# The Nature of Time in String Theory

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Strings 2002 Cambridge UK

STRING

CFT

Mirror Symmetry

Topological FT

Duality

Over the last decade or so there has been a flood of mind-boggling results emanating from string theory. But most have a similar character: they involve static configurations with SUSY. We have learned much about the nature of space: it is not an absolute concept

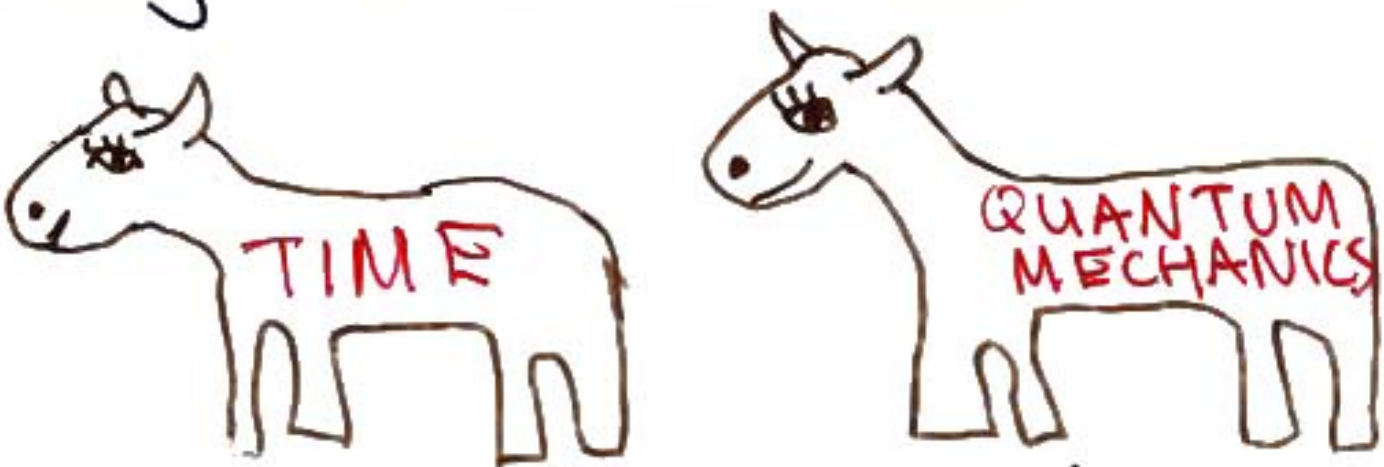
D-branes

Black Holes

Calabi-Yau

AdS


The nature of time in string theory is more elusive. If space has no absolute meaning, neither should time. But QM needs an exact notion of time. Is it time to challenge the sacred cows?



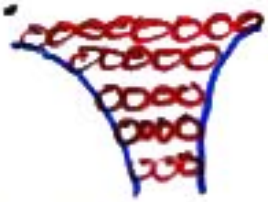

A next step in our stringy adventures is to study the nature of time & see where it leads us.

# Some Interesting Questions

1. What is the origin of the universe?


2. What happens if you fall inside a BH? What resolves the Schwarzchild singularity?

3. Are there continuous new degrees of freedom in an expanding universe?



4. Can the entropy of an observer horizon be statistically explained?


Our current bag of tricks can't answer these questions. We can look for new ones by studying time-dependent string configurations.

No obvious path to answers.
Some questions/approaches.

I.) What kind of phenomena should we expect in time-dependent string theory?

II.) How can our understanding of static cases be adapted to time dependent ones?

III.) What concrete calculations are possible?

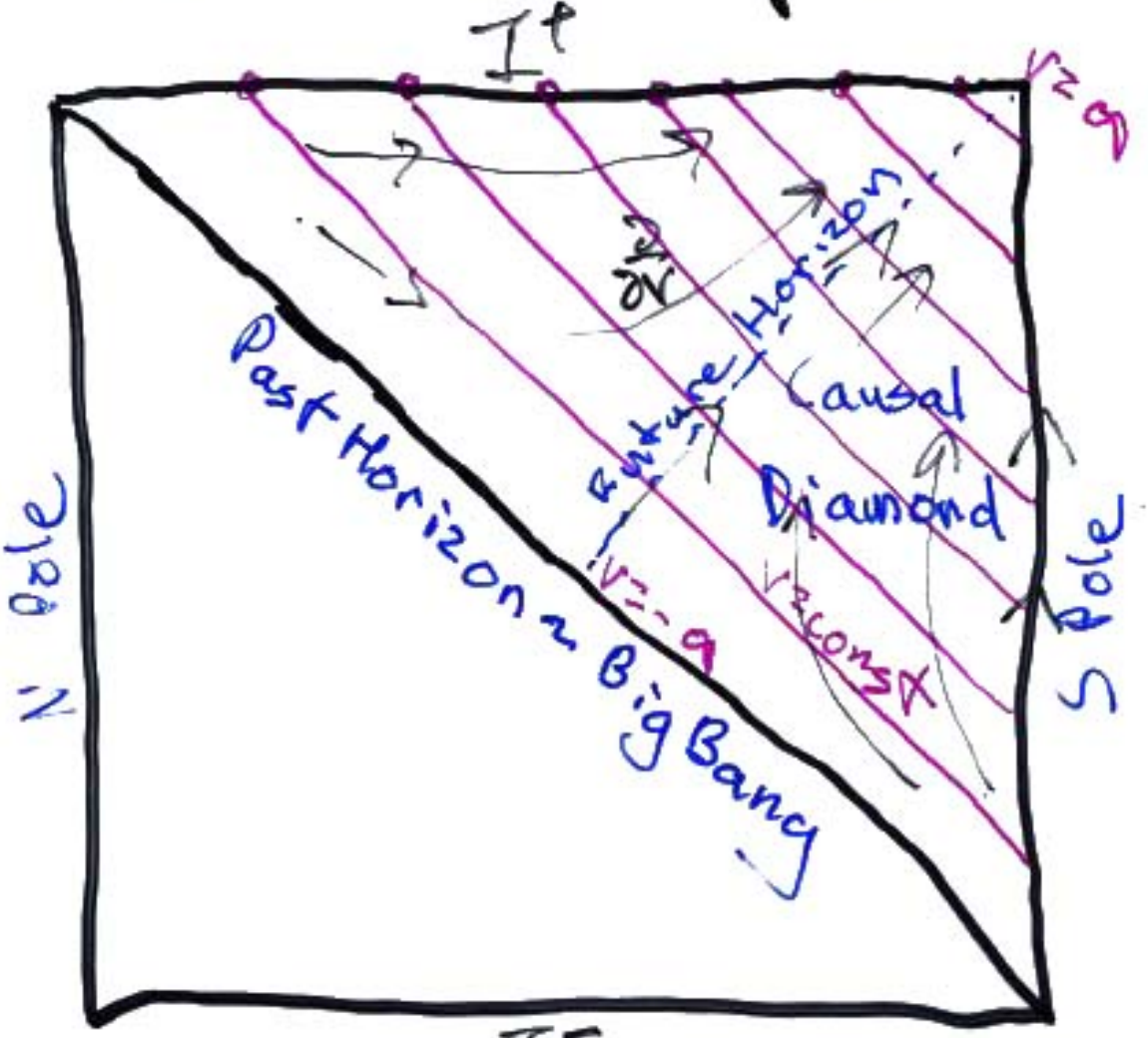
The rest of the talk will describe my own recent explorations.

Interesting recent work on these questions includes

Banks Fischler Susskind Bousso Hull
Liu Moore Seiberg Sen Horowitz
Polchinski Narayan Balasubramanian
Manic Gibbons Pope Witten Cornalba Myers
Fabinger McGreevy Kachru Veneziano Gueron...

My collaborators are
Bousso Gutperle Maloney Silverstein

# de Sitter Space




$$ds^2 = -(1-r^2)dv^2 - 2dvdr + r^2 d\Omega_2^2$$

covers future of S pole. In cosmological contexts, past horizon is replaced by big bang.

$L_0 \sim \partial_v$ is timelike in causal diamond and spacelike near $I^+$. Time translations at S pole are dilations at $I^+$.

# Some dS questions

(I) Does $S = \frac{1}{4}$ Area have a statistical origin for dS? Sharp

(II) Are there observables? Something like an S-matrix?

## A BASIC TENSION

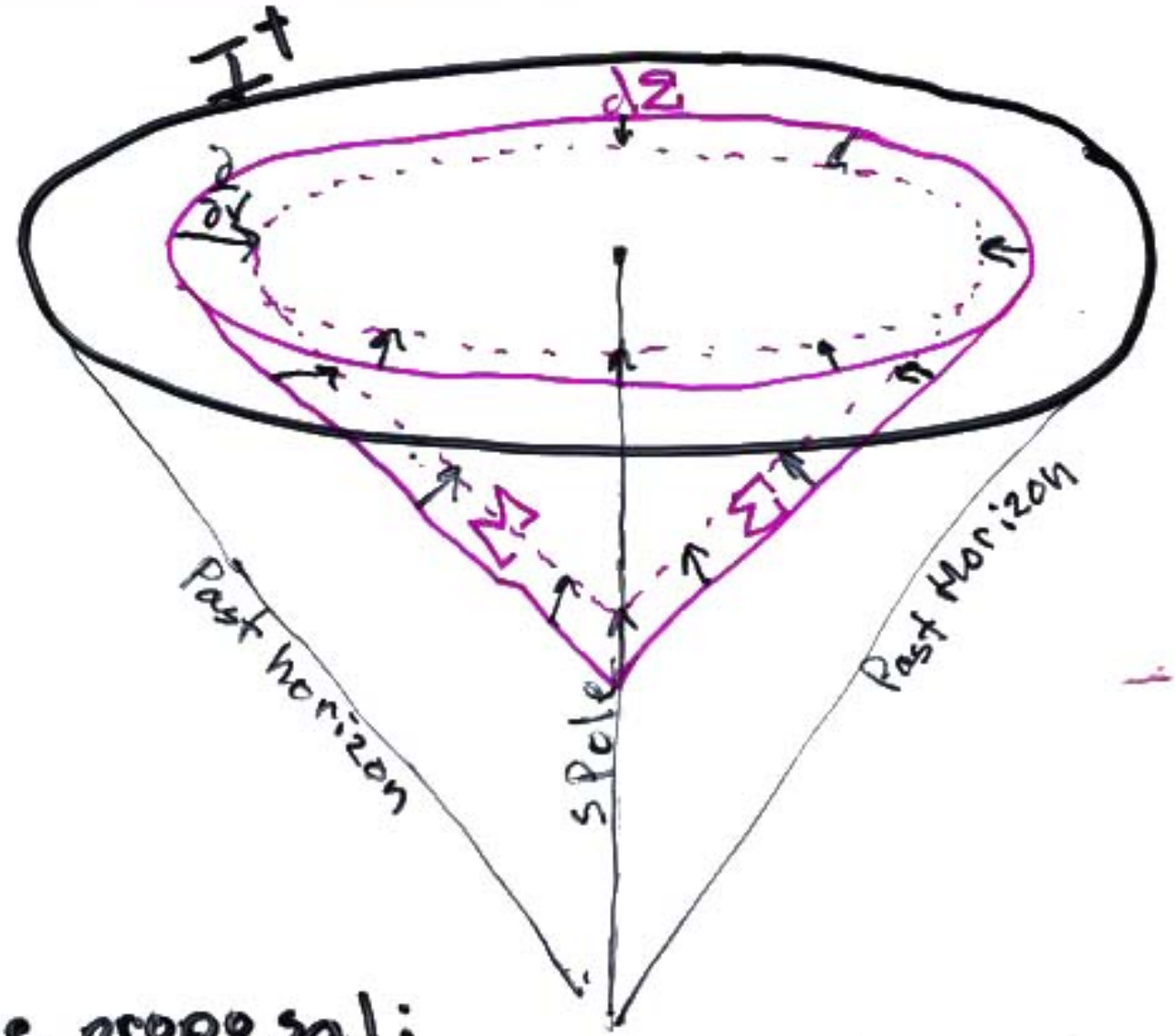
(I) There are no local diff-invariant observables in Q G. Invariant quantities seem best associated with asymptotic boundary data. ($I^{\pm}$ for dS)

(II) We should only discuss physically observable quantities. These seem to be confined to the interior of a single causal diamond of a single observer.

(III) The interior of the causal diamond does not intersect the asymptotic boundary $I^{\pm}$.

We will ignore II, III for now and forge ahead...

# Adapting AdS/CFT holography to dS/CFT holography




**The proposal:**

Bulk dS physics is dual to a boundary CFT on $I^+$. Bulk quantum states on $\Sigma$ are dual to a CFT state on $\partial\Sigma$. Bulk time translation is dual to boundary scale transformation.

Time is holographically reconstructed!

# Evidence

1. Bulk isometry groups boundary conformal group.

2. In $d=3$, Brown-Henneaux type argument shows boundary correlators obey Ward identities of $c = \frac{3\ell_{ds}}{2G}$ CFT. AS

3. Makes sense in proposed M-theory. Hull

4. Numerous gravity calculations flesh out consistent picture. Klemm Spradlin Volovich Bousso Maloney Danielsson McInnes Myers Vanzo Hahyo Medved Marolf Ardalan Nojiri Odintsov deBoer Minic Balasubramanian Cacciatori Li ....

5. Overall, evidence is intriguing but not compelling.

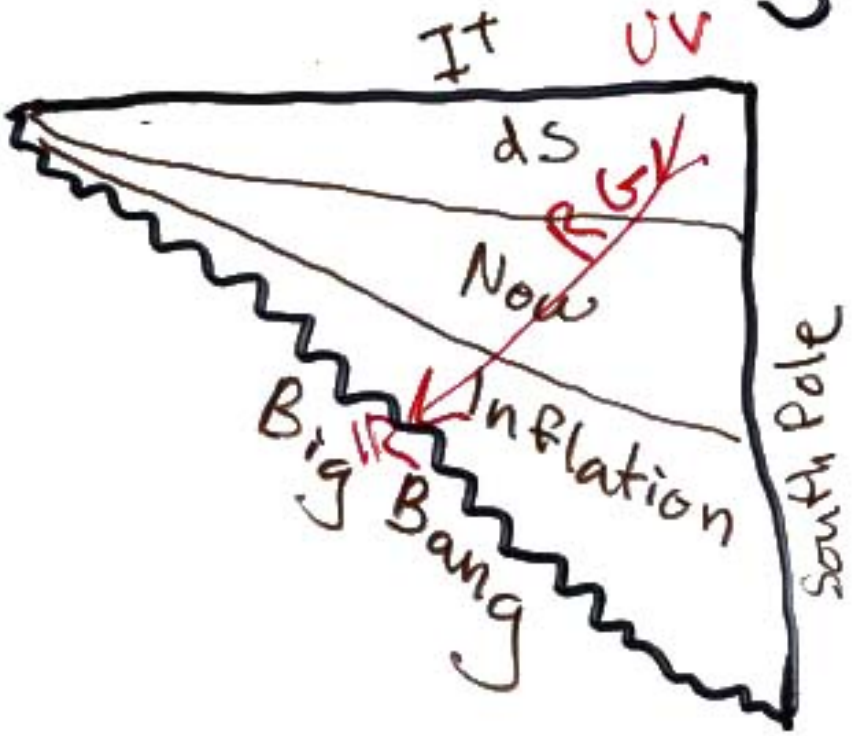
We need to embed into string theory (a bit more later).

# Cosmological Applications

Our own universe is not dS now, but may be asymptotically future dS. Could our universe be dual to a 3D QFT? ~~SO(4,1)~~ so scale transformations → RG flow.

Time evolution
= Inverse RG flow

# What is the Big Bang?




## A trivial IR fixed point!

The origin of the universe is nothing.

This is a timelike analog of the Klebanov-Polchinski-Strassler resolution of GR singularities by confinement.

Do other stringy resolutions of singularities have timelike counterparts?

This is (c) other in Horowitz classification

# Naturalness

Encoding bulk physics in a boundary QFT dramatically changes what is and isn't natural. E.g. the value of $\Lambda$ in the far future is related to the central charge of the UV QFT fixed point. This is input data (c.f. Banks) and is unaffected by any QFT quantum corrections. Also the $\epsilon, \eta$ "slow roll" parameters of inflation are naturally small IR fixed point $\beta$ functions.

Larsen, van der Schaar & Leigh
Halyo Danielsson
Kristjansson & Thorlacius

# Unitarity?

In this picture the d.o.f. of our universe are continuously integrated in with the inverse RG flow. Why is this unitary (or causal)? A similar puzzle arises for bulk causality in AdS/CFT.

More general, how is unitarity ever consistent with the beginning of time in the big bang?

A unitary dual picture? Ekpyrosis? LM's?

We must surely wrestle with this in developing stringy cosmology....

We'd like to make dS/CFT - or more generally timelike holography - precise by embedding in string theory.

Two approaches

(I) Find dS solutions of string theory

Silverstein Maloney AS Hull Gibbons Kallosh Fre Trigiante van Proeyen

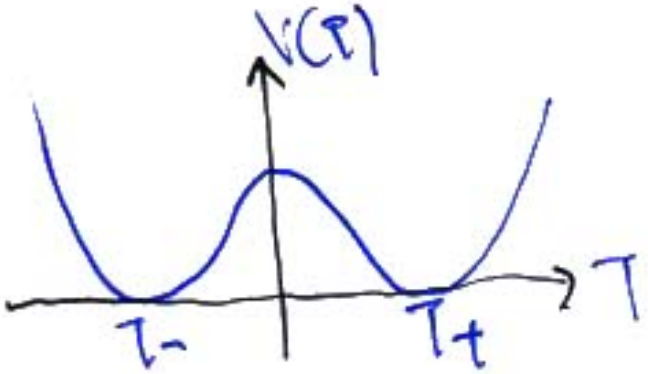
(II) Find euclidean field theories which are candidate duals in string theory

Hull, Gutperle & AS

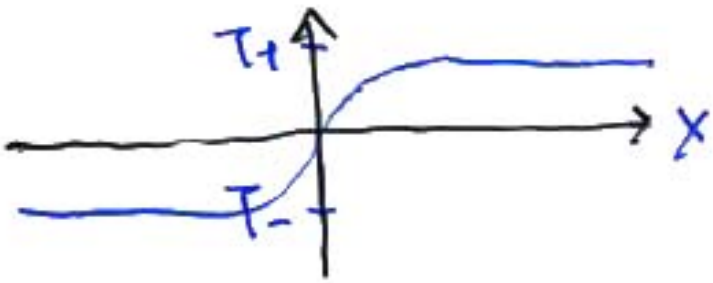
The rest of the talk will focus on the latter.

# Spacelike-Branes

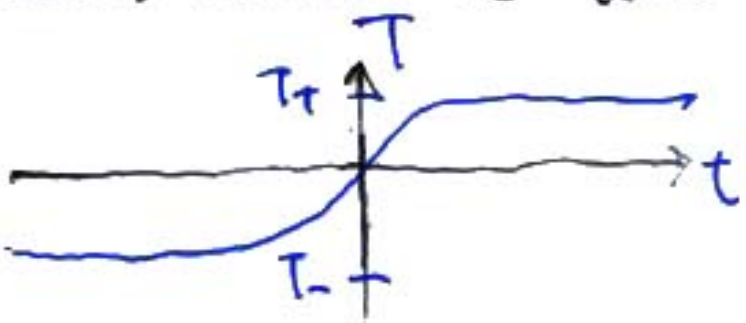
Consider the tachyon field $T$ on the unstable D3 of IIA string theory:




This has a kink solution

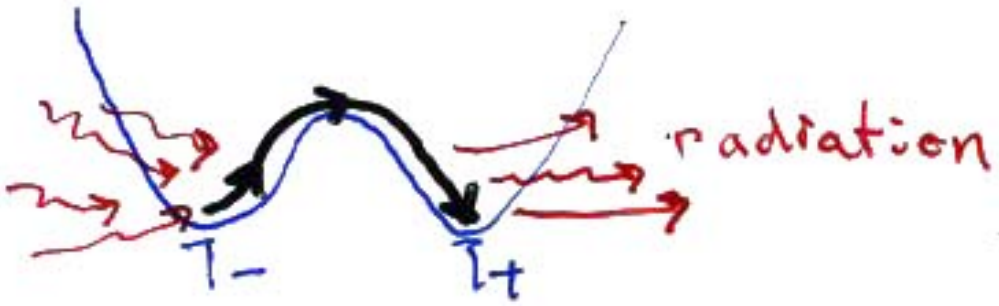



= D2-brane. There is also an S2-brane.



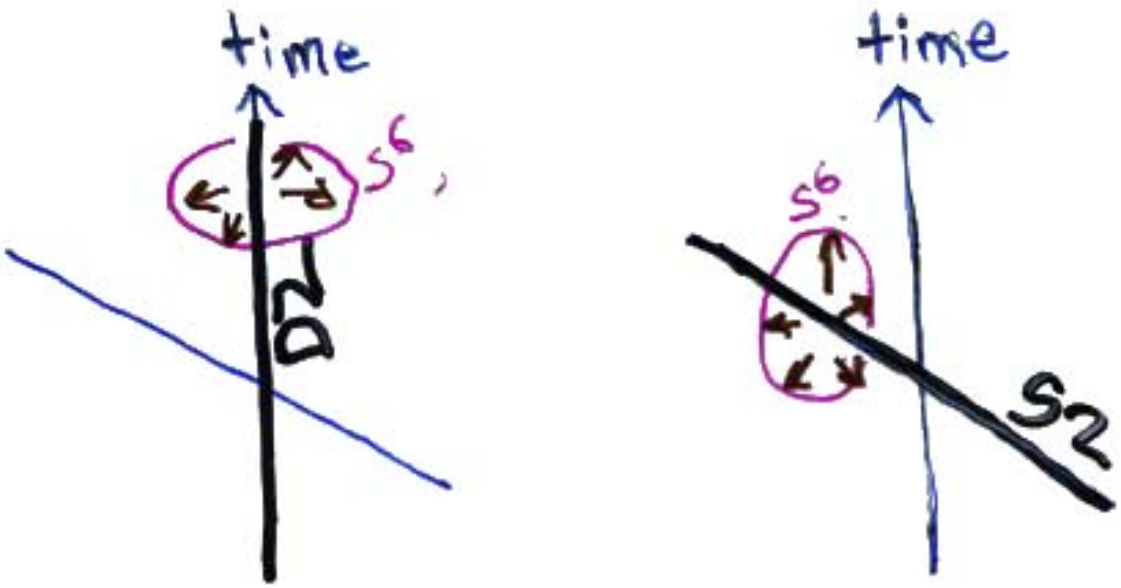

where now the kink is in time.

Energy conservation requires incoming and outgoing radiation




In both cases, $dT \wedge C^{(3)}$ coupling imparts a "charge" to the brane

$Q = \int_{S^6} * dC^{(3)}$




but integrated over different spheres.

For $g_s \to 0$, the S-brane is described by an exact CFT sinh-Gordon sen

$$S_{WS} \sim \int d^2z\, \eta_{\mu\nu} \partial X^\mu \bar{\partial} X^\nu + \oint_{\text{boundary}} T^2(X^0)$$

$$T(X^0) \sim \sinh X^0$$

is a (1,1) operator. There are also half S-branes

$$T(X^0) \sim e^{X^0} = \text{boundary Liouville}$$

Finding the open string spectrum is an interesting exercise in time-dependent string theory. Zamzam & Fateev Teschner

# Zero Mode Analysis

$$L_0 + \tilde{L}_0 = -p_0^2 + \left[p_i^2 + N_{osc} - 1\right] + T^2(X^0) = 0$$

Wave function obeys

$$\left[\frac{\partial^2}{\partial X^{02}} - T^2(X^0)\right]\psi(X^0) = [\text{constant}]\psi(X^0)$$

For $T(X^0) \sim e^{X^0}$, $\psi$ is a Bessel function

$\psi \to e^{i\omega X^0}$ $\quad X^0 \to -\infty$

$\to e^{-X^0/2}\left(ie^{-ie^{X_0} - \frac{\omega\pi}{2}} - ie^{ie^{X_0} + \frac{\omega\pi}{2}}\right)$

$X^0 \to +\infty$

Modes are heavy and oscillate rapidly in future. Particle production

$T \sim \sinh X^0 \to$ Mathieu function.

This is expected. The tachyon is a weight hanging at the


end of the open string which $\to \infty$. The pair production amplitude for anode with incoming energy $\omega$ has a factor

$$e^{-\omega/T_{SD}}$$

where the self-dual temperature

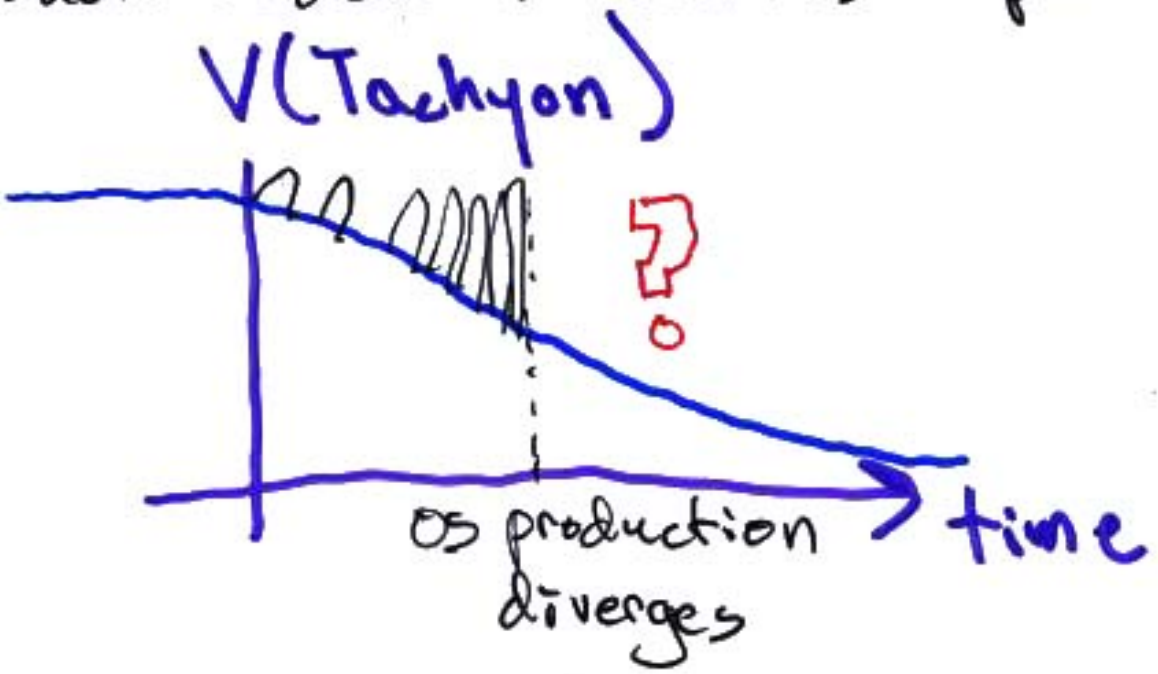
$$T_{SD} > T_{Hagedorn}.$$

Summing over all open string modes to get the total amplitude

$$\text{Total} \sim \sum_{\omega} N_\omega e^{-\omega/T_{SD}} \sim \sum_{\omega} e^{\omega/T_H - \omega/T_{SD}}$$

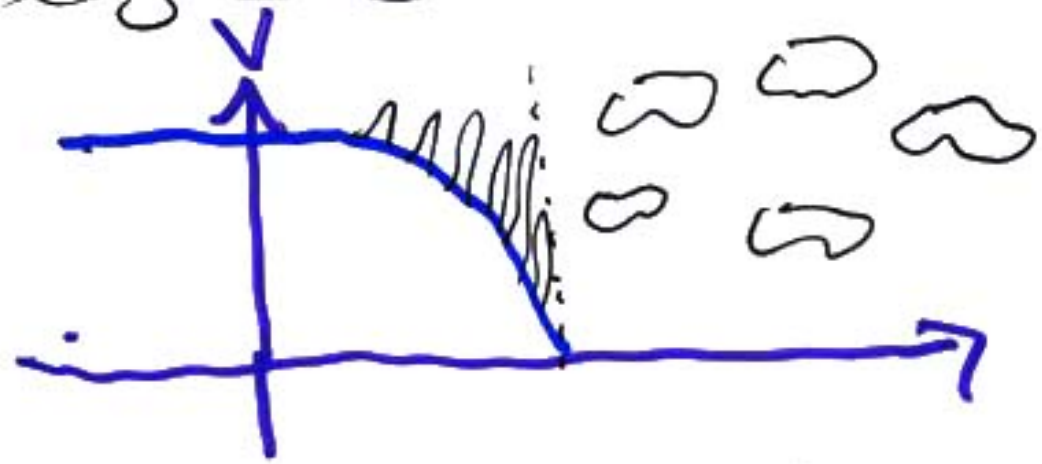
$$\to \infty !$$

The decaying brane tries to infinitely produce open strings. Back reaction becomes important.




What happens?

Conjecture




The brane dumps all its energy into close strings in a time of order $(g_s)^0$.

## Best of all possible worlds

The large N limit of open string theory on an S-brane is holographically dual to a time-dependent closed string cosmology.

## Worst of all possible worlds

We learn something about time dependent open string backgrounds.

# Conclusion

Understanding the nature of time in string theory is challenging. There are deep conceptual issues as well as concrete models to work on.