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Unwinding Inflation

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Inflation and FVEI

The universe is flat, homogeneous (and huge): a period of very fast expansion would explain how this happened

Causally disconnected patches of the sky could have time to thermalize

A modern theory of inflation can explain also the small departure from homogeneity that we observe

A system with more than a phase occurs pretty often in nature, why not for the universe?

Inflation and FVEI

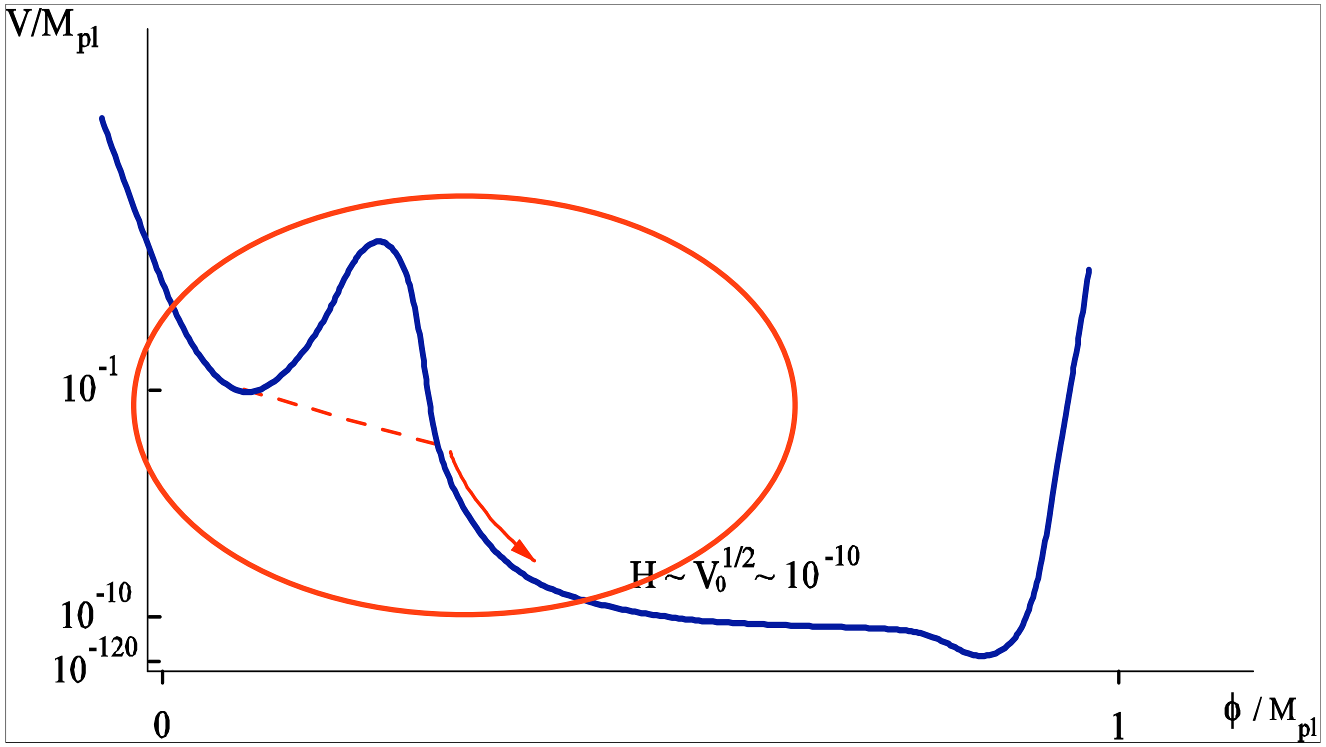
Imagine our universe is just a phase with a given vacuum energy, we call this scenario False Vacuum Eternal Inflation

FVEI is an attractor: at least 2 phases connected with first order phase transitions. If the universe is ever in higher energy state, then the system is dominated by phase transitions

Add gravity: energy gravitates and positive vacuum energy sets rate of expansion of the universe

Old Inflation

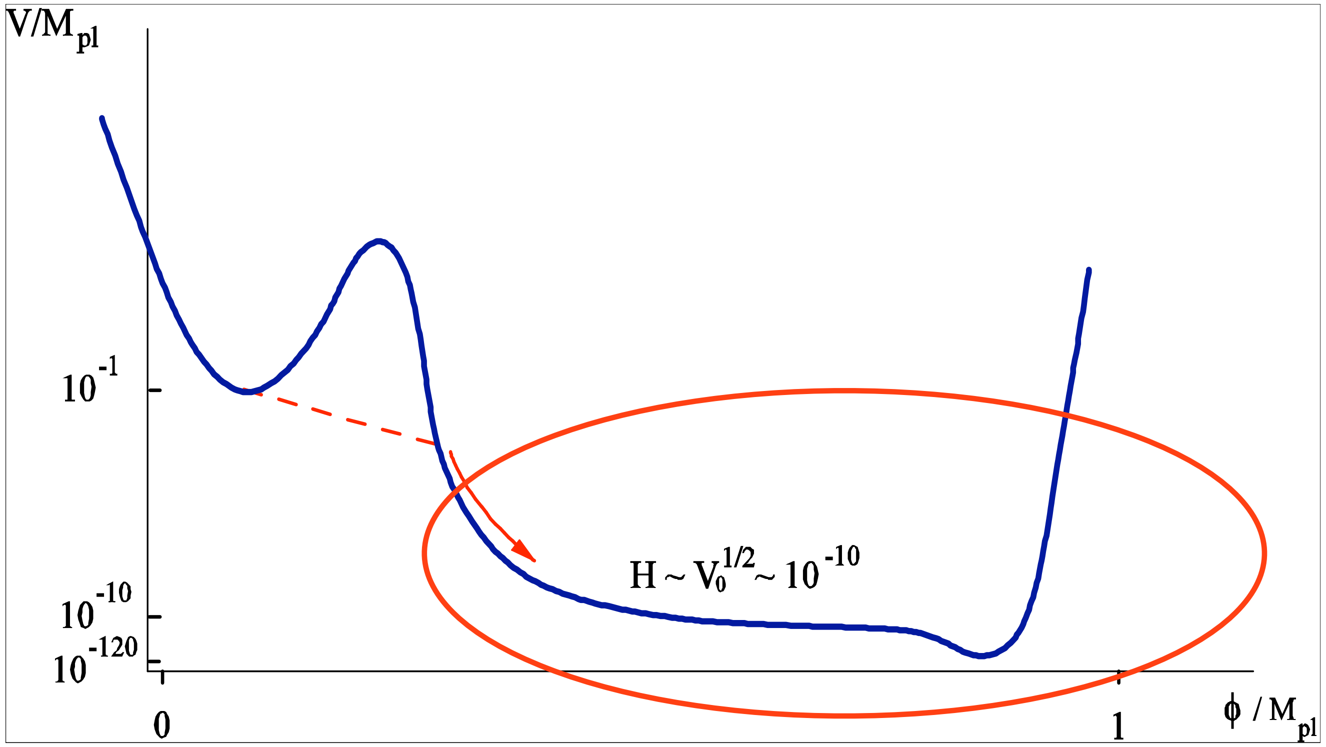
- Example of FVEI is Guth's old inflation model
- Two main problems: reheating and big negative curvature inside bubbles
- Inflation inside bubble is necessary to solve curvature problem



How do we end eternal inflation?

Slow roll Inflation

- Problem is solved adding a plateau inside the lower energy phase
- Why such a potential?
- Good EFT, but requires a certain amount of tuning and needs a microscopic explanation



Higher dimensions etc..

We want to find a UV completion that automatically gives slow roll inflation

Also, we want to have slow roll inflation arising naturally from FVEI, thus providing a way to exit from it

String Theory predicts a landscape, extra dimensions and branes, moreover, in d dimensions a d-form electric flux is a vacuum energy and can drive FVEI

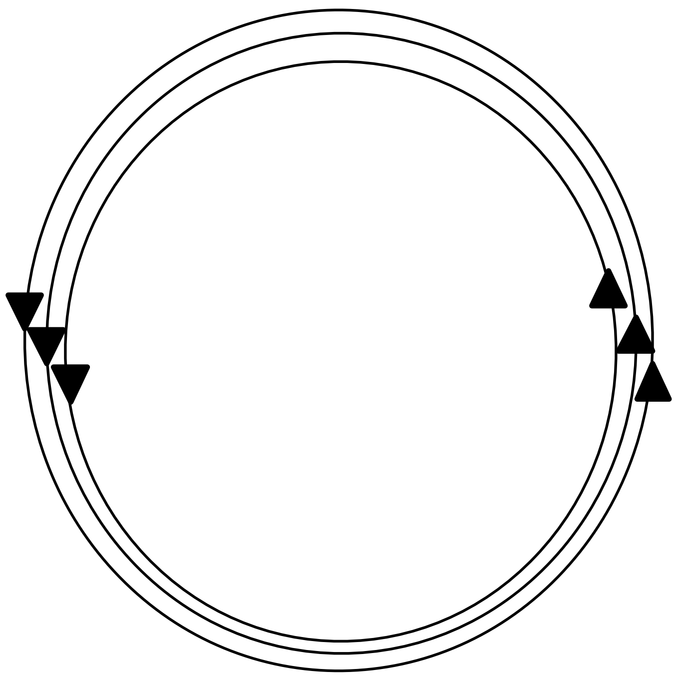
We look for a theory with extra dimensions, extended objects and high form fluxes

Let's start with an easy example of compactified dimension: electrodynamics on a circle

1+1: Schwinger on a circle

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

The energy density $\rho = F^2 = (Qe)^2$ is a vacuum energy: it is constant if I change the dimension of the circle



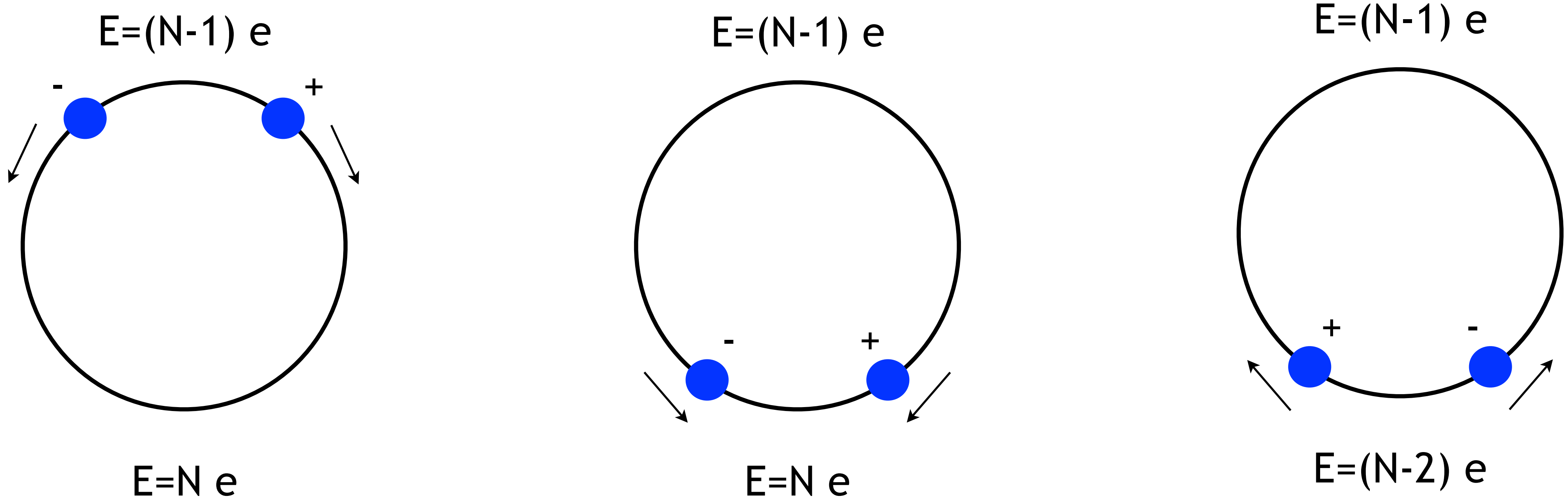
No fermions to begin with, but they can nucleate through quantum pair production

Think of a rubber band stretched around a circle

1+1: Schwinger on a circle

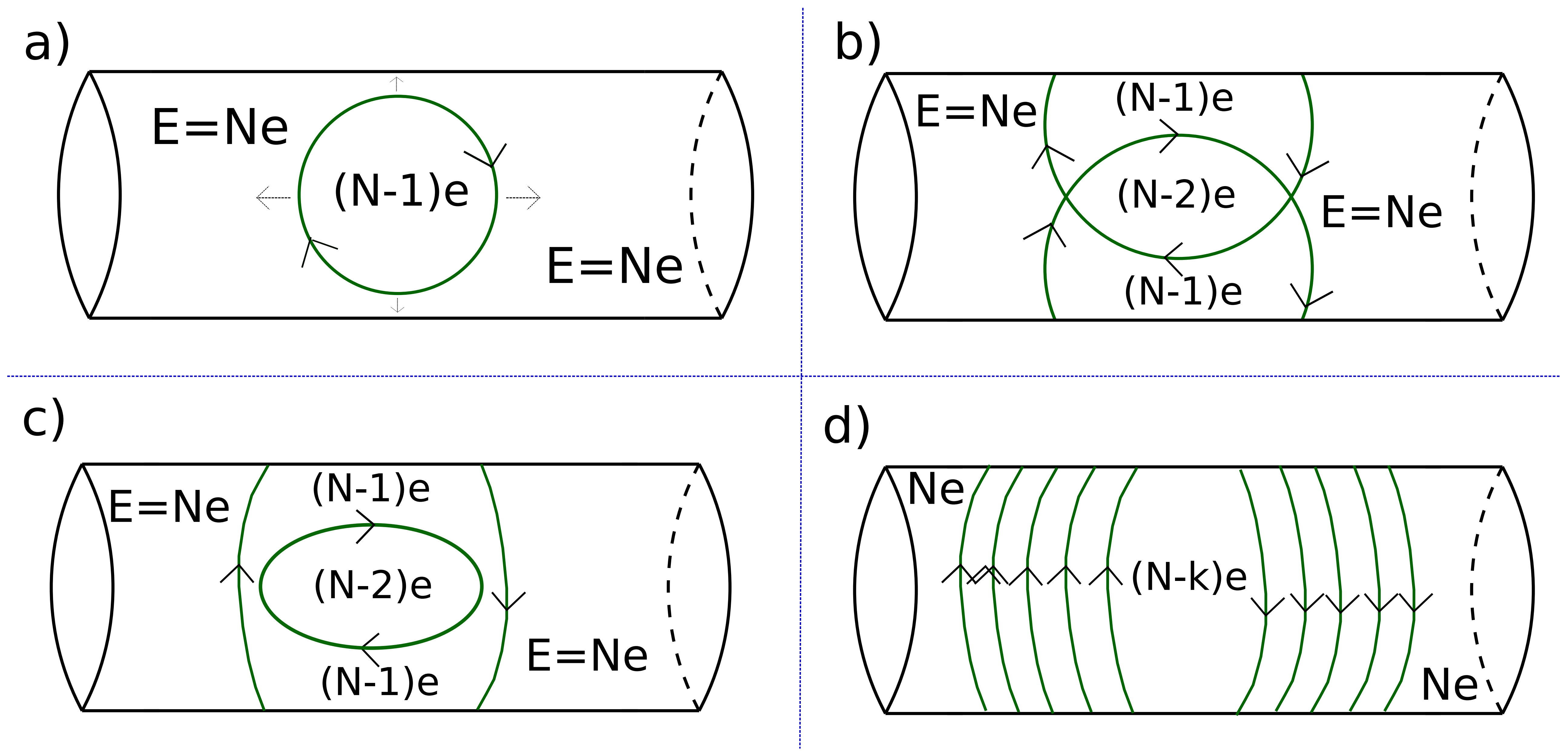
The electron and positron will start accelerating around the circle driven by the difference in the field across them, discharging the field and acquiring kinetic energy

When meeting on the other side, they pass through each other decreasing the vacuum energy

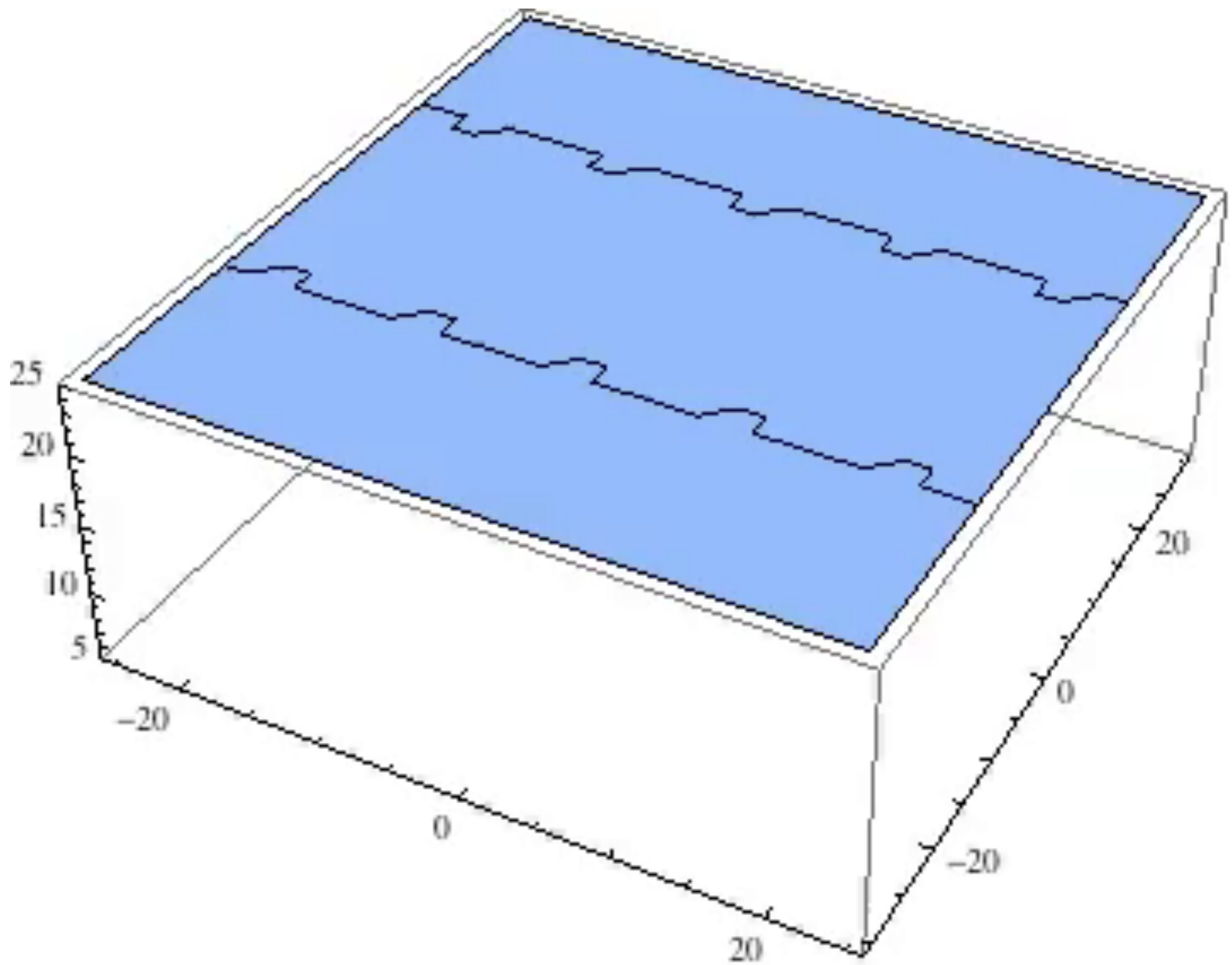


Kleban, Krishnaiyengar, Porrati (2011)

Adding dimensions...



And more picturesquely



Unwinding Inflation

Ingredients:
- extra dimensions
- branes
- high form fluxes

More "realistic" compactification: $dS_4 \times M$ (e.g. take M to be S_1)

A constant flux wraps all the dS dimensions

A brane bubble forms and start expanding in the compact as well as in dS dimensions, colliding with itself and thus discharging the flux, which provides a vacuum energy. The flux decreases steadily if I can not resolve the size of the compact dimensions

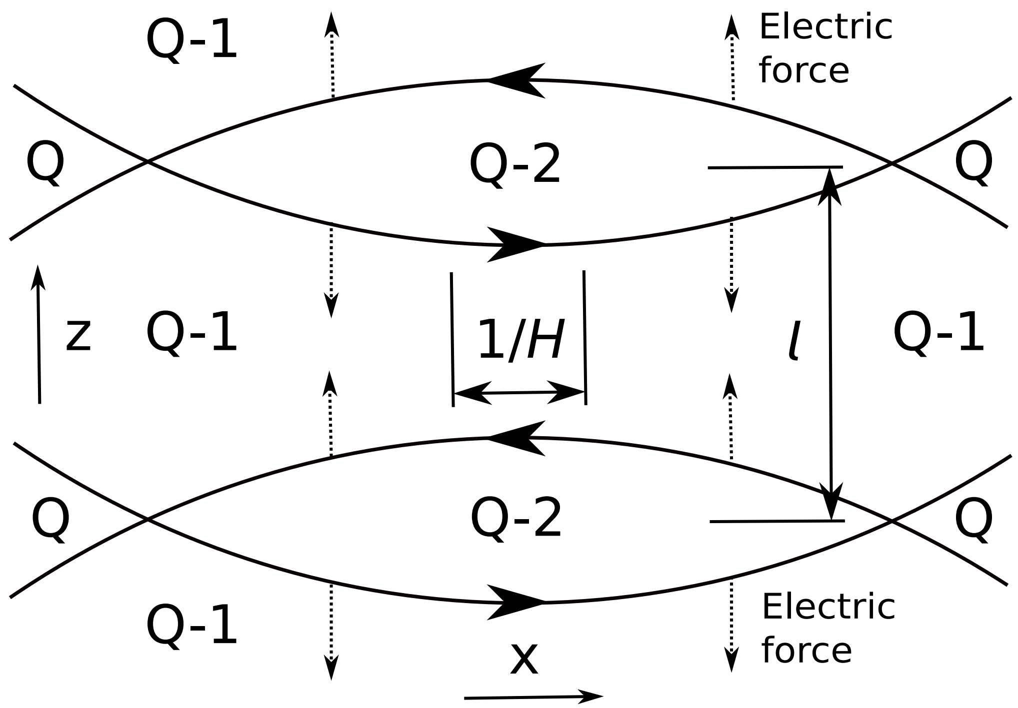
The bubble contains an open FRW cosmology. The system has a full SO(3,1) symmetry, thus each collision happens at constant FRW time

Unwinding Inflation

The brane start moving at constant ultra-relativistic velocity because of dS friction

Expansion in dS direction washes out curvature, after a few e-folds the system can be treated as a brane colliding with anti-brane (true as soon as $R \gg H^{-1}$)

Reheating happens when the bubble annihilates with itself



What's good?

Our mechanism provides a way to exit FVEI naturally

Brown (2008)

In a landscape scenario, it is guaranteed to happen!

It does not require any sensible fine tuning of the potential

It is naturally ignited by a quantum nucleation, but the evolution is totally classical

Giblin, Hui, Lim, Yang (2010)

No need to worry about nucleation rate

Graceful exit from slow roll phase through brane annihilation

4d effective theory

The 4d point of view "inflaton" is the distance between brane and anti-brane in the full theory.

Easiest example: M→S_1 . Let's compute the effective action

$$S = H^{-3} \int dz \int dH_3\, dt\, \sinh^3(Ht) \left(-2\sigma\delta(z - z_b)\sqrt{1 - (\partial z_b)^2} - \frac{F_5^2}{2 \cdot 5!} \right)$$

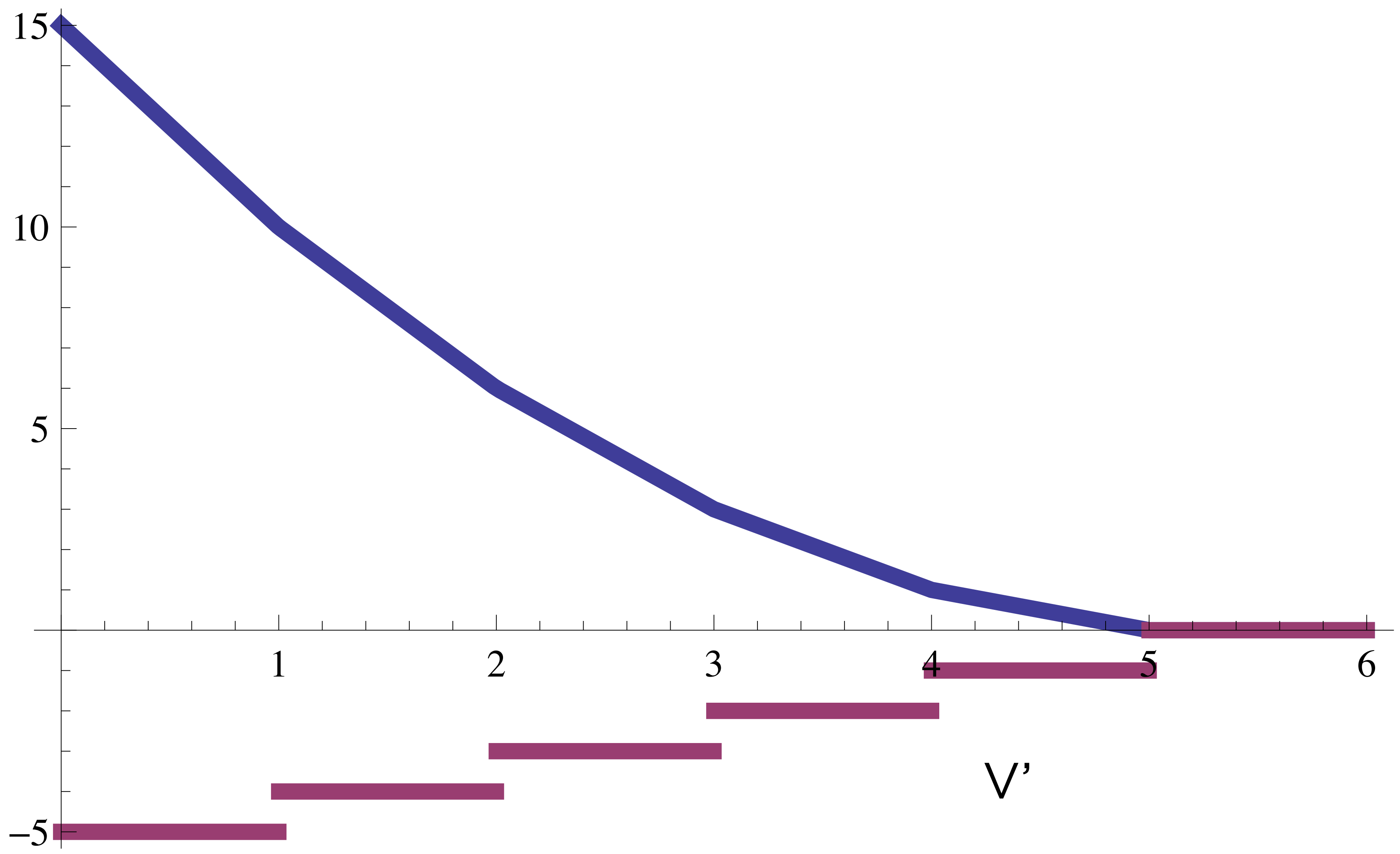
$$= \int dt d^3 x e^{3Ht} \left(-2\sigma \sqrt{1 - (\partial z_b)^2} - V(z_b) \right)$$

$$V'(z) = -2\mu^5 \left(Q_0 - \frac{1}{2} - \left[\frac{2z}{l} \right] \right)$$

$$V(z) = -2\mu^5 \left\{ \left(Q_0 - \frac{1}{2} \right) z - \left[\frac{2z}{l} \right] \left(z - \frac{l}{4} \left(\left[\frac{2z}{l} \right] + 1 \right) \right) \right\}$$

4d effective theory

The potential is piecewise linear, mimicking a quadratic



Perturbations

The “inflaton” is played by the distance z(x) between brane and anti-brane. Perturbations in z are converted into curvature perturbations because of delay at the time of reheating:

$$\zeta = \delta a/a = H\delta t = H\delta z/v = H\delta z/\dot{z}$$

There are two types of perturbations:

- de Sitter: usual quantum fluctuations
- Particles/Strings production: fluctuation in the density of produced particles/strings

de Sitter

If string production is a subdominant effect, the result from de Sitter fluctuation is the almost scale invariant spectrum

$$\mathcal{P}_\zeta = \frac{H^4}{8\pi^2 \sigma \dot{z}^2}$$

Where σ is the brane tension

The tilt is

$$n_s - 1 \simeq 4\frac{\dot{H}}{H^2} \simeq -\frac{2}{N_*}$$

The tensor modes

$$\mathcal{P}_h = \frac{16 G_N H^2}{\pi}$$

Tensor to scalar ratio

$$r = \dot{z}^2 \frac{R}{l} \frac{24}{Q}$$

Strings

The effect of string production gives a minor contribution to the background evolution of the system

$$2\gamma^3 \ddot{z} + 6H\gamma\sigma\dot{z} + V'(z) + f = 0$$

$$f = \frac{d\rho_s}{dz}$$

but not on the (already small) perturbations.

To compute the effect I will assume that string production is a Poisson process

We get both an additional friction term and a stochastic force

Strings

The brane interaction is locally brane vs anti-brane scattering.

The production rate can be calculated from the annulus diagram, similarly to Bachas (1995), with different boundary condition.

The main difference is a tachyon in the spectrum

$$\rho_s(\eta, z) = \sum_i \frac{m_s^{p+2}}{(2\pi)^p} \eta_i^{p/2} \frac{v}{\eta} F(b, \eta_i) e^{3H_i(t_i - t)} \sqrt{(z - z_i)^2 + b^2} \theta(t - t_i)$$

$$F(b, \eta) = 2e^{\frac{-\pi m_s^2 b^2 + \pi^2}{\eta}} + 16e^{-\frac{\pi m_s^2 b^2}{\eta}} + 36e^{-\frac{\pi m_s^2 b^2 + \pi^2}{\eta}} + 256e^{-\frac{\pi m_s^2 b^2 + 2\pi^2}{\eta}}$$

Full Power Spectrum

$$\ddot{\delta z} + 3H(1+\lambda)\dot{\delta z} + e^{-2Ht}\frac{k^2}{a^2\gamma^2}\delta z = -m_s^2\frac{v}{\eta}\frac{\delta n}{2\sigma\gamma^3}$$

$$\lambda \doteq \frac{\partial_{\dot{z}} f}{2H\sigma\gamma^3} \qquad \langle \delta n_{\vec{k}} \delta n_{\vec{k}'} \rangle = \frac{\langle n \rangle}{a^3}(2\pi)^3\delta^3(\vec{k}+\vec{k}')$$

So, combining the two effects together

$$P_\zeta(k) = \left(\frac{\gamma H}{m_s}\right)^\lambda \frac{2^{2\nu}\Gamma(\nu)^2 H^4}{16\pi^3\sigma v^2} + \left(\frac{\pi\Gamma(\nu)}{\Gamma(\frac{1}{4})\Gamma(\frac{1}{4}+\nu)}\right)^2 \frac{m_0^4 \bar{n} H}{32\pi^2\eta^2\sigma^2\gamma^3}$$

$$\nu = 3/2 + \lambda$$

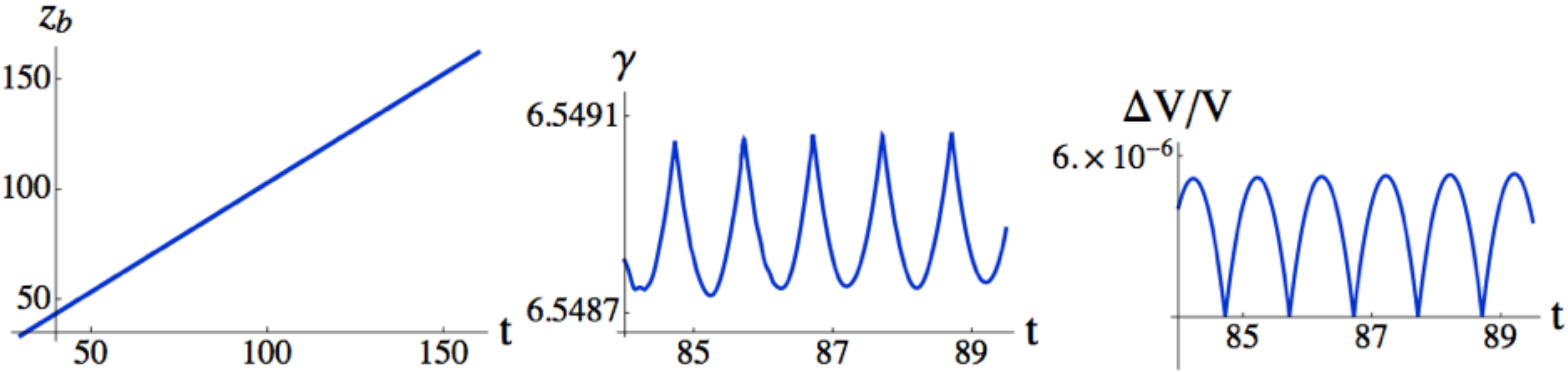
NG and more

The periodicity of the collisions causes oscillations in the power spectrum periodic in ln(k) with a period smaller than H^{-1}. Their amplitude is ~$1/Q^2$ for the S_1 case. The characteristics of these can be use to probe the extra dimensions.

The DBI kinetic term is a source of equilateral NG with $f_{nl} \sim 1/c_s^2 \sim \gamma^2$. Also the geometry of the compact dimensions can give non trivial features (still needs to be explored fully).

If the co-dimension is >1, we expect additional massless scalars that describe the position of the brane in the transverse dimensions. This impact parameter has to be ~0 at reheating and its fluctuations could be an additional source of features.

Oscillations



The brane position z, the Lorentz factor γ and the oscillations around the smooth approximation of potential for a 4-brane on S_1, with g_s=.01, $l=20/m_s$, $d=2/m_s$, $Q_0=400$

Stability

We assumed $dS_4 \times M$ metric, with H depending only on our flux and M compact and stable. Does it make sense?

M needs to be (almost) stable in order not to have a too large tilt

It does not seem too difficult, as long as the energy that stabilizes M is larger than the one being discharged

For $M=S_1$ it is possible to stabilize the extra dimension using Casimir energy and Casimir+magnetic flux works for S_n

Embed in String Theory

Unwinding Inflation fits naturally in the String Theory scenario. Moreover it avoids some of the usual problems of inflation in ST: there is no eta problem, no complicated geometries

Also, the parameters assume pretty natural values: the length of the extra dimensions need to be ~O(10)×l_s and the initial number of flux quanta ~O(100).

Still, a realistic string theoretical model needs to be built and a proper compactification realized

Conclusions

- The model I presented is a UV completion of inflation
- It allows to exit FVEI and realize slow roll naturally
- It is in agreement with data so far
- It encompasses several other models (DBI, trapped, oscillating...)
- If observed, it would test a whole new structure of the universe

Happy Thanksgiving/ Hanukkah/ National Day

Embed in String Theory

$\mathbf{p = 4}$

$g_s = 0.01$	$\mathcal{P}_\zeta = 2.4 \times 10^{-9}$
$l = 20 m_s^{-1}$	$\mathcal{P}_h = 5.0 \times 10^{-11}$
$d = 2.0 m_s^{-1}$	$r = 2.1 \times 10^{-2}$
$b \approx 0$	$n_s - 1 = -0.032$
$Q_0 = 400$	$H = 0.05 m_s$
$Q_* = 304$	$\gamma = 11.5$

$\mathbf{p = 5}$

$g_s = 0.05$	$\mathcal{P}_\zeta = 2.4 \times 10^{-9}$
$l = 20 m_s^{-1}$	$\mathcal{P}_h = 1.4 \times 10^{-11}$
$d = 4.9 m_s^{-1}$	$r = 5.8 \times 10^{-2}$
$b \approx 0$	$n_s - 1 = -0.032$
$Q_0 = 400$	$H = 0.04 m_s$
$Q_* = 314$	$\gamma = 22.9$