Chapter 12:
Black Holes

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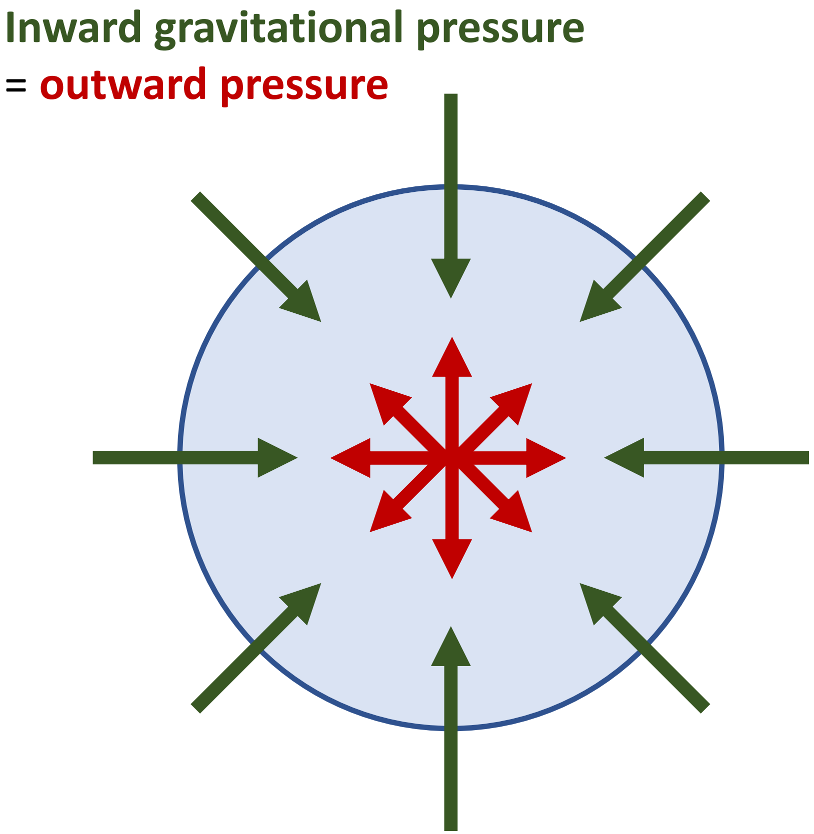
End Product of Stellar Evolution

- Recall that gas fragments with very low mass ($M < 0.08M_{\odot}$) produce brown dwarfs, which aren't stars since they don't burn hydrogen.
- Gas fragments with low mass ($M < 0.4M_{\odot}$) produce red dwarfs, which are fully convective stars that die "gentle" deaths.
- Gas fragments with high mass ($M > 0.4M_{\odot}$) produce main sequence stars, which die "violent" deaths: stellar explosions, such as planetary nebulae and supernovae.
    - After a stellar explosion, if the mass is below the Chandrasekhar limit ($1.4M_{\odot}$) a white dwarf is produced. If the mass is above the Chandrasekhar limit but above the Tolman-Oppenheimer-Volkoff limit ($3M_{\odot}$) a neutron star is produced. If the mass is greater than the TOV limit a black hole is produced.

Why are Black Holes Produced?

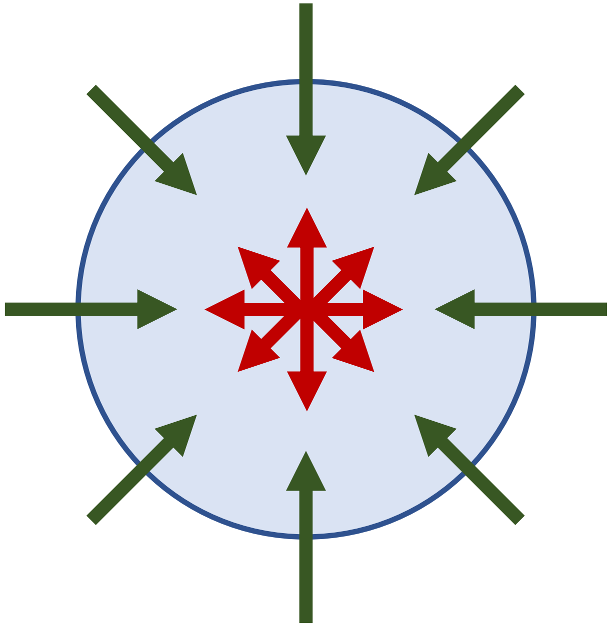
- The inward gravitational pressure of a star depends on its mass. The larger the mass, the larger the gravitational pressure.
- In healthy stars, gravitational pressure is balanced by outward thermal pressure due to fusion. In dying stars, outward pressure is generated by quantum mechanical effects 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.



What is a Black Hole?

- A 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**.

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

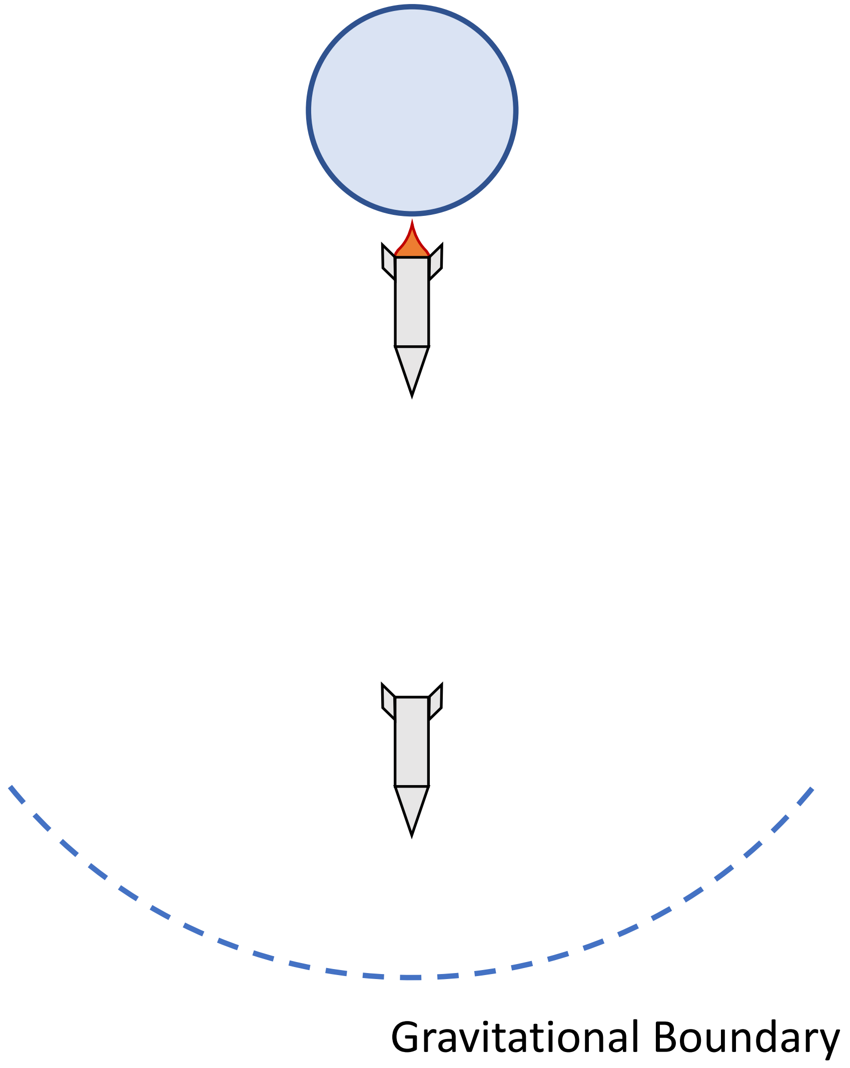


Inward gravitational pressure collapses the mass to a single point

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.



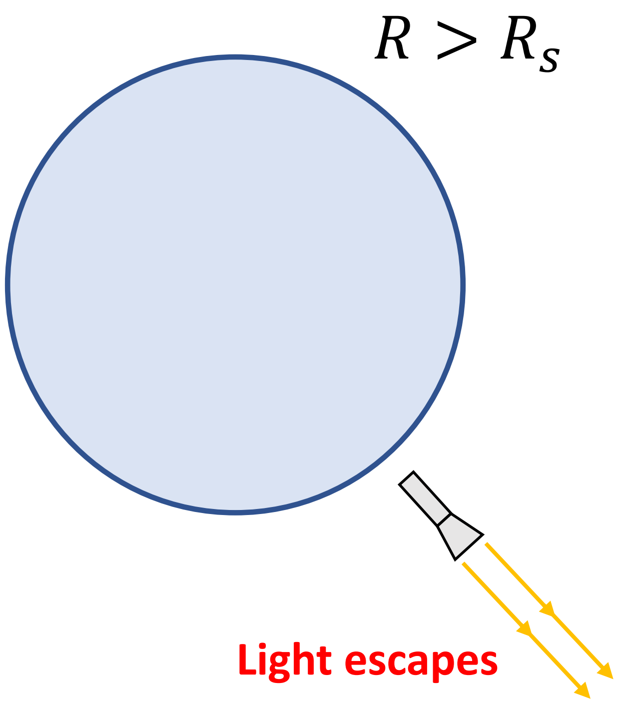
Escape Velocity and Black Holes

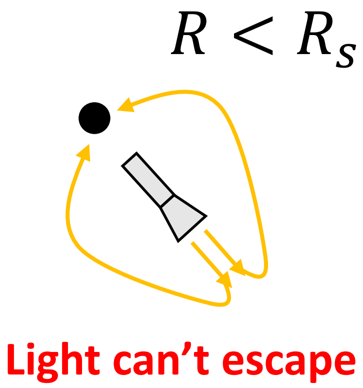
- A black hole is a star with an escape velocity faster than the speed of light.
- Black holes are black because light cannot escape them!
- There is a maximum radius that a black hole can have, known as the **Schwarzchild radius**, R_s. Any star with a radius less than R_s will be a black hole.

$$R_s = 3M$$

Radius in km

Mass in units of $M_\odot$





No Hair Theorem

- “Black holes have no hair” – this means that black holes are basically featureless.
- Black holes are completely described by three 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.

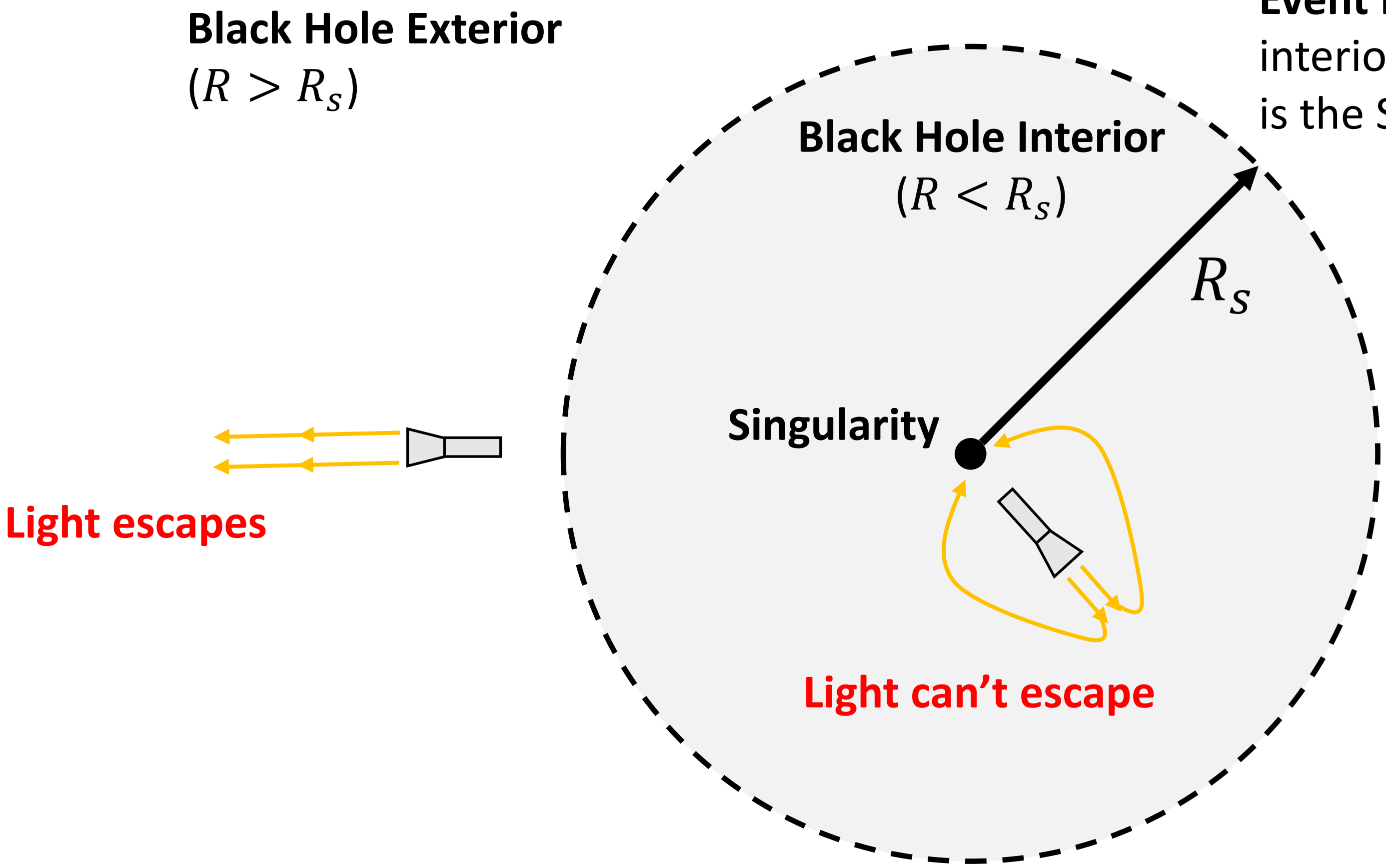
Types of Black Holes

- All black holes have mass, since they are just stars that have collapsed in on themselves.
- Thus, there are four types of black holes:

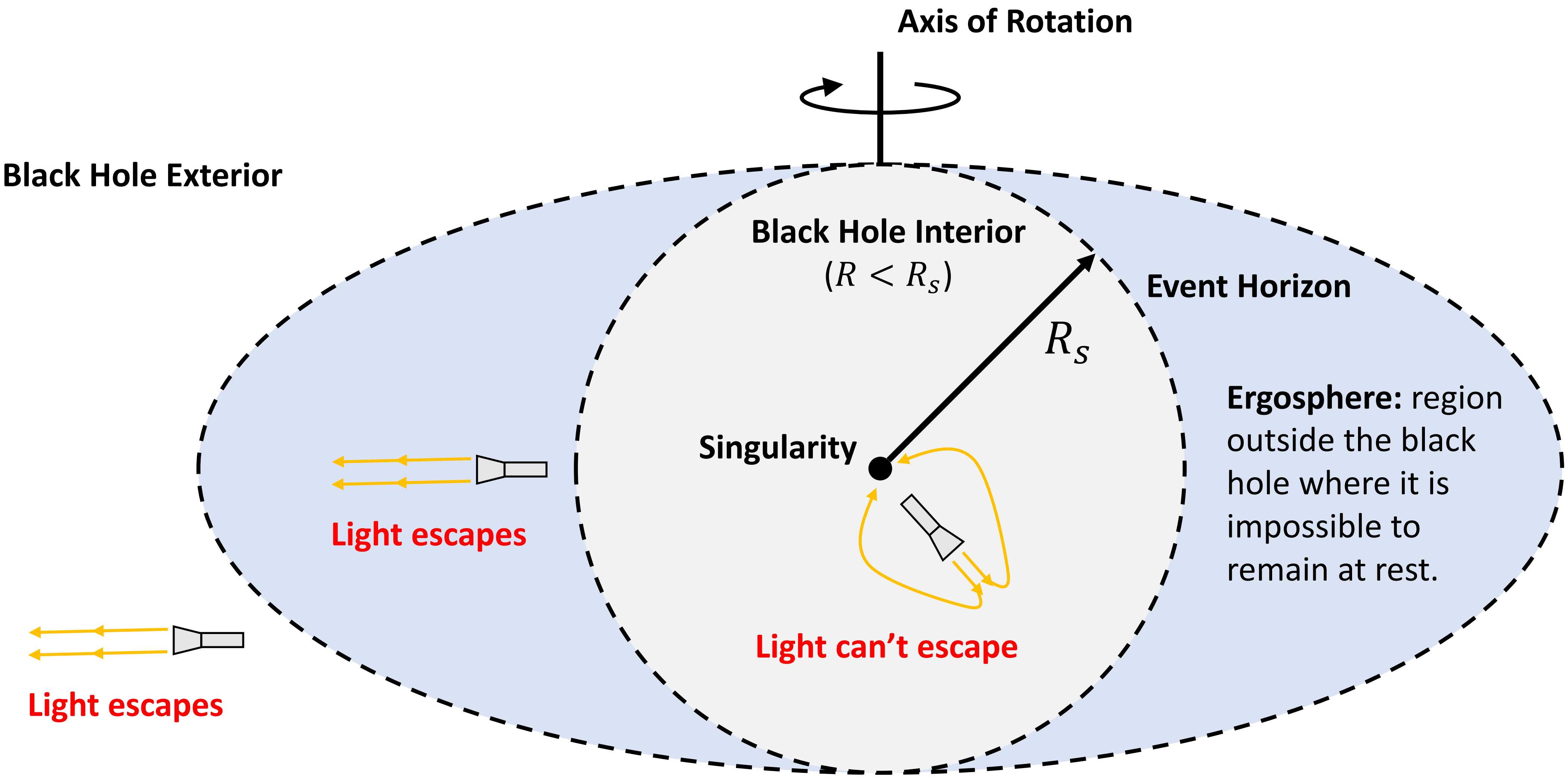
	$Q = 0$	$Q \neq 0$
$a = 0$	**Schwarzchild Black Hole**	**Reissner-Nordstrom Black Hole**
$a \neq 0$	**Kerr Black Hole**	**Kerr-Newman Black Hole**

Structure of a Schwarzchild Black Hole

Event Horizon: the boundary between the interior and exterior of a black hole. It's radius is the Schwarzchild radius of the black hole.

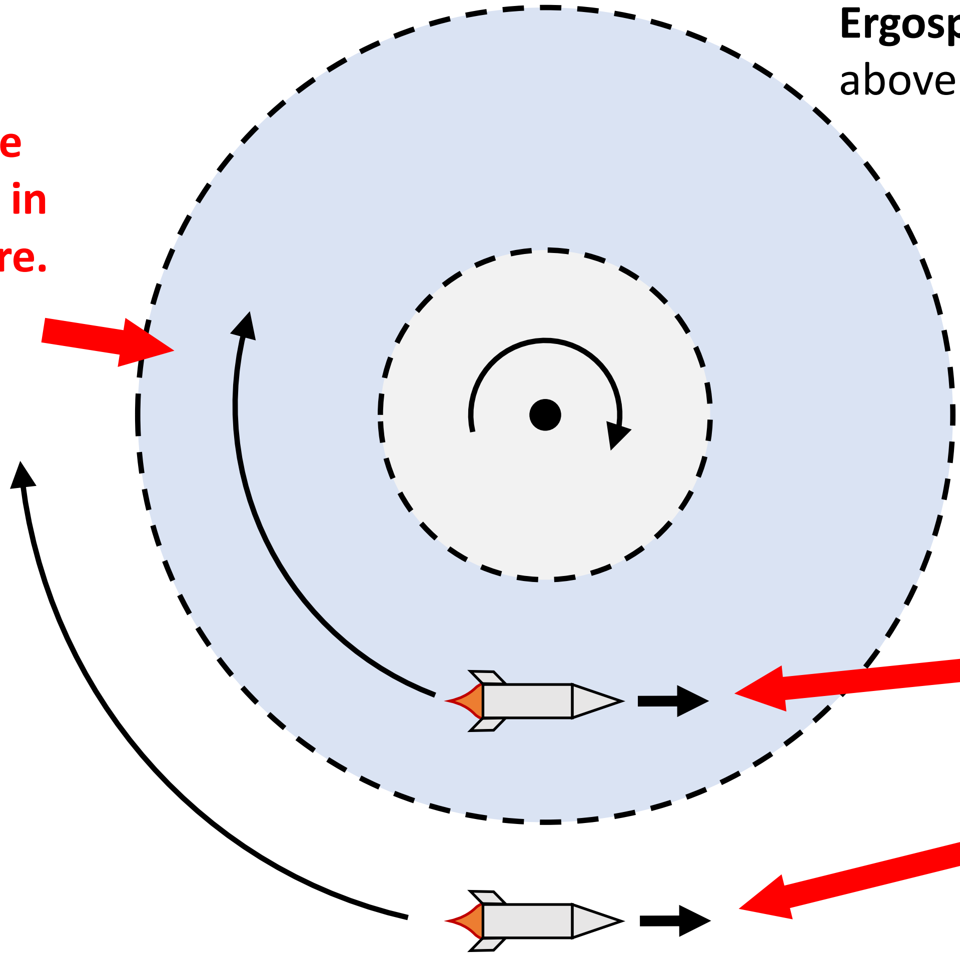


Structure of a Kerr Black Hole



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!