Chapter 22:
Neutron Stars and Black Holes

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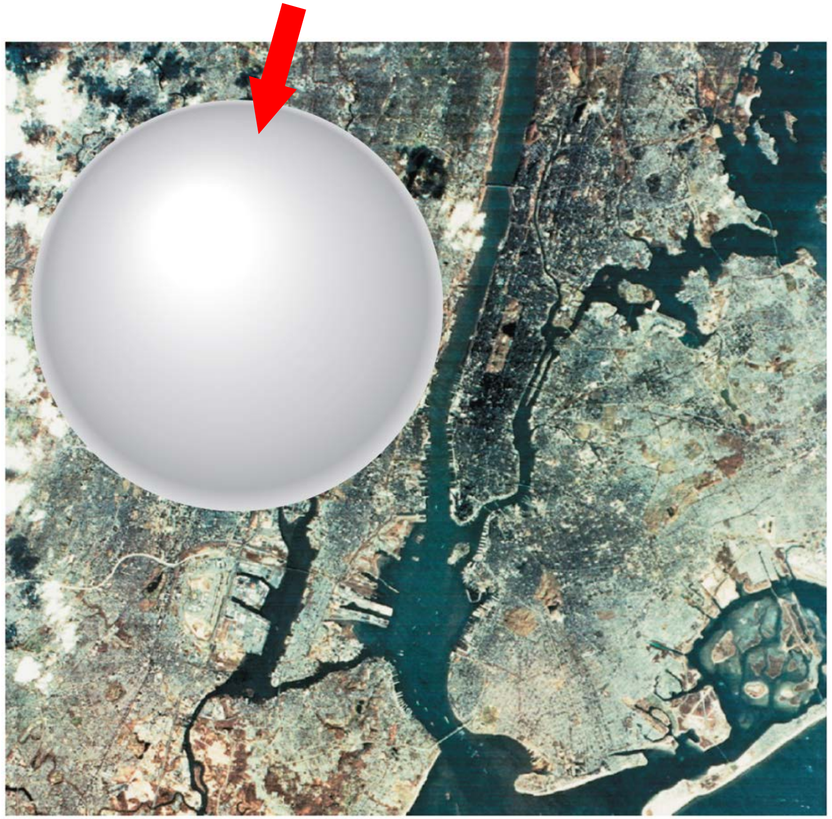
Compact Objects

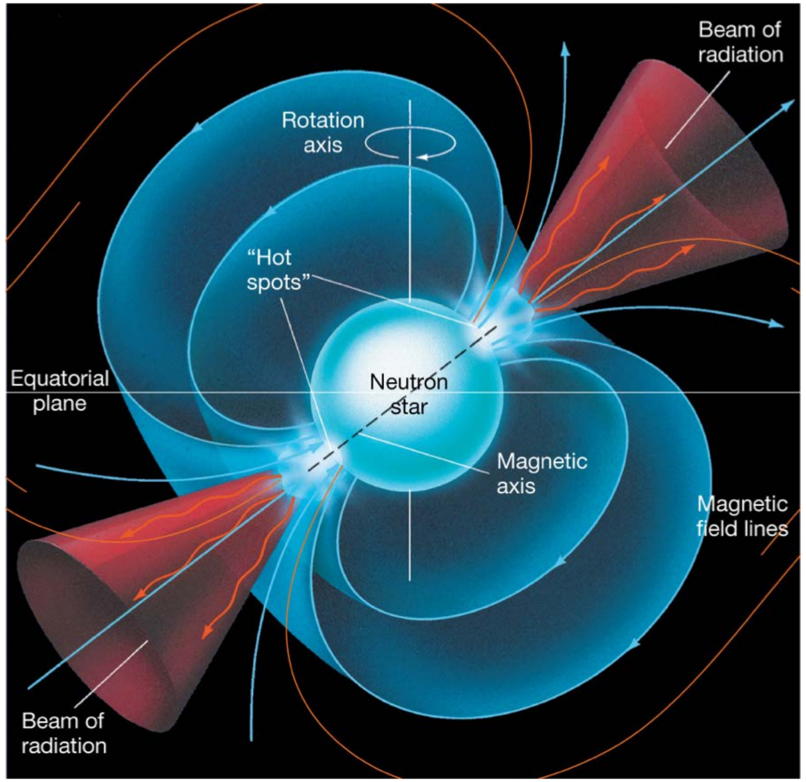
- Recall that heavy stars (masses $> 8M_{\odot}$) will form either neutron stars or black holes.
  - We call these, generally, as **compact objects**.
- A typical neutron star, with a remnant mass of about $1.5M_{\odot}$, will have a radius of 10km.
  - A thimbleful could be ~100 million tons; the mass of a sizeable mountain on Earth.
- A black hole will have a smaller radius than a neutron star, and be even more compact.
  - A $1.5M_{\odot}$ black hole will have a “radius” of 7.5km.
- Compact objects are produced by Type II supernovae. (Type I destroy any remnant.)

I think this is a radius of 20km, though the point is still made.



Neutron Stars

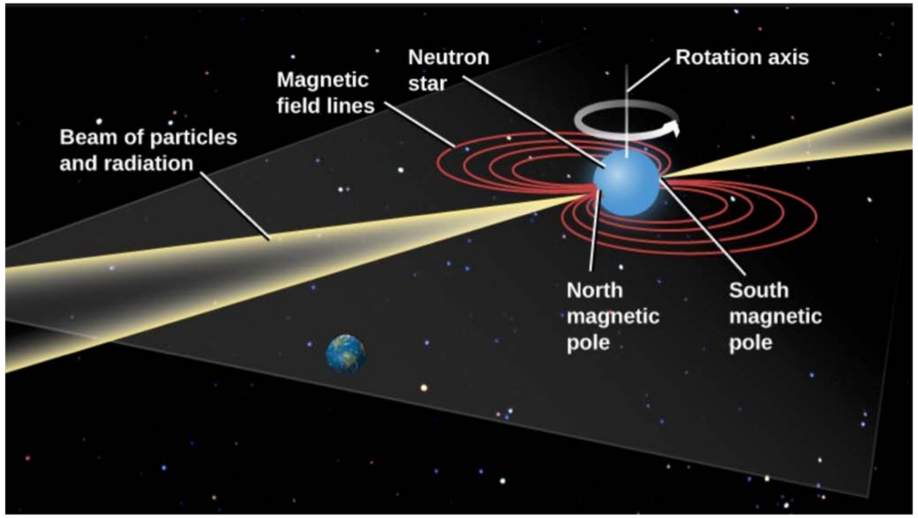
- Neutron stars have the following properties:
  - **Rapidly rotating**: rates of several hundred rotations per second, caused by **angular momentum conservation**.
  - **Extremely hot**: surface temperatures of around 600,000 K (100 times the Sun).
  - **Strong magnetic fields**: common strengths are between 10^8 and 10^{15} times the Earth's.
  - **Radiation jets**: charged particles moving along magnetic field lines emit radiation in a beam.
  - **Axis tilt**: there is an angle between the rotation axis and the magnetic field axis.

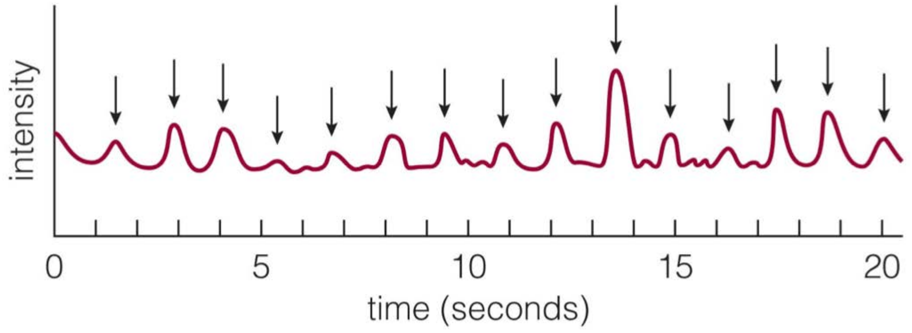


Pulsars

https://www.youtube.com/watch?v=71u13n93-Hs

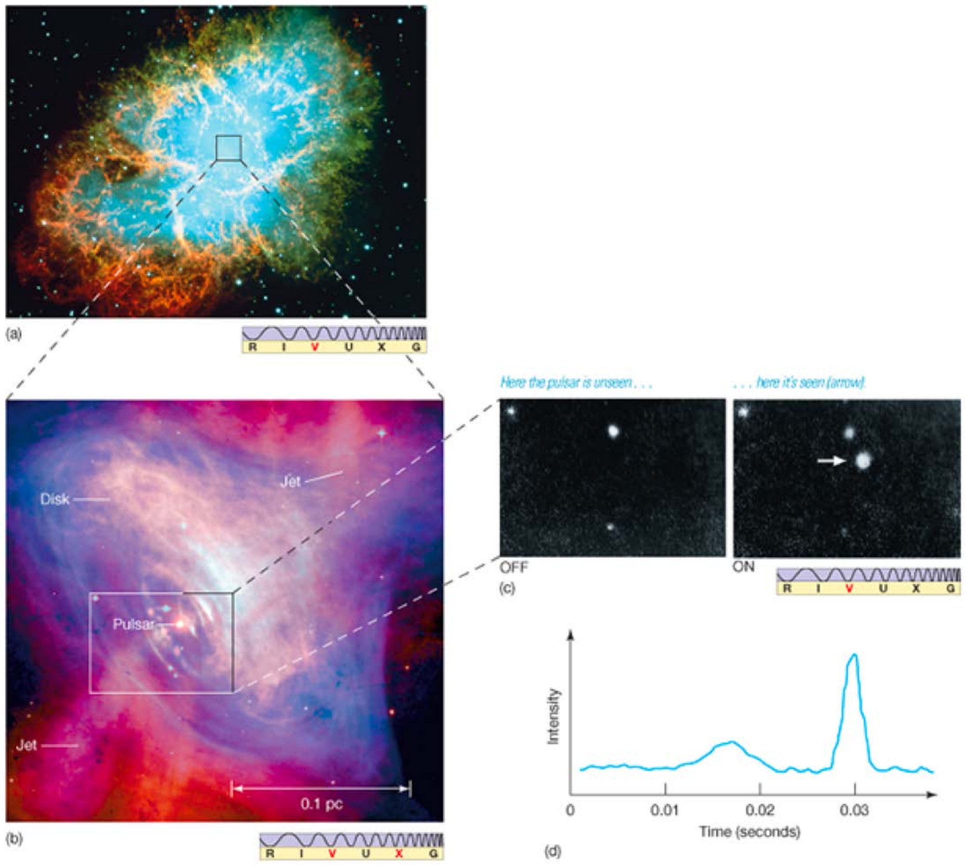
- The axis tilt of a neutron star causes **precession**.
- Precession can lead to appearance and disappearance of the radiation beam on Earth.
  - This lead to the name **pulsar** for these objects, since they seemed to pulse in and out of existence.
- Pulsars will flash with an **extremely consistent** period. (More consistent than atomic clocks.)
  - Periods range from milliseconds to seconds.
- This description of a pulsar is known as the **lighthouse model** of a pulsar.





Pulsars and Neutron Stars

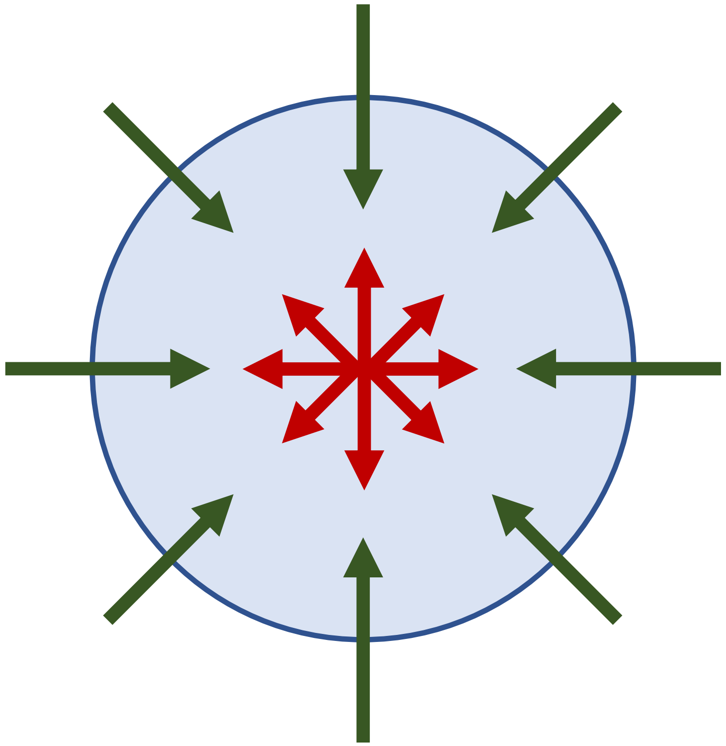
- It is believed that all neutron stars are, or were at some time, pulsars, though not all neutron stars are observed to be pulsars.
- There are **two main reasons** why a neutron star is not a pulsar:
  - The radiation beam is not along our line of sight, so we never see the pulsar.
  - The neutron star has radiated so much energy that it slows down and its magnetic field dies, causing the pulses to die off.



Why are Black Holes Produced?

- The inward gravitational pressure depends on mass. The larger the mass, the larger the gravitational pressure.
  - If remnant mass $> 3M_{\odot}$, a black hole is formed!
- In healthy stars, gravitational pressure is balanced by outward thermal pressure due to fusion. In dying stars, outward pressure is generated by quantum mechanical effects in white dwarfs and neutron stars.
- If the mass is too large, the gravitational pressure will be larger than any quantum mechanical pressure, and the mass will collapse in on itself. The forms a black hole.

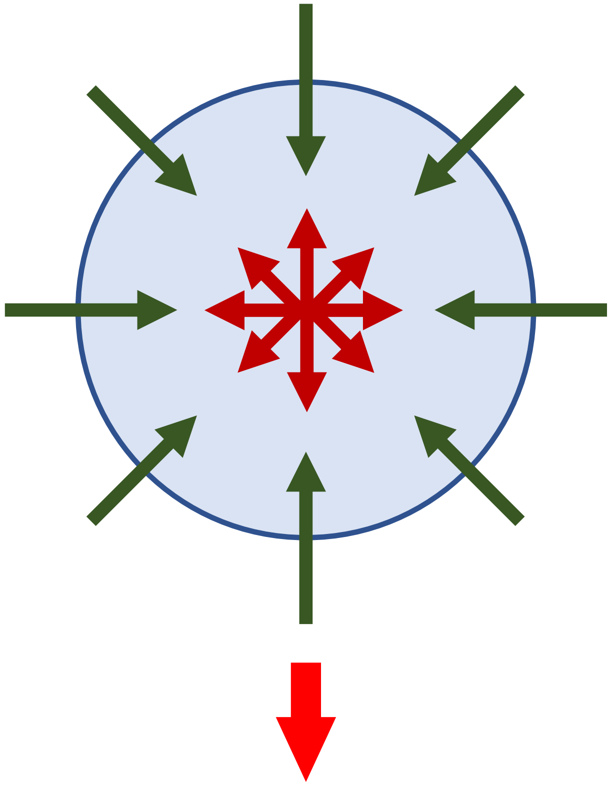
Inward gravitational pressure
=
outward pressure



What is a Black Hole?

- A (classical) black hole is formed when all the mass of a star is crushed down to a single point due to gravity.
  - This single point has zero volume and an infinite density.
  - This point is known as a **singularity**.
- Because we have no theory of quantum gravity, we **don't know what happens inside a black hole or near the singularity**.
  - We can only guess based on our current theories.

Inward gravitational pressure is much larger than **outward pressure**

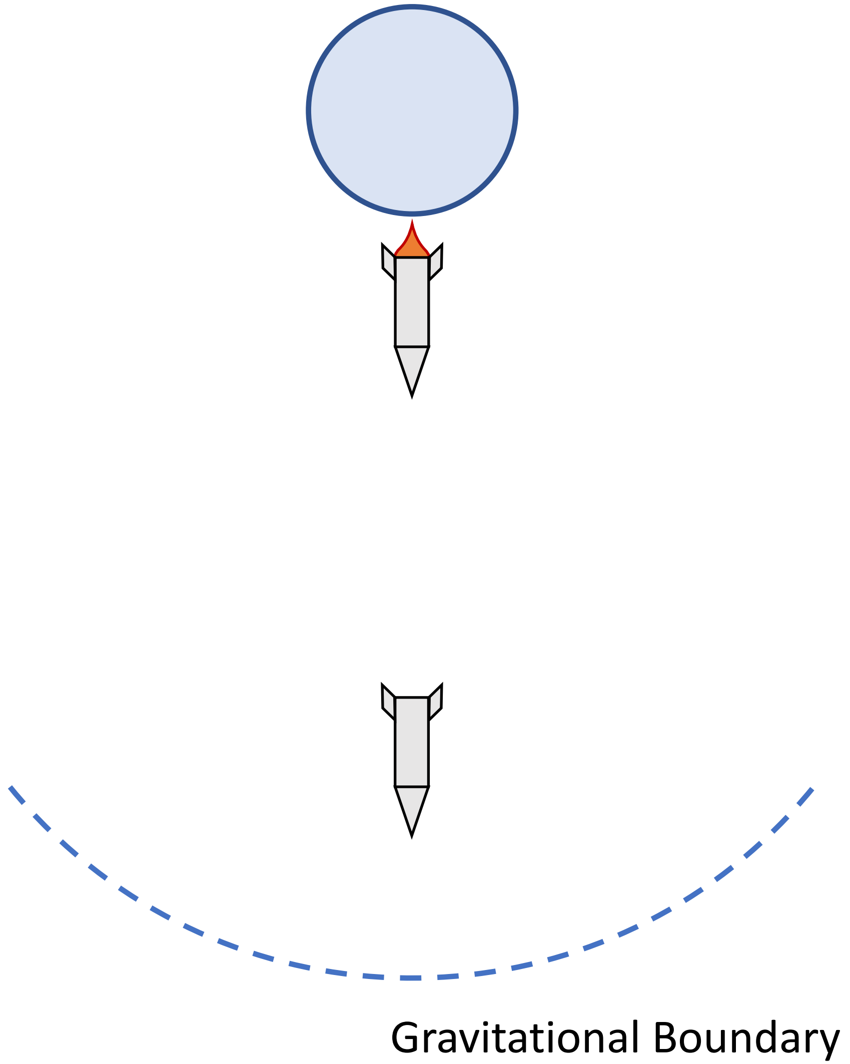


Inward gravitational pressure collapses the mass to a single point

known as a singularity.

Escape Velocity

- Imagine a spaceship taking off from some planet. It fires its engine for a brief period of time, gathering some velocity, and then coasting the rest of the way.
- As the ship moves away from the planet, the planet's gravity constantly pulls on the ship, slowing it down.
- Imagine some invisible boundary, beyond which gravity no longer acts on the ship. For the ship to reach and cross this boundary, it needs to have some minimum speed when it left the planet.
- This minimum velocity is known as the **escape velocity** of the planet. It depends on the mass of the planet; the larger the mass, the higher the escape velocity.



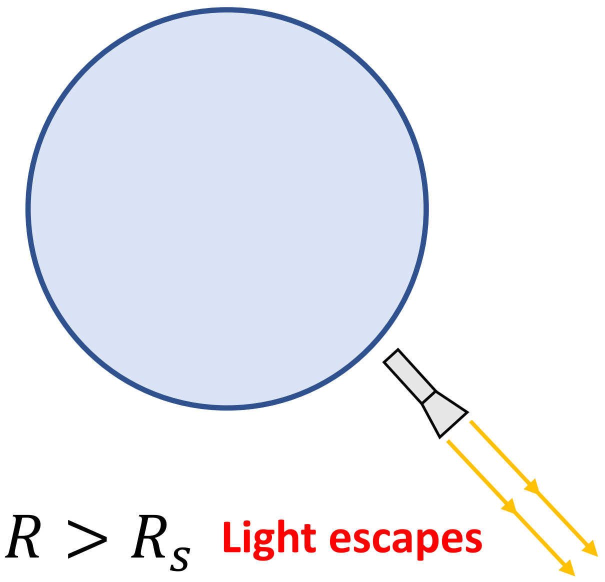
Escape Velocity and Black Holes

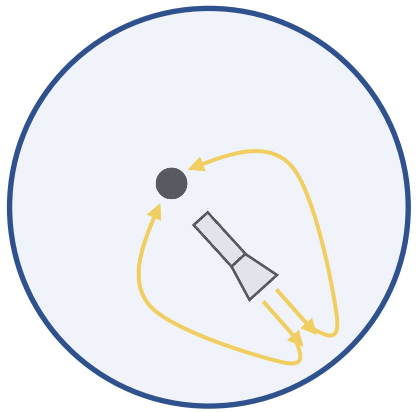
- A black hole is a star with an escape velocity faster than the speed of light.
- Black holes are black because light cannot escape them!
- There is a maximum radius that a black hole can have, known as the **Schwarzchild radius**, R_s. Any star with a radius less than R_s will be a black hole.

$$R_s = 3M$$

Radius in km

Mass in units of $M_{\odot}$





No Hair Theorem

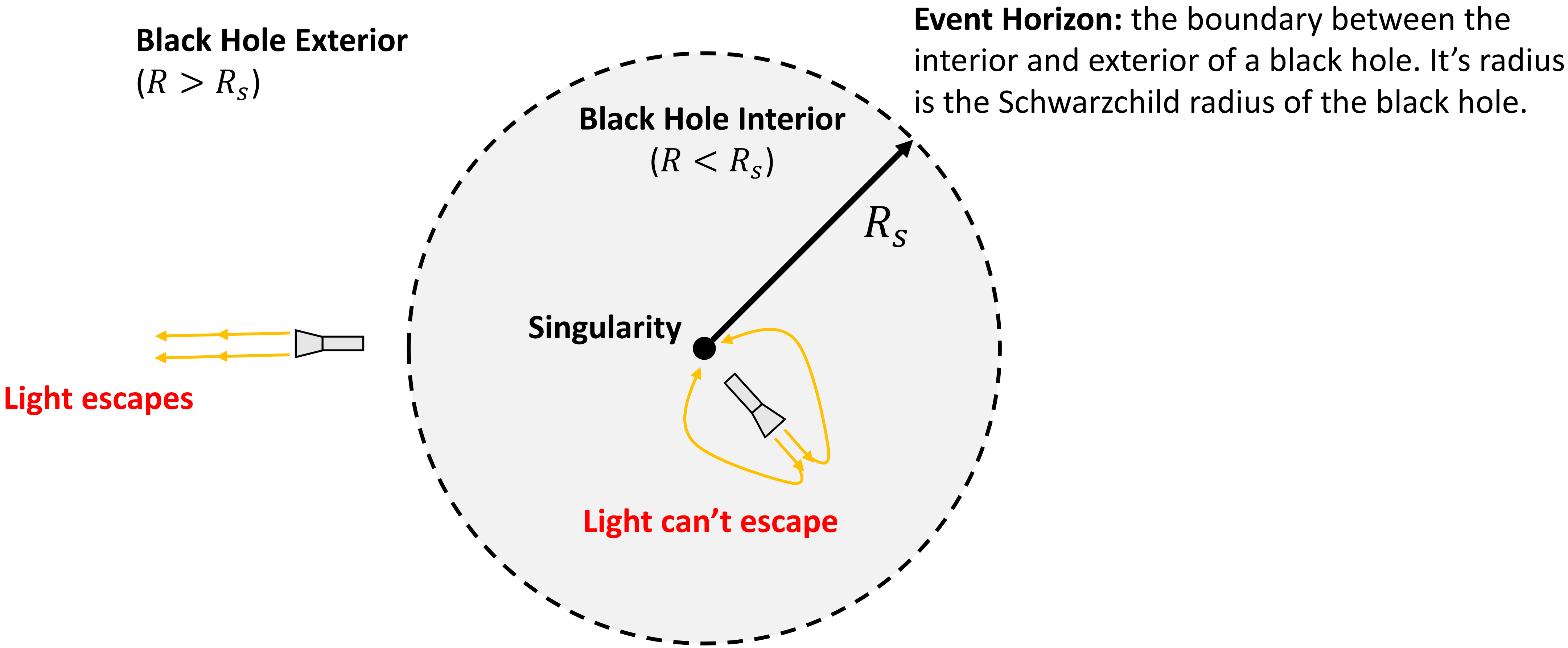
- "Black holes have no hair"
- Black holes are featureless other than for **3 variables**:
  - Mass, M
  - Rotation rate, a
  - Electric charge, Q
- If there are two black holes, each with the same mass, rotation, and charge, they would be impossible to tell apart from one another.

4 types of black holes:

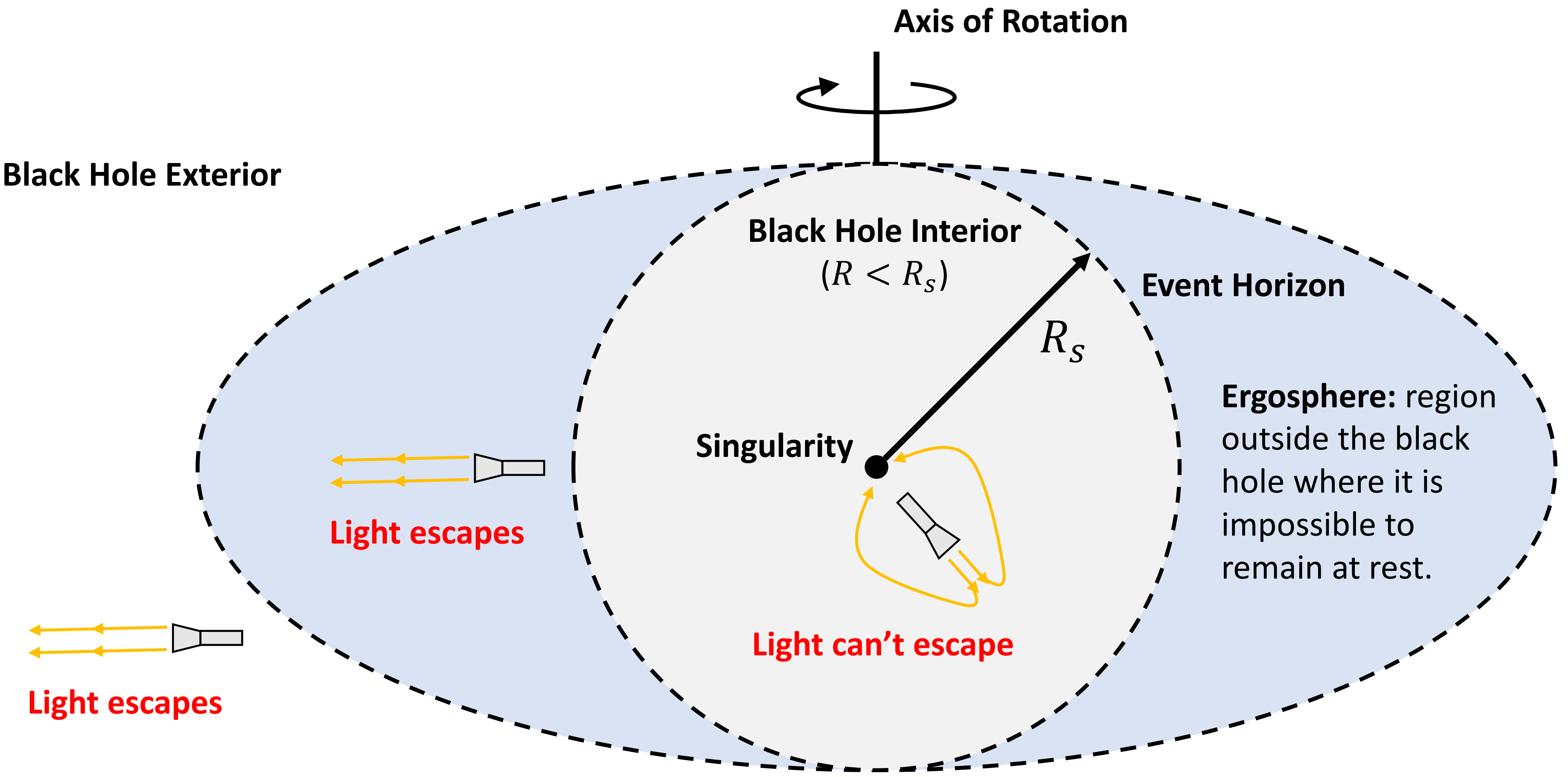
	$Q = 0$	$Q \neq 0$
$a = 0$	**Schwarzchild Black Hole**	**Reissner-Nordstrom Black Hole**
$a \neq 0$	**Kerr Black Hole**	**Kerr-Newman Black Hole**

The 2 that are important to know!

Structure of a Schwarzchild Black Hole



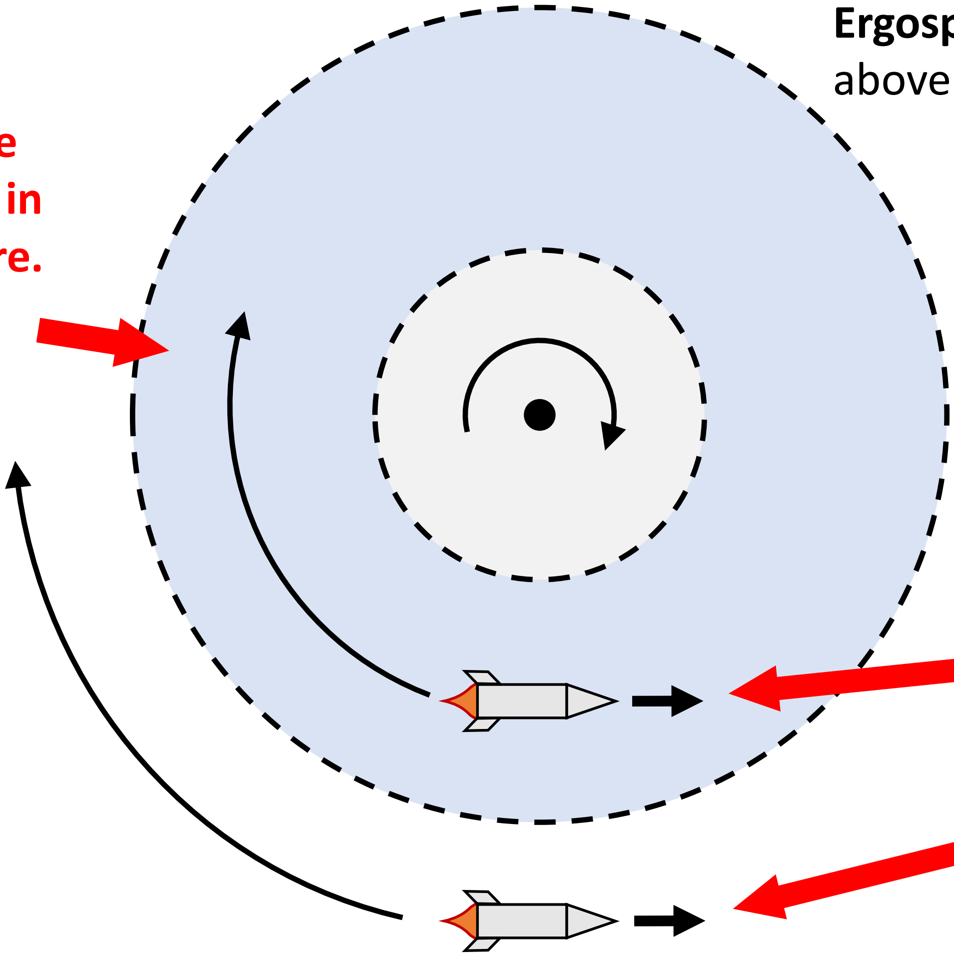
Structure of a Kerr Black Hole



The Ergosphere

Ergosphere (viewed from above the rotational axis)

The rotation of the ergosphere causes the ship to be dragged in an orbit around the ergosphere. This happens both inside and outside the ergosphere.



If the ship fires its engines, it can move forward and counteract the dragging effect of the ergosphere. Inside the ergosphere, the ship would have to go faster than the speed of light to remain still. Outside the ergosphere, the ship would need to go slower than the speed of light to remain still.

Since nothing can move faster than the speed of light, it's impossible to remain still inside the ergosphere!