Fuzzballs, Firewalls, and all that .....

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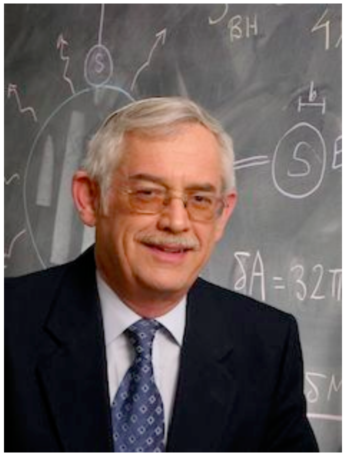
Avery, Balasubramanian, Bena, Carson, Chowdhury, de Boer, Gimon, Giusto, Halmagyi, Keski-Vakkuri, Levi, Lunin, Maldacena, Maoz, Niehoff, Park, Peet, Potvin, Puhm,Ross, Ruef, Saxena, Simon, Skenderis, Srivastava,Taylor,Turton,Vasilakis, Warner ...



(Bekenstein 72)

(Hawking 75)

Bekenstein, Hawking and others have taught us that the quantum physics of black holes is very puzzling …

In particular, the formation and evaporation of black holes violates quantum mechanics, if we assume that semiclassical physics holds at the horizon of the hole

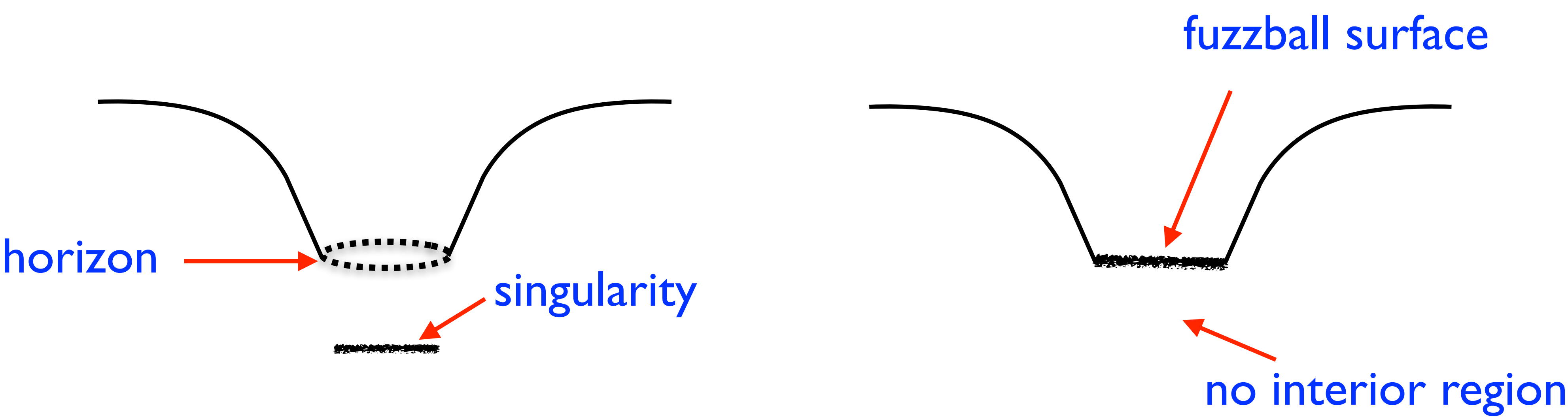
This is the Black Hole Information Paradox

In string theory there has emerged a picture called the 'Fuzzball paradigm', which seems to give a complete and consistent quantum picture for black holes

In particular it resolves the Information paradox

It also gives a manifest construction of degrees of freedom that live just outside the horizon of the black hole.

In fact there is no horizon and no interior for the hole; thus there is no singularity either

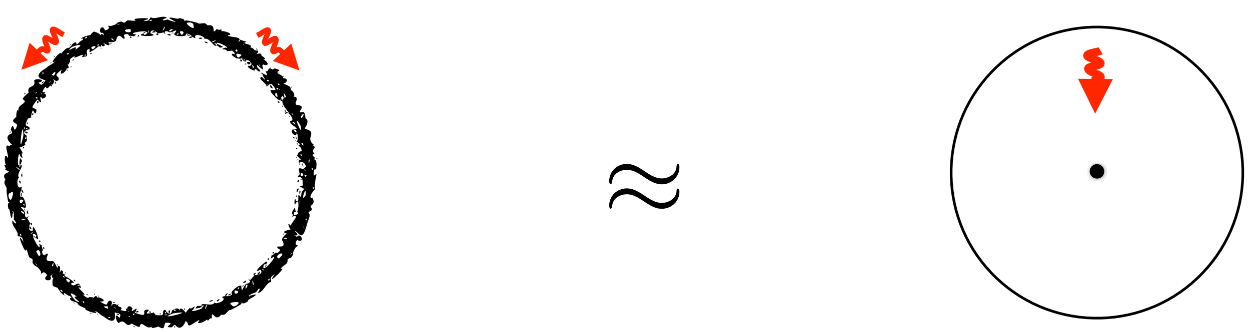


The semiclassical approximation is violated because the number of fuzzball states is very large

$$N \sim Exp[S_{bek}] \sim Exp[\frac{A}{4}]$$

The smallness of the transition amplitude to each fuzzball is offset by the large number of fuzzball states …

The classical intuition is recovered by through a conjecture of 'Fuzzball complementarity', which is a modification of the ideas proposed by 't Hooft and Susskind to a situation where black hole states are 'fuzzballs'



Recently the idea of ‘firewalls’ has created much confusion and puzzlement ..

There is no ‘firewall paradox’ … The ‘paradox’ part of the firewall argument is the same as Hawking’s original information paradox

The paper by Almheiri, Marolf, Polchinski and Sully (AMPS) is called ‘Complementarity or Firewalls’, and does the following:

AMPS: Hawking’s argument + Additional assumption

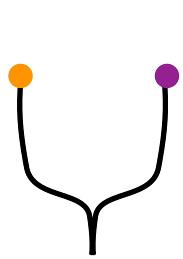
$\longrightarrow$ Rules out complementarity as formulated by Susskind

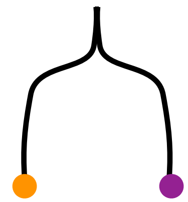
But this additional assumption is questionable …

In particular the AMPS argument does not rule out fuzzball complementarity …

The information paradox

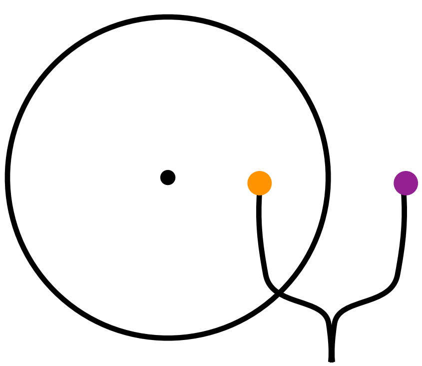
In quantum mechanics, the vacuum can have fluctuations which produce a particle-antiparticle pair





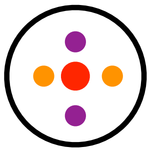
$$\Delta E \; \Delta t \sim \hbar$$

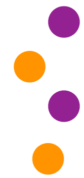
But if a fluctuation happens near the horizon, the particles do not have to re-annihilate : The negative gravitational potential gives the inner particle negative energy



$$\Delta E = 0 \quad \rightarrow \quad \Delta t = \infty$$

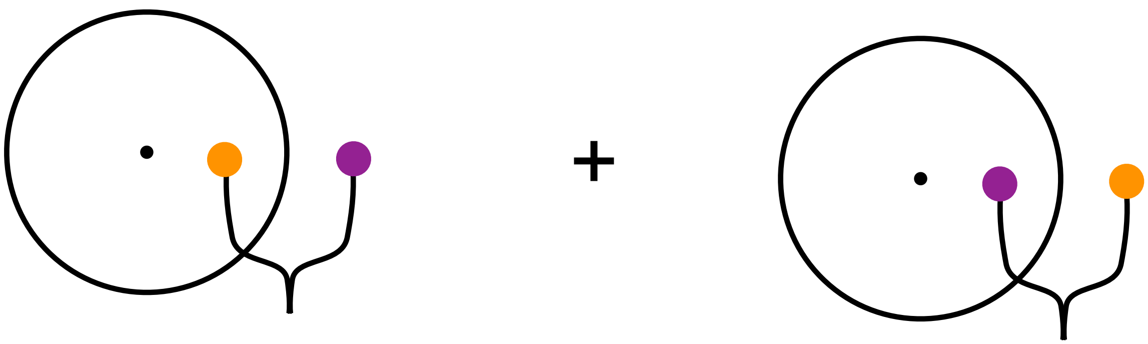
Thus real particle pairs are continuously created (Hawking 74)





Hole shrinks to a small size

The essential issue: Vacuum fluctuations produce entangled states



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(e^+e^- + e^-e^+\right)$$
$$= \frac{1}{\sqrt{2}}(01 + 10)$$

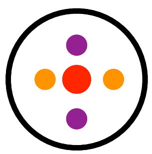
So the state of the radiation is entangled with the state of the remaining hole …

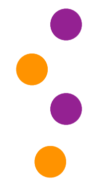
The radiation does not have a state by itself, the state can only be defined when the radiation and interior are considered together

The amount of this entanglement is very large ...

If N particles are emitted, then there are 2^N possible arrangements

We can call an electron a 0 and a positron a 1





	111111	000000
	....	....
+	010011	101100
+	000000	111111

Possibility A: Information loss — The evaporation goes on till the remnant has zero mass. At this point the remnant simply vanishes

vacuum

000000

....

101100

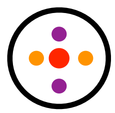
111111

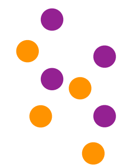
The radiation is entangled, but there is nothing that it is entangled WITH

The radiation cannot be assigned ANY quantum state ... it can only be described by a density matrix ... this is a violation of quantum mechanics (Hawking 1975)

Possibility B : Remnants: We assume the evaporation stops when we get to a planck sized remnant.

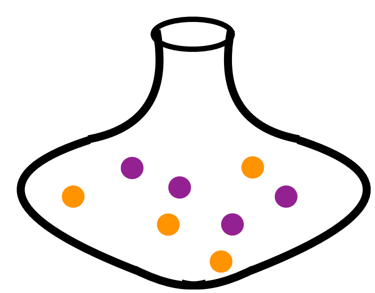
The remnant must have at least 2^N internal states





	111111	000000
	....	....
+	010011	101100
+	000000	111111

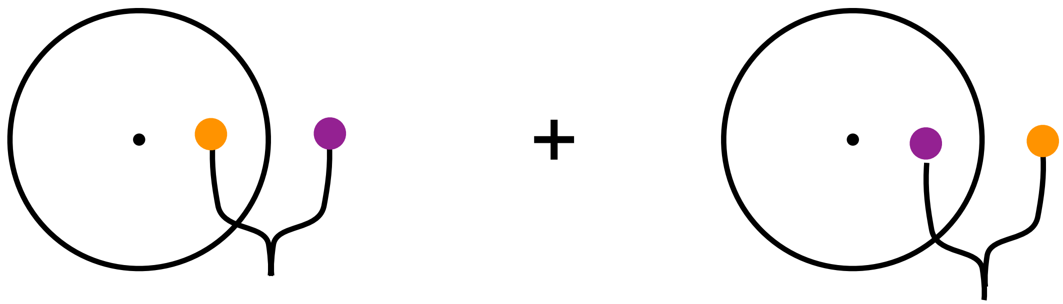
But how can we hold an unbounded number of states in planck volume with energy limited by planck mass? (Baby Universe ?)



An erroneous belief

Can there be a cumulative effect of small corrections ?

(Maldacena 2001, Hawking 2004)



10 + 01

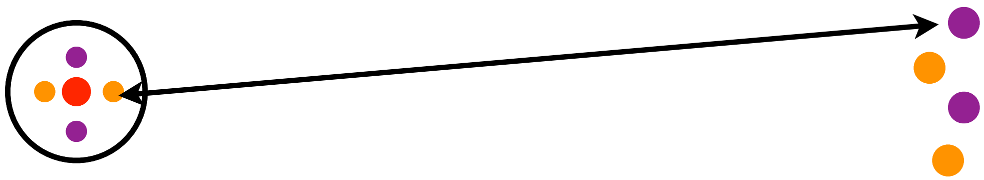
Leading order
Hawking computation

?? $(1+\epsilon)$ 10 + $(1-\epsilon)$ 01

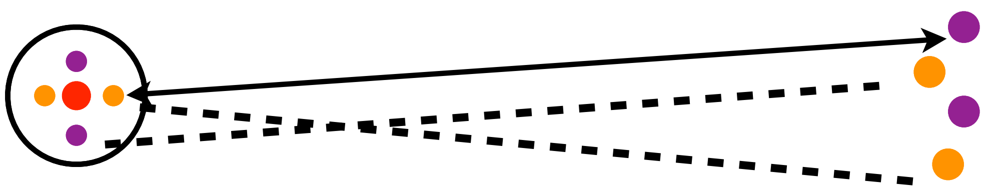
Small corrections,
perhaps due to
gravitational instanton
effects

ϵ is very small, perhaps of order $Exp[-(M/m_p)^2]$

But the number of radiated quanta is very large ….

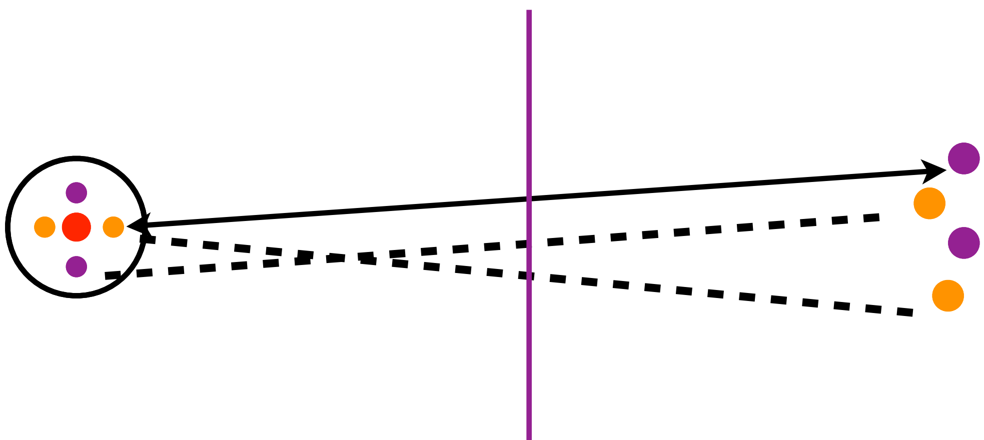


leading order



leading order +
subleading effects

Number of emitted quanta is very large $\sim (M/m_p)^2$



Perhaps with all these corrections,
the entanglement goes down to zero …

In 2009 an inequality was derived which showed that NO set of small corrections could reduce the entanglement

$$\frac{\delta S_{ent}}{S_{ent}} < 2\epsilon$$

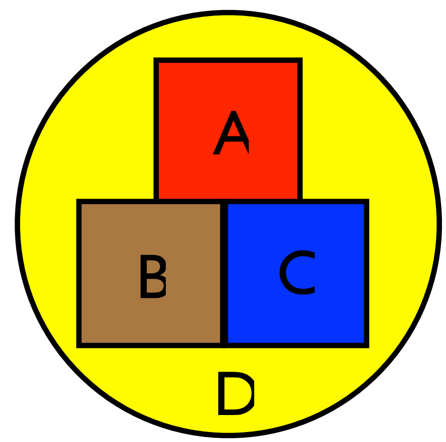
(SDM 2009)

The nontrivial power came from something called the strong sub-additivity theorem for quantum entanglement entropy

This was derived by Lieb and Ruskai in 1973 ..

(No elementary proof is known ...)

$$S(A+B) + S(B+C) \geq S(A) + S(C)$$

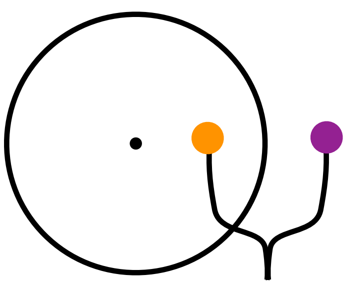


Partial summary

SDM 2009: Hawking argument (1975) → Hawking 'Theorem'

If the evolution of low energy modes (wavelength 1 meter to 10 Km) at the horizon is 'normal' upto small corrections, then we MUST have either (i) information loss or (ii) remnants

In usual gravity, 'Black holes have no hair'



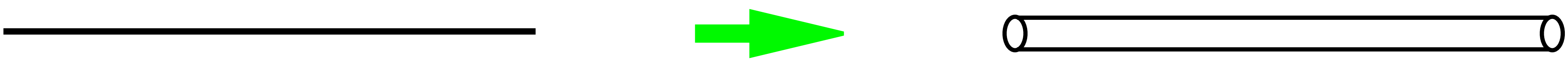
In that case we will get information loss or remnants

The solution in string theory: Fuzzballs

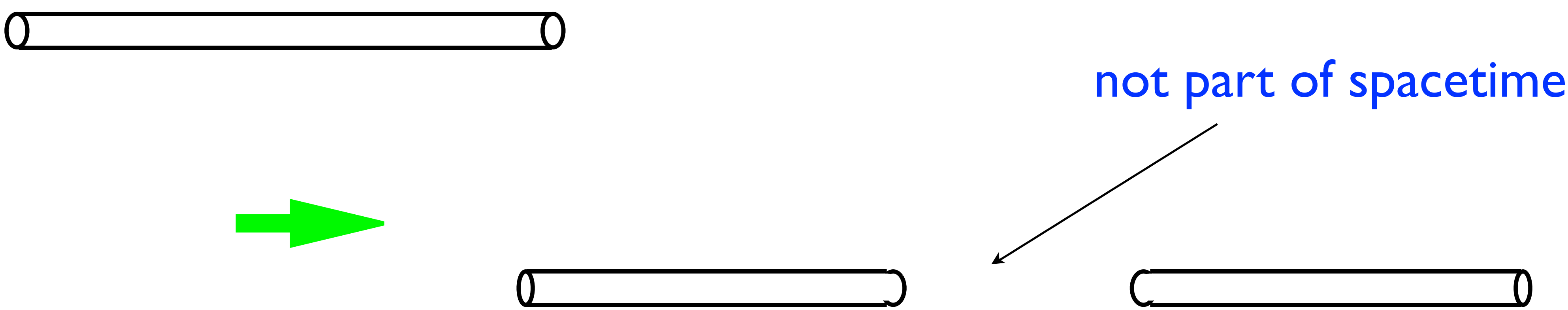
First consider a rough analogy …

Witten 1982: ‘Bubble of nothing’

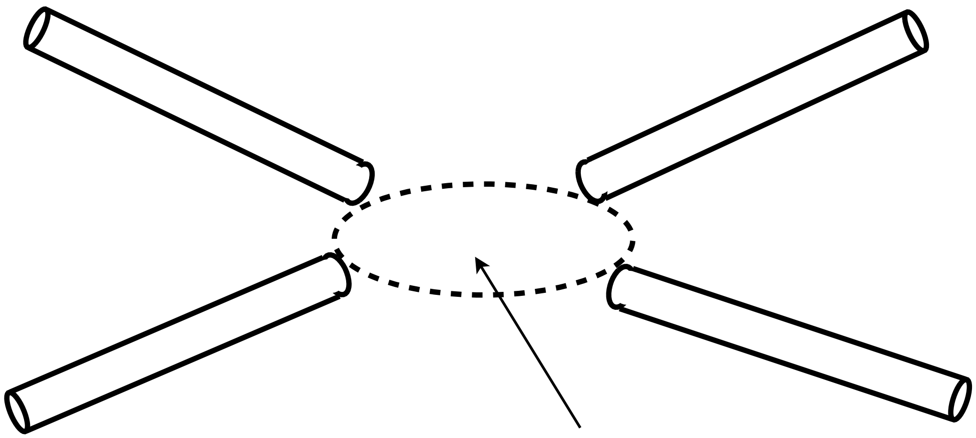
Consider Minkowski space with an extra compact circle



This space-time is unstable to tunneling into a ‘bubble of nothing’



In more dimensions :



not part of spacetime

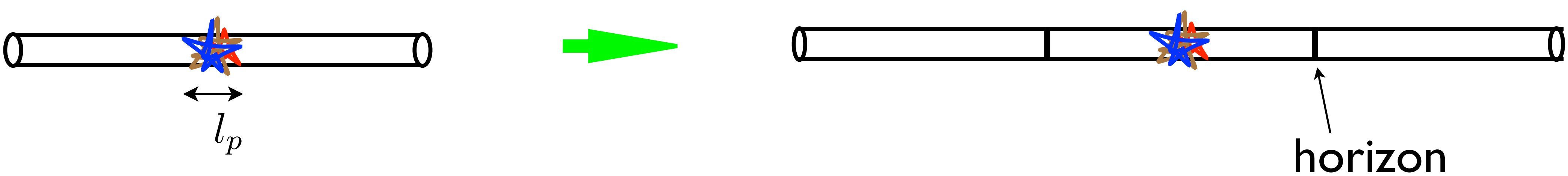
People did not worry about this instability too much, since it turns out that fermions cannot live on this new topology without having a singularity in their wave function …

But now consider the black hole …

Black holes:

The traditional expectation ...

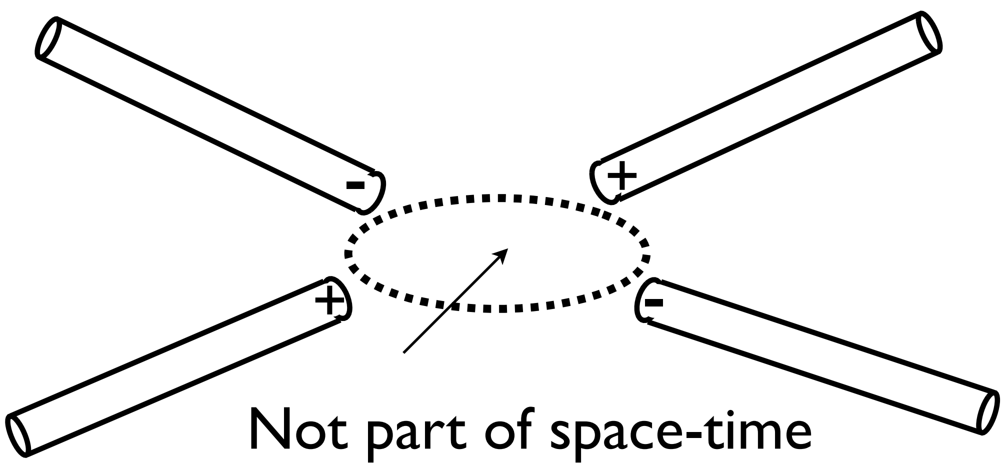
1-d spacetime + 1 compact direction



But one finds that something different happens ...

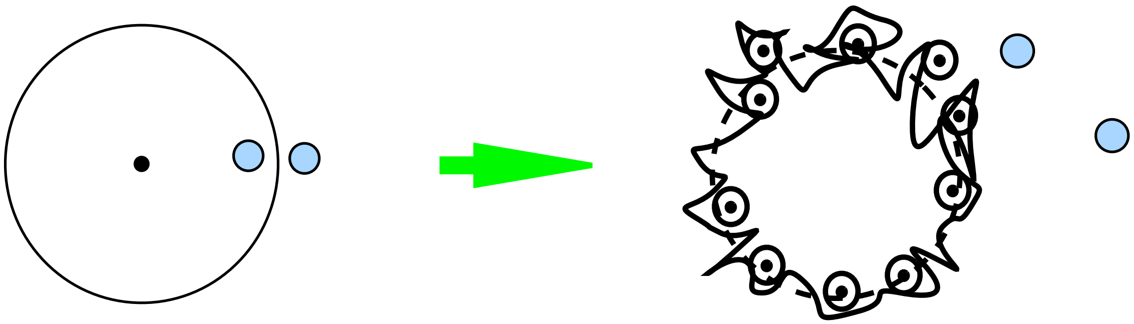
The geometry ‘caps off’
just outside the horizon
(KK monopoles in simplest
duality frame)

Mass comes from
curvature, fluxes,
strings, branes etc ..
(spacetime ‘ends’
consistently in a set
of valid sources in
string theory)



Not part of space-time
(no horizon forms)

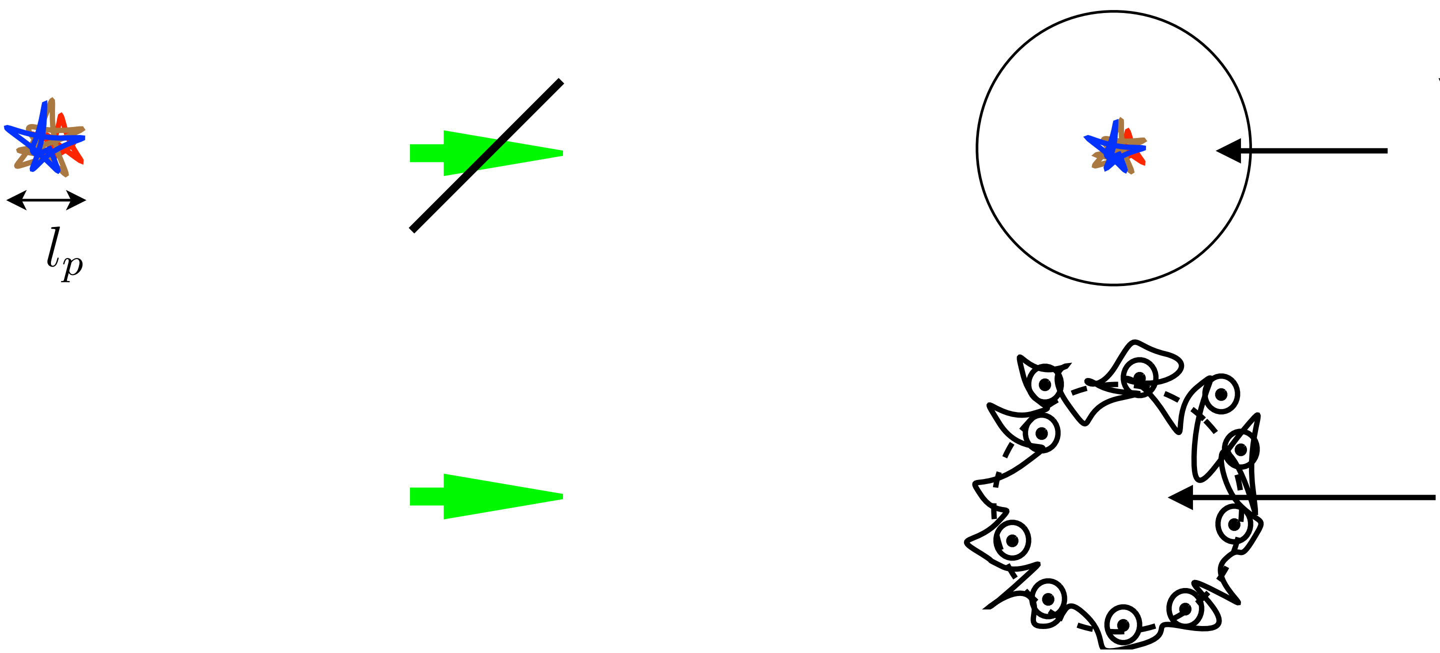
Fuzzball proposal:
All states of the hole
are of this topology …
No state has a smooth
horizon with an ‘interior’



The 'fuzzball' radiates from its surface just like a piece of coal, so there is no information paradox

All states investigated so far have a fuzzball structure (extremal, near extremal, neutral with max rotation …)

Fuzzball conjecture: no state in string theory has a traditional horizon

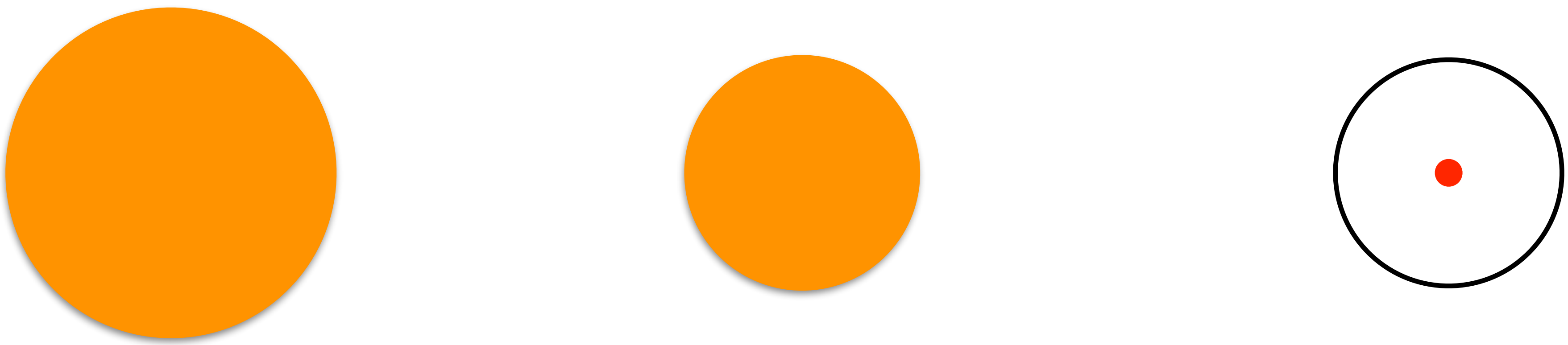


vacuum to leading order

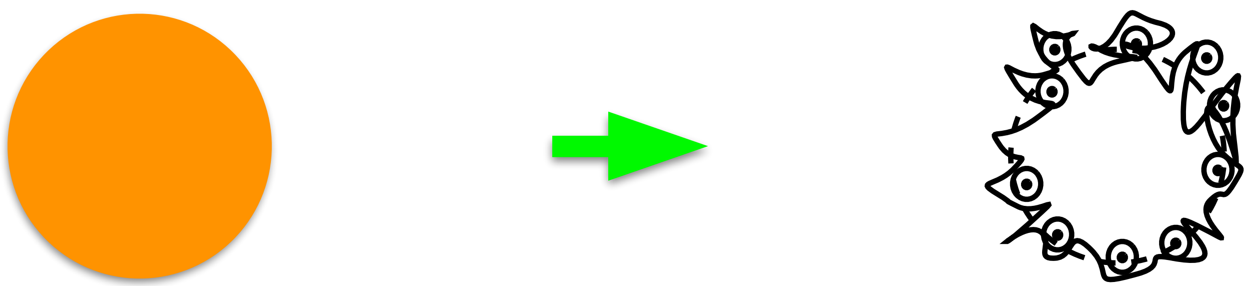
no horizon or interior

How could the black hole structure change
in this radical way ?

Classically expected collapse of a star:



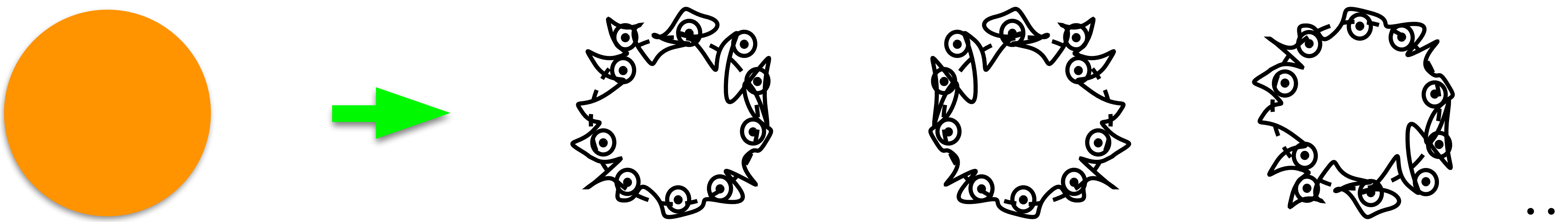
There is a small probability for the star to transition to a fuzzball state



$$\mathcal{P} \sim Exp[-S_{cl}] \sim Exp[-GM^2] \sim Exp[-S_{bek}]$$

(SDM 08, SDM 09, Kraus+SDM 15)

But we have to multiply this probability with a very large number of possible fuzzball states that the star can transition to …



Thus this very small number and this very large number *cancel* ...

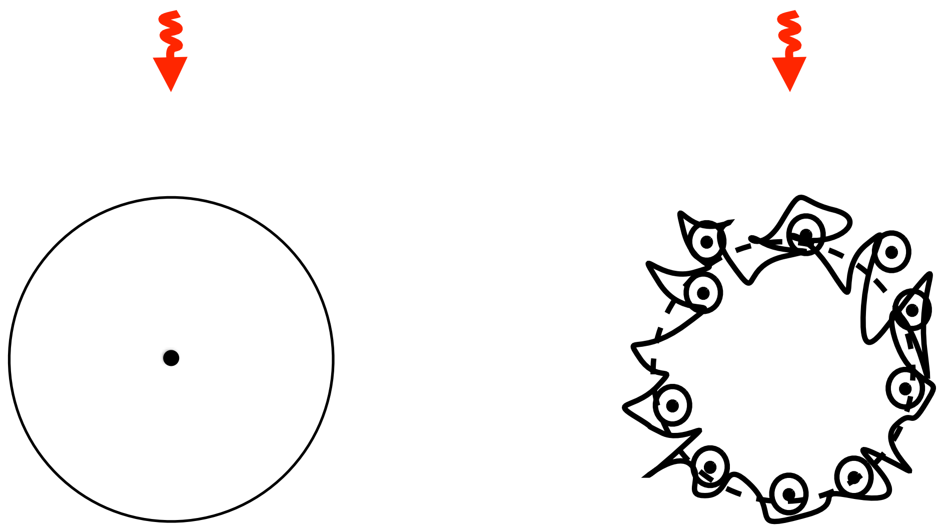
$$\mathcal{P}\, N \sim Exp[-S_{bek}] \times Exp[S_{bek}] \sim 1$$

Thus the semiclassical approximation is broken because the measure competes with the classical action:

$$\mathcal{Z} = \int D[g]\, Exp[-S_{cl}(g)]$$

Fuzzball complementarity

What happens if an energetic photon falls towards the hole ?



In the old picture, it would fall in

In the fuzzball picture, there is no interior of the hole to fall into

One might think that the photon has hit a "brick wall" or a "firewall"

But there is a second, more interesting, possibility ….

→ ***The idea of fuzzball complementarity***

The dynamics of infall into a black hole are described by some frequencies

$$\nu_1^{bh},\ \nu_2^{bh},\ \nu_3^{bh},\ \ldots \nu_n^{bh}$$

Oscillations of the fuzzball are also described by some frequencies

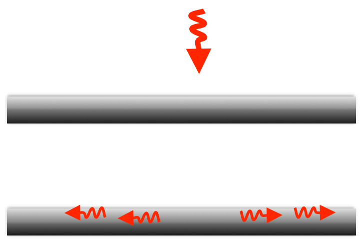
$$\nu_1^{fb},\ \nu_2^{fb},\ \nu_3^{fb},\ \ldots \nu_n^{fb}$$

What if

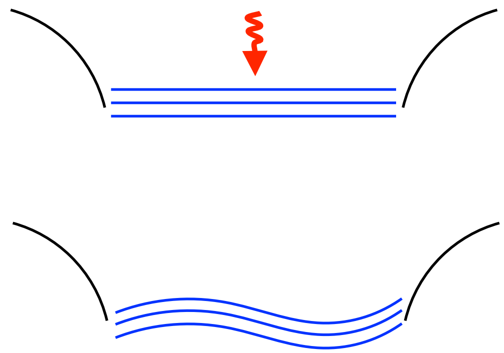
$$\nu_1^{bh},\ \nu_2^{bh},\ \nu_3^{bh},\ \ldots \nu_n^{bh} \quad \approx \quad \nu_1^{fb},\ \nu_2^{fb},\ \nu_3^{fb},\ \ldots \nu_n^{fb} \qquad ?$$

In that case falling onto the fuzzball will feel (approximately) like falling into a classical horizon …

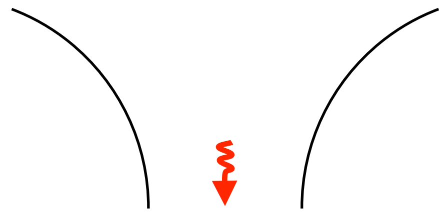
This may seem strange, but something like this happened with AdS/CFT duality …



Create random excitations



D-branes oscillate with some frequencies

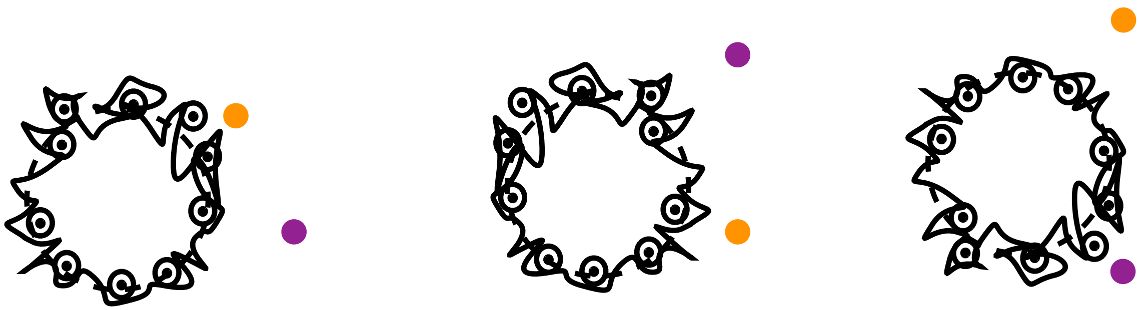


Gravitons in AdS space have the same frequency spectrum

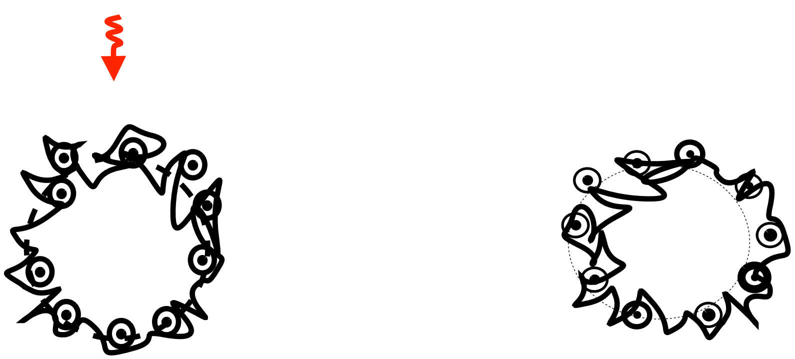
Maldacena 97

In our case, the frequencies of the traditional hole and of the fuzzball can be only approximately equal, since the fuzzballs are all a little different from each other …

This is crucial, since this is what allows information to escape !!

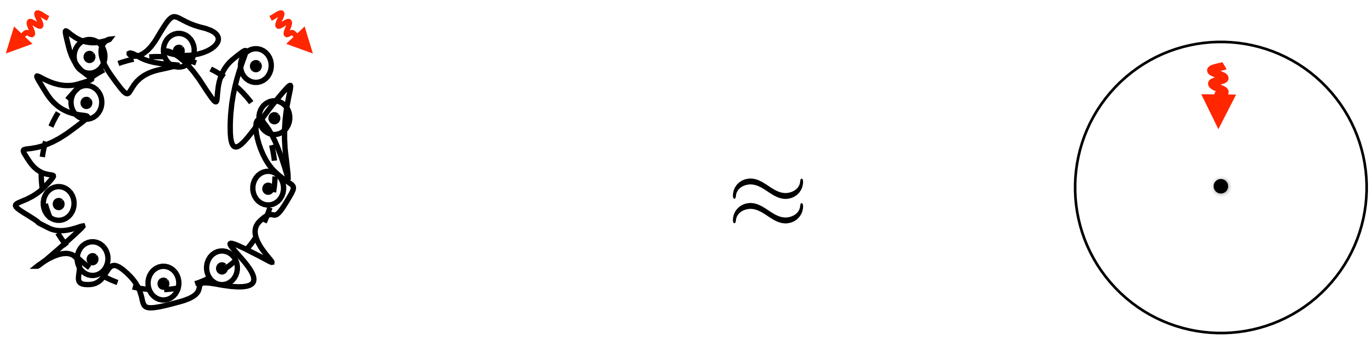


Low energy radiation ($E \sim T$) is different between different fuzzballs, carries information



High energy impacts ($E \gg T$) give a near-universal set of frequencies, which reproduces the frequencies of classical infall

Thus we recover information, and also preserve, approximately, our classical intuition !!



The surface of the fuzzball behaves approximately like the membrane of the membrane paradigm, but this time with real degrees of freedom at the horizon, and spacetime does really end at this 'membrane'

(SDM+PLumberg 2011)

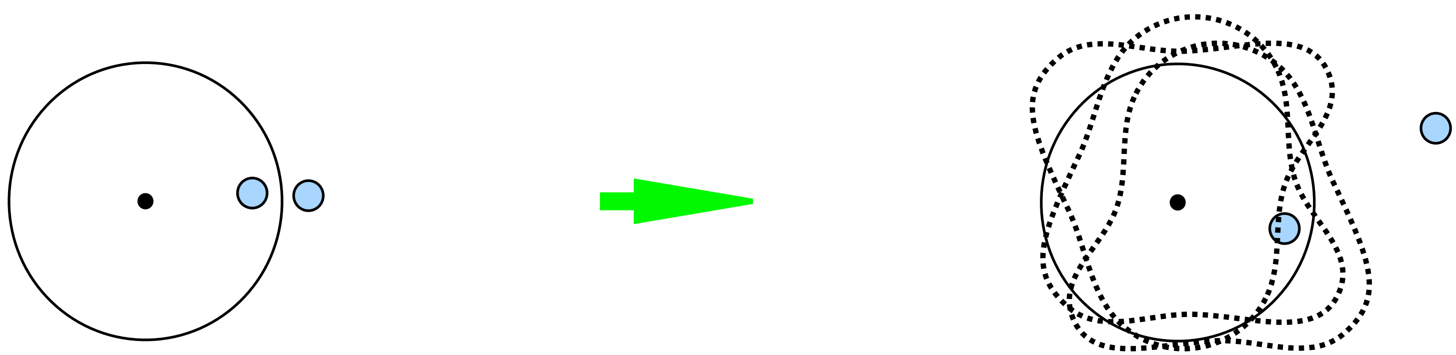
What is a firewall ?

Hawking ‘theorem’ (Hawking 75, SDM 09)

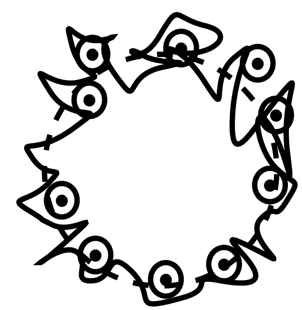
If the evolution of low energy modes at the horizon is ‘normal’ upto small corrections, then we MUST have either (i) information loss or (ii) remnants

This is exactly equivalent to:

If we don't want information loss or remnants, then we cannot have ‘normal physics to leading order at the horizon



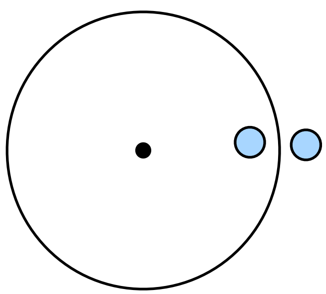
Besides, states in string theory were already conjectured to be fuzzballs …



AMPS: Assume that an infalling observer feels nothing but semiclassical physics till he reaches within planck distance from the horizon

Then we cannot get complementarity in the form proposed by Susskind

Susskind: Information is returned from the surface of the hole, but an infallling observer sees the vacuum at the horizon



The reason is simple: if there is a description where the horizon is the vacuum, then one has Hawking's creation of entangled pairs, and the consequent information paradox

But:

(a) AMPS focus on Hawking pairs, which are $E \sim T$, and do not take any limit $E \gg T$

We already know from fuzzballs that complementarity should be defined only in the $E \gg T$ limit (fuzzball complementarity)

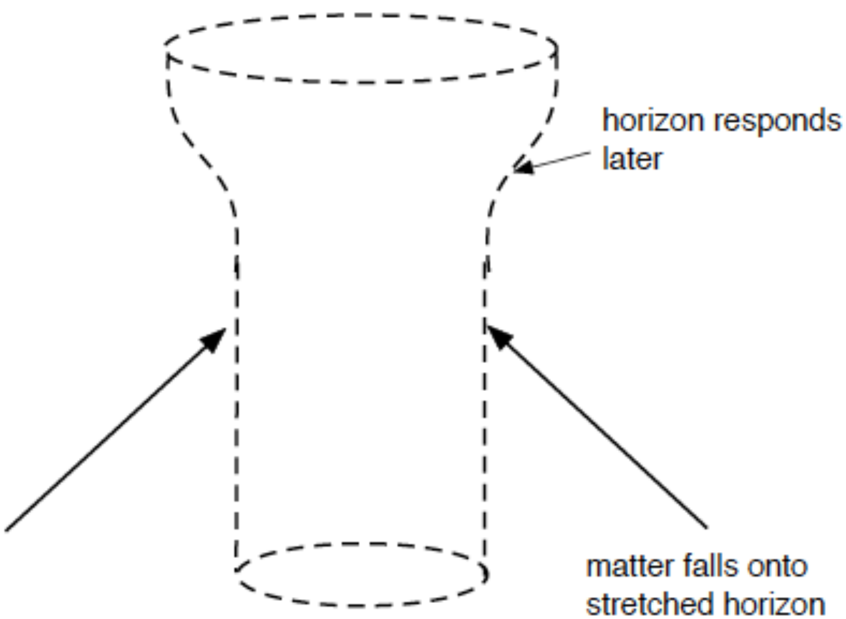
(b) AMPS assume that an infalling observer feels nothing but semiclassical physics till he reaches within planck distance from the horizon

In particular, the surface of the black hole does not respond till it is hit by an infalling shell

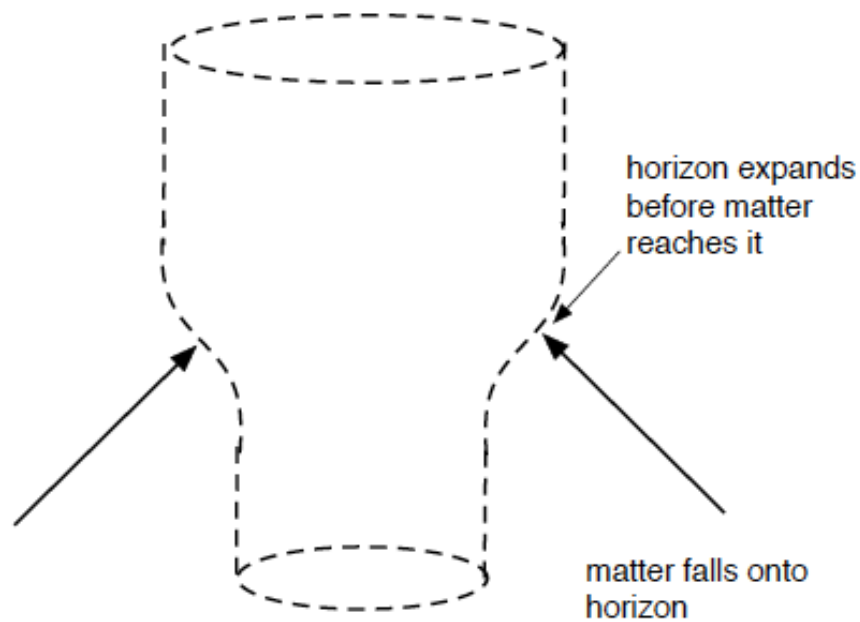
This violates a general belief that the entropy within an area is bounded as

$$S \le \frac{A}{4}$$

Black hole surface for AMPS



Horizon of a black hole



If shell lands on the black hole surface carrying entropy S , then we get entropy

$$S_{bh} + S = \frac{A}{4} + S \geq \frac{A}{4}$$

within area A

Summary

(A) The original Hawking argument can be made rigorous using string subadditivity, so one necessarily needs to break the no-hair theorem (or some other fundamental assumption of physics) (SDM 09)

(B) In string theory we find that black hole states are fuzzballs with no horizon; the novel features of the theory like extra dimensions and extended objects allow this violation of the no-hair theorem

(C) The semiclassical approximation is violated due to an abnormally large measure factor in the path integral coming from the number of fuzzballs

(D) The classical picture of infall is obtained for freely falling observers (which naturally have $E \gg T$), through the notion of fuzzball complementarity