Title: Cosmology and the AdS/CFT

Date: Nov 22, 2005 02:00 PM

URL: http://pirsa.org/05110018

Abstract:

AdS/CFT & Cosmology

A. Maloney

→ Freivogel, Hubeny, A.M., Myers, Rangamani & Shenker

→ A.M.

Goal : To Understand Quantum Gravity in Time Dependent & Cosmological Backgrounds

→ Expanding Universe (c.f. inflation)

→ Big Bang / Crunch Singularities

Strategy : Use AdS / CFT

Goal : To Understand Quantum Gravity in Time Dependent & Cosmological Backgrounds

→ Expanding Universe (c.f. inflation)

→ Big Bang / Crunch Singularities

Strategy : Use AdS / CFT

→ Big Bang / Crunch Singularities

Strategy : Use AdS / CFT

→ Dual CFT provides non-perturbative Definition of QG in this bkg.

Glaring Problem : AdS is not (really) a cosmology

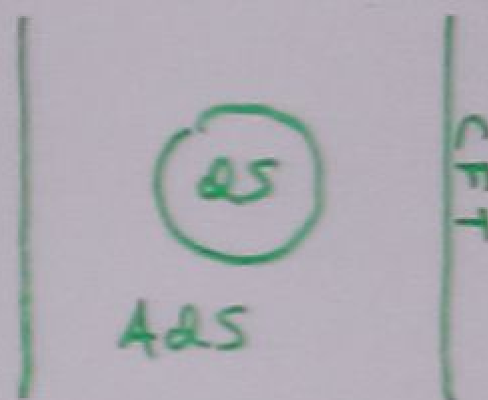
→ Static, SUSic, ...

Solution : Variants of AdS ...

I) Inflation : Couple to a bulk gravitational theory with inflating false vacuum bubbles

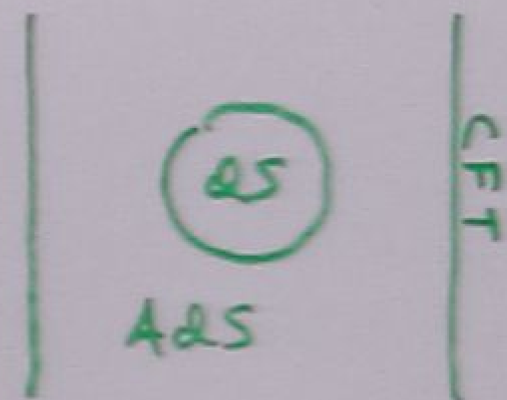
Solution : Variants of AdS ...

I) Inflation : Couple to a bulk gravitational theory with inflating false vacuum bubbles

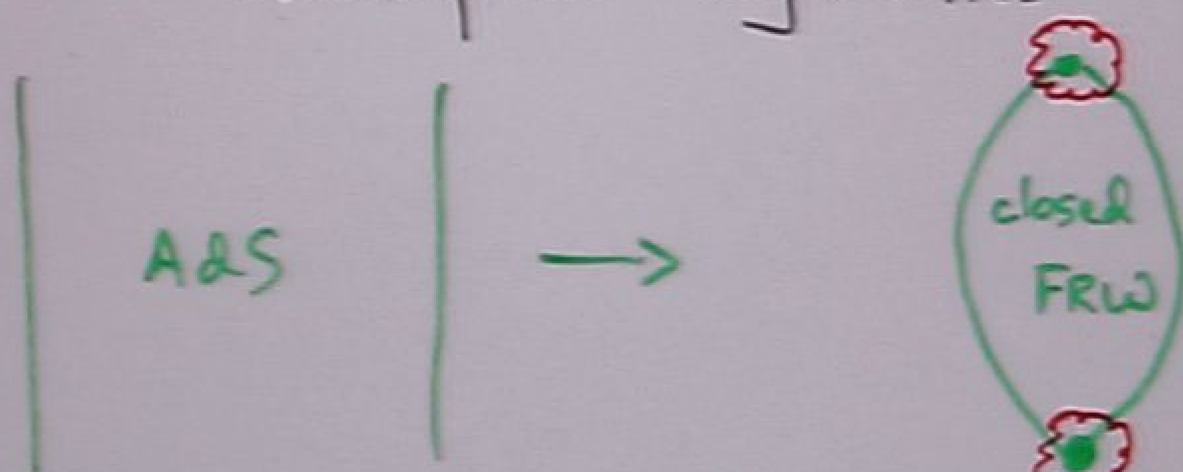


II) Big Bang : Orbifold to introduce cosmological singularities

theory with inflating false vacuum bubbles



II) Big Bang : Orbifold to introduce cosmological singularities



Plan

I) Inflation

→ Set-up : inflating bubbles $\in$ AdS

→ Mixed State in bdy CFT

→ CFT Probes of inflation

→ Payoff : rule out Guth-Farhi instanton

II) Cosmological Singularities

→ Set-up : Orbifolds of AdS_3

→ Two Euclidean CFTs

→ CFT Probes of inflation

→ Payoff : rule out Guth-Farhi instanton

II) Cosmological Singularities

→ Set-up : Orbifolds of AdS_3

→ Two Euclidean CFTs

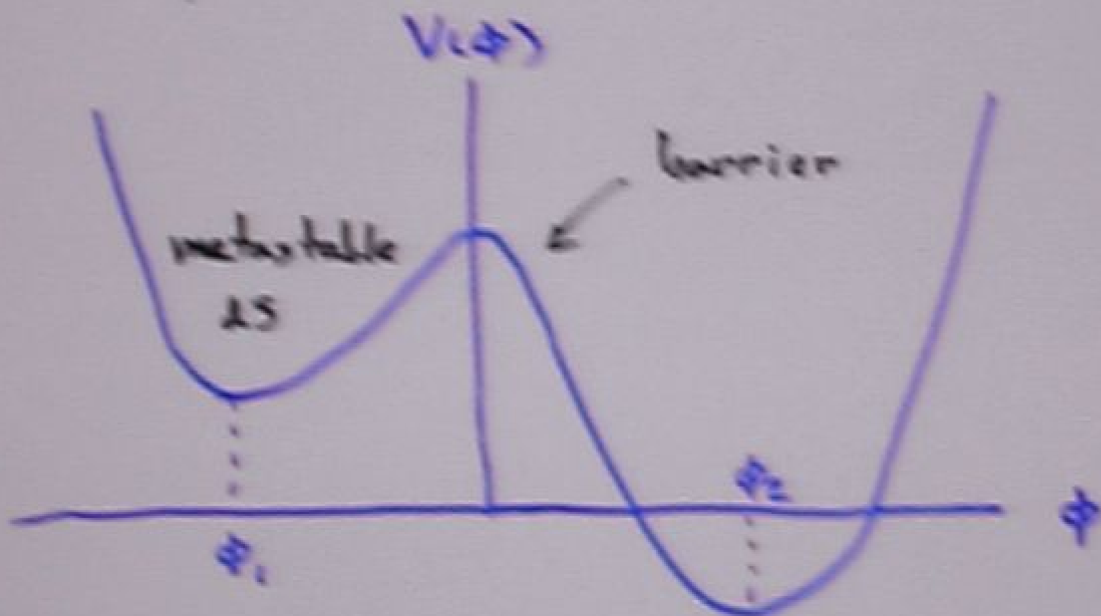
→ Define Hartle - Hawking state

→ Payoff : CFT probe of B.B.

III) Future Directions

Inflating Bubbles $\in$ AdS

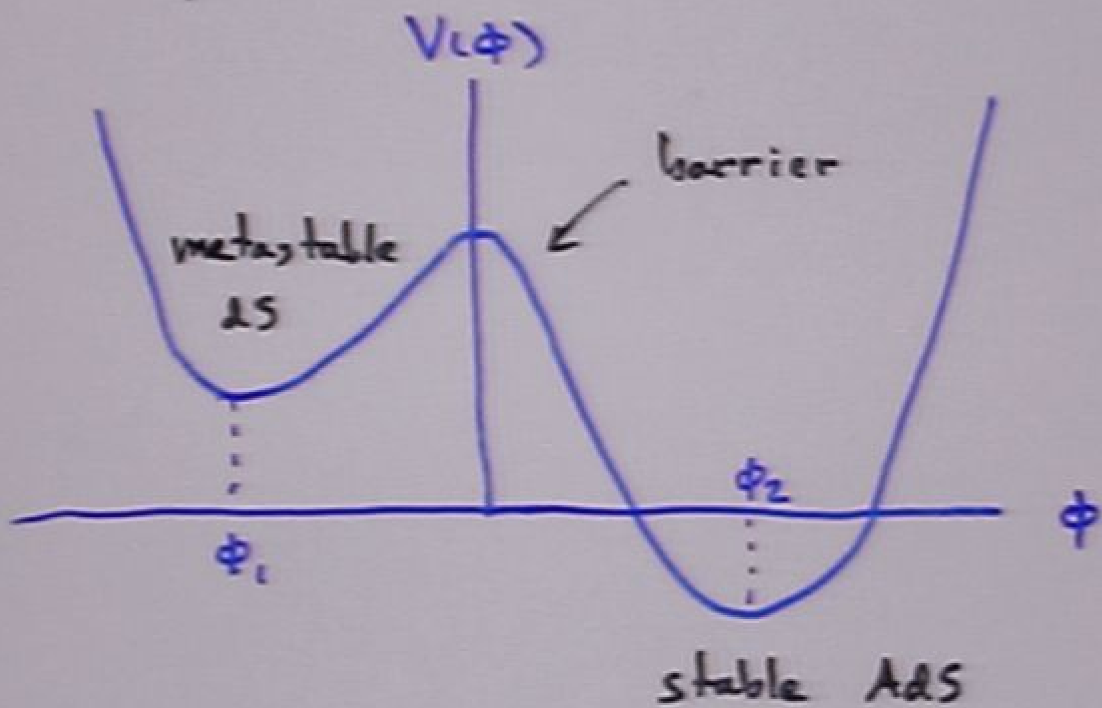
Many Flux compactifications of String Theory are described at low energy by 4D Gravity + scalar ϕ



KKLT

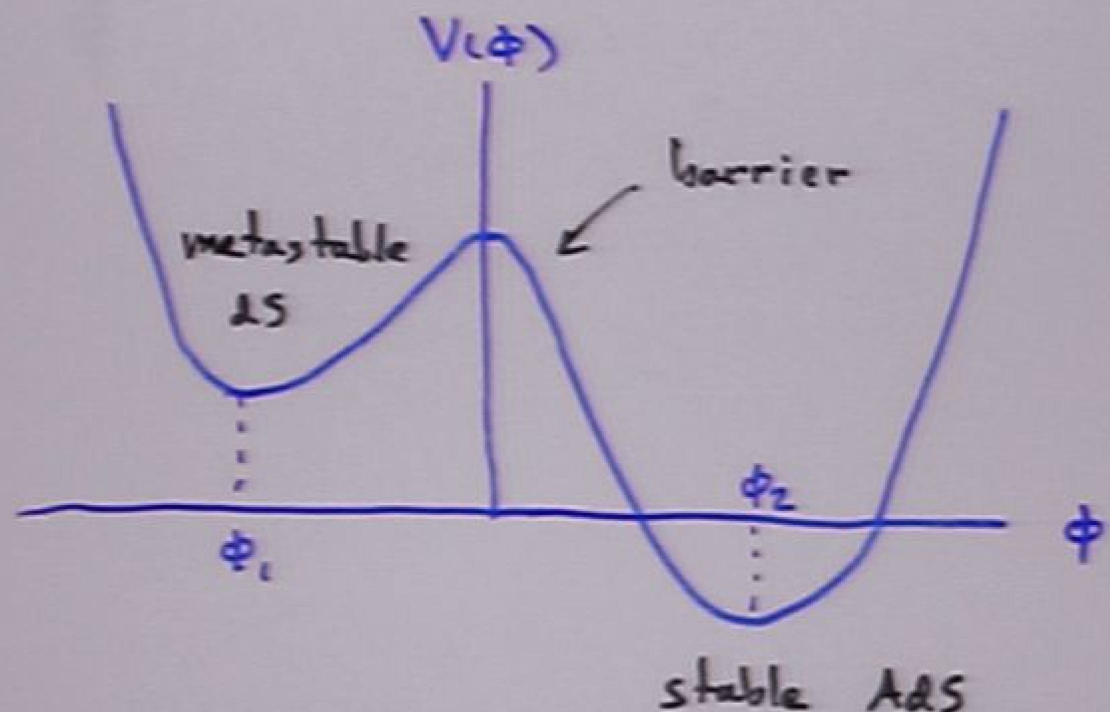
Inflating Bubbles $\in$ AdS

Many Flux compactifications of String Theory are described at low energy by 4D Gravity + scalar ϕ



KKLT
⋮

Many Flux compactifications of String Theory are described at low energy by 4D Gravity + scalar ϕ



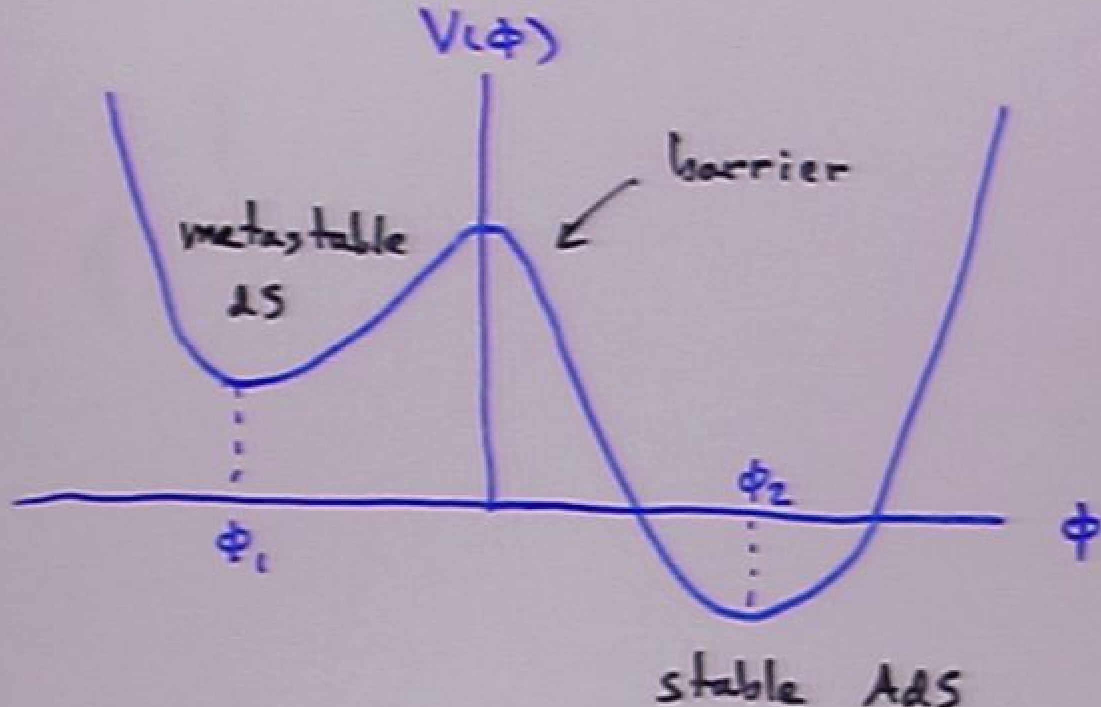
KKLT
⋮

Has stable AdS solutions : $\phi = \phi_2$

$\rightarrow$ defines bdy CFT

... low energy by 4D

Gravity + scalar ϕ

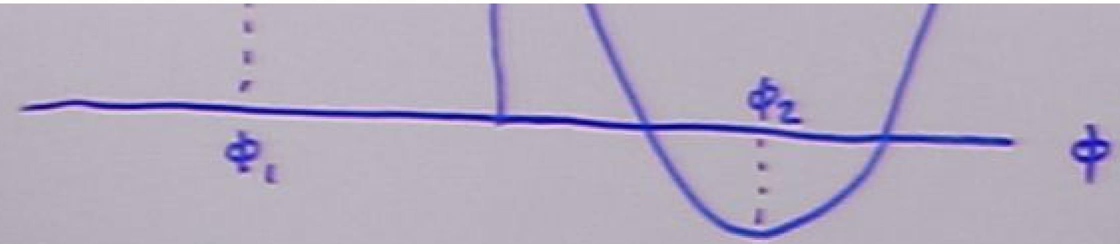


KKLT
⋮

Has stable AdS solutions : $\phi = \phi_2$

$\rightarrow$ defines bdy CFT

Also, False vacuum bubble solutions :

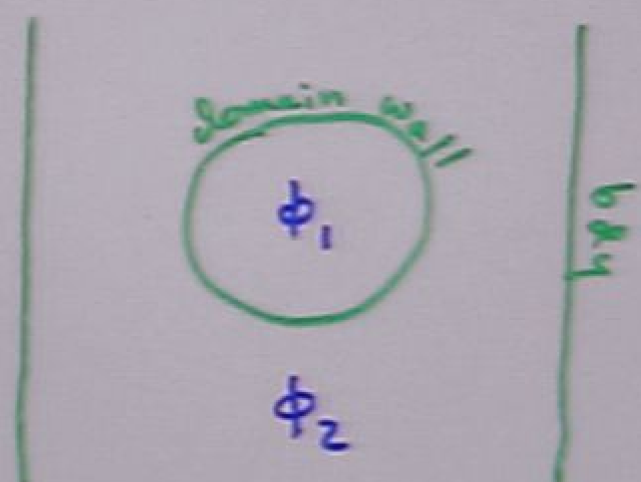


stable AdS

Has stable AdS solutions : $\phi = \phi_2$

→ defines bdy CFT

Also, False vacuum bubble solutions :



Similar to Farhi & Guth solutions in flat space

There exist inflating solutions, but

1) bubble has mass $\Rightarrow$ inside it's own horiz

$\rightsquigarrow$ like BH

2) must have had singularity in far past

$\rightsquigarrow$ like eternal BH

In asymptotic AdS, this is ok -

→ we know how to study eternal BH

What do the solutions look like?

There exist inflating solutions, but

1) bubble has mass ⇒ inside it's own horizon

~> like BH

2) must have had singularity in far past

~> like eternal BH

n asymptotic AdS, this is OK -

→ we know how to study eternal BH

hat do the solutions look like?

hin Wall ⇒

Bubble Size $R(t)$

there exist inflating solutions, but

1) bubble has mass $\Rightarrow$ inside it's own horizon

$\rightsquigarrow$ like BH

2) must have had singularity in far past

$\rightsquigarrow$ like eternal BH

In asymptotic AdS, this is OK -

→ we know how to study eternal BH

What do the solutions look like?

Thin Wall $\Rightarrow$

Bubble Size $R(t)$

$$\Rightarrow \dot{R}^2 + V(R) = E$$

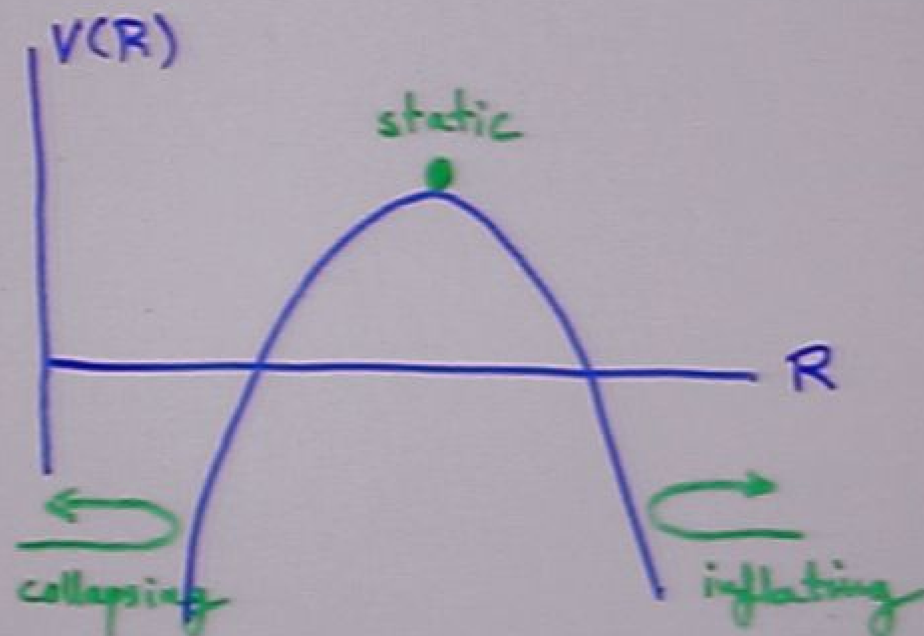
→ we know how to study eternal BH

What do the solutions look like?

Thin Wall ⇒

Bubble Size $R(t)$

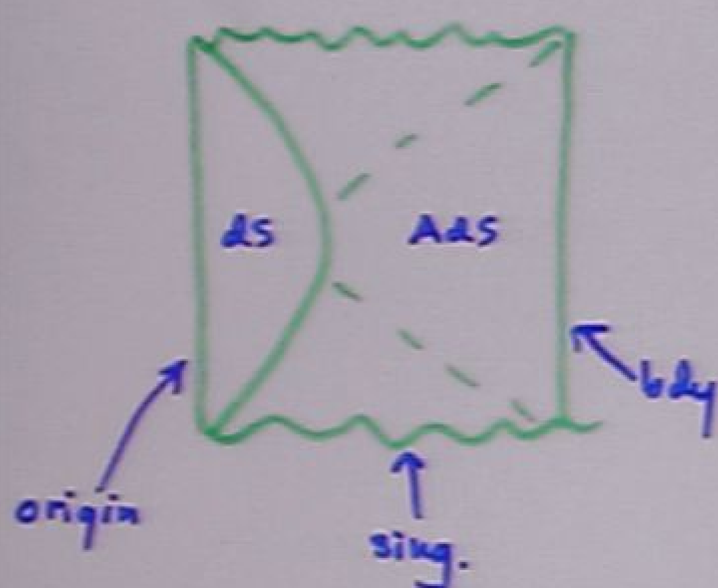
$$\Rightarrow \dot{R}^2 + V(R) = E$$

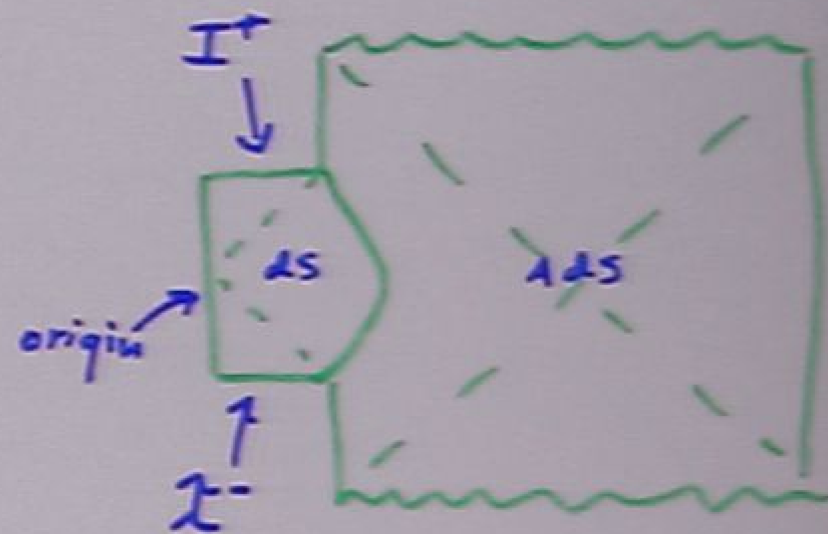


Causal Structure :

Collapsing

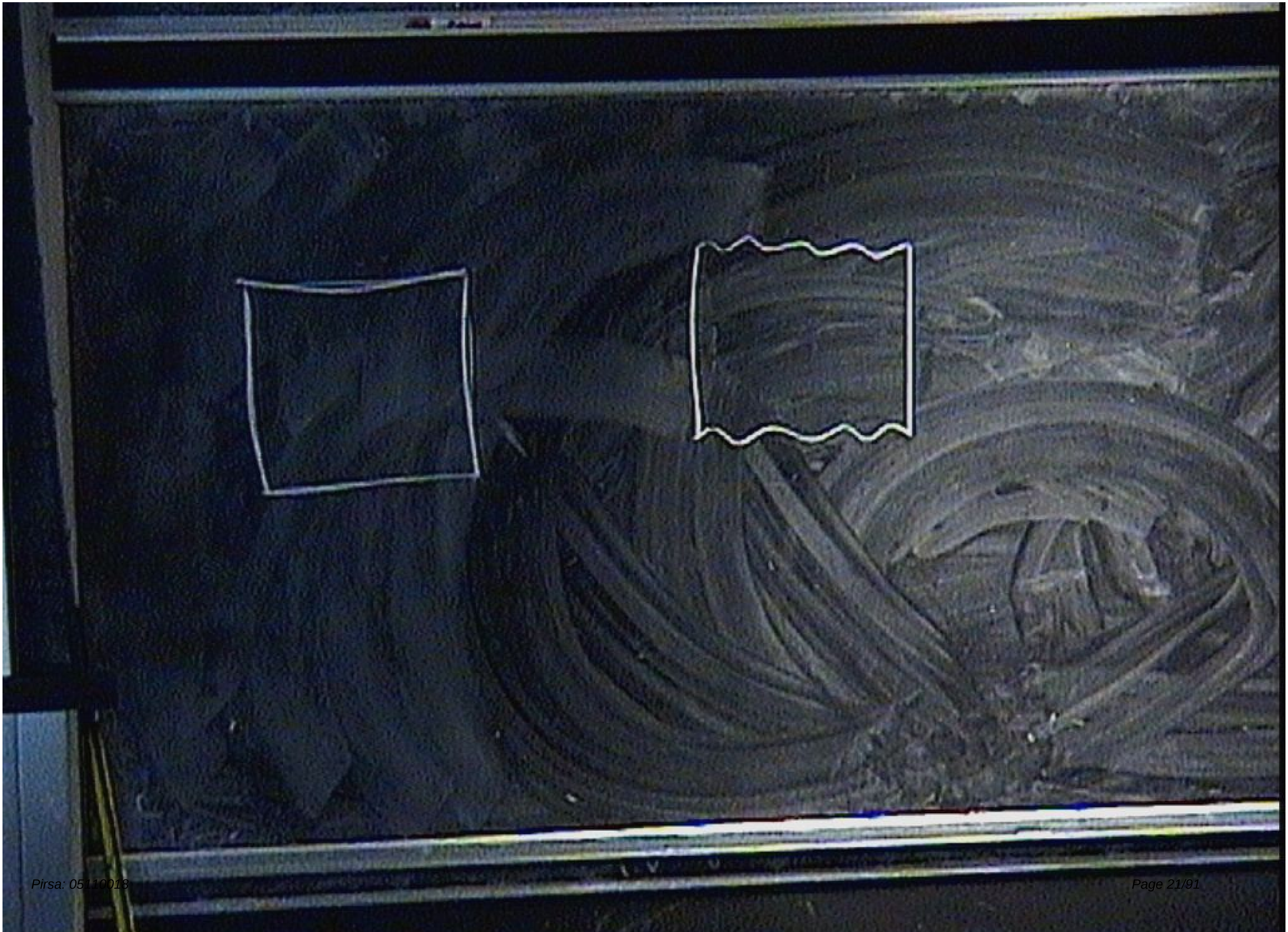
Inflating



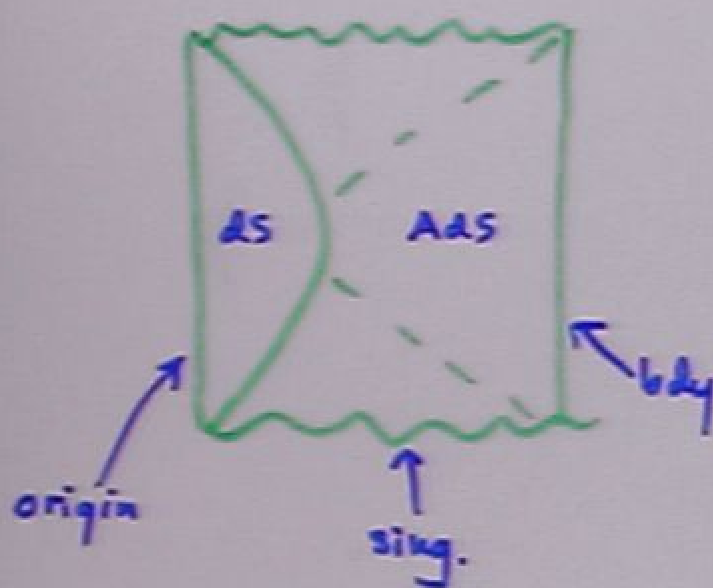


→ $R_{dS} > R_{bh}$

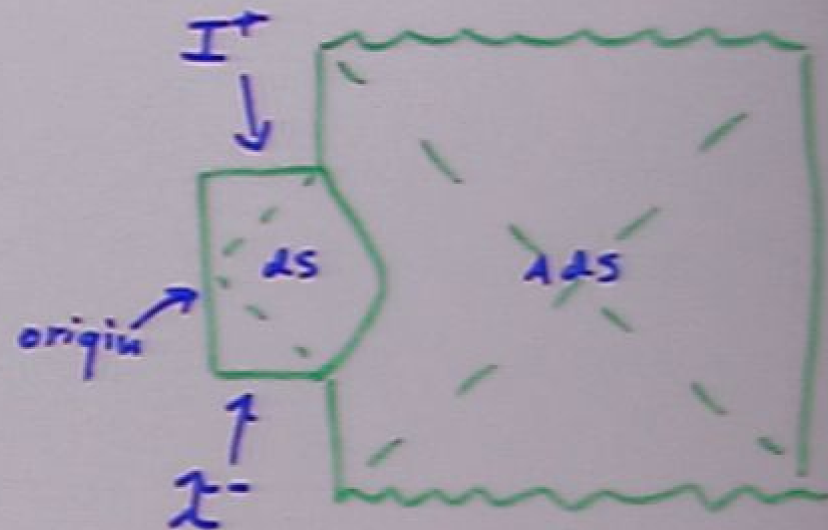
→ dS $\mathcal{I}$ causally separate from AdS bdy



Collapsing



Inflating



→ $R_{dS} > R_{bh}$

→ dS $\mathcal{I}$ causally separate from AdS bd...

→ Only Half of dS

origin

sing.

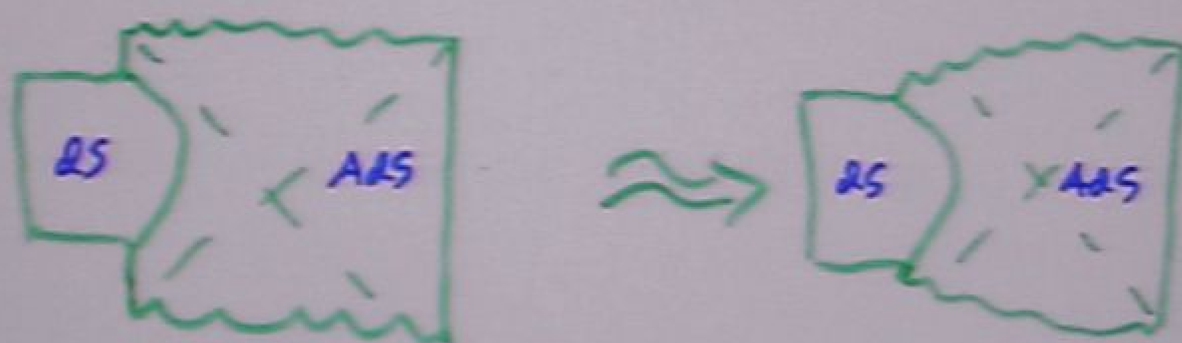
$\mathcal{I}^-$

$\rightarrow R_{dS} > R_{bh}$

$\rightarrow$ dS $\mathcal{I}$ causally separate from AdS

$\rightarrow$ Only Half of dS

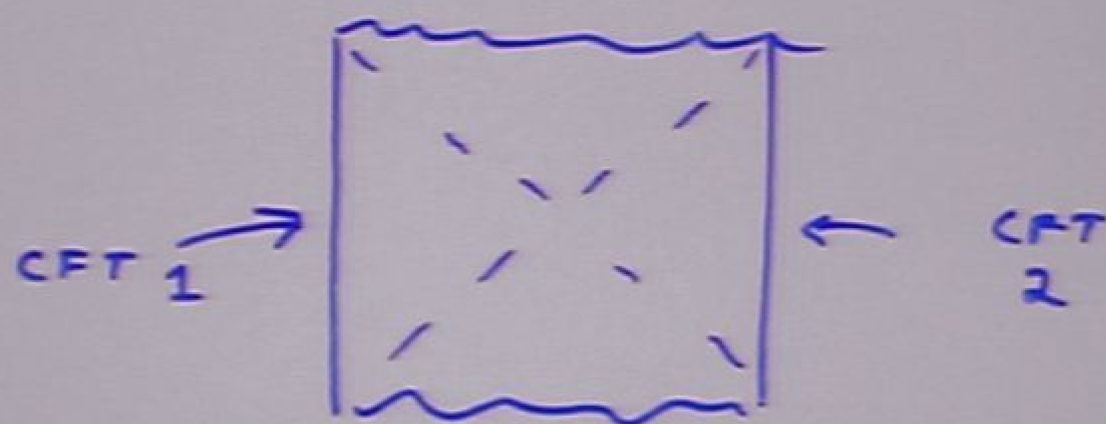
In fact, once we go beyond thin wall..



The Boundary CFT

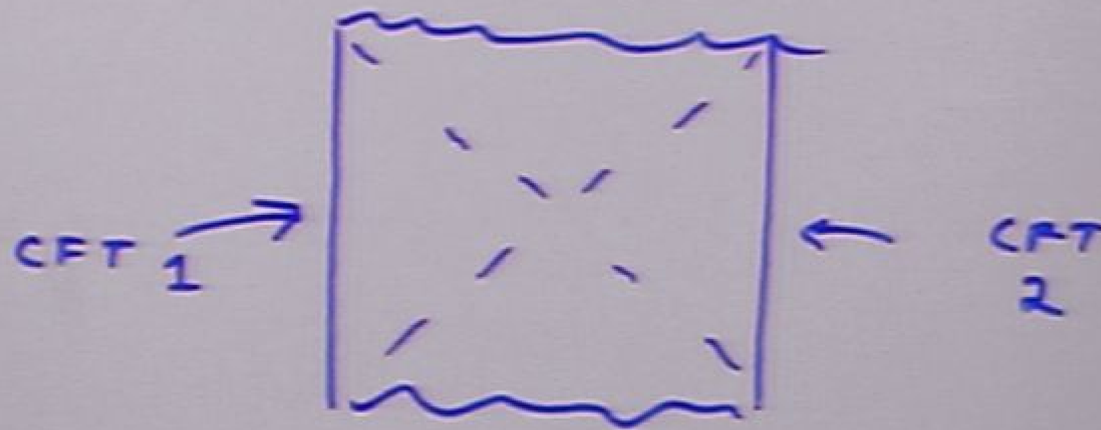
From the outside, the bubble resembles an AdS - Schwarszchild BH.

Recall AdS - BH:



$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \rightarrow \text{two identical CFTs}$$

The CFTs are entangled :



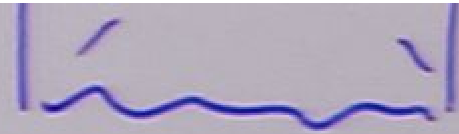
$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \rightarrow$$ two identical CFTs

The CFTs are entangled :

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} \quad |n_1\rangle \otimes |n_2\rangle$$

Correlators in CFT 2 are in a Mixed State :

$$\rho = \mathrm{Tr}_1 |\Psi\rangle\langle\Psi| = e^{-\beta H}$$



$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \longrightarrow$ two identical CFTs

The CFTs are entangled :

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} \quad |n_1\rangle \otimes |n_2\rangle$$

Correlators in CFT 2 are in a Mixed State :

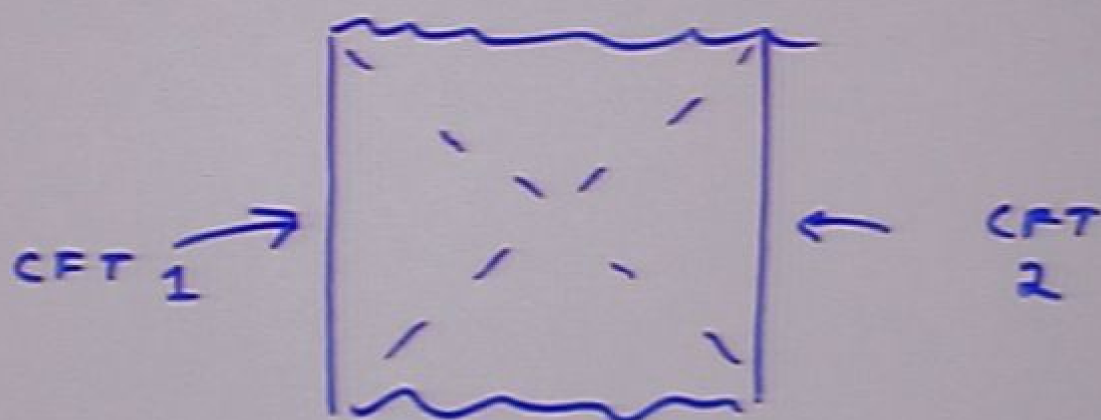
$$\rho = \mathrm{Tr}_1 |\Psi\rangle\langle\Psi| = e^{-\beta H}$$

Mixed State $\longleftrightarrow$ Behind the Horizon Physics

The Boundary CFT

From the outside, the bubble resembles an AdS - Schwarszchild BH.

Recall AdS - BH:



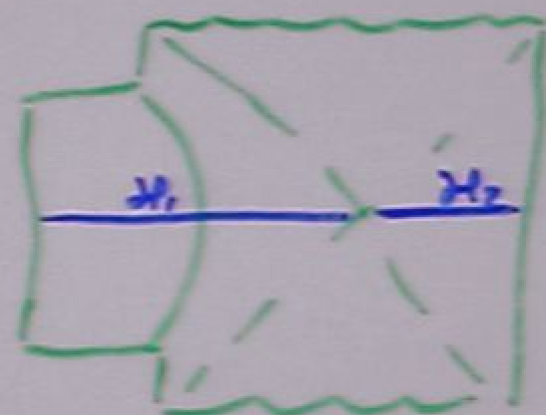
$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2 \rightarrow$ two identical CF[T]

Claim: Bdy CFT of inflating bubble is also in a mixed state

$$\rho = e^{-\beta H} + \text{corrections}$$

Evidence: 1) Bulk QFT

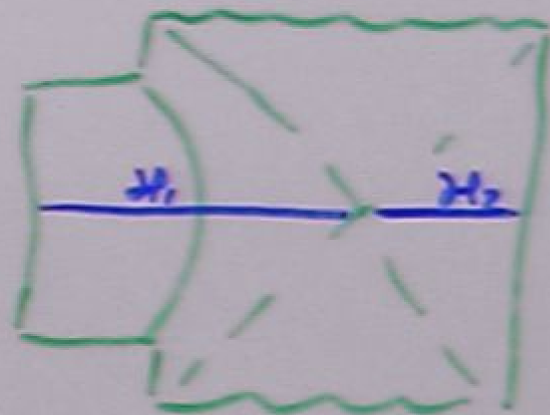
$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$



$\rho = Tr_{\mathcal{H}_1} |\Psi\rangle\langle\Psi|$ has non-zero entropy

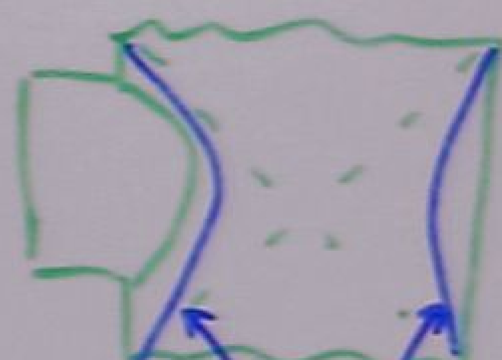
1) Bulk QFT

$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$



$\rho = \mathrm{Tr}_{\mathcal{H}_1} |\psi\rangle\langle\psi|$ has non-zero entropy

2) Cutoff CFT



Summarize :

AdS region described by CFT with S_{BH} DOF

dS described by some mystery theory with S_{dS} DOF

ENTANGLEMENT

...te that because $R_{dS} > R_{bh} \Rightarrow S_{dS} > S_{BH}$

so the entanglement is weak.

To Summarize :

AdS region described by CFT with S_{BH} DOF

dS described by some mystery theory with S_{dS} DOF

ENTANGLEMENT

Note that because $R_{dS} > R_{bh} \Rightarrow S_{dS} > S_{BH}$

so the entanglement is weak.

Nevertheless we can still probe the

AdS region described by CFT with S_{BH} DOF

dS described by some mystery theory with S_{dS} DOF

ENTANGLEMENT

Note that because $R_{dS} > R_{bh} \Rightarrow S_{dS} > S_{BH}$ so the entanglement is weak.

Never the less, we can still probe the inflating region by studying the CFT...

To Summarize :

dS described by some mystery theory with S_{dS} DOF

AdS region described by CFT with S_{BH} DOF

ANGLEMENT

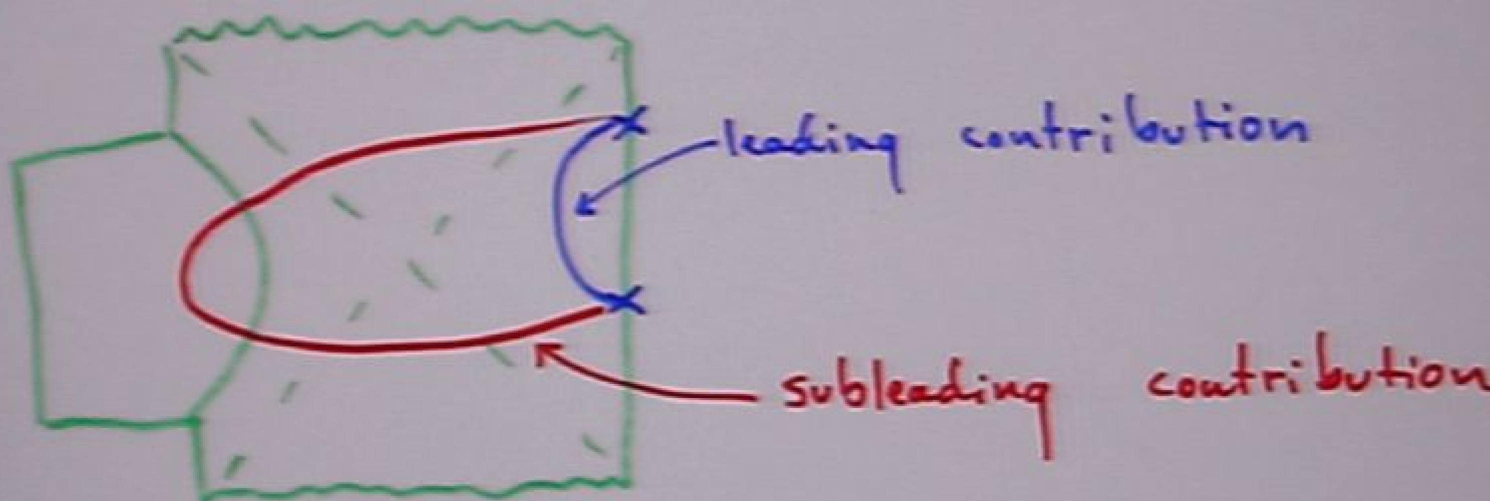
CFT Probes of Inflation

Boundary Correlators :

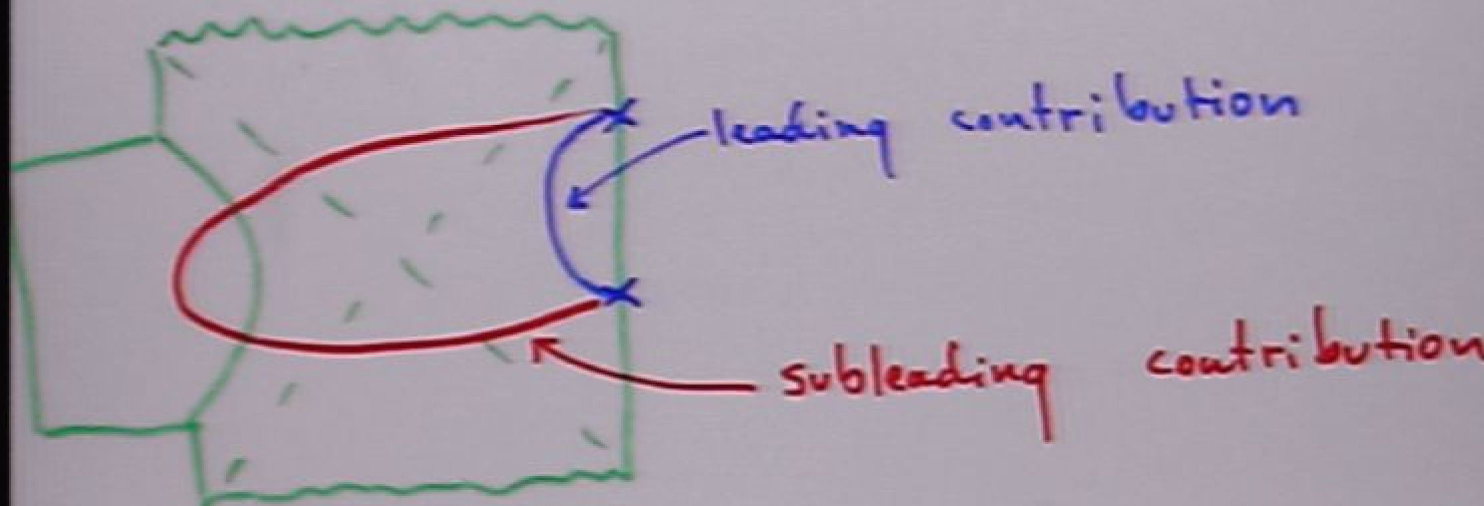
$$\langle O \; O' \rangle = \sum_{\text{paths}} e^{-S} \sim e^{-\Delta \, \mathcal{L}}$$

dimension

geodesic length



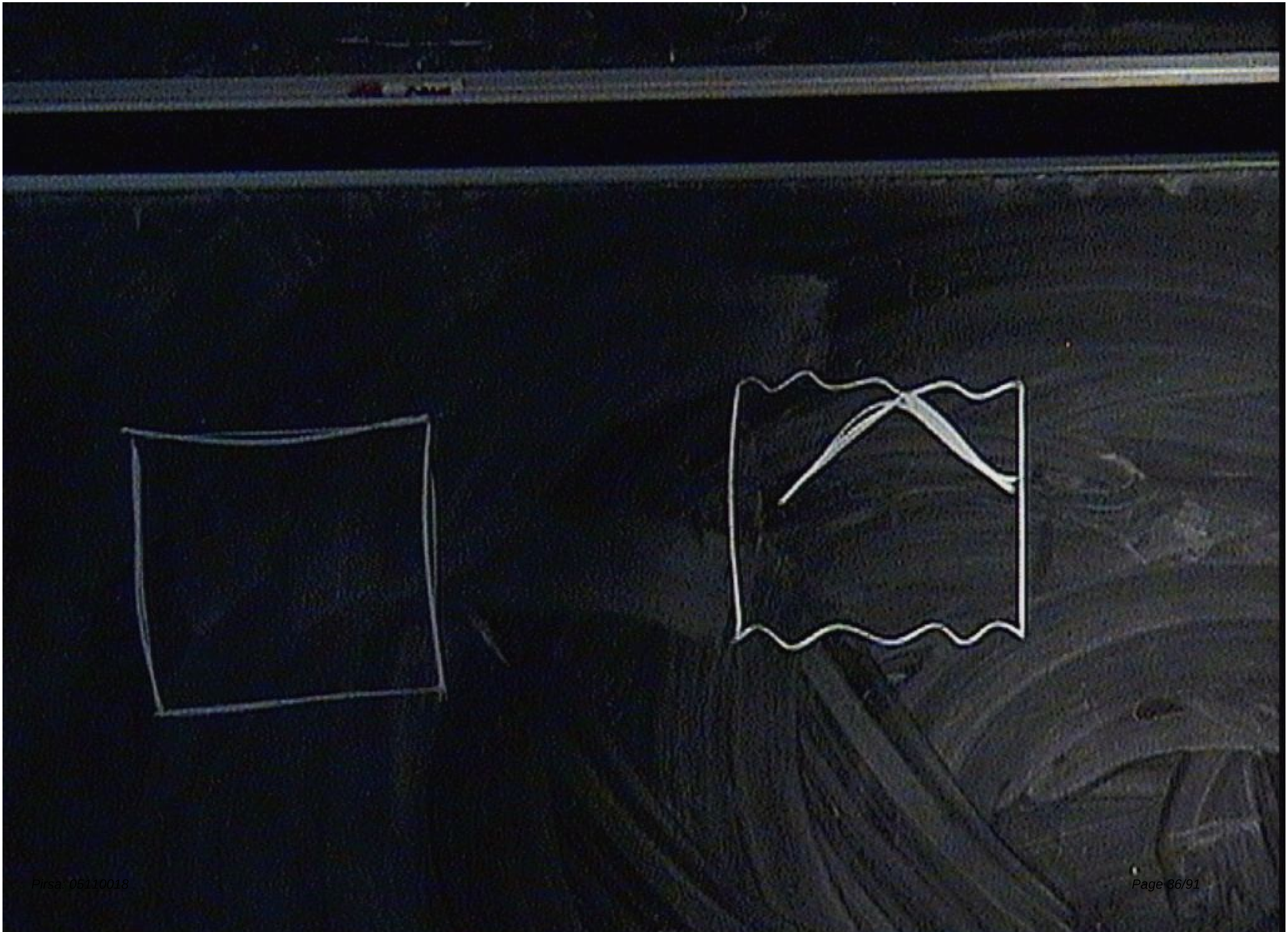
So $\langle O \; O' \rangle \sim \frac{1}{\;\;^{2\Delta}}$ + subleading paths dimension length



So $\langle O\, O' \rangle \sim \dfrac{1}{(\text{Distance})^{2\Delta}}$ + subleading

info about inflation

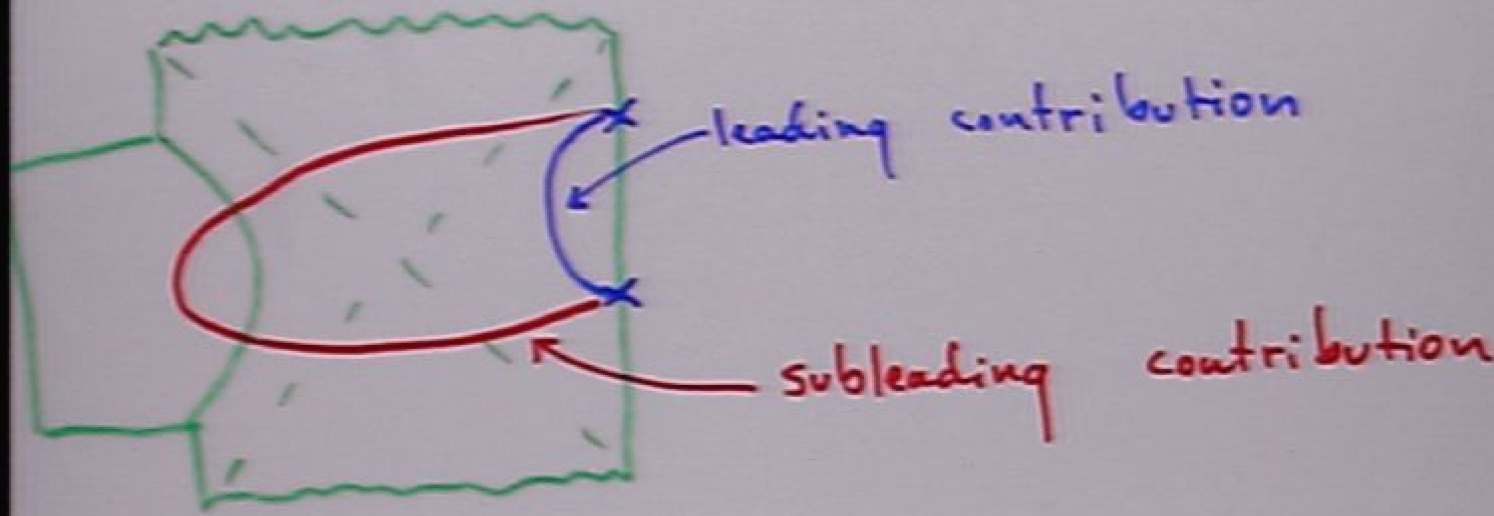
In fact, these subleading paths can become null $\Rightarrow$ singularity in $\langle O\, O' \rangle$



paths

dimension

length



So $\langle O\, O' \rangle \sim \dfrac{1}{(\text{Distance})^{2\Delta}}$ + subleading

info about inflation

In fact, these subleading paths can become null $\Rightarrow$ singularity in $\langle O\, O' \rangle$

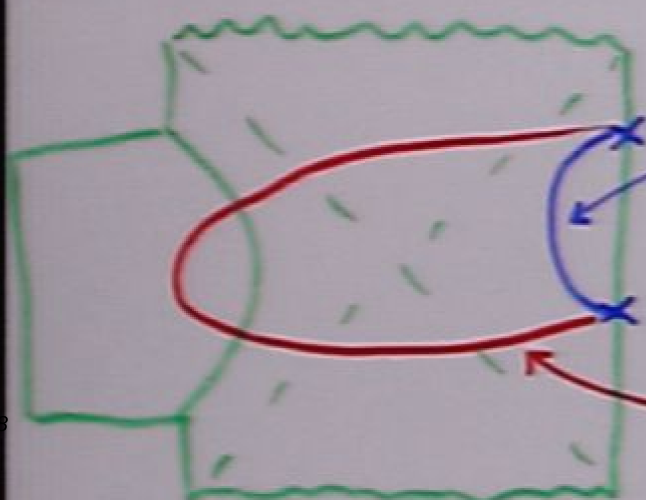
CFT Probes of Inflation

Boundary Correlators :

$$\langle O \, O' \rangle = \sum_{\text{paths}} e^{-S} \sim e^{-\Delta \mathcal{L}}$$

dimension

geodesic length



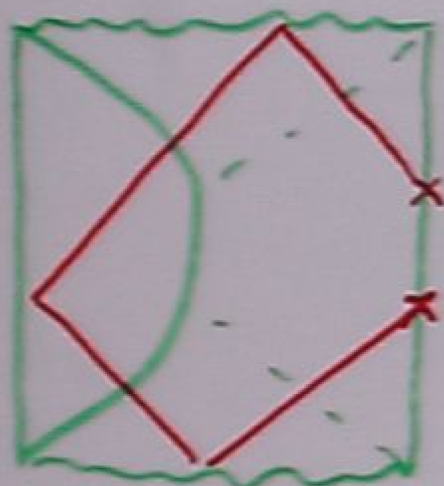
leading contribution

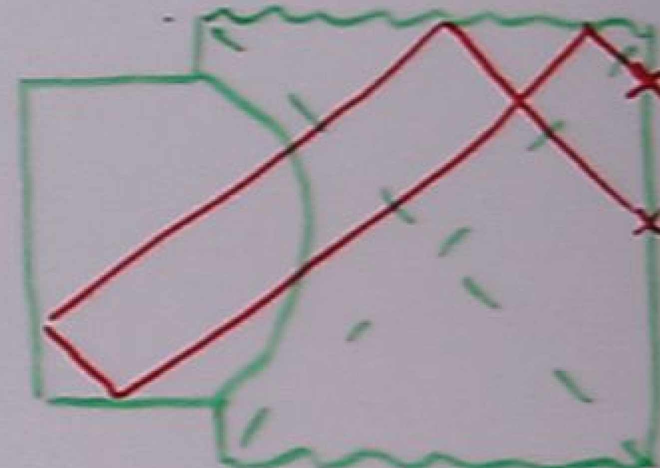
subleading contribution

information about the inflating region :

No Inflation

Inflation



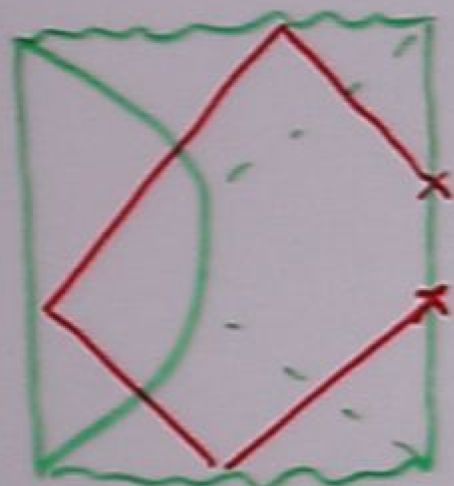


$\Rightarrow$ Different Singularity Structure !

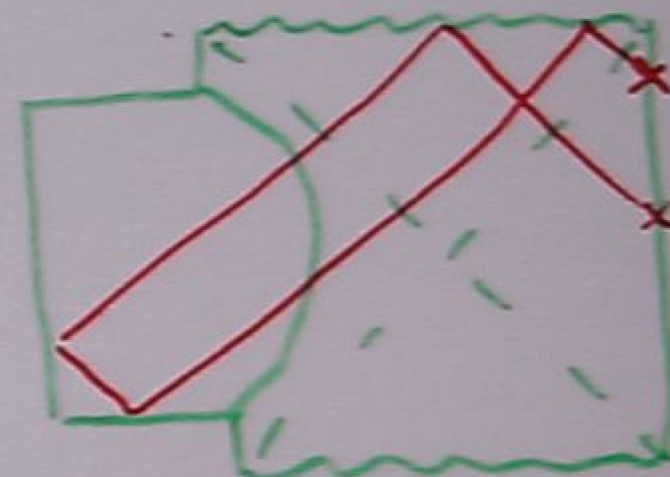
In fact, there are other probes using analytic continuation :

The structure of these singularities contains information about the inflating region :

No Inflation



Inflation



⇒ Different Singularity Structure !

... there are other probes using

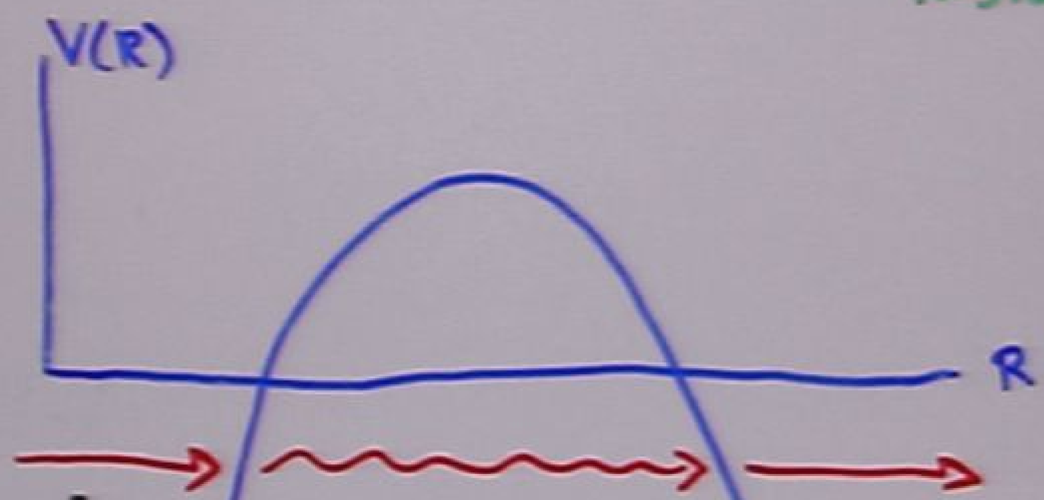
Making the Universe in a Lab

Can we create an inflating region using non-singular initial data ?

Classically : F & G $\Rightarrow$ No

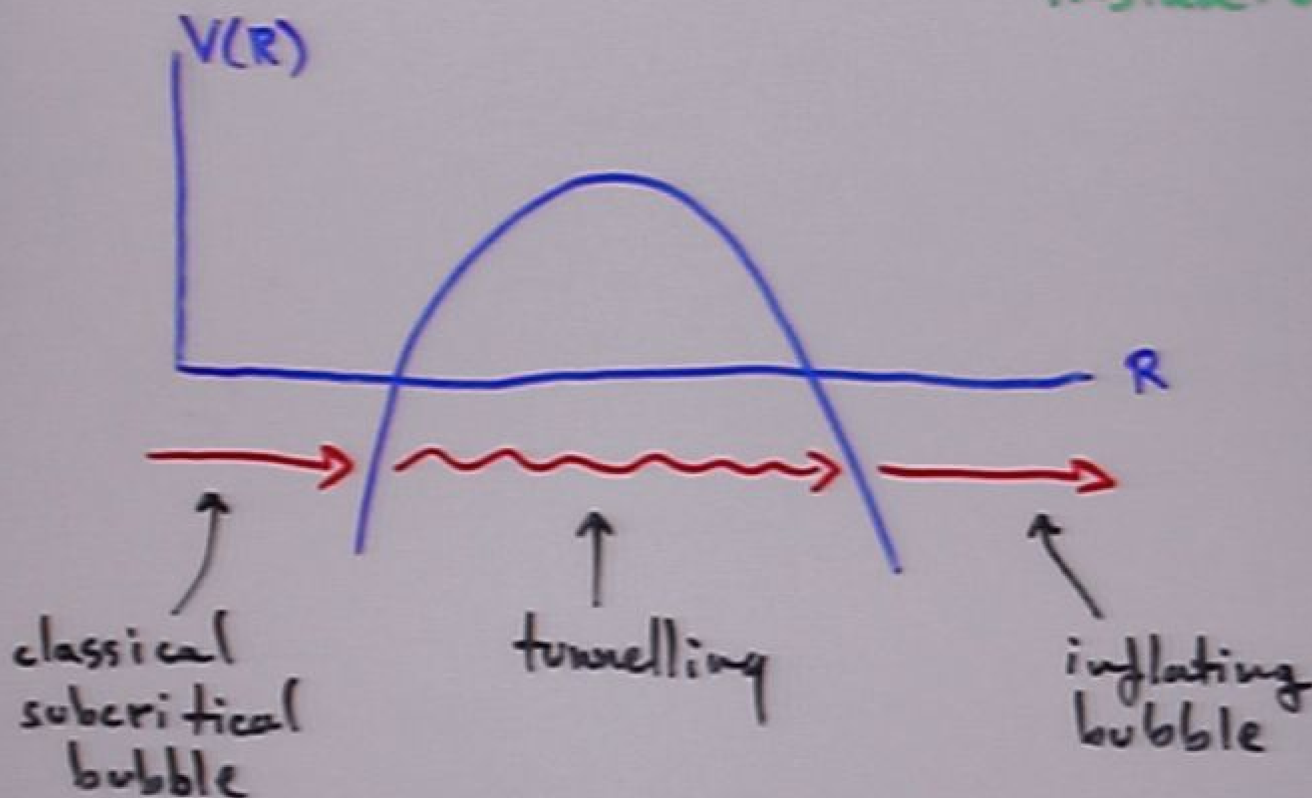
Quantum : FG & G $\Rightarrow$ Maybe, using instantons ...

⋮



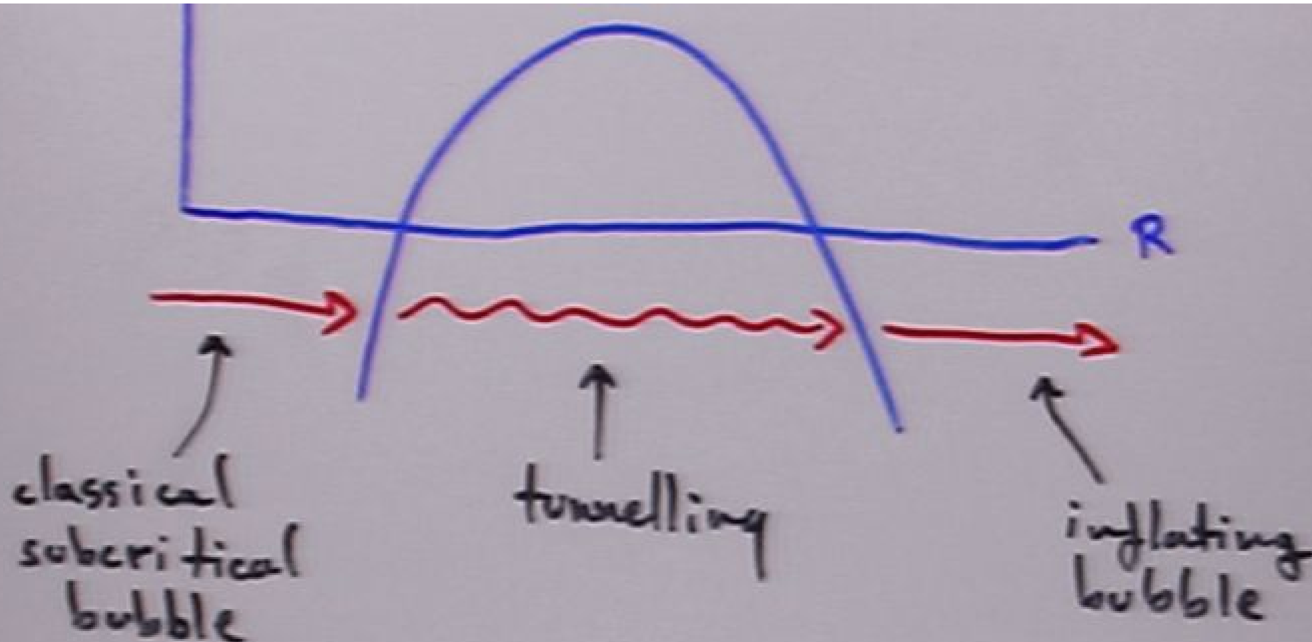
Classically : F & G $\Rightarrow$ No

Quantum : F G & G $\Rightarrow$ Maybe, using instantons ...



In AdS, this would require evolving from

Pure State $\longrightarrow$ Mixed State



In AdS, this would require evolving from

Pure State $\longrightarrow$ Mixed State

This is impossible under Unitary Evolution!

Summary

In flux compactifications, an AdS Bound[...]
CFT can be coupled to inflation

→ Bdy theory is weakly entangled with dS theory

→ Information about dS appears in subleading correlators

Nevertheless, we can learn about inflati[...]

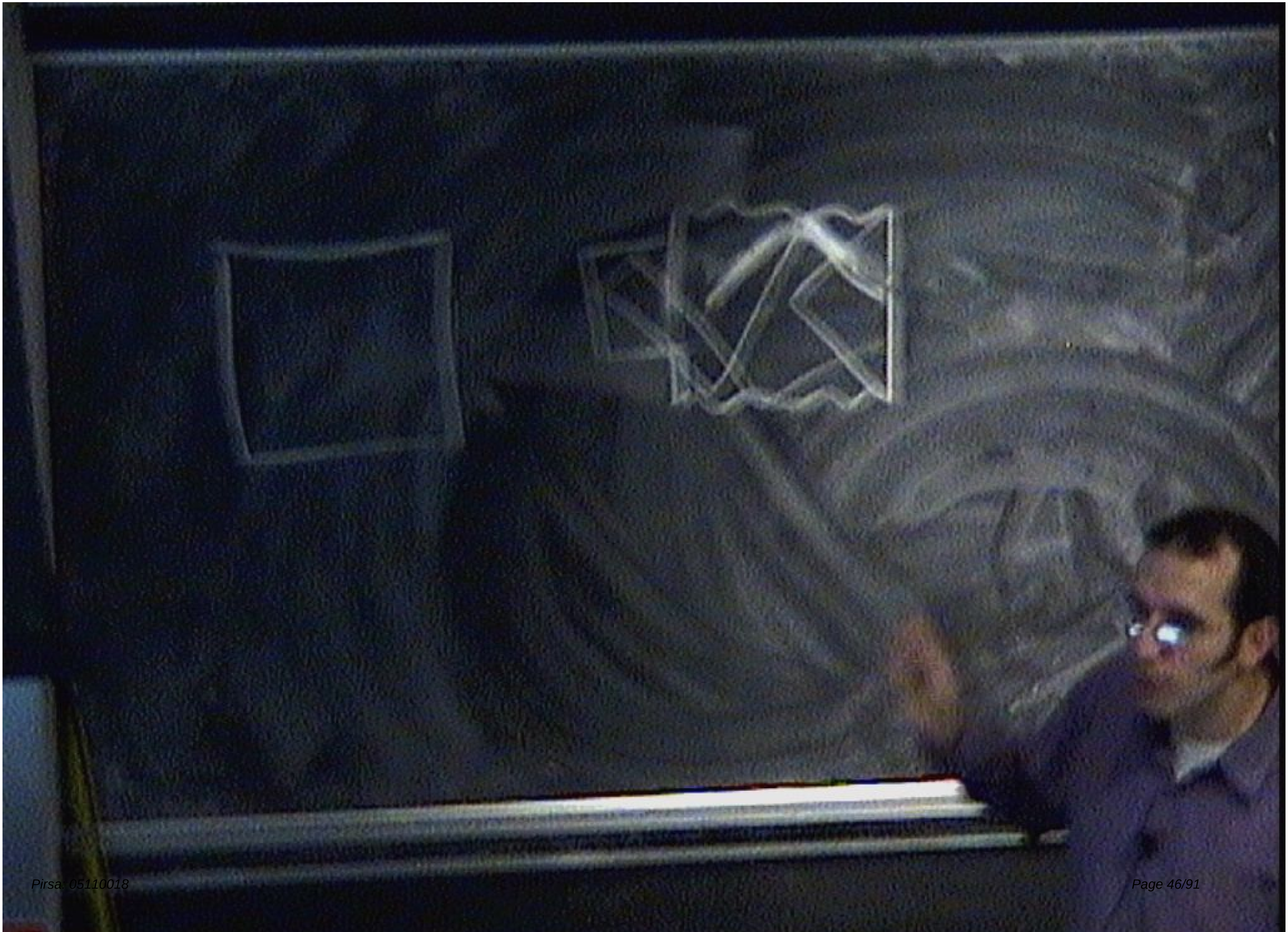
with dS theory

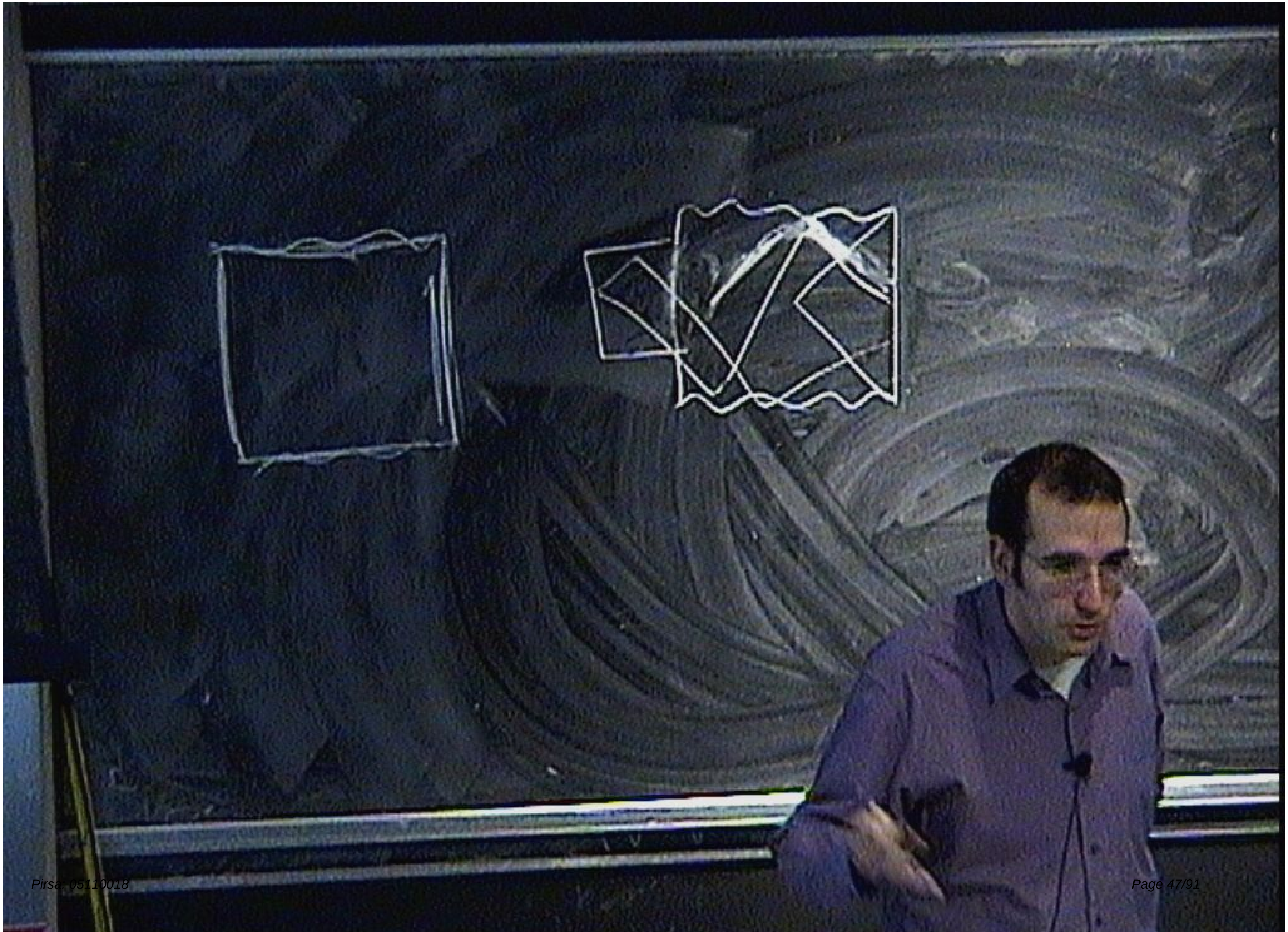
→ Information about dS appears in subleading correlators

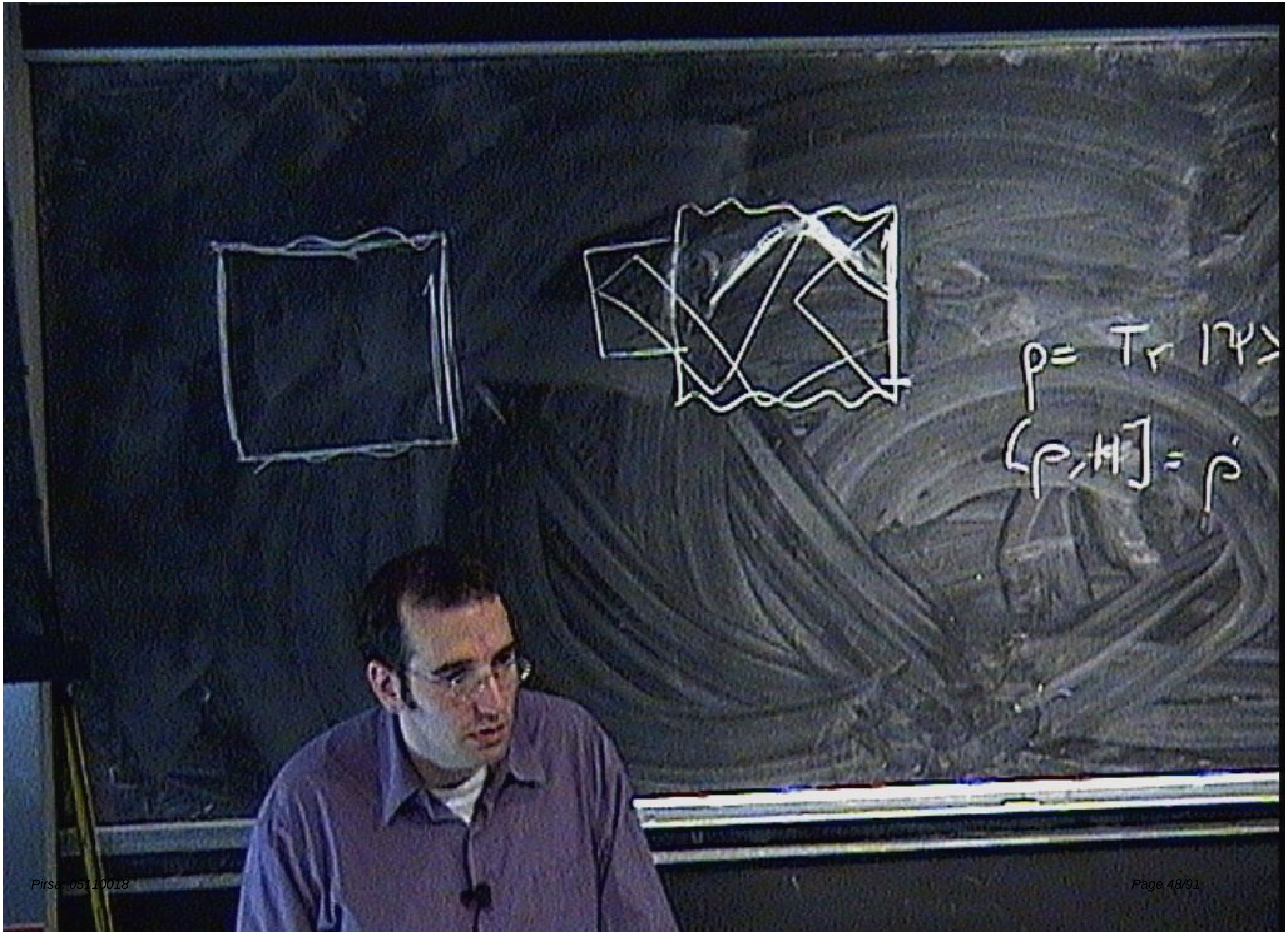
Nevertheless, we can learn about inflatio[n] using Bdy probes

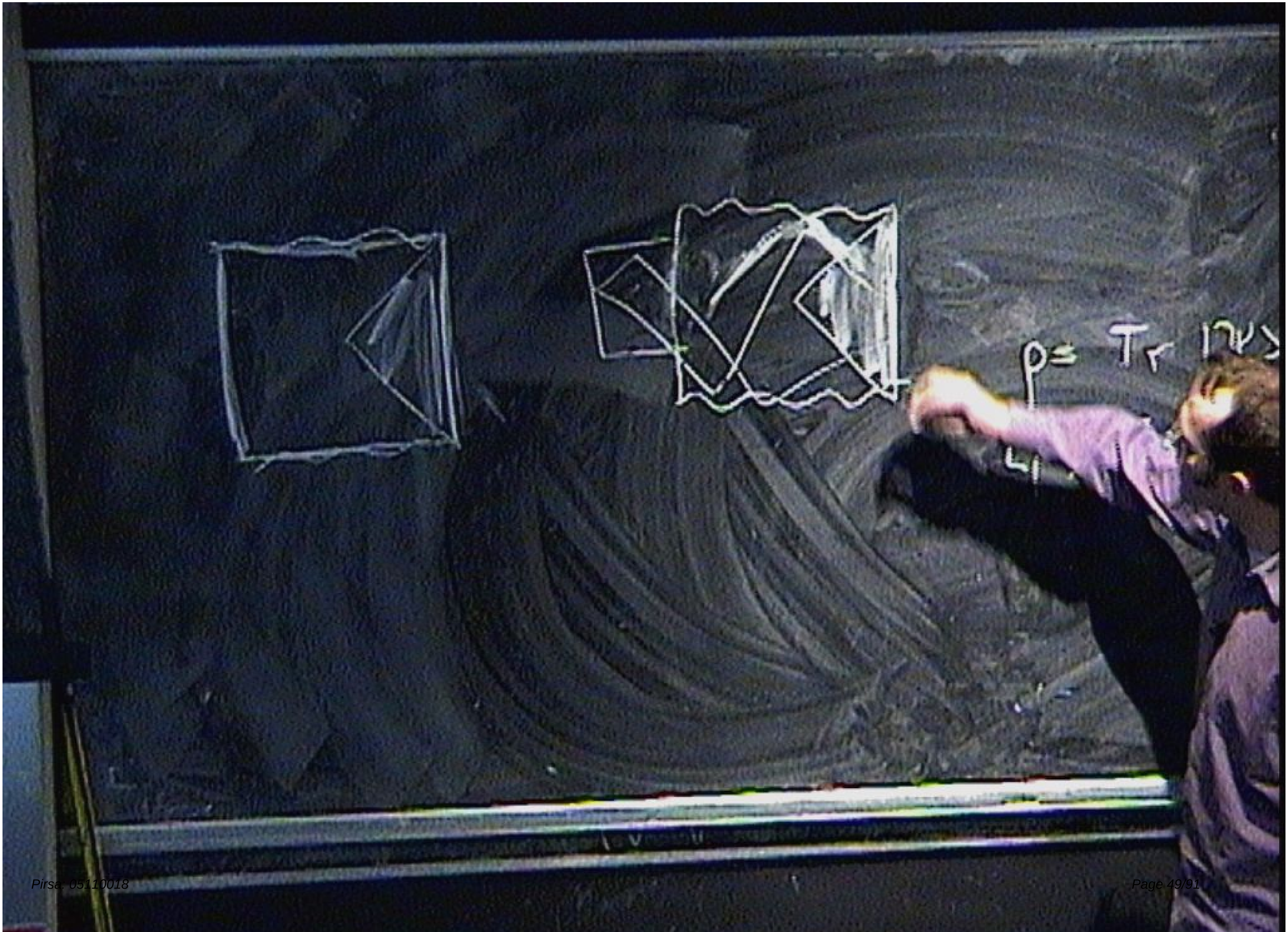
→ Geodesic probes of $\mathcal{I}^+$

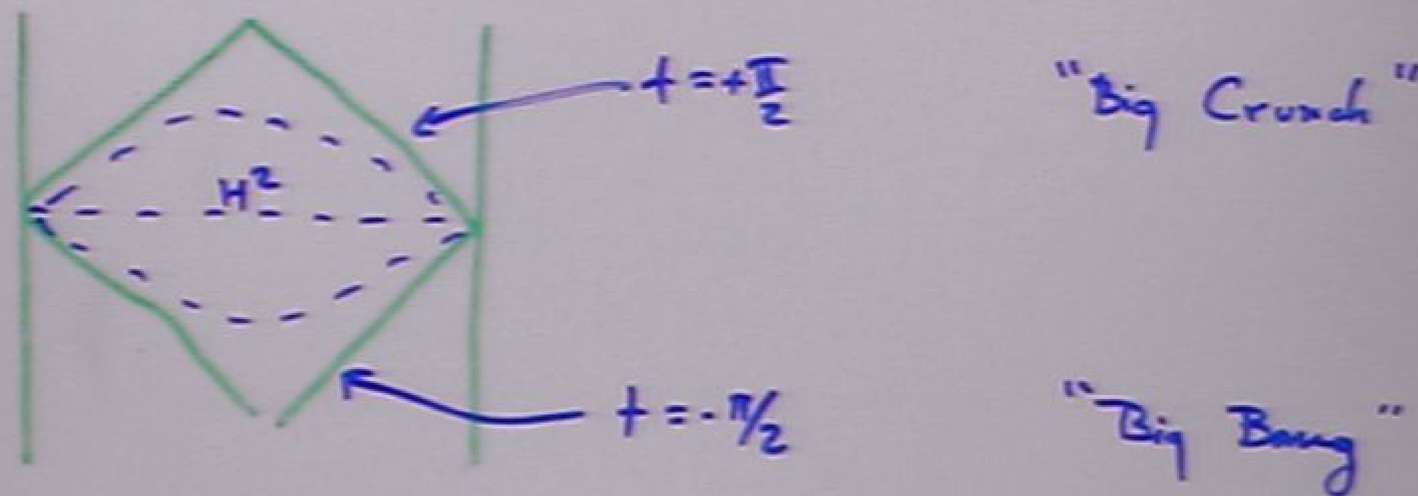
→ Rule out FGG instanton via general arguments






ρ= Tr |ψ⟩
[ρ, H] = ρ'





$\rightarrow$ Coord don't reach boundary

$\Rightarrow$ Holographic encoding is subtle

$\rightarrow$ $t = \pm \frac{\pi}{2}$ are just coord. sing.

$\approx$ Milne singularities of flat space

Trick :

$t = -\pi/2$ "Big Bang"

→ Coord don't reach boundary

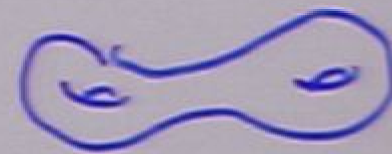
⇒ Holographic encoding is subtle

→ $t = \pm \frac{\pi}{2}$ are just coord. sing.

≈ Milne singularities of flat space

Trick : turn into real cosmology by orbifolding

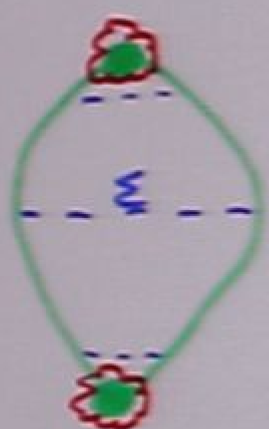
$$H_2 \to \Sigma = H_2 / \Gamma \qquad \Gamma \subset SL(2,\mathbb{R})$$

We can take $\Sigma =$ 

$\rightarrow$ compact Riemann Surfaces

genus $g \geq 2$

$\Rightarrow$ Closed FRW Cosmology



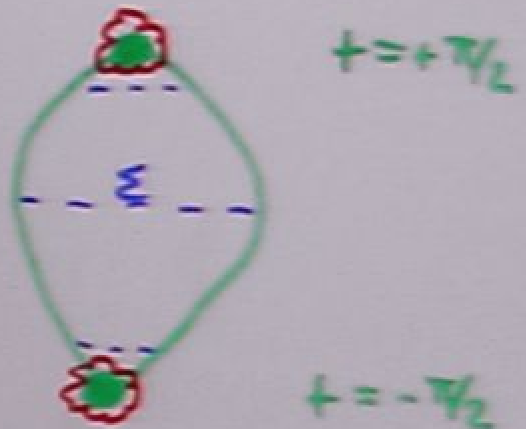
$t = +\pi/2$

$$-dt^2 + \cos^2 t \, d\Sigma^2$$

$t = -\pi/2$

No boundary ! How to apply AdS/CFT ?

1) Orbifold Bdy CFT ... Hard !



$$-dt^2 + \cos^2 t \, d\Sigma^2$$

No boundary ! How to apply AdS/CFT ?

1) Orbifold Bdy CFT ... Hard !

→ $\Gamma \sim$ radial direction $\sim$ orbifold by RG

→ Action of Γ is ergodic

→ 2) Apply Euclidean AdS/CFT ...

$dt_E^2 + \cosh^2 t_E \, d\Sigma^2$ has two smooth

$t = -\pi/2$

No boundary! How to apply AdS/CFT ?

1) Orbifold Bdy CFT ... Hard !

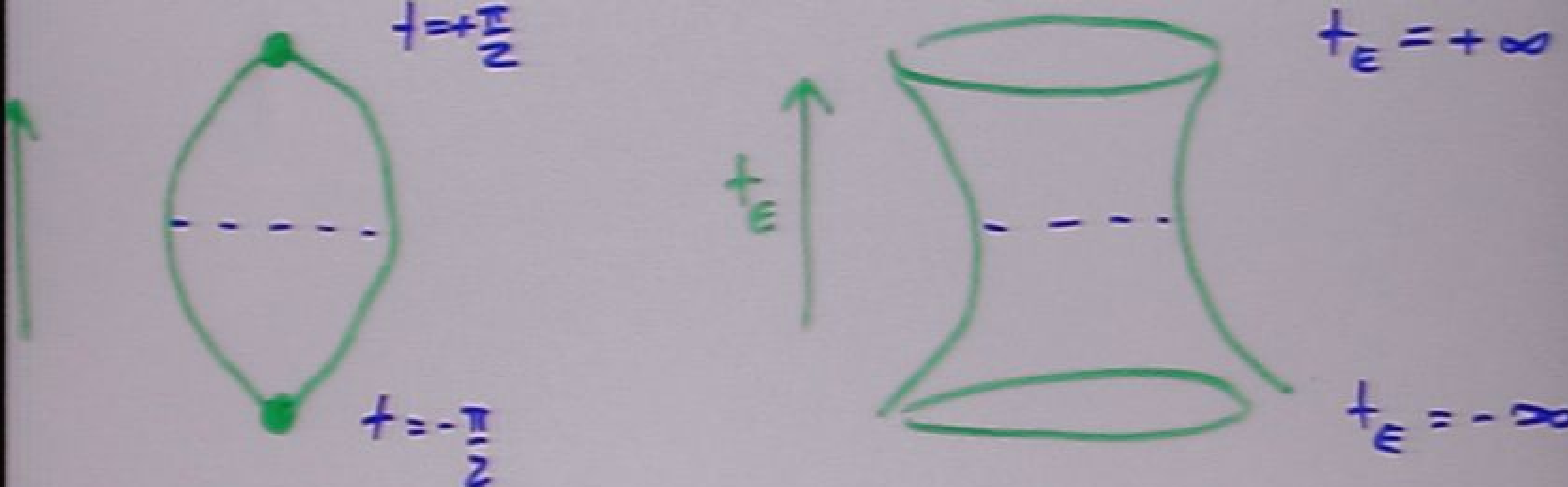
$\rightarrow$ $\Gamma \sim$ radial direction $\sim$ orbifold by RG

$\rightarrow$ Action of Γ is ergodic

$\rightarrow$ 2) Apply Euclidean AdS/CFT ...

$dt_E^2 + \cosh^2 t_E \, d\Sigma^2$ has two smooth Euclidean boundaries at $t_E \rightarrow \pm\infty$

Goal: translate Euclidean AdS/CFT Dictionary into language of cosmology.



Use Euclidean CFT to define state of the theory $\approx$ Hartle-Hawking wave function

Recall AdS-Sch BH :

$$dt_E^2 + \cosh^2 t_E \, d\Sigma^2$$

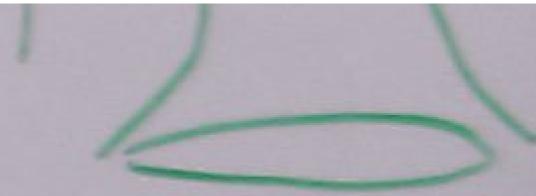
Use Euclidean CFT to define state of the theory $\approx$ Hartle-Hawking wave function

Recall AdS-Sch BH :

Euclidean CFT on torus 

defines the mixed state $\rho = e^{-\beta H}$ of the Lorentzian CFT.

$t = -\frac{\pi}{2}$



$t_E = -\infty$

Use Euclidean CFT to define state of the theory $\approx$ Hartle - Hawking wave function

Recall AdS - Sch BH :

Euclidean CFT on torus 

defines the mixed state $\rho = e^{-\beta H}$ of the Lorentzian CFT.

Here, we have no Lorentzian Bdy CFT,

Recall AdS - Sch BH :

Euclidean CFT on torus 

defines the mixed state $\rho = e^{-\beta H}$ of

the Lorentzian CFT.

Here, we have no Lorentzian Bdy CFT,

but we can still use Euclidean CFT to

define a Bulk state ...

QFT Approx.

Scalar ϕ in fixed background ...

The state $|E\rangle$ is defined by a choice of mode decomposition:

$$\phi = \sum_K a_K \phi_K + c.c. \quad \Rightarrow \quad a_K |E\rangle = 0$$

How to choose basis of modes ϕ_K ?

At $t_E \to \infty$, two possible B.C. :

$\phi \sim e^{-(1+\mu) t_E} \to 0$ normalizable : $\langle O \rangle_{CF}$

mode decomposition:

$$\phi = \sum_K a_K \phi_K + c.c. \quad \Rightarrow \quad a_K |E\rangle = 0$$

How to choose basis of modes ϕ_K ?

At $t_E \to \infty$, two possible B.C. :

$\phi \sim e^{-(1+\mu)t_E} \to 0$ normalizable : $\langle O \rangle_{CFT}$

$\phi \sim e^{-(1-\mu)t_E} \to \infty$ non-normalizable : $\delta \mathcal{L}_{C}$

Demanding normalizable B.C. & analytically continuing:  defines $|E\rangle$

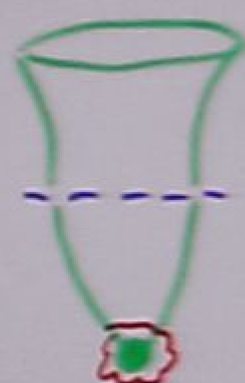
How to choose basis of modes ϕ_K ?

At $t_E \to \infty$, two possible B.C. :

$\phi \sim e^{-(1+\mu) t_E} \to 0$ normalizable : $\langle O \rangle_{CFT}$

$\phi \sim e^{-(1-\mu) t_E} \to \infty$ non- normalizable : $\delta \mathcal{L}_{CFT}$

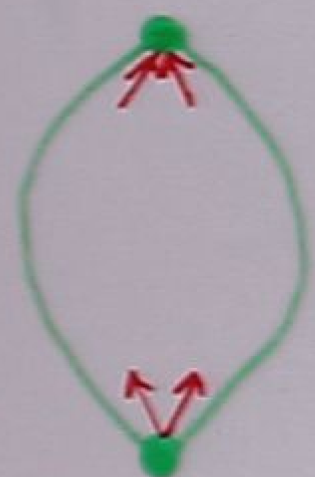
Demanding normalizable B.C. & analytically continuing :



defines $|E\rangle$

What does $|E\rangle$ look like ?

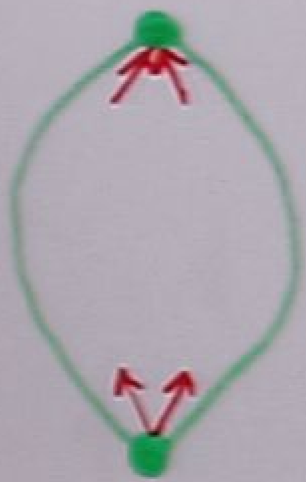
There are two other natural vacua



$|out\rangle$ = no particles entering B.C

$|in\rangle$ = no particles emerging from B.B.

with respect to which $|E\rangle$ looks like a squeezed state $|E\rangle = e^{\gamma_k a_k^{+\,2}} |in\rangle$



$|out\rangle$ = no particles entering B.C.

$|in\rangle$ = no particles emerging from B.B.

with respect to which $|E\rangle$ looks like a squeezed state $|E\rangle = e^{\gamma_k a_k^{+2}} |in\rangle$

with occupation numbers

$$N_k \sim |\gamma_k|^2 = \frac{1}{e^{-E/T} - 1}$$

$|in\rangle$ = no particles emerging
from B.B.

with respect to which $|E\rangle$ looks like a squeezed state $|E\rangle = e^{\gamma_k a_k^{+2}} |in\rangle$

with occupation numbers

$$N_k \sim |\gamma_k|^2 = \frac{1}{e^{-E/T} - 1}$$

$\Rightarrow$ Thermal Bose Distribution !

→ Here, we mean thermal w.r.t.

$$H = \frac{1}{\cos t} \nabla^2_\Sigma$$

laplacian on Σ

redshift factor

so temperature near B.B. & B.C.

is $T \sim (\cos t)^{-1} \times \frac{1}{R_{AdS}}$

⇒ large backreaction

→ Also seen from unruh argument

redshift
factor

so temperature near B.B. & B.C.

is $T \sim (\cos t)^{-1} \times \frac{1}{R_{AdS}}$

$\Rightarrow$ large backreaction

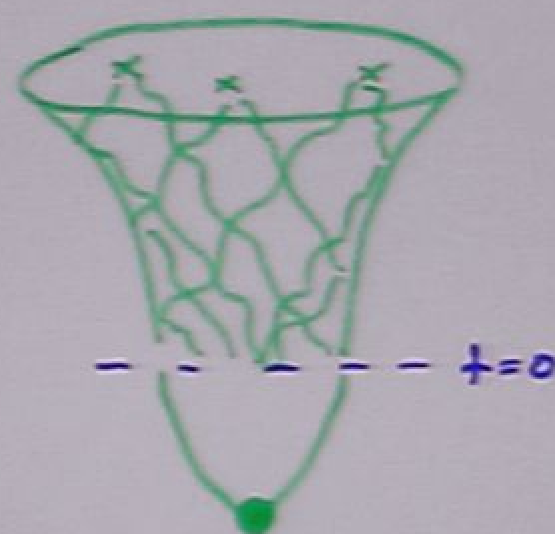
$\rightarrow$ Also seen from unruh argument

$\rightarrow$ Strange : thermal behavior w/o periodicity in Euclidean time !

$\rightarrow$ Check : in B.H. case it gives the usual Hawking Temperature

Higher States

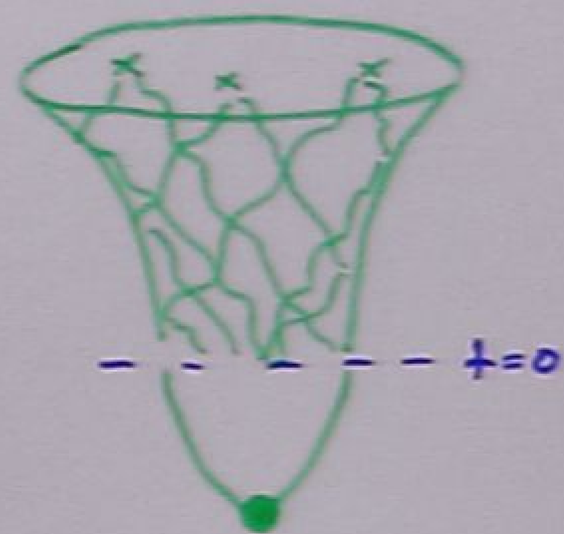
Excited states are found by inserting CFT Operators on the Euclidean Bdy :



Collection of CFT Operators $\qquad\qquad$ Bulk State

$$O_1(\sigma_1)\dots O_n(\sigma_n) \Longleftrightarrow a^{+}(\sigma_1)\cdots a^{+}(\sigma_n)\,|E\rangle$$

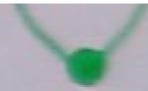
CFT Operators on the Euclidean Bdy :



Collection of CFT Operators $\Longleftrightarrow$ Bulk State

$$O_1(\sigma_1)\dots O_n(\sigma_n) \Longleftrightarrow a^\dagger(\sigma_1)\dots a^\dagger(\sigma_n)\,|E\rangle$$

$\Rightarrow$ Euclidean CFT operators as a way of Organizing Lorentzian Hilbert Space



Collection of CFT Operators $\qquad$ Bulk State

$$O_1(\sigma_1) \ldots O_n(\sigma_n) \Longleftrightarrow a^{+}(\sigma_1) \ldots a^{+}(\sigma_n) \, |E\rangle$$

$\Rightarrow$ Euclidean CFT operators as a way of Organizing Lorentzian Hilbert Space

$\rightarrow$ c.f. Witten's QG on dS

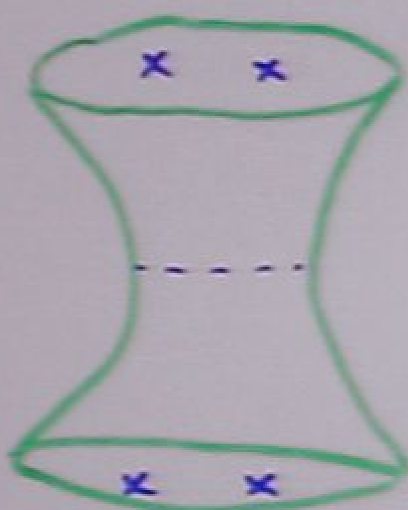
Moral: Here Γ destroyed lorentzian conformal group, but Euclidean group is still useful

$\rightarrow$ toy model of dS

So ECFT operators define a Hilbert space $\mathcal{H}$ of this cosmology.

Then ECFT correlation functions define an inner product on $\mathcal{H}$:

FT 1 $\qquad f(o) \longrightarrow$ state $|f\rangle$

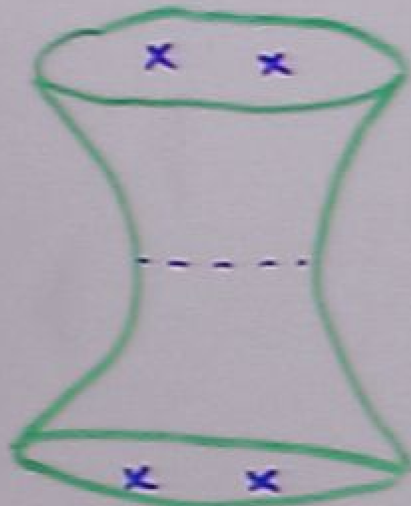


FT 2 $\qquad g(o) \longrightarrow$ state $|g\rangle$

$$\left\langle e^{\int f O_1 + \int g O_2} \right\rangle_{CFT} = Z_{GRAVITY}(f, g)$$

inner product on $\mathcal{H}$:

FT 1 $\qquad f(\sigma) \longrightarrow$ state $|f\rangle$



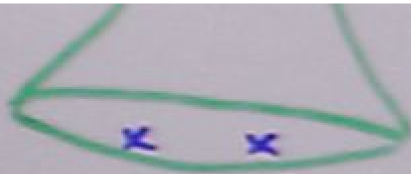
FT 2 $\qquad g(\sigma) \longrightarrow$ state $|g\rangle$

$$\left\langle e^{\int f O_1 + \int g O_2} \right\rangle_{CFT} = Z_{GRAVITY}(f, g)$$

$$= \langle f | g \rangle$$

At the level of bulk QFT,

$|f\rangle = e^{\int f a^{+}} |E\rangle$ is a coherent state

T 2  $g^{(0)} \longrightarrow$ state $|g\rangle$

$$\left\langle e^{\int f O_1 + \int g O_2} \right\rangle_{CFT} = Z_{GRAVITY}(f, g)$$

$$= \langle f | g \rangle$$

At the level of bulk QFT,

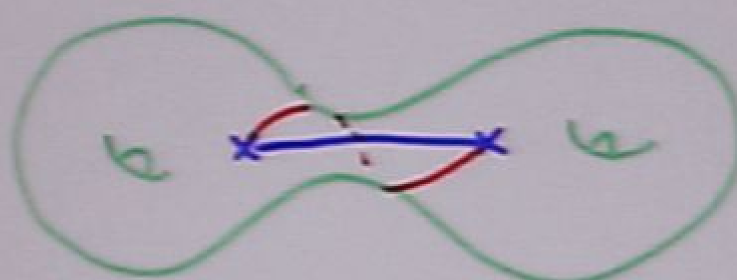
$|f\rangle = e^{\int f a^{+}} |E\rangle$ is a coherent state

and the overlap $\langle f | g \rangle$ really is a CFT generating function.

Euclidean CFT Correlators

In the semi-classical approximation :

$$\langle O(\sigma_1)\, O(\sigma_2) \rangle = \sum_{\substack{\text{bulk}\\\text{geodesics}}} e^{-\Delta \ell} = \sum_{\substack{\text{bdy}\\\text{geodesics}}} (\sinh \ell_i)^{-\Delta}$$



For two points on the same boundry.

This is what we would expect for CFT on negative curvature Riemann Surface.

For two points on the same boundy.

This is what we would expect for CFT on negative curvature Riemann Surface.

In fact, for two points on opposite boundaries:

$$\langle O(\sigma_1)\, O'(\sigma_2) \rangle = \sum (\cosh l_i)^{-\Delta}$$

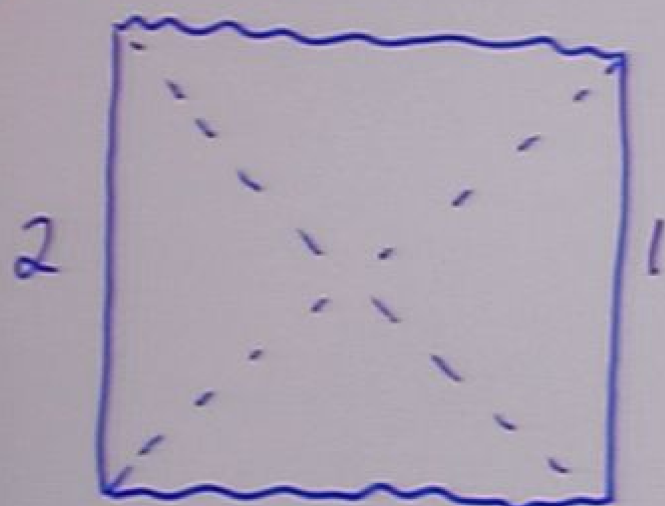
So correlators between two bdies are non-zero & related by analytic continuation

$$l \to l + \pi i$$

Geodesic Probes of B.B. Sing.

Q: How does the ECFT encode information about the B.B. Sing. ?

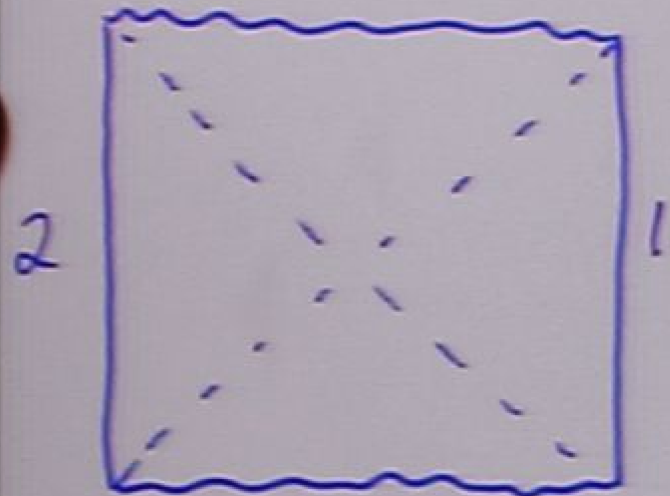
Motivation : BTZ



2 identical bdy CFTs

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$$

$$\mathcal{H}_1 = \mathcal{H}_2$$



2 identical bdy CFTs

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$$

$$\mathcal{H}_1 = \mathcal{H}_2$$

CFTs don't interact, but are in an entangled state

$$|\Psi\rangle = \sum_{|i\rangle} e^{-\beta E_i/2} \, |i_1\rangle \otimes |i_2\rangle$$

which leads to correlations between the two sides...

So the observables of the system

1) $\langle O_1 O_{a_1} \rangle = \mathrm{Tr}_2 \langle \Psi | O_1 O_{a_1} | \Psi \rangle$

$\sim$ thermal correlators

2) $\langle O_1 O_2 \rangle \neq 0$ due to entanglement

are formally related by analytic continuation of the boundary time coordinate

$$\langle O_1(t)\, O_2(t') \rangle = \langle O_1(t)\, O_1(t' + \tfrac{i\beta}{2}) \rangle$$

From the bulk point of view we can calculate

$\langle O_1 O_2 \rangle \neq 0$ due to entanglement

are formally related by analytic continuation of the boundary time coordinate

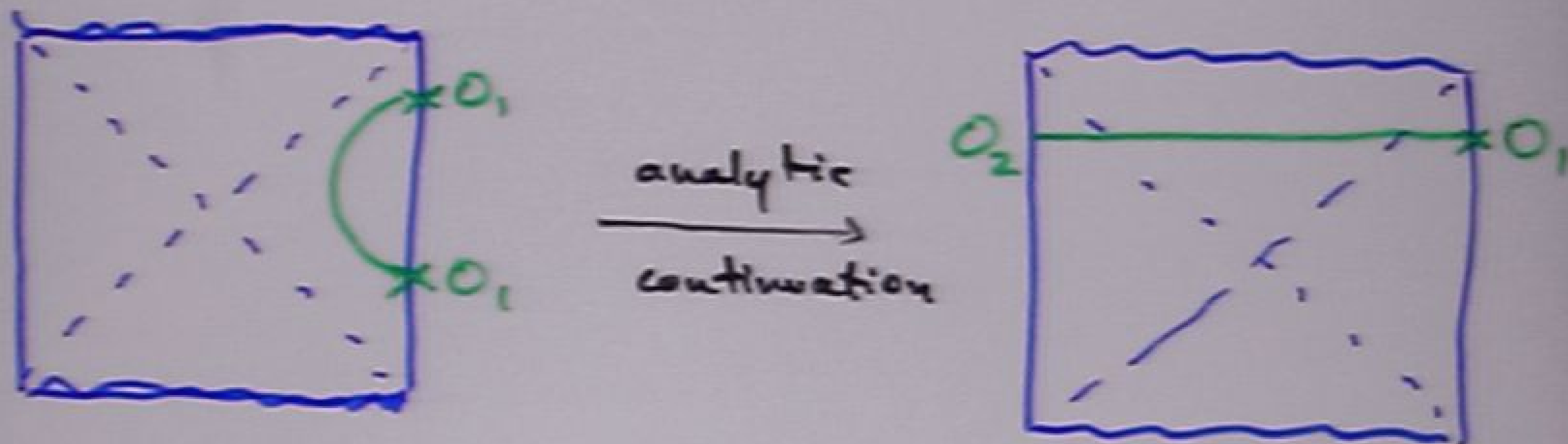
$$\langle O_1(t)\, O_2(t') \rangle = \langle O_1(t)\, O_1(t' + \tfrac{i\beta}{2}) \rangle$$

From the bulk point of view, we can calculate these correlation functions semi-classically

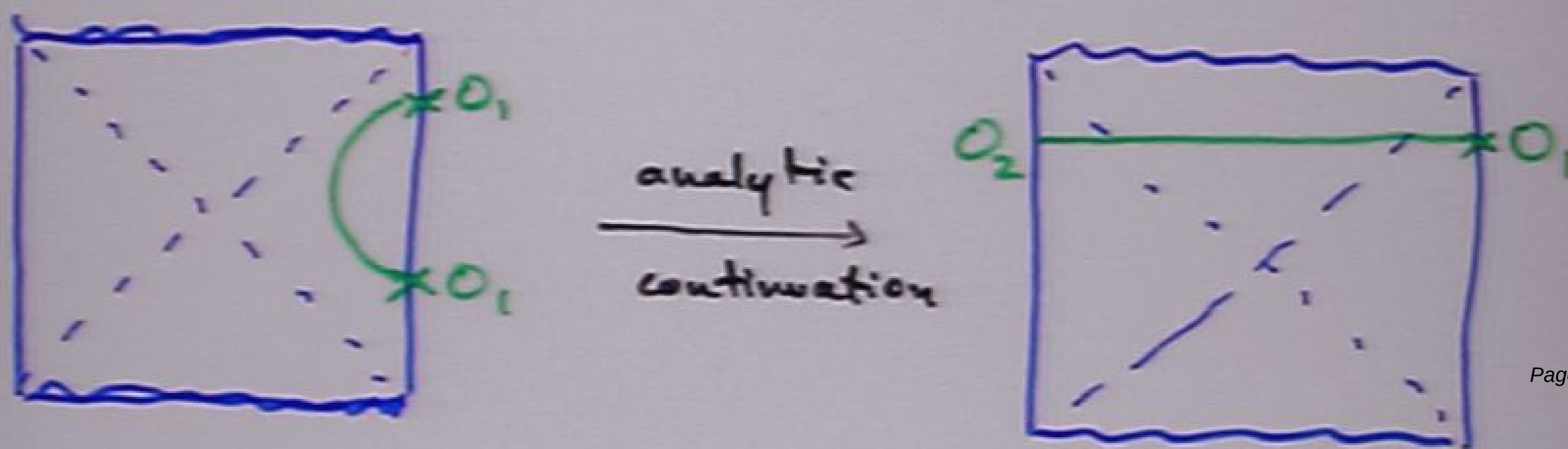
$$\langle O\, O' \rangle \sim e^{-\Delta \ell}$$

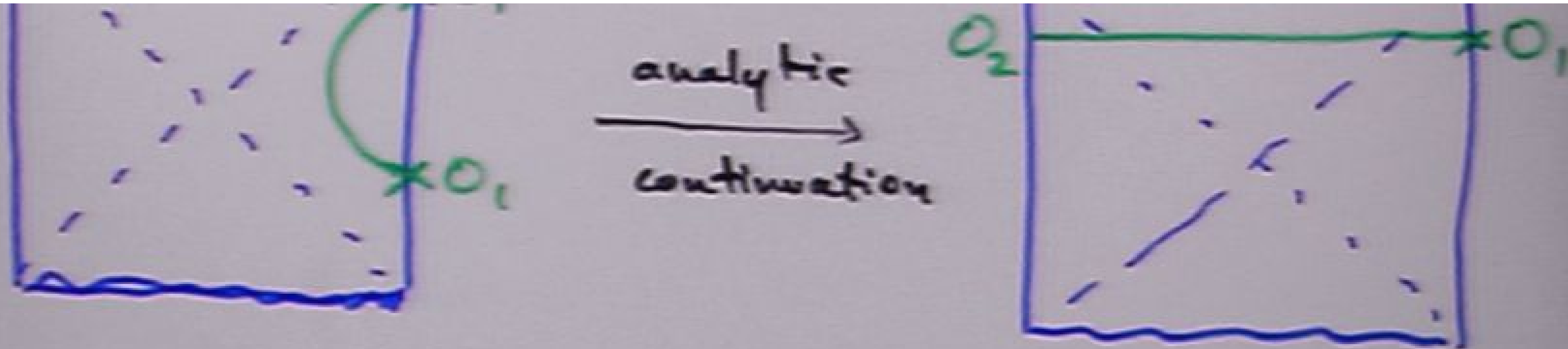
geodesic length in bulk

dimension



So by analytically continuing correlation functions $\langle O_1 O_1 \rangle$ in CFT_1, we find out about the geometry of the BH


O_1
O_1
analytic
continuation
O_2
O_1



So by analytically continuing correlation functions $\langle O_1 O_1 \rangle$ in CFT_1, we find out about the geometry of the BH behind the horizon. In particular, we can learn about the singularity.

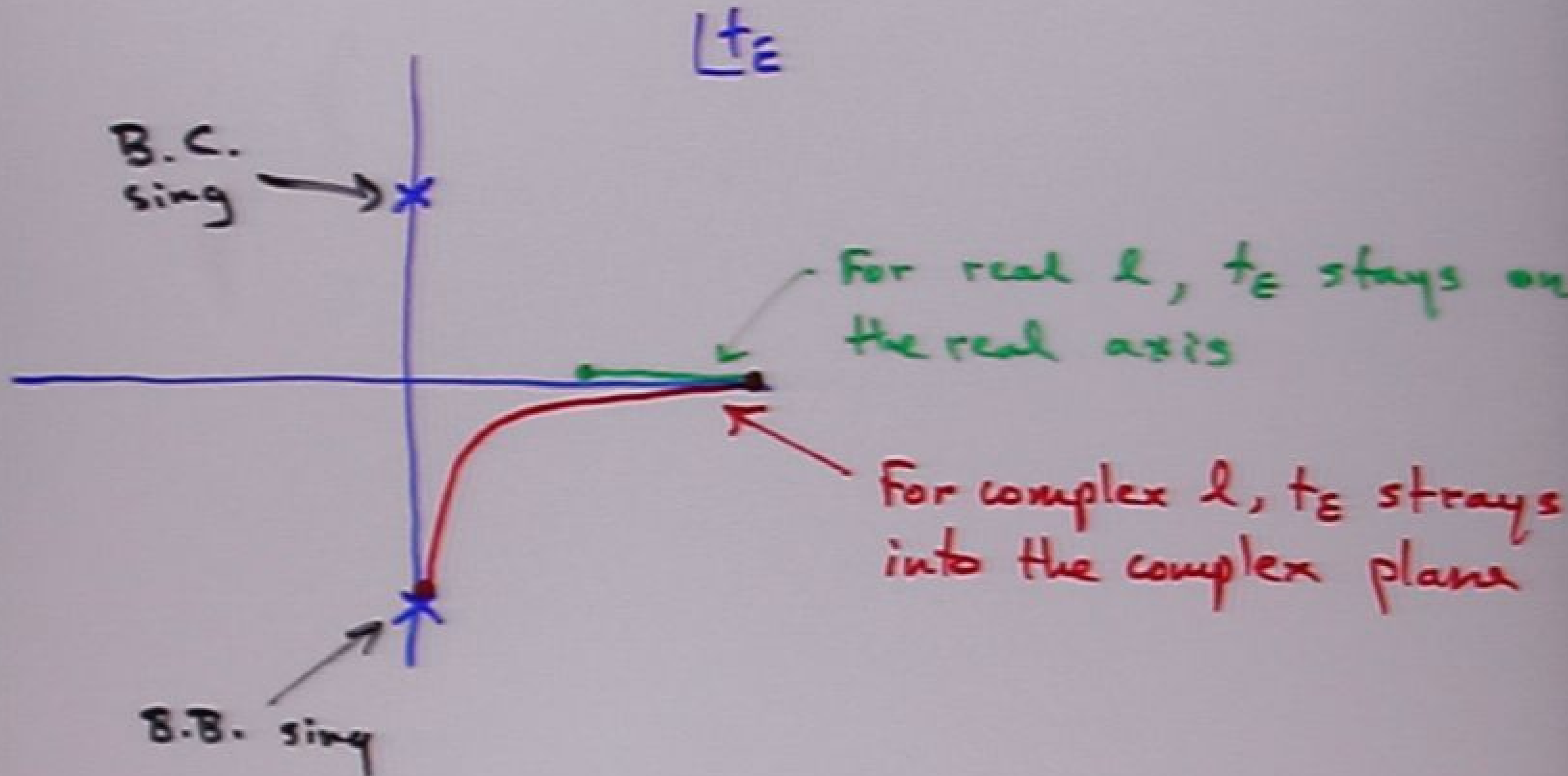
Can we do the same for our cosmological

find out about the geometry of the B
behind the horizon. In particular, w
can learn about the singularity.

Can we do the same for our cosmological
singularities? In the leading approx,
$\langle O(\sigma_1) O(\sigma_2) \rangle$ depends only on ℓ
⇒ calculate geodesic profile $t_E(\ell)$

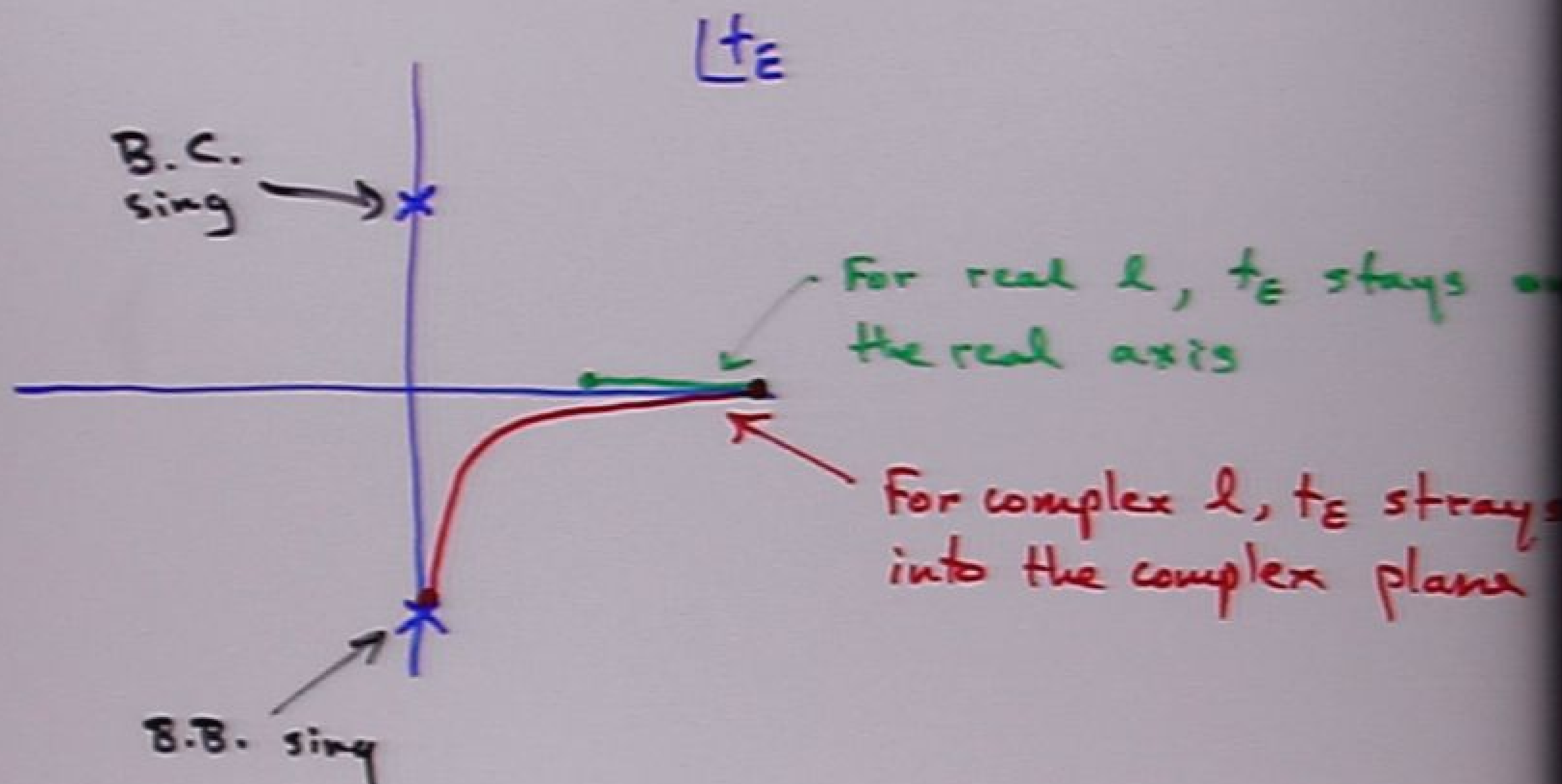
⇒ Analytically continue ℓ

Where does the geodesic go?



r certain complex values $\ell = (2n+1)\pi i$ the geodesic hits a B.B./B.C. singularity!

(depending on a branch choice)



For certain complex values $l = (2n+1)\pi i$ the geodesic hits a B.B./B.C. singularity!

(depending on a branch choice)

Open Problems

Can we understand more interesting (non δ fn) singularities ?

→ Higher dimensional Examples

(actually, for Σ compact, our cosmology will already develop more severe curvature sing. once back-reaction is included)

Can we actually do any CFT calculations?

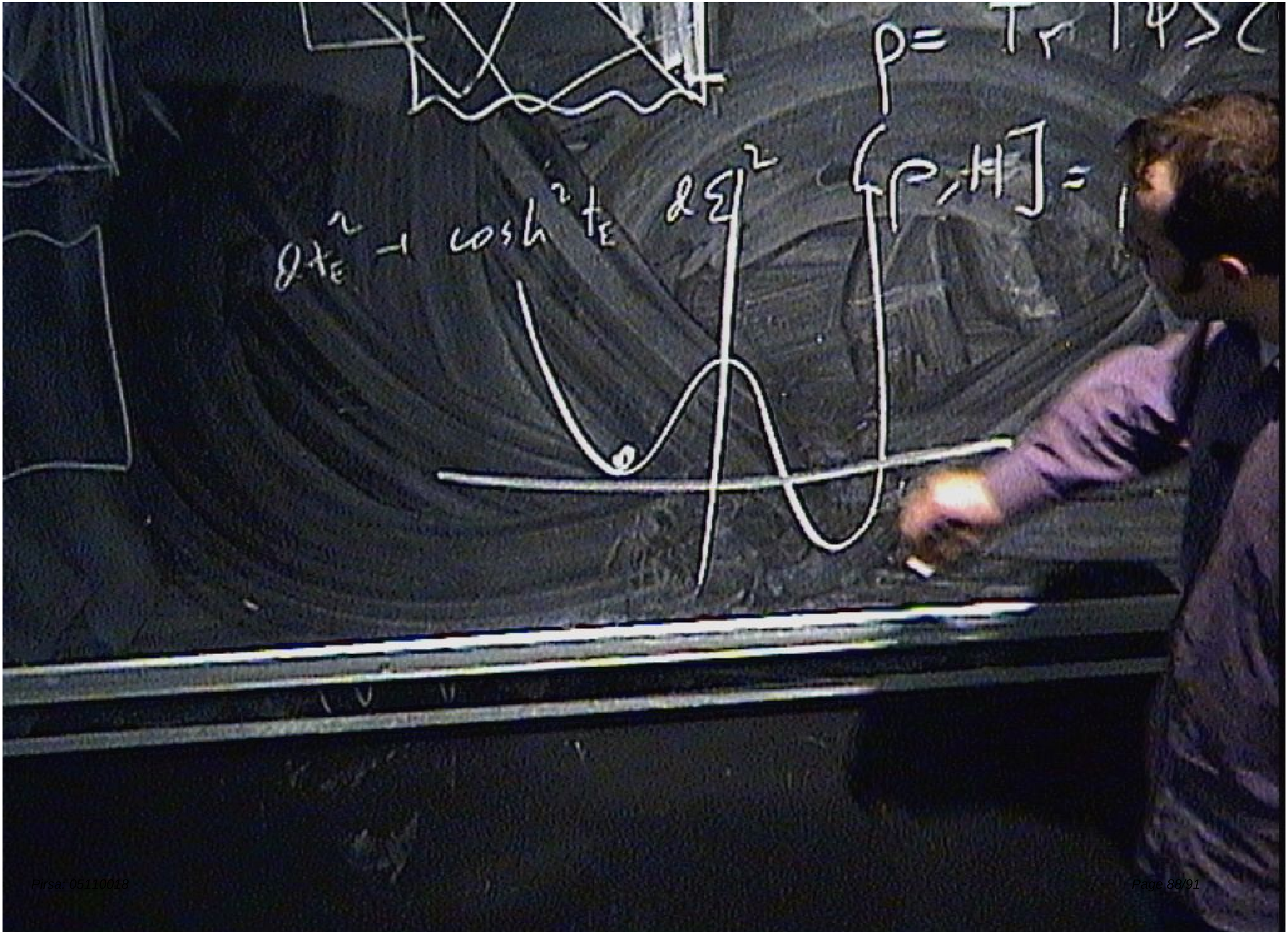
→ Higher dimensional Examples

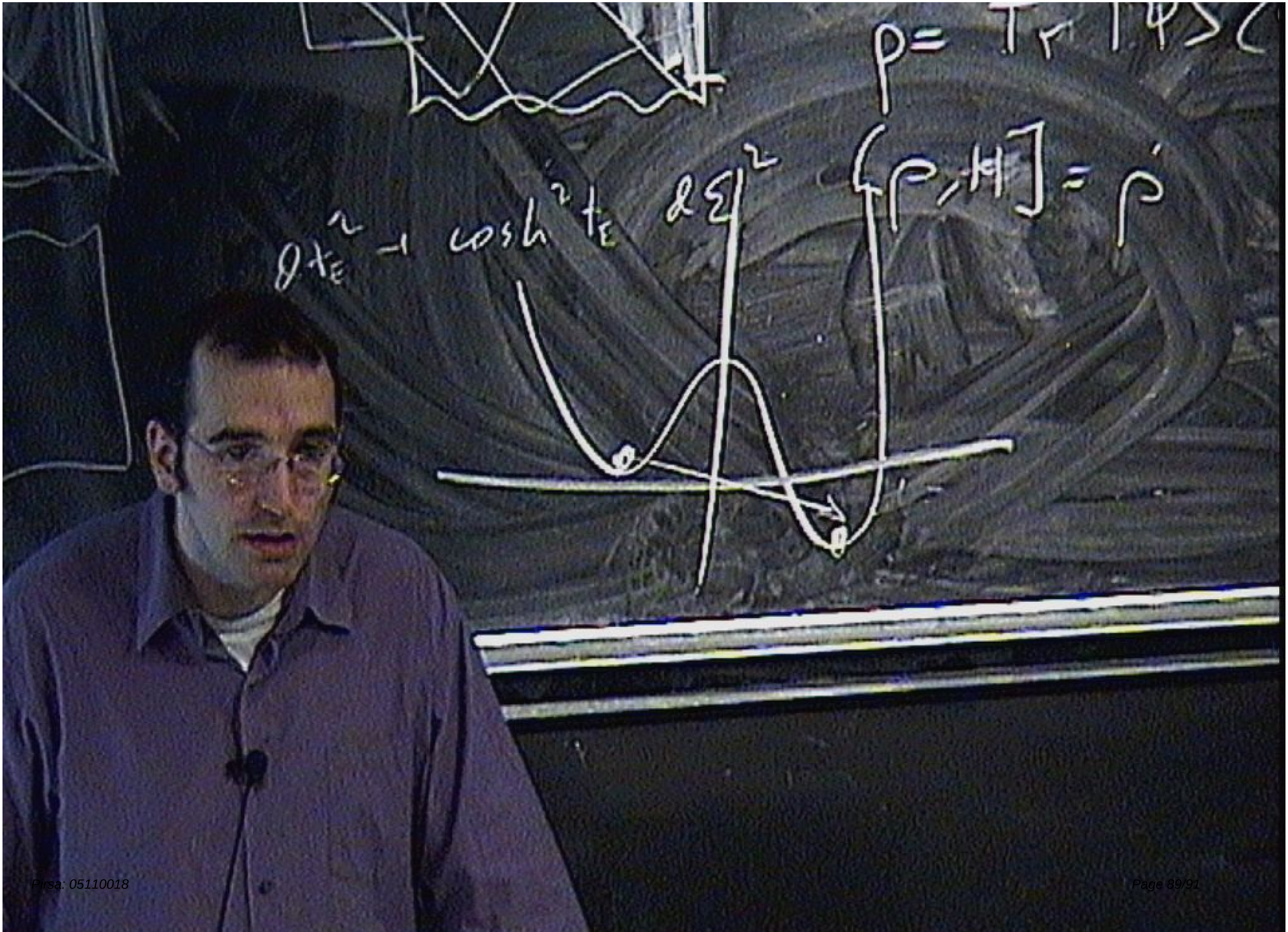
(actually, for Σ compact, our cosmology will already develop more severe curvature sing. once back-reaction is included)

Can we actually do any CFT calculations?

→ See resolution of singularity

→ requires mathematical machinery


ρ= Tr |ψ⟩⟨
[ρ, H] =
dt_E^2 − cosh^2 t_E dΣ^2



→ Higher dimensional Examples

(actually, for Σ compact, our cosmology will already develop more severe curvature sing. once back-reaction is included)

Can we actually do any CFT calculations?

→ See resolution of singularity

→ requires mathematical machinery