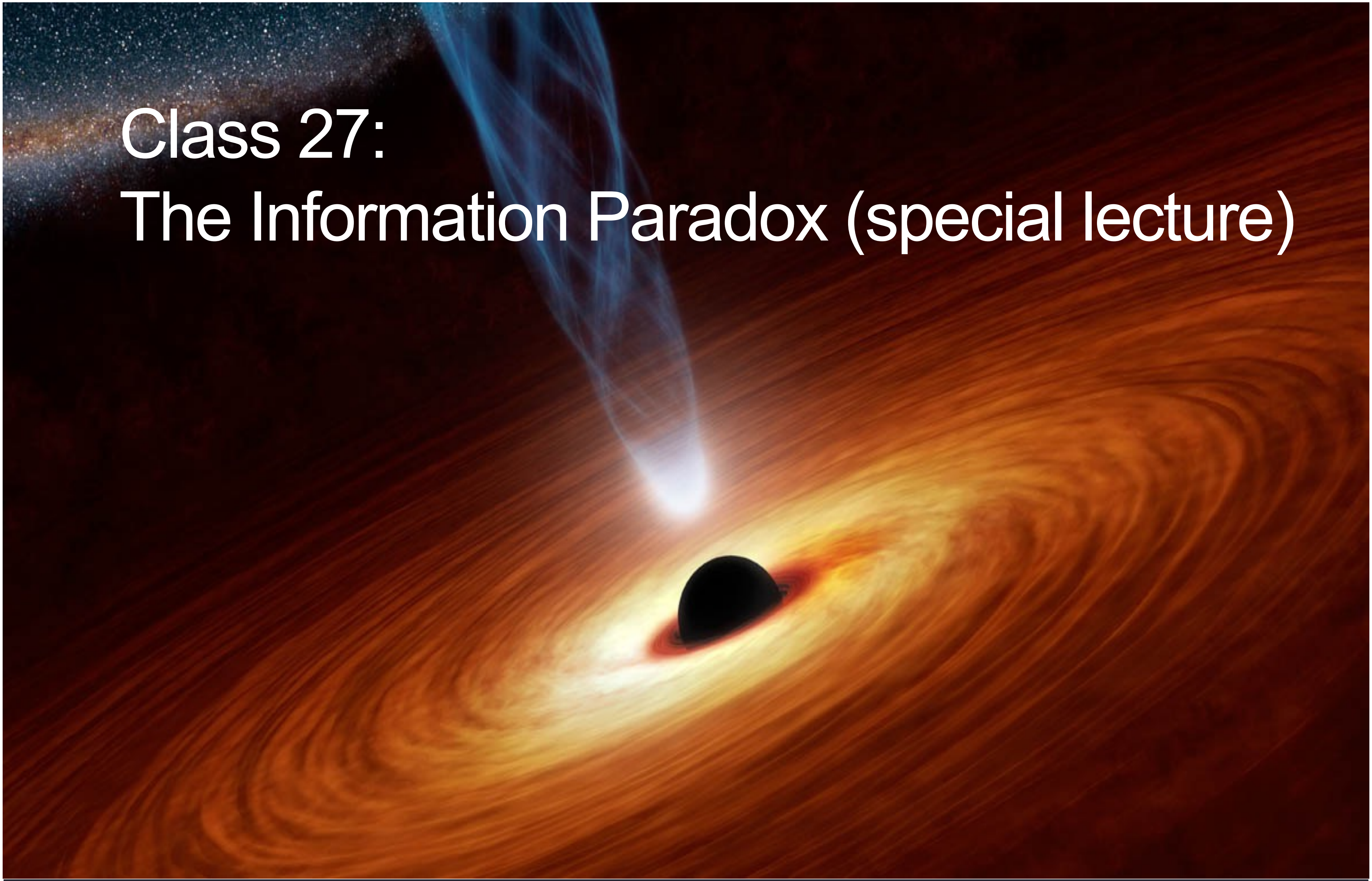


Class 27:
The Information Paradox (special lecture)

ASTR350 Black Holes (Spring 2022)
Cole Miller

QM and GR

- In the last two lectures we have talked about some possible consequences of pairing quantum mechanics with general relativity
- Hawking radiation: given an extremely long time and no matter/energy falling in, black holes are expected to evaporate
- Wormholes: probably not, but maybe it is possible to have shortcuts in spacetime? Self-consistency is key
- But neither of these addresses quantum gravity
- Today: a conflict between QM and GR that some people think might point a way to quantum gravity as a resolution... or maybe not!

The basic idea

- Details in a bit, but...
- Remember the wavefunction in quantum mechanics?
- There's an equation that tells you how it evolves with time.
- Thus although you don't know the result of a measurement in advance (it's probabilistic), it means that all paths through time are unique: if you know the wavefunction at one time, you know it for all times earlier in later (in principle! In practice it's impossible to compute)
- Colloquially: quantum "information" is preserved
- But a black hole has no hair; anything with the same mass, angular momentum, and electric charge is the same
  And Hawking radiation also depends just on M, J, Q
- Thus QM and GR seem to contradict each other

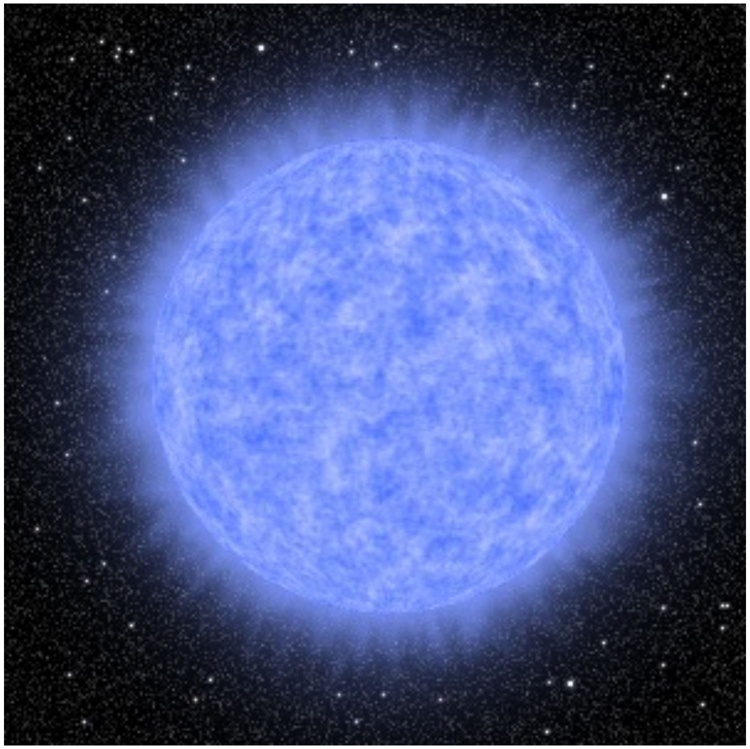
A key point

- Insight from Sabine Hossenfelder (I strongly recommend her blog "Backreaction" and her videos)
- Lots of people have proposed answers to the information paradox
- But the problem is basically unsolvable.
- Why? Because you have two axiomatic systems (GR and QM) that conflict with each other. Proposed answers each suggest which axiom(s) to give up
- But this is physics, not math; we need empirical guidance to get nature's answer
- And Hawking radiation can't be observed unless we find some mini, mini black holes
- Maybe if we get a theory of everything that explains particle physics perfectly we could use its implications?

Let’s press on

- But with that (I hope) firmly in mind, this frees us to just enjoy some of the many proposed solutions
- Remember that any ***new*** material in this lecture is not fair game for the final exam, so you can just enjoy being taken on a trip to nowhere in particular ☺

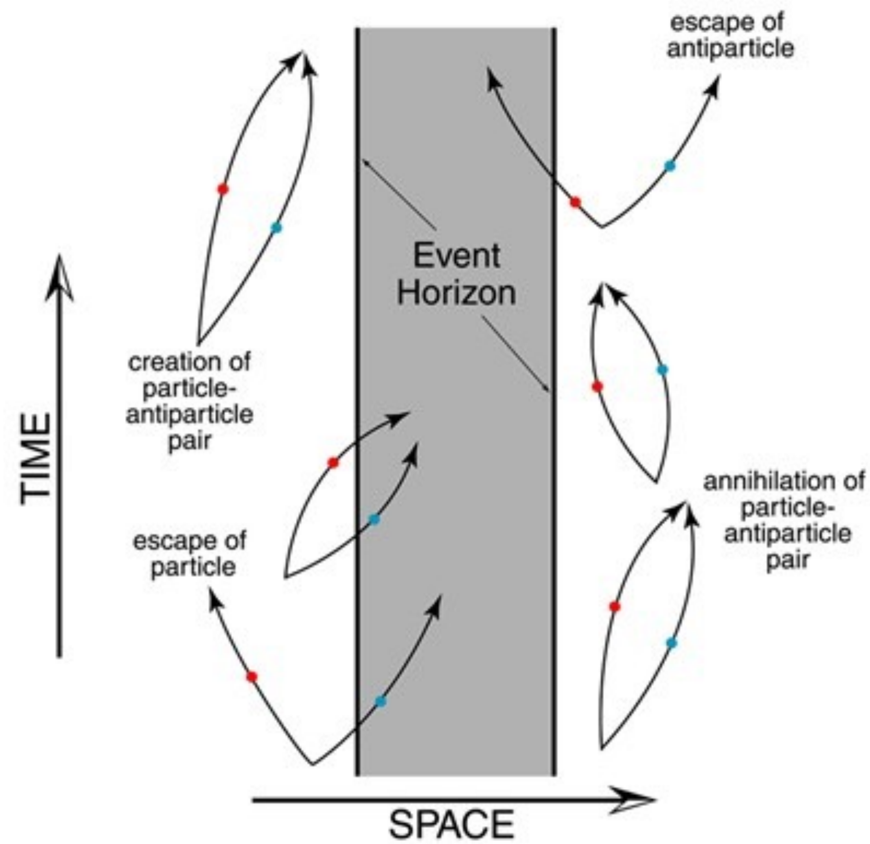
Quantifying the problem



- A 30 M_{sun} star has few x 10^{58} particles, so we'd need that many bits/bytes to describe it fully
- When it collapses to a BH, we need just three numbers: mass, angular momentum, and charge. Big difference!

Does Hawking radiation save us?

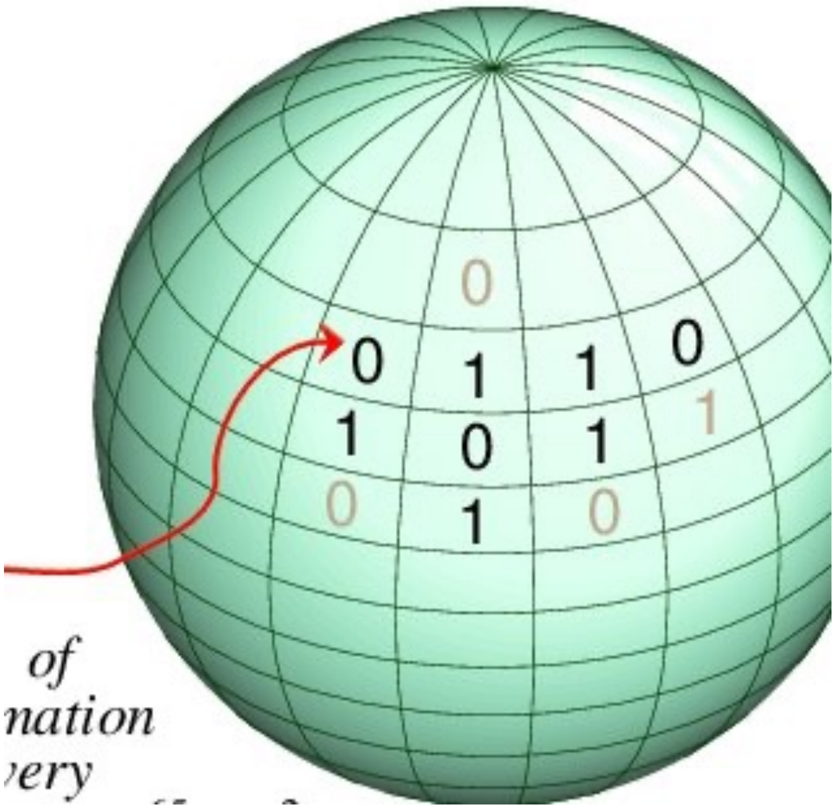
- Not in standard understanding
- Might think so: BH eventually radiates, so maybe all the information comes out?
- But in standard picture, the radiation is pure blackbody and thus depends only on the temperature, which again depends only on M, J, Q
- How non-blackbody would it have to be to keep the info?
- Time for weird diversions...



Stackexchange

Holographic principle

- How much info could a black hole have?
- String theory arguments say that it's the area (not volume!) of the BH divided by the Planck length l_P squared
- $l_P=1.6\times10^{-35}$ m, and surface area of BH is $\sim10^{10}\ m^2\ (M/10M_{sun})^2$
- So that's $\sim10^{80}\ (M/10\ M_{sun})^2$ bits of information
- Note: holographic principle is not accepted by everyone



Original source: Gerard 't Hooft

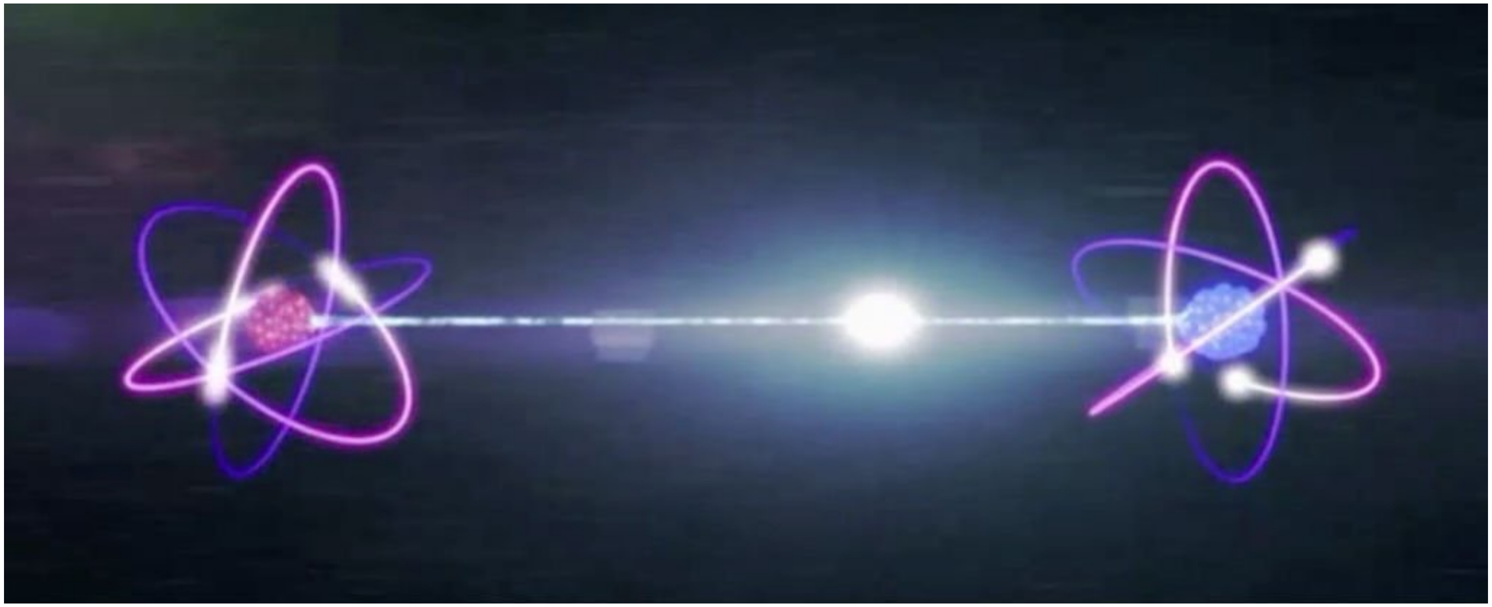
What does this imply?

- Pre-BH star might have 10^{59} bits of information
- BH can be described by three numbers, ***but*** there's enough room on the surface for 10^{80} bits of information
- This means that the entropy increases (yay thermodynamics), but relevant to the information paradox it gives us some hope
- If Hawking radiation is even slightly different from a pure blackbody, then it could easily contain the full information from the pre-collapse star

What chance?

- Calm down, Lloyd.
- Just because we have a huge difference between the information we might encode on a BH, and the information we need, isn't enough
- Is there a mechanism?
- Maybe, but it involves more weirdness that we now need to discuss...

Quantum entanglement



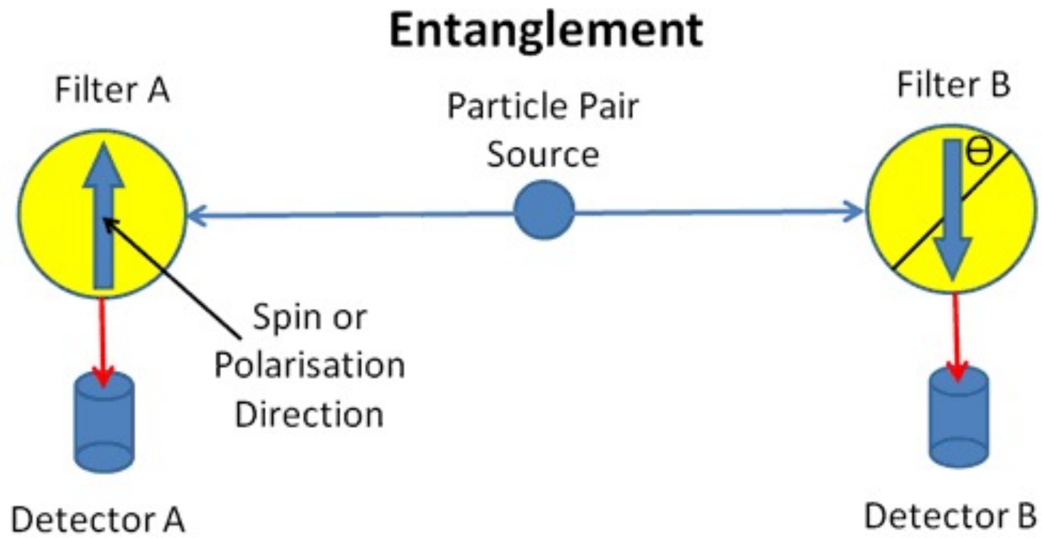
ScienceAlert

- Utterly bizarre principle, first elucidated by Einstein, Podolsky, and Rosen
- You can prepare a pair (or more) of particles so that they have to be described collectively, not individually
- Until there are separate interactions with them, their properties are “entangled”. What does that imply?
- Time for a diversion; it’s relevant to the information paradox

Entangled pairs

- Let’s suppose that you produce two particles with correlated properties
- An example is the virtual pairs that are essential to Hawking radiation: their total angular momentum is zero. In particular their intrinsic angular momenta (called their “spin”) must be opposite; say one up, one down
- If you know that one is up and one is down, then after they have been separated (and, critically, assuming that neither interacts with anything else in the meantime), if you measure the spin of one you know the spin of the other, even if they are separated by light years

Entangled pairs part 2



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- As in the figure, you produce a pair in the center, then send it (with zero interactions!) to two detectors: A and B
- If the detectors are oriented in the same way then if A measures up, B measures down, and vice versa
- True no matter how far they're separated
- But what's the problem?

Spooky action at a distance

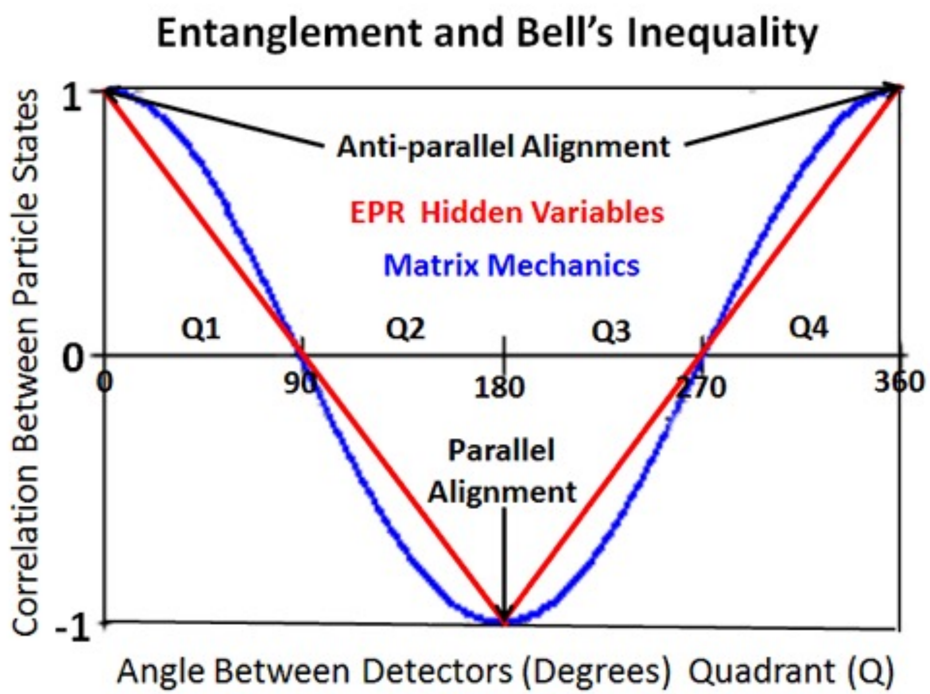
- We might imagine that if the particle measured at A is up it was always up, and the particle measured at B was always down
- But the problem, as pointed out by Einstein, Podolsky, and Rosen (EPR) is that according to quantum mechanics the individual members of the pair did not have fixed states until they interacted with something (were "measured")
- Thus it might seem that if A and B are separated by light years, that somehow measuring "up" at A causes the particle at B to be "down", transmitting information instantly. Doesn't that violate special relativity?

No violation of special relativity

- Special relativity says that no mass, energy, or information can travel faster than light
- And the example we just gave doesn't violate that!
- Why? Because you can't use this to send information
- We might have in mind that you could use this approach to send Morse code; A measures up, up, down, so B measures down, down, up.
- But A cannot decide to measure up or down; it is random. Thus A cannot send information to B even though A and B know that they are measuring opposite spins
- Is there a more common-sense interpretation?

Hidden variables and Bell's inequalities

- Maybe there are "hidden variables"? That is, in reality everything is deterministic, but we just don't have the full info
- Good idea, but John Bell showed in 1964 that when you angle the detectors in the previous experiment, hidden variables predicts different things than QM
- ...and expt supports QM!!!



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Does that solve the problem?

- Not necessarily
- Hawking pairs are indeed entangled pairs
- And if entanglement persists past the event horizon then once half the particles have escaped you know the properties of the remaining half, so it's not actually purely thermal radiation
- But it's still not at all clear how the state of the pre-BH thing would be imprinted on these pairs
- So we might not have made much progress, although it's been fun!

A Break for Billiards

- We need perspective
- In classical physics, information is perfectly preserved
- But in practice, come on!
- Billiards, no friction, much less than a minute after a hit the motions are unpredictable if you forget about the gravitational influence of an electron at the edge of the universe...
- Not special to QM

Willie Hoppe

Possibility 1: information is lost

- Einstein>QM
- Somehow, the axioms of QM aren't quite right; the evolution of the wavefunction doesn't perfectly preserve information
- Only BH formation would make this acute, but probably there would be other effects as well
- Would need to modify QM so that it adjusts to this possibility but still makes the huge number of staggeringly precise correct predictions that it does currently

Possibility 2: soft hair

- Hawking's last paper (published posthumously)
- The idea is that although the only macroscopic properties of a black hole are M, J, and Q, there are a huge number of microscopic "degrees of freedom" that could be near the horizon
- The drawback is that this is rather arbitrary; there isn't a clear physical motivation

Possibility 3: fuzzballs

- Favored by many string theorists
- The suggestion is that if we look closely at the horizon, we'll see that it's actually made up of lots of strings
- Plenty of room for lots of information
- Similar in spirit (kind of) to soft hair
- But for this to communicate with the outside, information has to travel a bit faster than light

Possibility 4: firewalls

- Suggestion is that entanglement is broken near the horizon
- This takes a lot of energy
- So a freely-falling observer would encounter a high-energy “firewall” near the horizon; no interior of BH
- Drawback: this violates the equivalence principle!

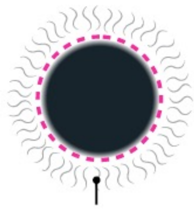
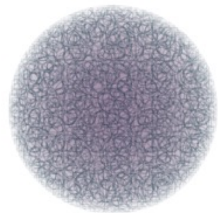
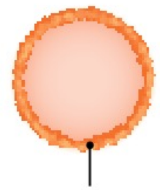
Possibility 5: quantum nugget

- Classical ideas of Hawking radiation must break down when the BH has shrunk so much that quantum mechanical principles have to apply
- At least by the Planck mass, $m_P \sim 2 \times 10^{-8}$ kg
- Maybe then we are left with an unevaporated quantum nugget, or the radiation is definitely not blackbody?
- Problem: if we have to go to m_P, how do we encode arbitrary amounts of information, as would have existed in the mass needed to form the (possibly) supermassive black hole?

Possibility 6: baby universes

- Or maybe, when mass falls into a black hole, a baby universe is created and the mass spews out there
- No fuss, no muss, no information loss!
- Problem: by definition, the new universe would be disconnected from ours, so we have no way of telling...

A few of the possibilities. Which is your favorite?

	INFORMATION IS DESTROYED	**INFORMATION IS NOT DESTROYED**			
HYPOTHESIS	**“Classical” black hole**  Event horizon	**Soft hair**  Imprint of information	**Fuzzball** 	**Firewall**  Wall of particles	**Quantum halo** 
DESCRIPTION	Black hole with an event horizon; information that enters the black hole is destroyed when the black hole evaporates.	Information does not fully enter the black hole but instead leaves an “imprint” just outside the event horizon.	A type of massive remnant in which the black hole horizon is replaced by strings and higher-dimensional geometry.	A type of massive remnant in which a “wall” of high-energy particles replaces the horizon; there is no black hole interior.	A quantum black hole interacts with its surroundings, possibly through small fluctuations in spacetime, allowing information to transfer out.
PROBLEM	Contradicts quantum mechanics and energy conservation, which say that information cannot be destroyed.	Most experts do not regard this picture as providing a convincing resolution.	All three of these scenarios require modification of the conventional notion of locality—that is, the idea that nothing, including infomation, can travel faster than light.		

https://www.scientificamerican.com/article/escape-from-a-black-hole/

Connection to Cosmology?!

- The other profound problem of quantum gravity—making sense of cosmology.
- Observers behind black hole horizons have many common features with observers in expanding universes
  - (e.g., at the Big Bang things are very small and energetic and strongly connected to GR).
- The black hole singularity is somewhat similar to the singularity at the beginning of the Universe, just its time reversed, a big crunch rather than a big bang.