Quantum black holes

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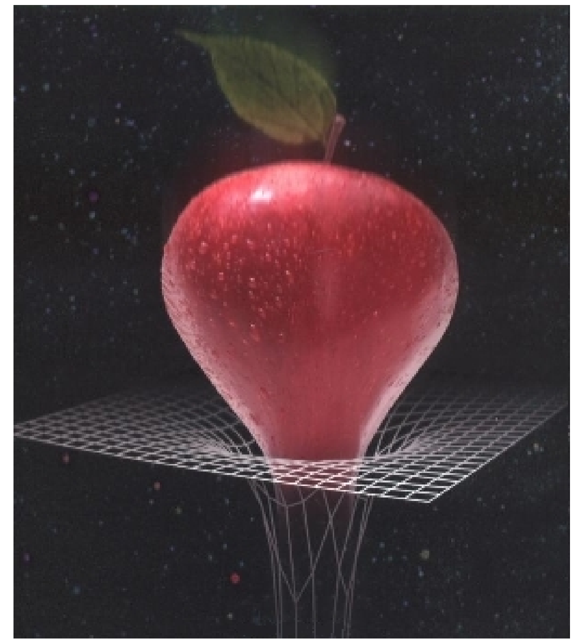


Vancouver
April 2015

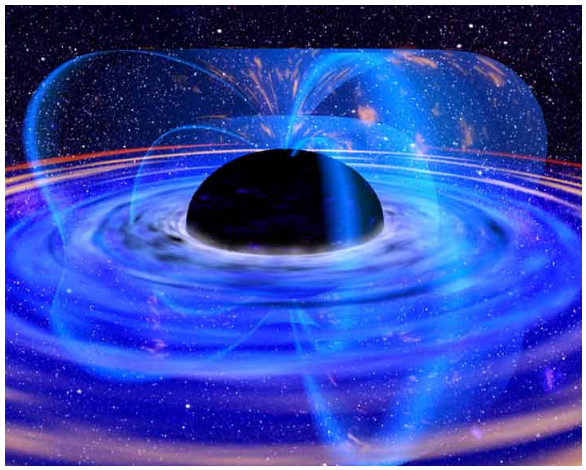
2015 is the 100th anniversary of General Relativity

. . . and the 100th anniversary of black holes

Karl Schwarzschild:
“[T]he war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas.”

(although we didn’t really understand what Schwarzschild and Droste had found for more than forty years)

Black Holes



$\neq$

A black hole has a strong gravitational field because it’s so small!

gravitational attraction $\sim$ mass$/$(distance)^2

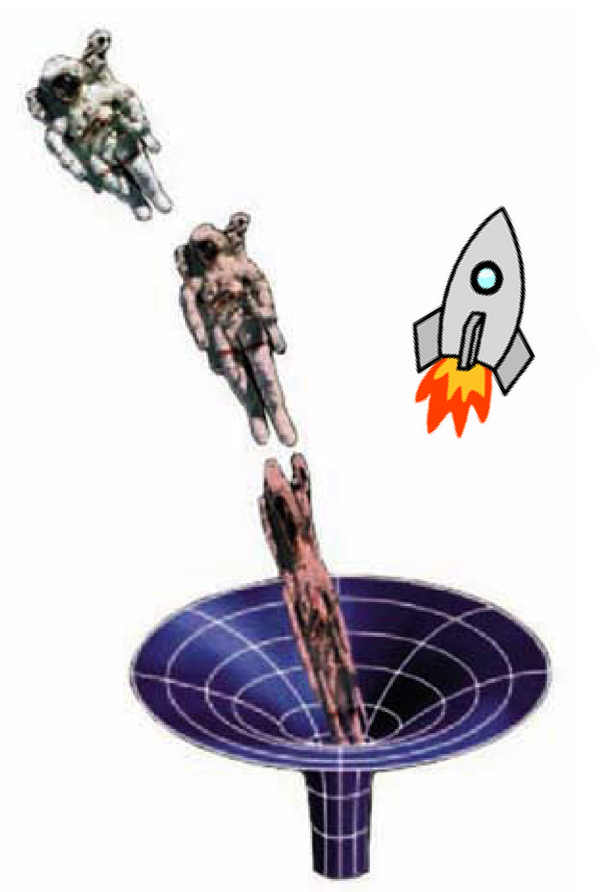
smaller distance $\Rightarrow$ stronger gravity
but you can only get so close. . .

– radius of Earth ~ 6400 km
– imagine shrinking it to ~ 1 cm
$\Rightarrow$ gravity at the surface would be $\sim 400,000,000,000,000,000$ times stronger

Rough description:

black hole occurs when escape velocity at surface is greater than the speed of light

The Event Horizon



General relativity:

– “Natural” state of an object is free fall

– Relative to a freely falling reference frame, an object at rest is moving upward!

Falling into a black hole:

– relative to rocket, astronaut is falling

– relative to astronaut, rocket is rising

– Einstein: use astronaut’s reference frame

Event horizon: place where this upward speed reaches the speed of light

The event horizon expands at the speed of light while keeping a constant area

“Spaghettification”

As you fall into a black hole,

– your feet are closer, and fall faster than your head

– your two sides are squeezed toward the center

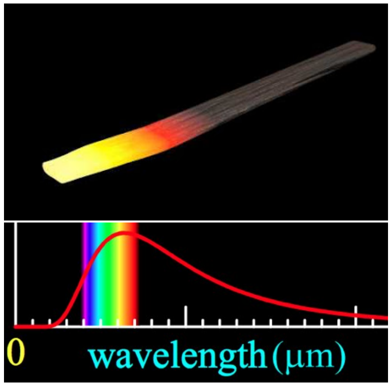
– “tidal forces” pull you apart

Smaller black hole $\Rightarrow$ you get nearer to the center $\Rightarrow$ greater tidal forces

Black holes are hot

Bekenstein (1972): black holes have entropy

Hawking (1973): black holes radiate as black bodies



black hole temperature $\sim 1/$mass

Solar mass black hole: $T \sim .00000006$ K (above absolute zero)

“But you said nothing could escape the event horizon. . . ”

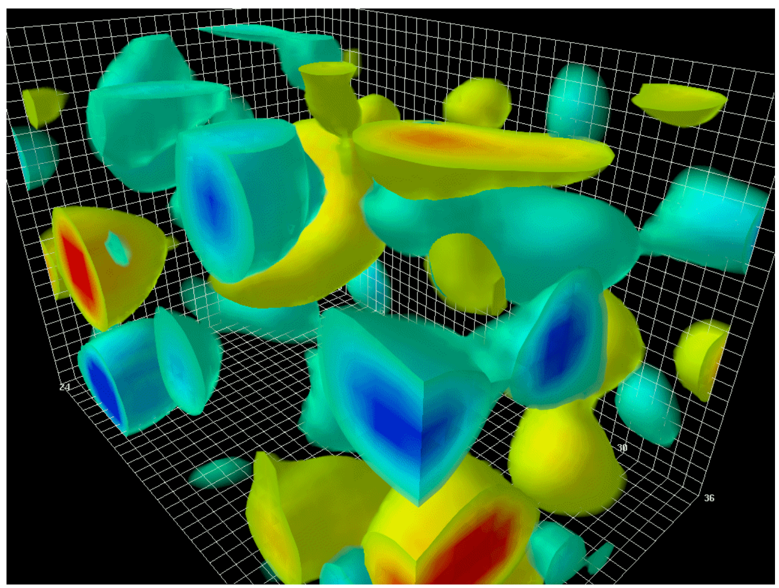
Quantum tunneling —
walking through walls

Heisenberg uncertainty principle:
always some chance that a particle “inside” the black hole is really “outside”

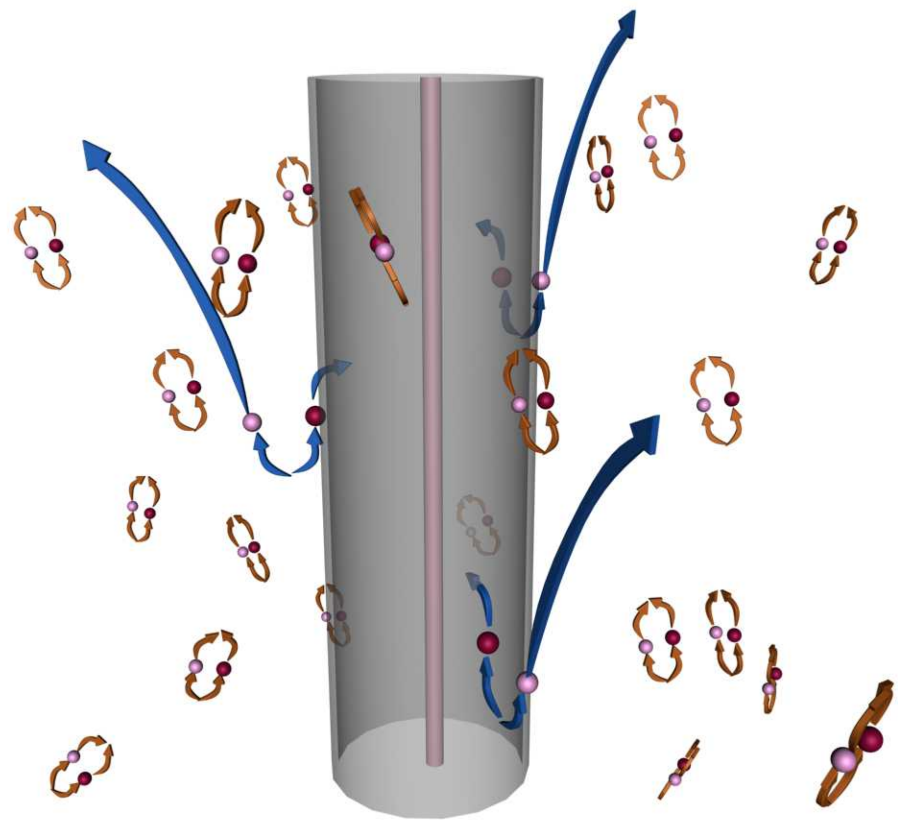
Smaller black hole ⇒ greater chance of tunneling ⇒ higher temperature

Black holes tear apart the vacuum

The quantum vacuum is not empty

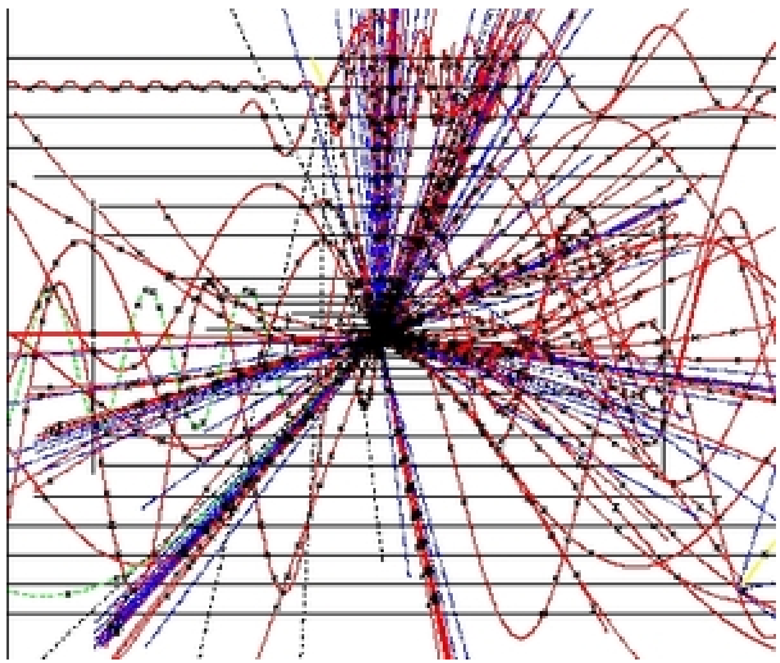


Near a black hole,
tidal forces pull apart
pairs of “virtual particles”



Black Hole Explosions? (Hawking, *Nature* **248**, 30 - 31 (01 March 1974))

"…Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs."

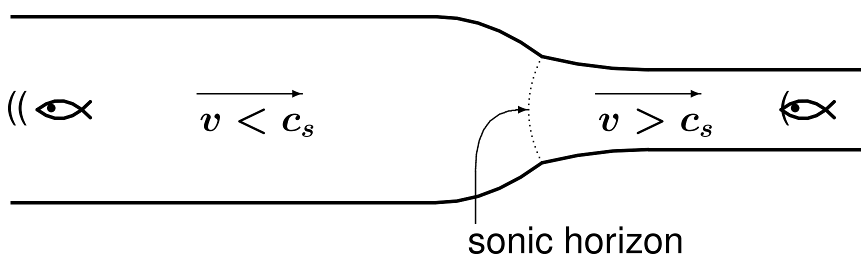


Can we see any of this?

For black holes: probably not (unless we're very lucky)

But there are black hole "analogs"

Unruh: Imagine fluid flowing through narrowing pipe:



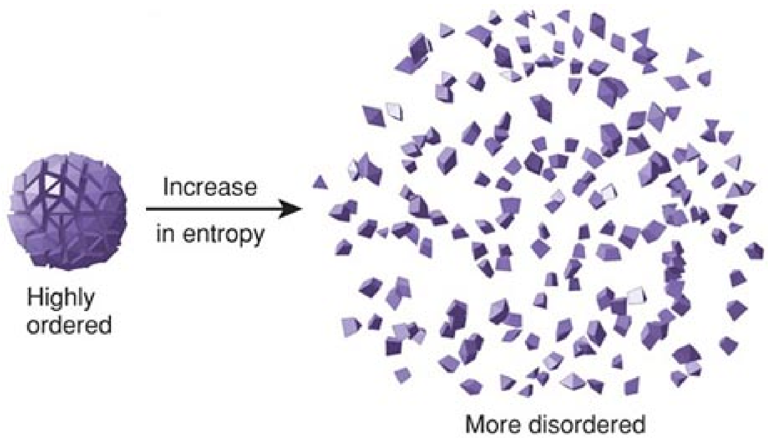
"Sonic horizon" when $v_{\text{fluid}} = c_{\text{sound}}$

Nothing can escape unless it has velocity $v > c_{\text{sound}}$

Hawking radiation of sound?

Advanced topic: entropy

Entropy measures “order” – the number of ways a “macrostate” can be made up from “microstates”



Second law of thermodynamics: entropy never decreases

John Wheeler to Jacob Bekenstein:
“What happens if I drop my cup of tea into a black hole?”

Black hole entropy: $S = \frac{A_{\text{hor}}}{4\hbar G}$

Depends only on area of the event horizon

– Why so simple?

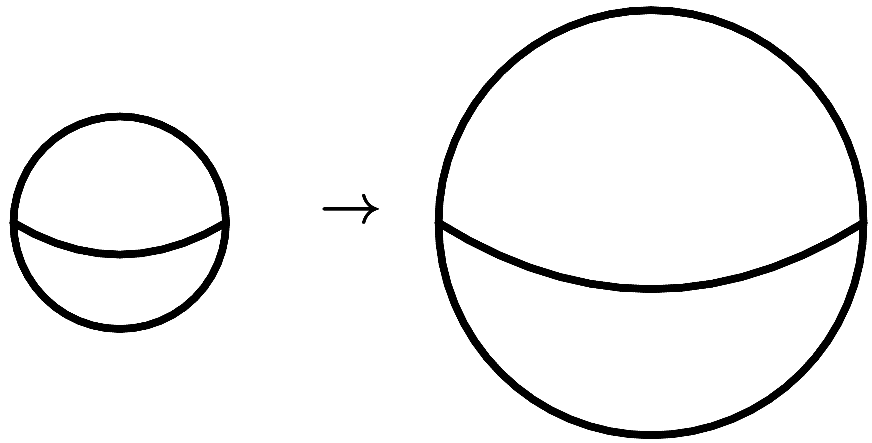
– What are the "atoms" responsible for the entropy?

Some answers from various approaches to quantum gravity (string theory, loop quantum gravity, induced gravity,. . .)

– Why do they all agree?

“Holography”

Entropy *inside* black hole depends only on area of *surface*



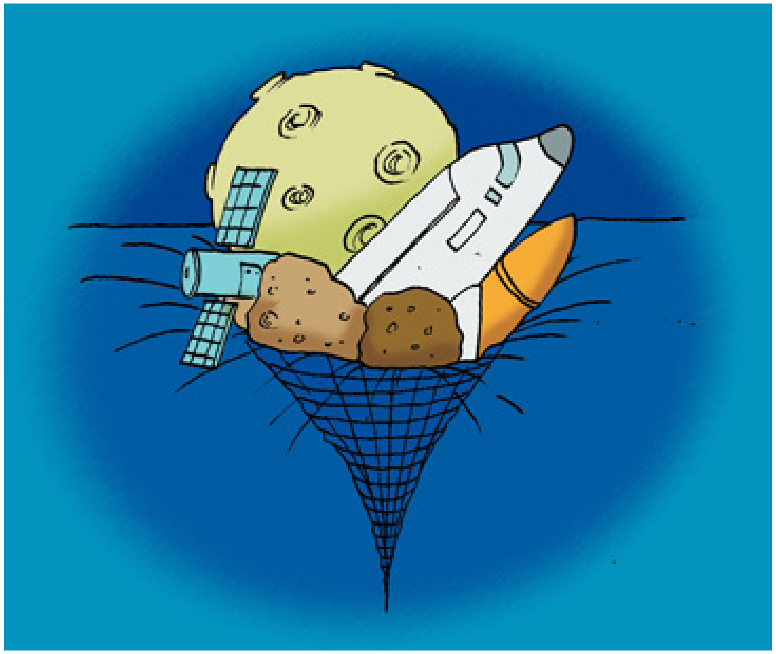
$\mathbf{2}\times$ the radius
$\mathbf{4}\times$ the area
$\mathbf{8}\times$ the volume

If you put too much stuff into a region, it forms a black hole

So perhaps all fundamental physics depends on surfaces and not volumes . . .

Advanced topic: the information loss problem

Back to Wheeler's question:
"What happens if I drop my cup of tea into a black hole?"



In: cup of tea (or refigerator, or elephant)

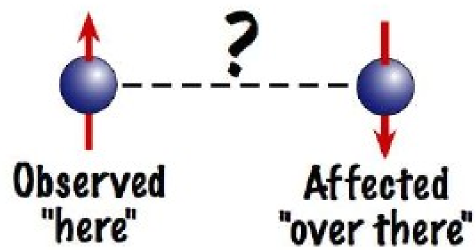
Out: Hawking radiation

But quantum mechanics is *reversible* (technically: unitary)

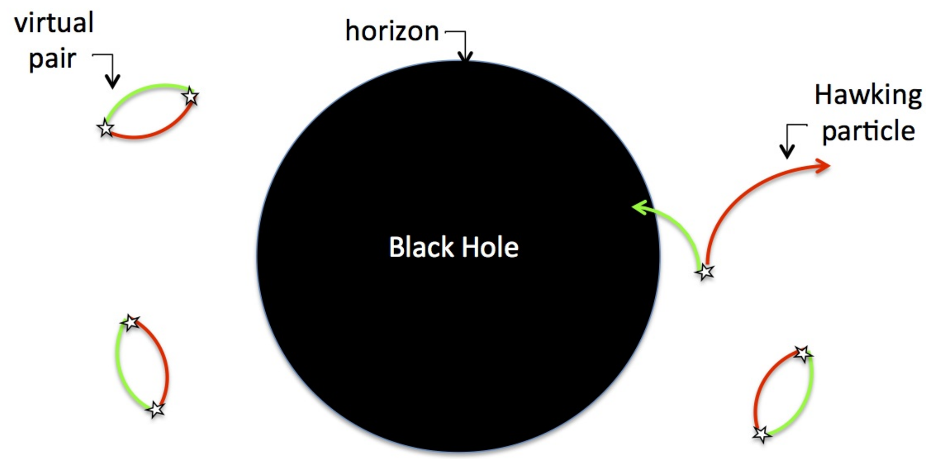
In principle, we should be able to reconstruct what went in from what comes out

How does the information get out of a black hole?

Problem: information is “encoded”
in quantum entanglement



In Hawking radiation,
“inside” and “outside” particles
are entangled



But after the black hole is gone,
“outside” particles must be entangled with each other

“Monogamy of entaglement” – only one entanglement at a time

But it takes energy to break an entanglement

We don’t know the answer

– Maybe information is really lost

– Maybe the horizon is a “firewall”

– Maybe entanglements break “gently” at a distance

– Maybe black holes don’t evaporate completely

Lots of action . . .

To end with a nice image:

stars orbiting the black hole in the center of our galaxy