Black Holes
and
Gravitational Waves

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What is a black hole?

**black hole**: a region in space and time from which nothing can escape. Its surface, the **event horizon**, acts like a one-way membrane.

**Black holes are interesting because:**

- they are places where space and time becomes extremely distorted and they display several weird properties
- they exist in nature and we can observe them
- they play important roles in evolution of stars and galaxies
What is a black hole?

**escape velocity**: speed need to escape the gravitational pull of a massive body

\[ V_{\text{esc}} = \sqrt{\frac{2GM}{R}} \]

(shrink radius, keep mass constant)

\[ V_{\text{escape}} = c = 3 \times 10^5 \text{ km/s} = 7 \times 10^8 \text{ mph} \]

V\text{escape} = 11 \text{ km/s} = 25,000 \text{ mph}
How do black holes form?

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How stars work:
How do black holes form?

Most form from the collapse of massive stars ($M > 15 \, M_{\text{sun}}$)
Resulting black holes have masses of $3 - 100 \, M_{\text{sun}}$ (9 – 300 km)
These are called **stellar mass black holes**.

**Other kinds of black holes:**

- **supermassive black holes**: millions to billions times $M_{\text{sun}}$
  Exist at the center of most galaxies.
  Start small but grow large by swallowing gas, stars, and other black holes.
- **intermediate mass black holes**: masses around $\sim 1000$ times $M_{\text{sun}}$
  (Form like supermassive black holes, but less evidence for them)
Black holes: a prediction of general relativity

General relativity: a theory of gravity developed by Albert Einstein in 1915. In Newton’s theory of gravitation, gravity is a force acting between two objects. According to Einstein, gravity is manifested as the curvature of space and time around an object.
What is the curvature of space?

Geometric properties and measurements tell us if space is curved.
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How can 3-D space be curved?

In what sense is time “curved”?

Clocks tick at different rates in a gravitational field.
A black hole is made of **nothing**. It is a region where the gravitational field is extremely strong. It is composed entirely of the warpage of space and time.

The **event horizon** is the surface of a black hole. It is not a physical surface, but a one-way boundary in space and time.
What happens near a black hole?

(General relativity predicts these effects near all massive bodies, not just black holes.)

1. Precession of orbits:
What happens near a black hole?

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2. Gravitational lensing
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3. strong tidal forces (spaghettification):

![Diagram showing tidal forces near a black hole](Image)
If black holes are black, how can we see them?

As matter nears a black hole, it moves more quickly, and collisions between atoms cause it to get very hot.
There is strong evidence that black holes exist:

The strongest evidence for black holes result from measurements of lots of mass contained within a small region.

\[ T = \text{orbit period} \]

Kepler’s 3\textsuperscript{rd} Law

\[ \frac{2\pi}{T} = \sqrt[3]{\frac{M_{\text{star}} + M_{\text{blackhole}}}{r^3}} \]

\(~ 20 \text{ candidate stellar-mass black holes with } M \sim 5-20 M_{\odot} (15-60 \text{ km})\)
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Motion of stars around the Milky Way’s central black hole (SagA*)
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Motion of stars around the Milky Way’s central black hole (SagA*)

[ video from Reinhard Genzel ]

[-10 light days-]
There is strong evidence that black holes exist:

Applying Kepler’s law to the motion of these stars implies a central mass of $4 \times 10^6 \, M_{\text{sun}}$.
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Powerful jets also indicate the presence of a black hole:
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Gravitational Waves:

Gravitational waves are ripples in the gravitational field, distortions in space and time that travel away from a source at the speed of light.

Binary black holes are the strongest source of gravitational waves.
Gravitational Waves:

We know that gravitational waves exist because of measurements from binary pulsars.
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Detecting Gravitational Waves:

A gravitational wave passing perpendicular through this screen has the following effect on a ring of freely-floating test masses:

Several instruments are currently trying to detect these waves.
Detecting Gravitational Waves:

Bar detectors:

passing gravitational waves vibrate the bar
Detecting Gravitational Waves:

LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA
Detecting Gravitational Waves:

LIGO: Laser Interferometer Gravitational-wave Observatory

Livingston, LA
Detecting Gravitational Waves:

LIGO: Laser Interferometer Gravitational-wave Observatory
Detecting Gravitational Waves:

LISA: Laser Interferometer Space Antenna
Gravitational Waves:

1. Two black holes start some distance apart, orbiting around each other. The yellow lines show the contours of their gravity fields.

2. As the black holes (zoomed-out view) spiral inward, weak gravitational waves (red) are released.

3. Stronger waves are released as the black holes get closer.

4. An intense burst of gravitational waves occurs when the cores of the black holes merge.

5. The resulting black hole, below, is flattened because it is spinning very quickly (zoomed-in view).

Gravitational waves:
Four percent of the two hole’s mass becomes gravitational waves. This power output is more than that of all the stars in the universe combined.

Merged holes:
When two black holes merge, they fasten into one larger hole that spins 70 times as fast as Earth.

Speed:
Traveling at the speed of light, gravitational waves never stop, just weaken with distance.

A Space-Time View:
Gravitational waves are ripples in space and time, a four-dimensional concept that Einstein called space-time. The waves are caused by vowing events in the distant universe.

Detecting Waves:
The successful calculation of the shape and pattern of gravitational waves gives scientists at two LIGO sites, in Washington and Louisiana, a blueprint of what to look for.
5 things to remember:

1. Black holes are predictions of Einstein’s theory of general relativity, which describes gravity, not as a force, but as the curvature of space and time.

2. Black holes act like one-way membranes from which nothing can escape.

3. Although they have several weird properties, observations strongly support their existence.

4. Gravitational waves are vibrations in the gravitational field that travel at the speed of light. Strong gravitational waves are generated by the rapid motions of very dense objects (like black holes).

5. We know gravitational waves exist because of the binary pulsars. LIGO will directly detect those waves for the and determine if black holes behave as Einstein predicted.