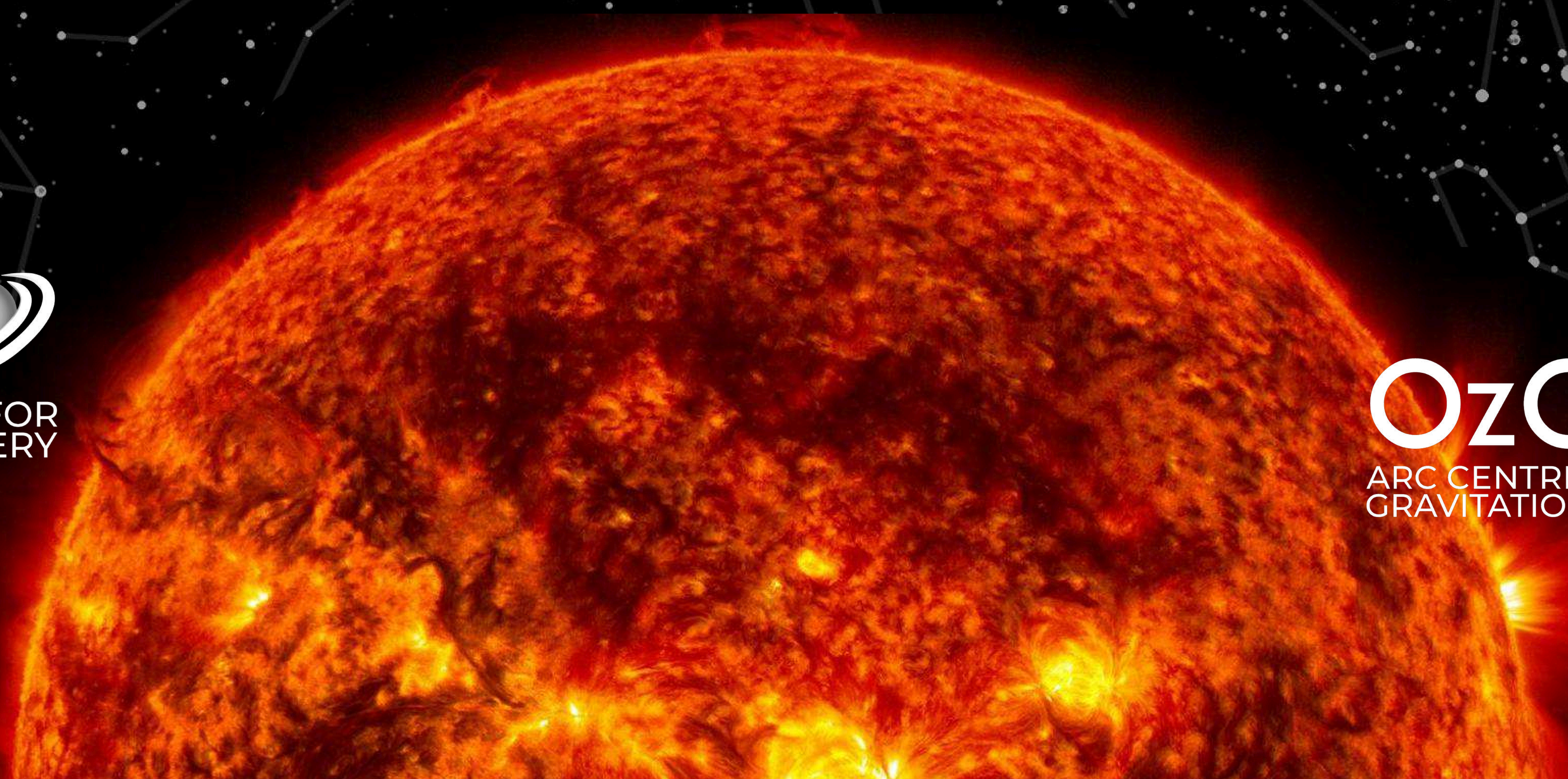
ASTRAL

EXPLORING THE STARS AND THE MILKY WAY



SPONSORED BY:

OzGrav
ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

SPONSORED BY:

OzGrav
ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

Credits:

This booklet was created by the ASTRAL 2024 and 2025 teams, and their mentors. This booklet was supported by the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav).

ASTRAL 2024 COHORT

- Hendrik Combrinck
- Rebecca Koehne
- Ruoyao Ni
- Rudra Sekhri
- Evie Spilias

MENTORS:

- Professor Matthew Bailes
- Dr Kirsten Banks
- Dr Emma Carli
- Dr Chris Flynn
- Diana Haikal
- Akhil Jaini
- Saurav Mishra
- Bailee Wolfe

ASTRAL 2025 COHORT:

- Lead Editor: Annabelle Leung
- Agatha Beare
- Aaron Choi
- Sevryn Danilov
- Rhea Fernandez
- Lucy O'Shea
- Henryk Przychodzen
- Daniel Rosina
- Tristan Than
- Evie Vale
- Nandini Vyas
- Kim Yan

SPONSORED BY:

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

OzGrav
ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

ASTRAL

EXPLORING THE STARS AND THE MILKY WAY

ASTRAL

Introduction

We humans live on a planet called Earth, which you might already know is orbiting our Sun. But the Sun is just one star among millions, stars of all different sizes and colours. Stars which explode spectacularly or fade quietly, surrounded by planets, or in a system with another star. Stars which are all grouped together in an object billions of billions of kilometres across.

We call this object the Milky Way.

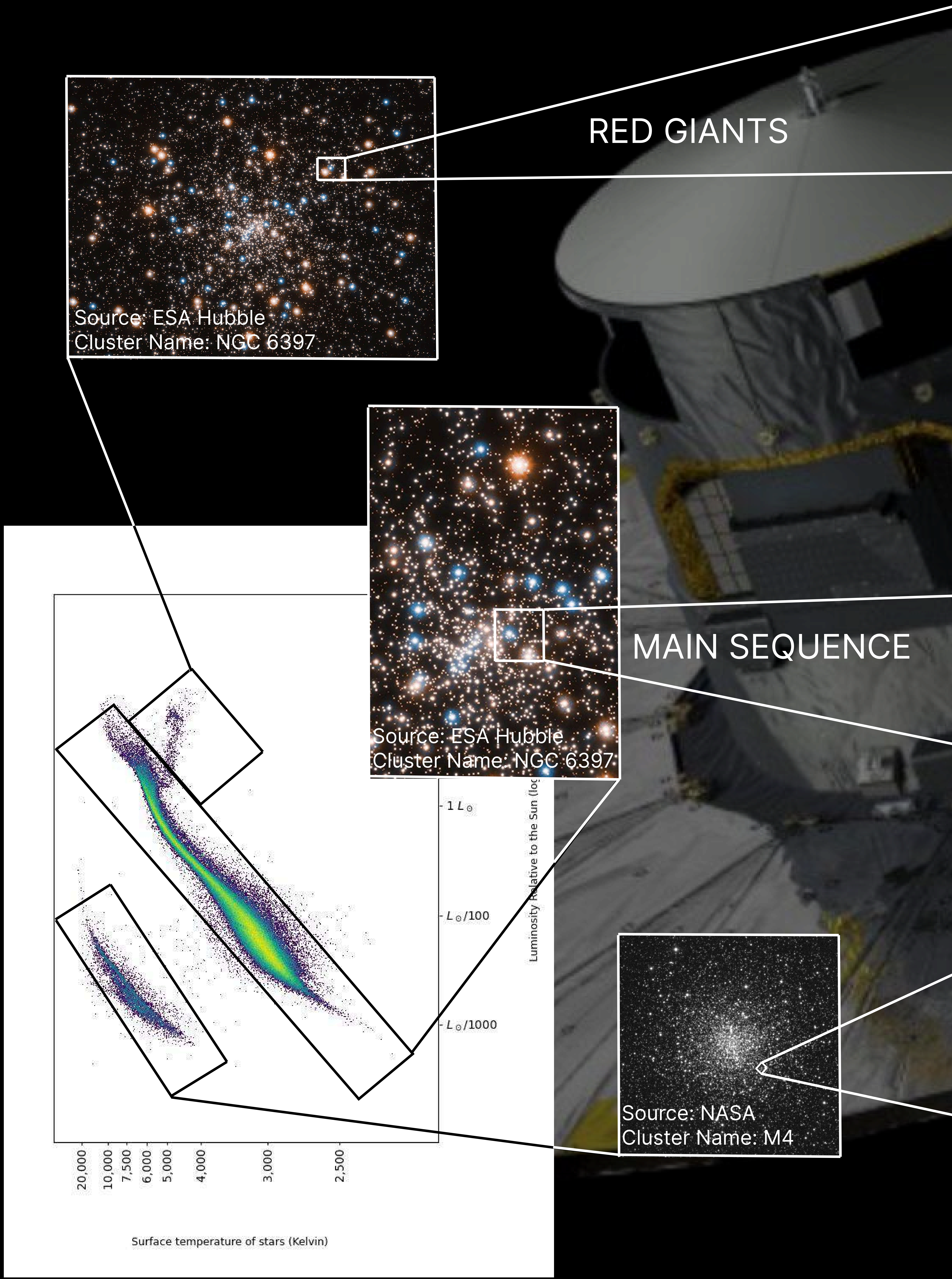
This booklet will take you on a journey through it, seeing all the different types of stars it is home to along the way.

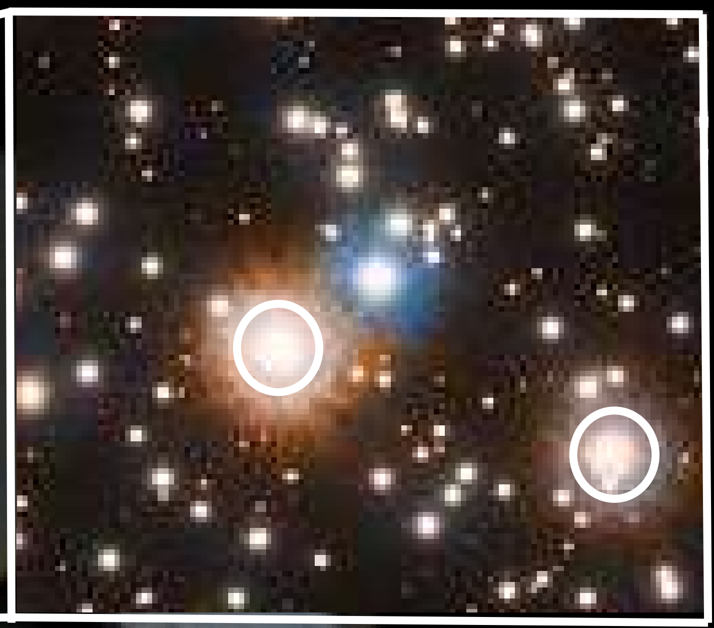
About ASTRAL

ASTRAL stands for Astrophysics, Supercomputing, Technology, Research, Analysis and Leadership. It was founded by Professor Matthew Bailes who also founded the Centre for Astrophysics and Supercomputing at Swinburne University of Technology. The program was founded to inspire students to explore their interests in these areas of studies through workshops, programs, and outreach projects (like writing this booklet). By providing students with mentors and unique opportunities, ASTRAL aims to build a cohort of STEM student leaders.

Table of Contents

Let’s delve into the Milky Way:

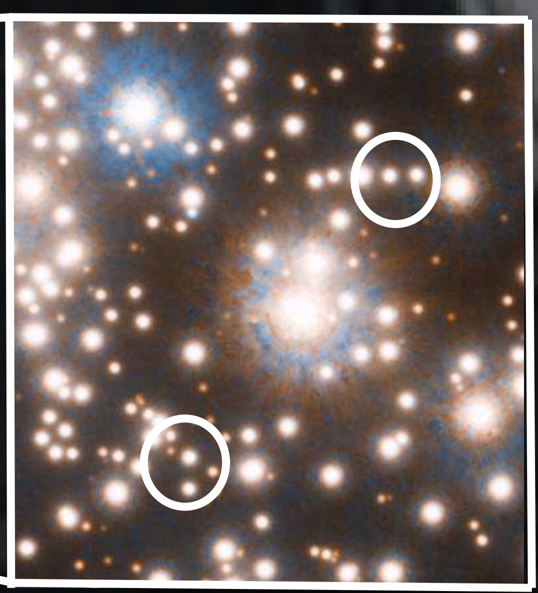

RED GIANTS
Source: ESA Hubble
Cluster Name: NGC 6397
MAIN SEQUENCE
Source: ESA Hubble
Cluster Name: NGC 6397
1 $L_\odot$
$L_\odot$/100
$L_\odot$/1000
Luminosity Relative to the Sun (log
Source: NASA
Cluster Name: M4
20,000
10,000
7,500
6,000
5,000
4,000
3,000
2,500
Surface temperature of stars (Kelvin)



Humans have been admiring stars for thousands of years, yet there is so much more to learn about them beyond the brightnesses and colours we see.

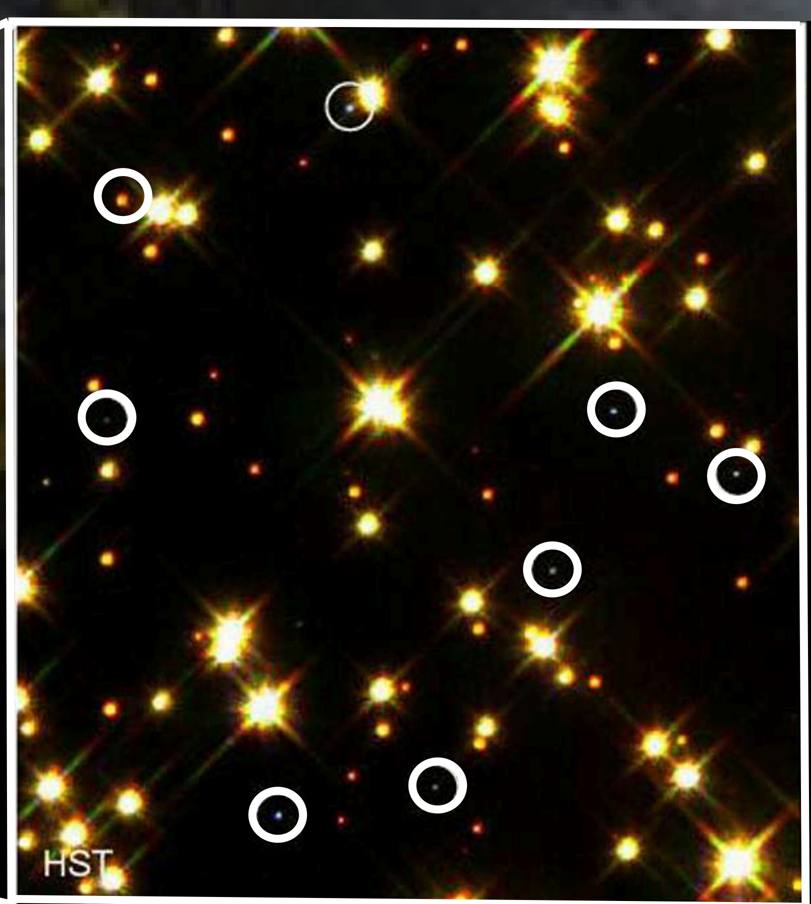
A temperature-luminosity diagram (or Colour-Magnitude diagram) sorts stars into three regions: Giants, Main Sequence, and White Dwarfs (lower left).

The GAIA telescope [background] measures the stars' colour, luminosity, and distance, plotting millions of new stars more accurately than ever before.



The images show stars in Globular Clusters, which consist up to a few 100,000 stars bound together through gravity.

WHITE DWARFS

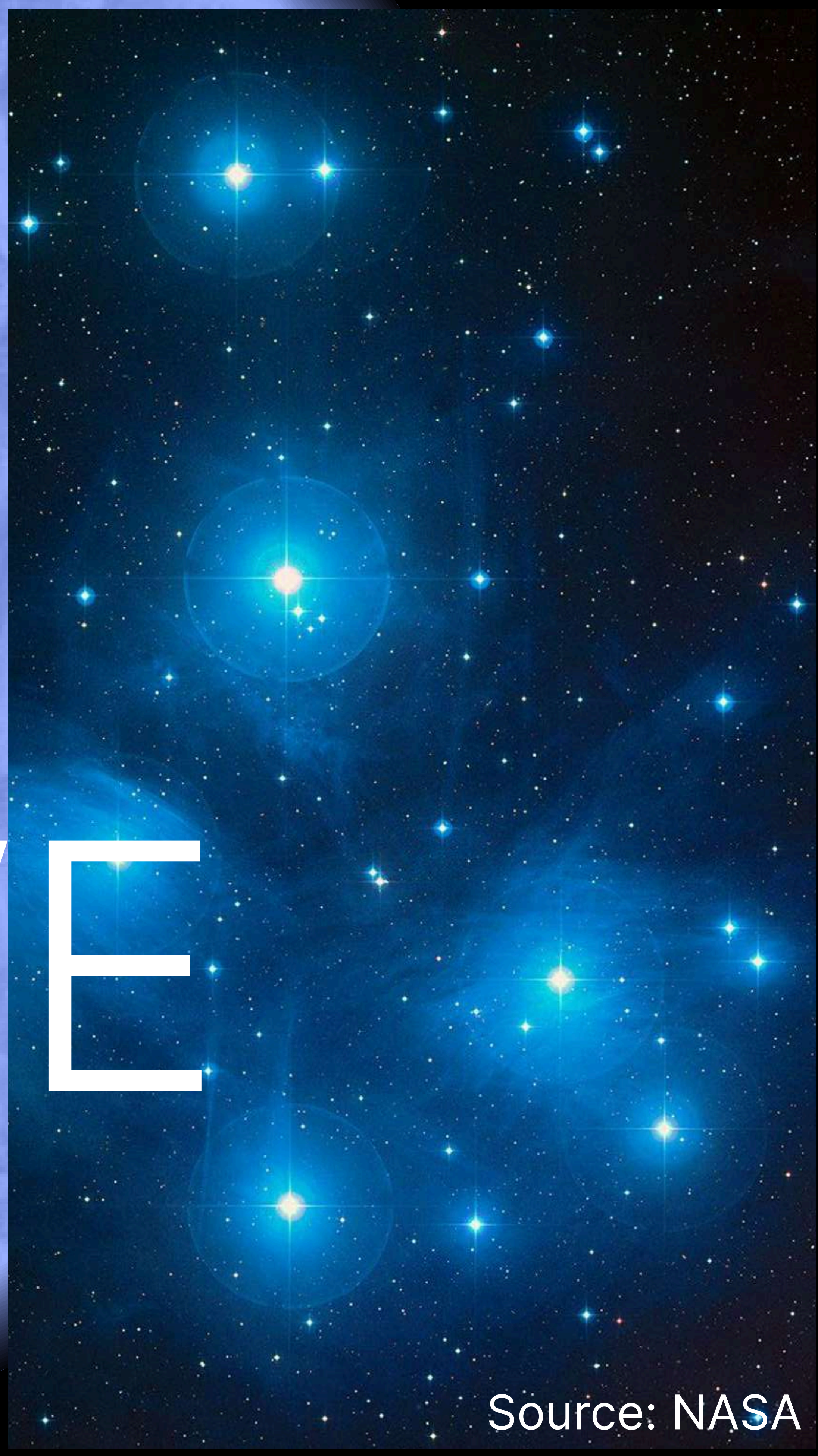


Background Image Source: Gaia

This booklet summarises properties of different stars, their fates in the long-term, and how they form galaxies.

ASTRAL

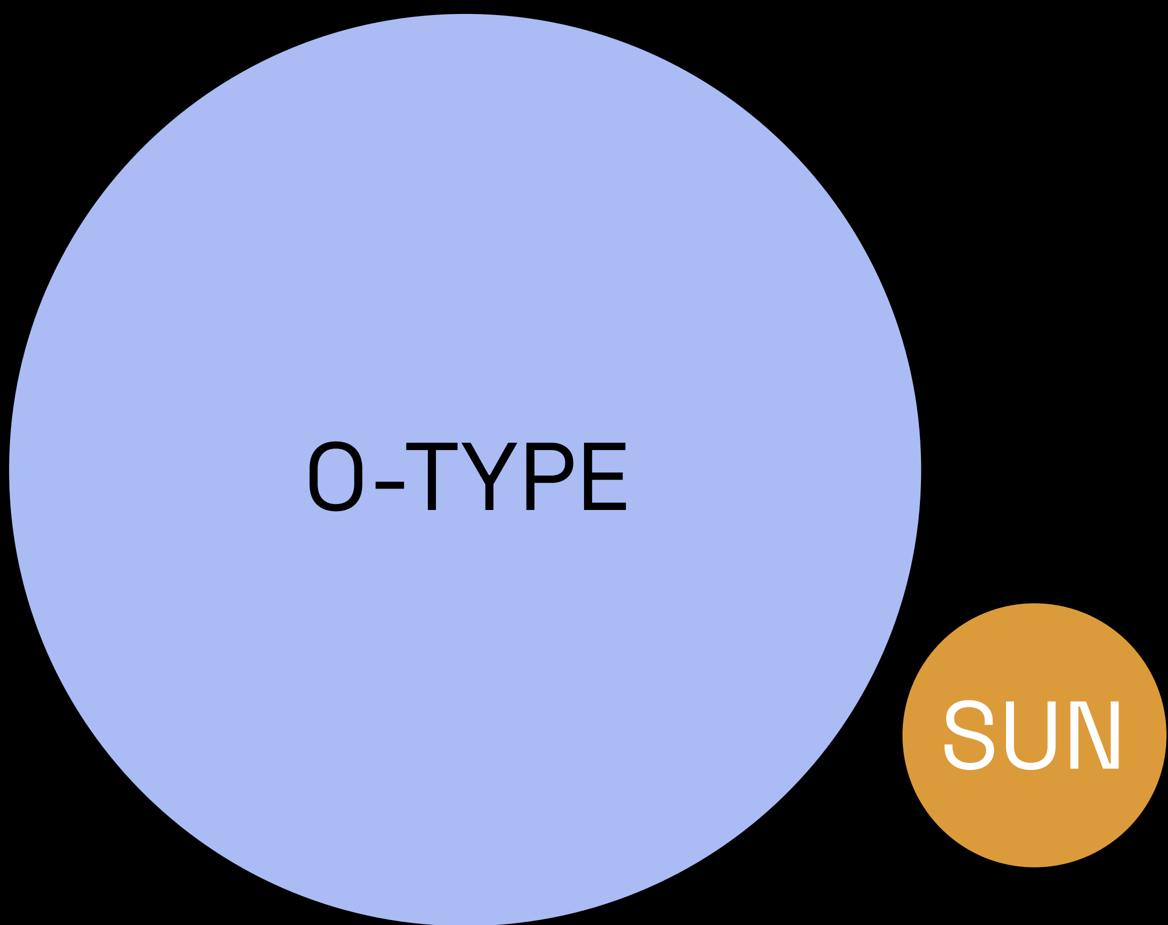
MASSIVE STARS

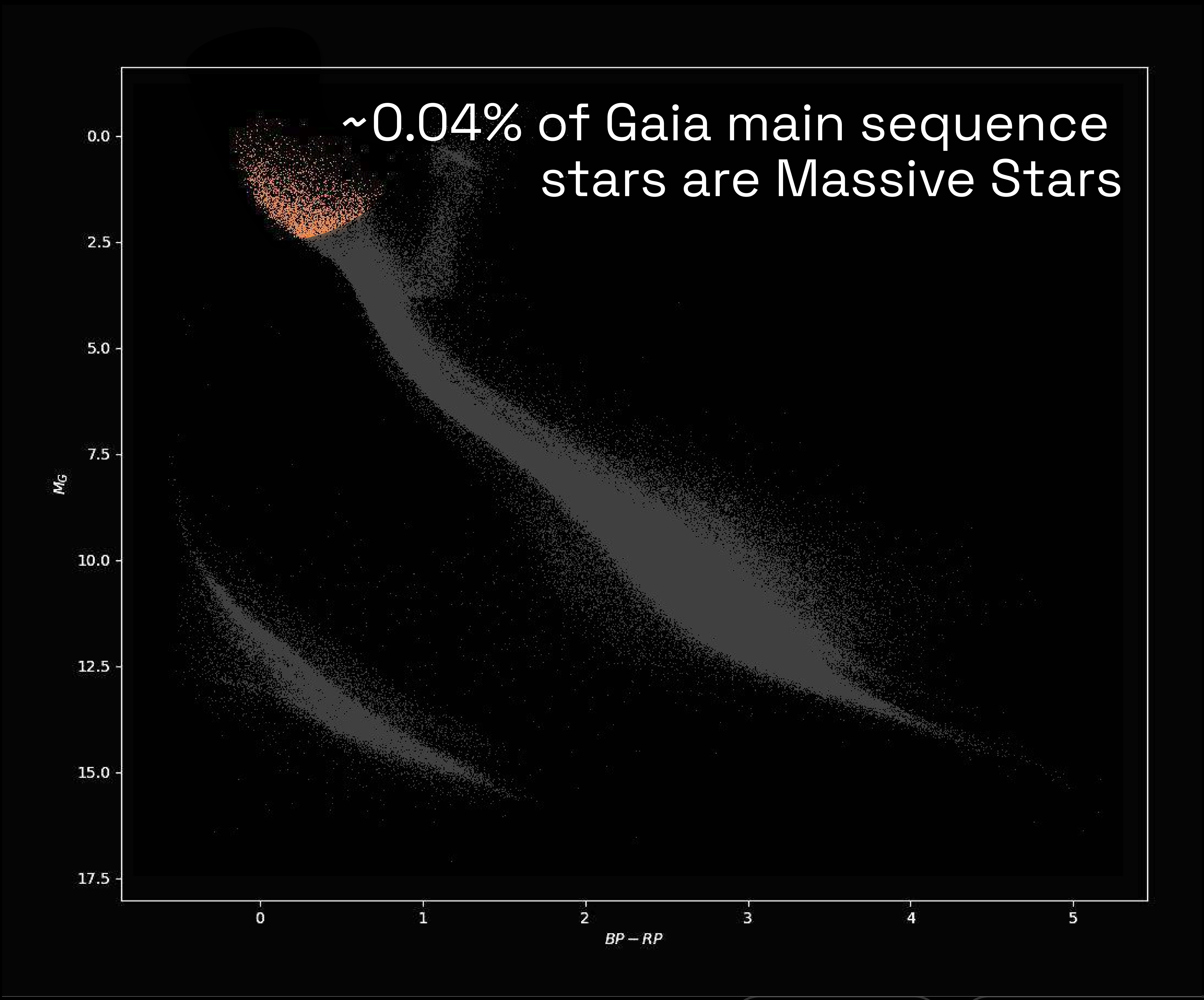


Source: NASA

TYPE	O and B
MASS	2-200 $M_\odot$
TEMPERATURE	10000-50000 K
LIFESPAN	10-100 million years
RADIUS	2-10 $R_\odot$
NEARBY EXAMPLE	ζ Ophiuchi
LUMINOSITY	1000-100000 $L_\odot$

O- and B-type stars are the largest types of stars. They are blue in colour.

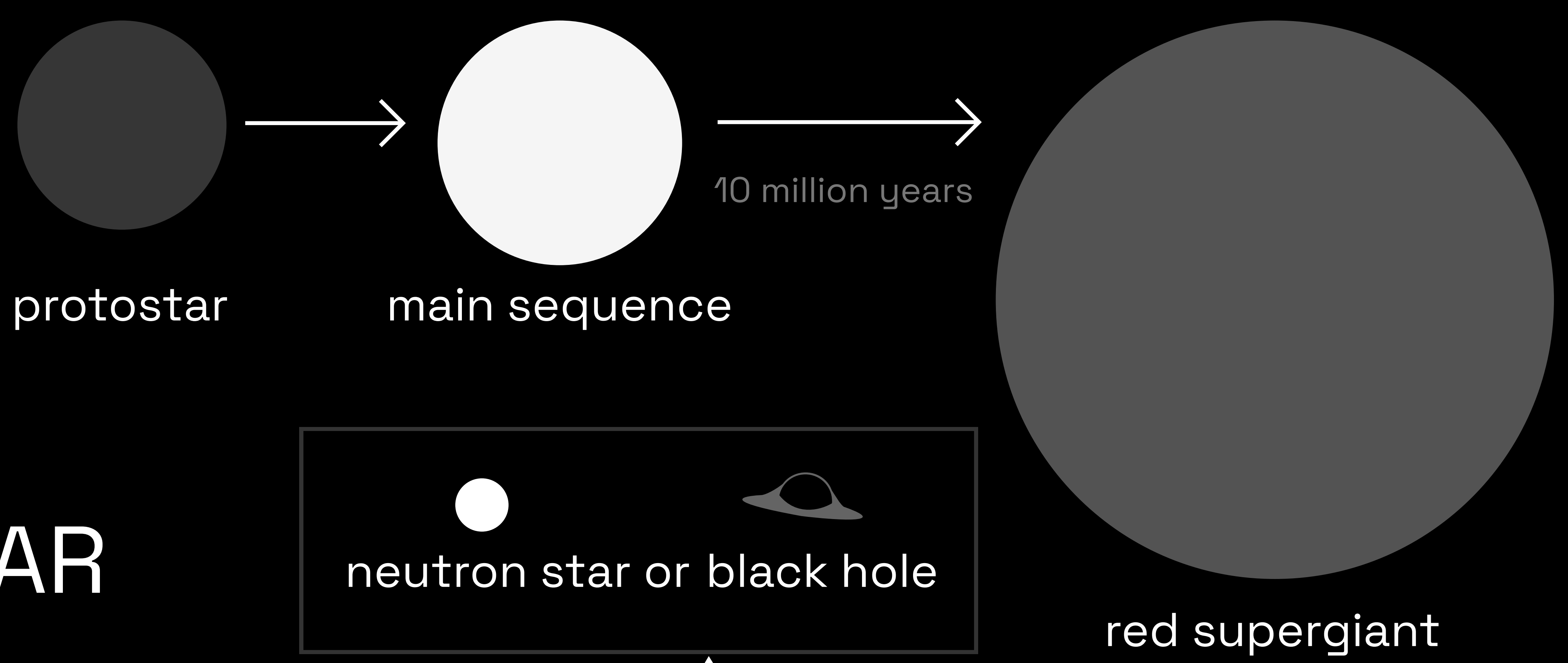




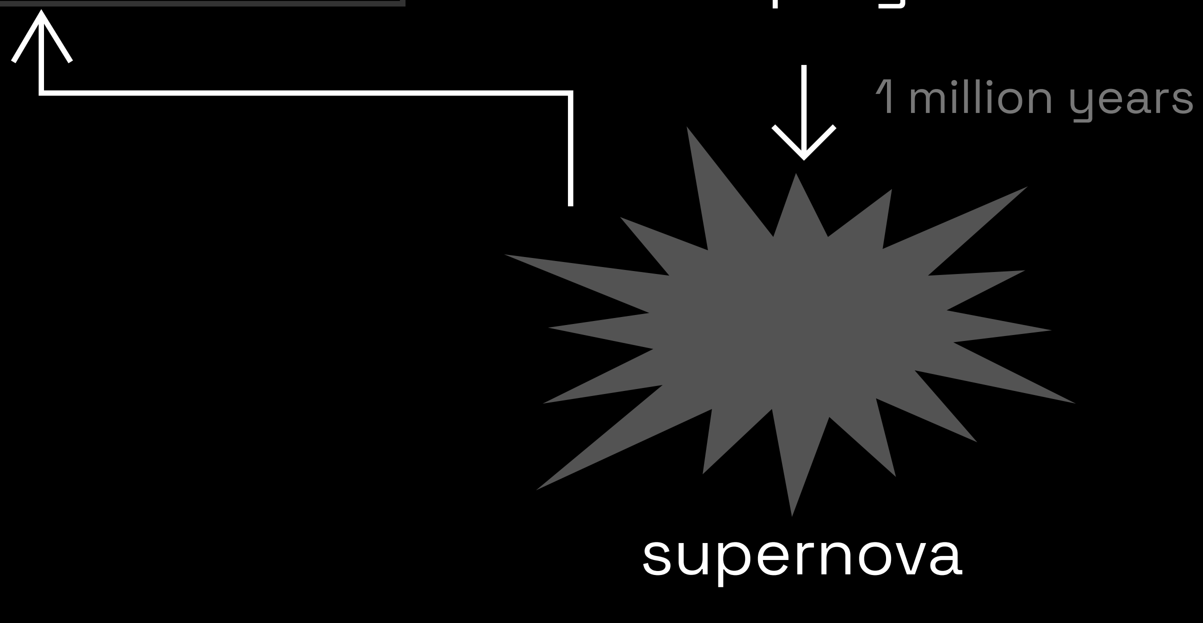
x-axis: colour

y-axis: brightness

LIFECYCLE



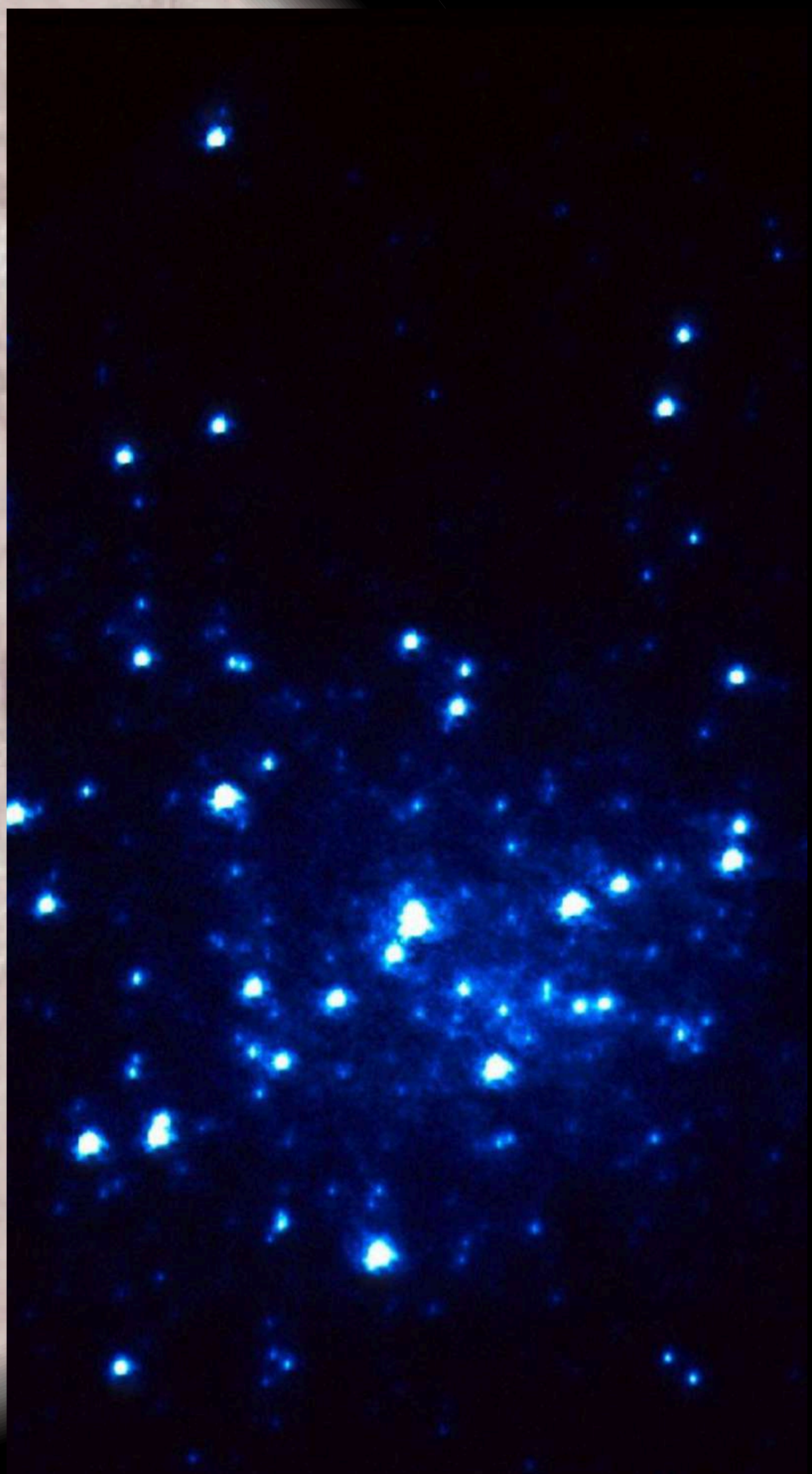
FATE OF STAR



ELEMENTS CREATED

79 196.97 **Au** Gold	82 207.20 **Pb** Lead	92 238.03 **U** Uranium	14 28.09 **Si** Silicon

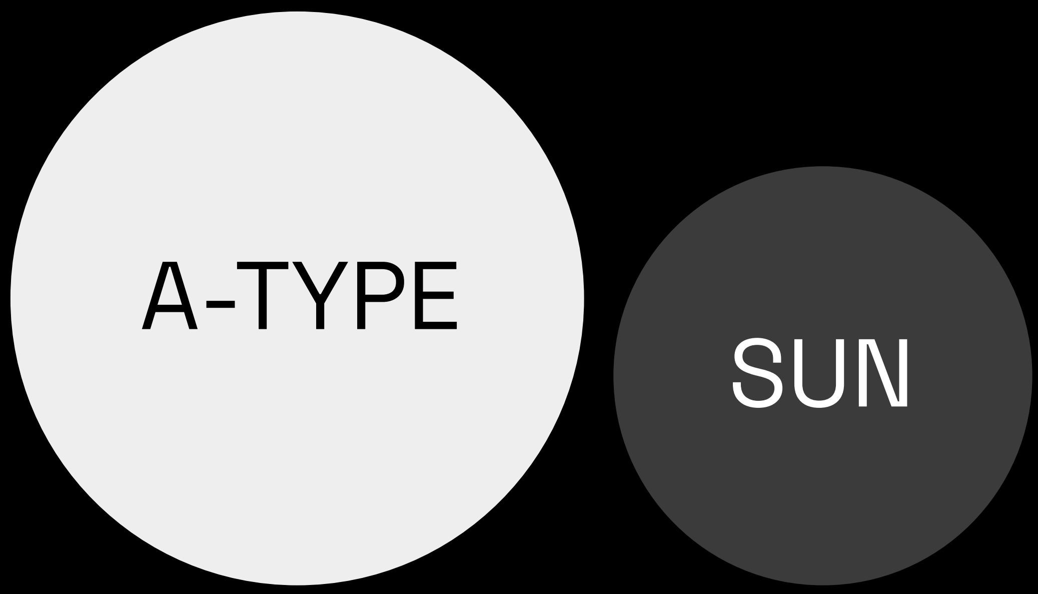
HOT STARS

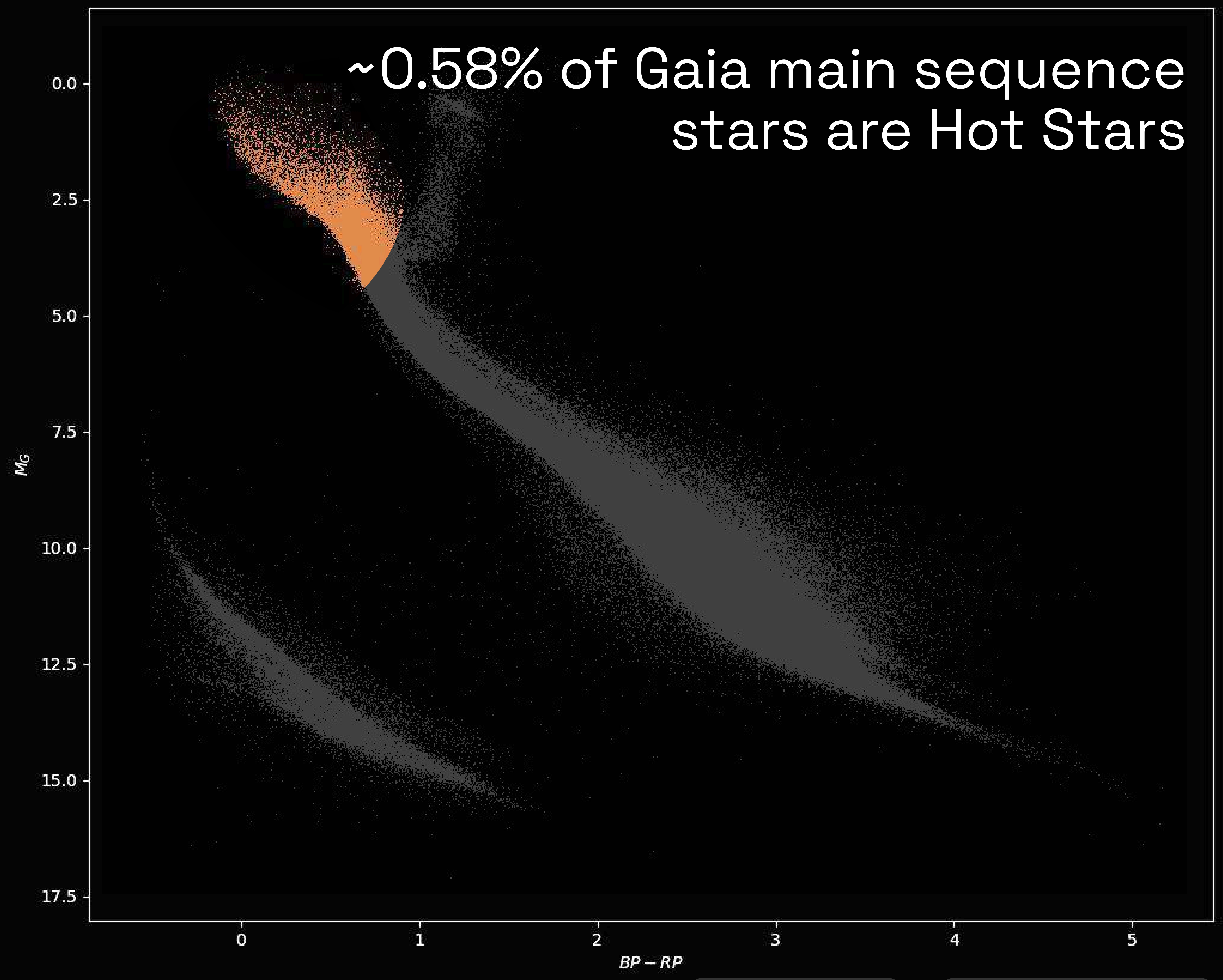


Source: Hubble Space Telescope

TYPE	A and F
MASS	1.1-2.1 $M_\odot$
TEMPERATURE	6000-10000 K
LIFESPAN	1-8 billion years
RADIUS	1.15-1.8 $R_\odot$
EXAMPLE	Polaris
LUMINOSITY	1.5-25 $L_\odot$

A- and F-type stars are brighter and larger than our Sun. Their surface is hotter which is why they appear white.





x-axis: colour

y-axis: brightness

LIFECYCLE

protostar → main sequence → (10 billion years) red giant

FATE OF STAR

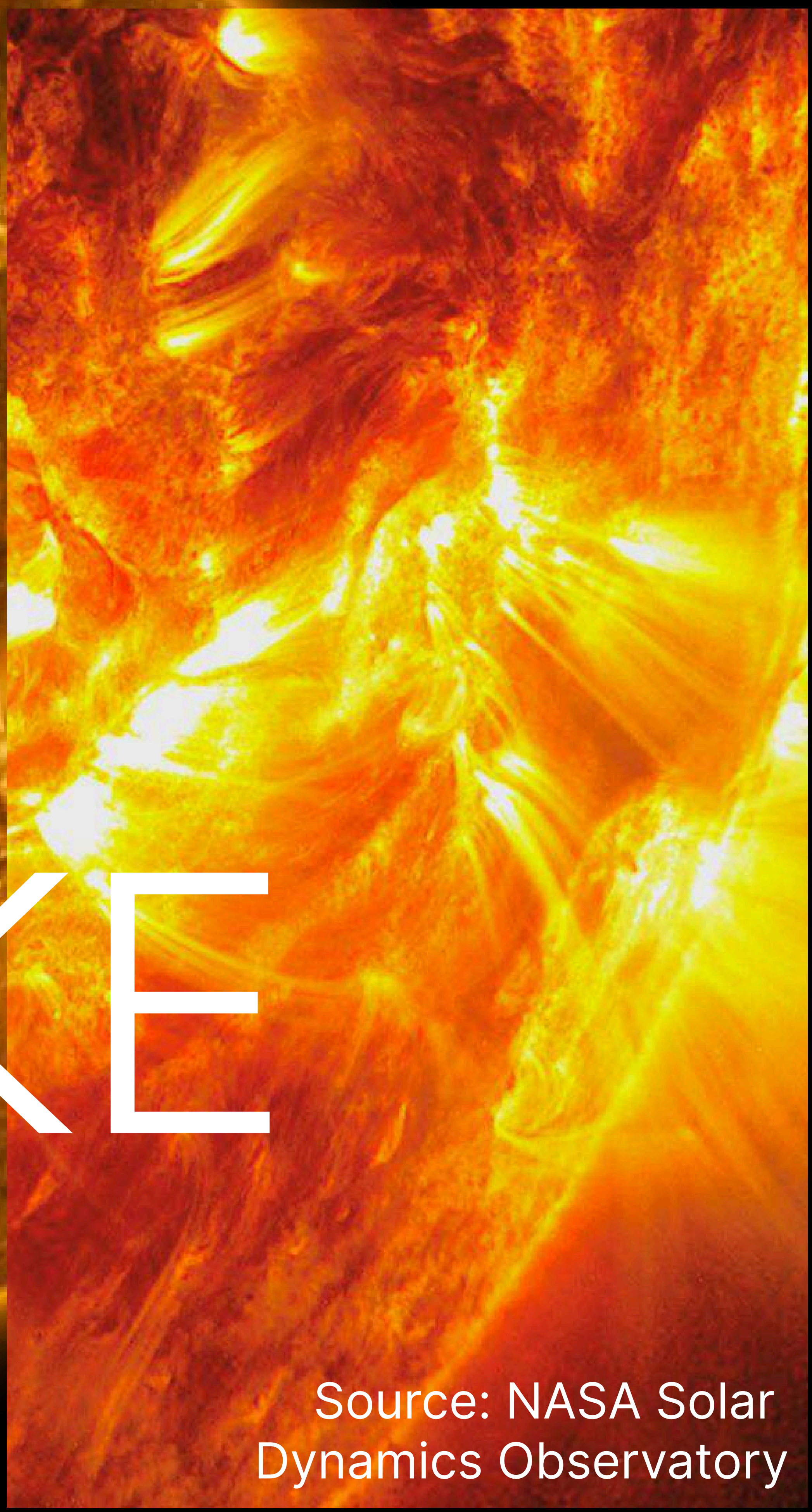
red giant → (1 billion years) white dwarf

ELEMENTS CREATED

2 4.00 He Helium	6 12.0 C Carbon	8 16.0 O Oxygen	10 20.2 Ne Neon

Some A-type stars can explode in a supernova.

SUN-LIKE STARS



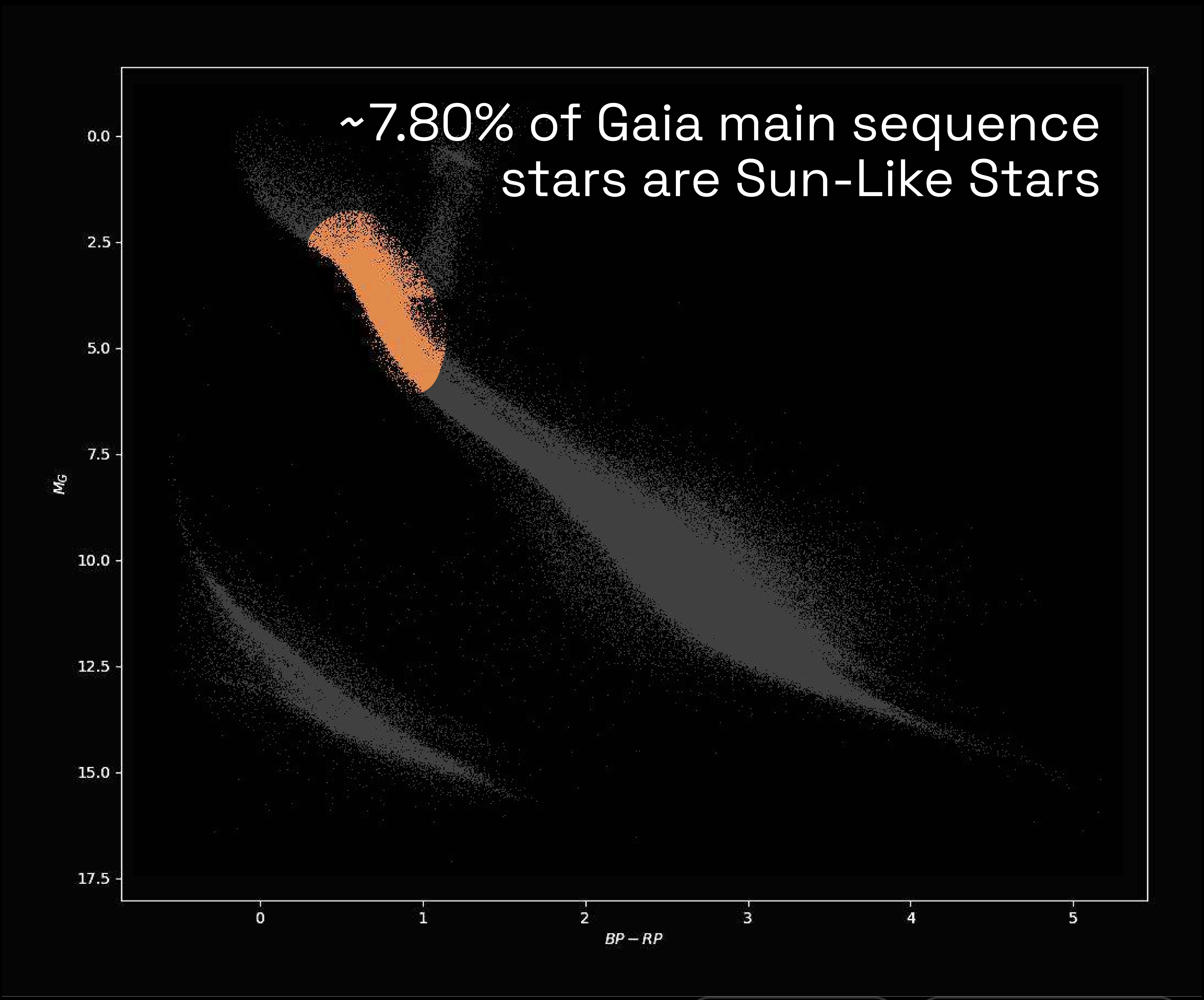
Source: NASA Solar Dynamics Observatory

TYPE	G
MASS	0.9-1.1 $M_\odot$
TEMPERATURE	5000 - 6000 K
LIFESPAN	7.9 - 20 billion years
RADIUS	0.8 - 1.1 $R_\odot$
NEARBY EXAMPLE	The Sun
LUMINOSITY	0.6 - 1.5 $L_\odot$

G-type stars are relatively stable yellow stars. Our Sun is categorised as a G-type star!

G-TYPE

SUN

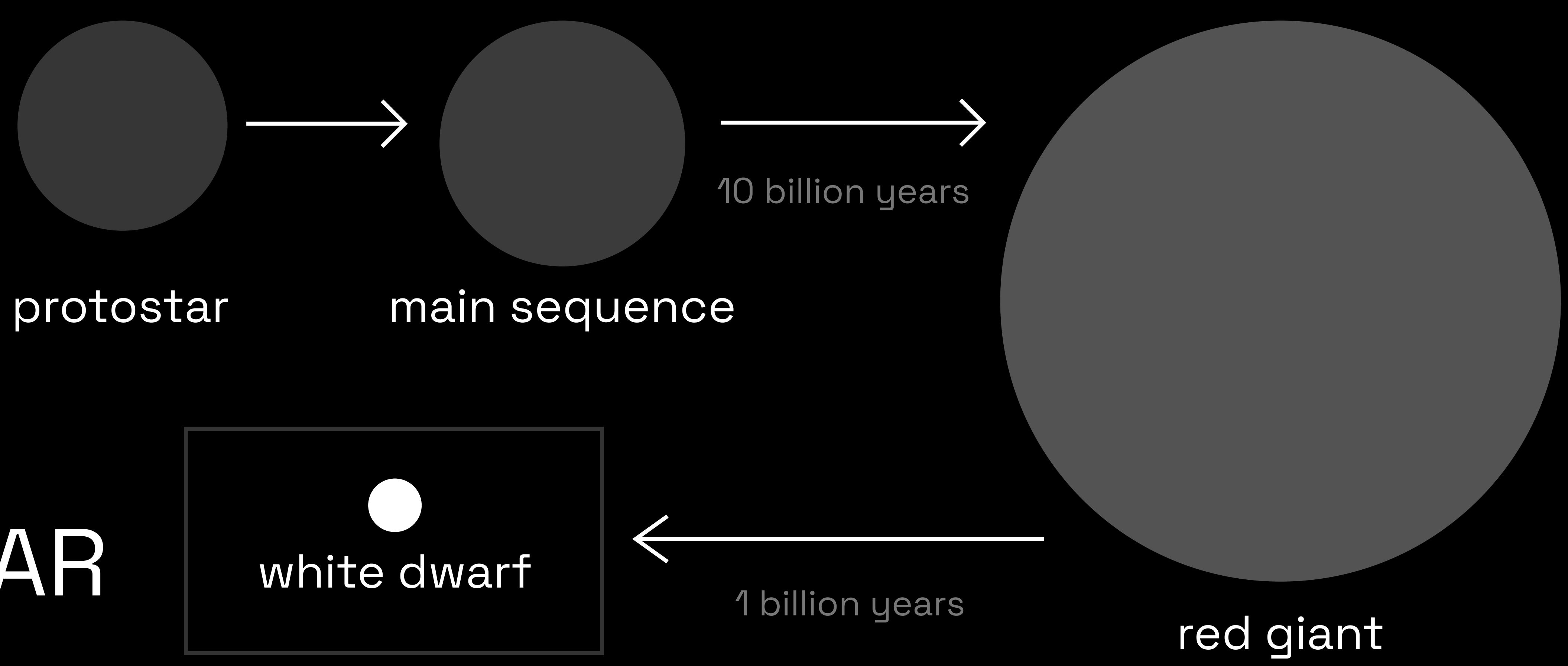


x-axis: colour

y-axis: brightness

LIFECYCLE

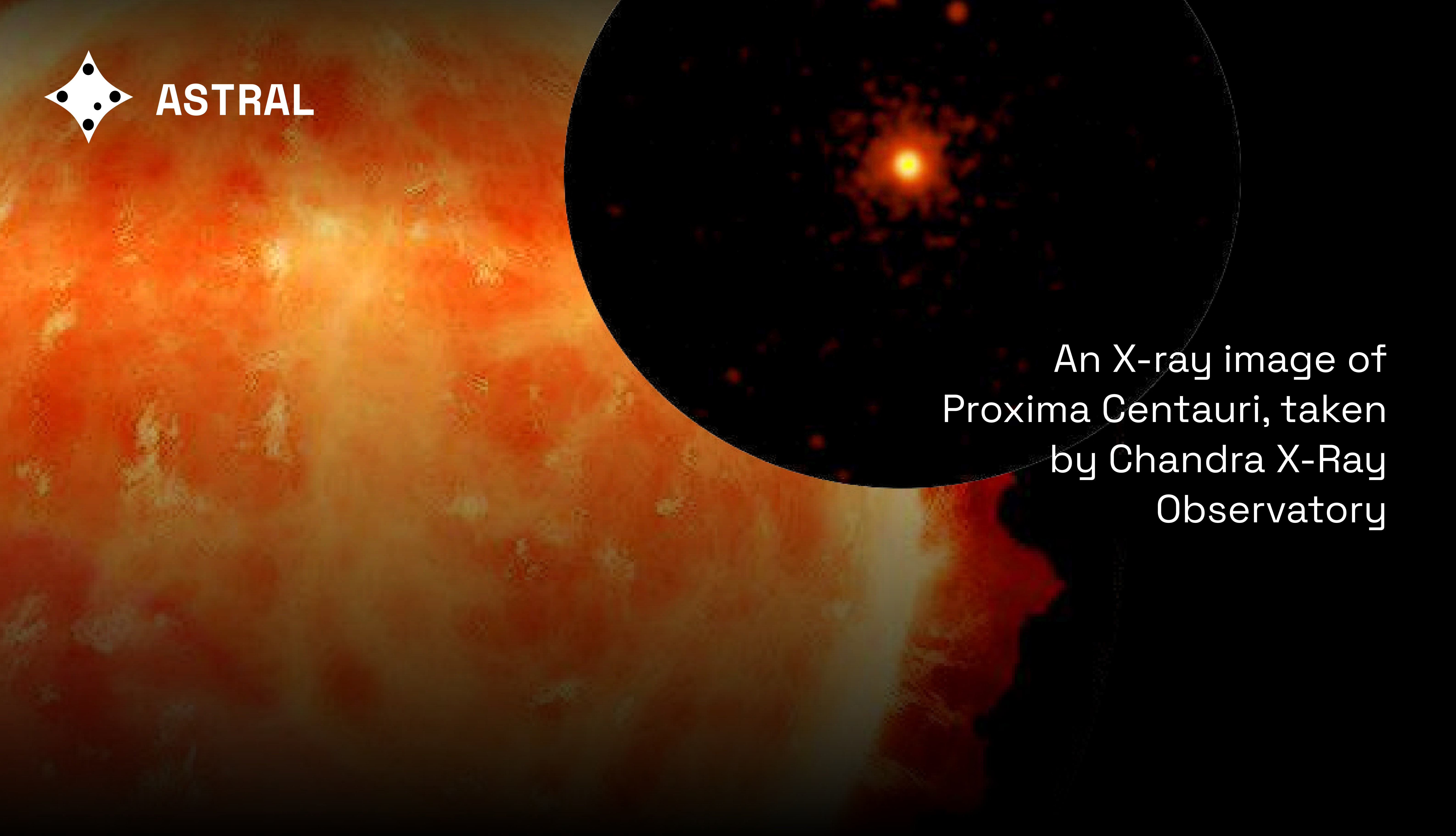
FATE OF STAR



ELEMENTS CREATED

2 4.00 He Helium	6 12.0 C Carbon	8 16.0 O Oxygen

The Sun's corona is ~200x hotter than its surface - no-one knows why!

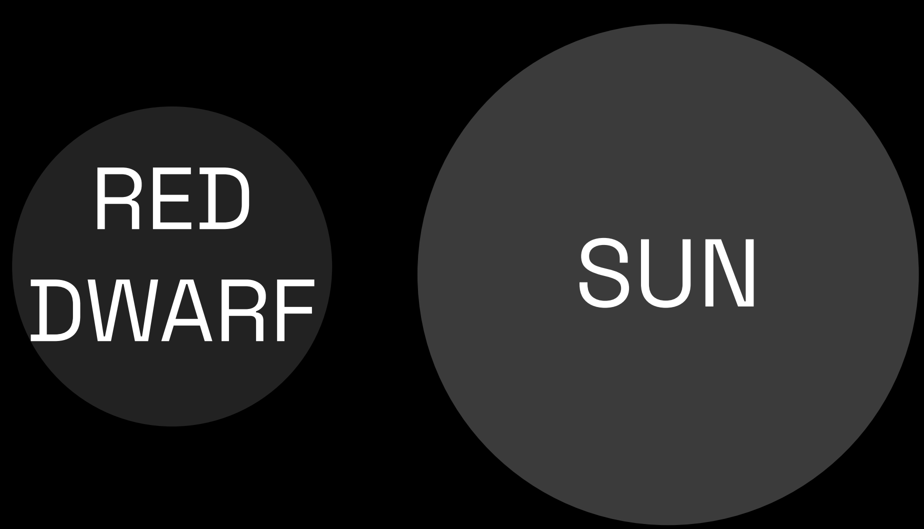


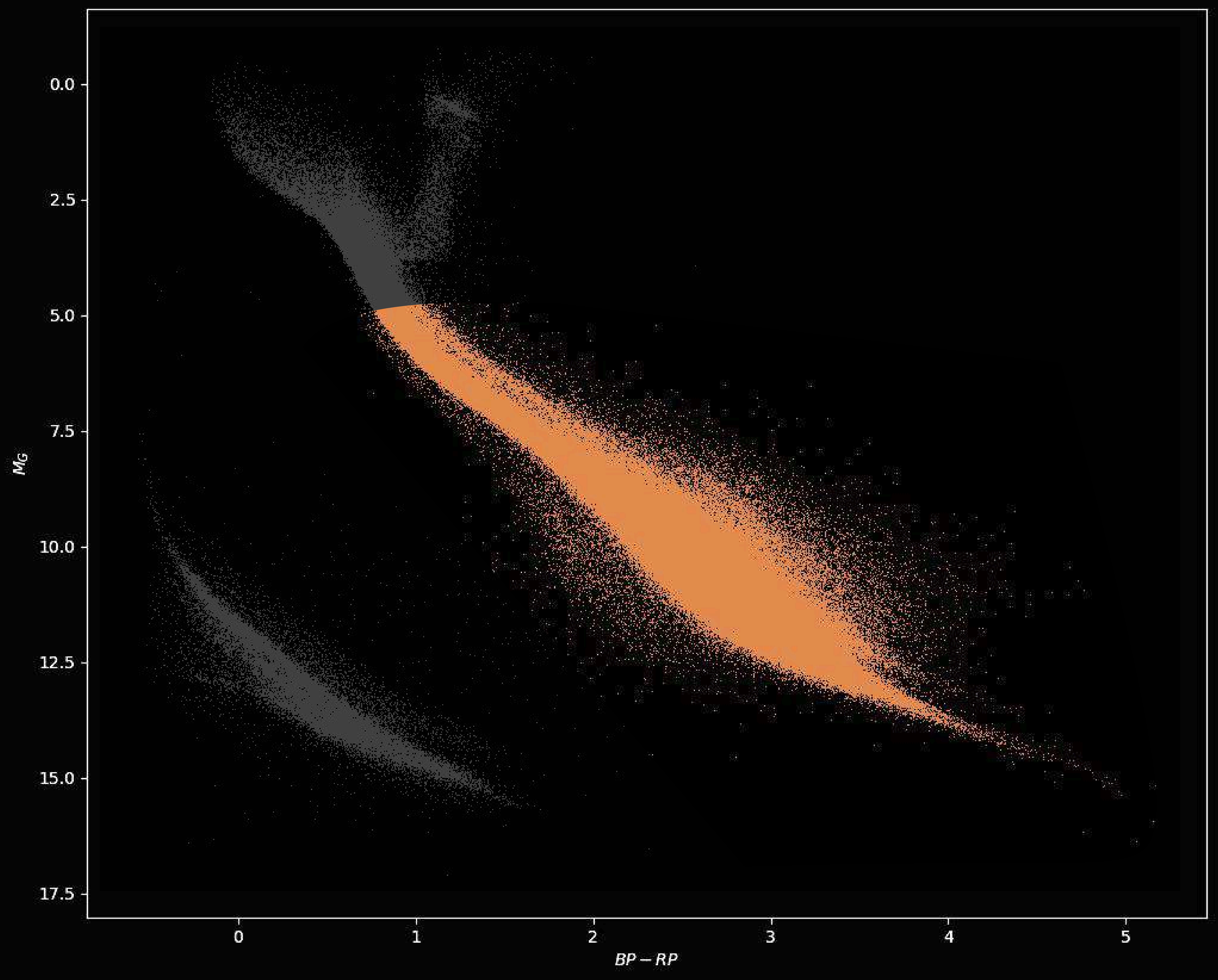
An X-ray image of Proxima Centauri, taken by Chandra X-Ray Observatory

RED DWARFS

TYPE	K and M
MASS	0.08 - 0.9 $M_\odot$
TEMPERATURE	2500 - 5300 K
LIFESPAN	100+ billion years
RADIUS	0.06 - 1.08 $R_\odot$
EXAMPLE	Proxima Centauri
LUMINOSITY	0.0001 - 0.5 $L_\odot$

M type stars are the most common in our universe. They live upwards of 100 billion years and burn a red-orange colour.





x-axis: colour

y-axis: brightness

LIFECYCLE

protostar → main sequence

100 billion years

FATE OF STAR

white dwarf

ELEMENTS CREATED

2 4.00
He
Helium

Even as the most common star type, making up 70-80% of the Milky Way, they are invisible to the naked eye

RED GIANTS

Source: : European Southern Observatory

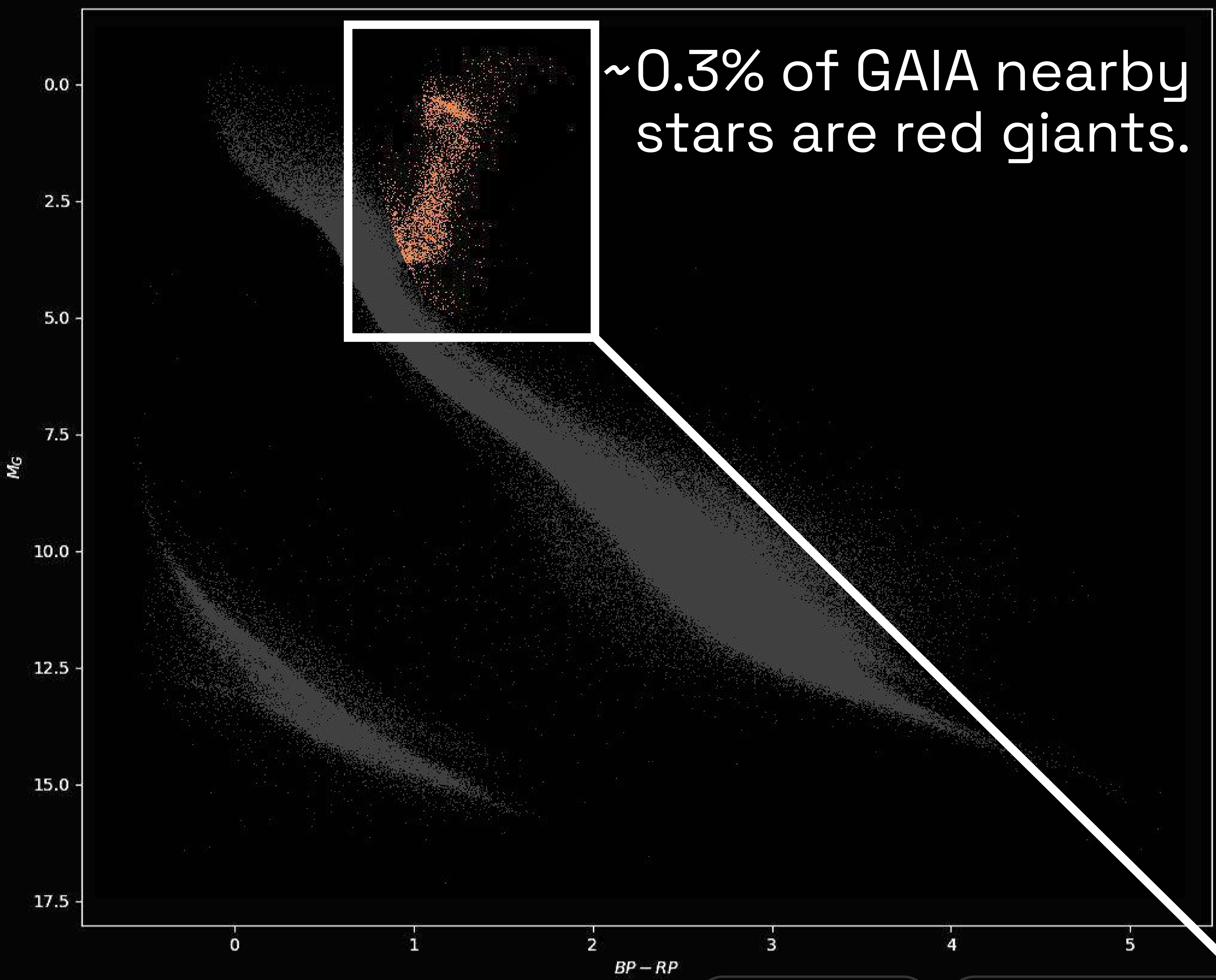
TYPE	RGB, HB and AGB
MASS	$0.5\text{-}5\, M_\odot$
TEMPERATURE	5000-3000 K
LIFESPAN	10^7 to 10^{10} years
RADIUS	$\sim 100\, R_\odot$
EXAMPLE	Antares
LUMINOSITY	$\sim 3000\, L_\odot$

ELEMENTS FOUND

Atomic number	Atomic mass	Symbol	Name
14	28.09	Si	Sillicon
6	12.00	C	Carbon
56	55.85	Fe	Iron

SUN

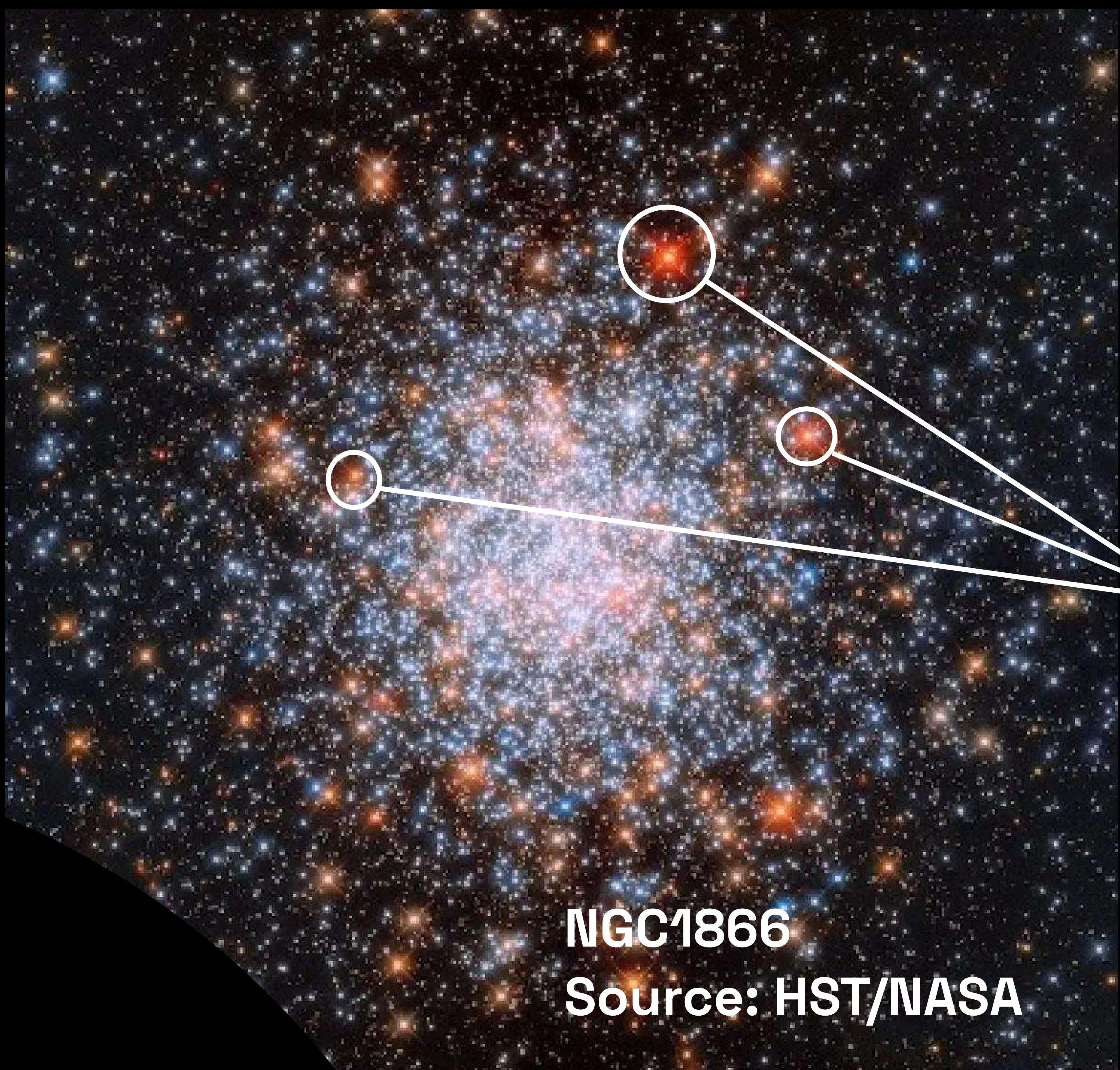
RED GIANT

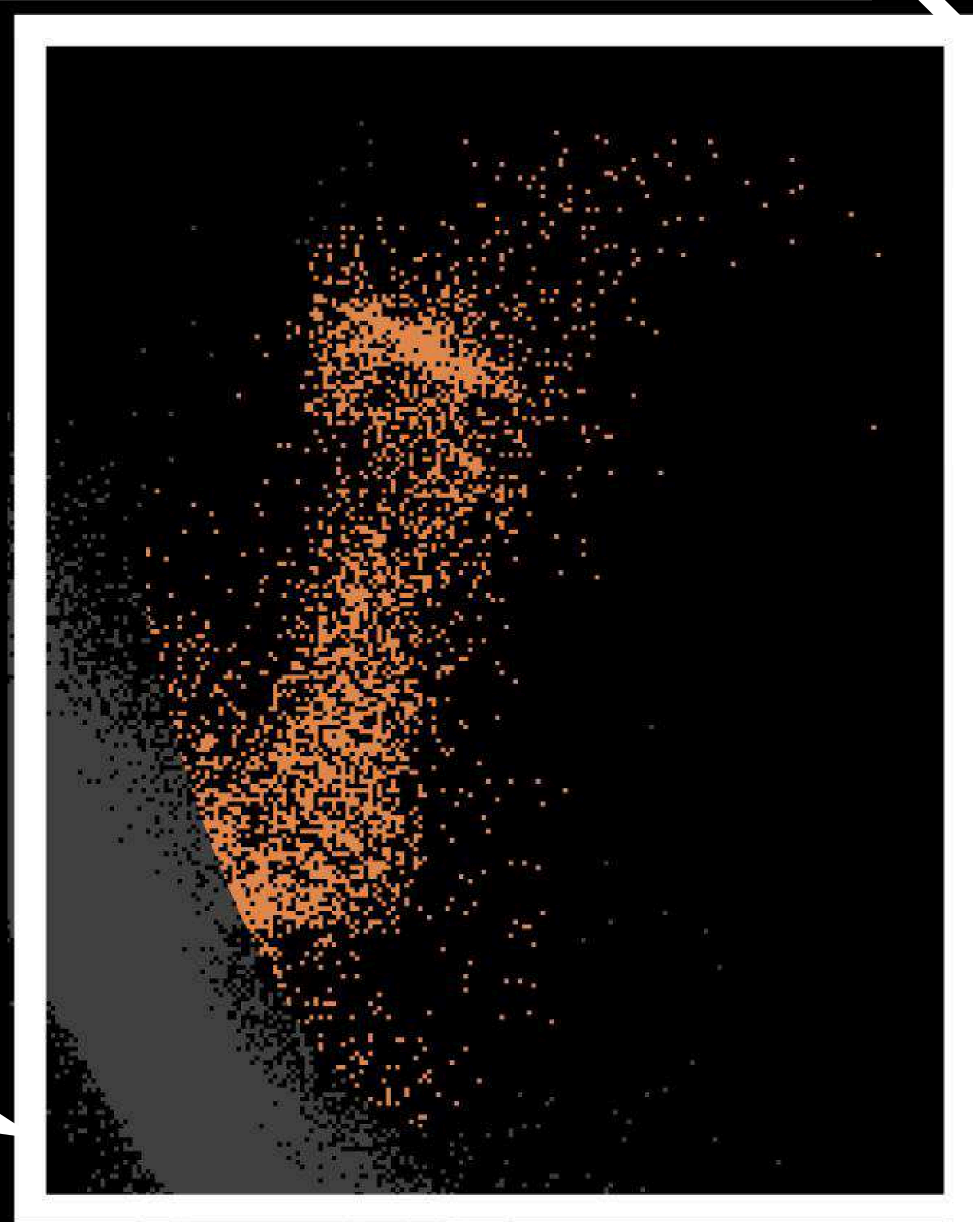


x-axis: colour

y-axis: brightness

Bright Red Giants in a Globular Cluster





Red in colour caused by cooler surfaces, and temperatures than the Sun

ASTRAL

WHITE DWARFS

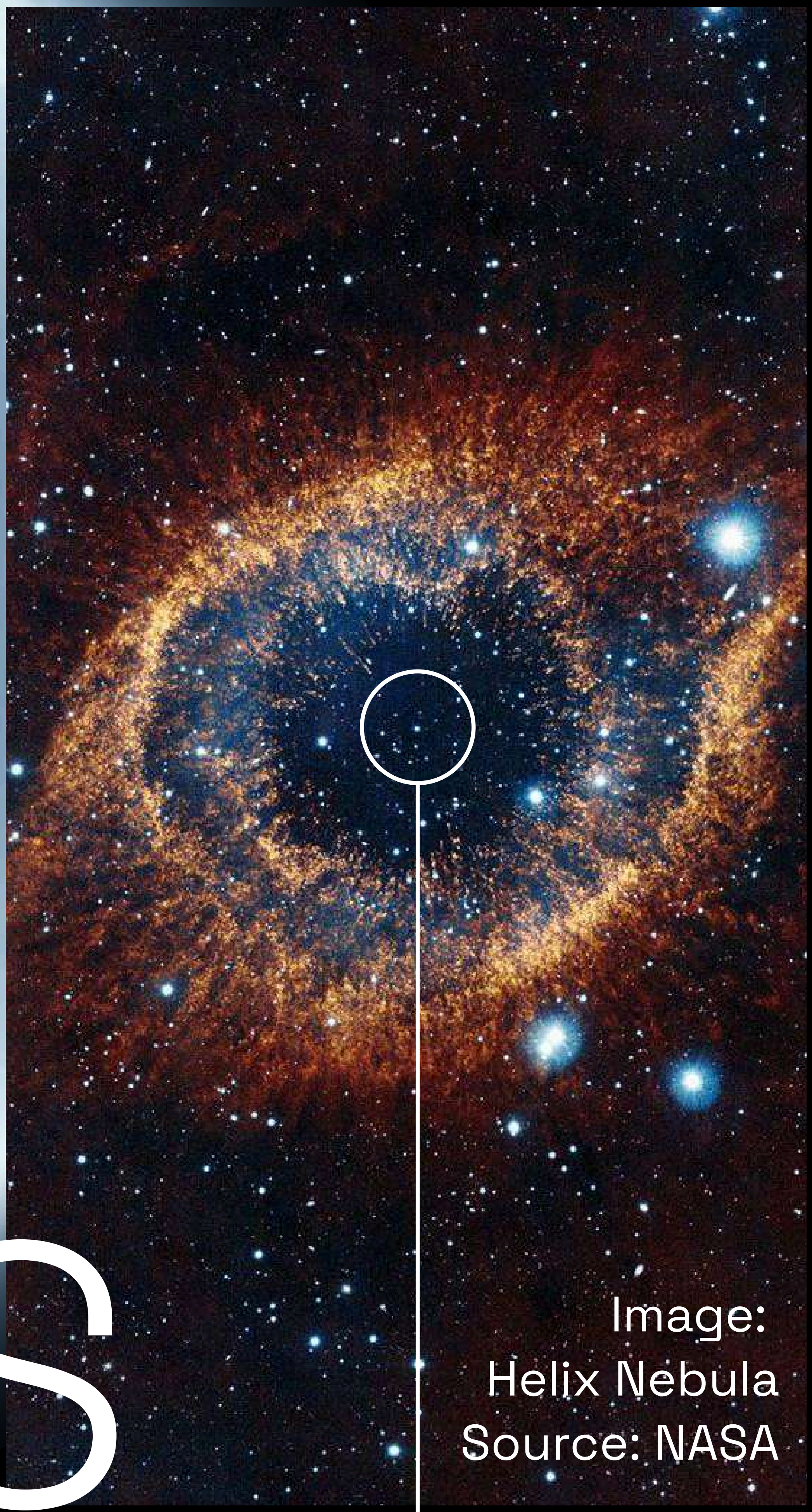
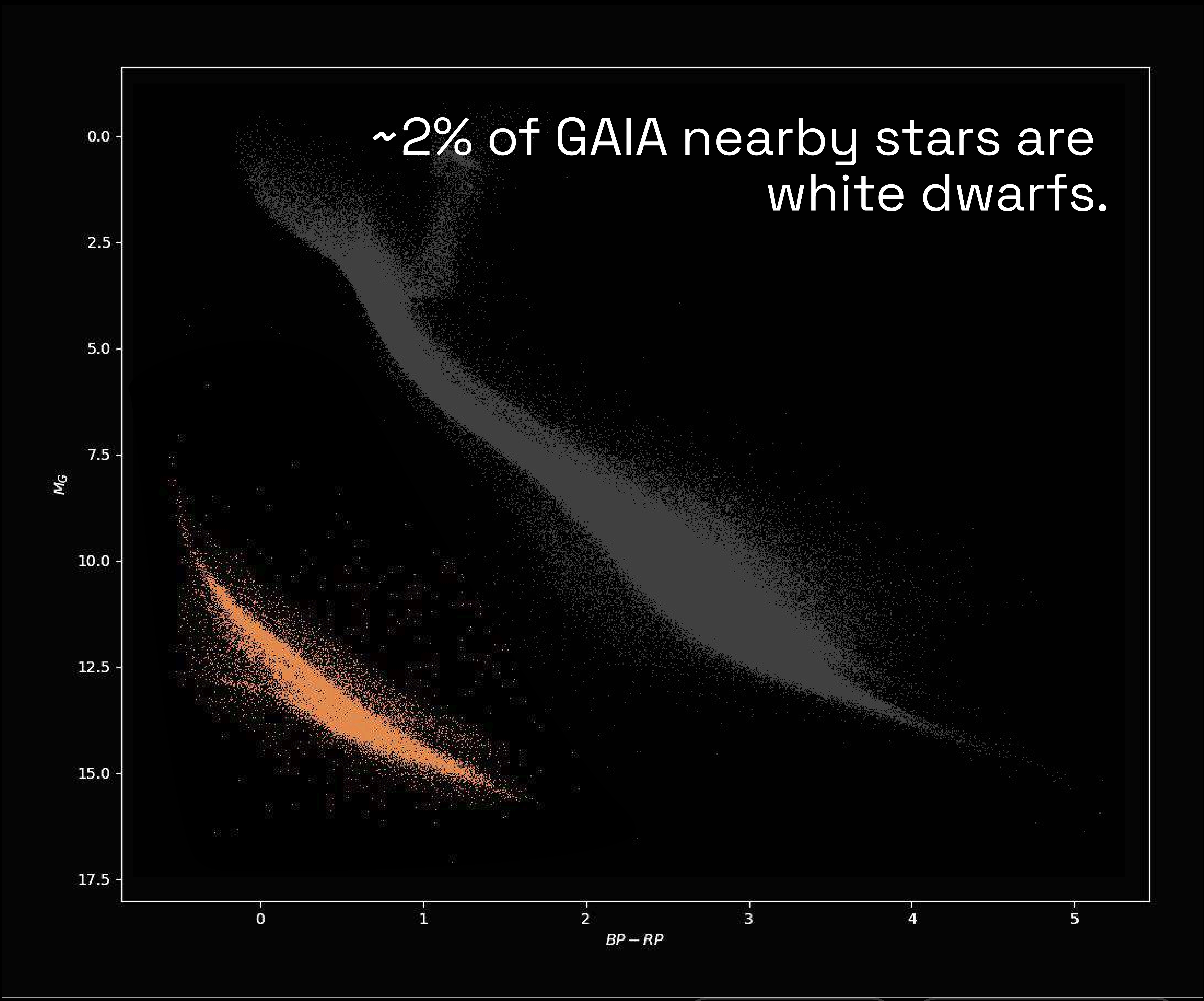


Image: Helix Nebula Source: NASA

TYPE	He, CO and ONeMg
MASS	0.2-1.3 $M_\odot$
TEMPERATURE	8000 - 40000 K
LIFESPAN	100+ billion years
RADIUS	6000-7000km
NEARBY EXAMPLE	Sirius B
LUMINOSITY	0.1 - 1 $L_\odot$

White dwarfs are the leftover dead cores of intermediate mass stars like our Sun. An example is the faint star in the centre of the Helix Nebula, shown above.



x-axis: colour

y-axis: brightness

White dwarfs are often denoted as “He”, “CO”, or “ONeMg”, based on their chemical composition after the red giant phase of stellar evolution.

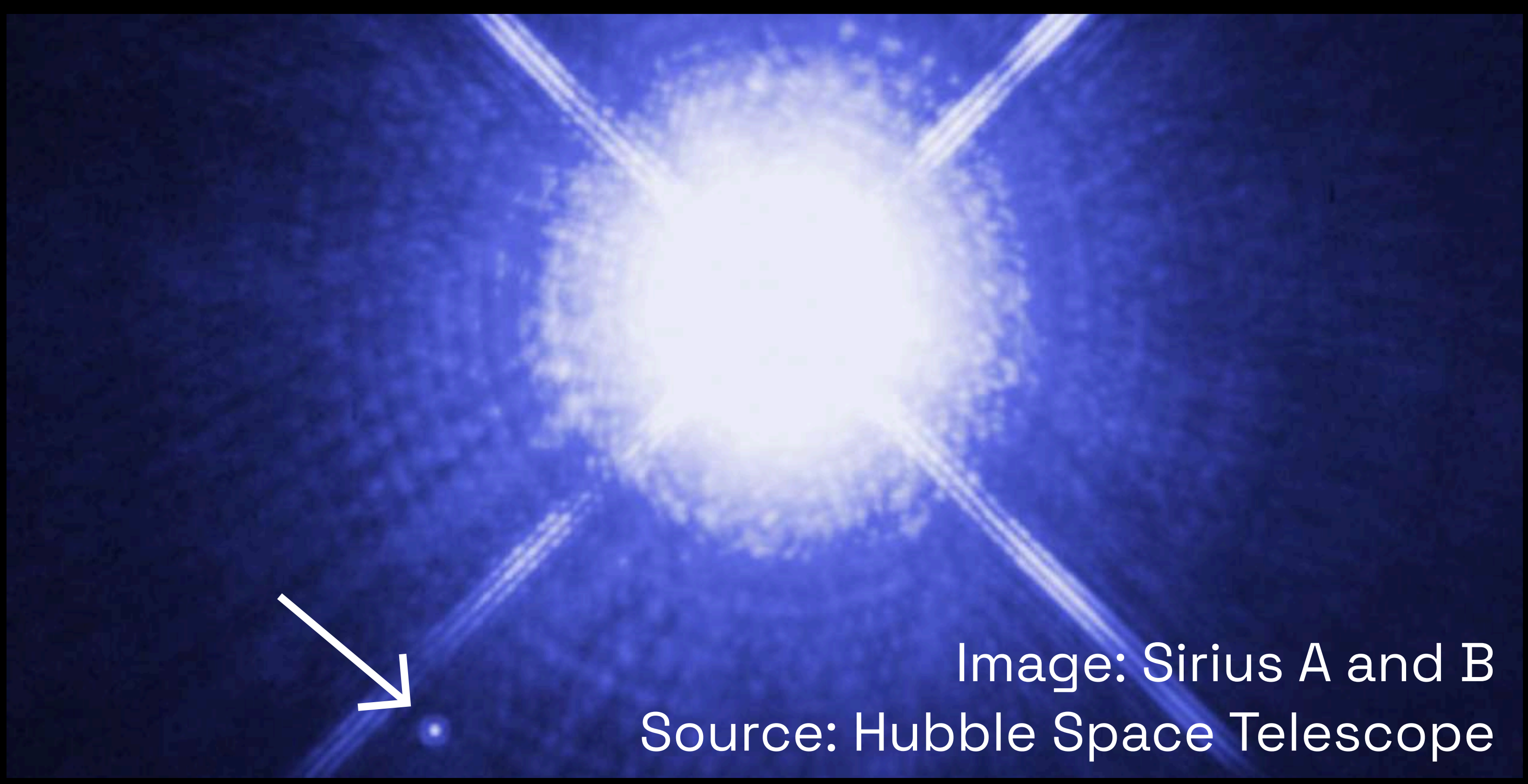


Image: Sirius A and B
Source: Hubble Space Telescope

Sirius A (highly luminous star) and Sirius B (tiny dot). Sirius B is a white dwarf.

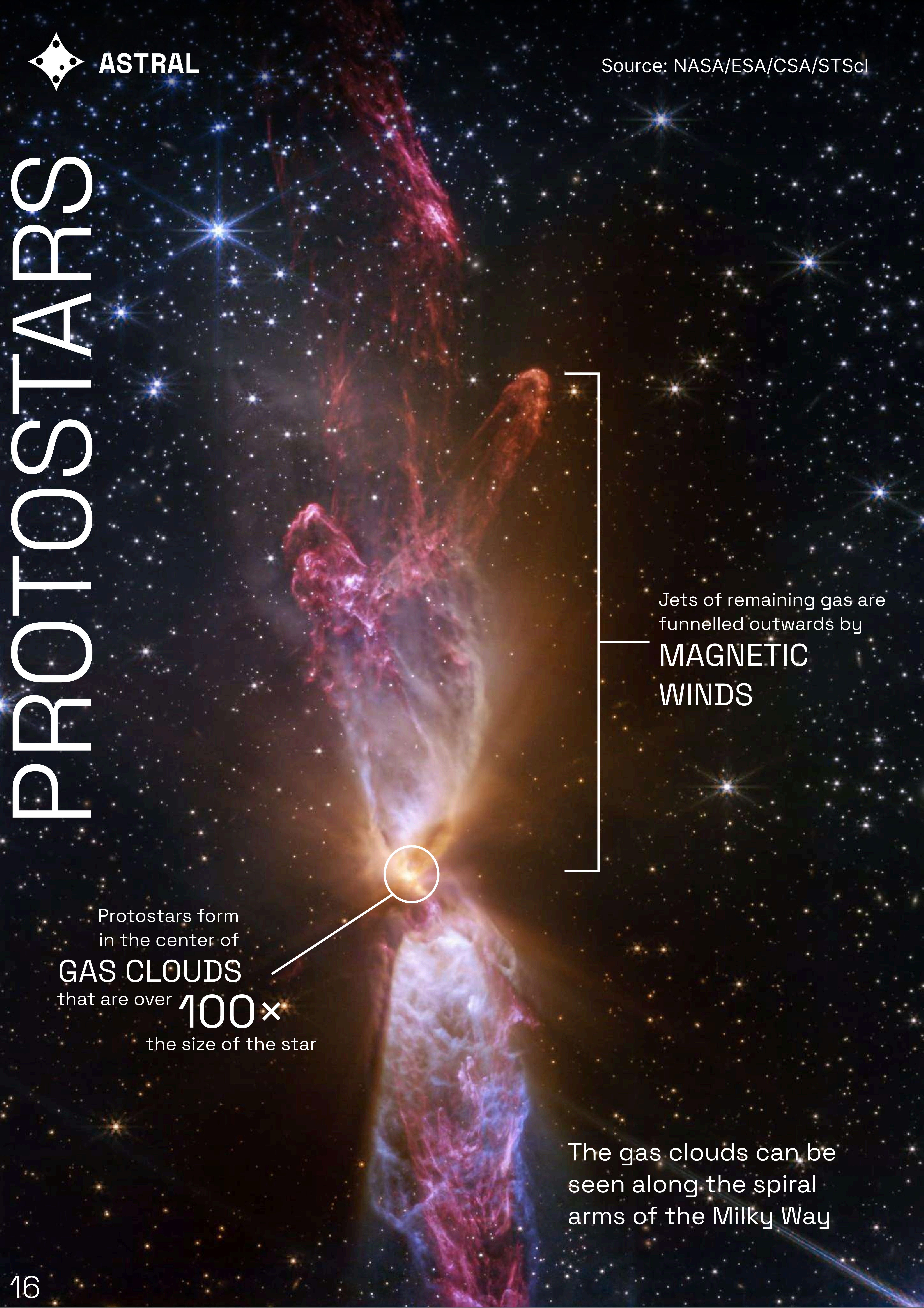
ELEMENTS FOUND

2 4.00	6 12.0	8 16.0	10 20.2
He	C	O	Ne
Helium	Carbon	Oxygen	Neon

One teaspoon of a white dwarf can weigh as much as **5 tons.**

Source: NASA/ESA/CSA/STScI

PROTOSTARS



Jets of remaining gas are funnelled outwards by

MAGNETIC WINDS

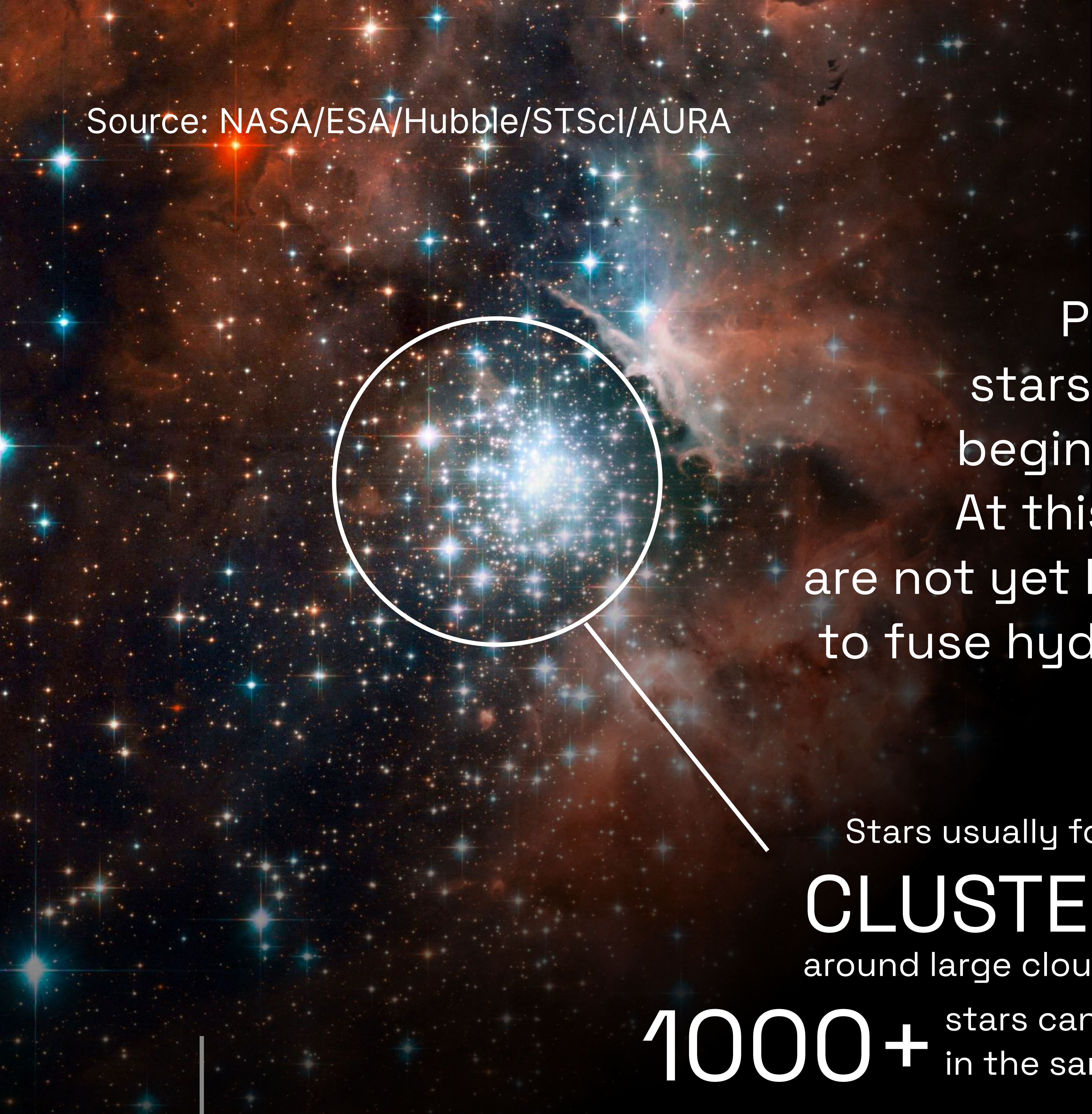
Protostars form in the center of

GAS CLOUDS

that are over 100× the size of the star

The gas clouds can be seen along the spiral arms of the Milky Way

PROTOSTARS



Source: NASA/ESA/Hubble/STScI/AURA

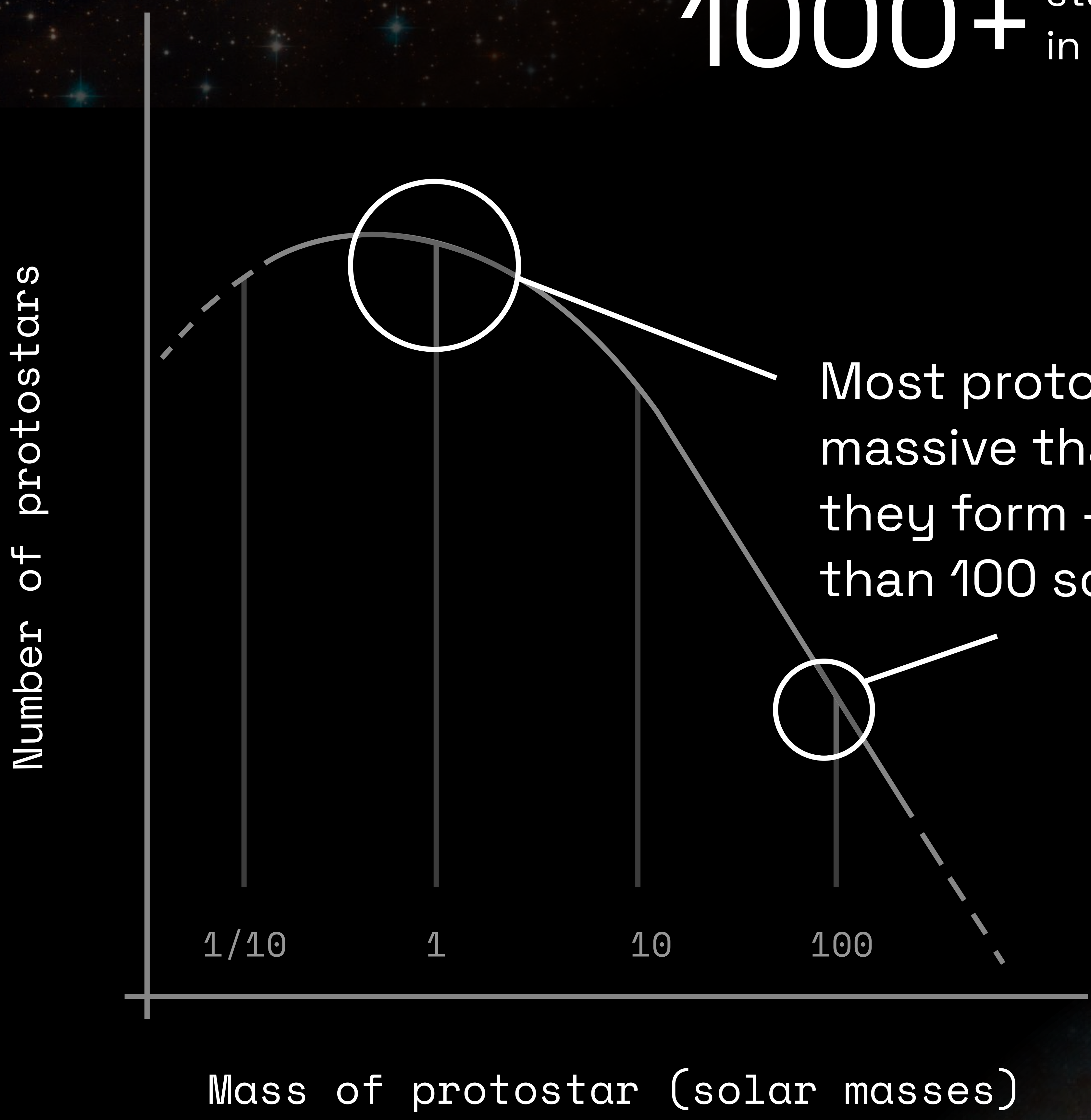
Protostars are stars that are just beginning to form. At this stage, they are not yet large enough to fuse hydrogen atoms into helium.

Stars usually form in

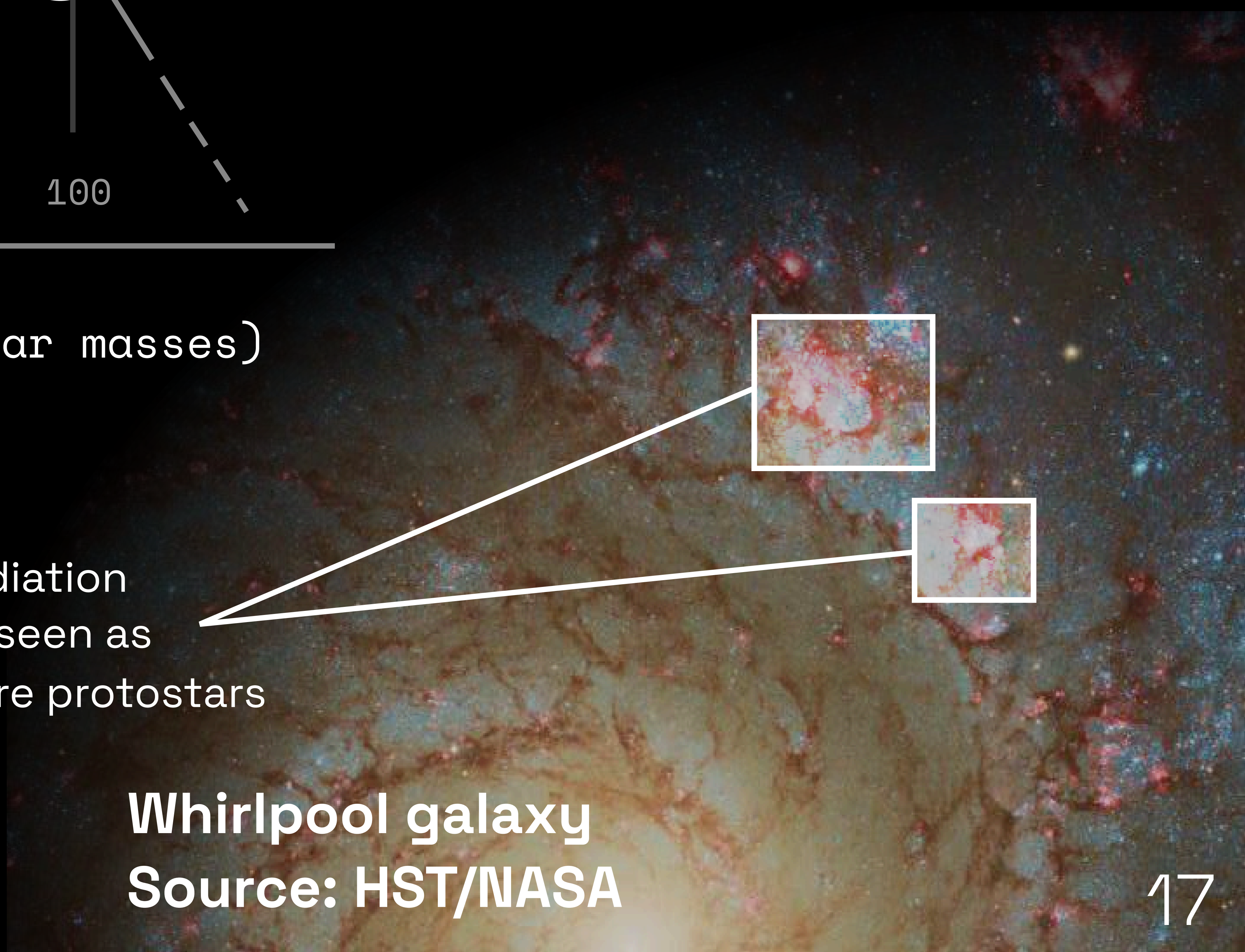
CLUSTERS

around large clouds of gas;

1000+ stars can form in the same area



Most protostars are less massive than the Sun when they form - very few are heavier than 100 solar masses



Hydrogen is ionised by the radiation from new stars, which can be seen as

PINK LIGHT

in areas where protostars are forming.

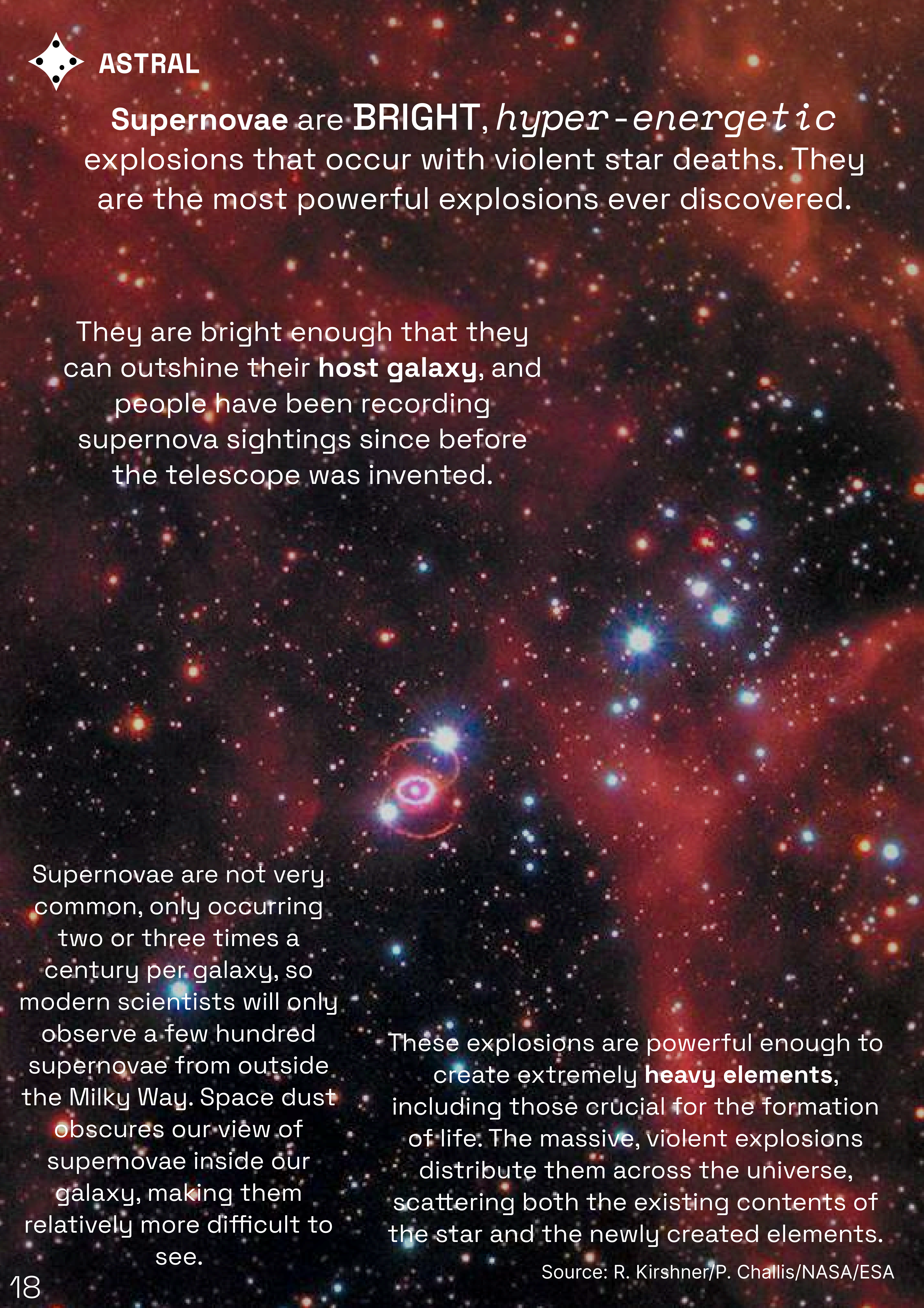
Whirlpool galaxy
Source: HST/NASA

Supernovae are BRIGHT, *hyper-energetic* explosions that occur with violent star deaths. They are the most powerful explosions ever discovered.

They are bright enough that they can outshine their **host galaxy**, and people have been recording supernova sightings since before the telescope was invented.

Supernovae are not very common, only occurring two or three times a century per galaxy, so modern scientists will only observe a few hundred supernovae from outside the Milky Way. Space dust obscures our view of supernovae inside our galaxy, making them relatively more difficult to see.

These explosions are powerful enough to create extremely **heavy elements**, including those crucial for the formation of life. The massive, violent explosions distribute them across the universe, scattering both the existing contents of the star and the newly created elements.



Source: R. Kirshner/P. Challis/NASA/ESA

SUPERNOVAE

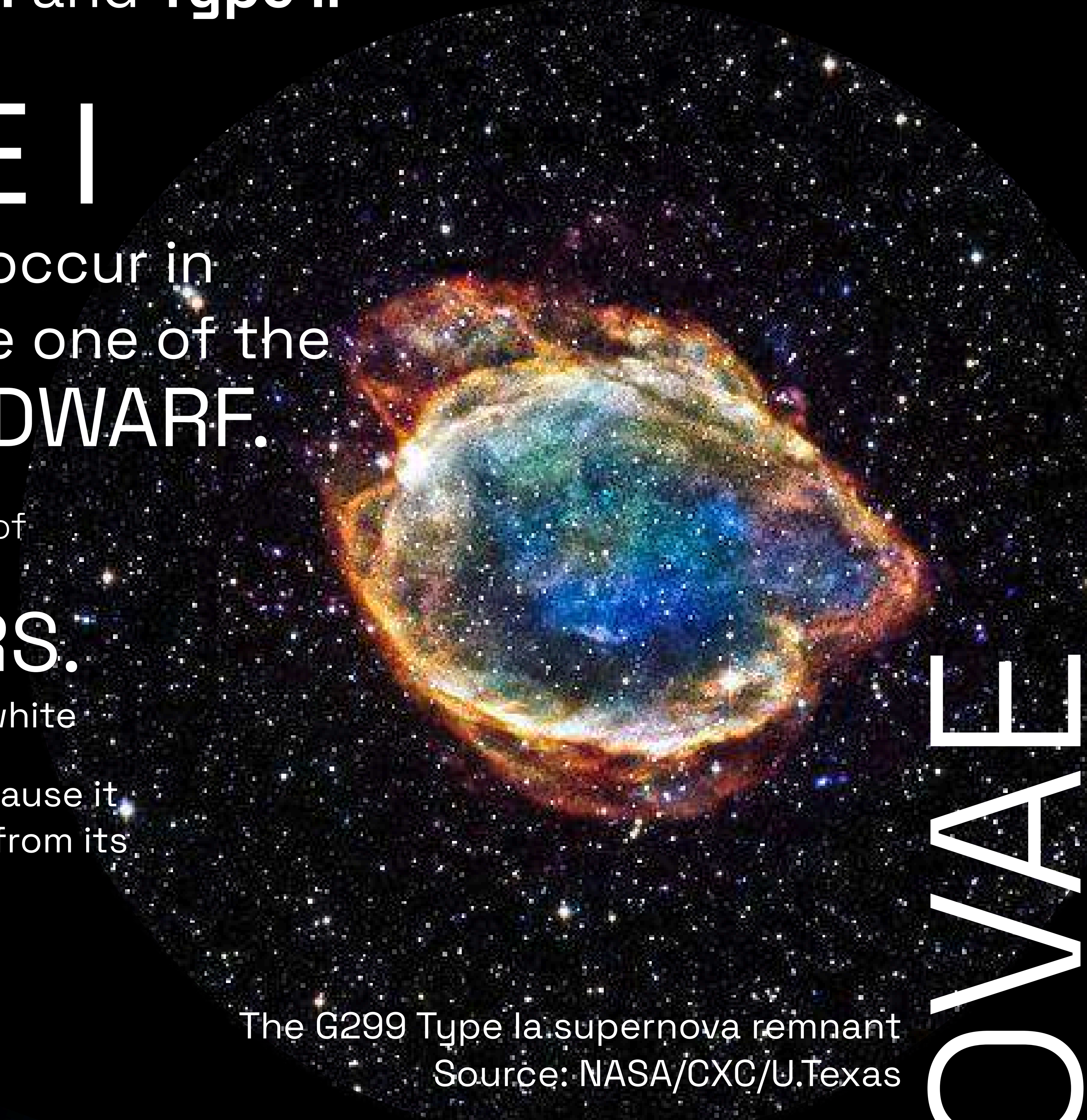
There are two main types of supernovae: **Type I** and **Type II**

TYPE I

Type I supernovae occur in binary systems where one of the stars is a WHITE DWARF.

These are the RAREST type of supernovae and occur around once every 500 YEARS.

Type I supernovae occur when a white dwarf EXPLODES because it sucks too much material away from its companion star.

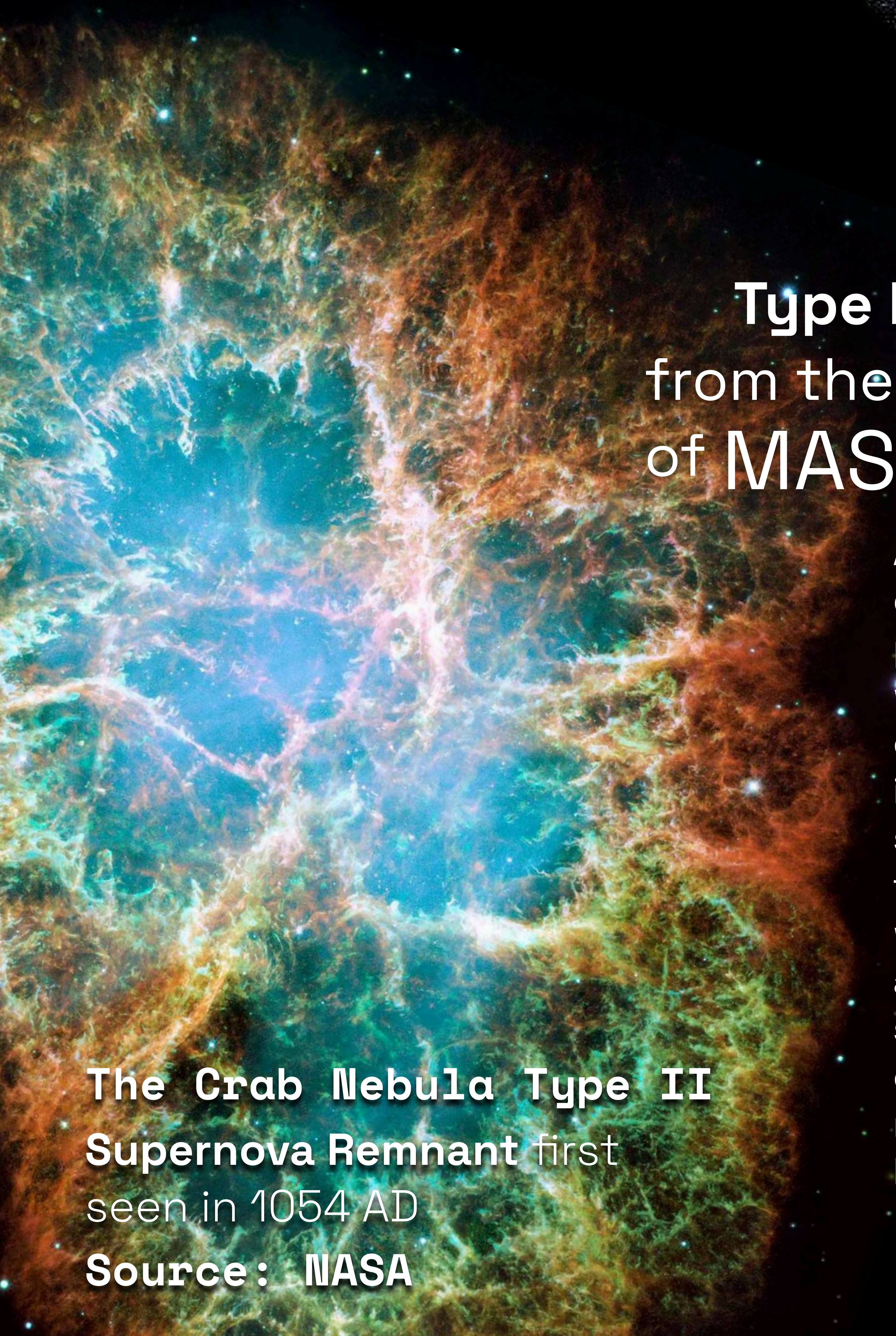


The G299 Type Ia supernova remnant
Source: NASA/CXC/U.Texas

TYPE II

Type II supernovae originate from the collapse and explosion of MASSIVE STARS.

As massive stars burn very hot, they quickly run out of fuel. The outward pressure generated at its core weakens without fuel, allowing gravity pushing inward to overpower it. The temperature drops, and the star collapses. Lasting only seconds, the implosion creates huge shock waves that rip the outer layers apart, leaving behind only a gaseous surrounding nebula and the dense core at its centre. In extremely massive stars, it may leave behind a black hole.



The Crab Nebula Type II Supernova Remnant first seen in 1054 AD
Source: NASA

Neutron stars are about the size of Melbourne, but weigh as much as

1.4 SUNS!

The Nebula around the Crab Nebula

A spoonful of neutron star weighs as much as a **MOUNTAIN**

When a star **COLLAPSES** on itself during a supernova, its protons and electrons are squeezed together into a

SUPER DENSE NEUTRON STAR

Source:
NASA/CXC/A. Hobart

Some spinning neutron stars point towards Earth, or have an extra strong

MAGNETIC FIELD

We call these

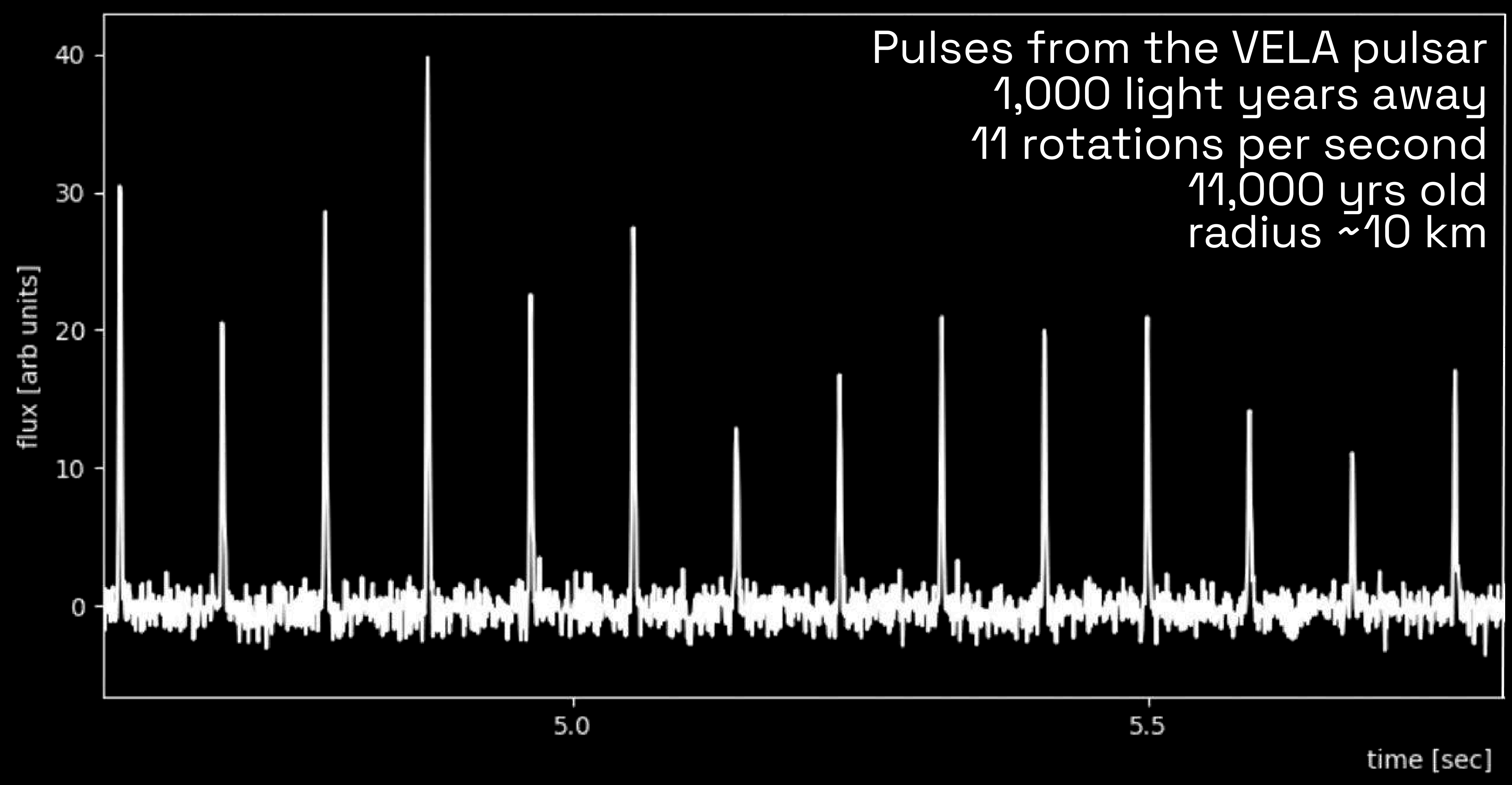
PULSARS and **MAGNETARS**

respectively.

Source:
Lizel Arina, Freepik

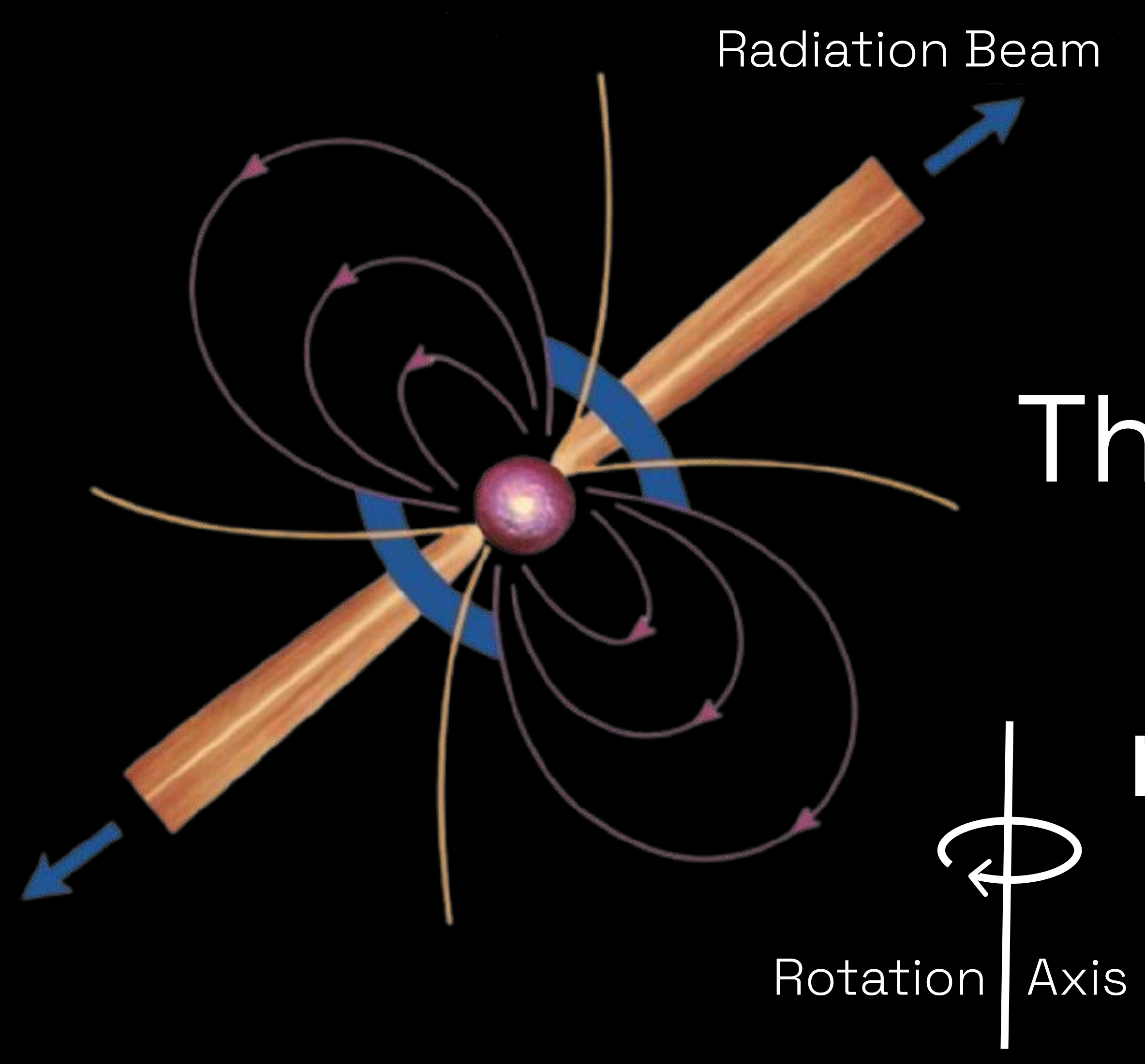
NEUTRON STARS

A pulsar is a rapidly-rotating neutron star that has a lighthouse-like beam of emission. When the beam crosses the Earth, we detect regular pulses of emission, hence the name “pulsar”.



Pulsars are most easily found using radio waves, and can be used as clocks.

TYPE	NEUTRON STAR
MASS	1.4 SOLAR MASSES
LIFESPAN	100 MILLION YEARS
RADIUS	10-12 KM
EXAMPLE OF NEUTRON STAR	VELA
DISTANCE OF VELA TO SUN	~1000 LIGHTYEARS



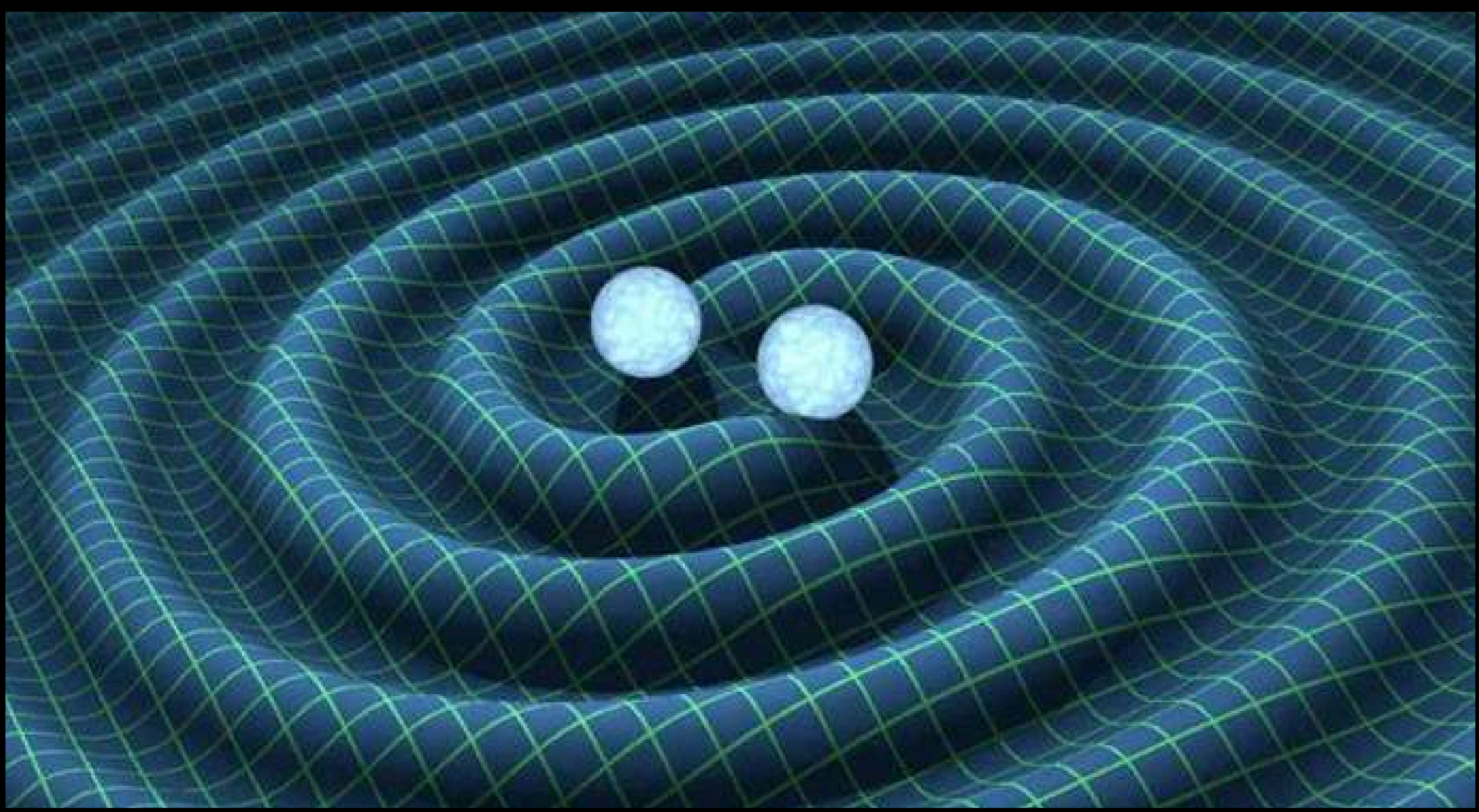
FUN FACT

The fastest known pulsar spins at over 700 revolutions per second.

We cannot directly see black holes. Instead, we see stars and gas in an accretion disk fall into them. The disk is very hot from the friction of the matter, emitting x-rays that we can detect!

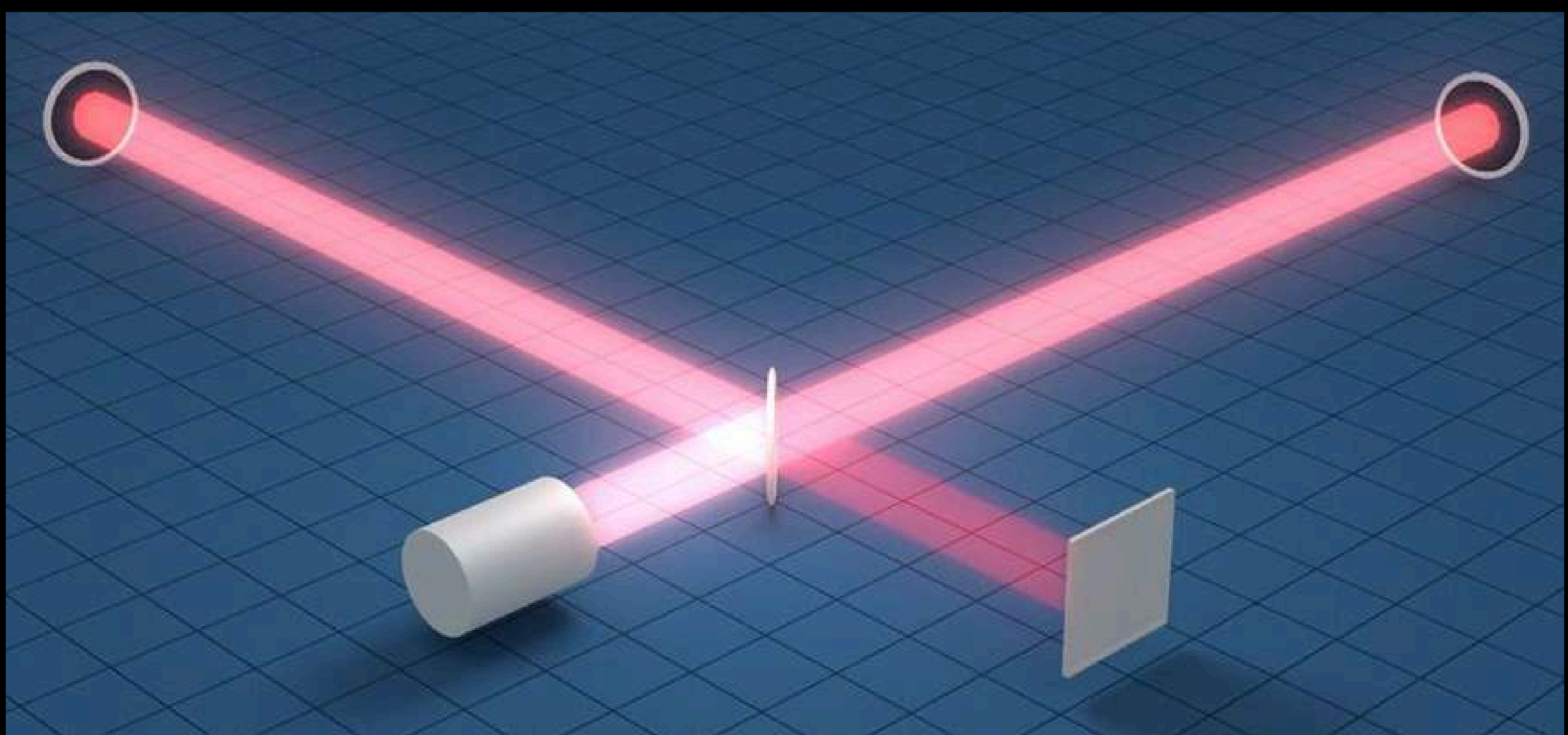
Source:
Event Horizon Telescope

This is a photograph of the supermassive black hole at the center of the galaxy Messier 87. Here we can see a bright ring as light bends around it due to its immense gravity.



Visualisation of orbiting black holes creating gravitational waves
Source: R. Hurt/Caltech-JPL

Black holes orbiting each other emit **gravitational waves** - ripples in the fabric of spacetime - which can be detected on Earth with special instruments.

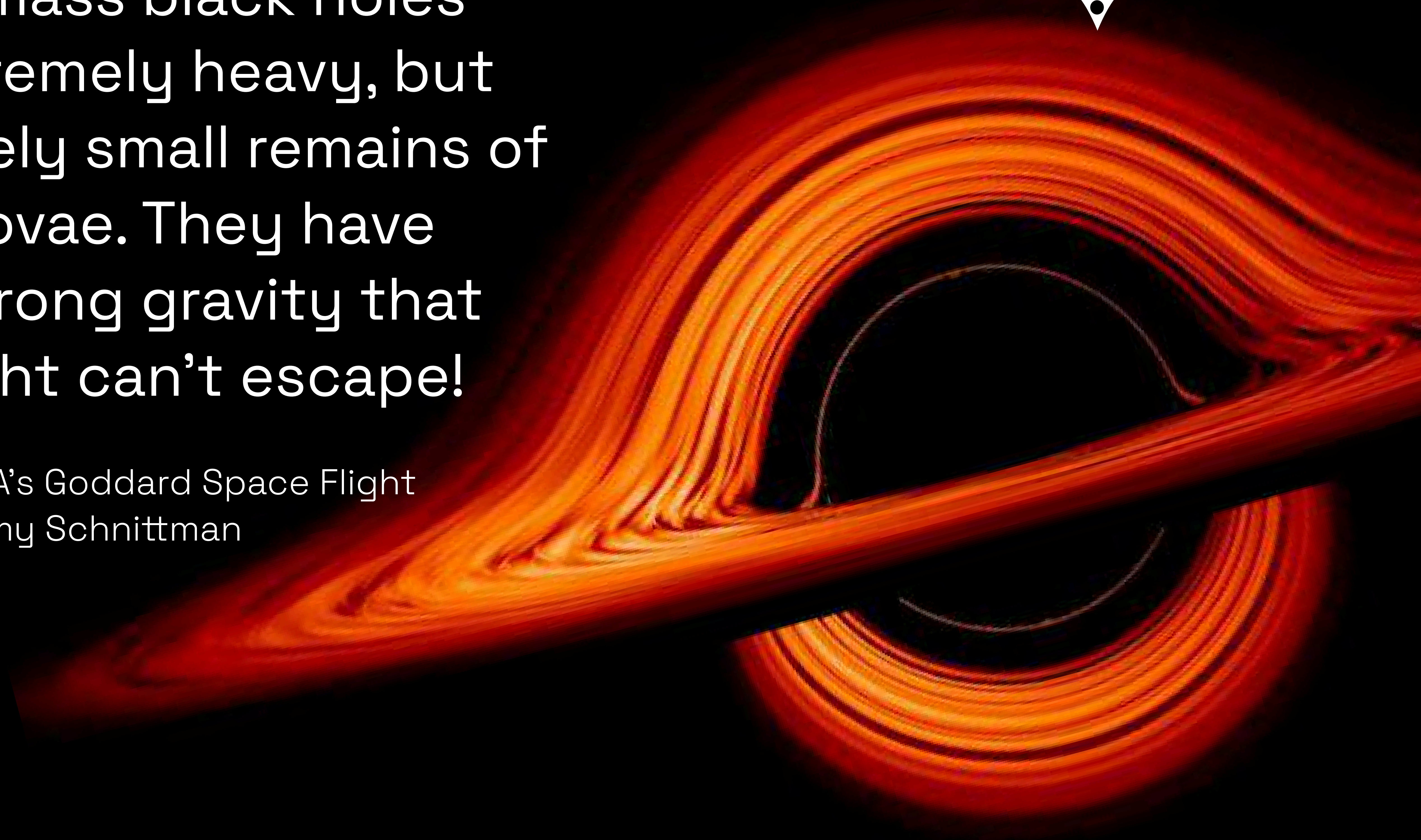


Visualisation of how gravitational wave detectors work, checking for changes in length between mirrors.
Source: LIGO

Devices like LIGO act like really precise rulers so we can detect when a gravitational wave passes through us.

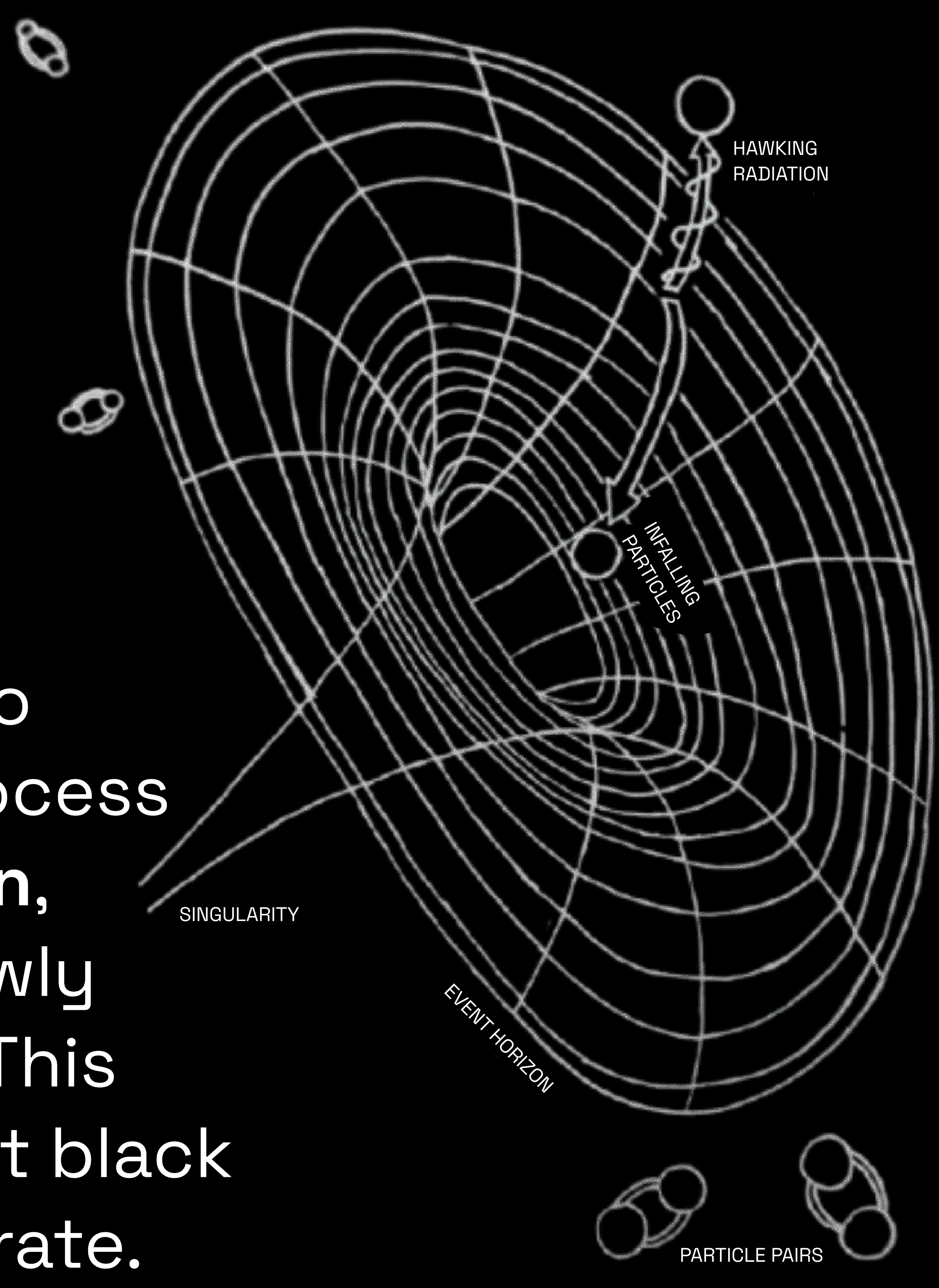
BLACK HOLES

Stellar mass black holes are extremely heavy, but extremely small remains of supernovae. They have such strong gravity that even light can't escape!

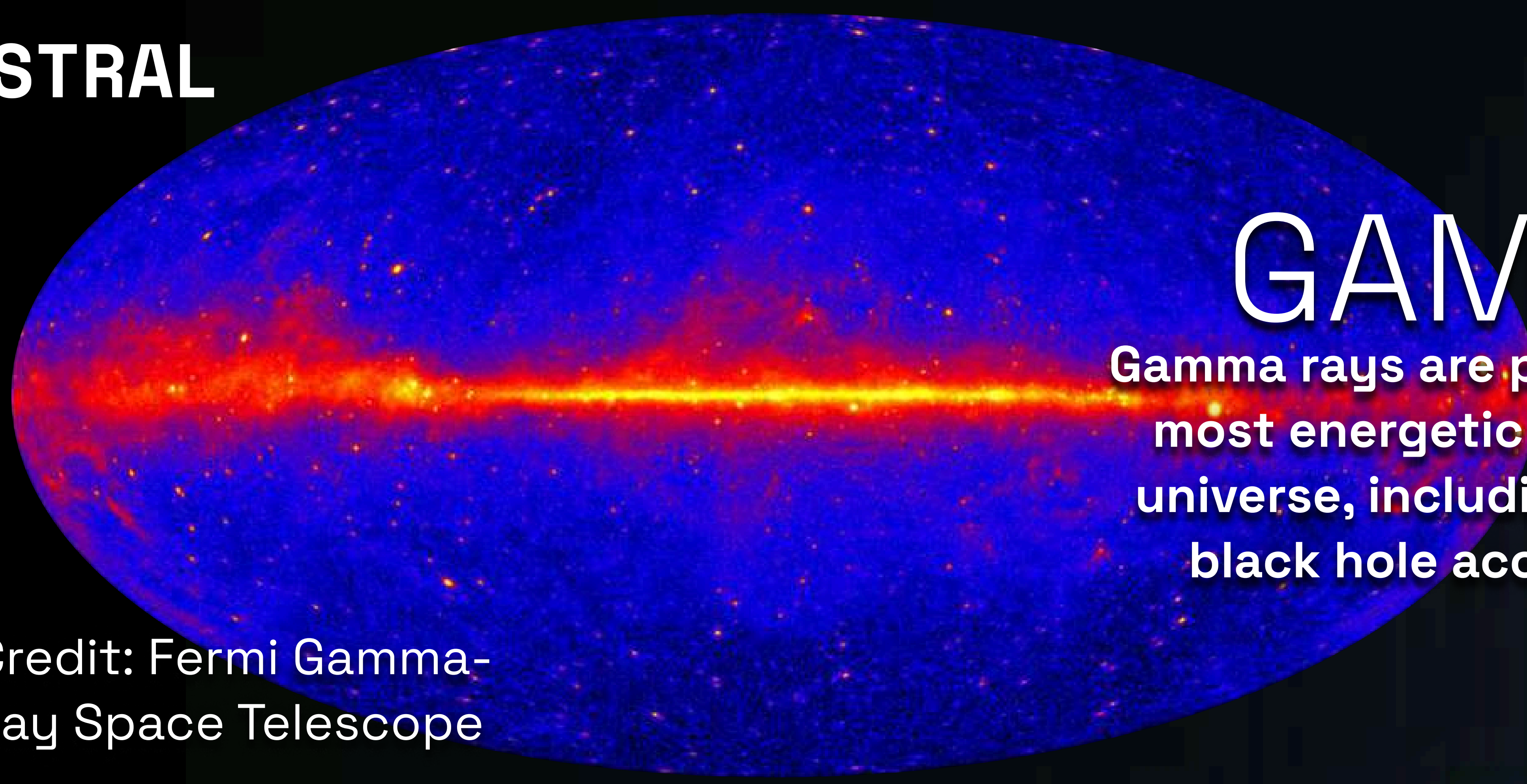


Source: NASA's Goddard Space Flight Center/Jeremy Schnittman

Any object can become a black hole if it is compressed enough. The radius for this to happen is called the **Schwarzschild Radius.** For the Earth to be a black hole, you would have to squish it to be less than 2 cm across.



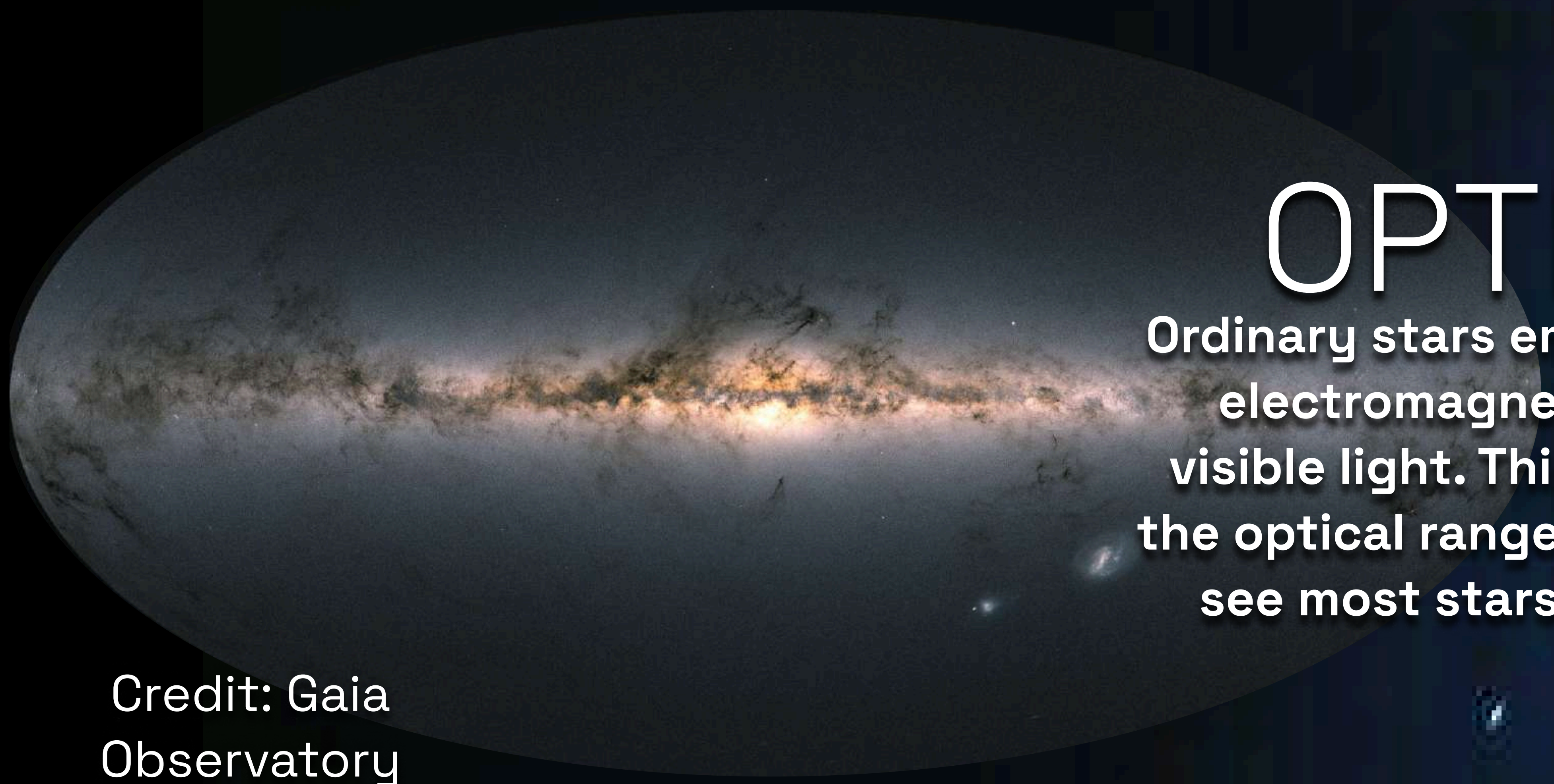
Black holes are theorised to slowly decay through a process known as **Hawking radiation**, which works extremely slowly through quantum effects. This would mean that even giant black holes will eventually evaporate.



GAMMA

Gamma rays are produced by the most energetic objects in the universe, including pulsars and black hole accretion disks.

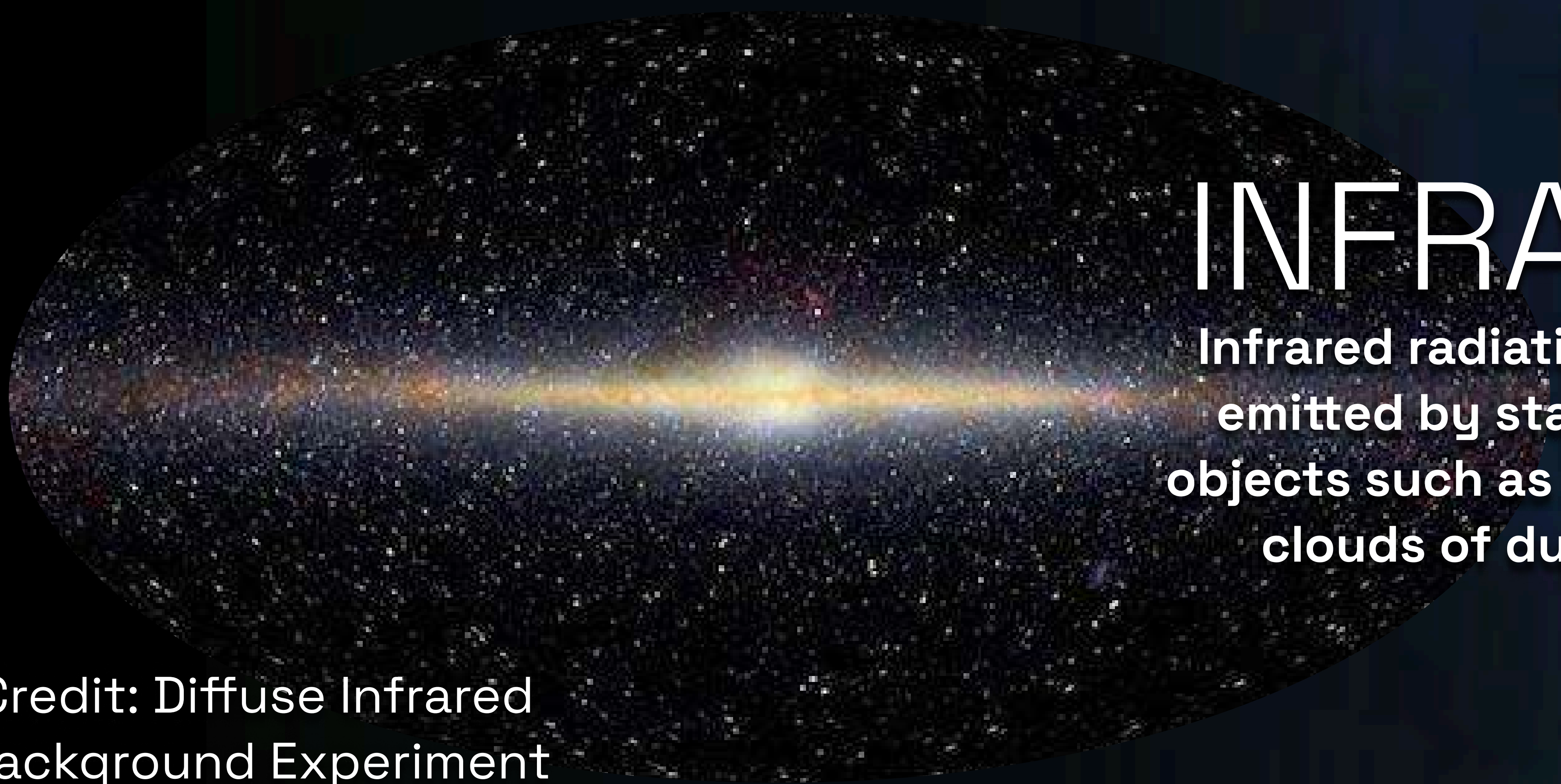
Credit: Fermi Gamma-ray Space Telescope



OPTICAL

Ordinary stars emit most of their electromagnetic energy as visible light. This means that in the optical range, telescopes can see most stars and galaxies.

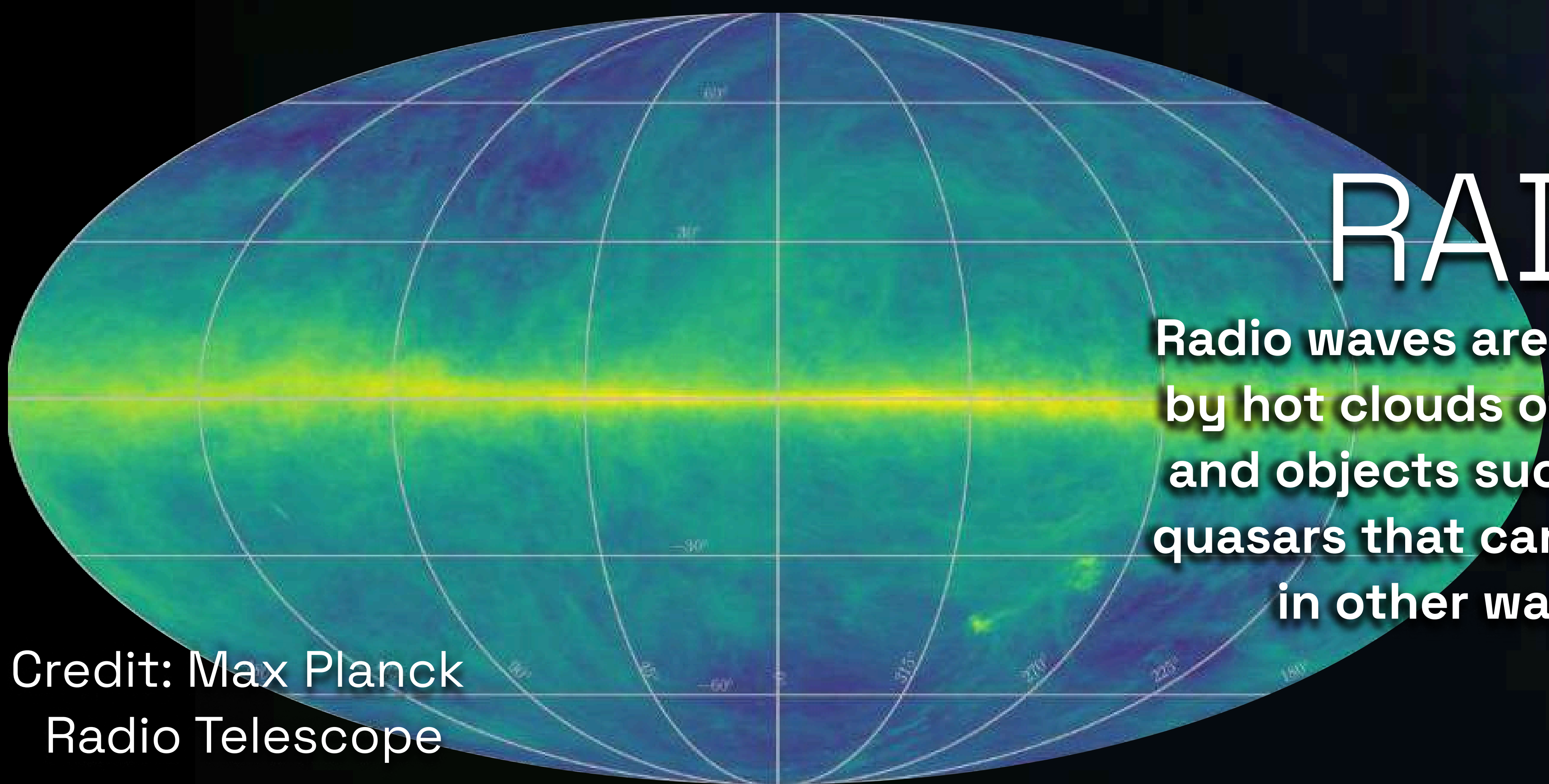
Credit: Gaia Observatory



INFRARED

Infrared radiation is primarily emitted by stars and cooler objects such as exoplanets and clouds of dust in space.

Credit: Diffuse Infrared Background Experiment

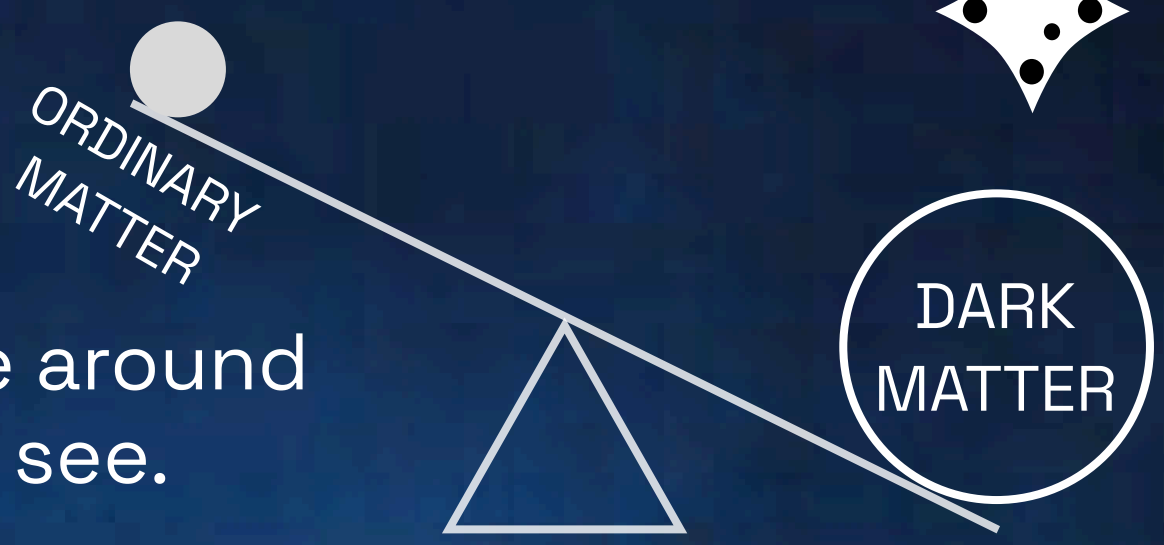


RADIO

Radio waves are mostly emitted by hot clouds of hydrogen gas and objects such as pulsars or quasars that can be hard to see in other wavelengths.

Credit: Max Planck Radio Telescope

THE MILKY WAY

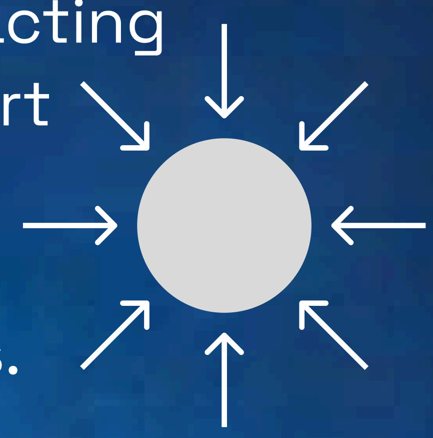


The Milky Way is believed to have around 10x more mass than the stars we see. Scientists call this invisible mass

DARK MATTER.

WIMPs

Some scientists think dark matter is made of 'Weakly Interacting Massive Particles' (WIMPs), which are heavy (so they exert a large gravitational force on other objects) but do not have a charge and are non-luminous.



MACHOs

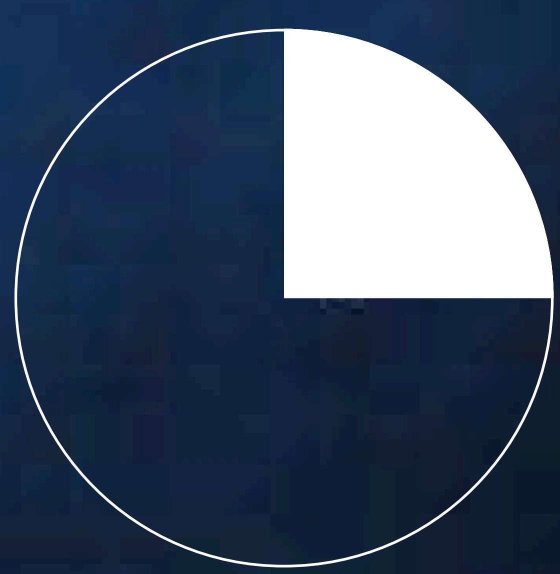
A popular theory used to be that dark matter was made of MACHOs (massively compact halo objects) that were the size of planets. These would be faint and very hard to detect, but eventually were ruled out as a dark matter candidate because they weren't found in large searches for them.

MOND

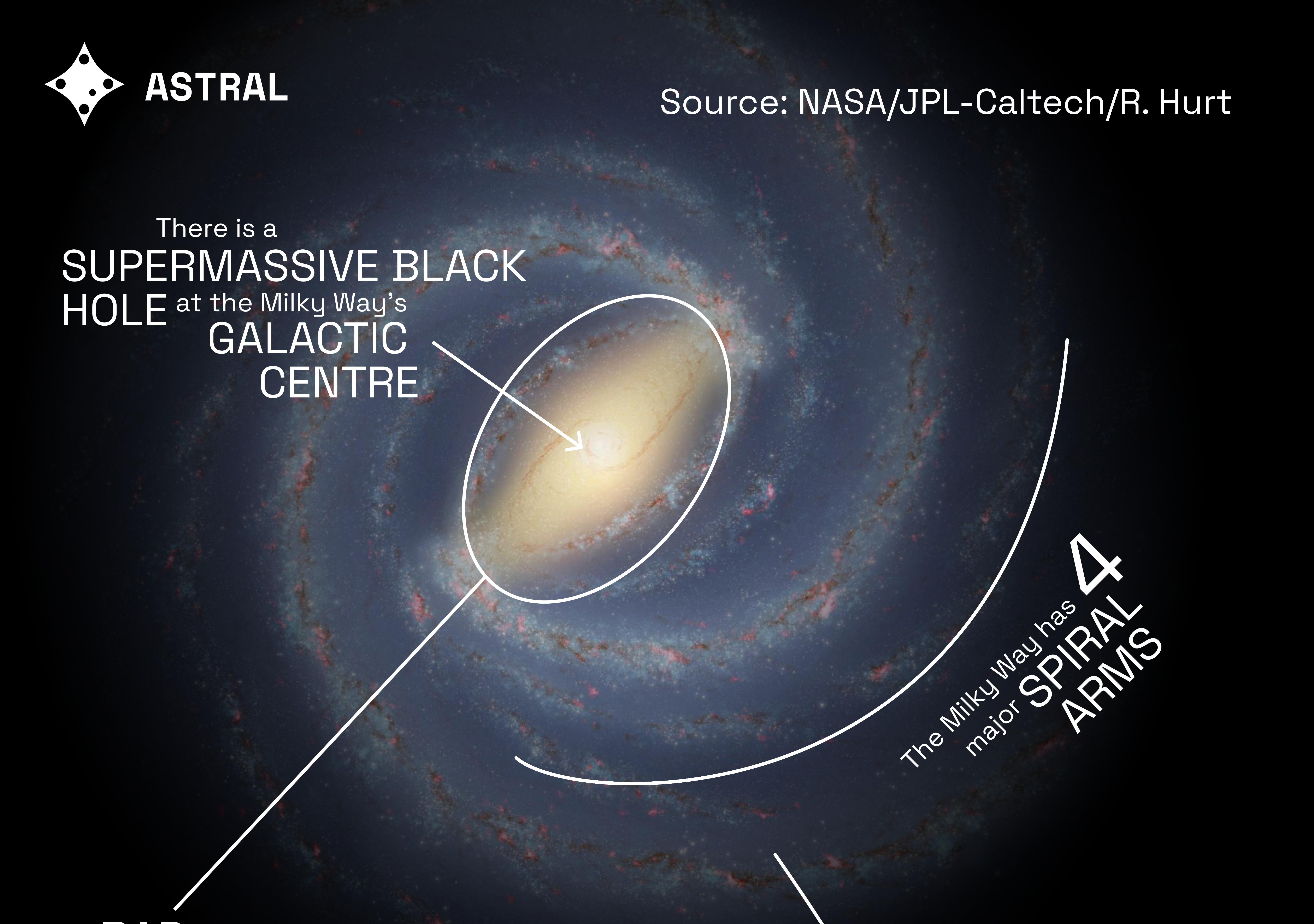
MOND (Modified Newtonian Dynamics) theorises that Newton's laws can be modified to account for differences between the predicted and observed motion of galaxies. This theory could explain how galaxies and other astronomical objects move without dark matter.

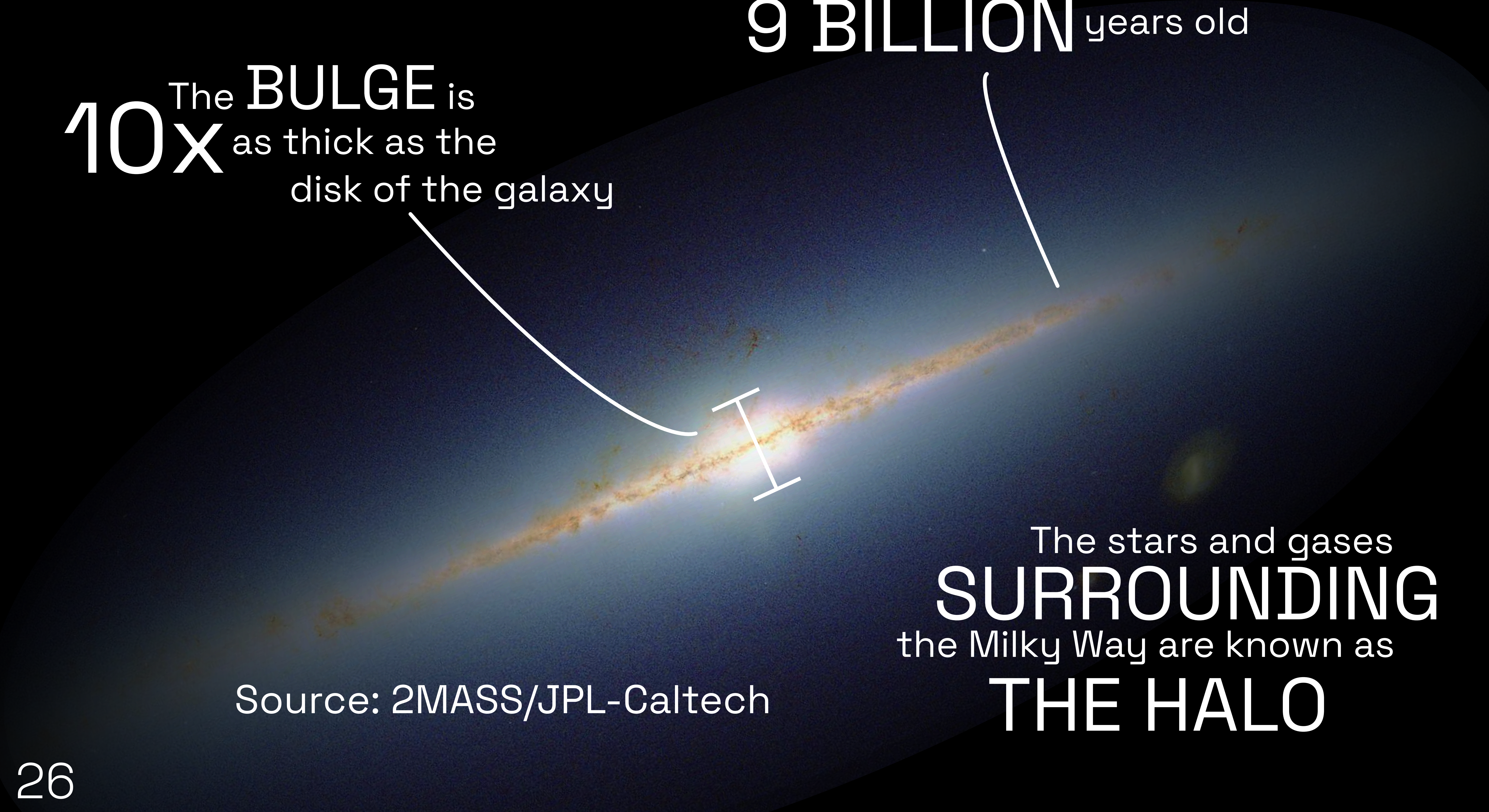
The blue haze in this image represents the DARK MATTER SURROUNDING our galaxy.

Dark matter makes up around 25% of our universe.



Background image credit: ESO/L. Calçada

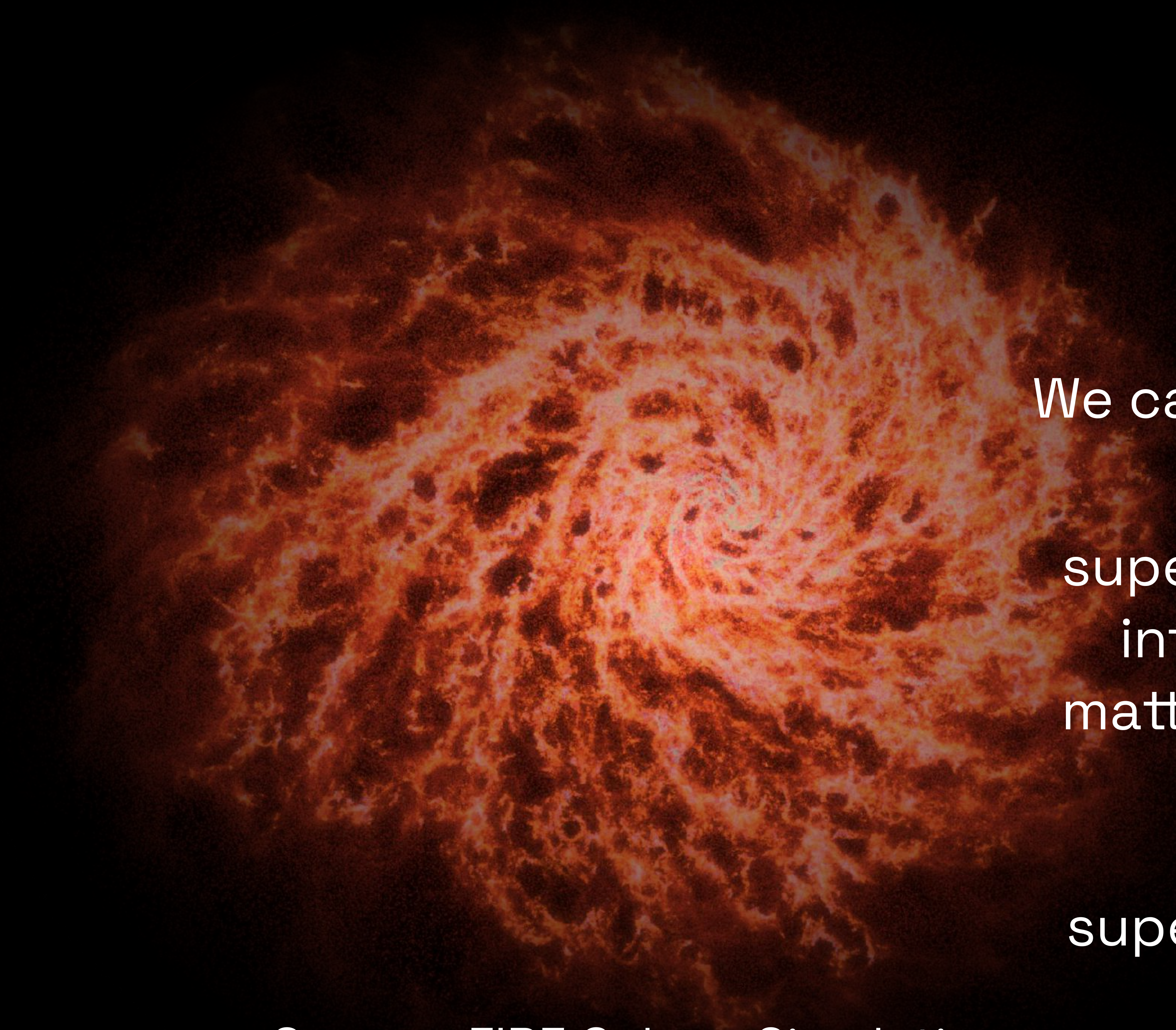

Source: NASA/JPL-Caltech/R. Hurt
There is a SUPERMASSIVE BLACK HOLE at the Milky Way's GALACTIC CENTRE
The Milky Way has 4 major SPIRAL ARMS
The BAR at the centre of the Milky Way is over 27,000 light-years across


The Milky Way's DISC is 9 BILLION years old
The BULGE is 10x as thick as the disk of the galaxy
The stars and gases SURROUNDING the Milky Way are known as THE HALO
Source: 2MASS/JPL-Caltech

GALAXIES

Source: NASA/Spitzer Telescope

This galaxy is called IC 342, also known as “The Hidden Galaxy” because it is obscured behind large CLOUDS OF DUST in the Milky Way.



Source: FIRE Galaxy Simulations

We can simulate galaxies like IC 342 on supercomputers, taking into account ordinary matter, gas, dark matter, dust clouds, star formation, and supernovae. The results can be very like real galaxies, as in the simulation shown here.

Bibliography

https://artsource-danielle.blogspot.com/2022/06/meerkat-telescopes-frb-artist-impression.html

https://www.uni-heidelberg.de/presse/meldungen/2019/m20190114_open-star-clusters-live-longer-than-previously-assumed.html

https://starcycleitjseaberg.weebly.com/types-of-stars.html

https://www.space.com/22471-red-giant-stars.html

https://www.esa.int/Science_Exploration/Space_Science/Hubble_sees_faintest_stars_in_a_globular_cluster

https://space-facts.com/galaxies/types/

https://www.nrao.edu/pr/2005/terzan5/

https://physicsworld.com/a/slowest-ever-neutron-star-is-found-in-cosmic-graveyard/

https://www.nationalgeographic.com/science/article/white-dwarfs

https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect17/lecture17.html

Scientific Notation

10^{10} = 10,000,000,000
10^{7} = 10,000,000

Astronomical symbols

$L_\odot$	The luminosity of the Sun - 3.8×10^{26} watts
$M_\odot$	The mass of the Sun - 1.989×10^{30} kilograms
$R_\odot$	The radius of the Sun - 696,000 kilometres

Glossary

Terms	Definitions
Accretion disk	A flattened, circular disk of gas and dust around a central object (such as a protostar, star or black hole) onto which matter is falling.
Dredge-up	A process which brings material to the surface of a star, from the regions deep within where nuclear fusion has occurred.
Globular Cluster	Compact systems of up to hundreds of thousand of stars bound together by gravity.
Ionization	The process of removing or adding electrons from atoms or molecules so that they carry a net electric charge.
Magnetic Winds	Ionised gas flowing outward from a star or other astronomical object, carrying along a magnetic field.
Protostar	A star in the process of formation. Protostars are often embedded deep in clouds of ionised gas and dust.
Quasar	A massive black hole in the central region of a galaxy, emitting bright radiation as matter falls on to it from an accretion disk.