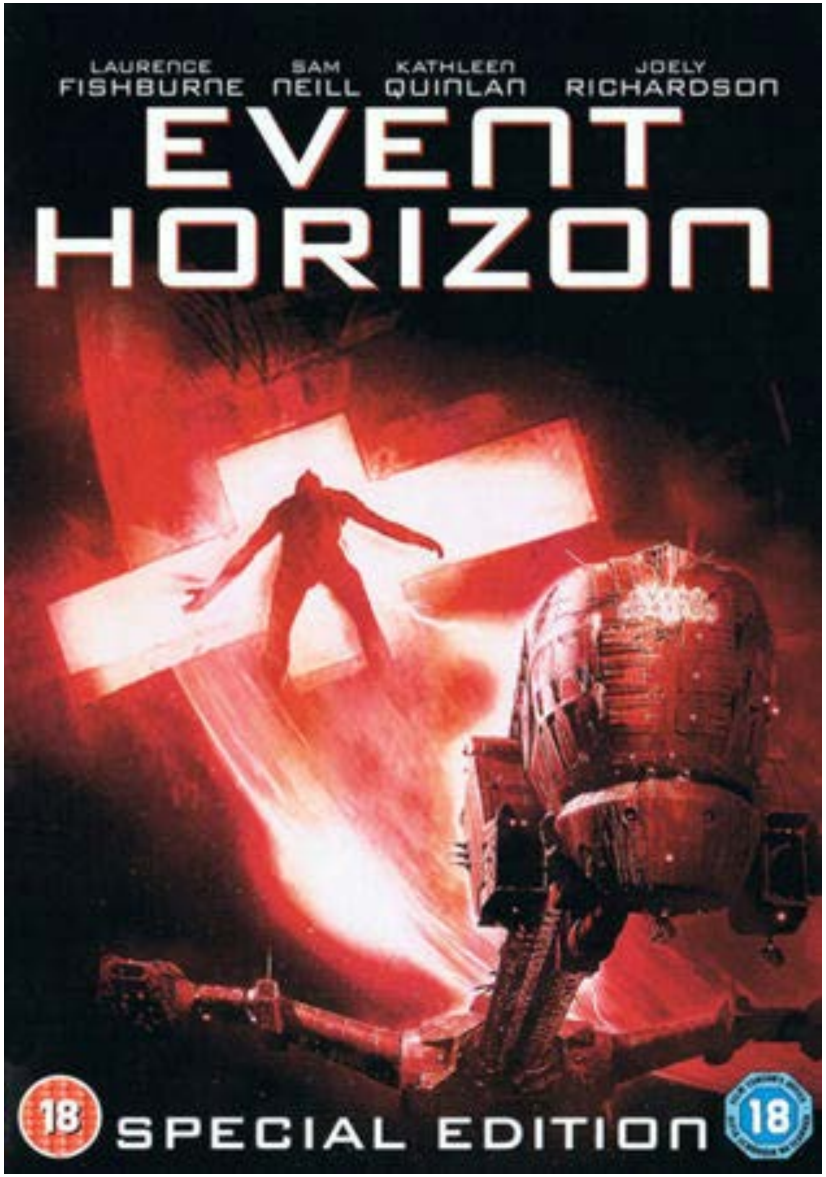
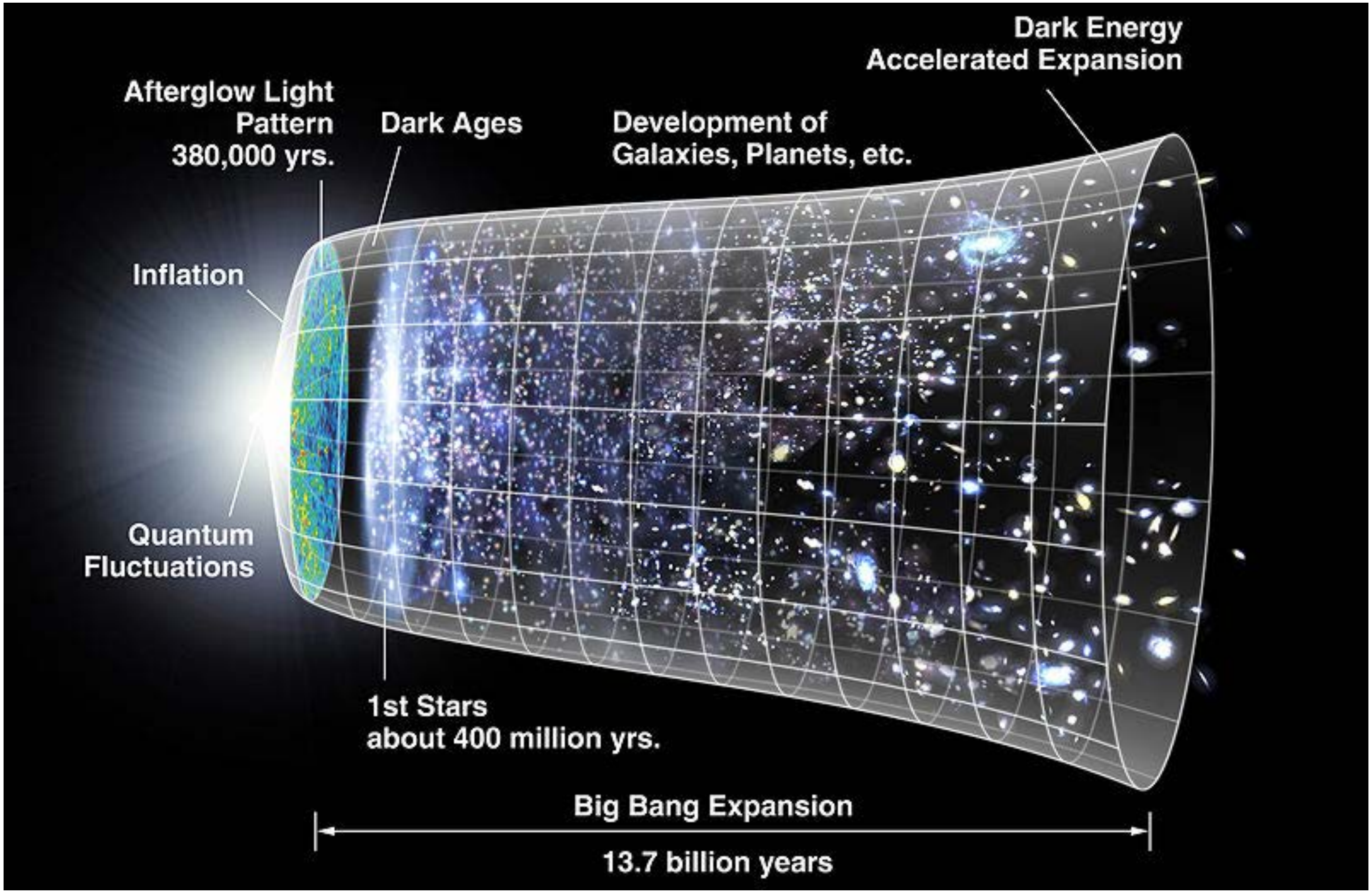
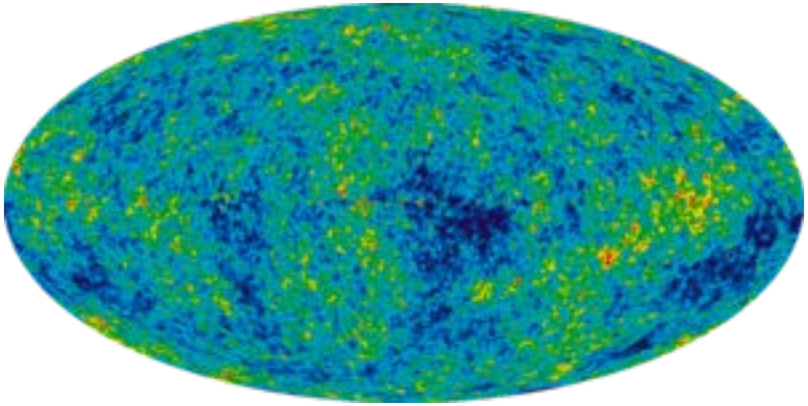
# Through The Event Horizon



# The Early Universe

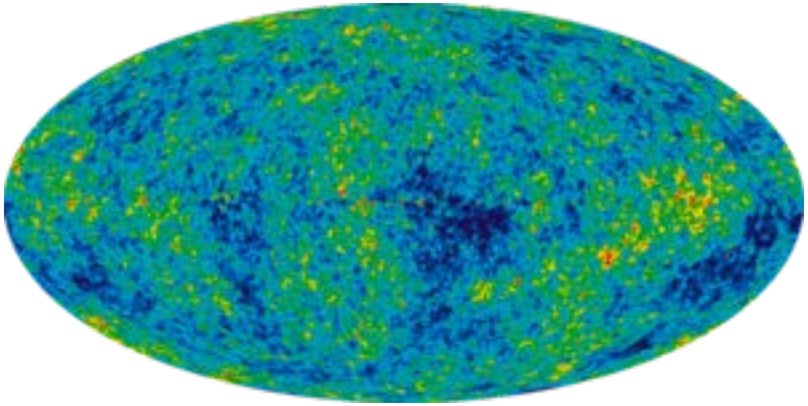




Temperature$_{\text{then}}$ ~ 3,000K
Temperature$_{\text{now}}$ ~ 2.725 K

Recombination Occurred ~
380,000 years after big bang

The image taken with WMAP shows how the Universe was **380,000 years after the big bang.** Free electrons would scatter photons preventing us from seeing further into the past. The variations shown above correspond to fluctuations in temperature. These fluctuations will later evolve into the complex structures we see in the Universe.



$T_{then}$ ~ 3,000K
$T_{now}$ ~ 2.725 K
Occurred ~ 380,000 years after big bang

Theorists estimate that **primordial black holes formed within the first second after the big bang**. Primordial black holes could have initial masses ranging from $10^{-8}$ kg (the so-called Planck relics) to more than thousands of solar masses. However, primordial black holes originally having mass lower than $10^{11}$ kg would not have survived to the present due to Hawking radiation.

A primordial BH with a mass $< 3\ M_{\odot}$ does not have a similar counterpart of a BH formed by core collapse.

There is no theory yet that can describe mini black holes because they combine conditions of large gravity and small scales. Understanding the physics of mini black holes would have to wait for a theory that combines gravity and quantum mechanics.

# The Early Universe: The Fundamental Forces

To understand what happened in the early universe we need to understand how particles interact at high energies.

Particles interact through four fundamental forces of nature.

1. **Gravity** (force between everything including massless objects like photons, infinite range)

2. **Electromagnetism** (force between charged particles, infinite range)

3. **Strong Force** (force between quarks that make up neutrons and protons, short-range force ~ $10^{-15}$m)

4. **Weak Force** (force acts on quarks, electrons, neutrinos and involved in certain radioactive decays, short-range force ~$10^{-16}$m)

# The Early Universe: The Fundamental Forces

What do we mean by a force between particles :

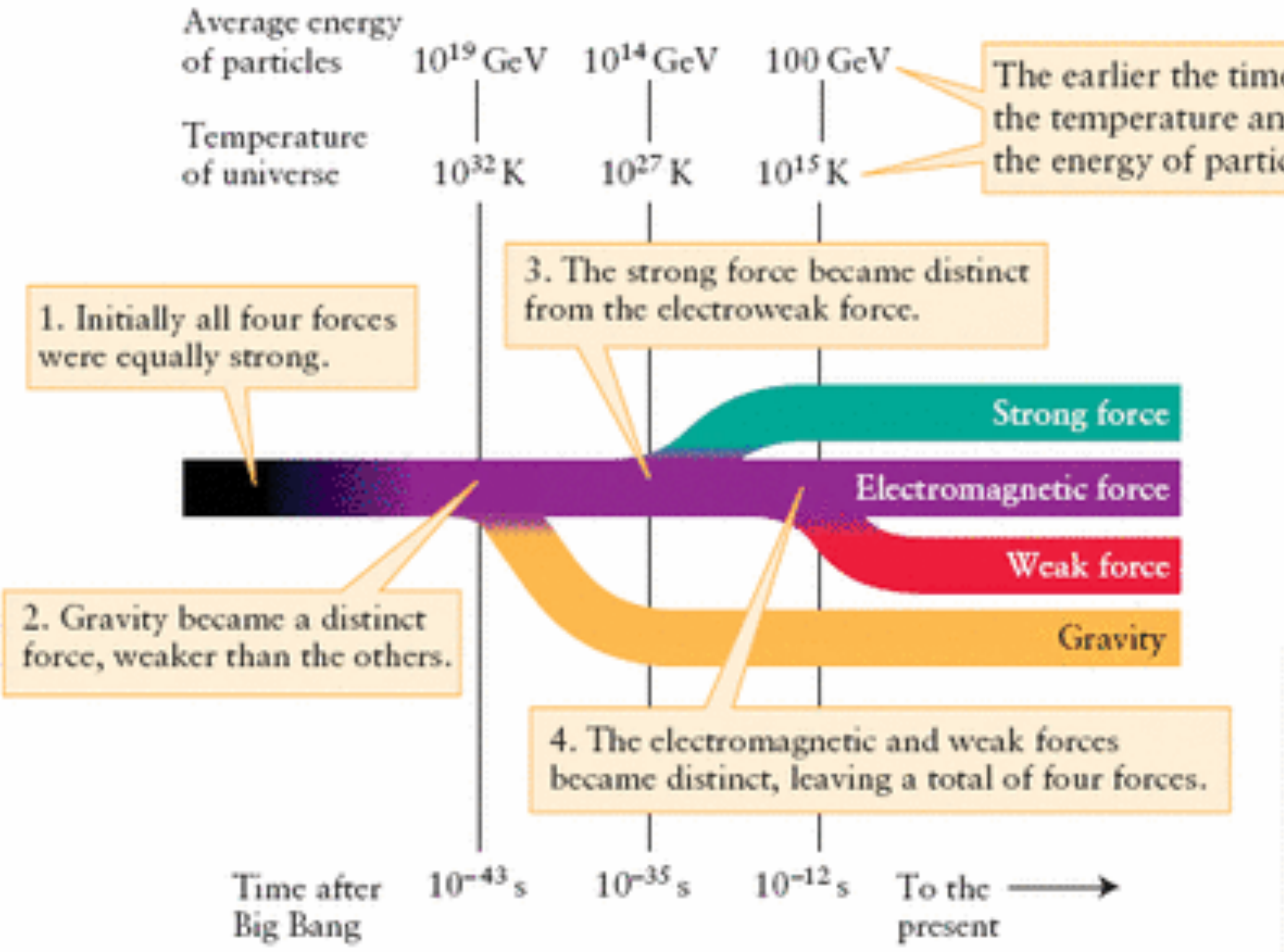
Particles interact by exchanging particles. Each force has its own **exchange particles**. The exchange particles cannot be directly observed and are called **virtual particles**.

1. **Gravity** (exchange particle=graviton)

2. **Electromagnetism** (exchange particle=photon )

3. **Strong Force** (exchange particle=gluon)

4. **Weak Force** (exchange particles=intermediate vector $W^+$, $W^-$ and Z bozons)



The earlier the time, the higher the temperature and the greater the energy of particles.

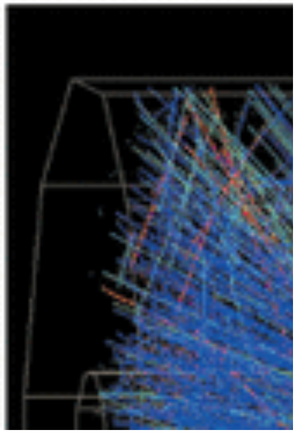
1. Initially all four forces were equally strong.

2. Gravity became a distinct force, weaker than the others.

3. The strong force became distinct from the electroweak force.

4. The electromagnetic and weak forces became distinct, leaving a total of four forces.

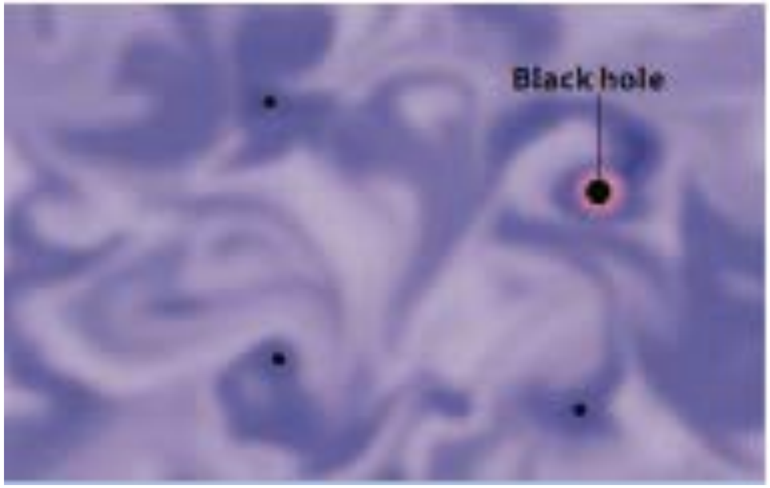
(a) How the four forces behave at different energies and temperatures



# Mini Black Holes

The size of a primordial black hole depends on when it formed. As the Universe expanded heavier primordial black holes are expected to have formed. **If primordial BHs formed they would have formed within one second of the big bang**.

The high densities of the early Universe did not guarantee the formation of mini-black holes. For a region to collapse into a black hole **density fluctuations are needed.**



**Primordial Density Fluctuations**
Early in the Universe space was filled with hot dense plasma. The density varied from place to place, and in locations where the relative density was high enough the plasma would collapse to form mini black holes.

# Evaporation of Quantum Black Holes

In 1974 Hawking came to the famous conclusion that black holes radiate due to quantum effects and have temperatures that are inversely proportional to their mass.

$$T_{BH} = \frac{\hbar c^3}{8\pi G k_B} \frac{1}{M_{BH}}$$

Notice that the temperature increases as the black hole evaporates. For a solar-mass black hole the temperature is about $10^{-6}$ K, for a $10^{12}$ kg black hole it is about $10^{12}$ K (hot enough to emit photons, electron and positrons.)

**Black hole entropy** is given by $S=k_B A/4l_p^2$ where A is the area of the event horizon and $k_B$ is Boltzmann's constant, and $l_p$ is the Planck length.

# Quantum Black Holes

As a black hole radiates it loses mass and becomes hotter, emitting increasingly energetic particles and shrinking faster.

We can estimate the amount of time it takes a black hole to evaporate.

For blackbody radiation, the energy emitted by an evaporating black hole per unit time is:

$$L_{evap} = A_S \sigma T^4 = 4\pi R_S^2 \sigma T^4 = \frac{\hbar c^6}{15360 \pi G^2 M_{BH}^2}$$

# Mini Black Holes

**How long does it take for a black hole to evaporate:**

$$t_{evap} = \frac{5120\pi G^2 M_{BH}^3}{\hbar c^4} = 8.4\times10^{-17}\left(\frac{\mathrm{m}^2\mathrm{kg}^{-2}}{\mathrm{J\ s}}\right)\times M_{BH}^3$$

Example: A $10^{11}$ kg = 0.5 × $10^{-19}$ $M_{\odot}$ black hole will take about 2.7 × $10^9$ years to evaporate.

Where are these ~$10^{11}$ kg black holes? Are they detectable?

As the black hole evaporates it loses energy and becomes hotter and shrinks. When the black hole gets to a mass of $10^6$ kg it is thought that within a second it will explode and produce a violent burst of gamma rays.

# Mini Black Holes

Gravitational and quantum mechanical effects are important in black hole evaporation.

Heisenberg's uncertainty principle allows virtual pairs of particles to be created out of vacuum but only exist for a very short amount of time.

$$\Delta E \Delta t \geq \frac{\hbar}{2},\ \hbar = 1.054 \times 10^{-34}\ Js$$

$$\Delta m \Delta t \geq \frac{\hbar}{2c^2},\ \mathrm{c} = 3 \times 10^8\ \mathrm{m/s}$$

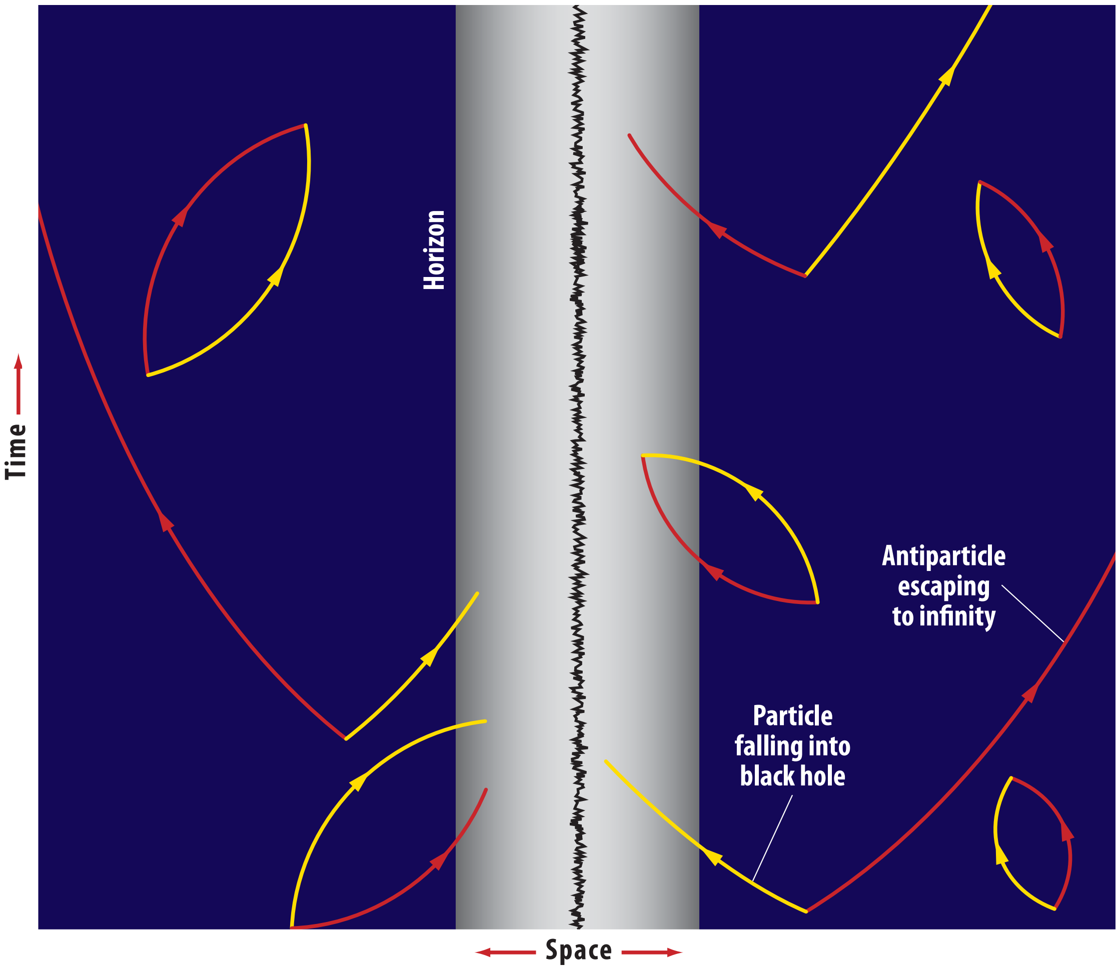
Calculate the amount of time that an electron-positron pair created out of vacuum can exit without violating the uncertainty principle.

$$\hbar = 1.05 \times 10^{-34}\,\mathrm{Js},\ m_e = 9.1 \times 10^{-31}\,\mathrm{kg},\ \mathrm{c} = 3 \times 10^8\,\mathrm{m/s}$$

# Mini Black Holes

An electron positron pair can be created out of vacuum and will exist for about 3 × $10^{-22}$ sec without violating the uncertainty principle.

$$\Delta m \Delta t \geq \frac{\hbar}{2c^2} \Rightarrow \Delta t \geq \frac{\hbar}{2c^2 \Delta m} = \frac{1.05\times10^{-34}\,\mathrm{Js}}{2\times(3\times10^{8}\,\mathrm{m})^2\times2\times9.1\times10^{-31}\,\mathrm{kg}} = 3.2\times10^{-22}\,\mathrm{s}$$



Particle pairs forming near the even horizon. If the tidal forces are strong enough, they can separate the virtual particles and **energy from the black holes gravitational field** can be used to create real particles. The particle near the event horizon may fall into the BH and the other may escape. This is equivalent to the black hole radiating.

# Limits on Mass of Mini Black Holes

According to quantum mechanics particles behave like waves and their boundaries are smeared out over a distance that decreases with energy. The effective size of a particle is inversely proportional to the particles mass.

The uncertainty principle states :

$$\Delta x \Delta p \geq \frac{\hbar}{2} \rightarrow \Delta x \geq \frac{1}{2}\left(\frac{\hbar}{mc}\right),\ \hbar = 6.582 \times 10^{-16}\ eVs$$

# Limits on Mass of Mini Black Holes

**QM says:** The effective size of a particle is inversely proportional to the particles mass: $\Delta x \geq \frac{1}{2}\left(\frac{\hbar}{\boldsymbol{mc}}\right)$

**GR says:** The Schwarzschild radius of a black hole is proportional to its mass: $R_s = \frac{2G\boldsymbol{m}}{c^2}$

These two properties combined imply that for an object with a very small mass the effective size of the object may become larger than the event horizon meaning you cannot form a black hole that's smaller than a limiting mass.

What is this limiting mass for a black hole?

$\hbar = 1.05\times10^{-34}\,\mathrm{Js}$, $\mathrm{G} = 6.67\times10^{-11}\,\mathrm{m^3kg^{-1}s^{-2}}$, $\mathrm{c} = 3\times10^{8}\,\mathrm{m}$

# Limits on Mass of Mini Black Holes

Gravity meets quantum mechanics:

$$\Delta x \geq \frac{1}{2}\frac{\hbar}{mc} \text{ (1)}$$

$$R_S = \frac{2GM_{BH}}{c^2} \text{ (2)}$$

We apply the uncertainty principle to a mini-black hole:

$$\text{(1)\^{}(2) } R_S \geq \frac{1}{2}\frac{\hbar}{M_{BH}c} \rightarrow \frac{2GM_{BH}}{c^2} \geq \frac{1}{2}\frac{\hbar}{M_{BH}c} \rightarrow M_{BH}^2 \geq \frac{c\hbar}{4G} \rightarrow$$

$$M_{BH} \geq 1.1\times10^{-8}kg$$

The limiting mass for a black hole is about $10^{-8}$ kg

# The Search for mini black holes

But all may not be lost!

At large energies $10^{19}$ GeV all four fundamental forces may become identical. This implies that gravity might be much stronger at smaller scales.

If the gravitational constant G is larger at smaller scales the size of event horizon

$r_g = GM_{BH}/c^2$

may be larger for mini-black holes and a black hole with a mass smaller than $10^{-8}$ kg might be possible to form.

https://www.youtube.com/watch?v=SxTyiqTM9F0
https://www.youtube.com/watch?v=328pw5Taeg0
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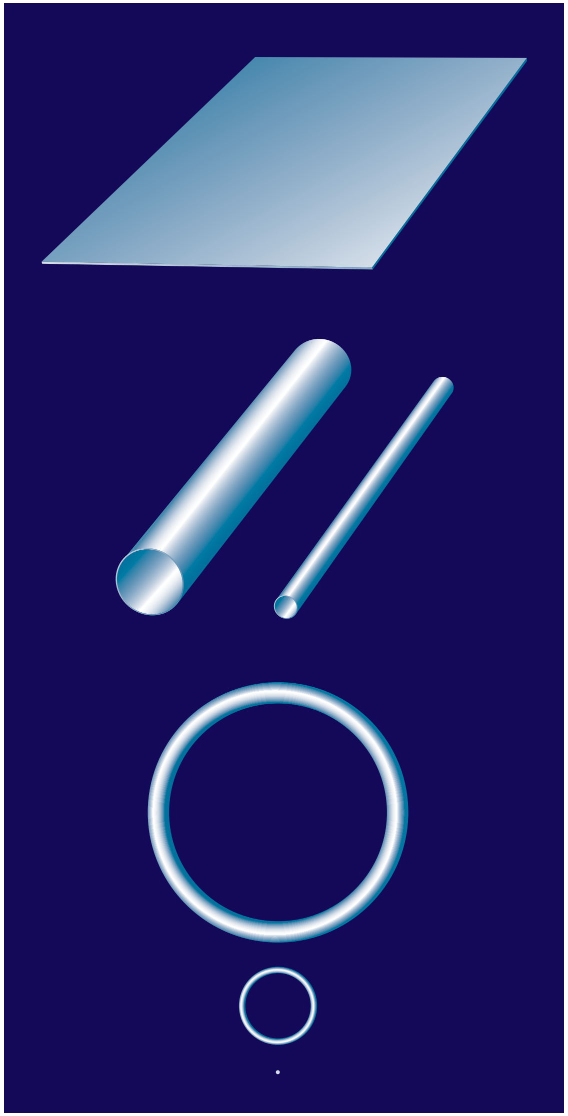
# The Search for mini black holes



**String theory** predicts that space has more than three dimensions. **Gravity** unlike other forces is expected to **propagate into these extra dimensions** and become stronger at smaller scales.

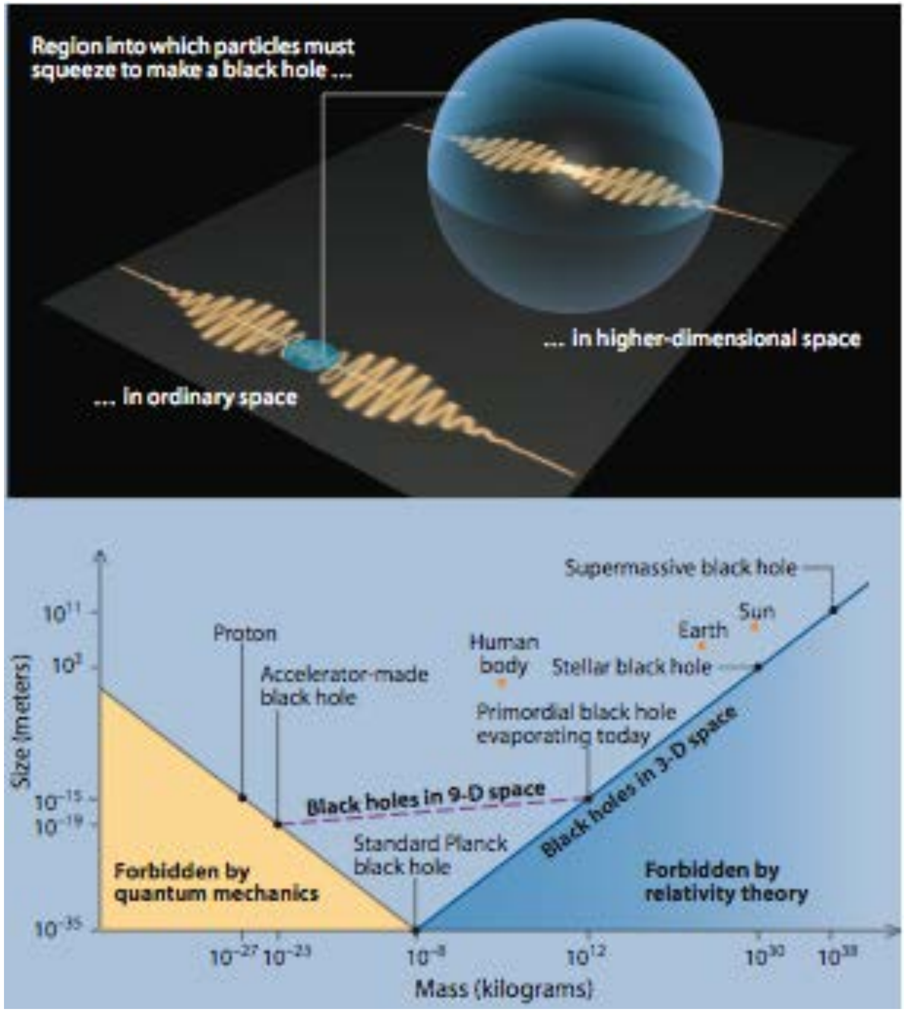
In three dimensions gravity increases by 4 as you halve the distance between 2 objects. In 9 dimensions the force would increase by 256 as you halved the distance.

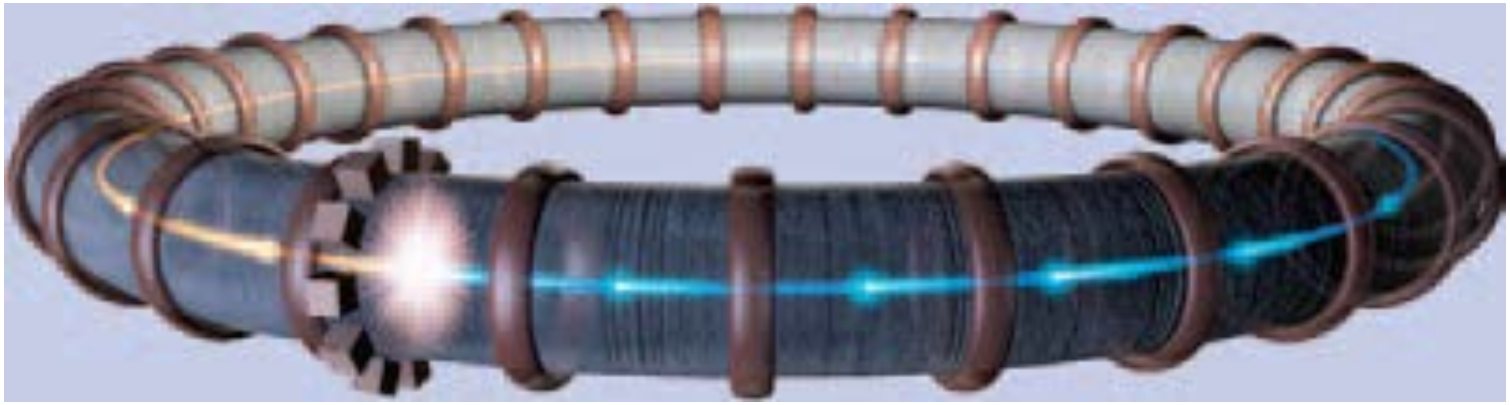
Because of possible extra dimensions the minimum mass required to form a black hole may be significantly lower than $10^{-8}$ kg. If this is true LHC might have a chance at producing mini black holes.

The lighter a body is, the more you must compress it before its gravity becomes strong enough to make a hole.

The wave nature of matter resists compression; particles cannot be squeezed into a region smaller than their characteristic wavelength, suggesting that no hole could be smaller than $10^{-8}$ kg.

But if space has extra dimensions, gravity would be inherently stronger over short distances and an object would not need to be squeezed as much to become a black hole.

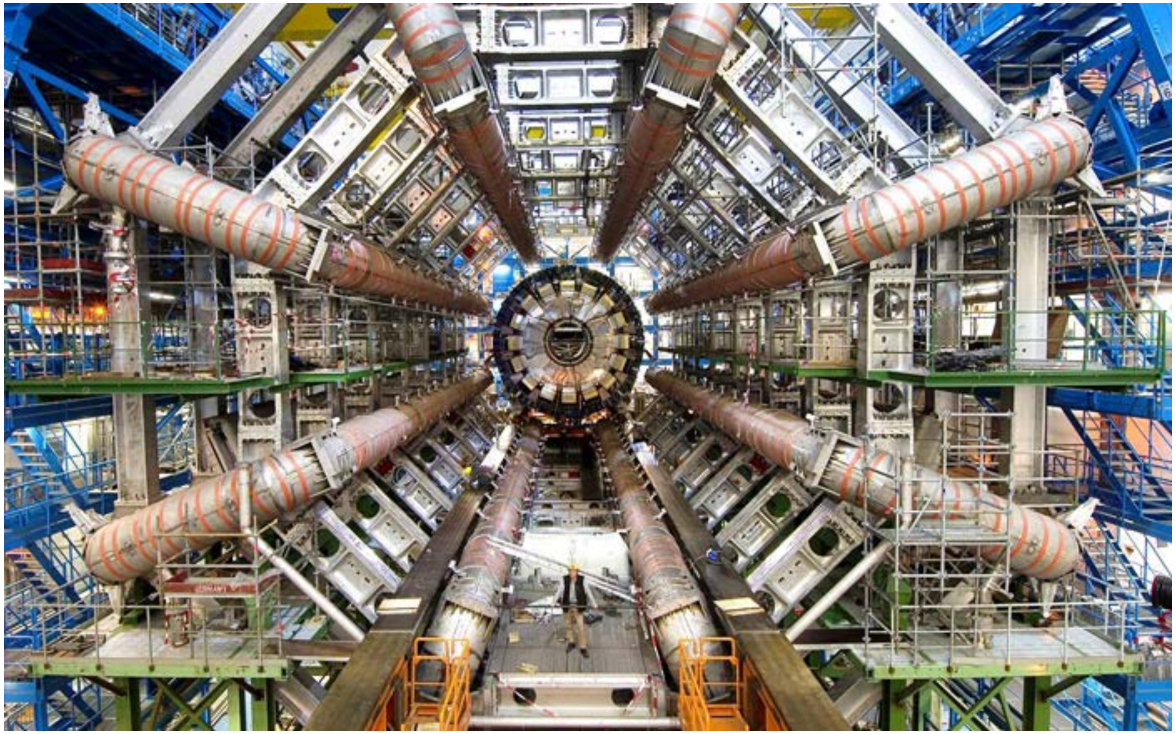




**Particle Accelerator**

A particle accelerator could crash two particles together at such an energy that they would collapse into a black hole. Detectors would register the subsequent decay of the hole.

# Producing Black Holes at LHC

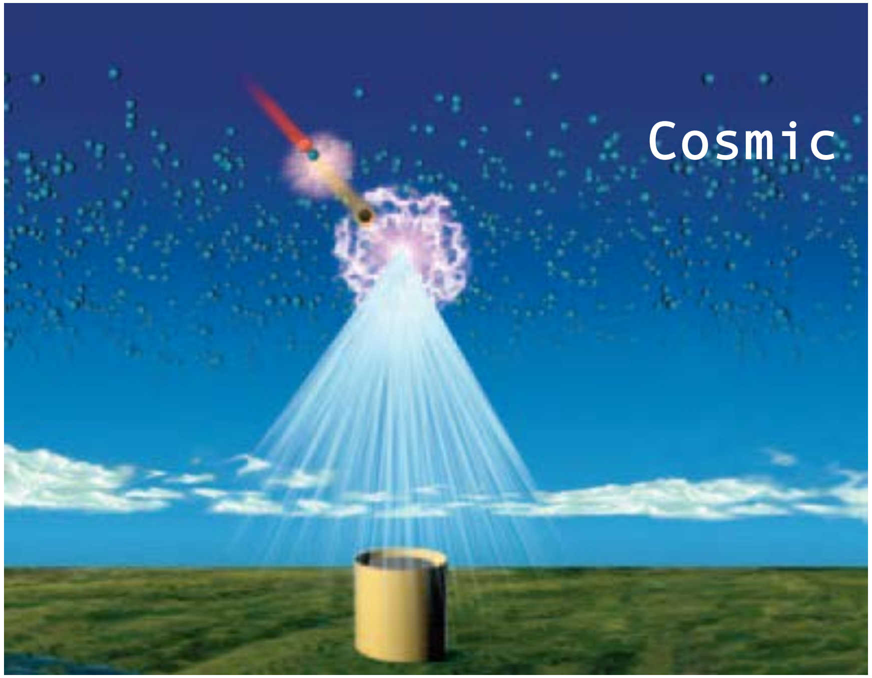


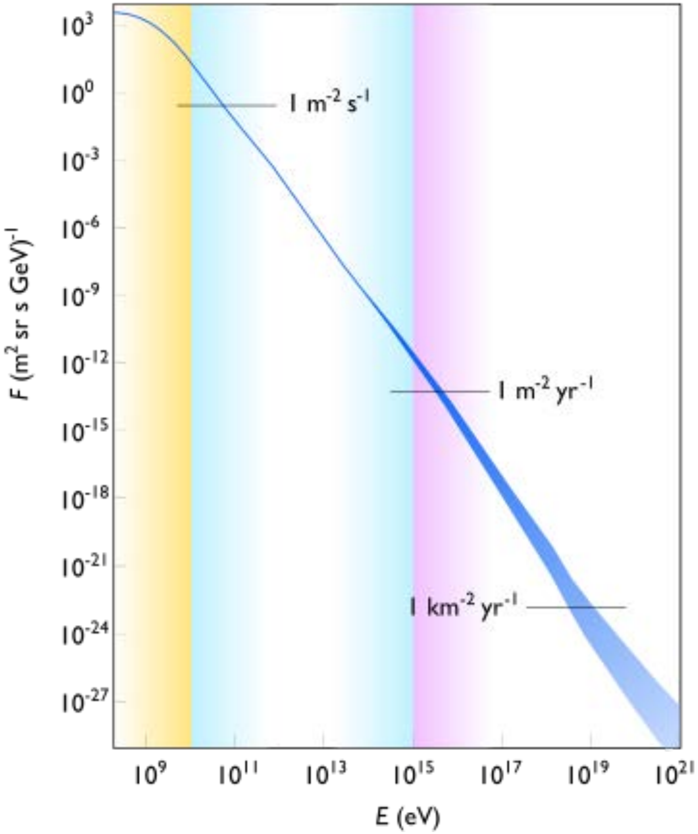
At LHC a proton will reach an energy of ~ 10 TeV which is equivalent to a mass of $E/c^2 \sim 10^{-23}$ kg. This is much smaller that the *conventional limit* for the mass of a black hole.

# Would mini black holes produced at LHC Swallow the Earth?

There is a possibility that the Large Hadron Collider at CERN will produce mini black holes.

These mini-black holes would be microscopic, comparable in size to elementary particles. According to Steven Hawking’s theory of BH these mini ones are expected to evaporate over short timescales and when doing so provide clues to whether higher dimensions in space-time exit.





Cosmic Ray Flux versus Particle Energy

**Cosmic-Ray Collisions**

Cosmic rays—highly energetic particles from celestial sources—could smack into Earth's atmosphere and form black holes. They would explode in a shower of radiation and secondary particles that could be detected on the ground.

# Black Hole Information Paradox

According to general relativity, **information that falls into a black hole is lost.**

What happens to information within a black hole as it evaporates? Hawking suggested that as the black hole evaporates the information is destroyed. This suggestion however appears to be in conflict with quantum mechanics and also appears to conflict with the law of energy conservation.

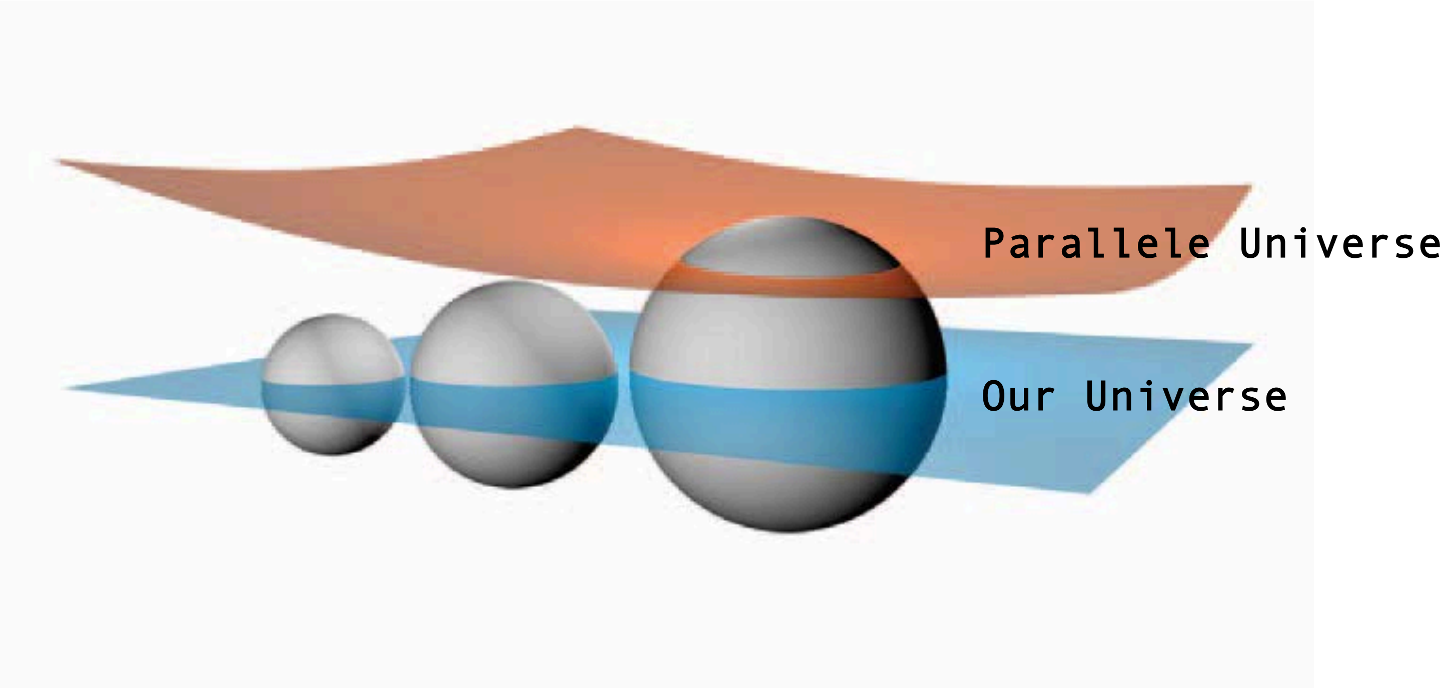
Several suggestions have been made as possible solutions to the black hole information paradox, however, this issue is still unresolved.

In 2004, after a debate that lasted more than 20 years, Hawking announced that he no longer believed that information was forever lost to the universe. In doing so, he lost a bet with physicist John Preskill.

# The Search for mini black holes

The evaporation of mini black holes with masses of $10^{12}$ kg are predicted to produce **gamma ray bursts** during their last few seconds of existence.

No such detections have been made so far but upper limits on the number of such mini black holes have been obtained.



BLACK HOLES OF DIFFERENT SIZES could probe extra dimensions that are otherwise inaccessible to us. Because gravity, unlike other forces, extends into those dimensions, so do black holes. Physicists would vary their size by tuning the particle accelerator to different energies. If a hole intersects a parallel universe, it will decay faster and appear to give off less energy (because some of the energy is absorbed by that other universe)

# Extra Slides

# The Early Universe: Unification of Forces

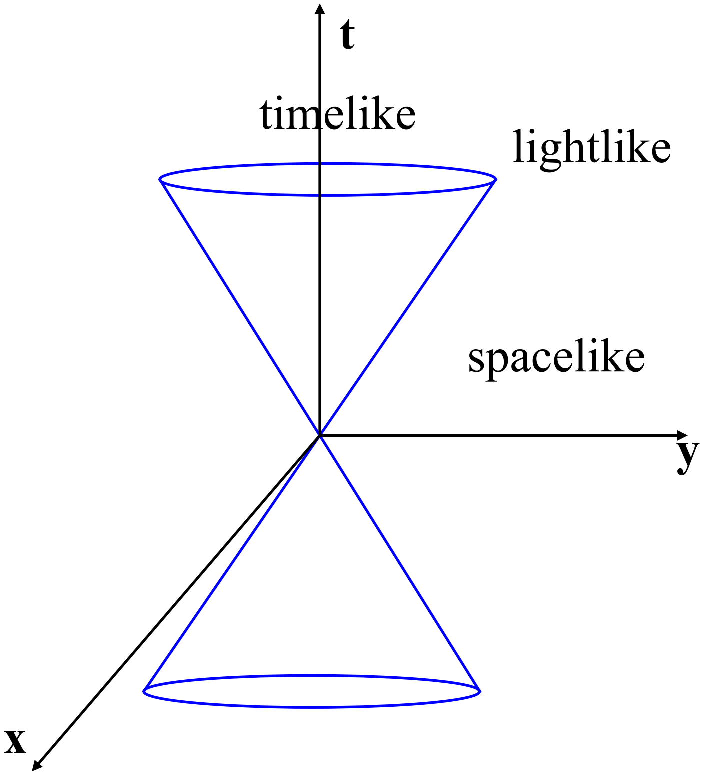
The **electromagnetic force and the weak force** between particles **are identical** for particles with energies **greater than 100 GeV**!

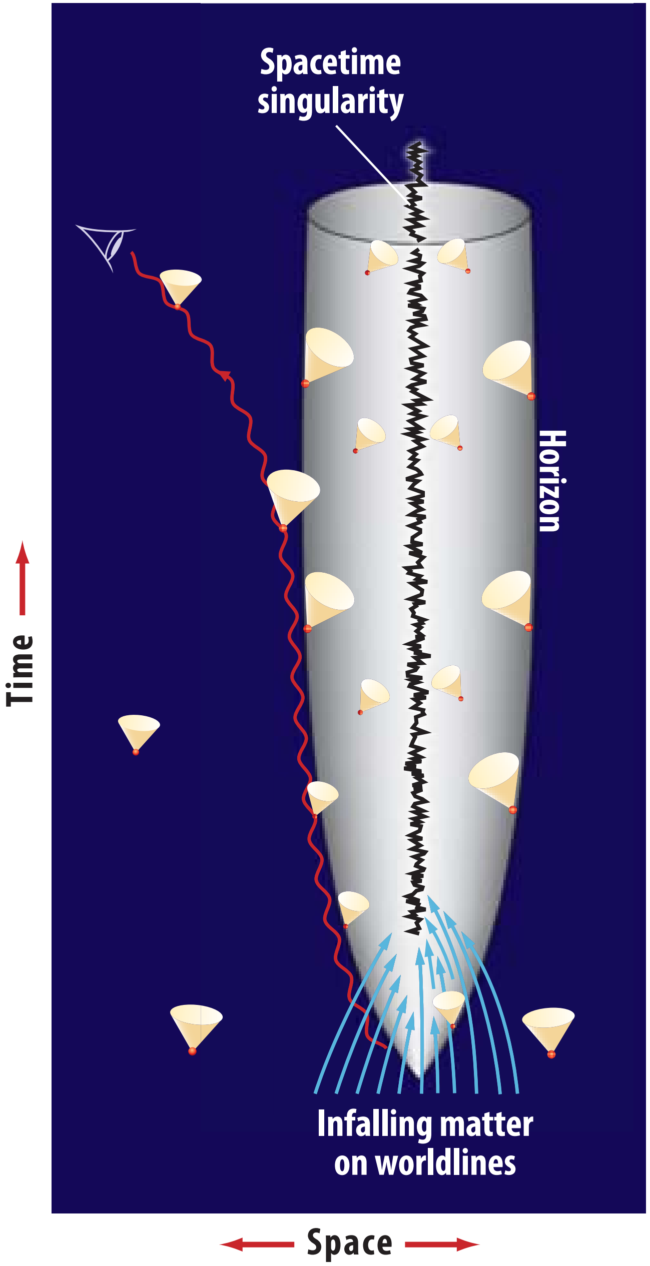
The $W^+$, $W^-$ and Z  bozons loose their mass at > 100 GeV and behave like photons!

**Grand unified theories** (or GUTs), predict that the strong force becomes unified with the weak and electromagnetic forces (but not gravity) at energies above $10^{14}$ GeV.

Combining all the forces would require a theory that could combine gravity at the microscopic scales (quantum gravity).

A spacetime diagram showing the collapse of an object into a black hole. A worldline is the trajectory of a particle in spacetime.





# Quantum Black Holes

If you could compress the Sun to 3 km you would form a black hole. Remember the Schwarzschild radius is $R_s \sim 3\ \text{km} \times (M/M_\odot)$

How does the **density to** which an object of mass $m_{BH}$ must be squeezed to **form a black hole** scale with the mass of the black hole $m_{BH}$?

$$\rho = \frac{m_{BH}}{V} = \frac{m_{BH}}{\frac{4}{3}\pi R_S^3} = \frac{m_{BH}}{\frac{4}{3}\pi\left(\frac{2Gm_{BH}}{c^2}\right)^3} \approx \frac{0.66\times10^{81}}{m_{BH}^2}\,kg/m^3$$

# Quantum Black Holes in the Early Universe

During the early stages of the big bang matter densities may have been as high as $10^{97}$ kg/m$^3$ (the Planck value). Such a density would have been enough to create a mini black hole with the size of a **Planck length**.

The Planck length $l_p$ is defined as:

$$l_P = \sqrt{\frac{G\hbar}{c^3}} \approx 1.616252 \times 10^{-35} \text{meters}$$

The Planck length is the only length that can be formed from the constants *c, G*, and *ħ*. Lengths of special significance in quantum gravity are likely to be small multiples of the Planck length.

# The Search for mini black holes

So the **largest density** that one can hope to obtain **at LHC** is:

$$\rho = \frac{m}{V} = \frac{10^{-23}kg}{\frac{4}{3}\pi(10^{-19}m)^3} \sim 0.2\times 10^{34}\,kg/m^3$$

where $10^{-19}$m is the smallest region that one can contain a mass of $10^{-23}$kg that can be produced by a particle of energy E ~ 10 TeV

This is large but not large enough to form a black hole… in 3D space.