Transplanckian Censorship and Global Cosmic Strings

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POSTERA CRESCAM LAUDE

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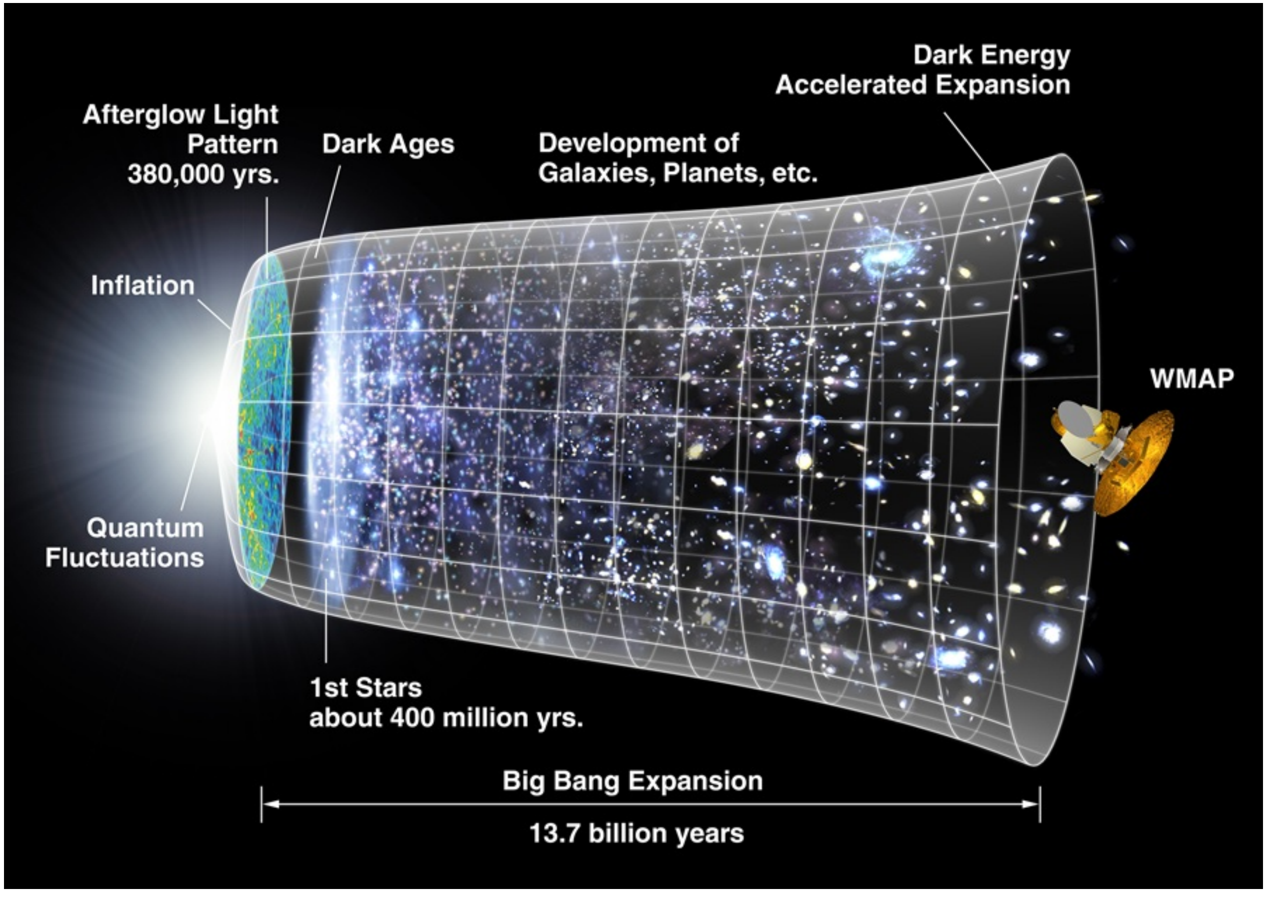
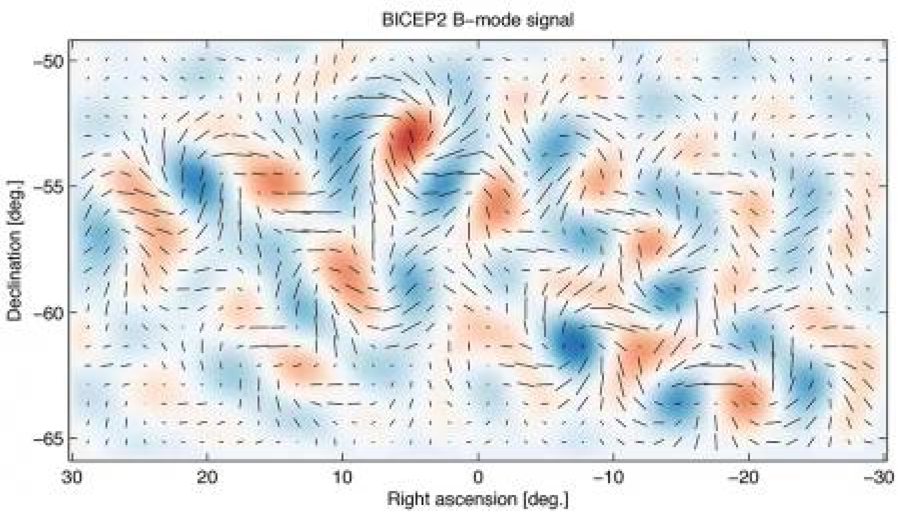
Cosmological Inflation

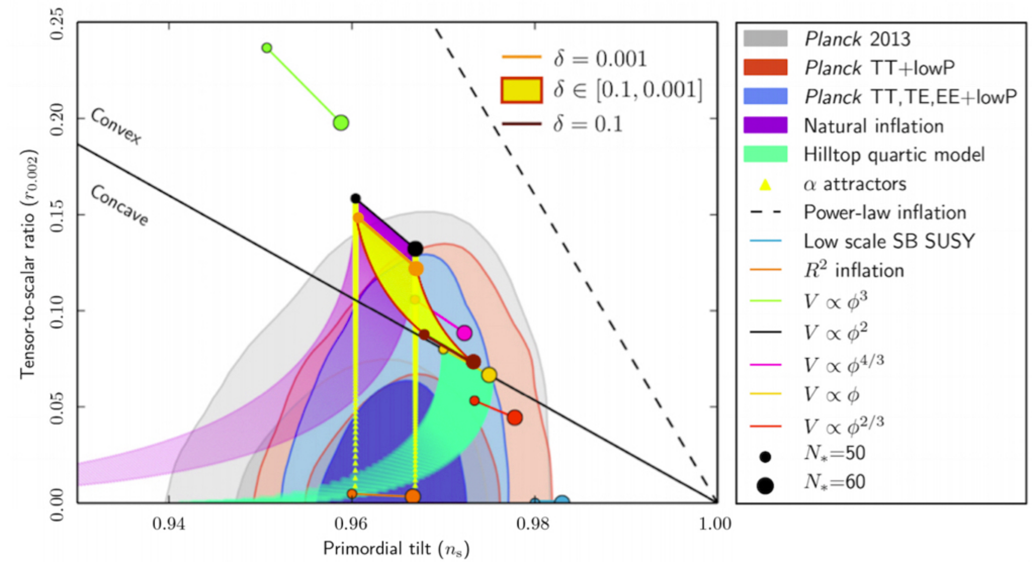
- A period of exponential expansion in the early universe is now widely accepted.
- How can we learn more about the inflaton?



Cosmological Inflation

- One possibility: Primordial gravitational waves, measured by tensor to scalar ratio r





However, the Lyth bound associates large values of r to **large** inflationary field excursions

$$\frac{\Delta\phi}{M_{\rm Pl}} = \mathcal{O}(1)\sqrt{\frac{r}{0.01}}.$$

Lyth, 1996

Cosmological Inflation

- However, for such large field excursions we worry about the validity of the EFT: breaks down for $\phi > M_P$

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial_\mu \phi)^2 - V_\phi(\phi)$$

$$V = \sum_n g_n \frac{\phi^n}{M^{n-4}}$$

Insure against this with a shift symmetry for inflaton

$$\theta \to \theta + \pi$$

$$\mathcal{L} = \frac{f^2}{2}(\partial\theta)^2 - V_0(1 - \cos(\theta))$$

$$\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \sim \frac{M_P^2}{f^2}\,, \quad \eta \equiv M_P^2 \frac{V''}{V} \sim \frac{M_P^2}{f^2}$$

Freese, Frieman, Olinto, 1990

Extranatural Inflation

- However, the EFT can be brought back under control in extra-dimensional models
- Inflation associated with radial mode of gauge field around 5th dimension, protected by higher dimensional gauge symmetry

$$\mathcal{L} = \frac{1}{2 \cdot g_4^2 (2\pi R)^2} (\partial\theta)^2 - V(\theta) + \cdots \qquad V(\theta) = -\frac{1}{R^4} \sum_I (-1)^{F_I} \frac{3}{64\pi^6} \sum_{n=1}^{\infty} \frac{\cos(nq\theta)}{n^5} ,$$

$$f_{\text{eff}} = \frac{1}{2\pi g_{4\text{d}} R}$$

→ Large effective decay constant associated with small gauge coupling

Slow roll satisfied when: $2\pi g_{4\text{d}} M_P R \ll 1$.

Arkani-HAmed et al, 2003

Monodromy Inflation

- Monodromy is mathematics for ‘when one things moves, something else does too’.
- Decay constant $f < M_P$, but can be traversed n times, so $n * f > M_P$

Silverstein, Westphal, 2008

McAllister, Silverstein, Westphal, 2008

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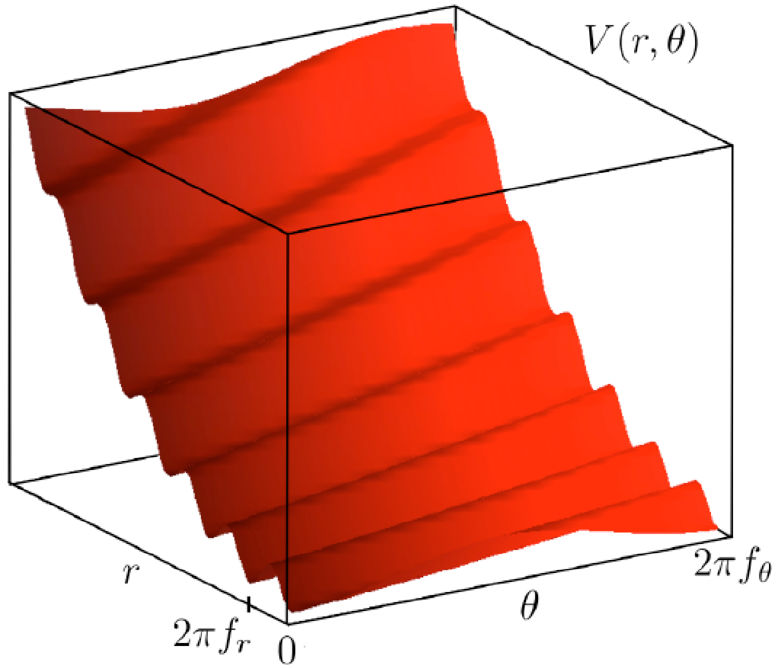
“Dante’s Inferno”



Berg, Pajer, Sjors 2009

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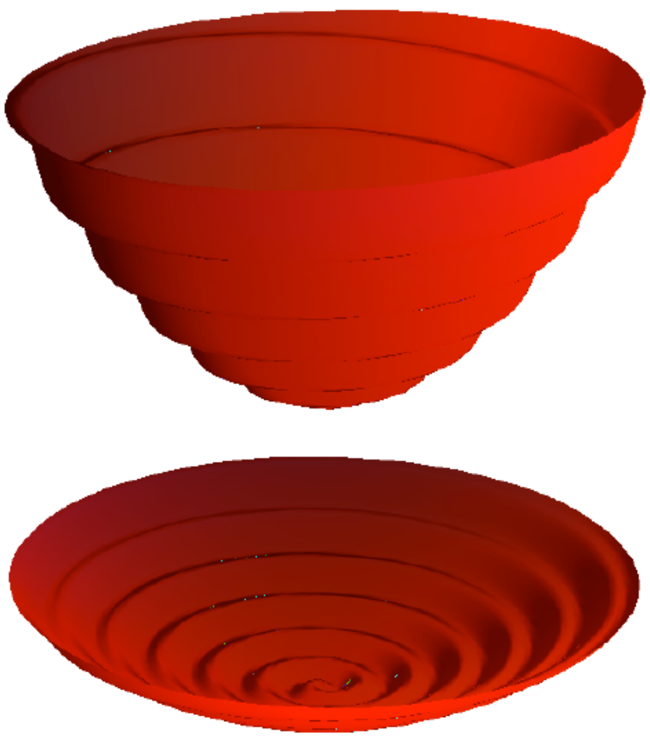


Berg, Pajer, Sjors 2009

The Weak Gravity Conjecture

- Banks, Dine, Fox and Gorbatov attempted to UV complete natural inflation in string theory.
- Generically found string theory does not accommodate transplanckian moduli spaces.
- Led Arkani-Hamed *et al*. to propose the Weak Gravity Conjecture.
- States gravity must be the weakest force (would rule out extranatural inflation).

There seems to be some connection between transplanckian flat directions in moduli space and gravitational consistency criteria.

Banks, Dine, Fox, Gorbatov, 2003

Arkani-Hamed et al, 2006

Super-Planckian Fields at Sub-Planckian Energies

- Surprisingly, Nicolis has found evidence of these ‘censorship’ properties already in classical gravity.
- Studied scalar field configurations sourcing Planckian field excursions: generically collapse into black holes.
- Possible to have large field variations inside source: an experimenter could measure Transplanckian excursions, but with an exponentially big experiment.
- Also work by Arkani-Hamed *et al* on wormholes in string theory with similar moral.

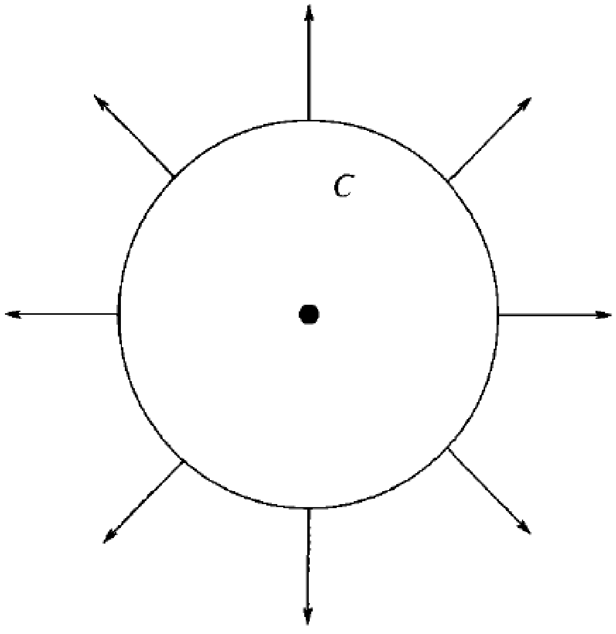
Nicolis 2008

Arkani-Hamed, Orgera, Polchinski 2007

Klaewer, Palti 2016

Monodromy Inflation

- Are there similar constraints on monodromy inflation?
- A common feature to all axion-based models is the presence of cosmic strings
- Cosmic strings of large winding number trace out a profile in *space* similar to what the inflaton is doing in *time.*



Consider a complex scalar field with a global U(1) symmetry.

$$\mathcal{L} = \left|\partial_\mu \phi\right|^2 - U(\phi)$$

$$U(\phi) = \lambda\left(|\phi|^2 - v^2\right)^2 .$$

In vacuum $|\phi| = v$ but the phase of ϕ may rotate. The winding of ϕ cannot be undone by a continuous deformation.

Supercritical Cosmic Strings

- Cosmic strings with $n * f > M_P$ are called super-critical.
- Want to solve Einstein and scalar field equations in presence of a super-critical cosmic string.
- Metric Ansatz: $ds^2 = dt^2 - e^{H(t,r)}dr^2 - e^{A(t,r)}r^2 d\theta^2 - e^{B(t,r)}dz^2$.

$$V(\phi) = \frac{\lambda}{4}(|\Phi|^2 - f^2)^2 \,, \quad \Phi = \phi e^{ia/f} \,, \quad a = n\theta f \,,$$

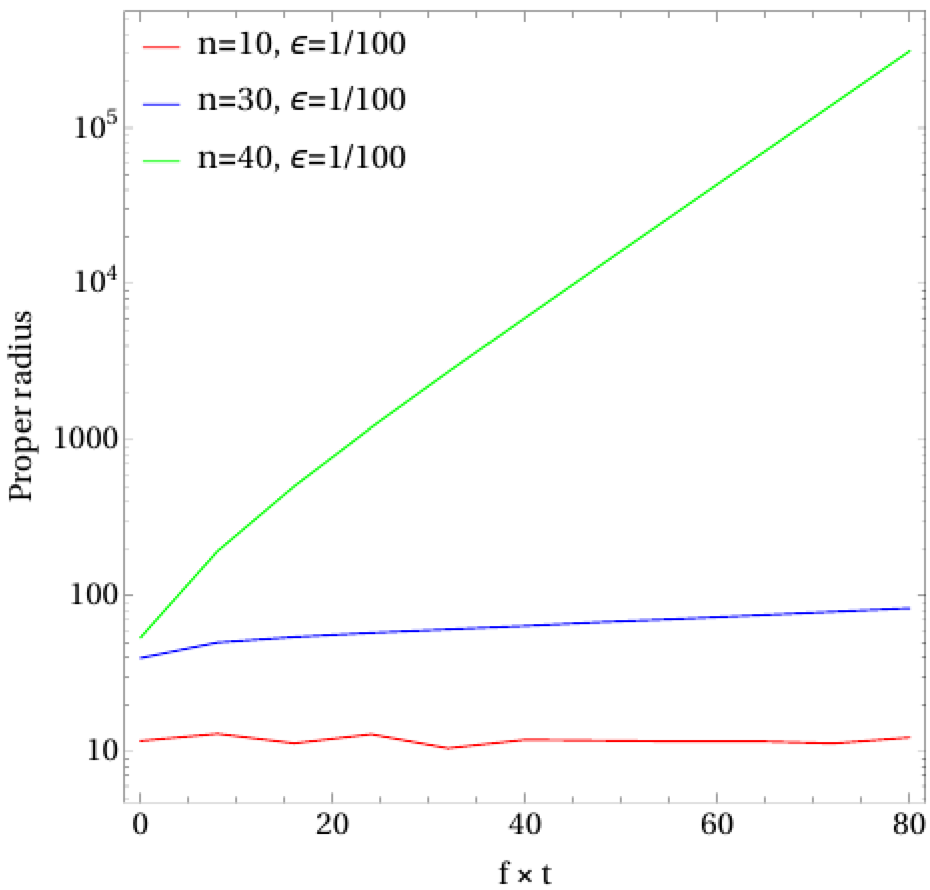
$$\epsilon \equiv \frac{f^2}{M_p^2} \qquad\qquad f \ll M_p \ll nf$$

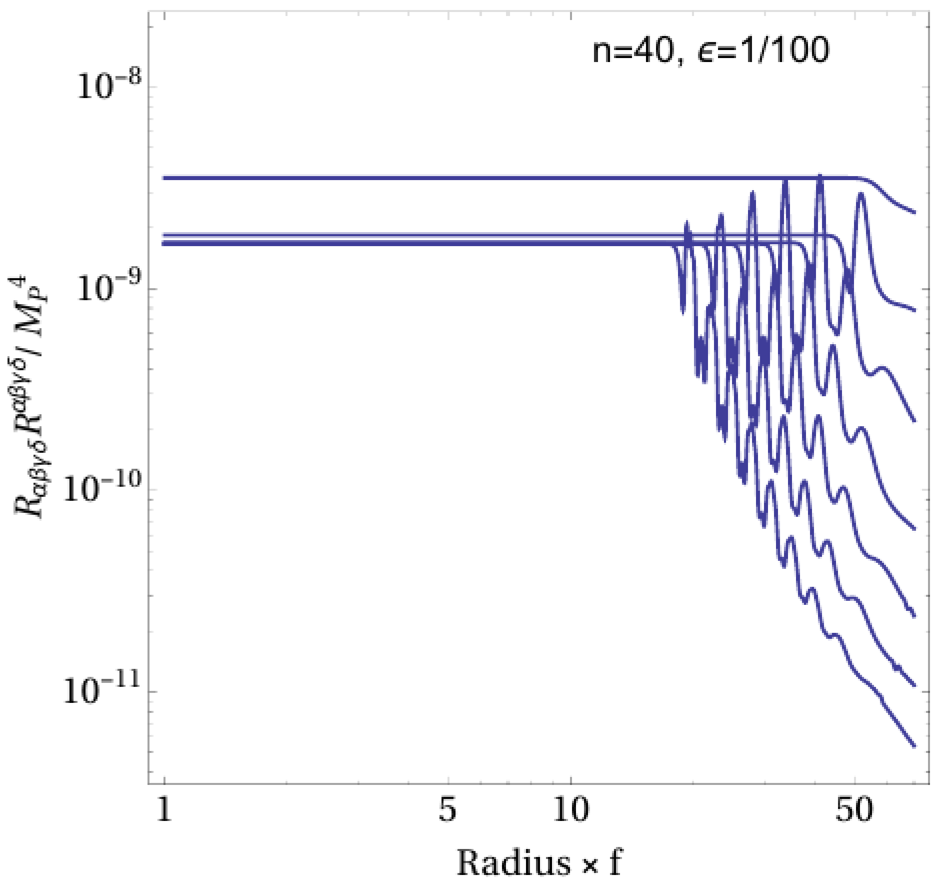
Gregory, 1996

Cho, 1998

Topological Inflation

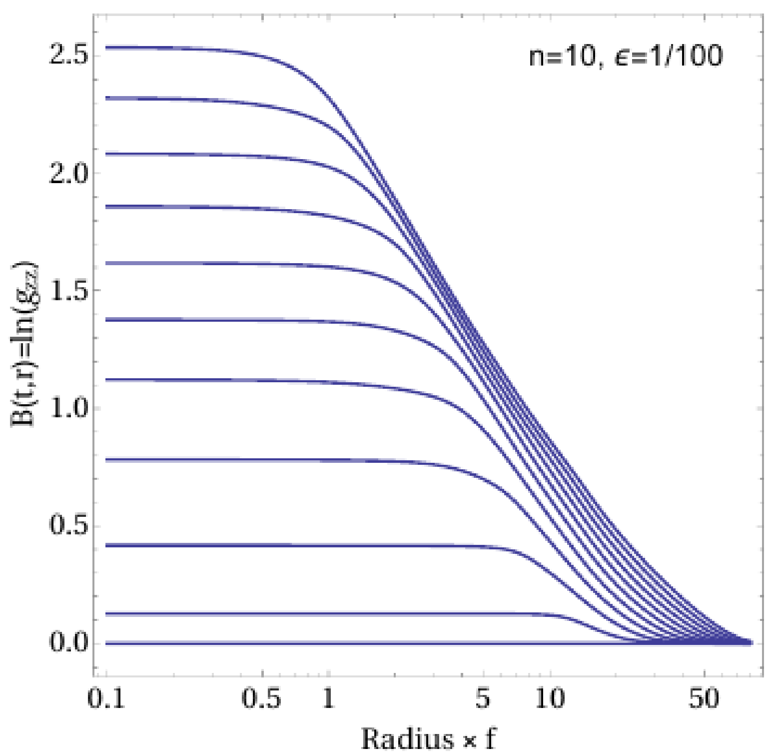
- The behaviour of the string changes as we dial up n: at a certain stage the core of the string starts inflating. This is called topological inflation.

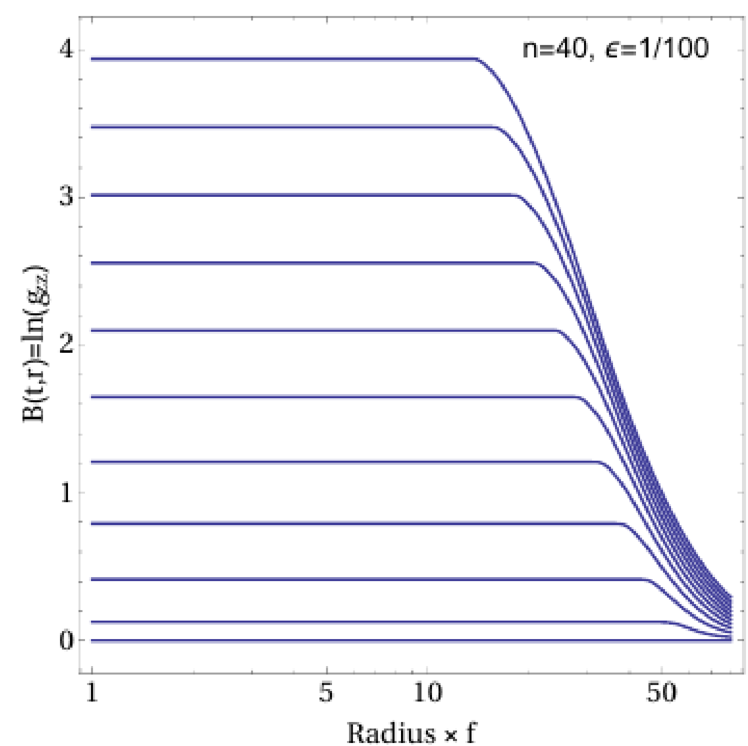




Topological Inflation

- Was argued in 90s that cores of topological defects will inflate when $f > M_P$
- We argue this should occur when $n\sqrt{\epsilon} \gtrsim 1$.



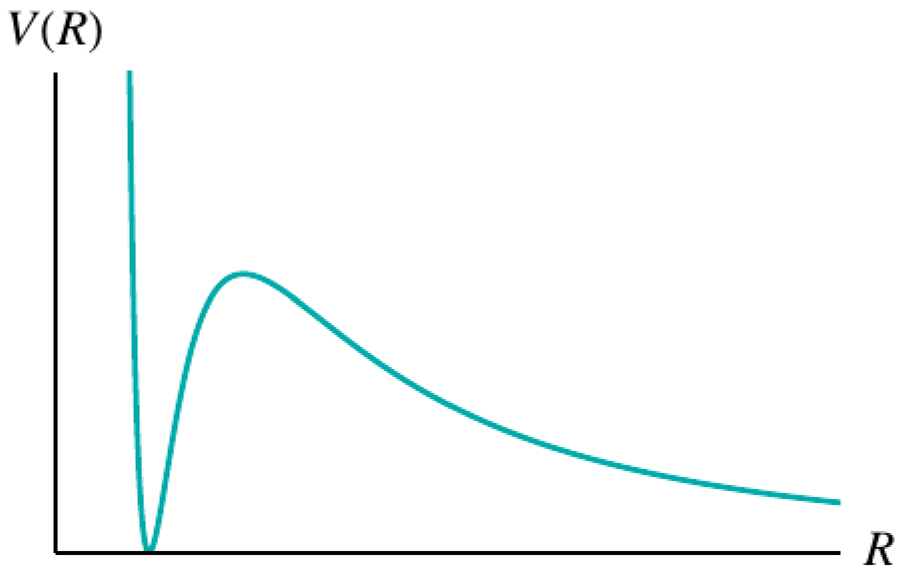


Vilenkin, 1994

Linde, 1994

Wilson Loop Inflation

- We also study strings for models with Wilson loop inflaton/axions.
- These models have a more complicated potential, which leads to domain wall formation.
- Still expect topological inflation for $\frac{n}{g \cdot v_R} > M_p$

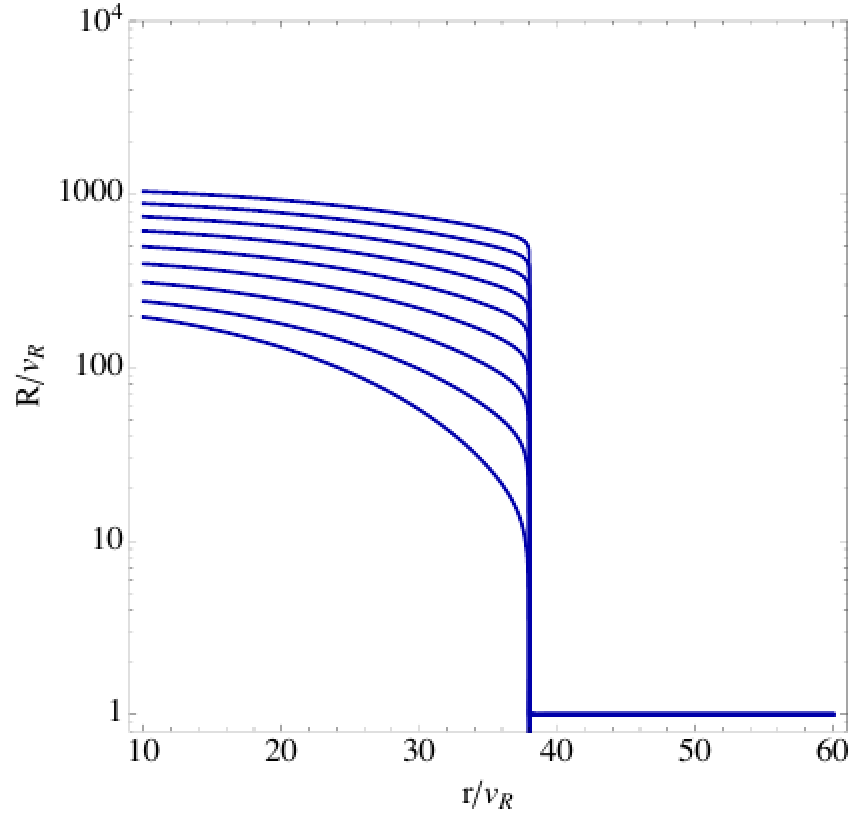


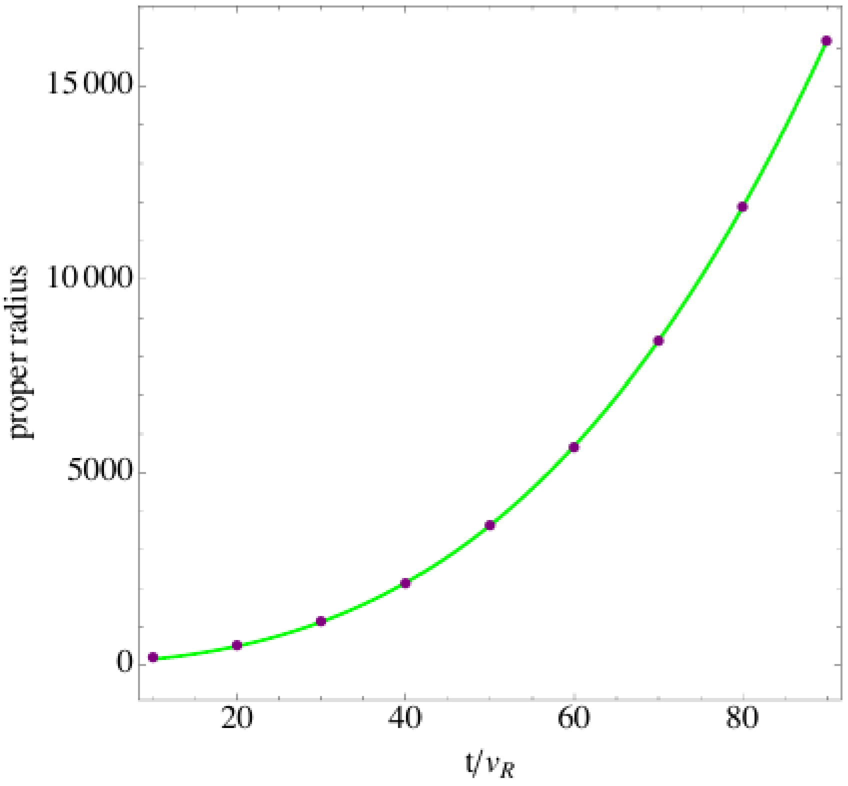
$$\mathcal{L} = \frac{3}{4} M_p^2 \left(\frac{\partial R}{R} \right)^2 - \frac{1}{4R} F_{\mu\nu} F^{\mu\nu} - V(R),$$

$$V = \frac{2}{R^6} - \frac{5}{R^3} + \frac{3}{R}$$

Wilson Loop Inflation

- We also study strings for models with Wilson loop axions.
- They undergo power-law inflation instead of exponential.

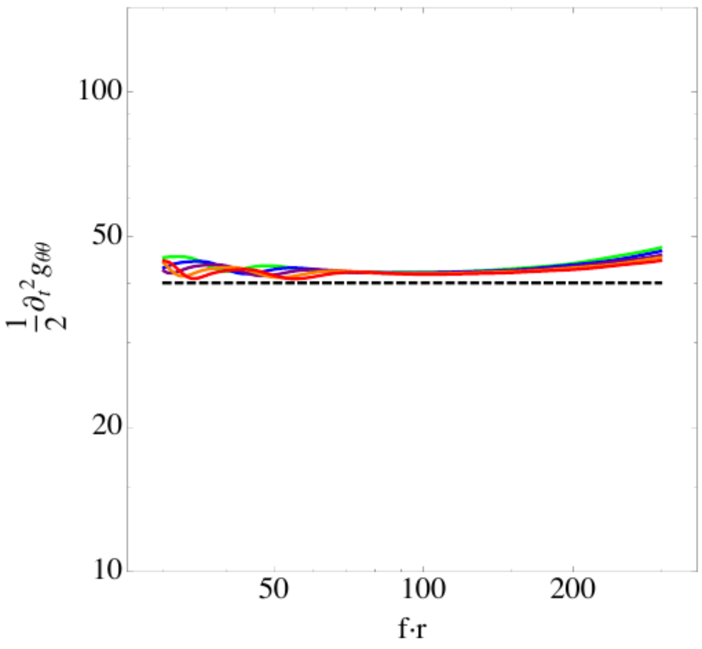


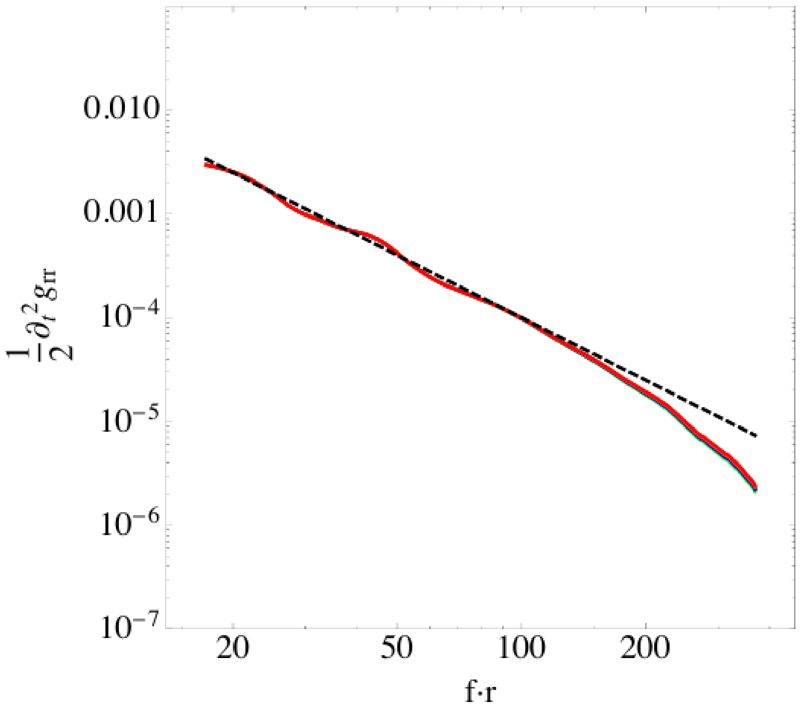


$$a(t) \sim (t+c)^3$$

Infinite String Exterior

- What does the metric exterior to the string look like?
- Based on Ansatz derive $ds^2 = dt^2 - t^2\left(r^{-2}dr^2 + n^2\epsilon d\theta^2 + (fr)^{-2\sqrt{2}}f^2dz^2\right)$
- Solves EFEs, scalar field equation to $\mathcal{O}(1/t^2)$





Measurability of the Transplanckian Excursion

- Can an observer access the Transplanckian excursions in these string spacetimes?
- Two simple thought experiments:

In the background of an infinite supercritical string, are there causal trajectories which circumnavigate the string?

In asymptotically flat space containing a large loop of string, are there causal trajectories that thread the loop and escape to infinity?

Measurability of the Transplanckian Excursion

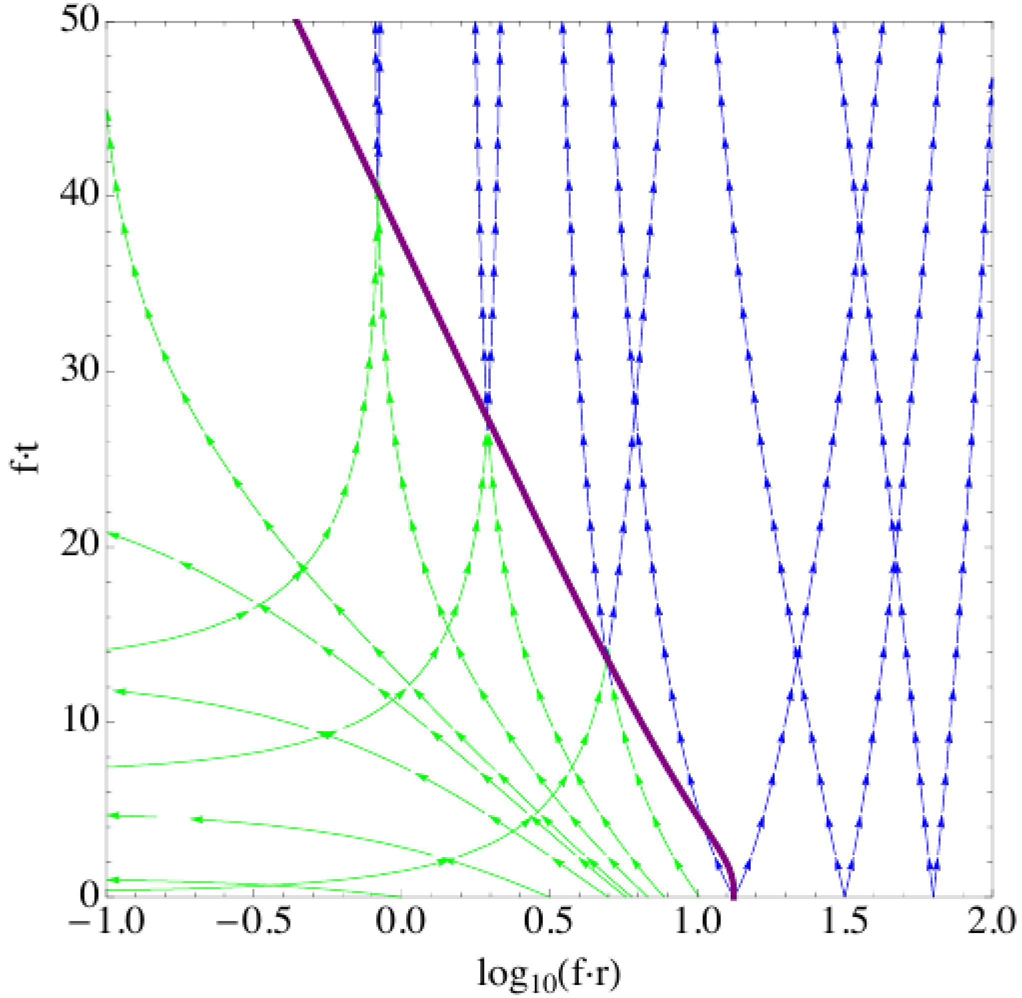
- Can answer first question using asymptotic metric above.
- Causal trajectories can circumnavigate string, e.g. null geodesics trace out circles of constant r,z.
- But time for signal to return to sender on one of these is exponential for supercritical strings: signal emitted at t_0 will be received at

$$t = t_0 e^{\frac{2\pi n f}{M_p}} .$$

Similar to Nicolis' result with exponentially large experiments.

Measurability of the Transplanckian Excursion

- A horizon forms around the collapsing core.



Measurability of the Transplanckian Excursion

- Consider a geodesic passing through a closed loop of string.
- Can this be smoothly deformed to a different trajectory not threading the string?
- No: causal observers cannot cross the horizon.

This contradicts the topological censorship theorem: causal curves through spacetime are deformable into one another.

So, such a geodesic should not exist: most likely the loop collapses.

Friedman, Schleich, Witt 1993

Jacobson, Venkataramani 1994

Conclusions

- Large-field inflation requires large field excursions.
- But it appears difficult to construct consistent models realising this.
- Global cosmic strings are natural probes of transplanckian field excursions occuring during inflation.
- Studied the geometry and causal structure of these solutions
- Infinite string: exponentially long time to circumnavigate
- String loop: violates topological censorship.
- What is the nature of the links between large field excursions, topological censorhip, the weak gravity conjecture, the cosmic censorship hypothesis….?