The Role of Tachyons in Black Hole Evaporation

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Strings 2006

Two aspects of the problem

View from outside

View from inside

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View from outside: A new endpoint for Hawking evaporation (G.H. 2005)

View from inside: Evidence for a unique state at the "singularity" (E. Silverstein and G.H. 2006)

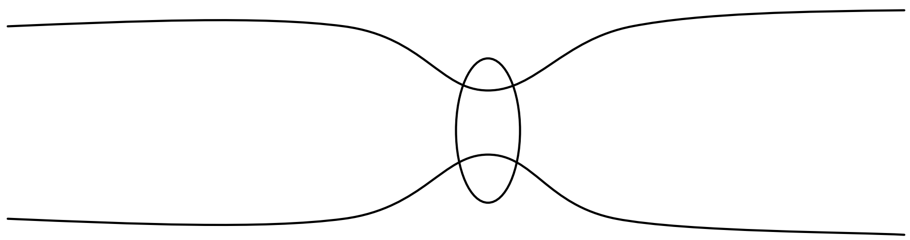
Old endpoints:

1970’s (Hawking): Black holes evaporate down to the Planck scale where the semiclassical approximation breaks down. Charged black holes approach extremality.

1990’s (Susskind; Polchinski and G.H.): Black holes evaporate down to the string scale, and then turn into excited strings and branes.

Tachyon condensation

Given a circle with antiperiodic boundary conditions for fermions, wound strings become tachyonic when the size of the circle is less than the string scale (Rohm 1984).



If this happens locally, the outcome of this instability is that the circle smoothly pinches off, changing the topology of space (Adams et al. 2005).

Application to black holes

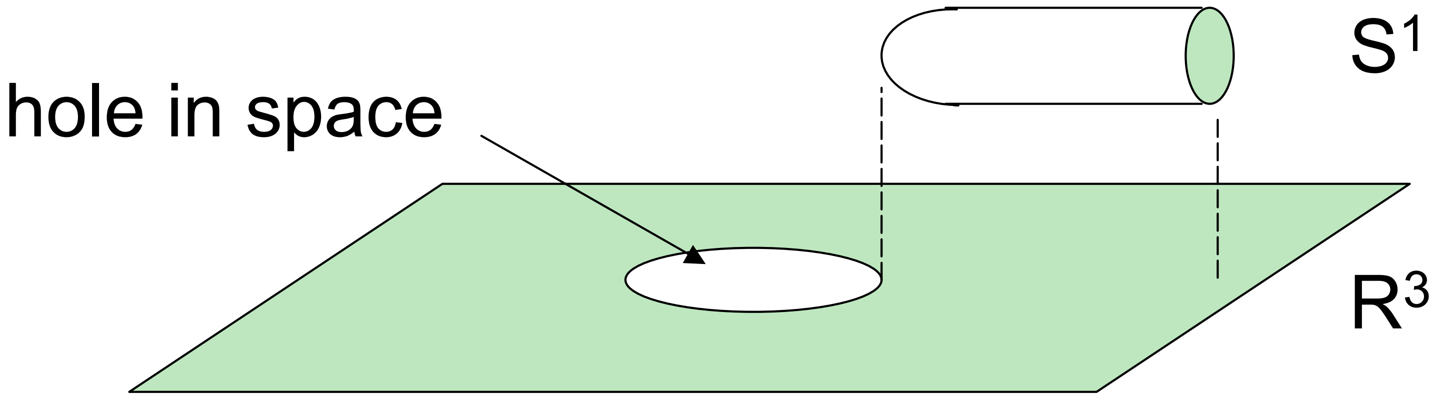
Consider a higher dimensional charged black hole wrapped around a circle. Hawking radiation causes the circle at the horizon to shrink. It can reach the string scale when the curvature at the horizon is still small.

If the circle has antiperiodic fermions, the tachyon instability will cause the circle to pinch off. The horizon is gone, and you form a …

Kaluza-Klein “bubble of nothing”

Review of Kaluza-Klein Bubbles

Witten (1981) showed that a gravitational instanton mediates a decay of $M_4 \times S^1$ into a zero mass bubble where the S^1 pinches off at a finite radius. There is no spacetime inside this radius. This bubble of nothing rapidly expands and hits null infinity.



This is just the tip of the iceberg:

Vacuum solutions exist for bubbles of all sizes

There is a static bubble:

4D euclidean Schwarzschild x time

It has positive mass but is unstable.

Smaller bubbles contract, larger ones expand.

When S^1 at the horizon reaches the string scale, tachyon condensation turns a black hole into a KK bubble of nothing.

Where does the entropy go? The transition produces radiation in addition to the bubble.

Since charge is conserved, the bubbles must have the same charge as the black hole.

Q is unchanged, but there is no longer a source for this charge. The sphere is now noncontractible and Q is a result of flux on this sphere. This is a nonextremal analog of a geometric transition:

branes → flux

There are static charged bubbles which are perturbatively stable. They can be thought of as vacuum bubbles that would normally contract, but are stabilized by the flux on the bubble.

There is a similar transition even with supersymmetric boundary conditions at infinity!
(Ross 2005)

If you start with a rotating (extended) charged black hole, then even if fermions are periodic around the S^1 at infinity, they can still be antiperiodic around another circle.

For certain choices of angular momentum, this other circle can reach the string scale when the curvature is small, and one has a transition to a bubble of nothing.

View from inside

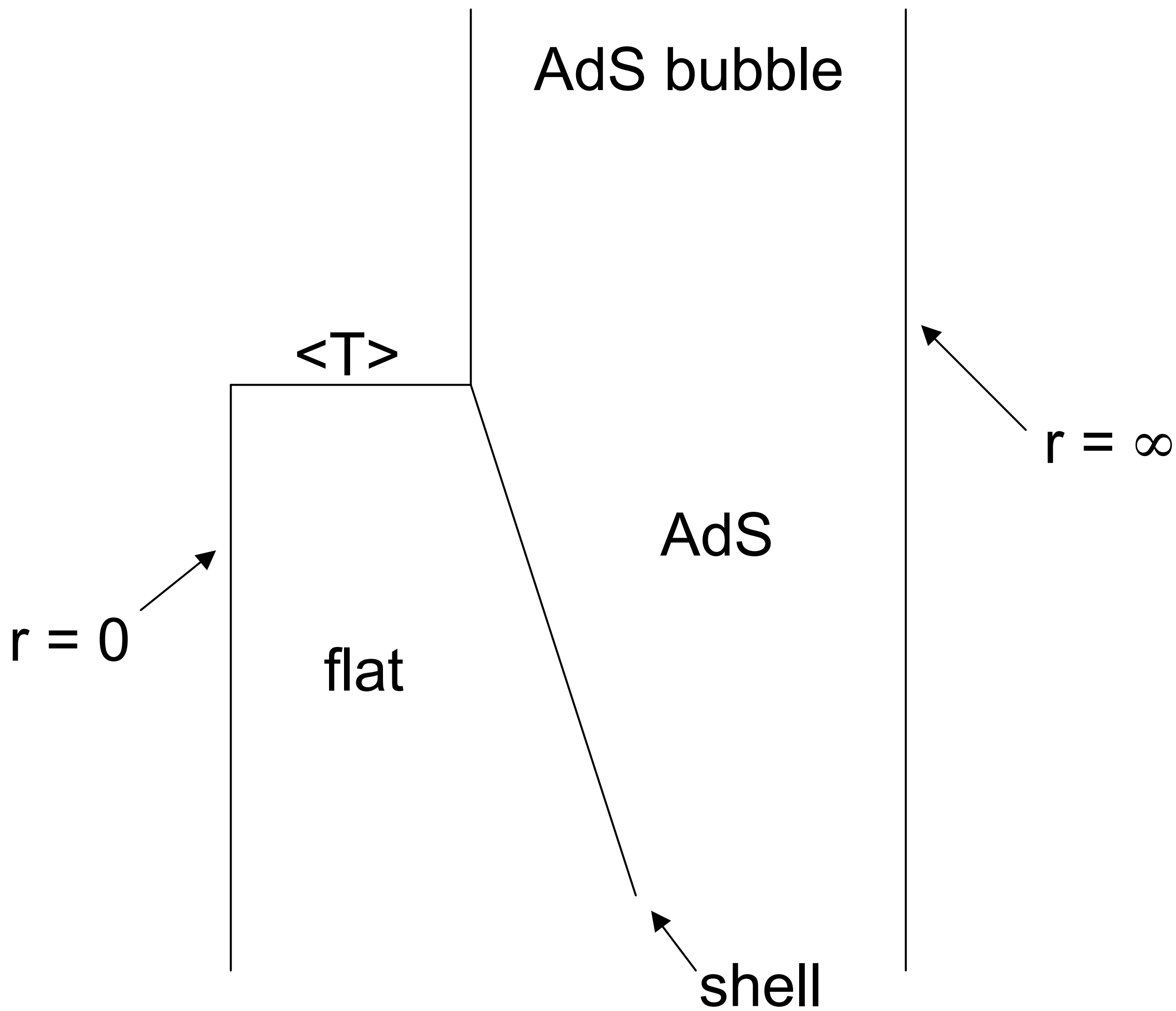
Initially, when the circle is large everywhere outside the horizon, it still shrinks to zero at the singularity. So tachyon condensation takes place along a spacelike surface inside the horizon.

This is analogous to the Milne orbifold with antiperiodic fermions (McGreevy and Silverstein 2005) but here tachyons are confined to a finite region.

Simpler Model of Black Hole Evaporation

Consider a spherical shell of D3-branes. The geometry is AdS outside the shell and flat inside. Compactify one direction along the brane with antiperiodic boundary conditions.

Now let the shell slowly contract. When the S^1 at the shell reaches the string scale, tachyon condensation takes place everywhere inside the shell and the region outside becomes an AdS bubble.



How do particles inside the shell get out?

Dual CFT Description

With susy boundary conditions, the shell corresponds to a point on the Coulomb branch of D=4 super Yang-Mills theory. When susy is broken, all fermions and scalars become massive. At low energies, the theory describes a confining phase of D=3 bosonic Yang-Mills. This is dual to the AdS bubble.

The CFT is unitary, but there are two possibilities:

1) Multiple states exist in the tachyon phase entangled with the outside. This would result in a loss of spacetime unitarity.
2) Only a single state is allowed in the tachyon phase. Evolution in the bulk remains unitary.

We find evidence in favor of (2).

Adding a tachyon to the closed string worldsheet is directly analogous to adding an exponentially growing mass term to a point particle.

This suggests that all closed string modes (including the graviton) are lifted, effectively removing spacetime (as in bubble of nothing).

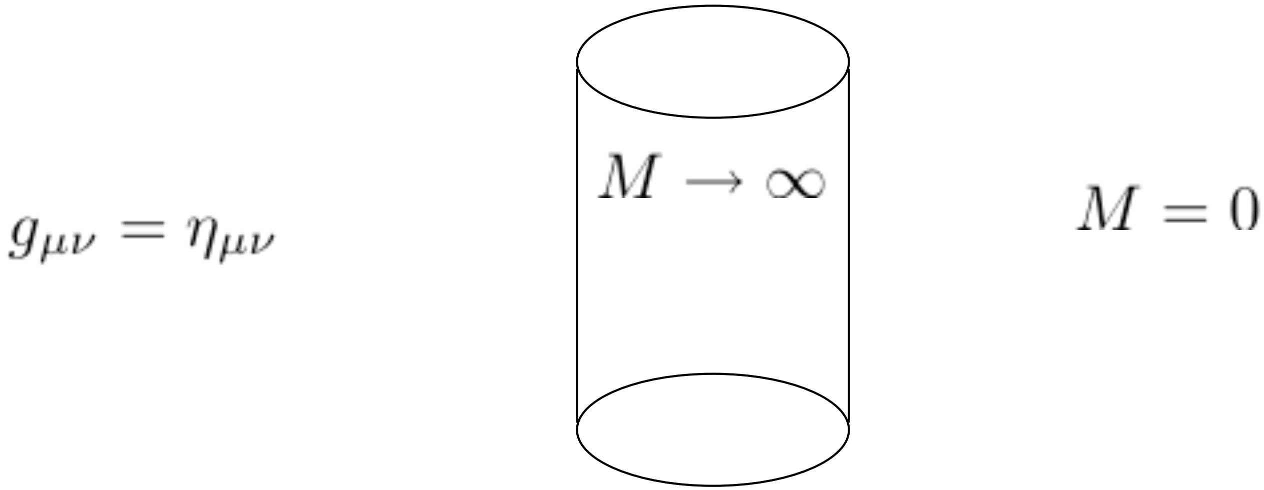
Energy conservation implies that no particles can remain in <T> phase. Energy would be “screened”.

Only zero energy excitations are allowed. If the CFT has a nondegenerate ground state, the state in <T> phase is unique.

Consider a scalar field theory with similar mass

$$\mathcal{L} = (\nabla\phi)^2 + M^2(x^0) f(r) \phi^2$$

where f(r) = 0 for r>R and M diverges at late time



(Strominger and Takayanagi 2003; McGreevy and Silverstein 2005)

Properties of this field theory depend qualitatively on whether M grows faster or slower than x^0.

If $M(x^0) > x^0$:

- classical relativistic particles can be trapped

- quantum wave packets stop spreading

This suggests free particles can get trapped. But if our particle is coupled to a field which is also getting massive, then it will cost enormous energy for particle to stay in region $r<R$.

Potential BRST anomaly

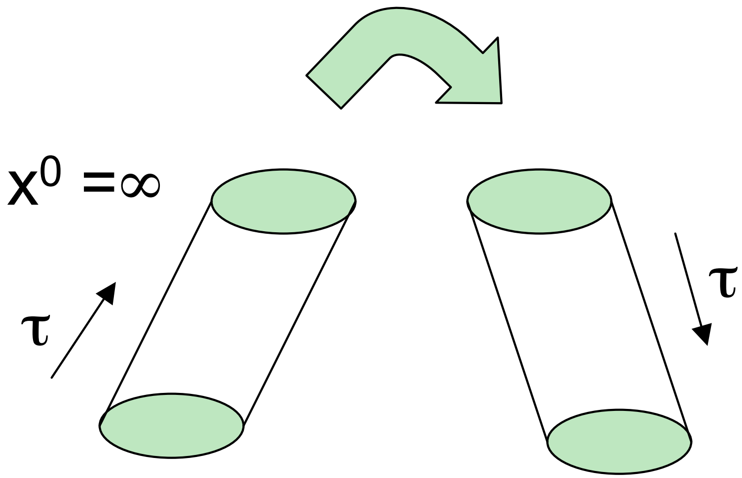
If $M(x^0) > x^0$, the worldline Hamiltonian

$$H_{wl} = -\partial_\mu \partial^\mu + f(r) M^2(x^0)$$

is not self adjoint (Fredenhagen and Schomerus 2003). In an interacting theory, this causes problems with worldline BRST invariance. Since $Q_B = c\, H_{wl}$, BRST trivial modes will no longer decouple:

$$< \psi | Q_B \epsilon > \neq < Q_B \psi | \epsilon >$$

We expect a similar problem in string theory. In conformal gauge, classical worldsheets reach infinity in finite worldsheet time - so the worldsheet has a hole in it. One way to avoid BRST anomalies is to require that worldsheets are correlated:



Need unitary map from one future boundary to the other.

So strings in the tachyon phase must be correlated.

This is reminiscent of the black hole final state proposal (Maldacena and G.H. 2003) except that here there is some evidence that the final state is determined dynamically, and does not have to be imposed by hand.

Summary:

View from outside: A new endpoint for Hawking evaporation - Kaluza-Klein bubbles of nothing. *Some black holes catalyze production of bubbles of nothing.*

View from inside: Evidence for a unique state in the tachyon phase that replaces the singularity. A complete description of this (even for the shell model) remains an open problem.

What about Schwarzschild?

The BRST anomaly seems to lead to a simple argument that ingoing matter must be correlated with ingoing Hawking radiation:

From the standpoint of an outside observer, strings reach $t=\infty$ in finite worldsheet time. To avoid BRST anomalies, these strings must be correlated with ingoing Hawking radiation.

This is independent of tachyons.

(E. Silverstein and G.H., in progress)