Title: Black Box

Date: Apr 01, 2005 12:15 PM

URL: http://pirsa.org/05040038

Abstract:

Inflation Requires 2 basic ingredients

1. Sufficient e-foldings of inflation
2. the universe must thermalize and reheat

Old inflation, with a single tunneling event, failed to do both.

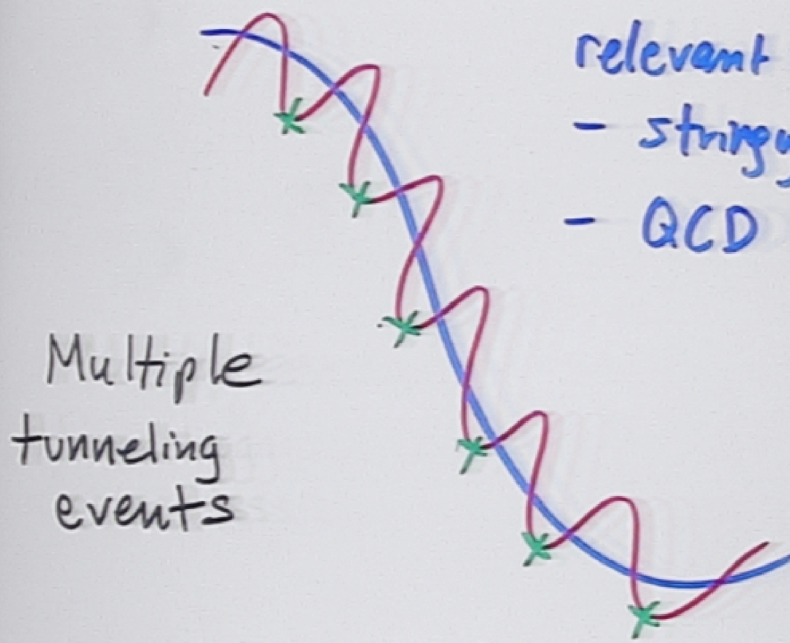
Here, multiple tunneling events

Each responsible for a fraction of an e-fold (adds to enough).

Graceful exit obtained:

Phase transition completes at each tunneling event.

Basic Scenario



relevant to:

- stringy landscape
- QCD (or other) axion

Graceful exit:

requires that the number of e-foldings per stage $\chi < 1/3$

Sufficient Inflation:

total number of e-folding

Short Comings of Inflationary Models

- Old Inflation: Fails- No Grace Full Exit

  Except through a time dependent β (Double Field)
  F. Adams And K. Freese, 1991

- New Inflation: Fine-Tuned

  Natural Inflation- avoids fine-tuning with a shift symmetry
  K. Freese, J Frieman AND A Olinto, 1990

Short Comings of Inflationary Models

- Old Inflation: Fails- No Grace Full Exit

  Except through a time dependent β (Double Fi
  F. Adams And K. Freese, 1991

- New Inflation: Fine-Tuned

  Natural Inflation- avoids fine-tuning with a shift symm
  K. Freese, J Frieman AND A Olinto, 1990

Short Comings of Inflationary Models

Inflation: Fails- No Grace Full Exit

Except through a time dependent β (Double Field) Adams And K. Freese, 1991

Inflation: Fine-Tuned

Natural Inflation- avoids fine-tuning with a shift symmetry Freese, J Frieman AND A Olinto, 1990

NEW FRAMEWORK for INFLA

Over Coming Short Comings

with Chain Inflation

- No Fine Tuning
- Large Range of Energy Scales

  $10^{16} GeV$ to $10 MeV$

- Saves Old Inflation

  Graceful Exit- phase transition occurs very quickly

Chain Inflation

1. Old Inflation

- Why it fails

2. What's needed:

time-dependent Γ/H^4

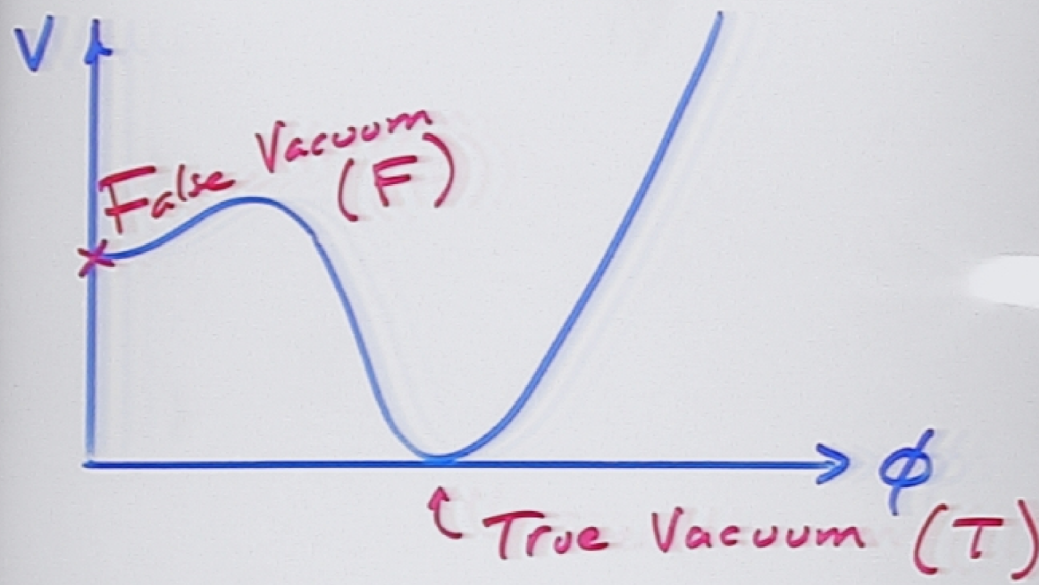
3. Current model:

Multiple tunneling events

each with $N_e \ll 1$

couple to graceful exit

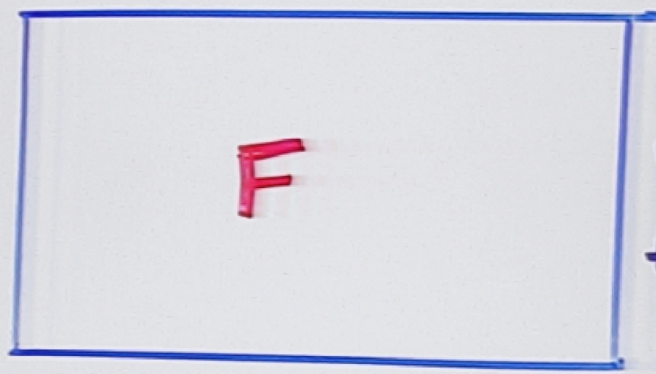
Old Inflation



Universe goes from
false vacuum → true vacuum

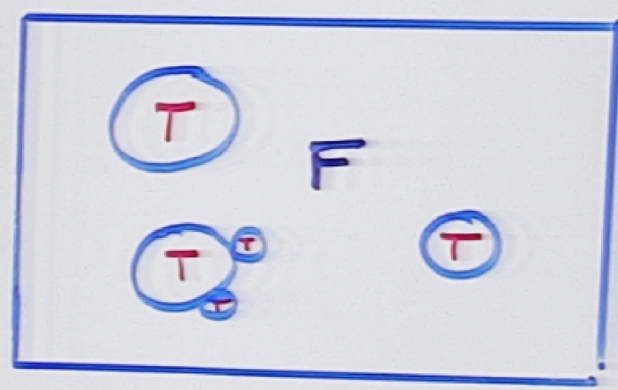
Bubbles of true vacuum
nucleate in sea of false vacuum
(first order phase transition)

Swiss Cheese Problem of Old Inflation



entire universe in false vacuum (F)

⇓



nucleate bubbles of true vacuum (T)

Problem: Bubbles never percolate + thermalize

What is needed for tunneling inflation to work?

Probability of a point remaining in false vacuum phase:

$$p(t) \sim e^{-\beta H t}$$

$$\text{where } \beta = \frac{\Gamma}{H^4}$$

Γ ← nuclea[illegible] rate of true vacuum bubbles

H ← expansion rate of universe

[Guth + Weinberg 1981]

Theories with constant β fail!

(e.g. old inflation)

Small β: phase transition proceeds slowly, universe inflates, but phase transition never completes

Large β: phase transition is fast, no inflation,

Graceful Exit Achieved

Guth and Weinberg,1983

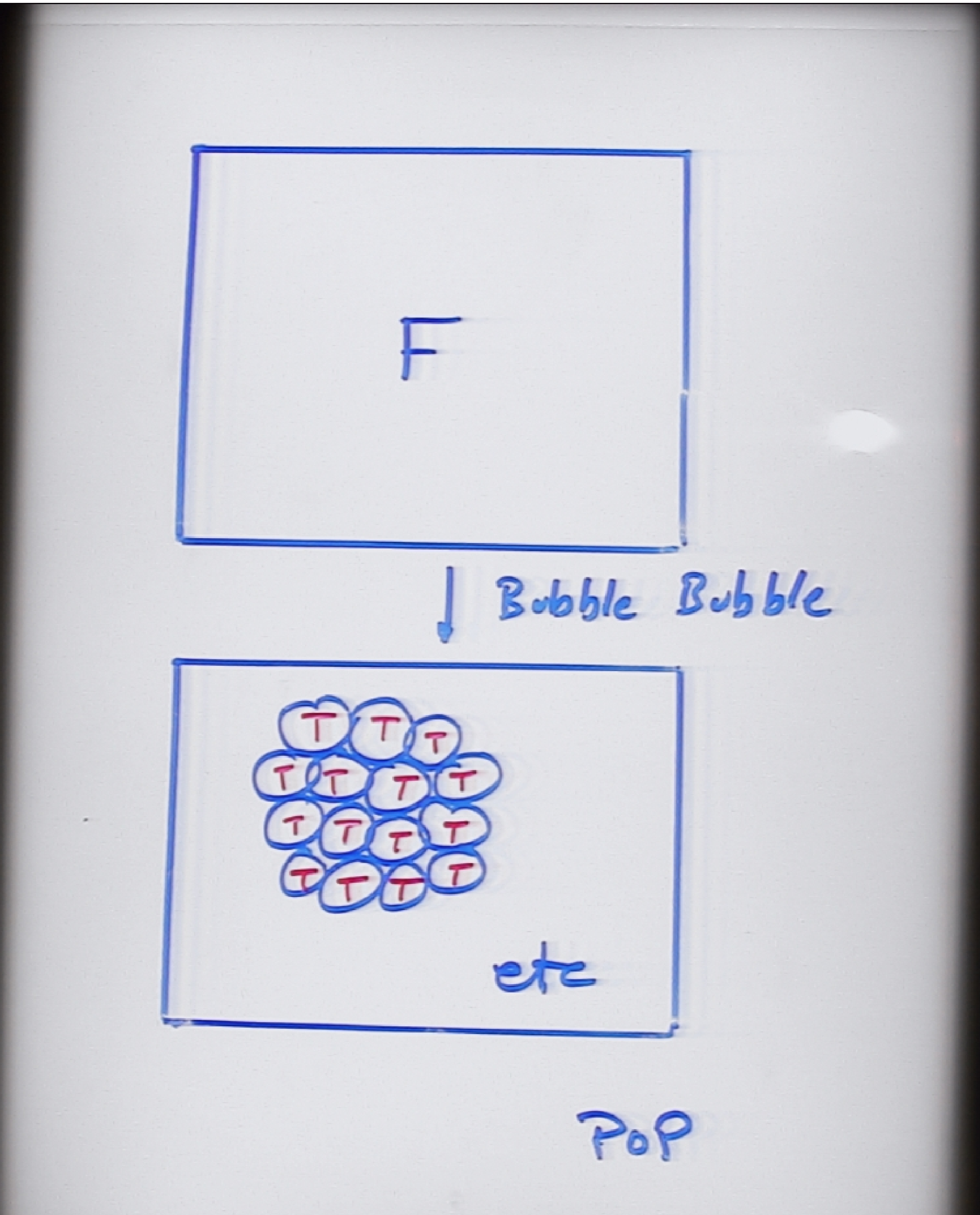
Turner, Weinberg, and Widrow, 1992

calculated that a critical value of

$$\beta = \frac{\Gamma}{H^4} \geq \beta_{crit} = 9/4\pi$$

is required in order for percolation and thermalization to
achieved. In terms of e-foldings, this is

$$\chi \leq \chi_{crit} = 1/3.$$


F
Bubble Bubble
T T T
T T T T
T T T T
T T T T
etc
PoP

2 requirements for inflation

$$p(t) \sim \exp\left(-\frac{4\pi}{3}\beta H t\right)$$

$$\sim \exp(-t/\tau)$$

$\beta \equiv \Gamma/H^4$

lifetime of field in metastable state:

$$\tau \simeq \frac{3}{4\pi H \beta} = \frac{3}{4\pi}\frac{H^3}{\Gamma}$$

Number of e-foldings from single tunneling event:

$$\chi = \int H dt \sim H\tau \sim \frac{3}{4\pi\beta}$$

Sufficient inflation:

$$\chi_{tot} > 60$$

Reheating (percolation + thermalization)

$$\beta \geq \beta_{crit} = 9/4\pi$$

How to achieve both criteria:

$\chi_{tot} \geq 60$ Sufficient inflation

$\chi \leq \chi_{crit} = 1/3$ Reheat

with single tunneling event:

"Double Field inflation" (Adams + Freese 1991)

- time dependent nucleation rate
- couple 2 scalar fields

with multiple tunneling events

- Chain Inflation

get a fraction of an e-folding at each stage,

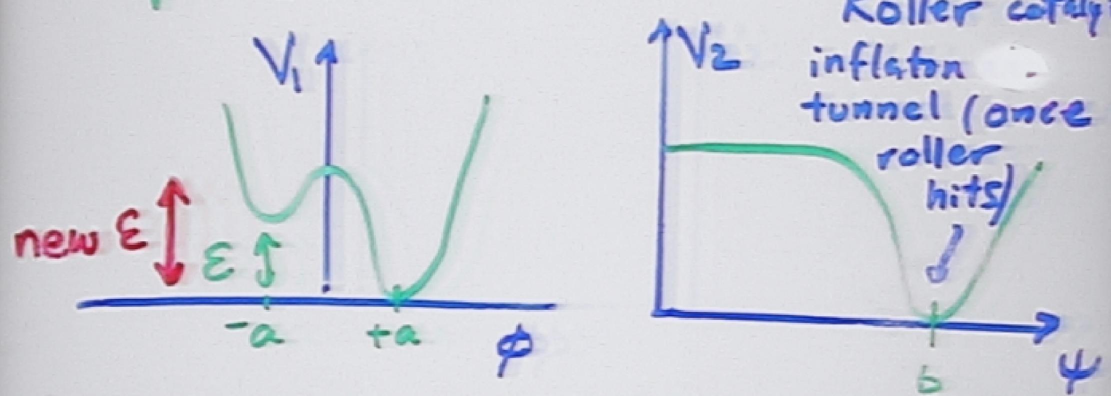
adds to more than 60 in the end

Double Field Inflation

Adams + Freese 1991

Time-Dependent Nucleation Rate

Couple 2 scalar fields



Once ψ rolls to its minimum, $\varepsilon_{eff} \uparrow$

Tunneling rate for ϕ increases

$$V_{tot} = V_1(\phi) + V_2(\psi) + V_{int}(\phi,\psi)$$

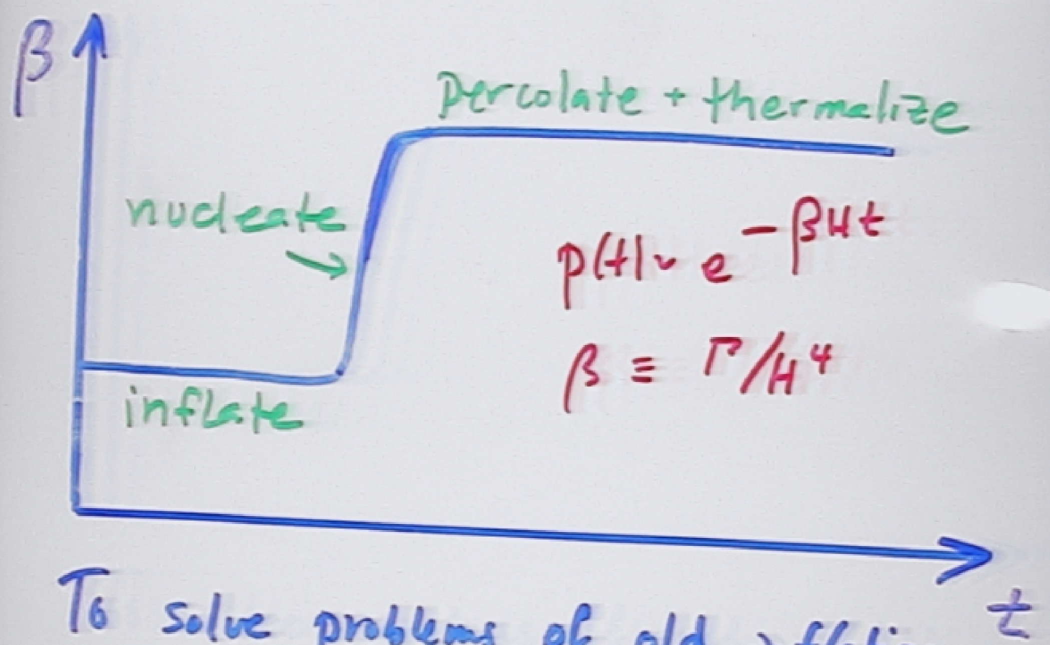
$$\uparrow \ \frac{a^4}{2a} f(\psi)(\phi - a)$$

$$\varepsilon_{eff} = \varepsilon + f(\psi)\, a^4$$

Tunneling rate: $\Gamma \sim e^{-S_E}, \quad S_E \sim \frac{1}{\varepsilon_{eff}^3}$

$\{$ 0 for ψ at top of potential

Need:



$$p(t) \sim e^{-\beta H t}$$

$$\beta \equiv \Gamma / H^4$$

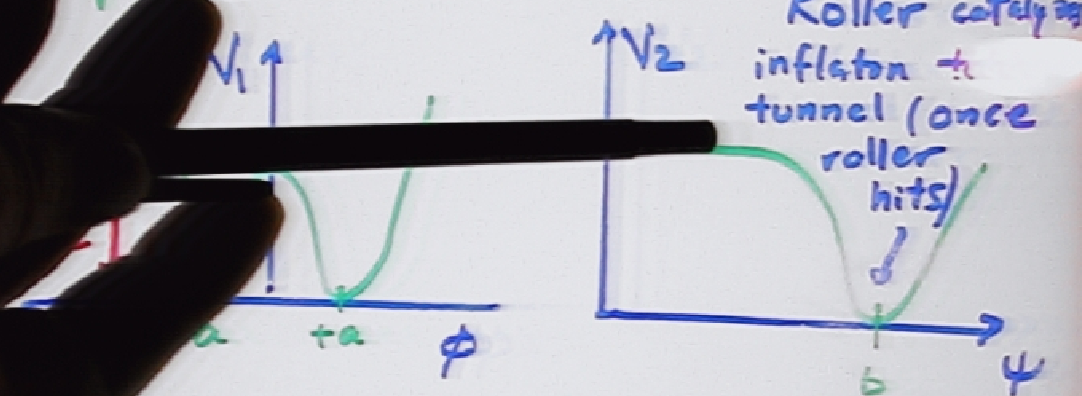
To solve problems of old inflation, need β initially small → get inflation. Then, suddenly, β gets large so that all of universe goes from false → true vacuum at once. All bubbles of same size. Get percolation + thermalization

Double Field Inflation

Adams + Freese 1991

Time-Dependent Nucleation Rate

ouple 2 scalar fields



Once ψ rolls to its minimum, ε_{eff} ↑

Tunneling rate for ϕ increases

$$V_{tot} = V_1(\phi) + V_2(\psi) + V_{int}(\phi,\psi)$$

$$\uparrow \frac{a^4}{2a} f(\psi)(\phi - a)$$

$$\varepsilon_{eff} = \varepsilon + f(\psi)\, a^4$$

Tunneling rate: $\Gamma \sim e^{-S_E}$, $S_E \sim \frac{1}{\varepsilon_{eff}^3}$

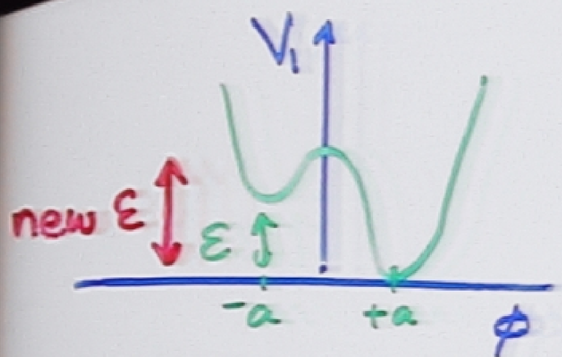
{ 0 for ψ at top of potential

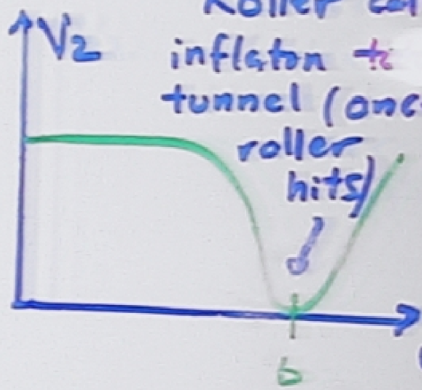
Double Field Inflation

Adams + Freese 1991

Time-Dependent Nucleation Rate

…ple 2 scalar fields





Roller catalyzing inflaton to [illegible] tunnel (once roller hits)

Once ψ rolls to its minimum, $\varepsilon_{eff}\uparrow$

Tunneling rate for ϕ increases

$$V_{tot} = V_1(\phi) + V_2(\psi) + V_{int}(\phi,\psi)$$

$$\uparrow \frac{a^4}{2a} f(\psi)(\phi - a)$$

$$\varepsilon_{eff} = \varepsilon + f(\psi)\, a^4$$

Tunneling rate: $\Gamma \sim e^{-S_E}$, $S_E \sim \frac{1}{\varepsilon_{eff}^{\,3}}$

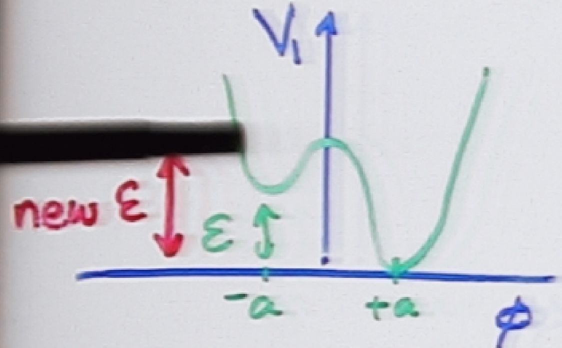
$\{$ 0 for ψ at top of potential

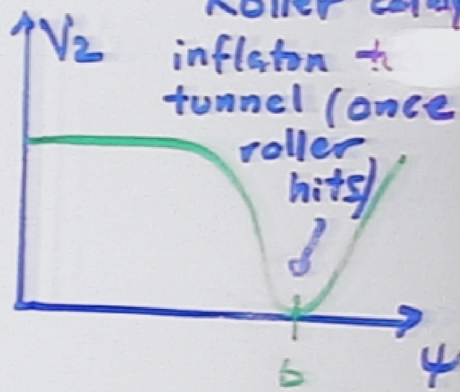
Double Field Inflation

Adams + Freese 1991

Time-Dependent Nucleation Rate

Couple 2 scalar fields





Roller catalyzes inflaton to [illegible] tunnel (once roller hits)

Once ψ rolls to its minimum, $\varepsilon_{eff} \uparrow$

Tunneling rate for ϕ increases

$$V_{tot} = V_1(\phi) + V_2(\psi) + V_{int}(\phi, \psi)$$

$$\uparrow \frac{a^4}{2a} f(\psi)(\phi - a)$$

$$\varepsilon_{eff} = \varepsilon + f(\psi)a^4$$

Tunneling rate: $\Gamma \sim e^{-S_E}$, $S_E \sim \frac{1}{\varepsilon_{eff}{}^3}$

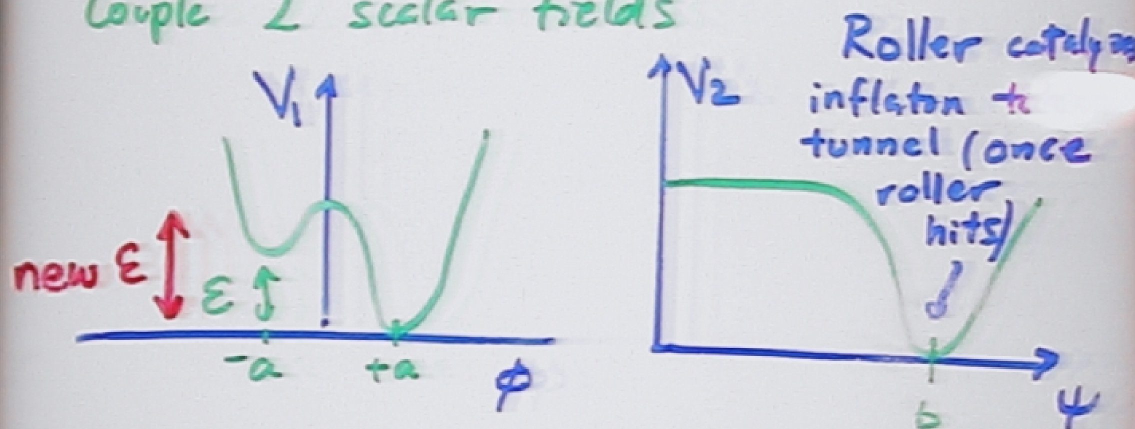
$\{$ 0 for ψ at top of potential

Double Field Inflation

Adams + Freese 1991

Time-Dependent Nucleation Rate

Couple 2 scalar fields



Once ψ rolls to its minimum, ε_{eff} ↑

Tunneling rate for φ increases

$$V_{tot} = V_1(\phi) + V_2(\psi) + V_{int}(\phi, \psi)$$

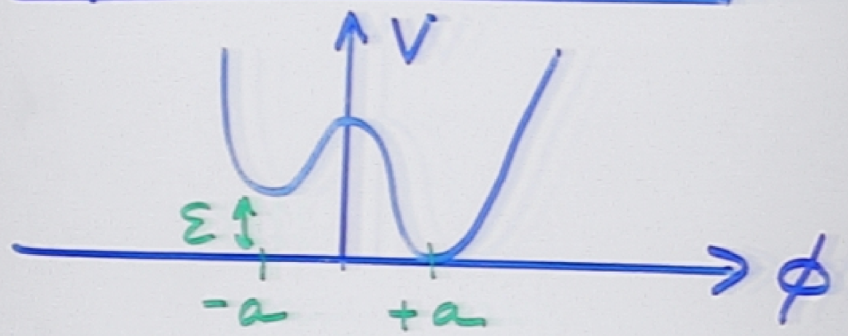
$$\uparrow \frac{a^4}{2a} f(\psi)(\phi - a)$$

$$\varepsilon_{eff} = \varepsilon + f(\psi) a^4$$

Tunneling rate: $\Gamma \sim e^{-S_E}$, $S_E \sim \frac{1}{\varepsilon_{eff}^{\,3}}$

{ 0 for ψ at top of potential

Asymmetric Double Well



Nucleation Rate

$$\Gamma \sim \varepsilon\, e^{-S_E}$$

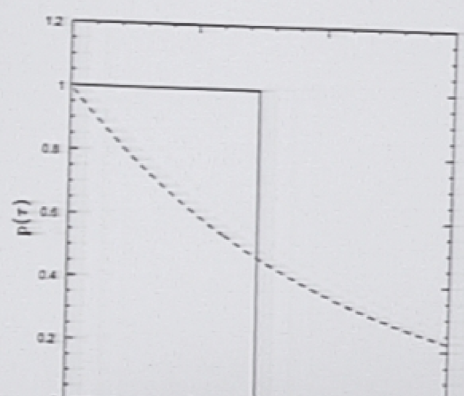
(Callan, Coleman, Voloshin, Okun, Obzarev)

$$S_E = \frac{\pi^2}{6}\,\frac{\lambda^2 a^{12}}{\varepsilon^3}$$

(thin wall)

n.b. as ε increases so does nucleation rate

Tunneling Rates, Graceful and not



How to achieve both

$\chi_{tot} > 60$ sufficient inflation

$\chi < \chi_{crit} = 1/3$ percolation

with single tunneling event:

Double Field Inflation Adams + Freese '91

time dependent nucleation rate

couple two scalars

with multiple tunneling events

Chain Inflation

- with QCD axion
- in landscape

QCD Axion: Tilted Cosine

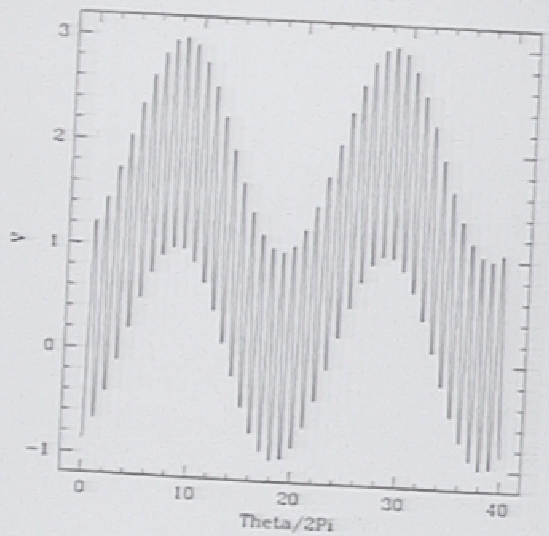


Figure 5: The soft-breaking potential is a tilted cosine as in th
potential. Here we have taken $N = 20$ and $\eta = V_0$.

Inflating with the QCD Axion

Freese, J.T. Liu And D. Spolyar, hep-th/0502177

While the axion is *a priori* a Goldstone boson of the
ontaneously broken Peccei-Quinn symmetry $U(1)_{PQ}$, QCD
tanton effects induce an axion potential with residual Z_N
mmetry. The model we consider includes an additional
plicit soft-breaking term, which tilts the instanton induced
tential. While the complete form of the axion potential is
pendent on non-perturbative effects, it is well modeled by a
tential of the form

$$V(a) = V_0\left[1 - \cos\frac{Na}{v}\right] - \eta\cos\left[\frac{a}{v} + \gamma\right]. \qquad (10)$$

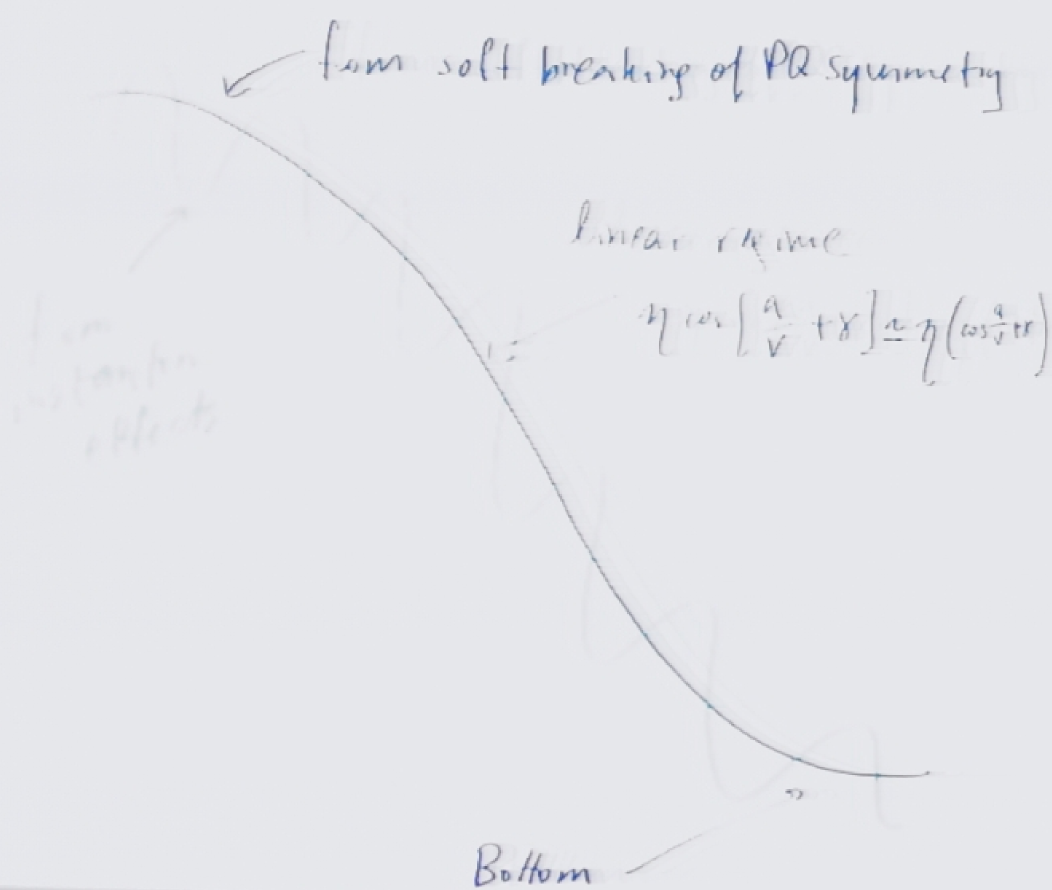
Inflating with the QCD Axion

K. Freese, J.T. Liu And D. Spolyar, hep-th 0502177

While the axion is *a priori* a Goldstone boson of the spontaneously broken Peccei-Quinn symmetry $U(1)_{PQ}$, QCD instanton effects induce an axion potential with residual Z_N symmetry. The model we consider includes an additional explicit soft-breaking term, which tilts the instanton induced potential. While the complete form of the axion potential is dependent on non-perturbative effects, it is well modeled by a potential of the form

$$V(a) = V_0 \left[1 - \cos\frac{Na}{v}\right] + \eta \cos\left[\frac{a}{v} + \gamma\right]. \qquad (10)$$

$$V = V_0\left[1 \quad \cos\frac{N\alpha}{v}\right] - \eta\cos\left[\frac{\alpha}{v}+\gamma\right]$$



Invisible axion (DFSZ)

Axion is identified as phase of a complex $SU_2 \times U_1$ singlet scalar σ below PQ symmetry breaking scale $\sigma = v/\sqrt{2}$

$$\sigma = \frac{1}{\sqrt{2}} (v + \rho) \exp(i a/v)$$

Soft breaking

$$\mathcal{L}_{soft} = \mu^3 \sigma + h.c.$$

$$\rightarrow V_{soft} = \eta \cos(a/v + \delta)$$

$$-\pi/N < \delta < \pi/N$$

Same Criterion and Some More

- Previous Conditions

  percolate each stage: $\chi \leq 1/3$

  Sufficient Inflation: $N_{tot} \geq 60$

- neutron Electric Dipole Moment

  Constrains Soft Breaking term

- Don't Go Over the Top

Tilted Cosine QCD Axion:tunneling Rate

In the thin wall limit, the tunneling rate is given
$\Gamma\ e^{-S_e}$. We need to calculate $S_1 = \int \sqrt{2U_+(a)}\, da$, whi
is integrated from one minimum to the next, where t
symmetric portion of the potential is $U_+(\theta) = V_0(1 - \cos$
so $S_1 = \sqrt{2V_0} f_a \int_0^{2\pi} \sqrt{1 - \cos\theta}\, d\theta = 8 f_a \sqrt{V_0}$. Hence t
Euclidean action is

$$S_E = \frac{27\pi^2 S_1^4}{2\epsilon^3} = 5 \times 10^5 \frac{V_0^2 f_a^4}{\epsilon^3}. \quad (1$$

Coleman, 1977

Voloshin, Kobzarev AND Okun, 1975

Callan AND Coleman, 1977

The Neutron Electric Dipole Moment Limit

We must ensure that the soft-breaking term in the potential
...oes not destroy the strong CP solution, *i.e.*, that the minimum
...f the potential is not shifted away from zero by more than is
...llowed by the electric dipole moment (EDM) of the neutron

$$\Delta\bar{\theta}\big|_{\mathrm{EDM}} < 6 \times 10^{-10}. \qquad (12)$$

...G. harris, 1999

Implied constraints

For large N, we find that the shift from $\bar{\theta} = 0$ is given by

$$\Delta\bar{\theta}\Big|_{\mathrm{EDM}} = \left|\frac{\eta}{V_0 N}\sin\gamma\right| \sim \left|\frac{\eta}{V_0 N}\gamma\right| \sim \frac{\eta\pi}{2V_0 N^2}. \quad (1$$

- determined by finding the relative shift of vacua near th bottom
- In the last equality, we have used the fact that $|\gamma| < \pi/N$ t estimate that a typical arbitrary value of $\gamma \sim \pi/(2N)$.

Bottom Regime

At the bottom of the potential, $\epsilon(n=0) \sim 2\pi^2\eta/N^2$, using Eq. (13),

$$\epsilon_{\text{bottom}} \sim 4\pi V_0 \Delta\bar{\theta}\big|_{\text{EDM}}. \quad (1$$

Combining this with the bound on the neutron EDM, we fi that

$$\epsilon_{\text{bottom}}^{1/4} \leq 2\text{MeV}. \quad (1$$

Chain Inflation

Inflating With the QCD Axion

- Necessary conditions for Chain inflation are met in the lin
  regime.
- Seem to get stuck at the bottom

  Too Soon to tell

  Some of the "fixes" just need to be looked at more carefully

More Generally

In this paper we have restricted discussion to axions which an solve the strong CP problem. Obviously, if we forego any ontact with real QCD, then the allowed ranges for parameters ecomes much larger. For example, the constraint from he neutron EDM vanishes. Then the ranges of potential idth, barrier height, and energy difference between vacua are ompletely opened up. A tilted cosine may arise due to (non- CD) "axions" in many other contexts, such as string theory, nd would easily provide an inflaton candidate. Such a general ase will be investigated in a future paper.

Landscape

- Similarly in the landscape: a small causually connected patc[h] (Our Universe) begins at some false vacuum state.
- this vacuum state couples to many other vacua
  - could tunnel to a large number of other vacuum states
- Ultimately there is only one single path through the variou[s] vacuum state in the landscape

The Landscape One More Time

– Toy model: a series of coupled asymmetric double wells.

each field provides a fraction of an e-fold

percolate and reheat every stage

provided if:

1. $\chi \leq 1/3$
2. $\chi_{tot} \geq 60$
3. need 200 vacua. Landscape has 10^{200} vacuum states.

- Don't get stuck

  many different vacua the universe could tunnel to

  avoid slow tunnelers
- Can't go too fast

  for this patch will not inflate enough
- There is ultimately only one path

  the slowest fast route

Coupled Double Wells

Considering a series of coupled double wells. The total potential for the system is

$$V_{tot}(\phi_1, \phi_2, ..., \phi_q) = \sum_i V_{tot,i} = \sum_i [V_i(\phi_i) + V_{i,i-1}] \quad (23)$$

where $0 < i \leq q$. We take asymmetric double-well potentials

$$V_i(\phi_i) = \frac{1}{4}\lambda_i(\phi_i^2 - a_i^2)^2 - \frac{\epsilon_i}{2a_i}(\phi_i - a_i) \quad (24)$$

Conclusion

- Chain inflation imposes some light conditions upon a workable model

  $\chi \leq 1/3$

  $\chi_{tot} \geq 60$

- two workable models

  Stringy Landscape

  QCD Axion

Conclusion

- many more workable models along the lines of
  Axion can be found
- Chain Inflation is a useful mechanism which can
  necessary inflation to solve the standard cosmology
- It offers an attractive alternative to other inflationary

  Wide Range of Scales

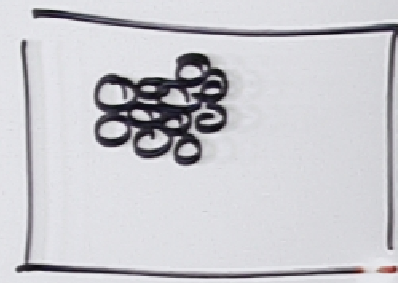
  No Fine-Tuning

  Graceful Exit

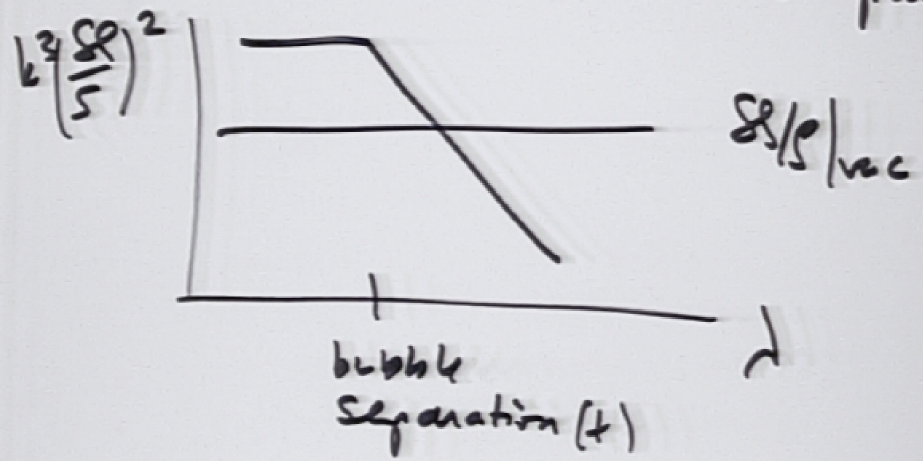
Chain Inflation

Density Perturbations

$\Gamma / H^4 \gg 1$



treat bumps as friction in slow-roll (vacuum part)



$$\frac{\delta\rho}{\rho} \sim \left(\frac{\rho_{bubble\ wall}}{\rho_{vac}}\right)^2$$

roughly scale invariant