Eternal Inflation

AND TUNNELING IN STRINGY LANDSCAPE

A. Linde

1. Various models of inflation
2. Stochastic approach to inflation and tunneling
3. Eternal inflation
4. Wandering in stringy landscape: diffusion, tunneling, and all that
5. Can we populate the landscape jumping from Minkowski space?

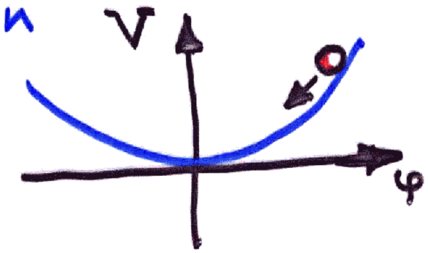
Inflation: Problems solved

1. Homogeneity
2. Isotropy
3. Flatness/entropy/mass
4. Horizon
5. Creation of large-scale structure
6. Monopoles, gravitinos,....

Example 1.

Chaotic inflation

$$V = \frac{m^2 \varphi^2}{2}$$



Inflation may begin in a domain of a smallest possible size $M_p^{-1} \sim 10^{-33}$ cm with a total mass 10^{-5} g and total entropy $O(1)$

Successful inflation requires long accelerated expansion and exponentially large increase of entropy

Eternal inflation provides good conditions for justification of anthropic principle

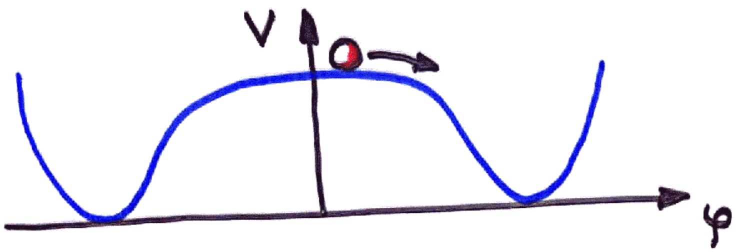
The main idea which simplifies investigation of inflation: no-hair theorem for dS space.

Inflation can start in a domain $O(H^{-1})$ and then this domain can grow indefinitely large. The processes inside the domain occur completely independently of initial conditions at the beginning of inflation, and ~~of~~ the processes at the boundary of infationary domain.

In this sense inflation is anti-holographic

Example 2.

New Inflation

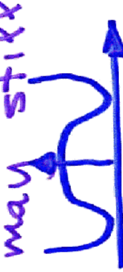


Inflation begins in a domain of size $H^{-1} \sim \frac{M_p}{M_X^2} \sim 10^6 M_p^{-1}$ with total mass $M_p \cdot \frac{M_p^2}{M_X^2} \sim 10^{12} M_p$ and with total entropy $\frac{M_p^3}{M_X^3} \sim 10^9$

This is not a real solution of flatness, horizon and entropy problems... unless one uses eternal inflation

Historically, new inflation was introduced as a result of supercooling in the process of high temperature phase transitions after the hot Big Bang.

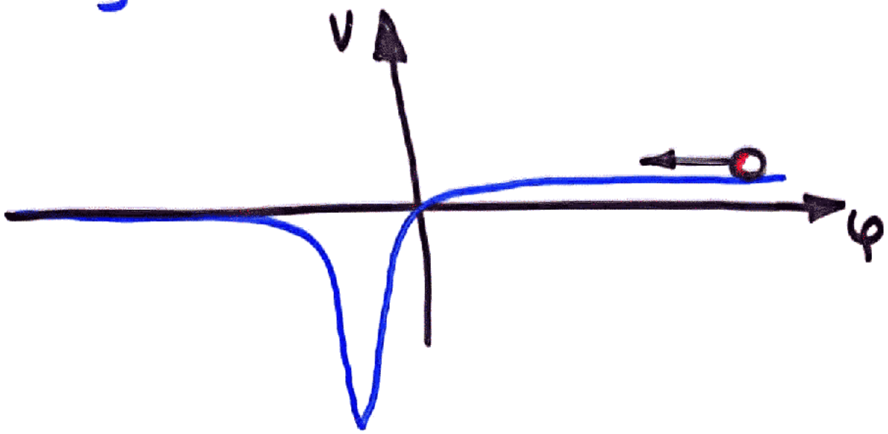
These ideas did not work, because to get $\frac{\delta\rho}{\rho} \sim 10^{-5}$ we need the inflaton out of thermal equilibrium. We may still use the potential



along the lines of chaotic inflation (i.e. assuming chaotic initial conditions)

Example 3.

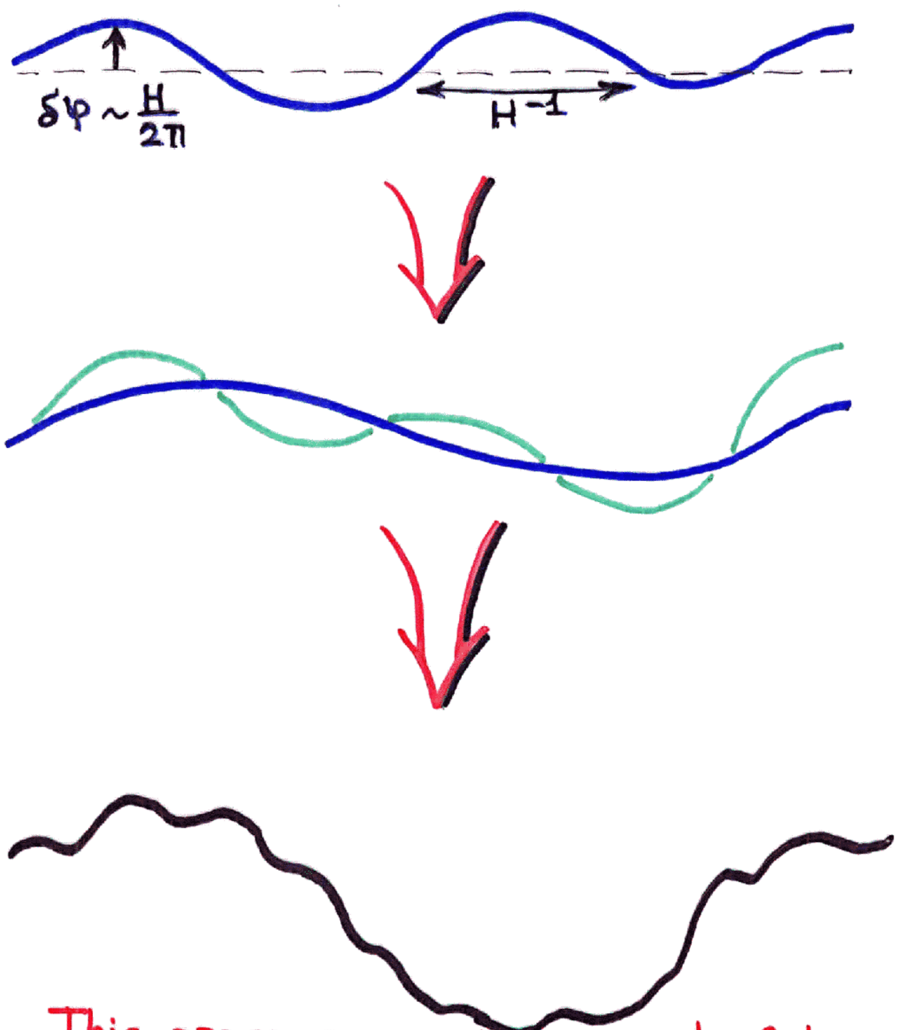
Cyclic inflation



Inflation begins in a domain of initial size 10^{28} cm with total mass 10^{+55} g and total entropy 10^{88}

Flatness/entropy/mass problem unsolved

Scalar field fluctuations



This process produces perturbations of density which lead to galaxy formation and CMB anisotropy

Diffusion equation describes the probability to find a field φ at a given point x, t

By φ we understand its component with wavelength $\gtrsim H^{-1}$

probability

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial \varphi}\left(\frac{H^3}{8\pi^2}\,\frac{\partial P}{\partial \varphi} + \frac{P}{3H}\cdot\frac{dV}{d\varphi}\right)$$

Stationary solutions
(as in thermal equilibrium)

$$P \approx \exp\left(\frac{3M_p^4}{8V(\varphi)}\right)\cdot \exp\left(-\frac{3M_p^4}{8V(\varphi_0)}\right)$$

Hawking, Moss 82
Starobinsky 85

solution

normalization factor

$$S = \ln P = \frac{3M_p^4}{8V(\varphi)}$$

entropy

dS entropy without use of Euclidean methods

True for ANY number of fields

$$P = e^{\Delta S}$$ as in thermodynamics

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Susskind 2002

$$P = \exp\left(-\frac{3M_p^4\,\Delta V}{8\,V(\varphi_0)V(\varphi)}\right)$$

Suppose $V(\varphi_0) \sim V(\varphi)$ $\quad(\Delta V \ll V)$

$P \simeq O(1)$ for

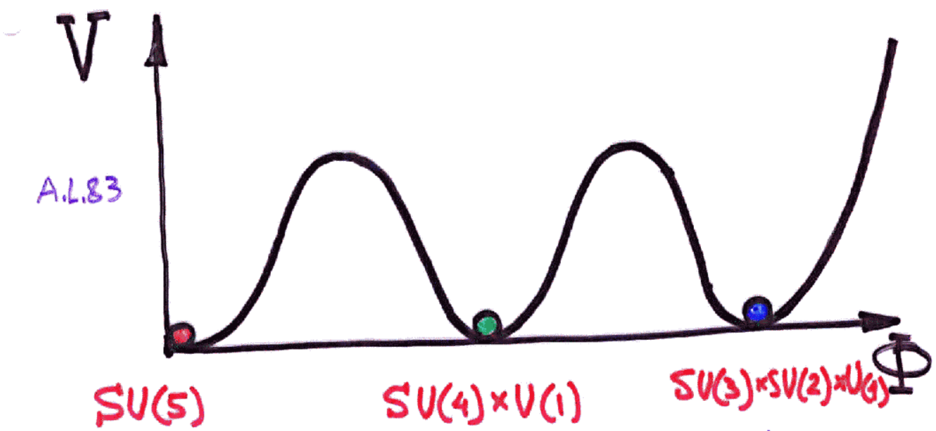
$$\Delta V \sim \frac{V^2}{M_p^4}$$

$$\boxed{\text{If } V \sim M_p^4, \text{ the field can easily jump over Planckian barriers}}$$

This can easily happen during eternal chaotic inflation.

In new inflation it is more difficult.

Supersymmetric SU(5)



no difference between weak, strong and electromagnetic interactions

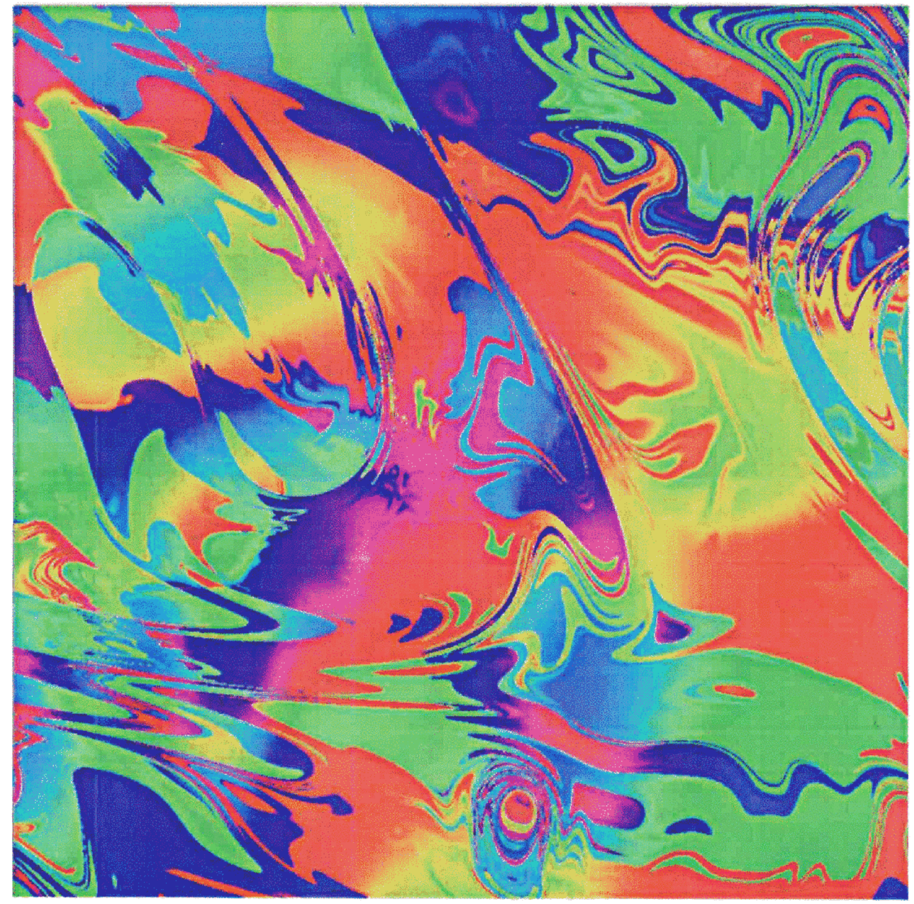
different interactions

weak, strong and e.m. interactions

Spontaneous decompactification

A.L., Zelnikov 87

Inflating d=4 and d=6 universes



Kandinsky Universe

Eternal Chaotic Inflation

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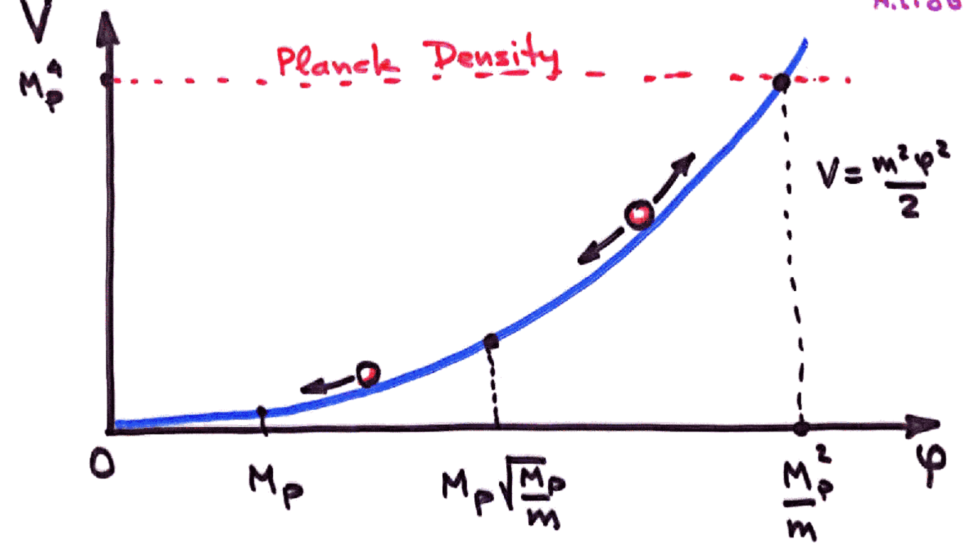
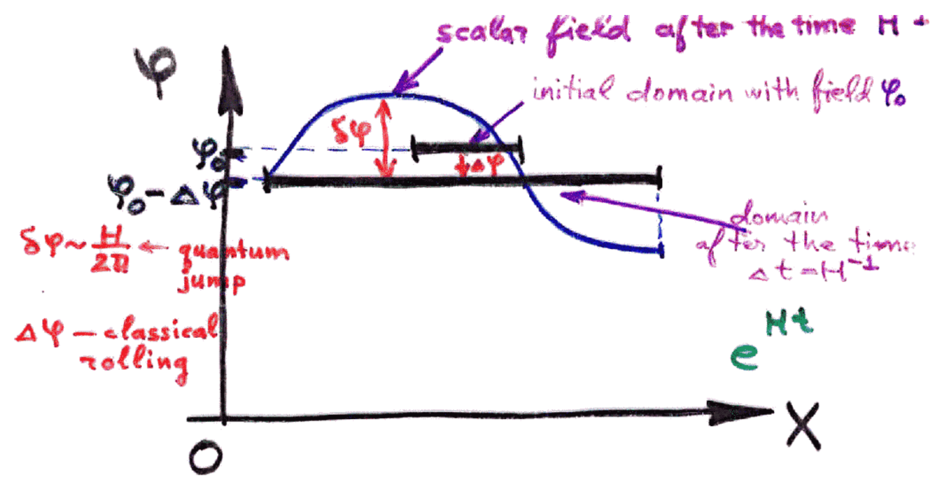


Produces fluctuations of all other fields with the amplitude that can be as large as $\delta\varphi \sim M_p$

This process continues eternally $\Longrightarrow$ the universe „probes" all of its possible vacuum states



$\delta\varphi \gg \Delta\varphi$ for $\varphi > \varphi^* = M_p\sqrt{\frac{M_p}{m}}$

Brownian motion more efficient than classical

In such case: During the time $\Delta t = H^{-1}$ the size of an inflationary domain grows e times, its volume grows $e^3 \sim 20$ times, and almost in a half of this volume (approximately 10 times greater than the volume of the original domain) the field φ increases rather than decreases.

As a result, the total volume of the universe filled by a large field φ ($\varphi > \varphi^* \sim M_p\sqrt{\frac{M_p}{m}}$) exponentially grows in time without end.

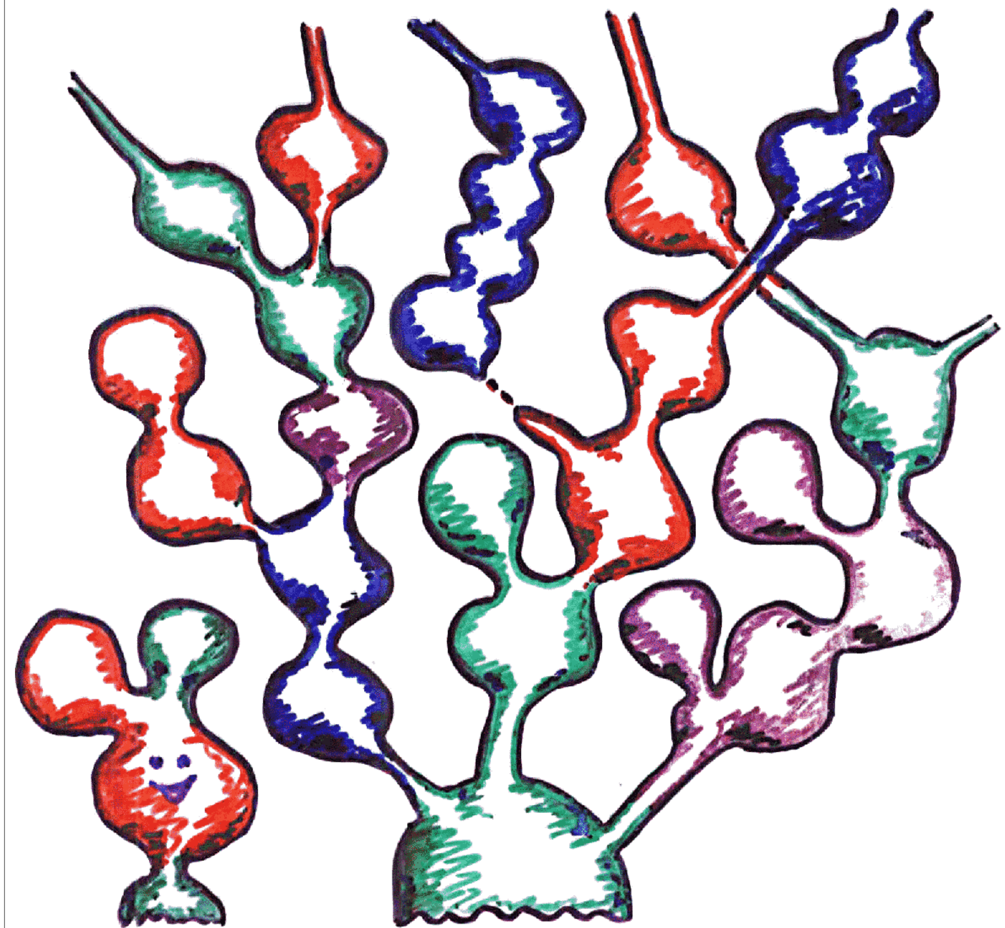
The tools to investigate the new theory:

$\mho(\varphi, \varphi_0, t)$ ← the total volume of all parts of the universe which began their evolution at $\varphi = \varphi_0$ and contain field φ at the moment t

It can be shown that in many theories

$$\mho(\varphi, \varphi_0, t) \sim e^{-\frac{3M_p^4}{8V(\varphi_0)}} P(\varphi) \times$$
$$\times\, e^{d\, H_{max} t}$$

Stationary distribution!



THE UNIVERSE
as it is

Is inflation future/past eternal ?

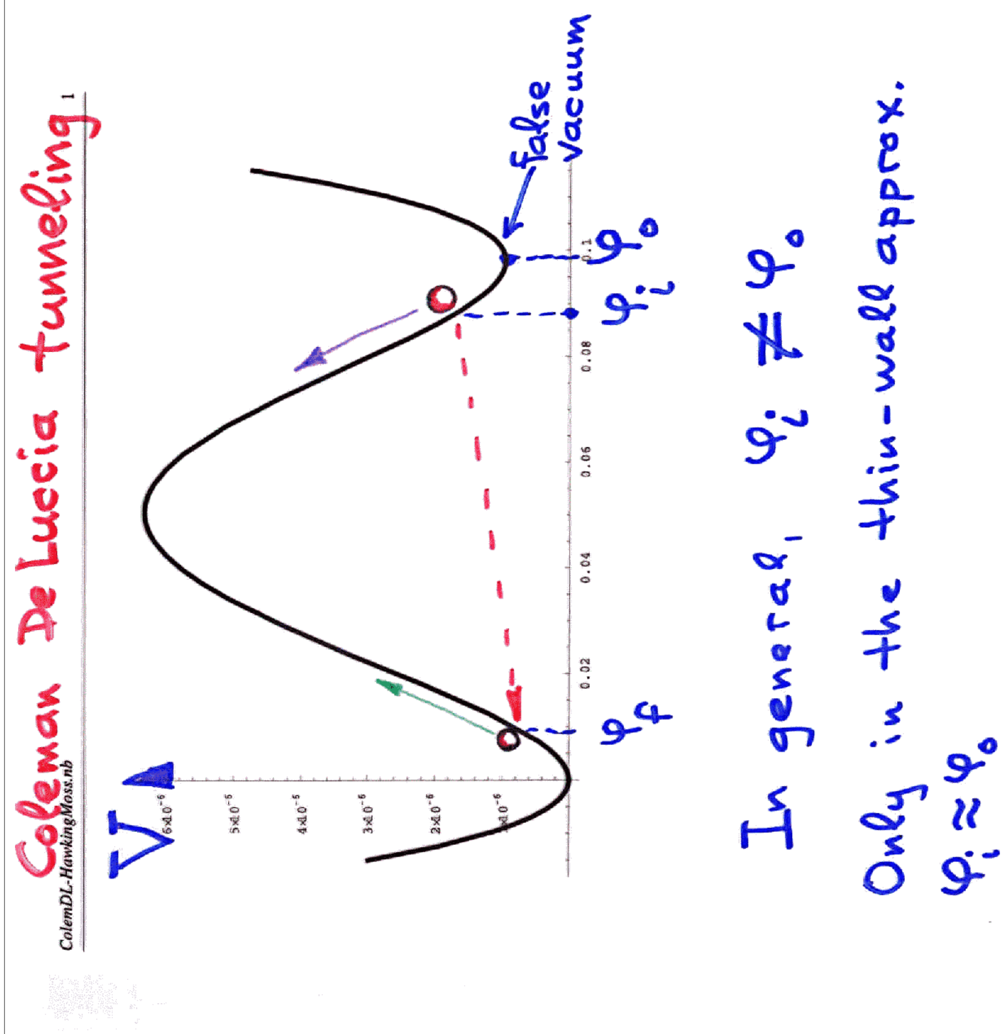
1) Inflation along each particular geodesic IS NOT future eternal, it ends within finite time.

We call inflation future eternal iff there is no upper bound on the proper time of duration of inflation along ALL geodesicals.

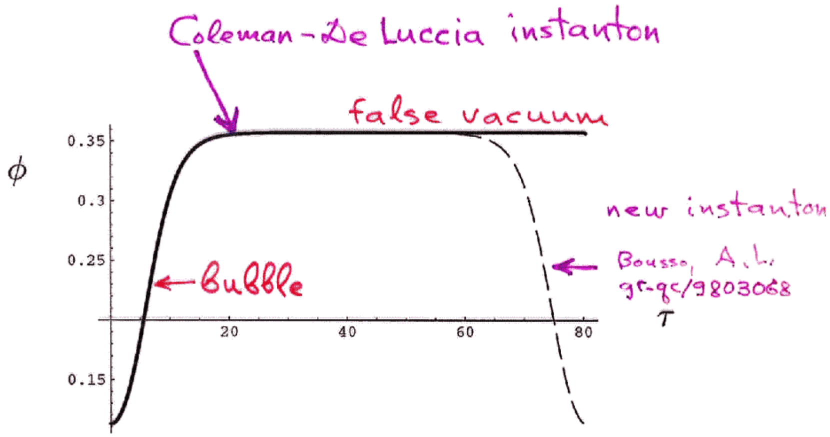
2) Inflation along each particula geodesic IS NOT past eternal (see talk by Guth).

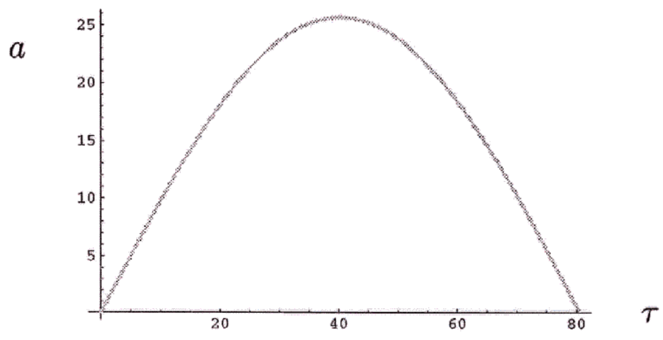
However, there are no statements about an upper bound of the duration of inflation in the past along ALL geodesicals.

In this sense, there is no information whether inflation is past-eternal or not.

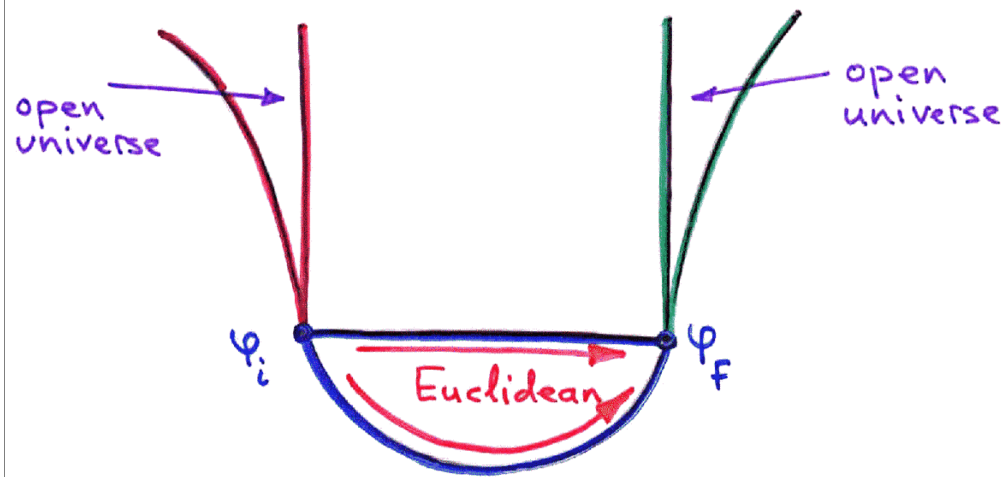


Coleman - De Luccia 1980





Making sense of CDL instantons

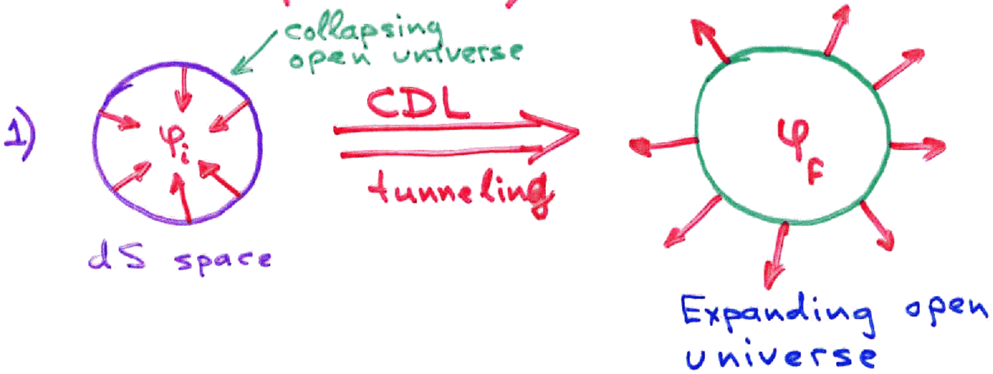


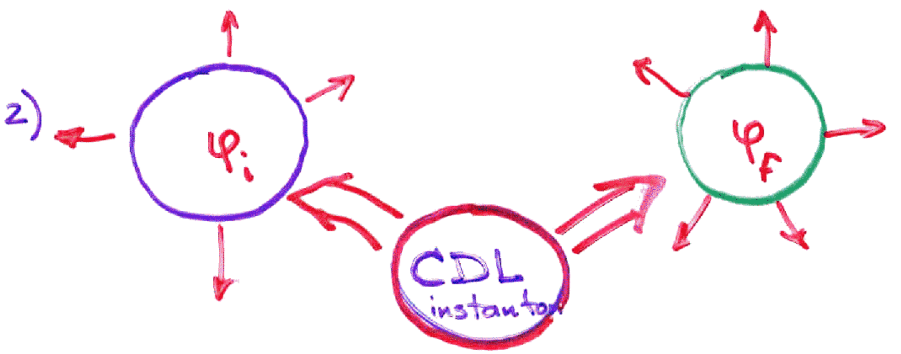
Note that φ_i does not correspond to the false vacuum.

So how these instantons can describe decay of the false vacuum??

Possible answers:

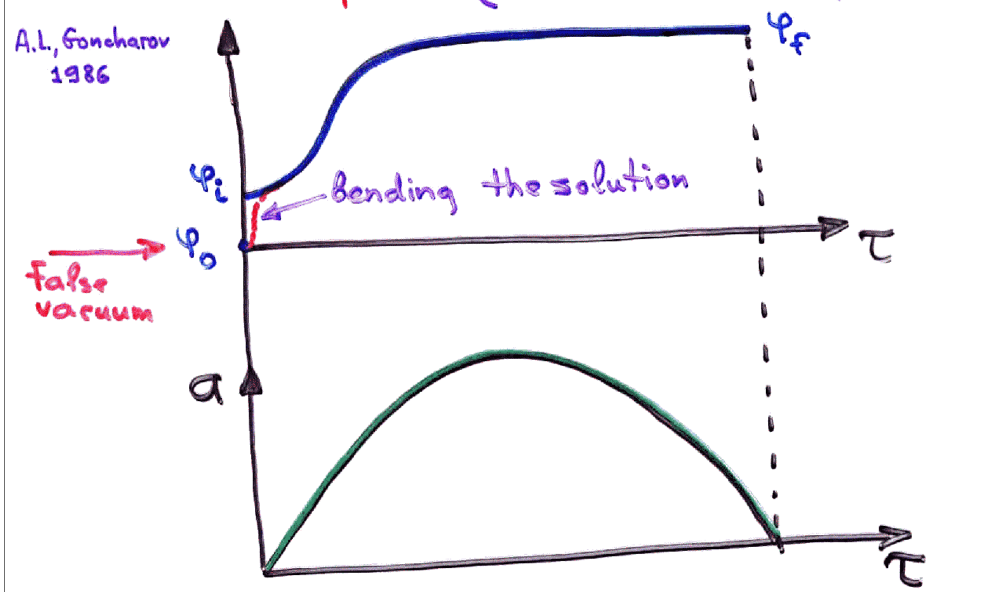
(Euclidean approach allows many interpretations)





Two expanding open universes (like in Hawking-Turok case but without singularities)

3) Deforming CDL at the North pole (at the initial point φ_i)



This procedure makes sense if the corresponding change of action is small,

$$\Delta S < 1$$

Estimate the price for bending CDL instantons:

$$\Delta S \sim \int \left(\frac{d\varphi}{d\tau}\right)^2 a^3(\tau)\, d\tau$$

kinetic energy (other terms can be made small)

$$\sim \int \left(\frac{d\varphi}{d\tau}\right)^2 H^{-3} \sin^3 H\tau \, d\tau$$

$\tau \sim d\tau \ll \frac{1}{H}$

$$\sim \left(\frac{d\varphi}{d\tau}\right)^2 (d\tau)^4$$

$\frac{d\varphi}{d\tau} < 1$ (sub Planckian)

$\Downarrow$

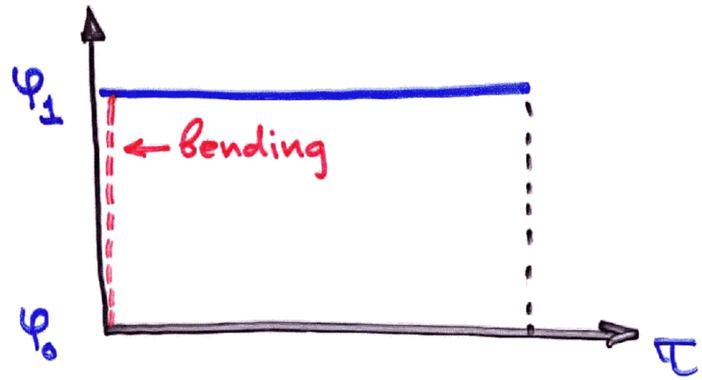
$$> (d\varphi)^4$$

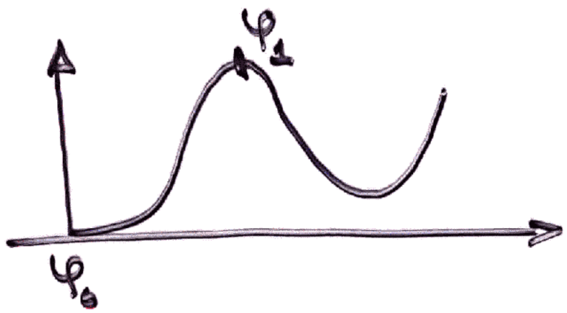
Must be smaller than 1 $\leftarrow$ $d\tau > d\varphi$

$$\boxed{\Delta\varphi < 1}$$

Super Planckian jumps from φ_0 to φ_i are forbidden

Example HM instanton

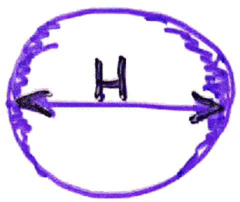


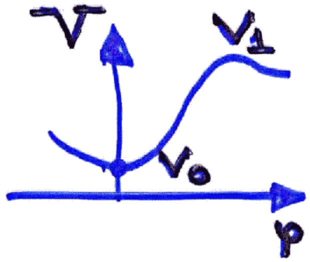


Legitimate if $\varphi_1 - \varphi_0 = \Delta\varphi < 1$

Does not work for typical inflationary potentials with $\Delta\varphi > 1$

Deviating from Euclidean path





$$T_0 = \frac{H_0}{2\pi} \sim \frac{\sqrt{V_0}}{M_p}$$

$$E_1 = V_1 \cdot H_1^{-3} = \frac{M_p^3}{\sqrt{V_1}}$$

$$P_1 \sim \exp\left(-\frac{E_1}{T_0}\right) = \exp\left(-\frac{M_p^4}{\sqrt{V_1 V_0}}\right)$$

But in fact jump probably must occur in the whole original causal patch

$$E_{10} = V_1 \cdot H_0^{-3}$$

$$P_2 = \exp\left(-\frac{M_p^4 V_1}{V_0^2}\right)$$

In either case, $P > 0$.

Is it possible than new universe will be formed from ours ?

Is it possible to create a new universe?

$100 k_g$

In inflationary cosmology the initial weight of the universe may be as small as 10^{-5} g.

Is it a big deal ?

Can we jump up from Minkowski space?

Creation of the universe in a laboratory due to quantum fluctuations

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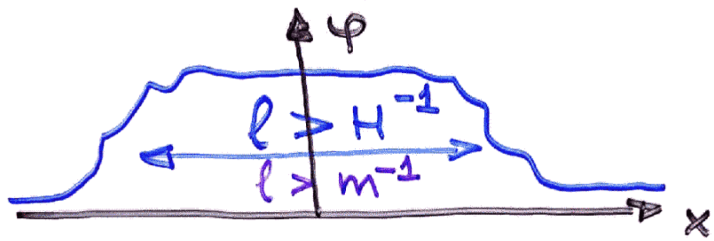
What do we need?



$$V = \frac{\lambda}{4}\varphi^4$$

1) φ must be greater than M_p

2) $\ell > m^{-1}, H^{-1}$

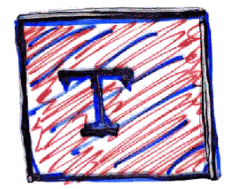
If $\varphi > M_p$, then the condition $\ell > H^{-1}$ is sufficient

$$\langle\varphi^2\rangle_{\ell > H^{-1}} \sim \int_0^H \frac{d^4k}{k^2} \sim H^2 \sim \frac{\lambda\varphi^4}{M_p^2}$$

$$P \sim \exp\left(-\frac{\varphi^2}{2\langle\varphi^2\rangle_{\ell>H^{-1}}}\right) = \exp\left(-\frac{M_p^2}{\lambda\varphi^2}\right)$$

For $\varphi \sim M_p \Rightarrow P \sim \exp\left(-\frac{1}{\lambda}\right)$

In a laboratory



$$\langle\varphi^2\rangle \sim \frac{T\, V(\varphi)^{1/2}}{2\pi^2\varphi}$$

$$P_T \sim \exp\left(-\frac{\varphi^2}{2\langle\varphi^2\rangle}\right) \sim \exp\left(-c\,\frac{\pi^2\varphi^3}{T\sqrt{V}}\right)$$

$$V \sim \lambda\varphi^4$$

$$P_T \sim \exp\left(-c\,\frac{\pi^2 M_p}{\sqrt{\lambda}\,T}\right)$$

But: $T^4 \ll V(\varphi)$

$$P_T < \exp\left(-c\,\frac{\pi^2}{\lambda^{3/4}}\right)$$

Interpretation