea: make use of the **new symmetries** and **new degrees of freedom** which string theory provides to construct a new theory of the very early universe.

Assumption: Matter is a gas of fundamental strings

Assumption: Space is compact, e.g. a torus.

Key points:

- **New degrees of freedom:** string oscillatory modes
- Leads to a **maximal temperature** for a gas of strings, the Hagedorn temperature
- **New degrees of freedom:** string winding modes
- Leads to a **new symmetry:** physics at large R is equivalent to physics at small R

String Gas Cosmology

R.B. and C. Vafa, *Nucl. Phys. B*316:391 (1989)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Idea: make use of the **new symmetries** and **new degrees of freedom** which string theory provides to construct a new theory of the very early universe.

Assumption: Matter is a gas of fundamental strings

Assumption: Space is compact, e.g. a torus.

Key points:

- **New degrees of freedom**: string oscillatory modes
- Leads to a **maximal temperature** for a gas of strings, the Hagedorn temperature
- **New degrees of freedom**: string winding modes
- Leads to a **new symmetry**: physics at large R is equivalent to physics at small R

T-Duality

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

T-Duality

- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \rightarrow 1/R$ $(n, m) \rightarrow (m, n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level \rightarrow existence of D-branes

Note: usual EFTs have lost the T-duality symmetry.

Adiabatic Considerations

R.B. and C. Vafa, *Nucl. Phys. B*316:391 (1989)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

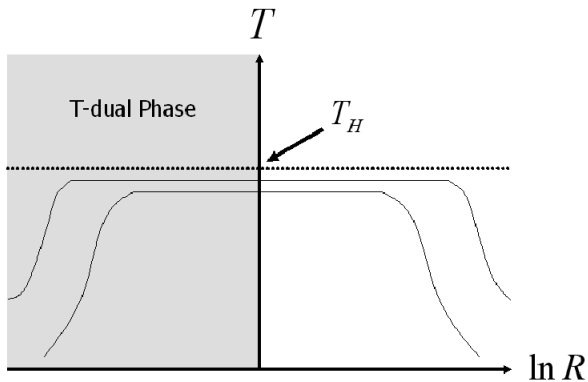
Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Temperature-size relation in string gas cosmology



Background for string gas cosmology

Emergent

R. Brandenberger

Introduction

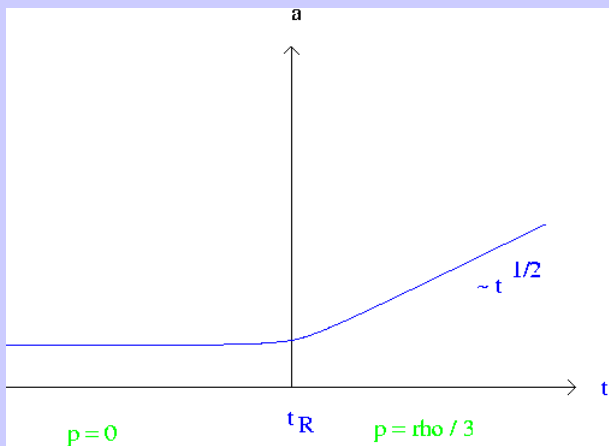
Trans-Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions



Origin of 3-d Space

R.B. and C. Vafa, *Nucl. Phys. B*316:391 (1989)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- A spatial dimension can only expand if string winding modes can annihilate into loops.
- This process only allows 3 spatial dimensions to become large.
- $SO(9) \rightarrow SO(6) \times SO(3)$ symmetry breaking.

Structure formation in string gas cosmology

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett.* 97:021302 (2006)

Emergent

R. Brandenberger

Introduction

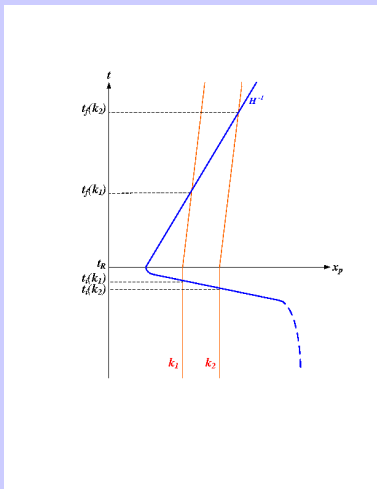
Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions



N.B. Perturbations originate as thermal string gas fluctuations.

Method

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Calculate matter correlation functions in the Hagedorn phase (neglecting the metric fluctuations)
- For fixed k , convert the matter fluctuations to metric fluctuations at Hubble radius crossing $t = t_i(k)$
- Evolve the metric fluctuations for $t > t_i(k)$ using the usual theory of cosmological perturbations

Note: the matter correlation functions are given by partial derivatives of the **finite temperature string gas partition function** with respect to T (density fluctuations) or R (pressure perturbations).

Method

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

- Calculate matter correlation functions in the Hagedorn phase (neglecting the metric fluctuations)
- For fixed k , convert the matter fluctuations to metric fluctuations at Hubble radius crossing $t = t_i(k)$
- Evolve the metric fluctuations for $t > t_i(k)$ using the usual theory of cosmological perturbations

Note: the matter correlation functions are given by partial derivatives of the **finite temperature string gas partition function** with respect to T (density fluctuations) or R (pressure perturbations).

Extracting the Metric Fluctuations

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^2 = a^2(\eta) \left((1 + 2\Phi) d\eta^2 - [(1 - 2\Phi)\delta_{ij} + h_{ij}] dx^i dx^j \right).$$

Inserting into the perturbed Einstein equations yields

$$\langle |\Phi(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^0_0(k) \delta T^0_0(k) \rangle,$$

$$\langle |h(k)|^2 \rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i_j(k) \delta T^i_j(k) \rangle.$$

Power Spectrum of Cosmological Perturbations

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Key ingredient: For **thermal fluctuations**:

$$\langle \delta\rho^2 \rangle = \frac{T^2}{R^6} C_V.$$

Key ingredient: For **string thermodynamics** in a compact space

$$C_V \approx 2 \frac{R^2 / \ell_s^3}{T (1 - T/T_H)}.$$

Power Spectrum of Cosmological Perturbations

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Key ingredient: For **thermal fluctuations**:

$$\langle \delta\rho^2 \rangle = \frac{T^2}{R^6} C_V.$$

Key ingredient: For **string thermodynamics** in a compact space

$$C_V \approx 2 \frac{R^2 / \ell_s^3}{T(1 - T/T_H)}.$$

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

Power spectrum of cosmological fluctuations

$$\begin{aligned}P_{\Phi}(k) &= 8G^2 k^{-1} \langle |\delta\rho(k)|^2 \rangle \\&= 8G^2 k^2 \langle (\delta M)^2 \rangle_R \\&= 8G^2 k^{-4} \langle (\delta\rho)^2 \rangle_R \\&= 8G^2 \frac{T}{\ell_s^3} \frac{1}{1 - T/T_H}\end{aligned}$$

Structure formation in string gas cosmology

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett.* 97:021302 (2006)

Emergent

R. Brandenberger

Introduction

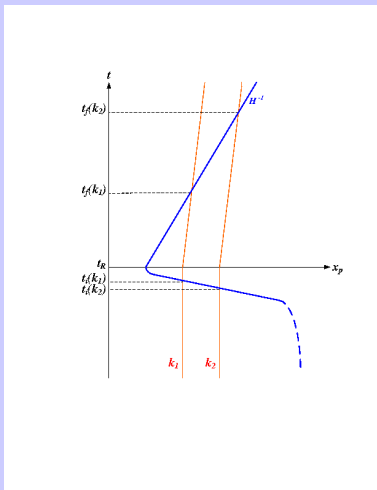
Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions



N.B. Perturbations originate as thermal string gas fluctuations.

Power spectrum of cosmological fluctuations

$$\begin{aligned}
 P_{\Phi}(k) &= 8G^2 k^{-1} \langle |\delta\rho(k)|^2 \rangle \\
 &= 8G^2 k^2 \langle (\delta M)^2 \rangle_R \\
 &= 8G^2 k^{-4} \langle (\delta\rho)^2 \rangle_R \\
 &= 8G^2 \frac{T}{\ell_S^3} \frac{1}{1 - T/T_H}
 \end{aligned}$$

Key features:

- **scale-invariant** like for inflation
- **slight red tilt** like for inflation

Spectrum of Gravitational Waves

R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett.* (2007)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

$$\begin{aligned}P_h(k) &= 16\pi^2 G^2 k^{-1} \langle |T_{ij}(k)|^2 \rangle \\ &= 16\pi^2 G^2 k^{-4} \langle |T_{ij}(R)|^2 \rangle \\ &\sim 16\pi^2 G^2 \frac{T}{\ell_s^3} (1 - T/T_H)\end{aligned}$$

Key ingredient for **string thermodynamics**

$$\langle |T_{ij}(R)|^2 \rangle \sim \frac{T}{\ell_s^3 R^4} (1 - T/T_H)$$

Key features:

- scale-invariant (like for inflation)
- slight blue tilt (unlike for inflation)
- Prediction: $n_t = 1 - n_s$.

Spectrum of Gravitational Waves

R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett.* (2007)

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

$$\begin{aligned}P_h(k) &= 16\pi^2 G^2 k^{-1} \langle |T_{ij}(k)|^2 \rangle \\ &= 16\pi^2 G^2 k^{-4} \langle |T_{ij}(R)|^2 \rangle \\ &\sim 16\pi^2 G^2 \frac{T}{\ell_s^3} (1 - T/T_H)\end{aligned}$$

Key ingredient for **string thermodynamics**

$$\langle |T_{ij}(R)|^2 \rangle \sim \frac{T}{\ell_s^3 R^4} (1 - T/T_H)$$

Key features:

- scale-invariant (like for inflation)
- **slight blue tilt (unlike for inflation)**
- Prediction: $n_t = 1 - n_s$.

Spectrum of Gravitational Waves

R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett.* (2007)

Emergent

R. Brandenberger

Introduction

Trans-Planckian Censorship Criterion

Matrix Theory

3D Space

Matrix Theory Cosmology

Conclusions

$$\begin{aligned} P_h(k) &= 16\pi^2 G^2 k^{-1} \langle |T_{ij}(k)|^2 \rangle \\ &= 16\pi^2 G^2 k^{-4} \langle |T_{ij}(R)|^2 \rangle \\ &\sim 16\pi^2 G^2 \frac{T}{\ell_s^3} (1 - T/T_H) \end{aligned}$$

Key ingredient for **string thermodynamics**

$$\langle |T_{ij}(R)|^2 \rangle \sim \frac{T}{\ell_s^3 R^4} (1 - T/T_H)$$

Key features:

- scale-invariant (like for inflation)
- **slight blue tilt** (unlike for inflation)
- **Prediction: $n_t = 1 - n_s$.**

Achilles Heel of String Gas Cosmology

Emergent

R. Branden-
berger

Introduction

Trans-
Planckian
Censorship
Criterion

Matrix Theory

3D Space

Matrix Theory
Cosmology

Conclusions

No dynamics for the Hagedorn phase!