TOPOLOGICAL DEFECTS FROM THE MULTIVERSE

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The multiverse

Bubbles nucleate and expand in the course of eternal inflation.
How can we test multiverse models?

Bubble collisions can leave an imprint on the CMB. This would be a direct test of eternal inflation.

_Aguirre, Freivogel, Kleban, Johnson, …_

**Indirect tests:**

Predictions for the cosmological constant, neutrino masses, negative spatial curvature, etc.

_Weinberg, …_

_Pogosian, Tegmark & A.V._

_Freivogel, Kleban, Martinez & Susskind_
Cosmic strings or domain walls nucleating in the parent vacuum may “intrude” in our bubble.

These can be fundamental or field theory strings. They can be very heavy.
Strings and domain walls in dS space

\[ ds^2 = dt^2 - e^{2Ht} d\vec{x}^2 \]

Tunneling is also possible from \( r = 0 \) spontaneous nucleation.

The instanton:

\[ S_E \approx 4\pi H^{-2} \mu \]

Nucleation rate:

\[ \Gamma \sim \exp(-S_E) \]

Similarly for domain walls:

\[ S_E \approx 2\pi^2 H^{-3} \sigma \]

String / wall worldsheet

\[ ds^2 = dt^2 - e^{2Ht} d\vec{x}^2 \]

Physical radius:

\[ R(t) = H^{-1} \left( 1 + e^{2H(t-t_n)} \right)^{1/2} \]

\[ R \approx H^{-1} e^{H(t-t_n)} \quad (t >> t_n) \]

\[ R \approx H^{-1} \quad (t << t_n) \]

Nucleation center: \((\vec{x}, t_n)\)

"Nucleation moment": \(t \sim t_n\)
Scale-invariant size distribution:

\[ dN \sim \lambda \frac{dR}{R^4} dV, \]

\[ \lambda = H^{-4} \Gamma \sim e^{-S_E} \ll 1. \]

Time independent: production balances stretching and dilution.

Lower cut-off: \[ R \gtrsim H^{-1} \]
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Strings & walls will collide with expanding bubbles
Simple model:

- Approximate the bubble wall by a light cone.
- dS space inside and outside the bubble with expansion rates $H_T$ and $H_F$, respectively.
- Disregard gravity of the bubble wall and of the defects.
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Approximate the bubble wall by a light cone.

dS space inside and outside the bubble with expansion rates $H_T$ and $H_F$, respectively.

Disregard gravity of the bubble wall and of the defects.

- String worldsheet can be continued into the bubble.
- The string appears to be infinite on FRW slices. (There are also some closed loops.)
FRW metric inside the bubble:

\[ ds^2 = d\tau^2 - a^2(\tau) \left( d\xi^2 + \sinh^2 \xi d\Omega^2_2 \right). \]

- The string “freezes” at \( \tau \gg H_T^{-1} \) in comoving coordinates.
- Asymptotic shapes of strings are circles on the Poincare disc.
- We can see only up to \( \xi_{\text{max}} \lesssim 0.1 \)
  (The curvature radius is \( \xi = 1 \).)
Observational effects

- A string within our horizon could cause gravitational lensing of the CMB and of distant galaxies.

\[ \delta \varphi \sim 8\pi G \mu \]

- A domain wall within or close to our observable region could account for the hemispherical power asymmetry.

Best fit to the data is for \( \xi_{\text{wall}} \sim 2 \xi_{\text{CMB}} \)

How likely is this?
Number of defects within our bubble as a function of distance:

- **Domain walls:**

  \[ N(\xi) \approx \frac{4\pi\lambda}{3} \left[ 2\xi + \left(1 + \frac{H_T^2}{H_F^2}\right) \sinh 2\xi \right] \]

  For \( \xi \approx 0.1 \): \( N(\xi) \approx \frac{8\pi\lambda}{3} \xi \lesssim \lambda \ll 1 \)

- **Strings:**

  \[ N(\xi) \approx \pi\lambda\xi^2 \quad \text{(for } \xi \ll 1 \text{)} \]

We are not likely to see defects in our neighborhood.
Collisions in our past light cone can produce observable effects.

The intruding defect can be very far away on the FRW slice when the signal reaches the observer.
Observing collision events

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The intruding defect can be very far away on the FRW slice when the signal reaches the observer.

Domain walls:

Disc-like hot or cold spots in the CMB (as in bubble collisions).

Freivogel, Kleban, Nicolis & Sigurdson (2009)

Expected number of spots:

\[ N \sim 16\pi\lambda \left( \frac{H_F}{H_T} \right)^2 \sqrt{\Omega_k} \]

Can be large even for \( \lambda \ll 1 \).

Angular size distribution:

\[ dN \propto d(\cos \theta) \]
Collisions with strings should give a very different signal in the CMB (or GW!) sky

*Head on collision:*

![Diagram of head on collision]
Collisions with strings should give a very different signal in the CMB (or GW!) sky.

Head on collision:

Collision at an angle:

A smile in the CMB.
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*Head on collision:*

*Collision at an angle:*

*A smile in the CMB.*
Other types of defects

- Walls bounded by strings
- Global monopoles