DIS Galactic Archaeology minor module

Lecture 3: Stars as probes of Galactic Archaeology I

Dr Anke Ardern-Arentsen

This block of 4 lectures

Today:

- Galactic Archaeology uses the properties of stars to study the past (of our Galaxy/Universe)
- Need to understand stars!
  - Stellar evolution
  - Nuclear fusion and chemical elements
  - Colour-magnitude diagrams

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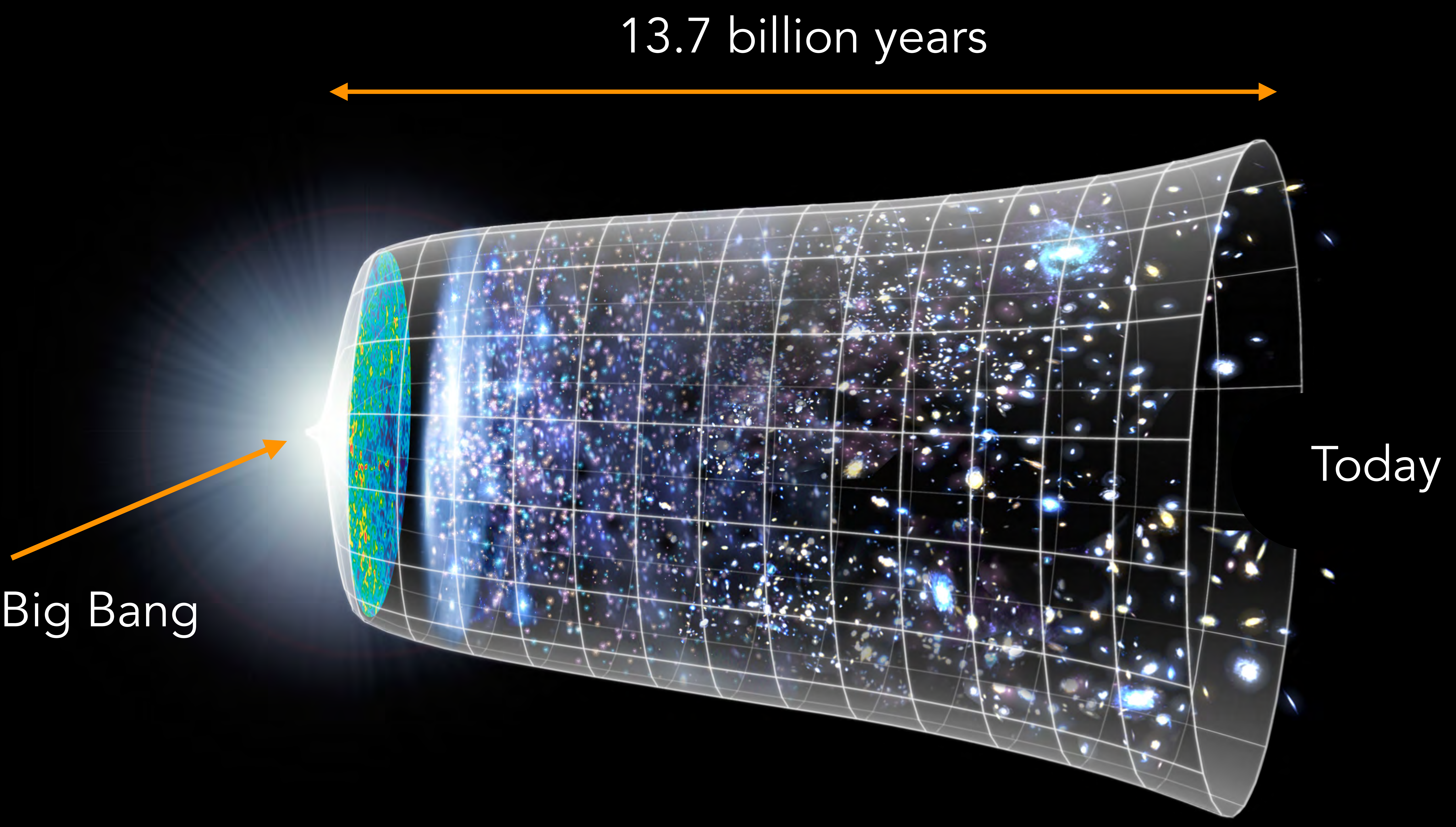
Next lectures:

- practicalities of measuring composition of stars & their application
- how to design and obtain astronomical observations?
- recent highlights from the literature + hands-on session

How do galaxies form?



Credit: NASA/WMAP team

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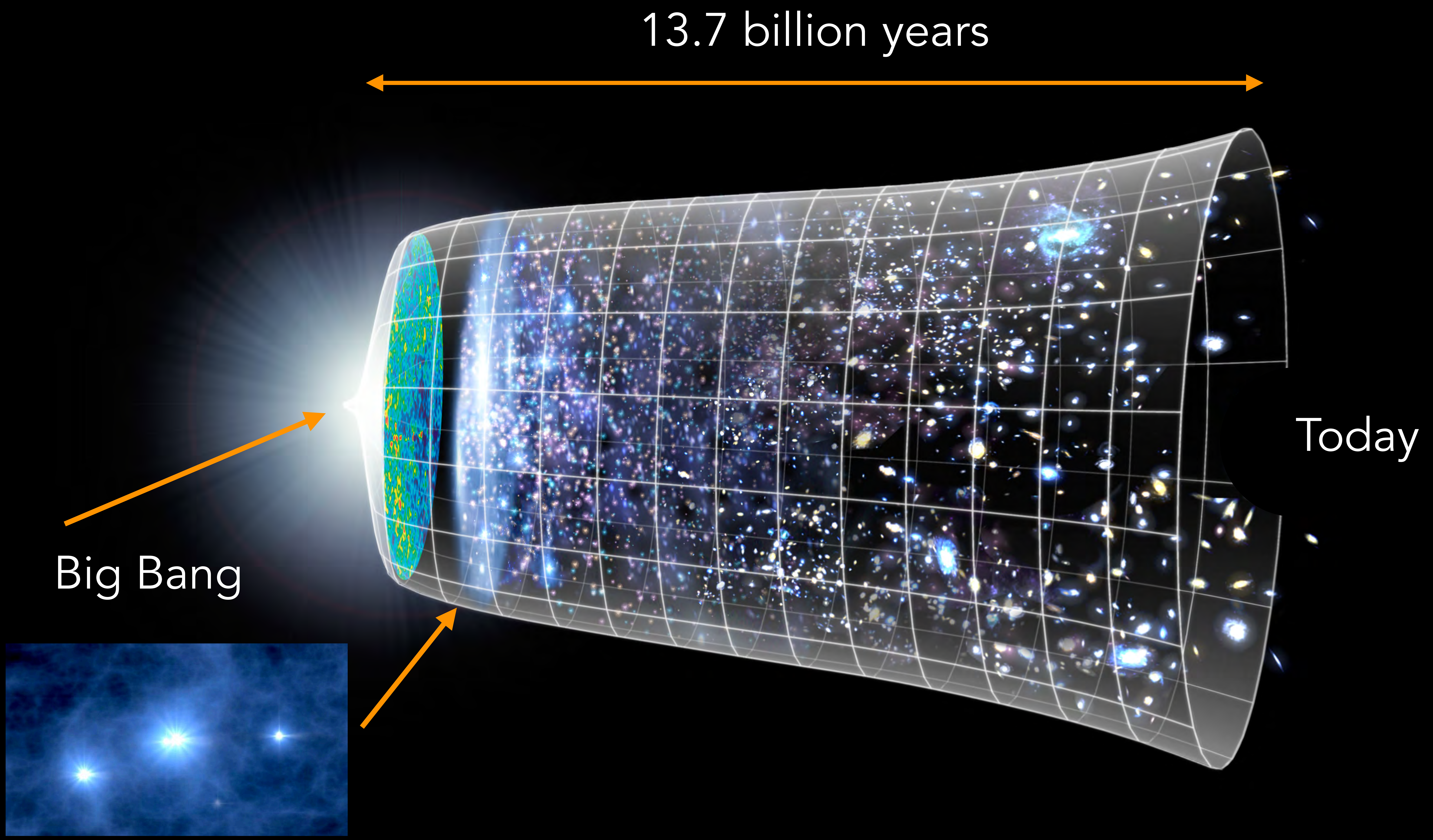

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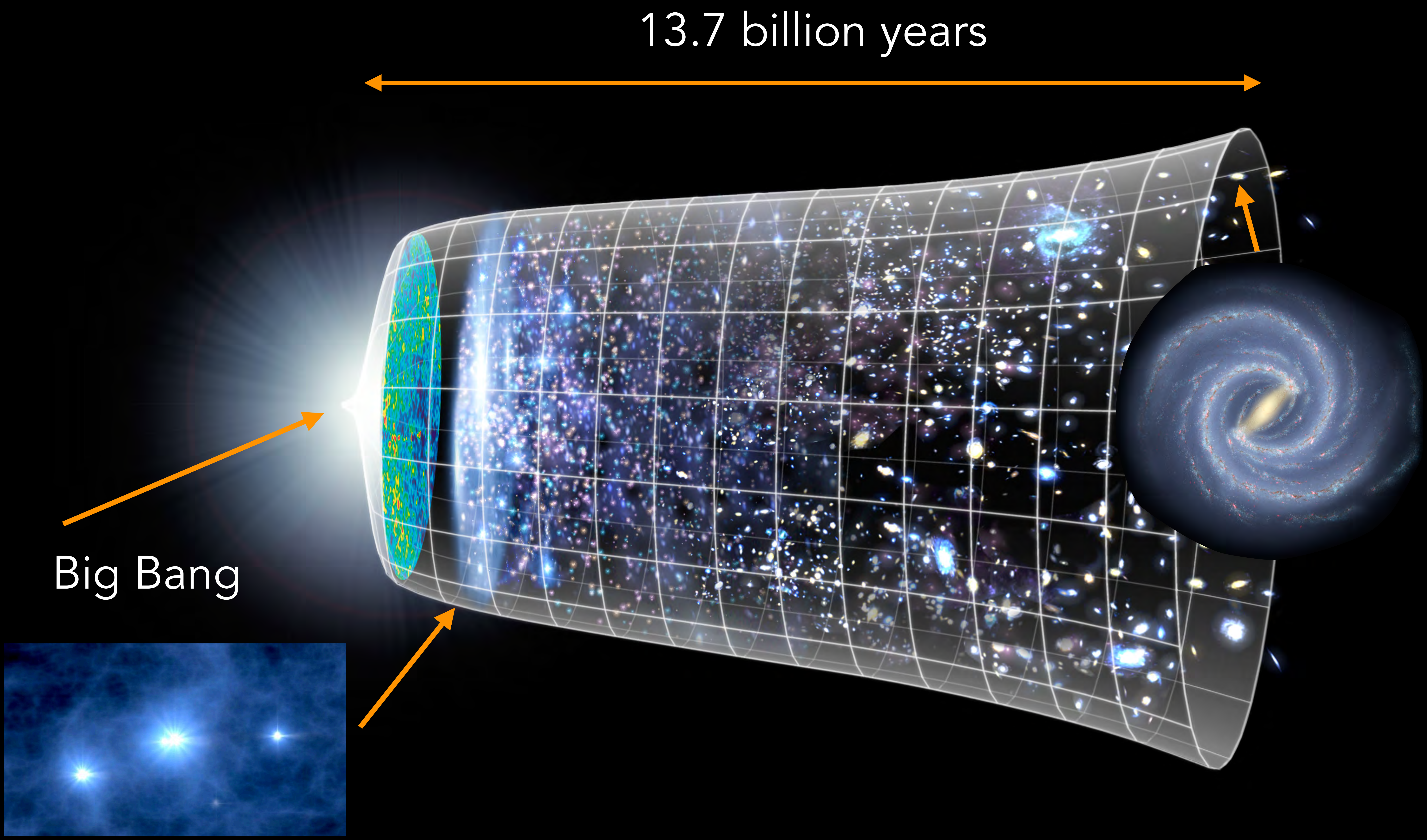

Credit: NASA/WMAP team / Credit: ESO/L. Calçada

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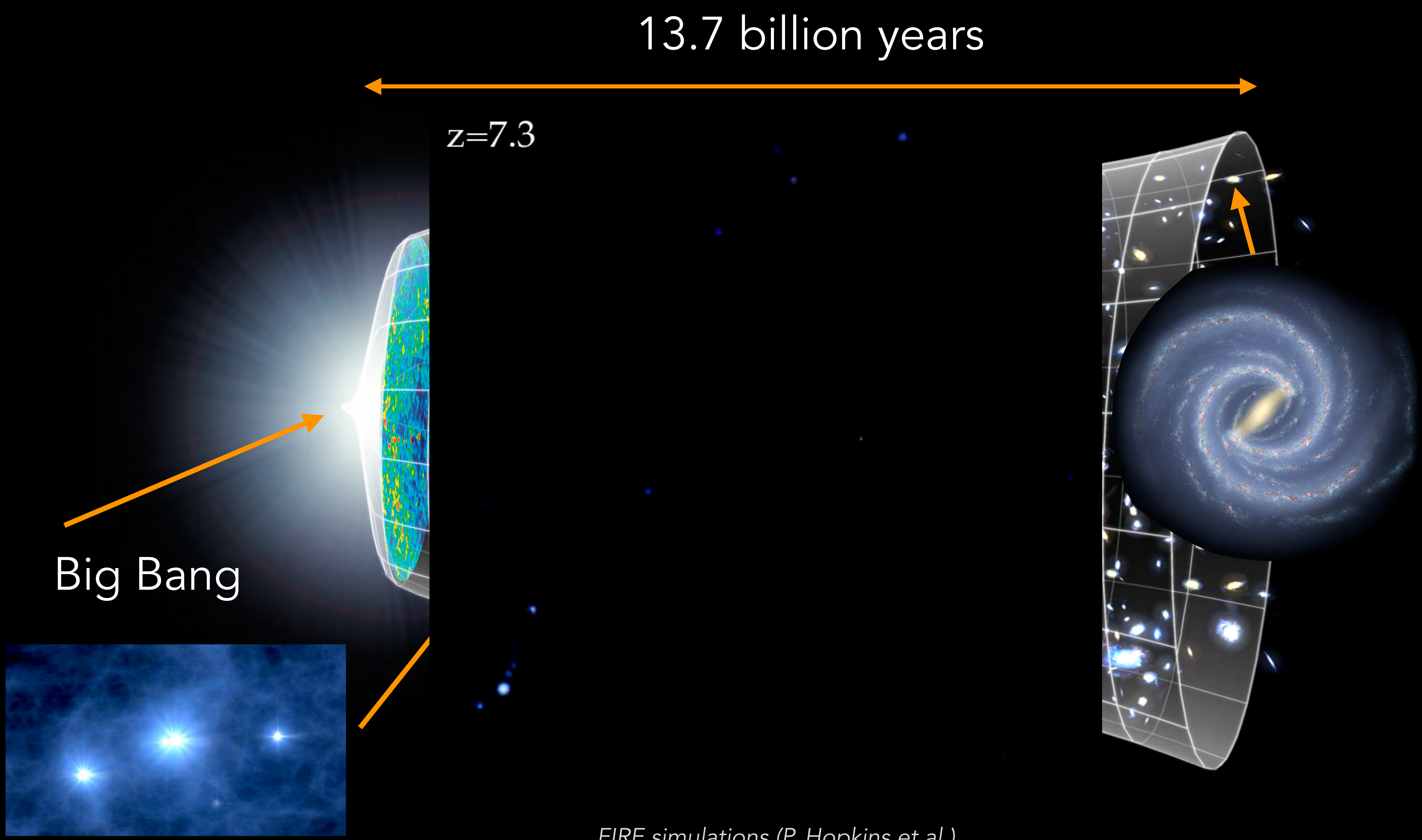

FIRE simulations (P. Hopkins et al.)

Credit: NASA/WMAP team / Credit: ESO/L. Calçada

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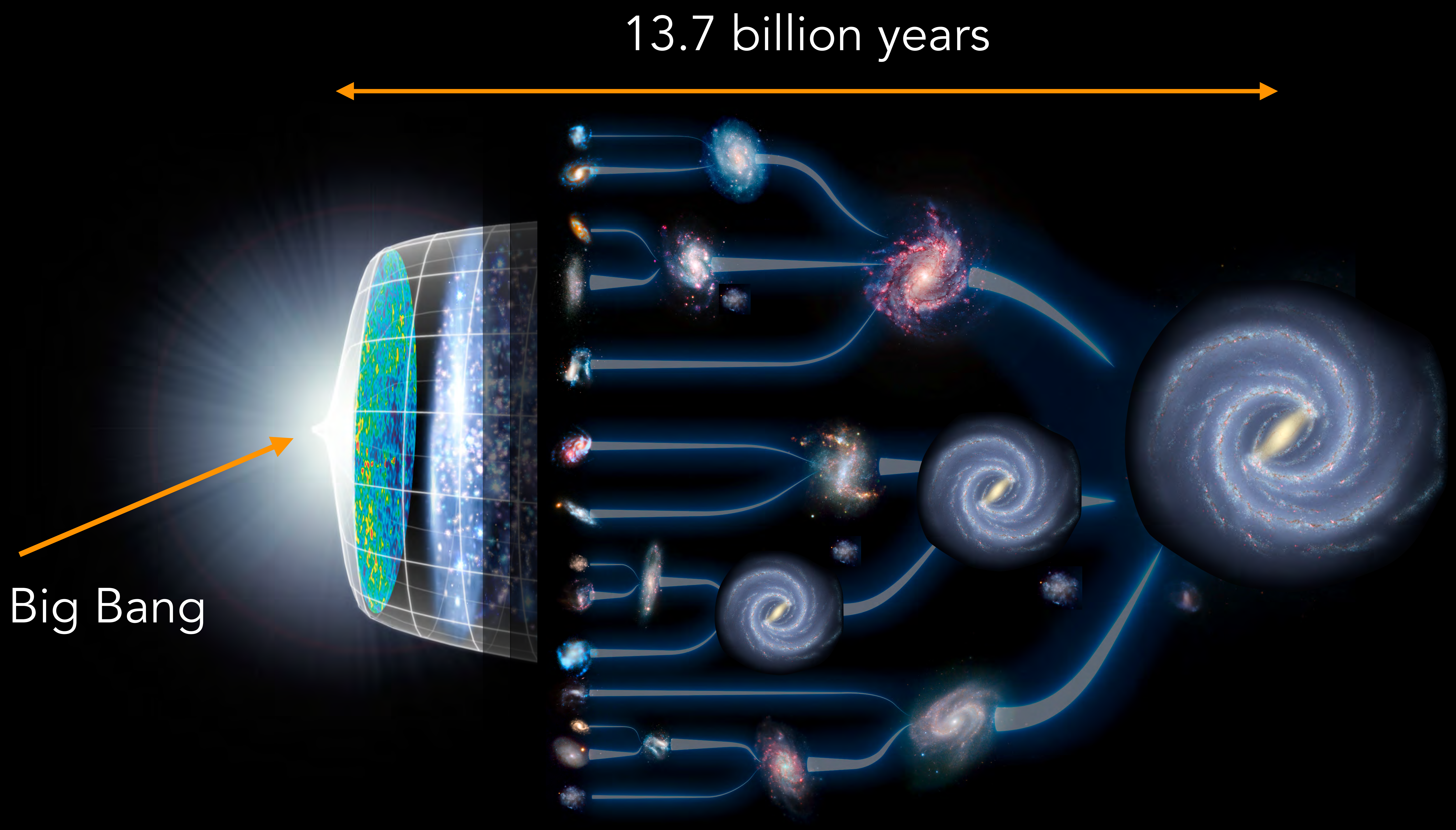

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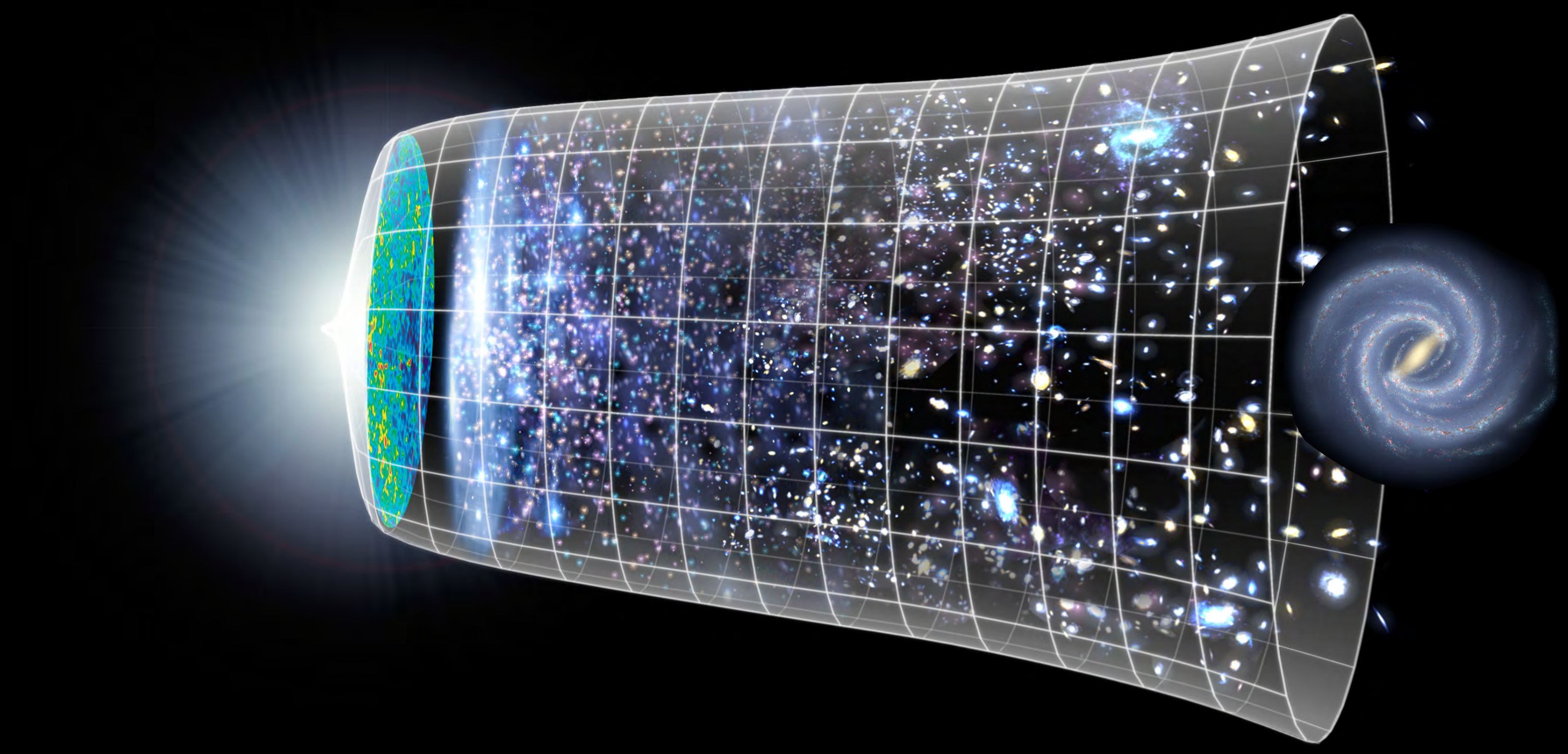
What is Galactic Archaeology?



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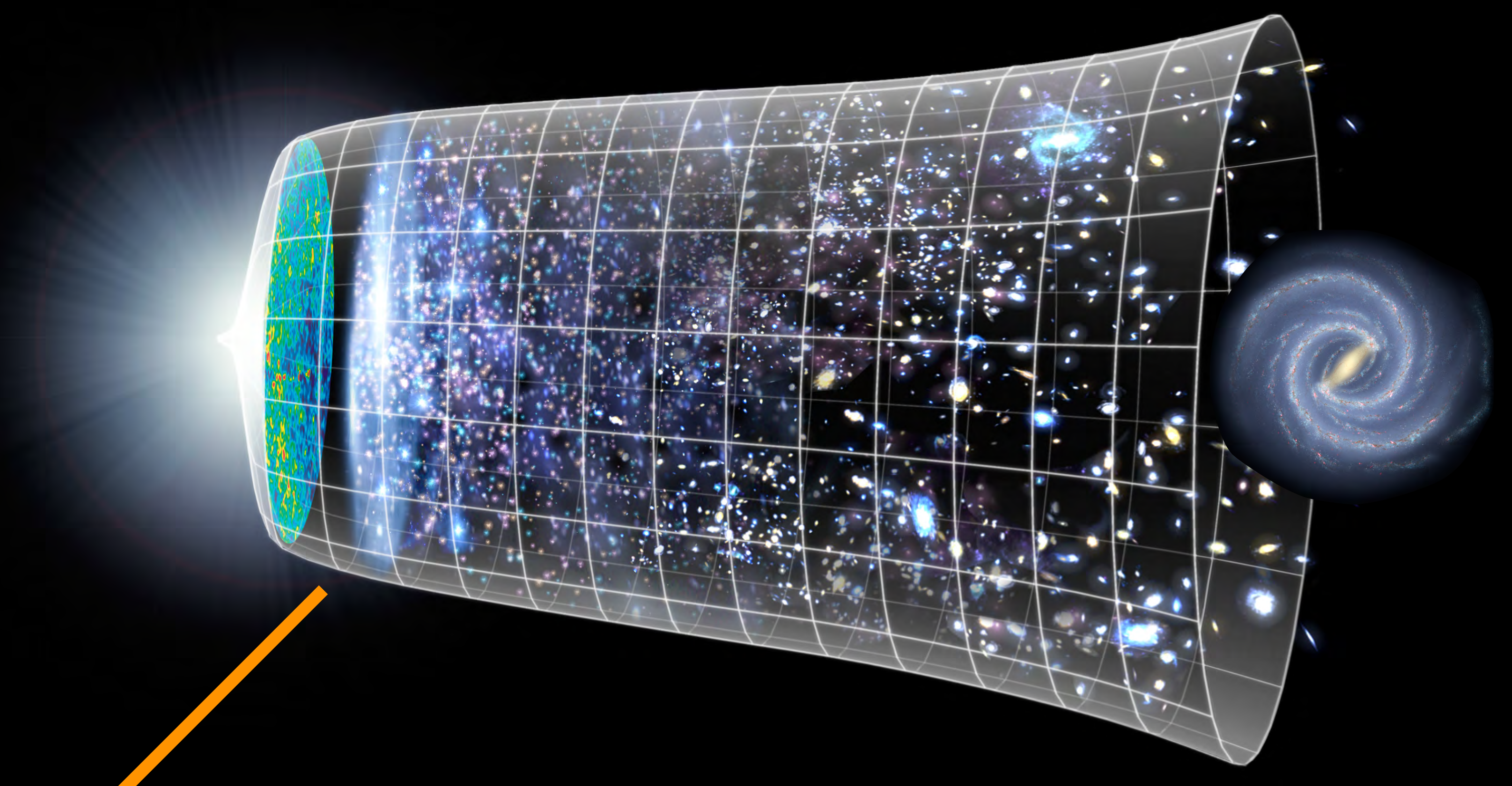
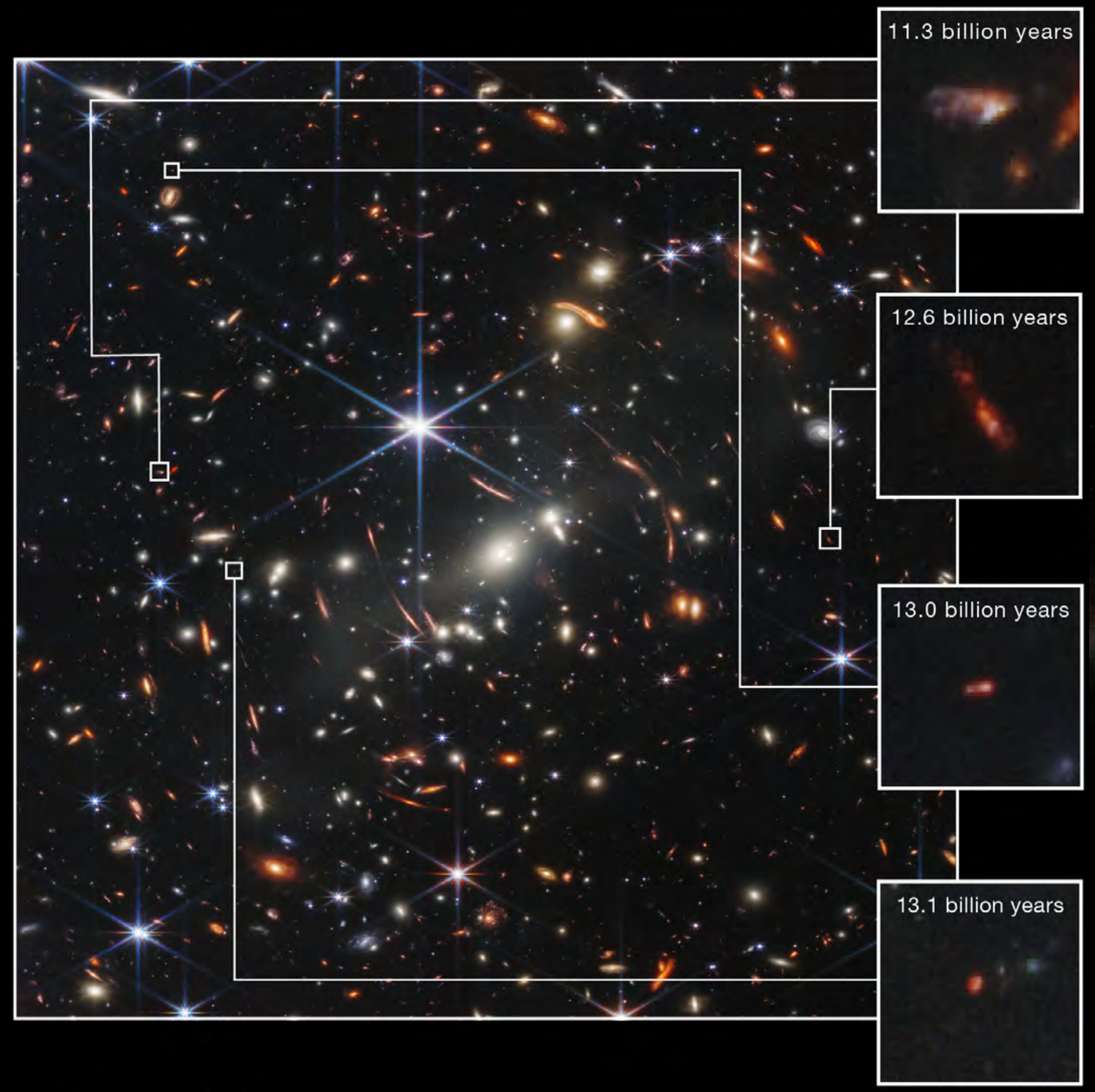
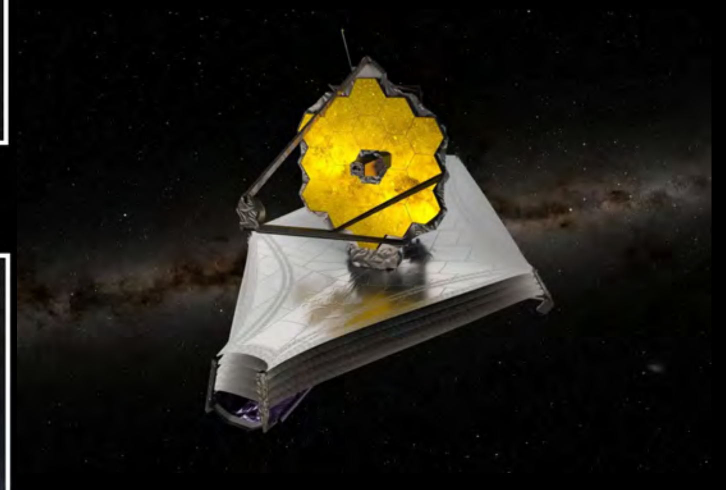


Distant galaxies
(at high redshift)





JWST

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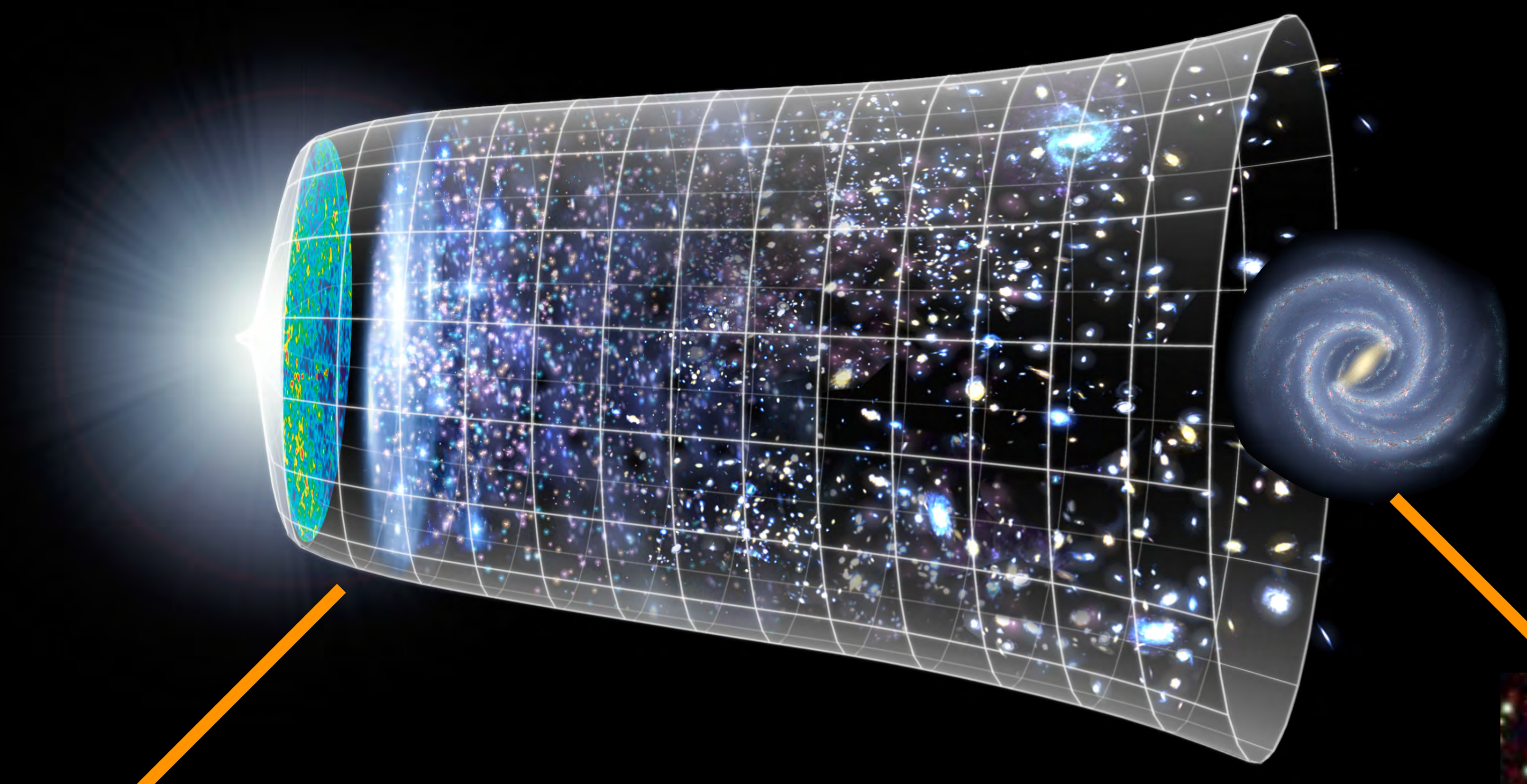

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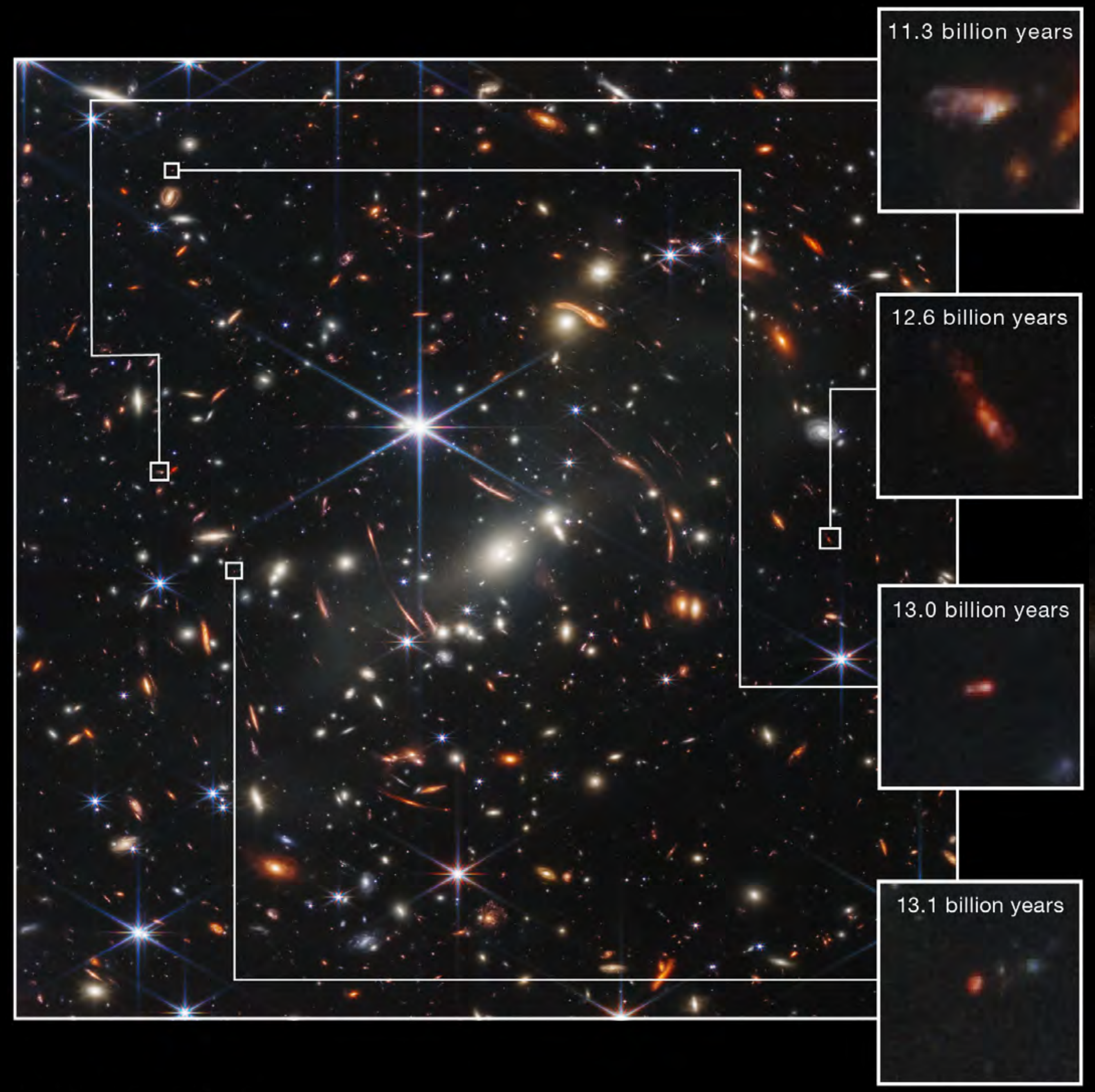
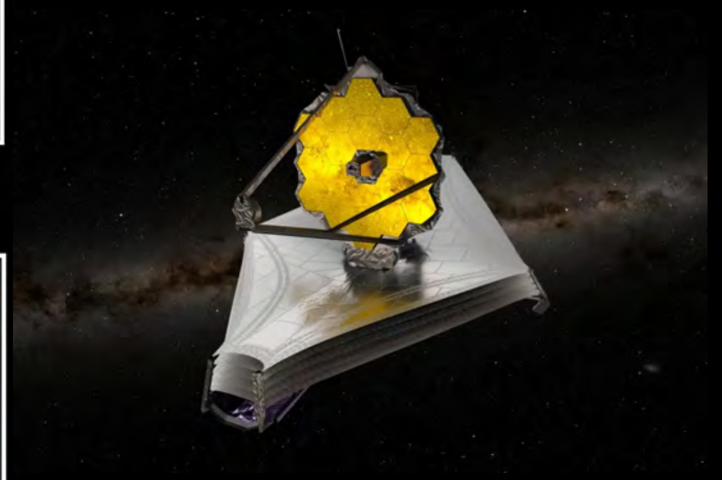
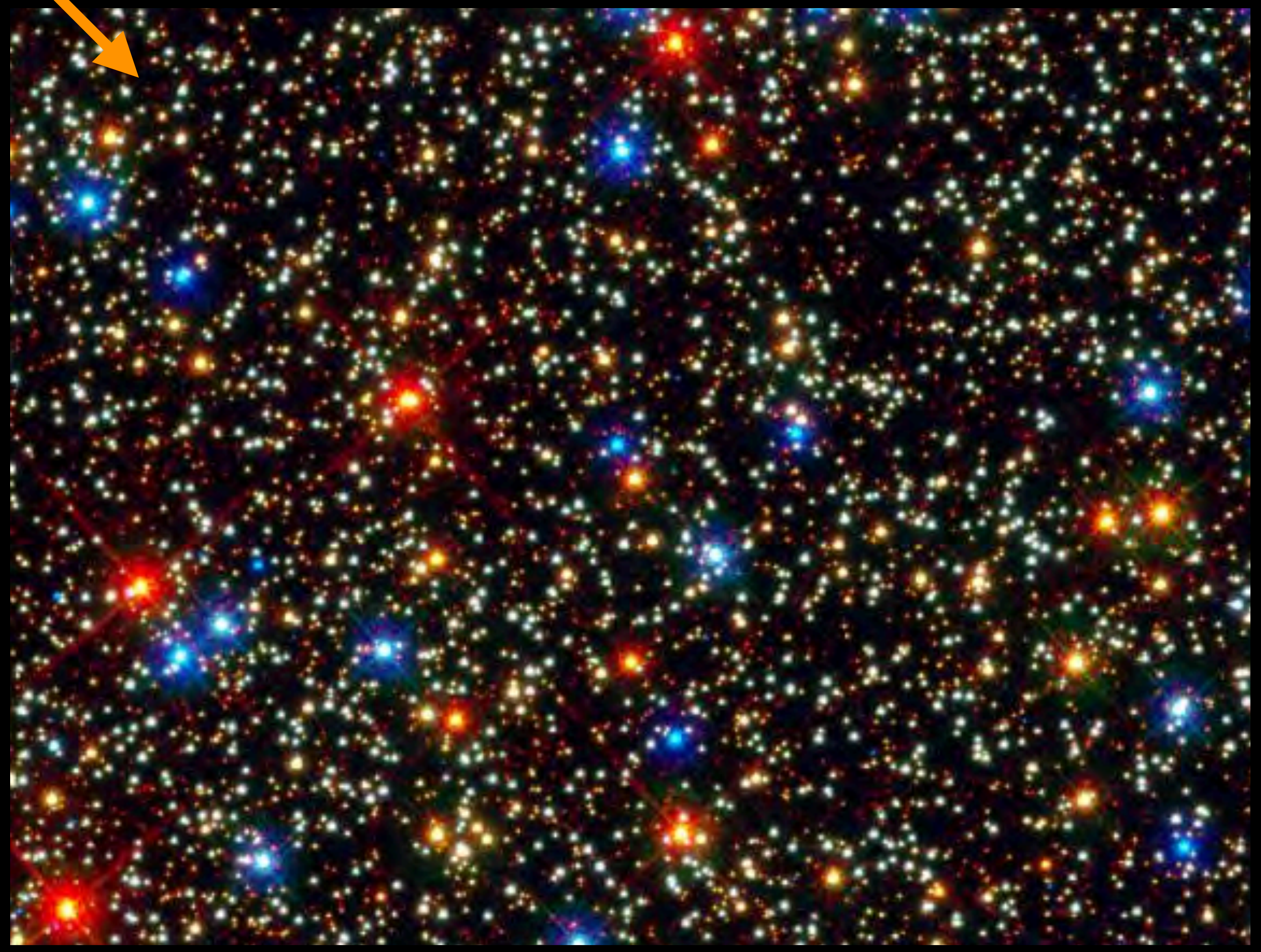




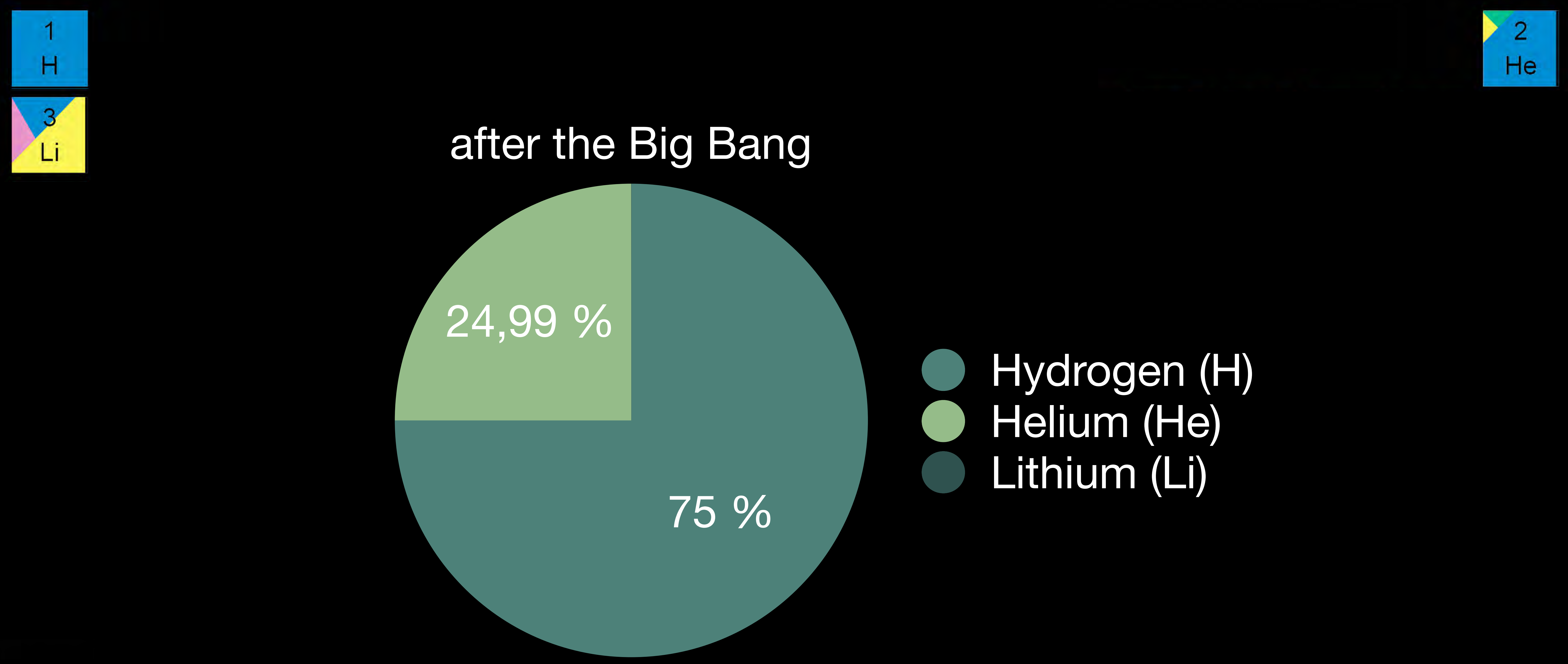
JWST

Stars in the Milky Way,
with different ages



Hubble

The chemical enrichment of the Universe



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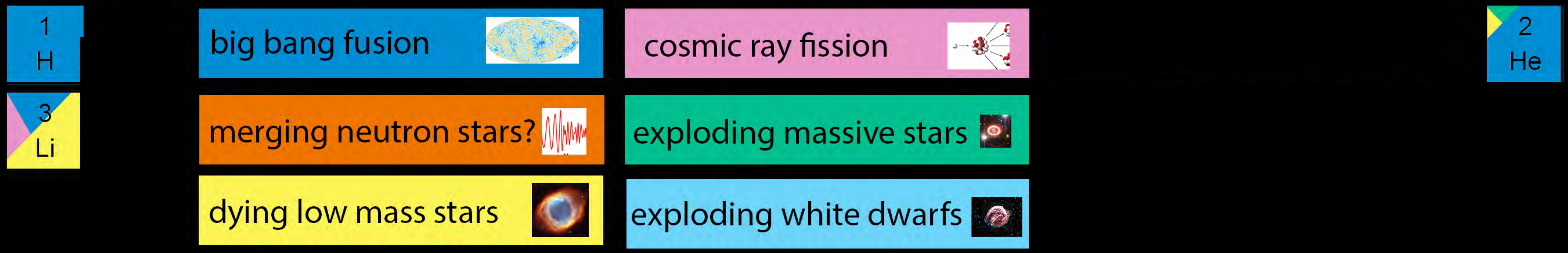


The chemical enrichment of the Universe

1
H

3
Li

2
He

big bang fusion

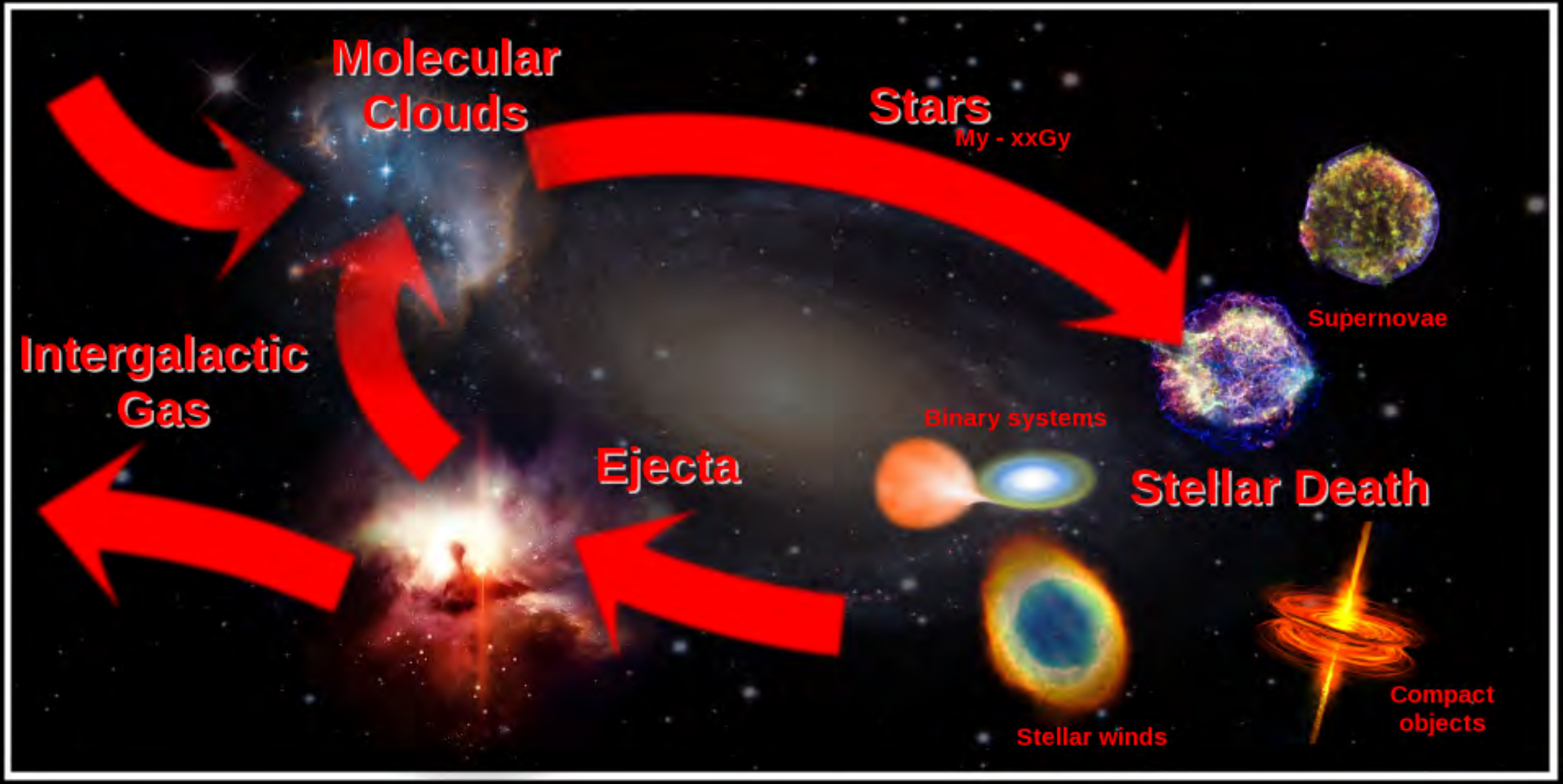
cosmic ray fission

merging neutron stars?

exploding massive stars

dying low mass stars

exploding white dwarfs



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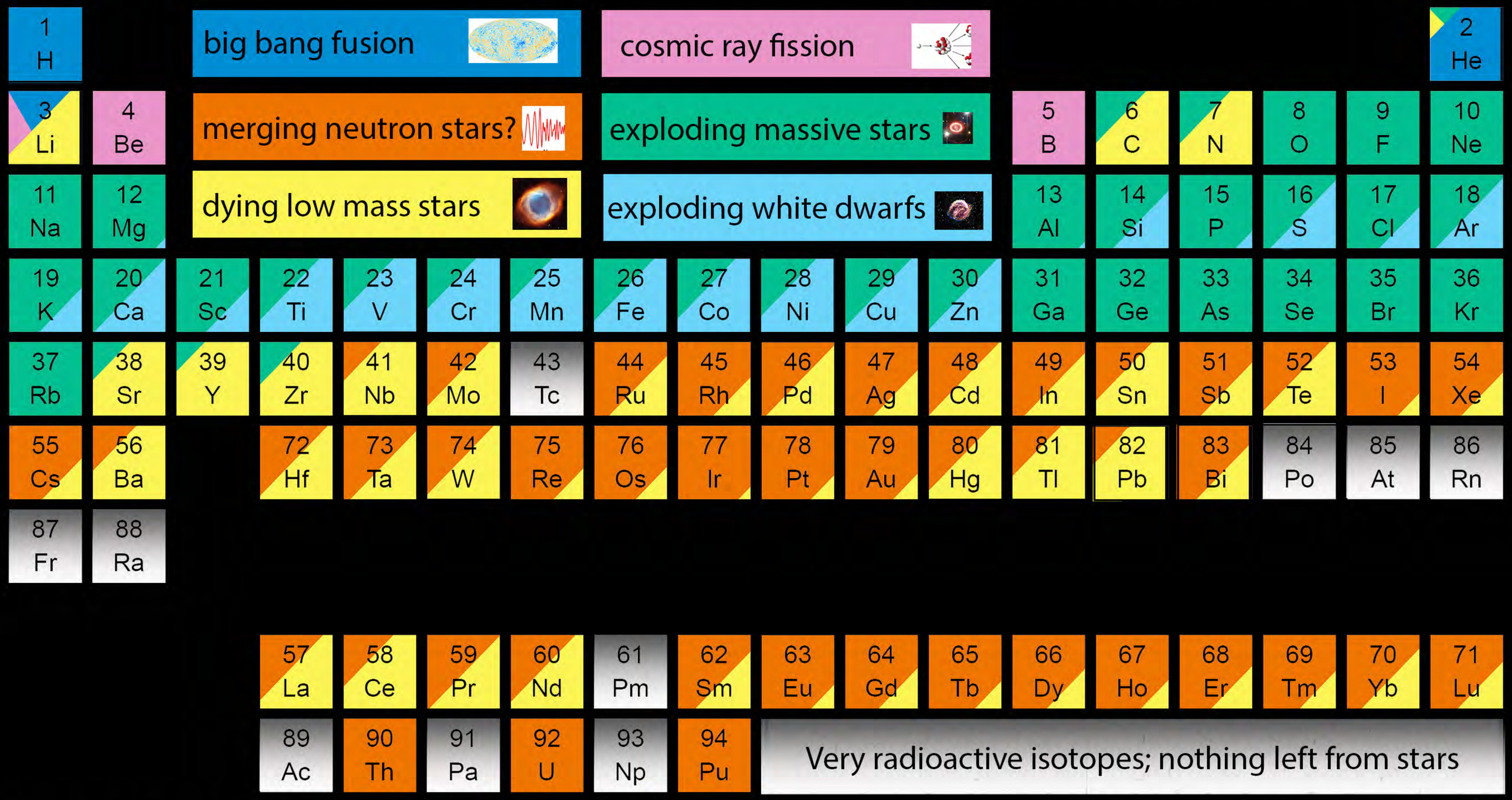

Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

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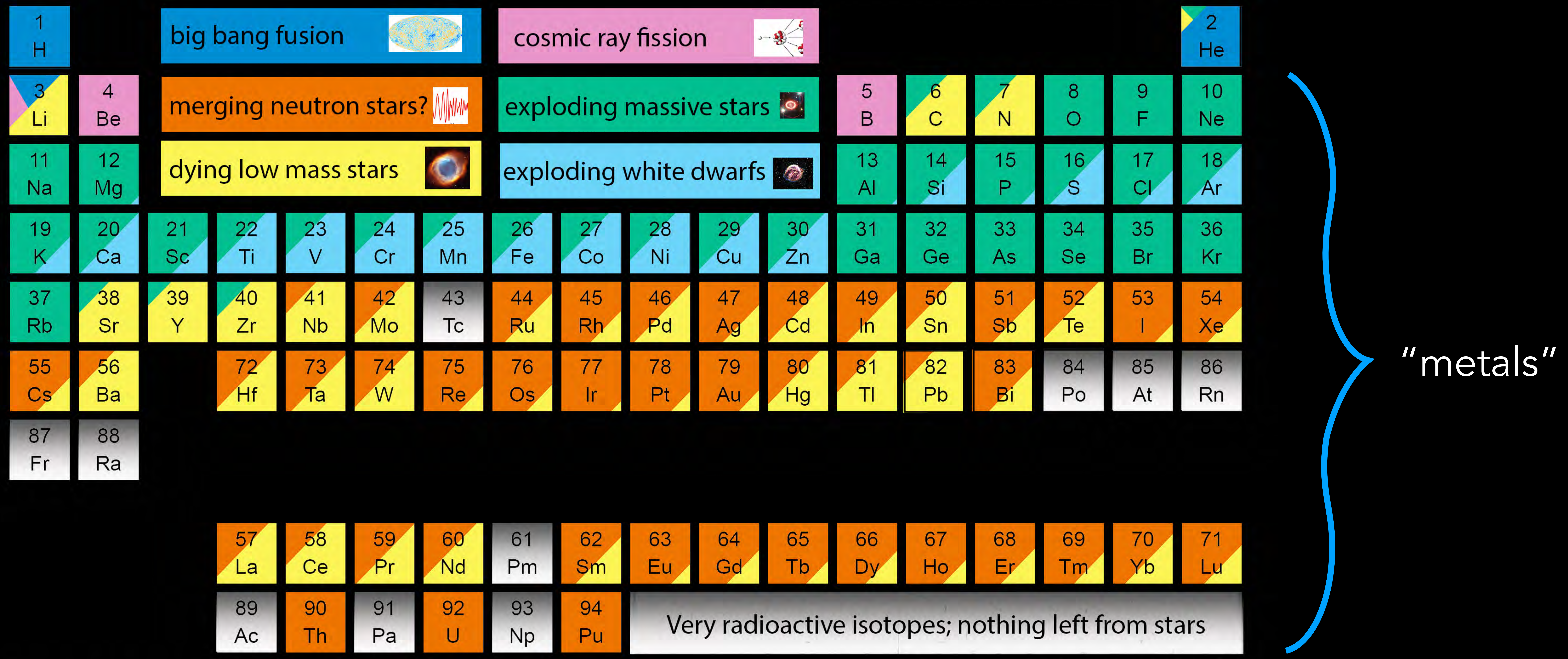

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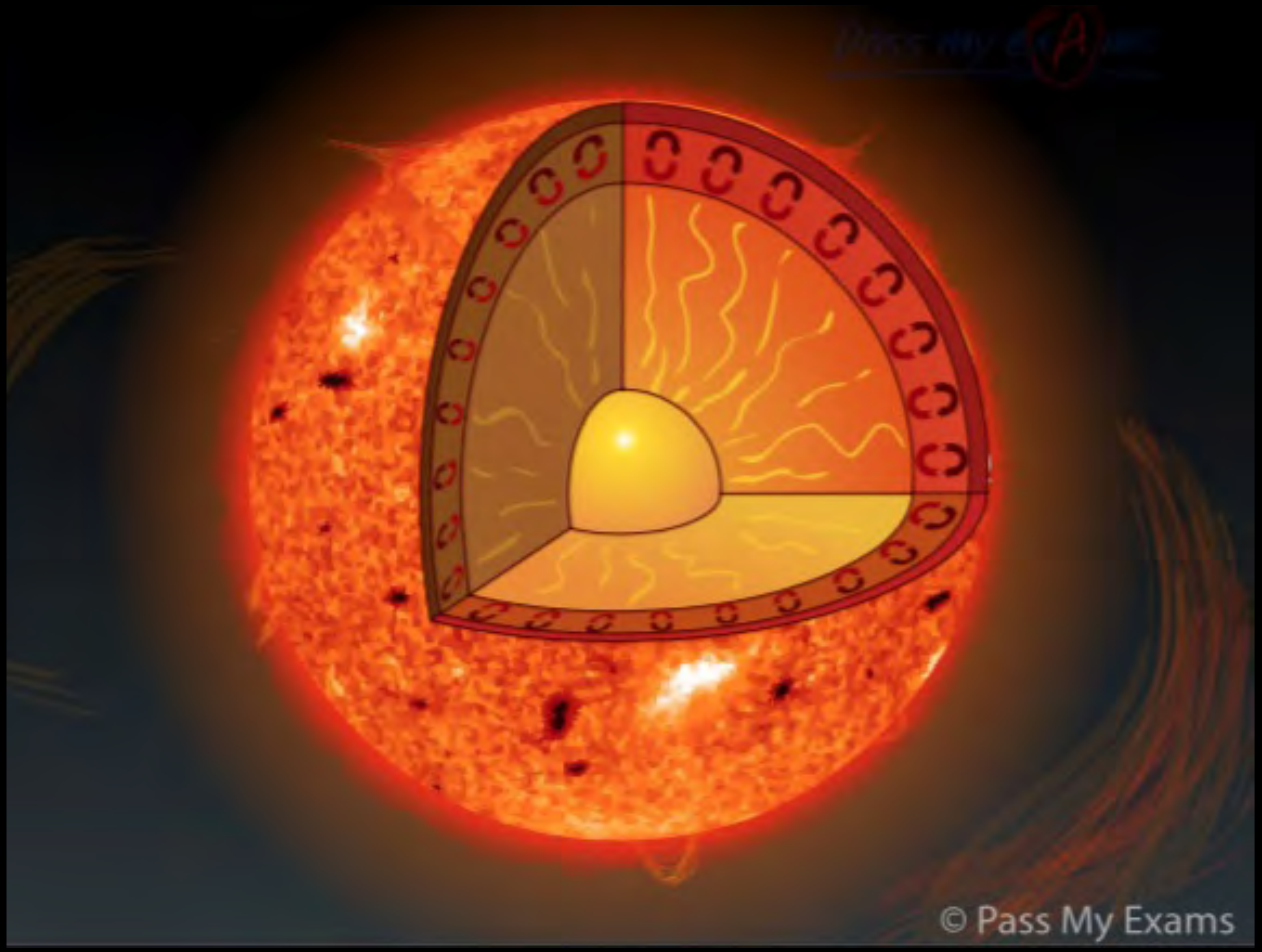
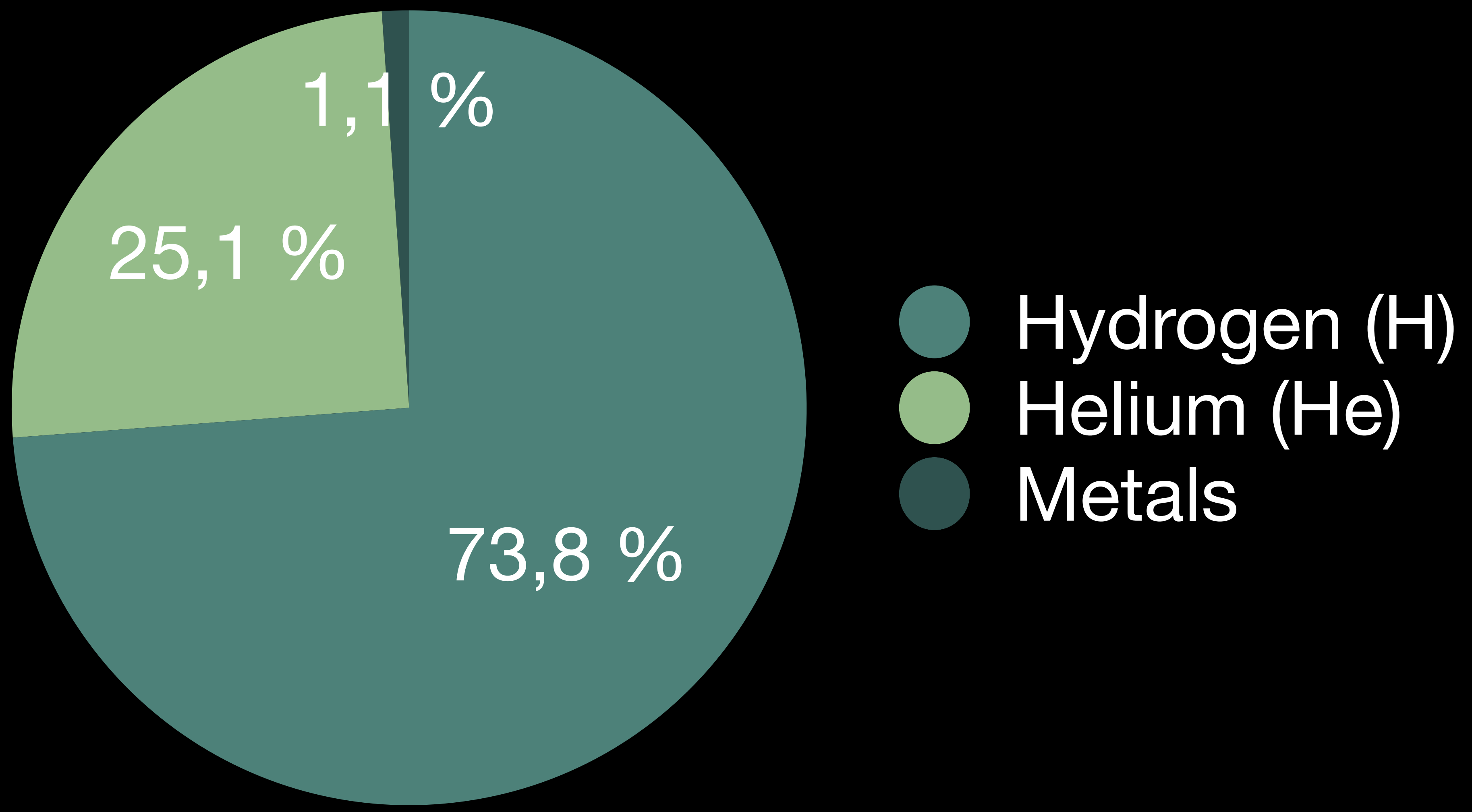
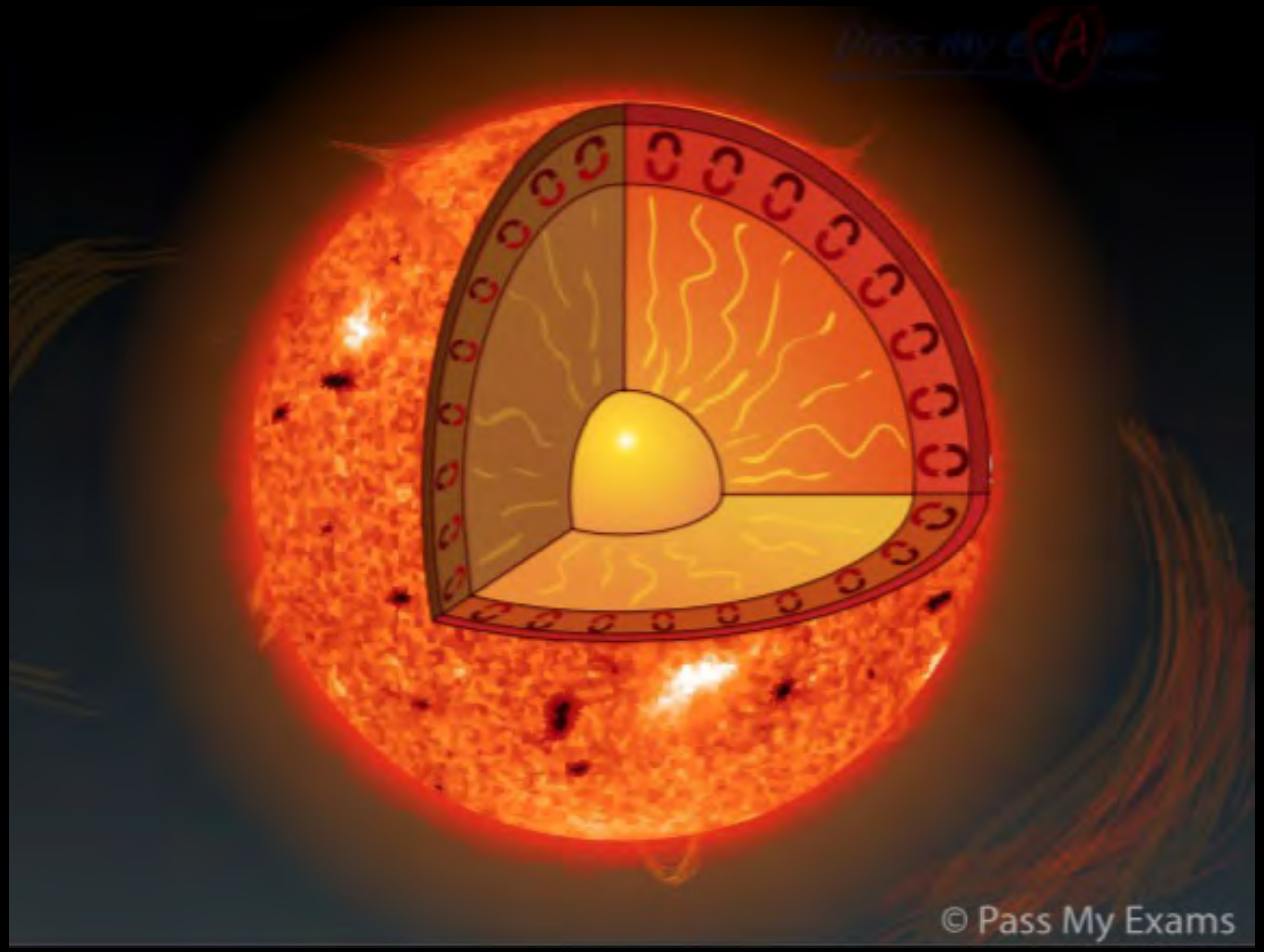
The composition of (main sequence) stars



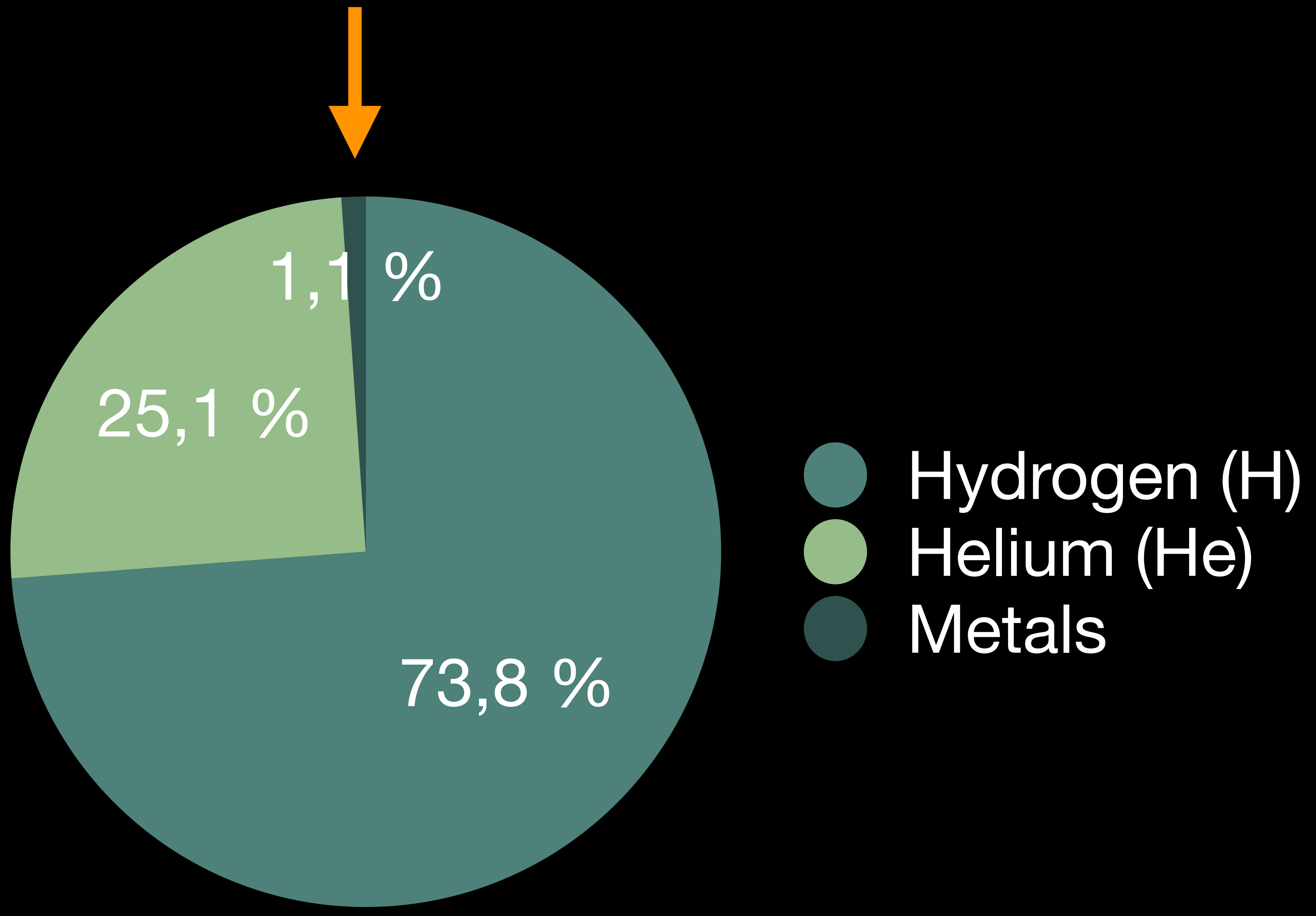


First evidence: Cecilia Payne, PhD (1925)

The composition of (main sequence) stars



We can measure this “metallicity” very precisely



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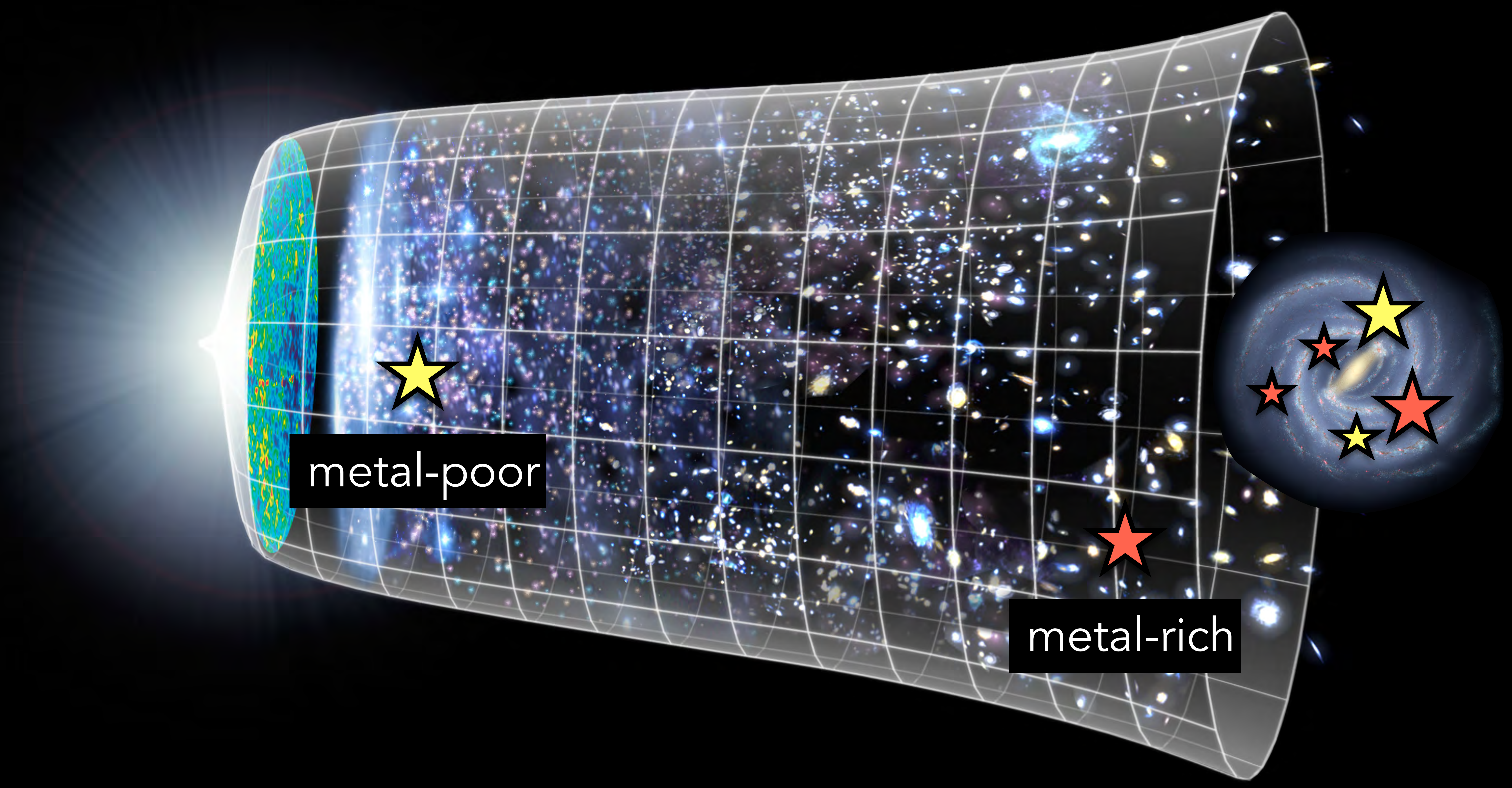
How do we know a star is older or younger?



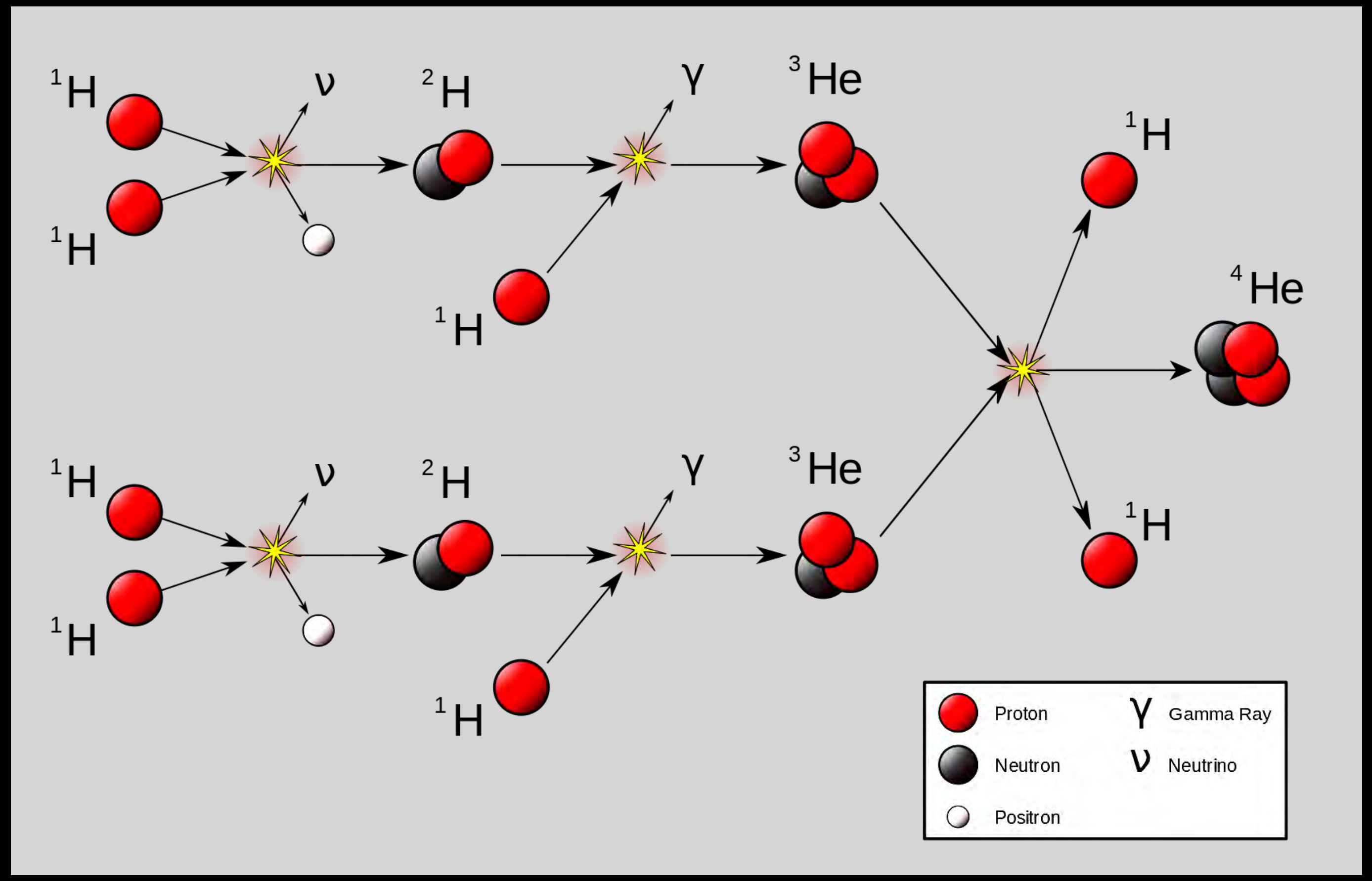
stars form from gas enriched with metals by previous stellar generations, with these fingerprints still present in their atmospheres

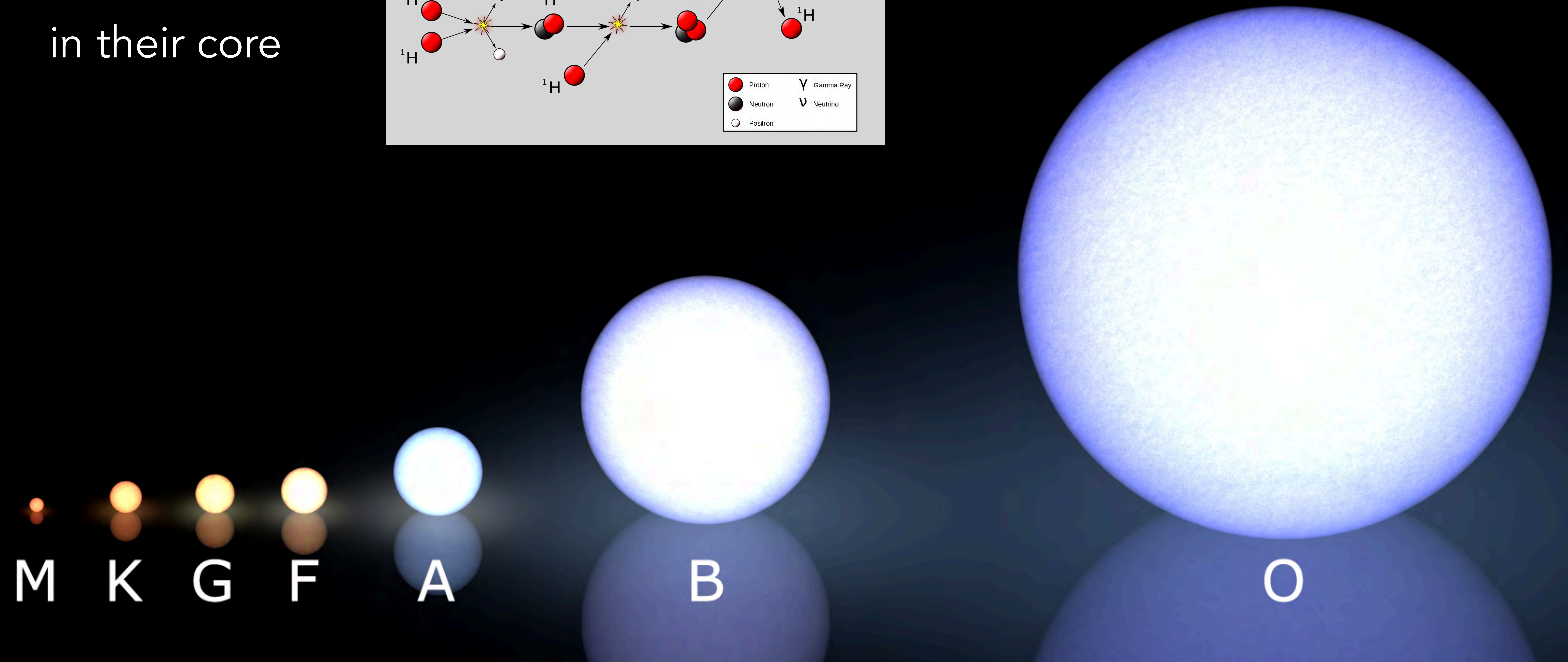
Credit: NASA/WMAP team

How long can stars live for?

Age of the Universe: 13.7 billion years

Powered by nuclear fusion in their core





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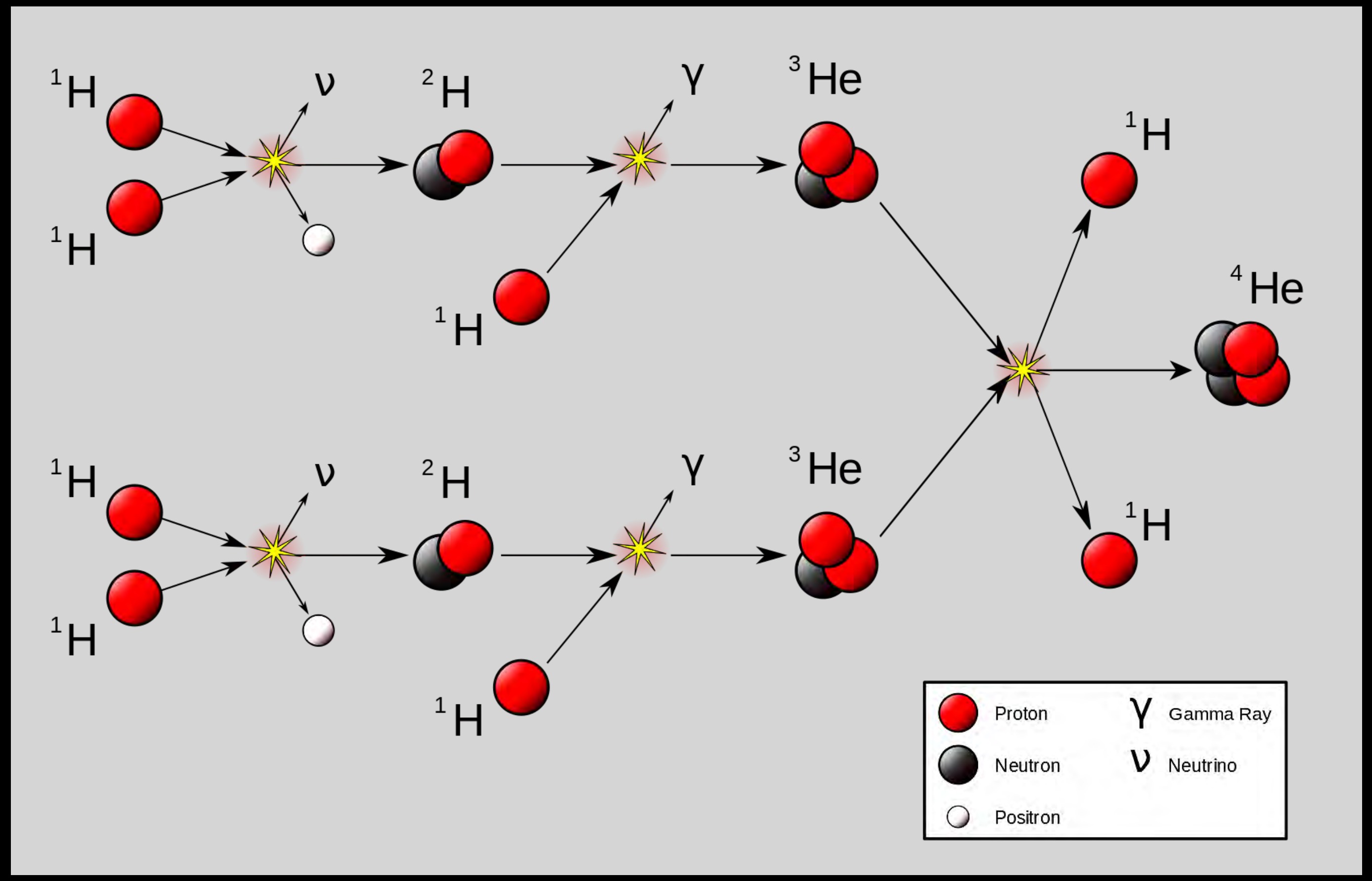

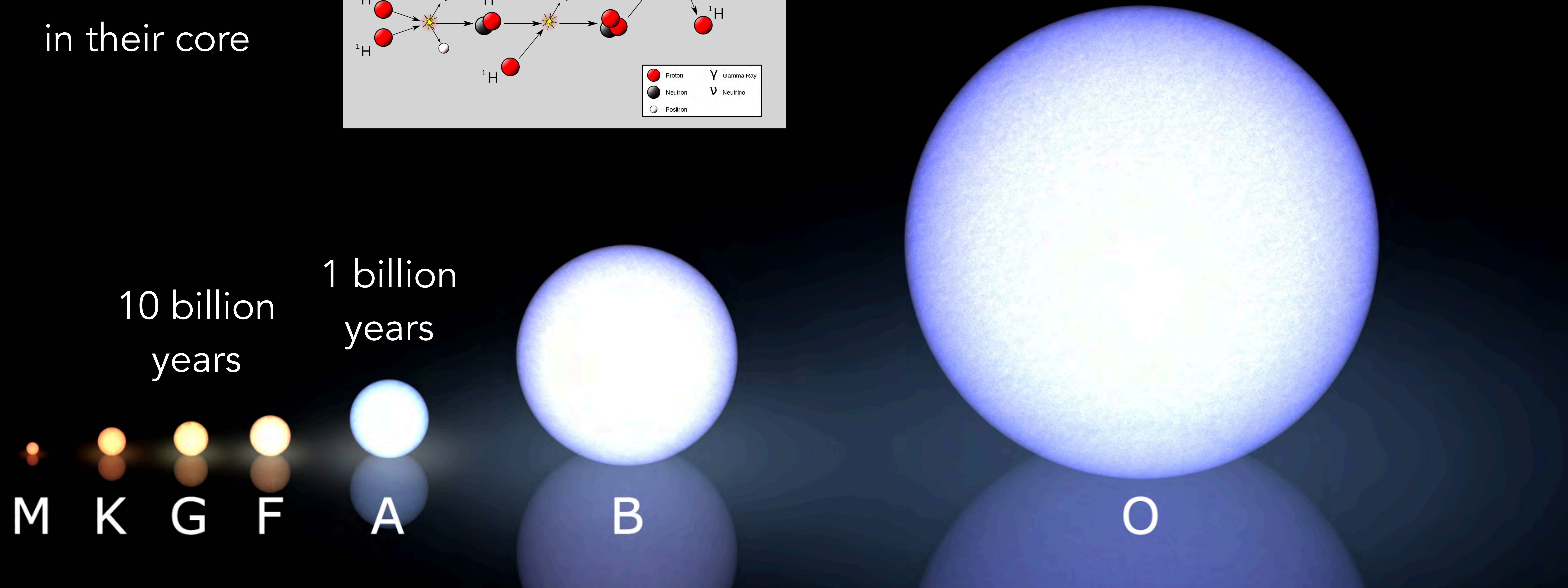

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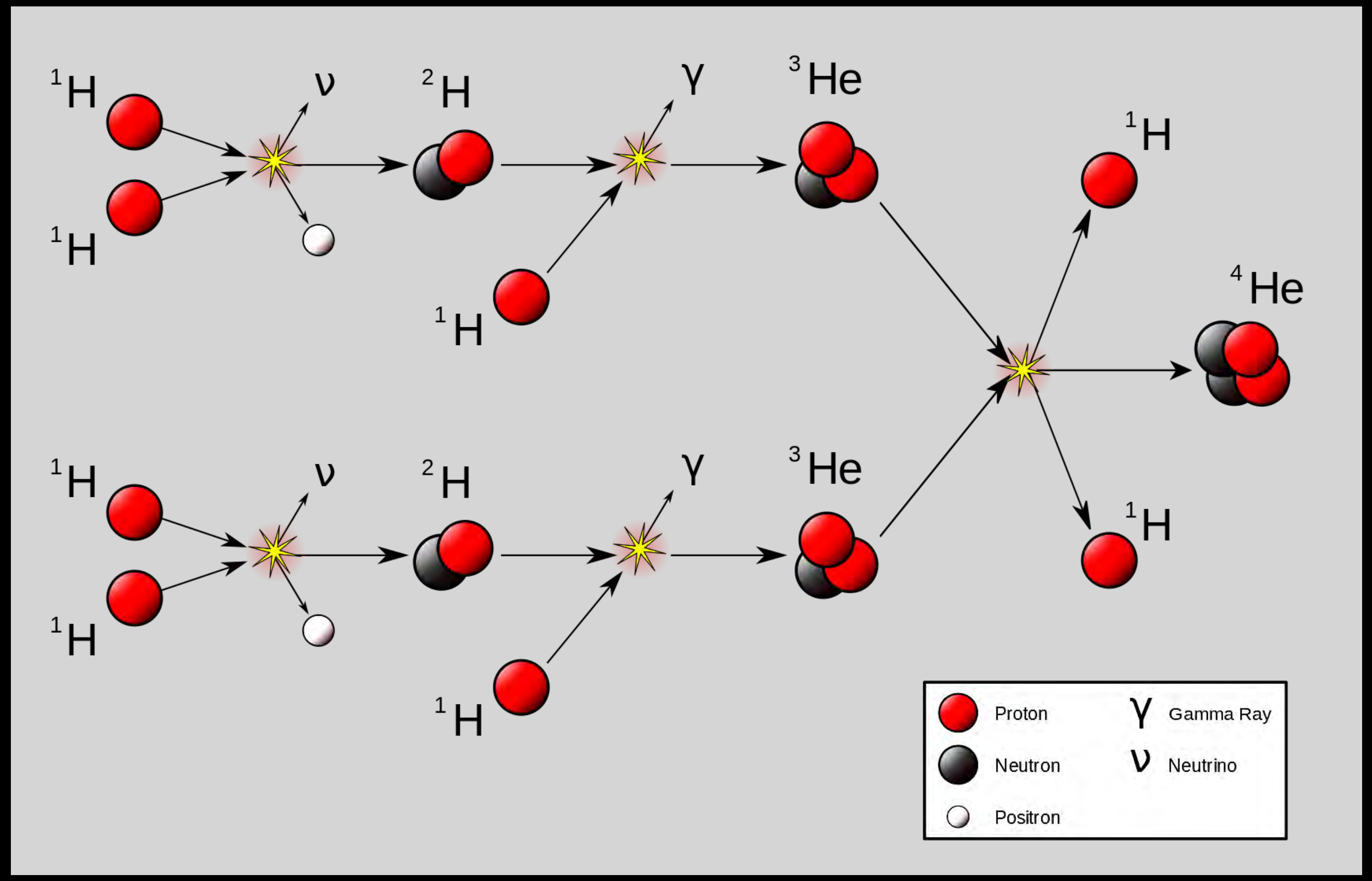
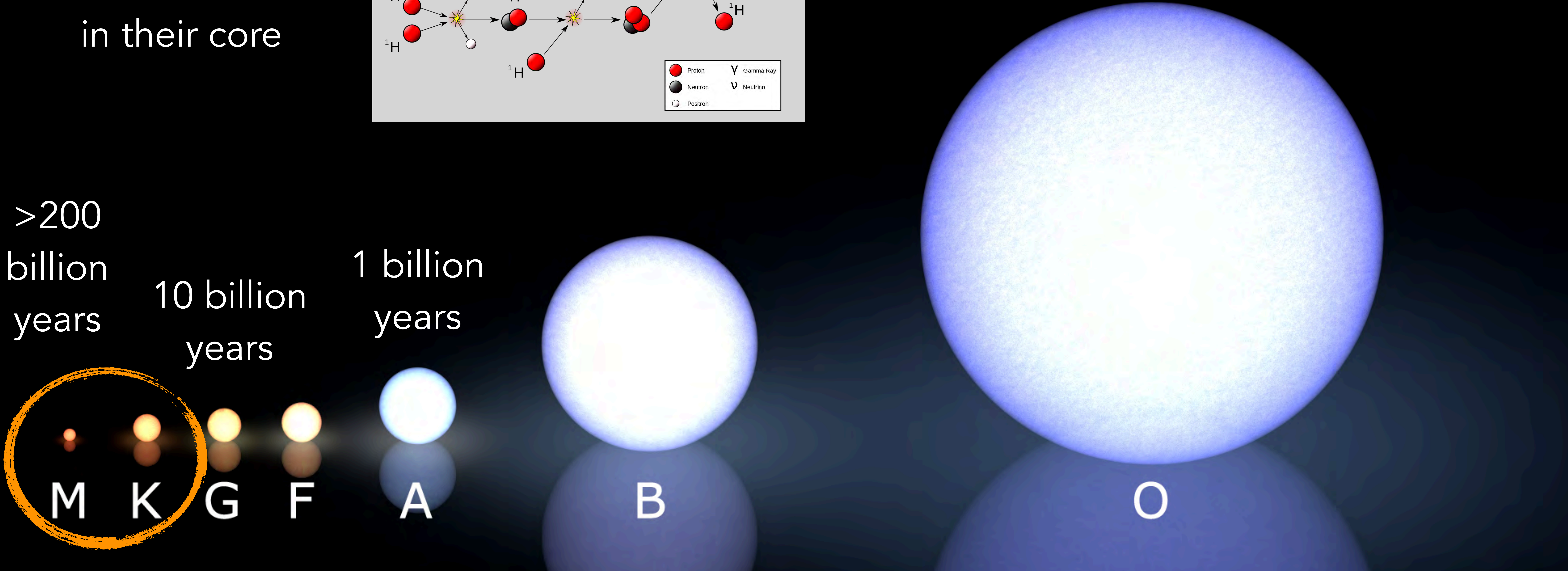


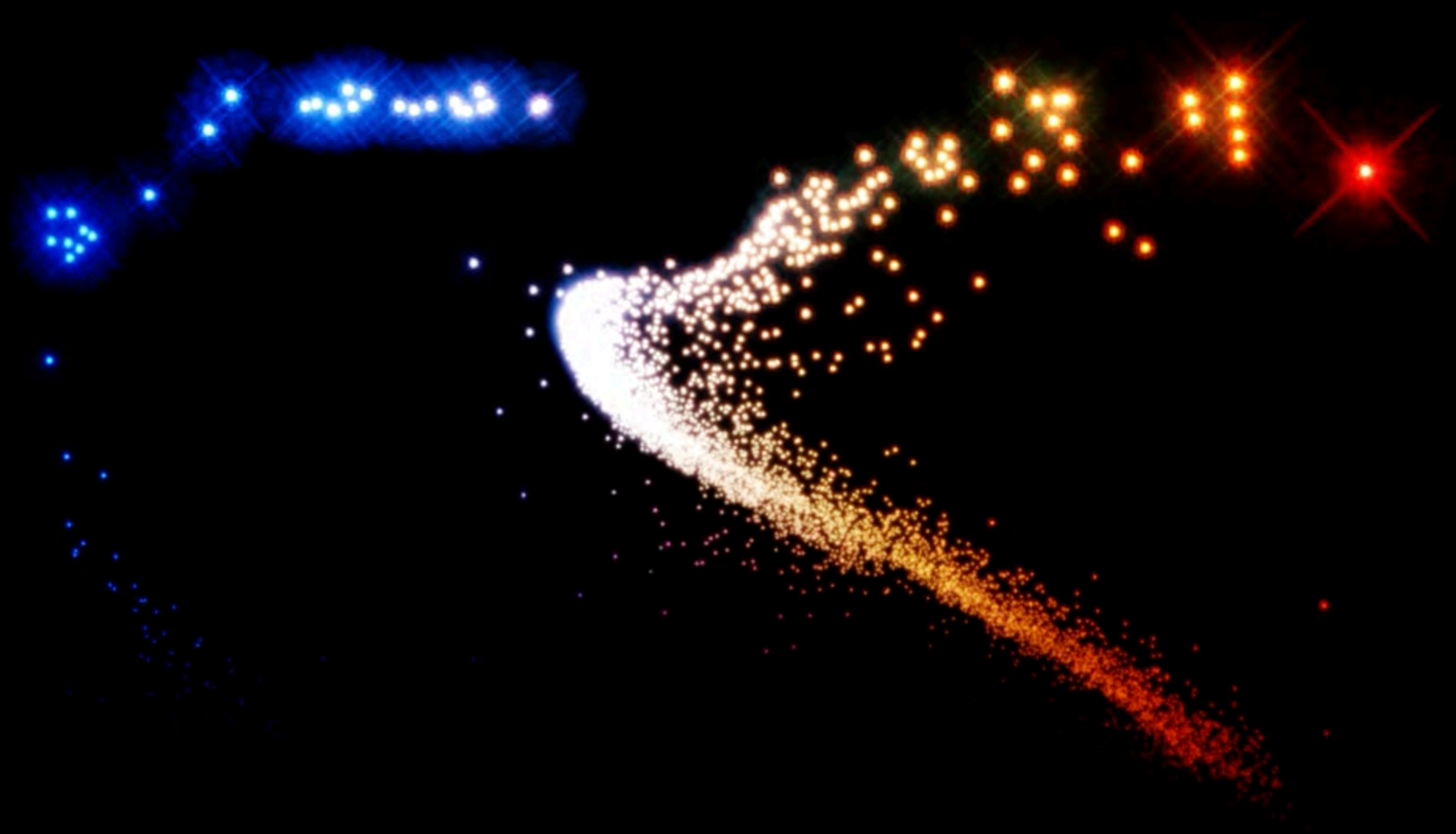
10 million years

>200 billion years

10 billion years

1 billion years





https://youtu.be/PsS80huL47c?si=XdxRWfNSEm32O7If

Video credit: Hubble — NASA, ESA, Jay Anderson (STScI), Roeland van der Marel (STScI), Greg T. Bacon (STScI), Mary Estacion (STScI)

What do we want to know about stars?

Q What do we *observe*?

What do we want to know about stars?

Q **What do we *observe*?**

The easiest:

- ➤ Position on the sky
- ➤ Apparent brightness
- ➤ Colours

What do we want to know about stars?

Q **What do we *observe?***

The easiest:

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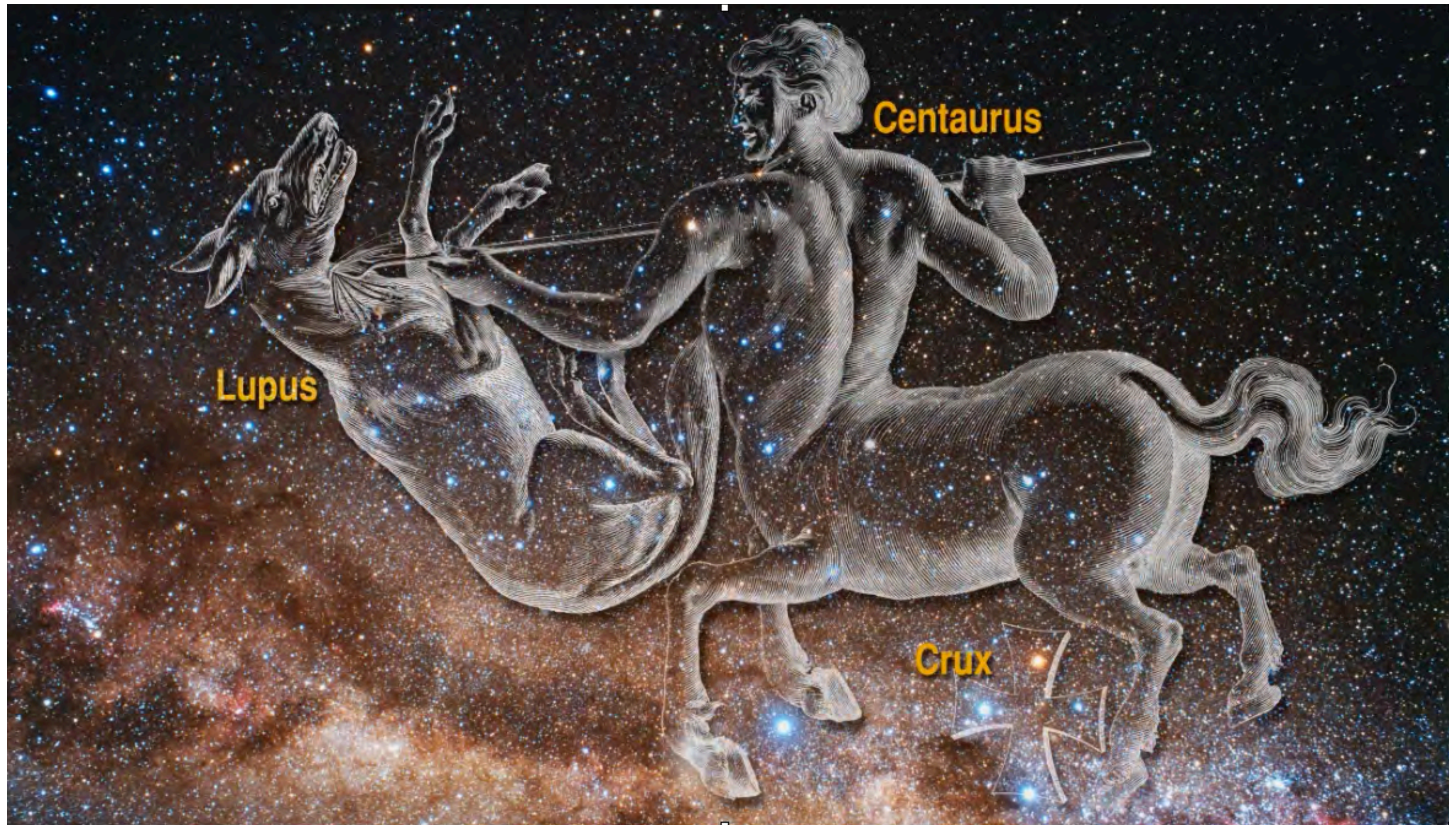
- **Chemical composition**: what is it made of? —> tracing ~time and their birth environment
- **Ages**: how long has this star been around for? (challenging to measure directly)
- **Dynamical behaviour**: how does a star move? —> memory of where the star came from

(not a comprehensive list)

Position



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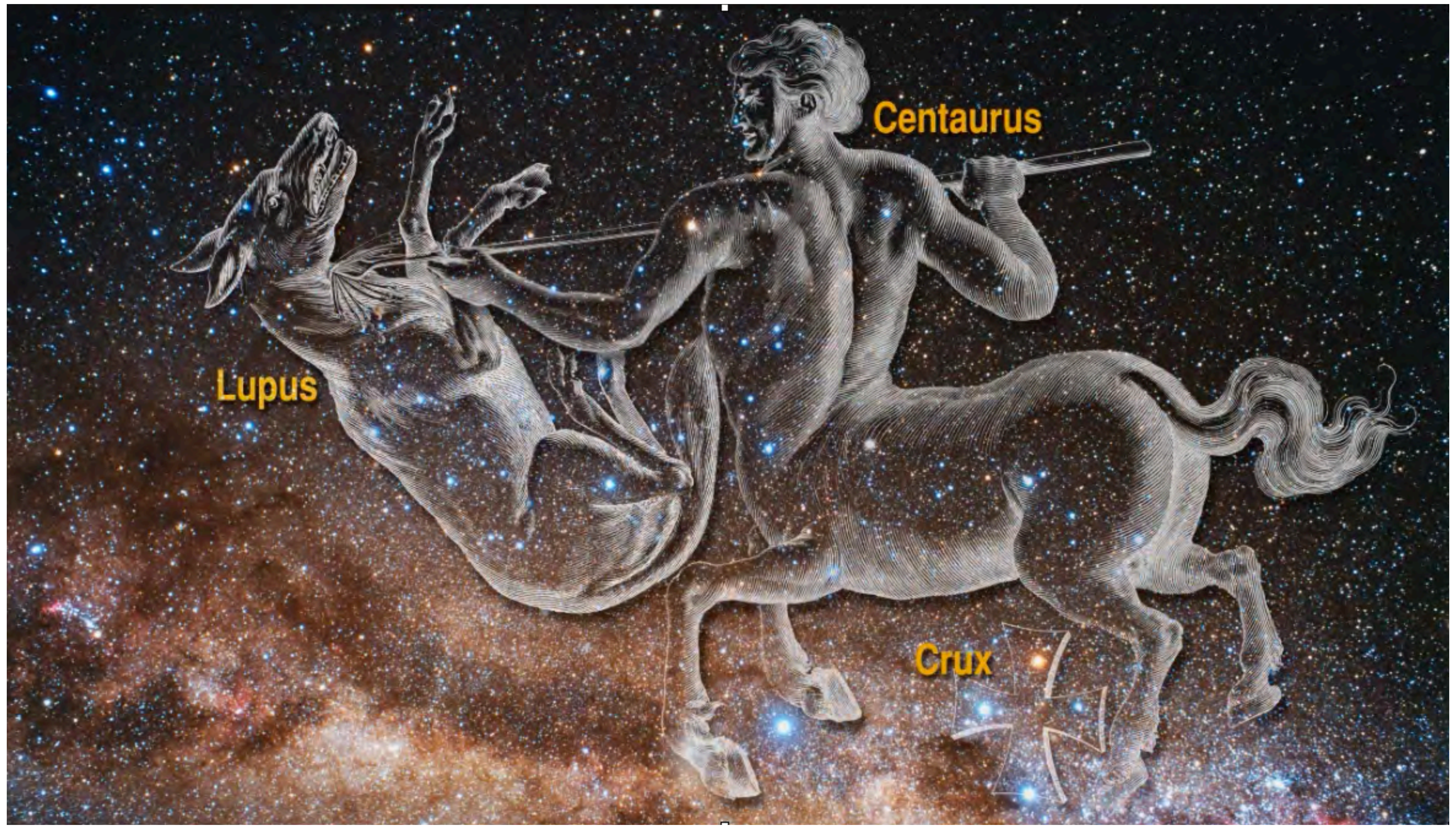
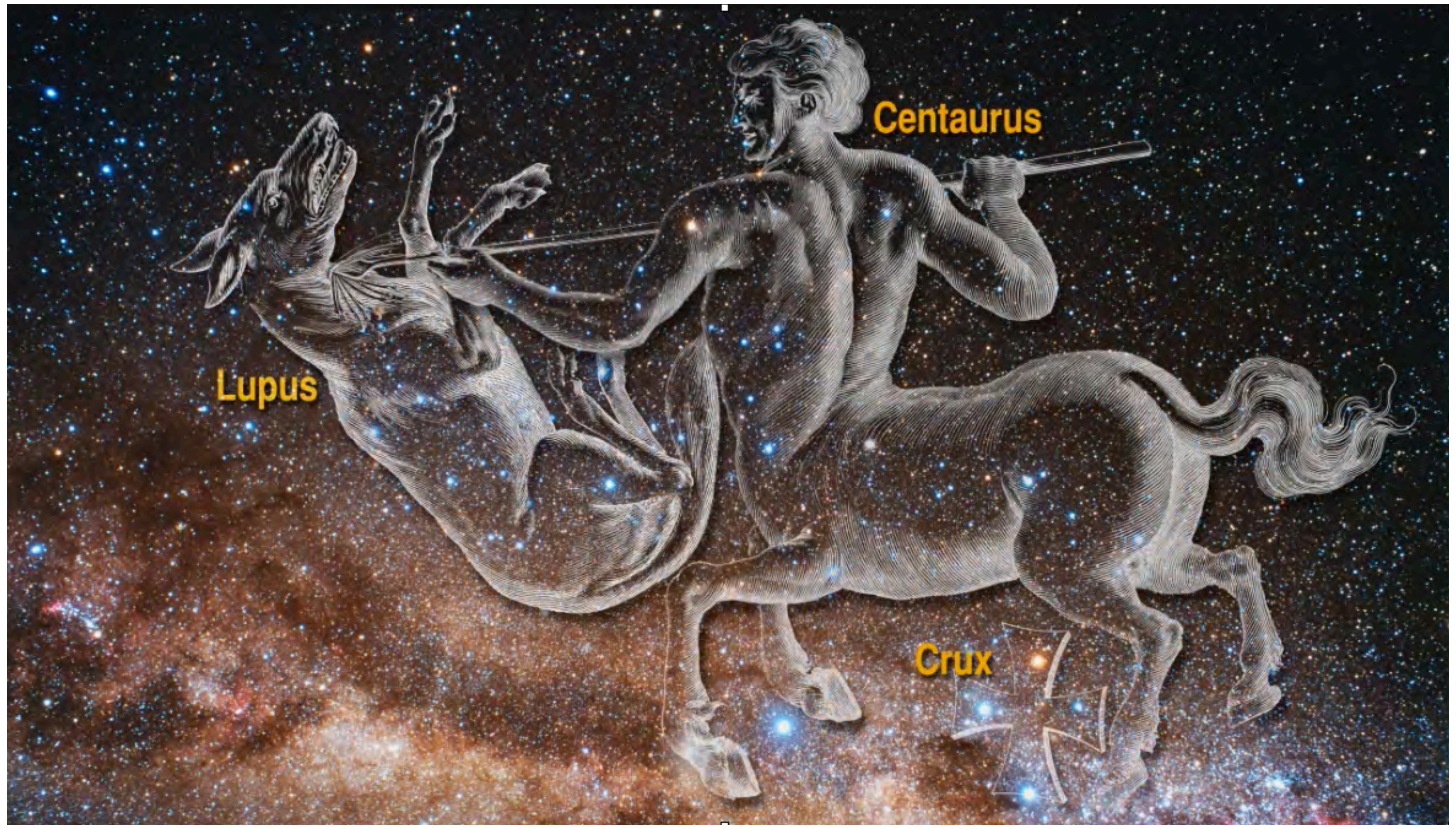
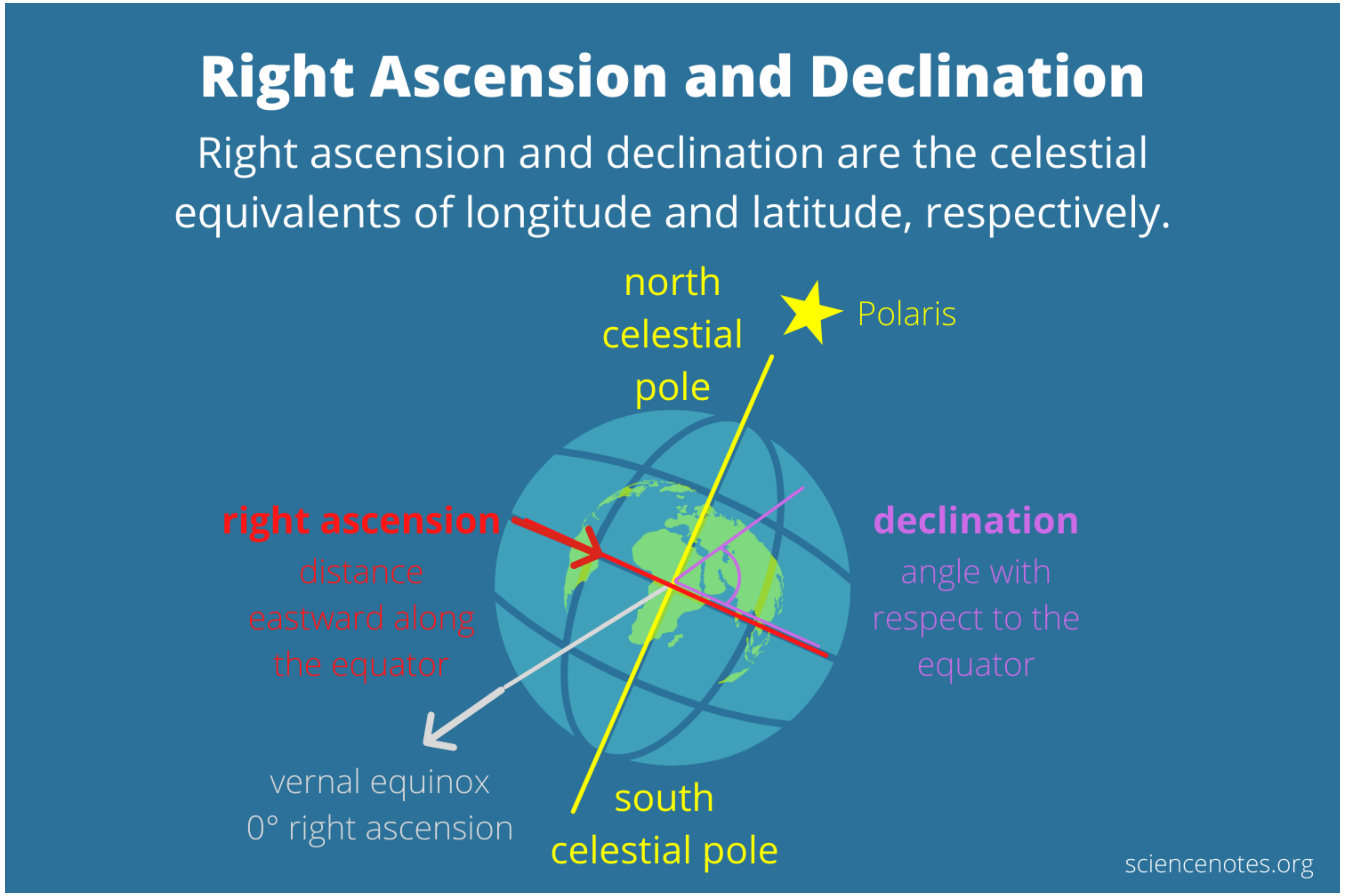


RA: 13h 26m 47s 201.697°

Dec: -47° 28′ 46″ -47.479°

Position





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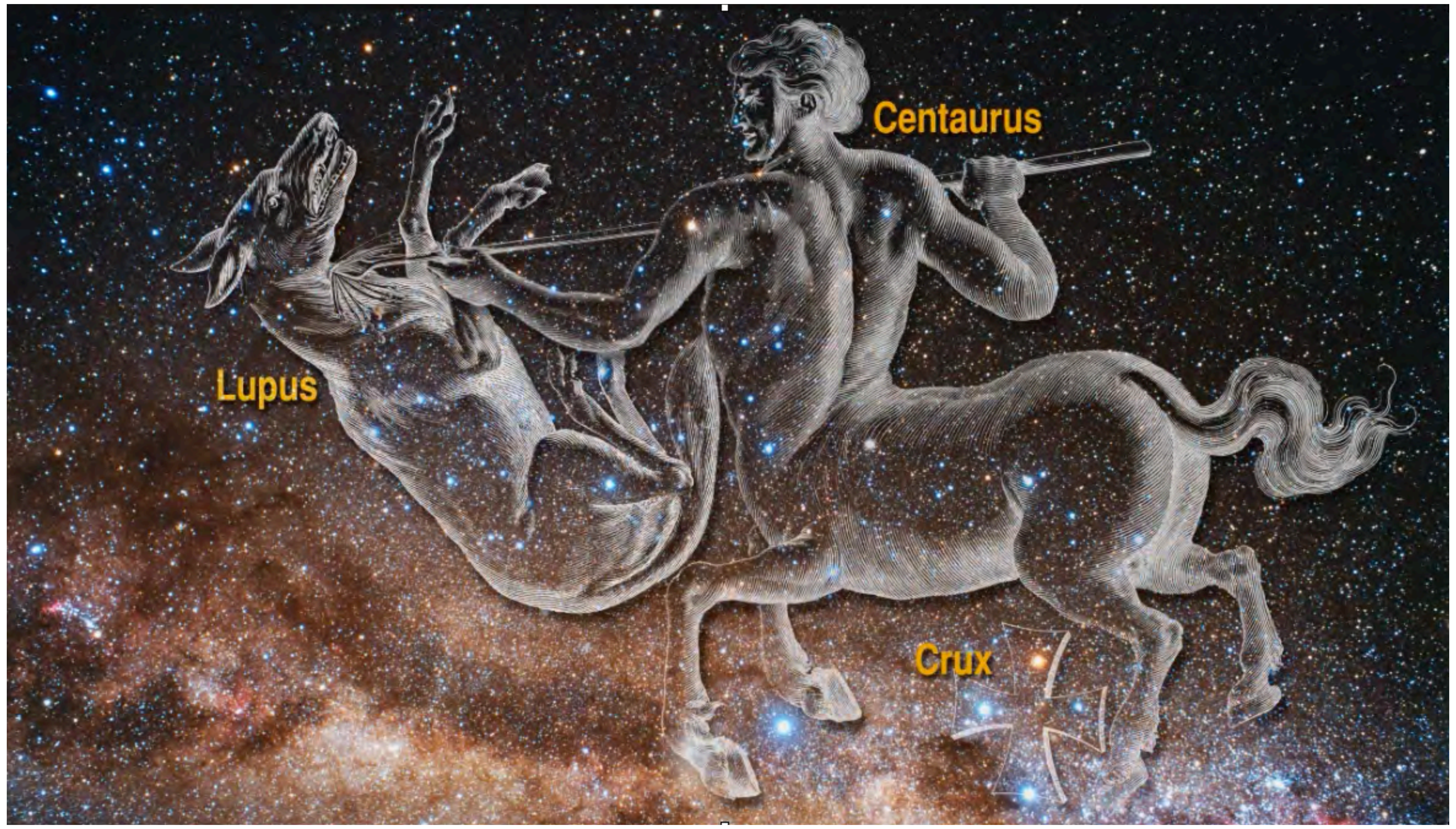

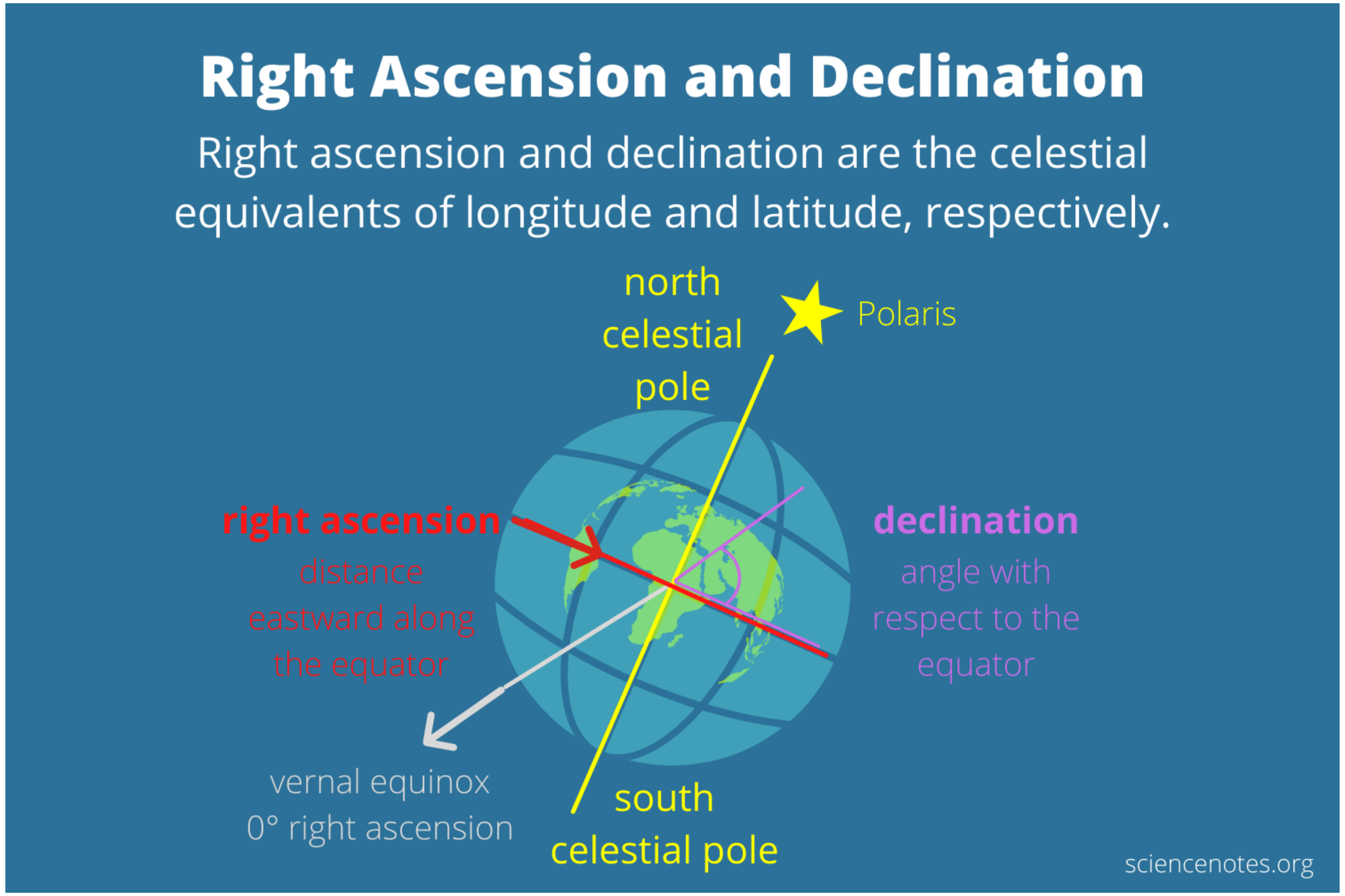

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Q **Is this object better visible from the Northern or the Southern Hemisphere?**

Density distribution

Omega Centauri: a globular cluster
(which we now know to be very old)

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- The Galaxy is mostly "empty": the distance to our nearest star is 4.2 light years (1.3 parsec)
- Globular clusters are ~1000x denser
- Thought to all have been born together: same age and composition

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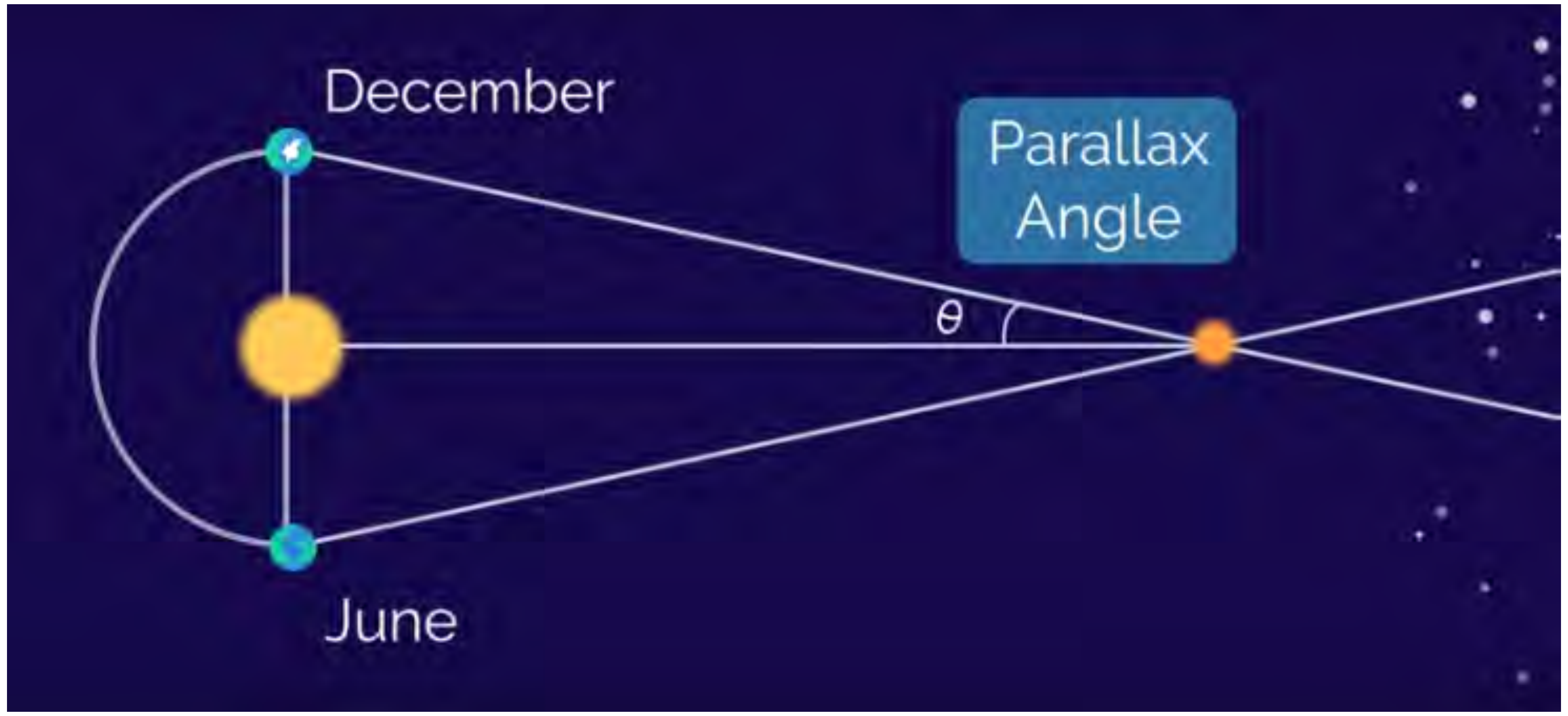
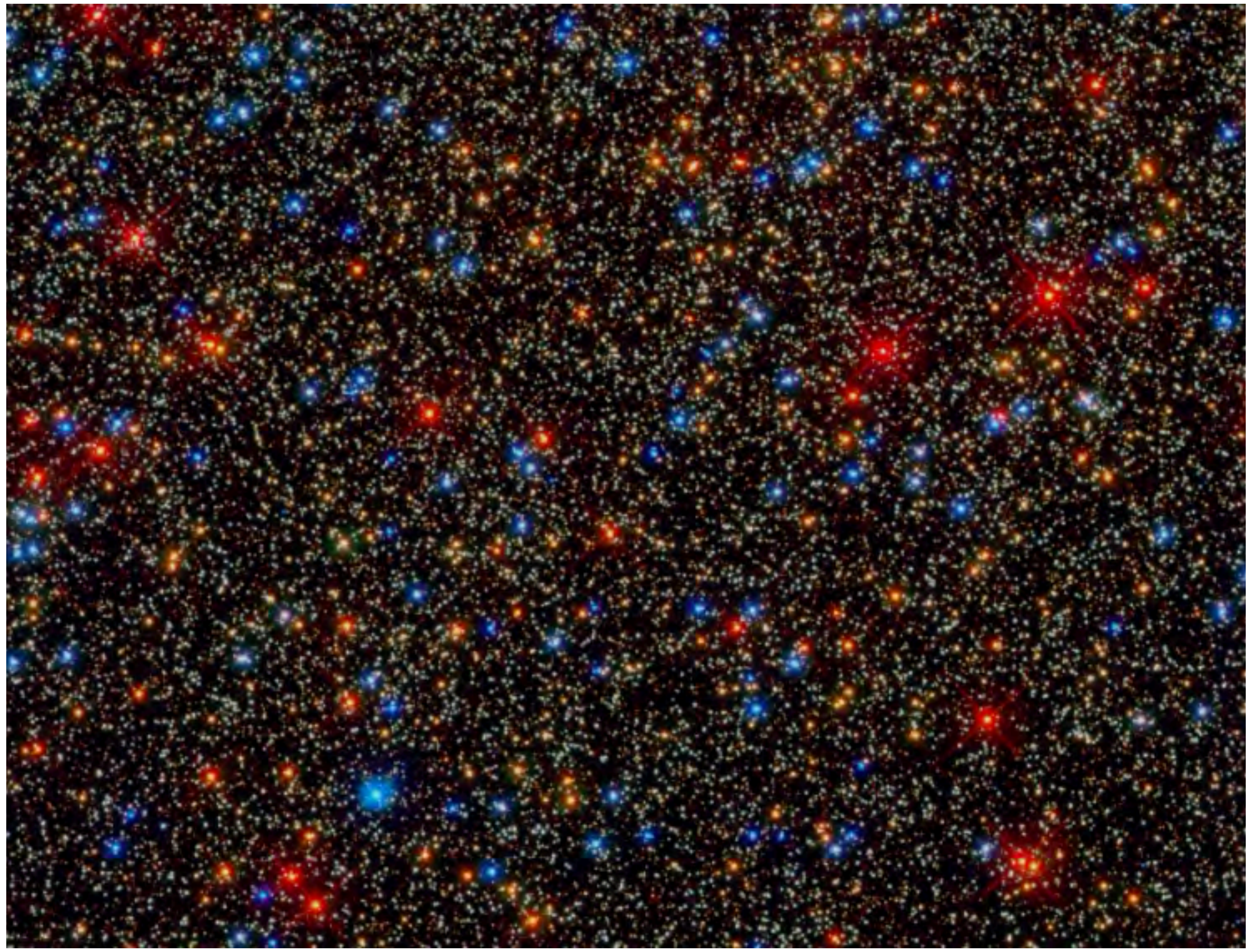


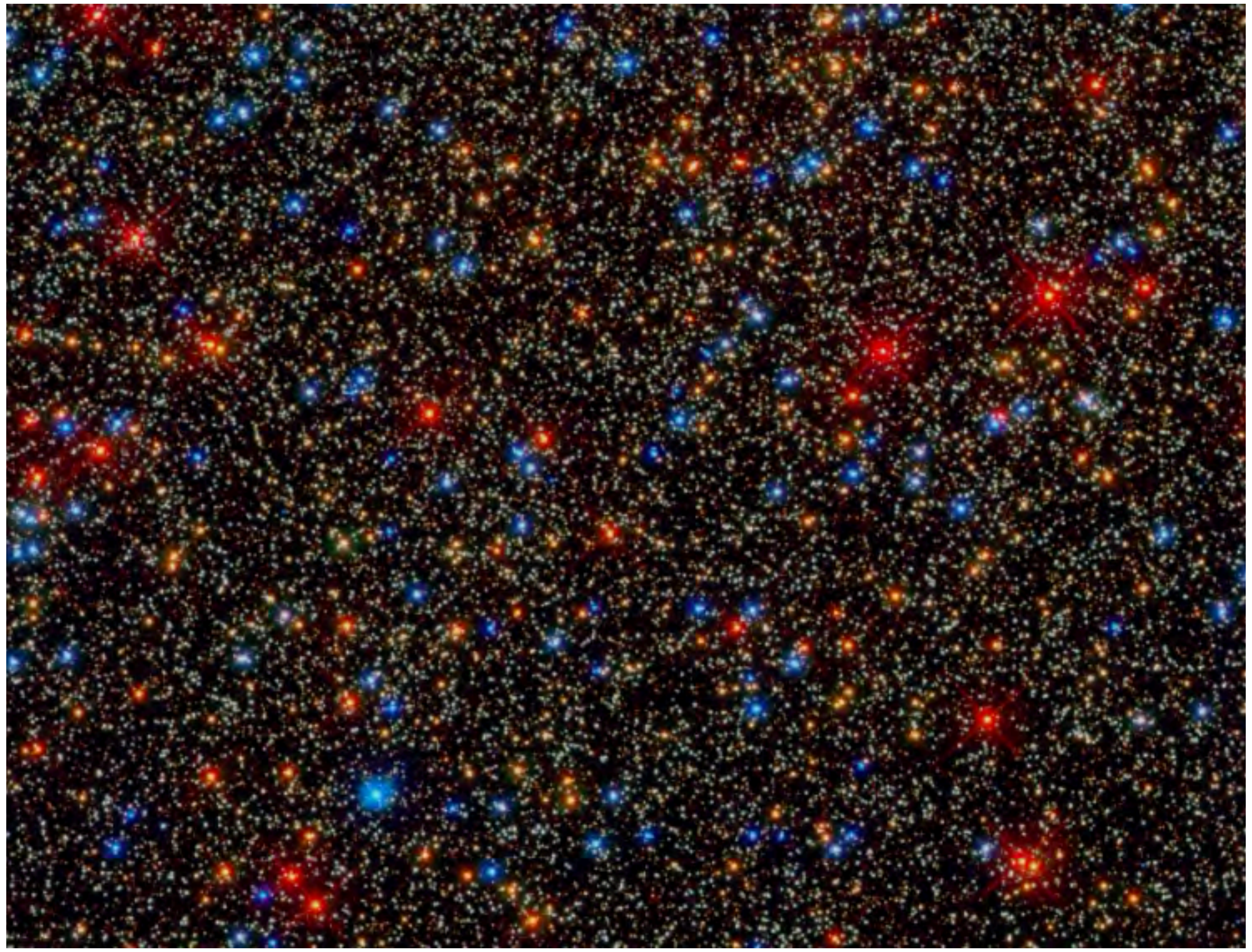
at a distance of 1 parsec, the parallax angle is 1 arcsec

Colours and magnitudes



Not all stars have the same colour,
nor the same brightness

Colours and magnitudes



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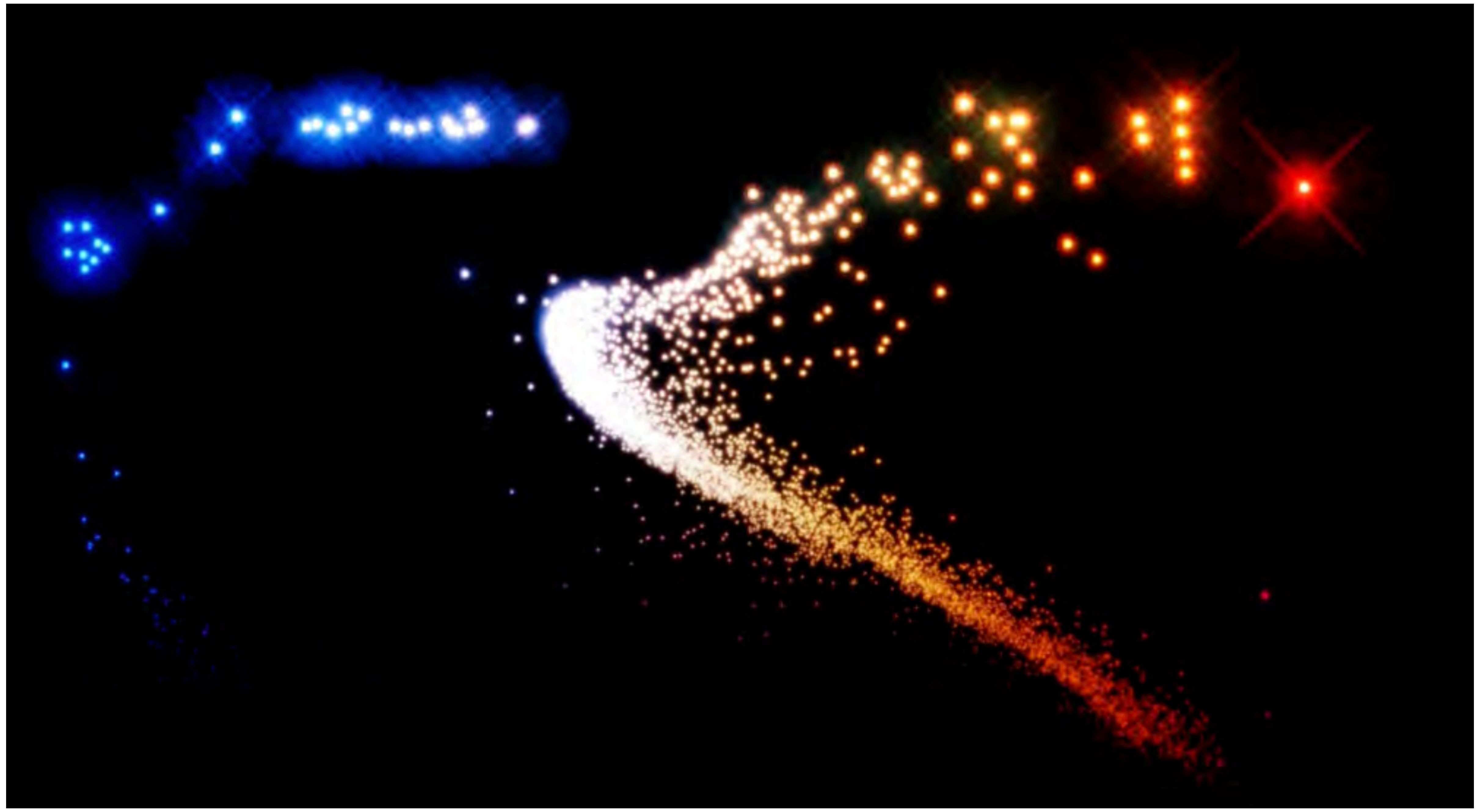
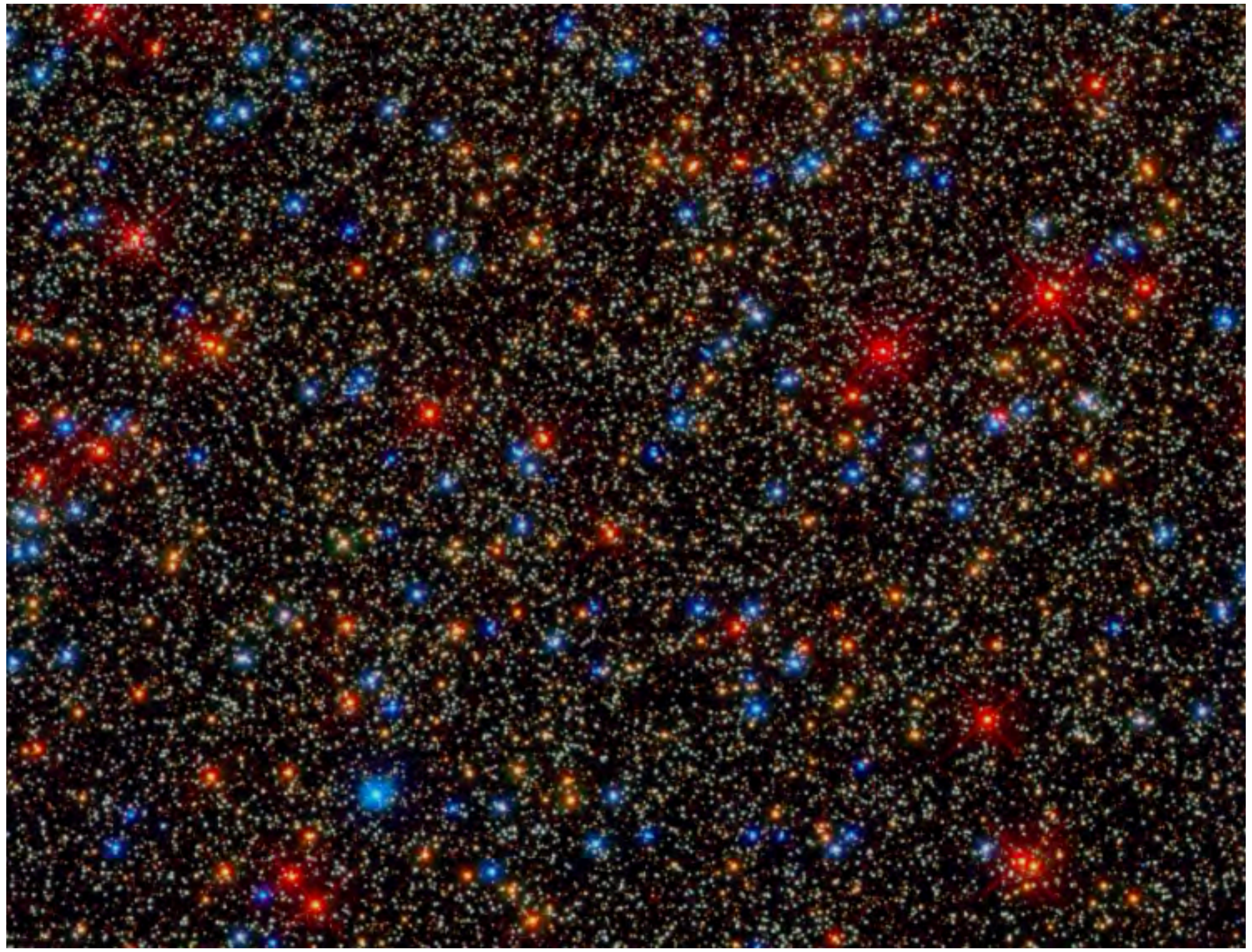


There is a *very* strong correlation between colour & brightness

Colours and magnitudes

Q **Why is that?**



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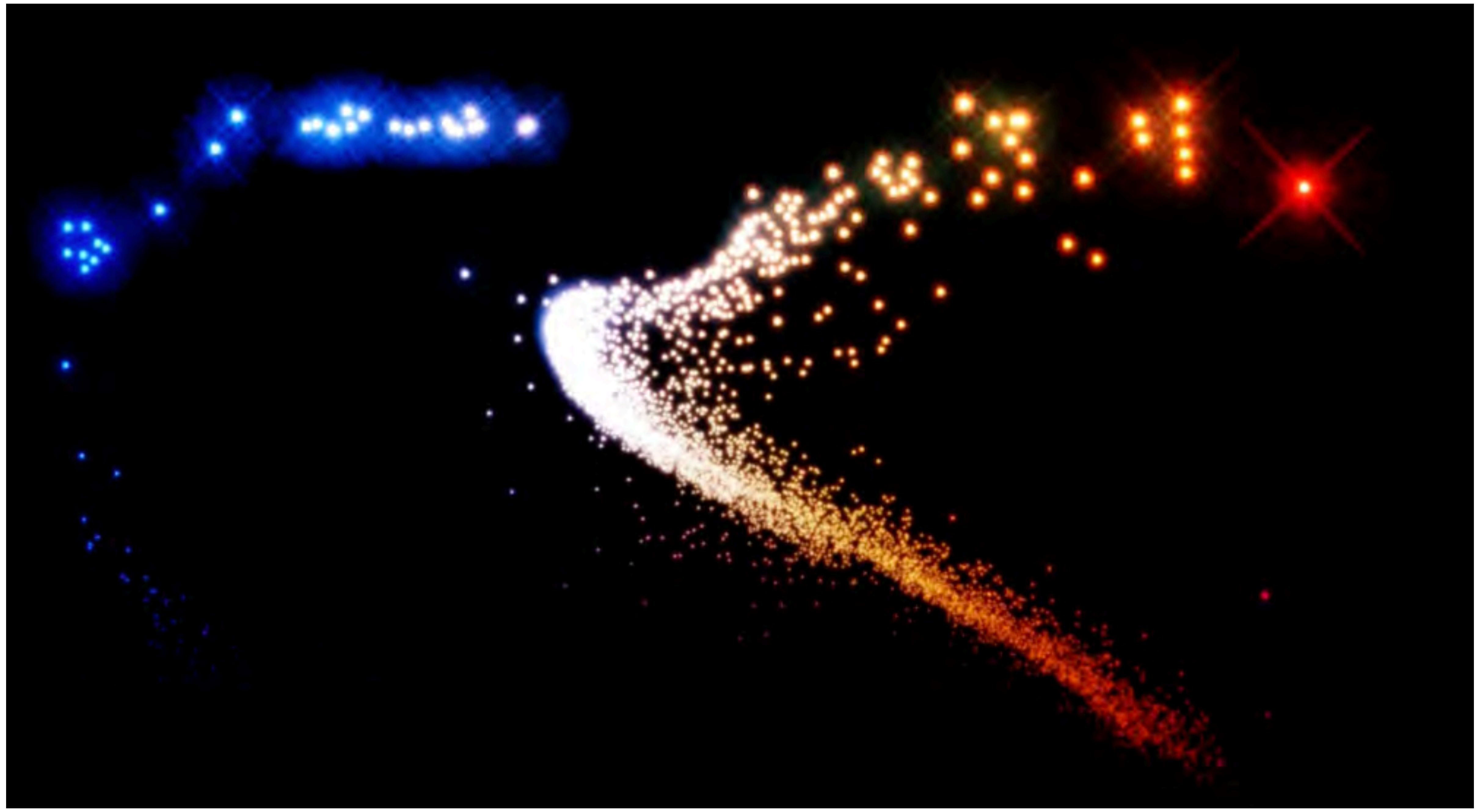

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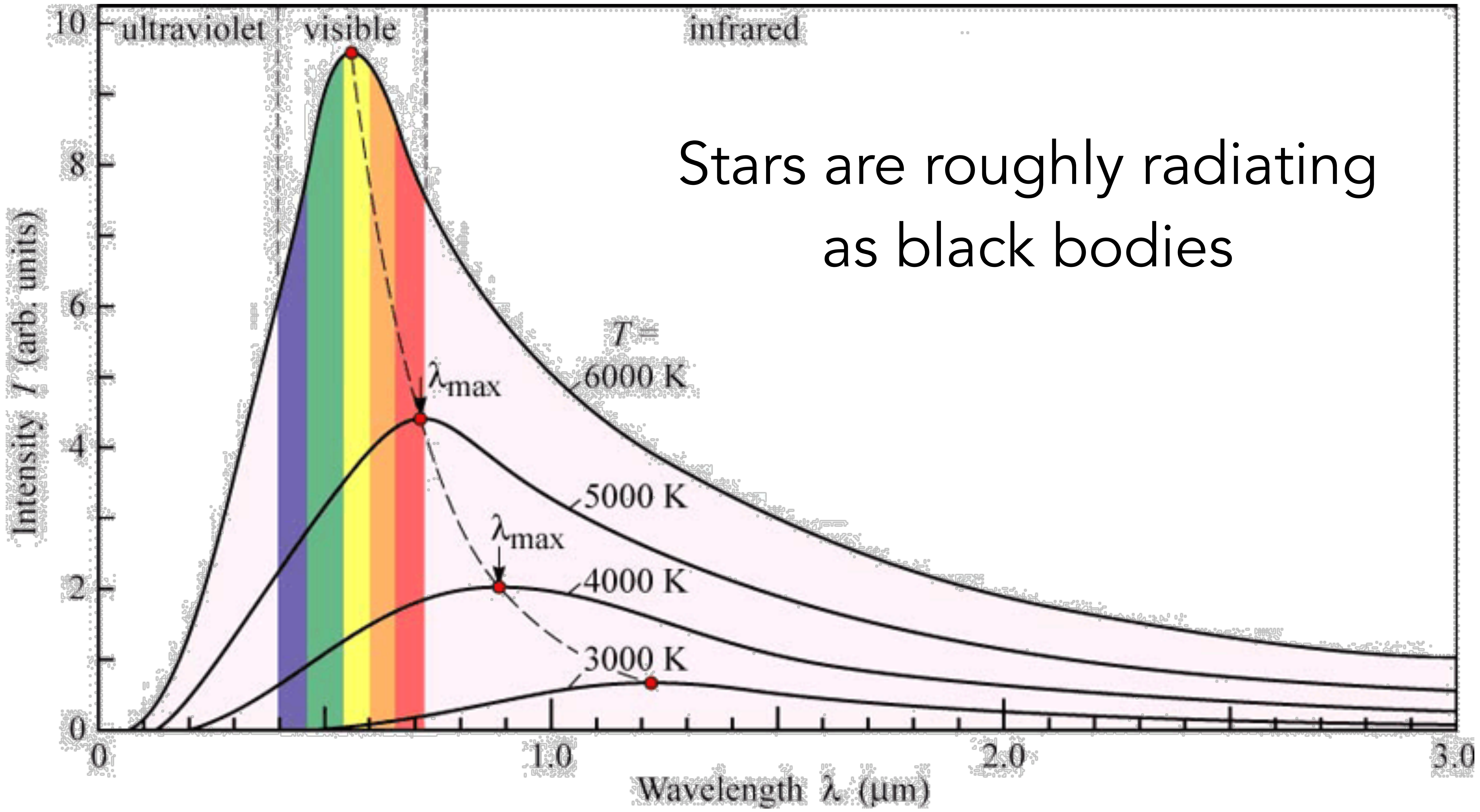
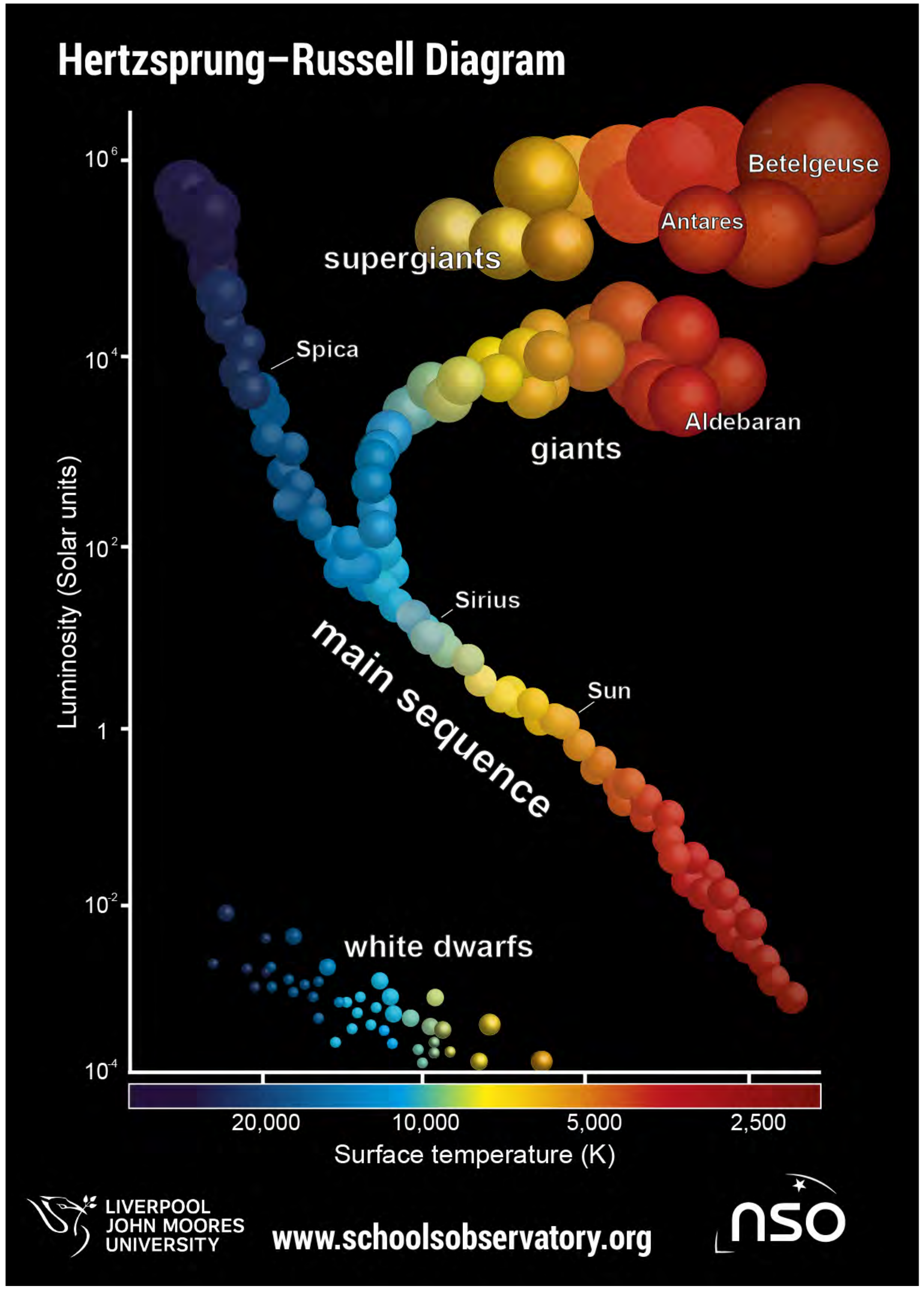
Herzsprung-Russell (HR) diagram

- colour vs. magnitude (previous slide) corresponds to **surface temperature** vs. **luminosity**
  - These are fundamental stellar properties



Stars are roughly radiating as black bodies



Herzsprung-Russell (HR) diagram

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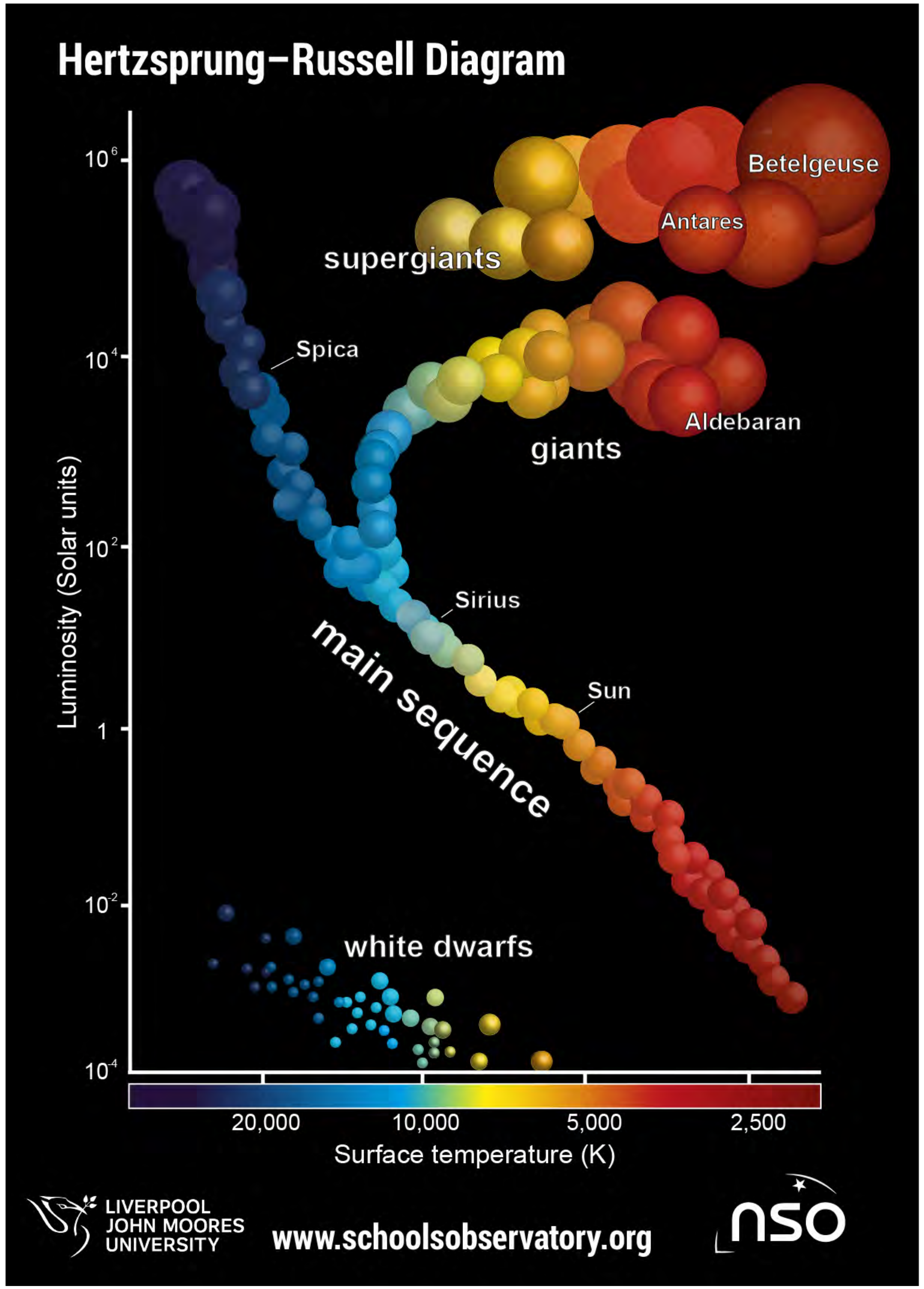
  - Meaning the gas pressure supports the star against the force of gravity



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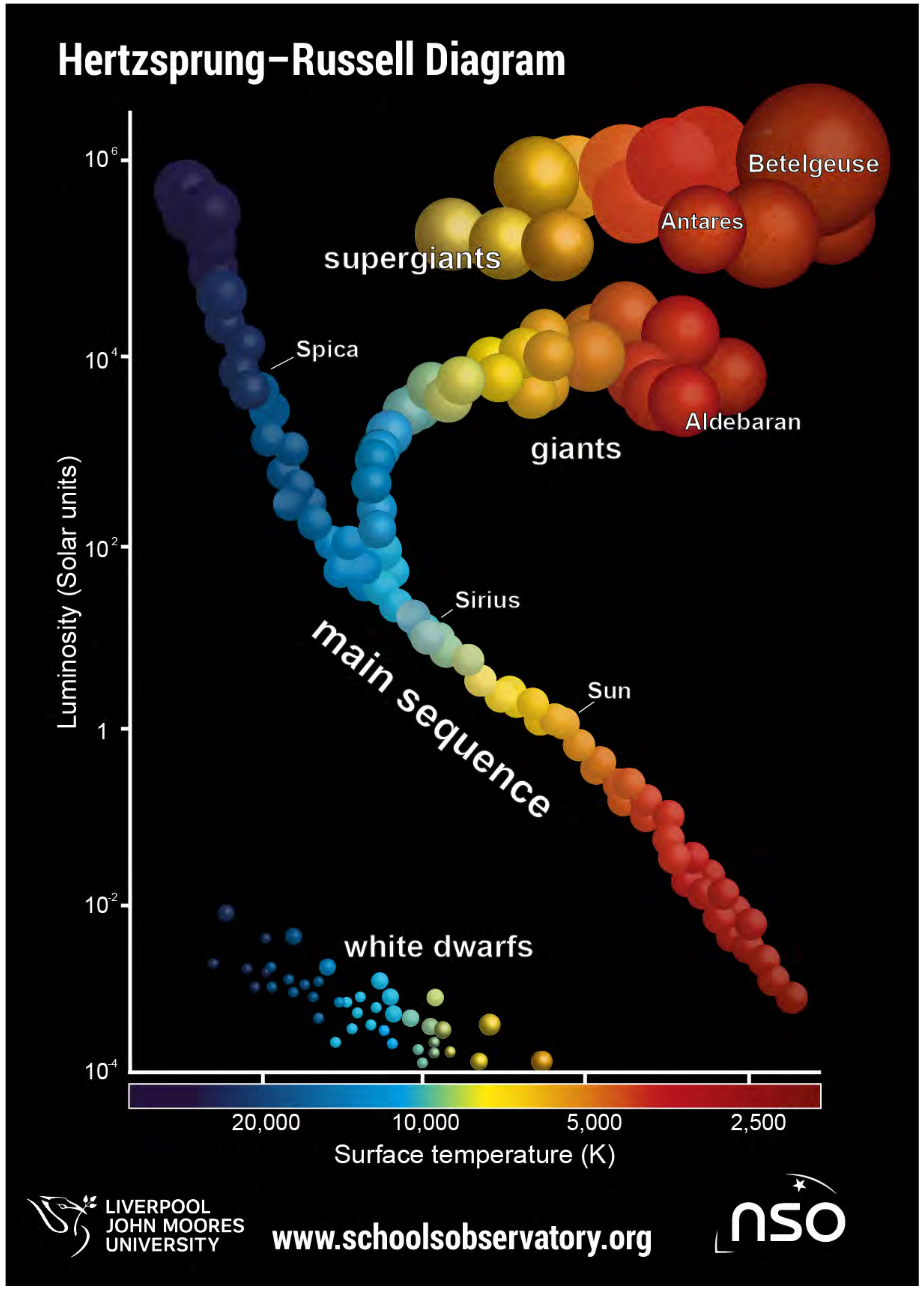
The luminosity (power output) of a star on the main sequence is a function of its mass:

$$L/L_{\odot} = (M/M_{\odot})^{\alpha}$$



Energy source of stars: nuclear fusion

- Fusion occurs when **particles** overcome the repulsive electrostatic force (pushing past the Coulomb barrier) to **bind via the strong nuclear force**
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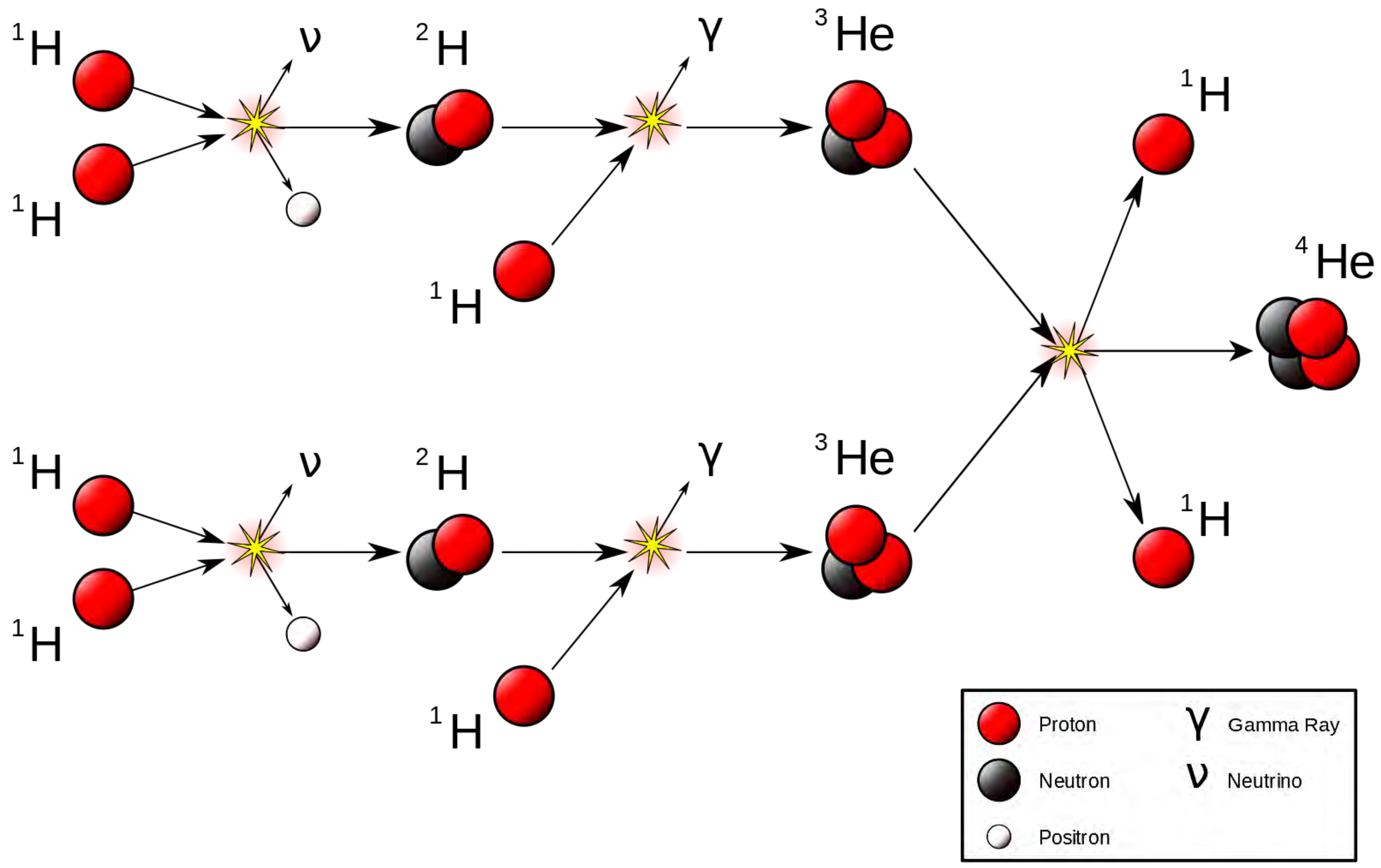

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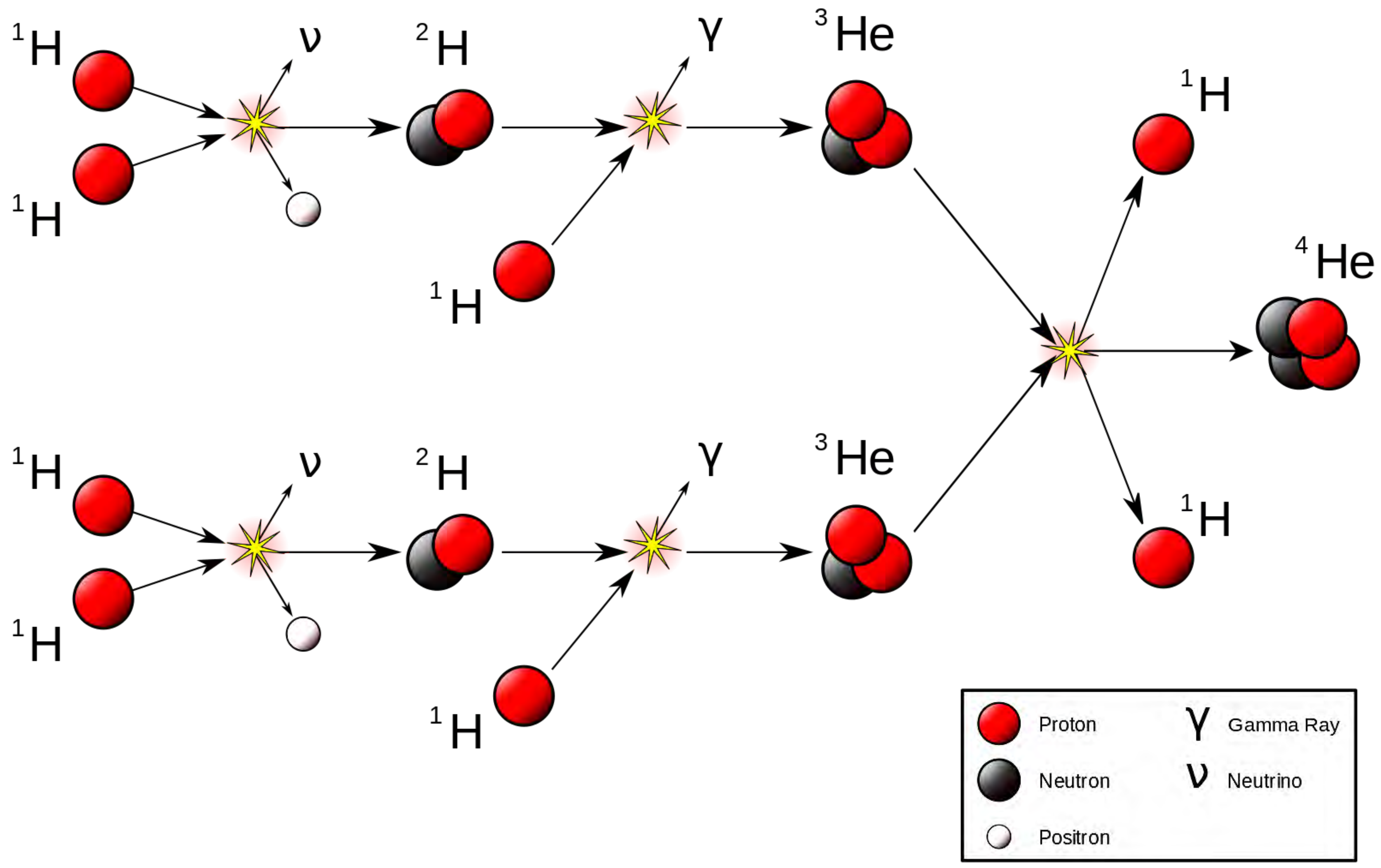
Proton-proton Chain



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- "Failed stars" are those that never fuse beyond deuterium

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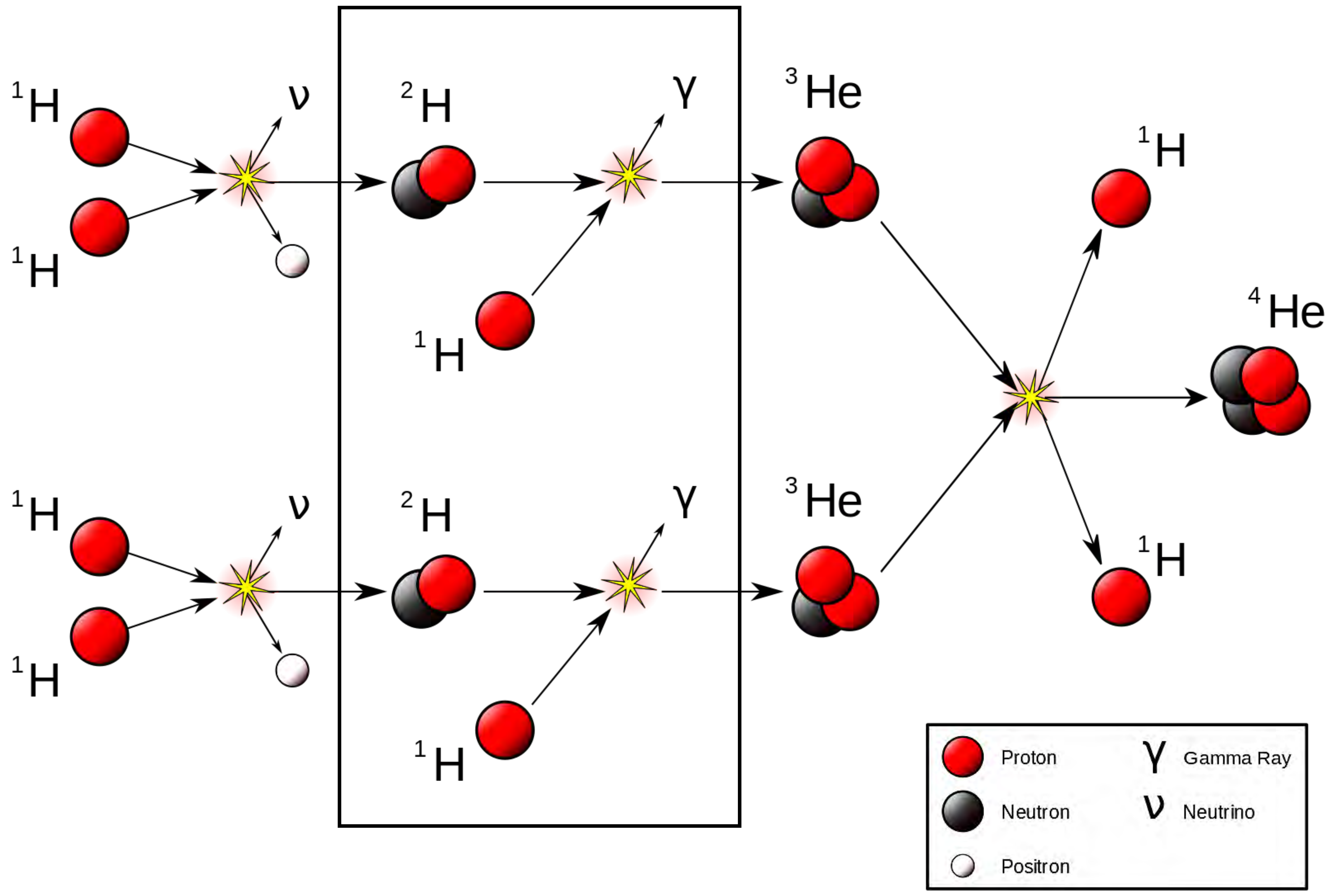

Deuterium Fusion

Binding energy

- Binding energy is the amount of energy needed to break apart a nucleus into its constituent protons and neutrons

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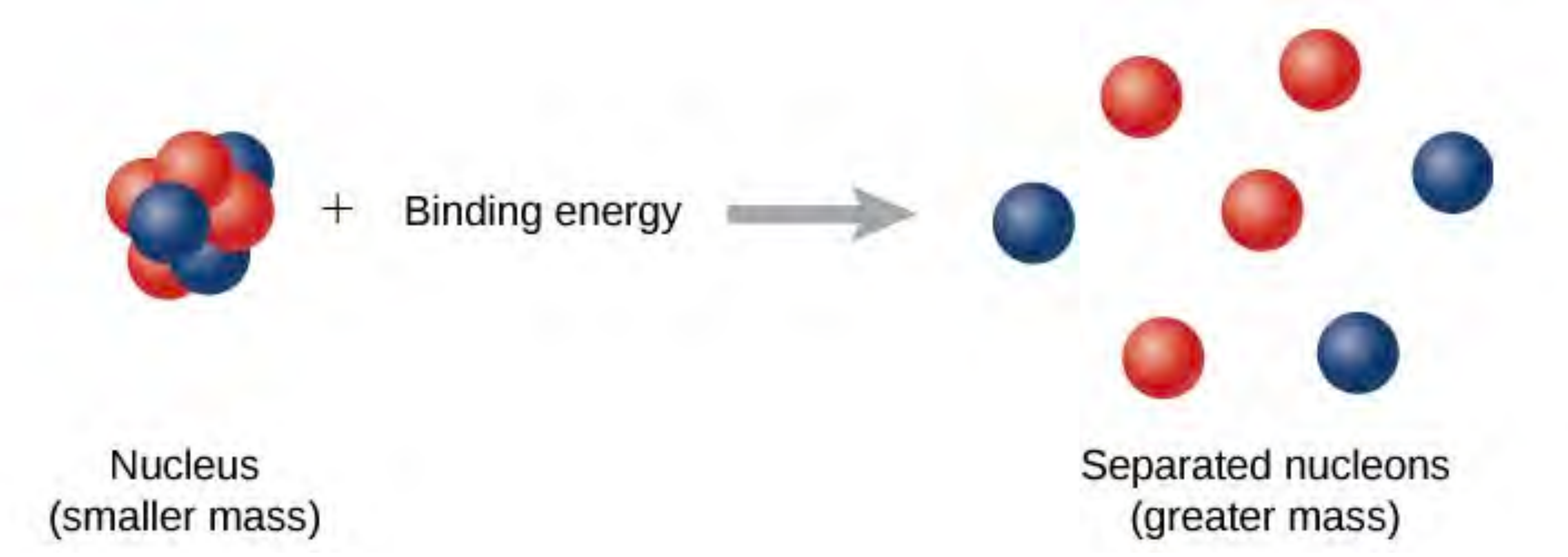

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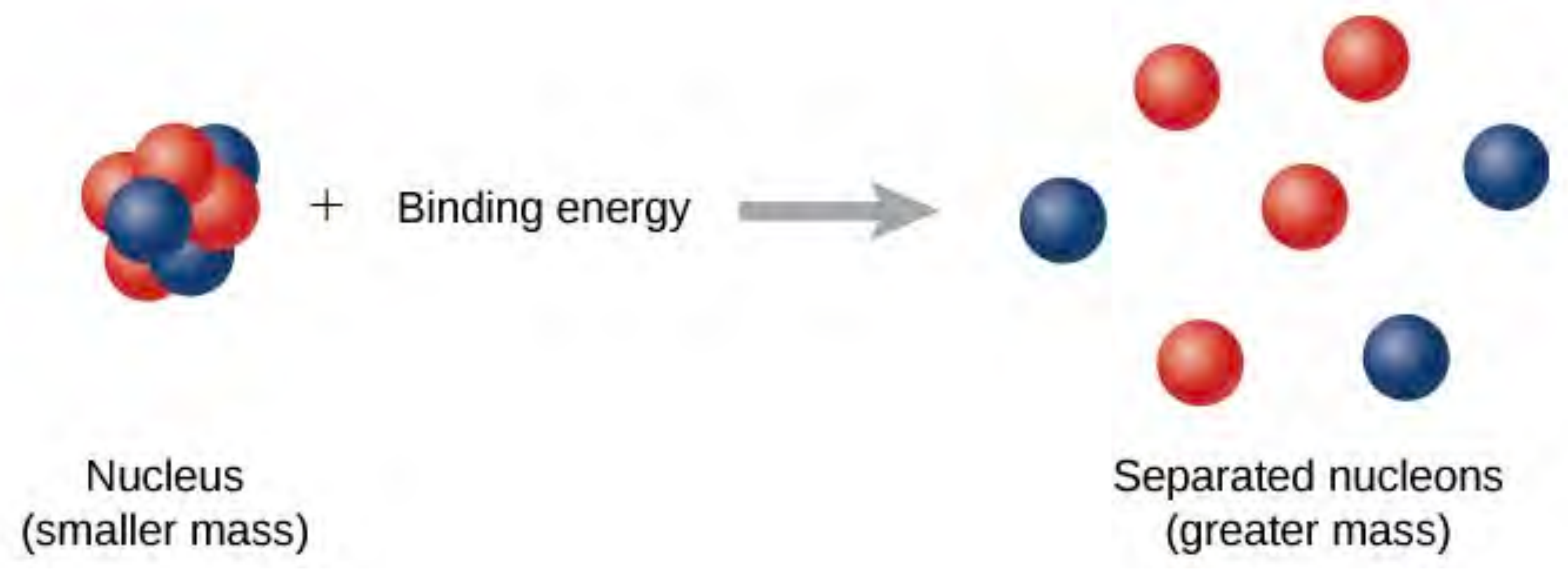

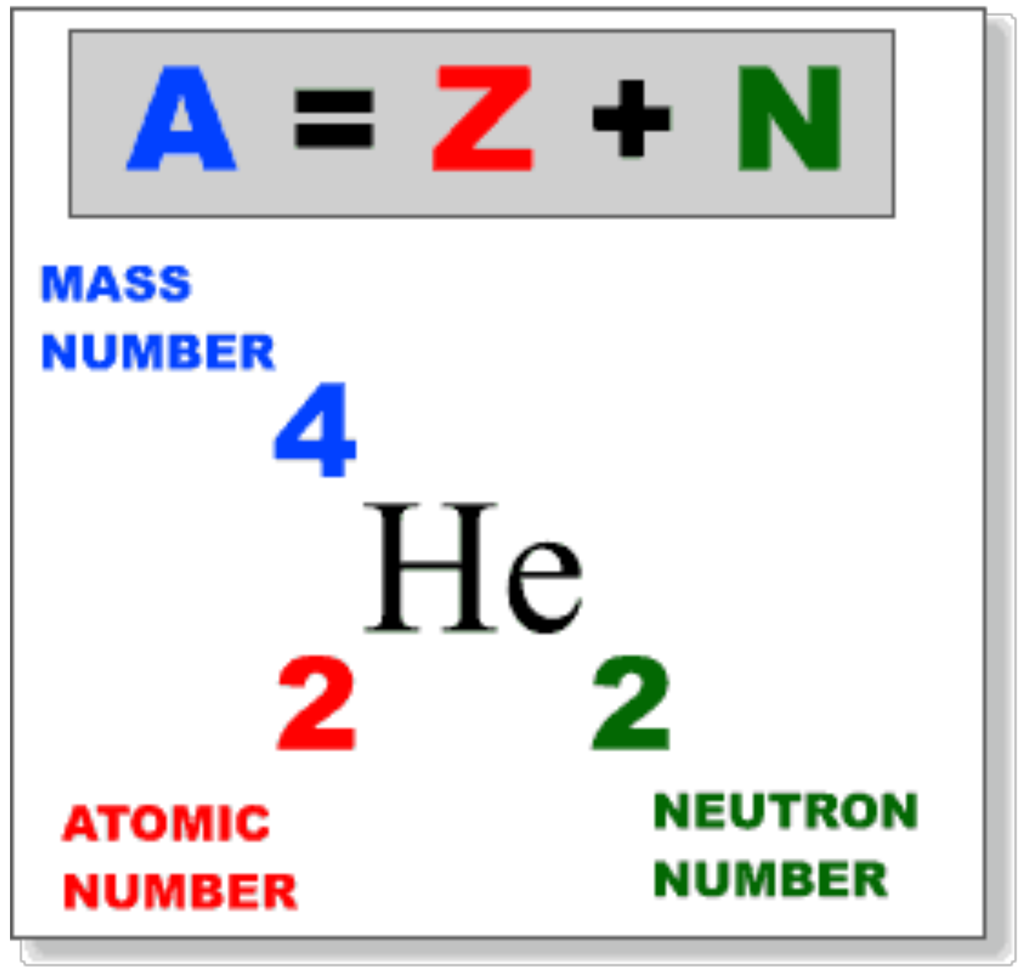

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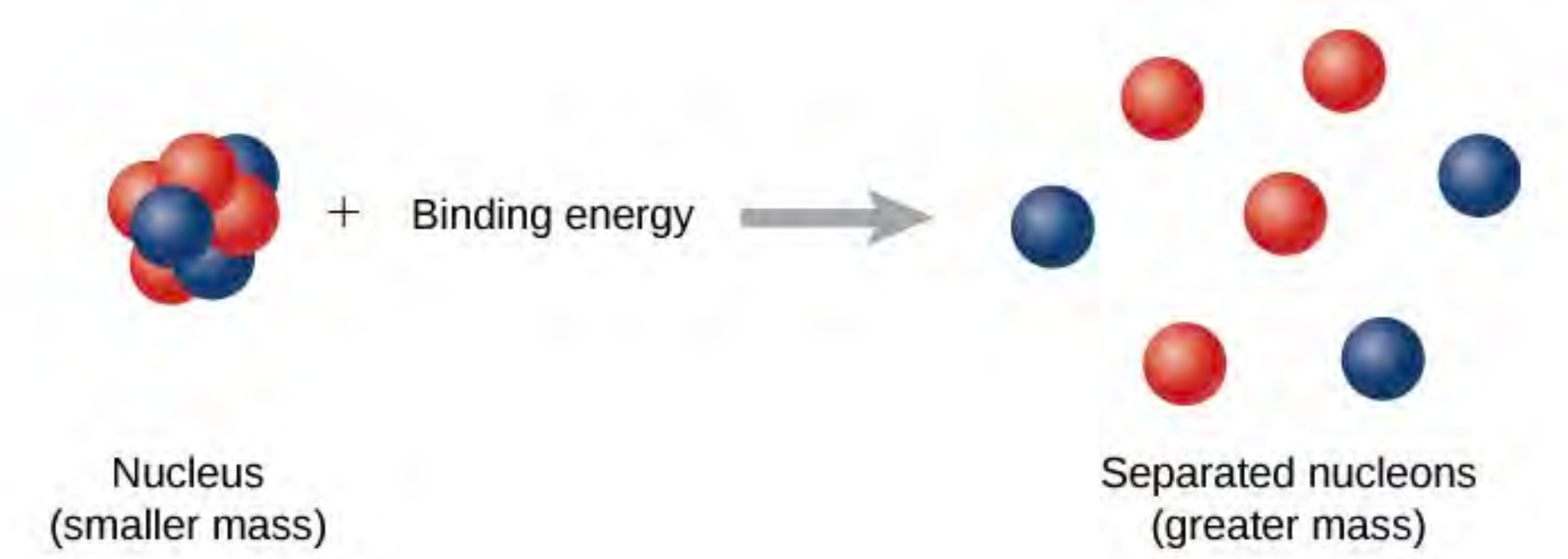
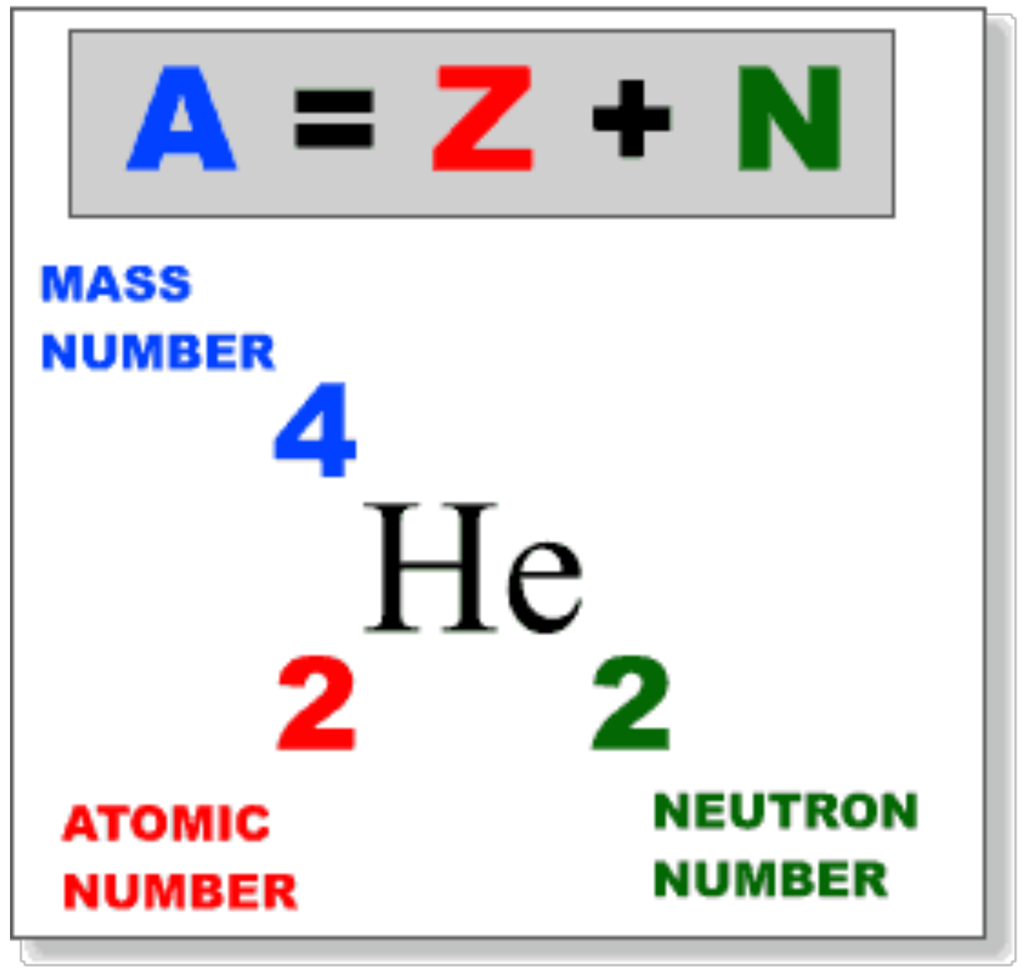


$$E = mc^2$$



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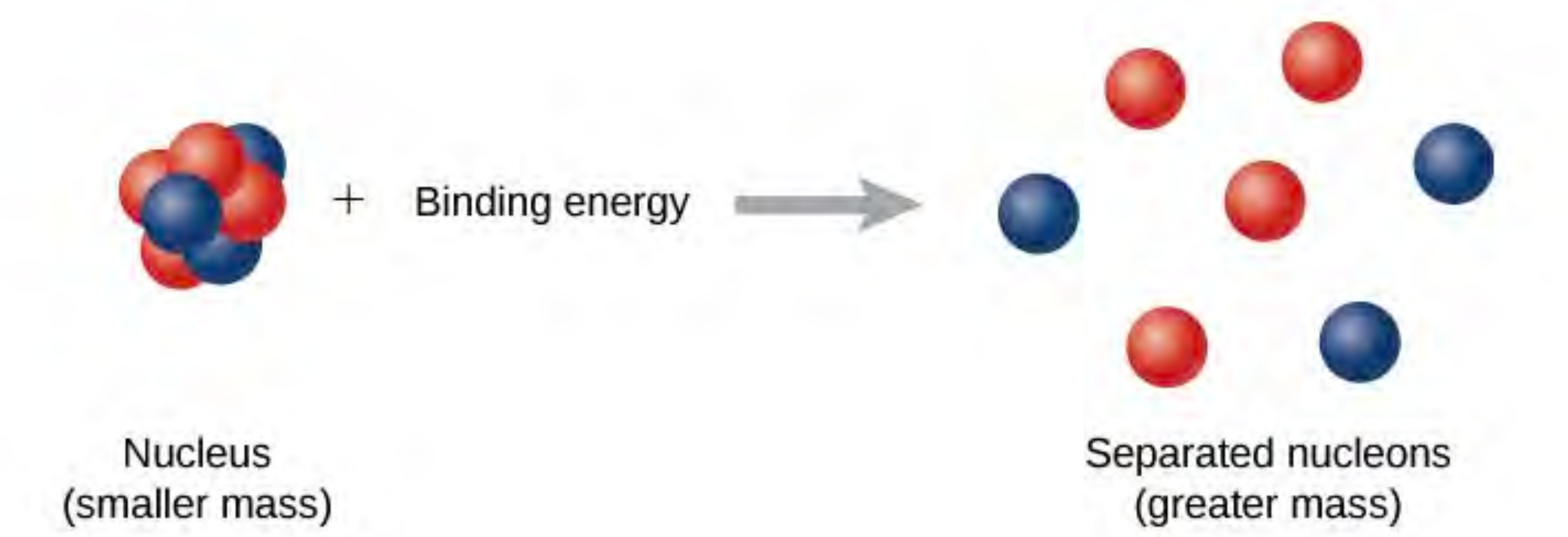

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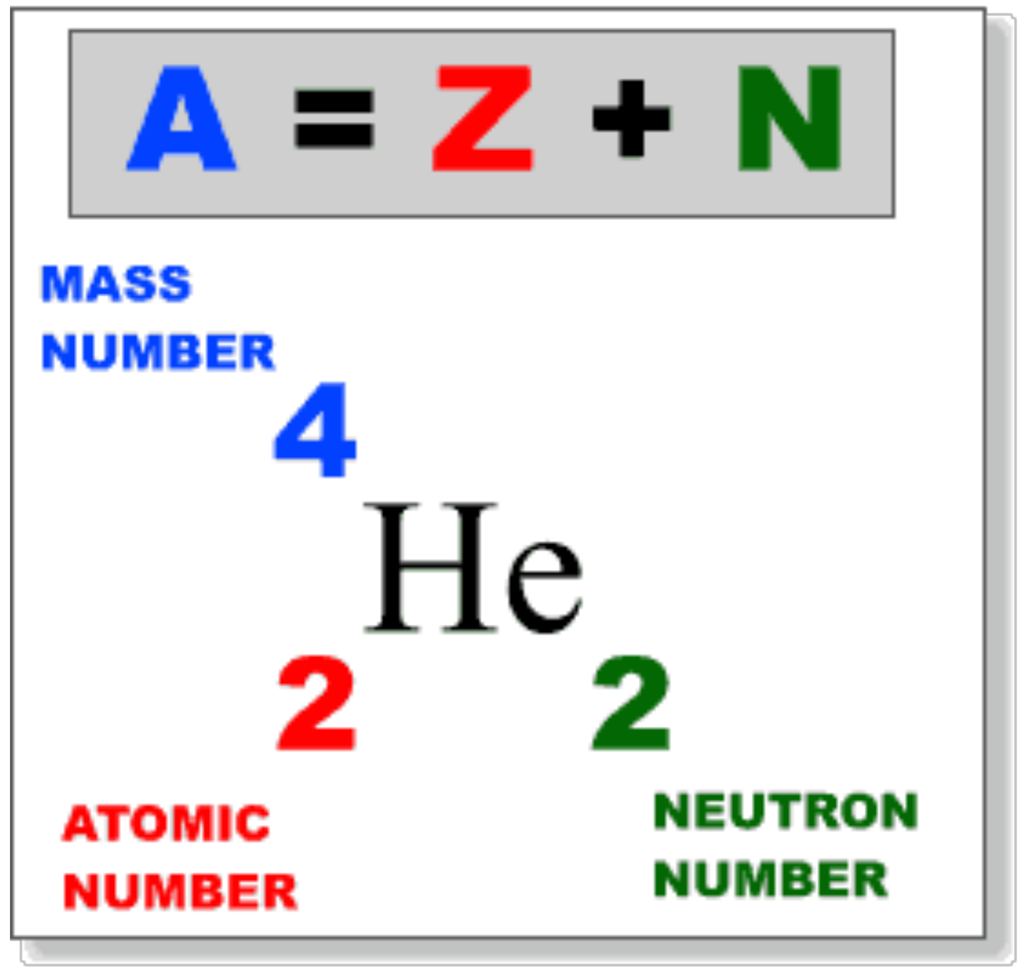

$$^{3}_{2}\mathrm{He} + ^{3}_{2}\mathrm{He} \rightarrow ^{4}_{2}\mathrm{He} + 2^{1}_{1}\mathrm{H} + 12.859\ \mathrm{MeV}$$

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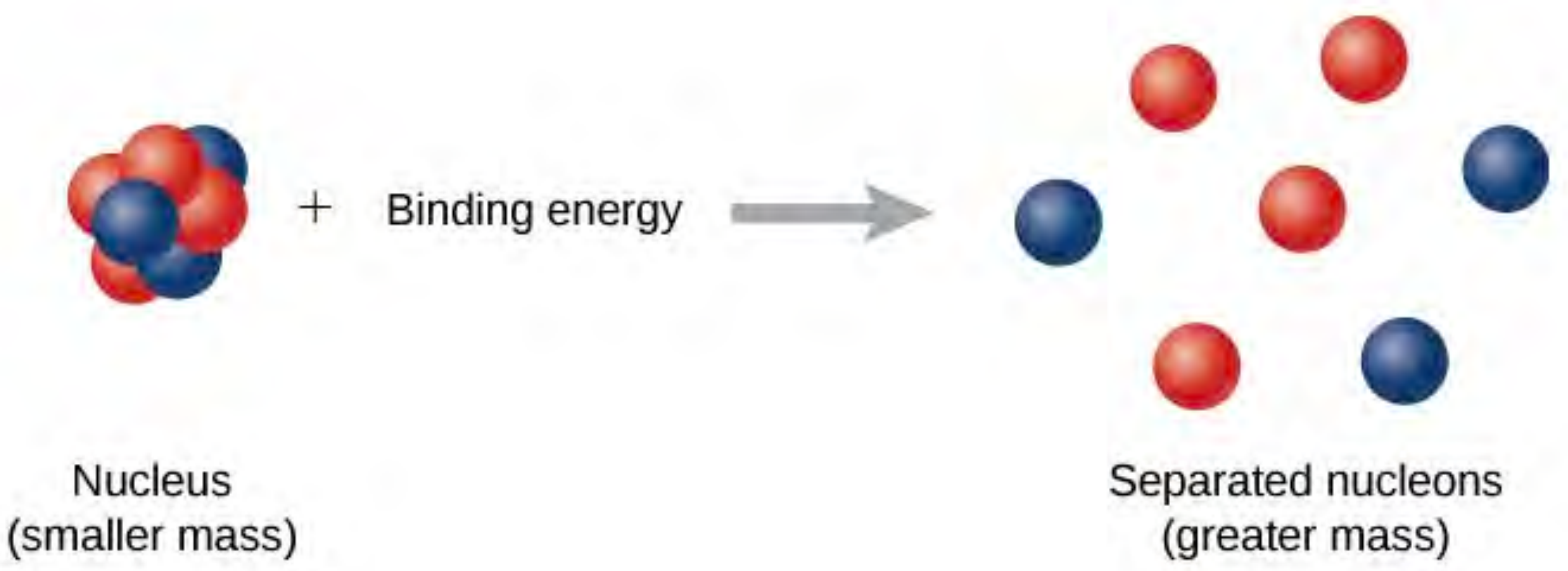
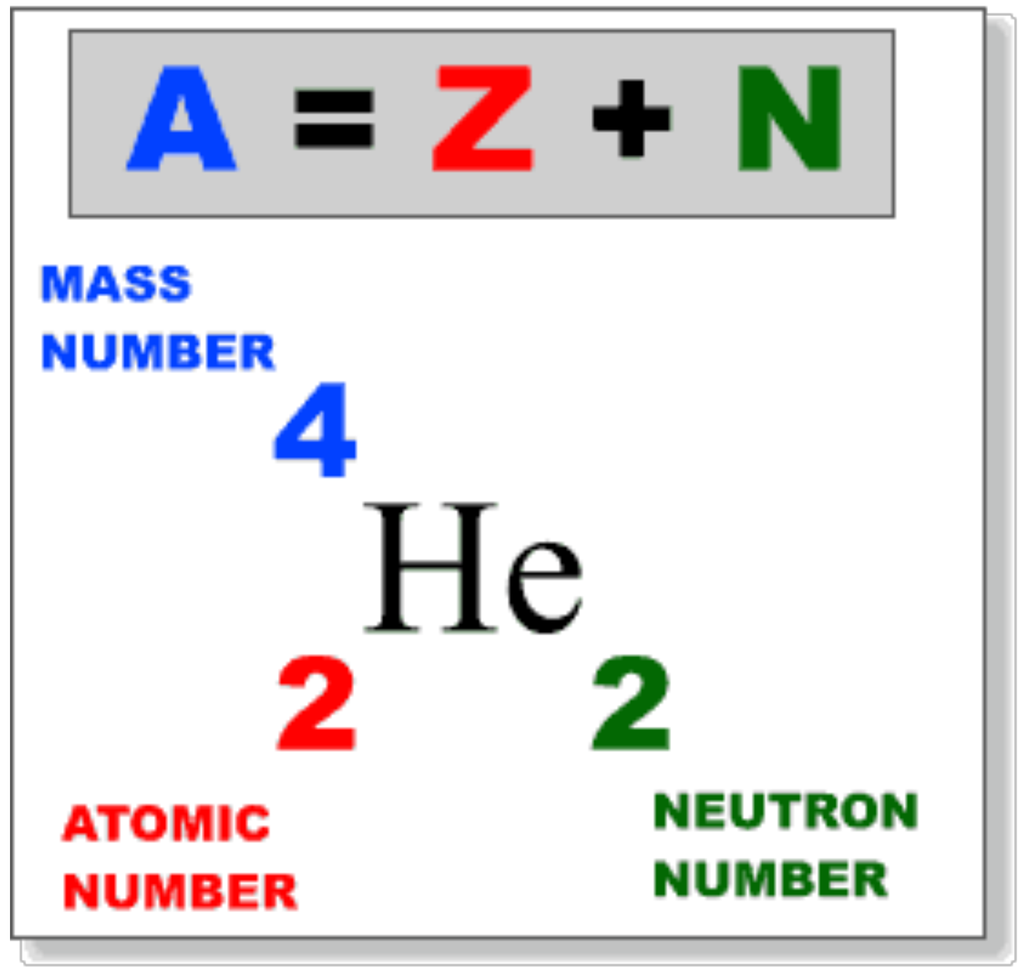


$$E = mc^2$$



Final step in the Proton-proton Chain

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} + 12.859\ \mathrm{MeV}$$

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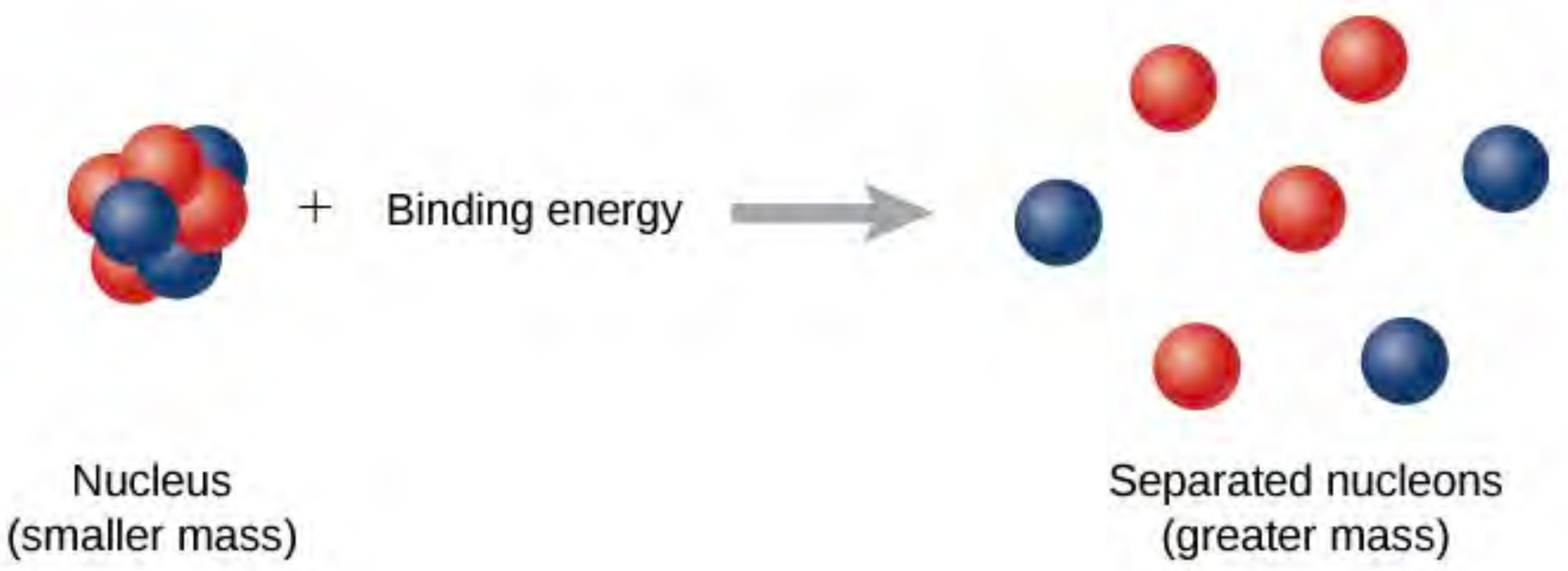

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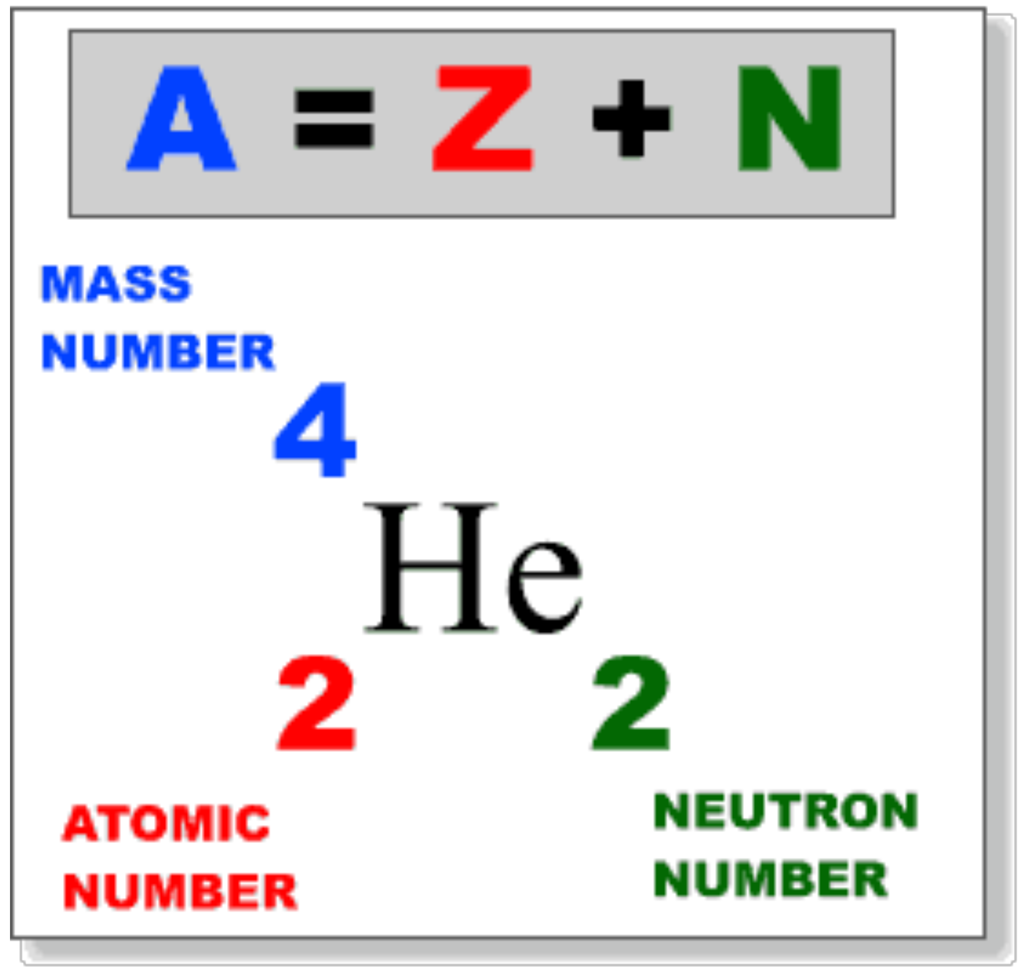

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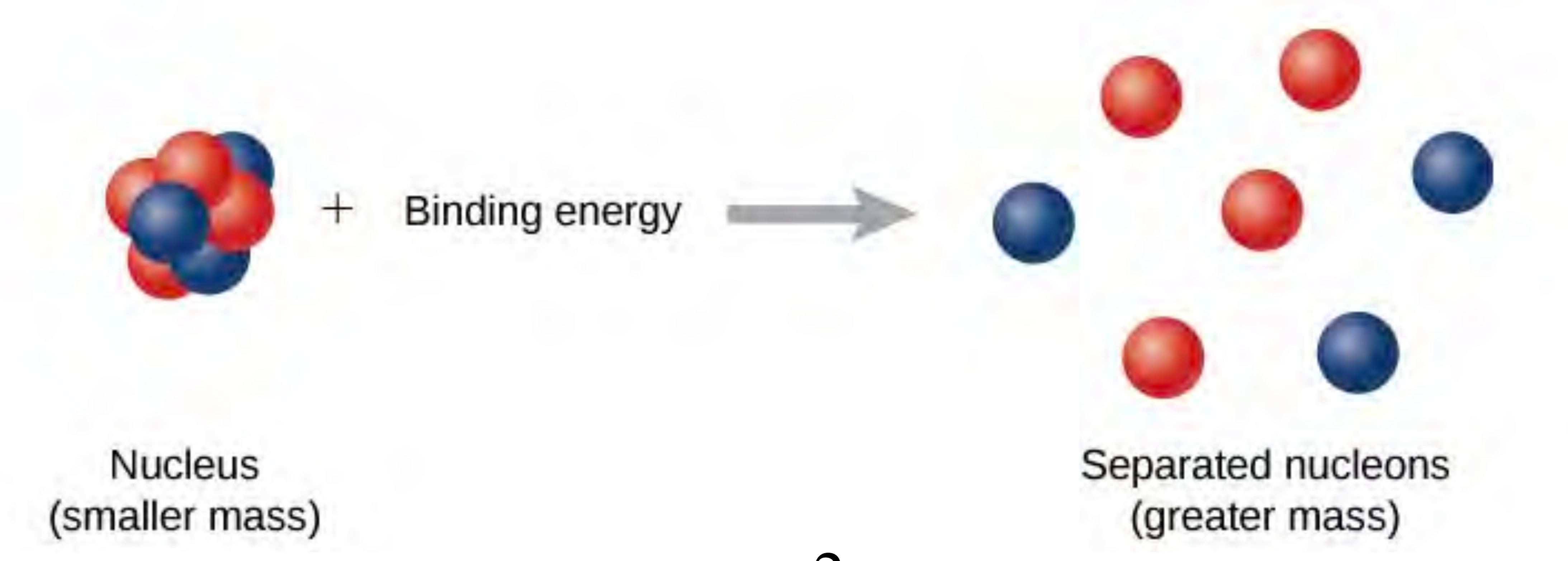

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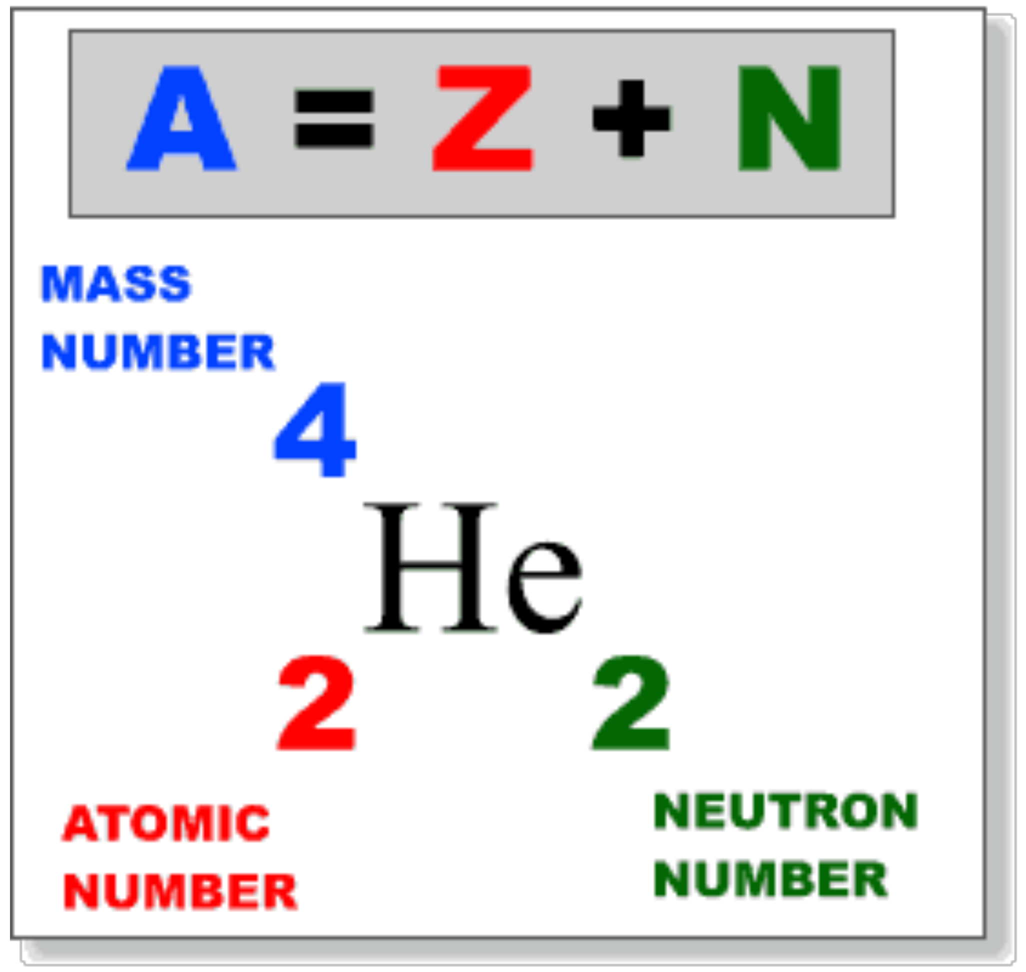

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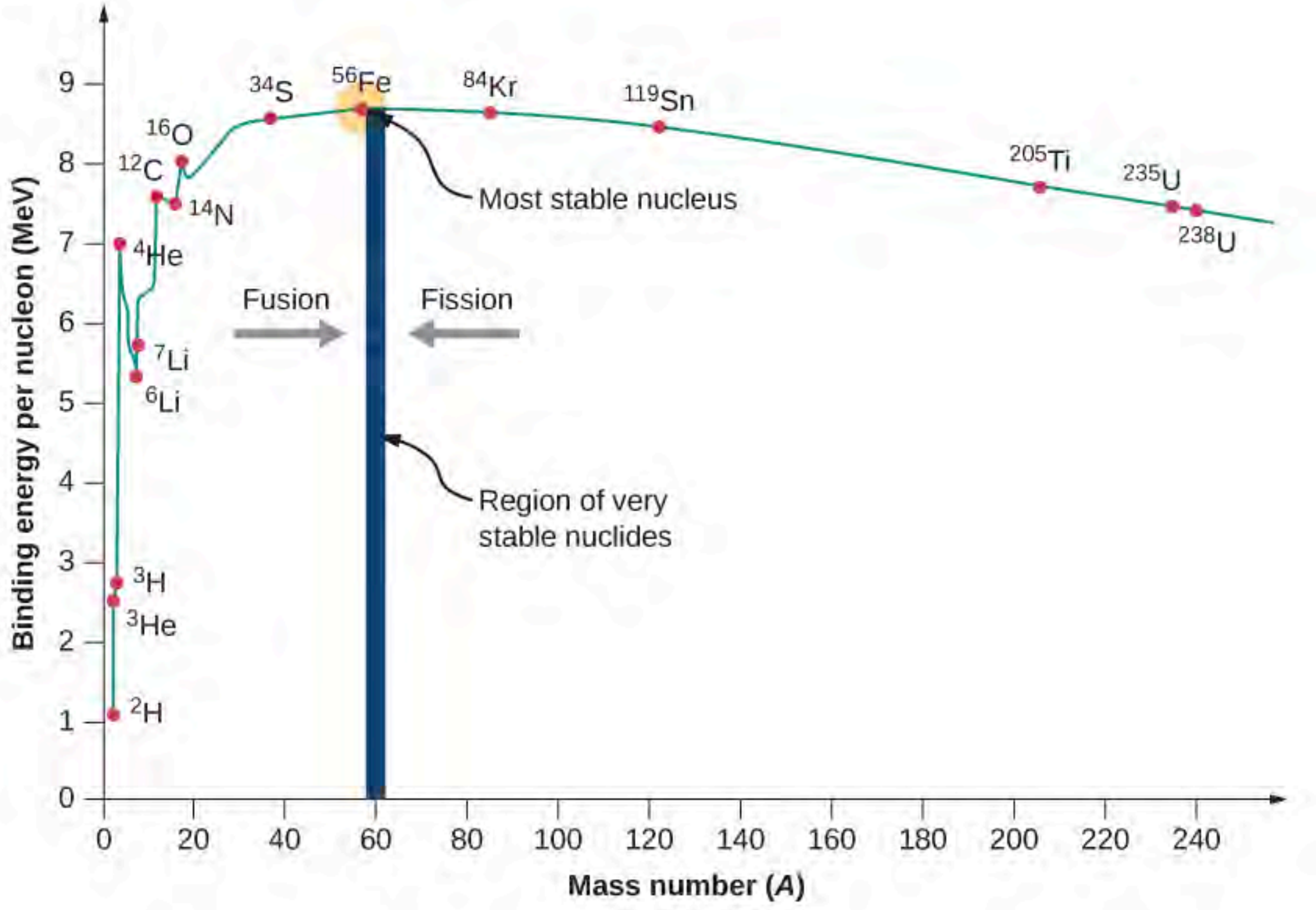
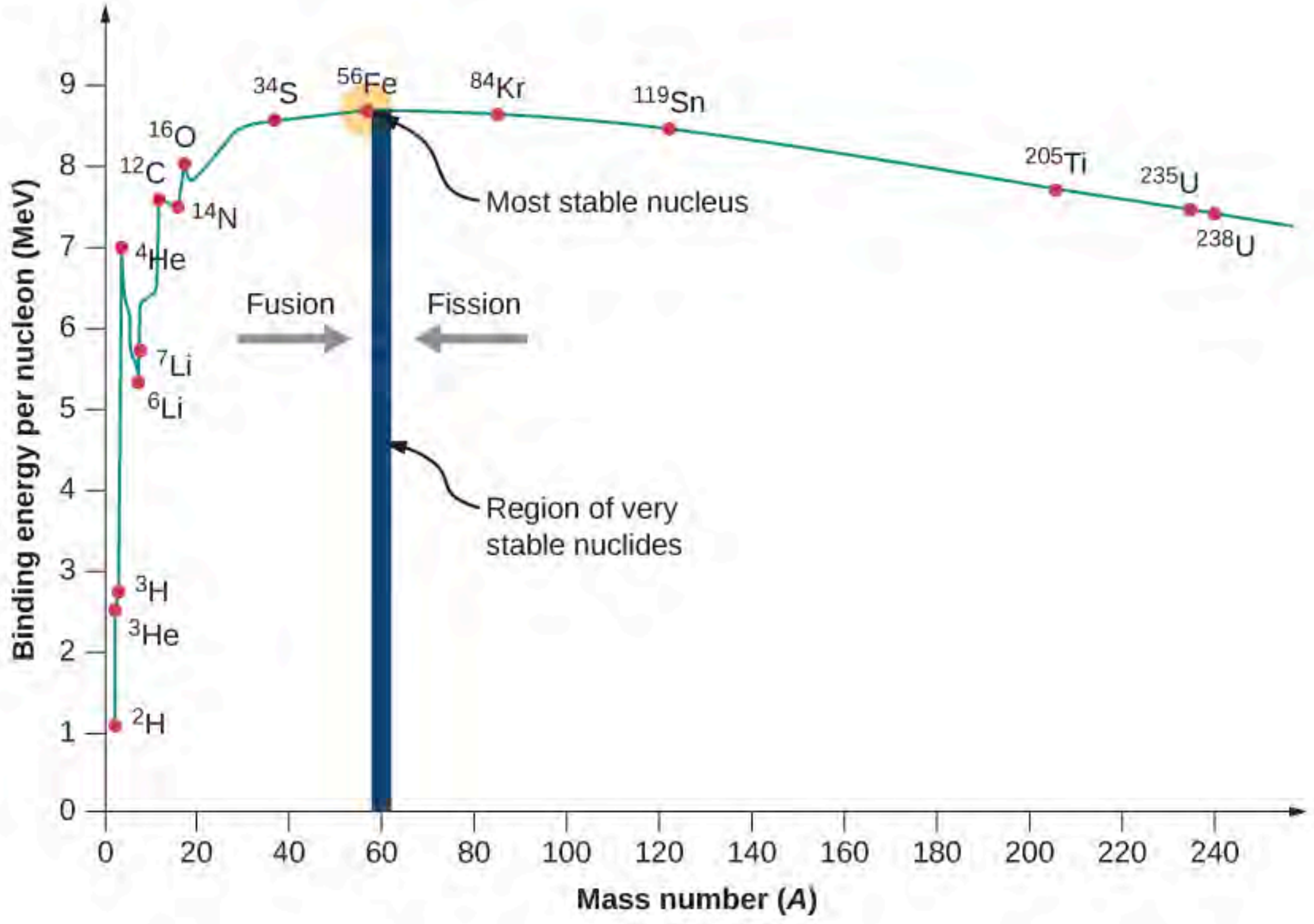
Powers the star

Binding energy



Binding energy

- **Iron is the most bound nucleus**, fusing two iron atoms requires energy (an endothermic reaction)



Binding energy

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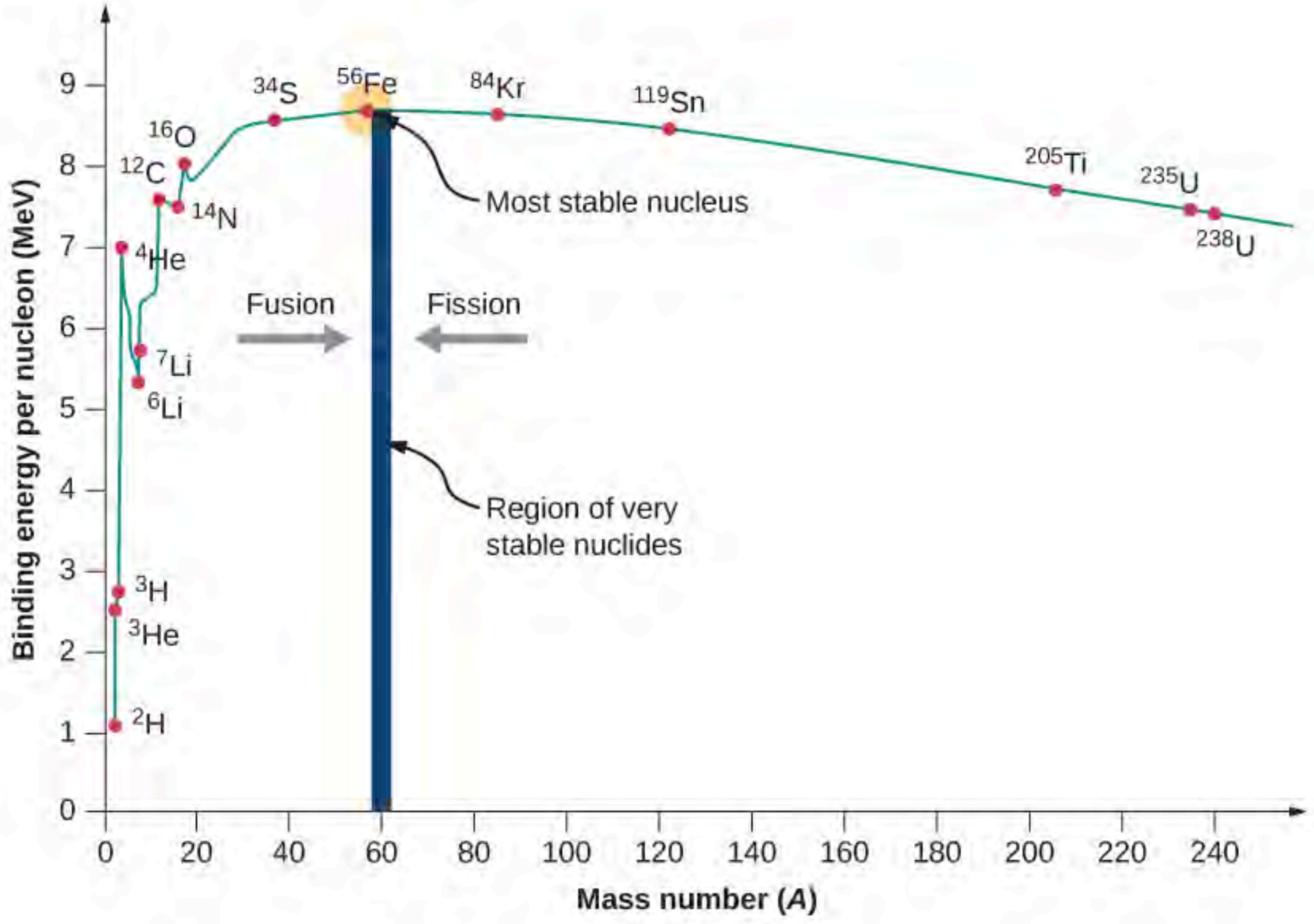
- The **mass of the star governs how far it can progress (fuse)** along the periodic table while maintaining hydrostatic equilibrium



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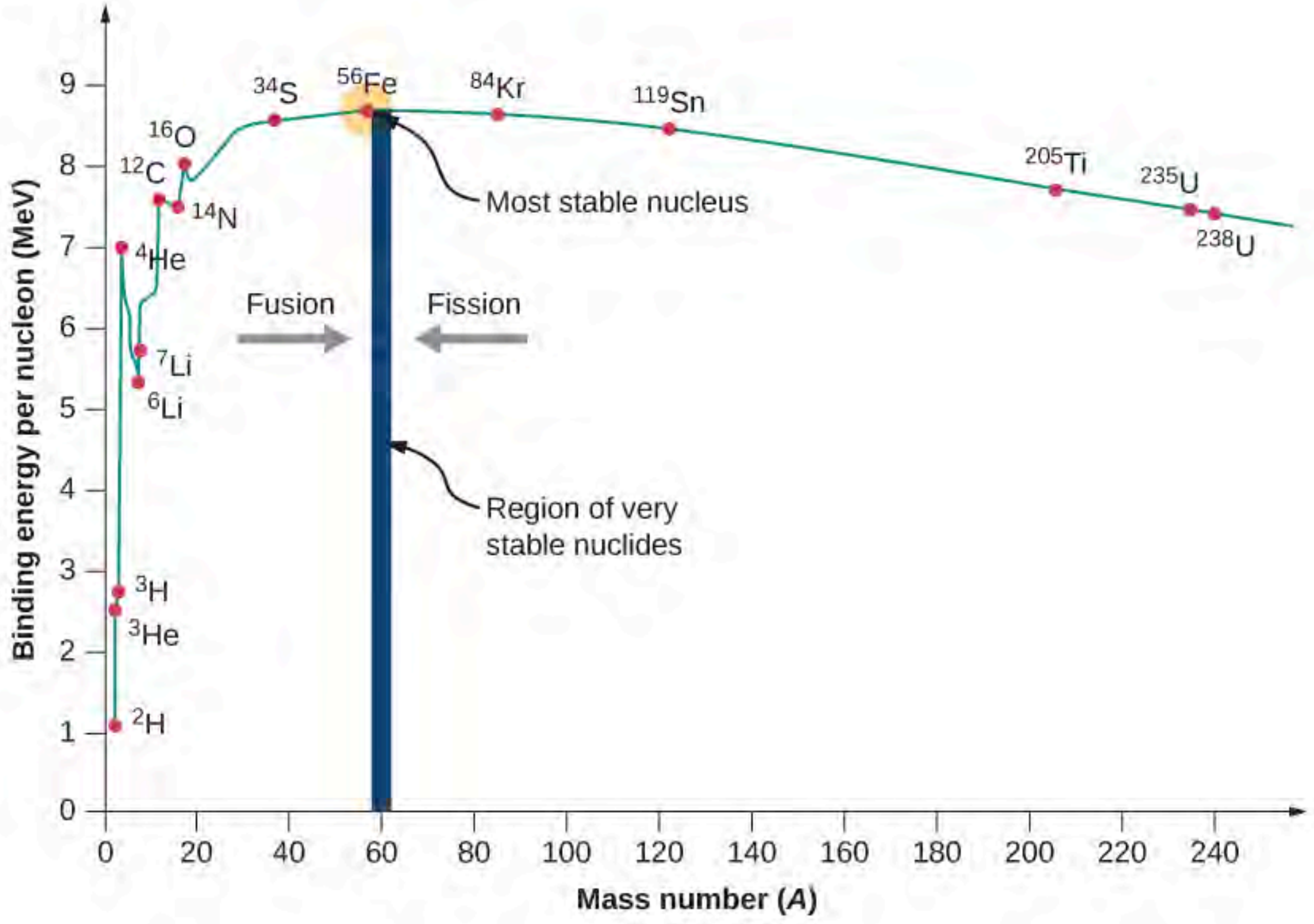

Binding energy

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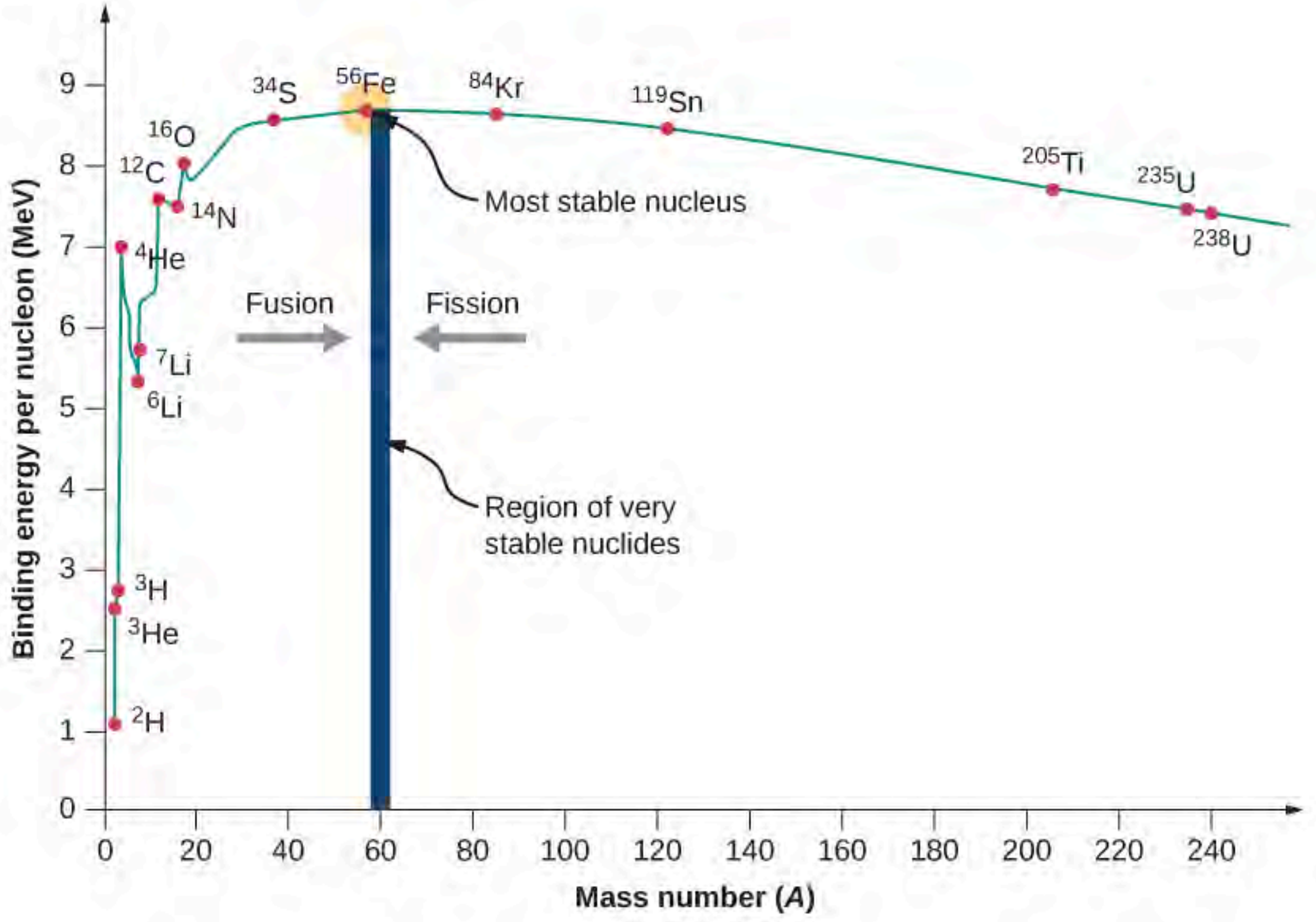
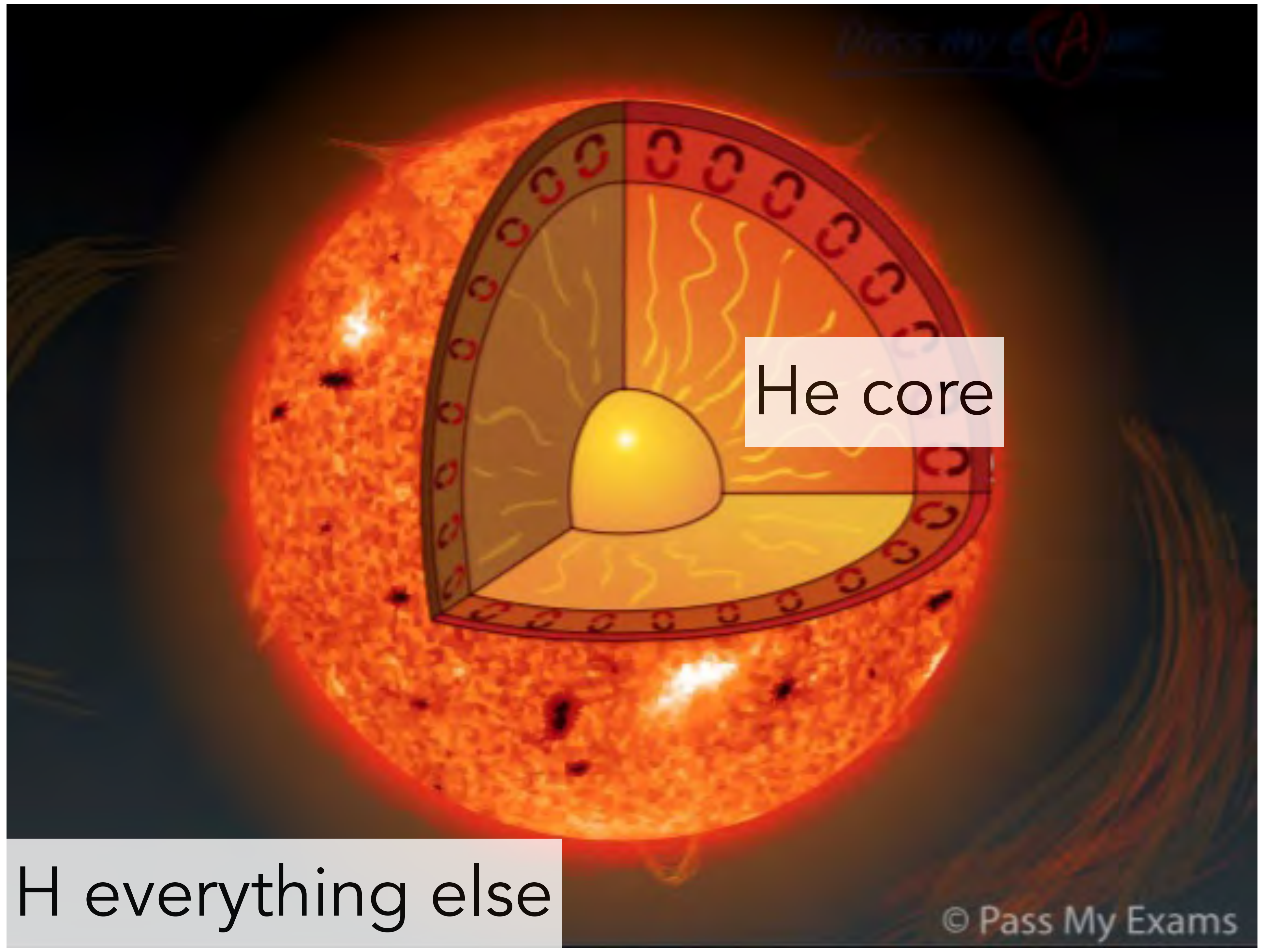
- Massive stars fuse up to **iron**

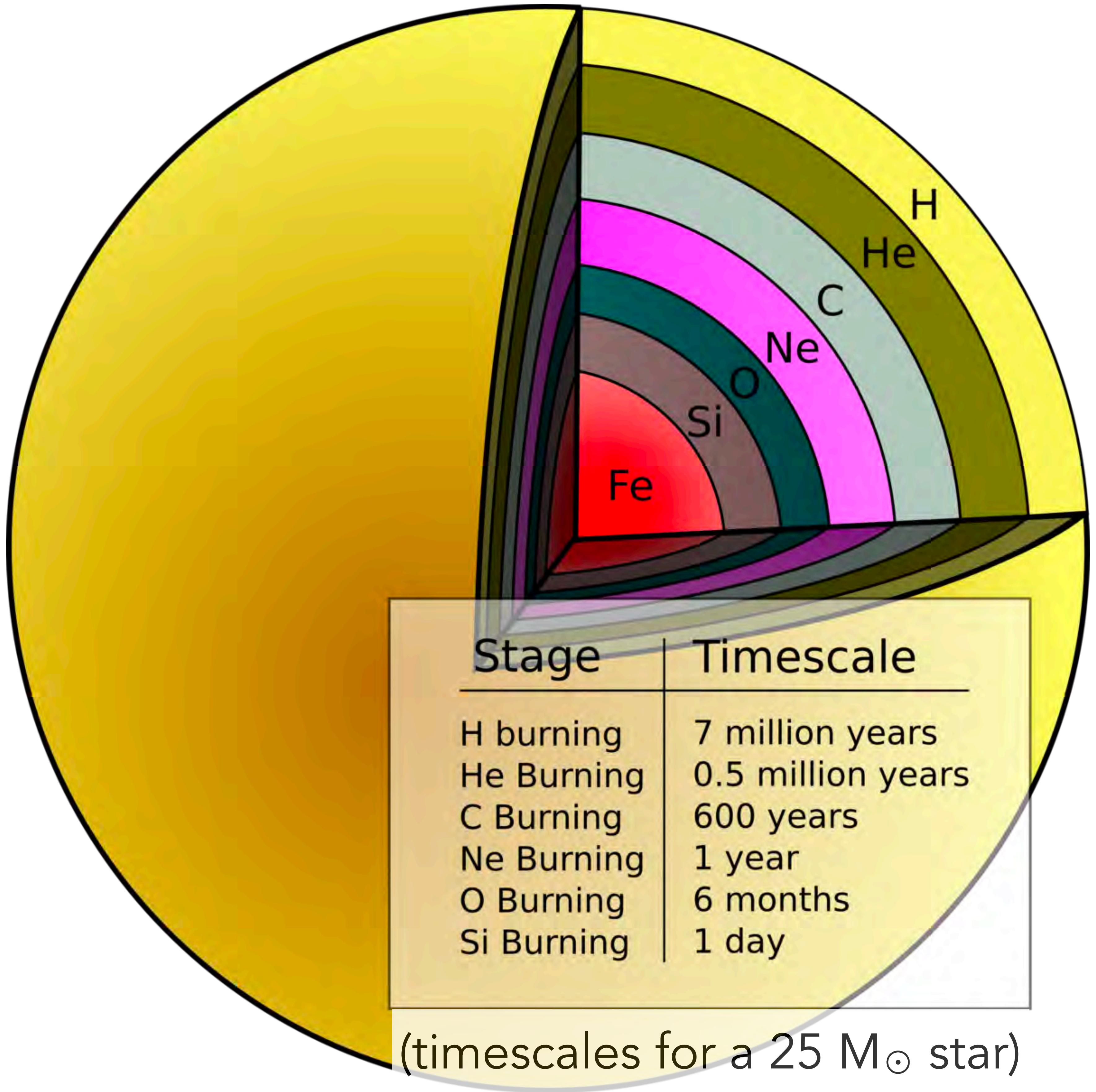


Internal structure of stars

Low-mass stars (like the Sun)



High-mass stars (>8$M_\odot$) at the end of their lives

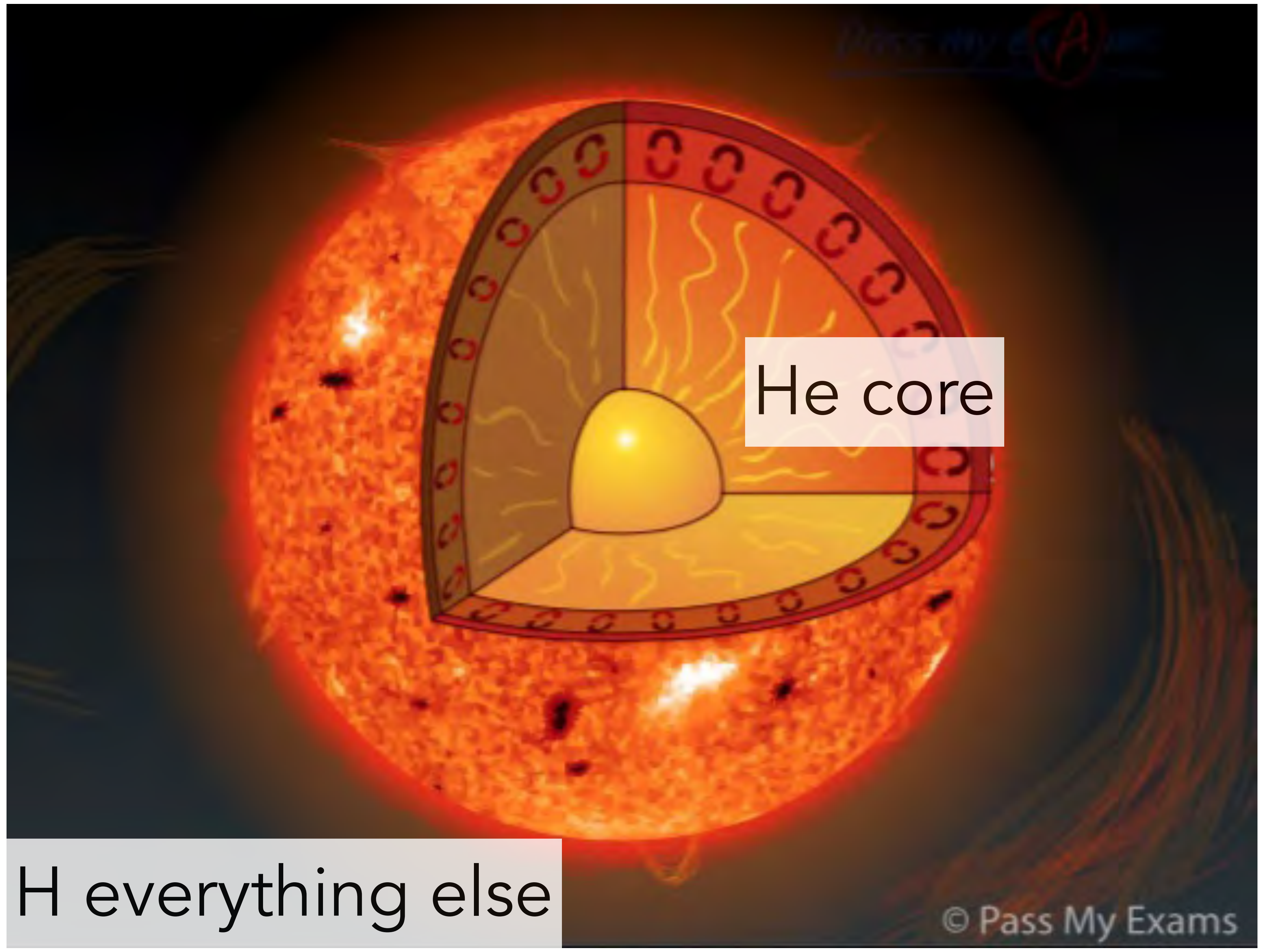


Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

(timescales for a 25 $M_\odot$ star)

Internal structure of stars

Low-mass stars (like the Sun)



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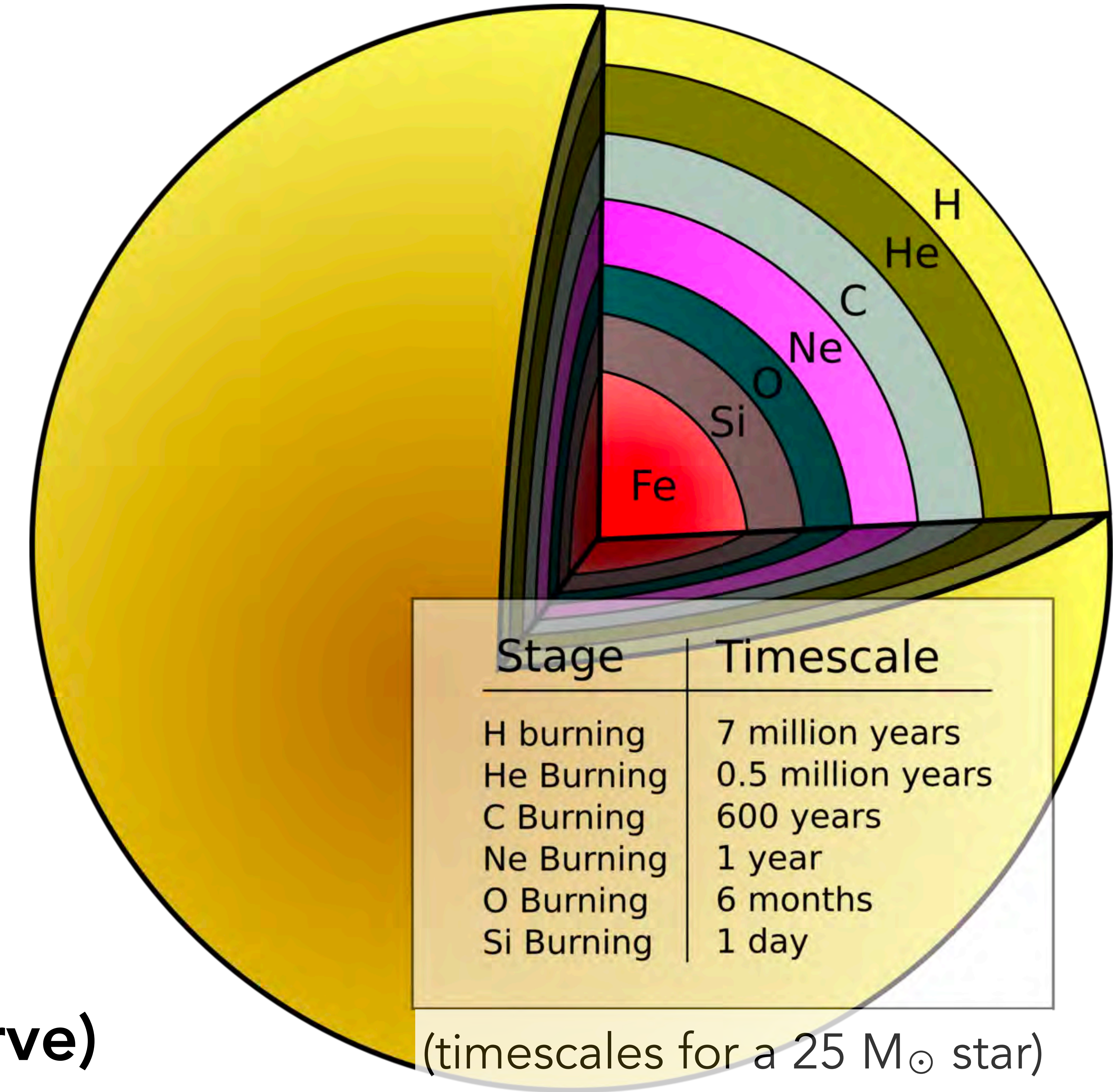


(timescales for a 25 M$_\odot$ star)

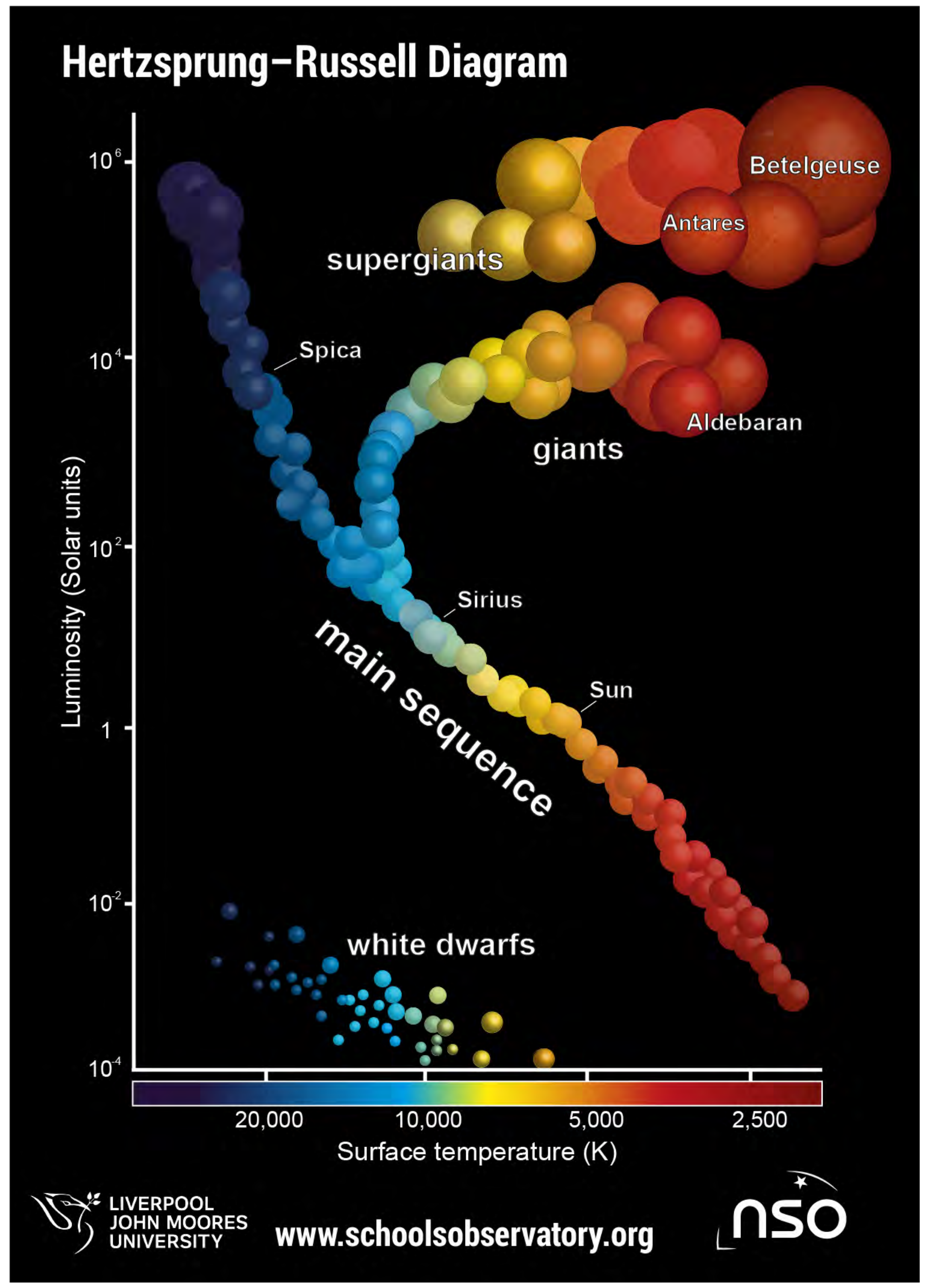
Important: the surface of a star (which is what we observe) barely changes over its lifetime!

Left: CSIRO, Lamers & Levesque, ESO/ALMA, NASA, NOAO

Right: Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Chandra X-ray Observatory; NASA/CXC/Rutgers, Curtis Schmidt optical telescope; NOAO/AURA/NSF/CTIO

The death of stars

Low-mass stars (like the Sun)



ascend the giant branch, "peacefully" shed outer layers in final phase (asymptotic giant branch), leave behind white dwarf

Left: CSIRO, Lamers & Levesque, ESO/ALMA, NASA, NOAO
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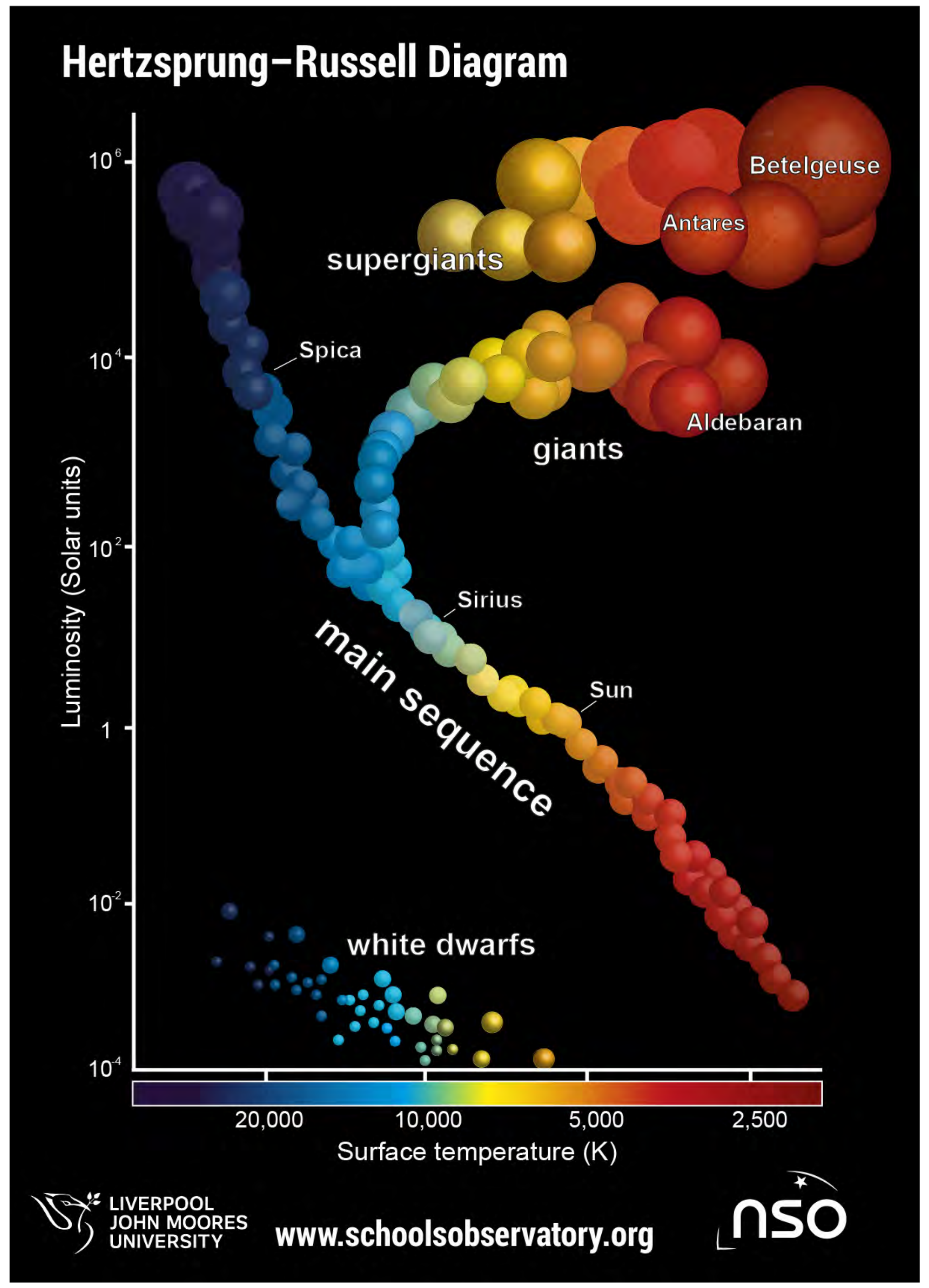

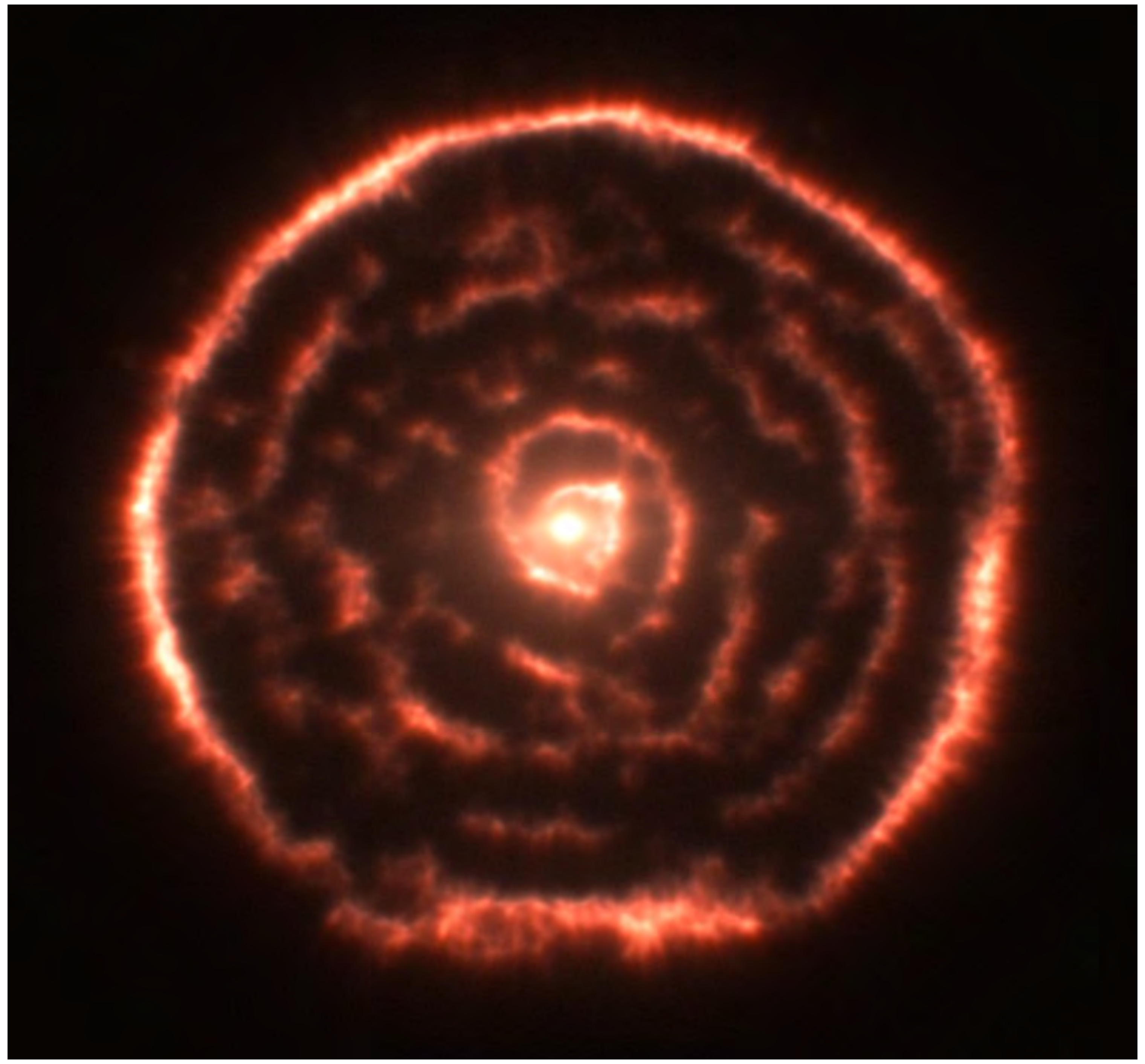

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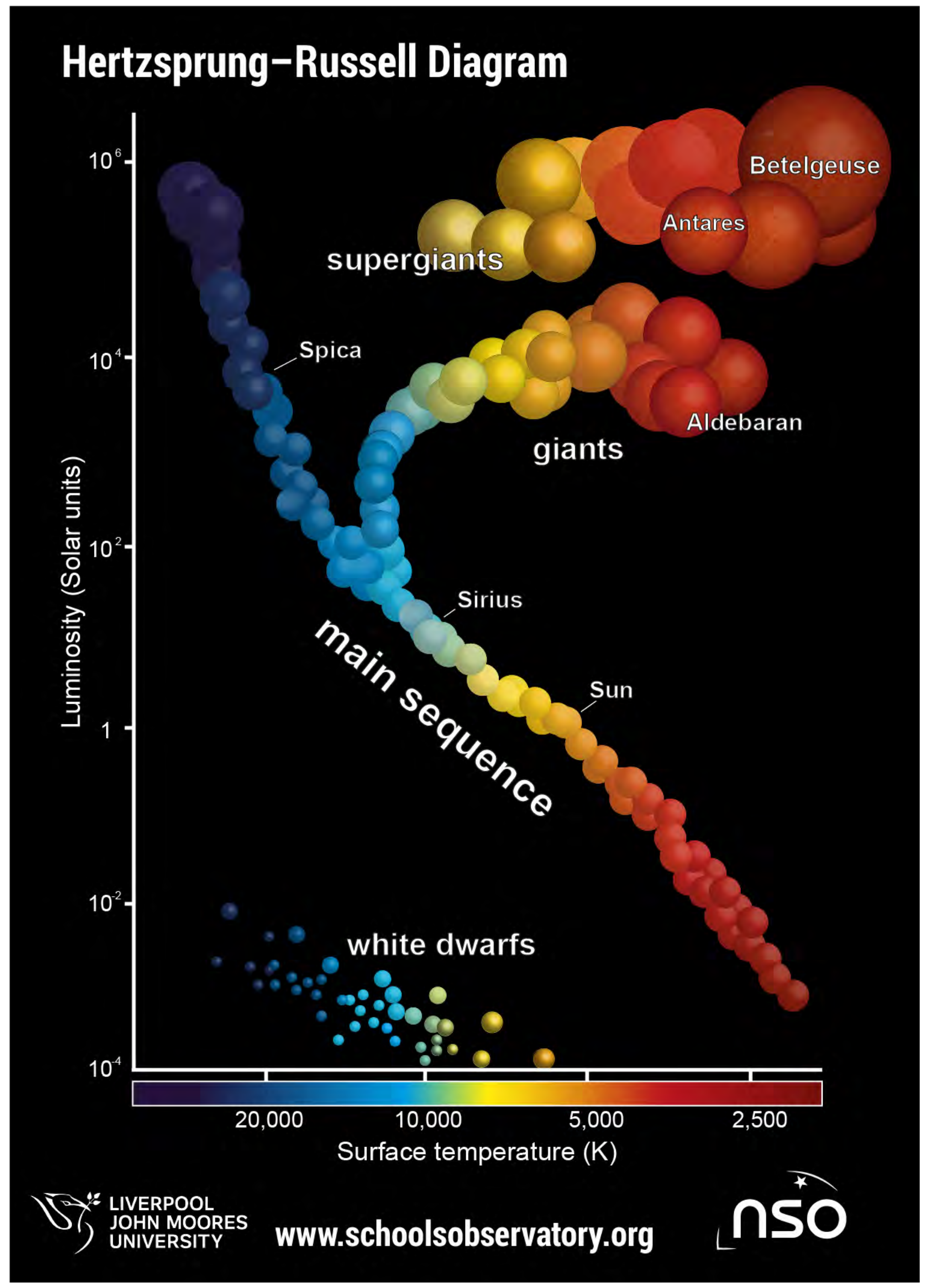
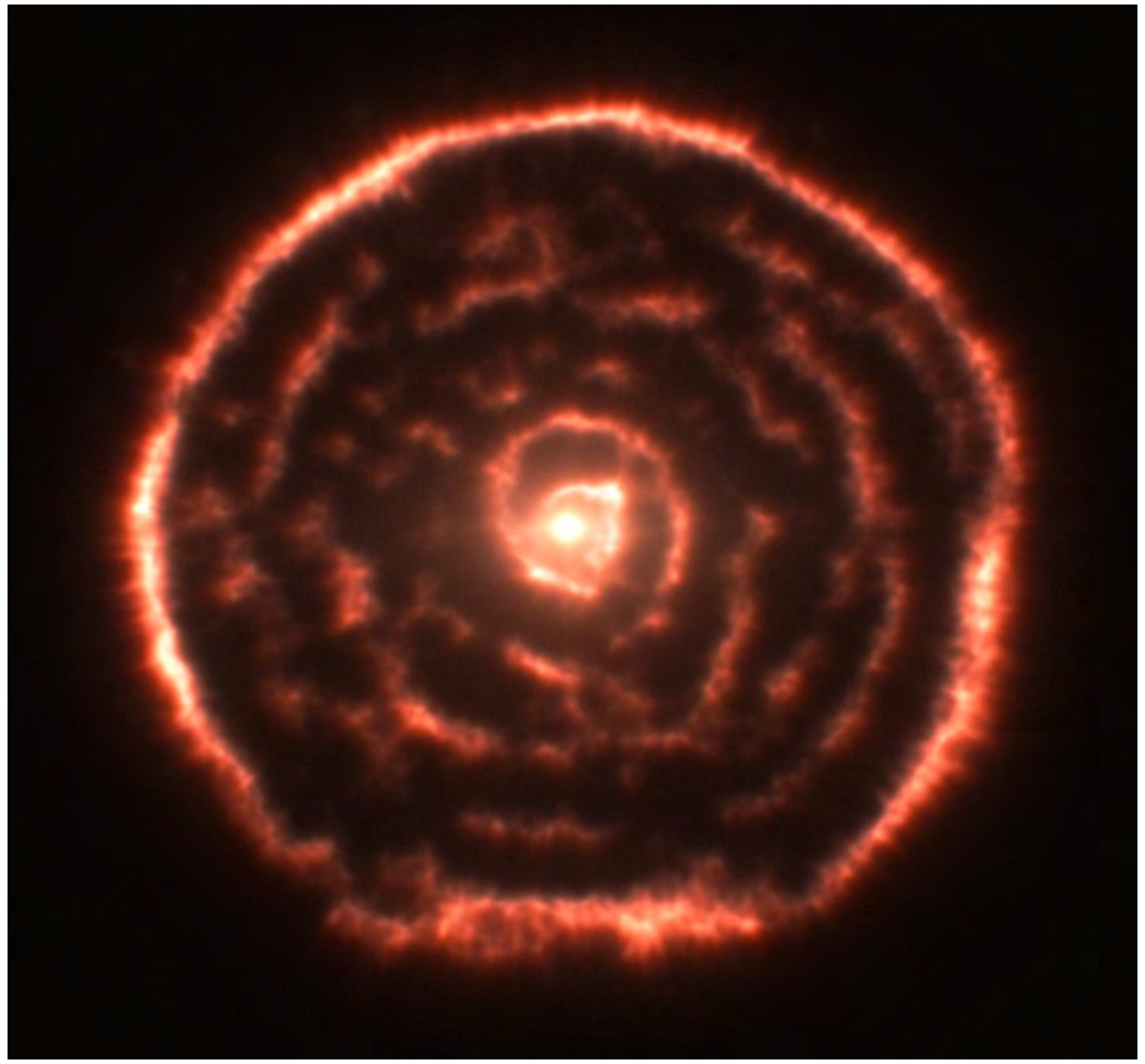
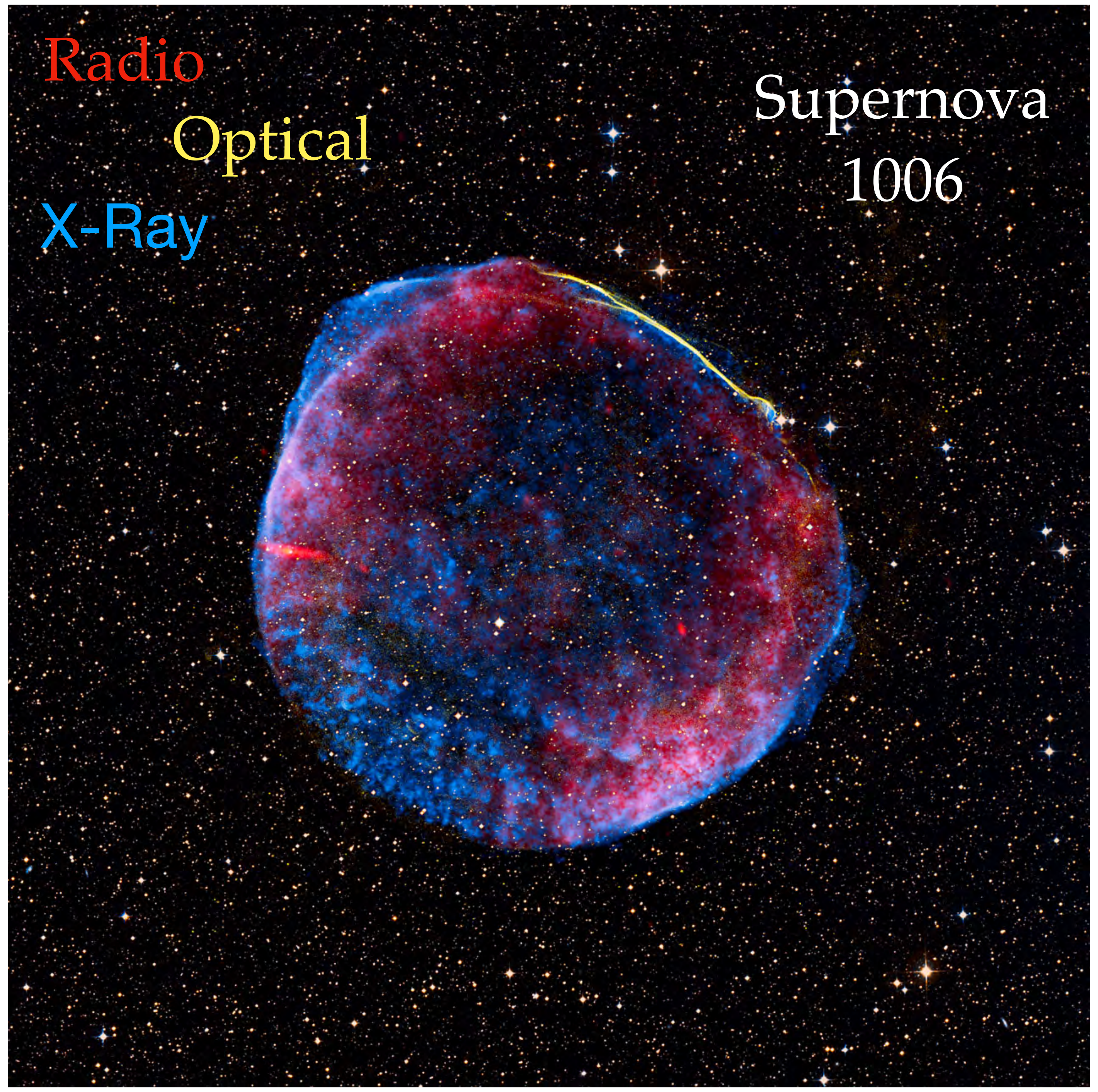
The death of stars

Low-mass stars (like the Sun)

High-mass stars (>8M☉)



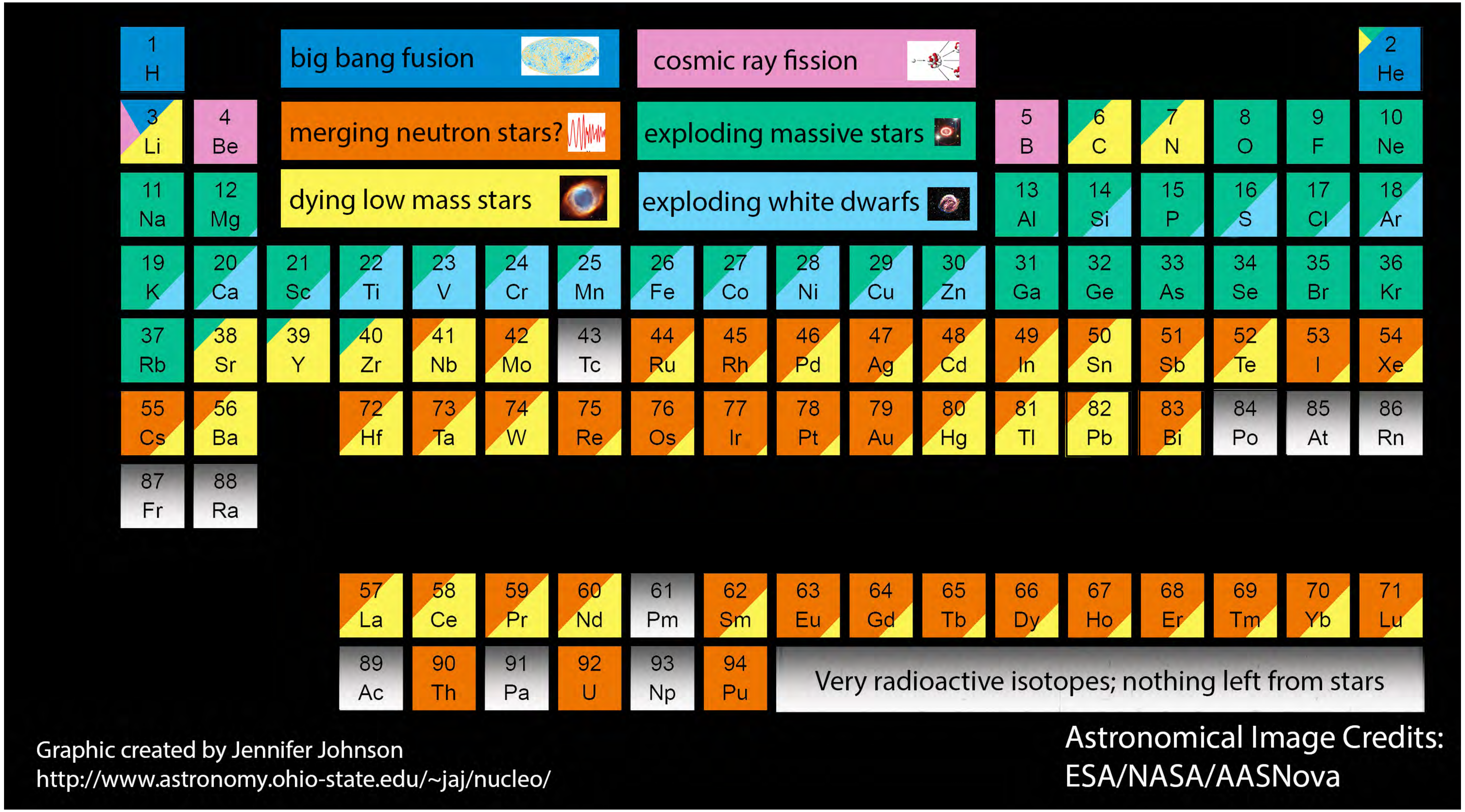




ascend the giant branch, "peacefully" shed outer layers in final phase (asymptotic giant branch), leave behind white dwarf

explodes as a supernova, leaves behind neutron star or black hole

The origin of the elements



The origin of the elements & associated timescales

Table from Stephanie Monty

Element Group	Tracer	Mode of entry into the Interstellar Medium	Timescale	Example Elements
Alpha	High mass stars $M > 8\ M_\odot$	Core collapse (CC) supernovae	0 - 100 Myr	O, Na, Mg, Al, Si, Ca, Ti
Iron peak	Low mass stars $M < 8\ M_\odot$	Type Ia supernovae (exploding white dwarfs)	100 Myr - 1 Gyr	Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn
Iron	Low AND high mass stars	CC SNe, Type Ia SNe	0 - 100 Myr 100 Myr - 1 Gyr	Fe
Slow neutron-capture (s-)process	Low mass stars $1\ M_\odot < M < 3\ M_\odot$	Winds during asymptotic giant branch phase	300 Myr - 5 Gyr	Sr, Y, Zr, Ba, La, Ce, Nd
Rapid neutron-capture (r-)process	High mass stars $8\ M_\odot < M < 22\ M_\odot$	CC SNe Neutron star mergers	0 - 100 Myr 50 Myr - 14 Gyr	Nd, Eu, Th, U

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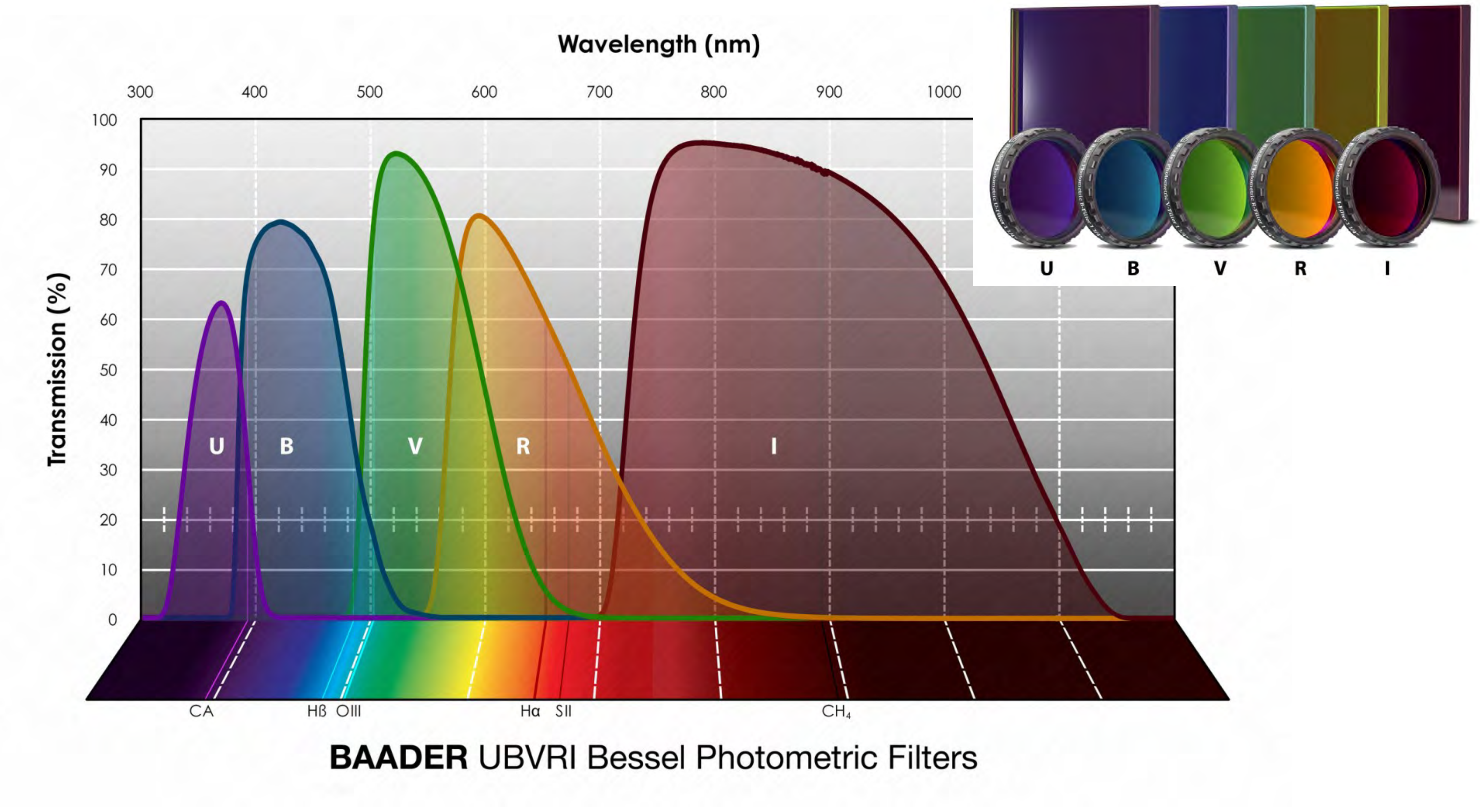
How to use this? Next lecture

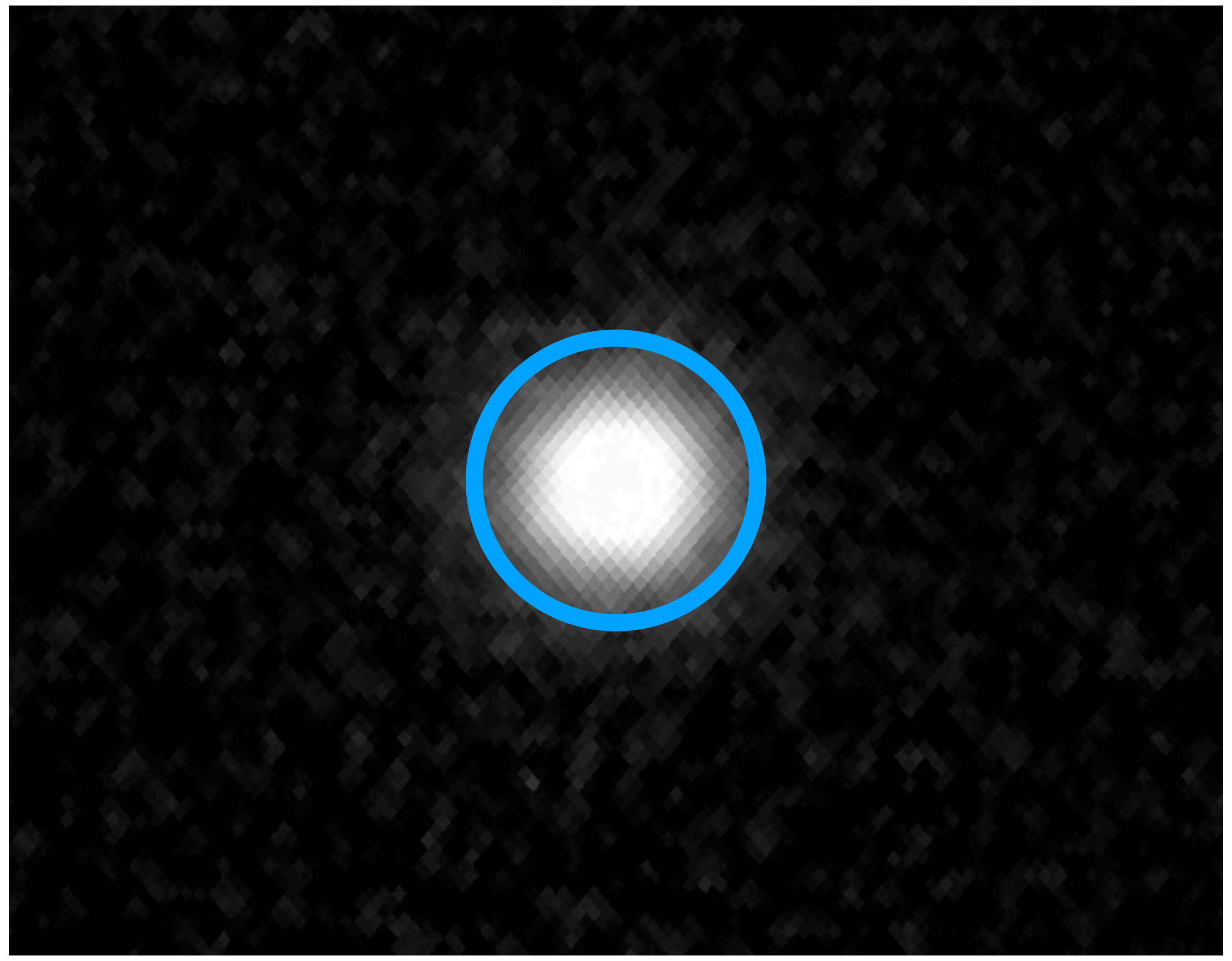
Back to observables of stars

Colour-magnitude diagrams (CMDs)

- Magnitudes are measured through colour filters (because of the way CCD cameras work)
- All magnitudes are relative to the star Vega (= 0) and **higher** magnitude = **fainter** star (both for historical reasons)

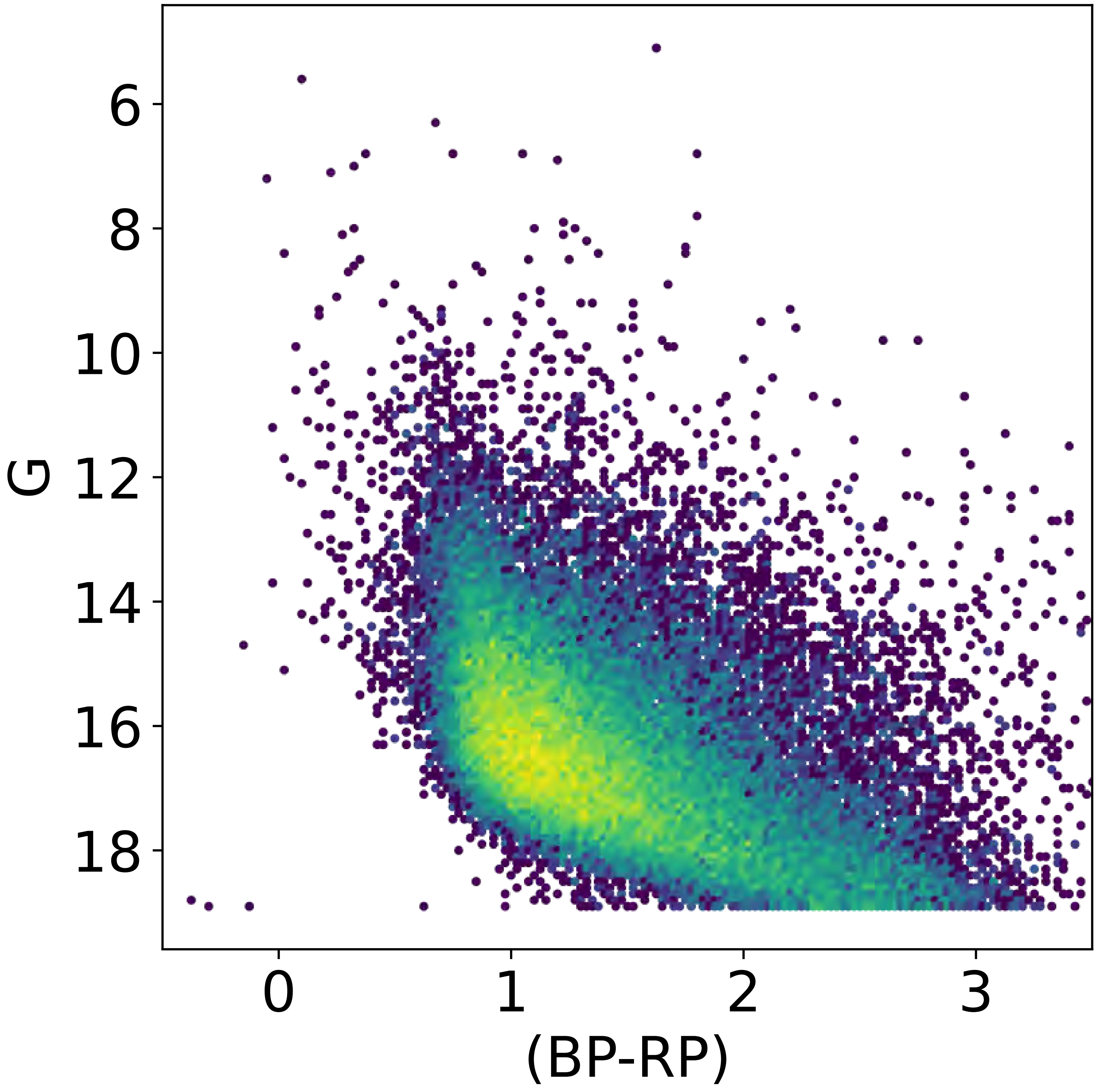


$$m_1 = m_{ref} - 2.5 \log_{10}(F_1/F_{ref})$$



Colour-magnitude diagrams (CMDs)

- Colour = (brightness through a redder filter – brightness through a bluer filter)
  - e.g. (B–V) is a standard combination, now a lot of people use Gaia filters (BP–RP)



CMD for a random dataset from Gaia

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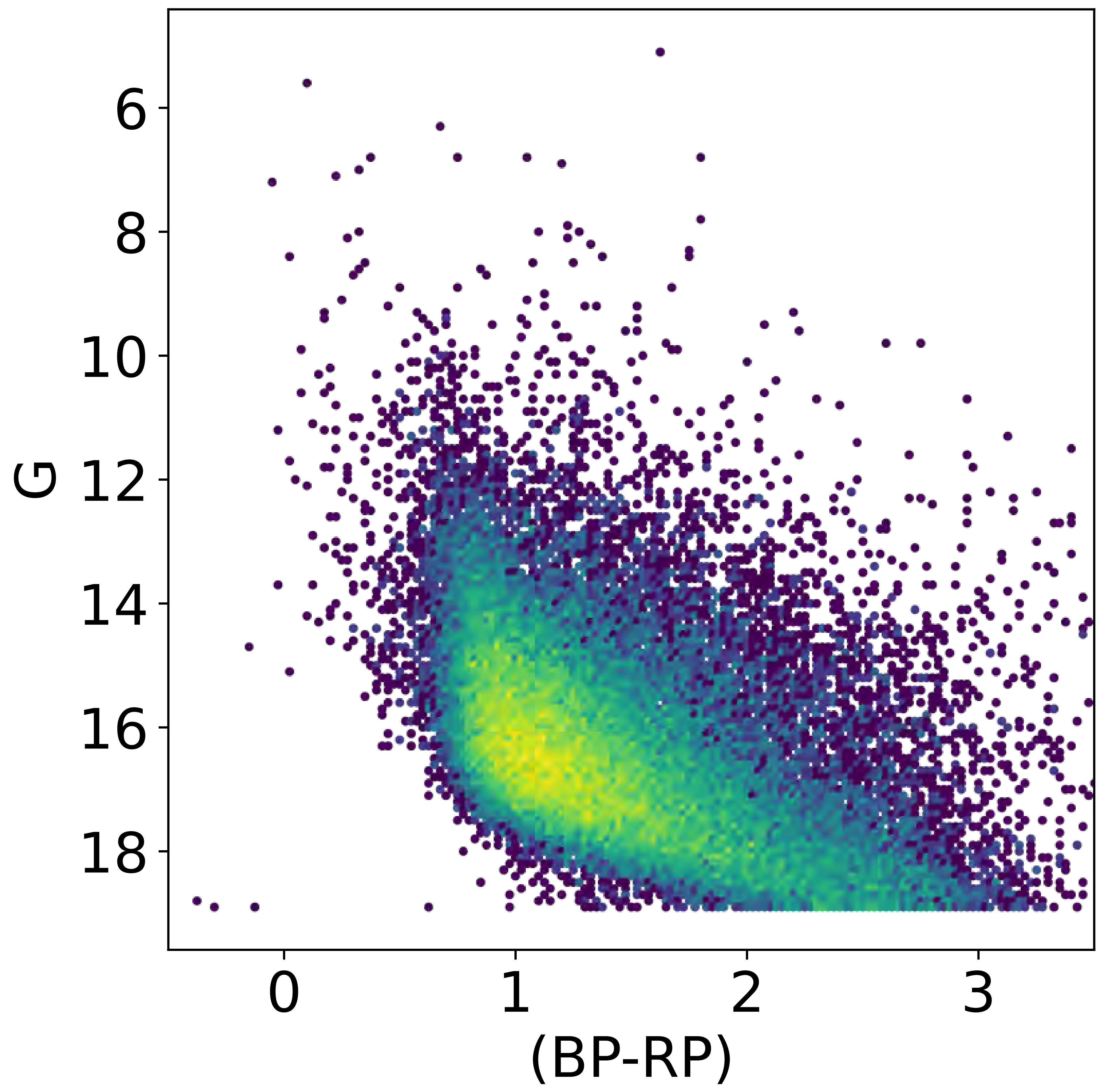

Q **Can you recognise the main sequence and a giant branch? Why (not)?**

CMD for a random dataset from Gaia

Colour-magnitude diagrams (CMDs)

with d in parsec (pc)

Two important concepts/effects:

1. **Apparent** vs. **Absolute** magnitudes

$$m - M = 2.5 \log_{10}(d/10)^2$$

The apparent brightness of an object reduces with 1/distance^2

Colour-magnitude diagrams (CMDs)

with d in parsec (pc)

Two important concepts/effects:

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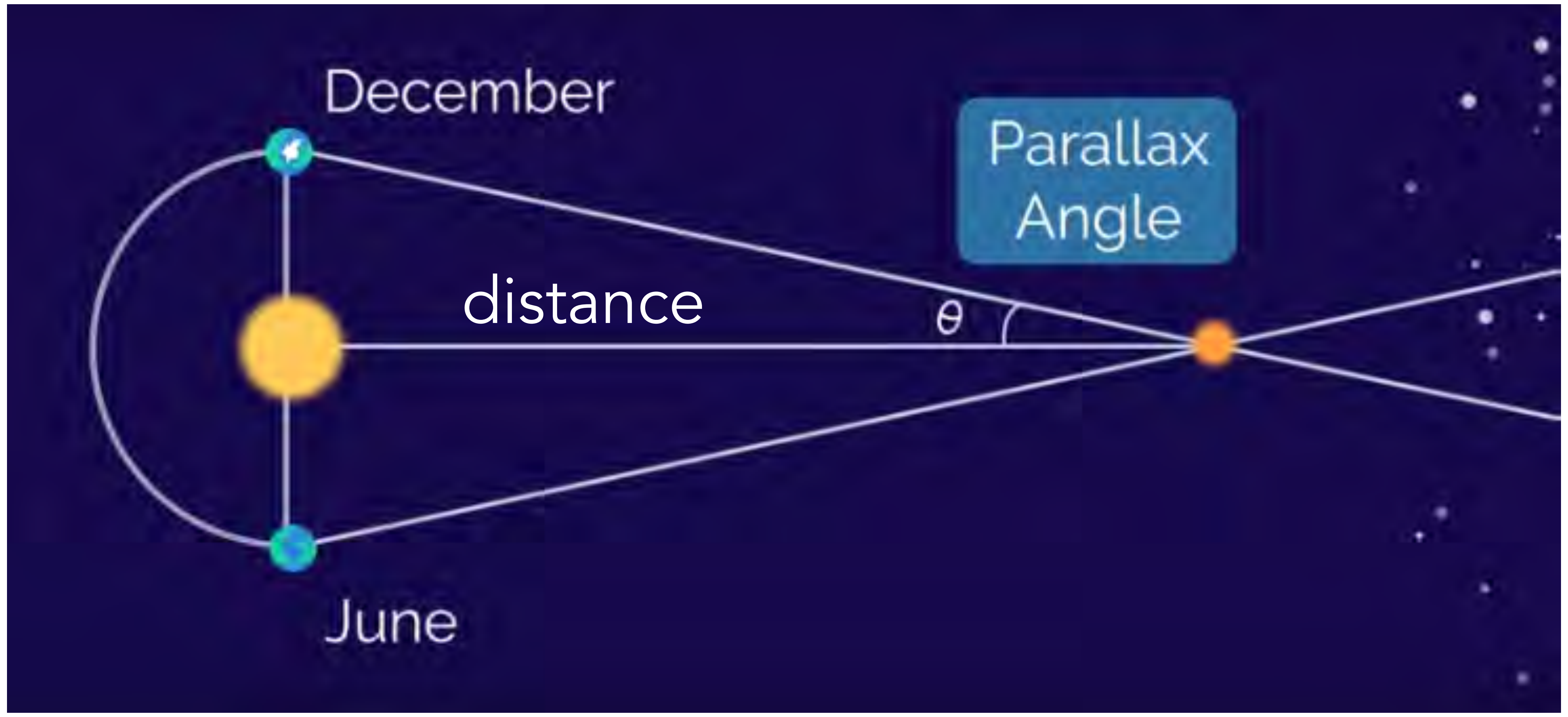

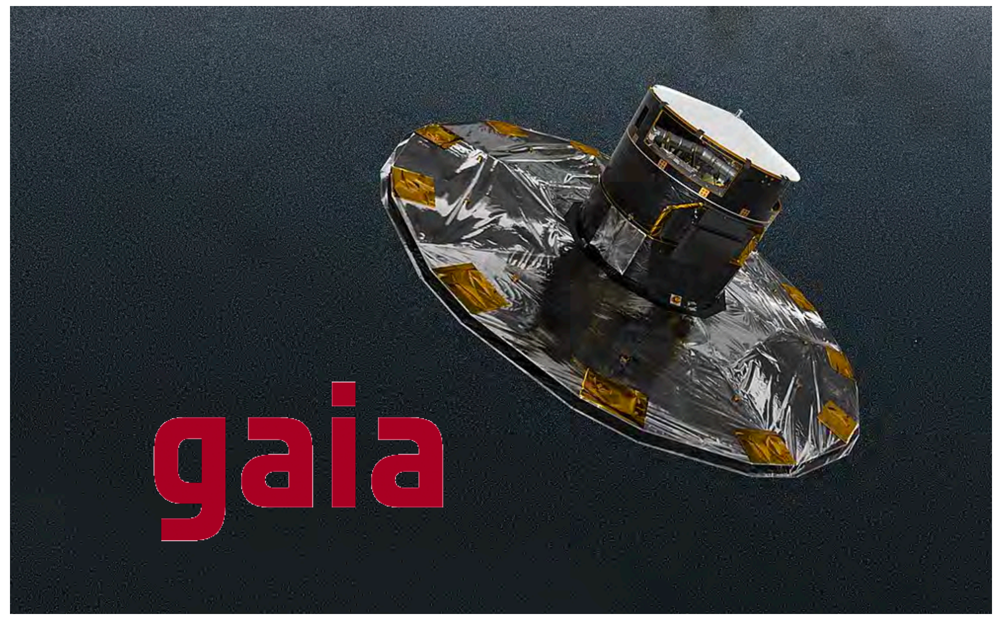

Note that we do not always have good Gaia parallaxes, need to get more creative for those stars

Colour-magnitude diagrams (CMDs)

Two important concepts/effects:

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with d in parsec (pc)

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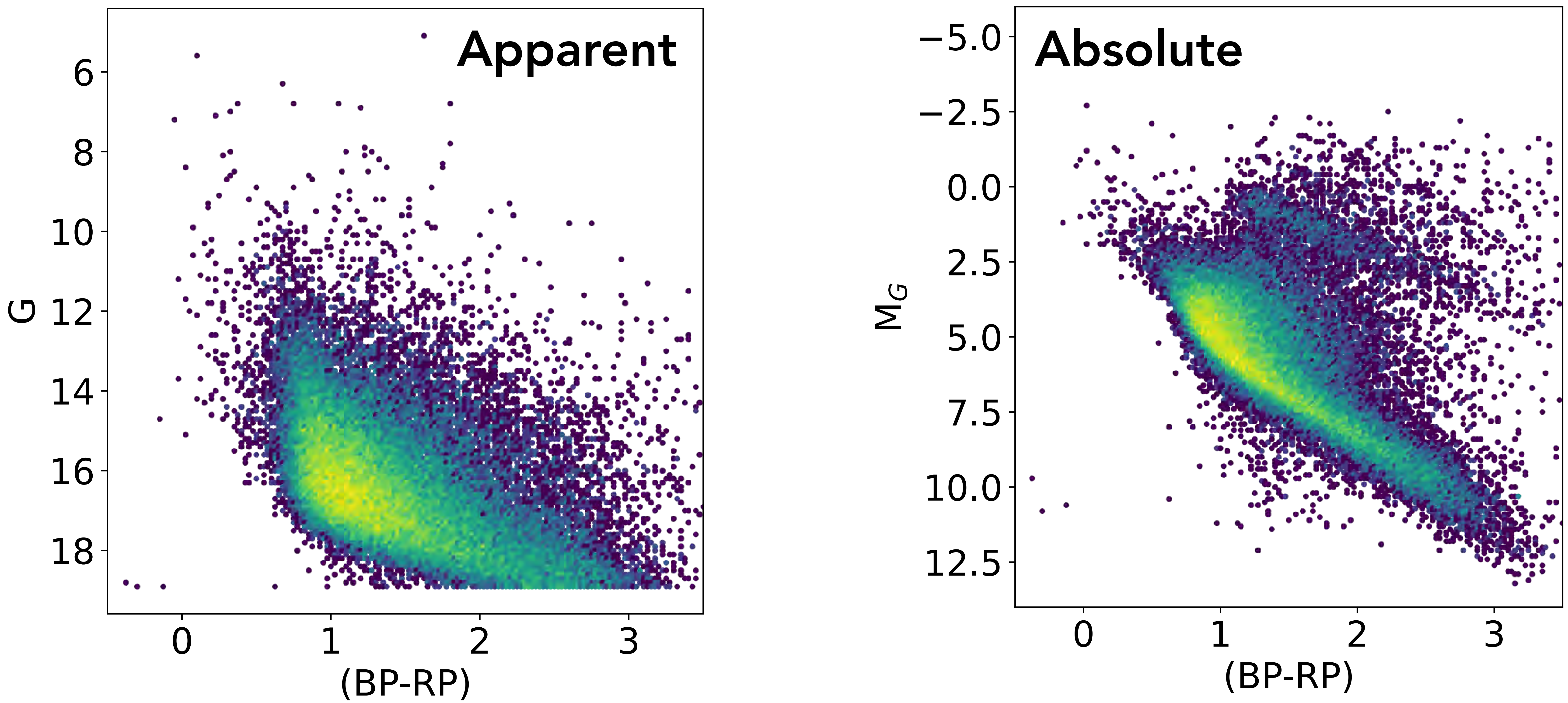


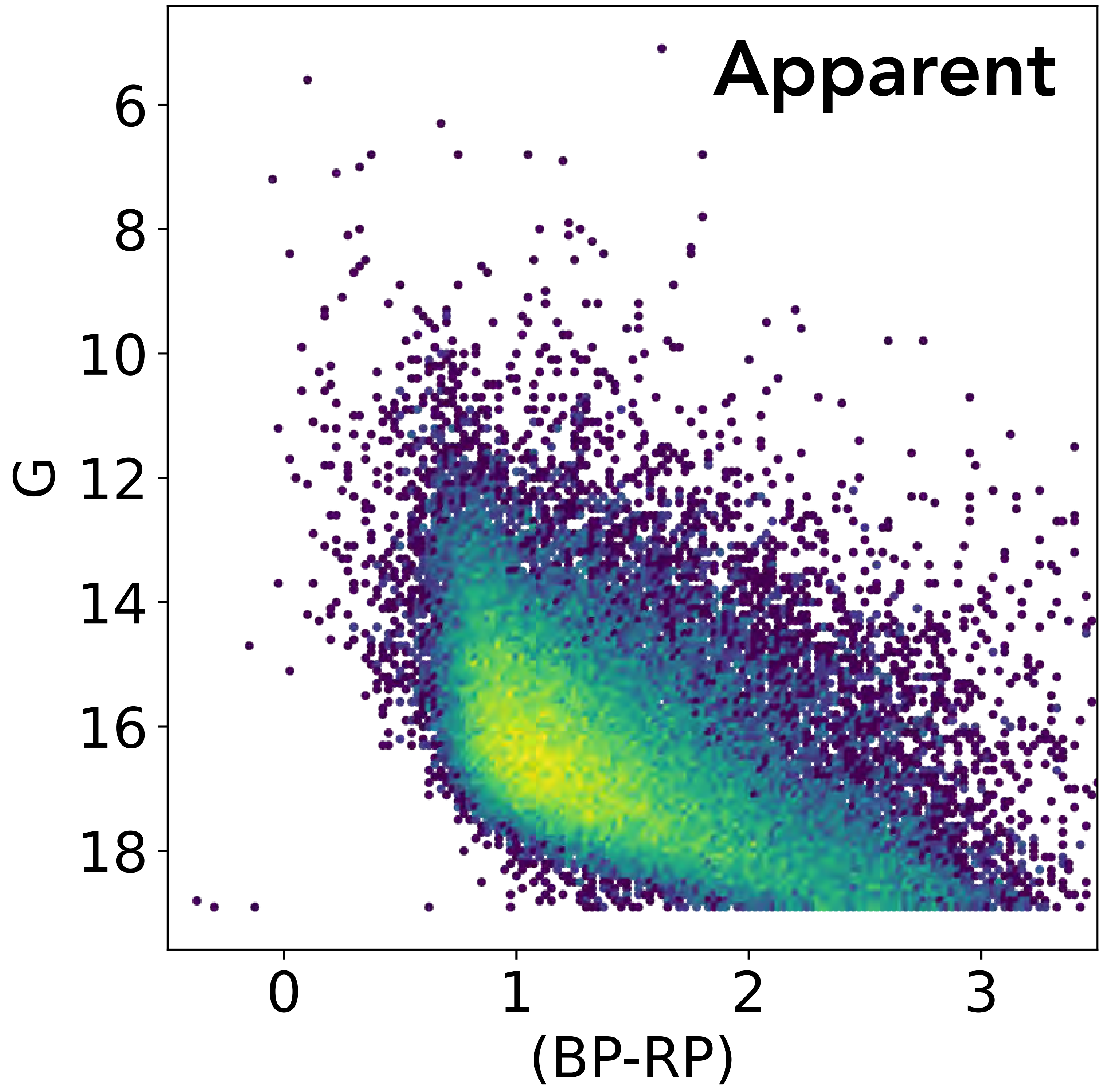
Colour-magnitude diagrams (CMDs)

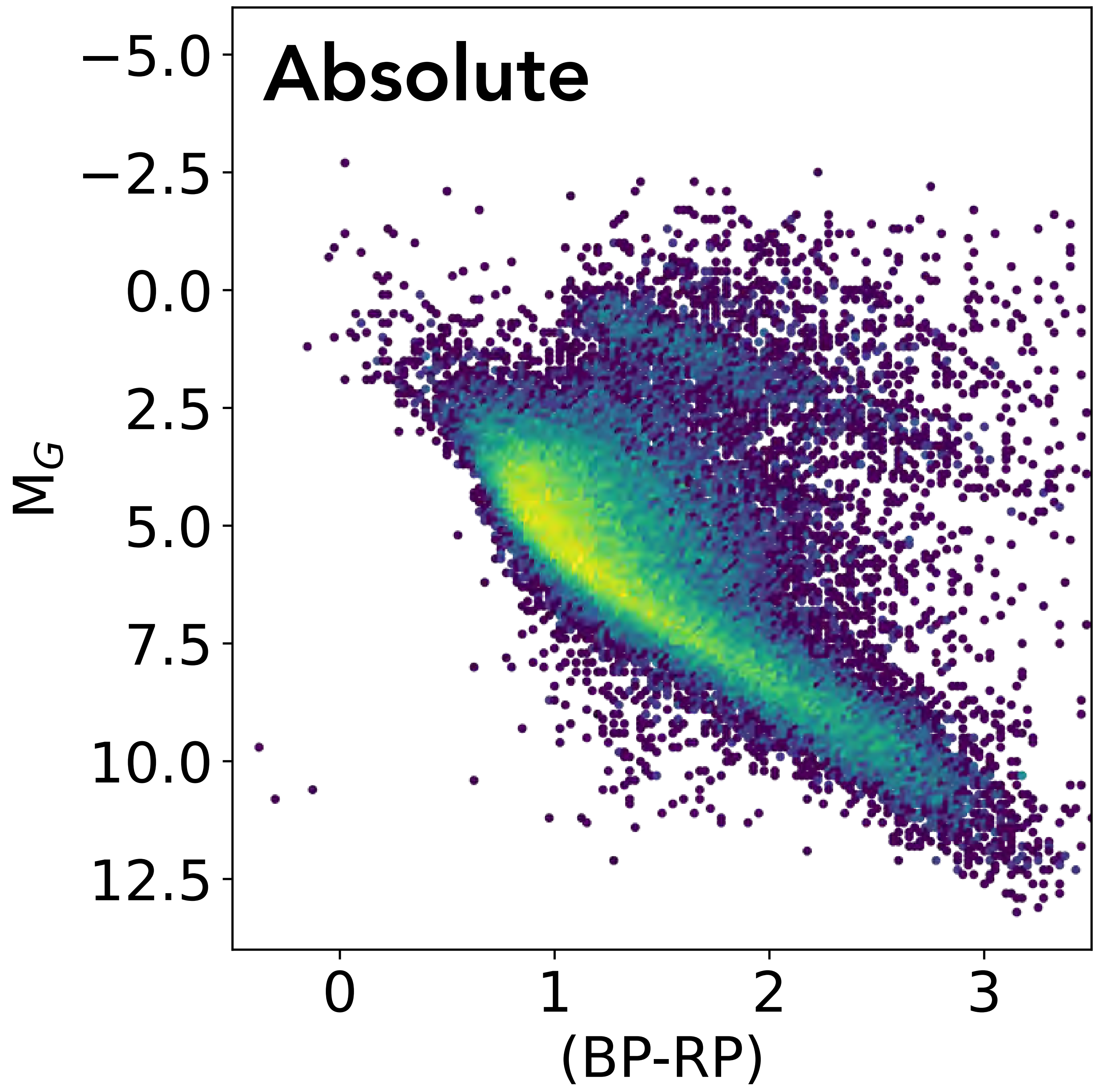
with d in parsec (pc)

$$m - M = 2.5\log_{10}(d/10)^2$$

Two important concepts/effects:

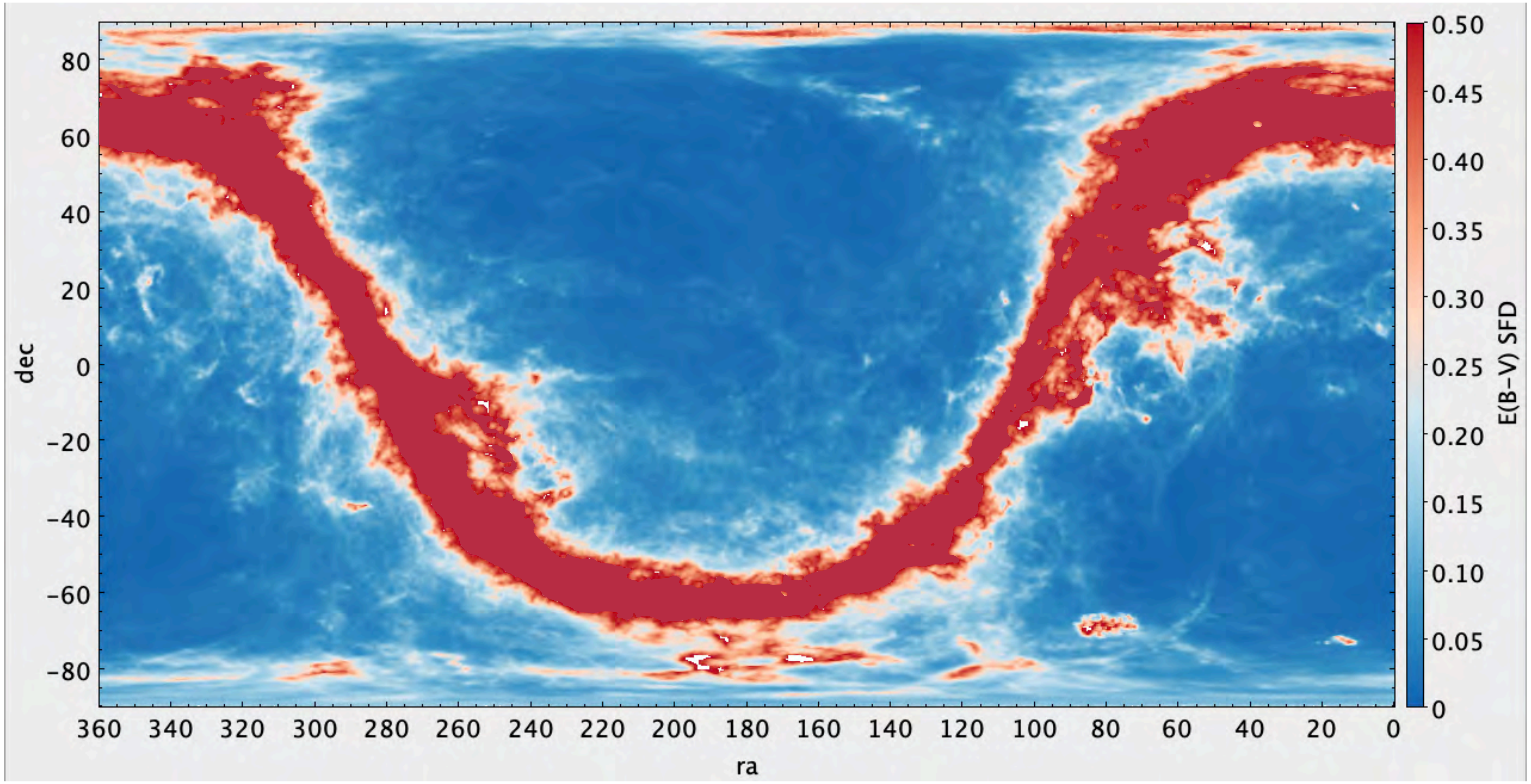
1. **Apparent** vs. **Absolute** magnitudes
2. Reddening effects due to interstellar dust





Reddening

- **Dust extinction**: loss of light because of absorption by dust grains



SFD dustmap

Reddening

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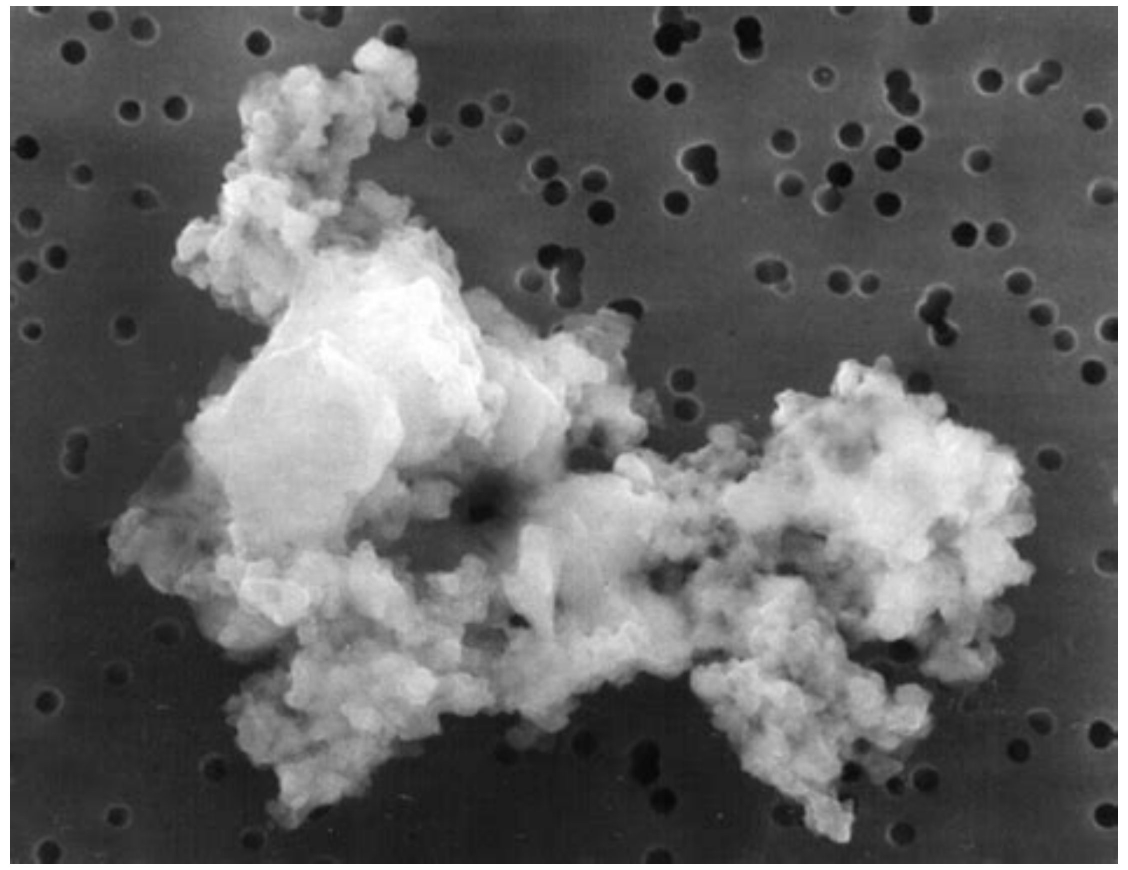

Reddening

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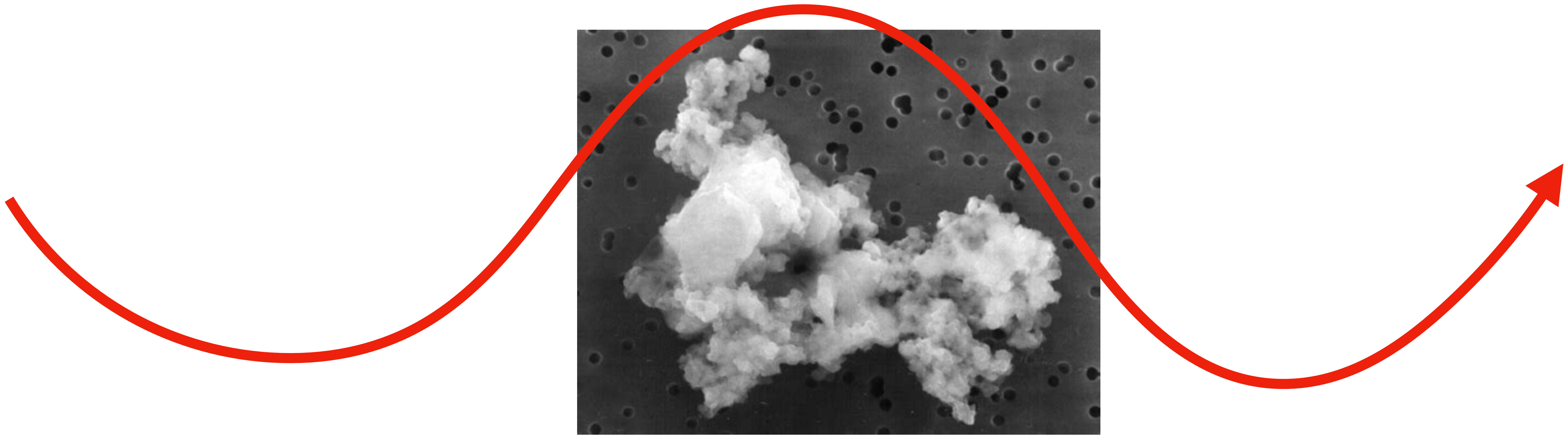

Reddening

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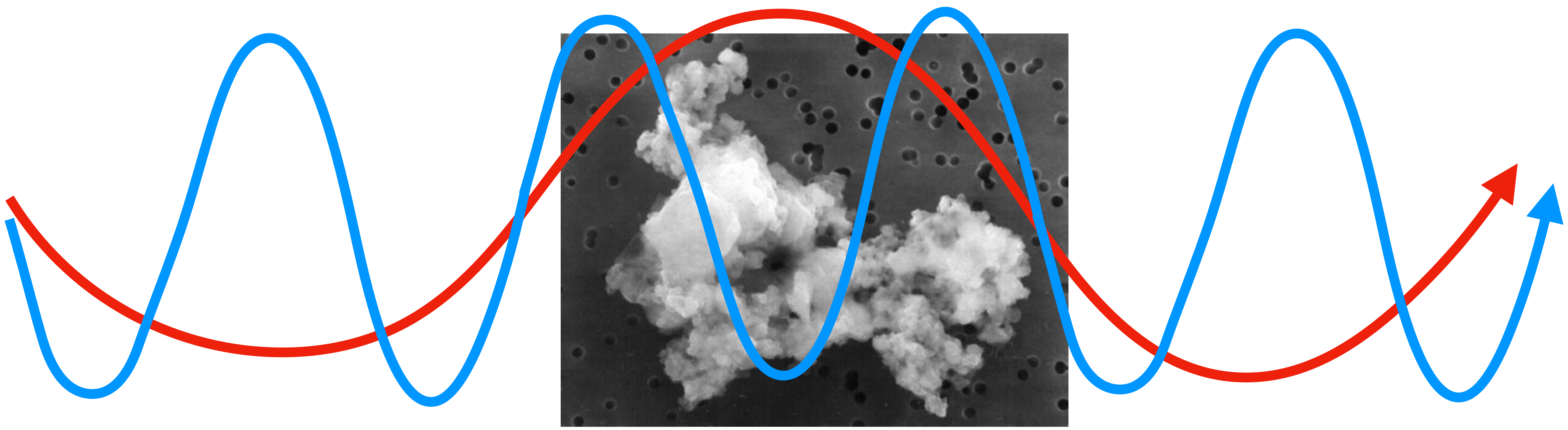
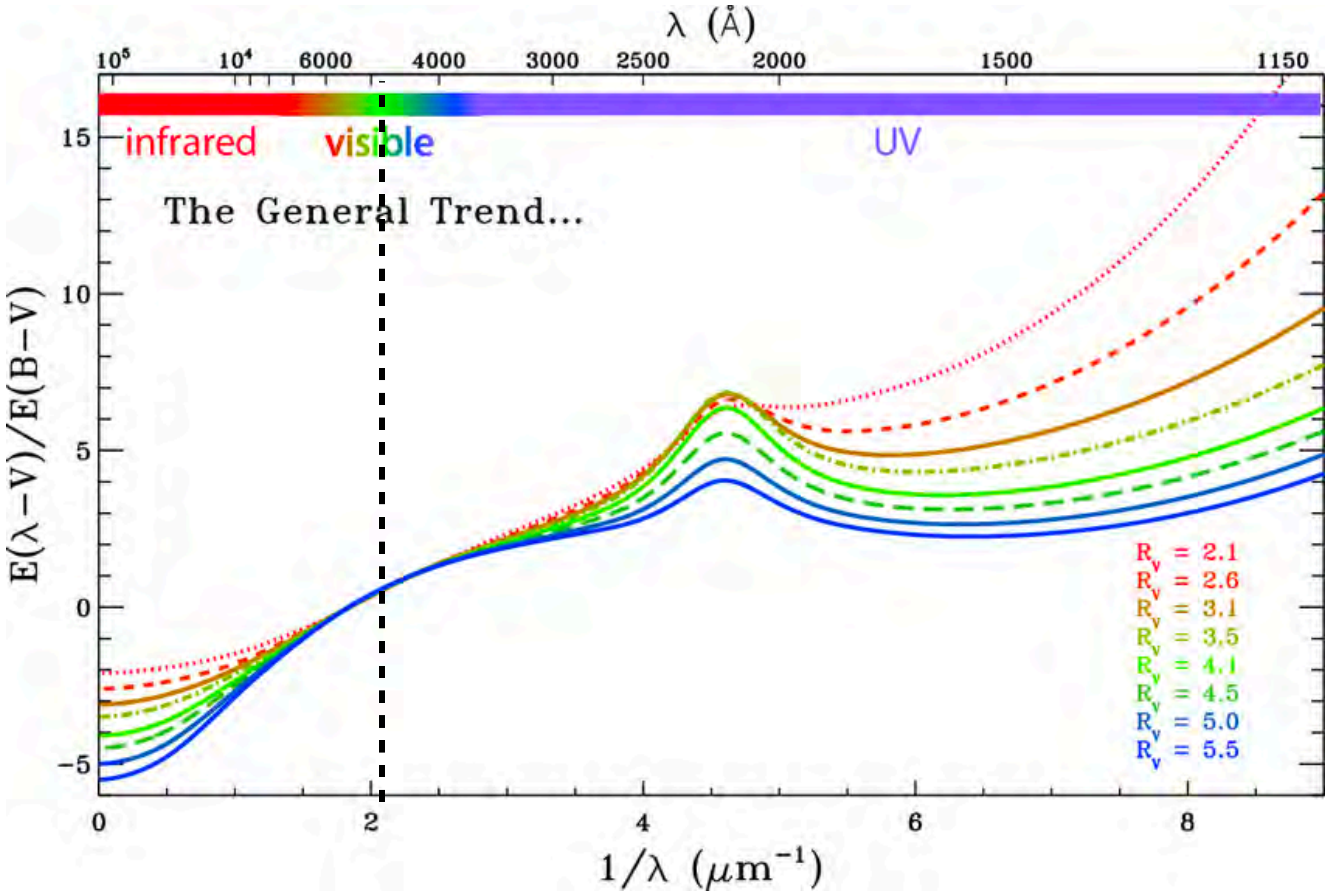


Blue light is absorbed more than red light

Reddening

- **Dust extinction**: loss of light because of absorption by dust grains

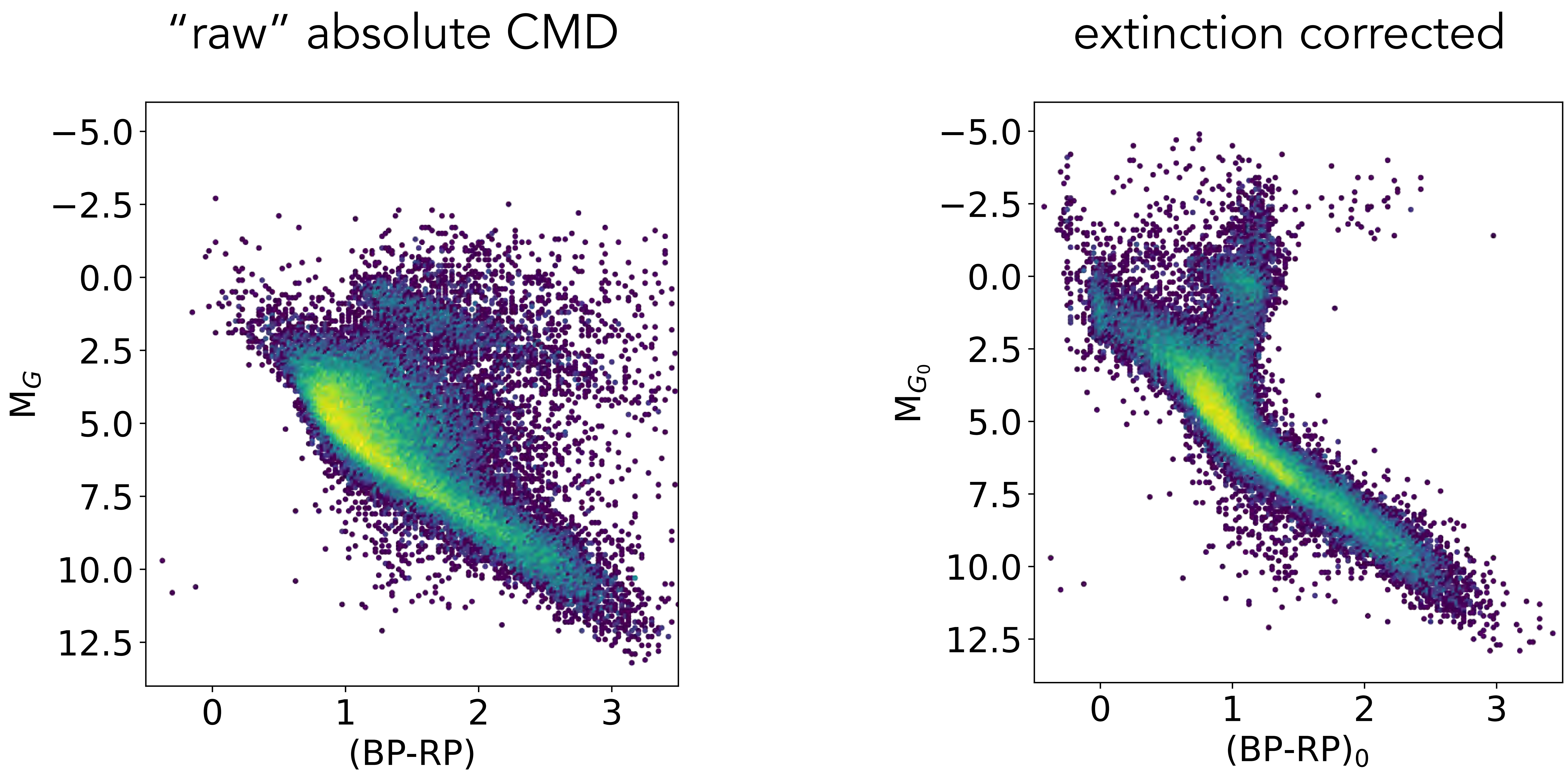


$$m_0 = m - R_m * E(B\text{-}V)$$

for many filters R is available in the appendix of Schlafly & Finkbeiner (2011)

for Gaia, see the Gaia collaboration website or e.g. Casagrande et al. (2021)

Reddening

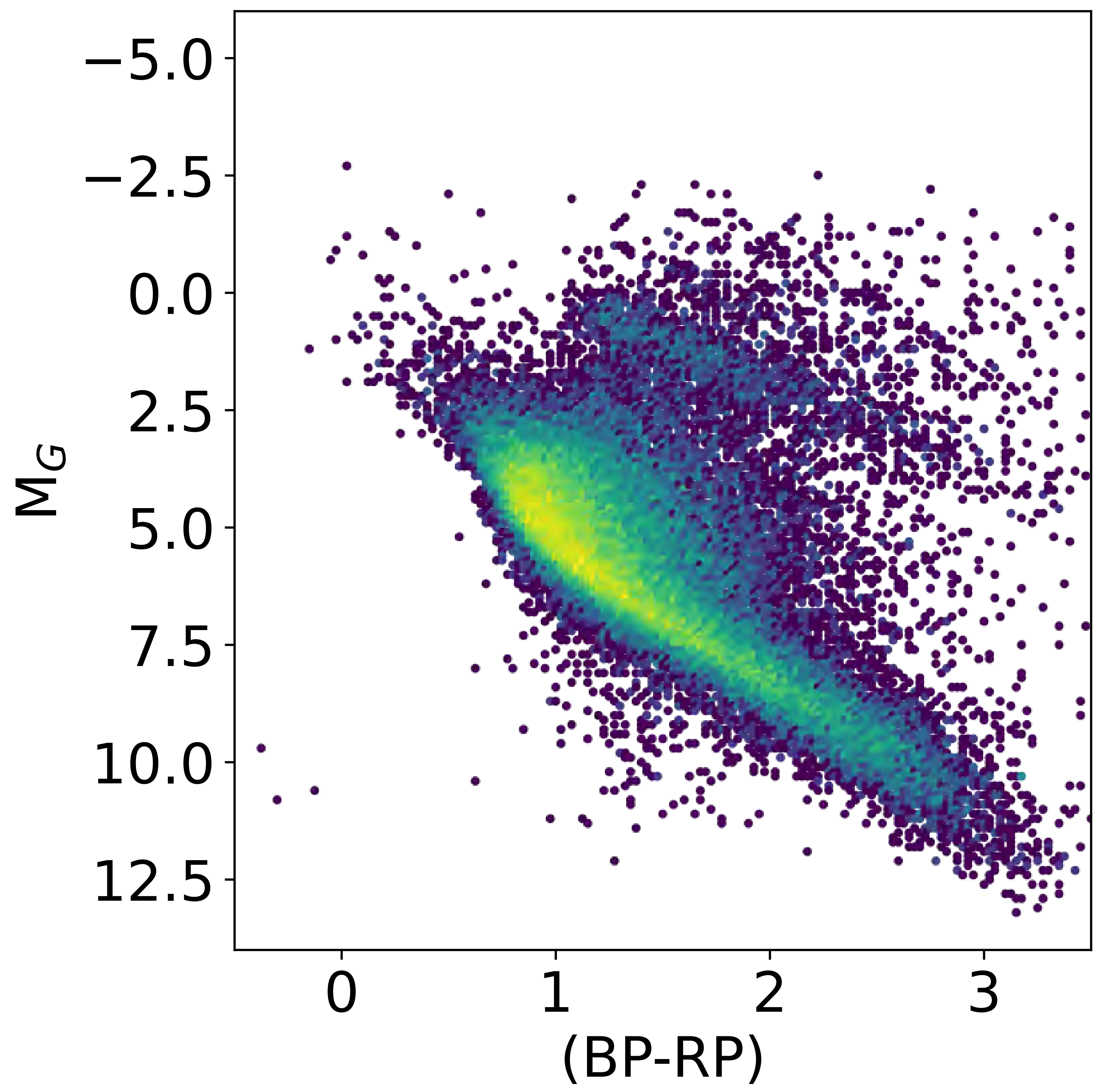


Random set of Gaia stars with good parallaxes

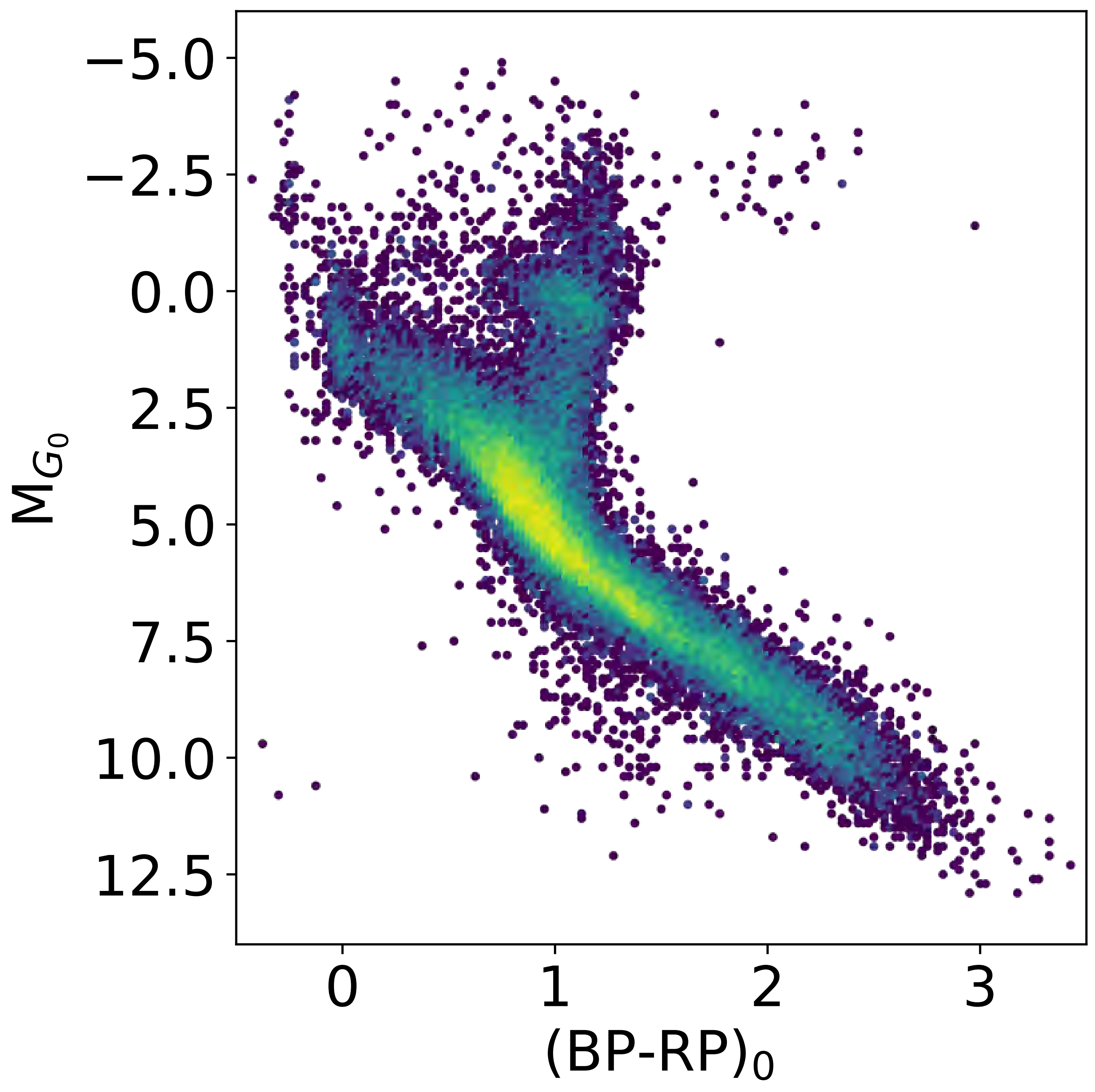
Reddening

Q **Can you recognise the main sequence and a giant branch?**

"raw" absolute CMD



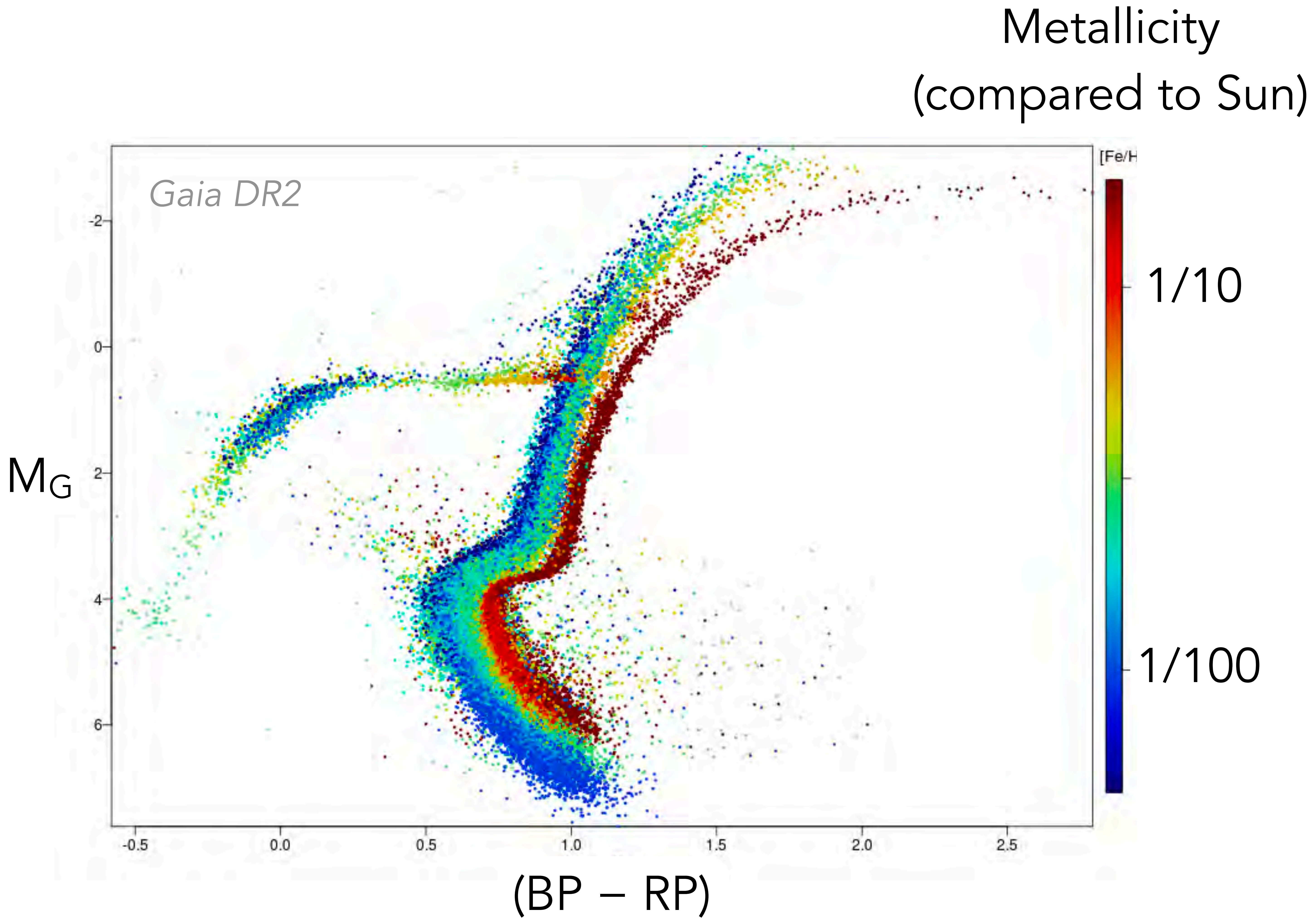
extinction corrected



Random set of Gaia stars with good parallaxes

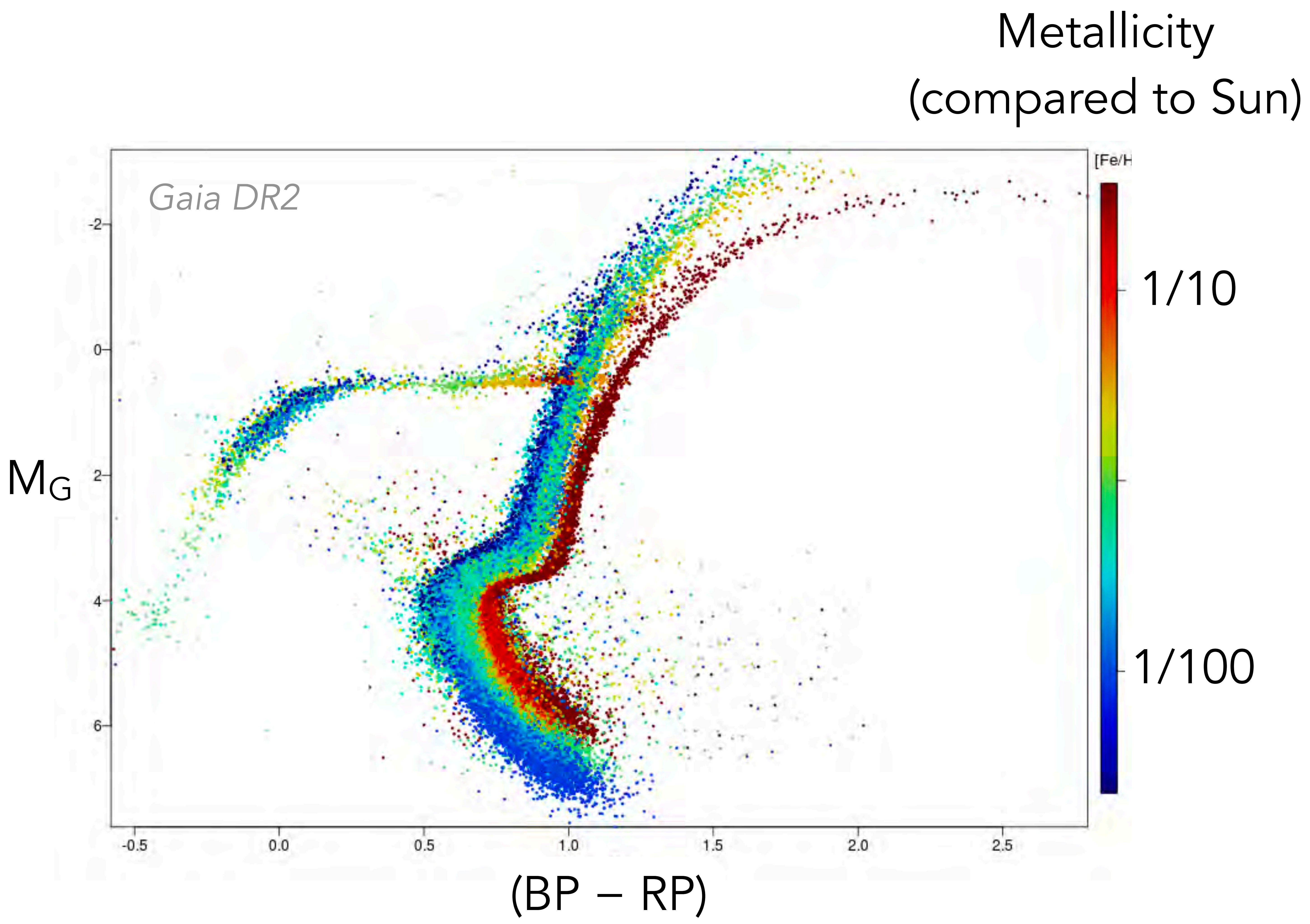
Colour-magnitude diagrams (CMDs)

- CMDs for various globular clusters
  - *Single age (all old)*
  - *Single metallicity*
- Colours and magnitudes depend on the metallicity!



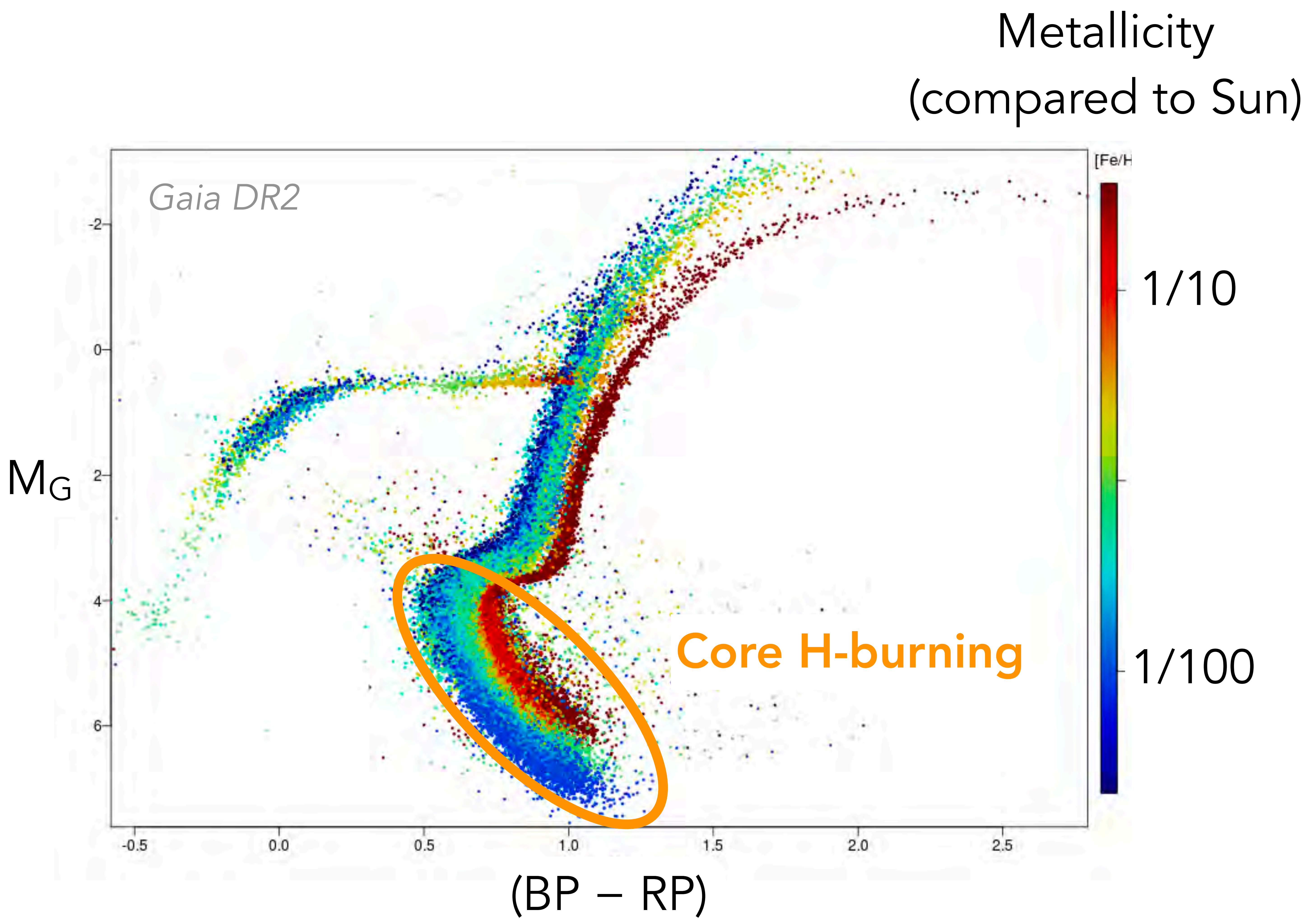
Colour-magnitude diagrams (CMDs)

- CMDs for various globular clusters
  - *Single age (all old)*
  - *Single metallicity*
- Colours and magnitudes depend on the metallicity!
- Why? Metal-poor stars are hotter and have less metal-absorption in the blue range (=> bluer)



Colour-magnitude diagrams (CMDs)

We can see different evolutionary stages



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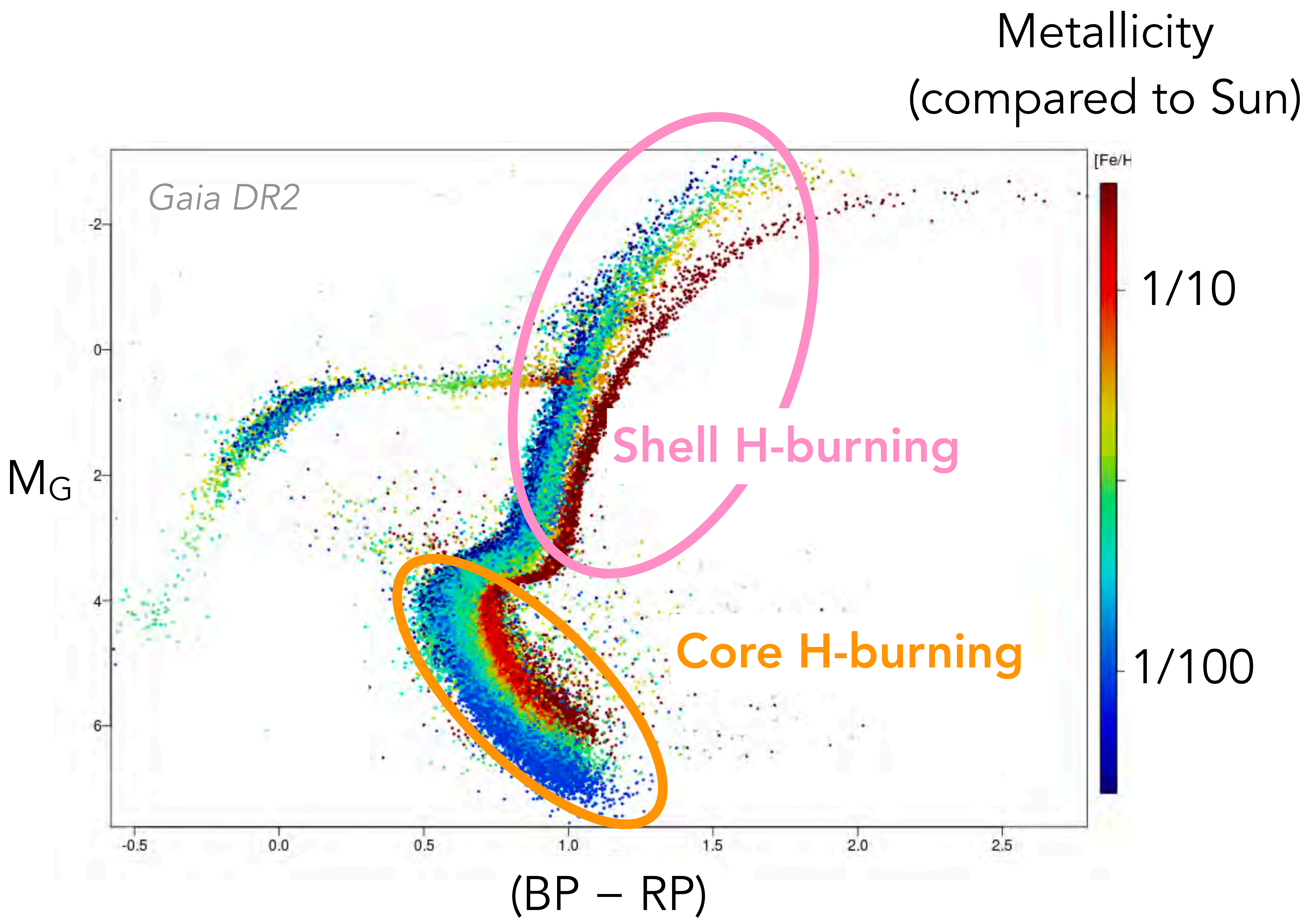

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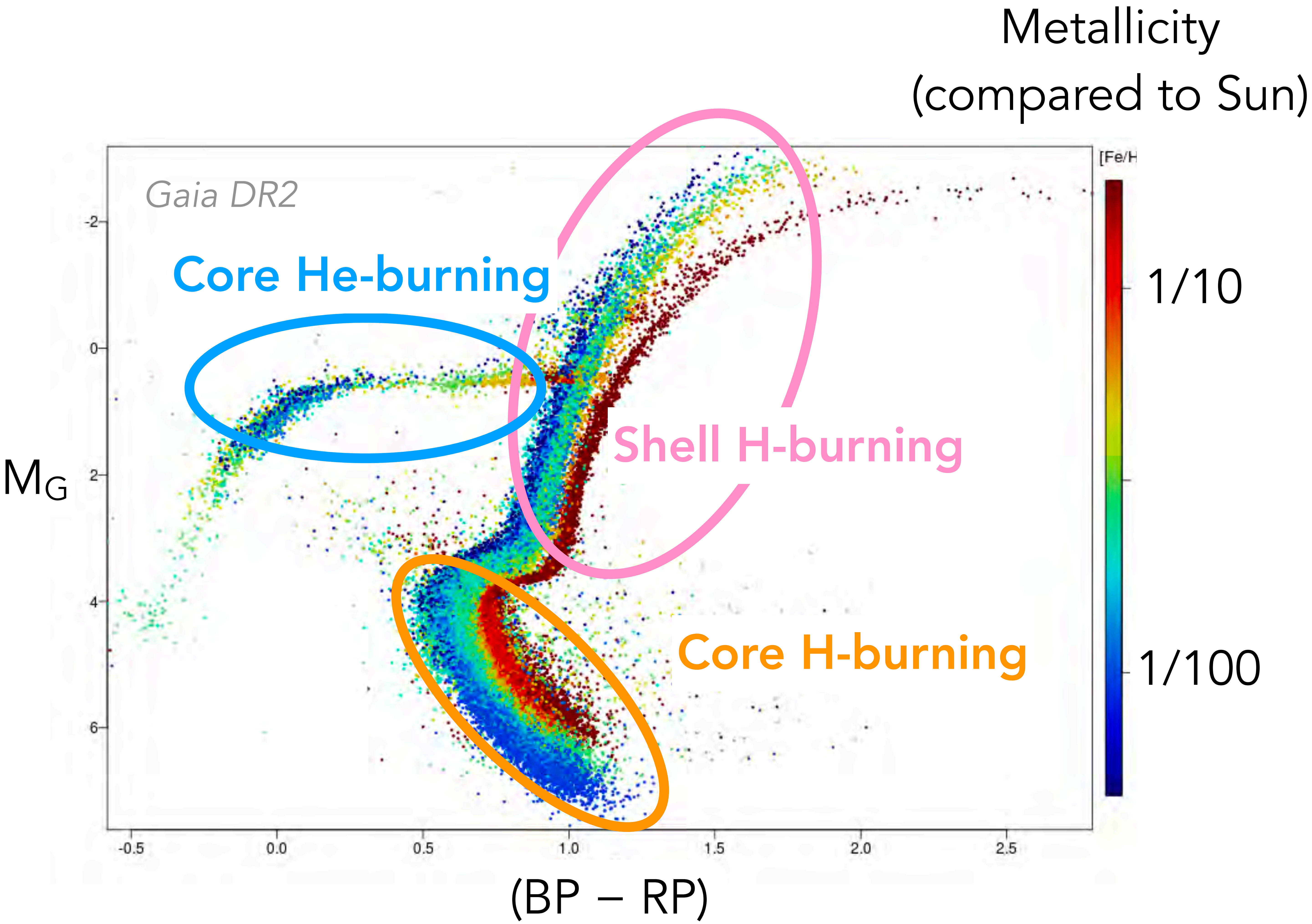
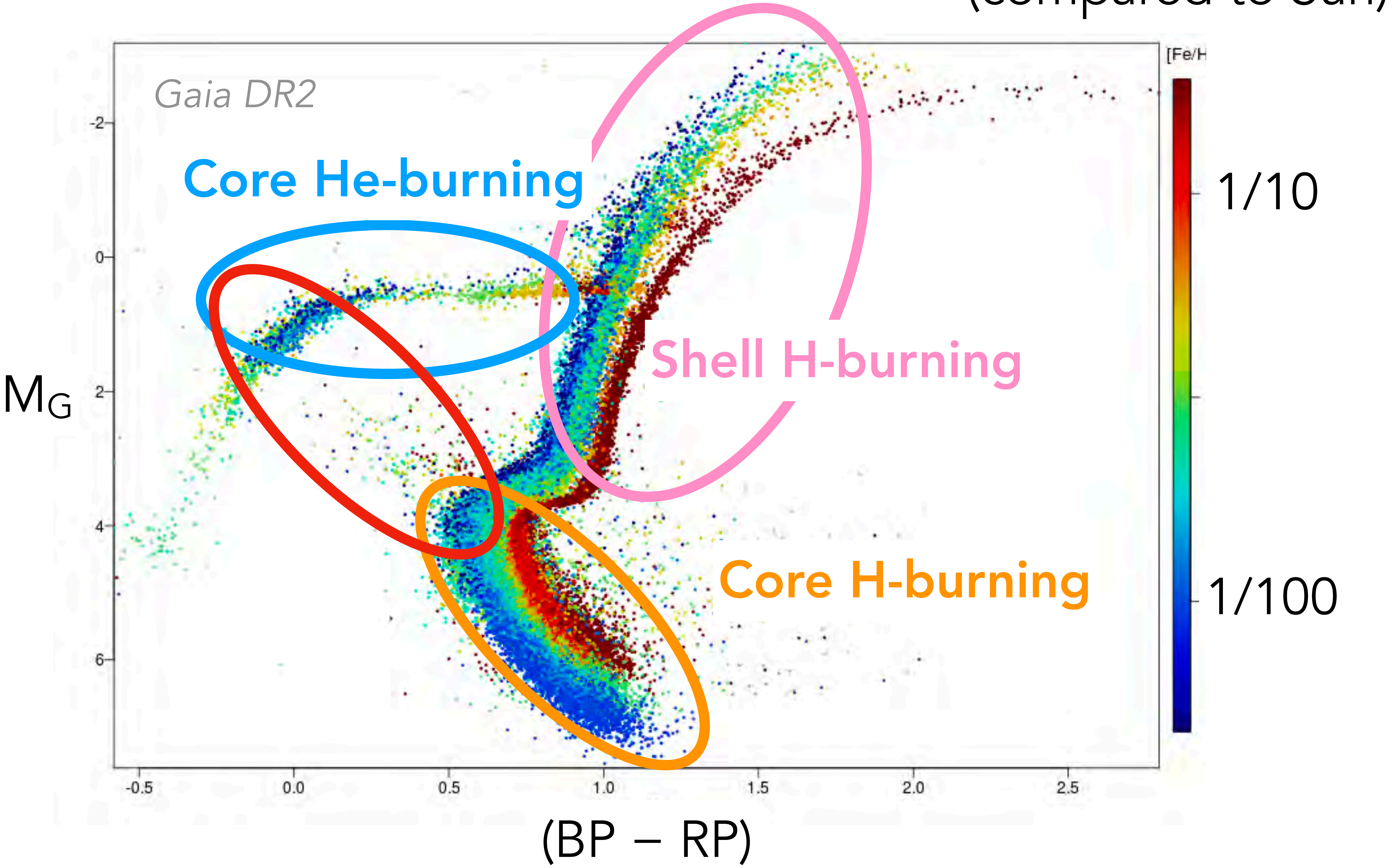


Colour-magnitude diagrams (CMDs)

We can see different evolutionary stages

Q **What happened to the upper main sequence?**



Ages for stellar populations

- Assuming all stellar populations are **born with the same initial mass function (IMF)**, and given that **more massive stars die faster**, we can use the *current* mass distribution to **estimate the age** of a stellar population (if we know the metallicity)

Ages for stellar populations

PARSEC: http://stev.oapd.inaf.it/cgi-bin/cmd
MIST: https://waps.cfa.harvard.edu/MIST/interp_isos.html
BaSTI: http://basti-iac.oa-abruzzo.inaf.it/isocs.html

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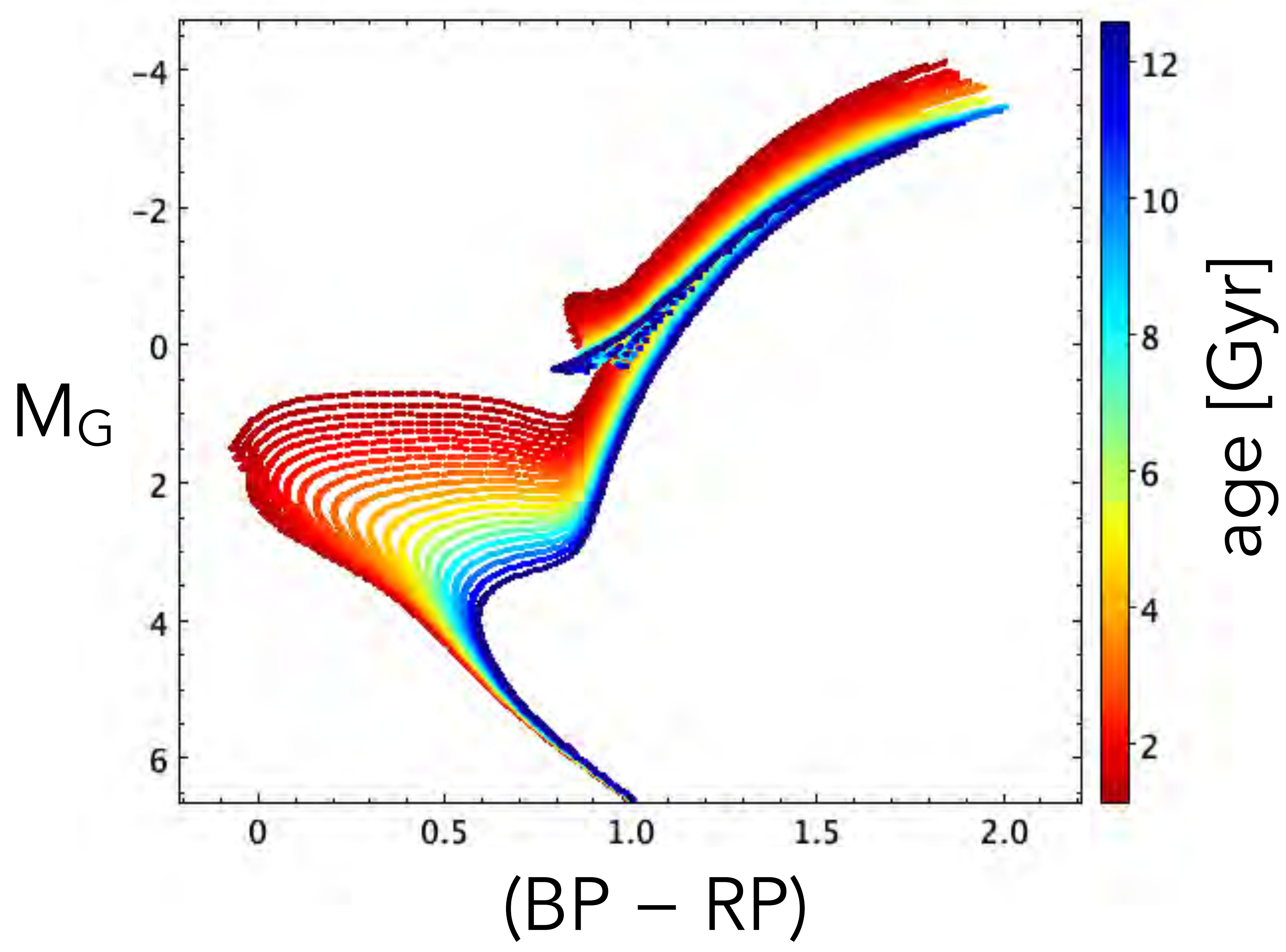
- Need stellar models that predict population CMDs: **isochrones** (iso -> equal, chrone -> time)

Example of
MIST isochrones
[Fe/H] = −1.5



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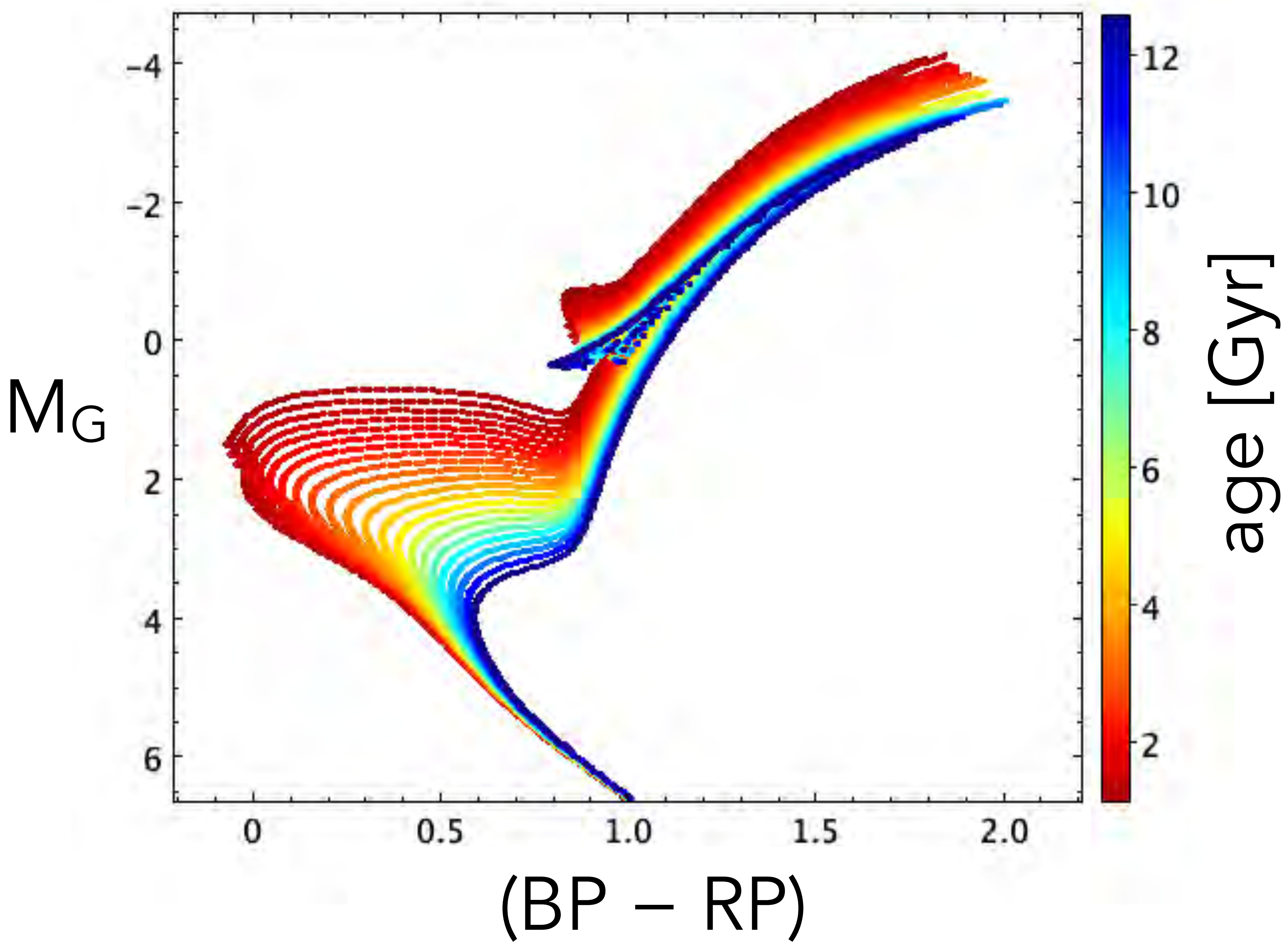
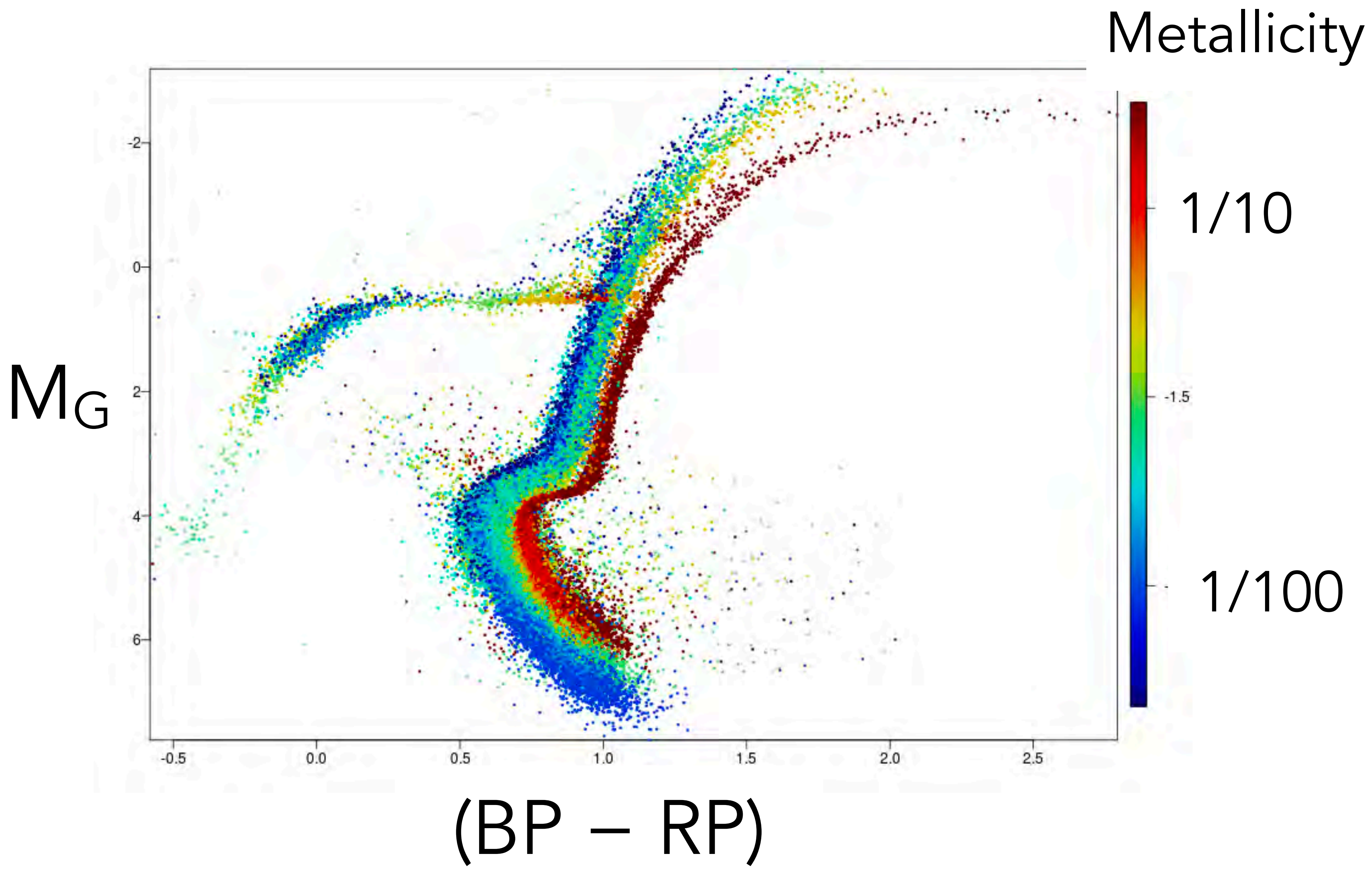
- Need stellar models that predict population CMDs: **isochrones** (iso -> equal, chrone -> time)

Example of MIST isochrones **[Fe/H] = −1.5**





Summary

- Galactic Archaeology uses the properties of stars to study the past (of our Galaxy/Universe)
- Need to understand stars!
  - Stellar evolution
  - Nuclear fusion and chemical elements
  - Colour-magnitude diagrams

Next lecture

- How to get metallicity and chemical abundances for stars?
  - Spectroscopy (background & techniques)
  - Some recent examples from the literature
- How to use chemical abundances to trace chemical evolution in galaxies?