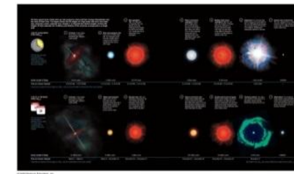
The Endpoint of Stellar Evolution

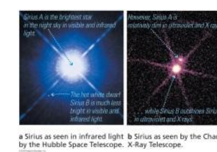
Today we want to examine the possible endpoints of stellar evolution:
White dwarfs, Neutron Stars, and (the most bizarre) Black Holes.



At the end of the previous chapter, your author gives this excellent summary – you won't be able to read it on the screen; see your text.

White Dwarfs:

- **White Dwarfs are the endpoint of stellar evolution for what type of star? (LC)**
  White dwarfs are the endpoint of stellar evolution for low mass stars, like the Sun.



- They are the product of Helium fusion, mostly Carbon and Oxygen, and are initially small and hot so they are faint in visible light, but are bright in UV and X-rays.

- There is no more fusion in a White Dwarf,
  so . . . what holds it up against further gravitational collapse?

White Dwarfs:

- **What holds a White Dwarf up against gravity?**
  - The star is made up of Carbon and Oxygen nuclei with free electrons.
  - At these extreme conditions, gravity is trying to squeeze the electrons into the same quantum state.
  - In quantum mechanics, particles like electrons can't be in the same state . . . *you've seen this in chemistry where the Pauli Exclusion Principle says that electrons can't be in the same state in an atom.*
  - In a White Dwarf, the electrons push back with what is called the **Electron Degeneracy Pressure** – this is what holds it up against gravity.

- **Is there a maximum White Dwarf Mass?**

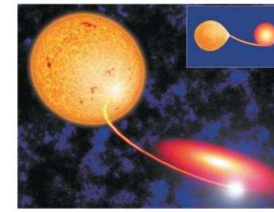
  Yes, for higher white dwarf mass, the electrons have to move faster and faster. When they reach the speed of light, the mass of the star can get no larger without something else happening. **The maximum white dwarf mass is:**

Chandrasekhar Limit ~ 1.4 M_{sun}

Subramanyam Chandrasekhar

- **If the white dwarf is not part of a close binary, its fate is to slowly cool and fade away, i.e. brightness will steadily decrease.**

White Dwarfs in Binary Systems

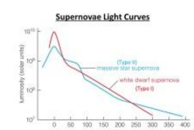


In a close binary system, tidal forces can cause matter to flow from one star to the other. In this case some interesting things can happen:

- **Classical Nova:**
  - Hydrogen is accreted onto the surface of the white dwarf where it is compressed and heated.
  - When it reaches fusion conditions, the hydrogen fuses to helium explosively causing the star to brighten considerably for a short time.
  - As the accretion of hydrogen starts again, the nova can repeat.

T. Coronae Borealis

- **White Dwarf (or Type Ia) Supernova:**
  - The accreting matter pushes the white dwarf over 1.4 M_{sun}.
  - This causes the Carbon to fuse explosively and destroy the white dwarf completely .
  - **WD (or Type Ia) supernovae** are distinguished from massive star (Type II) by a lack of Hydrogen absorption lines in their spectra.
  - However, WD supernovae are brighter, and play an important role in the discovery of **Dark Energy** (. . . more on this in a few weeks.)



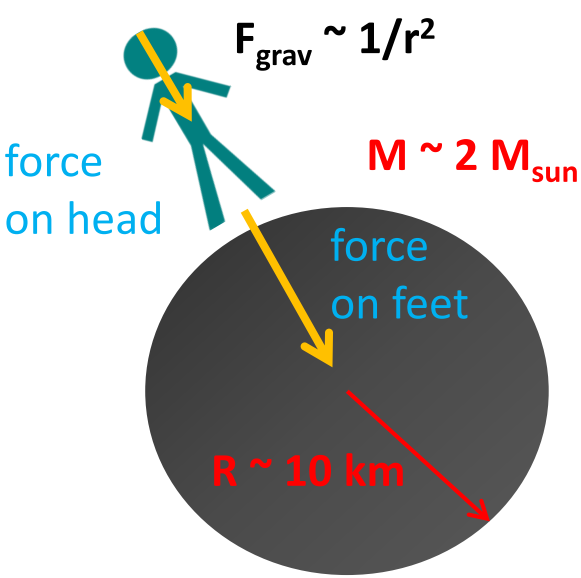
Neutron Stars

Recall that during a Massive Star (Type II) Supernova, the intense pressure during the core collapse produces:

Electron + Proton → Neutron + Neutrino

The neutrinos speed away carrying most of the energy – that leaves just neutrons, so, we have a star made up almost entirely of neutrons, **a Neutron Star.**

What is a Neutron Star like? Neutron Star density ~ 10^{15} g/cm^3



What is the most dense substance that you're familiar with? (LC)
(probably gold at 19.3 g/cm^3)

What happens to someone who gets near a Neutron Star?
Force on feet >> force on head, i.e. tidal forces!

These tidal forces would rip him apart:
Near NS surface: F_{tide} ~ (weight on Earth) X 10^{11} !!!!

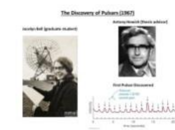
Neutron Stars

What holds a Neutron Star up from further gravitational collapse?

- Neutrons, like electrons, are particles that can't occupy the same quantum state – they push back with **Neutron Degeneracy Pressure**.

The Discovery of Neutron Stars:

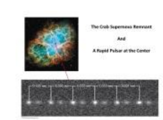
- Neutron Stars were first proposed in the 1930's, and due to their very small size, no one thought they could ever be observed.
- This changed in 1967 with the discovery of Pulsars, regular radio pulsations with period about 1 second by Bell and Hewish.



What are Pulsars?

- The only stellar object that could spin this fast is a neutron star.
- A neutron star formed in a supernova explosion should have a high spin rate and a large magnetic field.
- Radiation is beamed along the magnetic field axis, and if the spin axis is not aligned with the field, we see pulses.

- **Confirmed when they found 0.033s pulsar inside the Crab Nebula which is a known supernova remnant from 1054 AD.**



- What do Pulsars sound like?
- Now the scandal: in 1974 the Nobel prize in physics was awarded for the discovery of Pulsars. **Who received it? (LC)**

Hewish, not Bell

Black Holes

Is there an upper limit on the mass that a Neutron Star can have, like the Chandrasekhar limit for White Dwarfs?

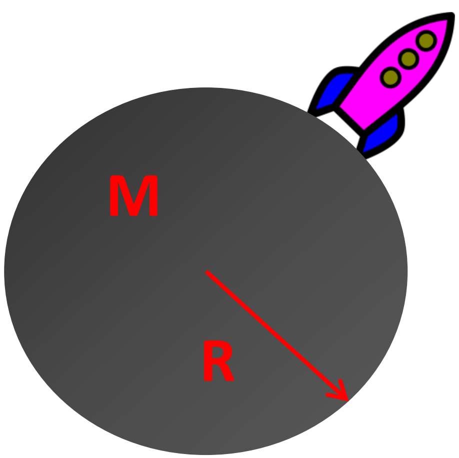
- Yes, but no one knows exactly what it is; it is believed to be somewhere between $3M_{sun}$ and $5M_{sun}$.

What happens if a 20 M_{sun} star explodes in a supernova, and more than 5 M_{sun} are left in the core?

- Nothing that we know of can provide a balance against gravity.
- The star shrinks to zero size and infinite density – **a Black Hole**.

Why is a Black Hole black?

- **Recall the Escape Velocity**: the minimum speed to escape an object.

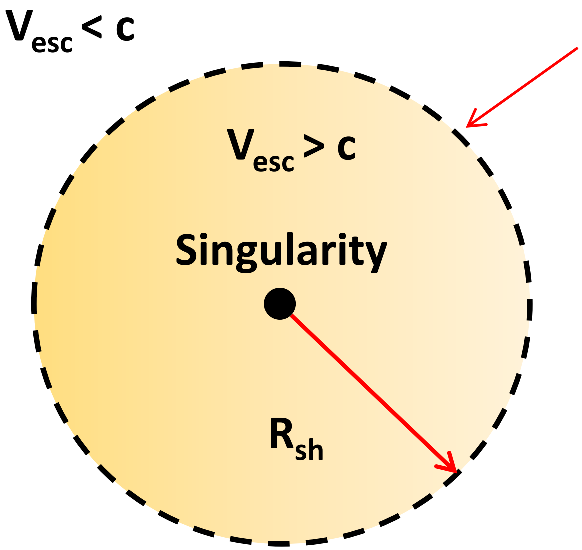


$$V_{\rm esc} = \sqrt{\frac{2GM}{R}}$$

- Earth: V_{esc} = 11.2 km/s
- White Dwarf: V_{esc} ~ 6500 km/s
- Neutron Star: V_{esc} ~ 1.6 X 10^5 km/s ~ c/2

As M increases and/or R decreases, V_{esc} approaches the speed of light, and nothing (not even light) can escape.

Structure of a Black Hole



Event Horizon is the spherical boundary around a black hole where $V_{esc} = c$.

Nothing from inside the event horizon can get outside the event horizon.

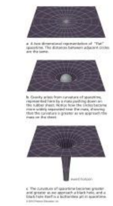
Radius of the Event Horizon is called the **Schwarzschild Radius**: for $M = 3M_{sun}$, $R_{sh} \sim 9$ km.

What's at the center of the black hole?
The Singularity, what does that mean?

- We have never observed the center of a black hole or anything inside the event horizon, so we don't really know what happens there.

- But, this is the point where **Einstein's General Relativity has to be combined with Quantum Mechanics to provide a description of the Singularity**. So presently, we can't even predict what happens at the Singularity.

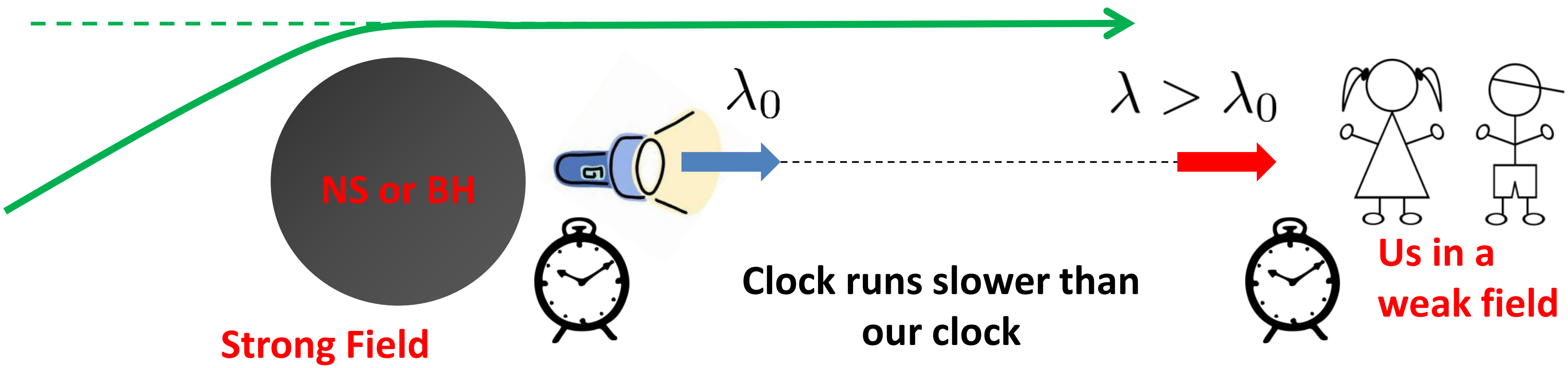
What Goes on Near a Black Hole?



To understand what happens near a black hole, we have to use Einstein's theory of gravity, **General Relativity** which describes gravity as a curvature of spacetime. *Can we visualize four-dimensional spacetime? Yes and No.*

The Mathematics of GR makes some definite unambiguous predictions for strong gravity that differ from Newtonian gravity:

1. **Gravitational Bending of Light**: light follows curved space.
2. **Gravitational Redshift:** light loses energy climbing out of gravitational field.
3. **Slowing down of Time**: clocks in a strong gravitational field run slow.



Which of these effects have been verified experimentally? (LC)

*All of them. Have you seen the movie "**Interstellar**"? It shows what gravitational time dilation can do.*

What would a black hole maybe look like?

<u>What Happens if you Fall into a Black Hole?</u>

Before we talk about what we would see watching someone go into a black hole, the poor guy going near a <u>stellar mass black hole</u> would be torn apart by tidal forces long before he could reach the event horizon.
Neil deGrasse Tyson has a nice description of this.

What happens if we watch someone go into a large black hole where the tidal forces would be small near the event horizon?

- Light from him would be redshifted as he approached the event horizon.
- His clock would be running slow compared to our clock.
- At the event horizon, we would see his clock stop, and the light from him would be infinitely redshifted.

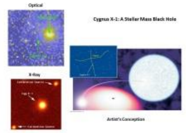
But what would he observe?

- In his frame, he would cross the event horizon – nothing special happens.
- He could see us all the time, albeit blue shifted, and he would see our clock run faster than his.
- Ultimately, he will be torn apart before he reaches the singularity.

Have Do We Observe Black Holes?

You might wonder, if black holes emit no radiation at any wavelength, how can we possibly observe them?

- **For stellar mass black holes**, we look for a close binary system that is emitting strongly in X-rays as matter from a normal star falls on an invisible massive companion.
- If the mass of the companion exceeds 3 to 5 M_{sun}, then it is likely a black hole. For example, Cygnus X-1 with a mass of ~15M_{sun}. Many of these stellar mass black holes have been found.

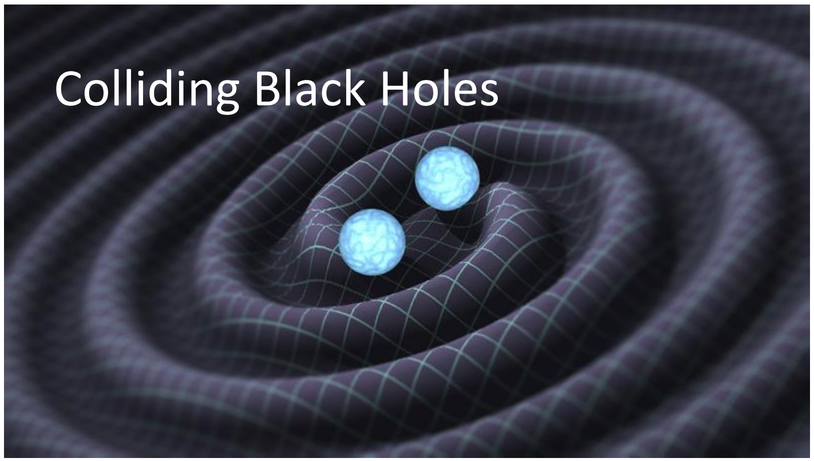


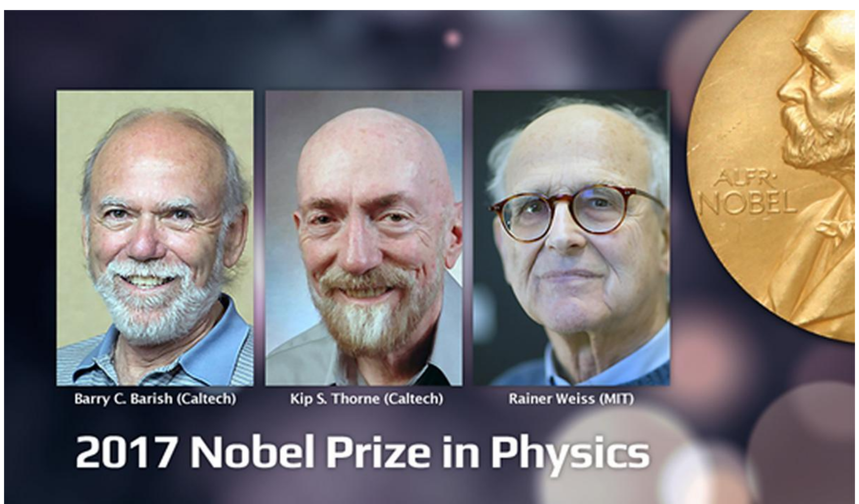
What are Supermassive Black Holes?

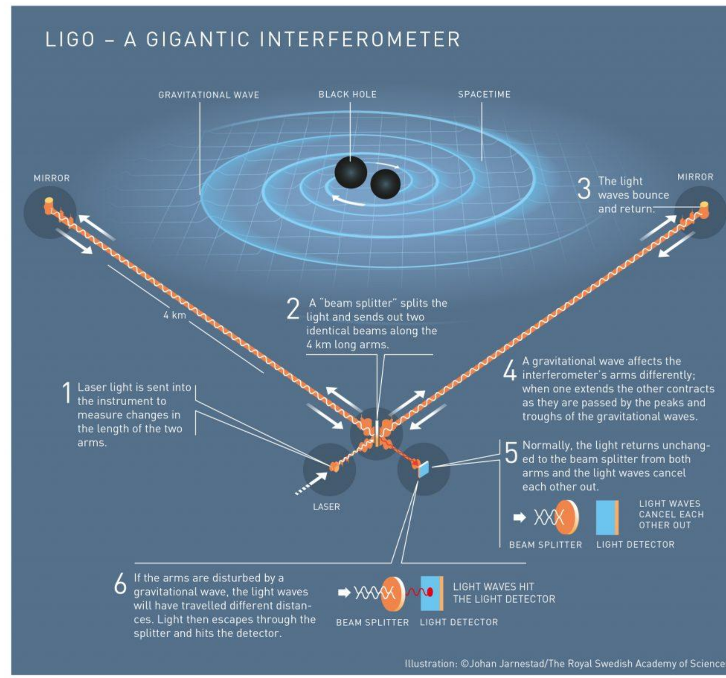
- During the last 25 years, it has been learned that **perhaps all galaxies contain a massive black hole at their centers**. For example, at the center of the Milky Way is a black hole with mass ~4 X 10^6 M_{sun} – we'll talk more about this after the exam.
- At the event horizon of these large black holes, the tidal forces would be just a small fraction of your weight on Earth. So you could cross it, and not even know it; **when would you realize it?**
- **When you tried to get out. Once you've crossed the event horizon, the singularity is always in your future!**

One More Thing About Black Holes: Gravitational Waves

- In 1916, Einstein predicted that waves in spacetime should exist – i.e. gravitational waves that oscillate both space and time.
- These would be very very difficult to detect – then came **LIGO in 2015**! (or Laser Interferometer Gravitational-Wave Observatory)

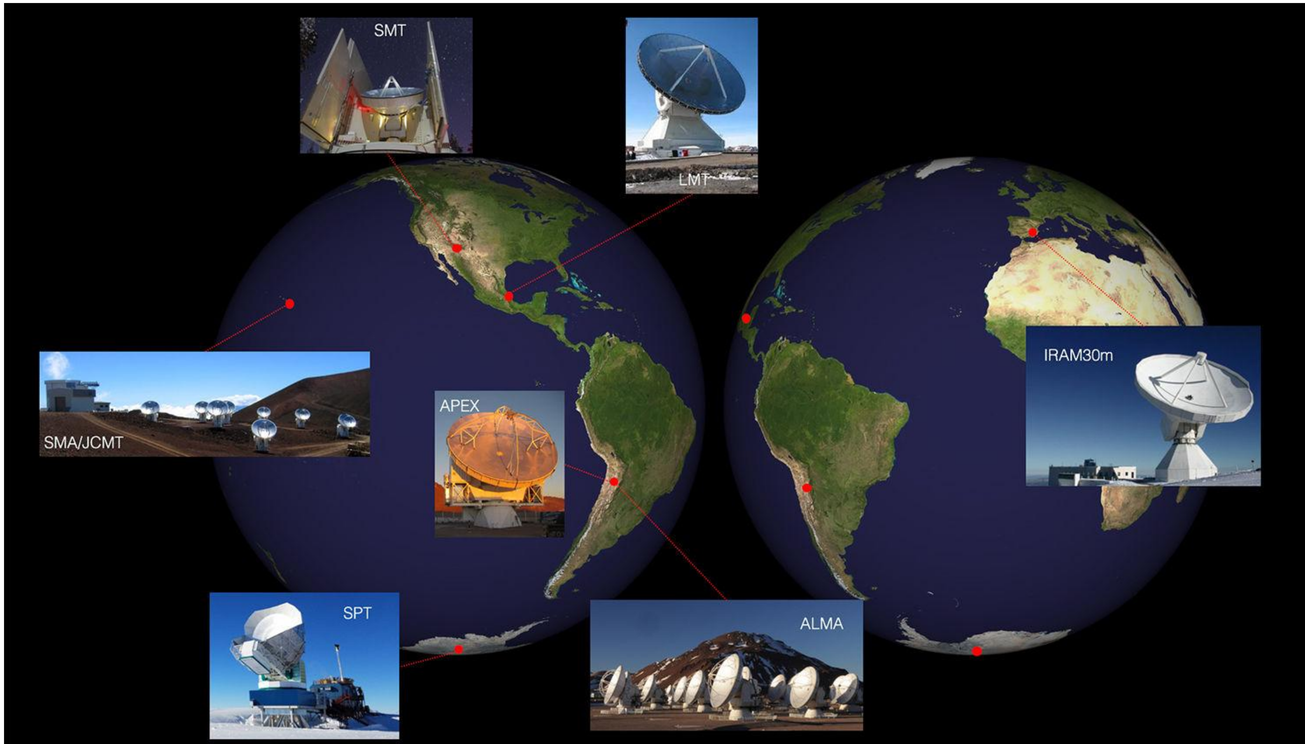






How does it work?

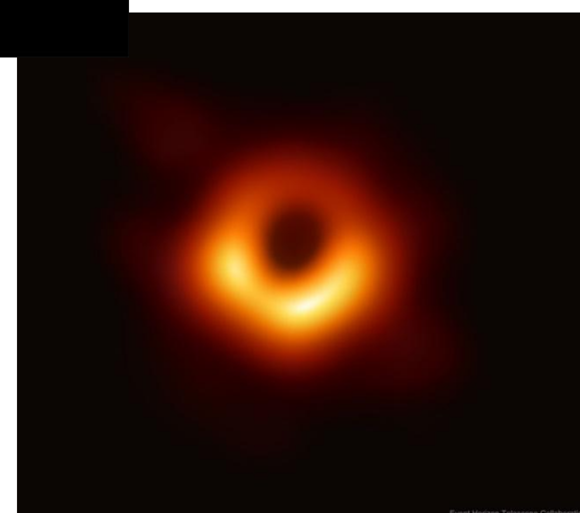
One Last Thing About Black Holes: The Event Horizon Telescope



EHT Array of Radio Telescopes (uses interferomtry)

The Image (actually shadow) of the the event horizon in the central BH of M87

(the BH mass ~6.5 billion solar masses, the EH is ~40 billion km in diameter and ~55 million ly away – so the angular size of the shadow ~4 X 10^{-9} degrees!)



How did they do it?