A New Endpoint for Hawking Evaporation

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(Silverstein's talk)

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 Strings

A charged black string in D=n+4 dimensions:

$$ds^2 = H_1^{-1}(r)[-f(r)dt^2 + dx^2] + f^{-1}(r)dr^2 + r^2 d\Omega_{n+1}$$

where

$$H_1(r) = 1 + \frac{r_0^n \sinh^2 \alpha}{r^n}, \qquad f(r) = 1 - \frac{r_0^n}{r^n}$$

Hawking radiation causes r_0 to decrease, α to increase keeping charge $Q=r_0^n \sinh 2\alpha$ fixed.

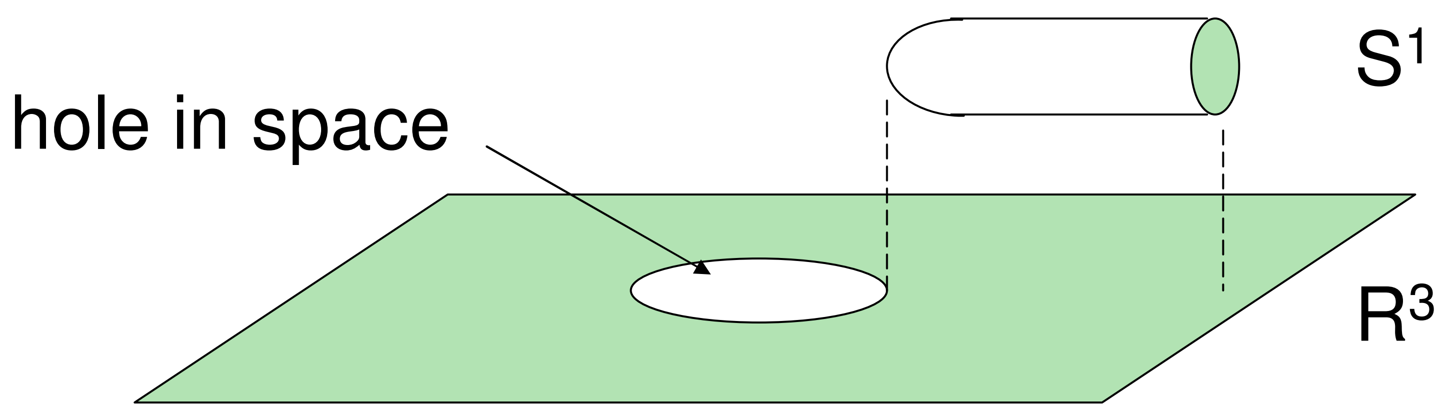
Curvature at the horizon is the string scale when $r_0 = l_s$. But if x=x+L, the size of the circle at the horizon is L/cosh α. This can reach the string scale when curvature at the horizon is still small.

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.

Bubbles larger than Witten's have negative mass. There is no positive energy theorem since (1) spinors must be antiperiodic around the S^1 for these solutions, and (2) S^2 is not the boundary of a three-surface.

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

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

Properties of the KK bubble produced:

1) Must have less mass than the black string

2) The size of the bubble should equal the horizon

3) Must carry charge equal to the black string

4) The size of the S^1 at infinity is unchanged

Consider the 6D black string with D1-D5 charges

$$ds^2 = H^{-1}(r)[-f(r)dt^2 + dx^2] + H(r)[f^{-1}(r)dr^2 + r^2 d\Omega_3]$$

$$H(r) = 1 + \frac{r_0^2 \sinh^2 \alpha}{r^2}, \qquad f(r) = 1 - \frac{r_0^2}{r^2}$$

Static bubbles with the same charges can be obtained by analytic continuation: t=iy, x=iτ

$$ds^2 = H^{-1}(r)[-d\tau^2 + f(r)dy^2] + H(r)[f^{-1}(r)dr^2 + r^2 d\Omega_3]$$

The 3-form (and dilaton) are unchanged. The first three conditions are automatically satisfied.

Q is unchanged, but there is no longer a source for this charge. The S^3 is now noncontractible and Q is a result of flux on this sphere. This is a nonextremal analog of a geometric transition:

branes → flux

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

Not all black strings can decay to a *static* bubble:

Regularity at $r=r_0$ requires that y be identified with period $L=2\pi\, r_0 \cosh^2\alpha$. Since the charge is $Q=r_0^2 \sinh 2\alpha$, we have

$$\frac{Q}{L^2} \propto \frac{\sinh\alpha}{\cosh^3\alpha}$$

which is bounded from above. You end up at a static bubble only if Q/L^2 is small enough. If Q/L^2 is too big, the bubble must expand.

In the near horizon limit, the black string reduces to S^3 x BTZ black hole:

$$ds^2 = -\frac{\hat{r}^2 - \hat{r}_0^2}{\ell^2}dt^2 + \frac{\ell^2 d\hat{r}^2}{\hat{r}^2 - \hat{r}_0^2} + \hat{r}^2 d\varphi^2$$

Fermions in AdS_3 are always antiperiodic, so any black hole formed from collapse must have antiperiodic fermions. When $r_0 = l_s$, tachyon condensation will occur. But the analog of the static bubble is just AdS_3. There is no Q/L^2 restriction, so all BTZ black holes that evaporate down to $r_0 = l_s$ turn into AdS_3 plus radiation. Never reach the M=0 black hole.

Other applications

Black p-branes: A similar story holds for black p-branes with RR charge. When they are wrapped around a circle, the size of the circle decreases with radius. During Hawking evaporation, this size can reach the string scale when the curvature at the horizon is still small. With the right spin structure, a tachyon instability will again produce a bubble.

AdS Soliton: If you periodically identify one direction in Poincare coordinates in AdS_5, the space has a singularity at the horizon. With antiperiodic fermions, there is a smooth, lower energy solution which was conjectured to be the ground state (Myers, G.H. 1998):

$$ds^2 = \frac{r^2}{\ell^2}\left[-dt^2 + f(r)d\chi^2 + dx^2 + dy^2\right] + f^{-1}(r)\frac{\ell^2}{r^2}dr^2$$

This is just the near horizon limit of the static 3-brane bubble. Tachyon condensation causes periodically identified AdS_5 to decay to this ground state.

Three charged black strings: One can add some momentum, and still have the S^1 shrink to string scale at the horizon. One again forms a bubble, but bubbles cannot carry momentum. So the momentum must go into the radiation.

Rotation: One can add rotation to the black strings and black branes and they will still form bubbles.

Comments

- It has often been said that closed string tachyon condensation should remove spacetime and lead to a state of “nothing”. We have a very clear example of this.

- Kaluza-Klein bubbles of nothing were previously thought to require a nonperturbative quantum gravitational process. We now have a qualitatively new way to produce them.

Summary

- Hawking radiation + tachyon condensation causes some black strings and branes to turn into Kaluza-Klein bubbles of nothing. These bubbles can be static or expanding.

- Since branes are replaced by fluxes, this is a nonextremal analog of a geometric transition.

Slogan:

Certain black holes catalyze production of bubbles of nothing.

Thanks to Silverstein
and Susskind

Next Step

Initially, when the circle is large everywhere outside the horizon, it still shrinks to zero inside. So tachyon condensation takes place along a spacelike surface (McGreevy and Silverstein, 2005). It should be possible to match this onto the bubble formation outside to get a complete description of Hawking evaporation free of singularities!

(work in progress with McGreevy and Silverstein)