Unusual Vacuum Decay Events in the Early Universe

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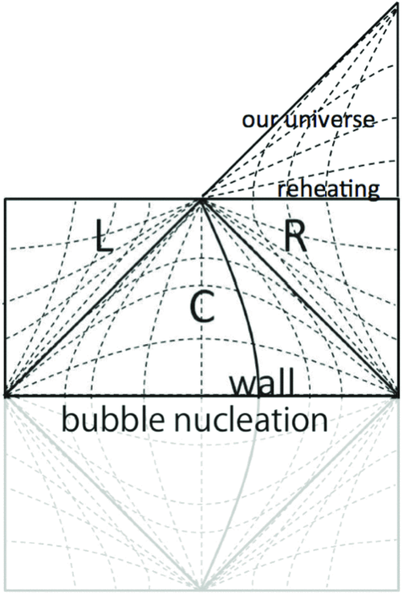
Motivation

- A landscape or multiverse of possible universes can ‘solve’ some (thought not all) naturalness problems through anthropic selection, and the existence and consequences of such, either in string theory or otherwise, is one of the key questions of theoretical physics today.
- To avoid this simply being a ‘solution of last resort’ one must consider the observational consequences.
- Cosmology has reached a level of precision where it now makes sense to do this.

A universe in a bubble

Many vacua implies quantum tunnelling, which can occur via bubble nucleation.

- *Inside* the bubble it is possible to construct an *open* FRW coordinate system. Coleman & de Luccia (1980)
- Bubble wall is infinitely far away.



Sugimura, Yamauchi, & Sasaki (2012)

Signatures of a previous universe

In general one has:

- $\Omega_{k0} > 0$ if inflation not too long.
- Scalar and tensor primordial power spectra are altered.

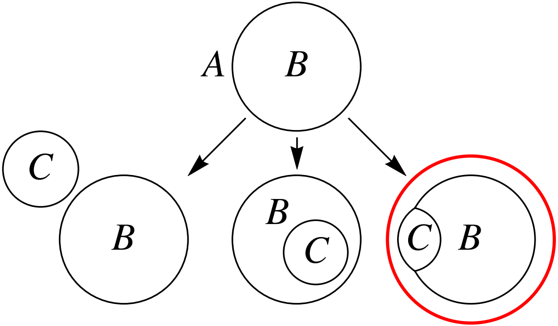
Is it possible to determine the nature of the parent vacuum?

I will consider two scenarios which go beyond simple $O(4)$ symmetric bubble nucleation, but which can be dominant and are especially motivated in the context of a landscape.

Decays involving more than two vacua

Usually one only considers two vacua involved in a decay, but landscapes have many vacua. What about three?

- Given an initial bubble, three things can happen:



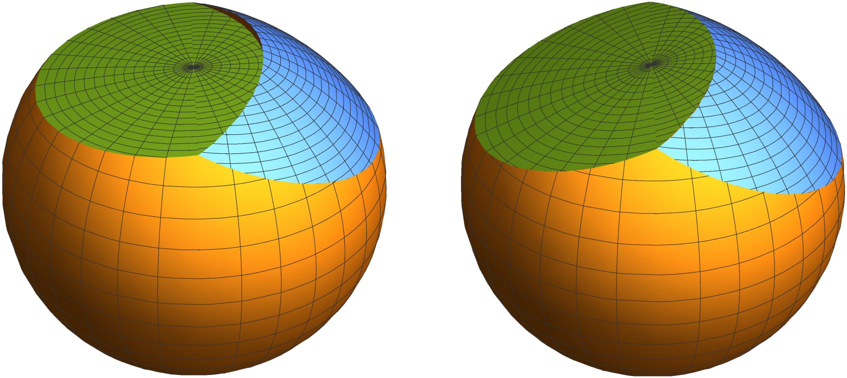
- 'Barnacles' have been considered in flat space by Balasubramanian, Czech, Larjo, & Levi (2011)

Barnacles and gravity

$$
\begin{aligned}
S_b = &\sum_i \left[\int_{\mathrm{Vol}_i} \mathrm{d}^4 x\, \sqrt{|g|}\left(V_i - \frac{1}{2\kappa}\mathcal{R}\right) - \frac{1}{\kappa}\int_{\partial \mathrm{Vol}_i} \mathrm{d}^3 y\, \sqrt{|\gamma|}\, \mathcal{K}\right] \\
&+ \sum_X \int_{(\partial \mathrm{Vol})_X} \mathrm{d}^3 y\, \sqrt{|\gamma|}\, \sigma_X + \int_J \mathrm{d}^2 z \sqrt{|h|}\left(\mu - \frac{\Delta}{\kappa}\right) \\
&- \left(-\frac{24\pi^2}{\kappa^2 V_A}\right)
\end{aligned}
$$

- Need to include the junction where three vacua meet, as the energy density there induces a conical singularity.
- Euclidean de Sitter is a four sphere, so this becomes an exercise in gluing together spheres...

Barnacle geometries



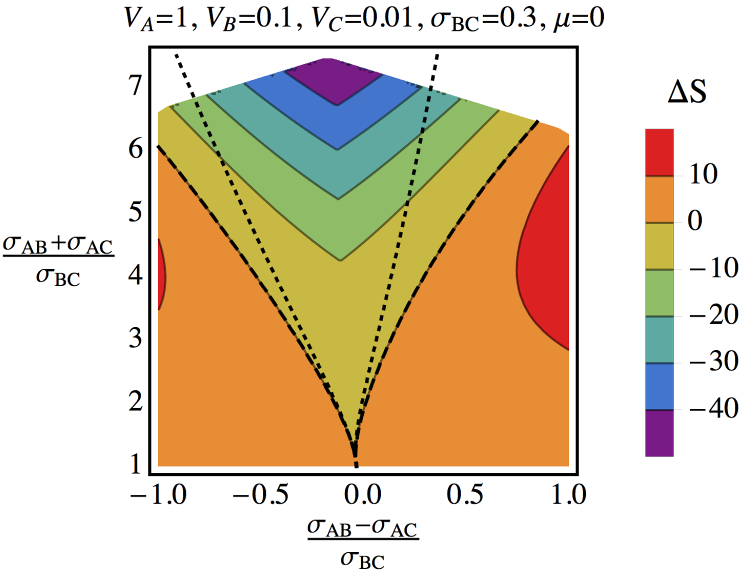
Barnacle actions—comparing to spherical decays

Approximating $\Gamma \sim \mathrm{e}^{-S}$, one can then compare the rate of production of barnacles versus other decay channels.

By considering merging bubbles, one finds:

- $S_b - S_{AB} < S_{BC}$
  - The wall of a bubble is more likely to decay than its interior
- $S_b - S_{AB} < S_{AC}$ and $S_b - S_{AC} < S_{AB}$
  - It is more likely for a wall of a bubble to decay than the parent vacuum to produce a bubble of the other vaccum

Barnacle actions—comparing to spherical decays



Observational consequences

Barnacles can be competitive with $O(4)$ symmetric decays, but what do they look like?

- When analytically continued, the barnacle has the same $SO(1,2)$ symmetry as in bubble collisions; thus if the wall of the bubble in which we are in decays, the signatures would be identical to a collision (as pointed out by Czech (2011)).
- On the other hand, if we are *inside* the barnacle, the initial quantum state would be anisotropic.
- Generally they may be important in any situation with more than two vacua: *e.g.* two stage models of electroweak baryogenesis.

Tunnelling from a smaller number of dimensions

What if the parent vacuum has a *smaller* number of large dimensions than ours?

- More ways to compactify more dimensions, so might expect *more* vacua with *fewer* large dimensions.
- Also possible within the standard model.
- Could tunnelling from these be favoured?
- Some studies have been done into the tunnelling process.
  Blanco-Pillado & Salem (2010), Adamek, Campo, & Niemeyer (2010)

What are the consequences of such a process?

$2 + 1 \to 3 + 1$: An anisotropic universe

$$ds^2 = -dt^2 + a(t)^2 \left(\frac{dr^2}{1 + r^2} + r^2 d\phi^2 \right) + b(t)^2 dz^2$$

Two types of anisotropy:

Shear: $H_a = \frac{\dot{a}}{a} \neq H_b = \frac{\dot{b}}{b}$

Curvature: $\Omega_k = \frac{1}{a^2 H_a^2}$, only in (r, ϕ), not z.

These are related:

$$\frac{H_a - H_b}{H_a} \propto \Omega_k$$

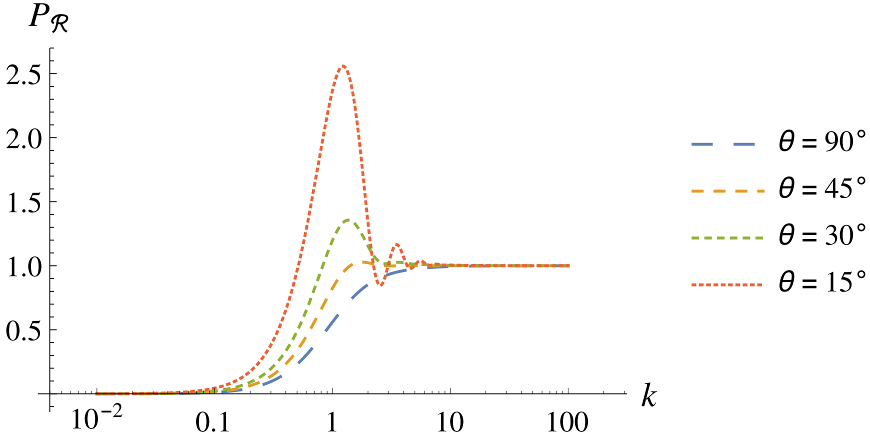
Monopole-quadrupole mixing on the CMB leads to an indirect constraint:

$$\Omega_{k0} \lesssim 10^{-4}$$

Late-time anisotropy has been studied by Graham, Harnik, & Rajendran (2010).

Primordial anisotropy

Power spectrum is no longer isotropic: $P_{\mathcal{R}}(k) \to P_{\mathcal{R}}(k, \hat{\mathbf{k}} \cdot \hat{\mathbf{z}})$



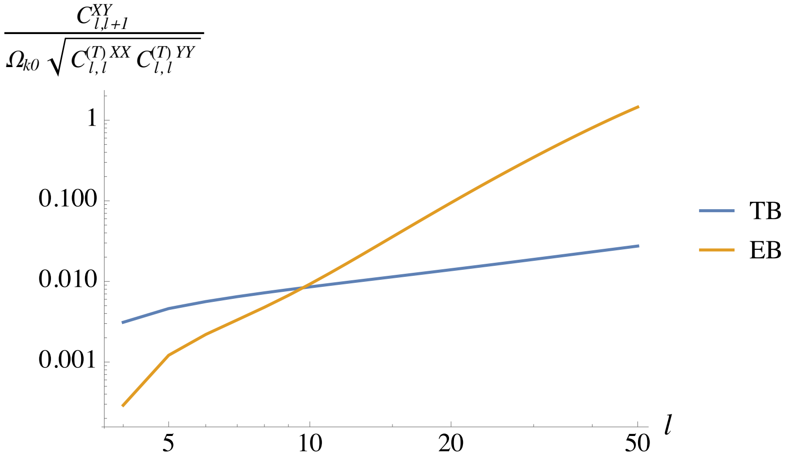
CMB in an anisotropic universe

Anisotropy modifies CMB correlators:

- $C_\ell^{XY} \to C_{\ell\ell'}^{XY}$
- Parity controls which modes mix:

XY	$\Delta\ell$	source
TT, TE, EE, BB	even	primordial and late-time anisotropy
TB, EB	odd	primordial anisotropy

TB and EB correlations



Summary

- If there is a landscape of vacua (functioning *e.g.* as a solution to a naturalness problem), then one would expect quantum tunnelling between the different vacua.
- As cosmological observations become more precise, it makes sense to ask if this is observable.
- Here we have considered two scenarios which are especially motivated in the context of a landscape:
  - Transitions in which the wall of a bubble decays
  - Transitions in which the parent vacuum has fewer large dimensions