Swampland and TCC Constraints on Inflation and Dark Energy

Robert Brandenberger
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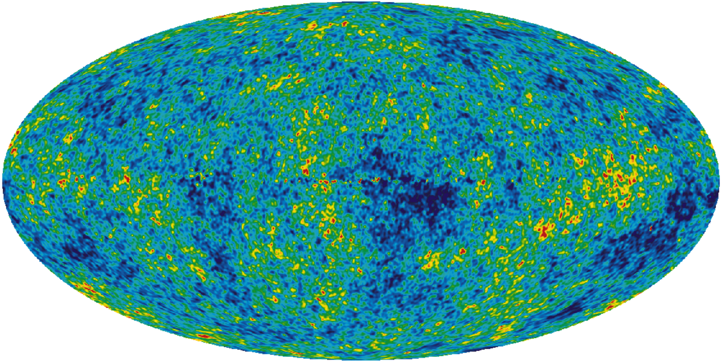
Pont Avignon Conference, Dec. 9, 2020

Outline

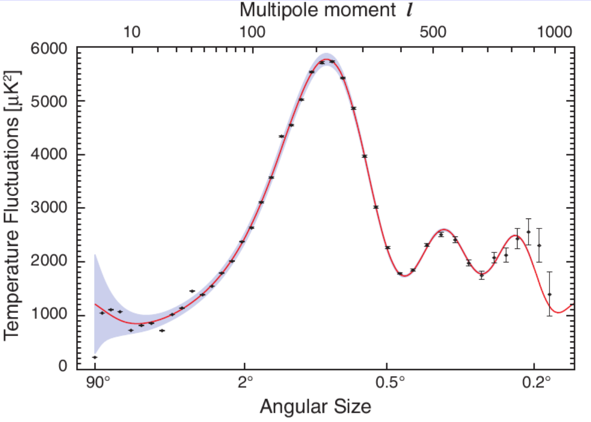
Plan

Map of the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Angular Power Spectrum of CMB Anisotropies



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Criteria

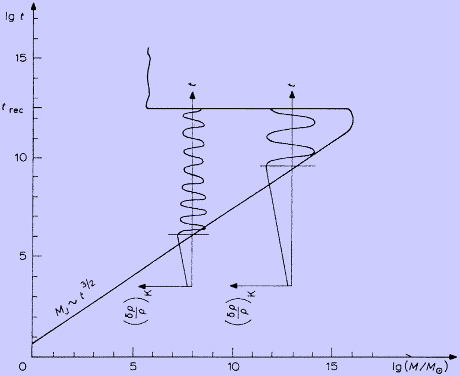

Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

1970 p

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).

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

Key Challenge

How does one obtain such a spectrum?

- Inflationary Cosmology is the first scenario based on causal physics which yields such a spectrum.
- But it is not the only one.

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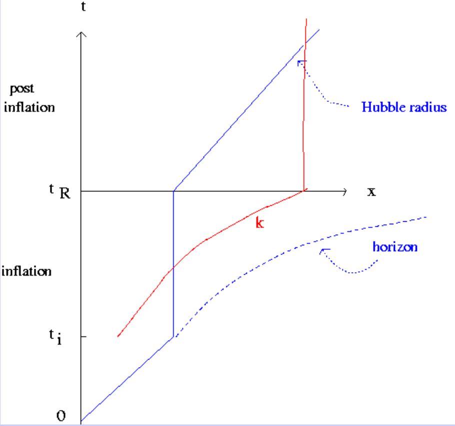
Hubble Radius vs. Horizon

- Horizon: Forward light cone of a point on the initial Cauchy surface.
- Horizon: region of causal contact.
- Hubble radius: $l_H(t) = H^{-1}(t)$ inverse expansion rate.
- Hubble radius: local concept, relevant for dynamics of cosmological fluctuations.
- In Standard Big Bang Cosmology: Hubble radius = horizon.
- In any theory which can provide a mechanism for the origin of structure: Hubble radius $\neq$ horizon.

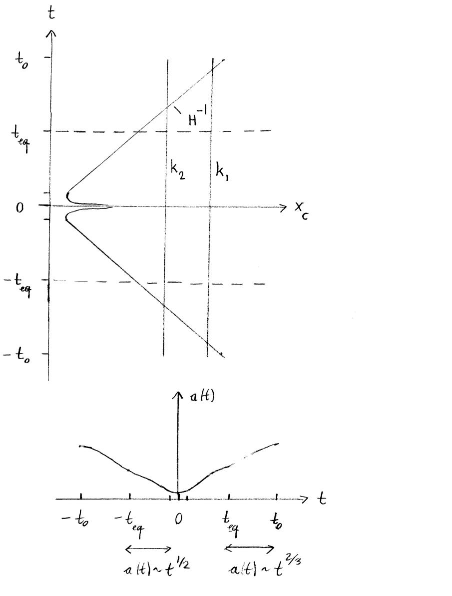
Criteria for a Successful Early Universe Scenario

- 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.
- Squeezing of fluctuations on super-Hubble scales in order to obtain the acoustic oscillations in the CMB angular power spectrum.
- Mechanism for producing a scale-invariant spectrum of curvature fluctuations on super-Hubble scales.

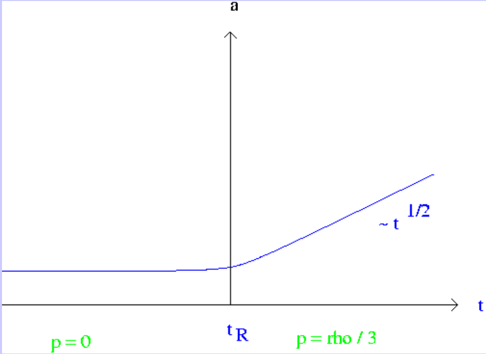
Inflation as a Solution



Bounce as a Solution



Emergent Universe
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

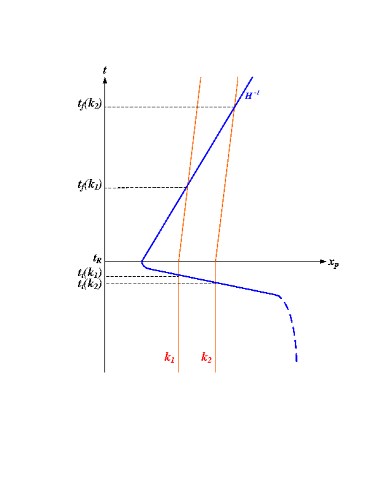


Emergent Universe as a Solution

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

String Cosmology

R. Brandenberger



Plan

Cosmological Inflation: The Current Paradigm of Early Universe Cosmology

- Cosmological Inflation has become the **paradigm of early universe cosmology.**
- Idea: phase of accelerated (almost exponential) expansion of space in the early universe, for $t_i < t < t_R$.
- Solves some problems of Standard Big Bang Cosmology (explains the isotropy and spatial flatness of the universe).
- Provides a causal mechanism for structure formation.
- Inflationary cosmology has an initial singularity [Borde and Vilenkin].

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Cosmological Inflation

- Space-time described by the Einstein-Hilbert action.
- Matter dominated by a slowly rolling scalar field φ.
- in order to obtain equation of state $p \simeq -\rho$.
- Quantum vacuum fluctuations during the inflationary phase evolve into an **almost scale-invariant spectrum of cosmological perturbations** (V. Mukhanov and G. Chibisov, 1982).

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Lagrangian for a Scalar Field

Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)$$

Energy density and pressure of a scalar field:

$$\rho = \frac{1}{2}\dot{\varphi}^2 + \frac{1}{2}(\nabla\varphi)^2 + V(\varphi)$$
$$p = \frac{1}{2}\dot{\varphi}^2 - \frac{1}{6}(\nabla\varphi)^2 - V(\varphi)$$

Conditions for Inflation

- Equation of motion

$$\ddot{\varphi} + 3H\dot{\varphi} = -V'(\varphi)$$

- Slow roll condition 1:

$$\frac{V'}{V} m_{pl} \ll 1 \, .$$

- Slow roll condition 2:

$$\frac{V''}{V} m_{pl}^2 \ll 1 \, .$$

- Large field range $\delta\varphi > m_{pl}$ required if inflation is to be a local attractor in initial condition space (R.B., arXiv:1601.01918 for a review).

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- Does inflation emerge from a UV complete theory?

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Obstacles to Obtaining Inflation

- Swampland conjectures: Inflation hard to realize in superstring theory.
- Trans-Planckian Censorship Conjecture: causality and unitarity problem for inflation.

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Swampland

- There is a vast landscape of **effective field theories.**
- Any space-time dimension, and number of fields, any shape of the potential, any field range.
- Superstring theory is very **constraining**.
- Only a **small subset** of all EFTs is consistent with string theory.
- The rest lie in the swampland.

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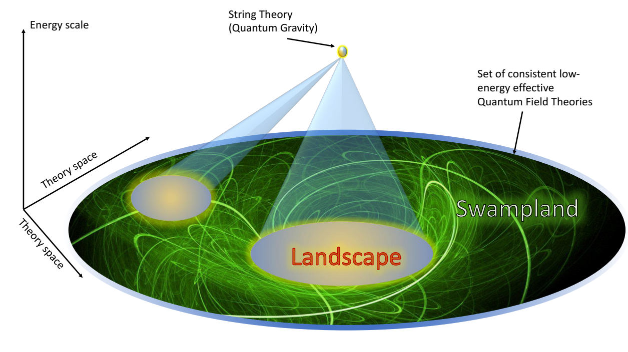
Energy scale
String Theory
(Quantum Gravity)
Set of consistent low-energy effective Quantum Field Theories
Theory space
Theory space
Swampland
Landscape

Swamplap Conjectures

H. Ooguri and C. Vafa, hep-th/0605264; G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, arXiv:1806.08362; S. Garg and C. Krishnan, arXiv:1807.05193; H. Ooguri, E. Palti, G. Shiu and C. Vafa, arXiv:1810.05506.

What are conditions for habitable islands sticking out from the swamp?

- The effective field theory is only valid for $\Delta\varphi < d m_{pl}$ (field range condition).
- The potential of φ obeys (de Sitter conjecture)

$$|\frac{V'}{V}| m_{pl} \geq c_1 \quad \text{or}$$
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Note: d, c_1, c_2 constants of order 1.

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Reasoning

- φ is a string theory modulus field.
- **Field range condition**: move $\delta\varphi \sim m_{pl} \rightarrow$ tower of string states becomes massless and must be included in low energy EFT.
- **De Sitter conjecture**: moduli stabilization $\rightarrow$ steep potential.
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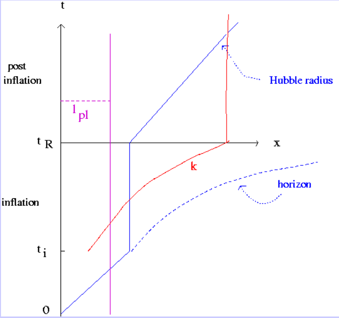
Inflation in the Swamp?

- Slow roll inflation in the swampland.
- False vacuum inflation in the swampland.
- Note: Warm inflation can escape from the swamp.

Plan

Trans-Planckian Problem

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



- **Success of inflation**: At early times scales are inside the Hubble radius → 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.
- → new physics MUST enter into the calculation of the fluctuations.

Trans-Planckian Censorship Conjecture (TCC)

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

No trans-Planckian modes exit the Hubble horizon.

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

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

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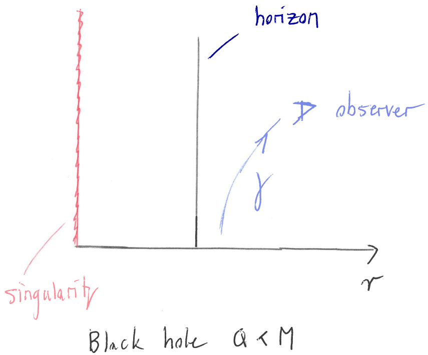
Analogy with Penrose's Cosmic Censorship Hypothesis:



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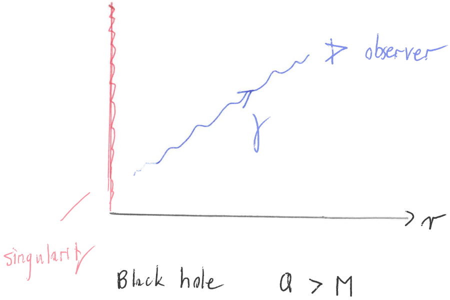

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- General Relatiivty allows for solutions with timelike singularities: super-extremal black holes.
- $\rightarrow$ Cauchy problem not well defined for observer external to black holes.
- Evolution non-unitary for external observer.
- Conjecture: ultraviolet physics $\rightarrow$ **external observer** shielded from the singularity and non-unitarity by horizon.

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Cosmological Version of the Censorship Conjecture

Translation

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

Observer outside of Hubble horizon must be shielded from the trans-Planckian modes.

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- 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.**
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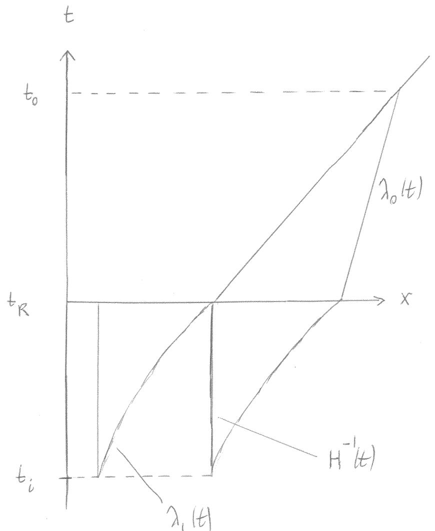
Application to Inflation

A. Bedroya, R.B., M. Loverde and C. Vafa., arXiv:1909.11106



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TCC implies:

$$\frac{a(t_R)}{a(t_*)} l_{pl} < H(t_R)^{-1}$$

Demanding that inflation yields a causal mechanism for generating CMB anisotropies implies:

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Upper bound on the **energy scale of inflation**:

$$V^{1/4} < 3 \times 10^9 \mathrm{GeV}$$

$\rightarrow$ upper bound on the **primordial tensor to scalar ratio** r:

$$r < 10^{-30}$$

Note: Secondary tensors will be larger than the primary ones.

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For **slow roll inflation**:

$$\epsilon < 10^{-31}$$

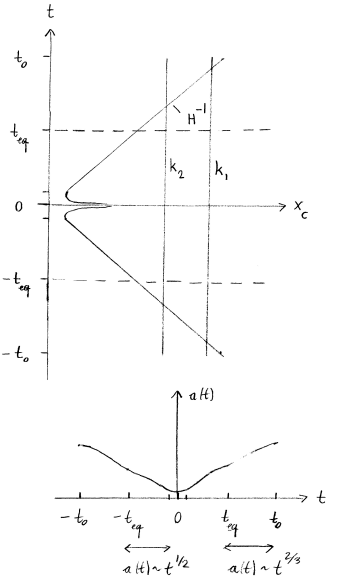
Up to logarithmic factors:

$$\Delta\varphi \sim \epsilon^{1/2} m_{pl}$$

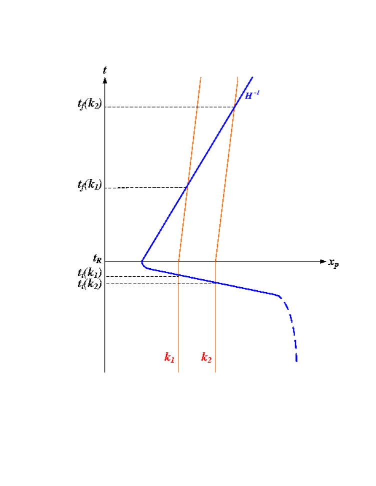
$\rightarrow$ extreme fine tuning oif the initial velocity is required

$$\frac{\dot{\varphi}_{SR}}{\dot{\varphi}_N} \sim \epsilon^{1/2}$$

Bouncing Cosmologies Consistent with TCC



Emergent Cosmologies Consistent with TCC



Conclusions concerning Inflation

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- Inflation is **highly fine tuned** assuming validity of the TCC.
- Alternatives to inflation are consistent with the TCC.
- String Gas Cosmology is a specific realization of the emergent scenario which directly comes from fundamental principles of string theory.
- The Ekpyrotic bouncing scenario can be easily embedded in string theory.

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Constraints from Swampland Considerations

Dark Energy cannot be a Cosmological Constant.

Note: This also follows from the TCC!

Quintessence is **constrained by observations.**

Consider a quintessence model with potential

$$V(\phi) = V_0 e^{-\lambda \phi / m_{pl}}$$

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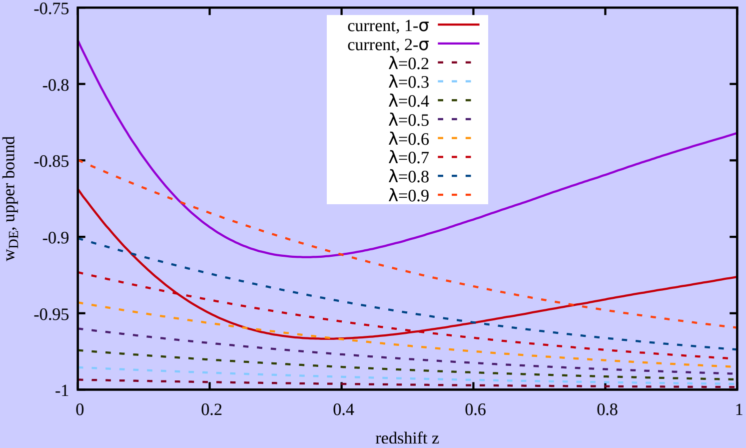
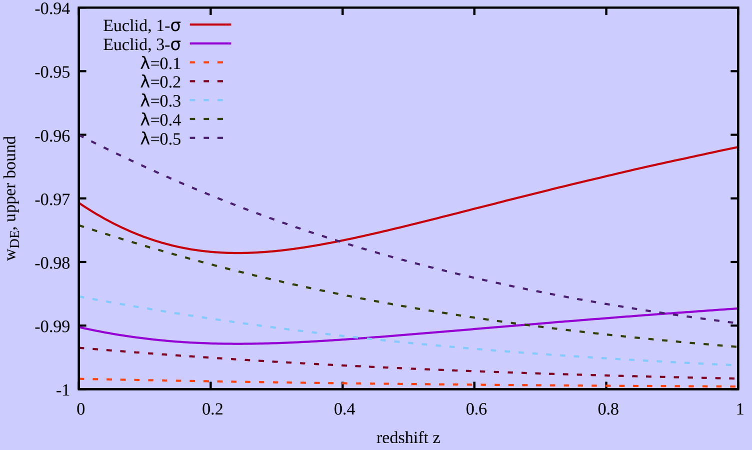
Current Constraints

L. Heisenberg, M. Bartelmann, RB and A. Refregier, arXiv:1808.02877



Projected Euclid Constraints

L. Heisenberg, M. Bartelmann, RB and A. Refregier, arXiv:1808.02877



Plan

Ekpyrotic Bounce

J. Khoury, B. Ovrut, P. Steinhardt and N. Turok, Phys. Rev. D, 2001

- Space-time described by Einstein-Hilbert action.
- Idea: Slow contraction given by matter with equation of state $w \gg 1$.
- Obtained by assuming that matter is dominated by a scalar field φ with a negative exponential potential.
- Anisotropies diluted, creates spatial flatness
- Local attractor in initial condition space.
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Obtaining an Ekpyrotic Universe

$$V(\varphi) = -V_0 \exp(-\sqrt{2/p}\varphi/m_{pl}) \quad p \ll 1$$

$$a(t) \sim (-t)^p$$

$$w \simeq \frac{4}{3p}$$

$$\varphi(t) = \sqrt{2p} m_{pl} \log(-\sqrt{\frac{V_0}{m_{pl}^2 p(1-3p)}} t)$$

Ekpyrosis: Small Field and Large Slope

Consider $\delta t = H^{-1}$:

$$\varphi \sim p^{1/2} \log(p^{-1/2}) m_{pl} \ll m_{pl} \, .$$

Relative slope of the potential:

$$|\frac{V'}{V}| m_{pl} \sim p^{-1/2} \gg 1 \, .$$

Relative curvature of the potential:

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Safe Ekpyrosis

- Ekpyrotic scenario consistent with the swampland criteria.
- Ekpyrotic scenario consistent with the TCC.

S-Brane and Ekpyrosis

RB and Z. Wang, arXiv:2001.00638, arXiv:2004.06437

Challenges for Ekpyrotic Cosmology:

- How do we get the bounce?
- How do we obtain a scale-invariant spectrum of curvature fluctuations?
- Can we obtain a spectrum of gravitational waves relevant to current observations?

Adding an S-Brane to the EFT action can solve all three problems, and leads to two consistency relations for cosmological observables.

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Consistency relations:

$$n_t = 1 - n_s$$
$$r \sim 36(k_C \tau_B)^{4q}(1 - n_s)^2$$

Reheating after Ekpyrosis

Coupling of the S-brane to Standard Model gauge fields $\rightarrow$ gauge field production during S-brane decay.

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Action

Idea: At the string scale a new tower of string states becomes comparable in mass to the usual low energy degrees of freedom;
$\rightarrow$ they must be included in the low energy effective action.

Included as an S-Brane.

$$S = \int d^4x \sqrt{-g} [R + \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - V(\varphi)] - \int d^4x \kappa \delta(\tau - \tau_B) \sqrt{\gamma} \, ,$$

$$\kappa \equiv N \eta_s^3 \, ,$$

Note: The S-brane has $\rho = 0$ and $p < 0$ $\rightarrow$ can mediate the transition between contraction and expansion.

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String Gas Cosmology: A Realization of the Emergent Scenario

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Based on new degrees of freedom and new symmetries of string theory.

New Degrees of Freedom
Assumption: All spatial dimensions toroidal, radius R.

String states:

- momentum modes: $E_n = n/R$
- winding modes: $E_m = mR$
- oscillatory modes: E independent of R

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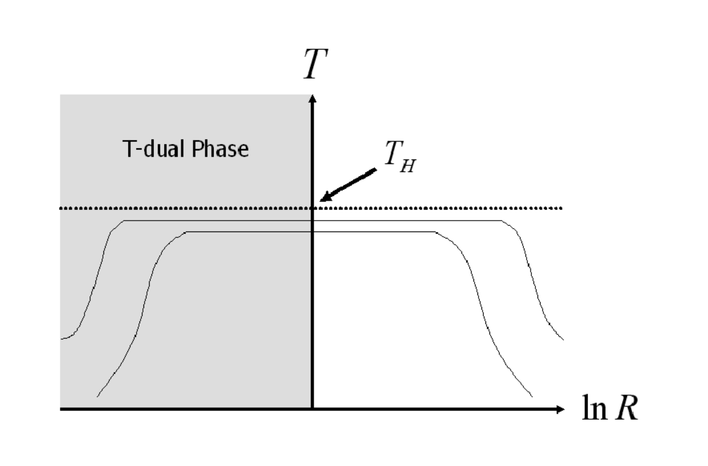
New Symmetries: T-Duality

T-Duality

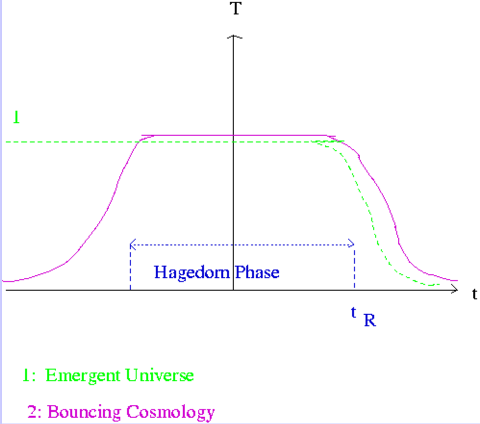
- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \to 1/R \quad (n, m) \to (m, n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level $\to$ existence of D-branes

Temperature-size relation in string gas cosmology



Dynamics

Assume some action gives us $R(t)$



Position Operators

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Position operators (dual to momenta)

$$|x> = \sum_p \exp(ix \cdot p)|p>$$

Dual position operators (dual to windings)

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Heavy vs. Light Modes

- $R \gg 1$: momentum modes light.
- $R \ll 1$: winding modes light.
- $R \gg 1$: length measured in terms of $|x>$.
- $R \ll 1$: length measured in terms of $|\tilde{x}>$
- $R \sim 1$: both $|x>$ and $|\tilde{x}>$ important.

Conclusion: At string scale densities usual effective field theory (EFT) based on supergravity will break down.

Conclusion: If an effective field theory description is valid, it must be an EFT in 18 spatial dimensions.

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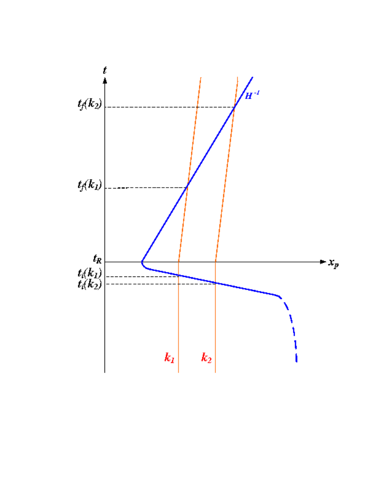
Physical length operator

$$
\begin{aligned}
l_p(R) &= R \quad R \gg 1 \\
l_p(R) &= \frac{1}{R} \quad R \ll 1
\end{aligned}
$$

Structure formation in string gas cosmology

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



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

Method

- 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

Extracting the Metric Fluctuations

Ansatz for the metric including cosmological perturbations and gravitational waves:

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

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

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

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

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Power spectrum of cosmological fluctuations

$$\begin{aligned}
P_\Phi(k) &= 8G^2k^{-1} < |\delta\rho(k)|^2 > \\
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Key features:

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

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Prediction: Spectrum of Gravitational Waves

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

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Requirements

- Static Hagedorn phase (including static dilaton) $\rightarrow$ new physics required.
- $C_V(R) \sim R^2$ obtained from a thermal gas of strings provided there are winding modes which dominate.
- Cosmological fluctuations in the IR are described by Einstein gravity.

Conclusions concerning String Gas Cosmology

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

- Consistent with swampland criteria.
- Emerges from string theory considerations.
- Consistent with the TCC

Plan

Conclusions Concerning Inflation

- Inflation does not **naturally** emerge from superstring theory.
- Inflation is **highly fine tuned** assuming validity of the TCC.
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Moduli Stabilization

Size Moduli [S. Watson, 2004; S. Patil and R.B., 2004, 2005]

- winding modes prevent expansion
- momentum modes prevent contraction
- $\rightarrow \; V_{eff}(R)$ has a minimum at a finite value of $R, \; \rightarrow \; R_{min}$
- in heterotic string theory there are enhanced symmetry states containing both momentum and winding which are massless at R_{min}
- $\rightarrow V_{eff}(R_{min}) = 0$
- $\rightarrow$ size moduli stabilized in Einstein gravity background

Shape Moduli [Y-K. Cheung, S. Watson and R.B., 2005]

- enhanced symmetry states
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Dilaton stabilization in SGC

- The only remaining modulus is the dilaton.
- Make use of gaugino condensation to give the dilaton a potential with a unique minimum.
- $\rightarrow$ diltaton is stabilized.
- Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008].
- Gaugino condensation induces (high scale) supersymmetry breaking [S. Mishra, W. Xue, R.B. and U. Yajnik, 2012].