COSMO 2013

Inflation on Random Landscapes

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Inflation on a Landscape?

Landscape in ST: plethora of metastable vacua – eternal inflation.

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Caveat I: Vacua may not be long lived

- Resonant tunneling (Tye; Saranki Shiu, Shlaer 07)
- Disorder (Podolsky et.al. 08)
- Giant Leaps (Brown, Dhalen, 10,11)
- Instabilities (Greene at.al.13)
- Classical unstable directions (D.Battefeld, T.B. 12)

Working hypothesis:
Landscape idea + eternal inflation OK

Inflation on a Landscape?

Landscape in ST: plethora of metastable vacua – eternal inflation.

Caveat I: Vacua may not be long lived

Caveat II: Measure Problem

no mathematically rigorous way to make predictions in the multiverse (dependence on choice of measure)

See e.g. Schiffrin and Wald 12, and Freivogel 11 for recent reviews

Approach:

Ignore it for the time being. (some predictions are insensitive to choice of measure)

Inflation on a Landscape?

Landscape in ST: plethora of metastable vacua – eternal inflation.

Caveat I: Vacua may not be long lived
Caveat II: Measure Problem
Caveat III: Potential on Landscape relevant for our universe is unknown - Constructions of concrete toy-models (e.g. Denev-Douglas, Random N=1 SUGRA, see i.e. Marsh, McAllister, Wrase 11; Pedro, Wetphal 13, …) - Use of random potentials (Easther, Aazami 05; Agarwal et.al.11; Frazer, Liddle 11; T.B., D.B., Schulz 12, …) Approach: Phenomenology: random potentials + random matrix theory.

Inflation on a Landscape?

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Caveat III: Potential on Landscape relevant for our universe is unknown

Let's assume that the basic idea is right.

Graceful exit: Tunnel out of false vacuum e.g. via Coleman, De Luccia instanton.

Tunnel directly to true vacuum?
Universe is cold, and dominated by spatial curvature (open)!

Need: subsequent phase of slow roll inflation (~ 60 e-folds to dilute curvature)

Open Inflation: Bucher, Goldhaber, Turock, 95; Yamamoto, Sasaki, Tanak 95; Linde 95; Linde, Mezhlumian 95; Garzia Bellido, Garriga, Montes, 97; …

Observable: spatial curvature $\Omega_k \gtrsim 10^{-4}$ Guth, Nomura 12 (measure depend.)

Some Known Results based on Random Matrix theory:

Super exponential suppression for non-diagonal Hessians with zero mean:
For large D, almost all critical points are saddle points.

Aazami, Easther 05;
Dean, Majumdar 06; Vivo, Majumdar, Bohigas 07;
Marsh, McAllister, Wrase 11;
Chen, Shiu, Sumitomo, Tye 11

If Inflation takes place, it will most likely occur at a single saddle point.

Aazami, Easther 05

If Inflation takes place, it is more likely to be of short duration.

Freivogel, Kleban, Rodriguez Martinez, Susskind 05;
Agarwal, Bean, McAllister, Xu 11; Schulz, D.B., T.B. 12;
Marsh, McAllister, Pajer, Wrase 13

Can we probe Topography of Landscape?

Sharp features,
cliffs, deep valleys, ..

or

Shallow hills?

Aside: the Role of Anthropics:

Anthropic bound on a positive (Weinberg 87) and negative (Bousso, Leichenauer 08) CC exist and work well (merely requiring gravitationally bound objects to form).

To use them, we need to invoke eternal inflation to sample all possible trajectories. Our universes' history in a high dimensional random inflaton potential thus requires:

- eternal inflation (i.e. in a rare long lived minimum high up in the potential)
- the unlikely encounter with a saddle point
- an unlikely long phase of inflation (N ~ 60)
- the extremely unlikely encounter with a metastable, low deSitter vacuum directly after inflation terminates (Schulz, D.B., T.B. 12).

Our Universe is all but generic.

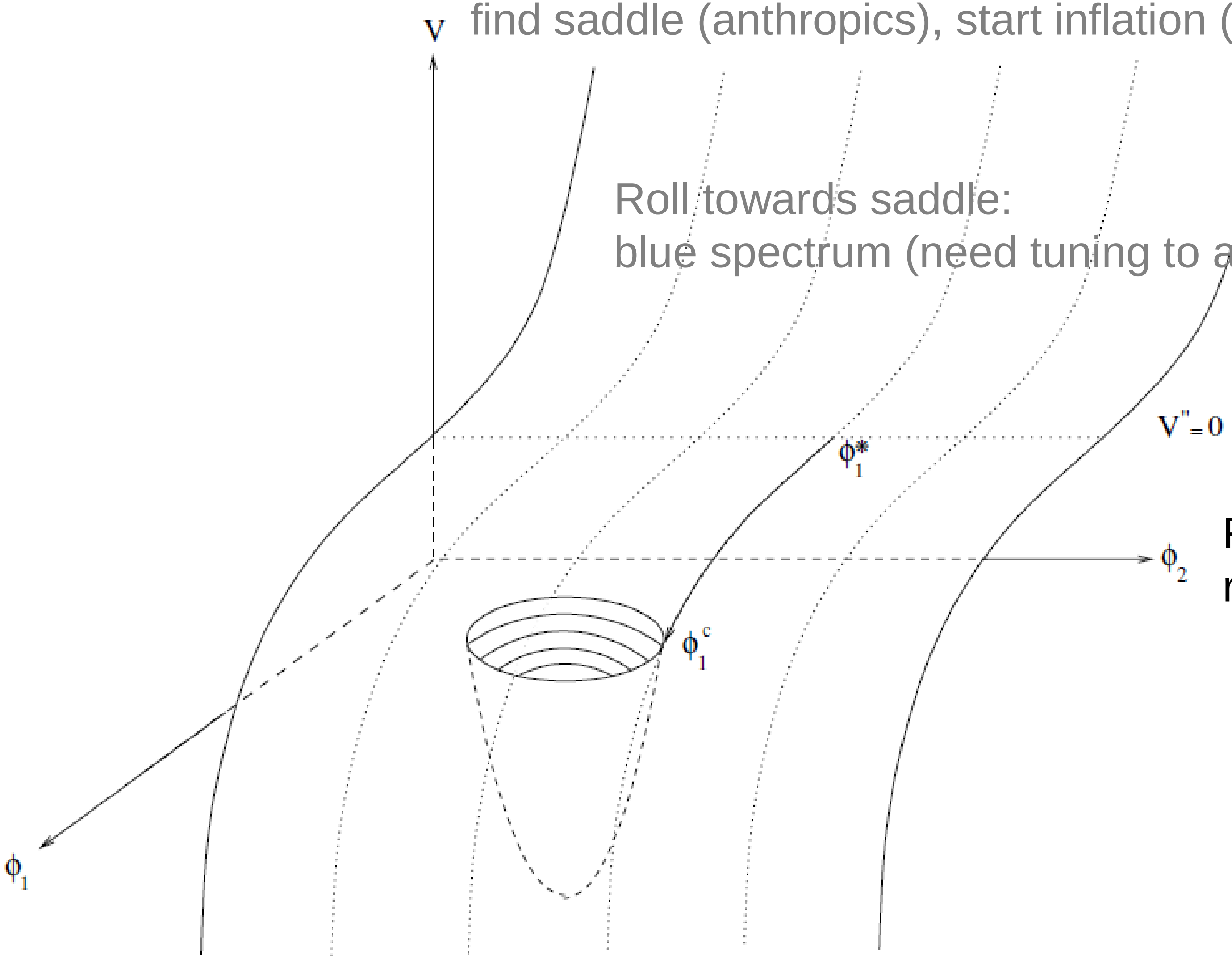
<u>Problem:</u> statistical predictions in eternal inflation are often hampered by our inability to define a unique measure on infinite sets (Measure Problem: i.e. Olum 12).

(Possible way out: inflation is not past eternal (Borde/Vilenkin); introduces a cutoff (a measure becomes justified) that is however inaccessible to direct tests.)

Schematic potential for ``anthropic inflation'':

Tunnel somewhere, curvature domination,
find saddle (anthropics), start inflation (not shown)

Roll towards saddle:
blue spectrum (need tuning to avoid!)



Fall off saddle:
red spectrum

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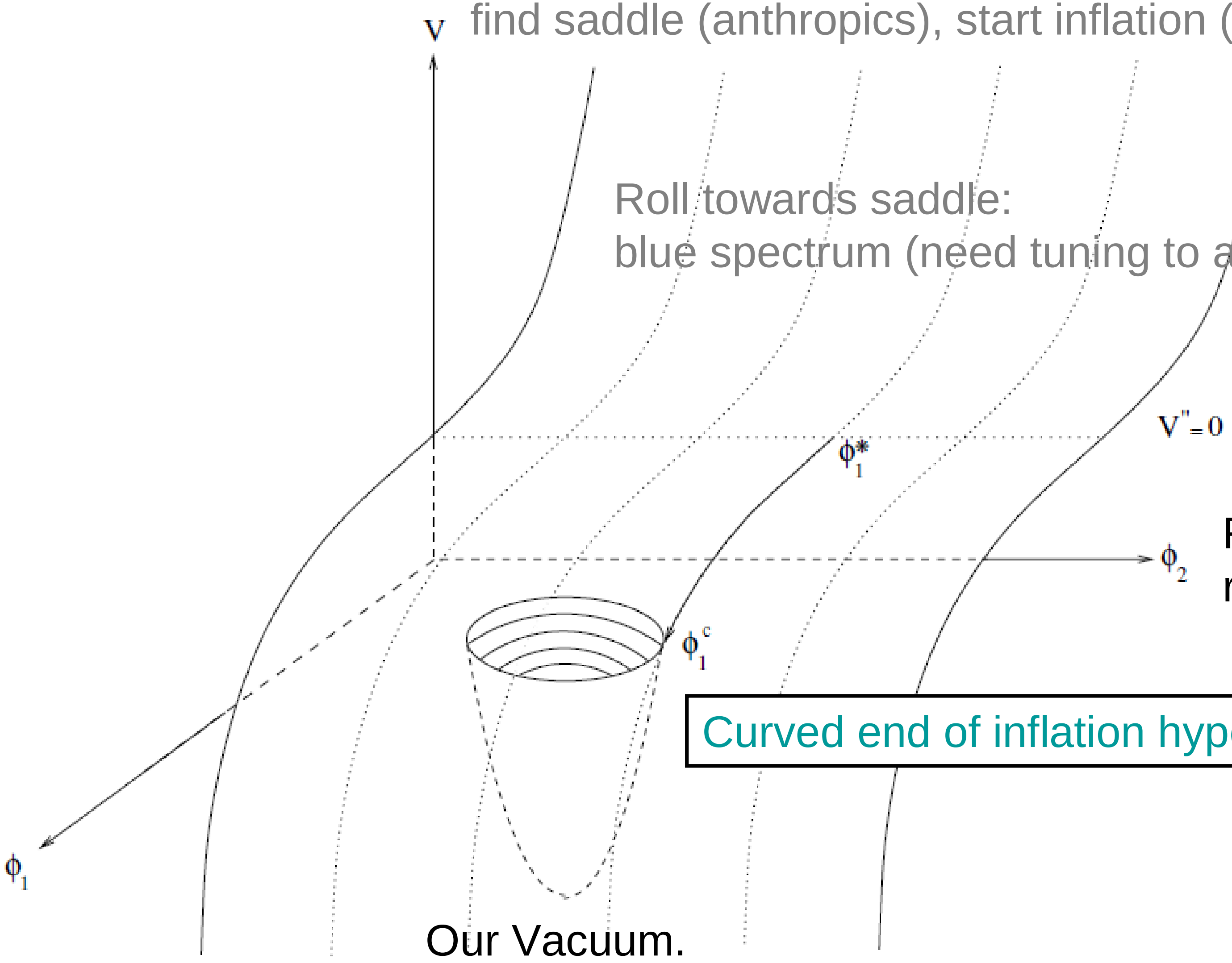

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Fall off saddle:
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Curved end of inflation hypersurface!

Our Vacuum.
Hole like ours should be generic (no anthropics)
But the saddle is not generic (anthropics).

Inhomogeneous End of Inflation (IEI):

Curved end of Inflation Hypersurface leads to non-Gaussianities.
Planck bound on local NG:

$$f_{NL} = 2.7 \pm 5.8$$

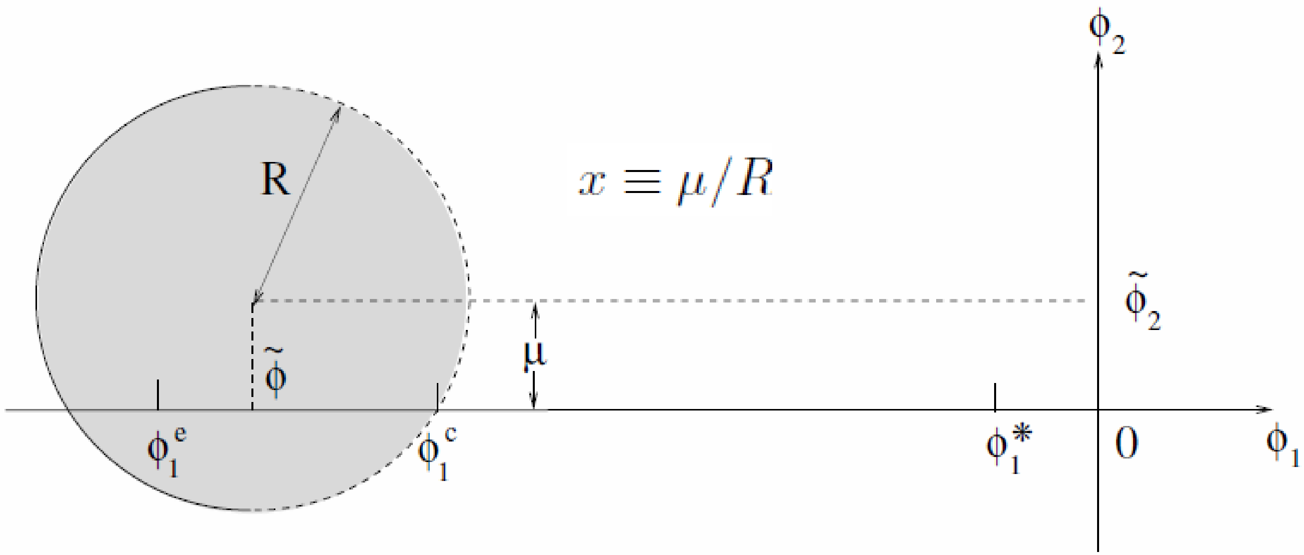
Use bound to constrain curvature of hypersurface

D. Battefeld, T.B. 13;
Elliston, Mulryne, Tavakol 13.

Since depth of hole is given (anthropics and inflation near saddle), we can constrain topography of landscape if the hole is generic (no anthropic pressure on shape)!

vs

Inhomogeneous End of Inflation: Setup



Model: straight trajectory, potential near saddle $V(\phi_1) = C_0 + C_1\phi_1 + C_3\phi_1^3$

Use Planck data to determine constants and initial conditions (possible analytically);
Require N=60 before entering hole. Hotchkiss, Mazumdar, Nadathur 11; D. B.,T.B. 13;

Only one free parameter: scale of inflation, bounded from above by

$$C_0 \leq \frac{8^3\pi^2 P_\zeta}{84}\left(\frac{\Delta\phi_{\max}}{2}\right)^2\left[\frac{\pi^2}{(N+2)^2} + \left(\frac{n_s-1}{2}\right)^2\right]^2$$
$$\approx 0.66 \times 10^{-13} \equiv C_0^{\max}\,.$$

(given a concrete landscape, the likely scale can be computed, e.g. Pedro, Westphal 13)

Non-Gaussianities

Compute bi-spectrum (and tri-spectrum, see paper) via delta-N formalism, leading to

$$\boxed{f_{NL} = A_1 f_1(x) - A_2 f_2(x) \left(\frac{C_0}{C_0^{\max}}\right)^{1/2} \frac{1}{R}}$$

$$A_1 \equiv \frac{5}{(2\pi)^4 P_\zeta^2 3^2} \frac{C_0^{\max\,5} C_3^{\max} \Delta\phi_{\max}}{C_1^{\max\,4}} \left(1 + 3\Delta\phi_{\max}^2 \frac{C_3^{\max}}{C_1^{\max}}\right)^{-4} \approx 3.3 \times 10^{-10},$$

$$A_2 \equiv \frac{5}{6(2\pi)^4 P_\zeta^2 3^2} \frac{C_0^{\max\,5}}{C_1^{\max\,3}} \left(1 + 3\Delta\phi_{\max}^2 \frac{C_3^{\max}}{C_1^{\max}}\right)^{-3} \approx 6.9 \times 10^{-11},$$

$$f_1(x) \equiv \frac{x^4}{(1-x^2)^2}$$

$$f_2(x) \equiv \frac{x^2}{(1-x^2)^{5/2}}$$

See D. Battefeld, T.B. 13 for details
As well as the tri-spectrum.

Non-Gaussianities

$$f_{NL} = A_1 f_1(x) - A_2 f_2(x) \left(\frac{C_0}{C_0^{\max}}\right)^{1/2} \frac{1}{R}$$

Always small: $A_1 f_1\left(\frac{\mu}{R}\right) \ll A_1 f_1\left(\frac{\mu_{\max}}{R}\right) \approx 1.0 \times 10^{-5}$

Natural values of impact parameters (no tuning allowed!): $\mu \sim R/2$

Steep Holes:

As wide as deep in natural units $R \sim C_0$

$$\boxed{f_{NL} \sim -530}$$

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Shallower holes:

quadratic potential in hole; $m \sim 1$ $\quad R \sim \sqrt{2C_0}$

(smaller `m` suppresses NG further)

$$\boxed{f_{NL} \sim -0.000097}$$

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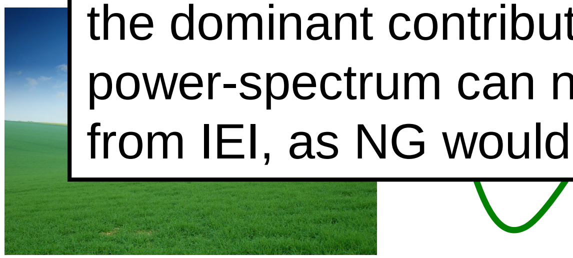

Note: without additional tuning the dominant contribution to the power-spectrum can not come from IEI, as NG would be too big.

A lot of work needs to be done:

What type of landscapes are `generic’ in string theory? (Random SUGRA? …)

- Dimensionality? (large D appears natural)
- Topography/Hilliness? Needed to concretize random potential, i.e.
  properties of Hessian (Tools: random matrix theory, Dyson random walk, ...).
- How many light fields during inflation? (Application of EFT?)
- Presence of Extra Species Loci? (Trapped inflation?)

What are generic predictions?

- Spatial Curvature
- Non-Gaussianities (multi-field effects, reheating)
- Gravitational waves
- Features (bumps, oscillations in correlation functions)

How dependent are predictions on the imposed measure?

Reheating/Preheating? (essentially unknown beyond simple phenomenological studies)

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