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Fundamental Questions in Cosmology
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Unwinding Inflation

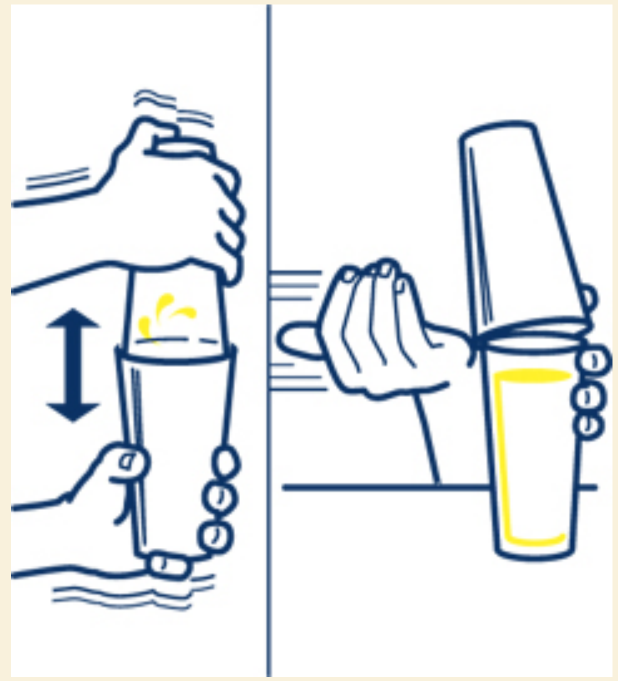
with Roberto Gobbetti, Matthew Kleban, Marjorie Schillo
arXiv:1211.3416 (short), arXiv:1211.4589 (long)

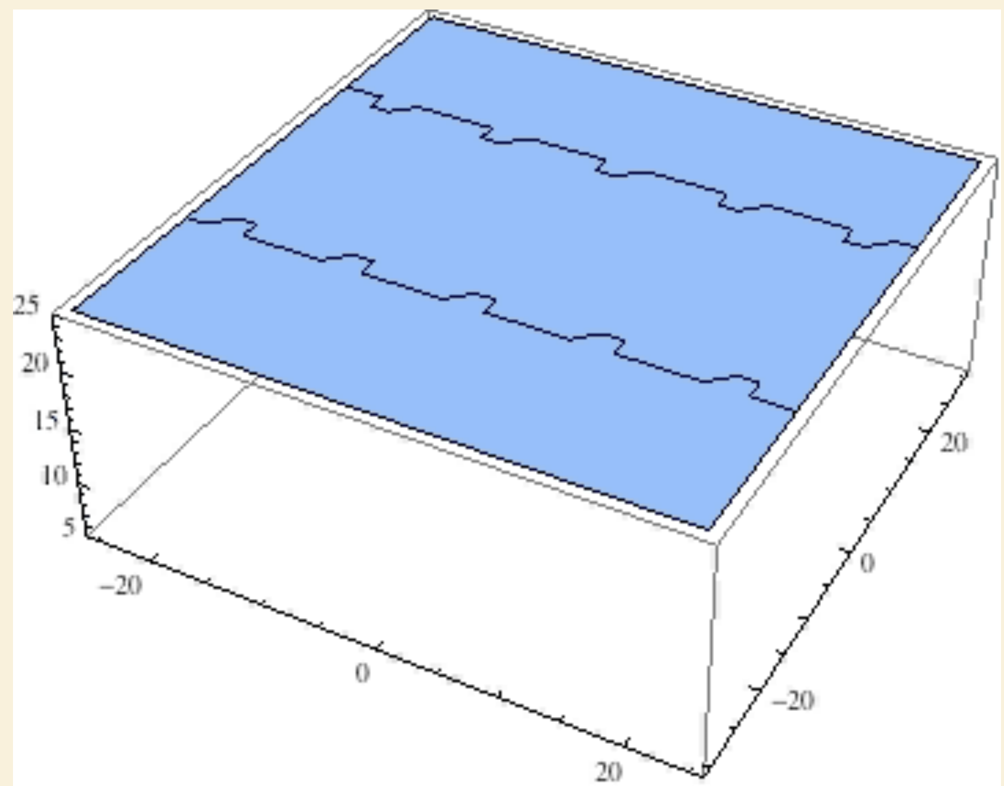
What our model is

Take:

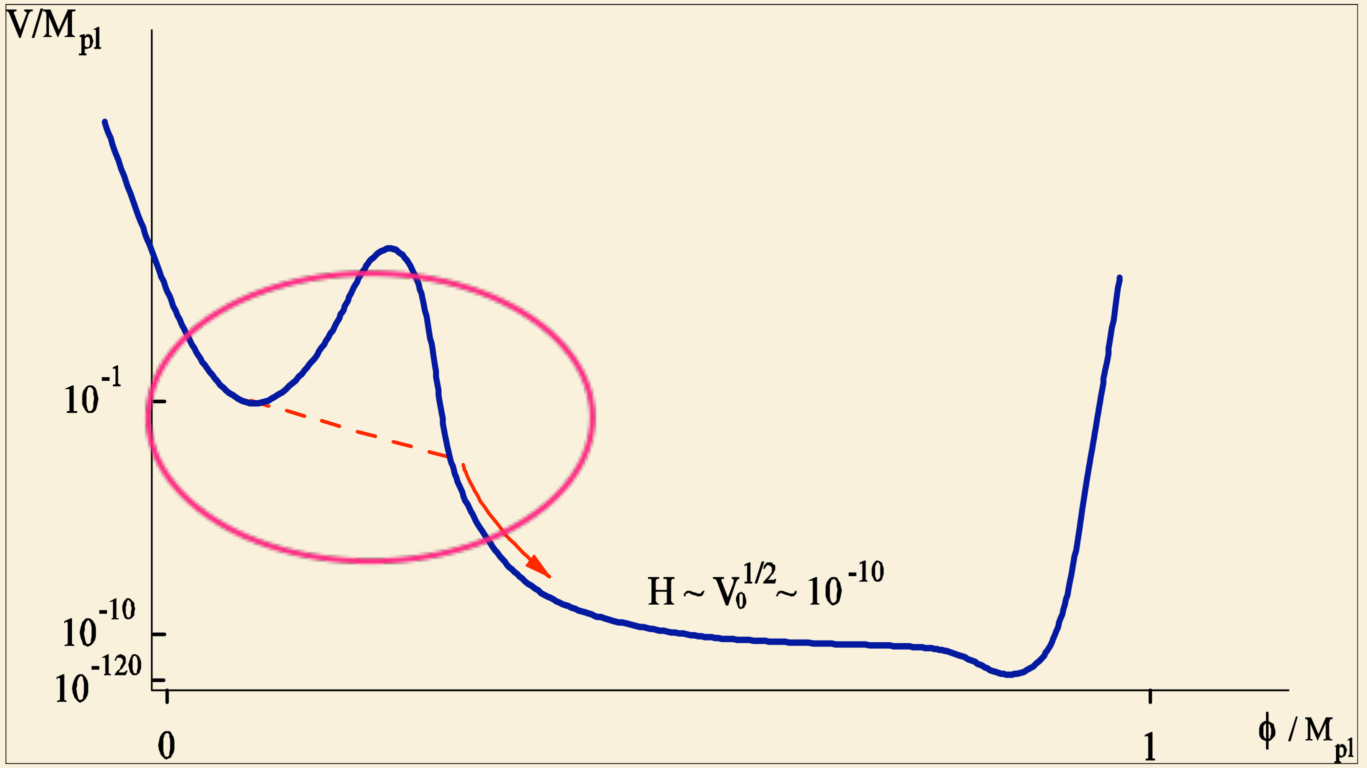
- Boom and bust inflation
- Monodromy inflation
- Chain inflation
- $m^2\ \varphi^2$
- DBI inflation
- Old inflation
- Cascade inflation
- Trapped inflation

in no particular order.
Shake well, and that’s what we got!
Better than a Wicky Wacky Woo...





False vacuum eternal inflation

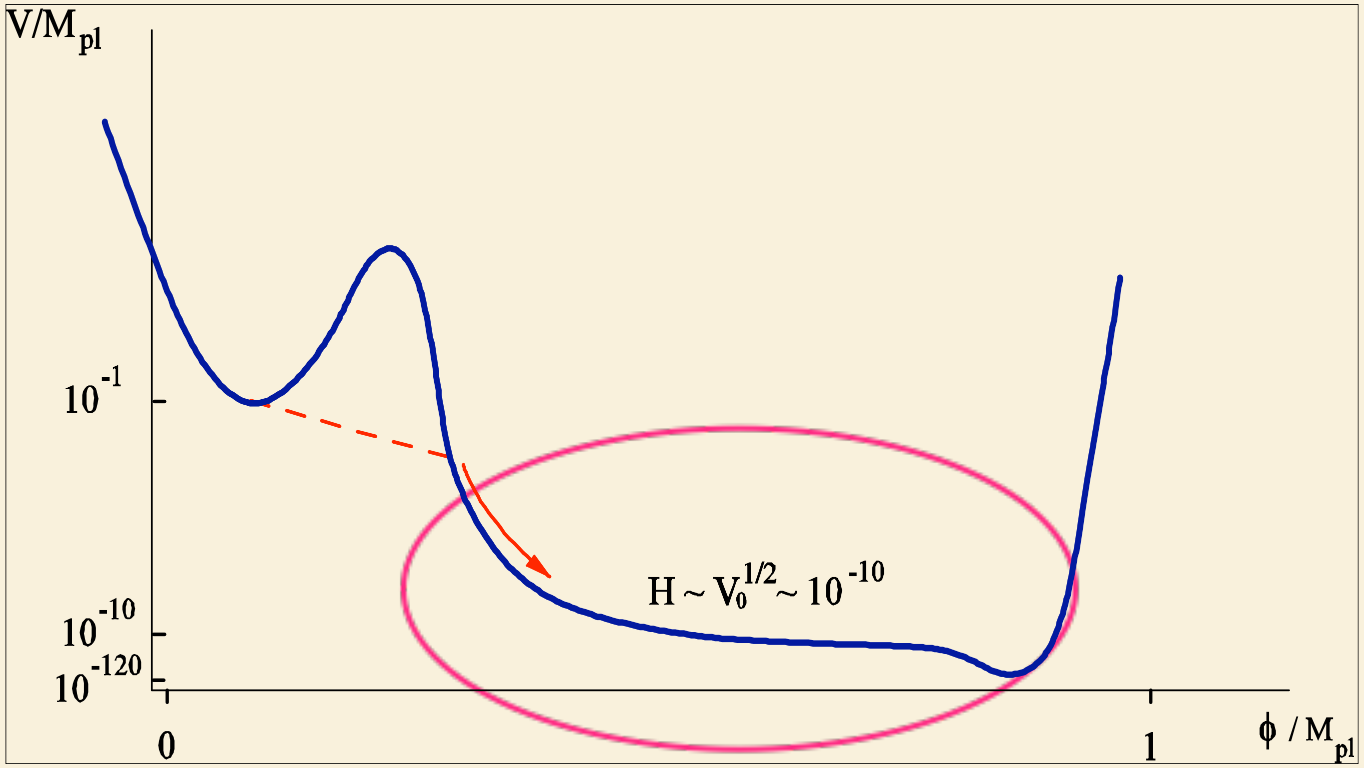


Guth's original idea: universe trapped in a metastable minimum
Inflation is eternal and a powerful attractor: some regions of the universe always inflate

How to end inflation (graceful exit)?
First order phase transition, but very difficult to percolate

Other problems: a bubble contains an *open* FRW universe...
and where is the matter?

Slow-roll (new) inflation



A better model: a very flat scalar potential (approximate shift symmetry)

The scalar slowly rolls and does the job: inflates the universe, and at the end it gets converted into radiation

All models constructed are basically EFTs, with some degree of fine-tuning and not simple to embed into a UV-complete theory

A UV-completion?

Suppose we want to realize inflation in string theory

Generic ingredients are

- Extra (compact) dimensions
- Extended objects (D-branes), which couple to
- Higher-form fields

In inflation we basically want to slowly decrease vacuum energy.
In d dimensions, a d-form electric flux (d antisymmetric indices) is vacuum energy!

1+1-d: Schwinger model

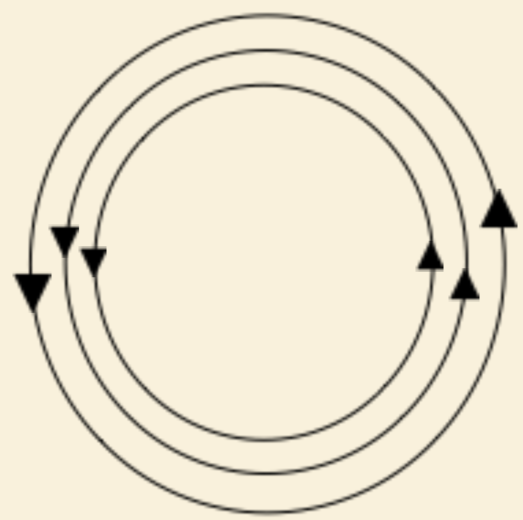
Electric field in 1+1-d is $F_{\mu\nu} = E\,\varepsilon_{\mu\nu}$

Compactify the space to S_1.

We can have a field flux that "wraps" the circle

Varying the size of the circle does not modify the field or its energy density: vacuum energy $\Lambda \sim E^2$

QM can discharge the field by the spontaneous nucleation of charge pairs!

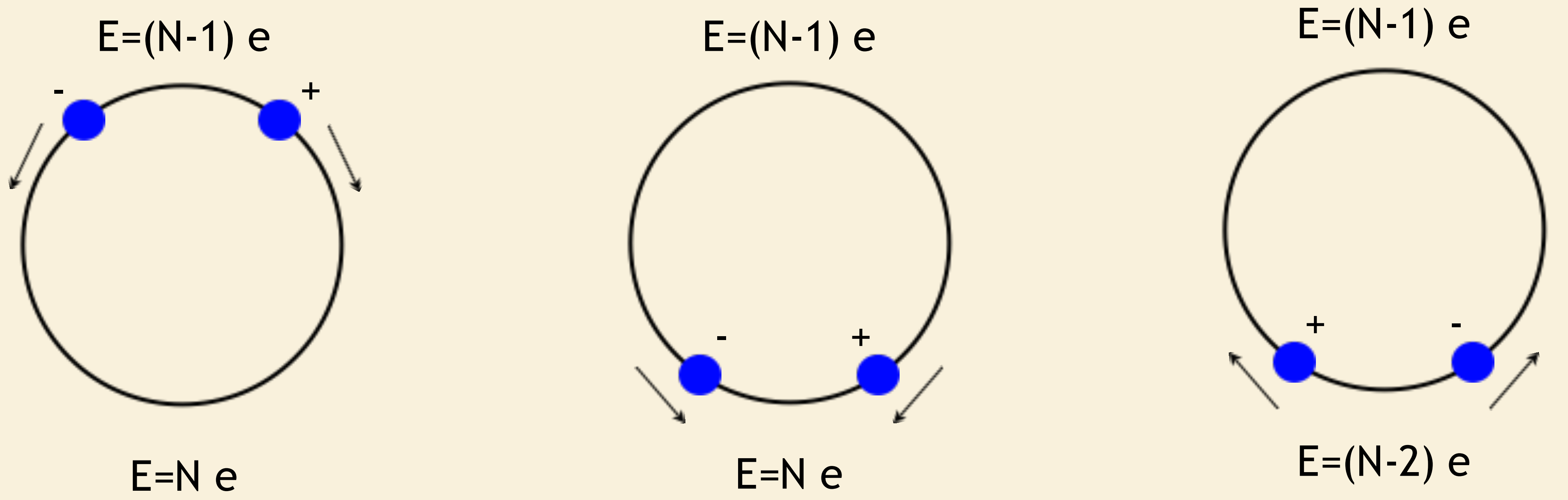


The story of a pair

- A quantum nucleation event happens: the field is discharged by e between the $e^+ e^-$ pair that appears

- Classically, the field accelerates the charges in opposite directions, until they meet on the opposite side of the circle

- Typically, they pass through each other and continue to accelerate

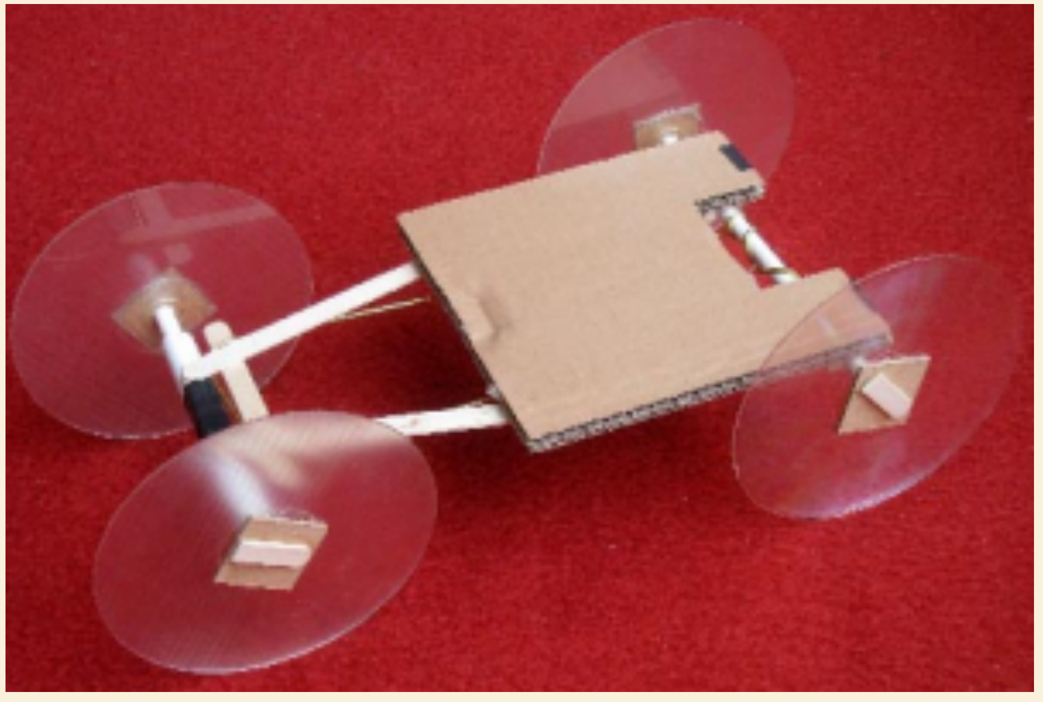


Inflating with a rubber band

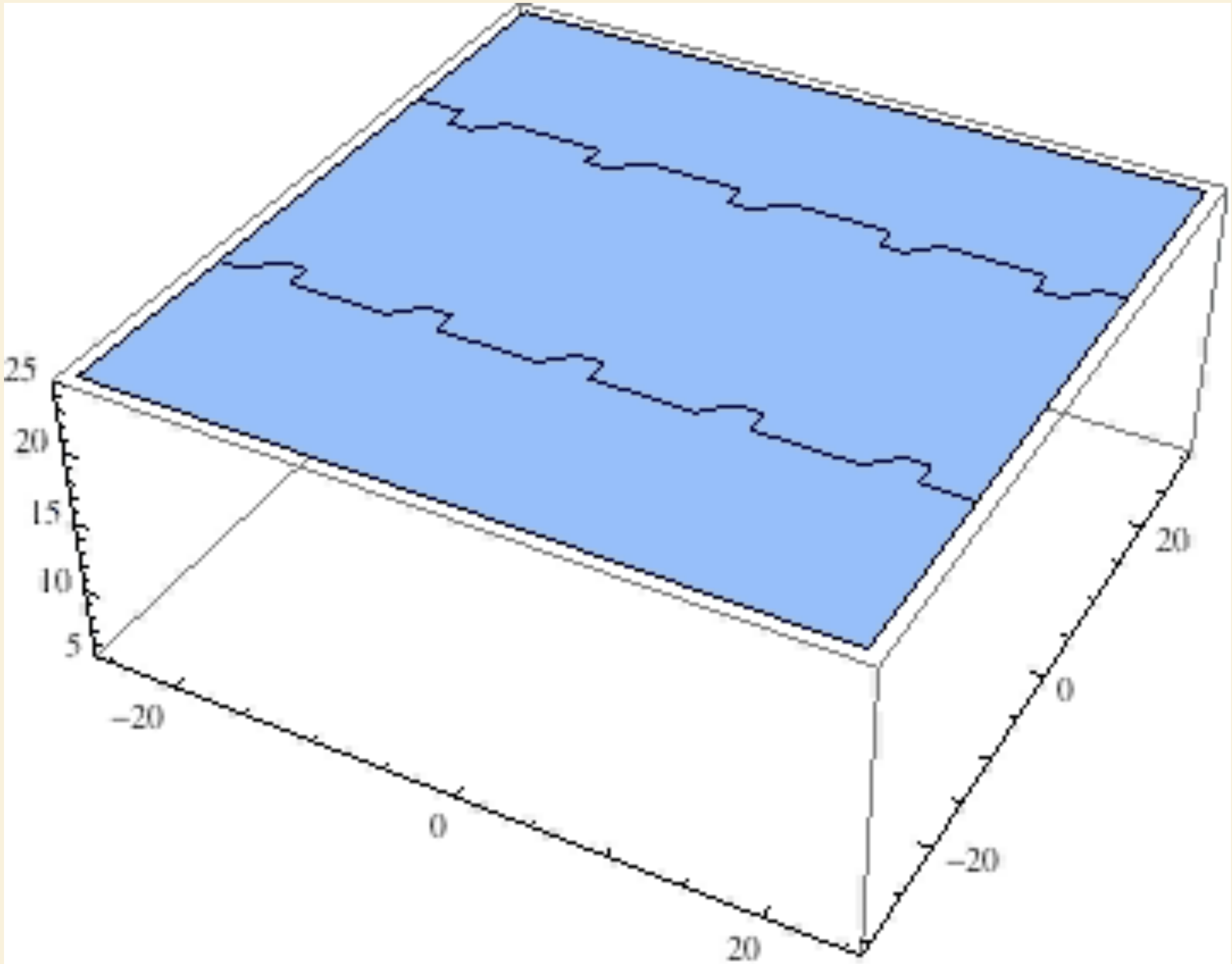
Very simple analogy: think of flux lines as a stretched rubber band, wound around the compact dimension(s)

At a certain point, somebody creates a hole in the band: the rubber band begins to unwind!

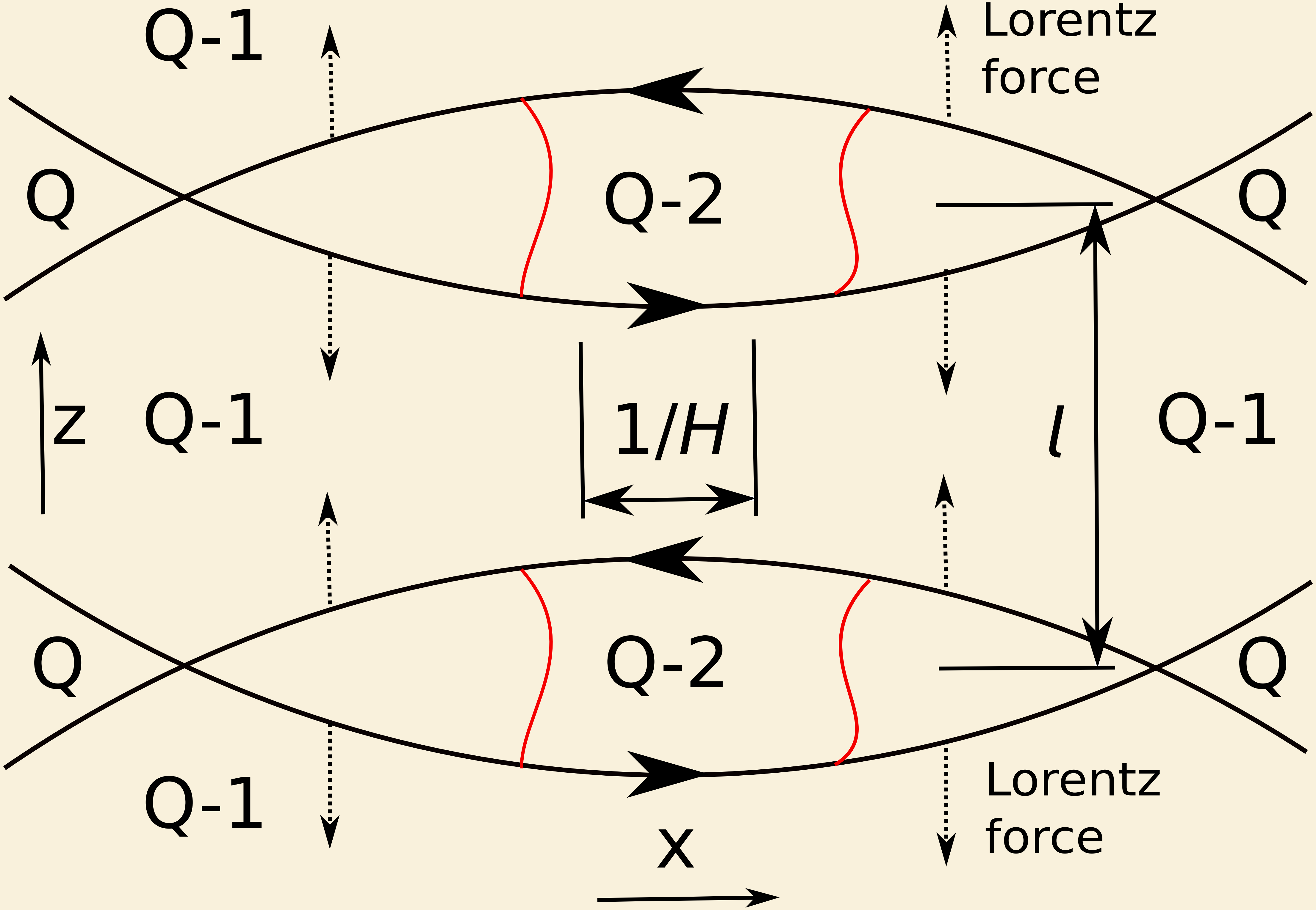
To some observer not sensitive to the compact dimension(s), this is just a decrease in potential energy



Animated evolution



Snapshot of collision



Let's (really) make inflation

- Basic setup: spacetime of the form $dS_4 \times M$.

Hubble constant is determined by the amount of flux.

- Configuration unstable to (QM) nucleation of a brane bubble

- The bubble expands in the dS directions and collides with itself in the compact directions, discharging the flux one unit at a time

- The cascade ends when the brane annihilates → reheating

How it works

- The bubble contains a *homogeneous* and *isotropic* open FRW universe. Expansion in dS directions inflates away the curvature!

- A crucial point: collisions happen at instants of FRW time, which preserve the full SO(1,3) symmetry of open FRW

- This is an exit from the FVEI, which produces a homogeneous and flat universe

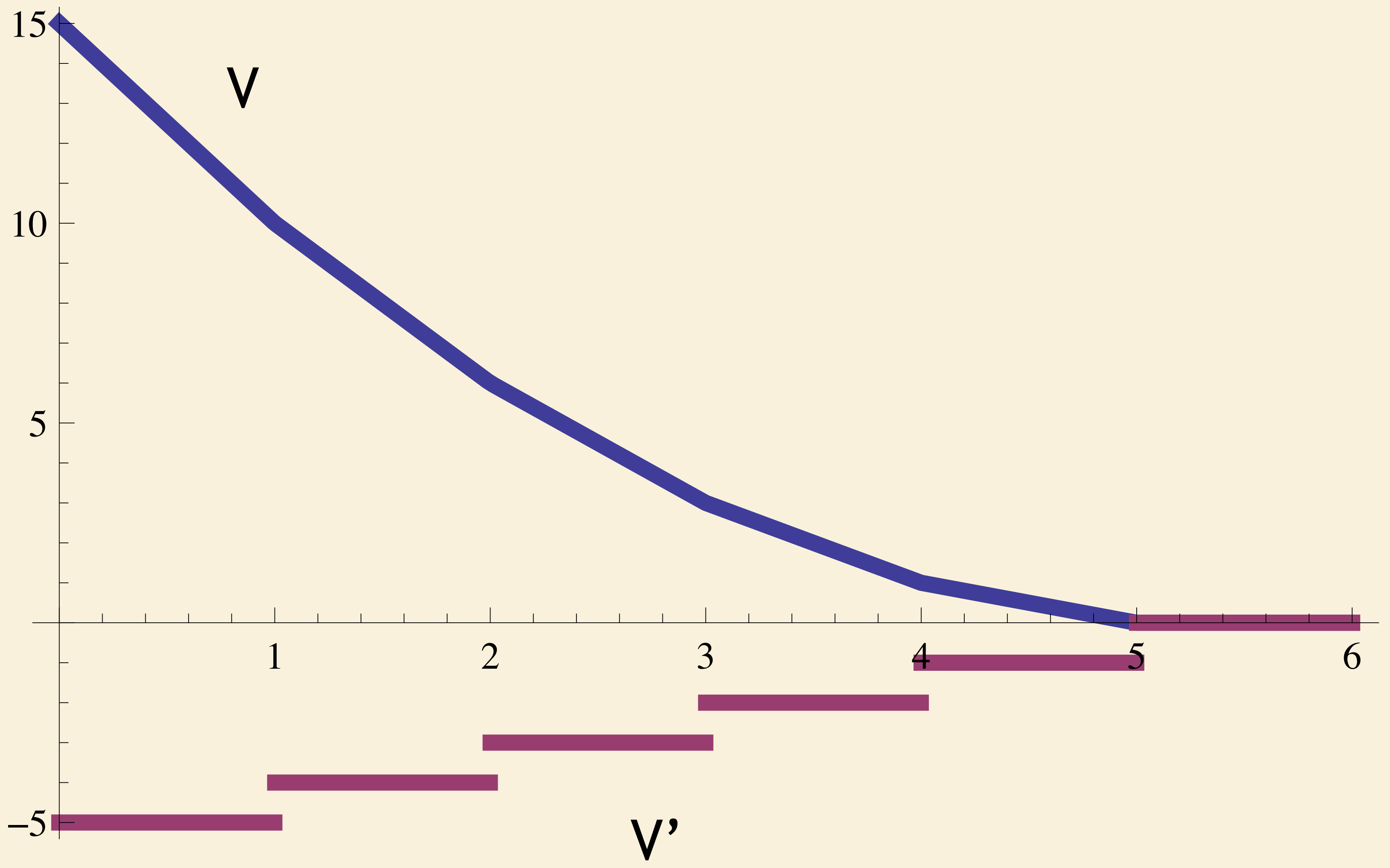
- How rare bubble nucleations are is irrelevant, because the cascade is classical and doesn't stop once it starts

- Reheating occurs naturally at or near zero flux, when the brane slows down and can self-annihilate (by tachyon condensation)

Effective action

4d effective inflaton is the brane separation.
Effective 4-d action for simplest model:

$$S_4 = -\int \mathrm{d}^3\Omega \, \mathrm{d}t \sinh^3 t \left[2\sigma \sqrt{1 - \dot{z}_0^2} + V(z_0) \right]$$



Fluctuations

The brane separation in the compact dimensions z(x) is a 4d light scalar field, which determines when reheating happens.

There are two sources of perturbations in z:

- de Sitter quantum fluctuations, as in ordinary inflation

- Brane self-collisions produce open strings, and variations in the density of these cause perturbations in z

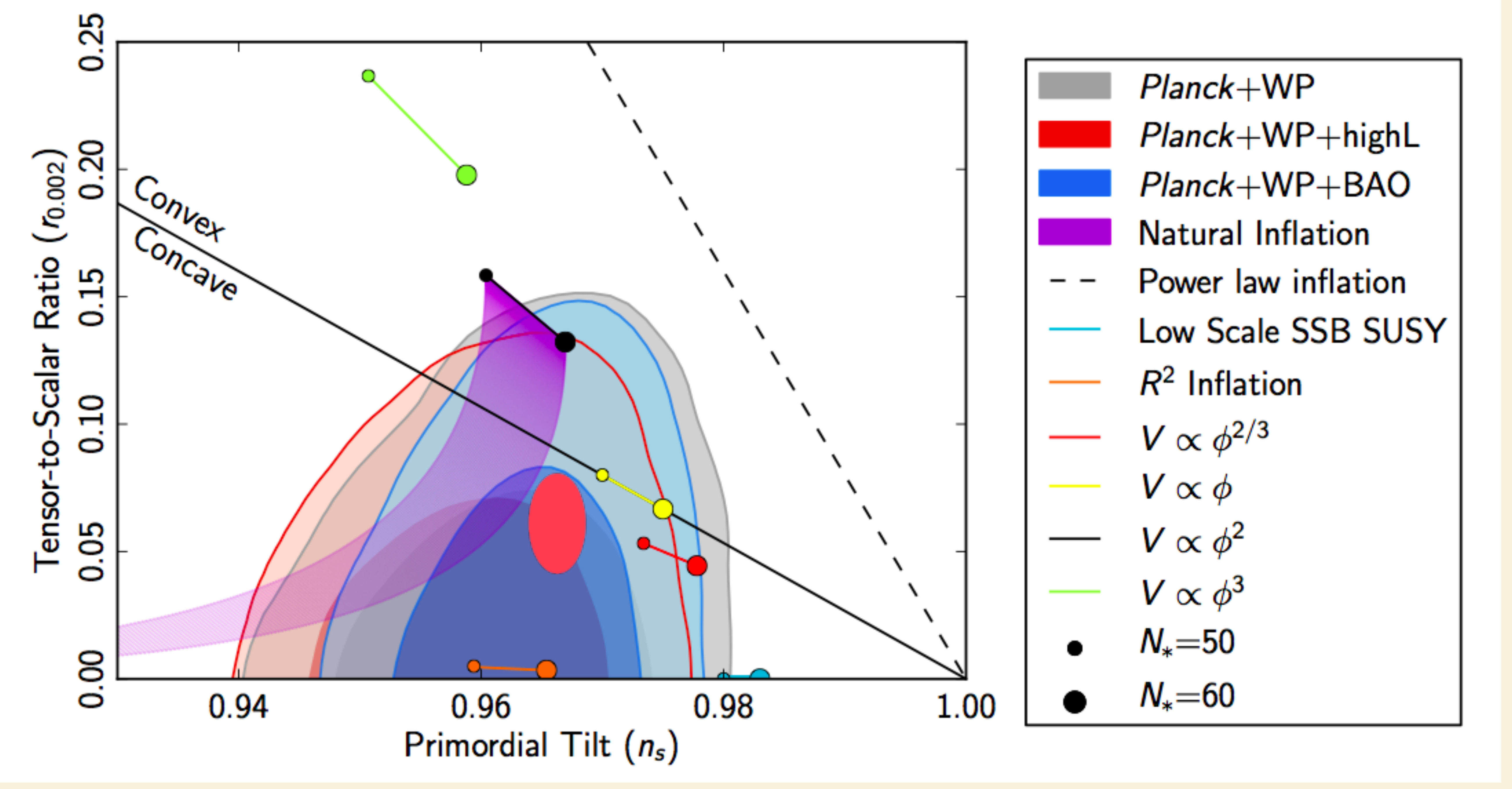
Power spectrum: $$\Delta_{\mathcal{R}}^2 = \frac{H^4}{8\pi^2 \sigma \dot{z}_0^2}$$

Tilt: $$n_s - 1 \sim -\frac{2}{N_e} \sim -0.3$$

Tensors: $$\Delta_h^2 = \frac{2H^2}{\pi^2 M_{\text{Pl}}^2}$$

Tensor-to-scalar ratio potentially observable $$r \sim \frac{1}{Q} \sim 10^{-2}$$

Where are we?



Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60

Strings, strings

In general, open strings stretched between branes contribute to the spectrum.
This is related to other scenarios, like warm, trapped, dissipative inflation.

The number density of strings produced is a Poisson process, which gives a scale invariant spectrum

In the perturbation equation, we get both an additional friction term and a source term, which represents a stochastic force

For interesting regions of parameter space, this contribution is subdominant.

Wiggles

Because of the periodic self-collisions, we have oscillations in the power spectrum, periodic in ~ ln k, with a period smaller than inverse Hubble

The amplitude of oscillations depends on the compact extra dimensions

For instance, the simplest model with S_1 has $1/Q^2$ amplitude.

But S_2 compact dimension gives $1/Q$, potentially observable.

Also, if string production is not negligible, it does produce wiggles.

What about non-Gaussianity?

Main source of NG is the DBI kinetic term.
This gives ~equilateral shape and we expect $f_{nl} \sim 1/c_s^2 \sim \gamma^2$
Given Planck's results, $c_s > 0.07$, we need $\gamma < 14$

Difficult to analyze NG due to fluctuations in string density.
If they are important, we can expect a folded shape, as in models with particle production (due to negative frequency modes)

In general, except for the codimension-1 case, we expect additional light scalars b_i which describe the position if the branes in transverse dimensions.
They determine the reheating moment, which could translate into local NG.
However, not if the inflationary trajectory has $\langle b_i \rangle = 0$ at reheating

Conclusions and future work

- Inflation is the best model we have for the early universe dynamics, and FVEI a generic prediction of String Theory

- Unwinding inflation is a model which naturally realizes slow-roll type inflation, starting from a FVEI landscape

- At the EFT level, it encompasses different effective models present in the literature (DBI, dissipative, oscillating), but with no fine-tuning of parameters

- Need to build a detailed model in the context of string theory

Thank you!