Title: Does Anything Ever Come Out of a Black Hole? - Netta Engelhardt

Speakers:

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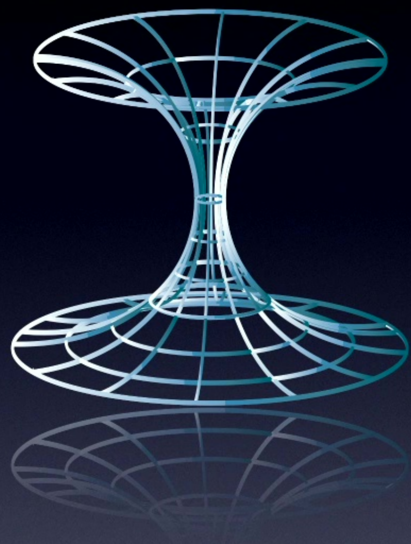
Abstract:

Stephen Hawking made a number of memorable contributions to physics, but perhaps his greatest was a puzzle: is information that falls into a black hole destroyed, in contradiction with the laws of quantum mechanics? The question sits squarely at the overlap of the quantum world and gravitation, a frontier of physics where direct experimental input is hard to come by. Recent progress has been revealing how subtle effects relate the radiation leaving a black hole to what happens inside. In this lecture, we will dive into the black hole information puzzle: what it is, what we have learned about it, and where it all might lead.

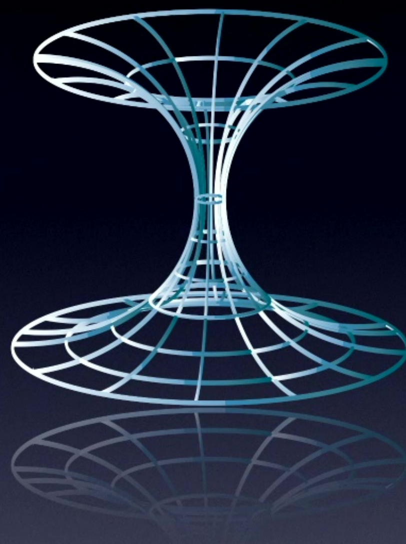
Can anything ever escape from a

BLACK HOLE?

What is a black hole?



What is a black hole?



"A region from which nothing, not even light, can escape."

So… can anything ever escape from a black hole?

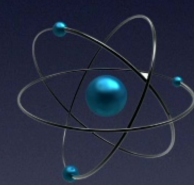
Clearly, the answer is no!

…

Right?

Not so quickly…

It turns out…
If nothing ever escapes from a black hole
then information can be destroyed
and that means that a basic aspect of *quantum mechanics*
is wrong.



And quantum mechanics has been tested

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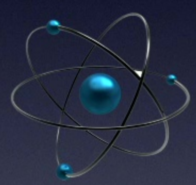
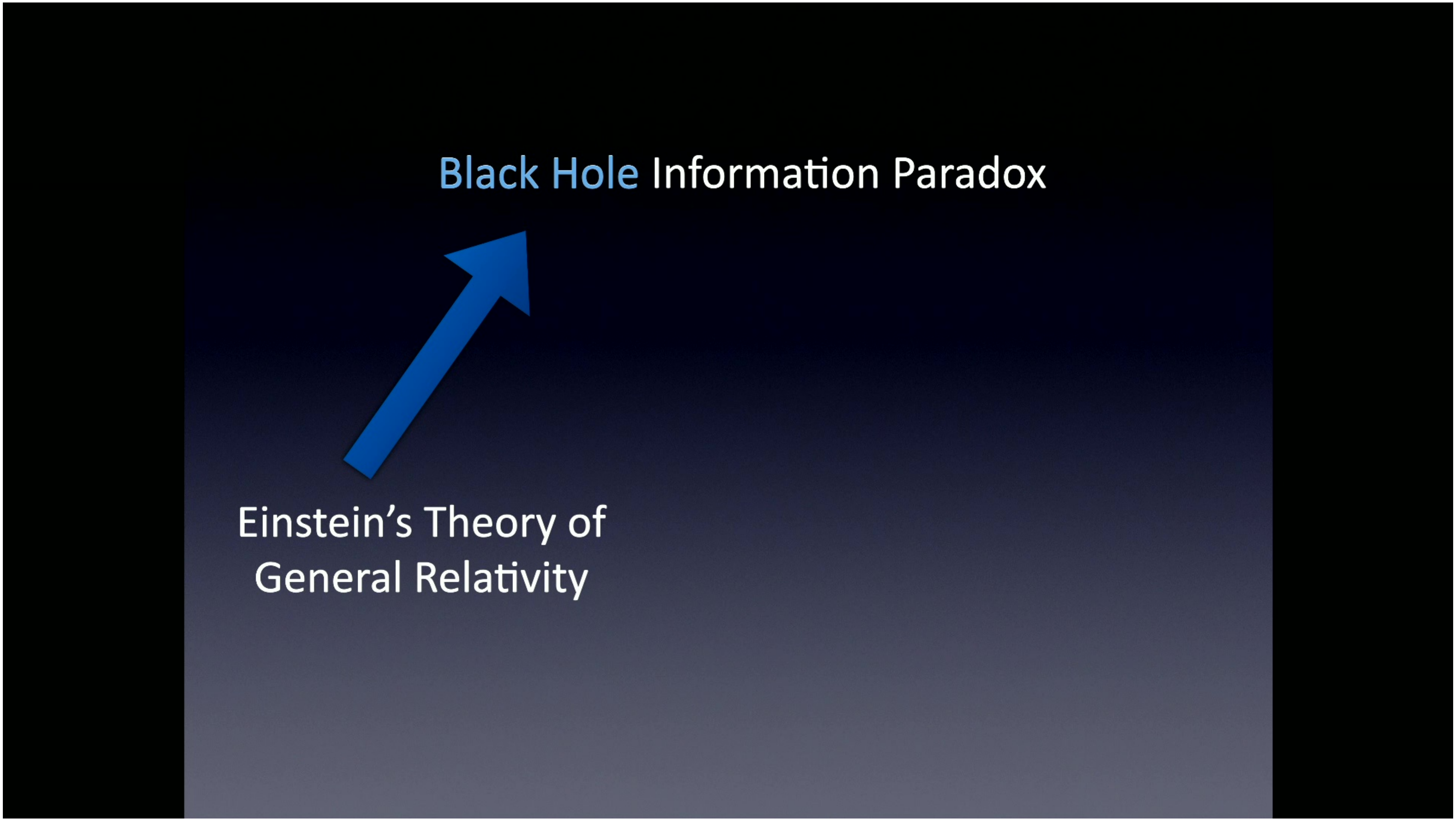
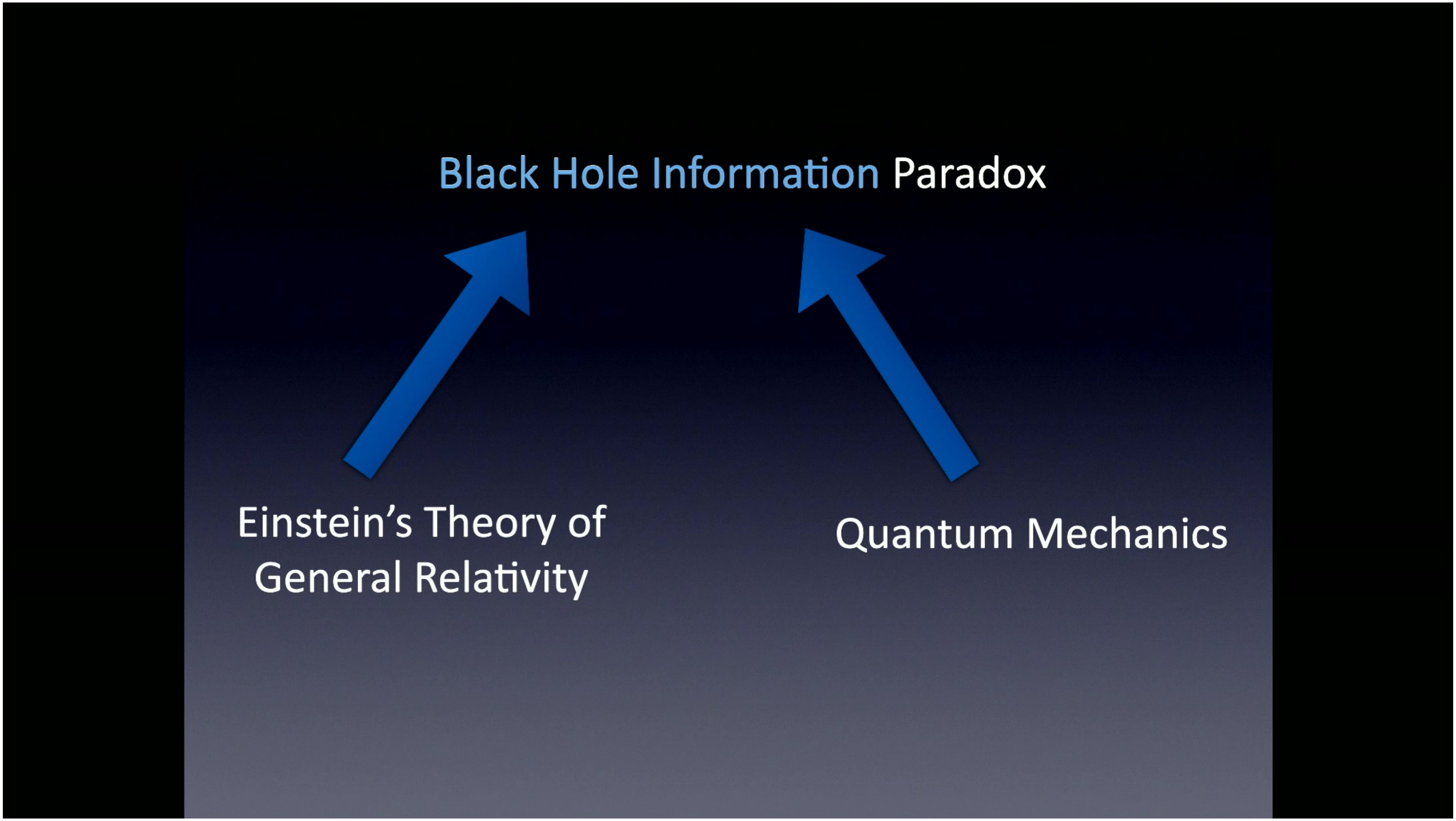


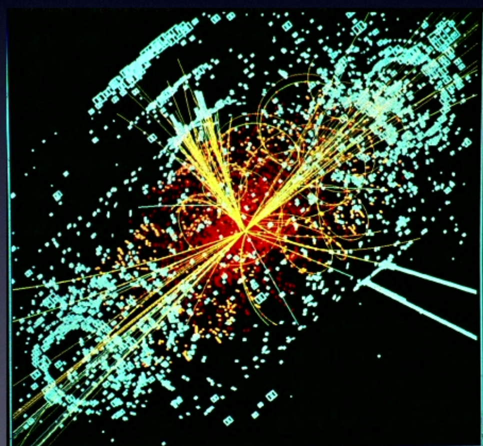
And quantum mechanics has been tested
again and again and again
and so far, it has not been wrong.

The Black Hole Information Paradox


Black Hole Information Paradox
Einstein's Theory of General Relativity

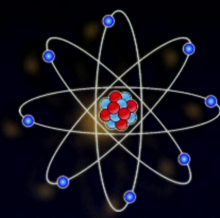

Black Hole Information Paradox
Einstein's Theory of General Relativity
Quantum Mechanics

The Black Hole Information Paradox is a **problem** that confronts the **quantum nature** of the universe with **General Relativity**.



Theories of the Extreme

Quantum Mechanics: small



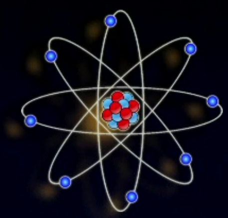
(associations: subatomic particles, quantum computers, really weird movie plots)

General Relativity: large

(associations: stars, galaxies, black holes, wormholes, really weird movie plots)

Theories of the Extreme

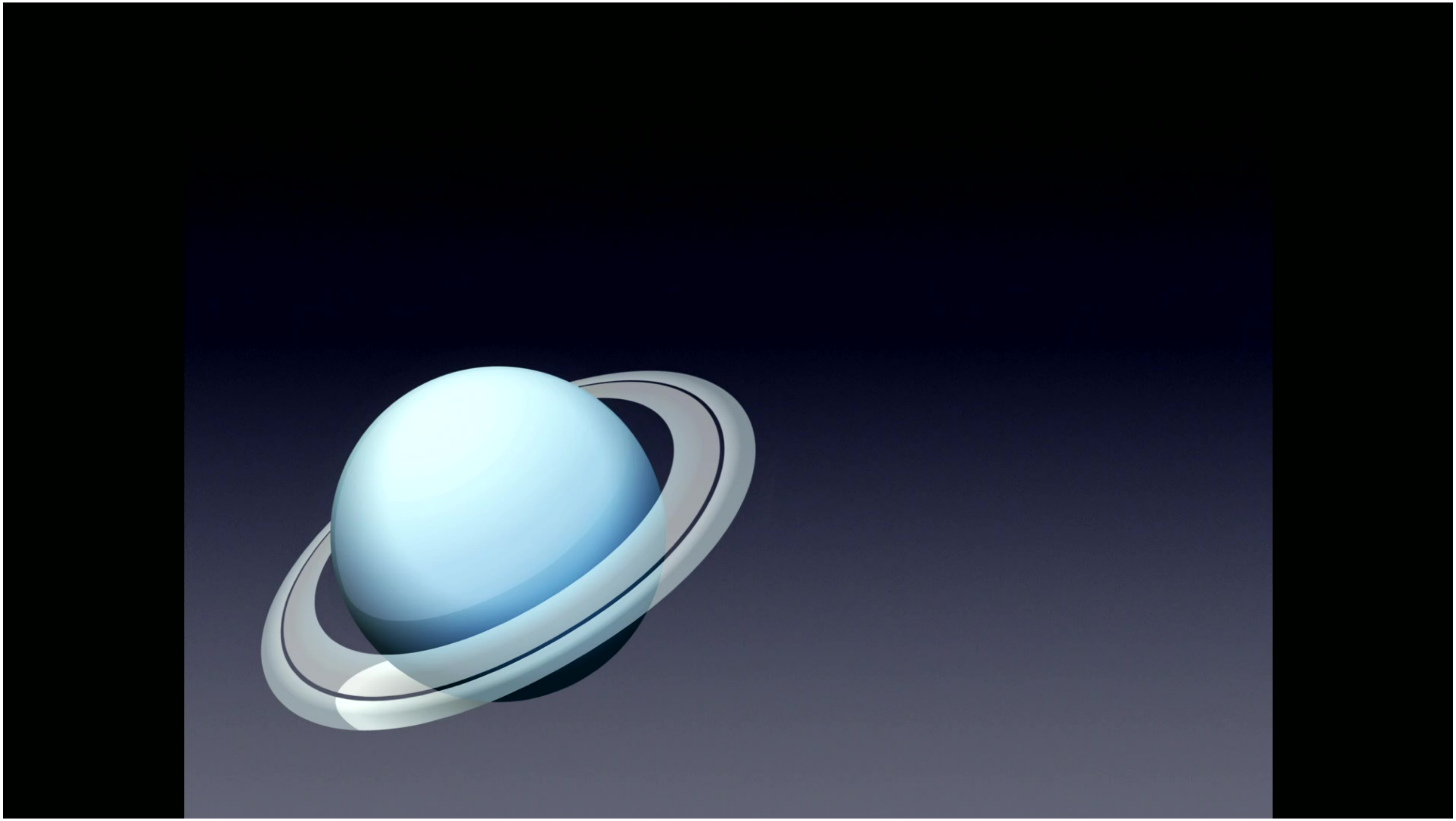
Quantum Mechanics: small SIZE



(associations: subatomic particles, quantum computers, really weird movie plots)

General Relativity: large MASS

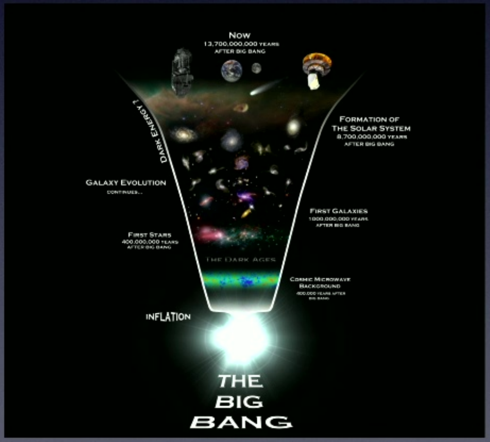
(associations: stars, galaxies, black holes, wormholes, really weird movie plots)



Quantum Gravity

Inside a black hole

QUANTUM GRAVITY



Big Bang

Particle accelerator
that's a whole lot bigger than what we have now

We don’t understand it well yet, but when we do, we will be able to explain:

How did the universe start?

Does “before the big bang” make sense?

What happens when you jump into a black hole?

Quantum Gravity is Hard

A strategy: gedankenexperiments.

Q: What would General Relativity do?

Q: What would quantum mechanics do?

If the two answers contradict, we've got ourselves a paradox.

Paradoxes!

We physicists love paradoxes.

They tell us when we're thinking about something the wrong way.

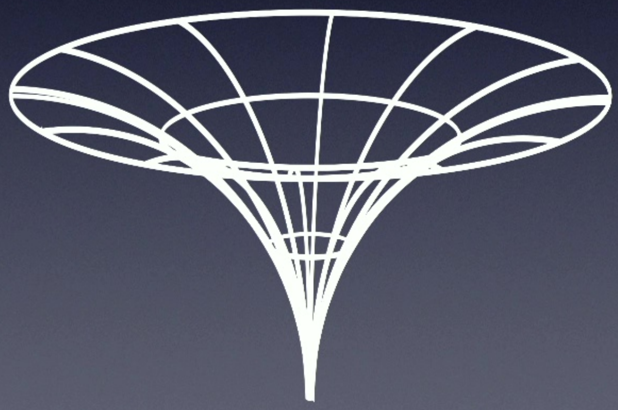
This particular paradox has been around for 50 years.

Black Hole Information Paradox

What is it? A contradiction between the predictions of **General Relativity** and **Quantum Mechanics** due to behavior of black holes.

General Relativity

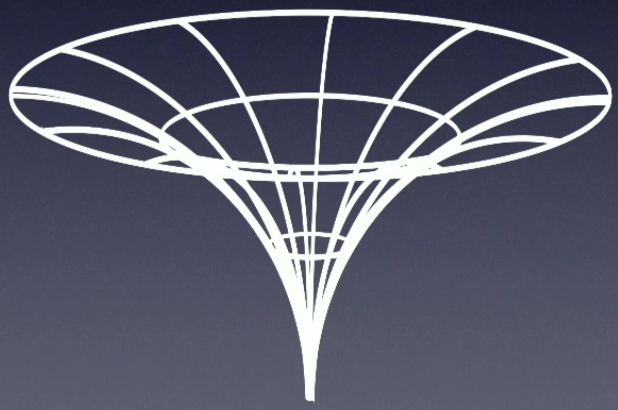
Basic idea: Mass curves space and time.



General Relativity

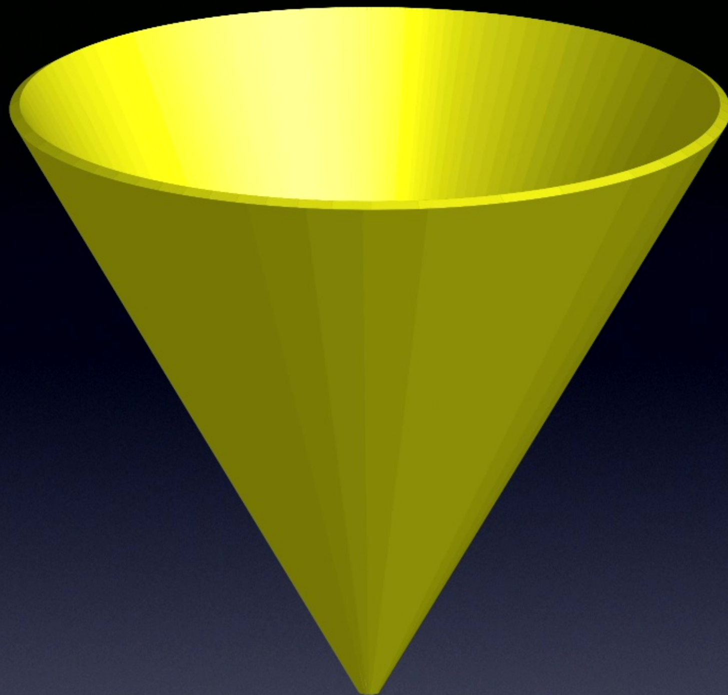
BASIC IDEA: MASS CURVES SPACE AND TIME.

A black hole concentrates so much mass into so little room that it curves space and time to the point where nothing can escape it.



Some numbers: a black hole which is 1,000 times the mass of mount Everest would be the size of a single coronavirus.

Basic idea: nothing travels faster than light.



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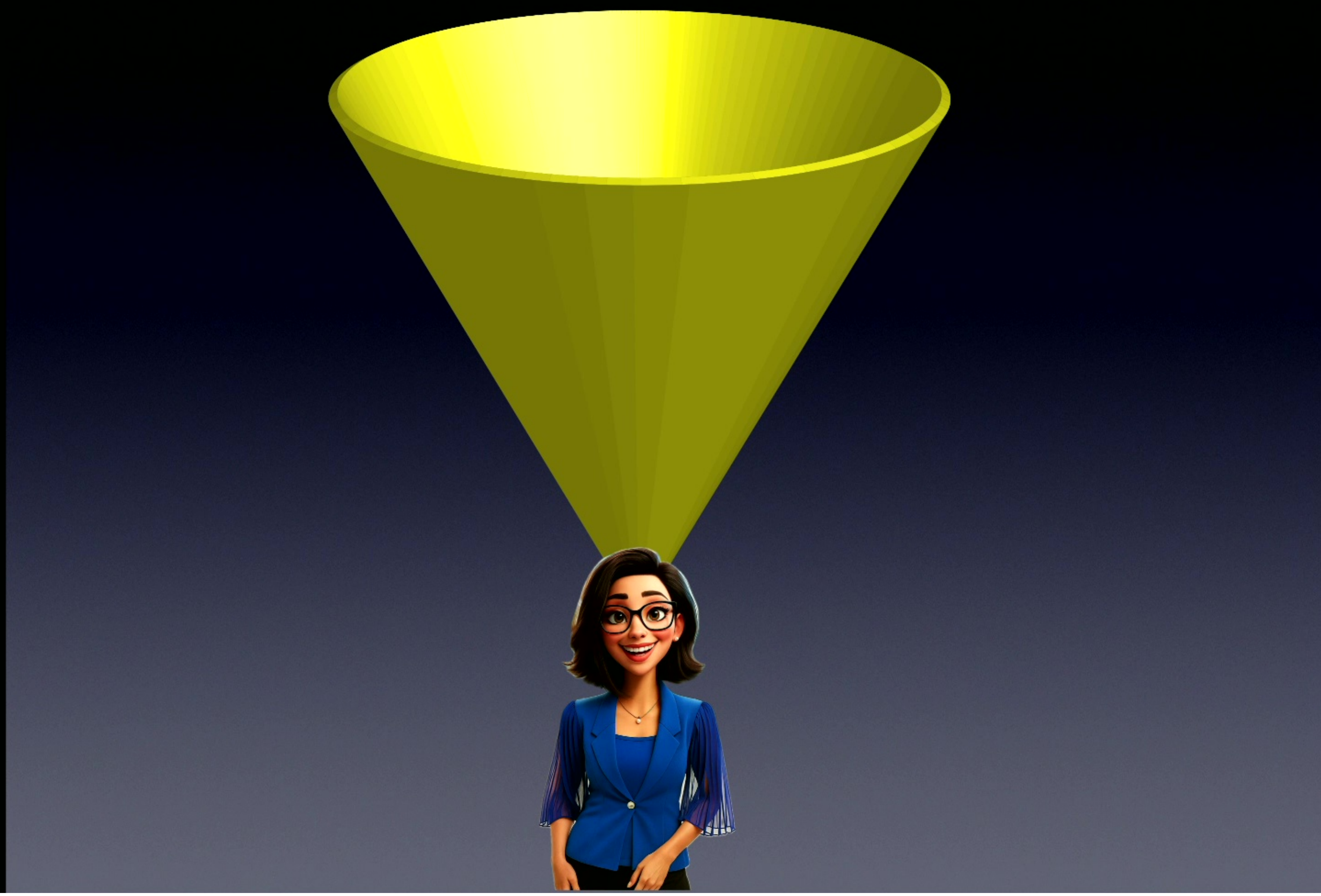

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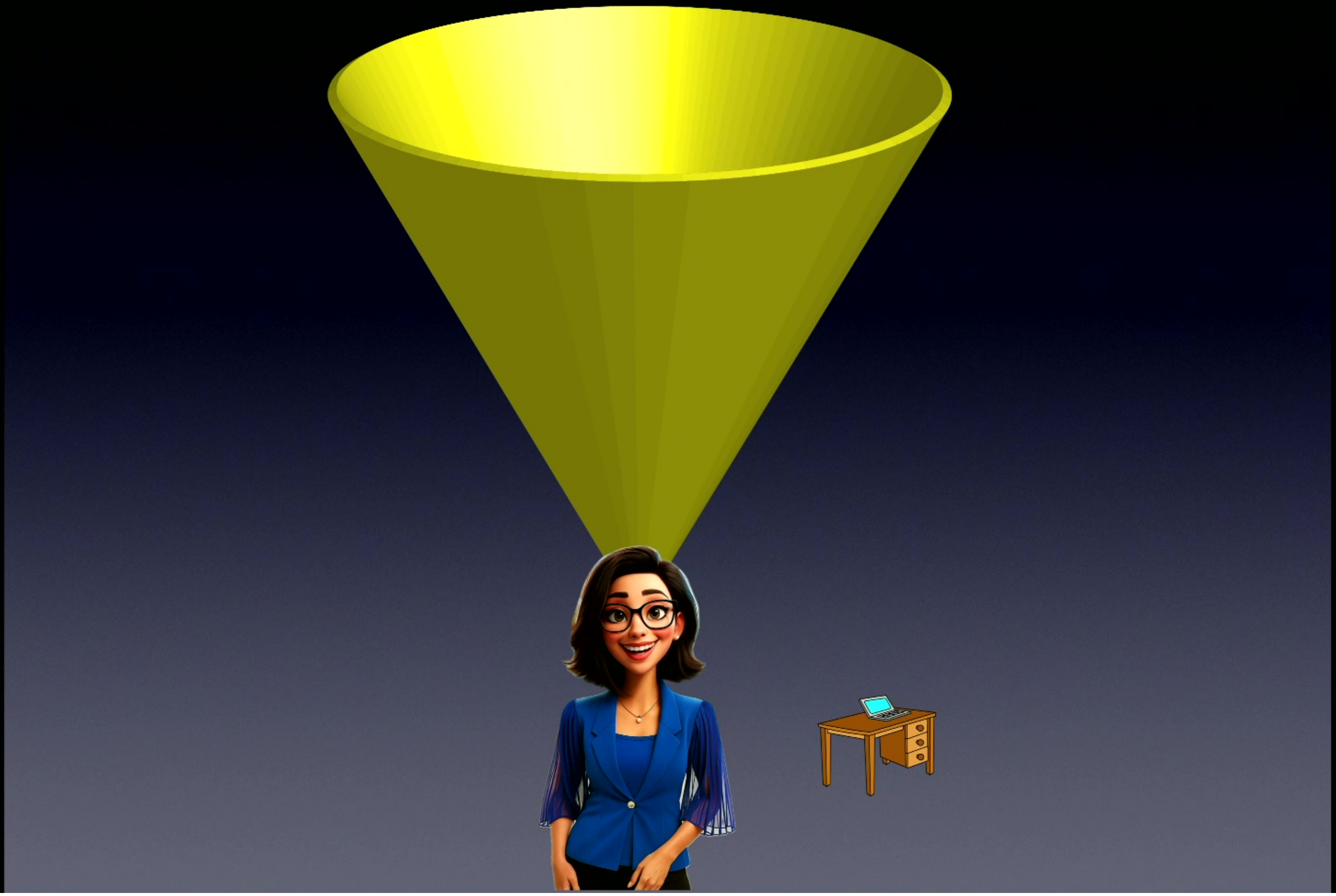
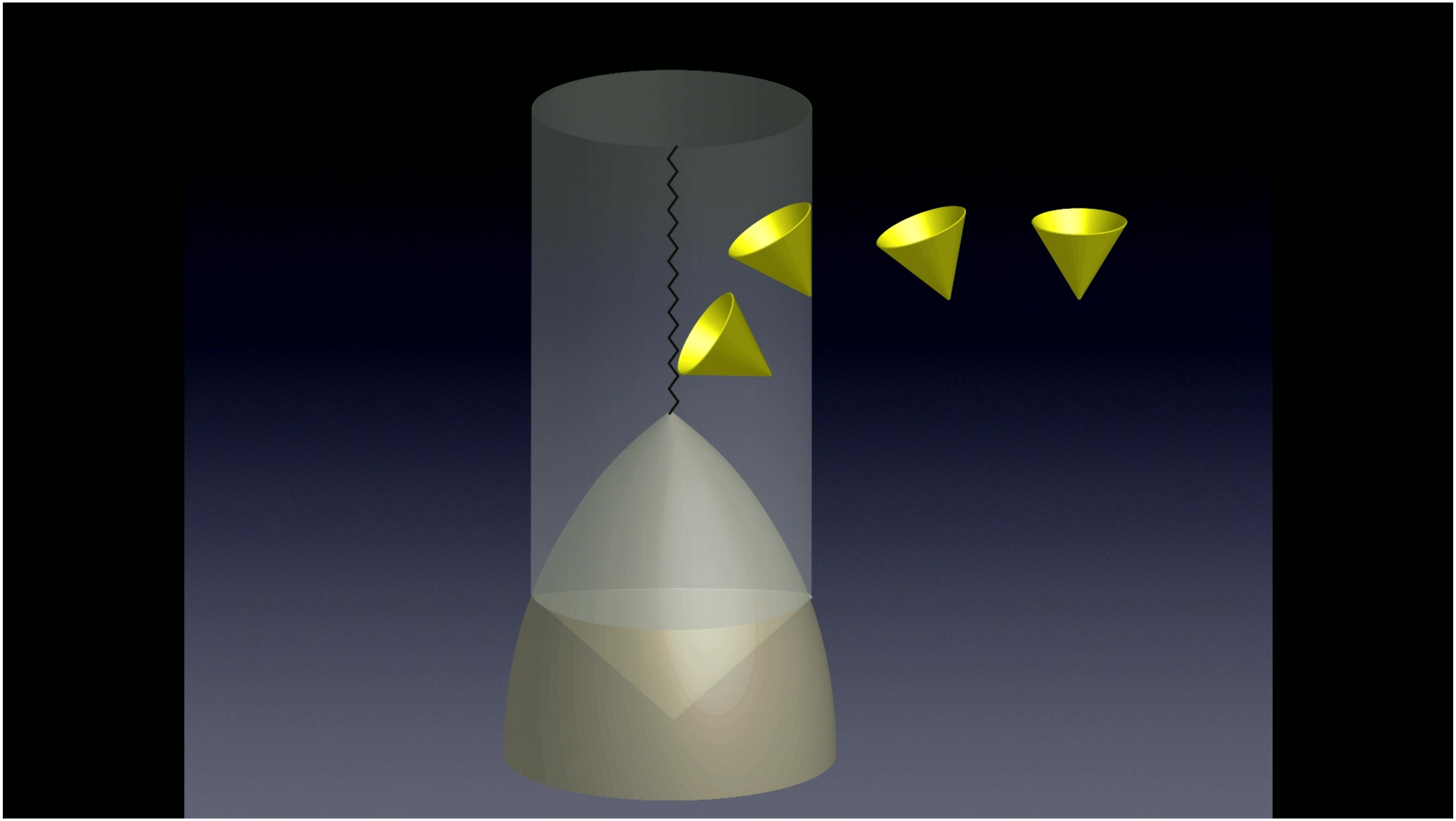




Quantum Mechanics

BASIC IDEA: OUTCOMES OF EXPERIMENTS ARE PROBABILISTIC.

"Anyone who is not shocked by quantum theory has not understood it."

- Niels Bohr

"I think it is safe to say that no one understands it."

- Paul Dirac

A Classical Coin

You have a coin inside a box.

50% chance of 

and 50% chance of 

Suppose you open the chest and find heads (“a measurement of the system”).

State of coin = 

If you have 1,000 identical treasure chests prepared in the exact same way, you will find that all 1,000 coins are heads.

Suppose you open the chest and find heads ("a measurement of the system").

State of coin = 

If you have 1,000 identical treasure chests prepared in the exact same way, you will find that all 1,000 coins are heads.

A Quantum Coin

State of coin = 50% 

+ 50% 

A Quantum Coin

Now you have a quantum coin in a chest.

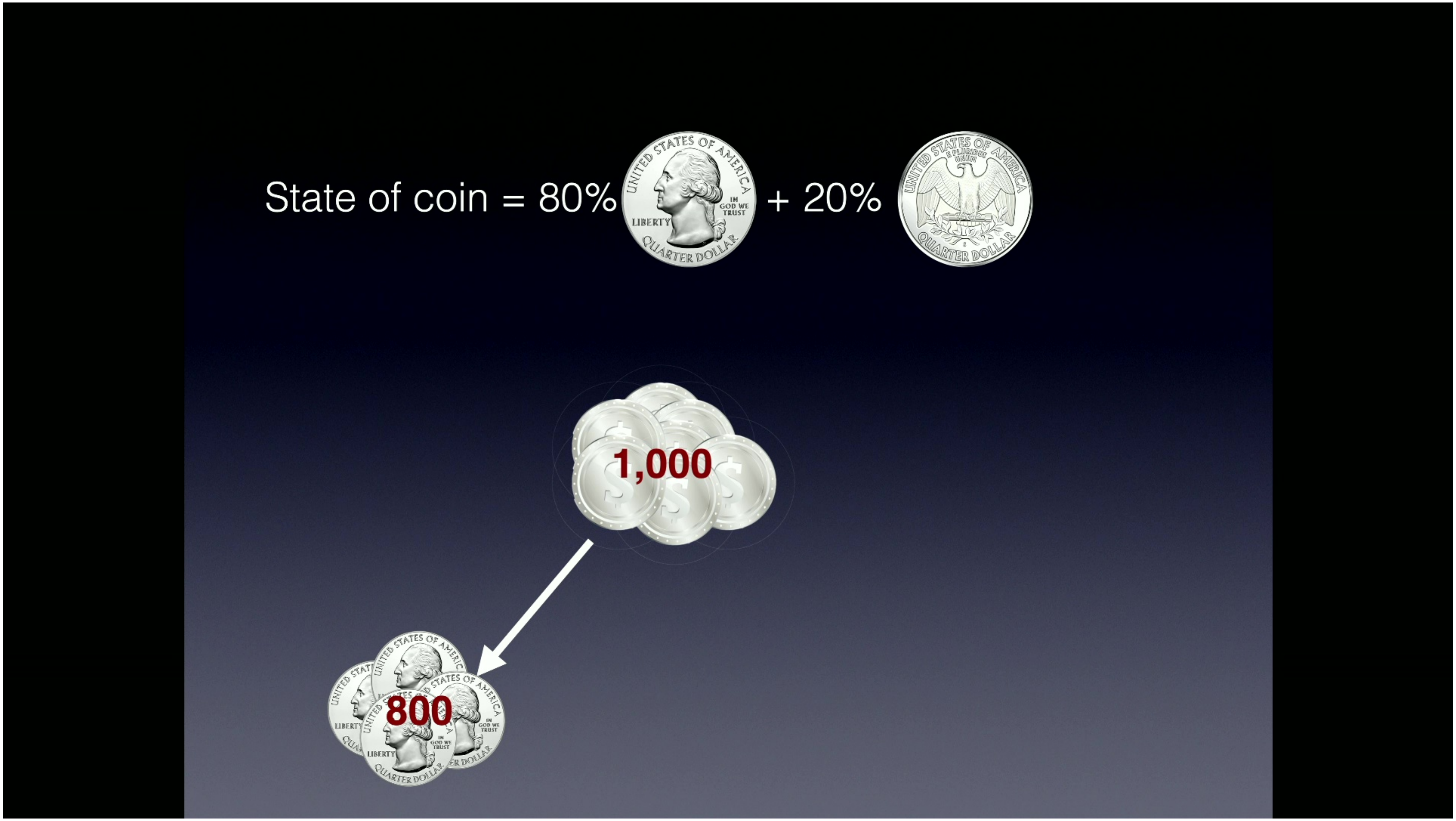
But now the outcome of your measurement is probabilistic.

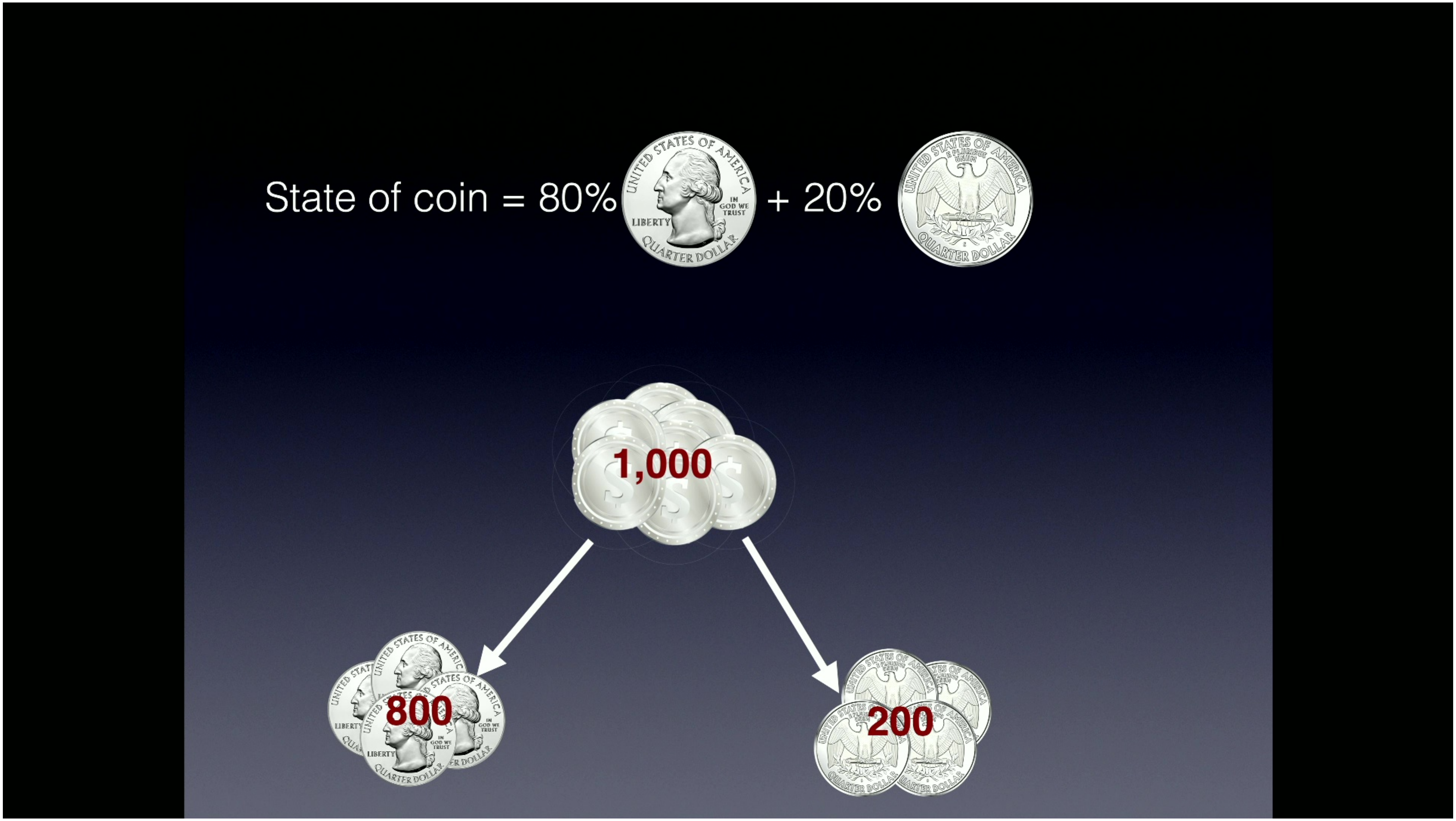
A quantum coin can be both heads and tails at the same time.

A “loaded” quantum coin:

State of coin = 80% 

+ 20% 


State of coin = 80% + 20%
1,000
800



State of coin = 80%
+ 20%
1,000
800
200

Basic Upshot

A single measurement doesn't tell you anything about the state of a quantum coin.

Measurements about many identical copies tell a lot about the state of the quantum coin.

You can get the information you want about the quantum coin with enough measurements.

Two quantum coins in the treasure chest.

Possibilities:

Coin 1 Coin 2

“Spooky Action at a Distance”

State of some “loaded” pair of quantum coins:

50% 

+ 50% 

If we open the treasure chest and find that the first coin is heads, the other coin immediately stops being “heads and tails” and becomes just heads. There is **entanglement** between the two coins.

Entanglement

50% 

+ 50% 

Entanglement is a relation between the two coins.

If you just measure coin 1 or just measure coin 2 without knowing how they are entangled, you miss out on crucial information about the two-coin system.

Entanglement

State = ??%

+??%

+??%

+??%

When two particles are **entangled**, making measurements about just one of the two particles misses **information**.

Entanglement

Two entangled coins:

50%  +50% 

If you measure coin 1 and get heads, coin 2 is now definitely heads.

Another pair of entangled coins:

50%  +50% 

If you measure coin 1 and get heads, coin 2 is now definitely *tails*.

Entanglement

Suppose we don't know the state of the two coins.

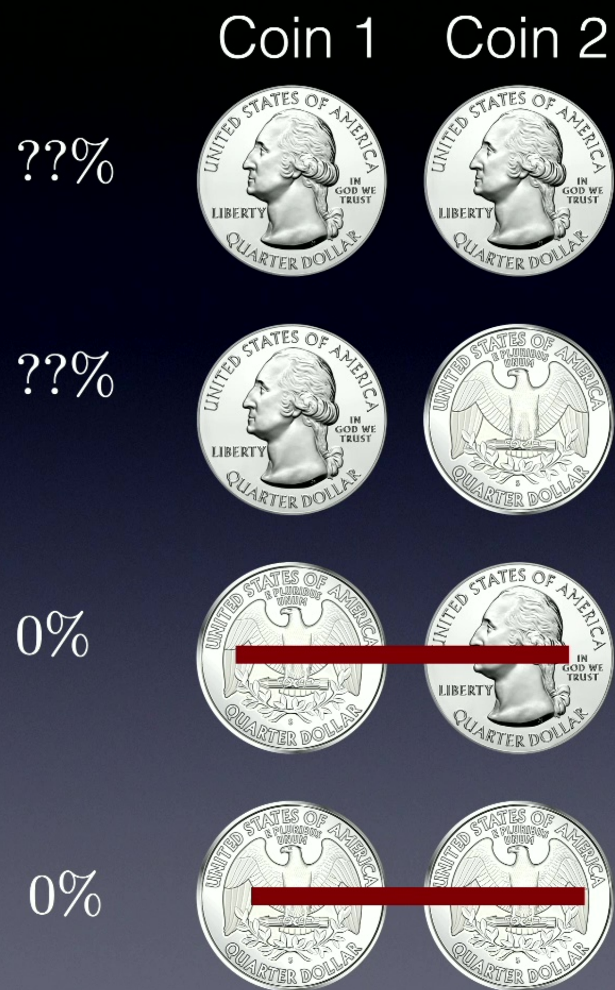
Measuring coin 1 puts coin 2 in a 'definite state', but we don't know which state that is!

When two particles are **entangled**, having access to just one of the two particles misses **information**.

We have a thousand identical chests with two pairs of coins, all prepared in the same state. We just don't know what that state is.

We look at coin 1 in each of the 1,000 chests. We find heads each time.

All we can rule out are the last two possibilities:



That is, we don’t know if the state of the 2 coins is now

or

We are *missing* all the information about the state of coin 2, even though it is completely determined by our measurement of coin 1.

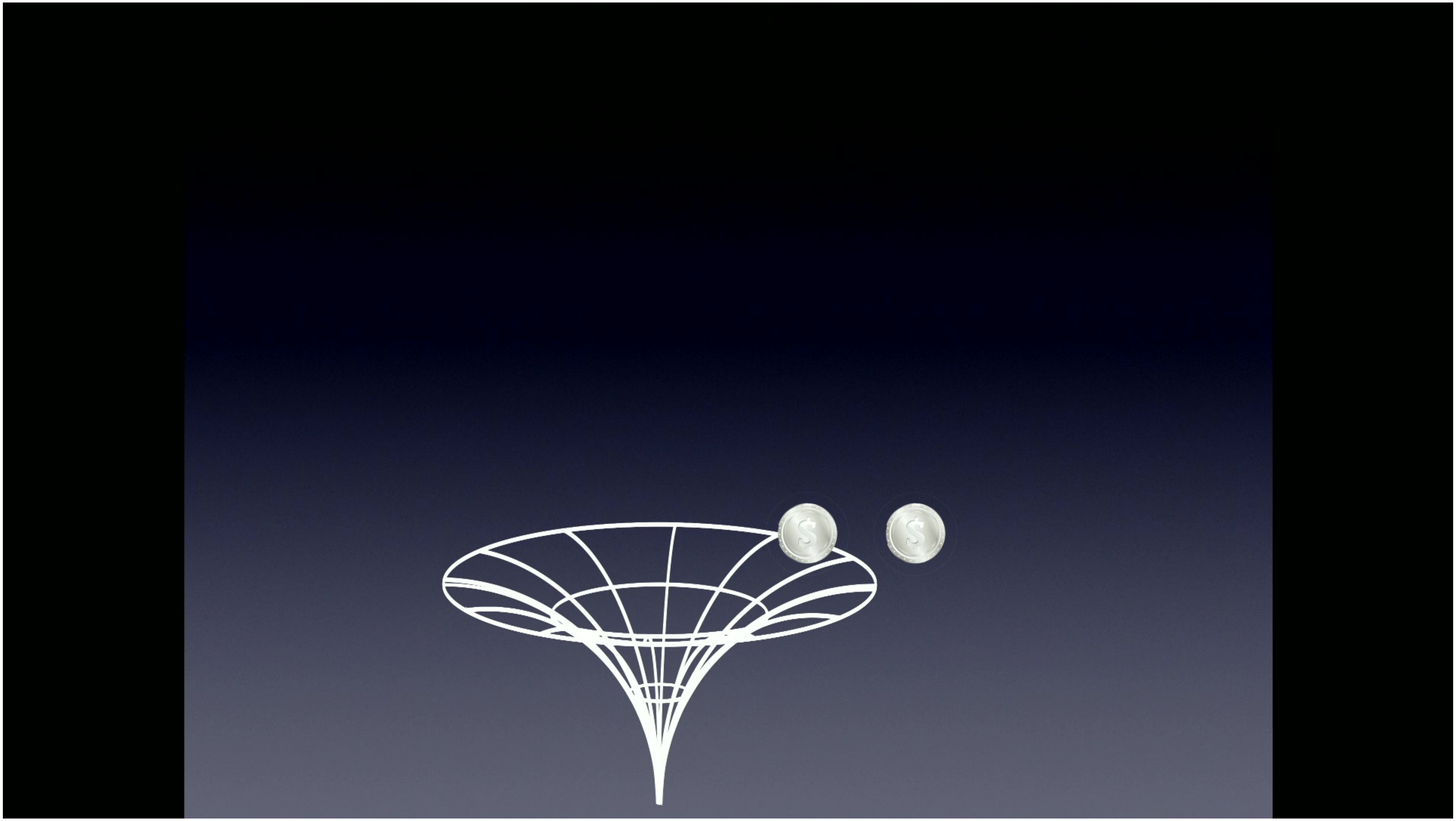
??% 

+ ??% 

When two particles are **entangled**, having access to just one of the two particles misses **information**.

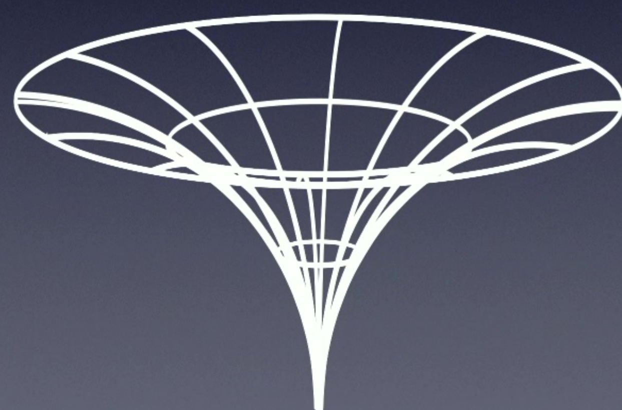
Fact: pairs of entangled particles are “popping in and out of existence” all the time.

Including across event horizons of black holes.



The outgoing coin (particle) carries away energy (radiation).

The black hole loses energy and shrinks.



The outgoing coin (particle) carries away energy (radiation).

The black hole loses energy and shrinks.

Eventually evaporating altogether.

Let’s now look at the coin that flew away.

Entanglement

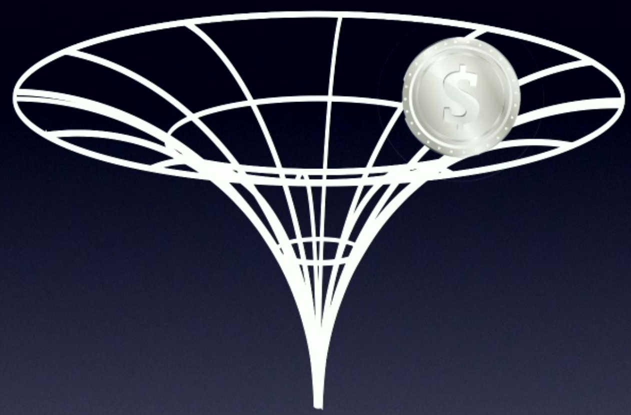
Remember this?

State = ??% 

+??% 

When two particles are **entangled**, having access to just one of the two particles misses **information**.

To determine full information about the two-coin system, we need to measure coin 2.



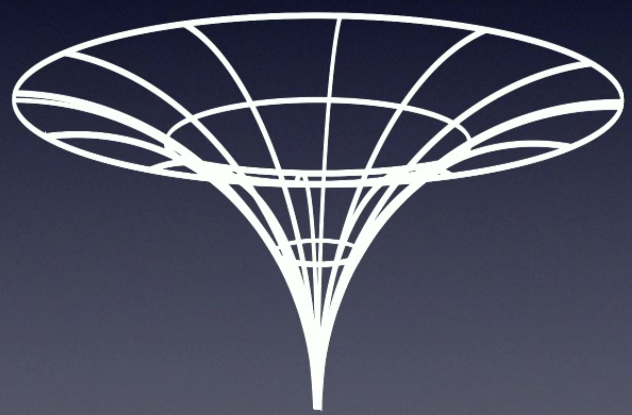
To determine full information about the two-coin system, we need to measure coin 2.

There is no observer in the universe who can measure coin 2 - because coin 2 went into a black hole that evaporated and disappeared!

Stephen Hawking, 1976: because of quantum entanglement, the disappearance of coin 2 from the universe is a net loss of information.

The Paradox

Black holes can evaporate.



The Paradox

General Relativity: due to evaporation, information about coin 2 is irrevocably lost.

State = ??% 

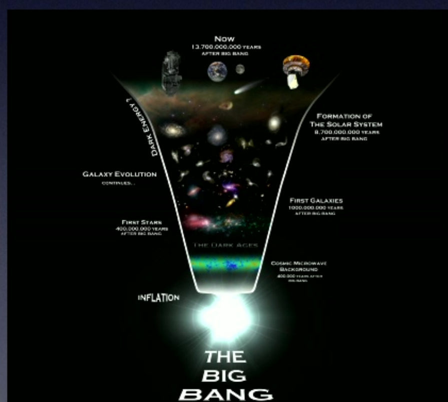
+??% 

Quantum mechanics: no process in the universe can ever lose information.

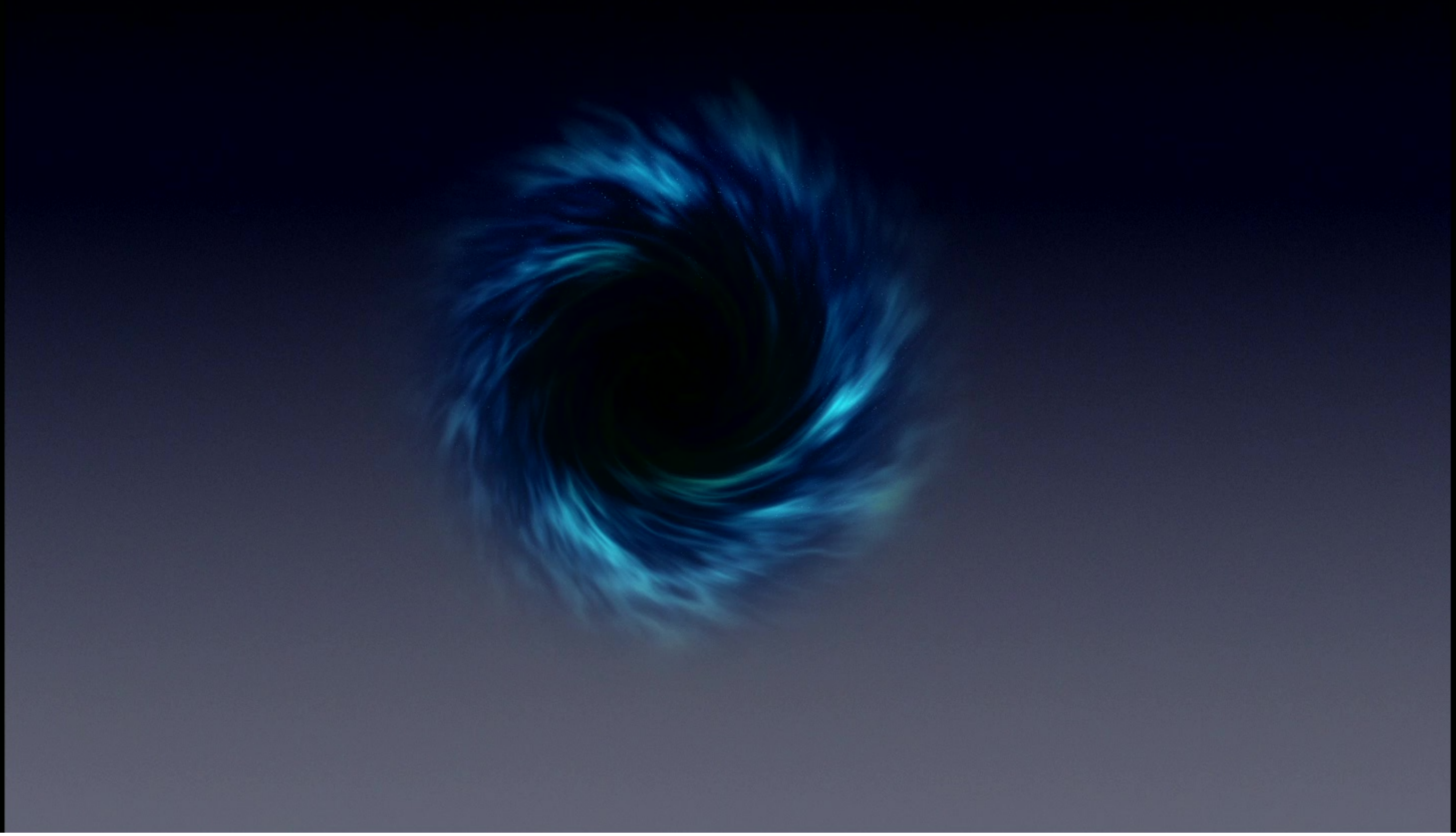
PARADOX

Remember, paradoxes give us a hint of how to modify our theories so they describe nature properly.

In this case:



The Black Hole Information Paradox



The Black Hole Information Paradox

WHERE ARE WE NOW?

What is missing?

What do we need for a resolution?

COMPLETE UNDERSTANDING OF QUANTUM GRAVITY

INTERPLAY OF GRAVITY WITH ENTANGLEMENT

PROCESS OF BLACK HOLE EVAPORATION

May 2019

Penington

905.08255v1 [hep-th] 20 May 2019

Entanglement wedge reconstruction and the information paradox

Geoffrey Penington[1]

[1] *Stanford Institute for Theoretical Physics, Stanford University, Stanford CA 94305 USA*

December 15, 2024

Abstract

When absorbing boundary conditions are used to evaporate a black hole in AdS/CFT, we show that there is a phase transition in the location of the quantum Ryu-Takayanagi surface, at precisely the Page time. The new RT surface lies slightly inside the event horizon, at an infalling time approximately the scrambling time $\beta/2\pi \log S_{BH}$ into the past. We can immediately derive the Page curve, using the Ryu-Takayanagi formula, and the Hayden-Preskill decoding criterion, using entanglement wedge reconstruction. Because part of the interior is now encoded in the early Hawking radiation, the decreasing entanglement entropy of the black hole is exactly consistent with the semiclassical bulk entanglement of the late-time Hawking modes, despite the absence of a firewall.

By studying the entanglement wedge of highly mixed states, we can understand the state dependence of the interior reconstructions. A crucial role is played by the existence of tiny, non-perturbative errors in entanglement wedge reconstruction. Directly after the Page time, interior operators can only be reconstructed from the Hawking radiation if the initial state of the black hole is known. As the black hole continues to evaporate, reconstructions become possible that simultaneously work for a large class of initial states. Using similar techniques, we generalise Hayden-Preskill to show how the amount of Hawking radiation required to reconstruct a large diary, thrown into the black hole, depends on both the energy and the entropy of the diary. Finally we argue that, before the evaporation begins, a single, state-independent interior reconstruction exists for any code space of microstates with entropy strictly less than the Bekenstein-Hawking entropy, and show that this is sufficient state dependence to avoid the AMPSS typical-state firewall paradox.

Almheiri, Engelhardt Marolf, Maxfield

arXiv:1905.08762v1 [hep-th] 21 May 2019

The entropy of bulk quantum fields and the entanglement wedge of an evaporating black hole

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Abstract: Bulk quantum fields are often said to contribute to the generalized entropy $\frac{A}{4G_N} + S_{\text{bulk}}$ only at $O(1)$. Nonetheless, in the context of evaporating black holes, $O(1/G_N)$ gradients in S_{bulk} can arise due to large boosts, introducing a quantum extremal surface far from any classical extremal surface. We examine the effect of such bulk quantum effects on quantum extremal surfaces (QESs) and the resulting entanglement wedge in a simple two-boundary $2d$ bulk system defined by Jackiw-Teitelboim gravity coupled to a 1+1 CFT. Turning on a coupling between one boundary and a further external auxiliary system which functions as a heat sink allows a two-sided otherwise-eternal black hole to evaporate on one side. We find the generalized entropy of the QES to behave as expected from general considerations of unitarity, and in particular that ingoing information disappears from the entanglement wedge after a scambling time $\frac{\beta}{2\pi} \log \Delta S + O(1)$ in accord with expectations for holographic implementations of the Hayden-Preskill protocol. We also find an interesting QES phase transition at what one might call the Page time for our process.

Gravity contributes to entanglement.

The way in which gravity impacts entanglement
in a black hole that evaporates
is just exactly enough to offset the loss of information
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Gravity contributes to entanglement.

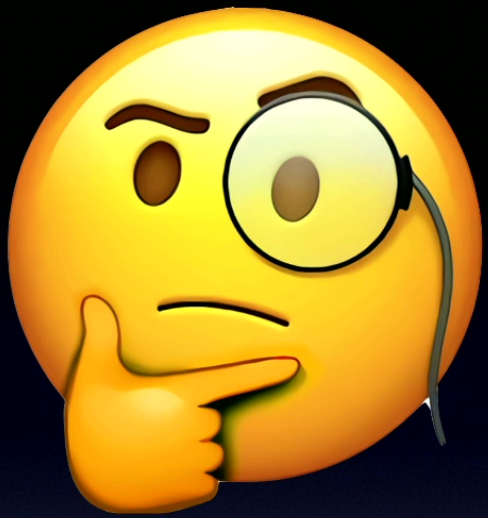
The way in which gravity impacts entanglement
in a black hole that evaporates
is just exactly enough to offset the loss of information
due to the evaporation.

So it is clear the information gets out, and there is a way in which gravity manages to get it out of the black hole.

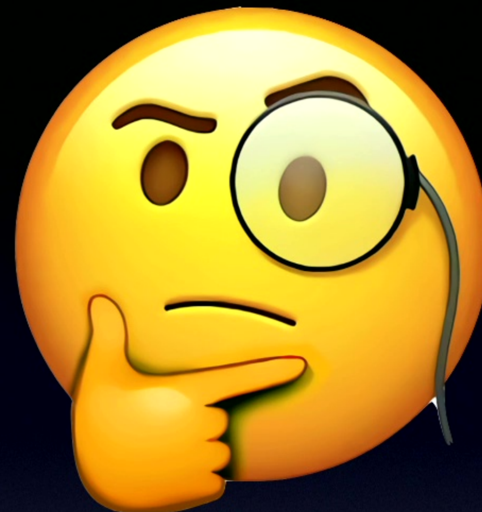
And yet, nothing travels faster than light…

And light cannot escape from a black hole.

So… HOW does the information get out?



Quantum gravity can transport information faster than light?



But if so… shouldn’t we have already seen such a mechanism?

Why have we never seen information being transported faster than light?

Towards a Resolution…

Even though the information has been transported outside of the black hole…

It has been scrambled in the process…

So it is incredibly difficult to tell that information about what went into the black hole ended up in the radiation.

Could that be why we haven't "seen" faster than light information travel?

Towards a Resolution…

Just how difficult is "difficult"?

The information comes out in some quantum state:

If there are *n* coins in a box, there are 2^n possible combinations of coins.

Towards a Resolution…

Just how difficult is “difficult”?

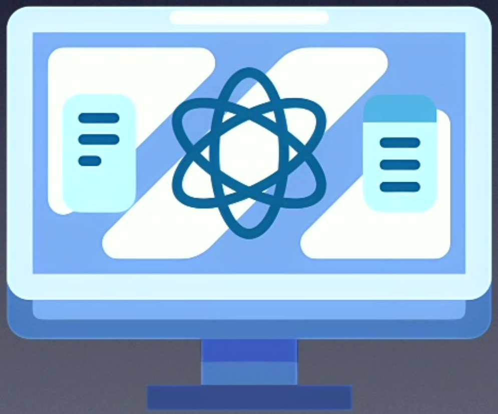
The information comes out in some quantum state:

If there are *n* coins in a box, there are 2^n possible combinations of coins.

If you want an algorithm that figures out which combination you actually have, it has to sift through 2^n possibilities.

Towards a Resolution…

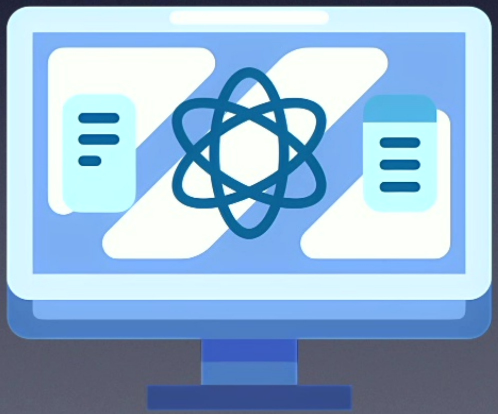
For a solar mass black hole, $n \approx 10^{70}$. The best algorithm has to find a needle in a haystack of size $2^{10^{70}}$!!



Towards a Resolution…

For a solar mass black hole, $n \approx 10^{70}$. The best algorithm has to find a needle in a haystack of size $2^{10^{70}}$!!

Maybe a quantum computer can do better than just sifting through all the options?



Towards a Resolution…

As it turns out, even a quantum computer can't speed up the process very much.

So… nothing appears to travel faster than light.

To see that faster than light travel happened requires unscrambling - which is incredibly difficult to do!

So… DOES ANYTHING ESCAPE FROM A BLACK HOLE?

YES! EVERYTHING that falls into a black hole can escape from it if the black hole evaporates.

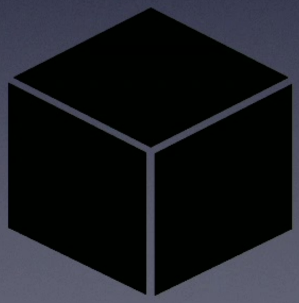
But it escapes in an extremely mangled way!

It takes a very, very, VERY long time to rearrange the mangled up stuff into its original form.

Is this the final resolution of the black hole information paradox?

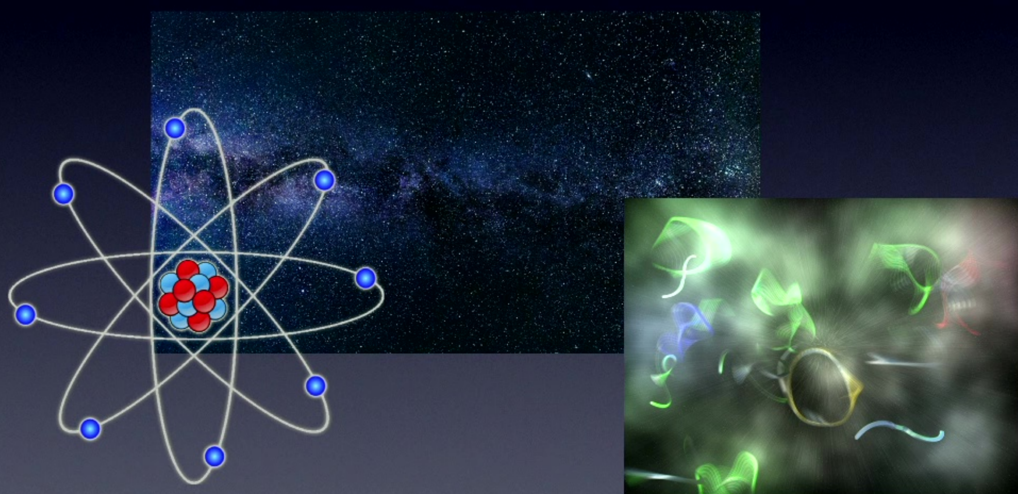
What is the basic mechanism in quantum gravity that mangles up the information in the black hole?

And what really happens to coin 1 in the black hole interior?



Resolving the Black Hole Information Paradox is a stepping stone to understanding fundamental building blocks of the cosmos, the big bang, and black holes.

And to answering the question that has fascinated humanity for as long as human thought has existed:



WHERE DID IT ALL COME FROM?