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Unwinding Inflation

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submitted to PRL, long paper to come soon

Outline

- Why another model of inflation?
- Eternal/False vacuum Inflation and how to end it
- The idea: Bubble colliding with itself (a lot!)
- How to realize it: Schwinger model and flux discharge
- How it works and what gives us
- Conclusions and future work

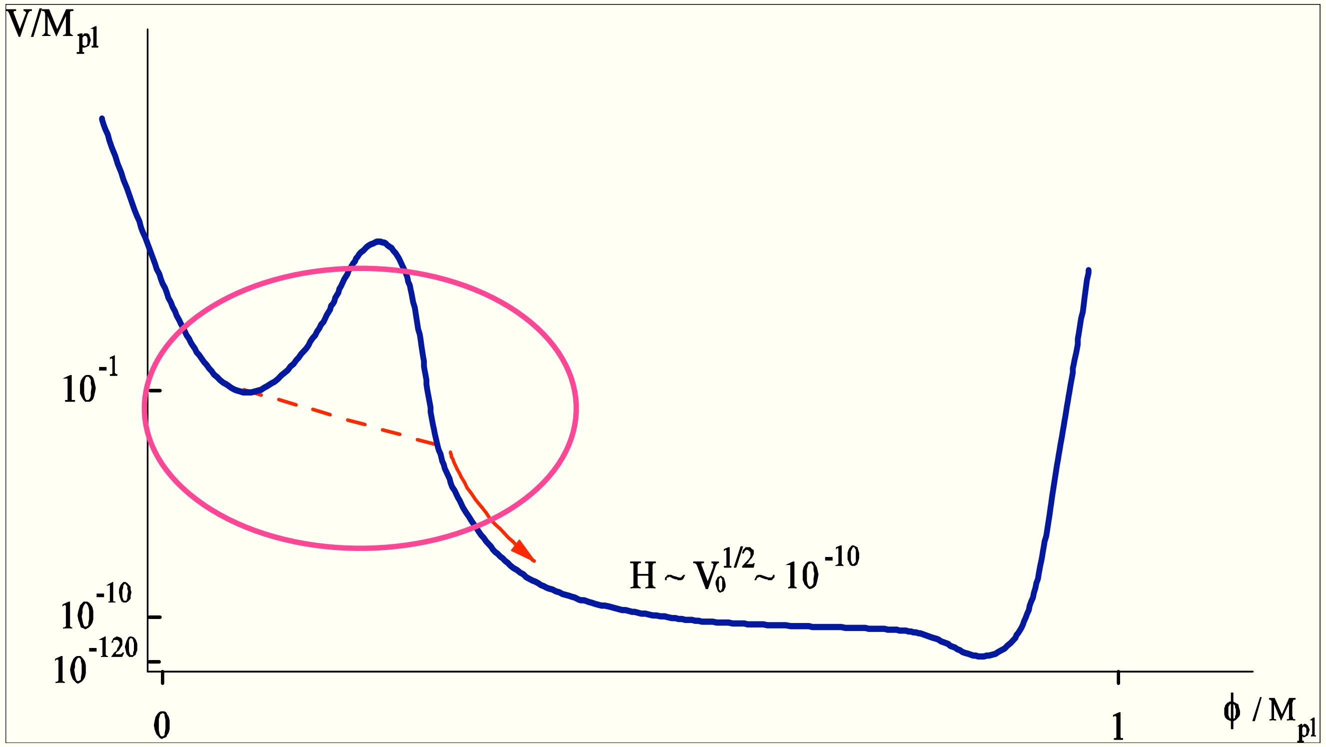
What is inflation?

(Almost) de Sitter spacetime for ~ 60 efolds

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2Ht}\mathrm{d}\vec{x}^2$$

It gives a huge, homogeneous, flat universe.
It gives a causal mechanism to generate super-horizon perturbations, with (almost) scale-invariant spectrum and (almost) Gaussian statistics

False vacuum eternal inflation

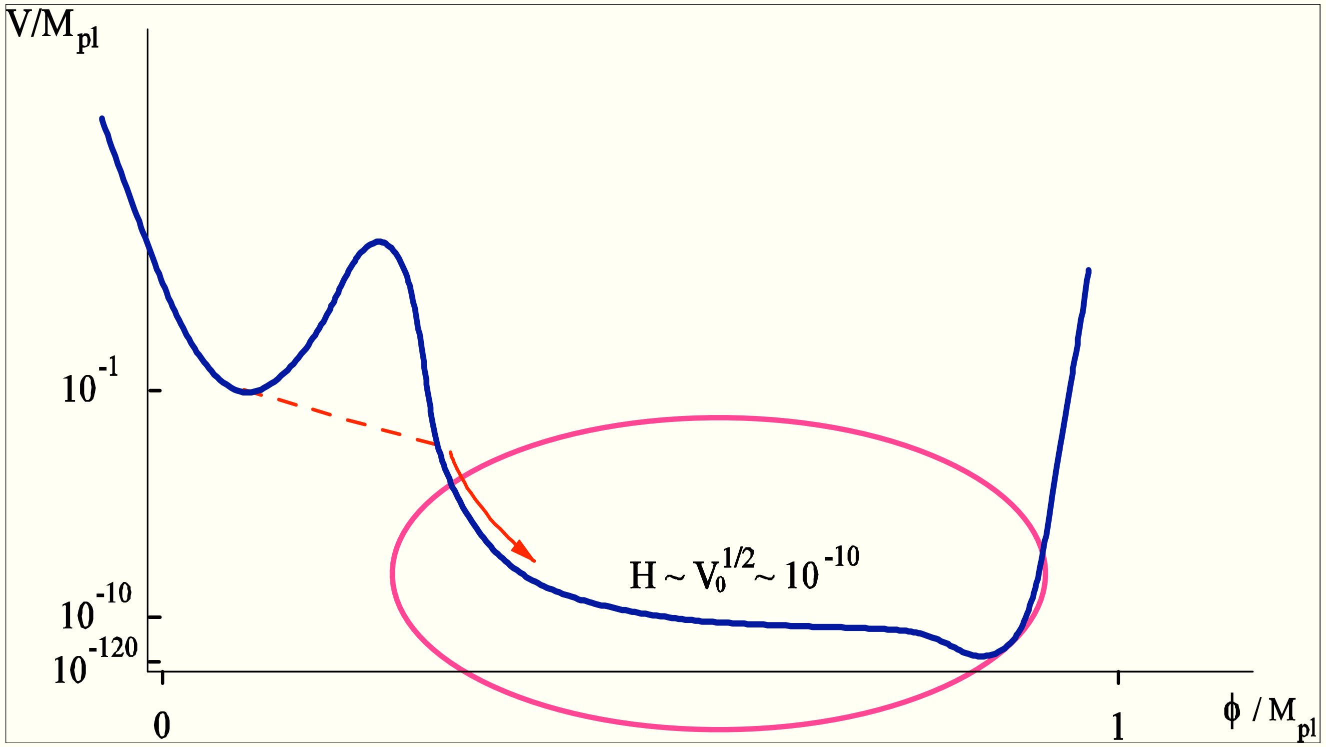


Guth's original idea: scalar trapped in a metastable minimum
Inflation is eternal: some regions of the universe always inflate

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: suppose the scalar potential is very flat (approximate shift symmetry)

A slowly rolling condensate does the job: inflates the universe, and at the end it gets converted into radiation

All these models are basically EFTs, with some degree of fine-tuning and it's complicated to embed them into string theory

A UV-completion?

Suppose we want to realize inflation in string/supergravity theory

Generic ingredients are

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

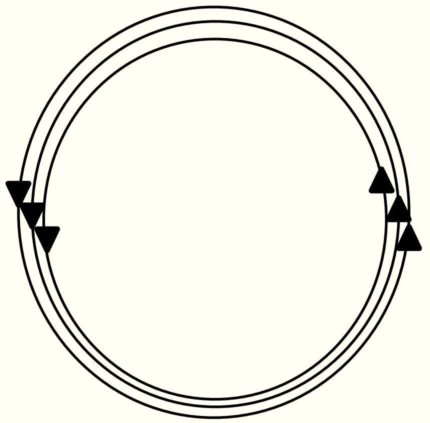
In inflation we basically want to slowly discharge vacuum energy.
In d dimensions, a d-form electric flux (d antisymmetric indices) is vacuum energy!

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!



E=Ne

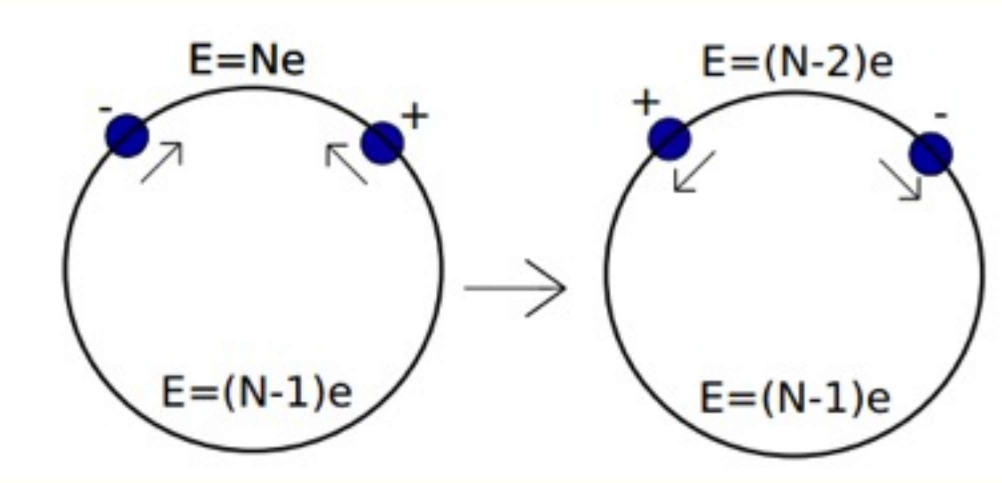
Schwinger pair production

Quantum mechanically, electric fields can discharge by the spontaneous nucleation of charge pairs

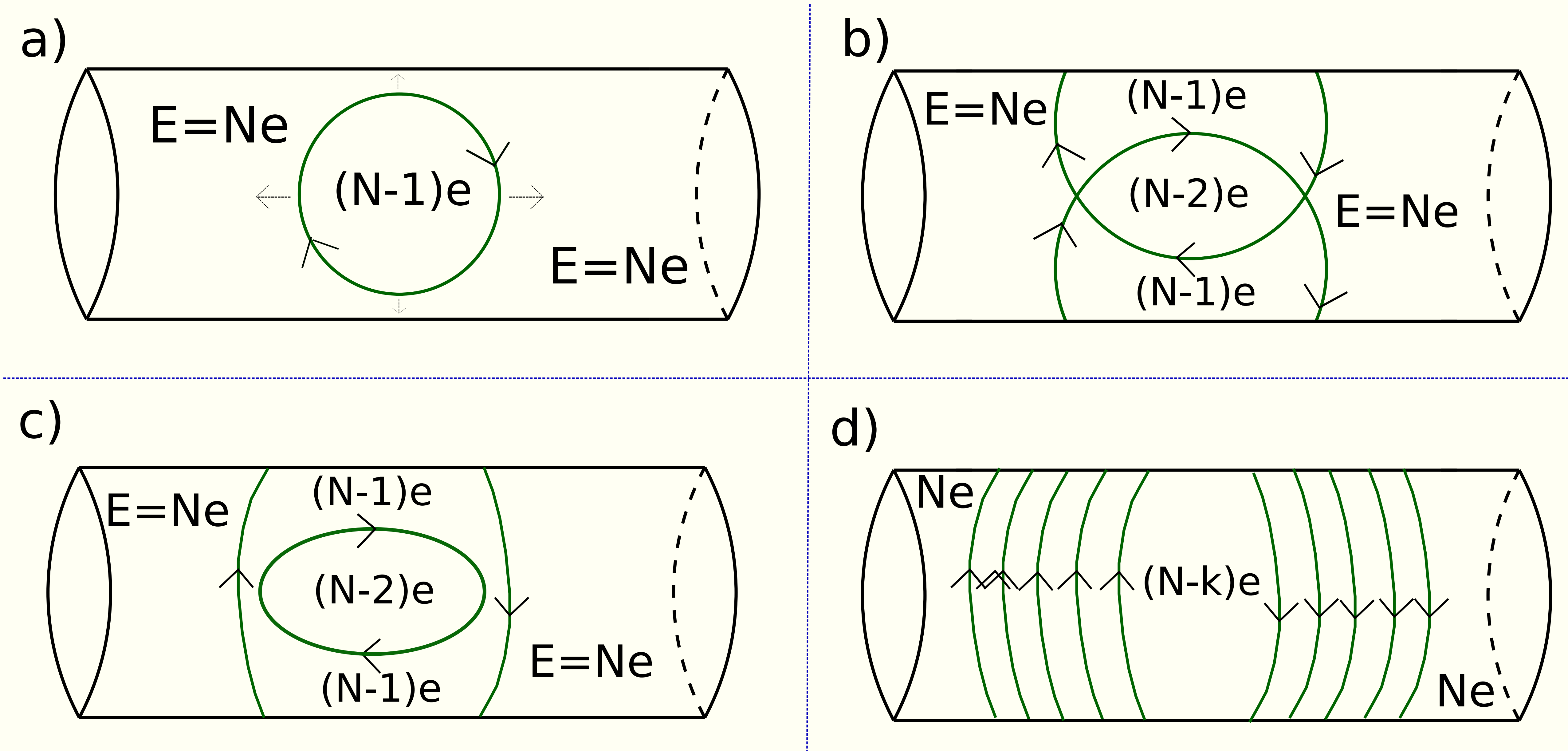
In 1+1 dimensions, the field is reduced by e between the "electron"-"positron" pair that appears

The field pushes 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



Discharge cascade



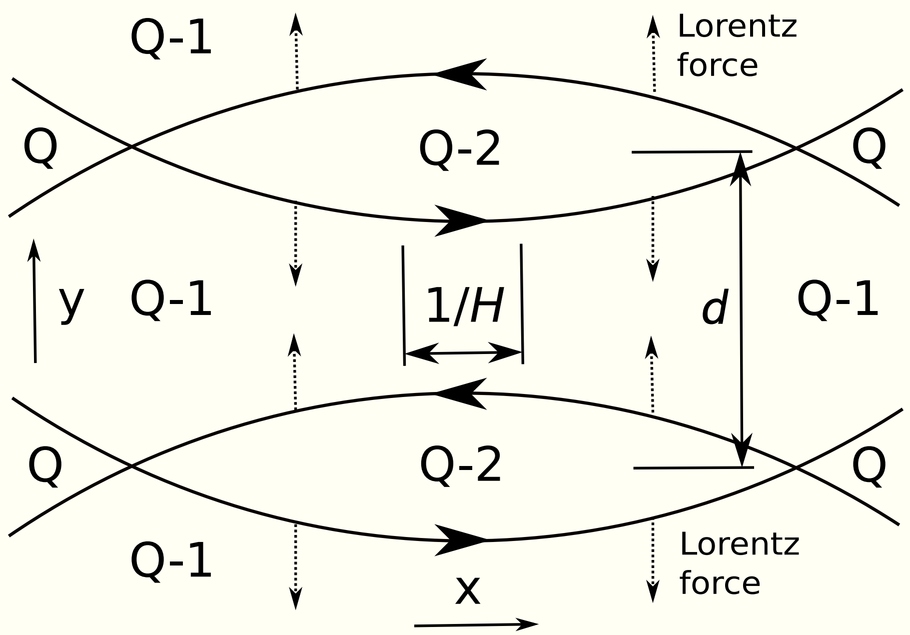
Our model

• Basic setup: spacetime of the form $dS_4 \times M$. Hubble constant is determined by the amount of flux.

• Configuration unstable to nucleation of a brane bubble

• This 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

- However, expansion in dS directions inflates away the curvature!

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

- We simply need N ~ 60 efolds of expansion to solve the big bang problems

How graceful we are?

- This is a kind of “graceful exit” from old inflation, producing a homogeneous and isotropic cosmology

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

- No fine tuning of potential involved

- Reheating occurs naturally at or near zero flux, when the brane slows down and can self-annihilate

- Are we ok with perturbations? Yes!

Effective action

4d effective inflaton is the brane separation. Effective action:

$$S = \int_0^d \mathrm{d}y \int \mathrm{d}\Omega \mathrm{d}t \sinh^3 t \left[\sigma \left(\delta(y - y_0) + \delta(y + y_0) \right) \sqrt{1 + \frac{dy_0}{d\xi}^2} - F^2/4 \right]$$

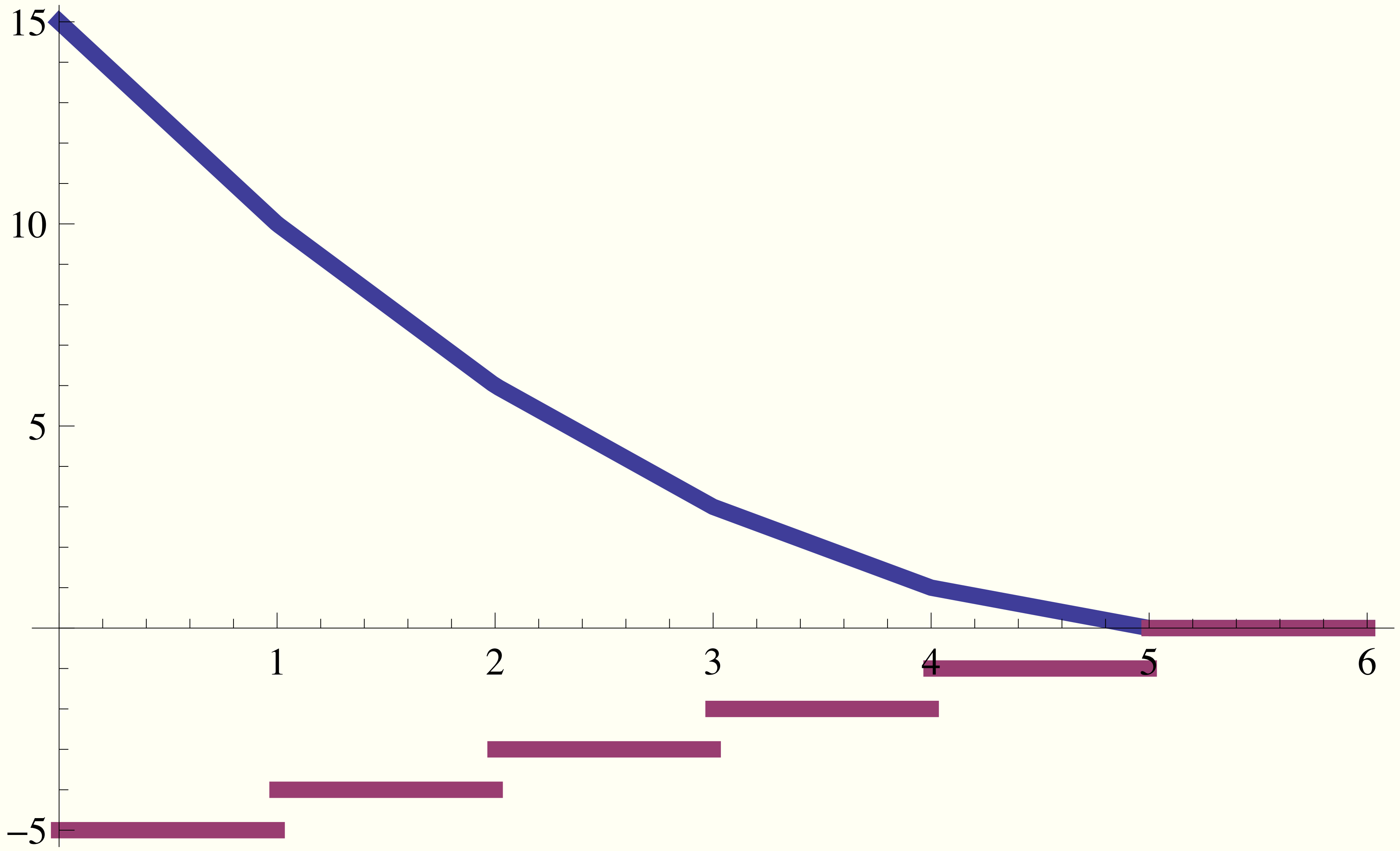
$$= \int \mathrm{d}\Omega \mathrm{d}t \sinh^3 t \left[2\sigma \sqrt{1 + \frac{dy_0}{d\xi}^2} - V(y_0) \right]$$

$$V(y_0) = -\int_0^d dy \frac{\mu^5}{2} \left[Q + \sum_{j=-\infty}^{\infty} \left(\Theta(y - y_0 + jd) - \Theta(y + y_0 + jd) \right) \right]^2$$

$$\Longrightarrow V'(y_0) = 2\mu^5 \left(-Q + \frac{1}{2} + \left[\frac{2y_0}{d} \right] \right)$$

Effective potential

$$V'(y_0) = 2\mu^5 \left(-Q + \frac{1}{2} + \left[\frac{2y_0}{d} \right] \right)$$



Fluctuations

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

There are two sources of perturbations in y:

- de Sitter quantum fluctuations, as in ordinary inflation
- Brane self-collisions produce open strings, and variations in the density of these cause perturbations in y

Spectrum of perturbations

If the string production is subdominant, there are only few parameters.
The power spectrum is almost scale-invariant, with amplitude

$$\Delta_{\mathcal{R}}^2 = \frac{H^4}{8\pi^2\sigma\dot{y}^2}$$

Here σ is the brane tension, ẏ is close to 1 and almost constant

The tilt is given by $$n_s - 1 \sim -\frac{2}{N_e} \sim -0.3$$

Tensor perturbations obey the standard $$\Delta_h^2 = \frac{2H^2}{M_{\rm Pl}^2\pi^2}$$

Tensor-to-scalar ratio potentially observable $$r = \dot{y}^2 \frac{R}{l}\frac{24}{Q}$$

String production

In general, open string production has to take into account for calculations of the PS.
This is related to other scenarios, like warm, trapped, "dissipative" inflation.

We assume 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

We do not need to assume that the contribution is dominant, we calculate it.
It is actually easy to solve the full problem analytically

Calculating it

Locally, the collisions are a scattering between a brane and an anti-brane moving at constant velocity

We can use the imaginary part of the annulus diagram to calculate the rate, with brane-antibrane boundary conditions

The result is similar to the Bachas one for brane-brane scattering, but with important differences, mainly because of the tachyon in the spectrum

$$\rho_s = \sum_i \frac{m_s^{p+2}}{(2\pi)^p} \eta_i^{p/2} \frac{v_i}{\eta_i} F(b, \eta_i) e^{3H_i(t_i - t)} (y - y_i) \theta(t - t_i)$$

$$F(b,\eta) = -2\,\mathrm{Li}_{1+p/2}(-e^{\frac{\pi^2 - b^2}{\eta}}) + 16\,\mathrm{Li}_{1+p/2}(e^{-\frac{b^2}{\eta}}) - 72\,\mathrm{Li}_{1+p/2}(-e^{-\frac{\pi^2 + b^2}{\eta}}) + 256\,\mathrm{Li}_{1+p/2}(e^{-\frac{2\pi^2 + b^2}{\eta}})$$

Full power spectrum

$$\ddot{\delta y}_{\vec{k}} + \left(3H + \frac{\partial_v(v\bar{f})}{2\sigma\gamma^3}\right)\dot{\delta y}_{\vec{k}} + c_s^2\frac{k^2}{a^2}\delta y_{\vec{k}} = -m_s^2\frac{v^2}{\eta}\frac{\sqrt{\bar{n}_s}}{2\sigma\gamma^3}a^{-3/2}X_{\vec{k}}$$

$$\bar{f} = \frac{\partial\rho_s}{\partial y} \qquad \langle X_{\vec{k}}X_{\vec{k}'}\rangle = (2\pi)^2\delta_D(\vec{k}+\vec{k}')$$

Assuming dS fluctuations and string-induced ones are uncorrelated

$$\Delta_{\mathcal{R}}^2 = \left(\frac{\gamma H}{m_s}\right)^{\lambda}\frac{2^{2\nu}\Gamma(\nu)^2H^4}{8\pi\sigma\dot{y}^2} + \left(\frac{\pi\Gamma(\nu)}{\Gamma(1/4)\Gamma(\nu+1/4)}\right)^2\frac{m_s^4\dot{y}^2\bar{n}_sH}{2\sigma\eta^2}$$

standard dS fluctuations

contribution from fluctuations in density of open strings

Here $\gamma = 1/c_s^2$, comes from the DBI kinetic term

$\nu = 3/2 + \lambda/2$ comes from the friction term, which now has the 3 H + the additional one from strings

Oscillations and non-Gaussianity

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

One source of NG is the DBI kinetic term. We expect $f_{nl} \sim 1/c_s^2$
Very difficult to analyze NG due to fluctuations in string density, if they are at all important

In general, except for the codimension-1 case, we expect additional ~massless scalars which describe the position if the branes in transverse dimensions.
In particular, the impact parameter has to decrease to 0 at reheating, and its fluctuations can induce a local non-Gaussianity, which can be sizeable

Stability

We have always assumed a metric $dS_4 \times M$, with H only depending on the flux and M compact and stable

A very important point is that M remains stable during the cascade.

It does not seem too difficult, as long as the contribution of the flux to the higher-d stress-energy is not too large

For example, Casimir energy works if $M = S_1$, or curvature + magnetic flux for S_p with $p>1$

Embedding in String Theory

The model seems to fit nicely into String Theory: it has compact extra dimensions, branes and higher-form fluxes.
It avoids the main problems with inflation in ST: no eta problem, no large field VEVs, no need for complicated geometries

Pretty natural: compact dimensions' dimension ~ 10 × string length, parameters of order unity.
The only O(100) parameter is the initial number of flux units

However, a realistic string theory model needs to be built, with a proper stabilization mechanism

Conclusions and future work

- Inflation is the best model we have for the early universe dynamics, and FVEI a generic prediction of String Theory. However, it still awaits a UV-complete description.

- Here I presented a model which naturally realizes slow-roll type inflation, starting from a large 4d vacuum energy.

- It encompasses many effective models present in the literature (DBI, dissipative, oscillating) but with no fine-tuning of parameters

- Preliminary analysis points to agreement with data

- A detailed model needs to be built

Thank you!