1. Introduction

What is a Black Hole?

- Object whose gravity is so strong that light cannot escape.
- Predicted by Einstein's theory of gravity (called General Relativity).
- Region within which light is trapped is called the "event horizon."
- Close to event horizon, gravity bends light onto strongly curved paths, radically alters geometry of space and flow of time.
- Stellar mass BHs form by collapse of stars 15-100 times mass of sun, after they run out of nuclear fuel.
- Supermassive BHs, up to several billion $M_\odot$, found at centers of galaxies. Formation poorly understood. ($M_\odot$ = mass of the sun)
- Orbiting BHs can spiral together and merge, emitting gravitational waves.

The course will largely be devoted to explicating these points.

Above all, understanding BHs requires understanding gravity, which has been a central theme of physics from the 1500s to the present day.

Properties of BHs are at core of current efforts to understand how gravity works on a microscopic scale.

Escape Speed

Throw a ball in the air. It slows to a stop, falls back down.

Throw ball faster. It goes higher.

Throw it faster than $11\,\mathrm{km\,s^{-1}}$. (Ignoring air resistance.) Ball never falls back.

$11\,\mathrm{km\,s^{-1}}$ is the *escape speed* from the earth's surface.

Formula for escape speed:

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}}$$

M =mass of object (planet, star, ...)

R =distance from center

G =Newton's gravitational constant (defines strength of gravity)

Plug in $M = M_{\rm earth}$, $R = R_{\rm earth}$, get $11\,{\rm km\,s^{-1}}$.

Compared to earth, moon is 80 times less massive, 4 times smaller.

Escape speed is $2.5\,{\rm km\,s^{-1}}$.

As an example of a kind of calculation we will use frequently throughout the course, let's work this out explicitly:

$$\frac{v_{\rm esc,moon}}{v_{\rm esc,earth}} = \frac{\sqrt{2GM_{\rm moon}/R_{\rm moon}}}{\sqrt{2GM_{\rm earth}/R_{\rm earth}}} = \sqrt{\frac{M_{\rm moon}}{M_{\rm earth}} \times \frac{R_{\rm earth}}{R_{\rm moon}}} = \sqrt{\frac{4}{80}} = \frac{1}{4.47}.$$

Therefore,

$$v_{\rm esc,moon} = v_{\rm esc,earth}/4.47 = 11\,{\rm km\,s^{-1}}/4.47 = 2.5\,{\rm km\,s^{-1}}.$$

Deimos (the smaller of Mars's two moons) is 3 billion times less massive, 1000 times smaller.

Escape speed is 6 *meters*-per-second. (Could almost jump off.)

Trapping Light

Suppose we squeezed earth to be 100 times smaller in radius, with same mass.

$v_{\rm esc} = 110\,{\rm km\,s^{-1}}$.

Suppose we squeezed it to be 10,000 times smaller?

$v_{\rm esc} = 1100\,{\rm km\,s^{-1}}$.

If we squeezed earth to be 1 *centimeter* in radius, $v_{\rm esc} = 300,000\,{\rm km\,s^{-1}}$, the speed of light.

If earth were this small, light could not escape.

Nothing can go faster than light, so nothing else could escape either.

We can get the radius of the event horizon (the region from which light cannot escape) by rearranging the escape speed equation.

$$\sqrt{\frac{2GM}{R_{\rm Sch}}} = c \quad \Longrightarrow \quad R_{\rm Sch} = \frac{2GM}{c^2}$$

where

$$c = 300,000\,{\rm km\,s^{-1}} = \text{speed of light}.$$

For reasons that will become clear later in the course, the radius $2GM/c^2$ is called the *Schwarzschild radius* and denoted $R_{\rm Sch}$.

A Caveat: In the book, Thorne is always careful to talk about the *circumference* of the horizon rather than the *radius*, because of the complicating effects of gravity on geometry.

While he is correct, I regard this level of care as unnecessary to our purposes, and I will almost always refer to the *radius* of the event horizon.

When it matters, you can understand the radius to mean the circumference divided by 2π.

The sun is 300,000 times more massive than the earth.

If it collapsed, it would form a black hole with a horizon radius $R_{\rm Sch} = 3$ km.

we can write this fact as a useful formula:

$$\frac{2GM_\odot}{c^2} = 3\,{\rm km},$$

where

$$M_\odot \;=\; \text{the mass of the sun} \;=\; 2 \times 10^{30}\,{\rm kg}.$$

Diving into a Black Hole

If the sun became a BH, the gravity at earth's orbit would be the same as before.

Earth would stay in the same orbit (but get cold).

BHs have “strong gravity” because you can get very close to them.

In a rocket, you go into orbit 6000 km ($2000 R_{\mathrm{Sch}}$) from the collapsed sun.

The angular size of the event horizon is about 0.05 degrees, one tenth the angular size of the (normal) sun as seen from earth. You could just distinguish this from a point with your naked eye.

You are going $5000\,\mathrm{km\,s^{-1}}$, so you orbit once every 8 seconds.

You fire rockets to bring yourself to rest, then fire them steadily towards the black hole so that they balance its gravity and your rocket hovers in place.

Your friend jumps out of the rocket and drops into the BH on a straight path, with a yellow flashlight that flashes 10 times per second.

As she approaches the event horizon, the light you see from the flashlight becomes red, then infrared, then microwave, then radio.

The pulses also come further apart.

Your friend still sees one pulse per second of yellow light, but the light loses energy as it climbs out of the black hole’s gravity.

Gravity affects the flow of time, so 0.1 second for your friend is a longer time for you.

You never see your friend cross the event horizon because your clocks get infinitely out-of-sync before she gets there.

However, from her point of view she crosses the event horizon after just a few seconds, and she is crushed into the singularity at the center of the black hole just 1/100,000th of a second after that.

Actually, her experience is worse than that, as she is stretched by the tidal gravity of the BH.

The gravitational pull on her feet is stronger than that on her head because her feet are closer to the black hole, so her feet are pulled away from her head.

When she has fallen 3/4 of the way to the black hole (1500 km), this tidal force is the equivalent of being suspended from the ceiling with a one-ton weight attached to her feet.

From your comfortable perch at 6000 km, the effect is noticeable (about 30 pounds) but tolerable.

Tidal stretching near the horizon is weaker for a more massive black hole with a bigger R_{Sch}.

To explore the region close to R_{Sch}, one should visit a supermassive BH.

In principle, one can even cross R_{Sch} without being destroyed.

But it's a one-way trip, and you never survive all the way to the center of the BH.

What Makes Black Holes Visible?

A black hole is a nifty idea. But if BHs really exist, how would we know? Nothing escapes.

Gas falling into a black hole accelerates to speeds close to c.

Gas that runs into itself at high speed heats up, glows.

We can see glowing gas *falling into* black holes and infer that the black hole is there.

Very hot gas emits X-rays instead of visible light, so X-rays are especially good for discovering black holes.

But we also find black holes in visible light, infrared light, and radio waves.

To show that an object is a black hole, we must determine its mass by measuring its effect on surrounding gas or stars.

Where Are Black Holes Found?

Stellar mass BHs form where massive young stars ($15 - 100 M_\odot$) are forming. These stars "burn out" quickly and can collapse to BHs.

Less massive stars, like the sun, do not become black holes.

To light up and become visible, a black hole must be fed by gas from an orbiting companion that is swelling up because it is beginning to run out of nuclear fuel.

Stellar mass black holes are found throughout the Milky Way and in other nearby galaxies, with some preference for star-forming regions.

Most or all big galaxies appear to have supermassive BHs at the center.

They are found indirectly through their impact on the motions of stars and gas.

Sometimes they are fed by gas and light up to produce very bright "active galactic nuclei" or "quasars."

The Milky Way has a 4 million $M_\odot$ BH at the center, with mass measured through its impact on the motions of stars.

Gas falling into this black hole produces X-rays and radio waves. However, not much gas is falling in, so it is not very luminous.

A Brief History of an Idea

The history of the discovery of black holes, both theoretically and observationally, is long, complicated, and interesting; hence the 500+ pages of Thorne's book!

Here is a capsule version; we'll come to the details throughout the course.

- 1686: Newton publishes his theory of motion and gravity in the book *Principia Mathematica*
- 1783: John Michell proposes the possibility of "dark stars" based on essentially the escape speed analysis we went through in lecture 1.
- 1796: Pierre Laplace incorporates this idea in his book *Le Systeme du Monde.*
- Around 1800, experiments show that light consists of waves rather than the "corpuscles" envisioned by Newton and his successors. This raises questions about the influence of gravity on light.
- 1907-1916: Albert Einstein develops his theory of General Relativity (GR), which (among other things) gives clear answers to the influence of gravity on light.
- 1916: Karl Schwarzschild discovers the first exact solution to Einstein's GR equations, describing the gravity of a spherically symmetric star. This solution shows that a sufficiently compact star would indeed trap light and form an event horizon. Schwarzschild's solution to Einstein's equations indicates that a black hole could exist in principle, if it could form.
- 1925-1930: Demonstration of the existence of white dwarf stars, mass similar to the sun but size similar to the earth. Supported against collapse by "degenerate electron pressure."

- 1930: Subrahamyn Chandrasekhar demonstrates that the maximum possible mass of a white dwarf is 1.4 solar masses. Indicates a formation mechanism for black holes: collapse of massive stars.
- 1930s-1950s: Theory of supernovae and neutron stars develops. Collapse of massive stars can lead to supernova explosions and formation of neutron stars. But neutron stars also have a maximum mass, of 2-3 solar masses. Seems that collapse of a more massive star *must* produce a black hole.

  [A white dwarf is made of "normal" chemical elements (hydrogen, helium, carbon, oxygen), which are themselves made of protons, neutrons, and electrons. A white dwarf is roughly the size of the earth. A neutron star is made mainly of neutrons, with few protons and electrons. It is roughly 20 km across.]
- 1960s: Theory of black holes developed substantially further.
- 1963: First discovery of quasars, "quasi-stellar radio sources." Enormously luminous objects, visible to large distances, varying in brightness on month timescales. Theorists later argue that they are powered by supermassive black holes.
- 1970: First X-ray satellite. Shows many bright X-ray sources. Some are powered by gas falling onto neutron stars, but studies show that some of the objects are too massive to be neutron stars. Black holes really exist.
- 1970s-1990s: Case for stellar mass black holes and supermassive black holes powering quasars gets steadily stronger, as alternatives are eliminated.
- Late 1990s and 2000s: Demonstration that most nearby large galaxies have "dormant" supermassive black holes at their centers. Sharp imaging of Hubble Space Telescope is important to making this demonstration convincing.
- 2000s: Increasing evidence, observational and theoretical, that supermassive black holes help govern the formation of the galaxies that host them. They are not just byproducts, but active participants. Details still a subject of (very) active research.
- 2015: First direct detection of gravitational waves from merging BHs, in a galaxy 1 billion light years away. Confirms crucial predictions of GR and BH theory.

- 2019: First direct image of the shadow cast by a BH event horizon, from the 6 billion $M_\odot$ BH at the center of the galaxy Messier 87, 50 million light years away. Enabled by a network of radio telescopes collectively called the "Event Horizon Telescope."

Theoretical predictions and empirical evidence

Throughout course, we will talk about scientific theories, astronomical observations, and experiments.

A theory is a set of hypotheses, often expressed in mathematical form, and conclusions that can be deduced from those hypotheses.

A good theory makes *predictions* that can be tested by experiments or observations.

Empirical evidence for a theory comes from experiments or observations that confirm the theory's predictions.

Alternatively, an experiment or observation may contradict a theory's predictions, casting doubt on the validity of its hypotheses.

Empirical = based on, concerned with, or verifiable by observation or experience rather than theory or pure logic.

Physicists usually refer to experiments, in which they control the conditions.

Astronomers usually refer to observations, in which they observe what is happening elsewhere in the universe with telescopes and instruments.

Experiments and observations are both forms of empirical evidence.