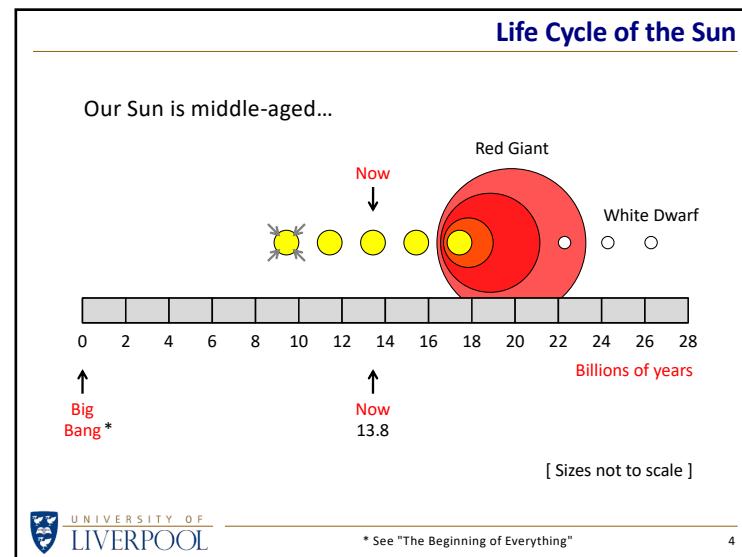
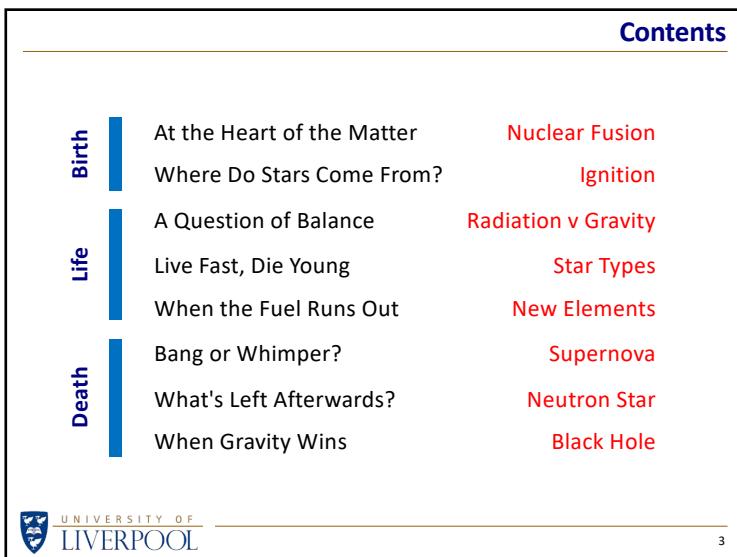
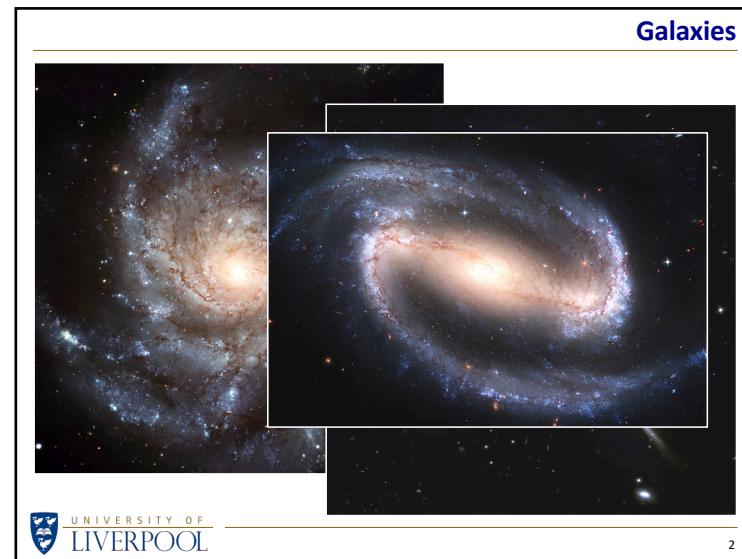
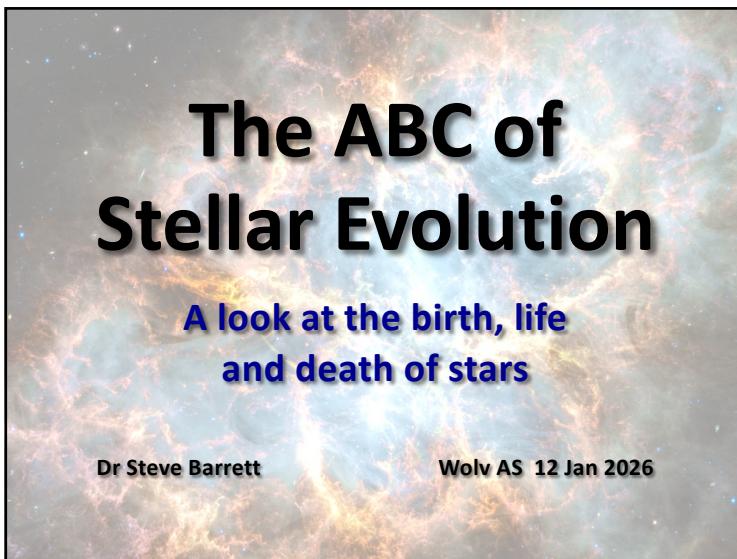


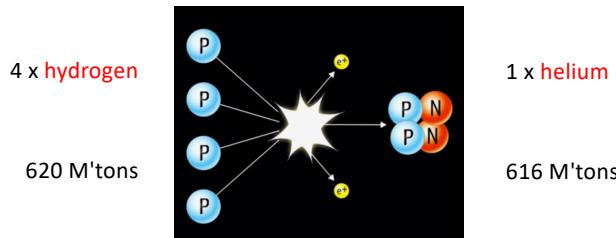
The ABC of Stellar Evolution



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.



5

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.*



* See "The Beginning of Everything"

6

Star Formation

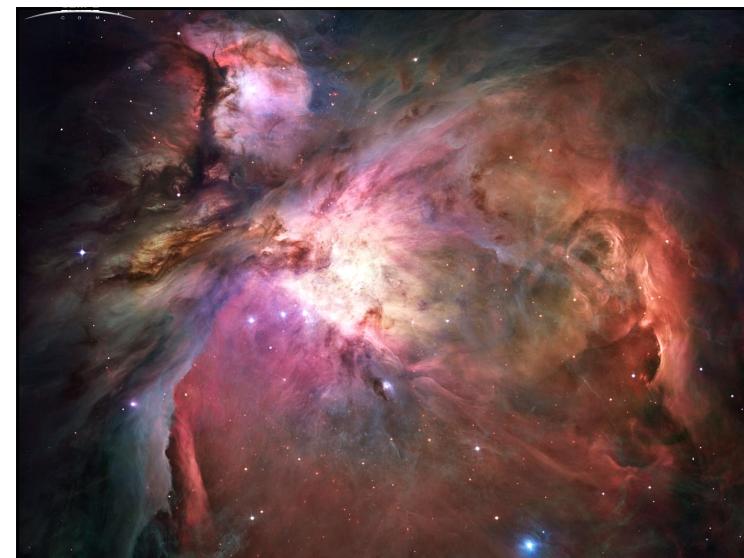
Where do stars come from?

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



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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 ...

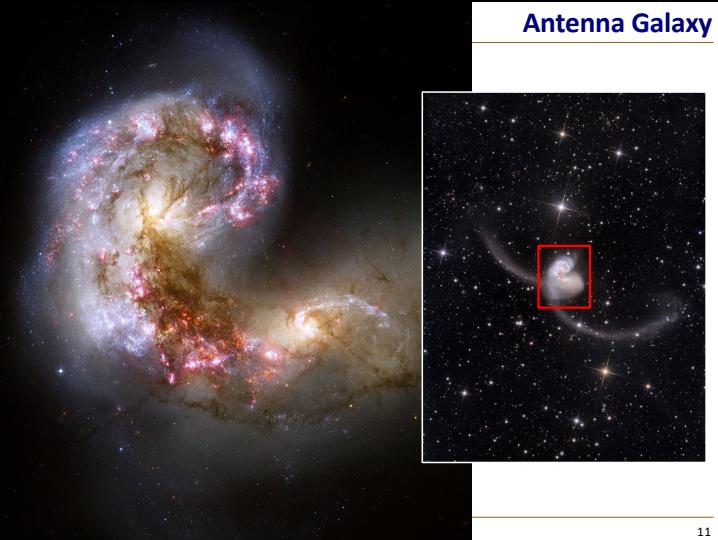
- One cloud colliding with another
- Shock waves rippling through the cloud
- Galaxy collisions (!)

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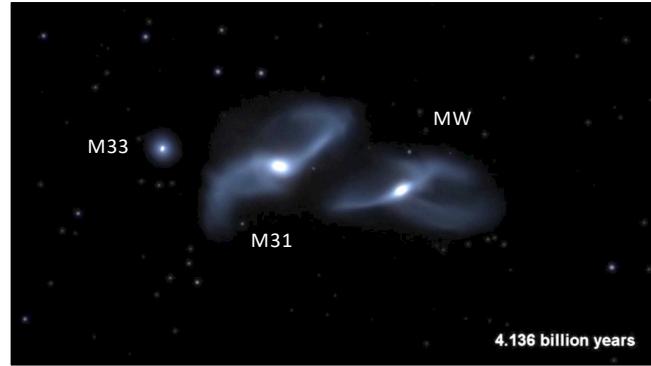


Antenna Galaxy



11

Milky Way–Andromeda Collision



4.136 billion years

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The ABC of Stellar Evolution

Milky Way–Andromeda Collision



1 Gyr



13

Milky Way–Andromeda Collision



3.9 Gyr



14

Collapsing Cloud



Matthew Bate EXETER

UK Astrophysical
Fluids Facility



15

Star Cluster

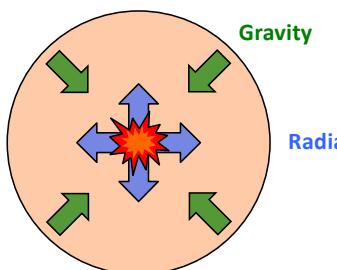


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The ABC of Stellar Evolution

A Question of Balance

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



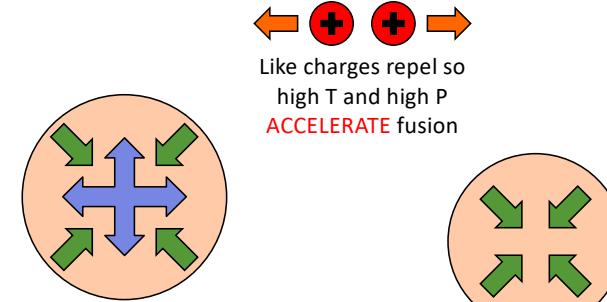
When the opposing forces are balanced, the star is stable.

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.

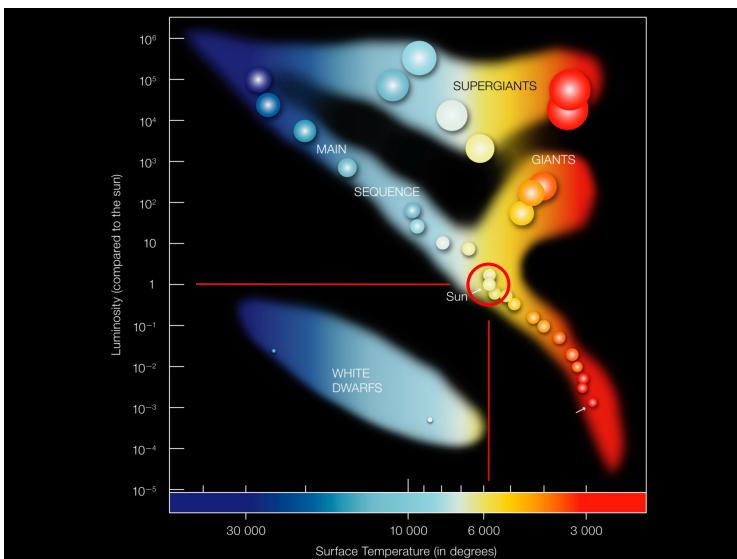
17

The ABC



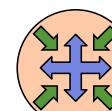
In a star in equilibrium gravity and radiation are in **BALANCE**

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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.

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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!

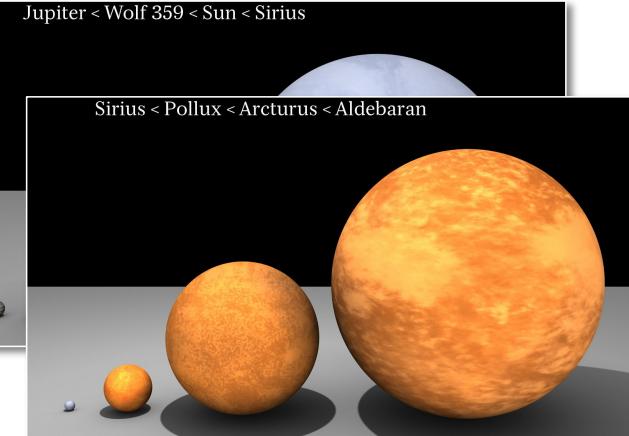


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How Big is a Star?

Jupiter < Wolf 359 < Sun < Sirius

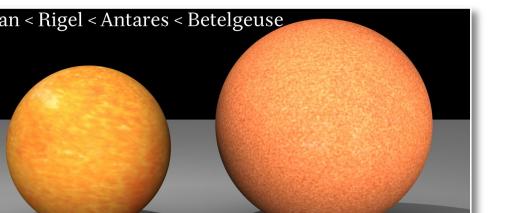
Sirius < Pollux < Arcturus < Aldebaran



22

How Big is a Star?

Aldebaran < Rigel < Antares < Betelgeuse



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



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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?



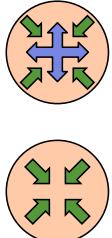
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The ABC of Stellar Evolution

What Happens When the Fuel Runs Out?

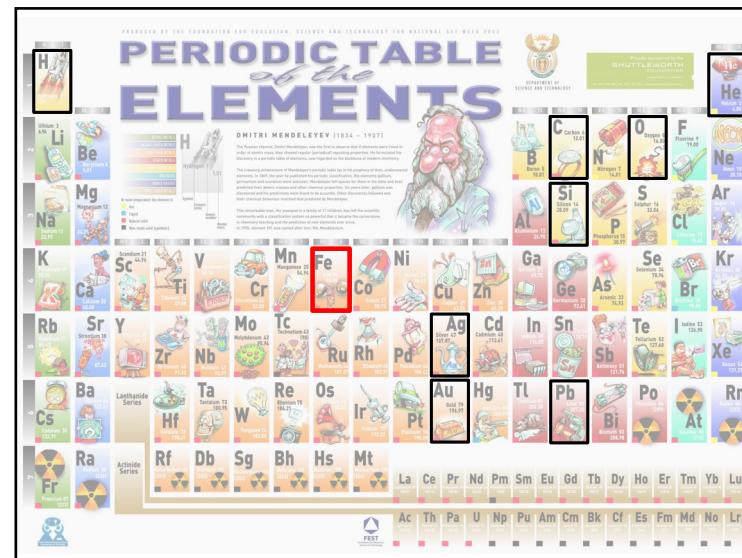
Remember the **ABC** of stellar evolution?

- 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



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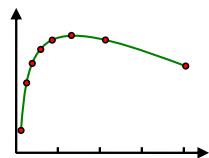
25



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.

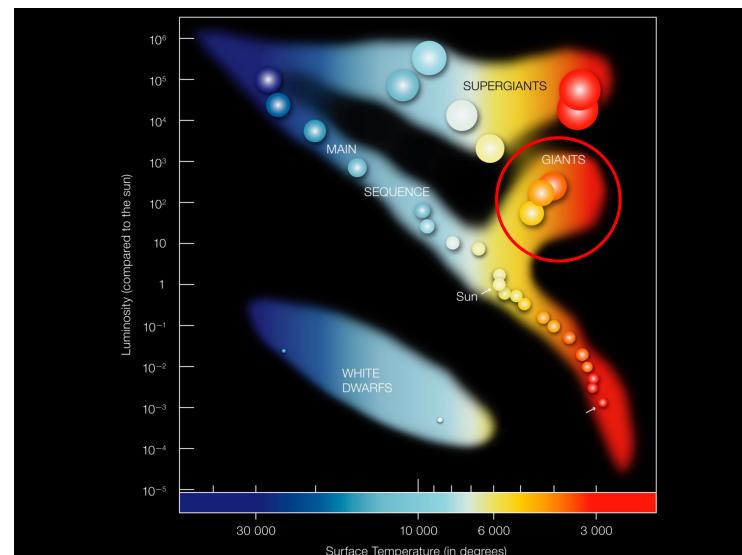


So where do all the heavy elements come from?

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

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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.

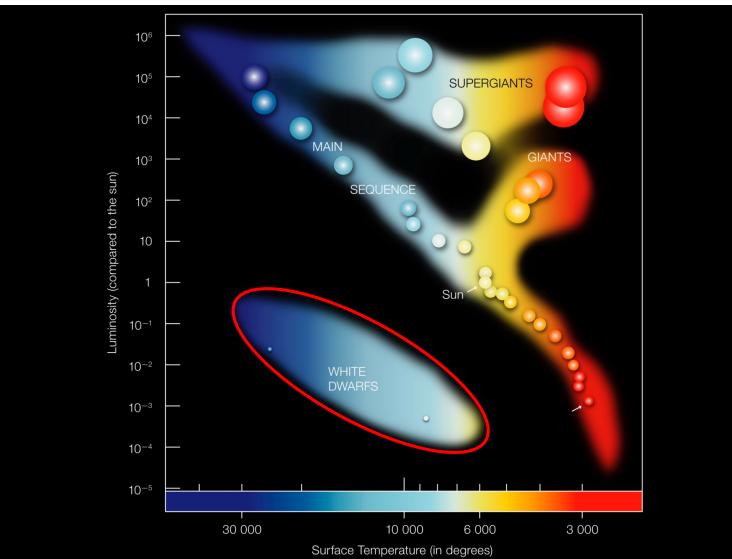
As the star expands the outer layers cool and redden — the star becomes a **Red Giant**.

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**.



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Planetary Nebula



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Planetary Nebula



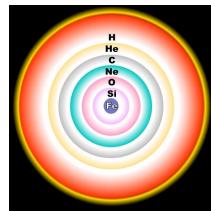
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The ABC of Stellar Evolution

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.

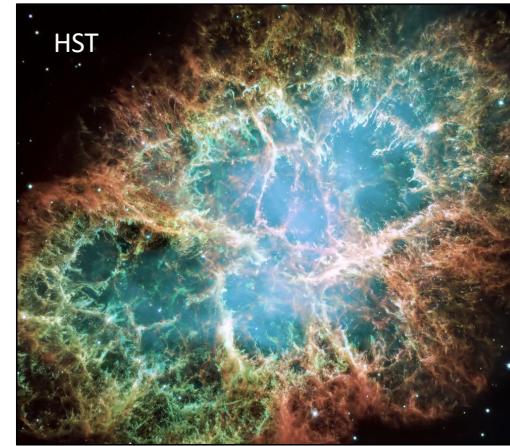


The collapse crushes the core to a size of a few kilometres. A shockwave rebounds from the core and ejects the rest of the star's material into interstellar space.



33

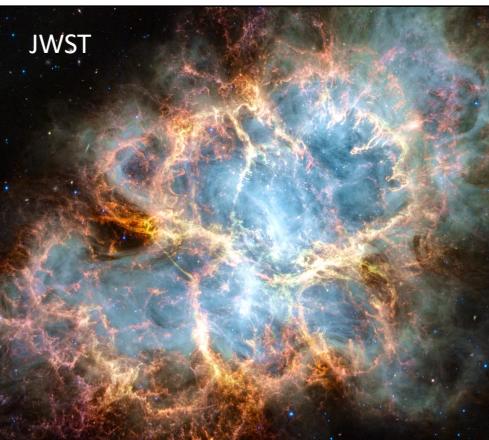
Crab Supernova Remnant



December 2005

34

Crab Supernova Remnant



October 2023

35

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.



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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.



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Supernova

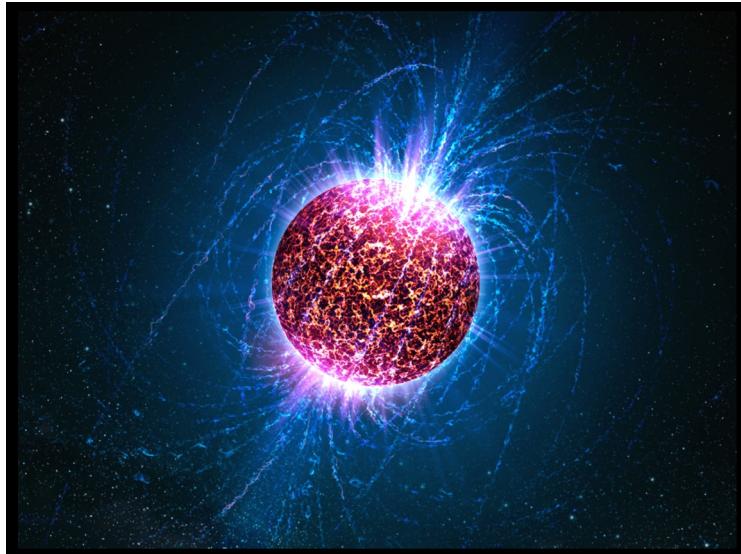
After a supernova has crushed the star's core and ripped apart all of the star's outer regions, what is left behind?

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

A **Neutron Star**.



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Inside a Neutron Star

Neutron Star

Mass ~ 1.5 times the Sun
~12 miles in diameter

Solid crust
~1 mile thick

Heavy liquid interior
Mostly neutrons,
with other particles



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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	



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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.

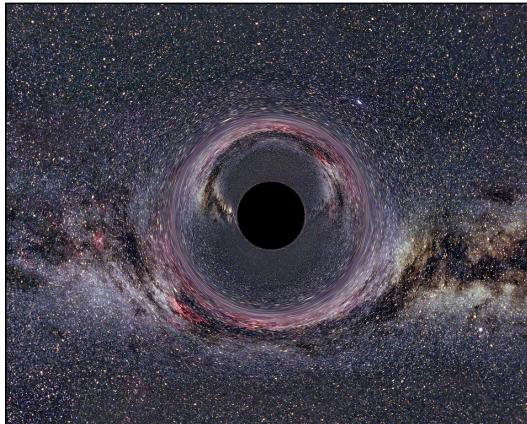
The result is the stuff of science fiction ... a **Black Hole**.*



* See "Warping Space and Time"

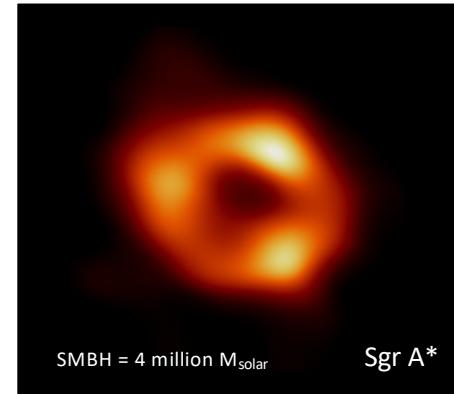
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Black Hole



43

Black Holes

SMBH = 4 million M_{solar}

Sgr A*



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The ABC of Stellar Evolution

