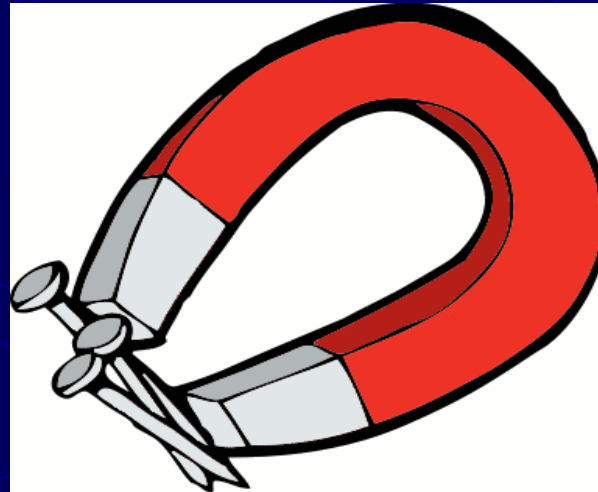
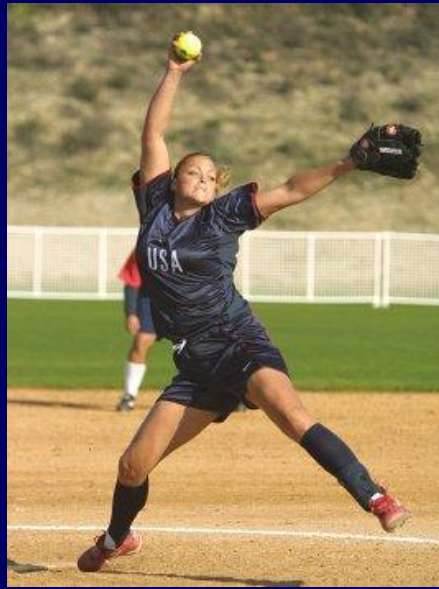


Gravity and Quantum Mechanics - The Quest for Unification

Joseph Polchinski
Kavli Institute for Theoretical Physics
University of California at Santa Barbara

KITP Public Lecture
March 6, 2013

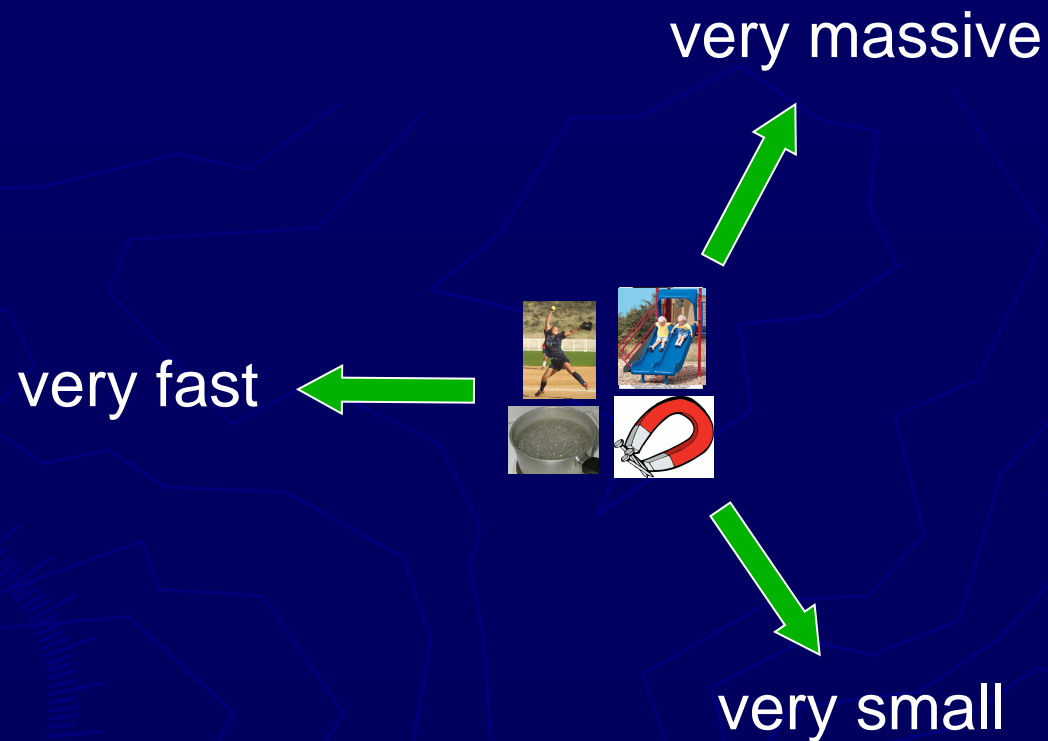
Some everyday physics:





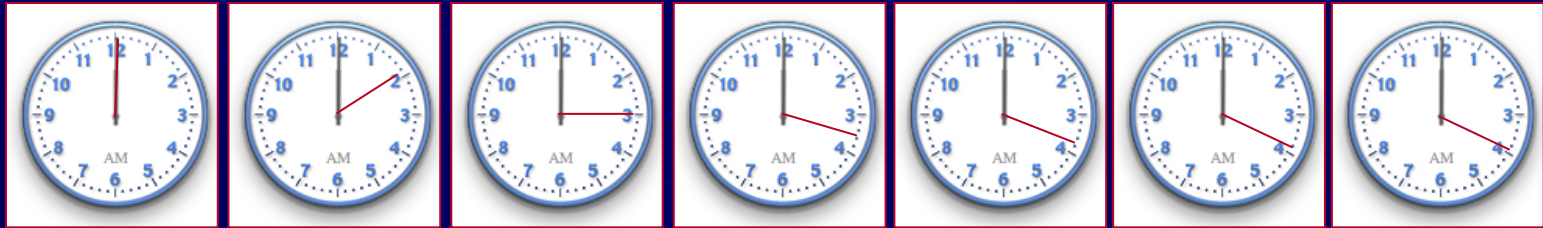
Everyday physics is at the scale of our senses --- meters, kilograms, and seconds --- but with scientific instruments we can look much farther., and sometimes what we find is very different from familiar experience.

Three extremes, where things get strange:

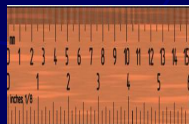
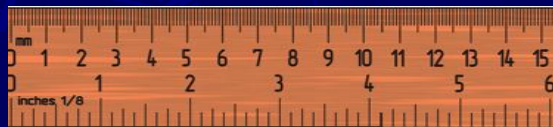


Near the speed of light, we find the strange phenomena of *Special Relativity*:

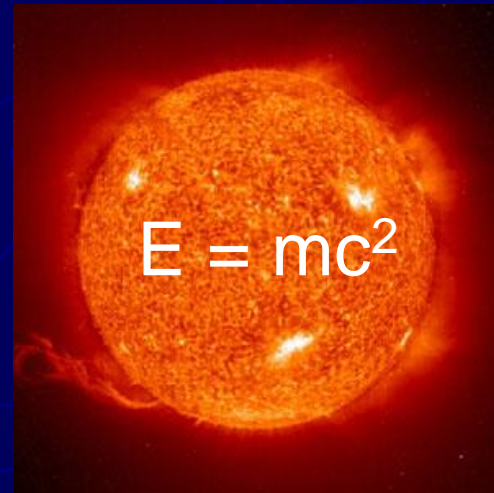
Clocks slow down:



Rulers shorten:



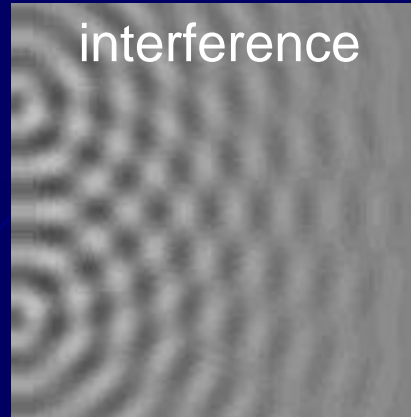
Mass converts to energy:



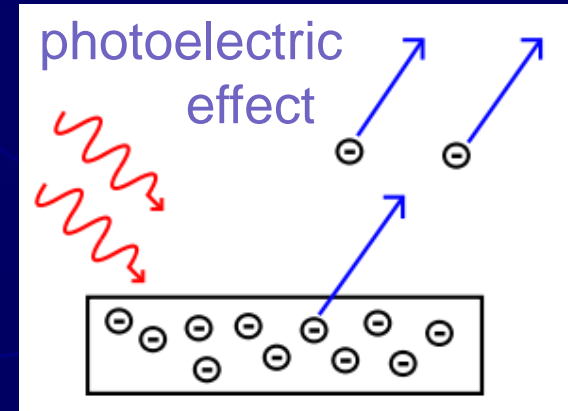
SOHO-EIT

At the atomic scale, we find the strangeness of *Quantum Mechanics*:

Light is both a wave and a particle (and so are electrons and everything else):

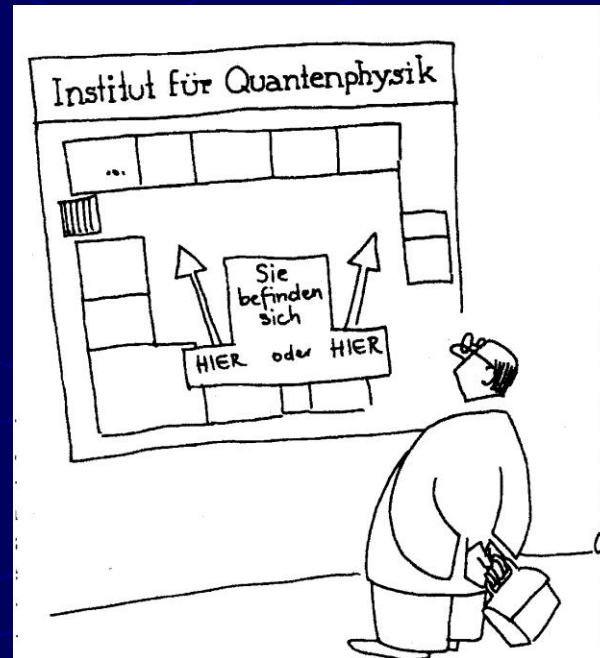


interference



photoelectric effect

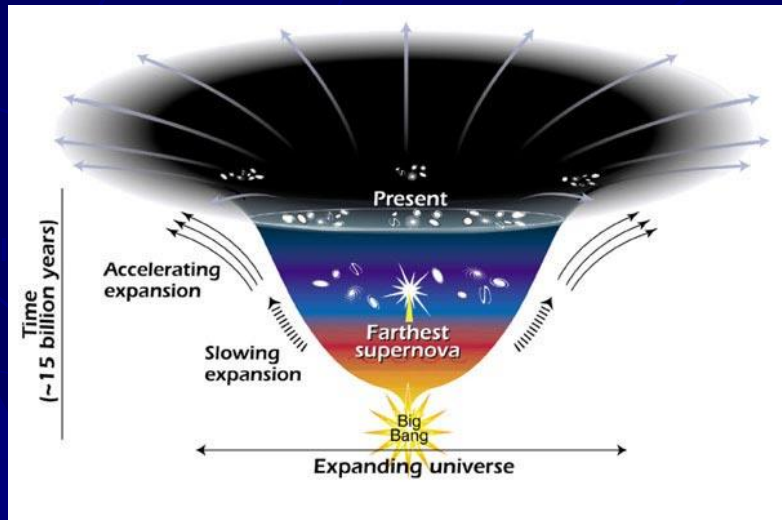
Things can behave as though they are in two places at the same time:



For very large masses, we encounter *General Relativity*:

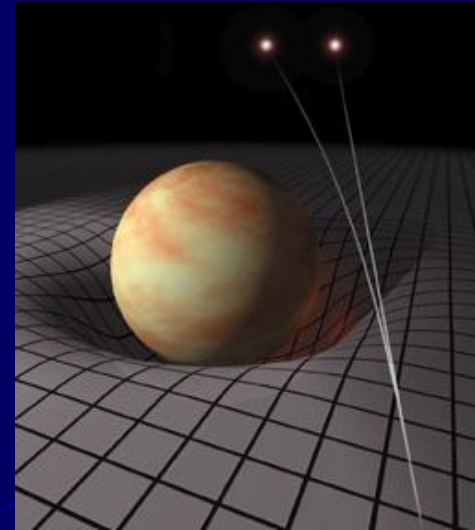
Space and time can bend, and this is the origin of gravity:

The universe expands:



NASA

Stars can collapse into black holes:



Sean Carroll



Ute Kraus

Three great revolutions in physics:

Very fast: **Special Relativity (1905)**

Very massive: **General Relativity (1916)**

Very small: **Quantum Mechanics (~1925)**



Three great revolutions in physics:

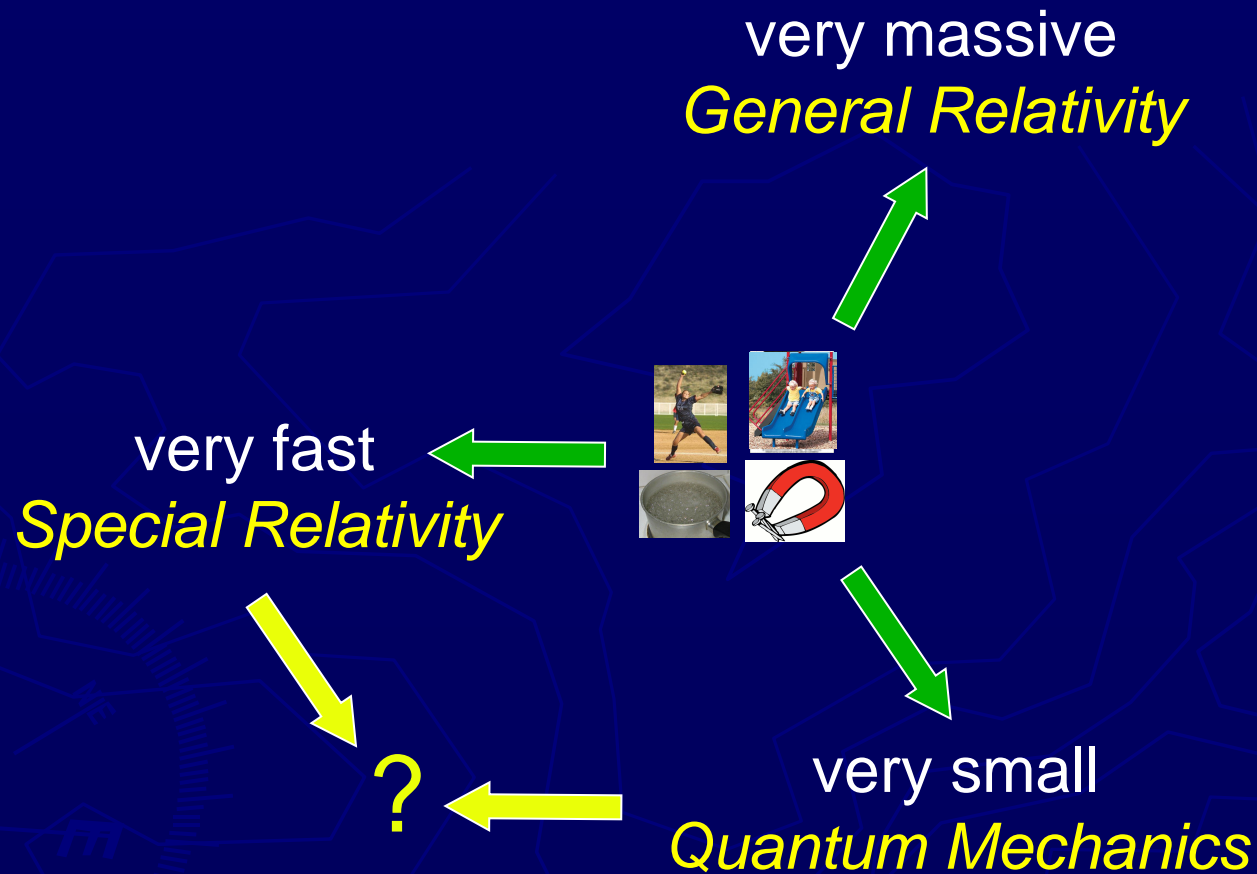
Very fast: **Special Relativity (1905)**

Very massive: **General Relativity (1916)**

Very small: **Quantum Mechanics (~1925)**

But these revolutions are not finished!

New answers raise new questions:



What if an object is *both* very small and very fast?

What if an object is *both*
very small and very fast?

This very good question led Dirac
to predict *antimatter* :

—
•

+
•

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What if an object is *both*
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This very good question led Dirac
to predict *antimatter* :



Dirac started with Schrodinger's equation for quantum mechanics:

$$i\hbar \frac{d\psi}{dt} = -\frac{\hbar^2}{2m} D^2 \psi + eA_0 \psi$$

This describes quantum behavior of atoms, molecules, but *fails* for particles moving close to the speed of light. Dirac solved this by finding an improved equation:



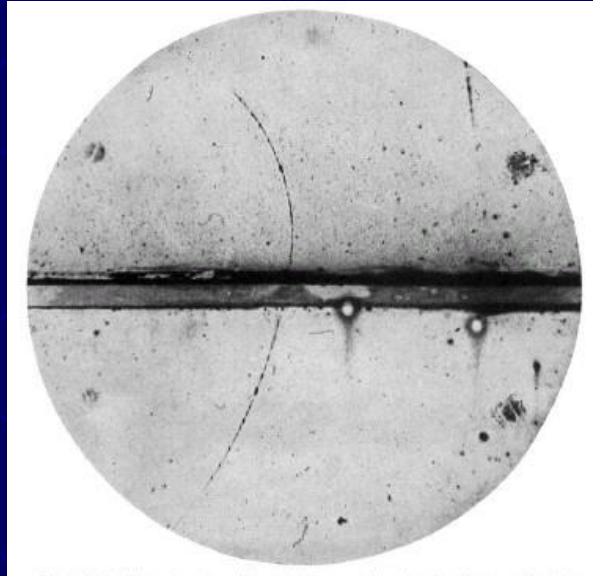
$$i\hbar \gamma^\mu D_\mu \psi = m\psi$$

$$i\hbar\gamma^\mu D_\mu\psi = m\psi$$

Dirac's equation agrees with Schrodinger's equation for 'slow' things like atoms and molecules, but it correctly incorporates the relativity principle.

The surprise: it has twice as many solutions as Dirac expected. The extra solutions represent *antimatter*.

Antimatter: predicted by Dirac 1930, discovered by Anderson 1932:



Track of cosmic ray positron (antielectron) curving in a magnetic field.

The story of Special Relativity + Quantum Mechanics
went on after Dirac:

Quantum field theory

The Standard Model (~1971). Predicted:

gluon (discovered 1979)

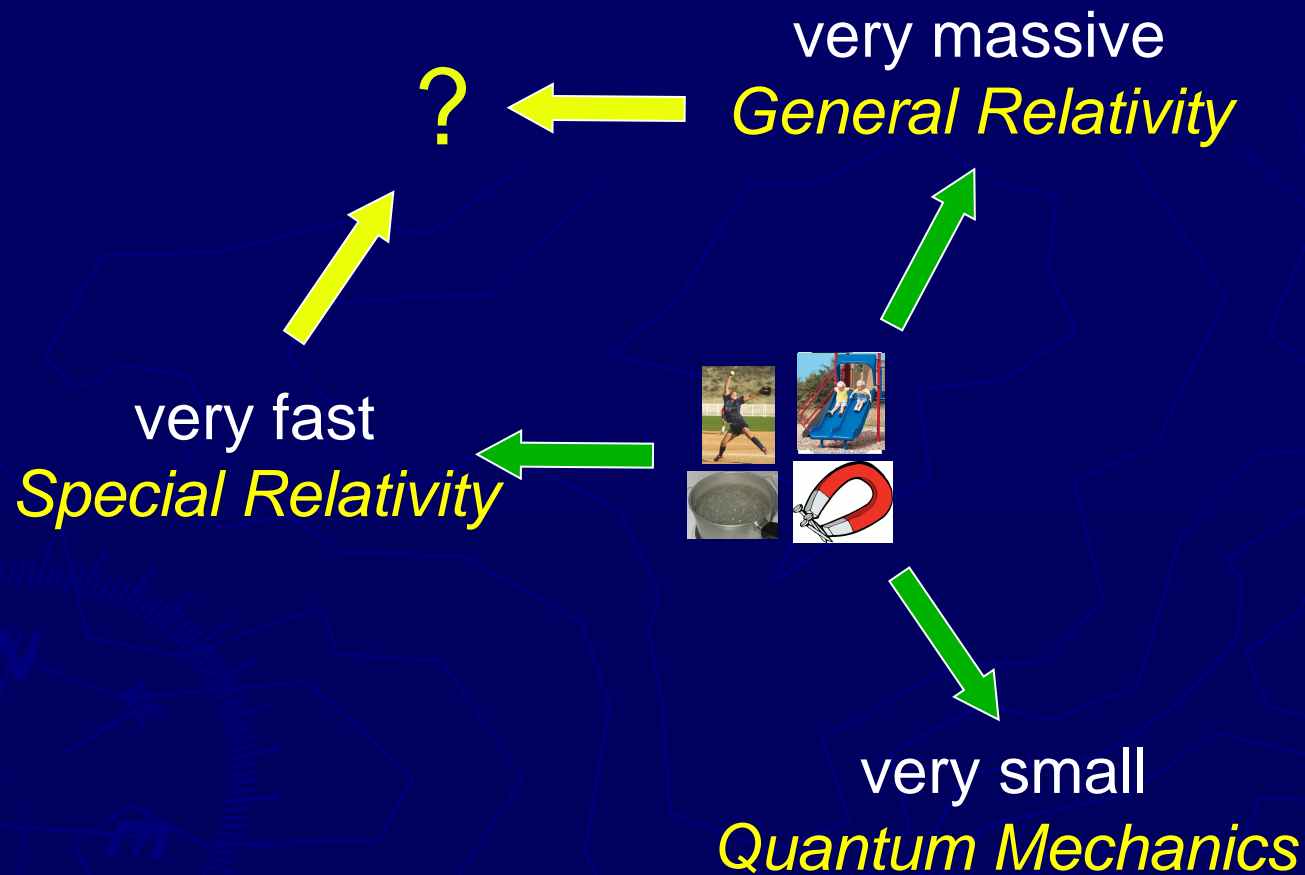
W boson (discovered 1983)

Z boson (discovered 1983)

top quark (discovered 1995)

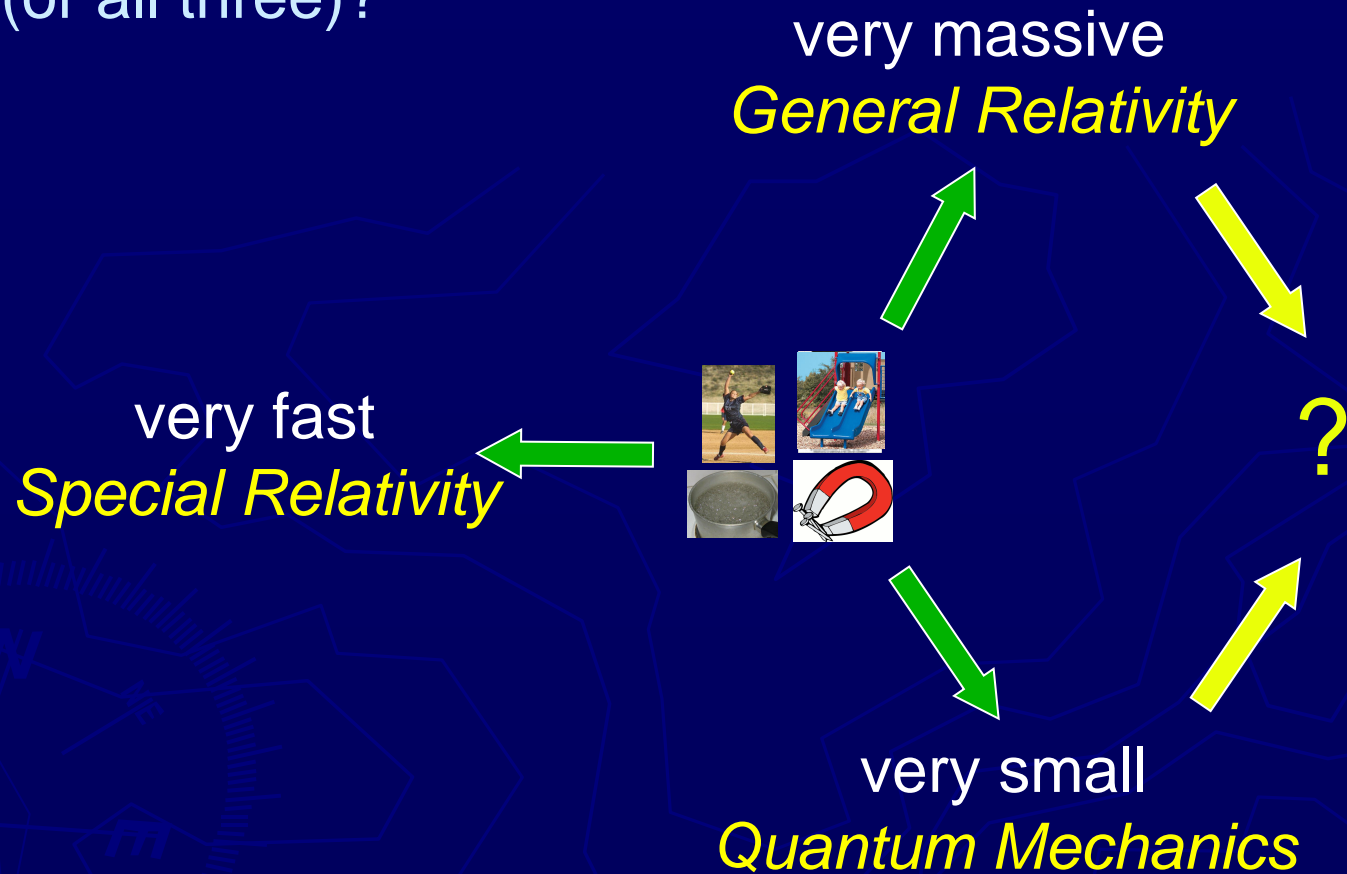
Higgs boson (discovered 2012)

What if an object is both very fast and very massive?



This is an easy one: general relativity takes care of both.

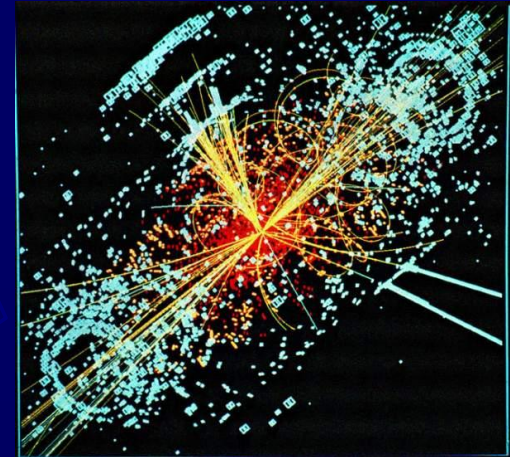
Finally, what if an object is very small and very massive (or all three)?



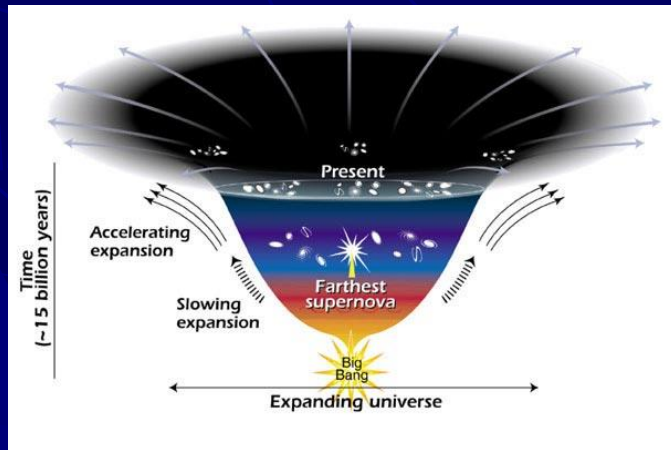
This is the difficult problem of *Quantum Gravity*.

Is it possible for something to be both very small and very massive? Yes:

- Particle collisions at *extremely* high energies

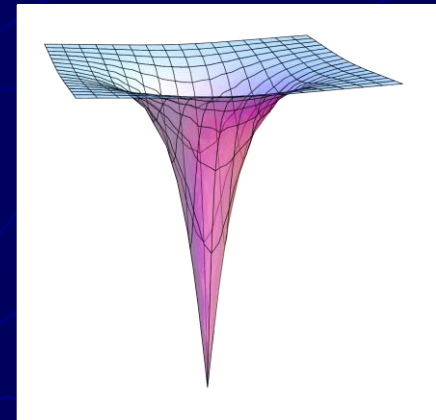


CMS



- The very early universe: the universe is expanding, and was once much smaller than it is today.

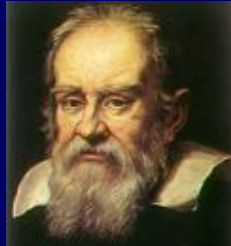
- The cores of black holes



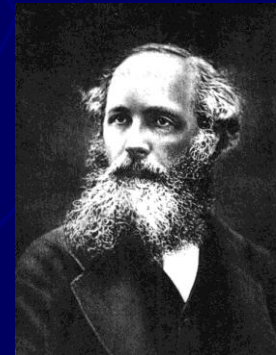
Because these situations are so extreme, we have to rely heavily on theoretical reasoning, like Dirac.

In particular, *thought experiments*, like

Galileo



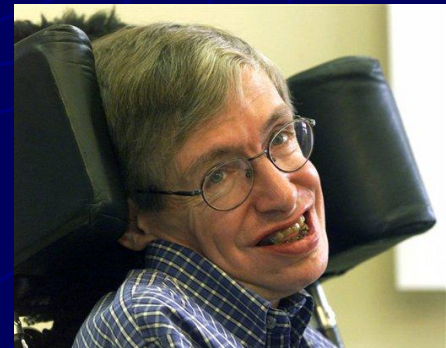
Maxwell



Einstein



Hawking



James Clerk Maxwell's thought experiment

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho_v$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

and then there was light.

The tee-shirt before Maxwell:

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho_v$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J$$

Before Maxwell:

$$\nabla \cdot \vec{B} = 0$$

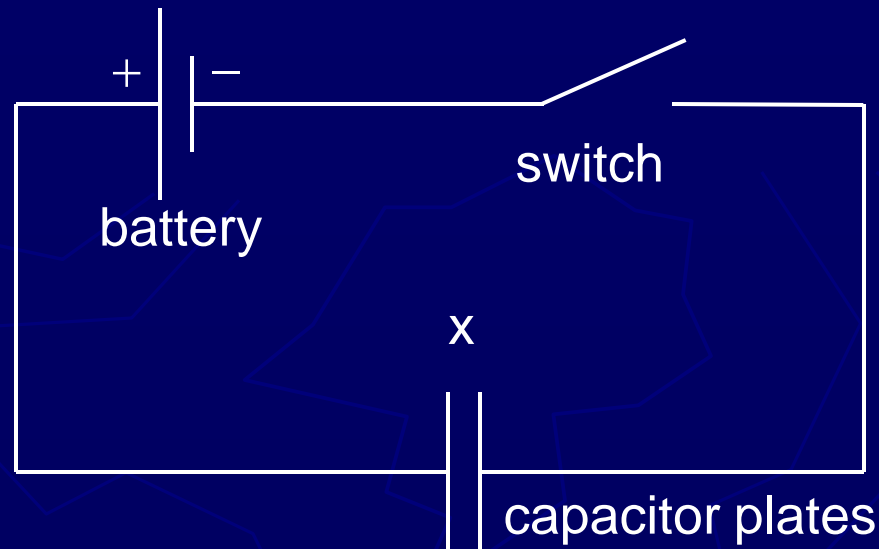
$$\nabla \cdot \vec{D} = \rho_v \quad \swarrow \text{Gauss's law}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \swarrow \text{Faraday's law}$$

$$\nabla \times H = J \quad \swarrow \text{Ampere's law}$$

Earlier terms discovered experimentally

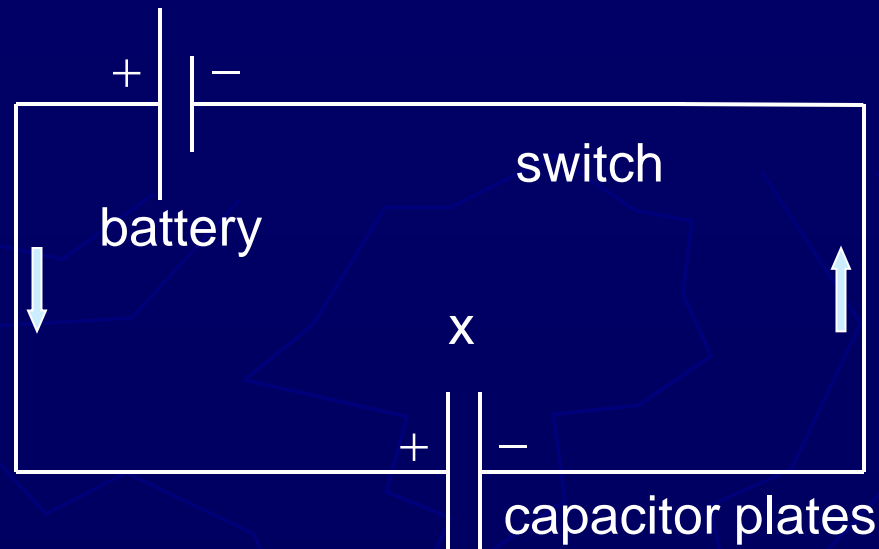
Maxwell's simple thought experiment:



Experiment: close the switch, and charge flows from the battery to the capacitor. Measure the magnetic field at x.

The incomplete set of equations gives two different answers. This can be fixed by adding one more term.

Maxwell's simple thought experiment:



Experiment: close the switch, and charge flows from the battery to the capacitor. Measure the magnetic field at x.

The incomplete set of equations gives two different answers. This can be fixed by adding one more term.

Before Maxwell:

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho_v$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J$$

After Maxwell (1861):

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho_v$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

and then there was light.

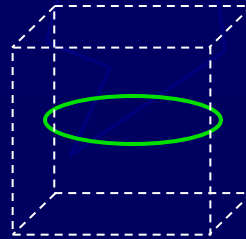
- Experimental confirmation of Maxwell's term took 25 years (Hertz 1886). In order to do this, he had to open and close the switch on the *nanosecond* time scale, a challenging feat in the 1800's.
- In order to probe quantum gravity, we need to reach the *nano-nano-nano-nano-nanosecond* time scale (the *Planck time* $\sqrt{\hbar G/c^5}$).
- Fortunately, a number of thought experiments have revealed inconsistencies between Quantum Mechanics and General Relativity, and so give us clues to the right theory.

Some useful thought experiments:

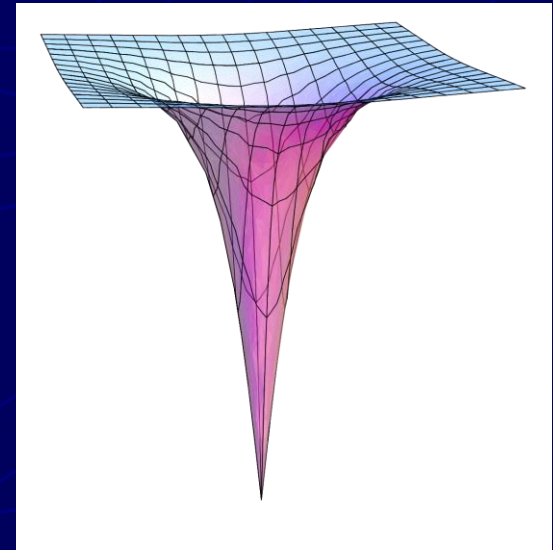
- Planck scale scattering



- Strings in a box

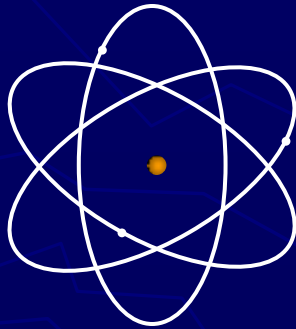
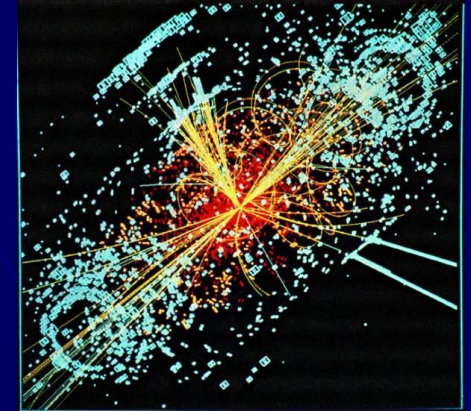


- Quantum black holes



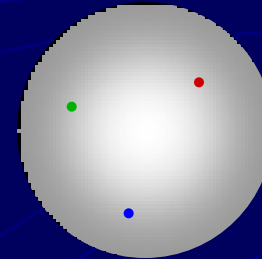
Planck scale collisions

Particle physicists like to crash particles together to see what's inside.



In this way, Rutherford found the nucleus inside the atom.

SLAC found quarks inside protons and neutrons.



Scattering at the nano⁵ scale:



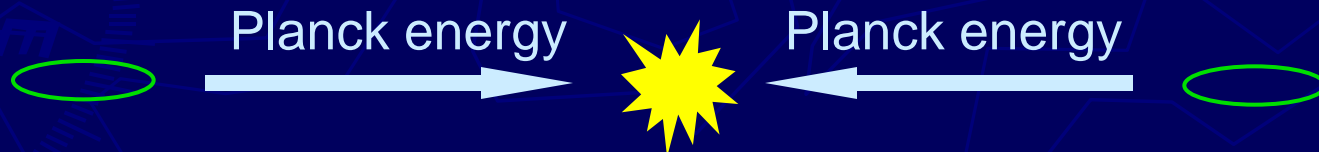
Applying the existing theories of Quantum Mechanics plus General Relativity gives a nonsense answer, an infinite rate of scattering.

Scattering at the nano⁵ scale:



Applying the existing theories of Quantum Mechanics plus General Relativity gives a nonsense answer, an infinite rate of scattering.

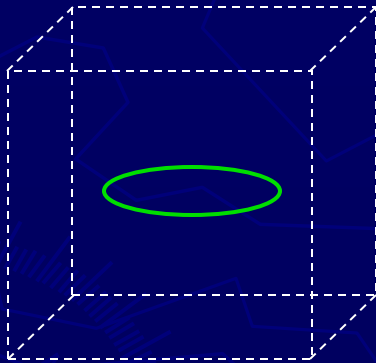
The correct theory must cure this, but it is a very difficult problem. It turns out that one can fix it if particles are not *points* but *strings*,



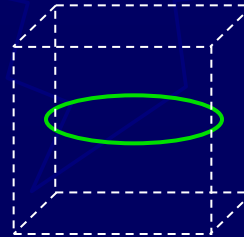
A strange idea, but it seems to work.

The string-in-a-box thought experiment

Strings were an unfamiliar idea, and many thought experiments have been useful in understanding their physics. Here is an important one:



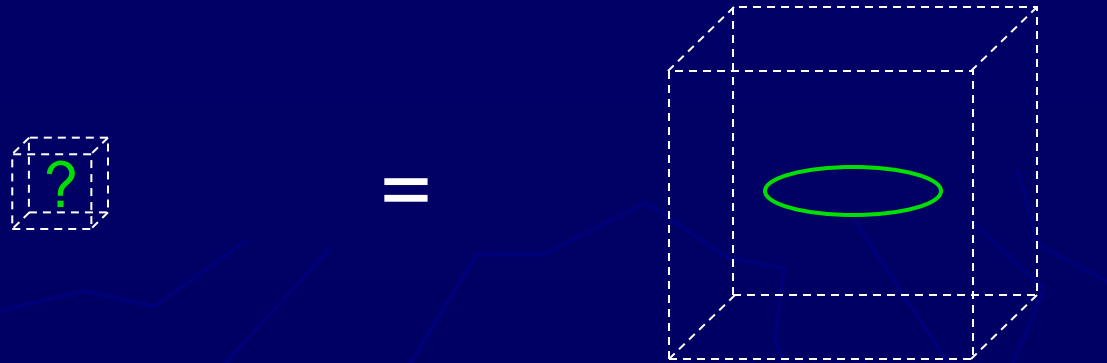
Put a string in a finite space



Make the space smaller...and smaller

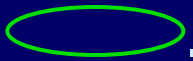


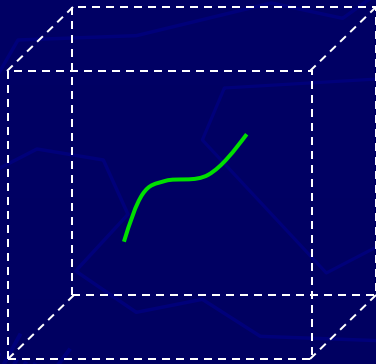
The mathematics gets interesting, and leads to a surprising picture:



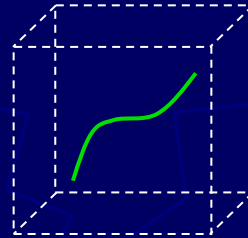
When the original space goes away, a new large space emerges ('T-duality'). Lessons:

- Space is emergent, not fundamental.
- There is a minimum distance.

That was for a closed string . Now try it for an open string:



Put a string in a finite space



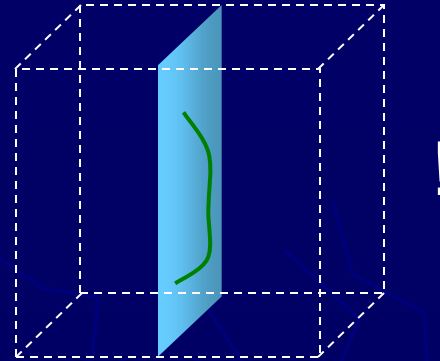
Make the space smaller...and smaller



Again, the trick is to figure out what is the physical picture that emerges from the math, and the answer is unexpected:



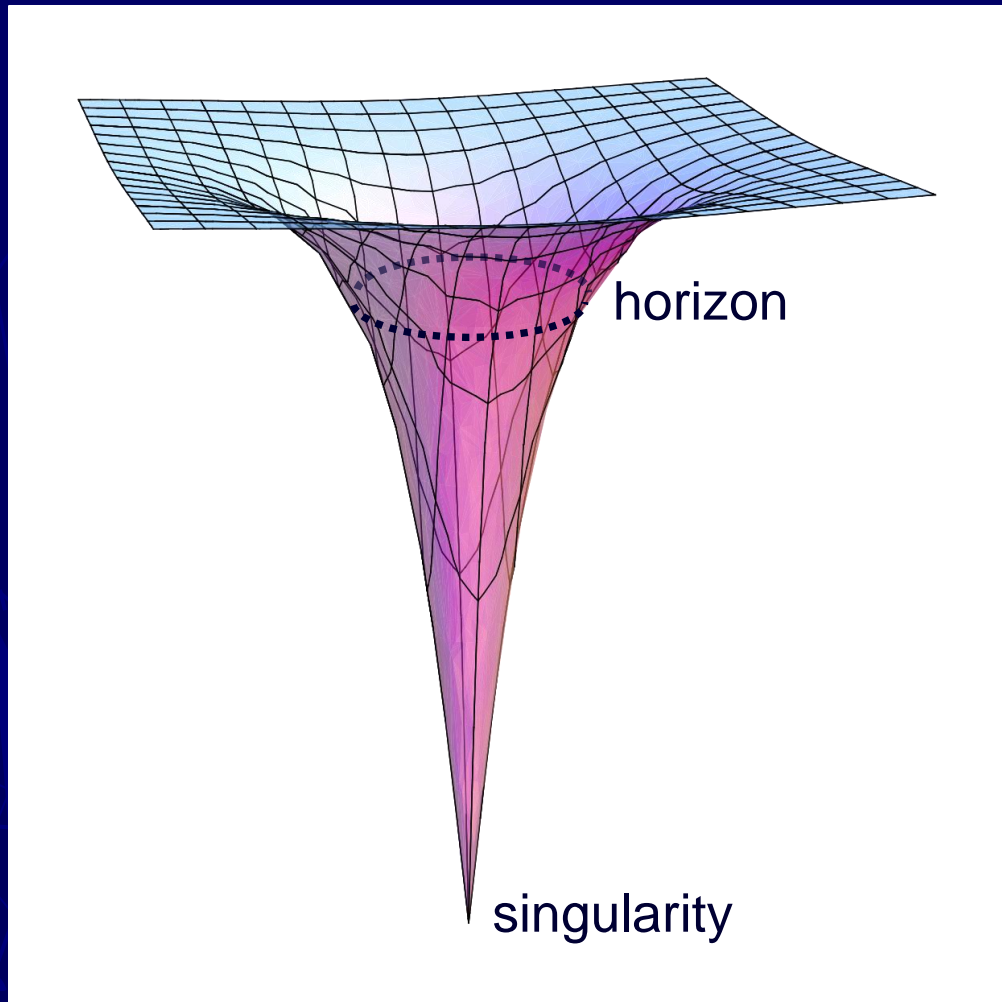
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The emergent space also contains a new object, a 'Dirichlet membrane,' or 'D-brane' for short.

We do not know the full and final formulation of 'string theory,' it is a work in progress. The strings were just a step toward the final answer, and the D-branes seem a little closer.

Black Hole Thought Experiments

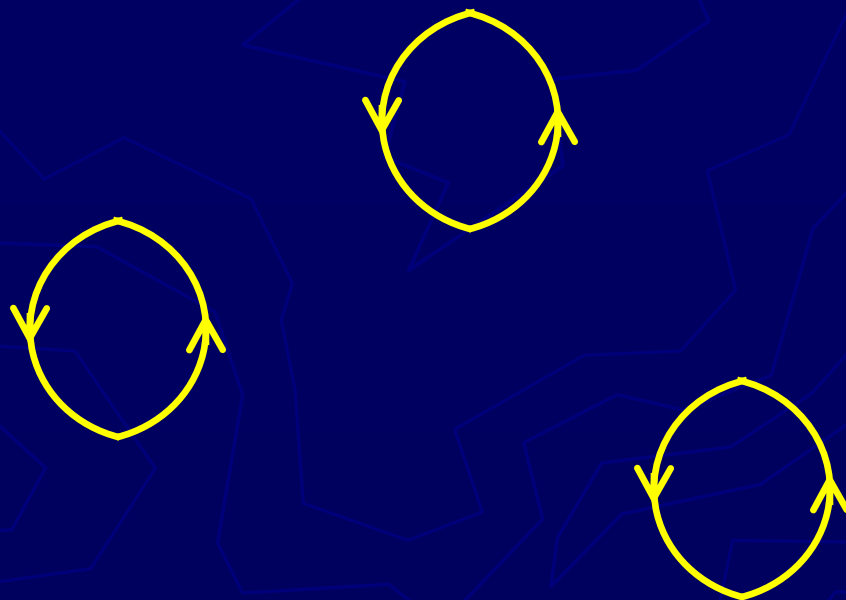


A black hole:

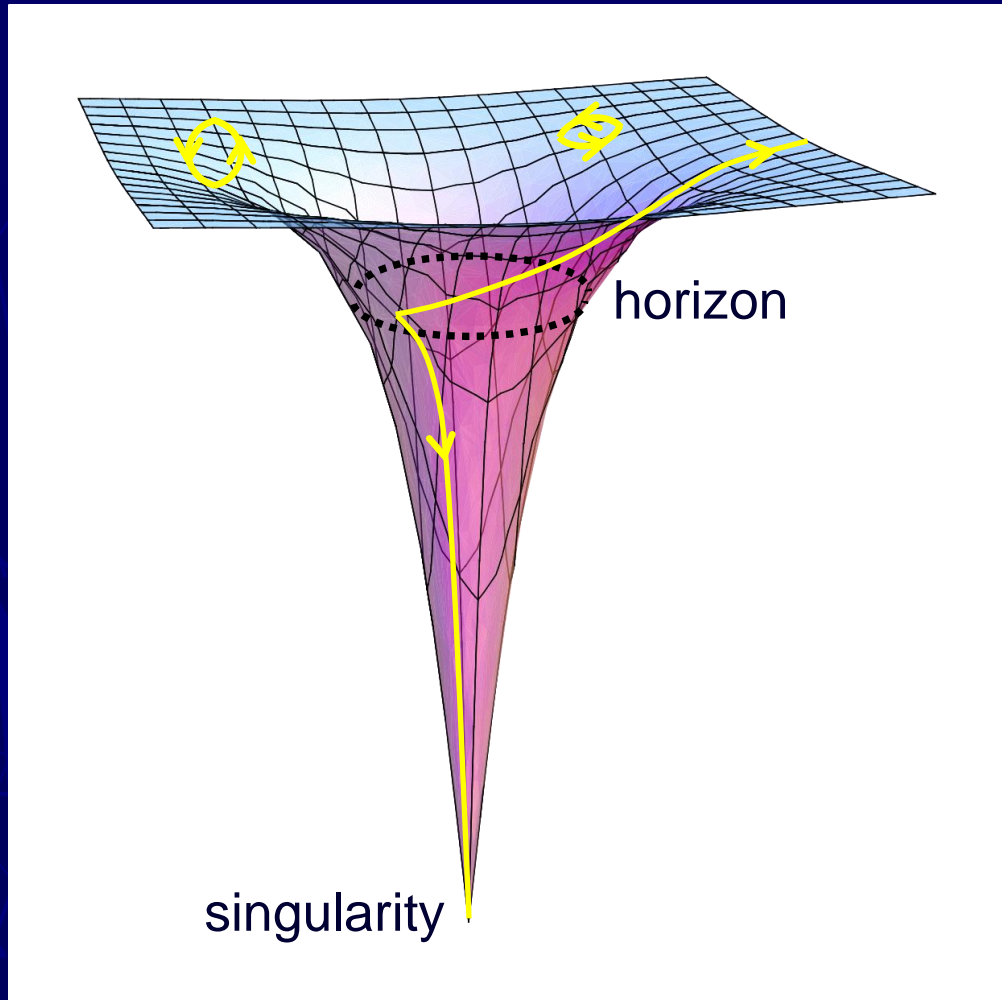
- The fate of very massive objects.
- An extreme bending of spacetime.
- 'Infinite' density at the singularity
- The horizon: the point of no return.

Quantum Mechanics at the horizon: Hawking radiation

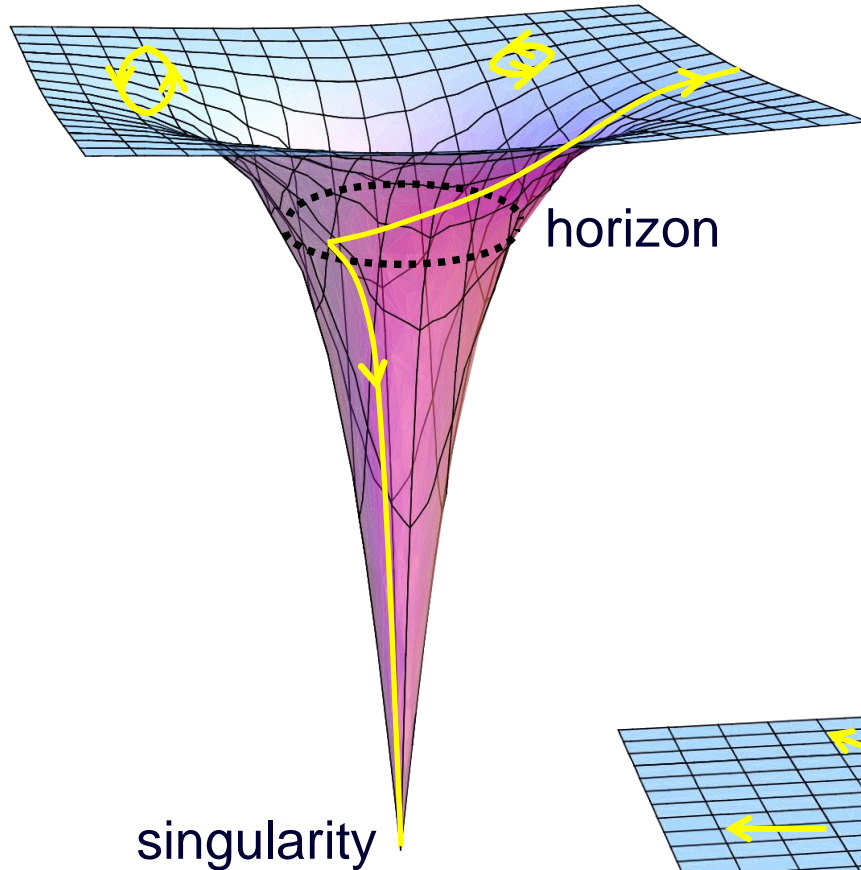
Quantum mechanics says that empty space is full of particle-antiparticle pairs that pop into and out of existence:



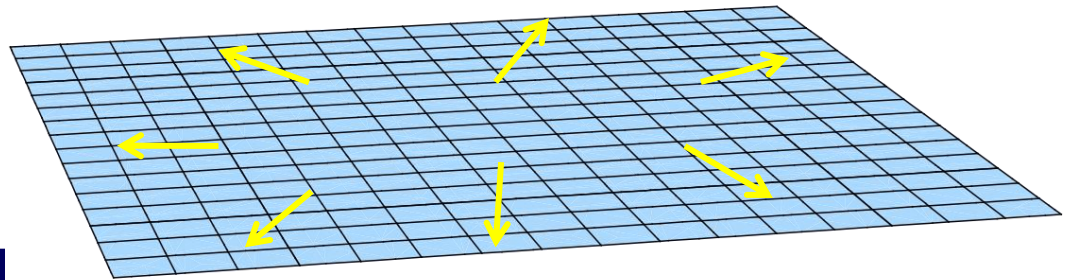
When this happens near the horizon, sometimes one falls into the singularity and one escapes:



When this happens near the horizon, sometimes one falls into the singularity and one escapes:



Without Quantum Mechanics, black holes always get bigger, but due to Hawking radiation they can 'evaporate' and eventually disappear.

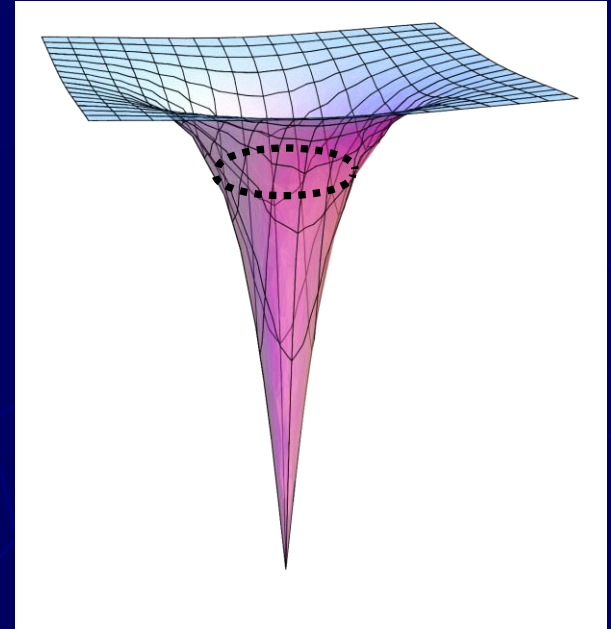


Black holes are settings for many interesting thought experiments, involving throwing things in and seeing what come out.

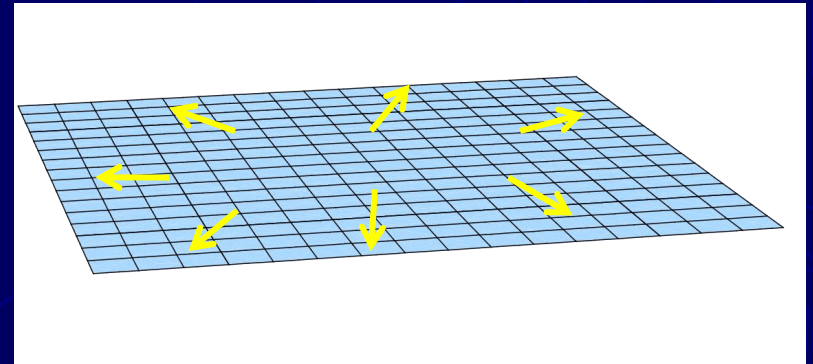
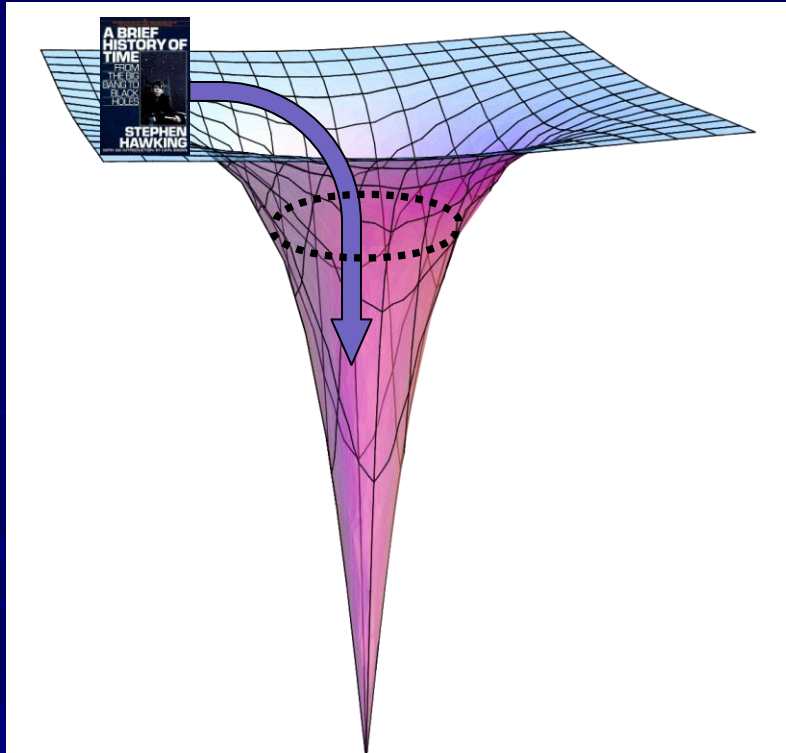
1970's:

Entropy puzzle (Bekenstein, Hawking).
Information paradox (Hawking).

The entropy puzzle: black holes have a *temperature* (and related quantities like entropy). But heat comes from the motion of atoms. So black holes should have some sort of *atomic* structure.



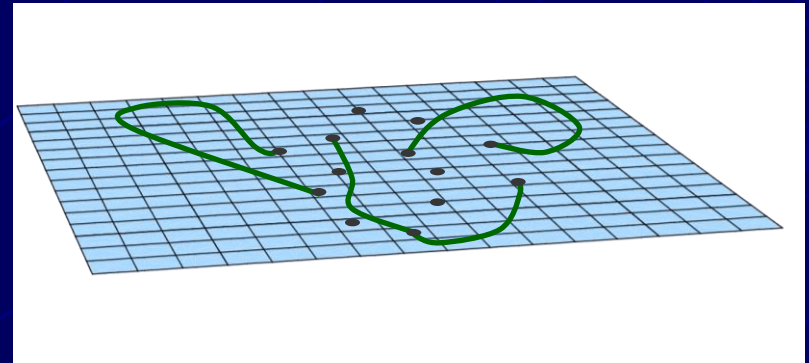
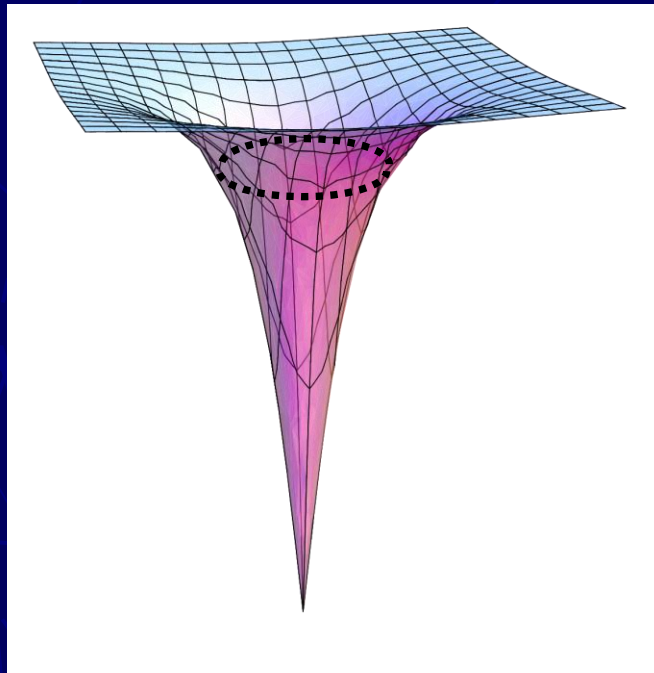
Information paradox: black hole evaporation destroys information about what falls into black holes.

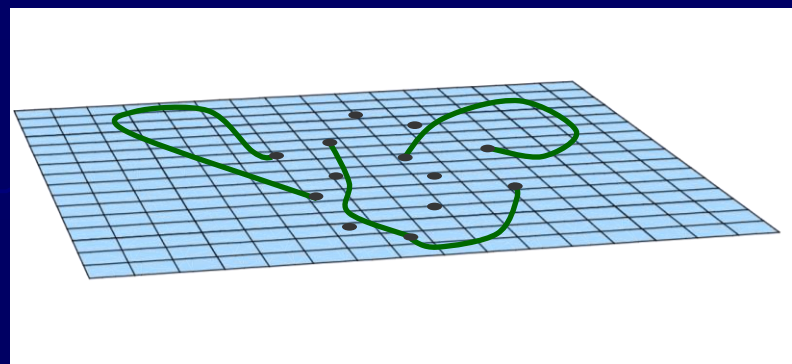
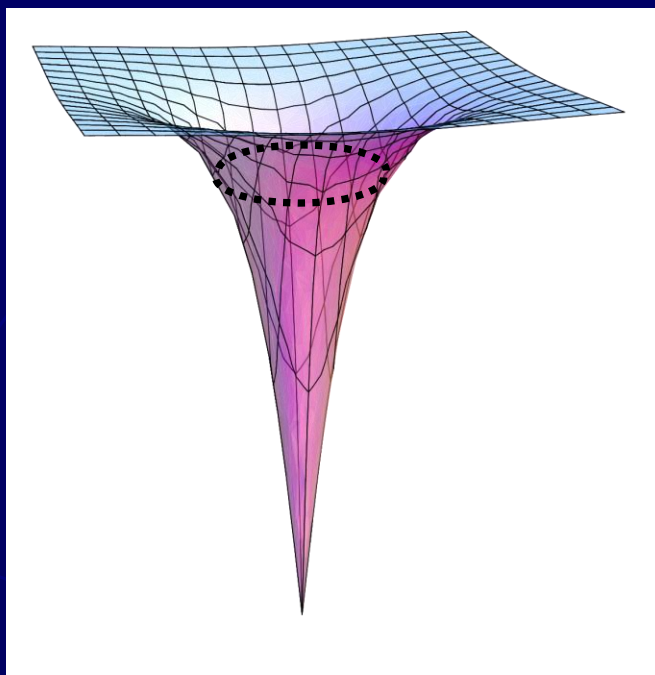


This requires a modification of Quantum Mechanics. But for the information to get out, it would have to travel faster than light! Quantum Mechanics versus Relativity!

In the 1990's, applying D-branes and other ideas from string theory:

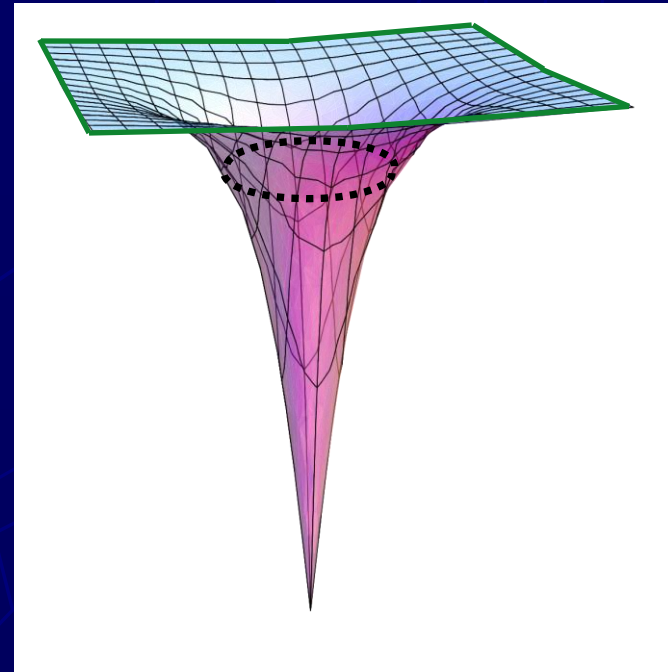
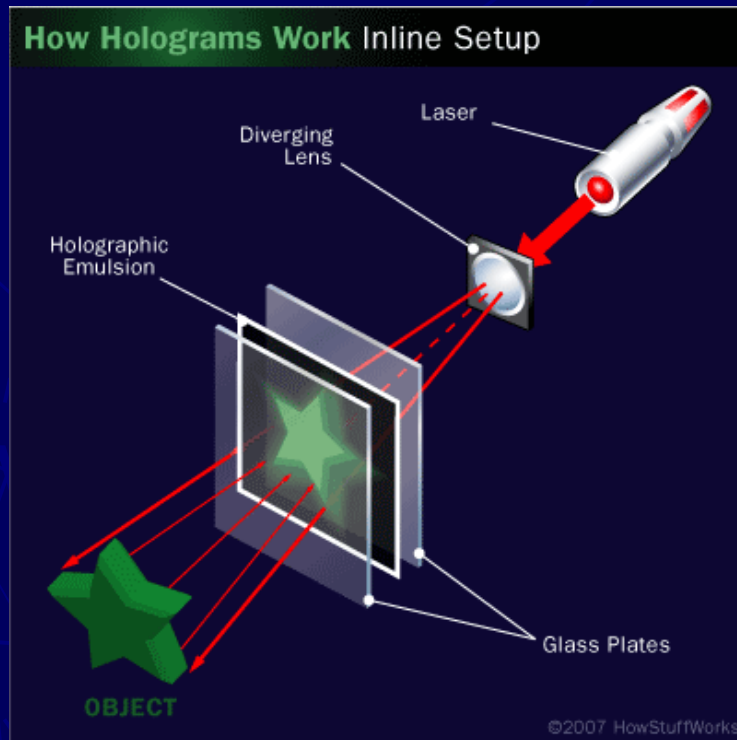
Entropy puzzle: D-branes provide the predicted atomic structure (Strominger, Vafa):





AdS/CFT duality: Building on this, Maldacena found a previously unexpected connections: one can build quantum gravity out of ordinary forces. A corollary: information cannot be lost. *Hawking was wrong.**

Holographic principle (Susskind, 't Hooft): The fundamental building blocks of quantum gravity are not local, but are projected from the 'boundary.'



So where do we stand?

- The holographic principle is very different from previous physical laws. How does it work in detail? Especially, how does it work in an expanding spacetime?
- The *interior* of a black hole is a lot like Big Bang (in reverse), so maybe this is a good place to start?
- Where exactly did Hawking go wrong?

KITP Bits, Branes, and Black Holes program, Spring 2012

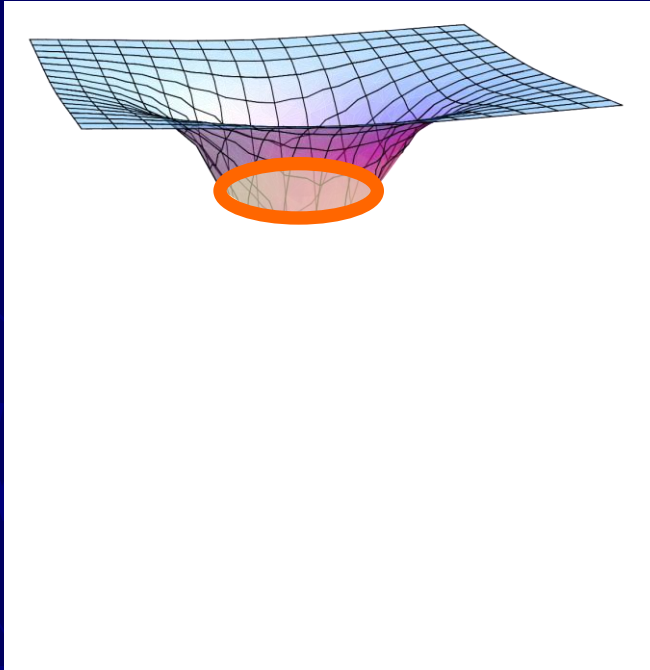
Things that were widely believed:

- Information is not lost.
- An observer who stays outside the black hole sees nothing unusual.
- An observer who falls through the horizon sees nothing unusual.

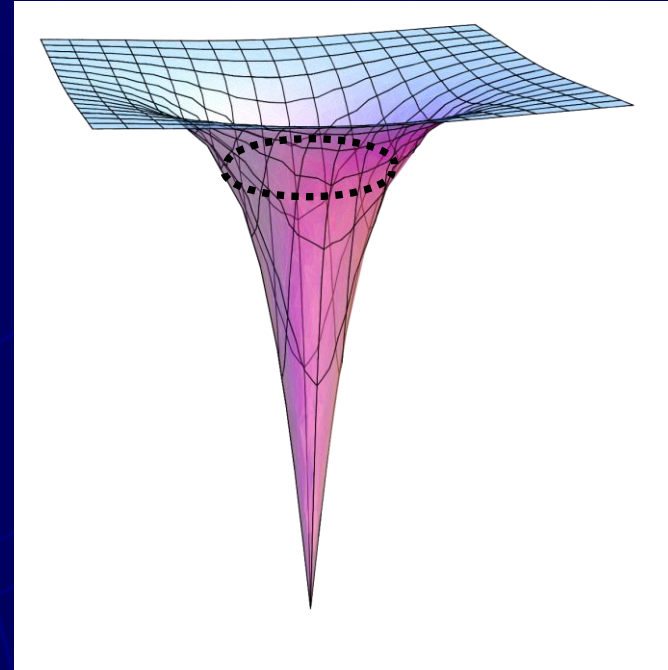
Actually these are inconsistent! They imply an impossible quantum state for the Hawking radiation.
(Ahmed Almheiri, Don Marolf, JP, Jamie Sully)



If nothing unusual happens outside the horizon, and infalling observer will hit a **firewall** of high energy particles:



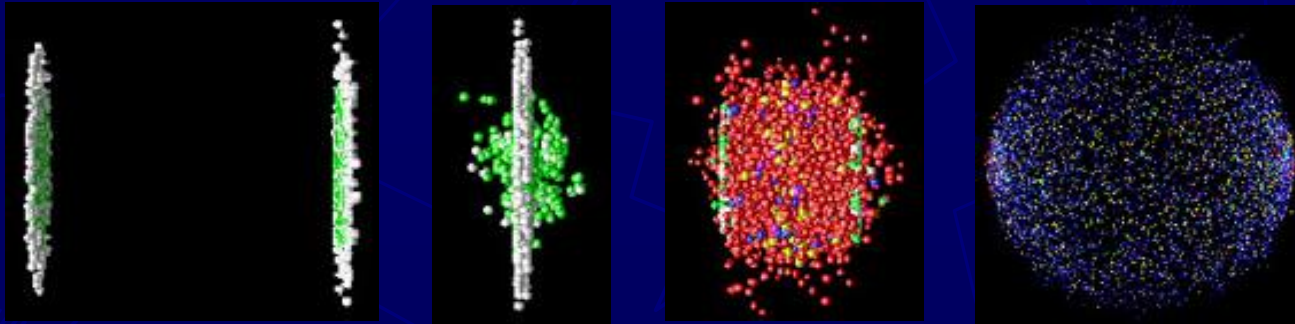
or



Once again, a sharp conflict between Quantum Mechanics and Spacetime...

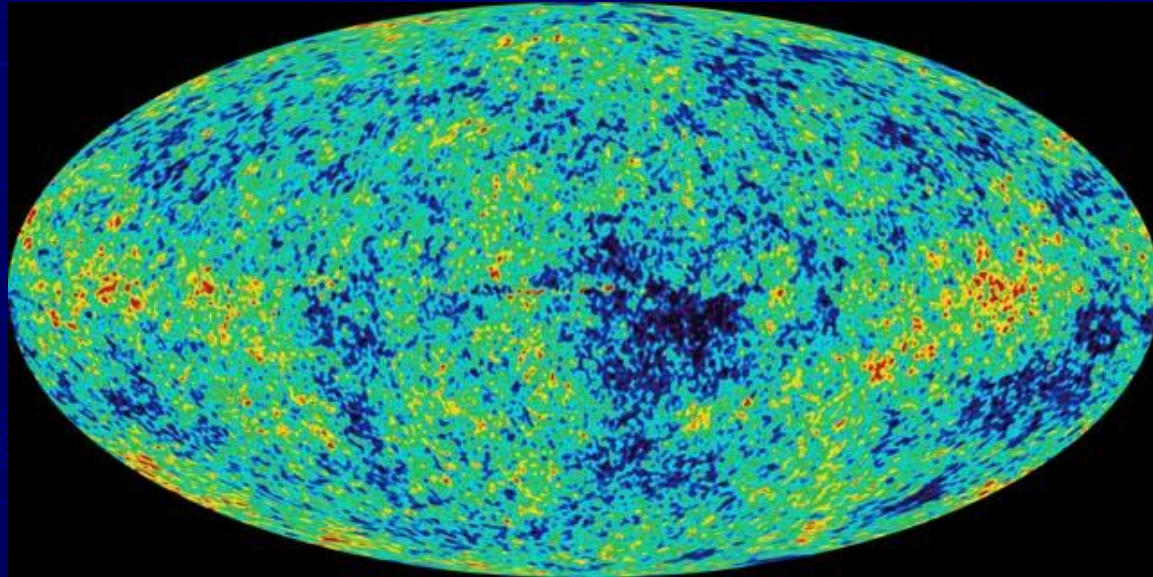
Real experiments?

Quantum gravity seems relevant only in extreme conditions, but already there have been surprises:



The **quark-gluon liquid**, produced at the RHIC accelerator in NY and by the LHC, is best modeled as a black hole, by applying AdS/CFT duality. Also describes other exotic phases of matter.

All the structure in our universe originates from quantum mechanical fluctuations:



In some ways this is well-understood, but there are many mysteries. Continually improving data reaches closer and closer to the Planck time.

Finally, and most interesting, we likely have some surprises ahead.

