Eternal inflation and the multiverse

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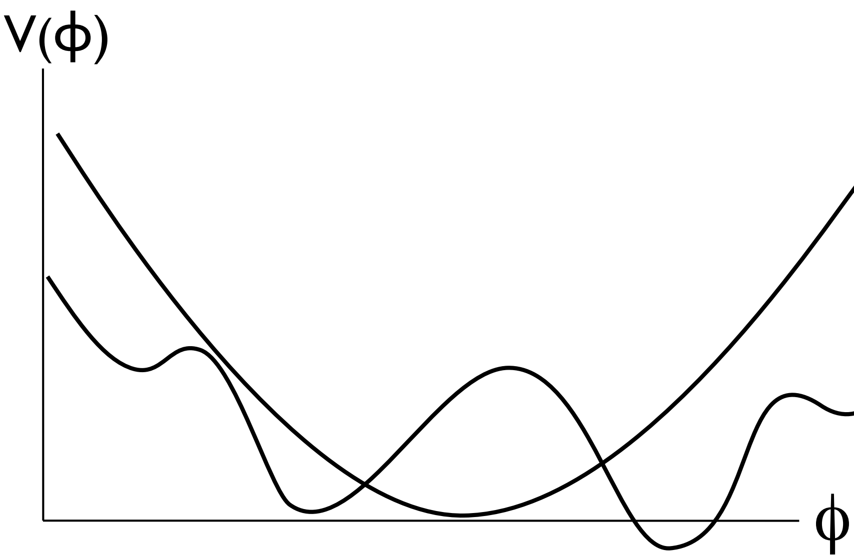
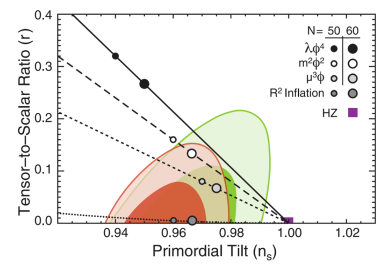
Outline

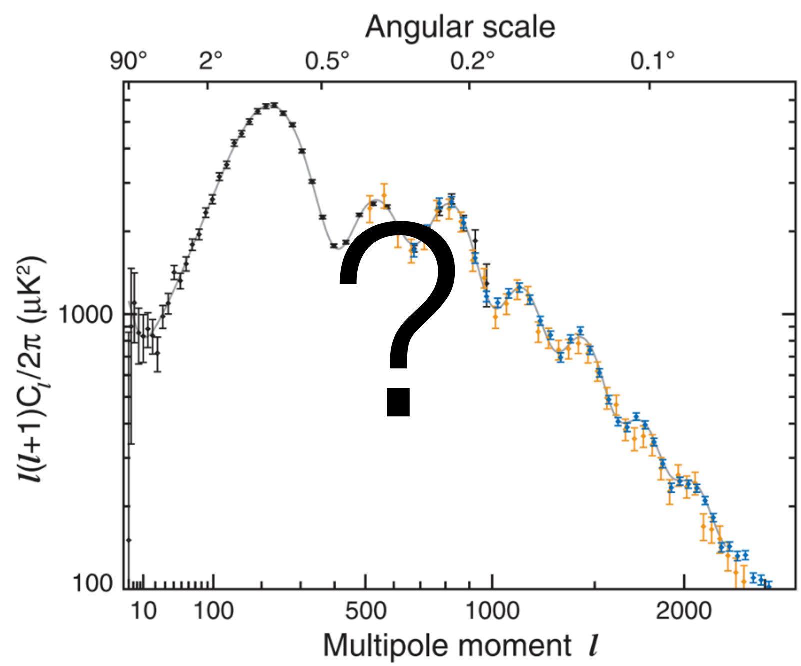
1. Everlasting inflation and the structure of an eternally inflating multiverse
2. How does inflation arise from non-inflation?
3. Does inflation start?

see also http://arxiv.org/abs/arXiv:0712.0571

I. Inflation to everlasting inflation

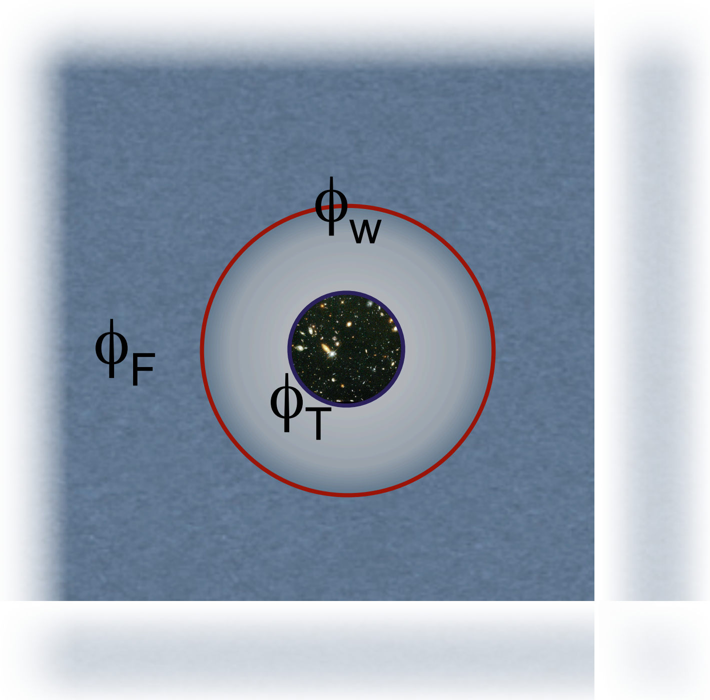


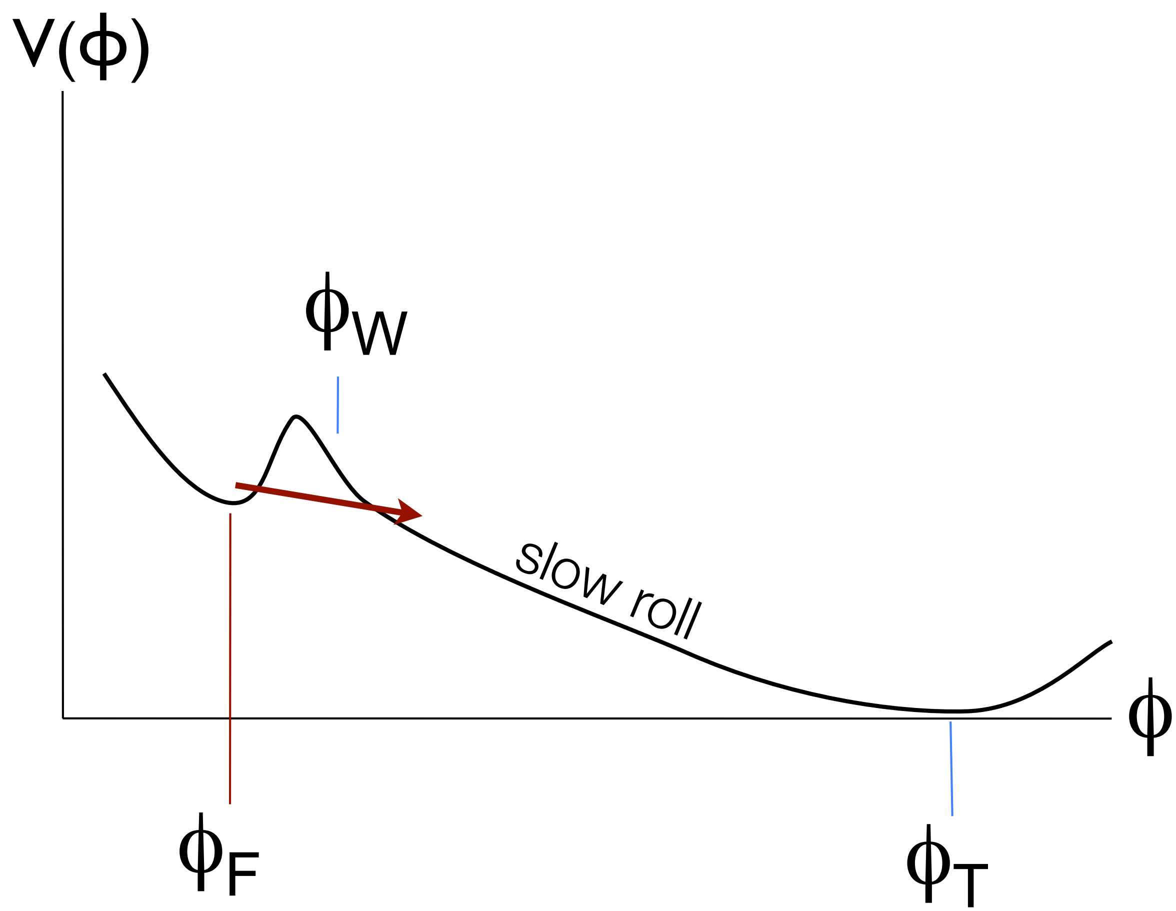




Everlasting bubbly inflation

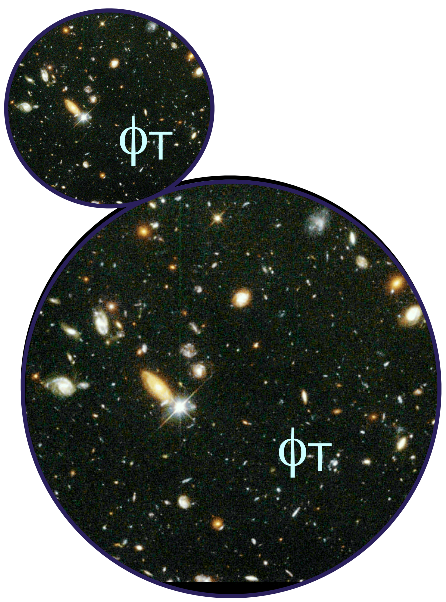
- Multiple minima → vacuum transitions.

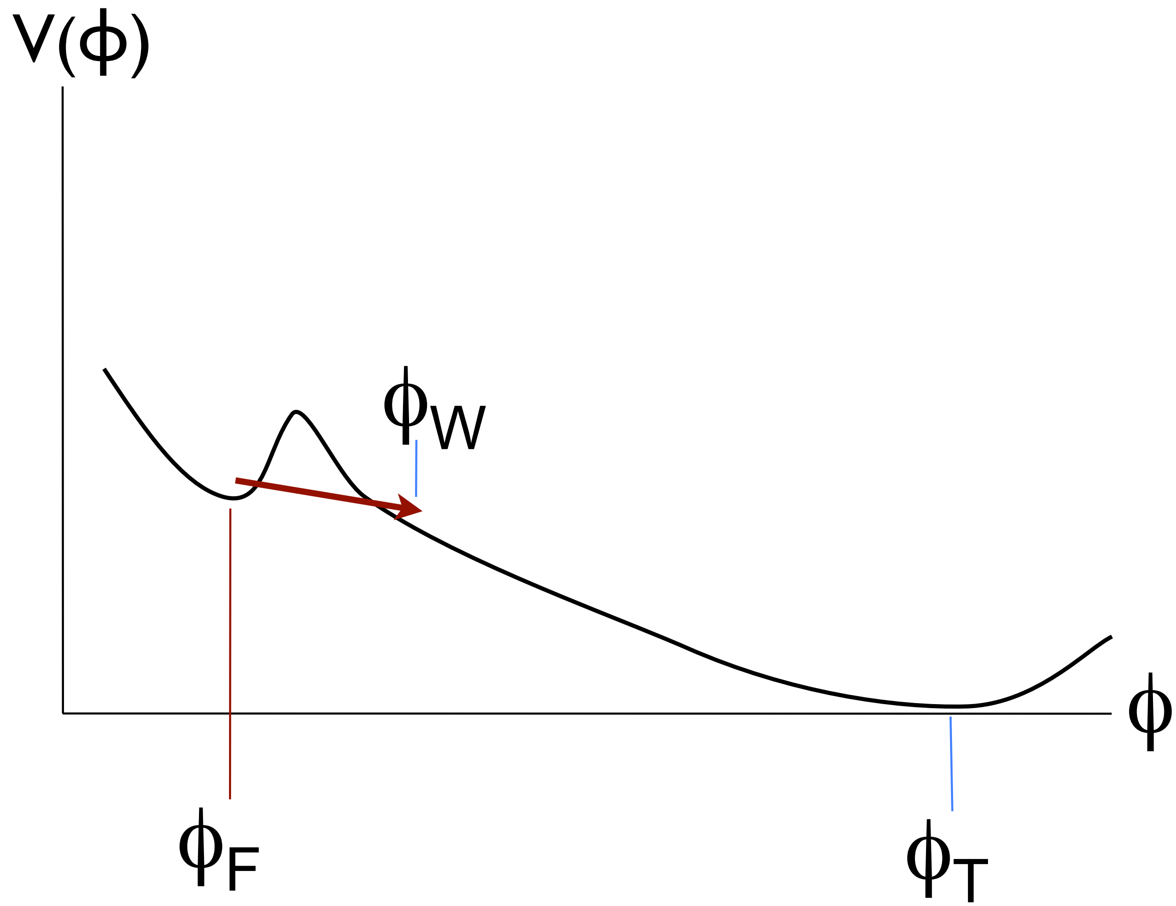




Everlasting bubbly inflation

- (Multiple minima) + (slow transitions) = **eternal inflation**





Everlasting bubbly inflation

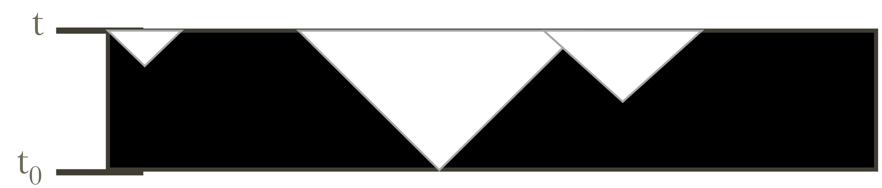
Inflating bulk endures:

Nucleation rate/4-volume

Inflating fraction:

$$f_{\rm inf} = \exp\left[-\lambda \frac{4\pi(t-t_0)}{3H^3}\right]$$

Available 4-volume



Inflating volume:

$$v_{\rm inf} \propto \exp(3Ht) f_{\rm inf} \propto \exp[(3 - 4\pi\lambda/3H^3)Ht]$$

***Grows* for small λ!**

Everlasting bubbly inflation

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Nucleation rate/4-volume

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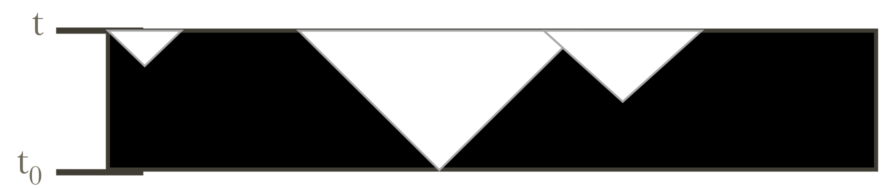


Inflating volume:

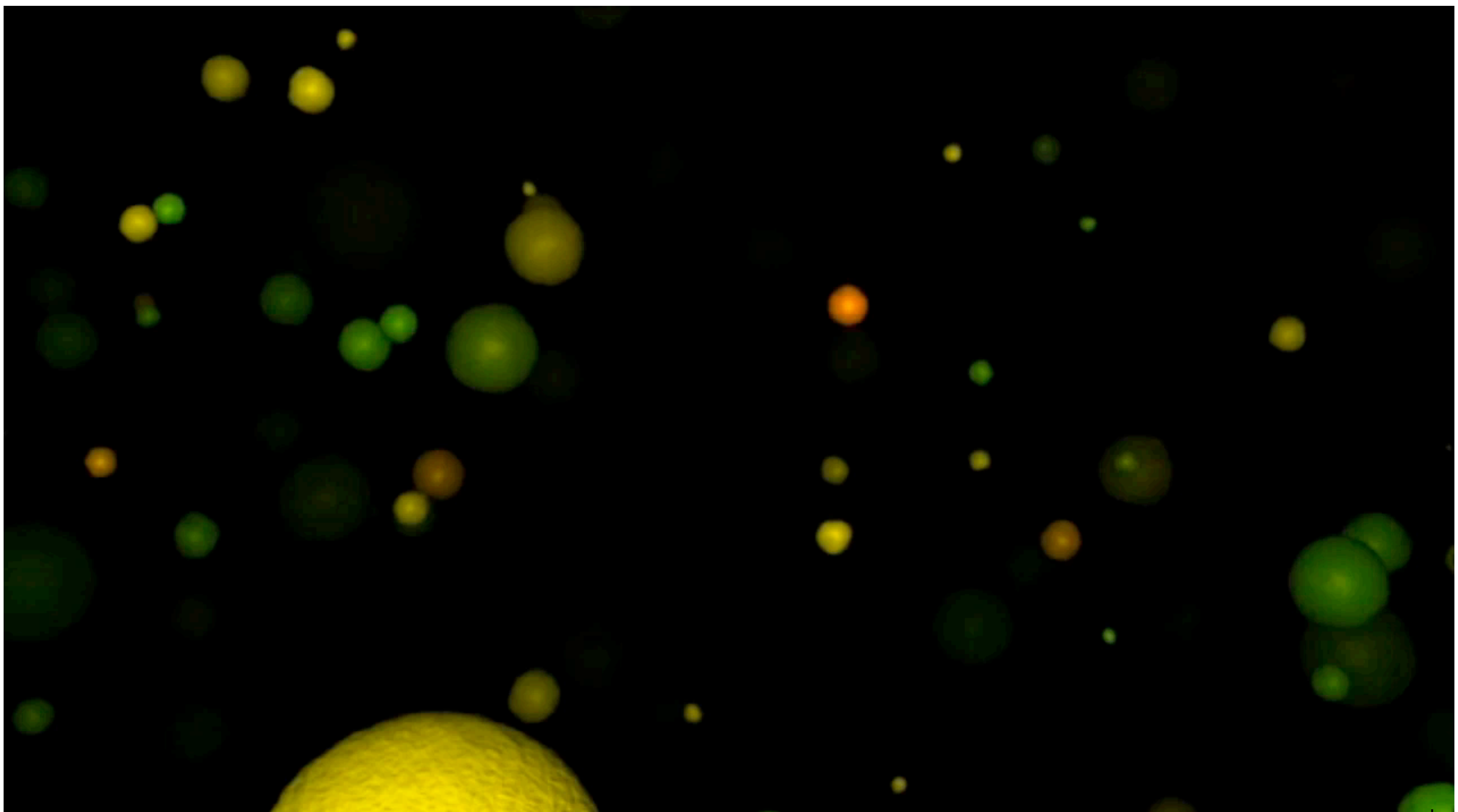
$$v_{\rm inf} \propto \exp(3Ht) f_{\rm inf} \propto \exp[(3 - 4\pi\lambda/3H^3)Ht]$$

The remaining inflating region approaches a fractal* of dimension 3-4π**λ**

* Q: What does the 'B'. In Benoit B. Madelbroit stand for?
A: Benoit B. Mandelbroit.

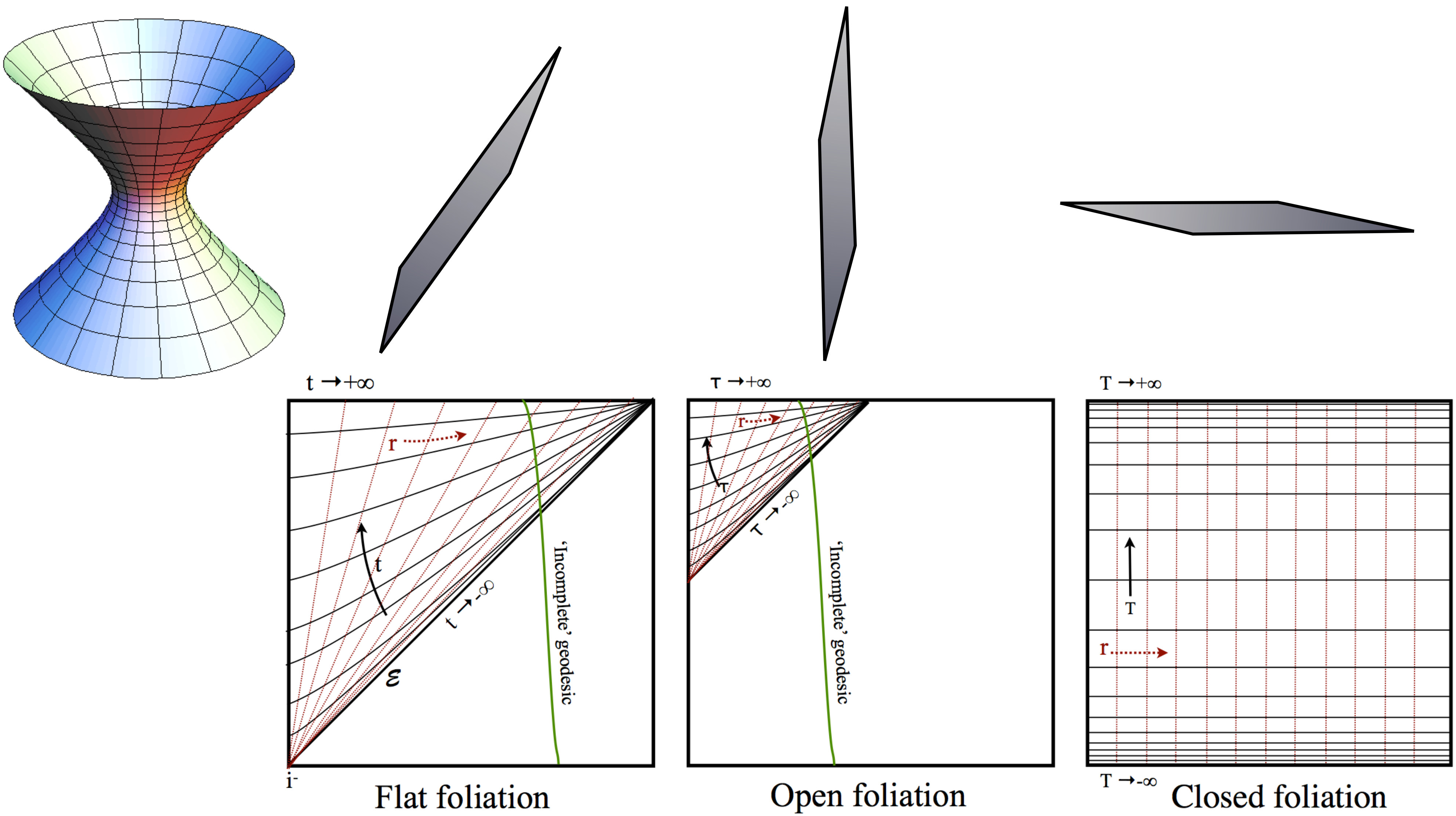
Everlasting bubbly inflation

- (Multiple minima) +
  (slow transitions)
  = **eternal inflation**



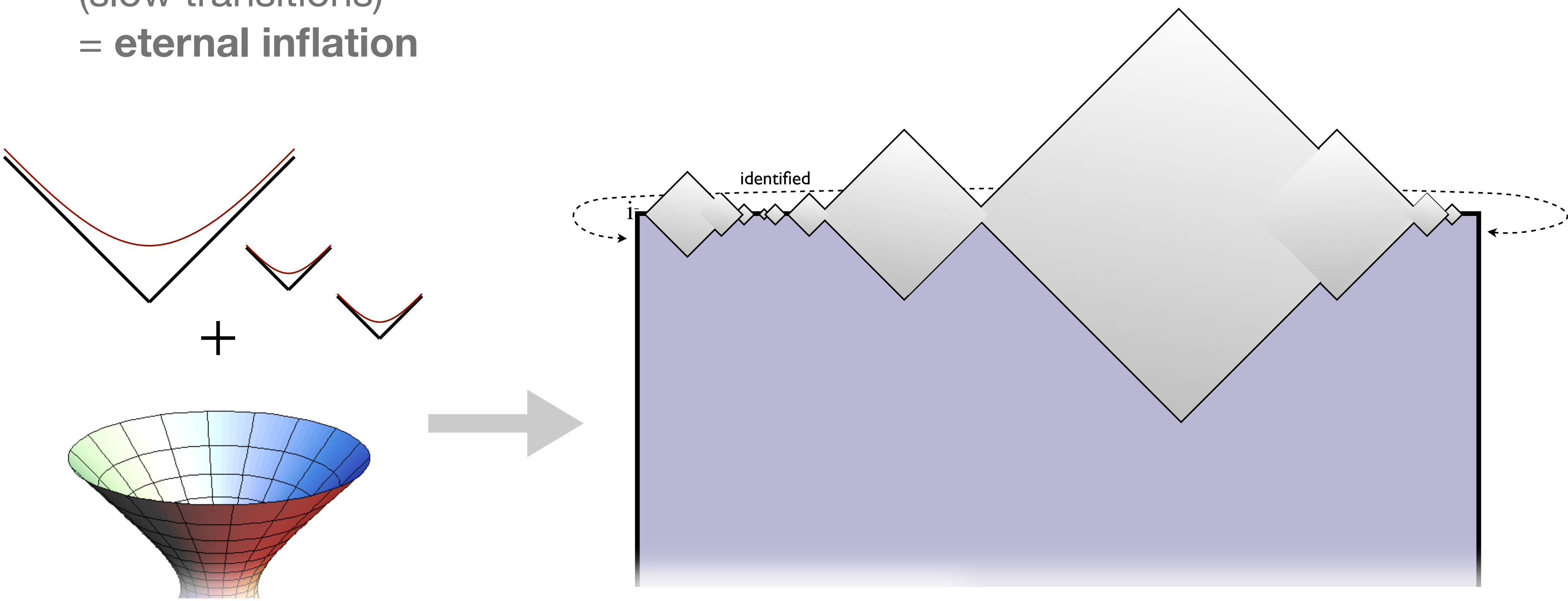
Nina McCurdy & AA

de Sitter space(time)



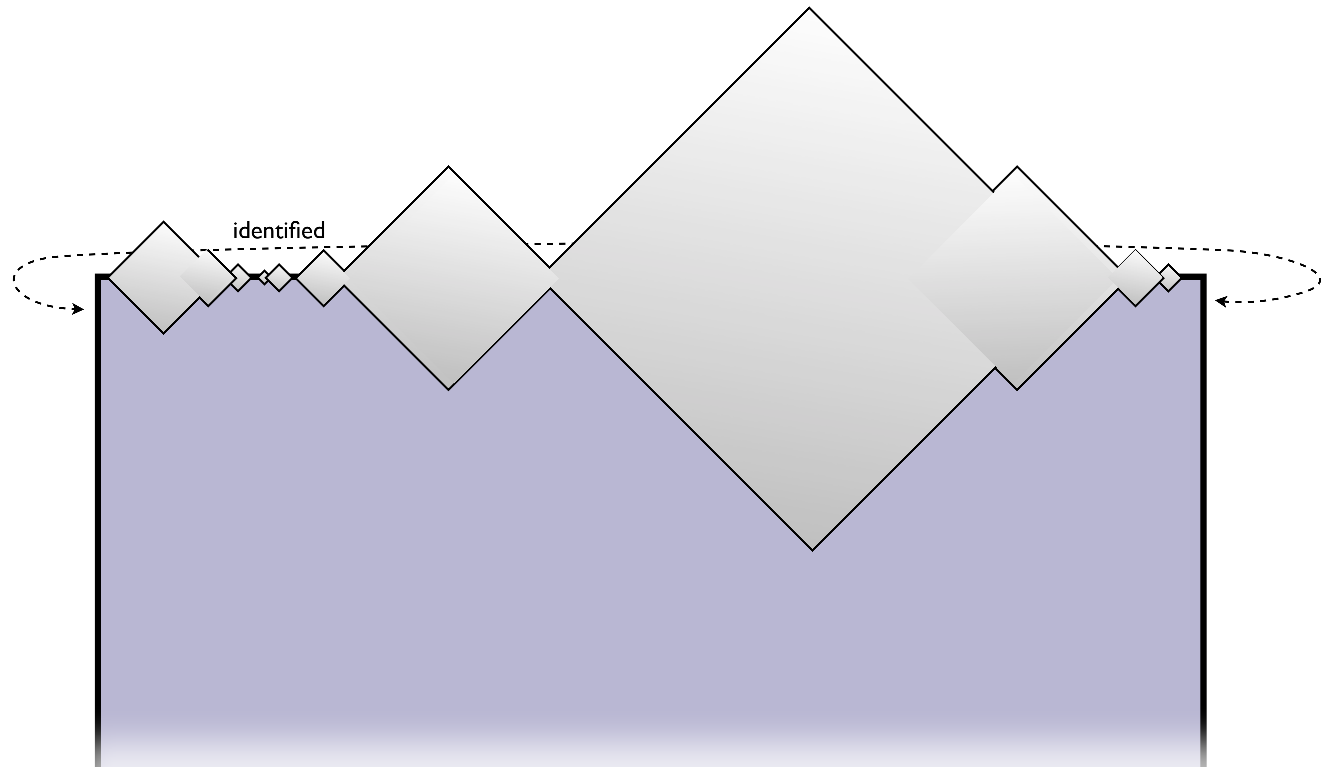
Everlasting bubbly inflation

- (Multiple minima) + (slow transitions) = **eternal inflation**



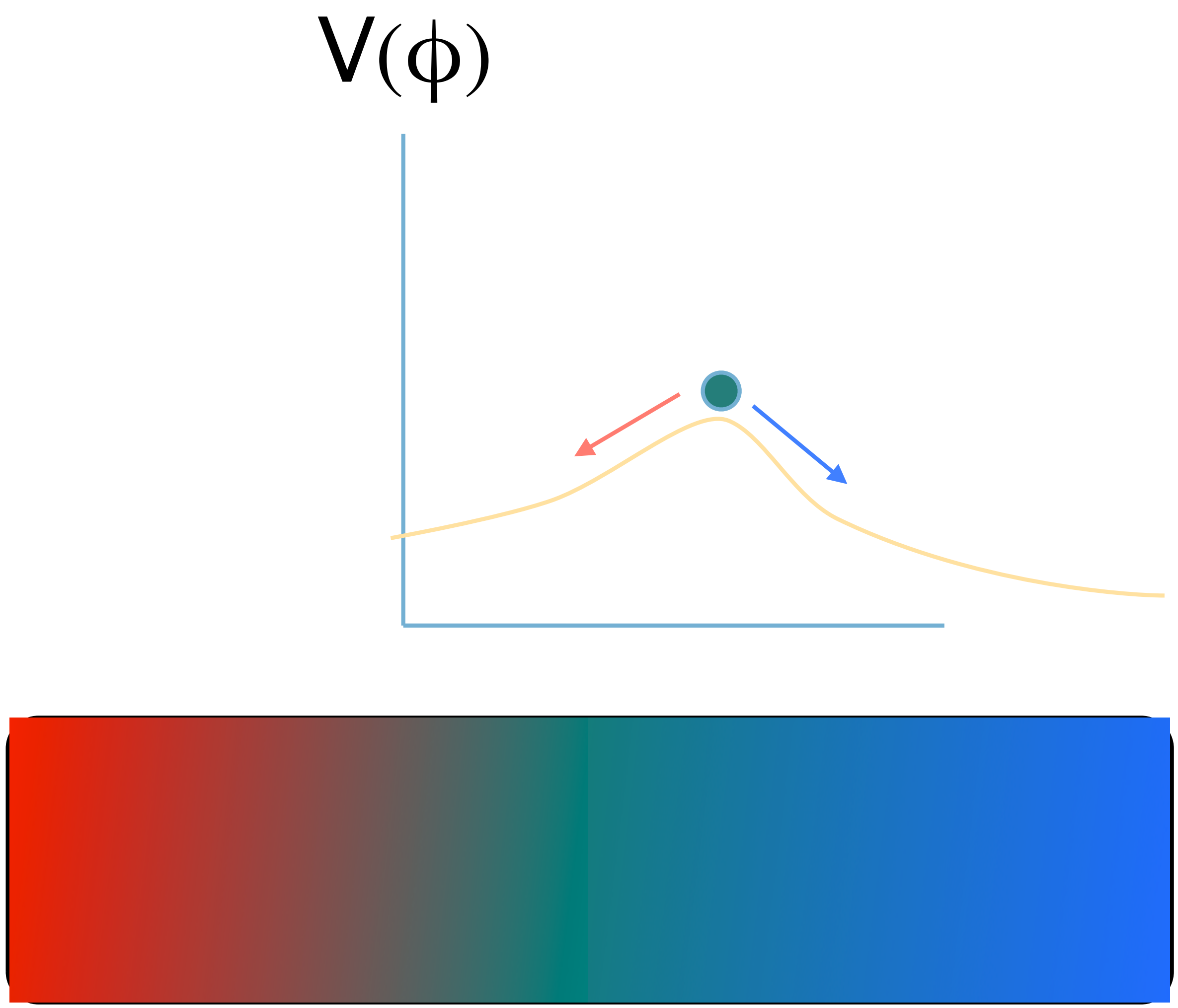
Everlasting bubbly inflation = infinite spacetime

- Spacetime has infinite proper volume.
- There are future-directed timelike worldlines of infinite proper length that stay in the inflating phase.
- The bubble distribution in the inflating background becomes stationary.



Other versions of everlasting inflation

Topological eternal inflation

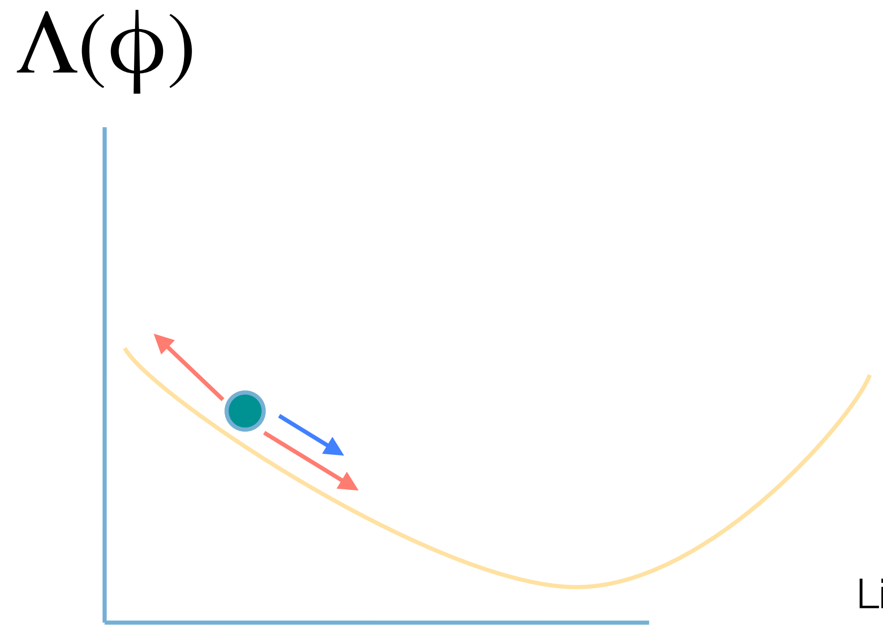


Vilenkin 94

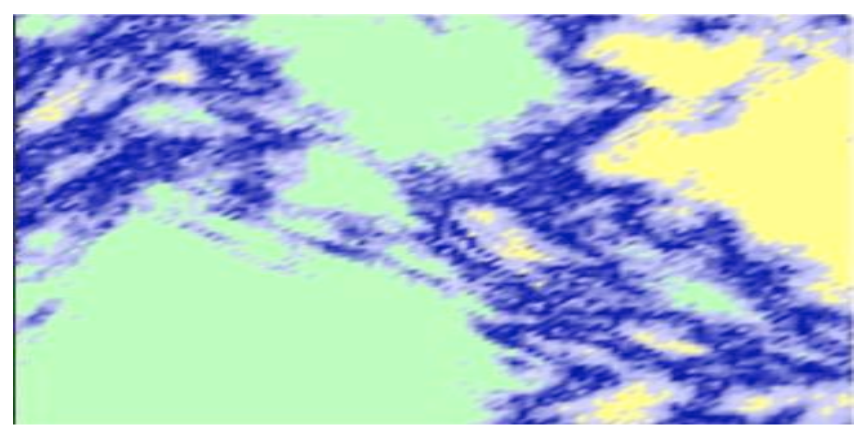
Other versions of everlasting inflation

Stochastic eternal inflation

Note: these are exactly the same fluctuations that lead to the fluctuations in the CMB.

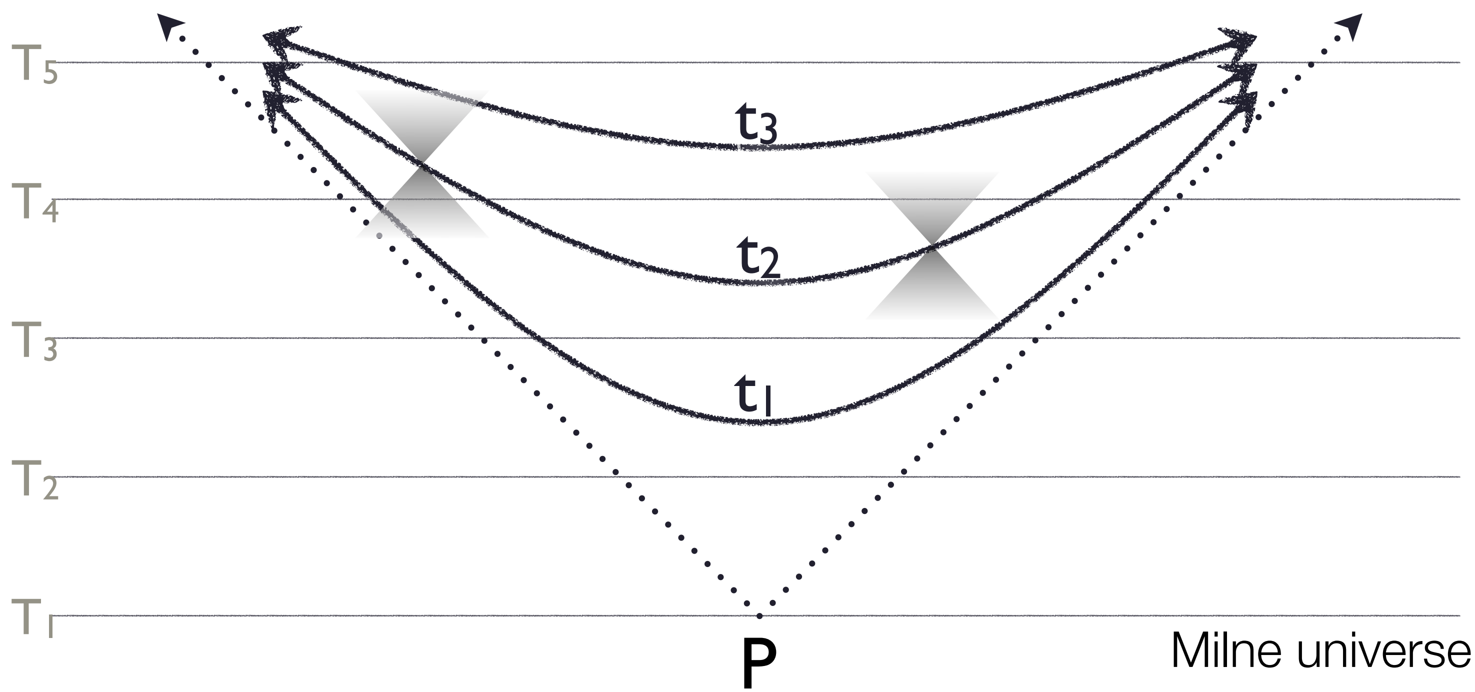


Linde 86



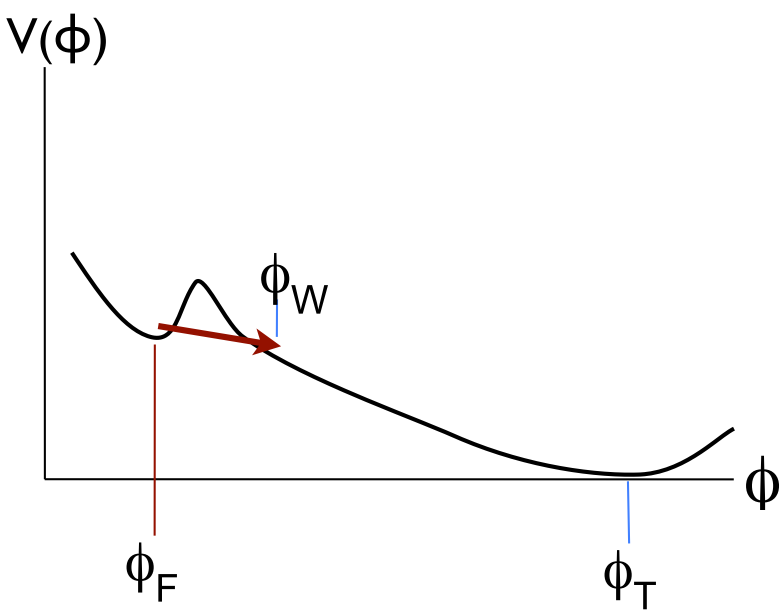
Is the universe spatially infinite?

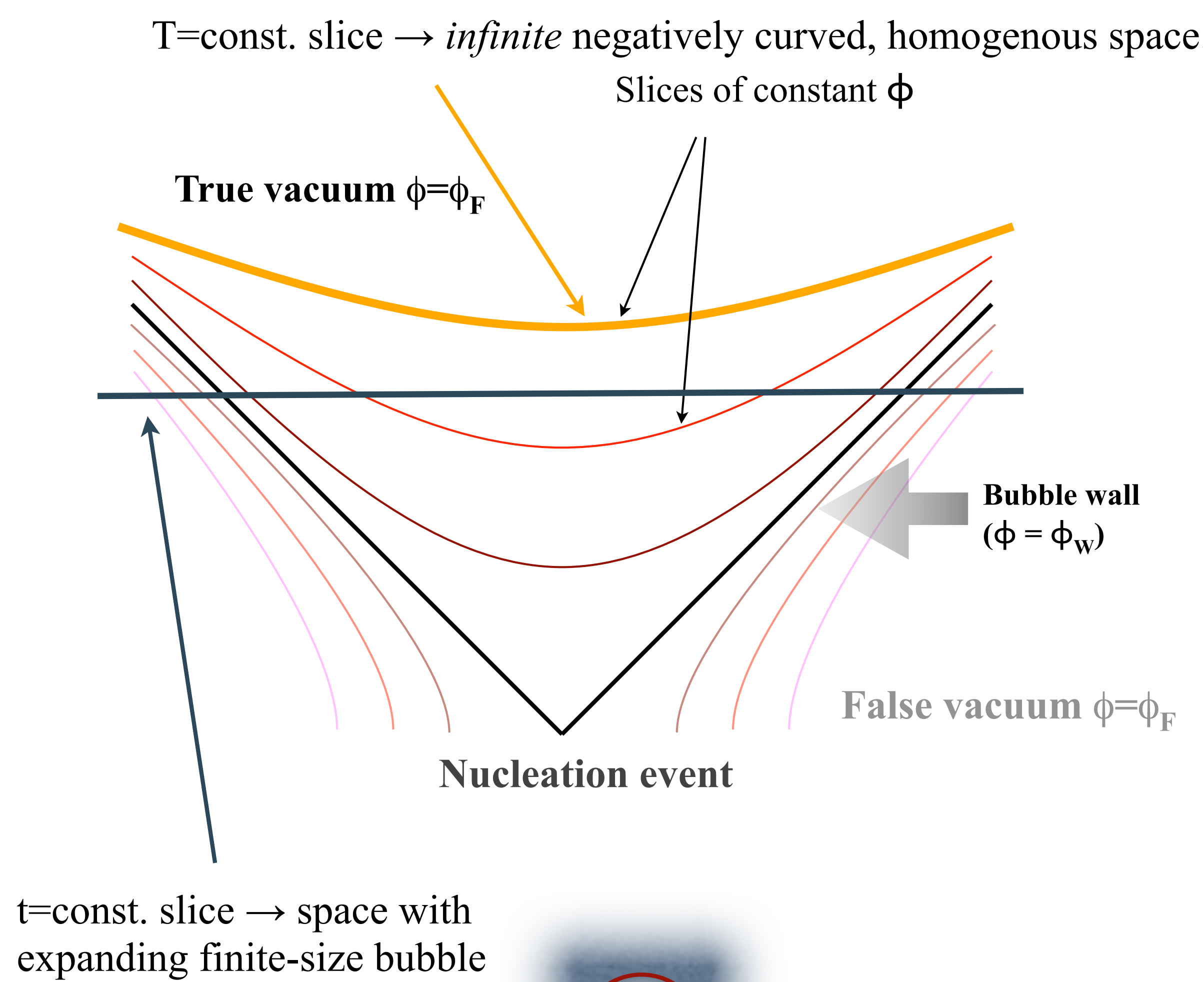
- *This can depend on the foliation of spacetime*

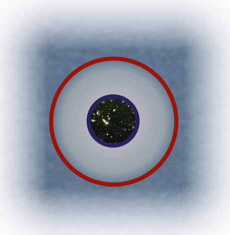


Infinite uniform spaces inside bubbles

- bubbly inflation: each (isolated) bubble has **open FRW cosmology** inside.



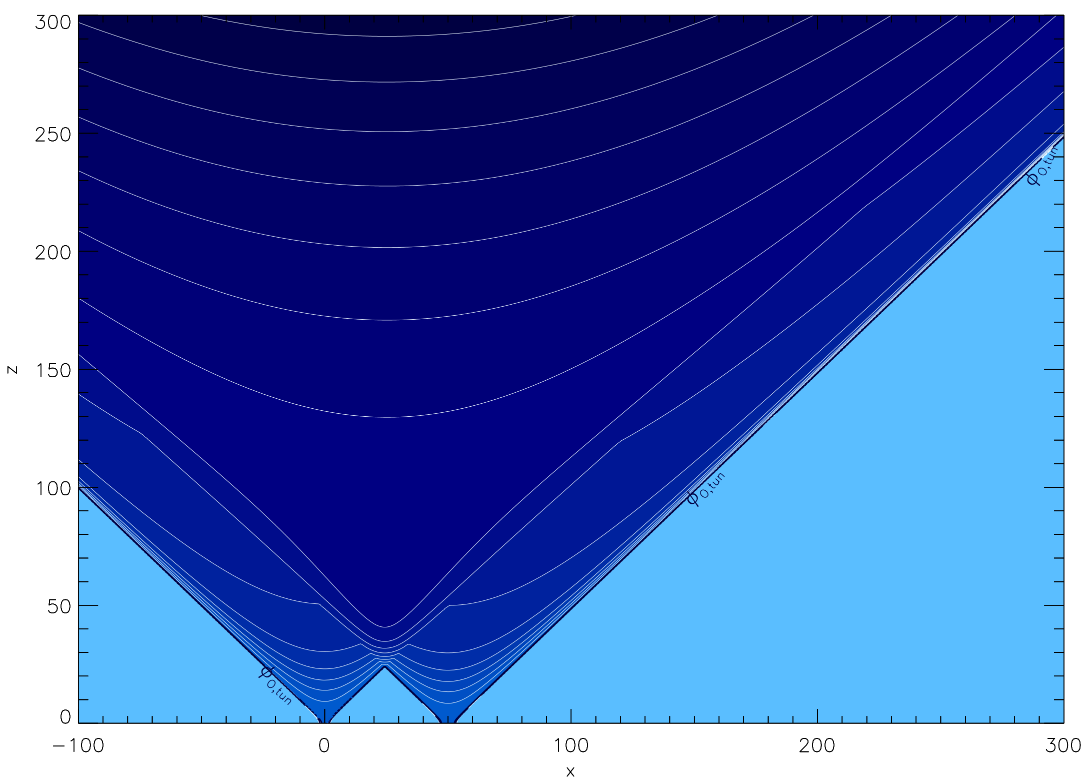




Coleman & DeLuccia 1980

Infinite uniform spaces inside bubbles that collide

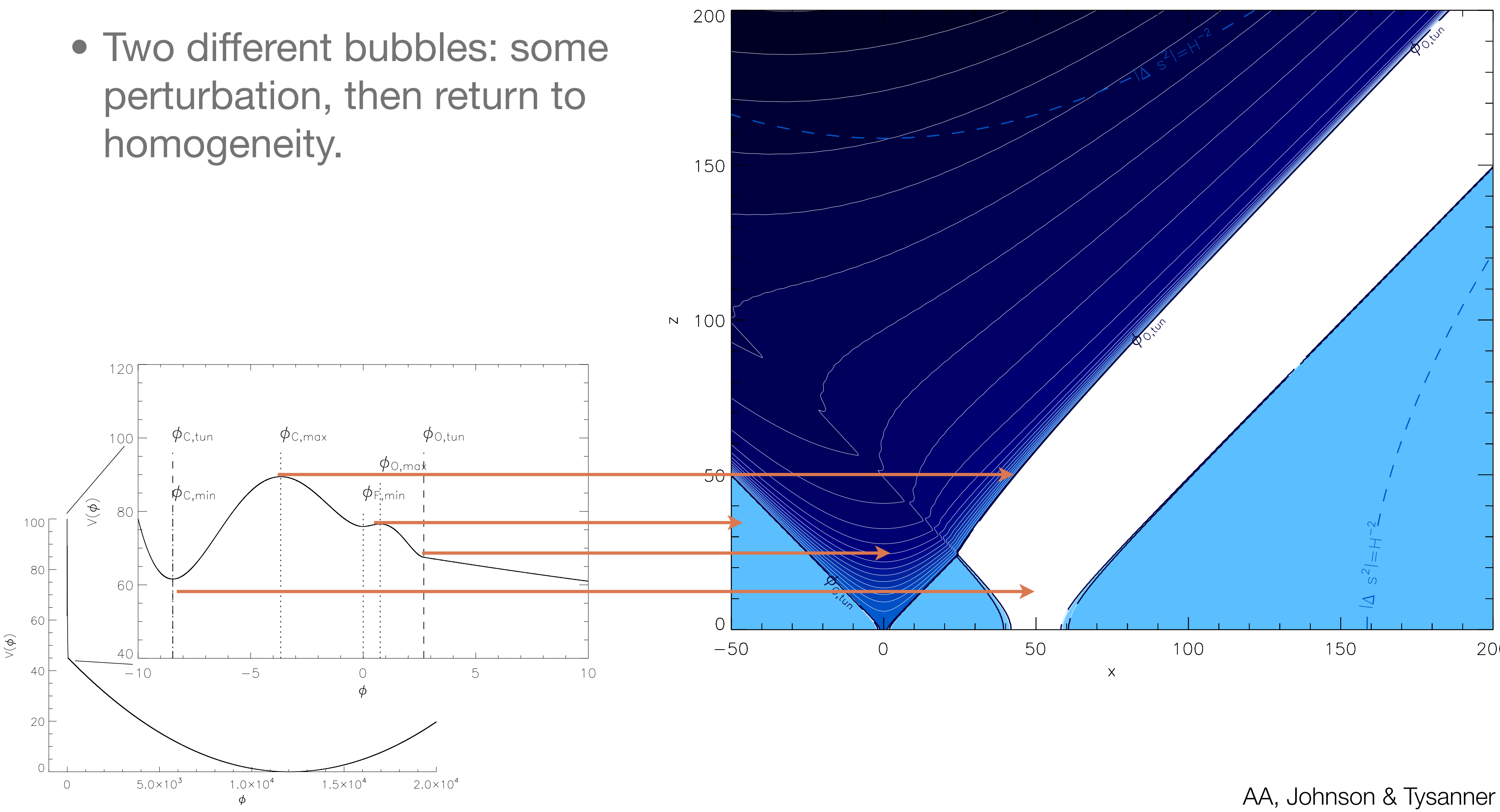
- Bubble self-collisions: merge into homogeneous slices (const. field lines are hyperbolas)



AA, Johnson & Tysanner 08

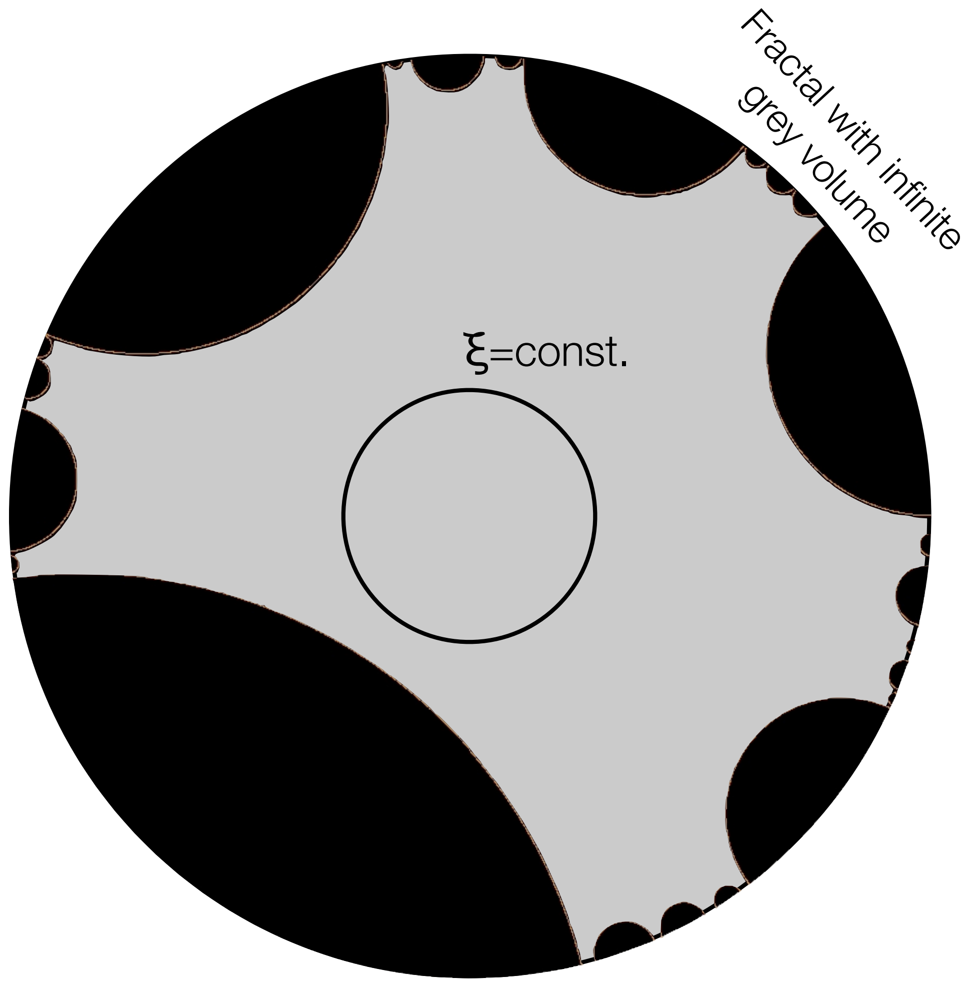
Infinite uniform spaces inside bubbles that collide

- Two different bubbles: some perturbation, then return to homogeneity.



AA, Johnson & Tysanner 08

Infinite uniform spaces inside bubbles that collide

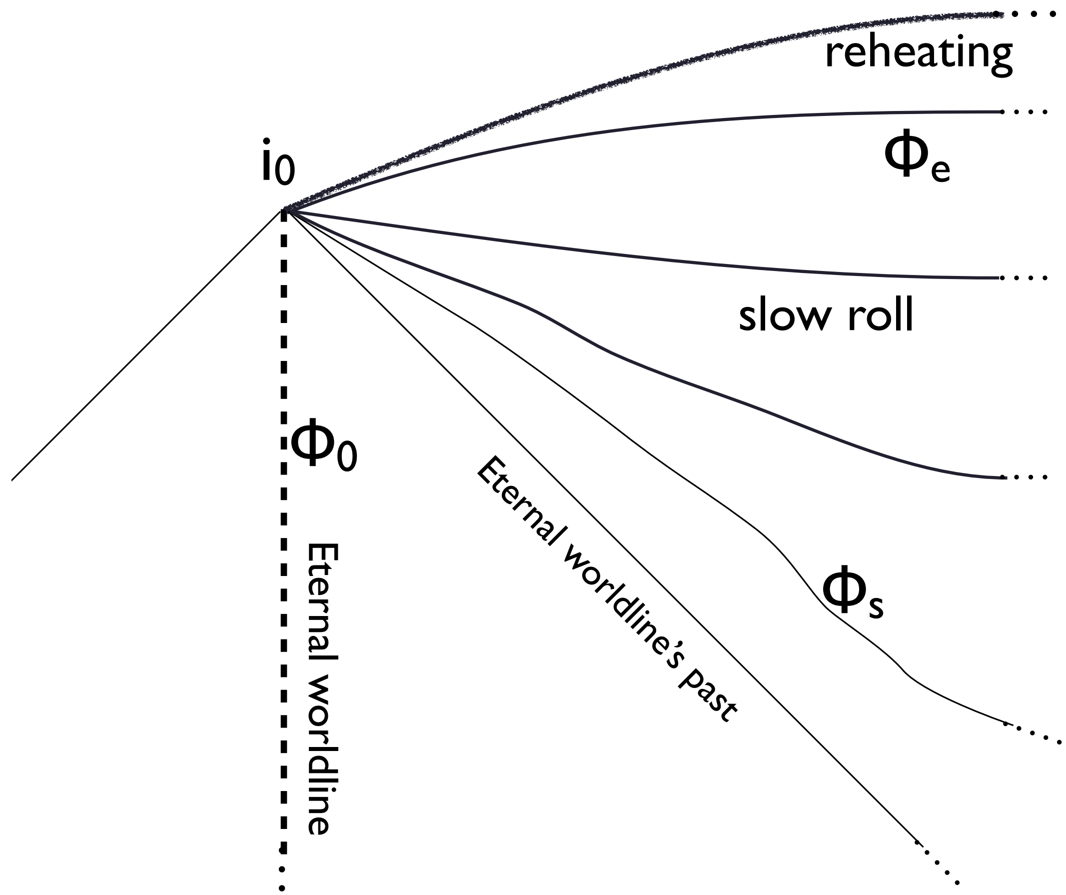


Poincare disk

Constant-field surfaces in other eternal models

- Open, topological, stochastic eternal inflation have same conformal structure.

- Note that this is true even if the ‘initial’ configuration of the universe is a closed universe.



Global structure of (everlasting) inflation.

- Observational and theoretical cosmology strongly suggests inflation*
- Inflation is ‘generically’ everlasting (or ‘future eternal’).
- The structure of eternal inflation can in some sense be thought of as an eternally inflating ‘background’ of some phase within which ‘pockets’ or ‘bubbles’ of another phase form. (These pockets may then be the background for more pockets, etc.) The overall structure is fractal.
- Everlasting inflation implies:
    - Infinite spacetime
    - Infinite time in (infinitely many) some places
    - (Unboundedly many) infinite homogeneous spaces.

*Most significant rival is probably cyclic model, with many similar properties.

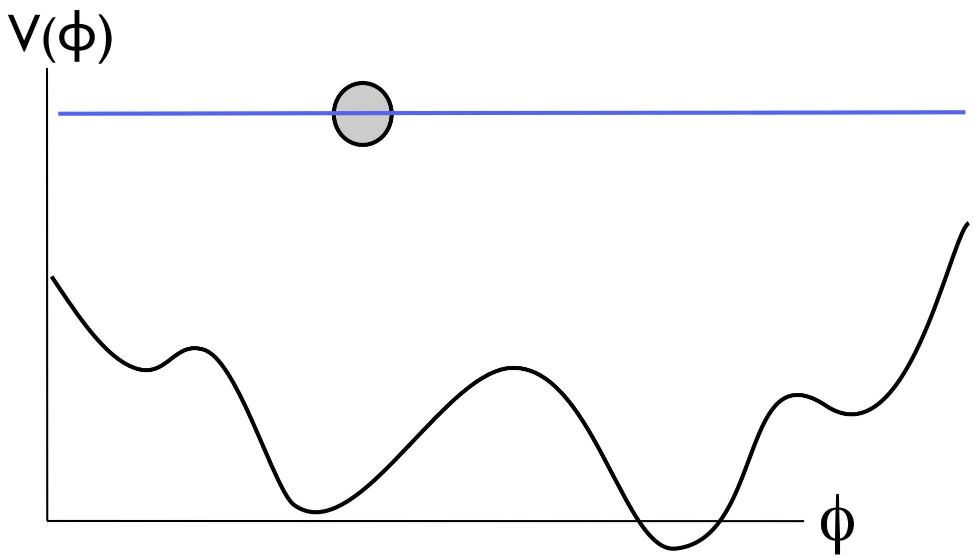
II. How does an inflationary phase start?

1. Easy: inflation from a high-energy, near-uniform background

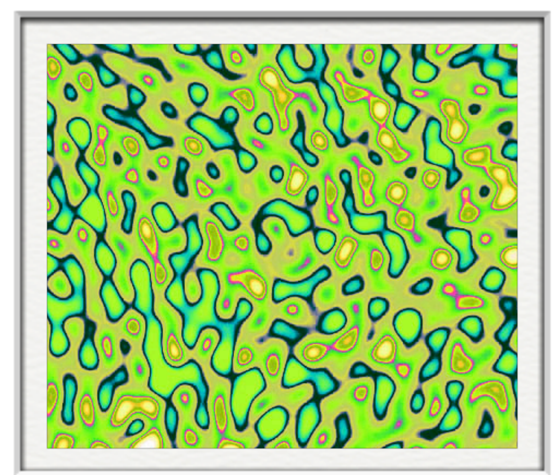
2. Understood: inflation from a higher-energy inflation phase

3. Hard: inflation from a lower-energy inflation phase

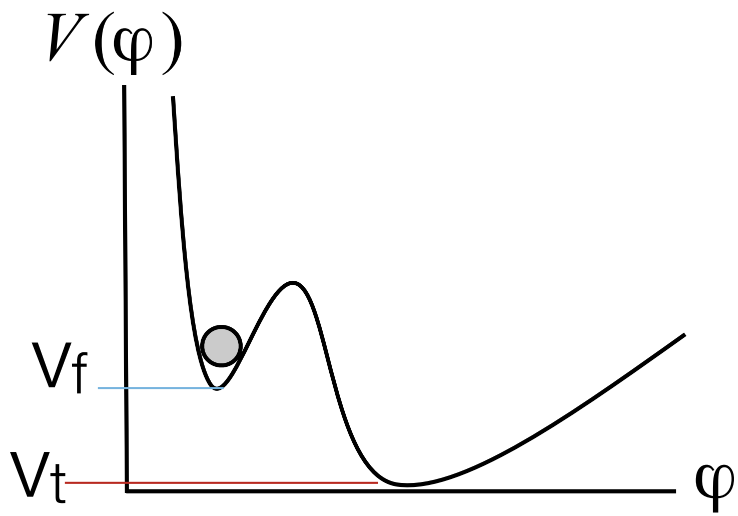
How does an inflationary phase start from a high-energy, near-uniform background?



Requirement: violate SEC →
Vacuum energy dominates over:
- thermal energy of other fields
- kinetic energy of inflaton
- ‘curvature’



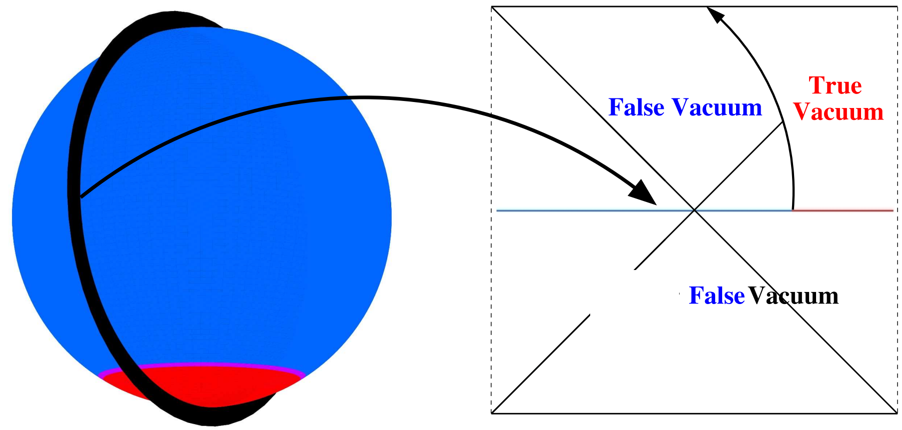
How does an inflationary phase start from a higher-energy vacuum phase?



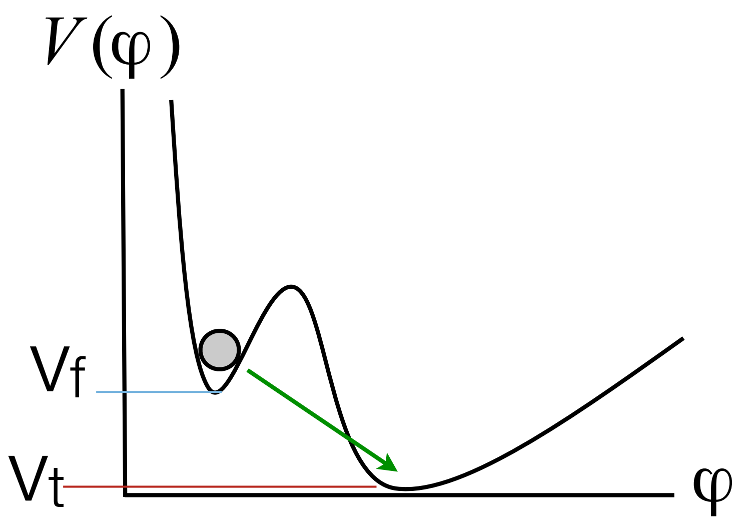
How does an inflationary phase start from a high-energy, near-uniform background?

Coleman-DeLuccia

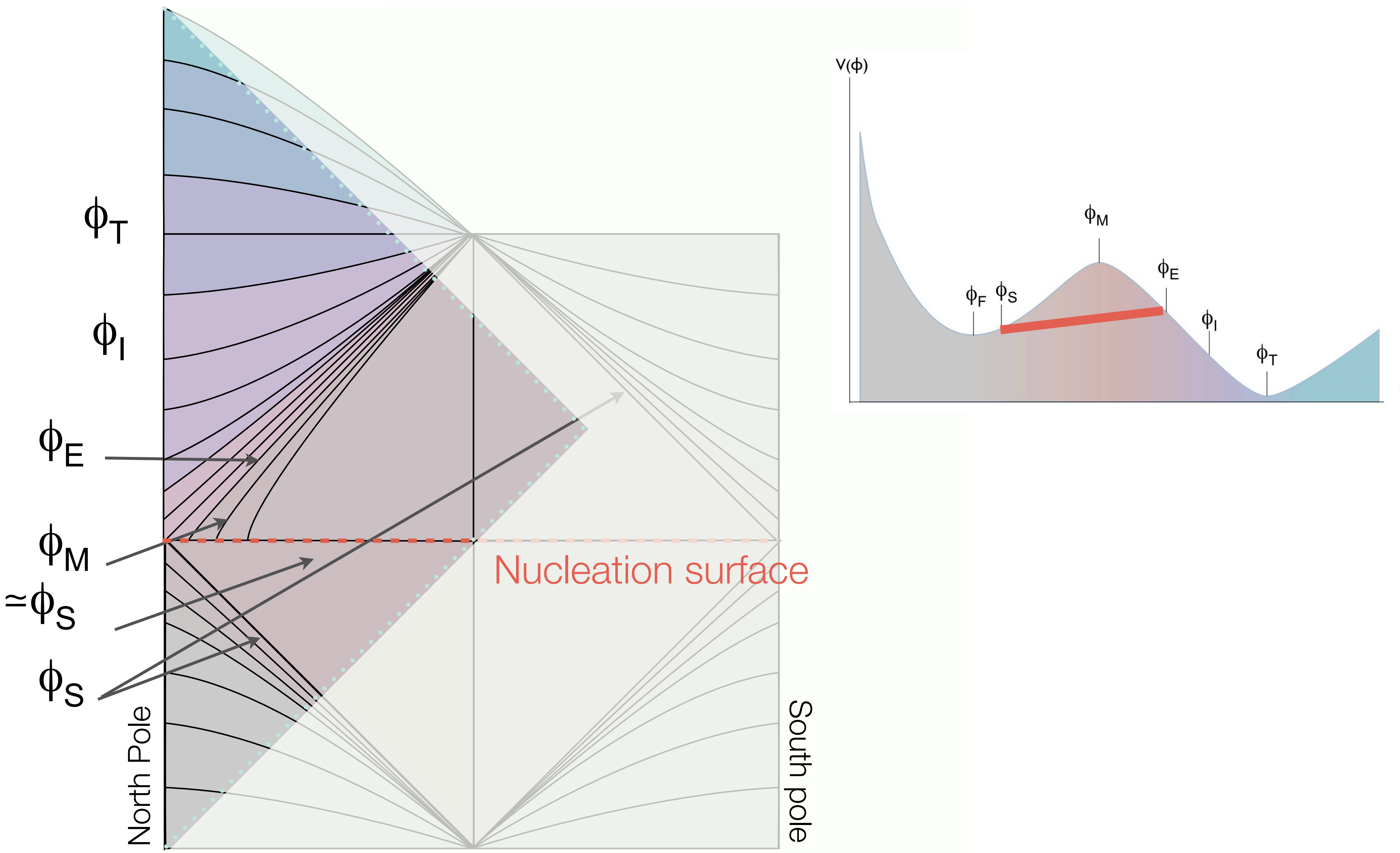
- False-vacuum dS background
- Small true vacuum bubble nucleates and expands



Coleman & De Luccia 80



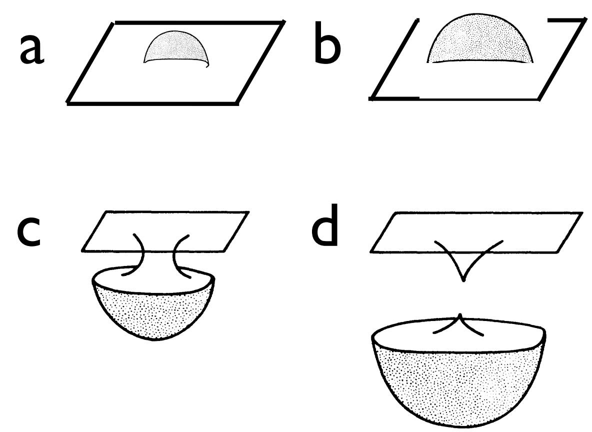
Coleman-DeLuccia tunneling



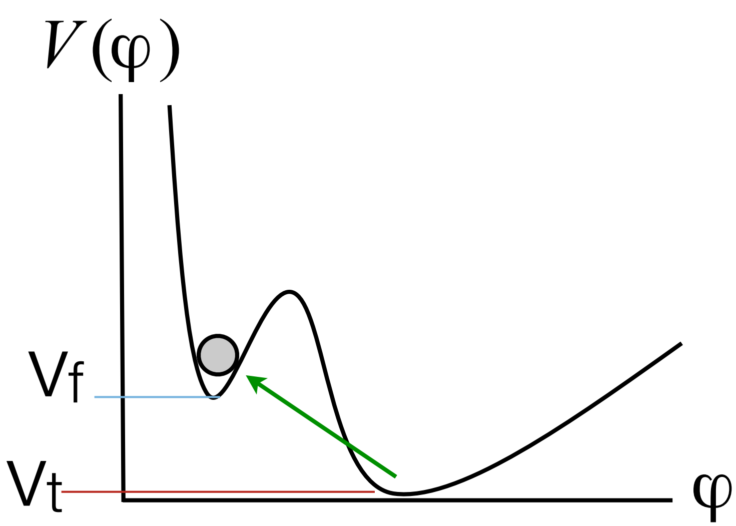
How does an inflationary phase start from a lower-energy vacuum phase?

I. Baby universe creation (a la Farhi, Guth & Guven)

- True-vacuum background
- Tiny bubbles of false vacuum nucleate.
- One tunnels through BH horizon, creating baby universe across Einstein-Rosen wormhole.



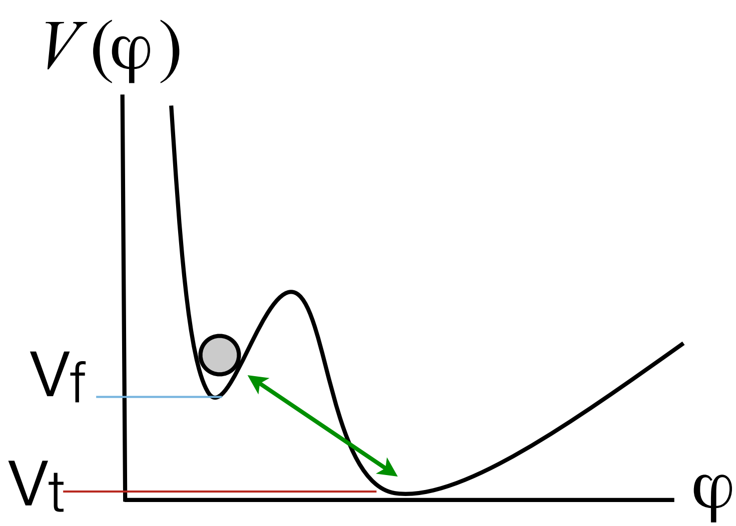
Farhi, Guth & Guven 90

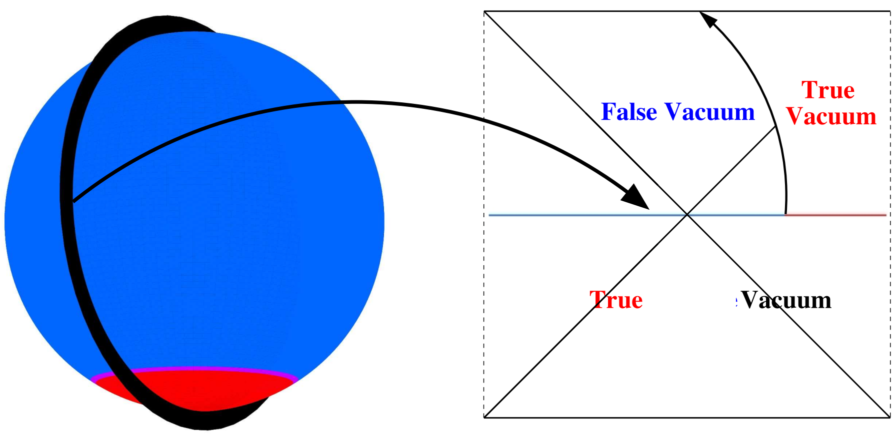


How does an inflationary phase start from a lower-energy vacuum phase?

II. “Reverse” Coleman-DeLuccia (Lee-Weinberg)

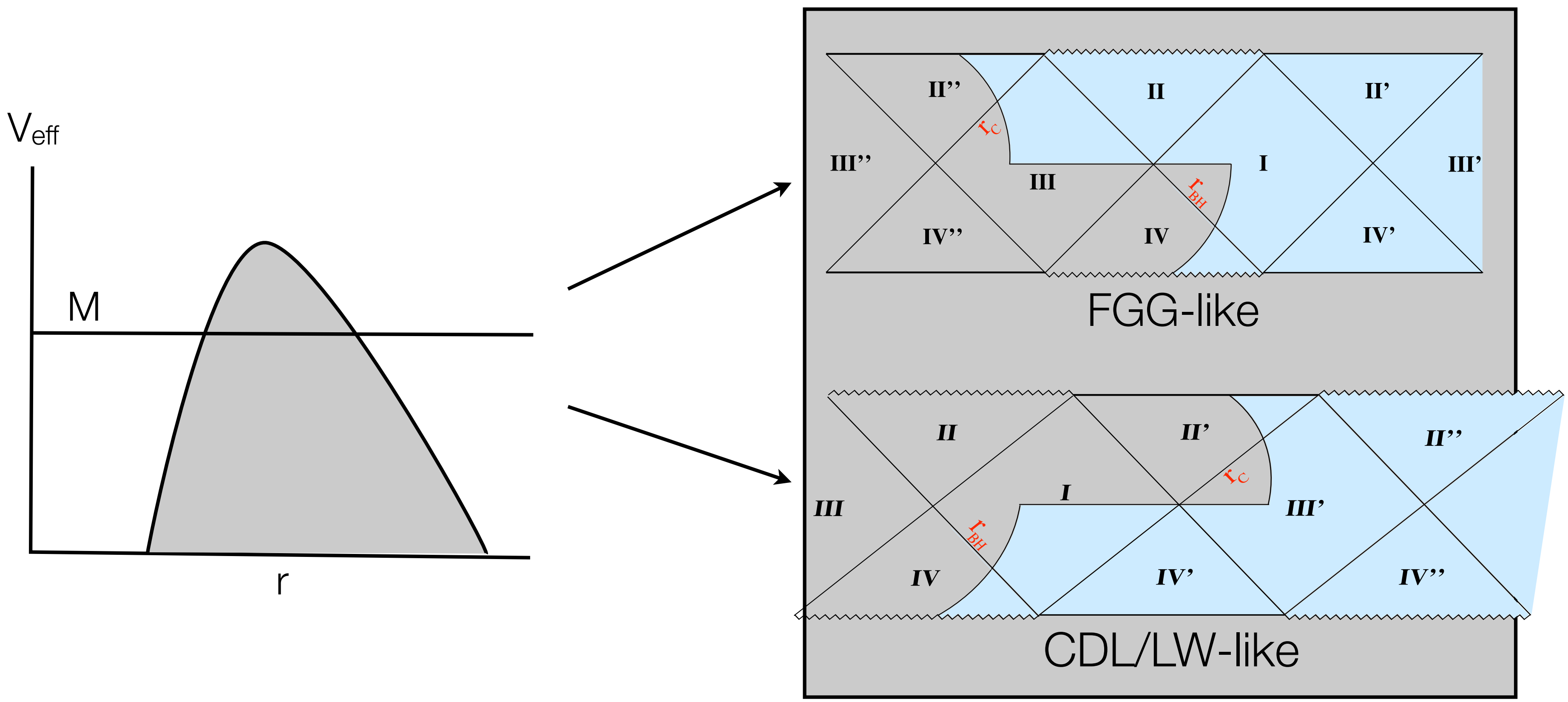
- True-vacuum dS background
- Enormous, **trans-horizon** bubble of false vacuum nucleates, vainly accelerates into false vacuum.





Lee & Weinberg 87

Two tunnels to inflation



(See AA & Johnson 06)

How does an inflationary phase start from a lower-energy vacuum phase?

II. “Reverse” Coleman-DeLuccia (Aguirre, Carroll, Johnson)

- Looks a lot like a downward fluctuation in entropy: P ~ $e^{-\Delta S}$
- Result (ACJ 2011): **Evolution* from equilibrium ☄ to a chosen macrostate A is☦ the time-reverse♆ of the evolution from A’s time reverse to equilibrium.♘**

* That is, the evolution of the probability distribution over macrostates.

☄ Or metastable equilibrium that is attained more quickly than, but does not decay more quickly than, the typical time it takes to fluctuate A.

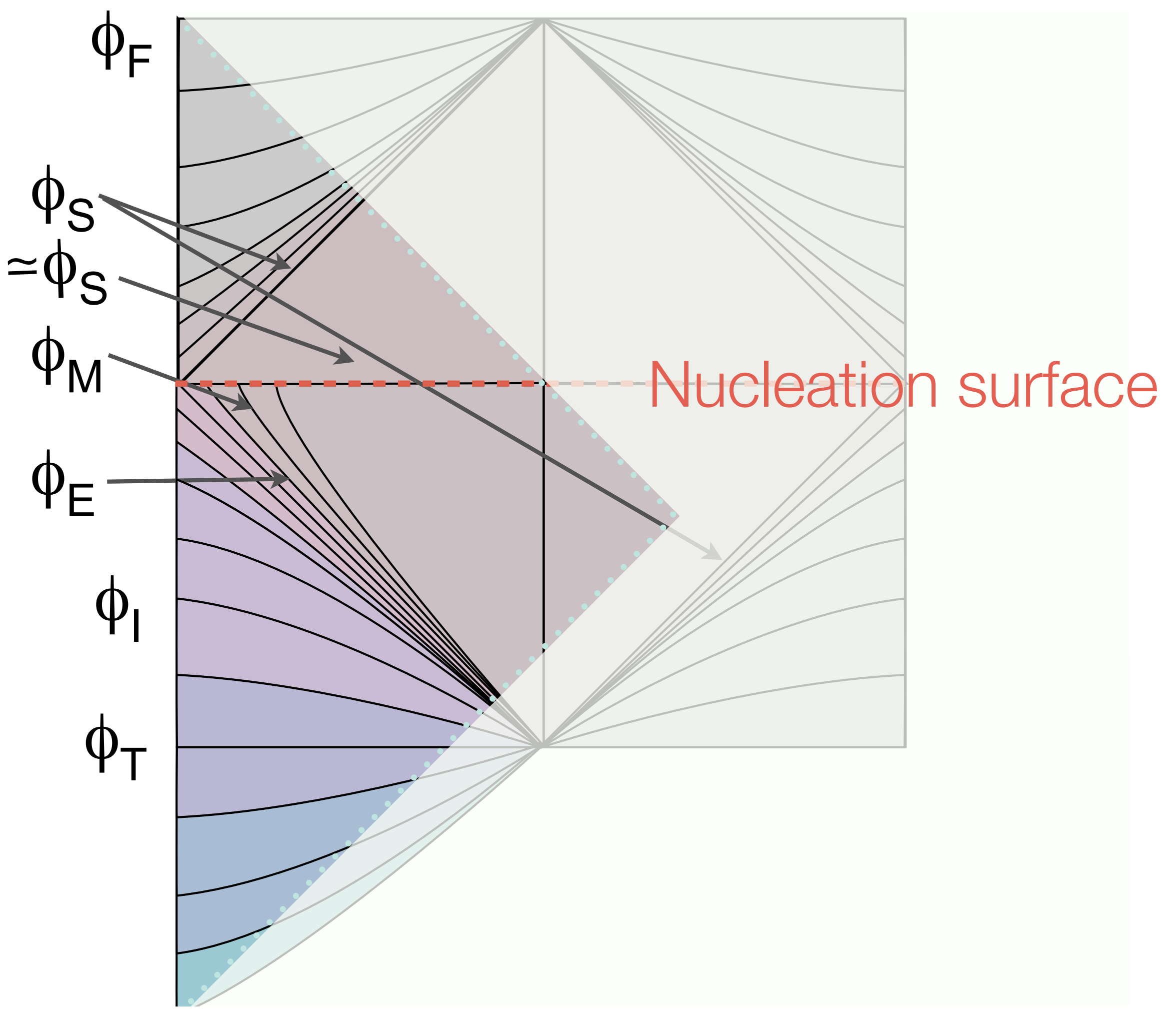
☦ Under assumptions of a unitary time evolution and democracy of microstates.

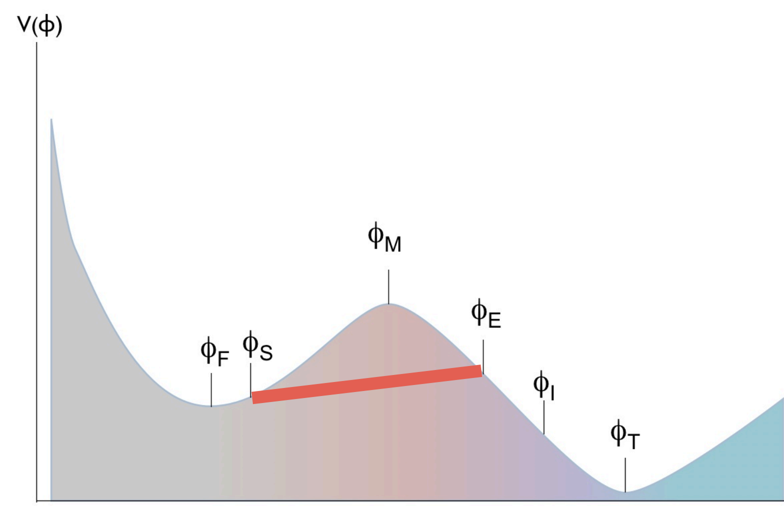
♆ Where this is the involution under which the theory is symmetric, and includes time-reversal.

♘ Even if it seems weird.

How does an inflationary phase start from a lower-energy vacuum phase?

II. “Reverse” Coleman-DeLuccia





III. Did inflation start?

Even in eternal inflation, it is often assumed that there is a singular, pre-inflation epoch. *Need there be?*

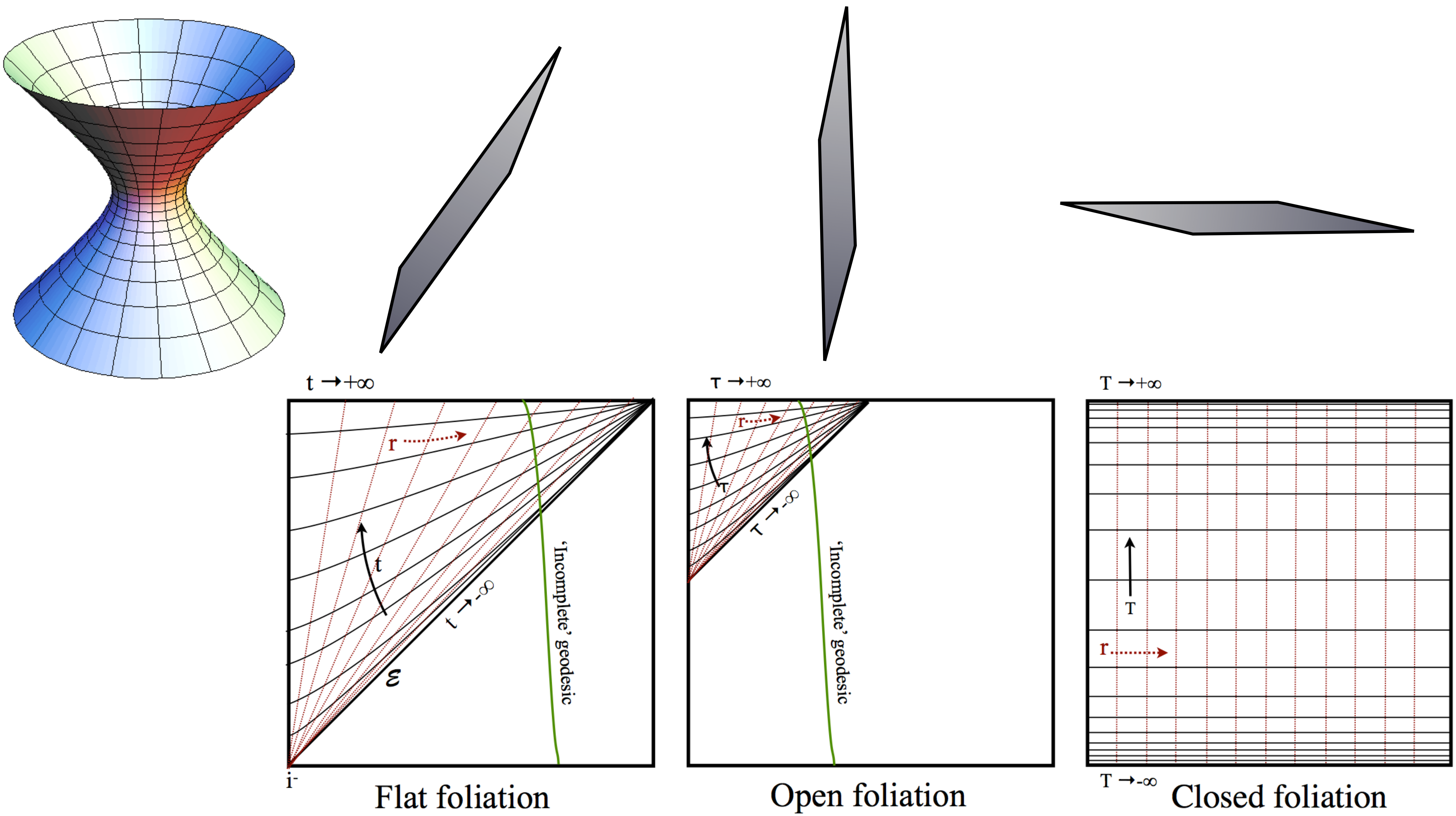
Key classic big-bang singularities theorems generally do not apply (assume Strong energy condition).

Several theorems proven that eternally inflating space-times must contain singularities (not all past null or timelike geodesics are complete):

- Requiring only conditions that ensure future-eternal inflation, and the weak energy condition (Borde & Vilenkin 1996).
- Requiring only that a certain "locally measured Hubble constant" $H > H_{\min} \geq 0$ (Borde, Guth & Vilenkin 2001).

Note: *singularity theorems indicate geodesic incompleteness of the spacetime region over which the theorem's assumptions hold.*

de Sitter space redux



Construct 1: Steady-State eternal inflation

Strategy: make state *approached* by semi-eternal inflation *exact*.

Steady-State eternal inflation

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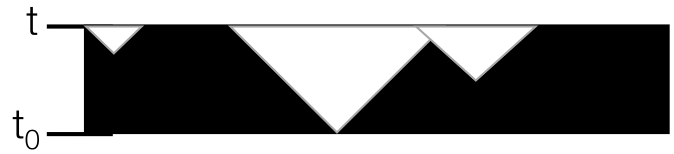
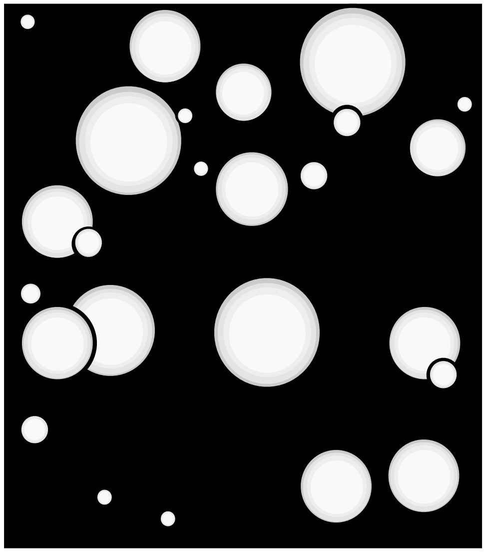
- Flat spatial sections.

Steady-State eternal inflation

Strategy: make state *approached* by semi-eternal inflation *exact*.



- Flat spatial sections.



- Consider bubbles formed between t_0 and t.

Steady-State eternal inflation

Strategy: make state *approached* by semi-eternal inflation *exact*.

- Flat spatial sections.
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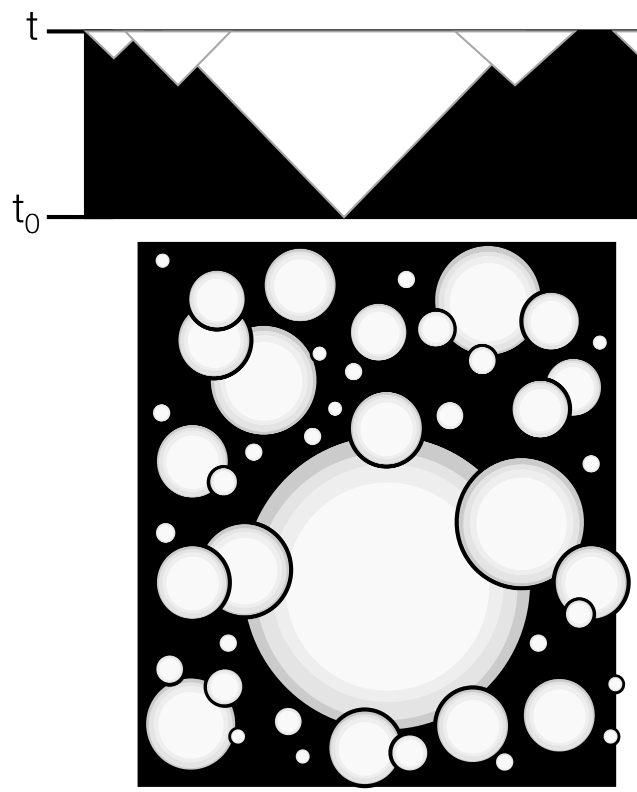
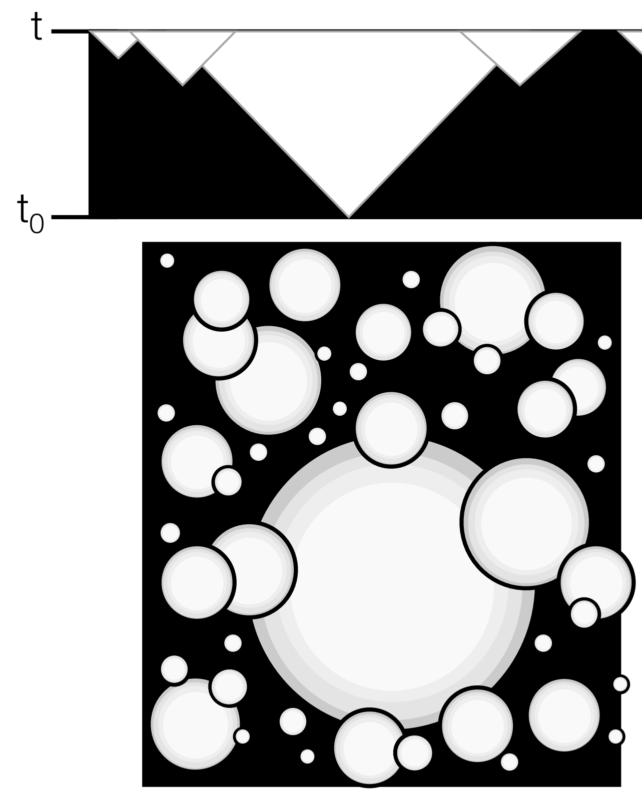


Steady-State eternal inflation

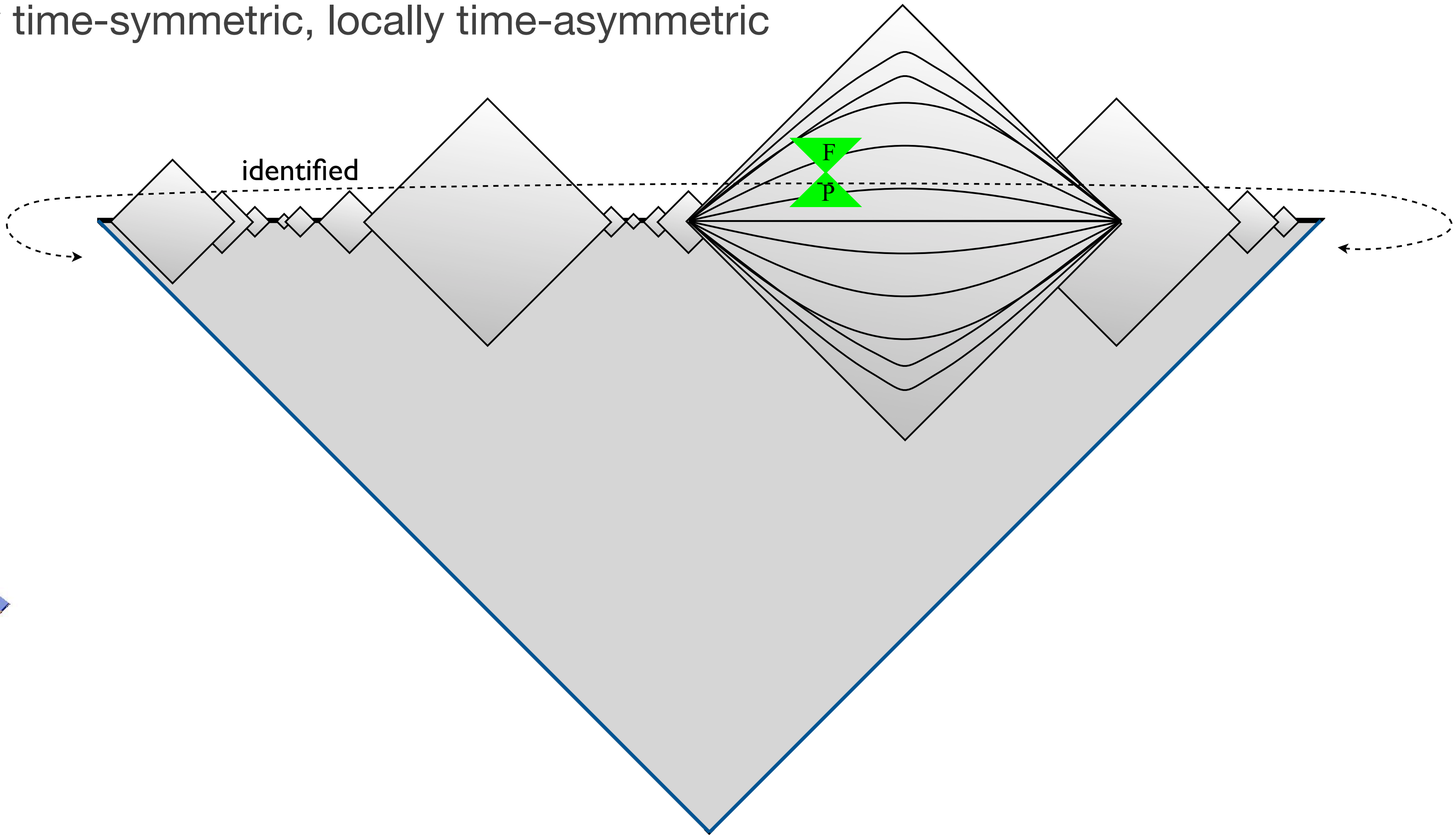
Strategy: make state *approached* by semi-eternal inflation *exact*.

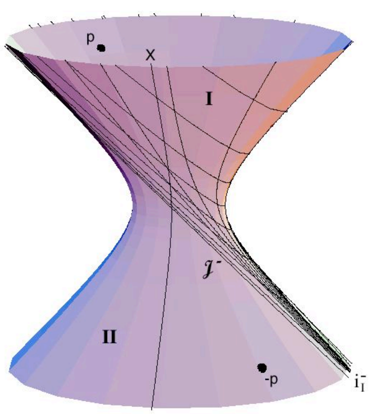


- Flat spatial sections.
- Consider bubbles formed between t_0 and t.
- Send $t_0 \rightarrow -\infty$.
- Inflation endures.

Steady-State eternal inflation

- Globally time-symmetric, locally time-asymmetric





AA & Gratton 02+03

Steady-State eternal inflation

There seems to be no basic problem (AA & Gratton 2002, 2003; also Vilenkin 13)

Like any theory describing a physical system, this model has:

a) Dynamics (stochastic bubble formation).

b) "Boundary" conditions. These can be posed as:

i) Inflaton field in false vacuum on an infinite null surface $\mathscr{I}^-$.

ii) Other (classical) fields are at minima on $\mathscr{I}^-$.

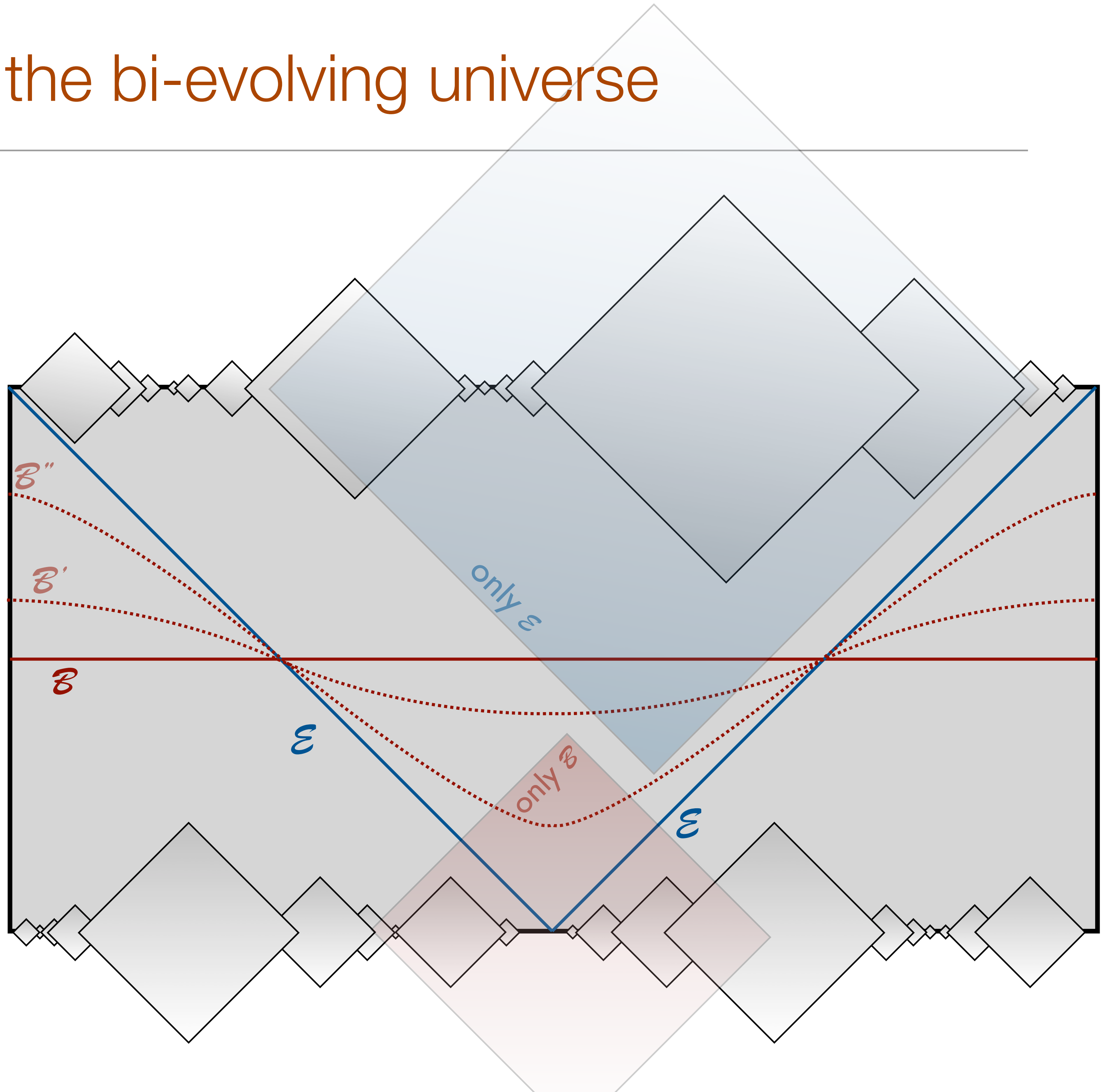
iii) Weyl curvature = 0 on $\mathscr{I}^-$.

Underlying symmetry principle: the "Perfect Cosmological Principle"

Construct 2: the bi-evolving universe

Version 1

- Low-entropy boundary condition surface B.
- Entropy increases away from this surface

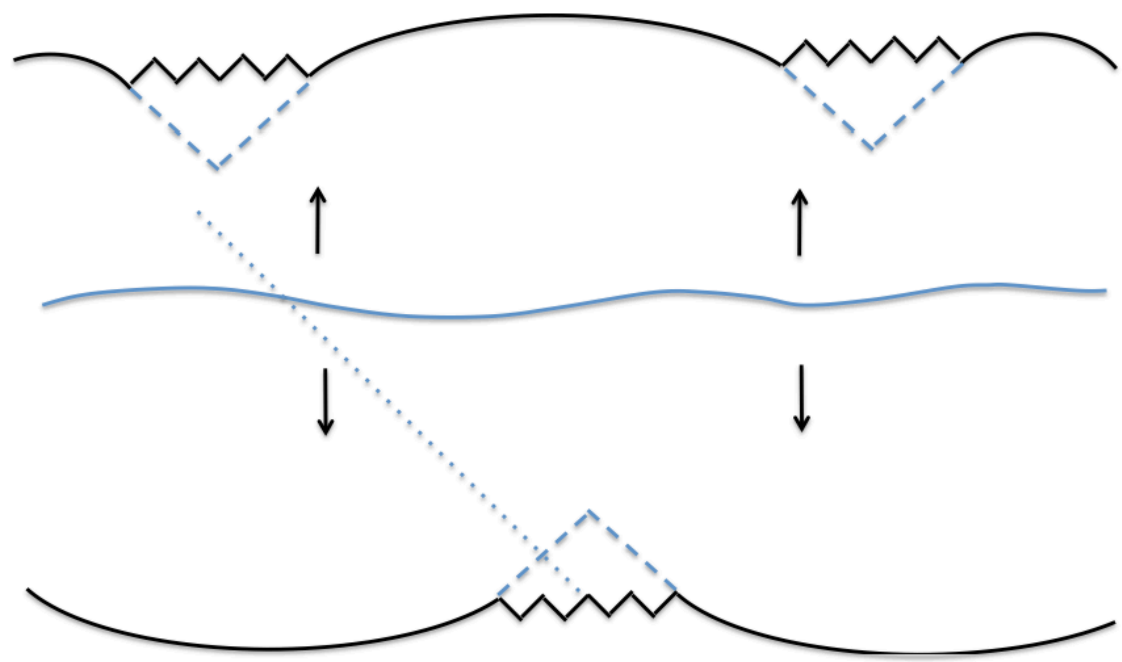


AA & Gratton 02+03
Carroll & Chen 04
AA 07

Construct 2: the bi-evolving universe

Version 2

- ‘generic’ condition on a spacelike surface.
- Entropy increases away from this surface.



Carroll & Chen 04
Carroll book

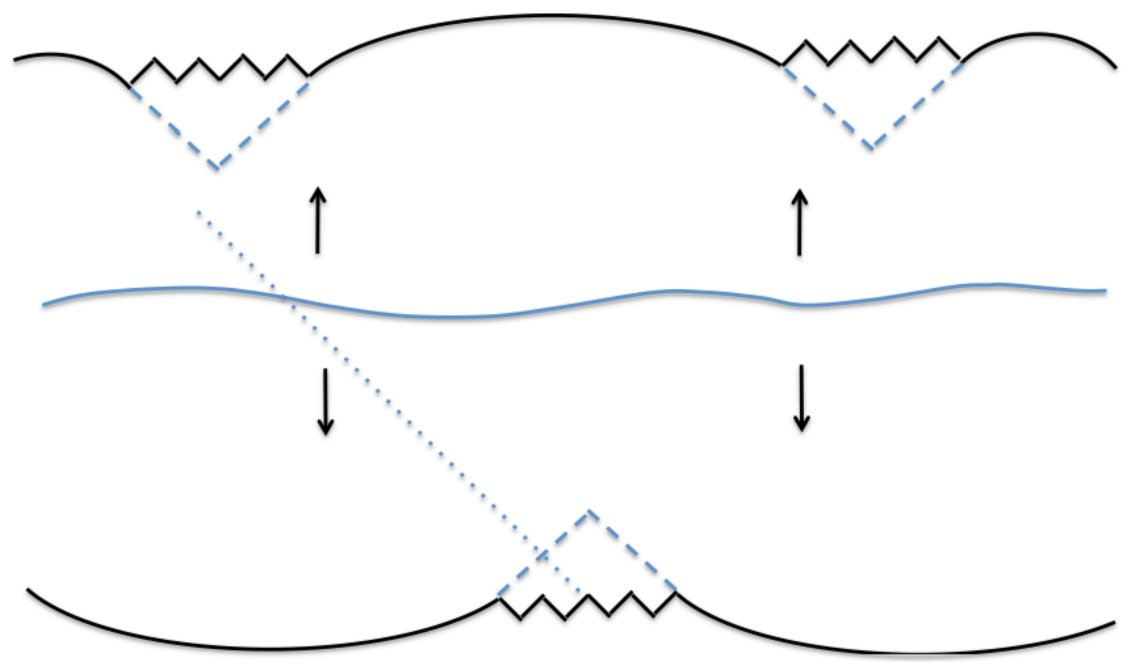
AA & Gratton 02+03

from Vilenkin ’13

Construct 2: the bi-evolving universe

Version 2

- How do higher-energy regions form?
    - 2a: Baby universes
    - 2b: Fluctuations



from Vilenkin ’13

Some Open Questions

- Where does the inflationary potential come from?
  - Model-building
  - String theory landscape (Aguirre; Susskind?)
- How can we test everlasting inflation, (Johnson?) and/or do cosmology in everlasting inflation? (Aguirre)
- How exactly do we think of the arrow of time, and ‘past hypothesis’? (Carroll)
- What do we make of the infinities? (Aguirre)