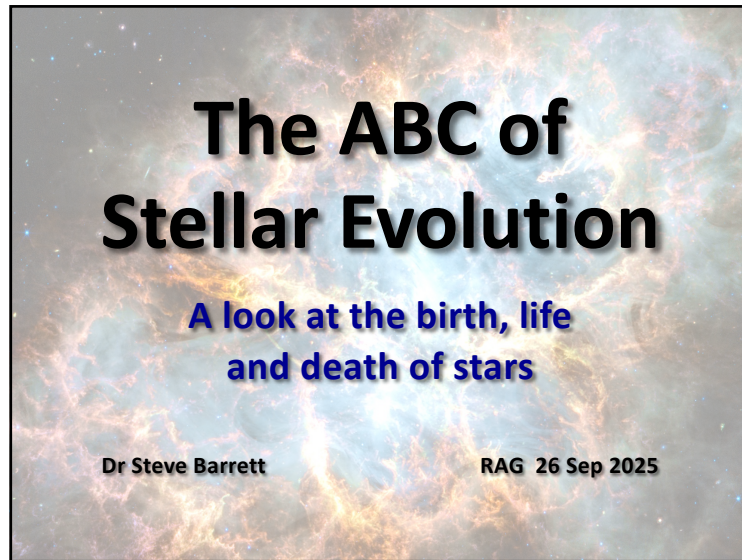


The ABC of Stellar Evolution

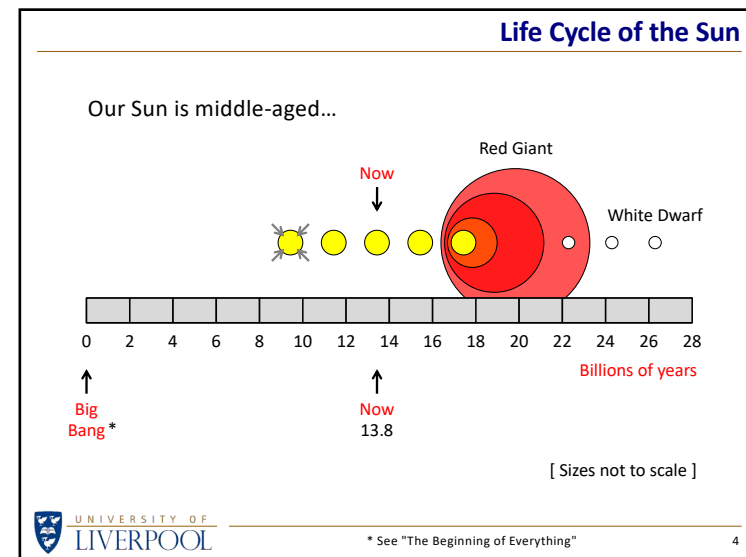


Contents

Birth	At the Heart of the Matter	Nuclear Fusion
	Where Do Stars Come From?	Ignition
Life	A Question of Balance	Radiation v Gravity
	Live Fast, Die Young	Star Types
	When the Fuel Runs Out	New Elements
Death	Bang or Whimper?	Supernova
	What's Left Afterwards?	Neutron Star
	When Gravity Wins	Black Hole

UNIVERSITY OF LIVERPOOL

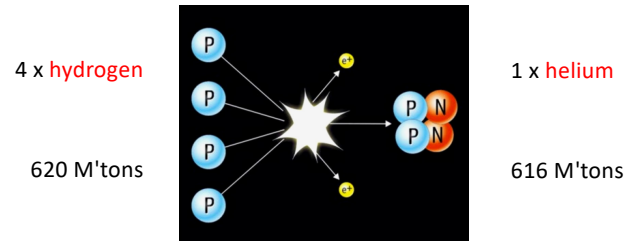
3



The ABC of Stellar Evolution

At the Heart of the Matter

In the core of a star, where the pressure and temperature conditions are right, the fusion of hydrogen into helium releases energy.



Fusion

Stars are not just nature's way of lighting up the universe ...

they are the "**fusion factories**" that make the elements heavier than hydrogen.

BUT ...

Where does the **hydrogen** come from in the first place?

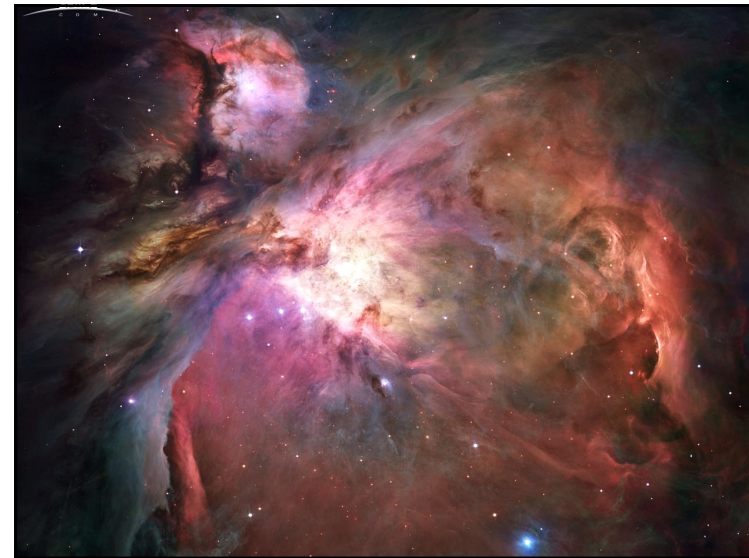
That's a very good question, but the answer is a bit too long to cover here and is the subject of a different talk.*

Star Formation

Where do stars come from?

Anyone can make a star in 5 easy-to-follow steps ...

1. **Start with a big cloud of hydrogen**
2. **Wait ...**
3. **Wait some more ...**
4. **Wait a bit longer ...**
5. **You now have a star**



The ABC of Stellar Evolution

What Triggers Star Formation?

Giant Molecular Clouds float around the galaxy

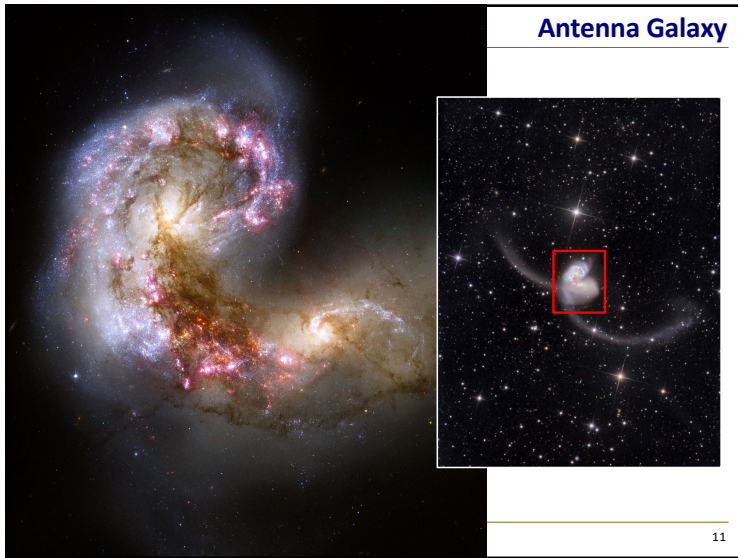
- They look like clouds
- They consist mainly of hydrogen molecules
- They are big (~100 light years across)

What makes a GMC collapse? Triggers may include ...

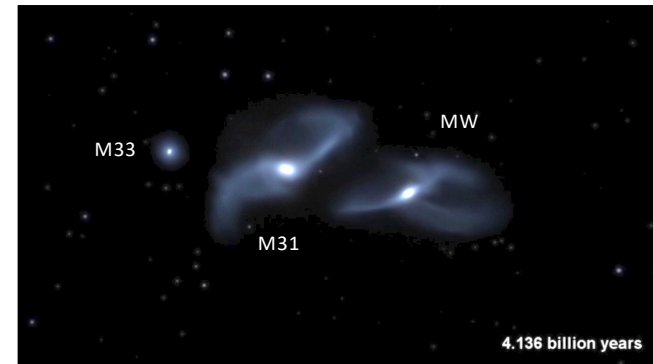
- One cloud colliding with another
- Shock waves rippling through the cloud
- Galaxy collisions (!)



Antenna Galaxy



Milky Way–Andromeda Collision



4.136 billion years

The ABC of Stellar Evolution

Milky Way–Andromeda Collision



Milky Way–Andromeda Collision



Collapsing Cloud



Star Cluster



The ABC of Stellar Evolution

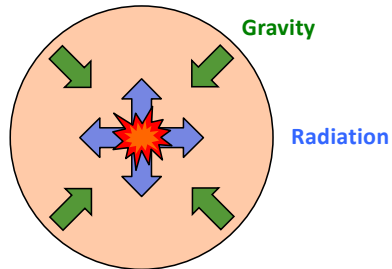
A Question of Balance

All stars are a balance between the opposing forces of gravity and radiation pressure.

When the opposing forces are balanced, the star is stable.

When out of balance, the star must evolve.

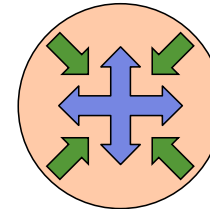
Many aspects of star birth, life and death can be explained in terms of this balance and the **ABC** of star evolution.



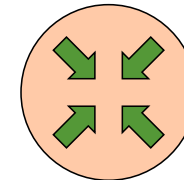
The ABC



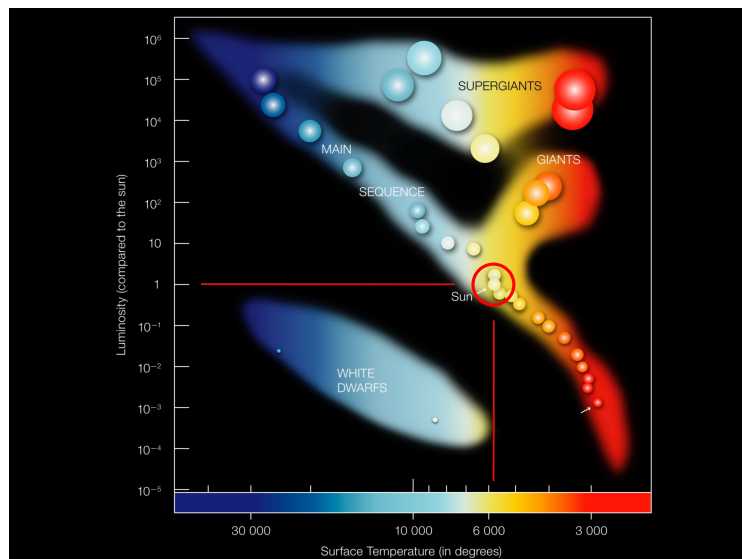
Like charges repel so
high T and high P
ACCELERATE fusion



In a star in equilibrium
gravity and radiation
are in **BALANCE**



COMPRESSION
produces heat

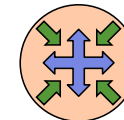


Live Fast, Die Young

Stars of different **mass** follow quite different lives.

High Mass stars have a lot of fuel, but ...

- Gravitational forces are very strong
- Balance requires a lot of radiation to be generated
- Nuclear fuel must be used at a prodigious rate



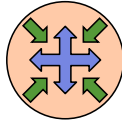
Rather than living for **billions** of years, like our Sun, high mass stars may live for only a few **million** years.

The ABC of Stellar Evolution

Live Slow, Die Very Old

Low Mass stars do not have a lot of fuel, but...

- Gravitational forces are relatively weak
- Hence radiation forces do not have to be high to maintain a balance
- Hence nuclear fuel lasts a long time

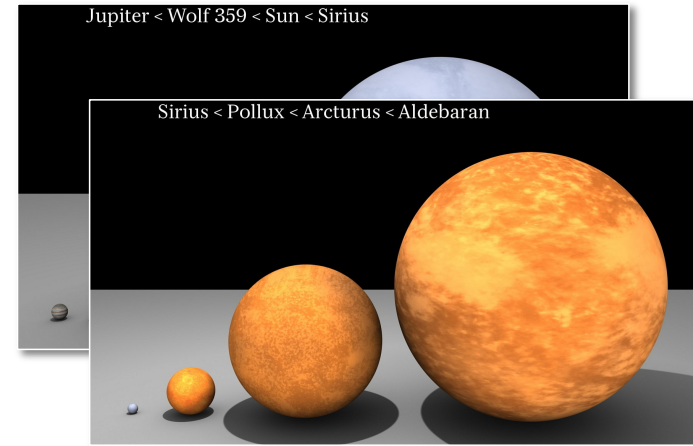


For stars of mass = 10% of the mass of our Sun, we are not even sure what happens when the fuel runs out — it hasn't happened yet in the history of the Universe!

How Big is a Star?

Jupiter < Wolf 359 < Sun < Sirius

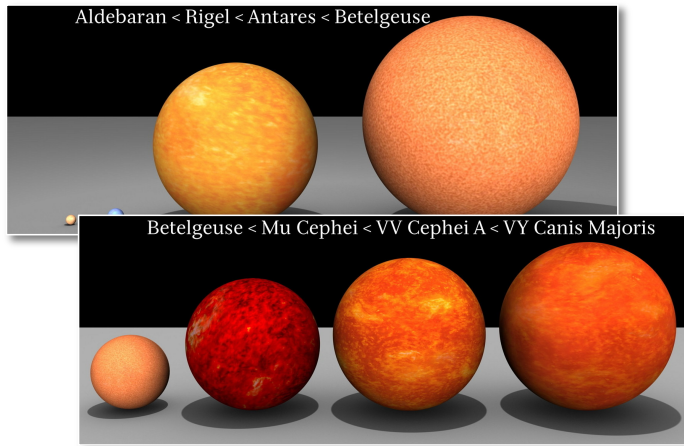
Sirius < Pollux < Arcturus < Aldebaran



How Big is a Star?

Aldebaran < Rigel < Antares < Betelgeuse

Betelgeuse < Mu Cephei < VV Cephei A < VY Canis Majoris



What Happens When the Fuel Runs Out?

Remember that nuclear fusion (or "**burning**") does not use up much of the star's mass.

620 million tons of H  616 million tons of He
every second

The 4 million tons that is "lost" is converted to energy that is radiated out from the core.

Even after billions of years, 99% of the mass is **still there**, transmuted from hydrogen into helium.

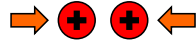
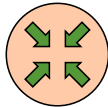
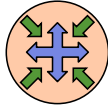
What happens when the hydrogen runs out?

The ABC of Stellar Evolution

What Happens When the Fuel Runs Out?

Remember the **ABC** of stellar evolution?

- When the hydrogen runs out, radiation drops
- The star is out of **BALANCE** as gravity > radiation
- The star shrinks and **COMPRESSION** heats the core to a higher temperature
- This forces nuclei together and **ACCELERATES** the fusion of helium into heavier elements
- Radiation increases and **BALANCE** is restored



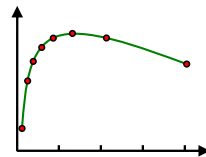
PERIODIC TABLE of the ELEMENTS

DMITRI MENDELEEV (1834 - 1907)

Why Does Gold Exist?

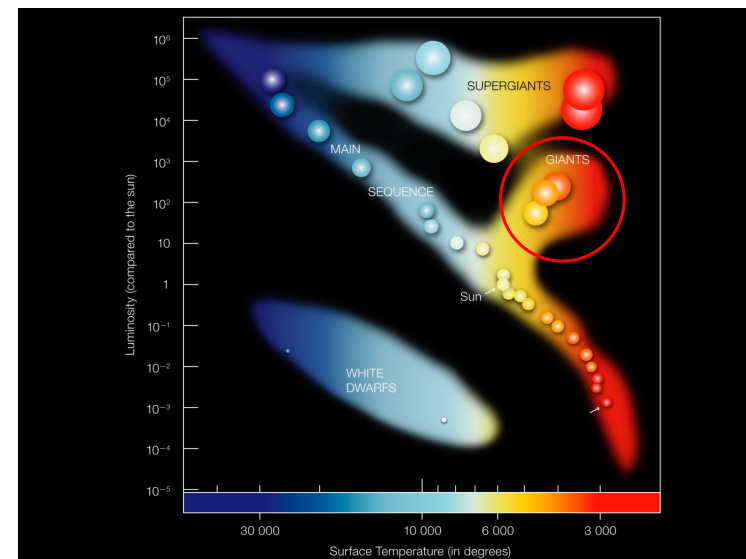
Stars' fusion factories can "burn" H to make **He**, and then He to make **C**, and then C to make **Ne**, and so on, creating all the elements up to **Fe**.

Nuclear physics tells us that fusion of Fe does not **release** energy. It needs an **input** of energy.



So where do all the heavy elements come from?

We have to look beyond star life — at star death.



The ABC of Stellar Evolution

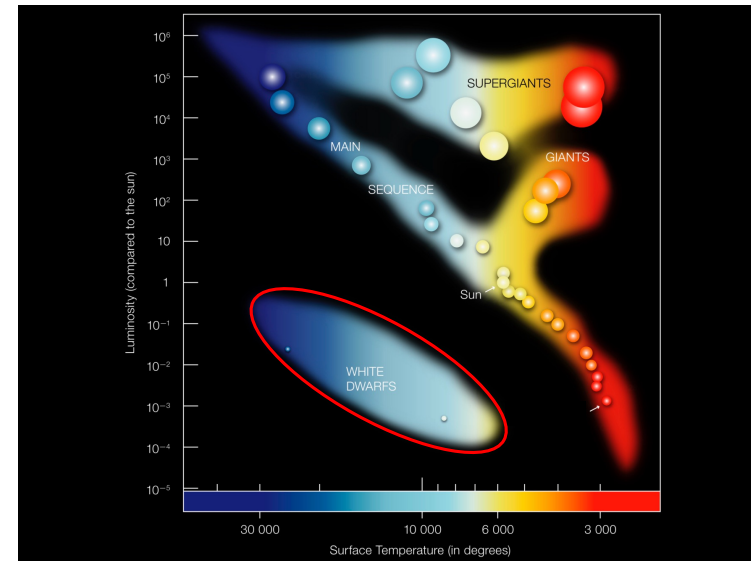
Red Giant or White Dwarf

For **Medium Mass** stars, gravity may not be strong enough to hold on to the outer layers of the star when He starts to burn in the core.

As the star expands the outer layers cool and redden — the star becomes a **Red Giant**.

The He burning in the core can become unstable. If the outer layers are given enough energy they can be blown off the star completely, leading to the formation of a **Planetary Nebula**.

The remaining core becomes a **White Dwarf**.



Planetary Nebula



Planetary Nebula



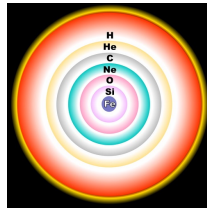
The ABC of Stellar Evolution

Supernova

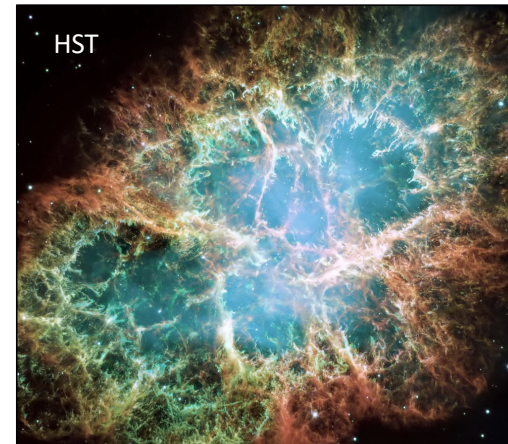
For **High Mass** stars the strong gravity holds the star together through all the stages of nuclear burning.

At the end of its life, when the Fe core can no longer provide the energy to support the star, the core undergoes a catastrophic collapse.

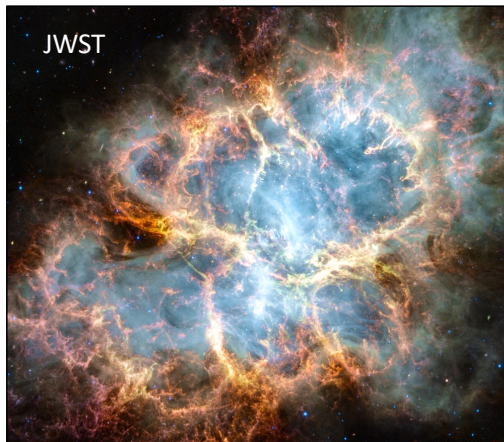
The collapse crushes the core to a size of a few kilometres. A shockwave rebounds from the core and ejects the rest of the star's material into interstellar space.



Crab Supernova Remnant



Crab Supernova Remnant



Supernova

The energy of a supernova explosion is incredible. A back-of-the-envelope calculation shows that to rip a star apart you need an energy of

10^{44} Joules

Imagine the total energy output of the Sun (not just the tiny fraction that falls on the Earth) in each and every second of its 10-billion-year lifetime.

Now imagine all that energy released in just a few seconds.

The word "explosion" just isn't big enough.

The ABC of Stellar Evolution

Supernova

In the chaos of a supernova explosion nuclei fuse together to create elements heavier than Fe.

All the elements generated during the star's life, and its spectacular death, are ejected into interstellar space.

The heavy metals found on Earth were made in a supernova ...



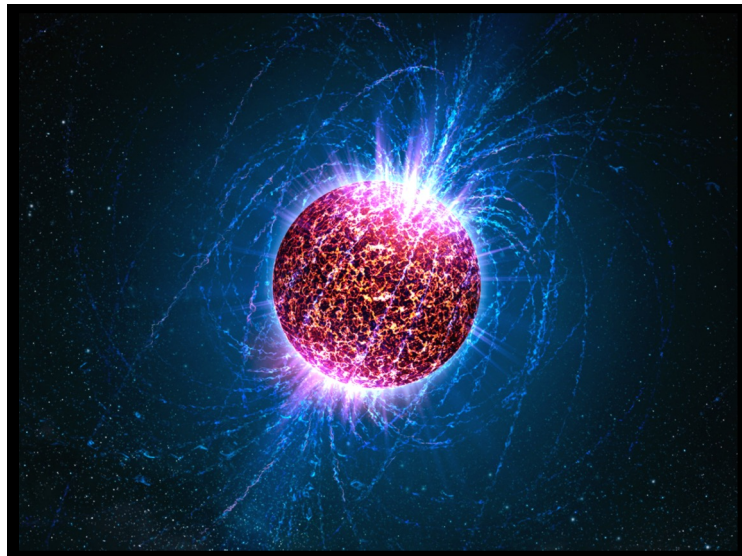
... so this means that the Sun must be at least a "second generation" star. An unknown star was born, lived and died billions of years ago to seed our region of space with the heavy elements that we see around us today.

Supernova

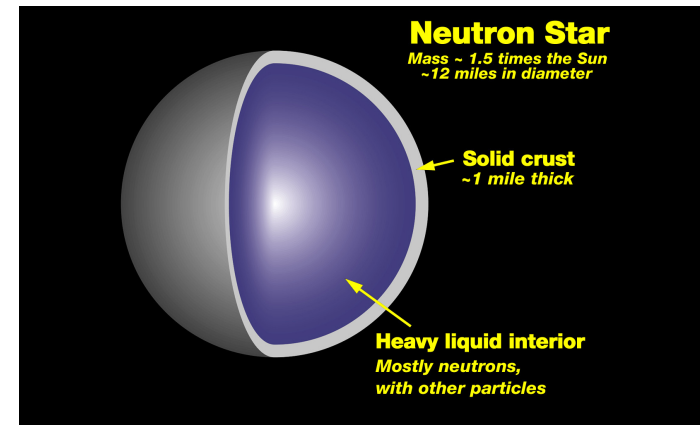
After a supernova has crushed the star's core and ripped apart all of the star's outer regions, what is left behind?

A **tiny** star a few kilometres in diameter.

A **Neutron Star**.



Inside a Neutron Star



The ABC of Stellar Evolution

Ticking Pulsars

Pulsar name		Period
B0329		814 ms
Vela Pulsar		89 ms
Crab Pulsar		33 ms
J0437		5.7 ms
B1937		1.5 ms
		1.55780644887275 ms

When Gravity Wins

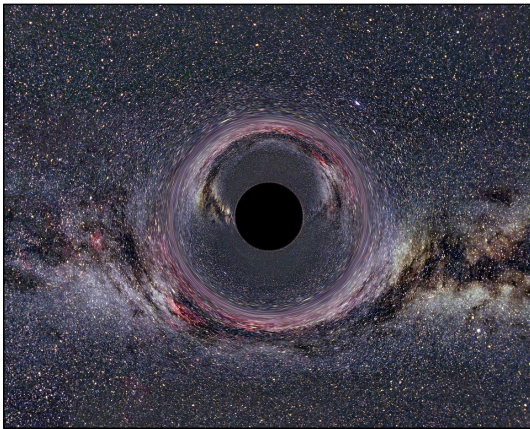
Neutron stars formed in supernova explosions have a size of a few kilometres because this is the point at which **neutrons** are forced to "**touch**" each other.

Getting them any closer means that they would have to overlap each other, which they really do not want to do.

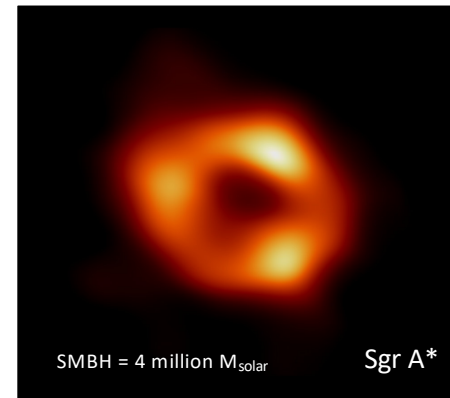
If the star has enough mass, then gravity wins and the neutrons are forced together despite their objections. Nothing can stop the collapse continuing.

The result is the stuff of science fiction ... a **Black Hole**.*

Black Hole



Black Holes



SMBH = 4 million M_{solar}

Sgr A*

The ABC of Stellar Evolution

