# Hawking's puzzle: The Black Hole Information Paradox

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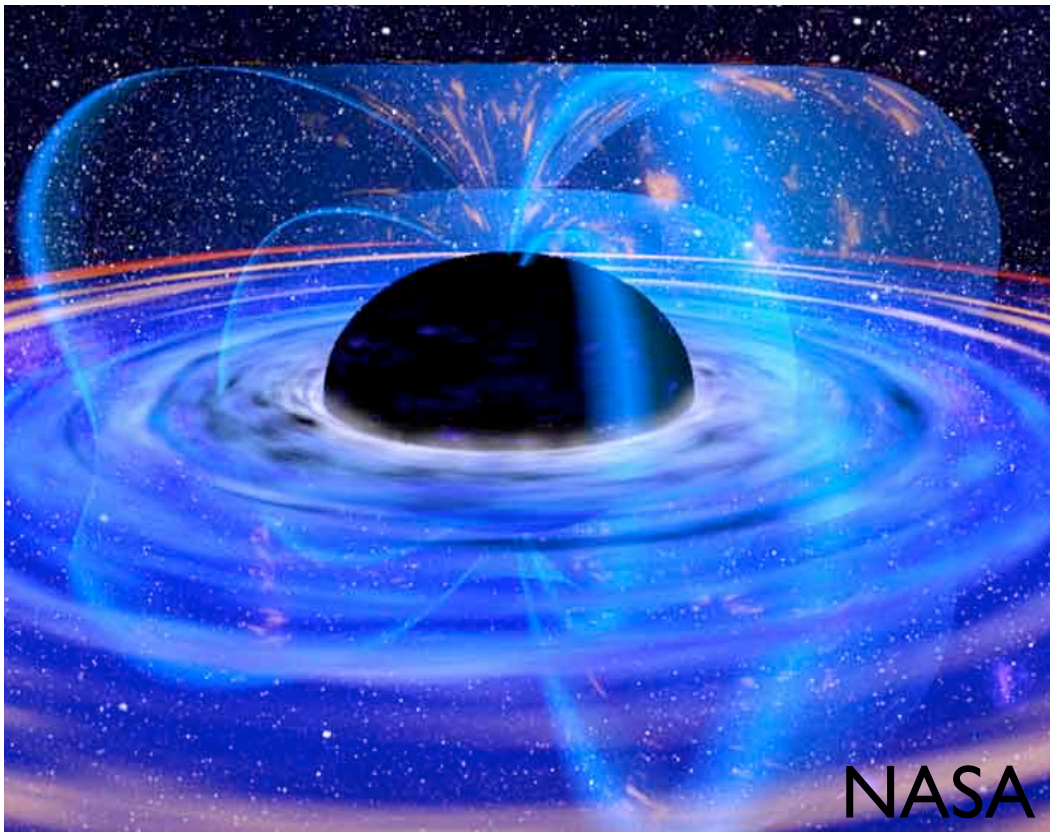
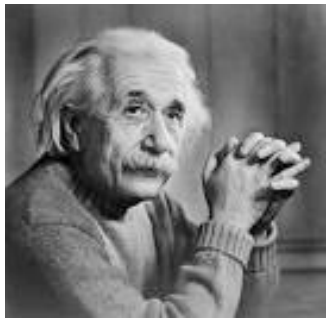




(Einstein)

(Heisenberg)

General relativity

Quantum theory

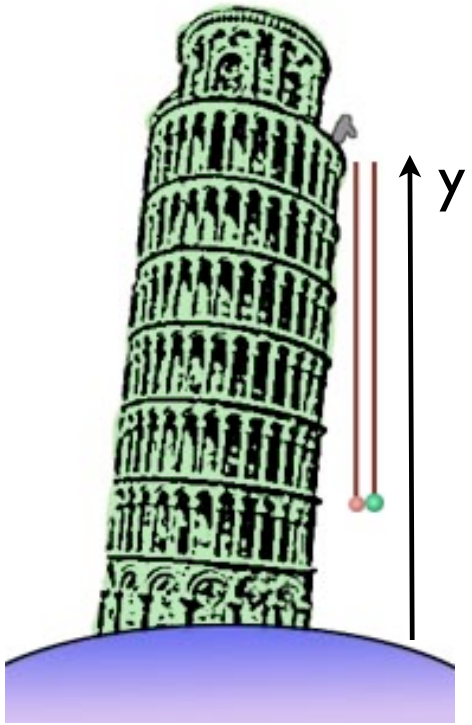
(Black holes)

(Hawking)

Hawking's work on black holes showed that General relativity and Quantum mechanics contradict each other

This puzzle is known as the Black Hole Information Paradox

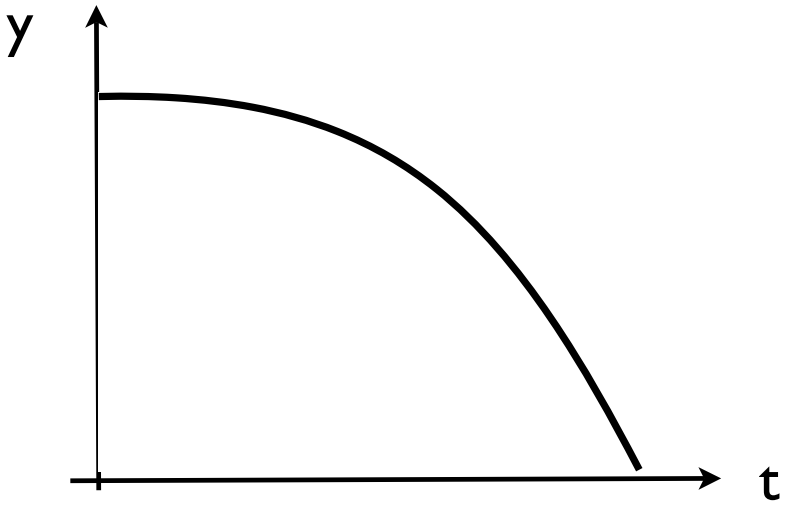
# General relativity




Galileo dropped two balls, one heavy and one light, from the leaning tower of Pisa

He wanted to know which would reach the ground first

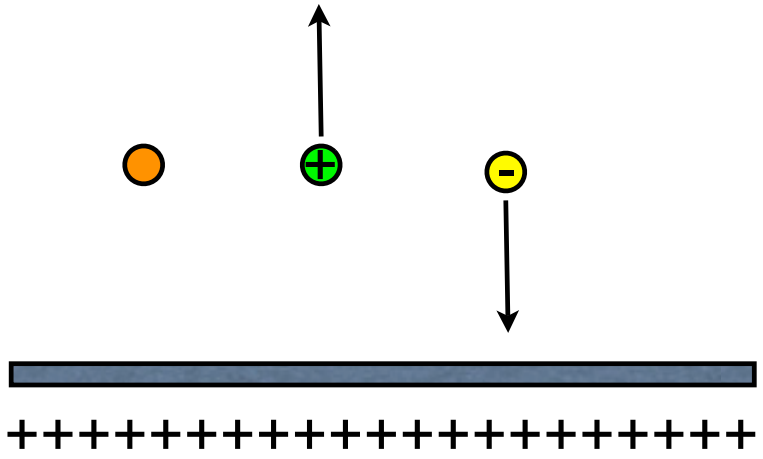
He found that they reached the ground at the same time

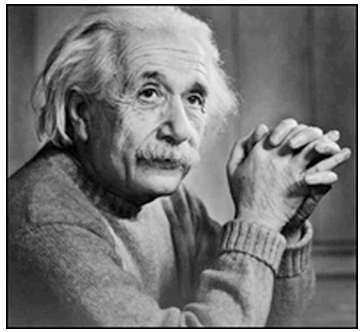


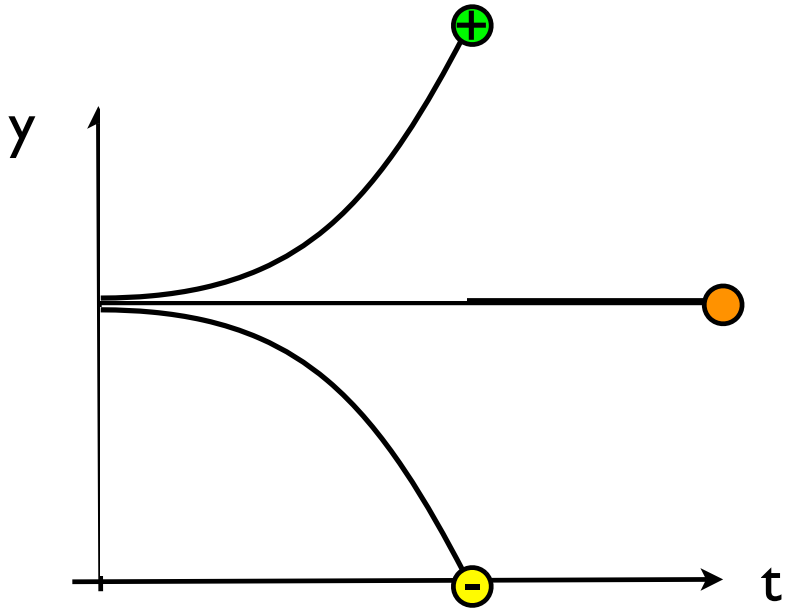

Both balls have the same graph, so we say they follow the same trajectory on the y-t plane

This situation is very special, it holds only for gravity

If we have electrostatic forces, then different objects have different trajectories ...



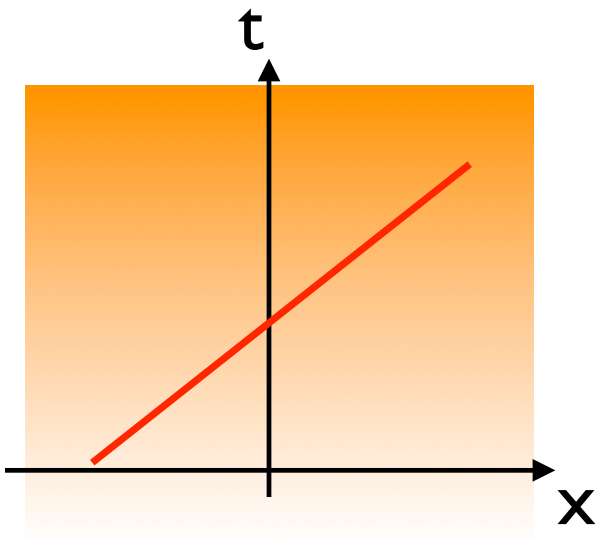


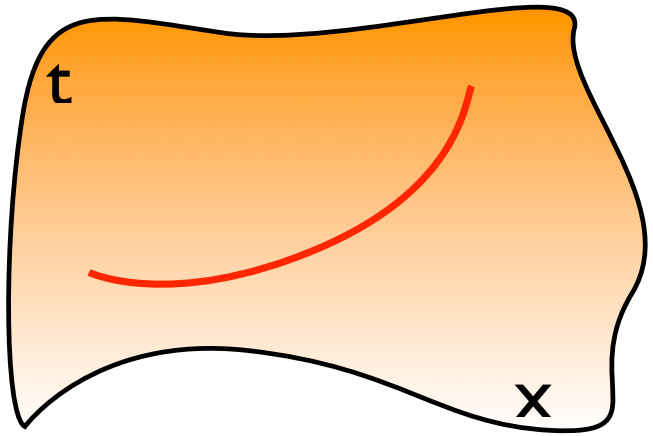

Since the graphs for gravity are special, we should be able to make a new kind of theory for gravity

Traditional approach: Particles have a straight line graph if there is no force

The graph is curved if there is a force

What we will do now is curve the graph paper instead ....




Flat graph paper: straight lines are the usual graphs for 'no force'

'Straight line' on curved surface is defined to be the shortest distance between two points

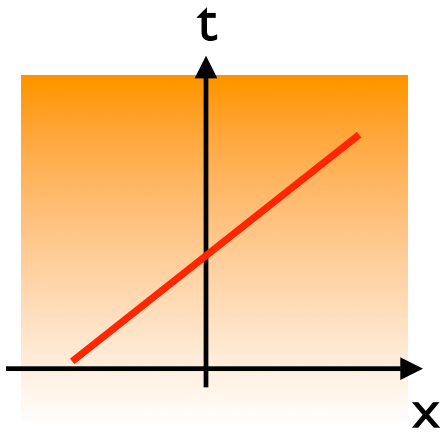
For example, the great circles on earth give the shortest distance between two points ...

Einstein's idea: Suppose there is gravity in some region

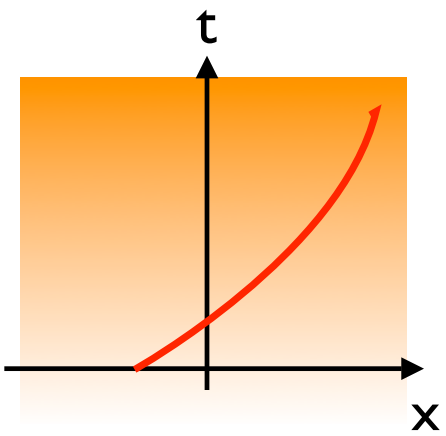
We want to describe the graphs of particles moving in this region

Newton would have taken a flat graph paper, and drawn a curved trajectory on it

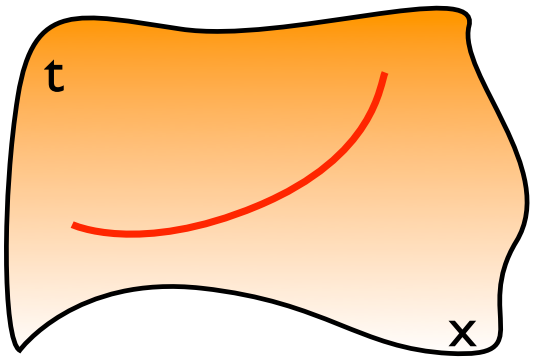
But we should instead take a curved graph paper, and draw a 'straight' line on it




No gravity: flat graph paper, path is straight line



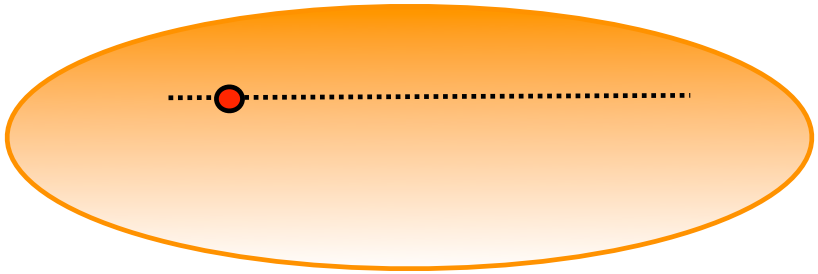

Gravity as described by Newton: Graph paper flat, path is curved

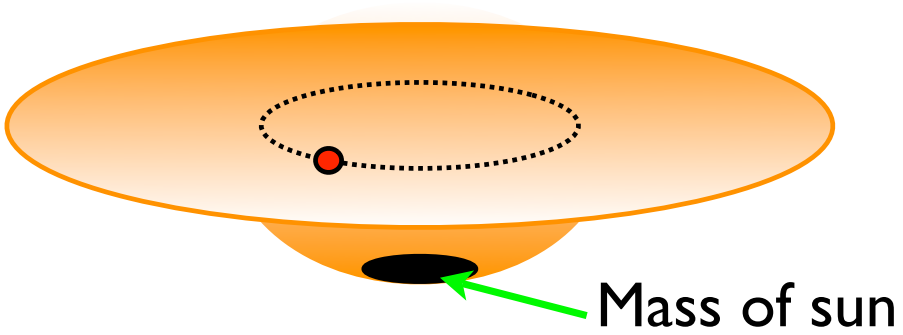



Gravity as described by Einstein: Graph paper curved, path is 'straight'

What is the advantage of doing it Einstein's way?

Answer: It gives the actual paths correctly !!





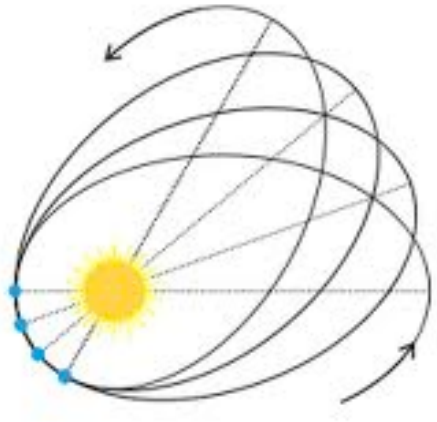

No masses around ...
spacetime is flat ...
particle moves in straight line

Sun curves the spacetime around it ...
Particles (like earth) make orbits that are curves ...

In Newton's theory, the orbit is a closed ellipse

In Einstein's theory, it is not quite closed ....

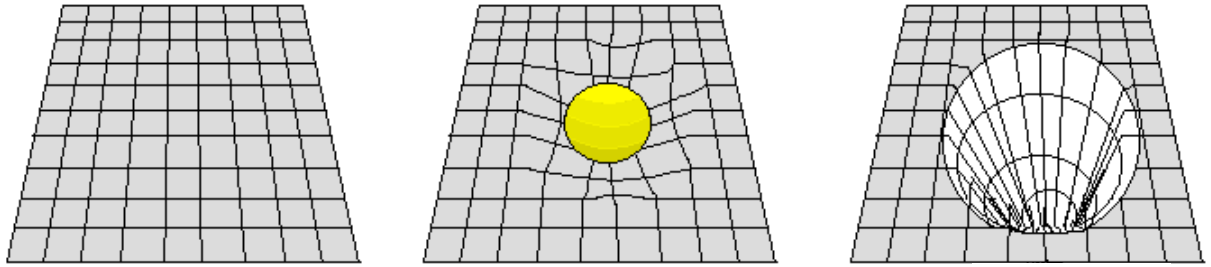
Observations agree with Einstein's theory !!



43 arc seconds per century

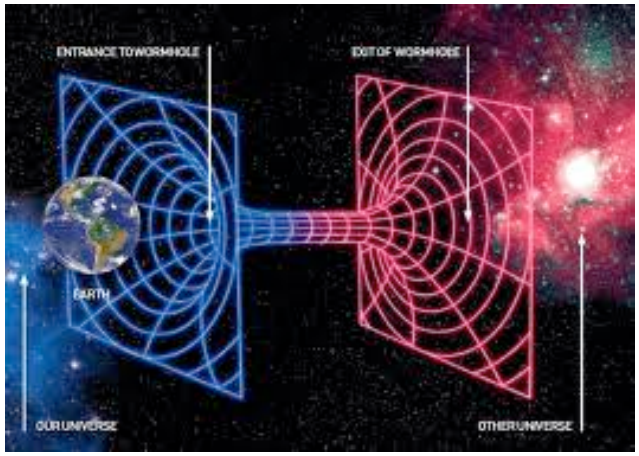
Once we know that spacetime should be curved, we find many interesting effects:

(a) Black holes



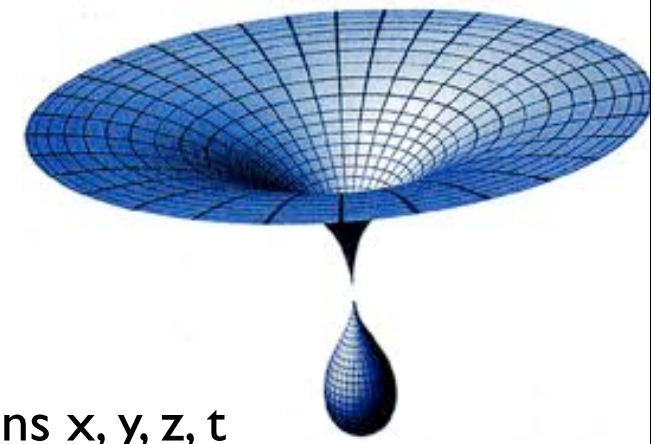
Tear a hole is spacetime; what falls in cannot get out

(b) Wormholes




Fall in somewhere, come out somewhere else

(c) A part of spacetime pinches off into a new Universe ... can we ever go there ?

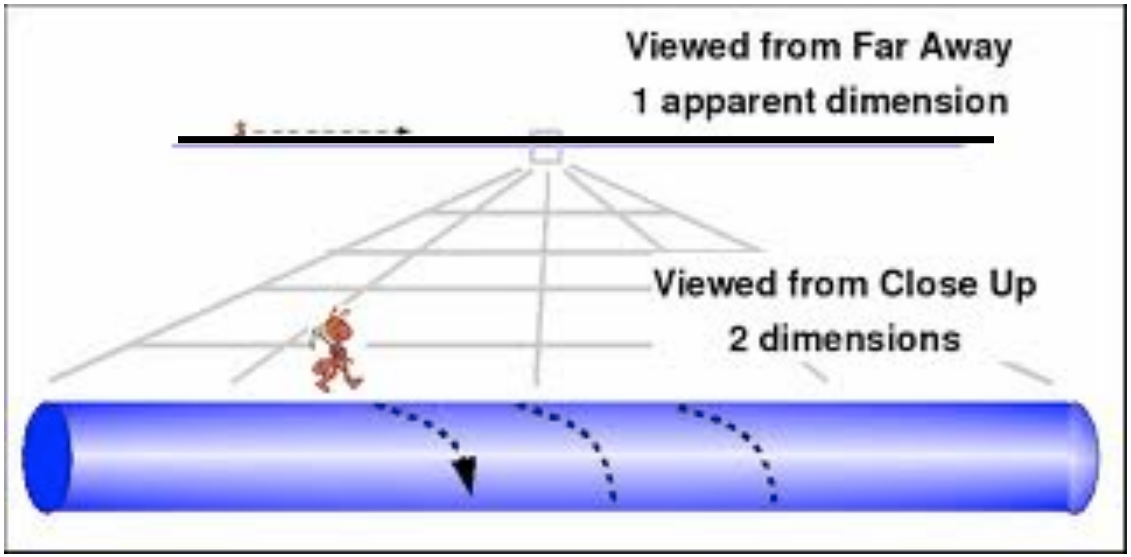


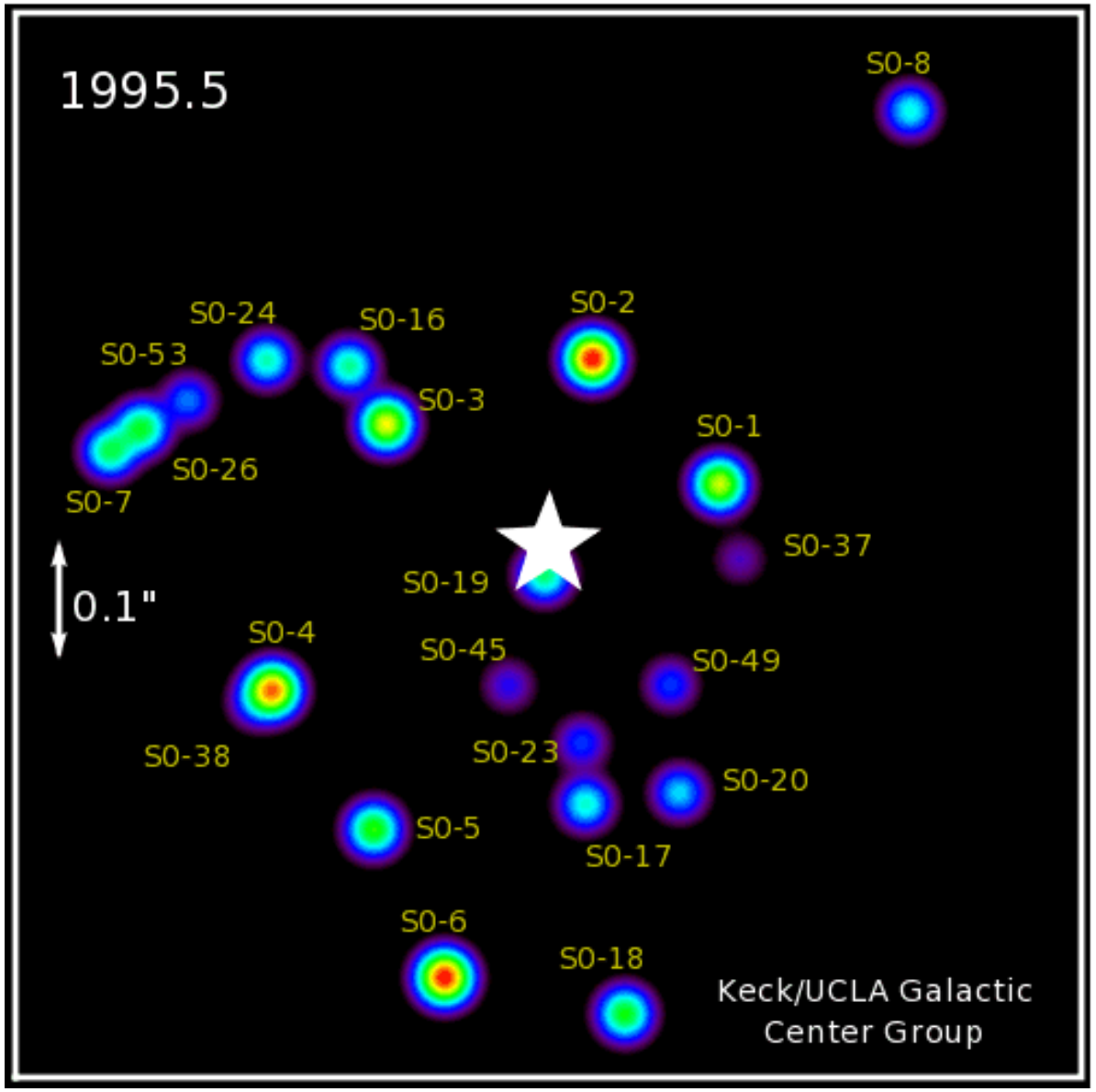
(d) Extra dimensions: We usually have the dimensions x, y, z, t

Can there be an extra direction w ?

If it is there, why don't we see it ?

Maybe it is too small ....

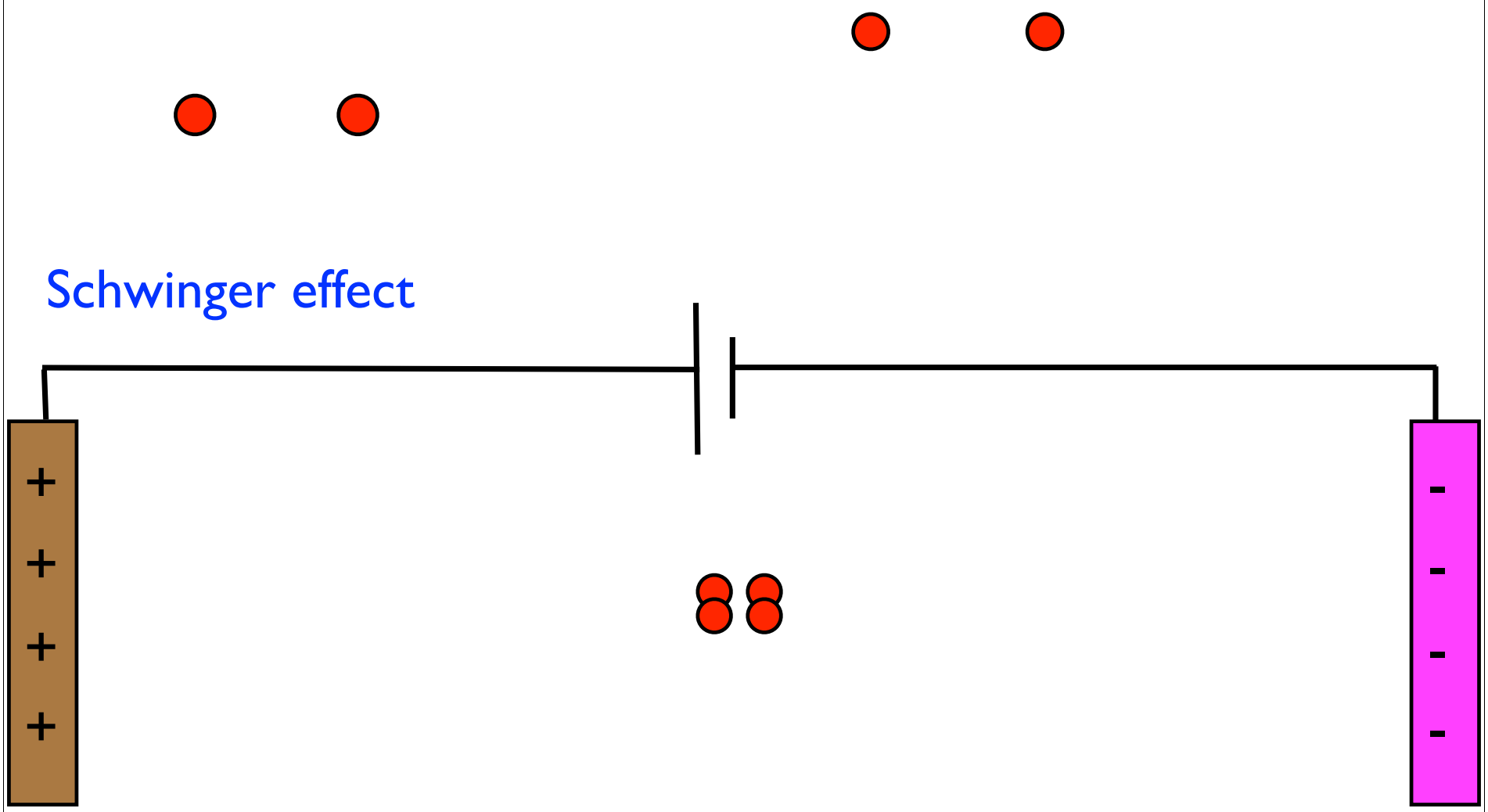





Black hole at the center of the Milky Way

# Black hole radiation

# An interesting effect (Schwinger effect)



Black hole

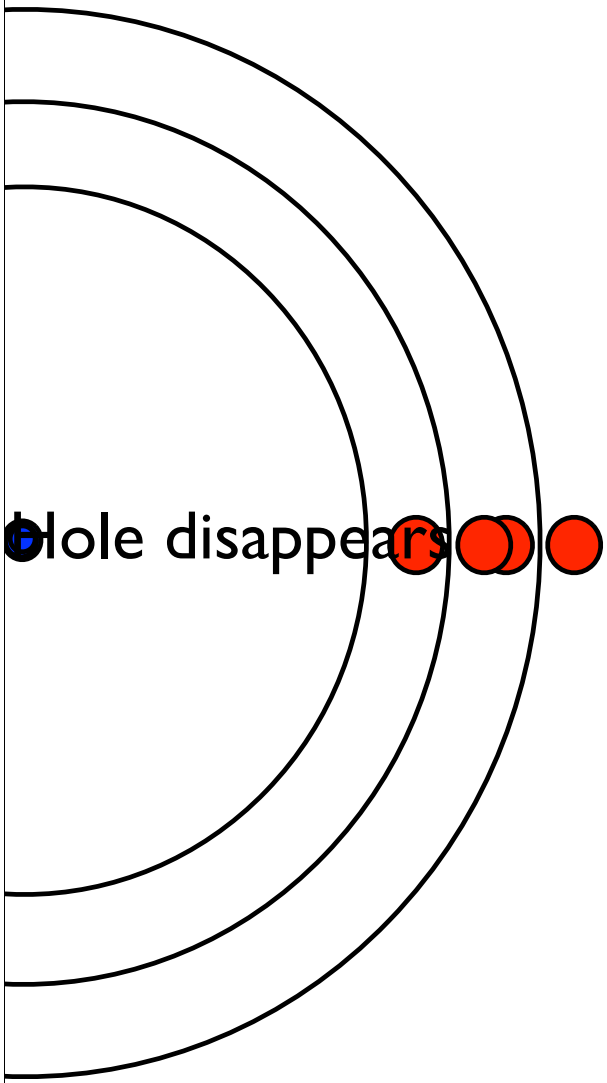
Stronger attraction

Weaker attraction

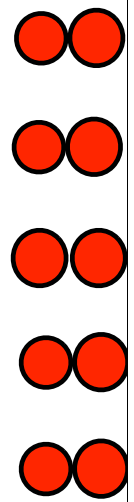
Hawking radiation

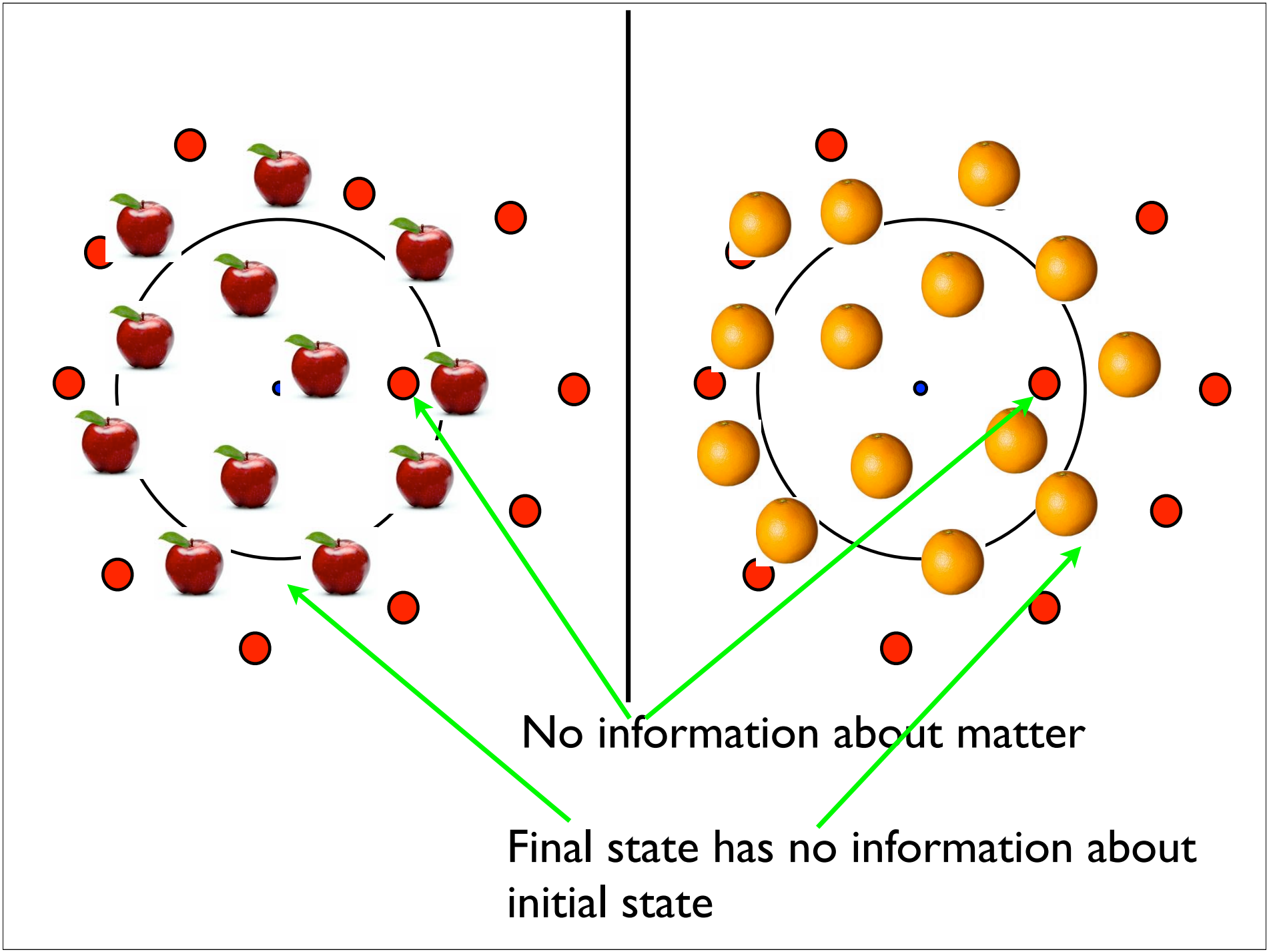
# The paradox

# A serious problem




Radiation left




No information about matter
Final state has no information about initial state

But in quantum mechanics the final state always has full information about the initial state

$$\Psi_f = e^{-iHt}\Psi_i$$

$$\Psi_i = e^{iHt}\Psi_f$$

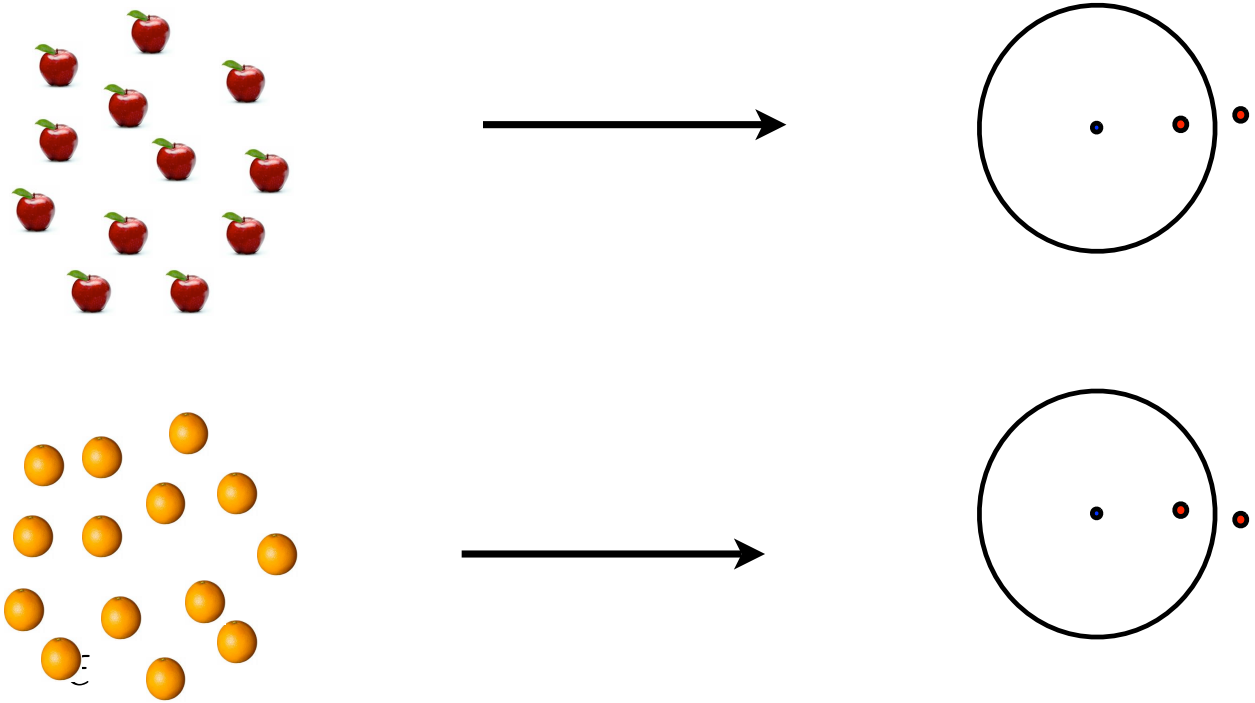
Thus the process of formation and evaporation of a black hole cannot be described by *any* quantum Hamiltonian

*This is known as the black hole information paradox*

What did string theorists say ?

It tuned out that string theorists made a mistake (Maldacena 2001) ...

They argued that small quantum gravity effects would make small changes to the state of the emitted radiation ...



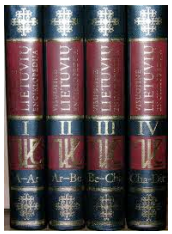
The correction is small for each emission, but the number of emitted particles is very large

Thus these small effects can encode the information of the matter that fell into the hole (apples vs oranges)

If this was true, then the Hawking puzzle was a 'non-puzzle' to start with: one would say that Hawking did an approximate computation, and doing the computation more carefully would resolve the problem ...

In 2004, Stephen Hawking surrendered his bet to John Preskill, based on such an argument of 'small corrections' ...

Stephen Hawking



John Preskill

Kip Thorne

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

So, who is right ?

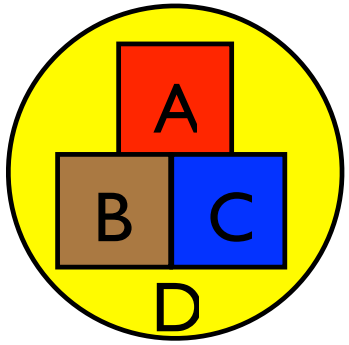
Theorem: Small corrections to Hawking's leading order computation do NOT resolve the problem

If the corrections are of order $\epsilon$, then the fraction of information that can be recovered is at most $2\epsilon$

(SDM arXiv: 09091038)

Basic tool : Strong Subadditivity (Lieb + Ruskai '73)

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



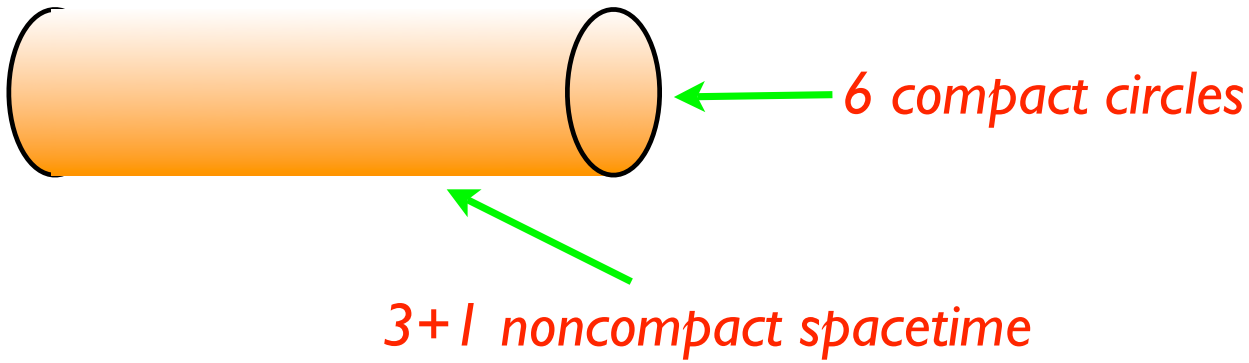

So if small corrections, do not work, what is the solution ?

# Solving the black hole puzzles with string theory

## *String theory*

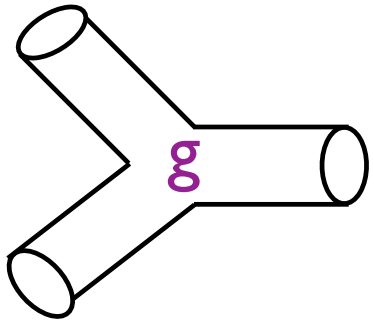
It looks like a strange theory at first, but what looks like undesirable features turn out to be just the ones that solve the puzzles of black holes

(a) The theory lives in 10 dimensions, so if we make a black hole in 4 dimensions, then there will be 6 compact dimensions



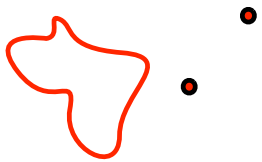
(b) There are extended objects like strings, branes etc.

(c) The coupling constant g is a field, so its value can be made small or large

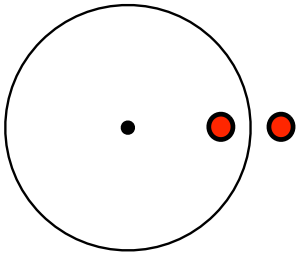


# The Hawking radiation problem

(A) Weak coupling, take a string with some energy, compute radiation rate



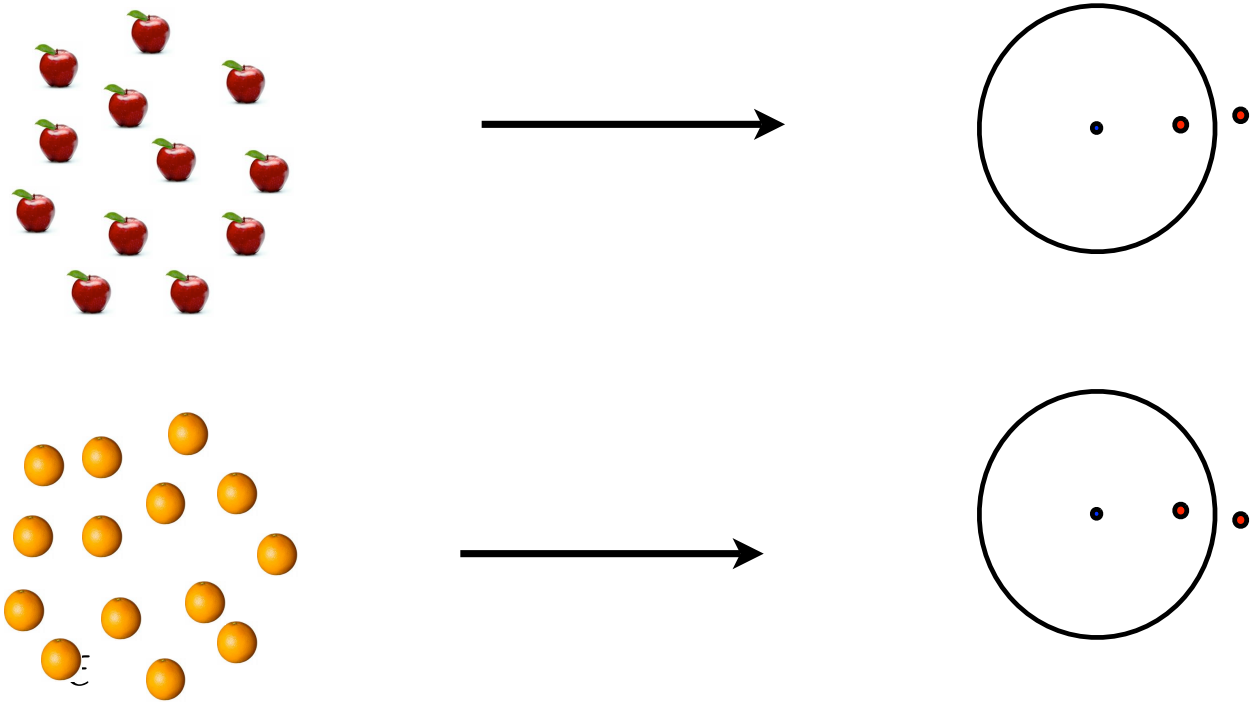
(B) Strong coupling, the same energy makes a black hole ... compute Hawking radiation rate



Get an exact agreement of radiation rates !! (Das+SDM 96)

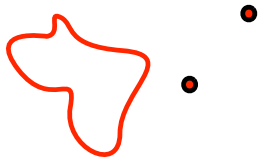
Thus the dynamics of string theory seems to know something about the physics of black holes ...

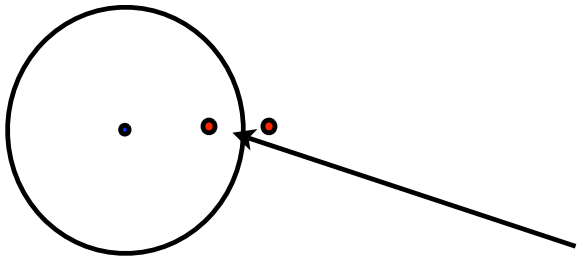
But we have not solved Hawking's puzzle ...



Different materials make the same mass hole, and then the radiation is the same ... so the radiation does not carry the information of the initial matter (information loss)

Weak coupling: we get the same rate as Hawking radiation rate from black holes, but this time different states of the string radiate differently ...





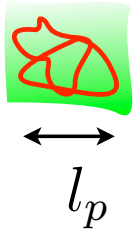
Problem is that the radiation is pulled out of the vacuum, and the vacuum has no information....

Could we put some 'stuff' at the horizon so that we dont have the vacuum there ?

Difficulty: Any stuff put near the horizon just falls in, and we are back to the vacuum

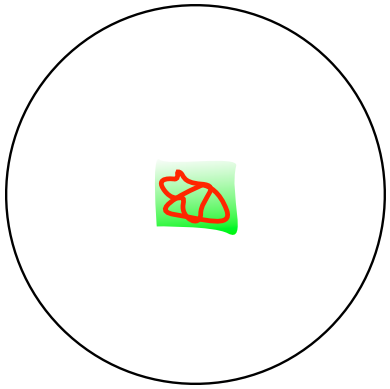
# Fuzzballs

(A) Weak coupling: Take some strings and branes, and join them to make a bound state in string theory

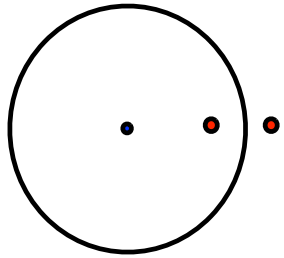



We expect that the size of this bound state will be order planck length $10^{-33}\,cm$

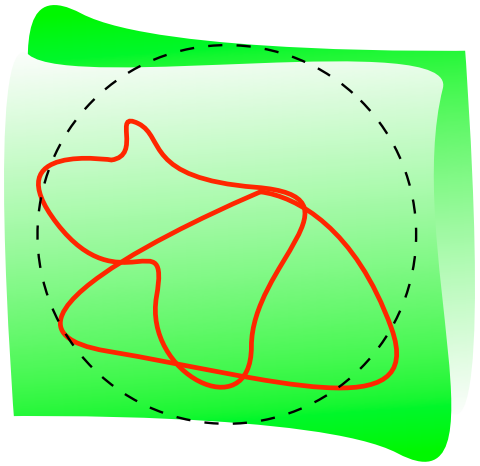
(B) At strong coupling we expect that a black hole horizon develops around this bound state



Then we have the usual Hawking pair production problem ...



(B') But there is a surprise ... something else happens at strong coupling ...

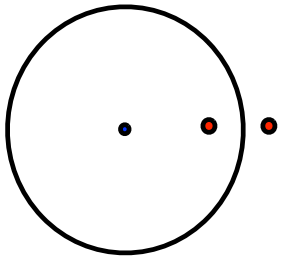


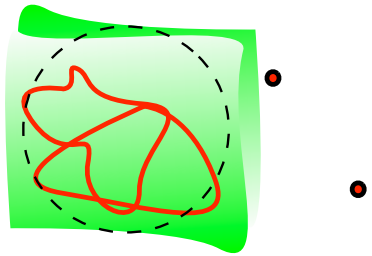
The strings and branes swell up as we increase the coupling, and become as big as the expected size of the horizon ...

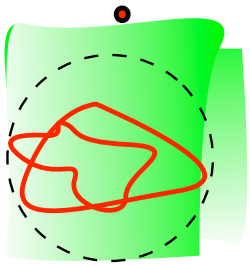
(SDM 97)

So a horizon never forms ...

So we never get the Hawking pair production process ...

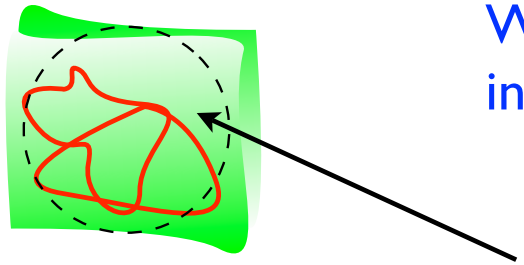






Different states radiate differently ... so the radiation carries the information of what makes the hole !!

This solves Hawking's black hole information paradox, so let us analyze in more detail what happened ...

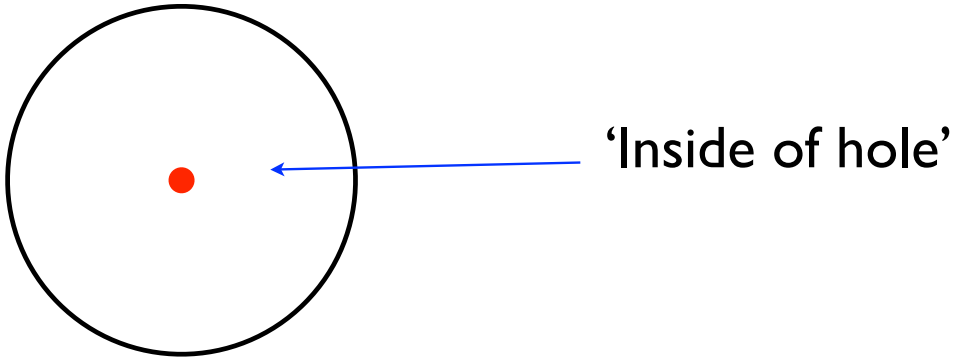


Why do the strings and branes not just get sucked into the center ?

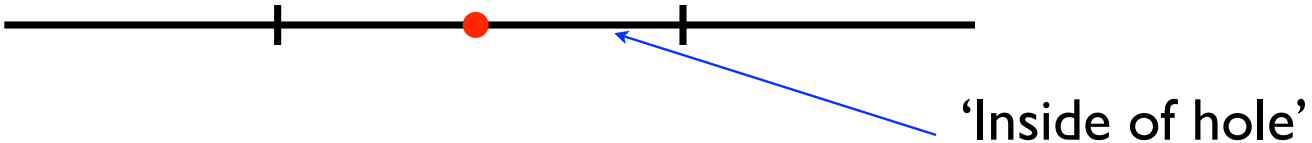
Fuzzball

The detailed structure of this fuzzball became clearer in the next few years (2000-2004)

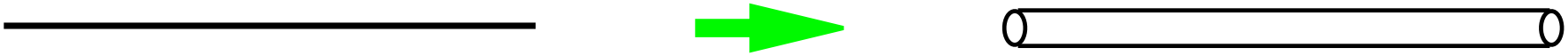
Recall that in string theory we have extra dimensions ....



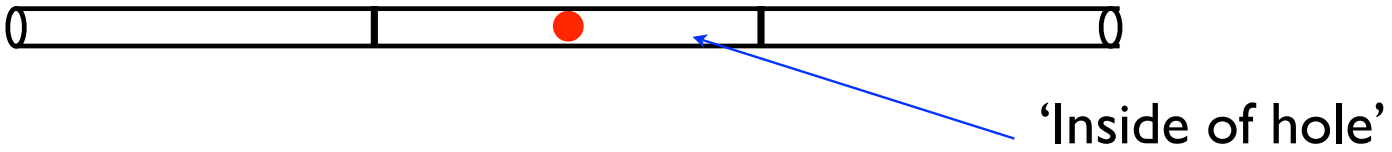

Let us draw just one space direction for simplicity



Now suppose there was an extra dimension (e.g., string theory has 6 extra dimensions)



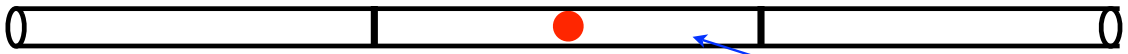
People have thought of extra dimensions for a long time, but they seemed to have no particular significance for the black hole problem



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

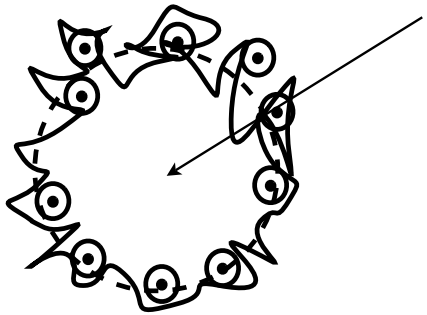
The mass
is captured by the
energy in the
curved manifold

Contrast this with



'Inside of hole'

1-dimension



not part of spacetime

Many dimensions

"Fuzzball"

The stuff at the horizon does not fall in because the stuff is actually a topology that provides to a smooth end to space

Hawking 2014:

There is no horizon in a black hole ....

But he gave no mechanism to avoid the formation of a horizon ...

At present it seems that the only mechanism to get what he is saying is the fuzzball mechanism of string theory ...

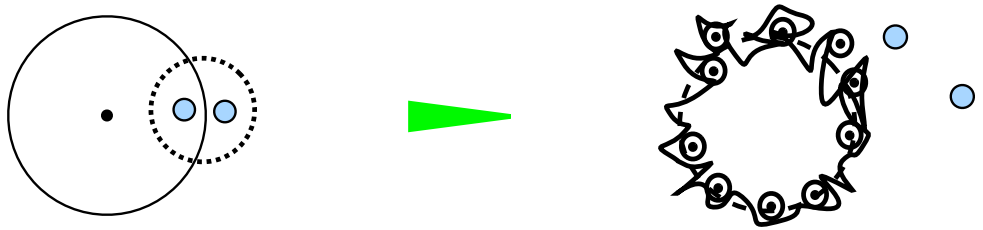
# Summary

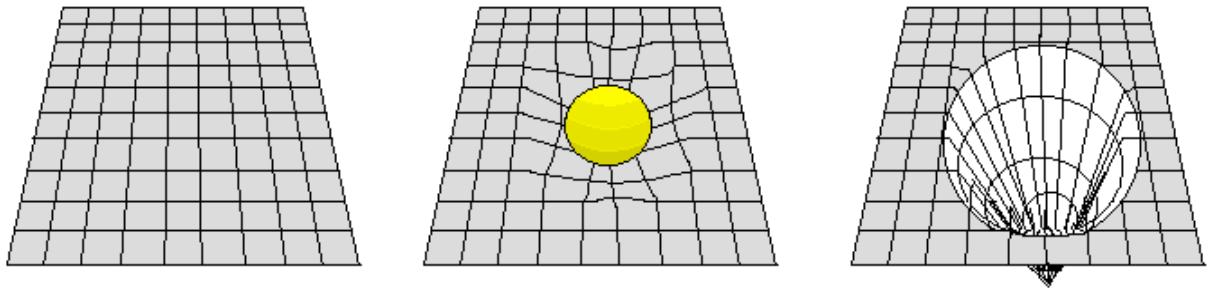
Hawking 1974:

General relativity predicts black holes

Quantum mechanics around black holes is INCONSISTENT

String theory: Quantum gravity effects alter the structure of the black hole radically ⟶ Fuzzballs

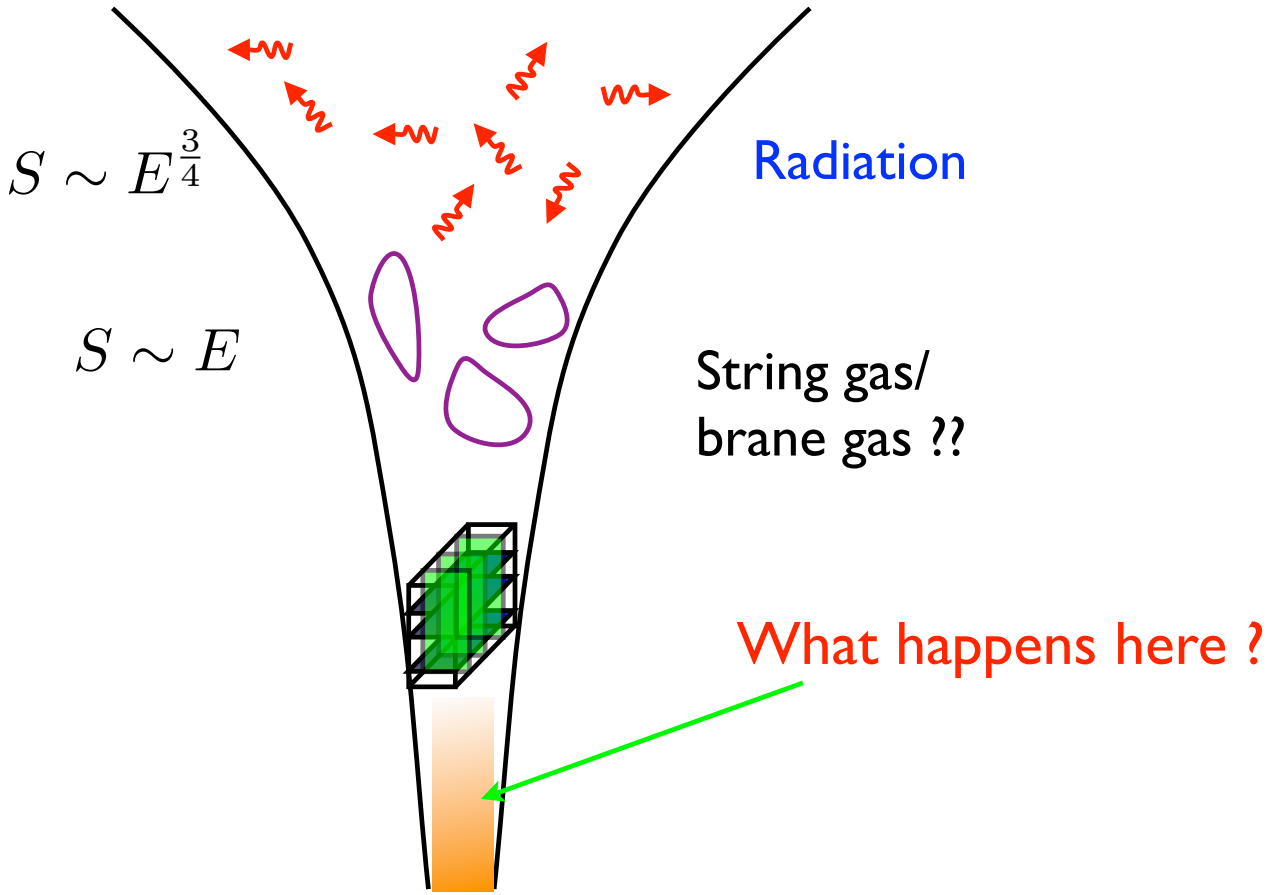




NO !!

When we try to crush matter into a black hole, then quantum measure terms start becoming important, even for macroscopic systems

Where else can we expect such a crushing of macroscopic amounts of matter ?



THANK YOU !!