Title: The fuzzball paradigm

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Abstract: The black hole information paradox poses a serious difficulty for theoretical physics. Over the last two decades there has emerged a resolution to this paradox in string theory, based on the discovery that heavy states in string theory swell up into horizon sized "fuzzballs". The talk will review the fuzzball construction and how the traditional semiclassical expectation of a vacuum horizon gets violated. It has been recently argued that objects with a surface like a fuzzball should behave like a "firewall" for infalling objects; we show that this firewall argument is inconsistent because its assumptions violate causality.

Black Hole Microstates in String Theory

David Turton

University of Southampton

"Quantum Black Holes in the Sky?" workshop
Perimeter Institute
Nov 9, 2017

Based on:
Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner arXiv:1607.03908, PRL
Bena, Bossard, Katmadas, DT arXiv:1611.03500, JHEP
Bena, DT, Walker, Warner arXiv:1709.01107, JHEP in press
Bossard, Katmadas, DT in preparation

The fuzzball paradigm

Samir D. Mathur

The Ohio State University

Outline:

1. The information paradox as a rigorous theorem

2. How fuzzballs resolve the paradox

3. How the semiclassical approximation get violated at the horizon - "entropy-enhanced tunneling"

4. Must fuzzballs behave like firewalls? --
   The flaw in the firewall argument

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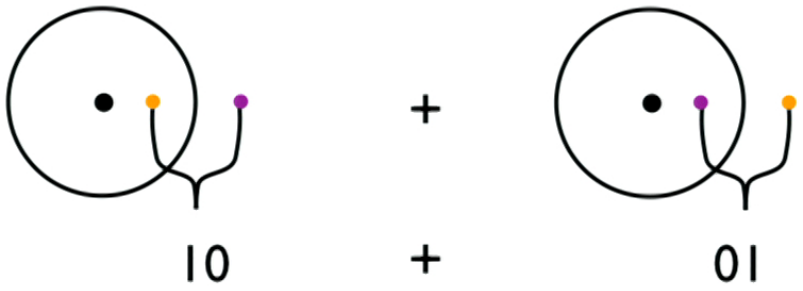
The information paradox:

Hawking (1975) found that particle pairs are produced at the horizon,
and these pairs are in an entangled state



As the evolution proceeds, the emitted radiation gets more and more entangled with the remaining hole

What happens at the endpoint of evaporation?

If the hole evaporates away, the radiation is entangled, but there is nothing that it is entangled *with*.

So the radiation can only be described by a density matrix:

⟶ violation of quantum unitarity

String theory is unitary, but for a while many string theorists were not particularly worried ...

A common belief: *Hawking (1975) did a leading order computation of entanglement, but if we look at subleading corrections, the problem will go away.*

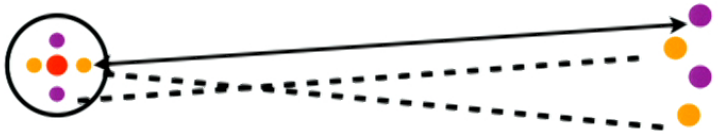
(Maldacena 2000, Hawking 2004)

Hawking computed the entanglement at leading order ...

But there could be small corrections to the state of each emitted pair, arising from subtle quantum gravity effects

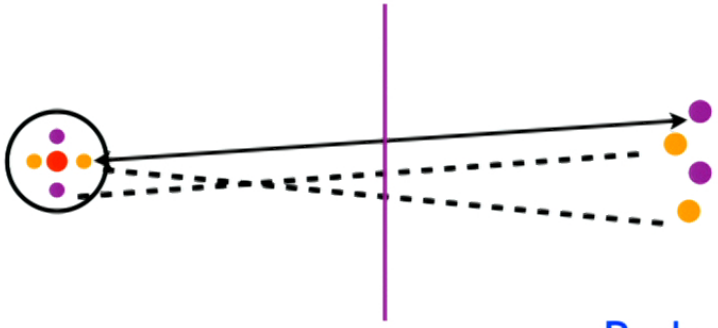
$$(1+\epsilon)\,|10\rangle \quad + \quad (1-\epsilon)\,|01\rangle$$

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 …

But in 2009 a theorem was proved that showed this idea was incorrect ...

At leading order, the emission of each pair leads to an increase in entanglement

$$S_{ent}(N+1) \;=\; S_{ent}(N) \;+\; \ln 2$$

Using the strong subadditivity of quantum entanglement entropy it can be shown that when we include the corrections,

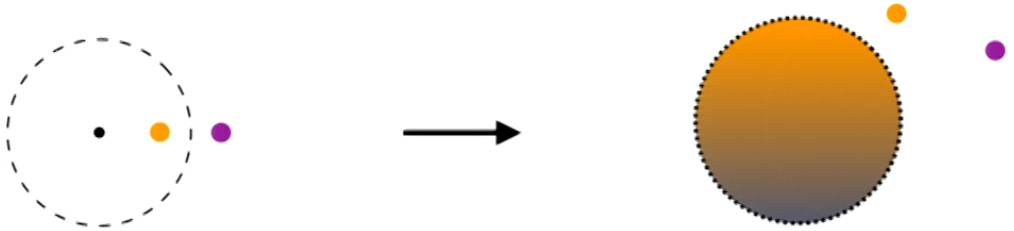
$$S_{ent}(N+1) \;>\; S_{ent}(N) \;+\; \ln 2 \;-\; 2\epsilon$$

(SDM 2009)

Thus to resolve the information paradox we need ORDER UNITY corrections at the horizon ... *i.e., the horizon cannot be a normal place like this room ...*

(see also Giddings 11, Avery 11)

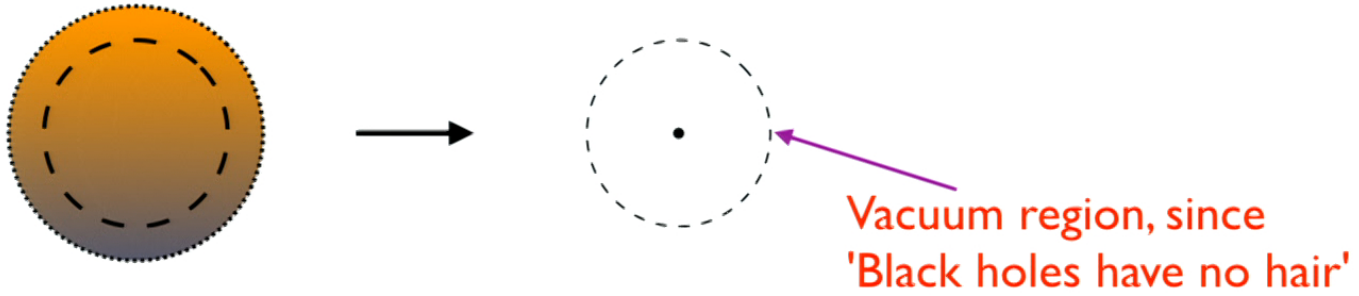
If we had a ball instead of a vacuum region, there would be no problem ...



But it is very difficult to support a horizon sized ball against collapse ...

Buchdahl theorem: Fluid sphere with pressure decreasing outwards must collapse if

$$R < \frac{9}{4} M$$



Remarkably, in string theory, the states of the black hole turn out to be horizon sized 'fuzzballs' ...

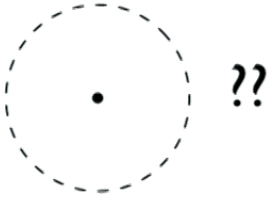
How do such states support themselves against gravitational collapse?

1997 - The fuzzball paradigm

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

String theory has a fixed brane content and interactions ....

Make a bound state of a large number of branes:



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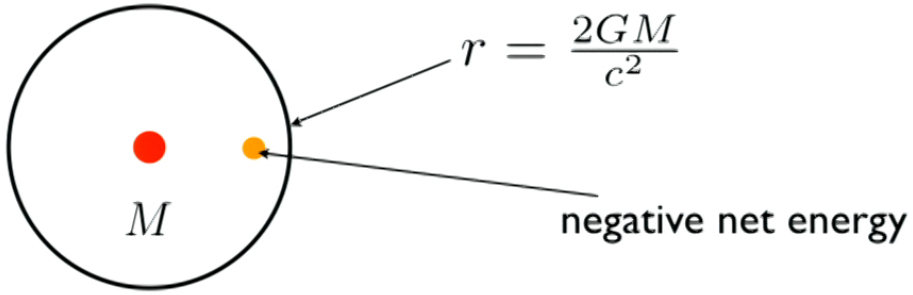
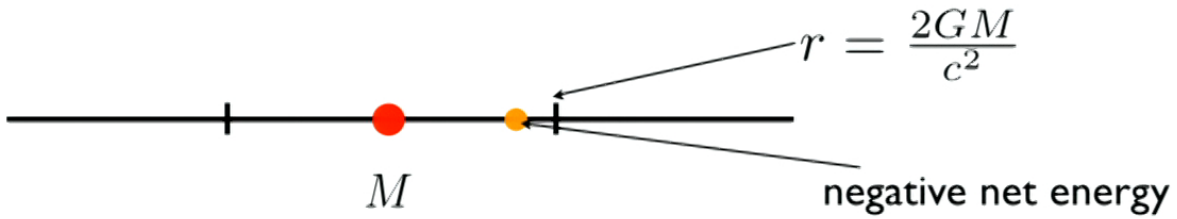
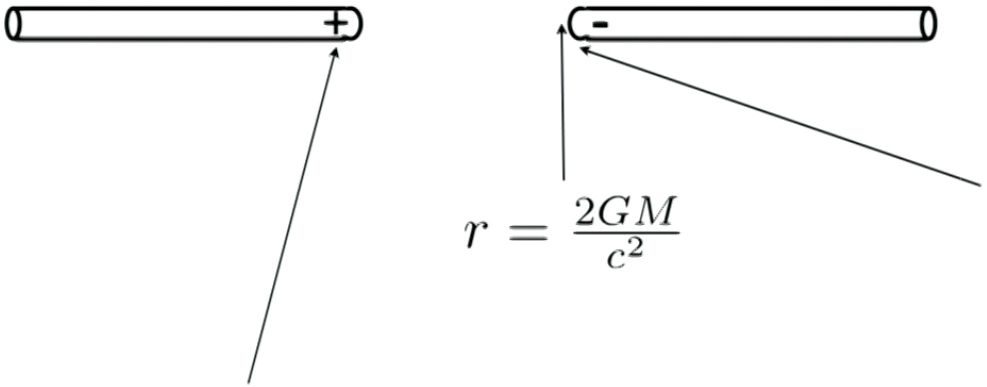
We live in 3 space and 1 time dimension. Recall the black hole ...



Let us draw just one space direction for simplicity



But there is a completely different structure possible with compact dimensions ...



No place to put particles with net negative energy

The mass M is captured by the energy in the curved manifold

There is an extra 'twist' in the space-time which makes it consistent to have both boson and fermion wave functions

(Kaluza Klein monopoles and anti-monopoles)

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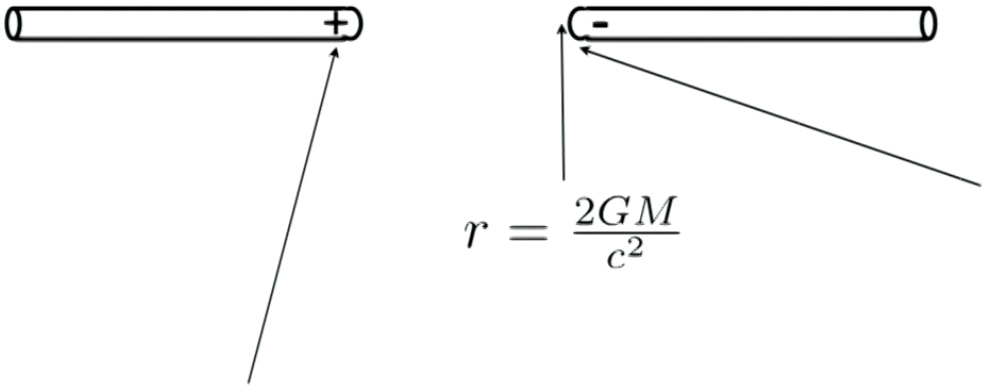

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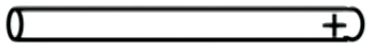
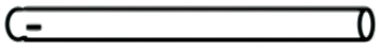
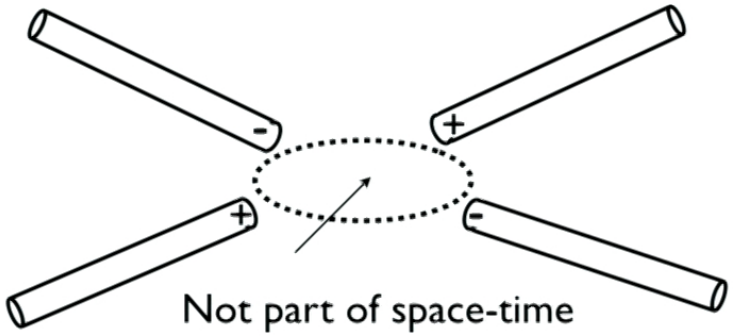


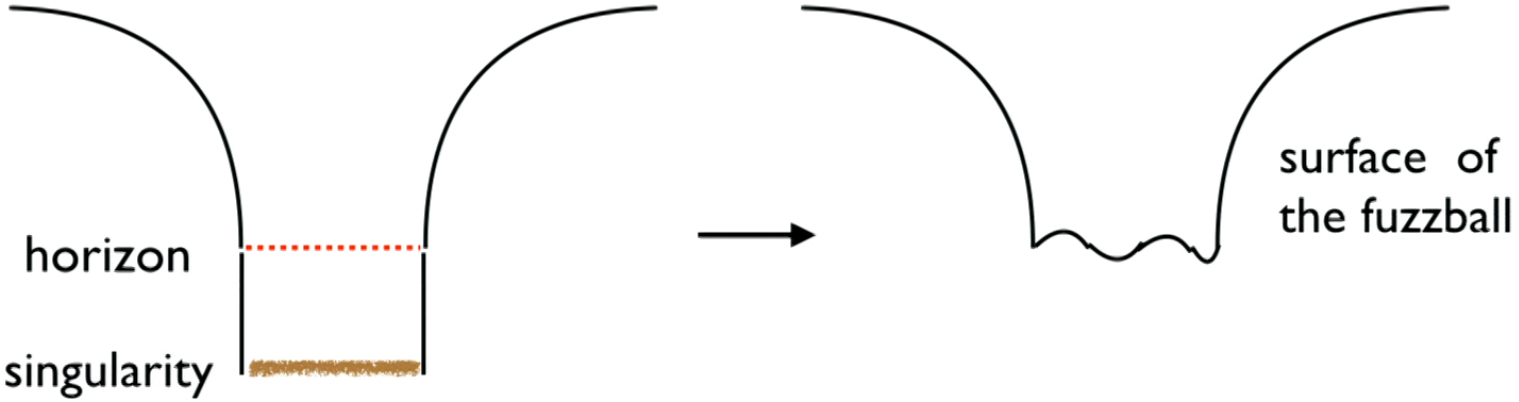


1-dimension

In more dimensions :

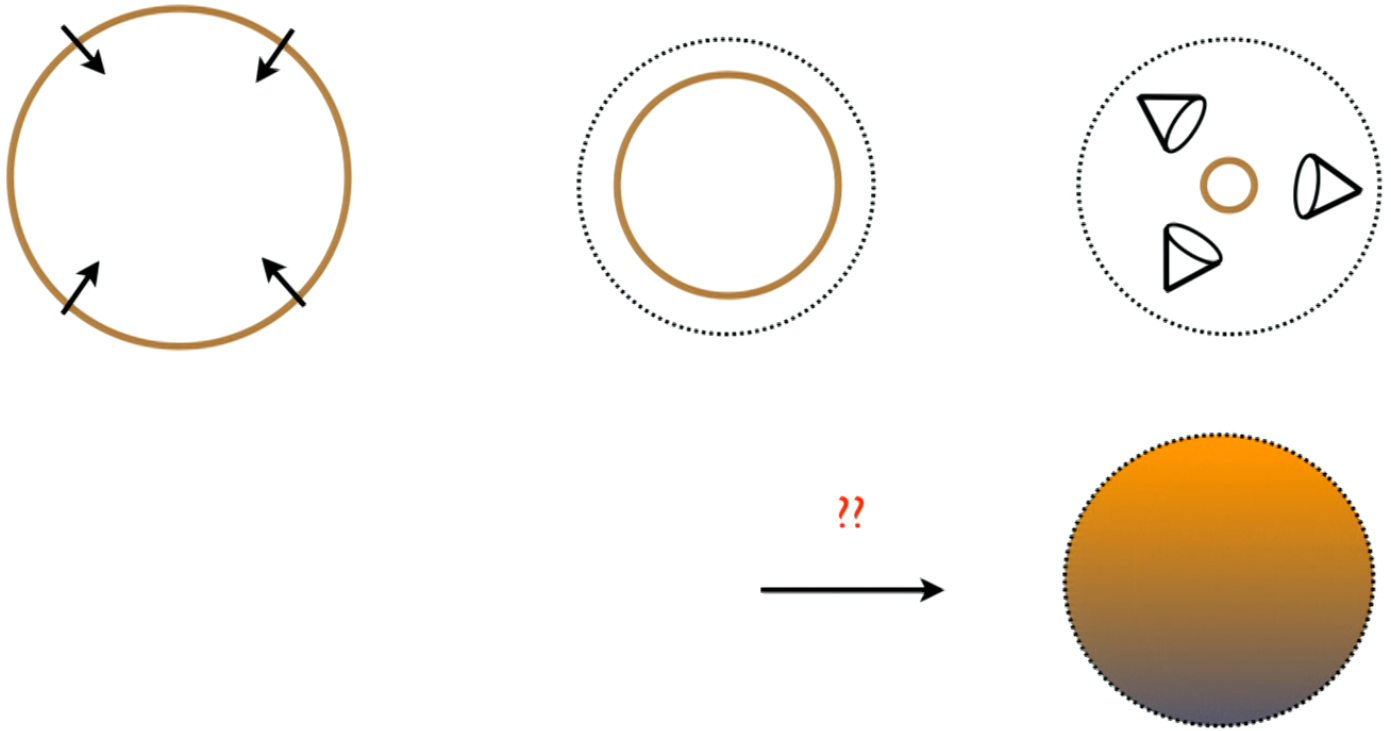


Not part of space-time
(no horizon forms)



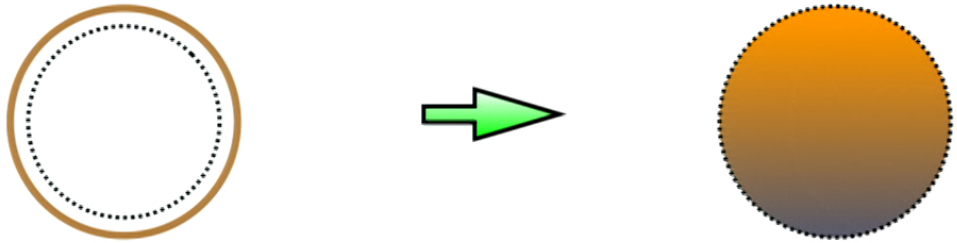
What makes the semiclassical approximation break down?

Shell collapses to make a black hole ...



How would we ever get a fuzzball ?

Consider the amplitude for the shell to tunnel to a fuzzball state



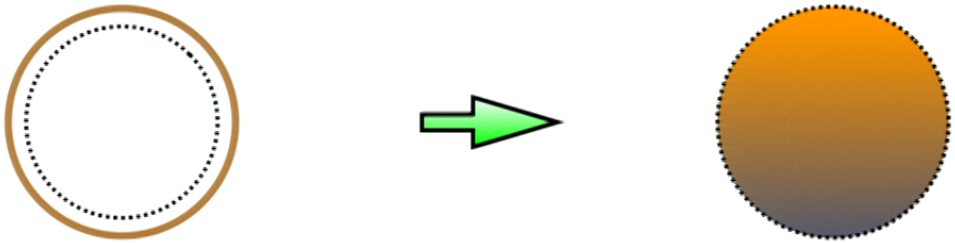
$$S_{tunnel} \sim \frac{1}{G}\int R d^4x \sim \frac{1}{G}\frac{1}{(GM)^2}(GM)^4 \sim GM^2$$

$\mathcal{A} \sim e^{-S_{tunnel}}$ Amplitude to tunnel is very small

$\mathcal{N} \sim e^{S_{bek}} \sim e^{GM^2}$ But the number of states that one can tunnel to is very large !

For black holes the entropy is so large that

$$P_{tunnel} \sim |\mathcal{A}|^2 \times \mathcal{N} \sim 1$$



Thus the collapse process is not described by semiclassical physics ...

We call this phenomenon " Entropy-enhanced tunneling "

(SDM 09, Kraus+SDM 15, Bena, Mayerson, Puhm, Vernocke 15)

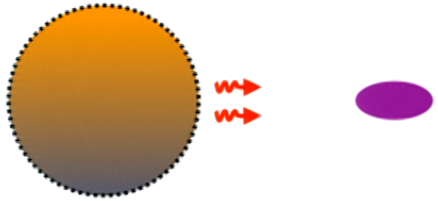
What is a *firewall* ?

A fuzzball is an explicit construction in string theory where the black hole is found to be replaced by planet like object

A firewall is NOT a construction in any theory

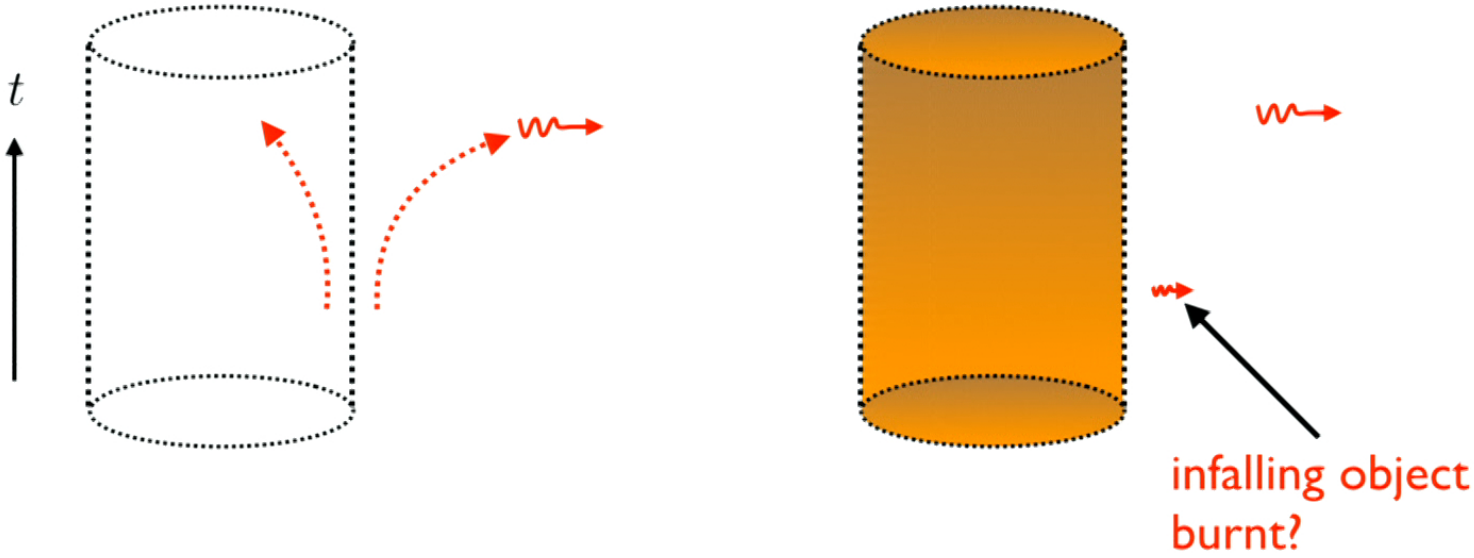
Instead, it is an *argument:*

IF we have a surface instead of a horizon, THEN radiation from this surface will burn infalling objects before they reach the surface



(Almeheiri, Marolf, Polchinsky, Sully 12)

The idea behind the firewall argument

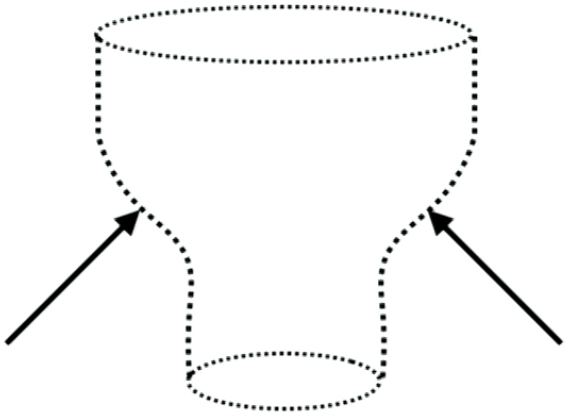


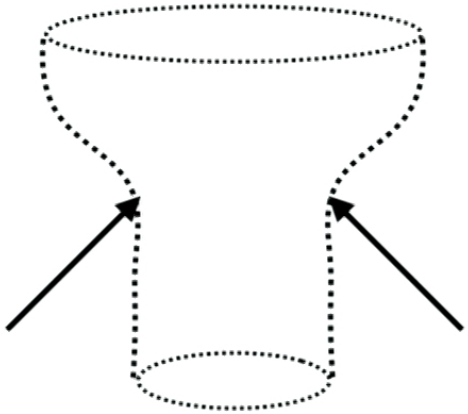
Traditional hole: Low energy Hawking quantum materializes far from horizon

Hot surface: High energy quantum starts near surface, redshifts to low energy far away

AMPS tried to make this rigorous using the bit model of the small corrections theorem

The flaw in the firewall argument (SDM + Turton 14)

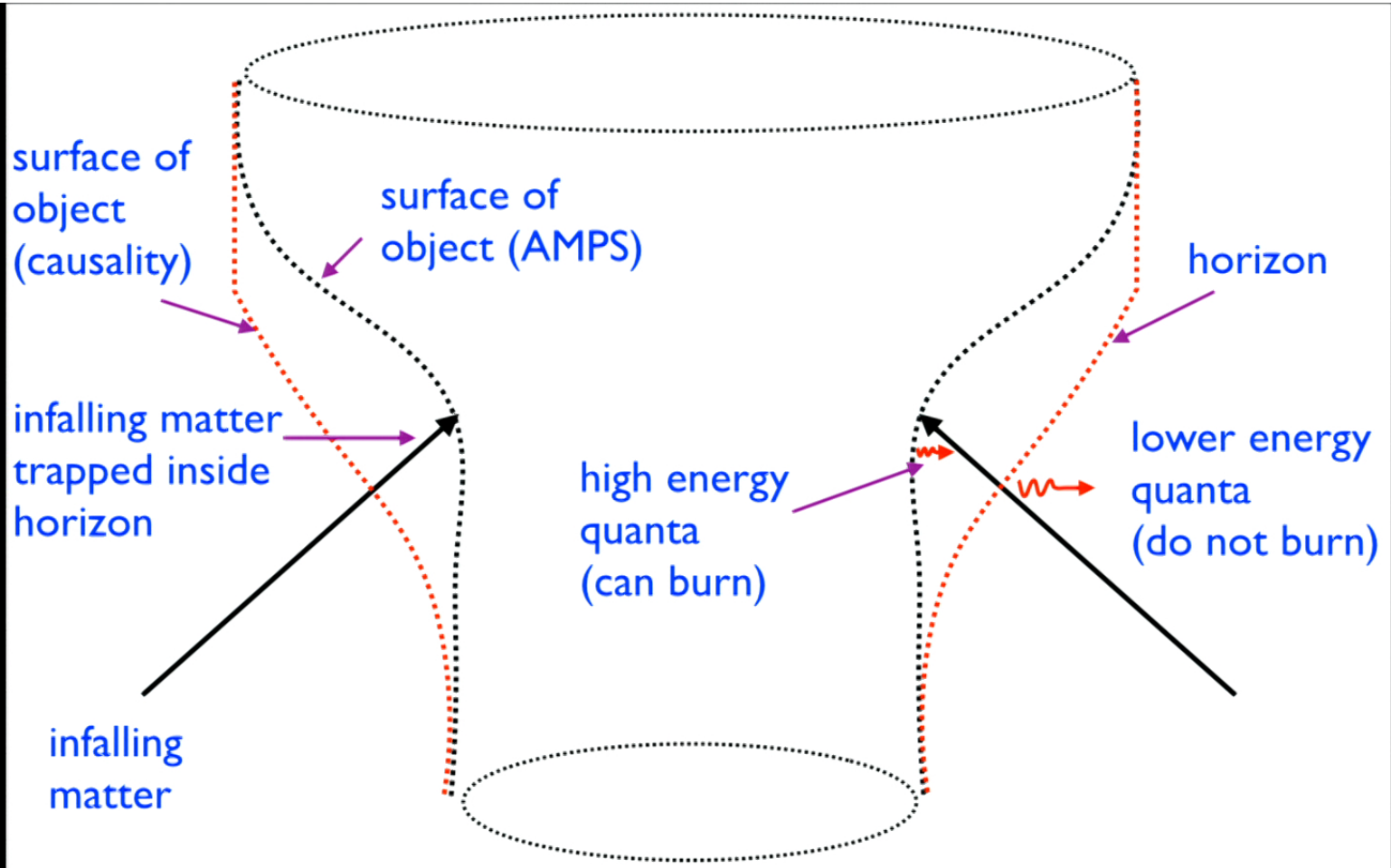




GR: The horizon expands before matter falls in

AMPS assume that the surface does not respond before it is hit.

The surface of the ball must be outside the horizon at all times, else information cannot come out without violating causality



Infalling matter with $E \gg T$ does not burn (Guo, Hampton, SDM 17)

Summary of the fuzzball paradigm

1. The small corrections theorem: Information paradox cannot be resolved by small quantum gravity effects

2. The fuzzball construction: Gravitational collapse automatically avoided in string theory by novel topologies, properties of branes etc.

3. Breakdown of semiclassical approximation: "Entropy enhanced tunneling" into fuzzballs

4. Conjecture of Fuzzball complementarity: Bit model respecting causality, effective free infall for $E \gg T$ quanta
(AMPS assumptions violate causality)

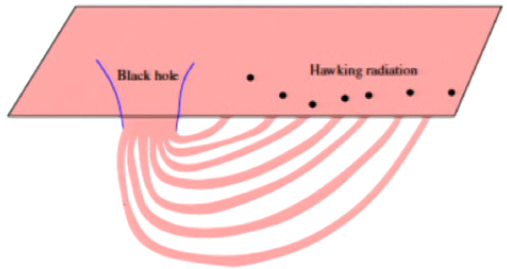
The nontrivial element of the fuzzball construction is that the fuzzball does not collapse (due to novel effects in string theory)

Alternatives to the fuzzball paradigm keep an approximate vacuum around the horizon ... but use some kind of *nonlocality* to resolve the information paradox

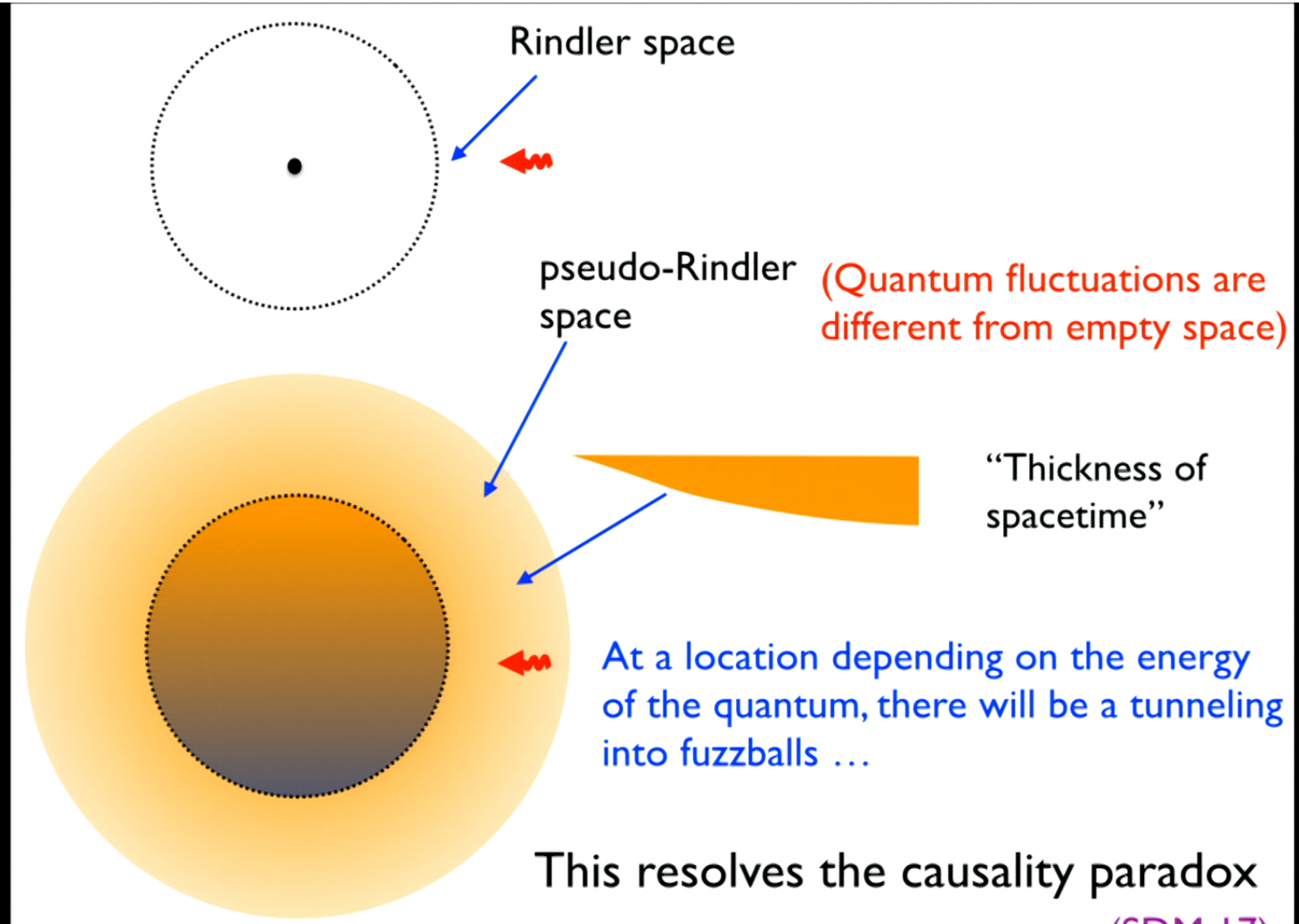
Horizon scale nonlocality (Giddings)

Wormholes between hole and its radiation (Maldacena-Susskind)

Gauge states at infinity (Hawking-Perry-Strominger)



But we have not seen any nonlocality or acausality in string theory ...


Rindler space
pseudo-Rindler space
(Quantum fluctuations are different from empty space)
"Thickness of spacetime"
At a location depending on the energy of the quantum, there will be a tunneling into fuzzballs …
This resolves the causality paradox
(SDM 17)