THE INSIDE STORY: QUASILOCAL TACHYONS AND BLACK HOLES

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In string theory, several types of GR singularities are replaced by a phase of <u>closed string tachyon condensate</u>:

e.g. Spacetimes* containing 1-cycles with antiperiodic Fermions have winding strings with mass²

$$M^2 = -m_s^2 + L^2 m_s^4$$

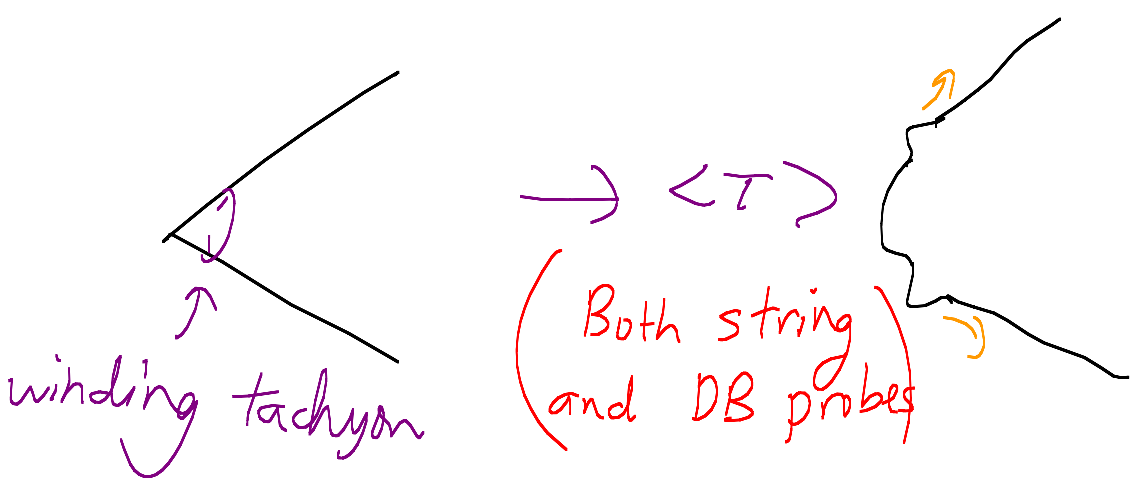
^ worldsheet Casimir energy

* Including ones with late-time long distance SUSY and/or AdS boundary conditions (globally stable).

when L shrinks below the string scale, these modes condense, deforming the system away from the $L < l_s$ extrapolation of GR. → avoid Planck-scale blueshifting

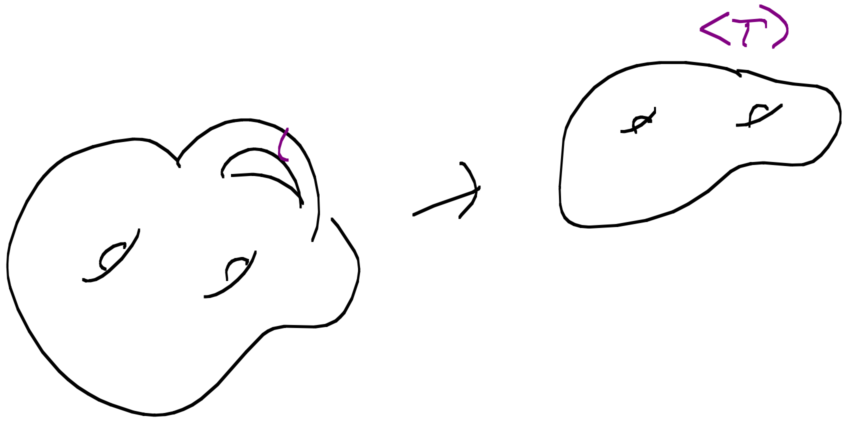
Examples:

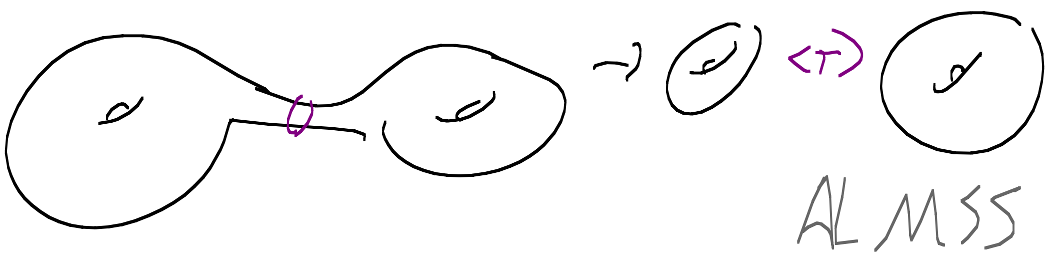
1) Generic timelike orbifold singularities



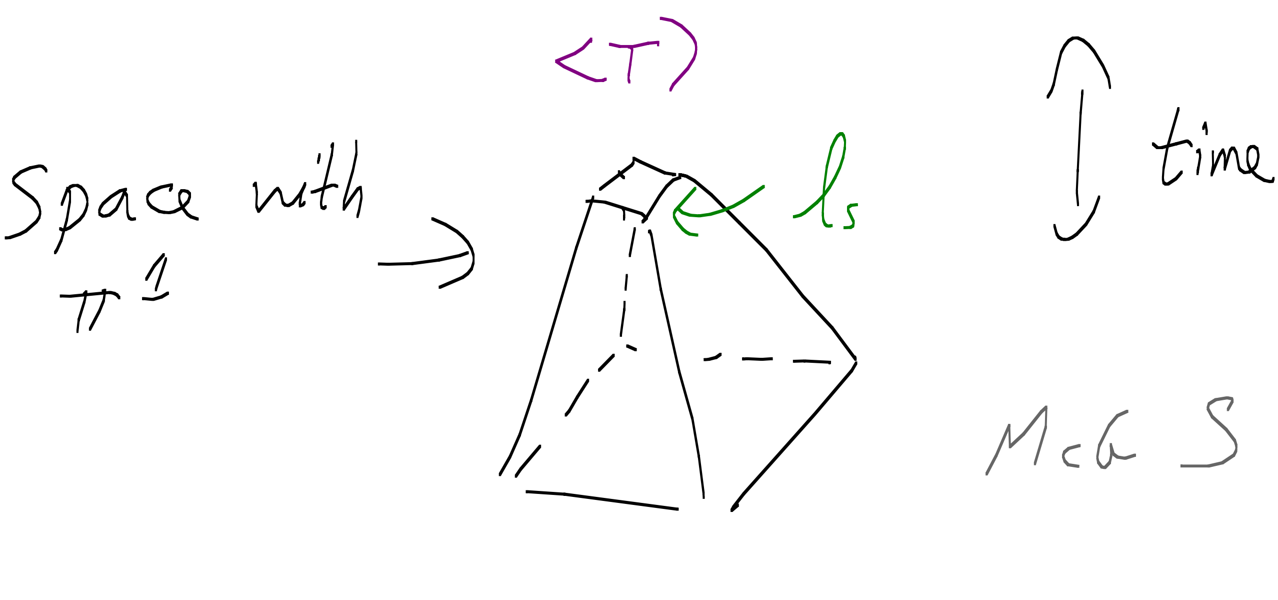
APS

2) Topology changing transitions



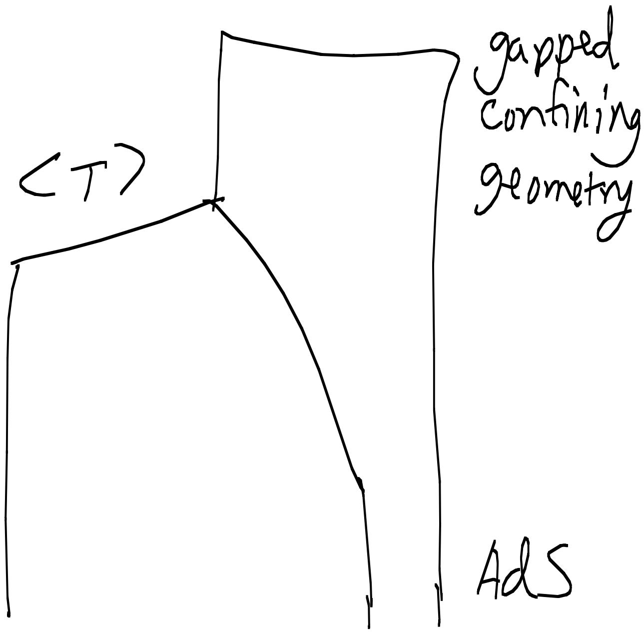


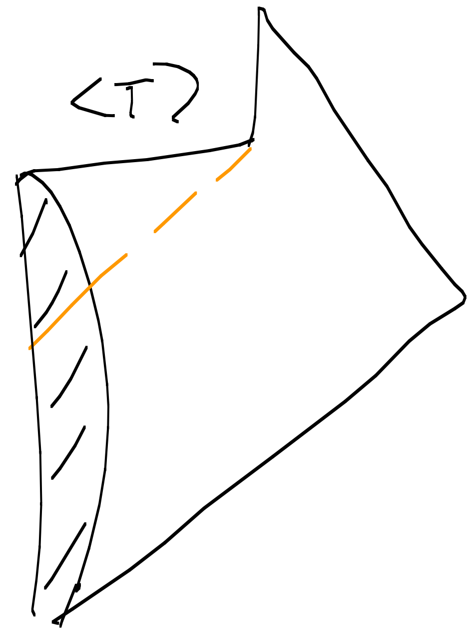
3) Spacelike singularities



4) Quasilocal tachyon condensation

(HS)





↑ time-dependently induced confinement

gravity/gauge duality

↙ <T> replaces region dual to QFT's IR

↘ confinement mass gap

↑ Black holes e.g. BTZ

cf Horowitz Black String → bubble of nothing

* How do black holes explode?

An instructive example:

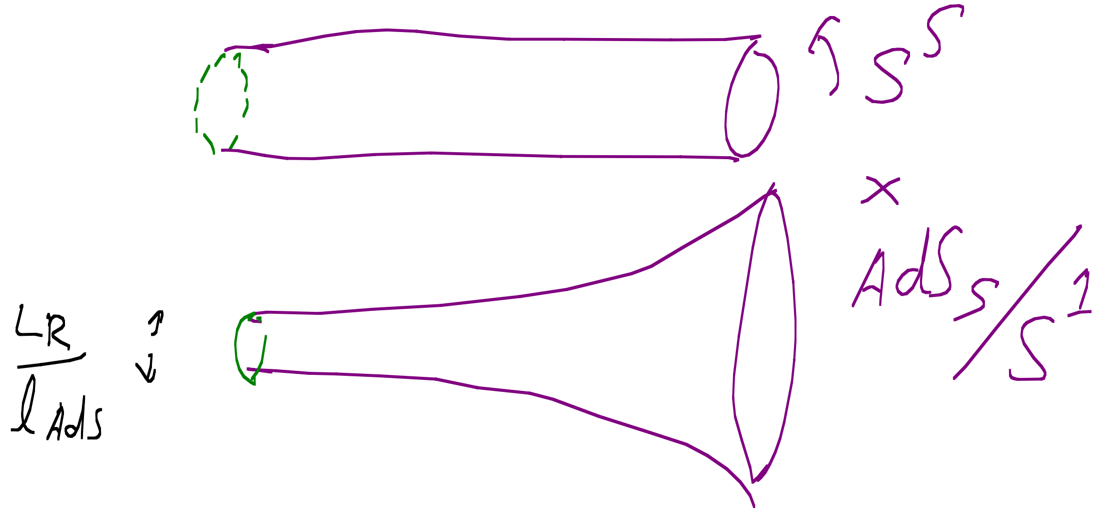
Consider AdS/CFT with Poincaré slicing, out on Coulomb branch: shell of D3-branes

$$ds^2 = H^{-\frac{1}{2}}\left(-dt^2 + d\vec{x}^2\right) + H^{\frac{1}{2}}\left(dr^2 + r^2 d\Omega_5^2\right)$$

$$H(r) = \begin{cases} 1 + \dfrac{\ell^4}{r^4} & r > R \\ 1 + \dfrac{\ell^4}{R^4} & r < R \end{cases} \qquad (R \ll \ell)$$

and compactify $x_1 = x_1 + L$ with antiperiodic boundary conditions Fermions.

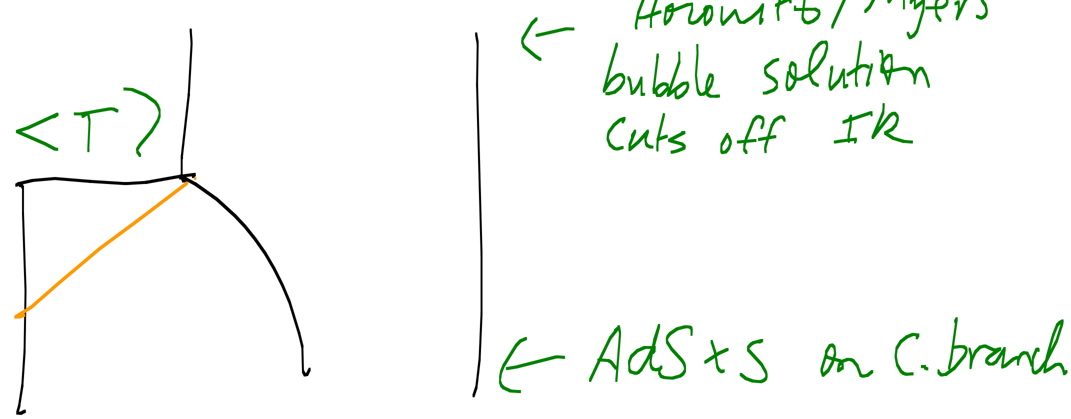
proper size of $S^1_{x_1}$ is then $\begin{cases} \infty & r \to \infty \\ \frac{LR}{\ell_{AdS}} & r < R \end{cases}$



Of course Coulomb branch will be lifted by quantum effects; anyway we will be interested in time-dependent evolution where branes roll back toward origin

Roll toward origin. S^1 radius starts at $\frac{LR}{l} > l_s$ but at some time (before black brane forms) R shrinks enough that $\frac{LR}{l} \to l_s$

$\Rightarrow \langle T \rangle$ sets in along spacelike slice $0 < r < R$



→ Question : what happens to excitations in the system in the region where T turns on?

2 basic possibilities:

1. Multiple states allowed in T phase (aka remnants). Bulk not unitary

2. Only a single state is allowed in ⟨T⟩ phase. Bulk unitarity.

Find evidence for 2 :

In the new example,

The dual QFT develops a confining mass gap as a function of time

The dual formulation guarantees

- overall unitarity
- global (bulk gauge) change conservation
- energy conservation
- If ground state not degenerate then $\langle T \rangle$ phase should have unique state.

$\Rightarrow$ Important to understand the physics of the $\langle T \rangle$ phase.

At the worldsheet level (whose self-consistency we must check in each background), $\langle T \rangle$ means that the path integral

$$\int DX^0 D\vec{X}\, e^{iS} \prod \int V$$

has a semiclassical action

$$S \to S_0 + \int d^2\sigma\, \mu^2 e^{2\kappa X^0}\, \hat{T}(\vec{X})$$

relevant in worldsheet matter sector

cf mass^2 of relativistic particle

Strominger et al

This is a time-dependent background, so no preferred vacuum state. As in GR, the <u>Euclidean vacuum</u> $|out\rangle$ is a simple choice, so let's start by analyzing this.

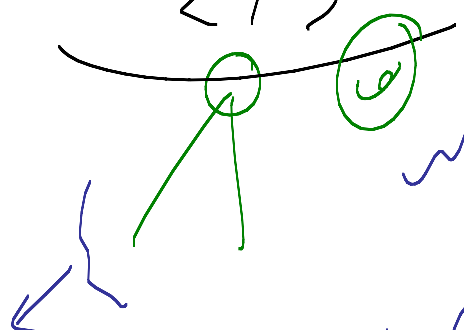
cf Polyakov: worldsheet amplitudes compute components of $|out\rangle$ in basis of bulk multi-free-string Hilbert space

Simplest State:

Euclidean / H-H vacuum $|out\rangle$

$a_{out}|out\rangle = 0$

$\langle T \rangle$



Polyakov, ST, McGS

loop correction to vac. energy

$\langle in | a_{in}^2 | out \rangle$ particle production

$$Re(Z) = -\frac{\ln \mu}{\kappa} \hat{Z}_{free}$$ McG-S

as opposed to $\delta(0) = Vol(X^0)$

$$\langle \Pi \int V_{in} \rangle = \int DX^0 D\vec{X} \, e^{-\int \left(S_{0E} + \mu^2 e^{2\kappa X^0} \hat{T}\right)} \Pi \int V_{in}$$

Suppresses otherwise singular contributions

In case of initial singularity, this gives perturbative string mechanism for Hartle/Hawking idea of starting time from nothing

2-point genus 0 ⇒ particle production with number density

$$|\beta_\omega|^2 \simeq \frac{1}{e^{\frac{\pi}{\kappa}(2\omega)} \pm 1} \quad \left\{ \begin{array}{l} F \\ B \end{array} \right.$$

pure squeezed state with distribution of particles as in $T = \frac{\pi}{\kappa}$ thermal system

Comes from Wick rotation of reflection off Liouville wall

⇆ mixing between positive & negative frequency

To understand this <T> phase in general, we need to assess the other putative states.

Above string calculations reproduce results of heuristic model

$$T(x^0, \vec{x}) \leftrightarrow M^2(x^0, \vec{x})$$

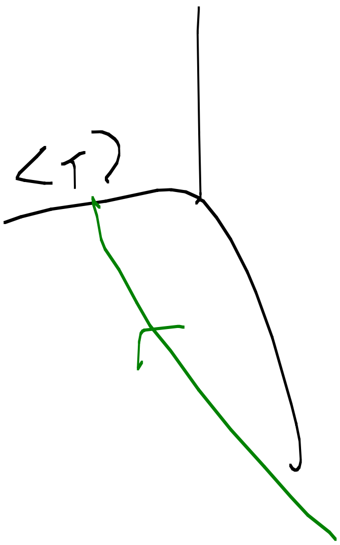
so will use this as a guide.

↳ free wavefunctions

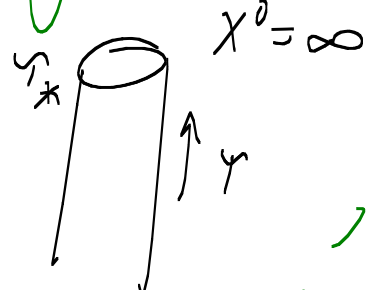
$$\psi \sim \frac{1}{\sqrt{M(x^0)}} \, e^{\pm i \int^{x^0} M(t') dt'}$$

More general states: particles propagating into the $\langle T \rangle$ void:

Simple Calculations $\Rightarrow$



- $\exists$ classical saddle point where free string propagates into T phase



- In QFT analogue $T \sim m^2(x^0, \vec{x})$ free particles get stuck and wavepackets stop expanding at late X^0 for $m(\vec{X}, X^0)$ growing faster than linearly in X^0.

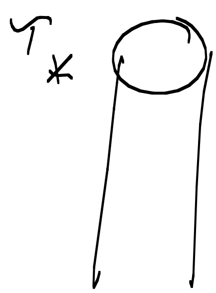
This alone would suggest loss of bulk unitarity. However, there is a dynamical effect and a worldsheet consistency condition which both serve to evacuate the tachyon phase.

Both arise when we go beyond the free theory.

1) Worldsheet BRST :

The saddle point configuration $X^0_{cl}(\tau)$ for a single free string has the property that $X^0_{cl}(\tau) \to \infty$ for finite $\tau \to \tau_*$

$\Rightarrow$ hole in worldsheet



Not generically BRST invariant

In QFT model,

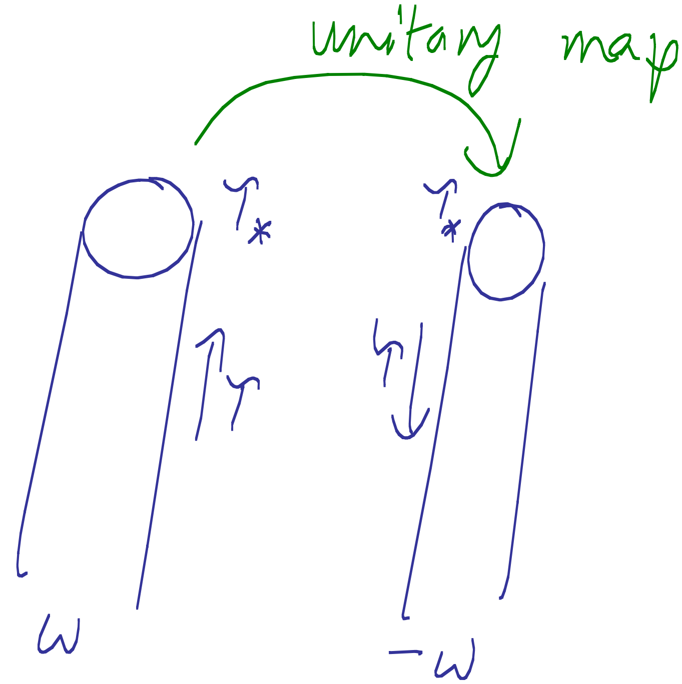
$$\hat{H}_{\text{worldline}} = \frac{\partial^2}{\partial X^{0\,2}} + m^2(X^0)$$

Not Hermitian on full space of eigenfunctions $\psi_\Delta \sim \frac{1}{(m^2+\Delta)^{\frac{1}{4}}} e^{\pm i \int^{X^0} \sqrt{m^2+\Delta}}$

(No pole as $\Delta \to 0$ in Greens ftns)

$\Rightarrow$ decoupling of BRST-trivial modes can fail.

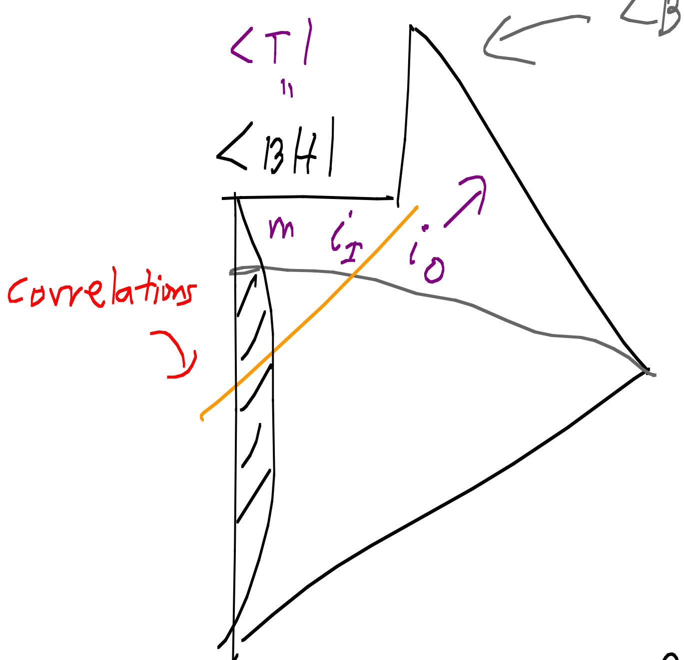
This anomaly is cancelled if we correlate our original string with another (or more)



cf self-adjoint extension (ES)

This is a microphysical realization of a version of the "Black Hole final state" proposal of Horowitz & Maldacena.

$$\langle BH|\psi\rangle = \underbrace{|i\rangle_O\, S^{im}}_{\text{unitary}} \langle m|\psi_M\rangle$$



$$|\psi\rangle = |\psi\rangle_M \otimes \sum |i\rangle_I \otimes |i\rangle_O$$

At linearized level,

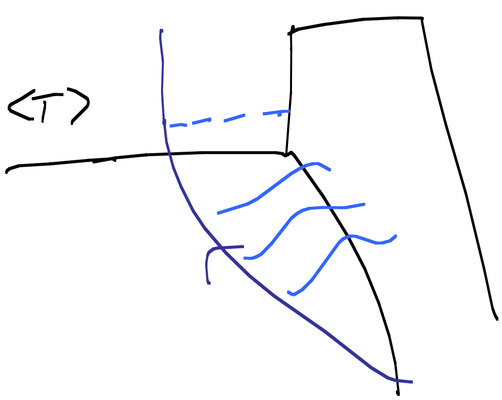
$$\langle BH| = S^{mi}\, \langle m| \otimes \langle i|_I$$

S^{mi}: prescribed unitary matrix

$\langle m|$: matter

$\langle i|_I$: inner Hawking

It is important to understand if these correlations appear dynamically. In the full problem, as ordinary spacetime ends, fluctuations of the dilaton, graviton, ... are lifted.



Simple calculation of energy of massive particle + sourced field

$$E = m_0^2 \lambda^2 M(x^0) \cos^2\left(\int^{x^0} M(t')dt'\right) \times \int d^{d-1} f(|\vec{x}|) \left(\int \frac{d^{d-1}\vec{k}}{(2\pi)^{d-1}} \frac{e^{i\vec{k}\cdot\vec{x}}}{\omega_{\vec{k}}^{3/2}}\right)$$

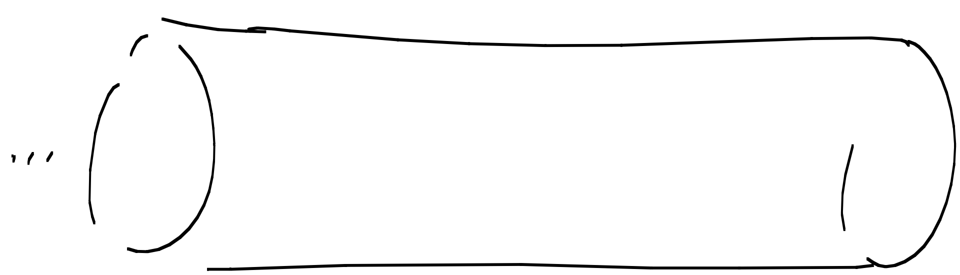
This large energy of the whole configuration $\Rightarrow$ forces driving out any configuration sourcing the field(s).

e.g. graviton: need 0 total energy in $\langle T \rangle$ phase: again yields need for combinations of positive & negative frequency modes.

Schwarzchild? shrinking S^2

No π_1-stabilized winding tachyon, but again worldsheet RG problem has a mass gap. (cf Polyakov)

But S^2 shrinks <u>rapidly</u> inside



↗ rapid shrinking
⇒ produce gas of strings/branes & anti-strings/branes

↖ slower shrinking, analogue of tachyon