Black Holes and the Structure of Space-Time

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Black Holes in Newton's Gravity

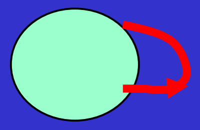
"Everything that goes up falls down again"

Only if it does not go up faster than **v_e = 11Km/s**

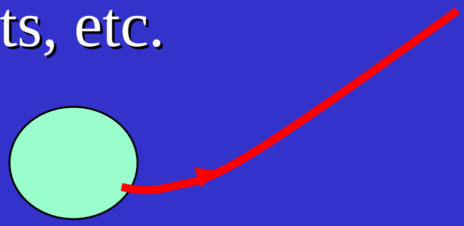
Why? Gravitational force

$$F = \frac{GmM}{r^2}$$

Force decreases with distance, so the decrease in velocity is slower. If the velocity is large enough → we can escape, e.g. spacecrafts sent to other planets, etc.



v less than v_e



v greater than v_e

What if the escape velocity were the velocity of light?

$$v_e^2 = \frac{2\,GM}{R}$$

If v_e greater than c the object would look black, no light could come out of it. This happens if there is a lot of mass in a small region.

It is convenient to define the "black hole radius" of an object as

$$R_h = \frac{2\,GM}{c^2}$$

This is the size it would need to be in order to be a black hole:

$R_{h,\ sun}$ = 3 Km
$R_{h,\ earth}$ = 1 cm
$R_{h,\ us}$ = smaller than any distance we can experimentally measure today.

Relativity

- ✓ The speed of light is the maximum speed at which information travels. Nothing can travel faster than light.
- ✓ Physics is the same no matter how fast an observer is moving. In particular, all observers measure the same speed of light.
- ✓ This can only happen if time flows differently for observers that are moving relative to each other.
- ✓ Space and time are related. How we perceive time depends on how fast we move.

Equivalence Principle

Aristotle: Heavy objects fall faster.

Galileo: All objects fall in the same way once we remove the effects of the air resistance.

$$F = \frac{mGM}{r^2}$$

$$F = m\,a$$

$$a = \frac{GM}{r^2}$$

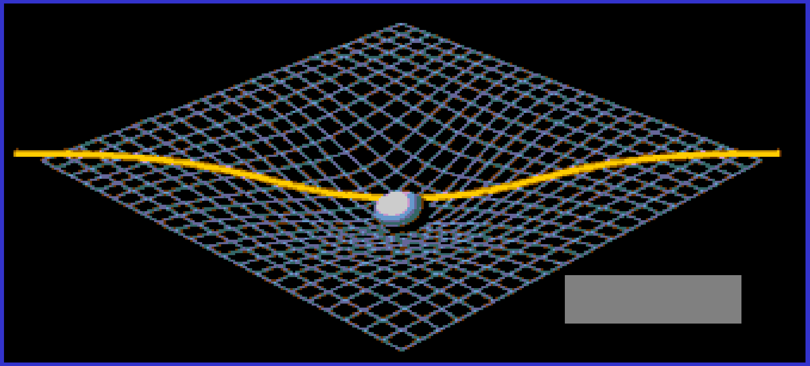
✓ The motion of a "light" particle in the presence of a heavy object is independent of the mass of the particle.

General Relativity

✓ Newton's theory of gravity did not obey the relativity principle.

✓ Einstein proposed that gravity is due to the fact that space-time is curved.

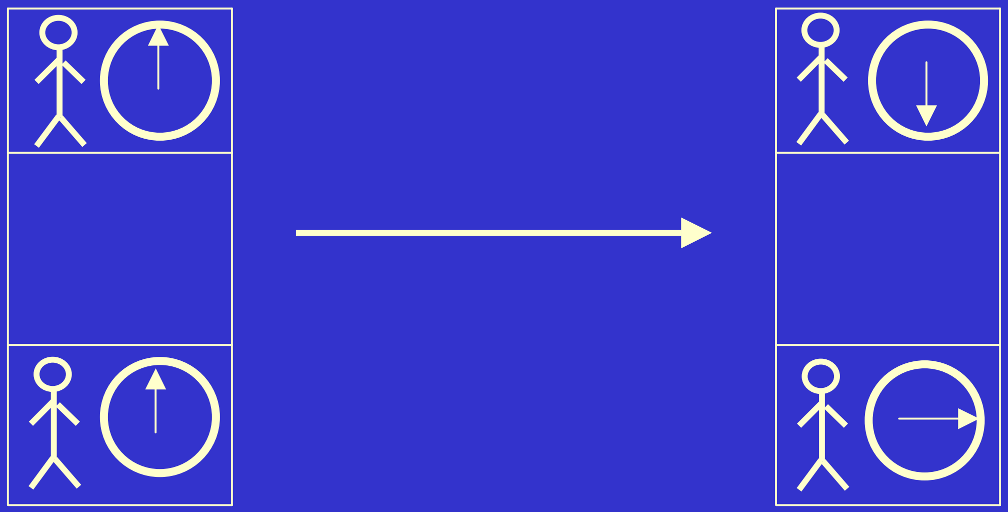
✓ A heavy mass curves space-time and the motion of a light particle just follows the "shortest" line along that space-time.



Slowing the Aging Processes

If we have two observers in a curved space-time, time can flow differently for each of those observers.

Example: A person living on the top floor of a building and a person living on the bottom floor of a building. The clock of the person below goes slower by one part in 10^{15} (one in one quatrillion). It is a very small effect in this case. If one were is a very strong gravitational field this difference would be much bigger.



Redshift Factor

An observer far from a heavy mass sees time going faster than an observer on the horizon. This is what they measure when they compare their clocks. Each observer does not feel anything weird, as everything slows down.

$$\text{Redshift factor} = \frac{\text{(flow of time at some position)}}{\text{(flow of time far away)}}$$

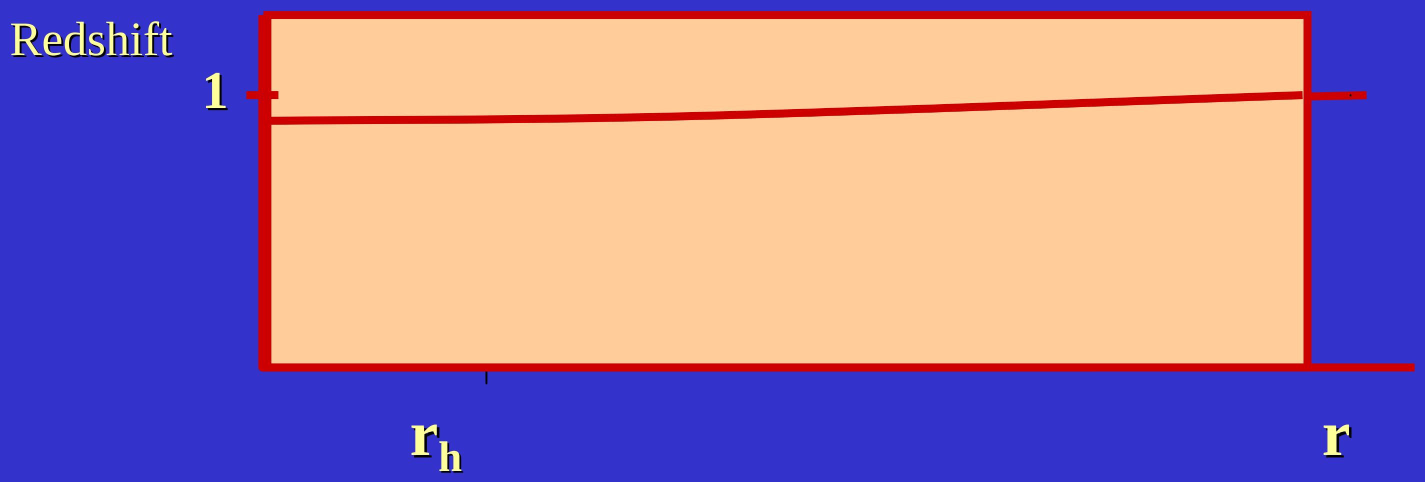
Examples: Redshift factor at:

Surface of the sun: $1 - 2\ 10^{-6}$
Surface of the earth: $1 - 8\ 10^{-10}$
Surface of a neutron star: 0.7

One can find the shape of the space-time outside a massive object. Then one can compute the slowing of the clocks.

One finds:

$$\text{Redshift} = \sqrt{1 - \frac{r_h}{r}} \qquad r_h = 2G\frac{M}{c^2}$$



Black Holes

What happens if an object has a size smaller than r_h ?

The redshift factor becomes zero, this implies that time stops there. It is black also because light cannot escape.

When this was first discovered it was thought that it was something unphysical, that maybe objects can never become that small.

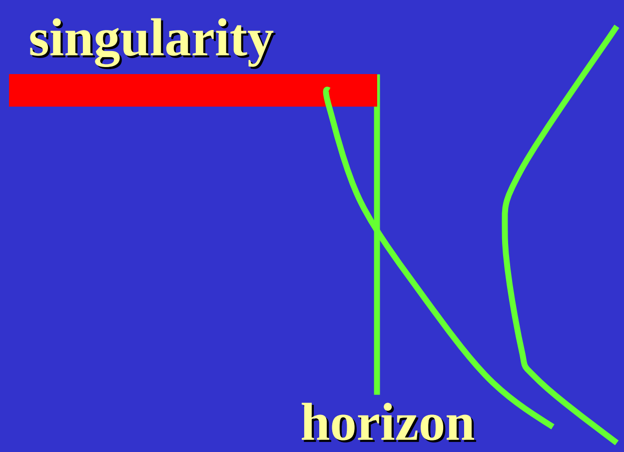
Later it was understood that:

1) Some stars can collapse into a black hole.
2) An observer who is falling into the object does not see anything special at $r = r_h$
3) There are some objects in the sky that are probably black holes.

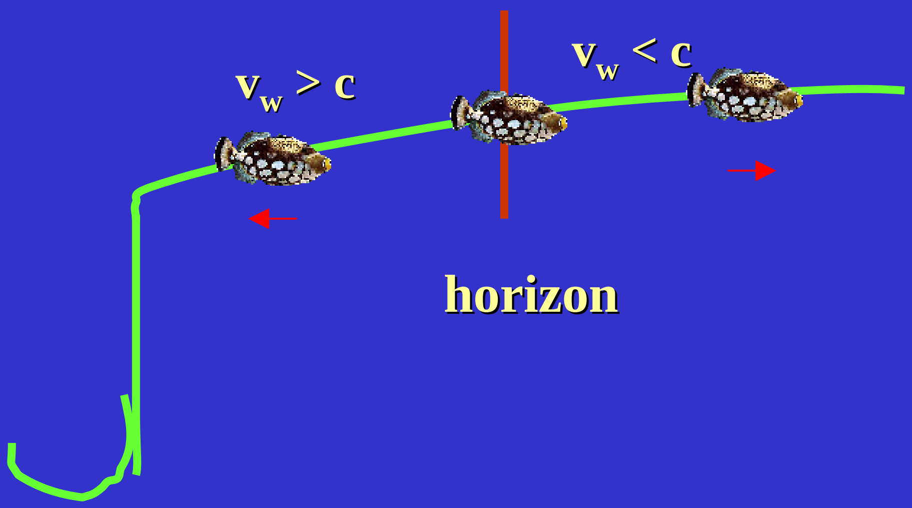
The Horizon and Beyond

The surface at $r = r_h$ is called a horizon. If you cross it you do not feel anything special, but you cannot come back out again.

Once you cross the horizon you continue to fall in and you are crushed into a "singularity." This is a region of very high space-time curvature that rips you apart.



The Waterfall Analogy



The fish can swim at most at a velocity c. If the velocity of the water increases beyond c then the fish will fall into the waterfall and be crushed by it.

The fish do not feel anything special happening at r_h.

Real Black Holes

Black holes can form in astrophysical processes. Some stars are so massive that collapse into black holes.
Black holes produced through these processes are of the following types:

1) Black holes that collapse from stars with masses of the order of a few times the mass of the sun

($r_h \sim 10$ km)

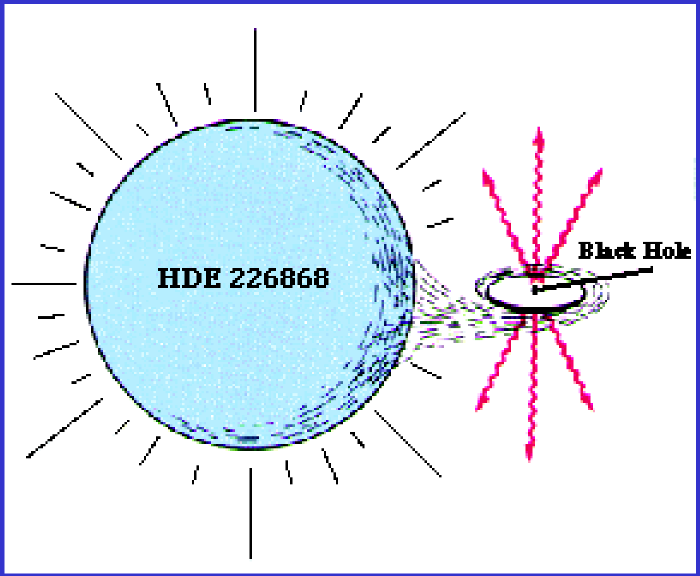
2) Black holes in the center of galaxies with masses of the order of a billion times the mass of the sun.

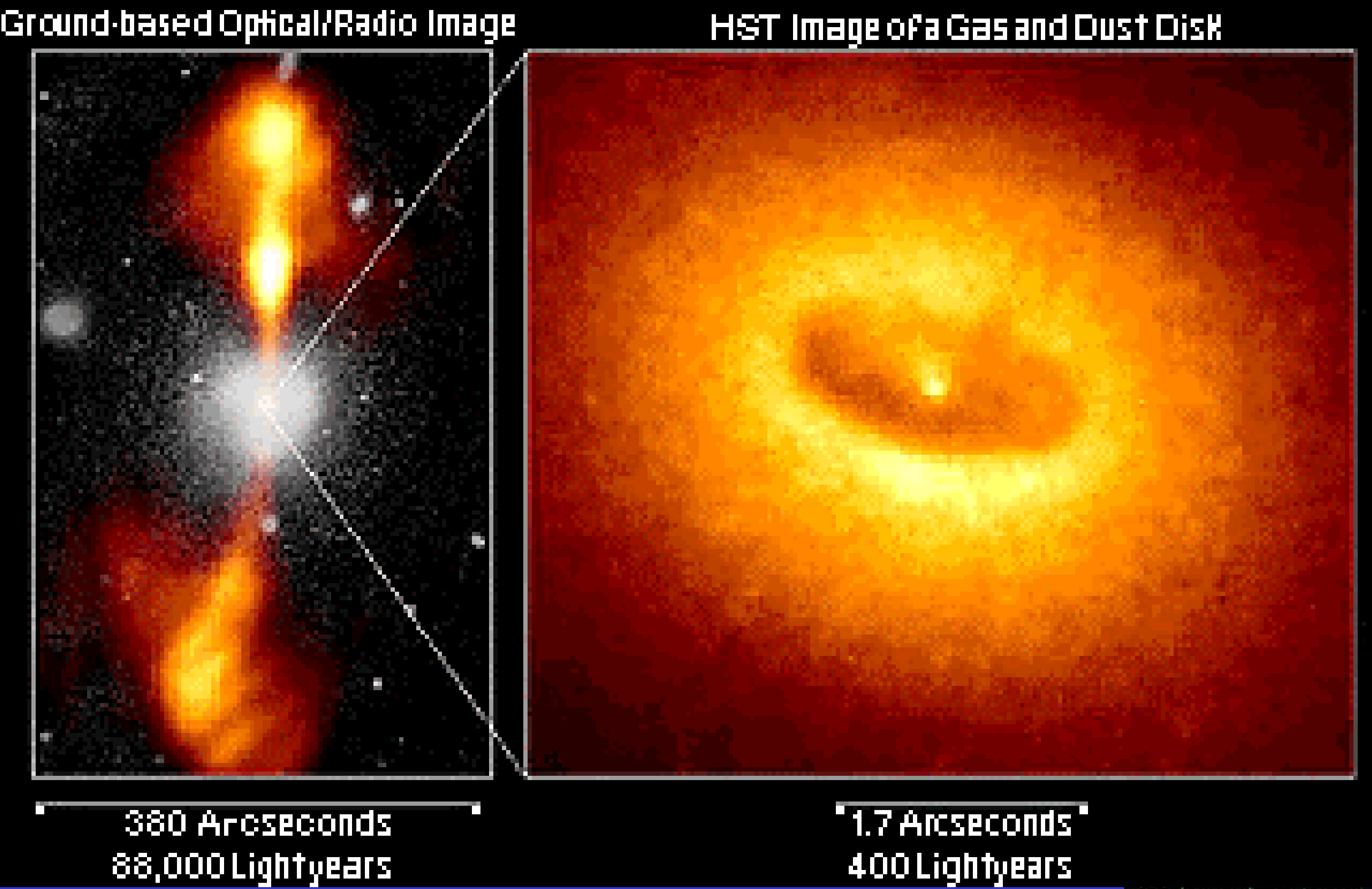
($r_h \sim 3\ 10^9$ km ~ size of the solar system)

How Do We See Them?

In principle we could see them by seeing how they deflect light, etc.

In practice these black holes are surrounded by some gas and this gas heats up in a characteristic way as it falls in and astronomers see the radiation coming from this hot gas.




Ground-based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arcseconds
88,000 Lightyears
1.7 Arcseconds
400 Lightyears

Universality

The final shape of a black hole as seen from the outside is independent of how we make it (up to the total mass, charge and angular momentum).

Area of the horizon always increases.

White Black Holes!

The laws of quantum mechanics imply that black holes emit thermal radiation. Their temperature is

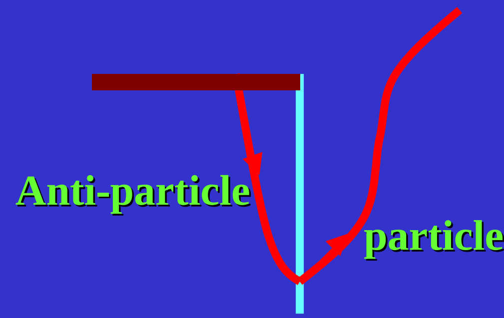
$$k\,T = \frac{\hbar}{r_h}$$

What is this temperature for black holes of different masses?

$T_{sun} = 3.6\ 10^{-7}$ K
$T_{earth} = .1$ K
$T_{M=10^{18}\,Kg} = 7000$ K (would look like a light bulb)

Why? → Pair creation

In flat space



In the presence of a horizon

The Life and Death of a Black Hole

✓ Since the black hole is emitting radiation it looses energy and will have a finite lifetime.

Lifetime for various black holes:

✓ For a black hole of the mass of the sun or the earth the life time is much bigger than the age of the universe.

✓ If a black hole had a mass equal to our weight it would evaporate in a millisecond.

✓ If a black hole of a mass of around 100 Kg was produced in the beginning of the big bang it would be evaporating today.

Theoretical Puzzles with Black Holes

Thermal properties of black holes mix quantum mechanics and gravity. It is hard to mix these two theories.

Puzzles:

- ✓ Entropy of the black holes.
- ✓ Information loss.

Roughly speaking, Einstein’s theory of gravity says that nothing should come out of black holes while quantum mechanics says that some things do come out of black holes.

Heat and Entropy

Normally heat comes from the motion of some microscopic components of the system. For example, the temperature of the air comes from the motion of the molecules. There is a way to measure how many microscopic degrees of freedom we are considering by measuring the "entropy" of the system (essentially by measuring the specific heat of the system).

First law of thermodynamics → Says that the entropy is related to the specific heat. System that need more energy for a given rise in temperature have more entropy.

How does the heat of the black hole arise? What is "moving" on a black hole? **Compute entropy from the first law:**

$$S = \frac{Area\,of\;the\,horizon}{4 G_N \hbar}$$

$$S = \frac{Area\,of\;the\,horizon}{(10^{-33}\,cm)^2}$$

The Structure of Space-time

Black holes are independent of what forms them. Their thermal properties only depend on gravity and quantum mechanics. This should be explained by a theory of quantum gravity.

Roughly speaking, the black hole entropy should come from the motion of the "space-time quanta," from the elementary quanta (or atoms…) that make space and time.

Understanding precisely these thermal aspects of black holes, we learn something about the quantum structure of space-time.

Information Loss

We can form a black hole in many different ways, but they always evaporate in the same fashion.

It can happen sometimes in physics that there are many initial conditions that lead to roughly the same answers. For example, if we open a bottle of perfume in a room, after a while the smell will spread more or less uniformly in the room, independently of where you open it. However, we have a theory that **in principle** allows us to compute precisely how the molecules of perfume spread in the air.

The principles of quantum mechanics imply that there should be a precise description of black holes, and that black holes do not evaporate in the same way, but only approximately in the same way. There should be subtle differences in what comes out of a black hole, depending on how we made the black hole.

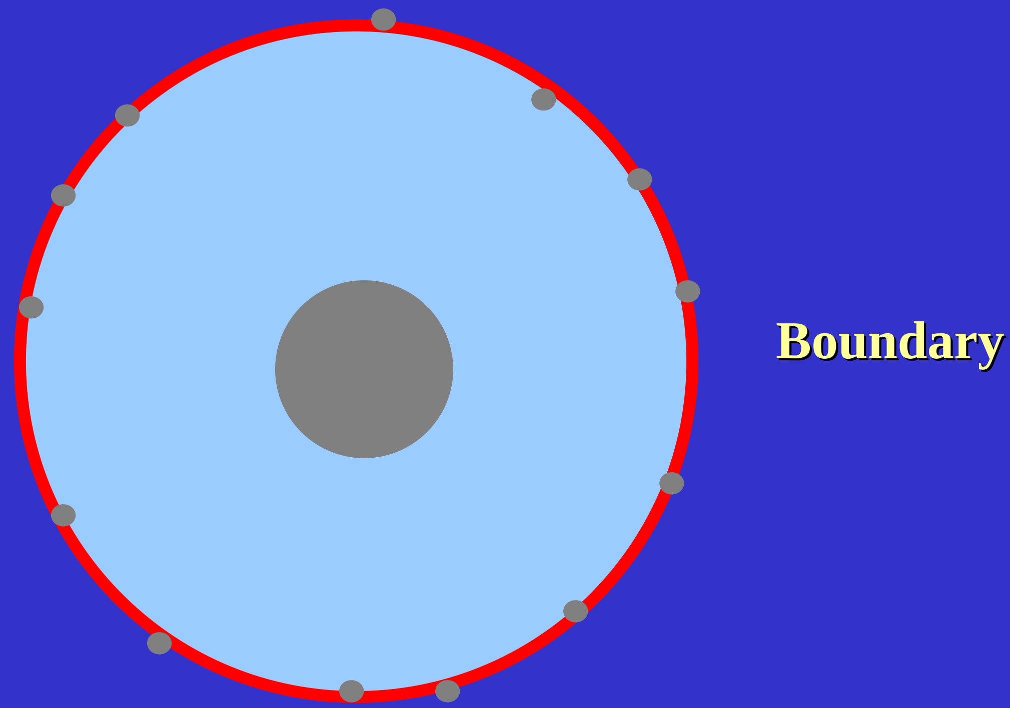
Holography and Black Holes

Since the entropy is proportional to the area it was suggested that the number of quanta ("atoms") necessary to describe a black hole should be proportional to the area. All information about the black hole should be stored on its horizon.

Usual hologram: a 2d surface encodes all information about a three dimensional object

In string theory, which is a theory of quantum gravity, one can understand this more precisely, in some cases, and say precisely what these "atoms" that describe the black hole are. They are similar to the particles we use to describe particle physics.

More on Holography



Quantum gravity in the interior is equivalent to a theory of quantum particles on the boundary. In some cases this theory on the boundary is precisely known. Then the "atoms" of space-time are the particles moving on the boundary.

Some Conclusions

✓ Black holes are fascinating objects where the effects of space-time curvature are dramatic.

✓ Black holes combined with quantum mechanics provide very interesting challenges to our understanding of space-time.

✓ We are beginning to formulate theories that are capable of putting together the classical aspects of black holes with their quantum aspects.