Title: Fuzzballs, Firewalls and all that

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Abstract: Some 40 years ago Hawking showed that if the black hole has a smooth horizon, then information will be lost when the black hole radiates. In string theory black holes appear to have a complete set of `hair'; these black hole states are called fuzzballs, and they radiate like normal bodies with no information loss. It was recently argued that structure at the horizon will necessarily feel like a `firewall' to an infalling observer. We will show that this need not be the case, since one can have `fuzzball complementarity' where an approximately smooth horizon appears as a `dual' description.

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

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The Ohio State University

Outline

(1) The black hole information paradox (Hawking 1974)

(2) Hawking's retraction (2004)

(3) The error in Hawking's retraction - the small corrections theorem (2009)

(4) The solution in string theory: fuzzballs (1997 -)

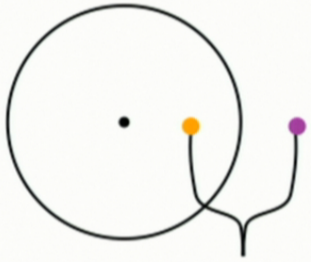
(5) What does an infalling observer see ? A Firewall ? (2012)

(6) The flaw in the firewall argument: The possibility of Fuzzball complementarity (2010, 2013)

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)

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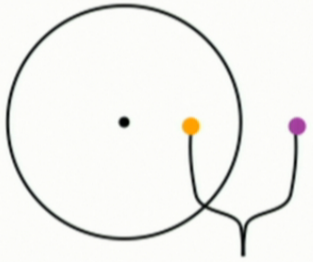

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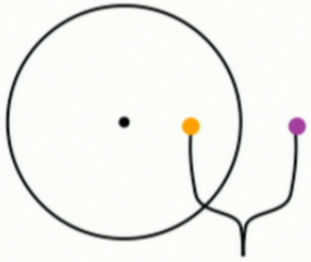

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Hole shrinks to
a small size

The essential issue: Vacuum fluctuations produce entangled states

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

$$= \frac{1}{\sqrt{2}}\left(01 + 10\right)$$

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

11111

...

\+ 01001

\+ 00000

00000

...

10110

11111

Wavefunction has the form

$$\frac{1}{\sqrt{2^N}} \sum_{i=1}^{2^N} \psi_i \otimes \chi_i$$

Can there be a cumulative effect of small corrections ?

(Maldacena 2001, Hawking 2004)

$|0\rangle + |1\rangle$

Leading order Hawking computation

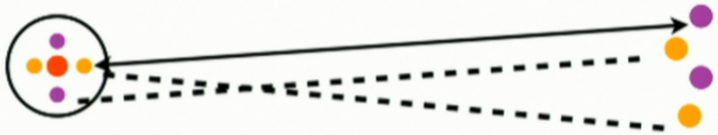
?? $(1+\epsilon)\,|0\rangle + (1-\epsilon)\,|1\rangle$

Small corrections, perhaps due to gravitational instanton effects

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

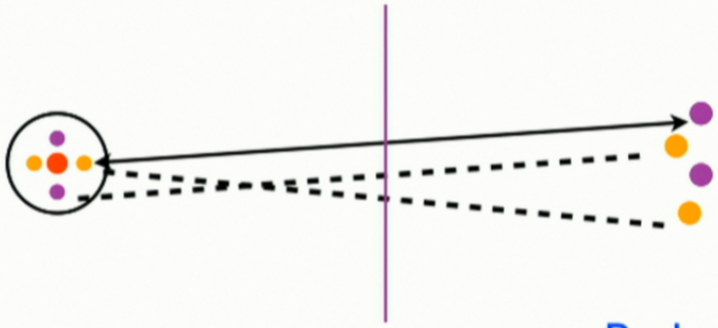
But the number of radiated quanta is very large ….

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 2004, Stephen Hawking surrendered his bet to John Preskill using similar arguments

(Subleading saddle point contributions in the Euclidean path integral give corrections that restore unitarity)

Stephen Hawking

John Preskill

Kip Thorne

But Kip Thorne did not agree to surrender the bet ...

Who is correct ?

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

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

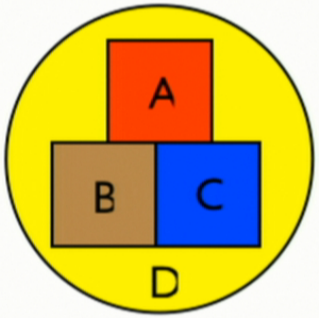
(SDM 2009)

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 …)

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

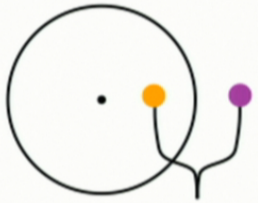


Summary

(SDM 2009): Hawking argument (1974) ⟶ 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

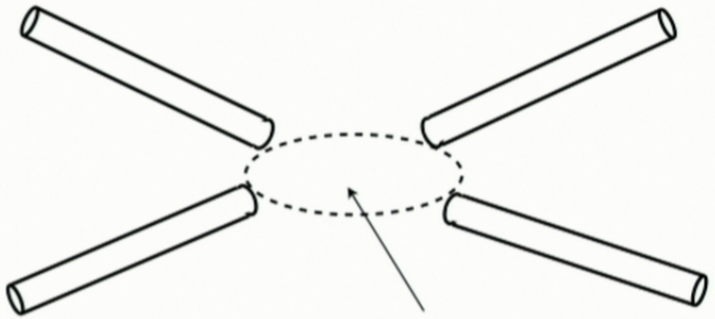
First consider a rough analogy …

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

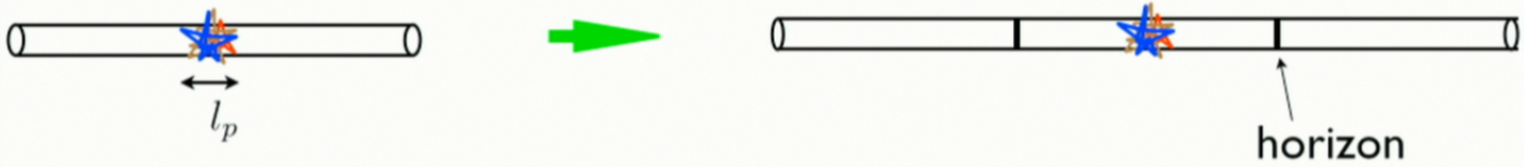
People did not worry about this instability too much, since it turns out that fermions cannot live on this new topology without having a singularity in their wave function …

But now consider the black hole …

Black holes:

The traditional expectation ...

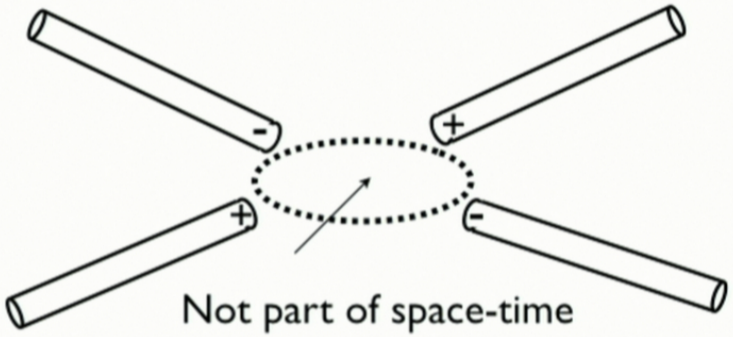
1-d spacetime + 1 compact direction



But one finds that something different happens ...

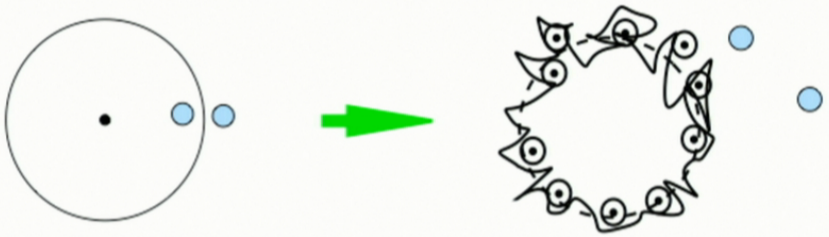
The geometry 'caps off' just outside the horizon (KK monopoles in simplest duality frame)

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)

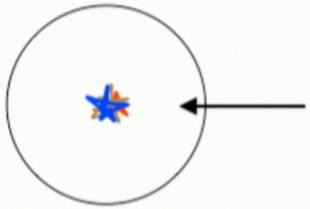
Fuzzball proposal:
All states of the hole are of this topology …
No state has a smooth horizon with an 'interior'



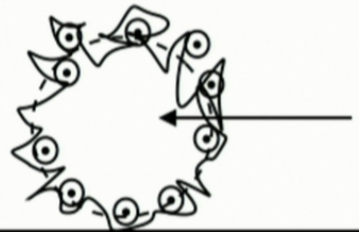
The 'fuzzball' radiates from its surface just like a piece of coal, so there is no information paradox

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

What is a firewall ?

Hawking 'theorem'

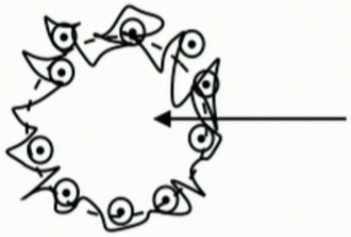
If the evolution of low energy modes (wavelength 1 meter to 10 Km) at the horizon is 'normal' upto small corrections, then we MUST have either (i) information loss or (ii) remnants

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

What is the mechanism and nature of the 'corruption' at the horizon ?

Fuzzballs: Found in all string constructions examined so far … has no horizon or interior



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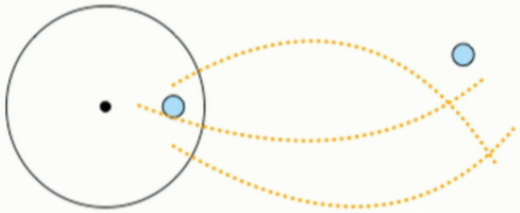
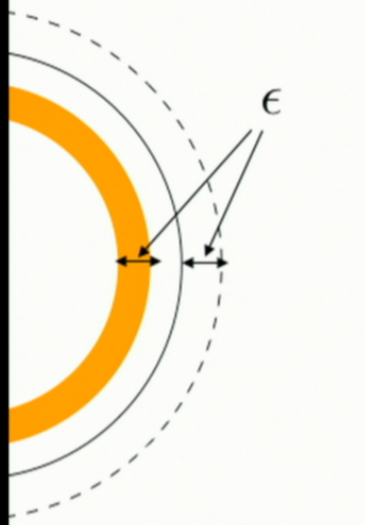


Some (so far unknown) gentle nonlocal effect changes the Hawking modes, but not the rest of physics (Giddings)

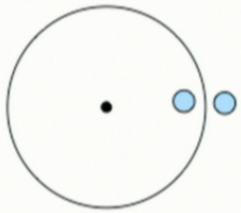
But in this case nonlocal physics can be observed by (sufficiently delicate) experiments at distances $4M$ from the horizon

The Firewall argument: AMPS (Almheiri, Marolf, Polchinski, Sully 2012)



If physics is 'normal' upto a distance ϵ from the horizon:

Then (by some mechanism) the modes of wavelength ϵ must be significantly corrupted on the other side of the horizon



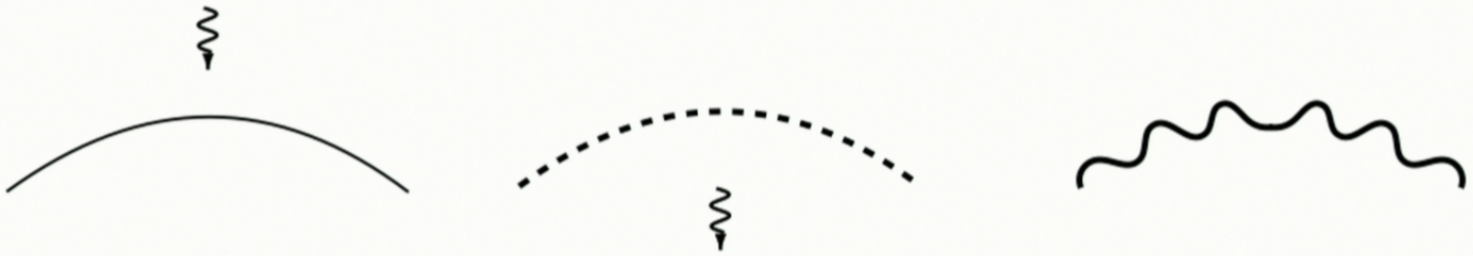
Reason: Such modes (inside and outside the horizon) give the Hawking pairs …

AMPS: An infalling observer will feel that he is burnt by a 'firewall' ..

Not necessarily true !!

Fuzzball Complementarity (Plumberg +SDM 2010)

Underlying idea based on AdS/CFT



(A) Traditional horizon: wave falls smoothly into interior

(B) Fuzzball: no interior, surface set into oscillations

If the frequency spectrum of excitations is the same, how can we tell the difference ? (Duality)

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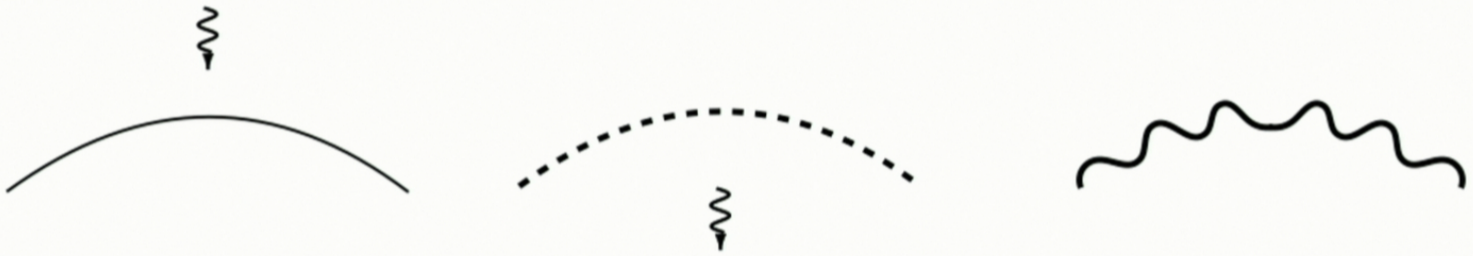

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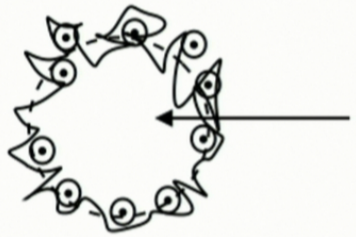
Summary:

(A) If we do not want information loss or remnants, then we must 'corrupt' physics at the horizon by order unity (SDM 2009)

(B) In string this seems to happen automatically by the fuzzball mechanism: black hole microstates are in a topological class different from the traditional geometry



(C) There is a possibility of 'fuzzball complementarity' where an infalling high energy particle hits the fuzzball surface, but 'feels' almost nothing: its wave function gets almost faithfully mapped into surface oscillations of the fuzzball