Gravitational Waves from String Cosmology

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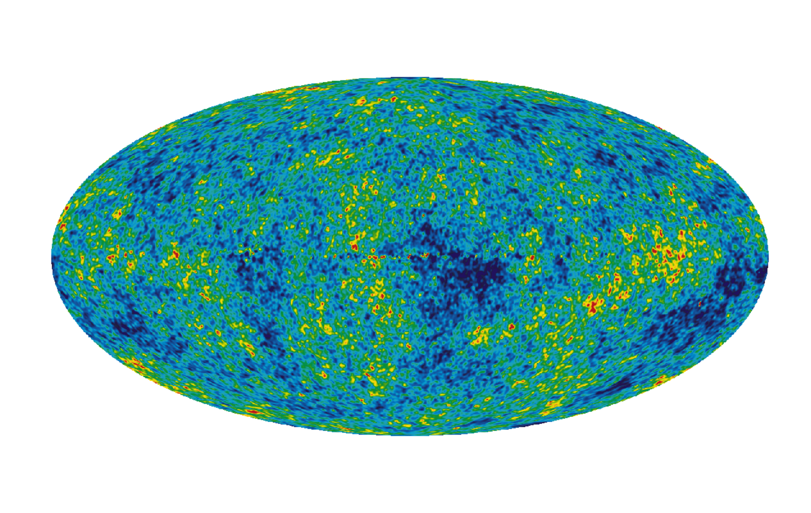
SUSY 2021

Outline

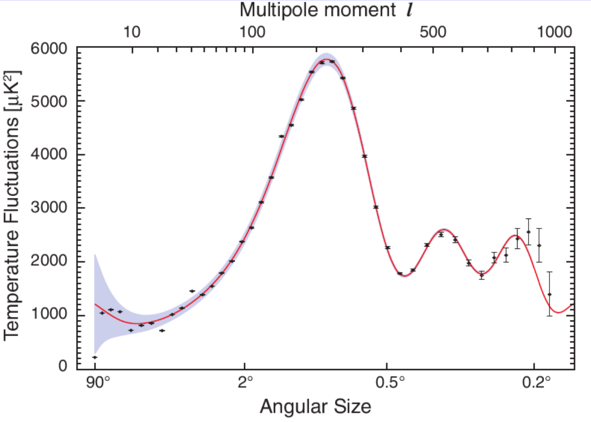
Plan

Map of the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Angular Power Spectrum of CMB Anisotropies



Credit: NASA/WMAP Science Team

Criteria

1970

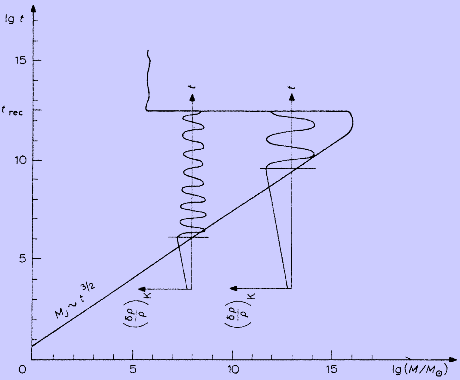


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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.

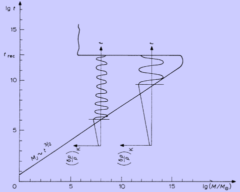
Key Realization

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_{rec}, i.e. standing waves.
- $\rightarrow$ "correct" power spectrum of galaxies.
- $\rightarrow$ acoustic oscillations in CMB angular power spectrum.

Early Work

1970 paper



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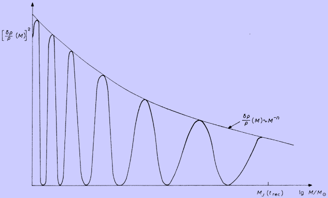

Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

R. Sunyaev & Ya. Zeldovich, Astrophysics and Space Science 7, 3-19 (1970)

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).

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- $\rightarrow$ "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 carries information about causality.
- Hubble radius: $l_H(t) \equiv H^{-1}(t)$.
- Hubble radius crucial for the evolution of fluctuations.

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.
- Mechanism for producing a scale-invariant spectrum of curvature fluctuations on super-Hubble scales.

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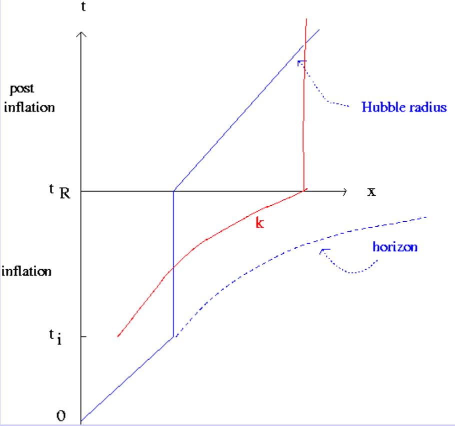
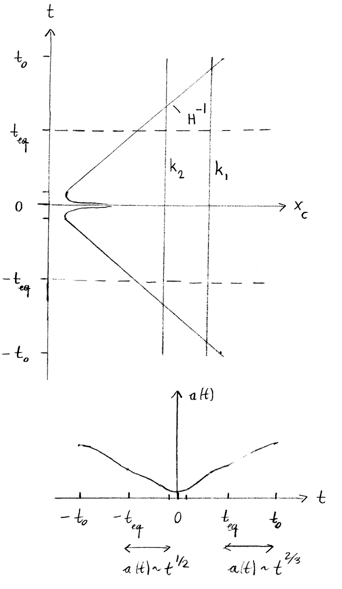
Inflation as a Solution

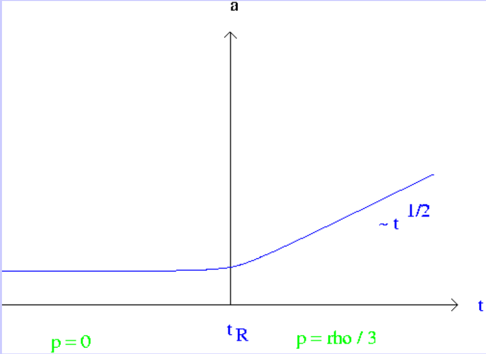


Bounce as a Solution



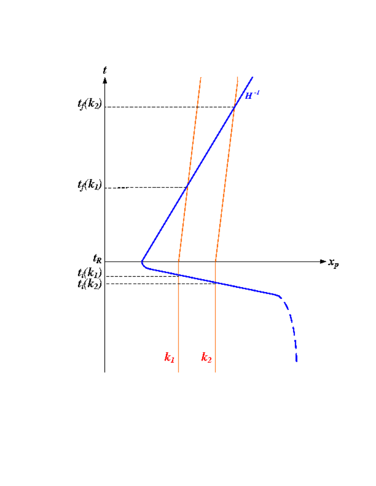
Emergent Universe

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)*



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
- Global attractor in initial condition space (A. Ijjas et al, arXiv:2103.00584)
- Note: **Negative exponential potentials are ubiquitous in string theory.**

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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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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.

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

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

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

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Gravitational Waves from S-Brane Ekpyrosis

RB and Z. Wang, arXiv:2004.06437

Computation of curvature fluctuations and gravitational waves:

- Begin with quantum vacuum fluctuations early in the contracting phase.
- Propagate using the usual theory of cosmological fluctuations until $t = 0$.
- Matching perturbations across the S-brane using the Israel matching conditions.
- $\rightarrow$ scale-invariant spectrum of curvature fluctuations and gravitational waves.

Consistency relations:

$$n_t = 1 - n_s$$
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Reheating from S-Brane Ekpyrosis

RB, K. Dasgupta and ZW, arXiv:2007.01203

Reheating after Ekpyrosis

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

Superstrings in the Early Universe

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: $E_n = n/R$
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New Symmetries: T-Duality

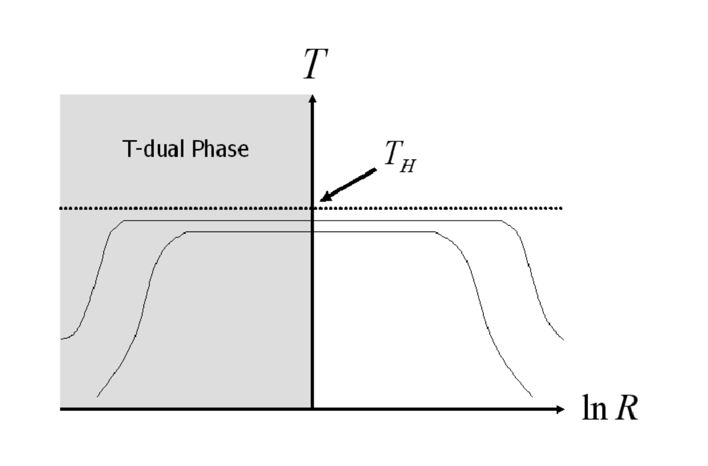
T-Duality

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

Absence of a Temperature Singularity in String Cosmology

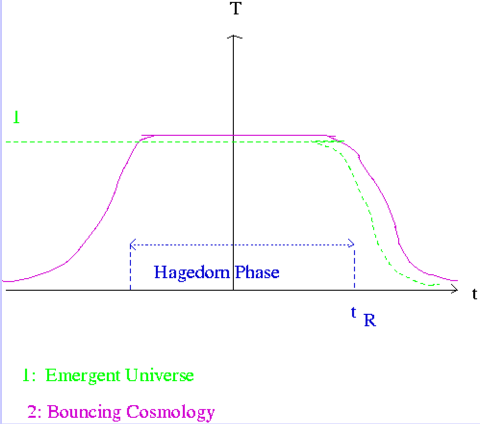
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

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)

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

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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

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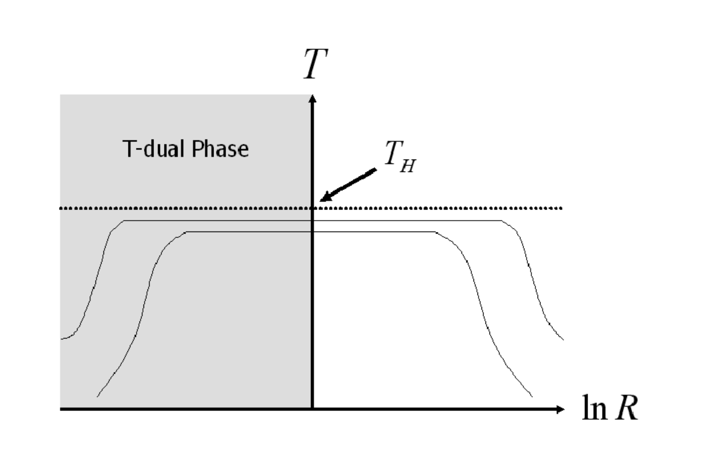

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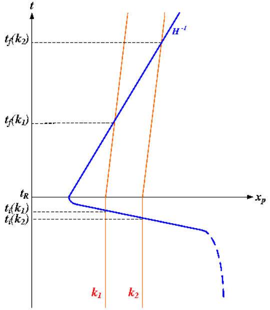

Fluctuations from String Cosmology

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)*, R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett. 98:231302 (2007)*

- Perturbations arise as thermal fluctuations of the string gas.
- Thermodynamic quantities have holographic scaling.
- $\rightarrow$ scale invariant spectrum of **curvature fluctuations**, red tilt.
- $\rightarrow$ scale invariant spectrum of gravitational waves, blue tilt.
- Consistency relation: $n_t \simeq 1 - n_s$
- Consistency relation: $r \sim (1 - n_s)^2$

Some Key Steps in the Calculation

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

$$\langle \delta T^0_0(k) \delta T^0_0(k) \rangle = \frac{T^2}{R^6} C_V .$$

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

$$\langle|h(k)|^2\rangle = 16\pi^2 G^2 k^{-4} \langle \delta T^i_j(k) \delta T^i_j(k) \rangle , \; i \neq j ,$$

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Plan

Obstacles to Obtaining Inflation

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

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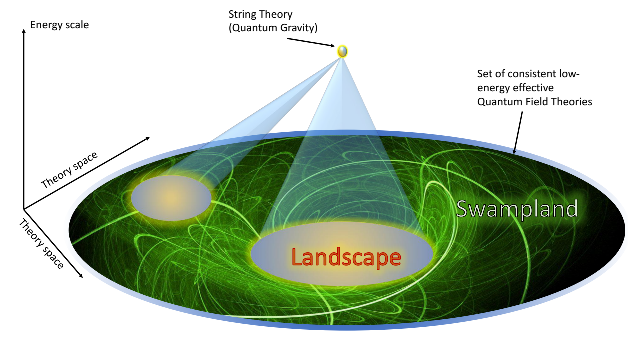
Energy scale
String Theory
(Quantum Gravity)
Set of consistent low-
energy effective
Quantum Field Theories
Theory space
Theory space
Swampland
Landscape

Swamplland 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)

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\begin{aligned}
|\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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Consequences

- No canonical single field inflation.
- No eternal inflation.
- No bare positive Λ.
- Dark Energy is not a bare cosmological constant.
- Quintessence dark energy is constrained (L. Heisenberg et al, arXiv:1808.02877).

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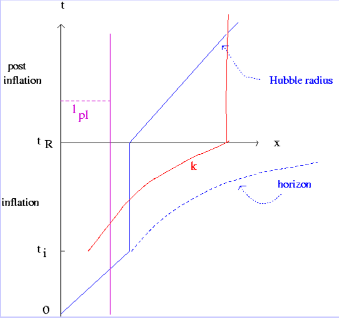
Trans-Planckian Problem

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



- **Success of inflation**: At early times scales are inside the Hubble radius $\rightarrow$ 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 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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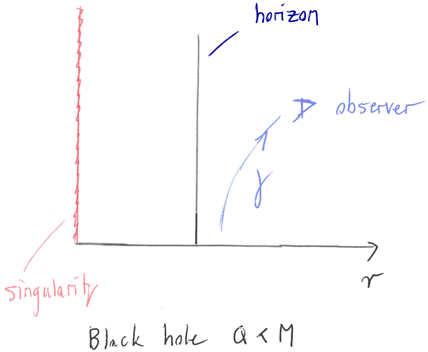
Justification

R.B. arXiv:1911.06056

Analogy with Penrose's Cosmic Censorship Hypothesis:



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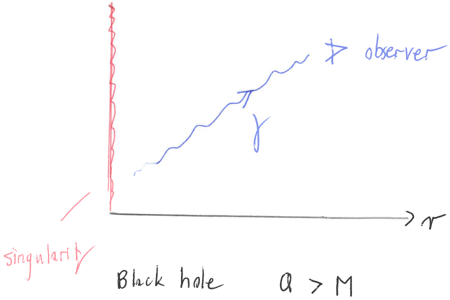

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- General Relatiivty allows for solutions with timelike singularities: super-extremal black holes.
- $\rightarrow$ Cauchy problem not well defined for observer external to black holes.
- Evolution non-unitary for external observer.
- Conjecture: ultraviolet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

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Cosmological Version of the Censorship Conjecture

Translation

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

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

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Why Hubble Horizon?

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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.
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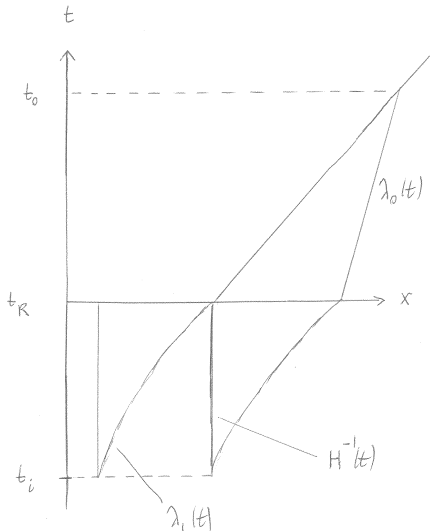
Application to Inflation

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



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:

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

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Implications for Dark Energy

Dark Energy cannot be a bare cosmological constant.

Plan

Conclusions

- Data do not require an initial period of cosmological inflation.
- String theory → breakdown of effective field theory at string scale.
- String theory → constraints on low energy effective field theory ("Swampland" program).
- Inflation does **not naturally** emerge from superstring theory.
- Inflation is **highly fine tuned** assuming validity of the TCC.
- String Cosmology models which do not involve inflation and which are consistent with the Swampland Criteria and the TCC exist (e.g. String Gas Cosmology, S-Brane Ekpyrosis).
- Superstring Cosmology models yield a scale-invariant spectrum of gravitational waves with a slight blue tilt.

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String Cosmology

R. Brandenberger

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