Populating the Landscape with Eternal Inflation: Causal Patch Description

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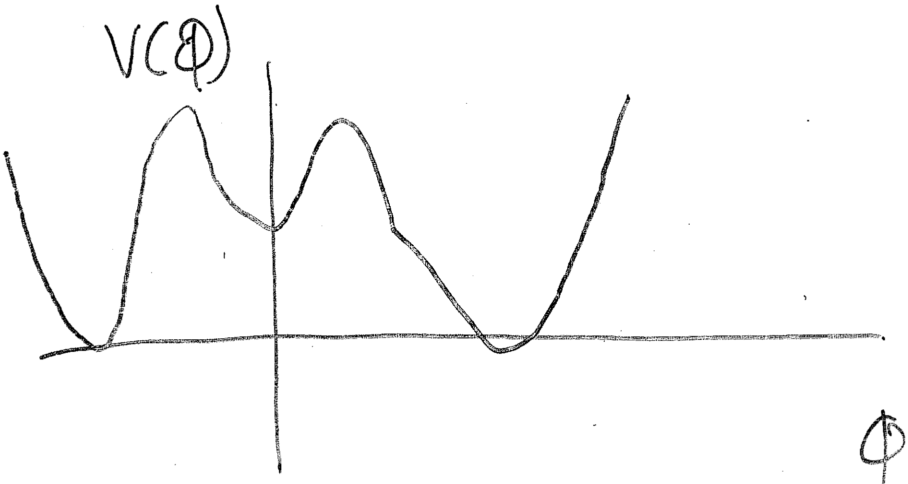
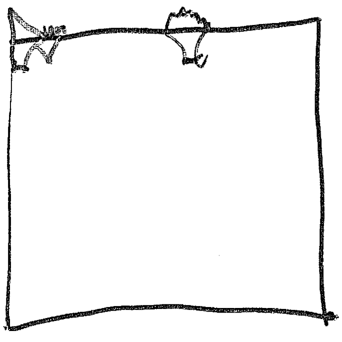
Importance of Eternal Inflation

We have no good theory of initial conditions, but believe some regions of space enter eternally inflating phase.

Simplest Example: False Vacuum Eternal Inflation (FVEI)





Every observer escapes to true vacuum, but false vacuum is not consumed.

Eternally inflating regions produce infinite number of bubbles – populate landscape.
Therefore, studying the landscape is a physics problem.

Where on landscape are we likely to live?

- Near false vacuum with maximum Hubble constant?
- In dS with minimum Λ?
- Wherever God put us?

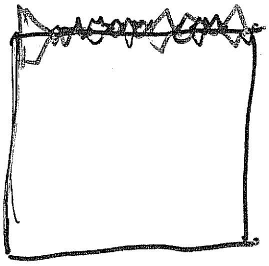
Until we have a probability distribution on the landscape, we ~~might~~ are stuck with the last answer.

Excellent work, & complete proposal by Vilenkin & collaborators:

Vanchurin & Vilenkin
Schwartz-Perlov & Vilenkin
+ Garriga, Winitzki

Why a new perspective?

- Different well-motivated slicings give different answers
- Confusing infinite volumes.

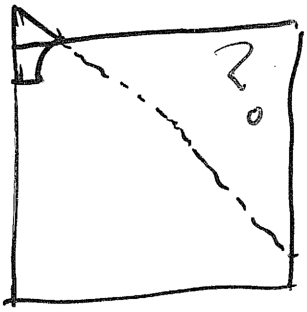


Reasons to Focus on One Causal Patch:

① Brainwashed by Bousso & Susskind

② Lessons from black hole physics

③ No unique semiclassical geometry–
causally inaccessible region described
by quantum superposition of geometries



What we hope to gain from causal patch description:

① Control over volume divergences

② Resolution of slicing ambiguities
(see Bousso)

③ String-Theory-friendly framework

Outline:

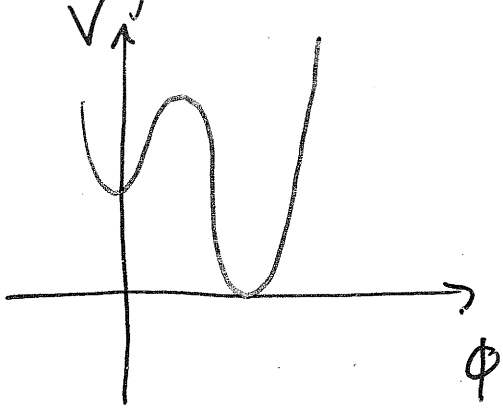
I. What can a single observer observe?

- A. False Vacuum Eternal Inflation (FVEI)
- B. Slow Roll Eternal Inflation (SREI)

II. Asyptotics of observer who exits FVEI to $\Lambda = 0$

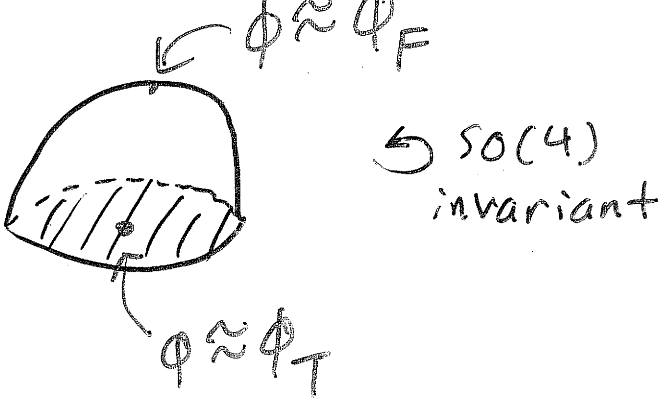
- A. Locally Minkowski - nice place to define "out" states
- B. Crazy idea! a CFT dual

Decay of Metastable False Vacuum

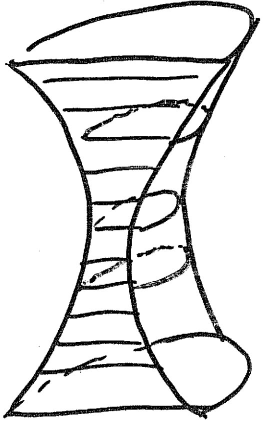


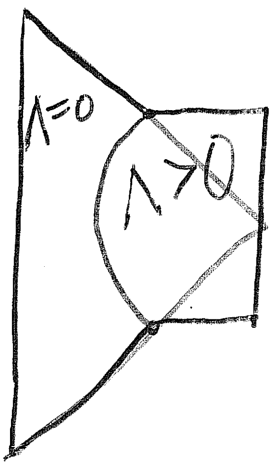
Coleman-de Luccia Instanton:

Euclidean Solution

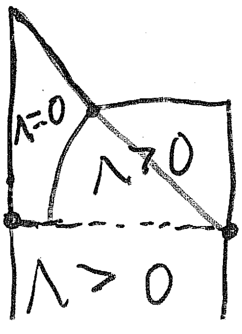


Lorentzian Solution "Bounce"

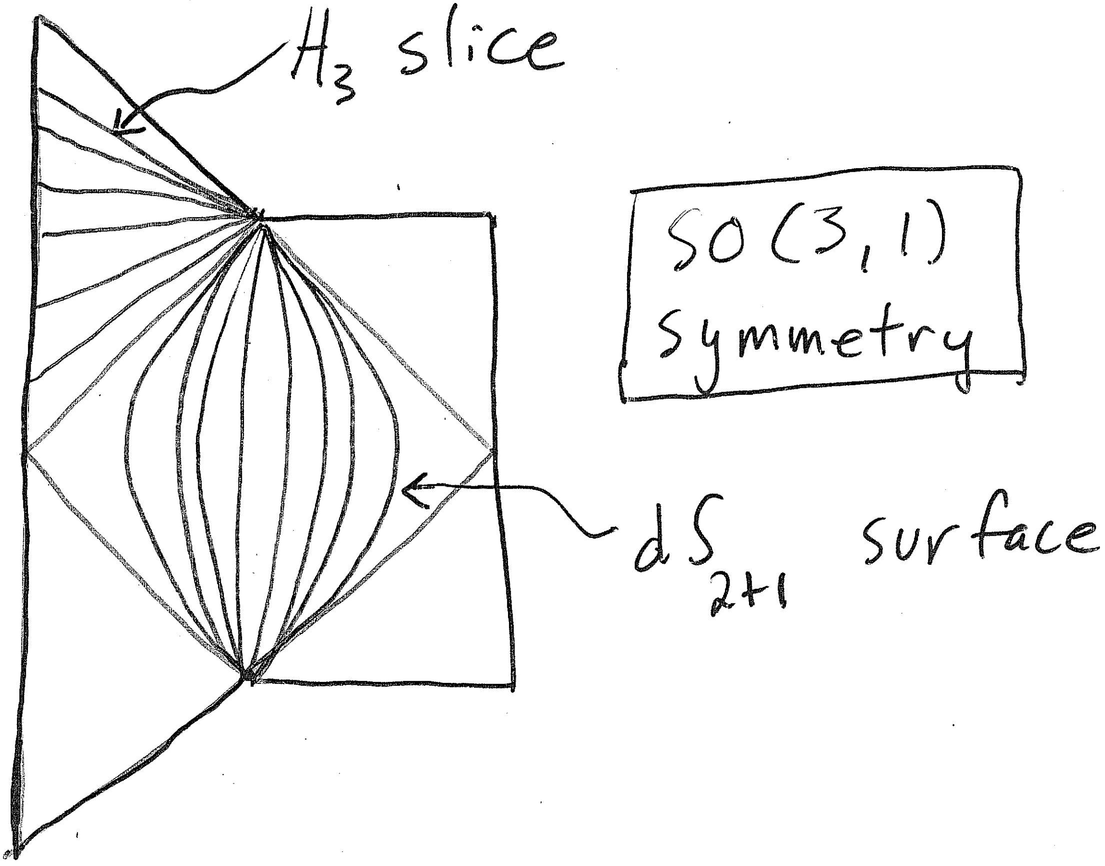




Tunneling "Solution"



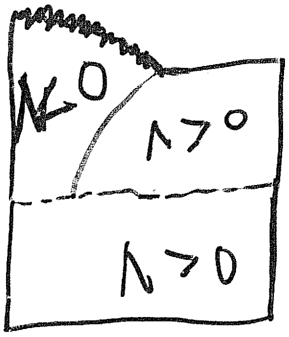
To examine late time behavior, focus on bounce solution



$\boxed{\text{SO(3,1) Symmetry}}$

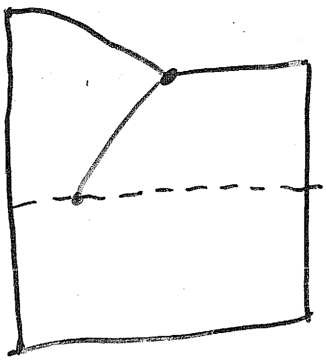
Open FRW universe
Curvature dominated at late time

Decay to $\Lambda < 0$: Crunch



Cosmological AdS →
Crunch in time ~ R_{AdS}

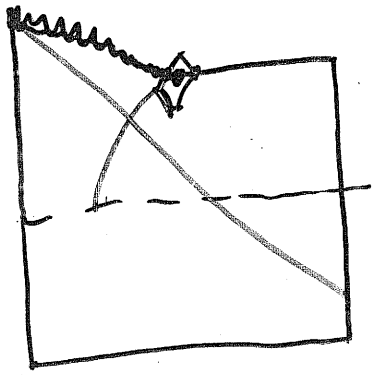
Decay to $\Lambda > 0$



<u>Correction!</u> True vacuum bubbles inevitably collide with an infinite number of other true vacuum bubbles.

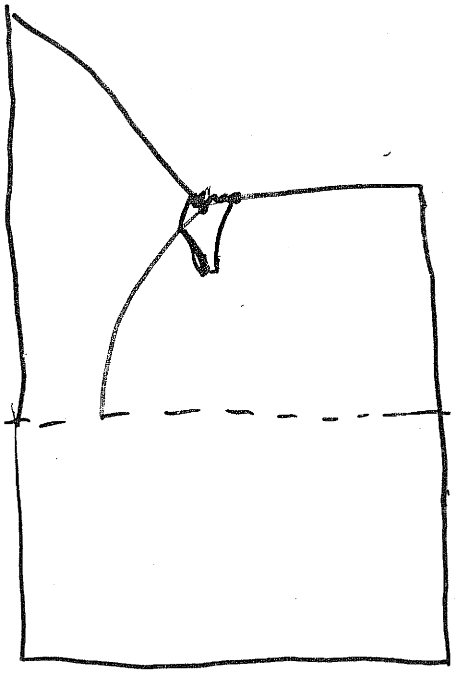
But rate is typically very small.

Observer who tunnels to $\Lambda < 0$ typically crunches before seeing collision.



However, observer who tunnels to $\Lambda = 0$ will see an infinite number of collisions in its backward lightcone.

(Guth & Weinberg)



The domain wall, before taking collisions into account, is

dS_{2+1}

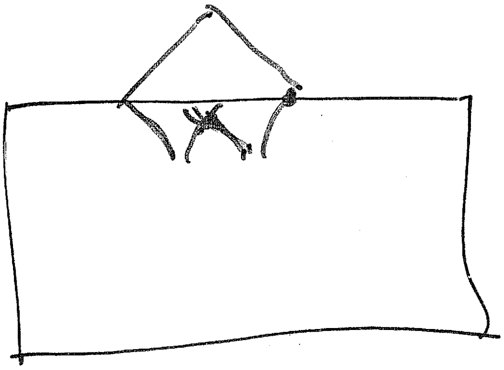
Any worldline along domain wall eventually collides,

but remaining volume of original domain wall continues to increase.

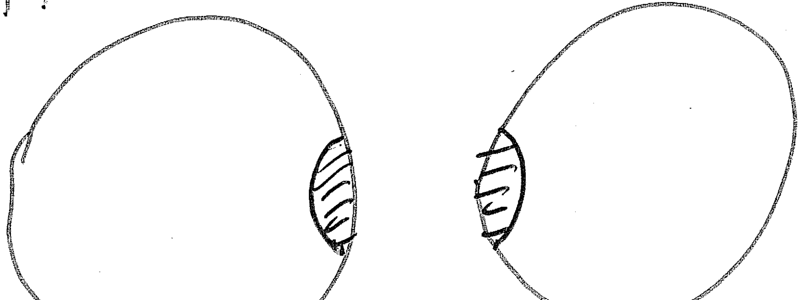
Bubble collisions do not destroy nice asymptotics of FRW.

<u>Ex.</u> Consider collision of 2 true vacuum bubbles.

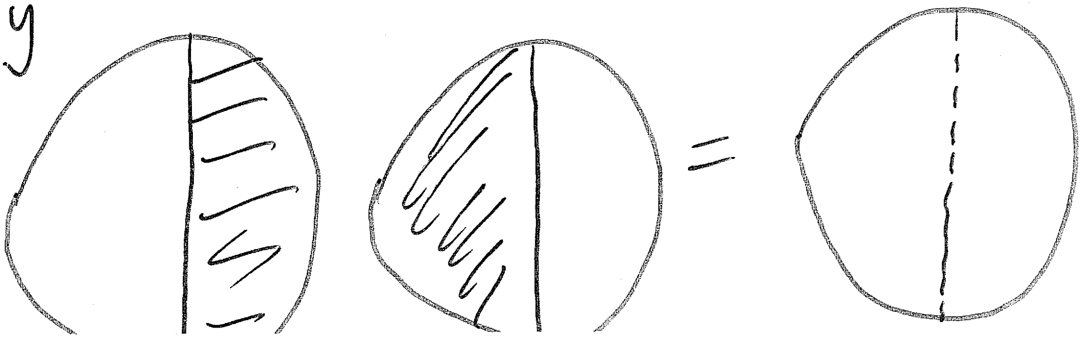
Assume that domain walls convert to dust upon collision.



At late time



Eventually



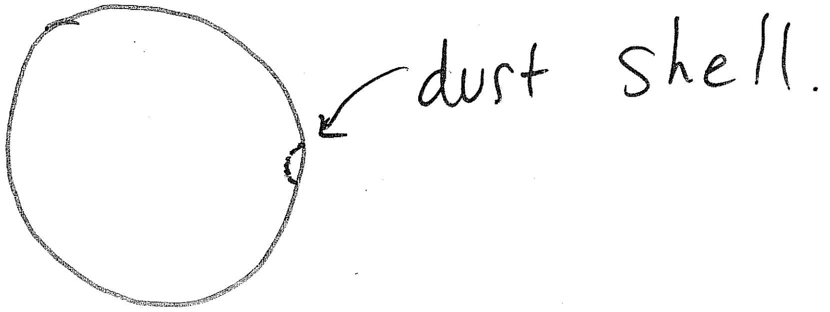
Intrinsic geometry of dust

$$ds^2 = -d\tau^2 + (\tau^2 - L^2)\, dH_2$$

another open FRW solution.

From point of view of observer at center of one bubble, the picture is a boost of the above:

Asymptotically,

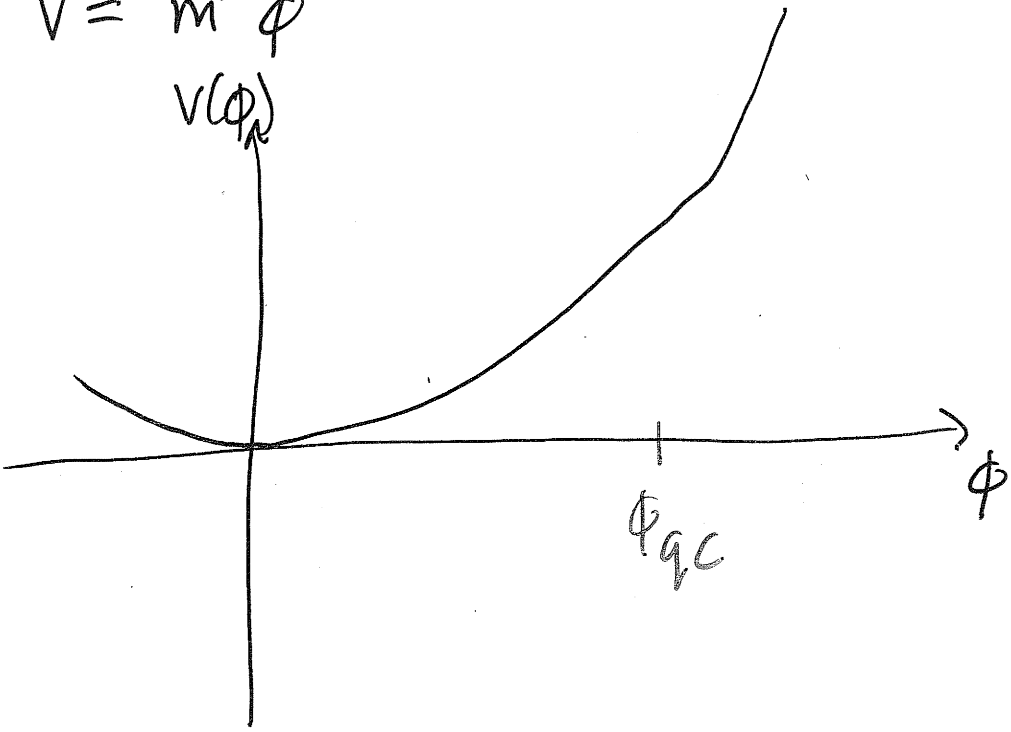


Additional collisions happen even later, so are even more boosted away.

Slow Roll Eternal Inflation

(Linde, ...)

Ex. $V = m^2 \phi^2$



Test for Eternal Inflation:

Begin with $\phi = \phi_0$ everywhere.

Evolve one efolding during which

- 1 Hubble volume → e^3 Hubble volumes
- Classical evolution $\delta_c \phi \sim \dot{\phi} H^{-1} \sim \frac{M_p^2 H'}{H}$
- Quantum fluctuations $\delta_q \phi \sim H$

Quantum fluctuation is uncorrelated.

Inflation is eternal if at least one of the e^3 Hubble volumes fluctuates up

$$\frac{M_p^2 H'}{H^2} < O(1)$$

For $V = m^2 \phi^2$, eternal for

$$\phi > M_p \sqrt{\frac{M_p}{m}}$$

Just like FVEI, any observer eventually escapes EI, but globally EI does not end.

Also like FVEI, true vacuum tries to eat up false vacuum.

Typical Observer's Experience

① Exit SREI in polynomial time. (vs exponential time for FVEI)

After N efoldings, classical roll

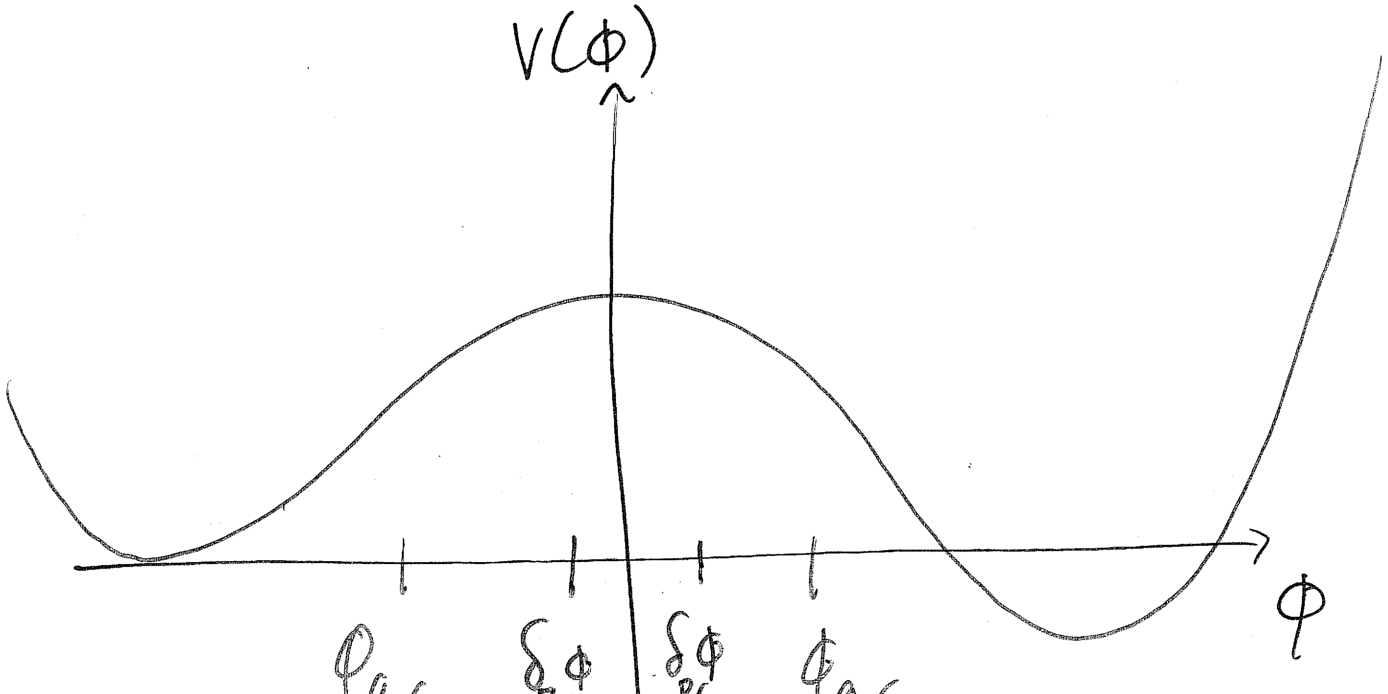
$$\delta_c \phi \sim (\dot{\phi} H^{-1}) N \sim \frac{M_p^2 H'}{H} N$$

Typical quantum fluctuation

$$\delta_q \phi \sim H\sqrt{N}$$

Classical evolution wins after $N = \left(\frac{H^2}{H' M_p^2}\right)^2$ efoldings

Before classical evolution wins, inflaton typically travels a distance $\delta_{BC}\phi \sim H \dfrac{H^2}{H' M_p^2}$



Typical observer knows which vacuum to evolve to unless starting point is within $\delta_{BC}\phi$ of maximum.

② Exit is a non-event:
smooth transition to ordinary
slow roll.

vs. Exit is dramatic in
FVEI: Hit by very
energetic bubble

③ Observer who exits to $\Lambda = 0$ is not as happy - <u>gravitational collapse</u>. (vs open expanding FRW from FVEI)

In linear theory, curvature perturbations are given by

$$P_R^{1/2}(k) = \frac{H_*^2}{H_*' M_P^2}$$

Starred quantities evaluated at horizon exit.

Once observer lives long enough to see modes which exited at quantum-classical transition,

$$P_R(k) = 1.$$

$\Omega - 1 \sim 1$

Collapse in time~ horizon size, if $\Omega > 1$.

If negatively curved, wait to see the next efolding.

SREI is more similar to FVEI than you might think:

Typical observer does not experience chaotic geometry.

Compute change in horizon area during quantum domination

$$A = H^{-2}$$

$$\delta A = H^{-3}\delta H = H^{-3} H'(\delta_{BC}\phi)$$

$$\boxed{\delta A = \frac{1}{M_p^2}}$$

$$\delta S \leq 1$$

Summary: Local description of Eternal Inflation

In both SREI & FVEI,

- Much of global geometry is unobservable
- Any worldline eventually exits the eternal phase
- Observers who exit to $\Lambda < 0$ are crunched
- Local description does not seem to care much about unusual observers who spend a long time in EI phase, while global picture tends to be dominated by them.

Differences

- For exit to $\Lambda = 0$, FVEI → open expanding FRW
  SREI → collapse on all scales

- Exit is non-event in SREI vs. dramatic event in FVEI

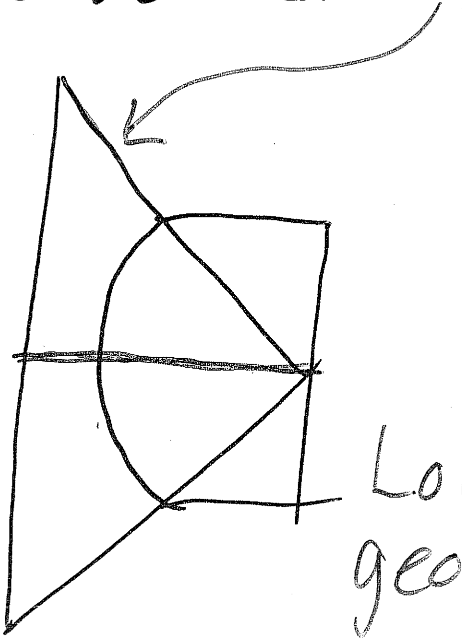
- Typical observer spends a polynomial amount of time in SREI vs exponential time in FVEI

- Typical SREI observer does not experience strong gravitational perturbations until long after exit from eternal inflation.

Use nice FRW asymptotics of observer who exits FVEI to $\Lambda=0$?

Asymptotically non-interacting particles.

S-matrix type object can be defined here?



Lower part of geometry is unphysical.

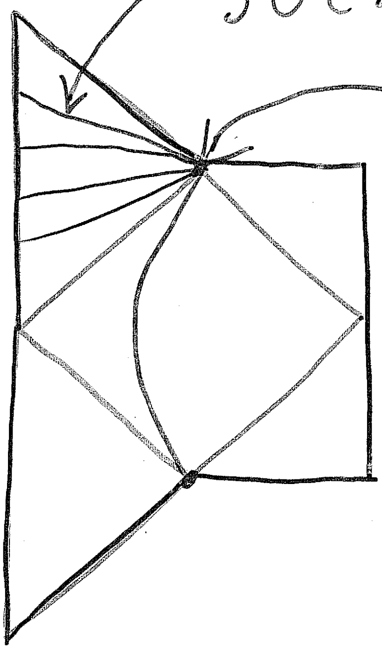
Other work on dual CFTs

Silverstein, Alishahiha, Karch, Tong

de Boer & Solodukhin

etc.

A CFT Dual?



SO(3, 1) symmetry on $EAdS_3$

conformal boundary S_2

SO(3, 1) acts as conformal group on boundary S_2.

But is it a CFT?

Compute $\langle h_\mu{}^\nu h_\rho{}^\sigma \rangle$ in bulk and take the limit as the points approach the boundary.

If there is a dual CFT,

$$h_\mu{}^\nu \Longleftrightarrow T_\mu{}^\nu$$

$$[T_{\mu\nu}] = 2 \qquad \partial^\mu T_{\mu\nu} = 0$$

Will find: Things are better ~~thatt~~ than one would expect, but not as clear as they might be.

Compute massless minimally coupled scalar correlator, which has all the interesting properties.

Method: Garriga, Montes, Sasaki, Tanaka '98

Turok, Hawking, Hertog, Gratton '98-'99

Compute in Thin Wall Approx.

$\langle \phi \phi \rangle = G(T_1, T_2, \ell)$

$ds^2 = e^{2T}(-dT^2 + dH_3^2)$

ℓ is geodesic distance on H_3

Take $\ell + T \to \infty$

$\ell - T$ large

Let $\bar{T} = T_1 + T_2$; $\delta T = T_1 - T_2$

Find.

$$G = \underset{\substack{\uparrow \\ \text{usual flat space} \\ \text{piece}}}{G_0(\delta T, \ell)} + \underset{\substack{\uparrow \\ \text{good}}}{G_1(\bar{T}, \ell)} + \underset{\substack{\uparrow \\ \text{interesting}}}{G_2(\bar{T}, \ell)}$$

$$G_1 = \sum_{\Delta=3}^{\infty} c_\Delta \left(\frac{e^{-(\Delta-1)\ell}}{\sinh \ell} \right) e^{(\Delta-2)\bar{T}}$$

$\uparrow$

correlation function for field of mass $m^2 = \Delta(\Delta-2)$ in AdS_3 $\rightsquigarrow$ boundary field with dimension Δ.

$$G_2 = \underbrace{a \left(\frac{e^{\ell}}{\sinh \ell} \right) (\ell + \bar{T})}_{\text{Leading term}} + \underbrace{b \left(\frac{e^{-\ell}}{\sinh \ell} \right)}_{\substack{\text{Dimension} \\ \Delta = 2}}$$

Since massless field has shift symmetry $\phi \to \phi + c$, physical quantities are $\partial \phi$.

Interpret leading term:

in Poincare coordinates, asymptotically

$$a\left(\bar{T} + \log \frac{(\Delta\vec{x})^2}{z_1 z_2}\right)$$

with $ds^2 = \frac{1}{z^2}(dz^2 + d\vec{x}^2)$ the metric on H_3.

$\bar{T}$ is "pure gauge," as is

$$\log(z_1 z_2) = \log(z_1) + \log(z_2).$$

So the physical leading behavior is $a \log(\Delta\vec{x})^2$ independent of z, the displacement from the boundary.

Bulk interpretation:

fluctuations do not die off at infinity

"Supercurvature" mode

Boundary interpretation:

massless scalar

For graviton, our real interest, all of the same features are present.

Bulk interpretation:

same as above; additionally, boundary S_2 is deformed.

Boundary interpretation:

metric fluctuates →

Liouville field

Unclear how to extract subleading behavior.

Why such big fluctuations at infinity?

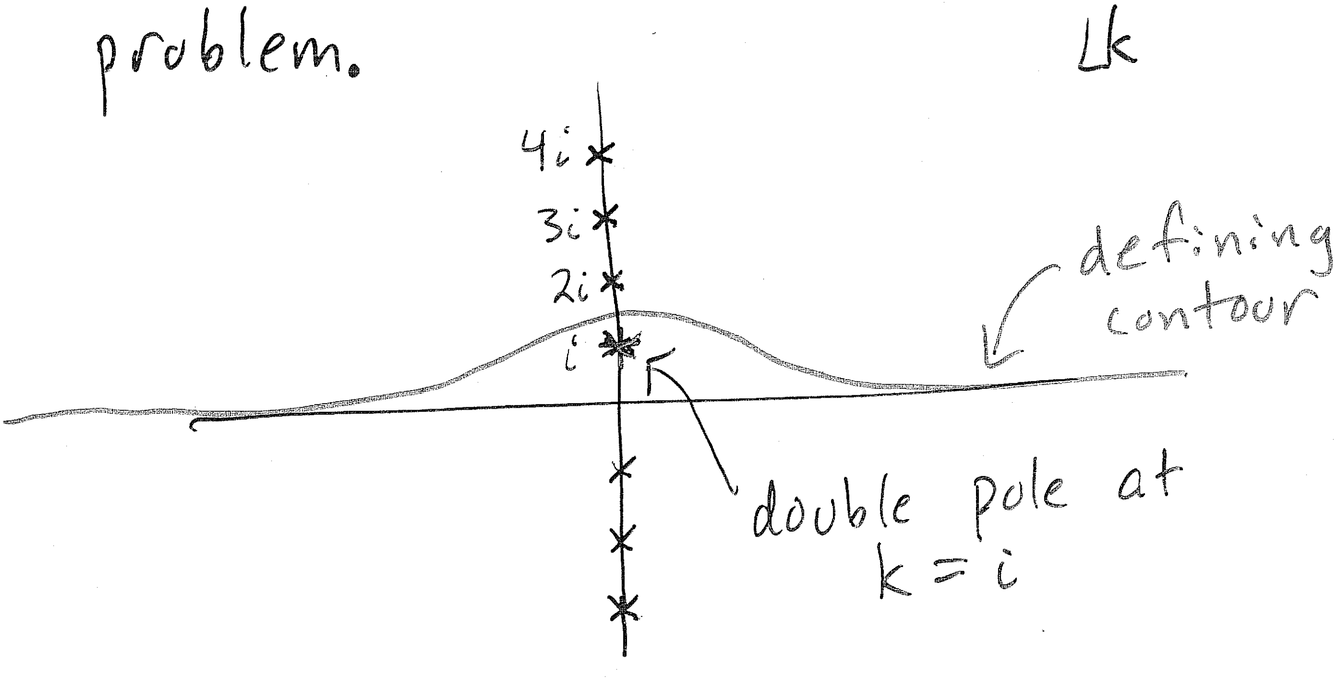
Why a discrete tower of fields?

$$\langle \phi\phi \rangle = \int dk \left(e^{-ki\delta T} + R(k) e^{-ik\bar{T}} \right) G_k(\ell)$$

+ "Super curvature mode"

$$G_k(\ell) = \frac{e^{\frac{k\pi}{2}} e^{ik\ell} - e^{-\frac{k\pi}{2}} e^{-i\ell k}}{\sinh k\pi \ \sinh \ell}$$

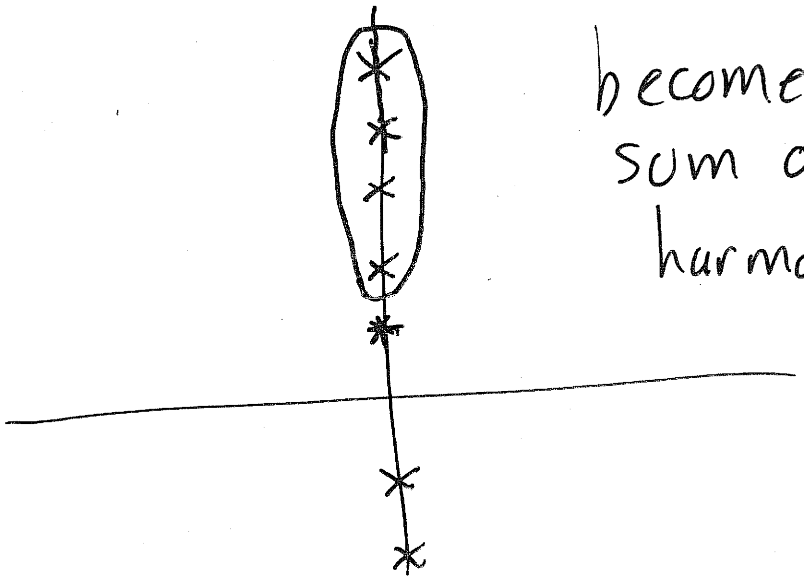
$R(k)$ is reflection coefficient in auxiliary quantum mechanics problem.



$G_k(\ell)$ has simple poles corresponding to spherical harmonics.

$\mathcal{R}(k)$ has a simple pole coming from a single bound state of the Euclidean potential

Euclidean contour:



becomes discrete sum over spherical harmonics

The double pole comes from the zero mode ~~on compa~~ in Euclidean space.

It is problematic to define the Green's function for a massless scalar in a compact space, because

$$\nabla^2 \langle \phi \phi \rangle = \delta(x-y)$$

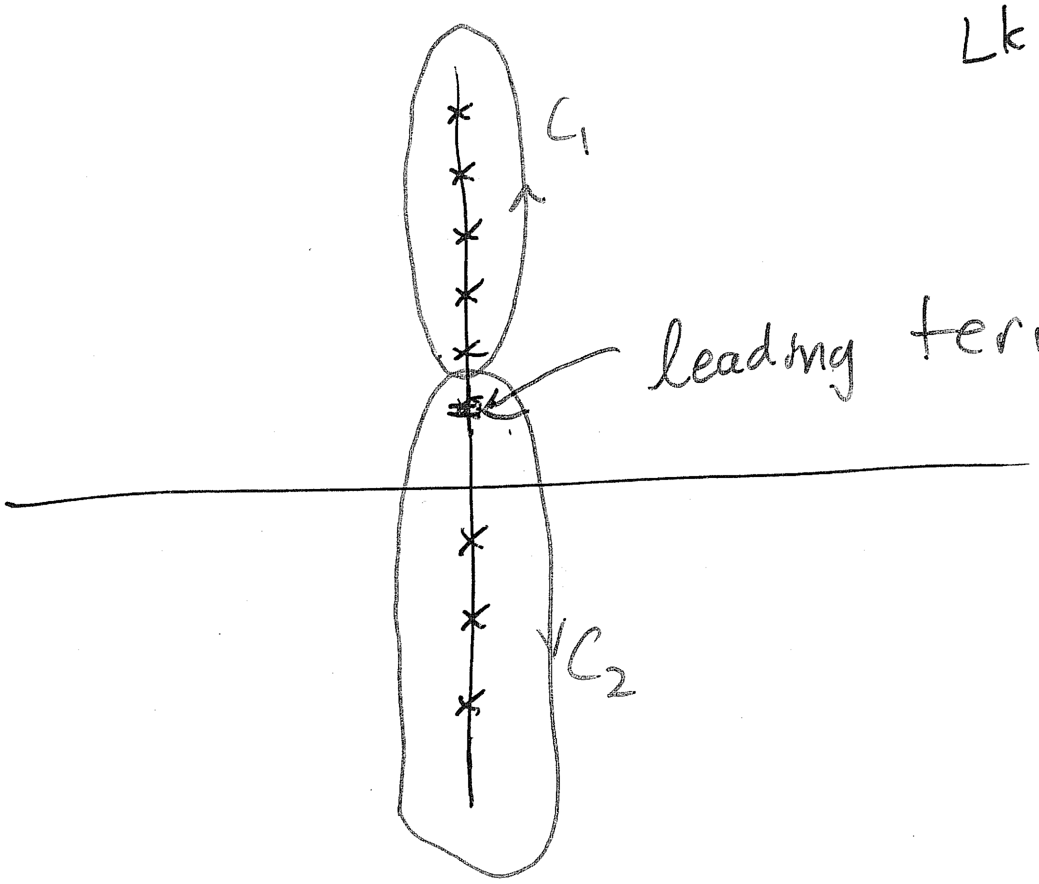
cannot be solved.

(Equivalent to saying that in electrostatics there can't be any net charge in a compact space)

Usual solution: zero mode is pure gauge $\Rightarrow$ project it out.

This leads to our choice of Euclidean contour

Contour in our limit:



$$\langle \phi \phi \rangle = G_0 +$$

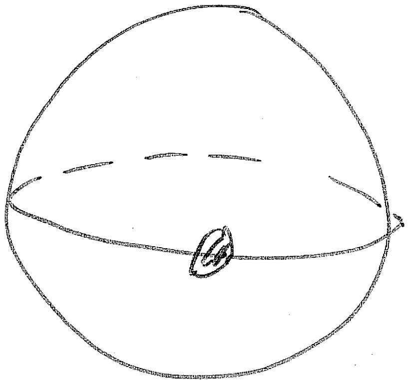
$$\int_{C_1} R(k) e^{-ik\overline{T}} \frac{e^{\frac{k\pi}{2}} e^{ikl}}{\sinh k\pi \sinh l}$$

$$+ \int_{C_2} R(k) e^{-ik\overline{T}} \frac{e^{-\frac{k\pi}{2}} e^{-ikl}}{\sinh k\pi \sinh l}$$

Compact Euclidean Geometry ⟹ Frozen in fluctuations at infinity. Must be there.

Many speculations about CFT, e.g.

- Sigma model with target space = moduli space of string theory
- Bubble collisions in bulk → instantons in CFT



- Above 4 bulk dimensions?

Conclusions

Local description of EI provides new perspective on probabilities

Locally Minkowski asymptotics for some observers may be useful for string theory

Rich structure of bubble collisions which should have an elegant description. If not CFT, then something else.