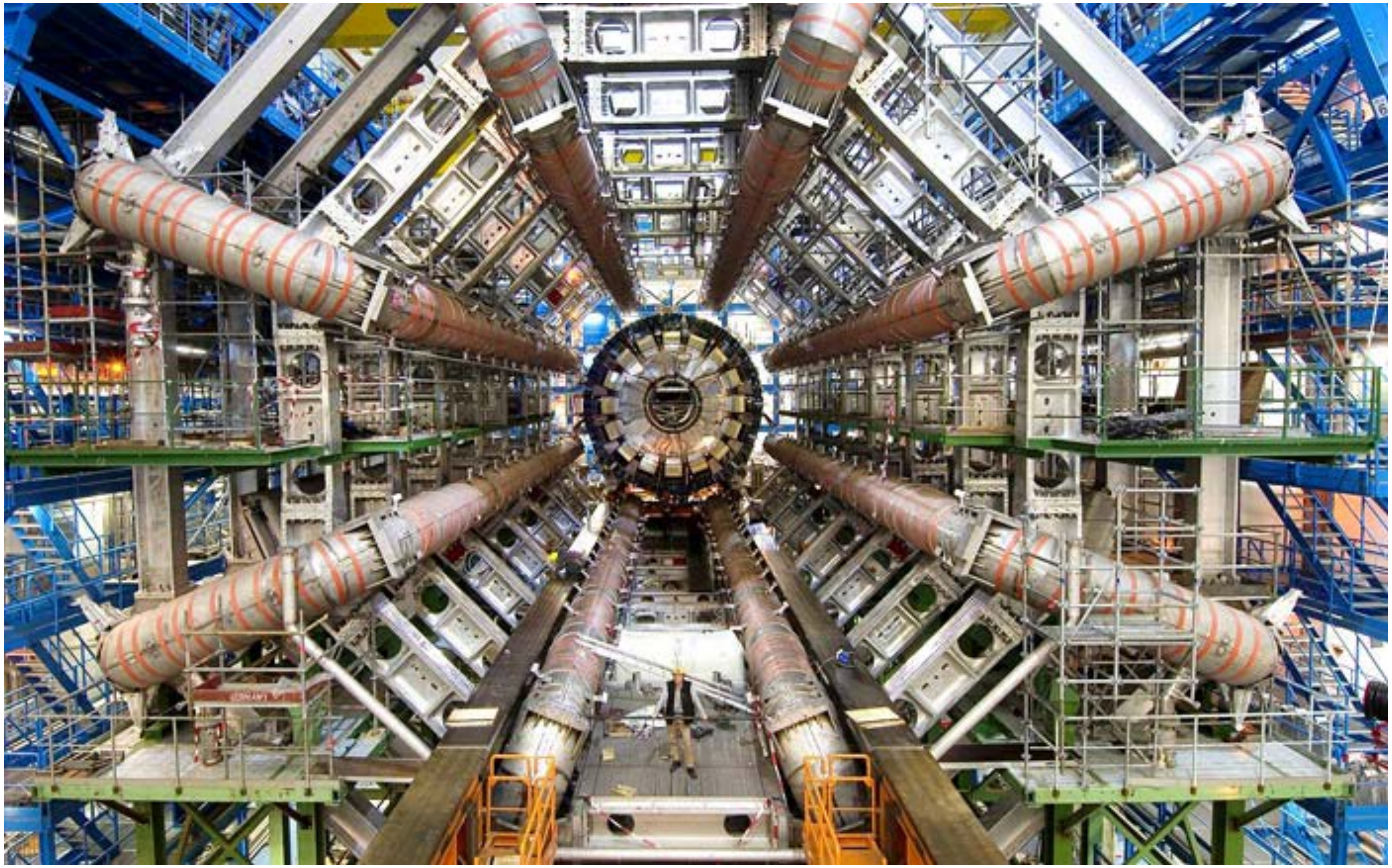
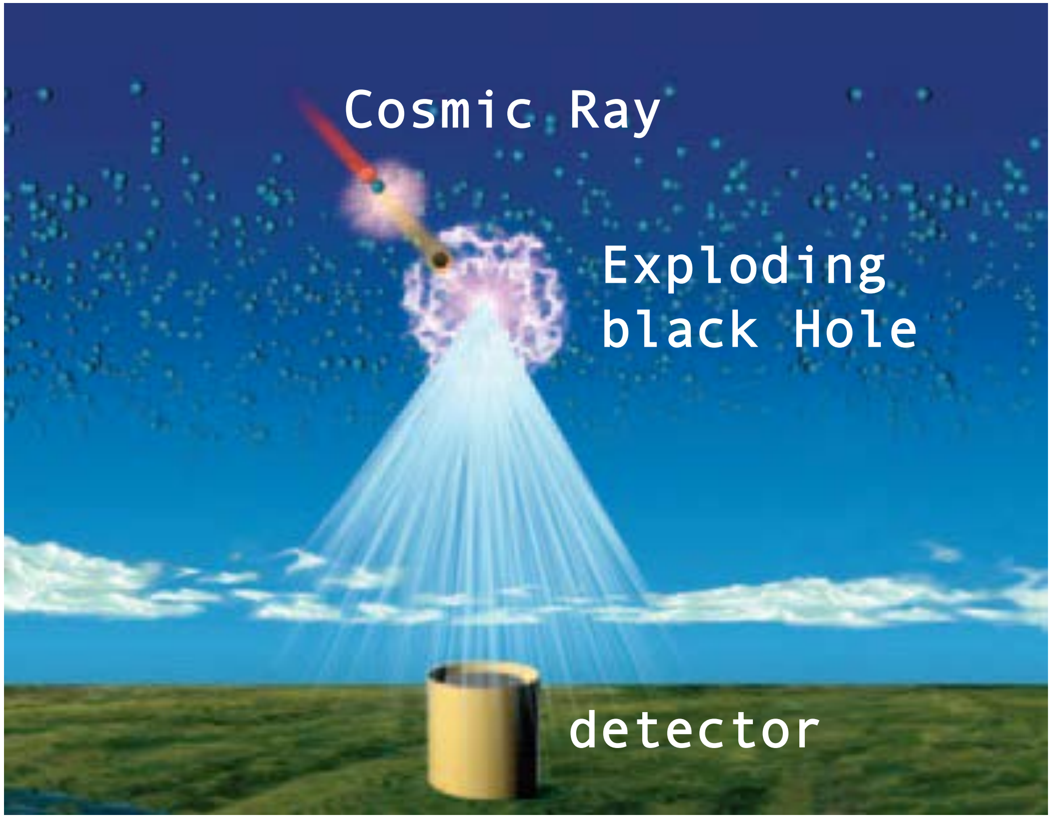
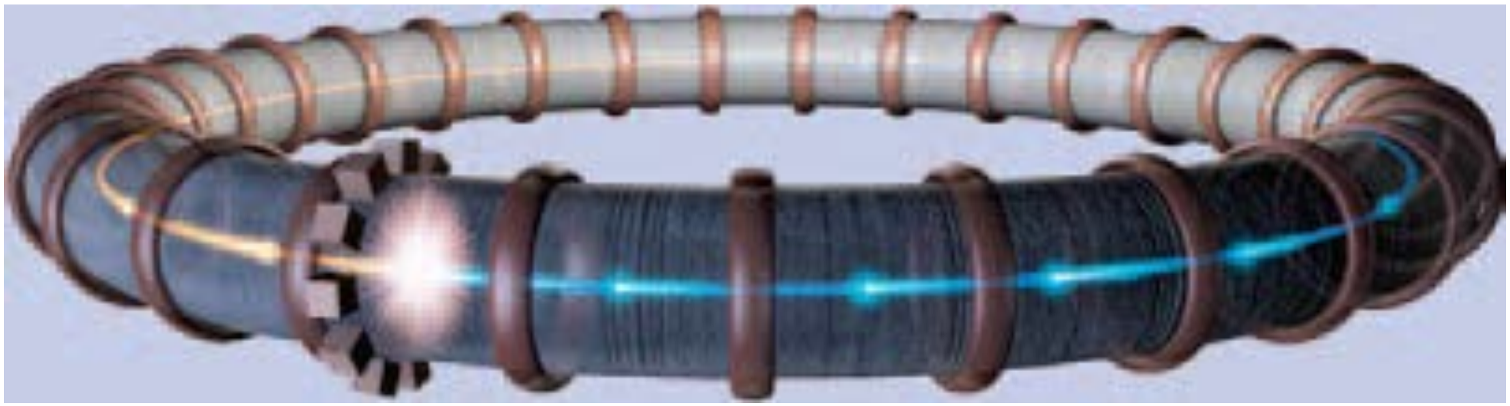
Quantum Black Holes





Cosmic-Ray Collisions

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



Particle Accelerator
An accelerator such as the LHC 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.

Quantum Black Holes

Particle accelerators have been used to split atoms, transmute elements, produce antimatter, create new particles and now perhaps create mini-black holes.

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.

Quantum Black Holes

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

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}?

$$\rho = \frac{m_{BH}}{V} = \frac{m_{BH}}{\frac{4}{3}\pi R_S^3} = \frac{m_{BH}}{\frac{4}{3}\pi\left(\frac{2Gm_{BH}}{c^2}\right)^3} \approx \frac{0.66 \times 10^{81}}{m_{BH}^2} kg/m^3$$

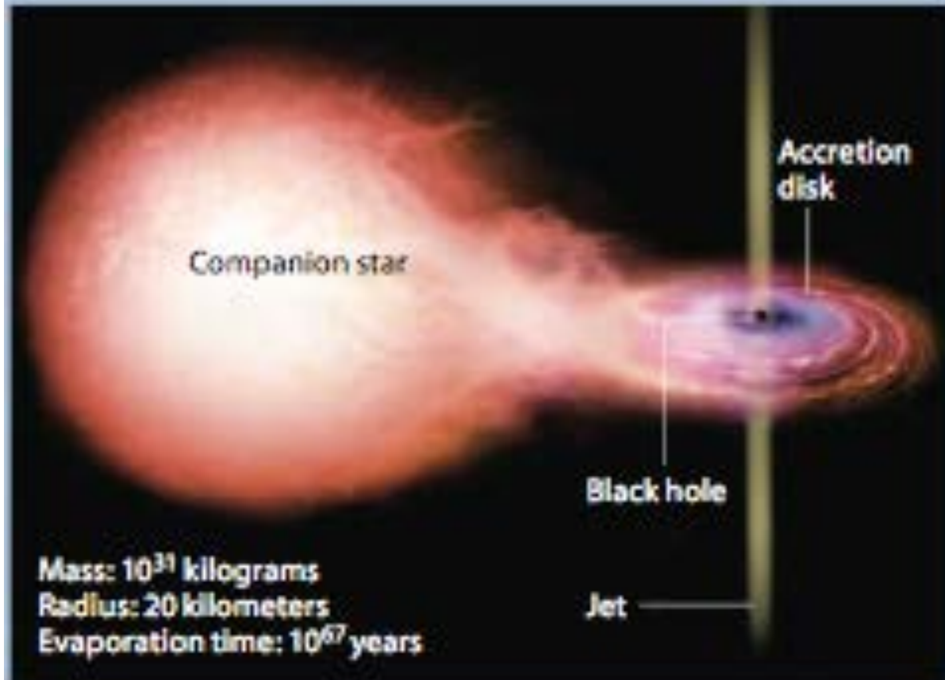
Quantum Black Holes

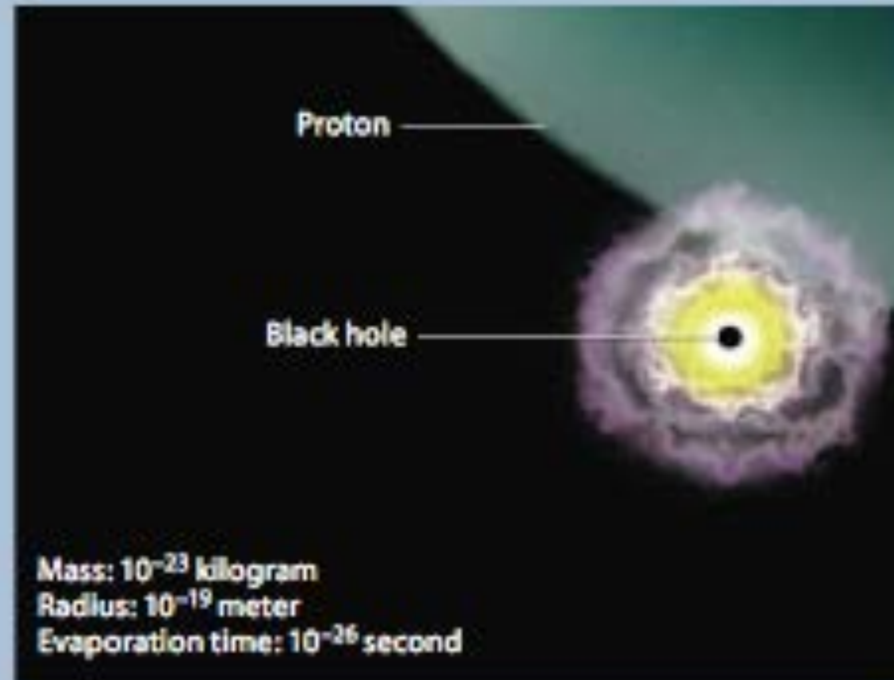
What is the **mass of the smallest observable black holes**?

Cosmologist predict that **mini black** holes may have formed in the early stages of the big bang. Astronomers might be able to detect some of them as they decay and explode today.

If space has extra dimensions, the threshold for mini black hole production is lower. If so, mini-holes might be produced by the LHC and in cosmic-ray collision high in the atmosphere.

A Tale of Two Black Holes





ASTROPHYSICAL BLACK HOLES are thought to be the corpses of massive stars that collapsed under their own weight. As matter falls into them, they act like cosmic hydroelectric plants, releasing gravitational potential energy—the only power source that can account for the intense x-rays and gaseous jets that astronomers see spurting out of celestial systems such as the x-ray binary shown here.

MICROSCOPIC BLACK HOLES have masses ranging up to that of a large asteroid. They might have been churned out by the collapse of matter early in the big bang. If space has unseen extra dimensions, they might also be created by energetic particle collisions in today's universe. Rather than swallowing matter, they would give off radiation and decay away rapidly.

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 $\hbar$. Lengths of special significance in quantum gravity are likely to be small multiples of the Planck length.

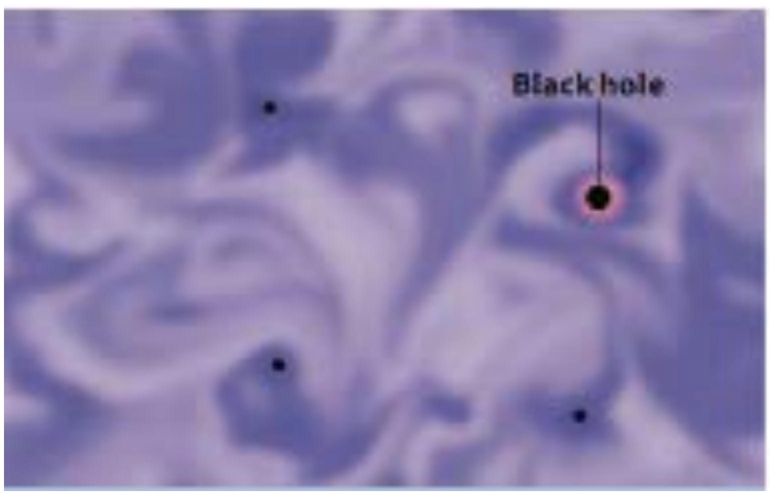
A black hole with an event horizon of l_p will have a mass of ~ 10^{-8} kg. So according to GR to smallest black hole has a mass of ~ 10^{-8} kg.

Quantum Black Holes

As the Universe expanded heavier primordial black holes may have formed.

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.**

Density fluctuation did exist in the early Universe because we know that these later on lead to the formation of galaxies and clusters of galaxies.



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's 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 mass is reduced due to evaporation. 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 $k_B A/4l_p^2$,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:

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

Quantum Black Holes

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

$$L = -\frac{dE}{dt} = -\frac{c^2 dM_{BH}}{dt} = \frac{K_{eV}}{M_{BH}^2} \Rightarrow M_{BH}^2 dM_{BH} = -\frac{K_{eV}}{c^2} dt \Rightarrow$$

$$\int_{M_{BH}}^{0} M_{BH}^2 dM_{BH} = \int_0^{t_{evap}} -\frac{K_{eV}}{c^2} dt \Rightarrow \frac{M_{BH}^3}{3} = \frac{K_{eV}}{c^2} t_{evap} \Rightarrow$$

$$t_{evap} = \frac{c^2 M_{BH}^3}{3K_{eV}} = \frac{5120\pi G^2 M_{BH}^3}{\hbar c^4}$$

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

As the black hole evaporates it loses energy and becomes hotter and shrinks. When the 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.

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.

Another way to make a mini-hole is through a **particle accelerator**.
At LHC a proton will reach an energy of ~ 1 TeV which is equivalent to a mass of $E/c^2 = 10^{-23}$ kg.

Conventional general relativity indicates that the smallest mass black hole that can be produced has a mass of $\sim 10^{-8}$ kg.

The Search for mini black holes

What's the smallest region that one can contain a mass with an equivalent energy ~ 1 TeV?

According to quantum mechanics particles behave like waves and their boundaries are smeared out over a distance that decreases with energy.

The uncertainty principle states :

$$\Delta x \Delta p \geq \frac{\hbar}{2} \rightarrow \Delta x \geq \frac{1}{2}\left(\frac{\hbar}{mc}\right), \ \hbar = 1.054 \times 10^{-34} \ Js$$

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1 TeV = $1.6021 \times 10^{-7} J$

$$E = mc^2 \rightarrow m = \frac{E}{c^2} = \frac{1.6021 \times 10^{-7}}{299792458^2} kg \approx 1.8 \times 10^{-24} kg$$

$$\Delta x \geq \frac{1}{2} \frac{1.054 \times 10^{-34} Js}{1.8 \times 10^{-24} kg \times (299{,}792{,}458 m/s)} \approx 1 \times 10^{-19} m$$

Gravity meets quantum mechanics:

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

$$R_S = \frac{2GM_{BH}}{c^2} \ (1)$$

$$(1)\ (2)\ R_S \geq \frac{1}{2}\frac{\hbar}{M_{BH}c} \rightarrow \frac{2GM_{BH}}{c^2} \geq \frac{1}{2}\frac{\hbar}{M_{BH}c} \rightarrow M_{BH}^2 \geq \frac{c\hbar}{4G} \rightarrow$$
$$M_{BH} \geq 1.1\times10^{-8} kg$$

The Search for mini black holes

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

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

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

Searching for Mini black Holes in Nine Dimensions

The standard estimate, that the **minimum mass required to form a black hole is 10^{-8} kg** may be too high according to some theorists.

String theory for example 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.

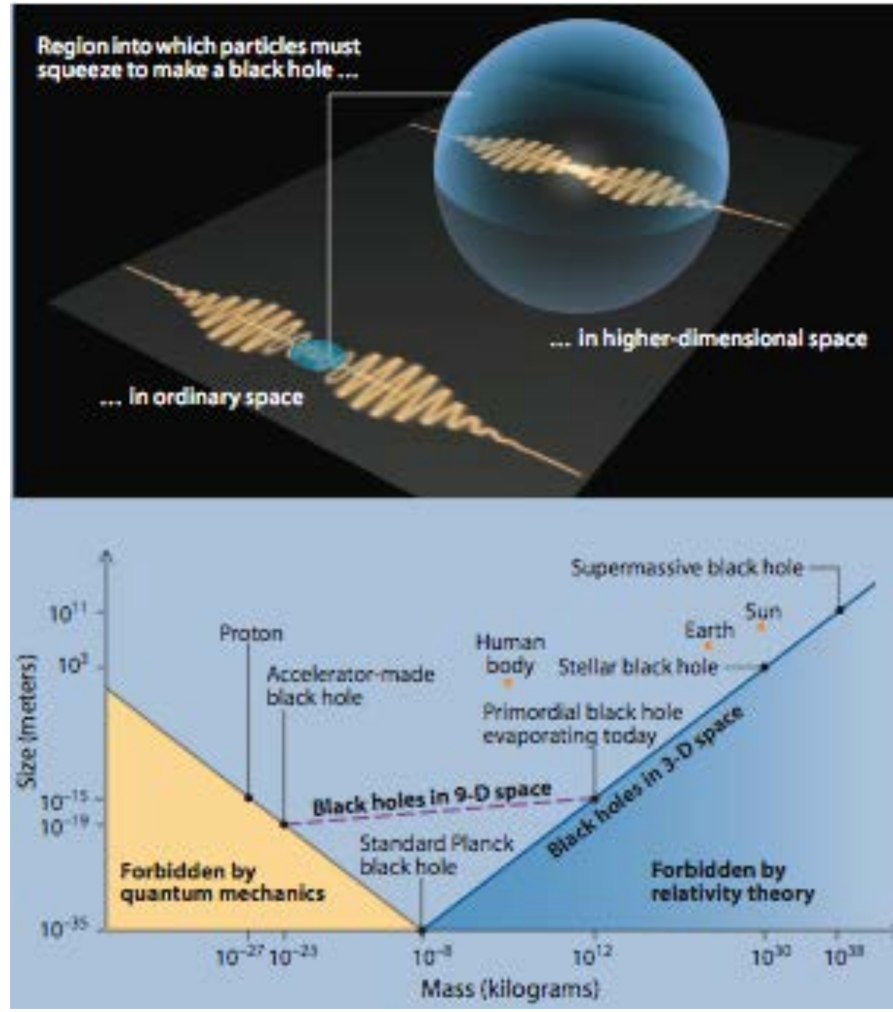
In three dimensions gravity increases by 4 as you halve the distance between 2 objects. In 9 dimensions the force would increase by 256 as you halved the distance.

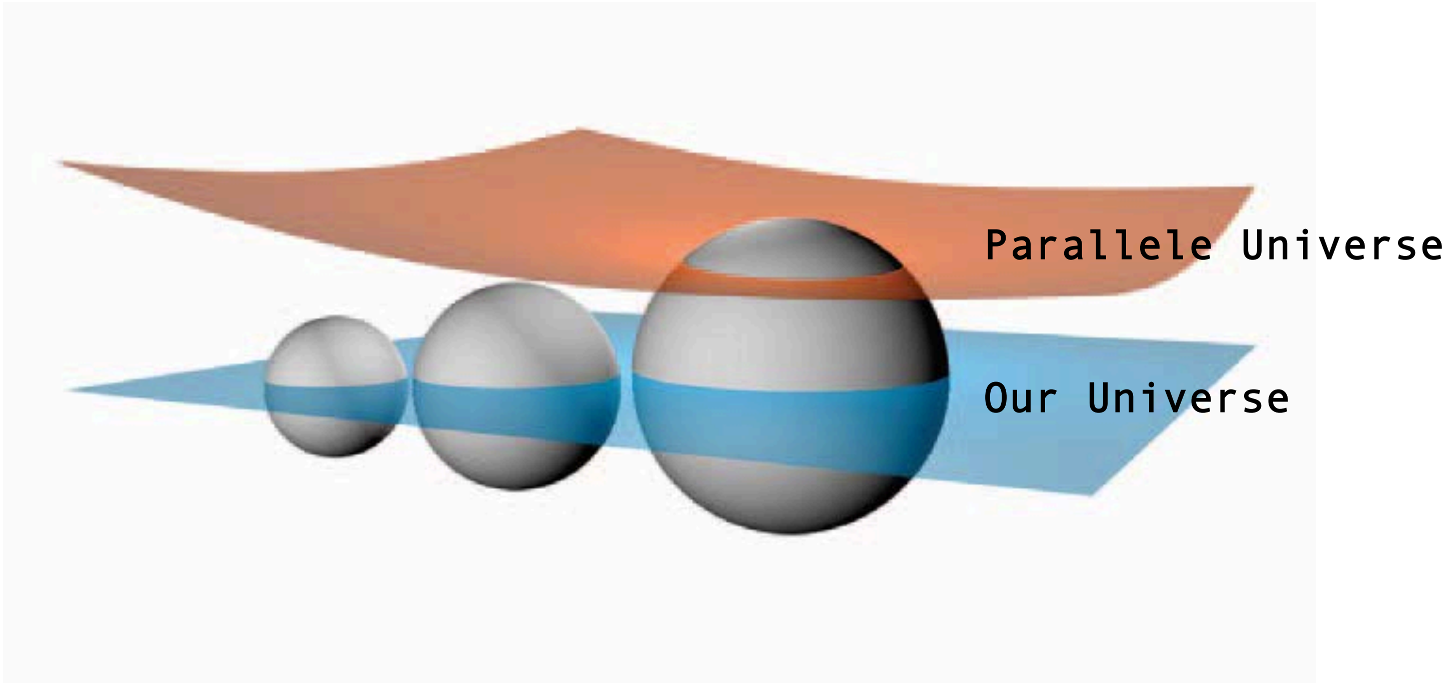
Because of possible extra dimensions the minimum mass required to form a black may be significantly lower than 10^{-8} kg. If this is true LHC might have a chance at producing mini black holes.

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.





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)

Could black holes produced at CERN consume the planet?

1. There is no **conservation law** to prevent a mini black hole from decaying. Stable particles do not decay because of conservation of electric charge or baryon number.

Baryons are made of 3 quarks and the baryon number is:

$$B = \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$$

2. High energy cosmic-rays are constantly hitting our atmosphere with energies of up to 10^9 TeV. Some theorists predict that these may be producing as many as 100 mini black holes per year.