Announcements

- **Quiz 7** due tonight, practice problems in **Problem Sets 7A, 7B**
- Approximate schedule for this week:
  - Today: Finish Chapter 12, Chapter 13
  - Remainder of the week: Solar system & Planets
- Next midterm: Wednesday Oct 29
- Midterm will cover Chapter 3 and Chapters 9-12 (first part of today's lecture) – this is the material since last midterm
- Review in class Monday March 24

Announcements II

- Reminder: this is the last week to turn in astronomy news summary for **extra credit**
- Summary in your own words of an astronomy-related story in the news
  - Explain what, how and why it's important
  - At least three sources required, must be cited
- Turn in any time in class until Friday, or email electronic copy
- Info on D2L
- +1% on final grade

Reminder: Two types of supernovae

- **Type I:**
  The collapse of an accreting white dwarf when its mass reaches 1.4 solar masses.
- **Type II:**
  The collapse of the iron core of a massive star when its mass reaches 1.4 solar masses. The energy of matter falling during the gravitational collapse (and then rebounding) is the energy that explodes the rest of the star. Remnant is either neutron star or black hole (+ nebula).

Astronomy 103

Neutron stars, black holes, and spacetime

Please read Chapter 13

Neutron stars

At the end of the life of a massive star, we have seen that its iron core collapses. When the core collapses, the electrons are pushed down onto the nuclei – the core collapses from the size of the Earth to the size of a city, about 20 km (13 mi) in diameter. 100 times more energy is released in these few seconds by the collapse than the star released during its entire lifetime.

This creates a **neutron star**: a star that is composed of neutrons – a star that is almost a giant atomic nucleus.

Neutron Stars

Immediately after the **neutron** was discovered in 1930, physicist Lev Landau suggested the possibility that the pressure in the cores of stars might push the electrons onto their protons to make a core entirely of neutrons. He wasn't quite right: The pressure is high enough only when the star collapses in a supernova.

proton

electron

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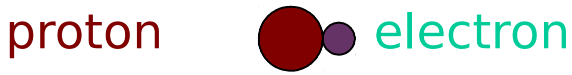

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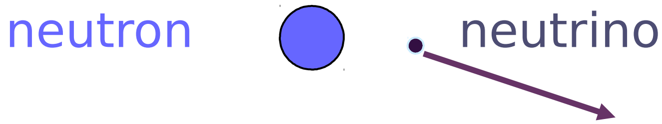
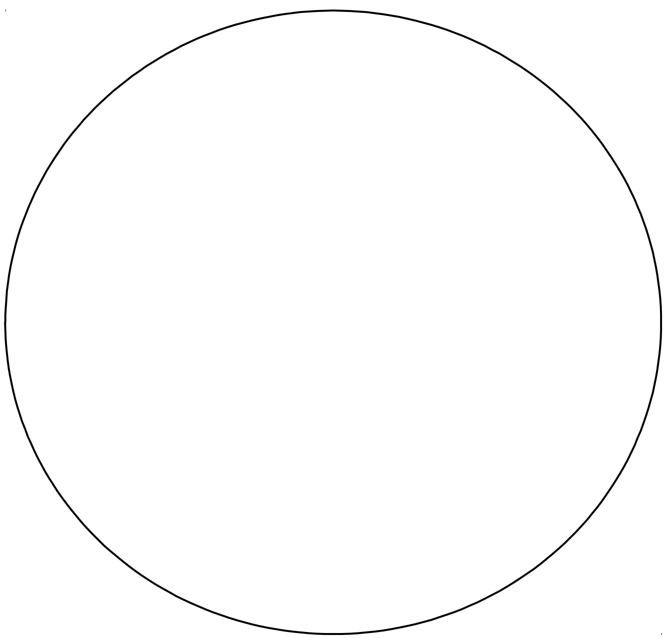
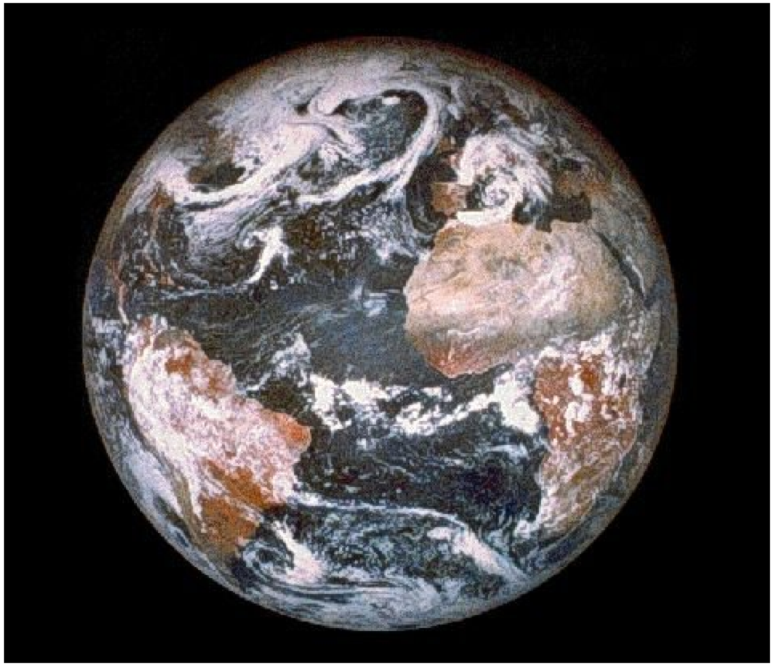


How does this work?

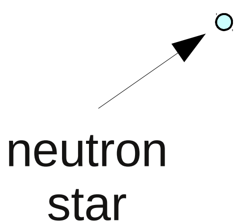
A white dwarf is roughly the size of the Earth

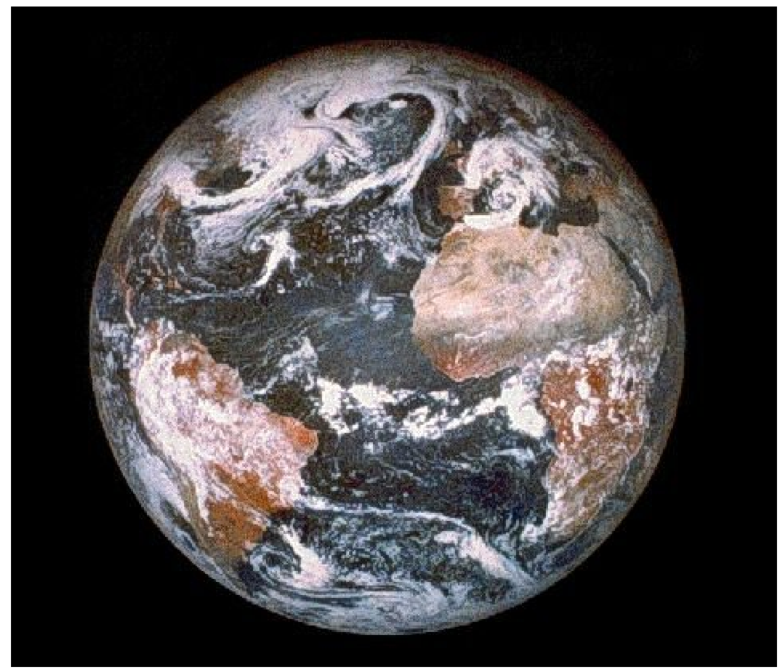




How does this work?

A neutron star has a radius of about 10 km, roughly 1/1000 that of the Earth





Remember that atoms are mostly empty space

If you compressed all of Mt. Everest, pushing its electrons onto their nuclei, you would get a single teaspoonful of neutron-star matter.

!

Neutron Star Fun Facts

- R≈15 km and M≈1.5 MSun
- Central density 2-10 times that of atomic nucleus
  - 1 teaspoon is about 10^{12} kg
  - a cube 300 meters on a side has the same mass as the Earth
- Magnetic field >10^{12} times that on Earth
  - erase credit cards from 30,000 km & kill from 200 km
- Spin frequencies from 0.1 Hz to 716 Hz → pulsars
  - faster than a kitchen blender!


MAPQUEST
0
4mi
4km
Ozaukee
Milwaukee
Meeker
Victory Center
Colgate
Menomonee Falls
41
Granville
Brown Deer
Lannon
Glendale
Fox Point
74
Willow Springs
41
145
Whitefish Bay
Marcy
45
Shorewood
Duplainville
Brookfield
Wauwatosa
Milwaukee
94
18
Lake Michigan
Elm Grove
West Allis
10 km
59
Calhoun
West Milwaukee
New Berlin
Greenfield
794
Hales Corners
119
43
South Milwaukee
Muskego
Franklin
Oak Creek
Big Bend
Saint Martins
45
Oakwood
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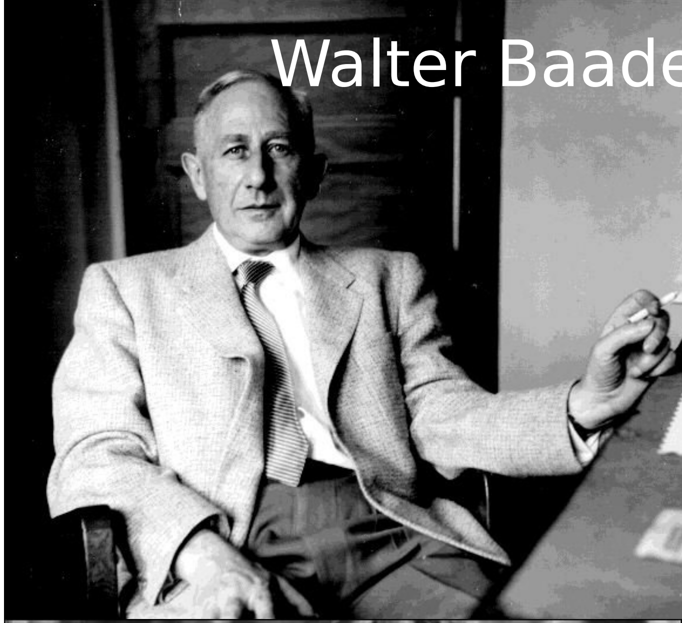
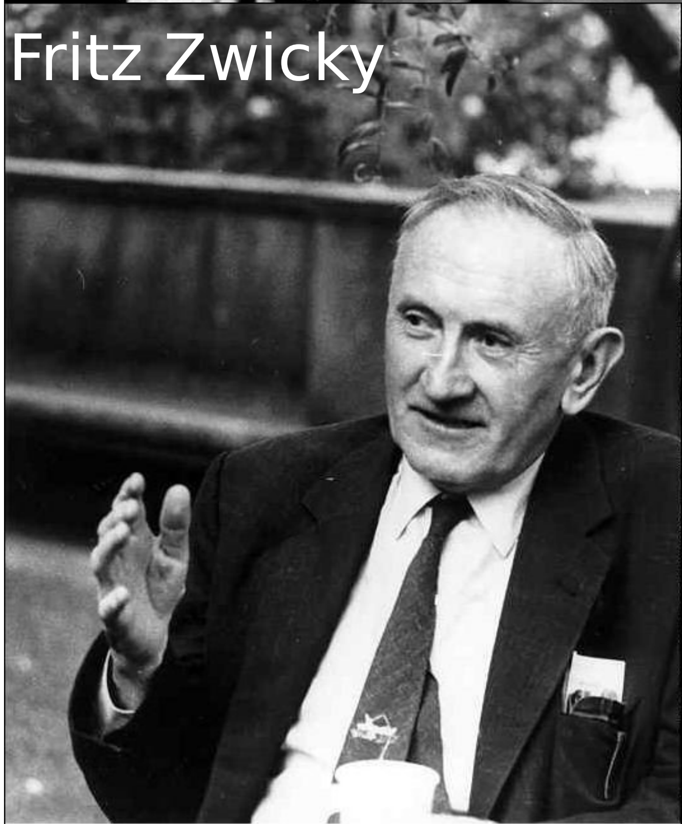
Energy of a supernova

Baade and Zwicky pointed out that the gravitational energy released by a star falling inward to become a neutron star would be about 1 billion times as large as the energy emitted by the Sun over its entire lifetime — the observed energy of a supernova. Based on this observation, they suggested that "...supernovae represent the transitions from ordinary stars into neutron stars." **This was two years after the discovery of neutrons and 33 years before discovery of neutron stars.**





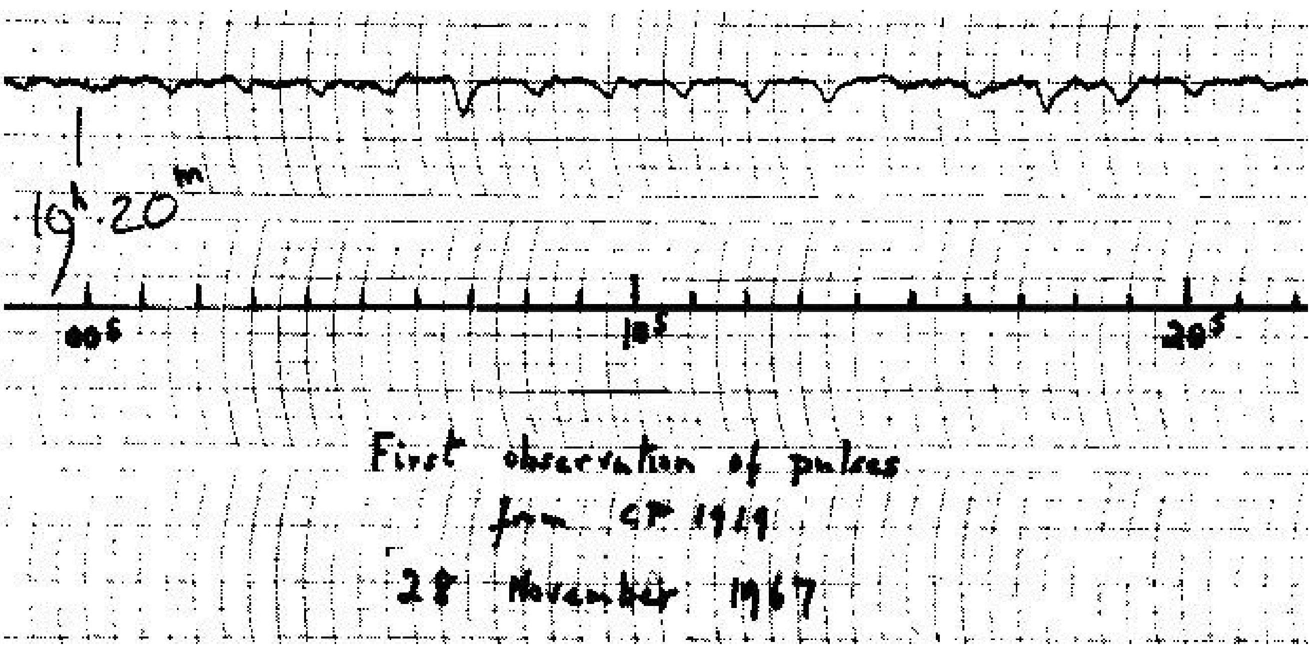
Supernovae and Neutron Stars

Although Baade and Zwicky suggested in 1934 that neutron stars might exist and might be the outcome of a supernova, no neutron stars were seen for the next 33 years.

In 1967 Jocelyn Bell, a graduate student at the University of Cambridge, saw a set of mysterious radio sources that they called pulsars, because they saw from each object a pulse of radio waves once every second or so, with extremely regular periods. What was Bell looking at?

Radio-emission from Pulsars

Jocelyn Bell and her radio telescope



Not the cause of the pulses!

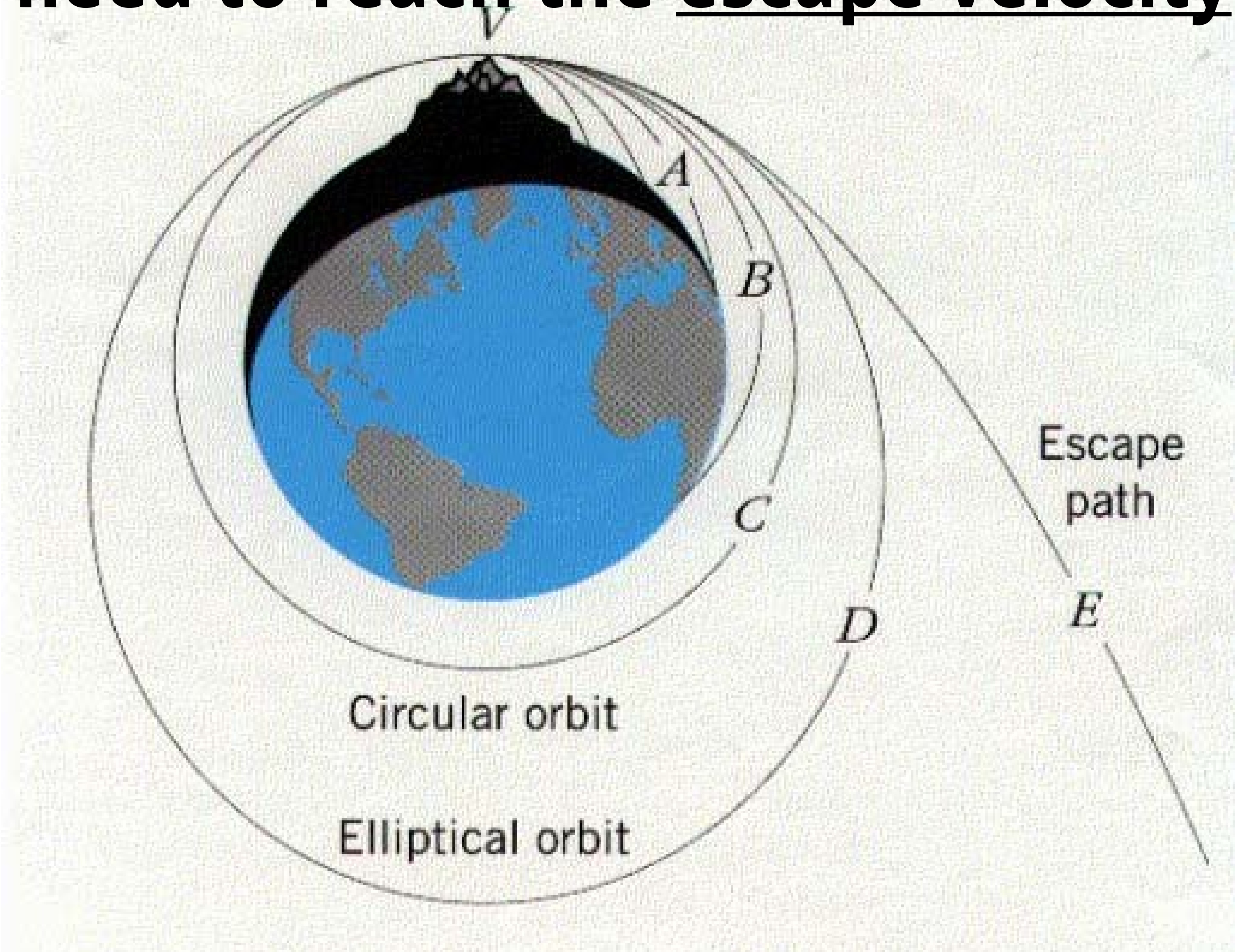
Jocelyn Bell, at about the time she discovered the first neutron stars.

Her discovery won the Nobel prize, but for her advisors and not for her – one of the great mistakes in Nobel Prize history.

Black holes and an upper limit on the mass of neutron stars

- The pressure from nuclear forces in a neutron star keep the star from collapsing.
- But there is a maximum pressure that nuclear forces can exert and beyond 3 times the mass of the Sun, gravity must win.
- At this point, the neutron star will collapse to a black hole, an object whose gravity is so strong that not even light can escape.
- Nothing can escape from a black hole. How does this work?

To escape from a star or planet, you need to reach the <u>escape velocity</u>



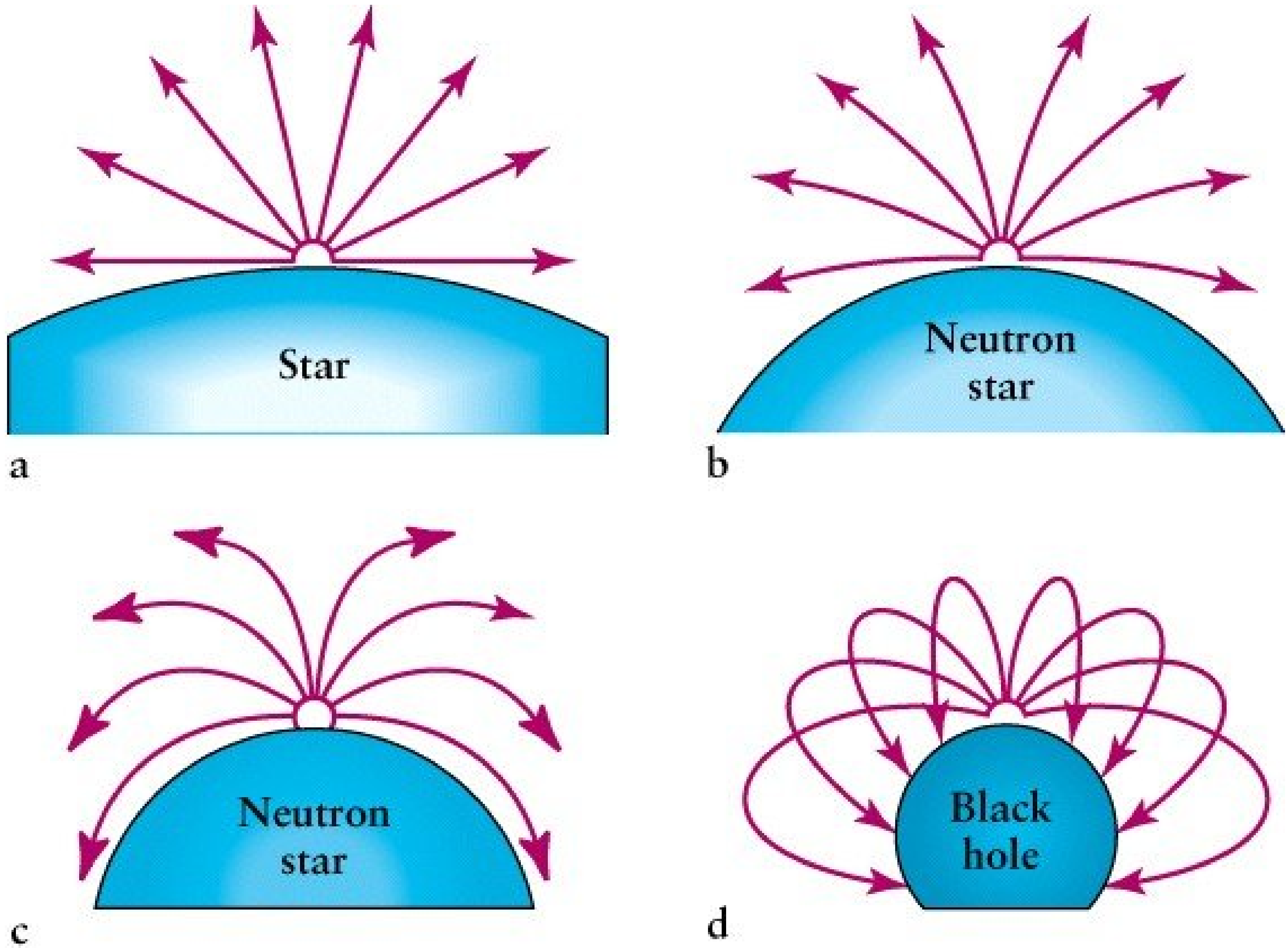
Escape velocity: Examples

- To escape from the surface of the Earth, never to return, you have to move at at least 11 km/s (7 miles/second)
- To escape from the Sun, you have to move at more than 600 km/s
- To escape from the surface of a neutron star, you need to travel at 100,000 km/s, one third the speed of light.

Escape velocity: Black Hole

As we add more mass to a neutron star, eventually the escape velocity matches and then exceeds the speed of light. At this point, everything (including light) falls inward toward a small speck.

This region in space becomes black because light cannot escape and thus a black hole is born.


Star
a
Neutron star
b
Neutron star
c
Black hole
d

Suppose that the Sun were suddenly replaced by a **black hole** of exactly the same mass. What would happen?

A

The Earth and the rest of the planets in the solar system would be sucked in very quickly.

B

The Earth and the rest of the planets would continue to orbit as usual.

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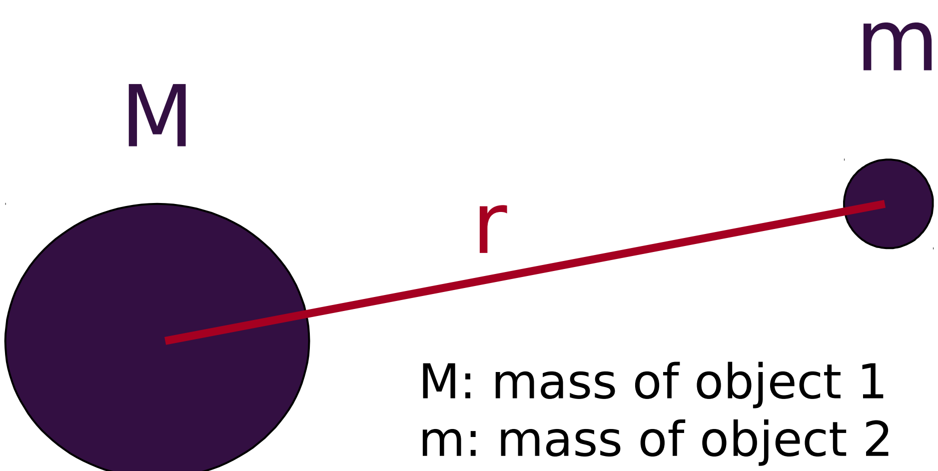
Newton's law of gravity: Any two objects in the universe attract each other with a force given by

$$F = G\frac{Mm}{r^2}$$



M: mass of object 1
m: mass of object 2
r: distance between the objects

As long as we're far enough away, this law doesn't care what sort of object has mass *M* – it could be a star or a black hole. It's only *very* close to the black hole where things get weird, as we'll see later.

John Michell 1784

First published suggestion of the existence of black stars

"supposing light to be attracted by the same force in proportion to its *vis inertiae*, all light emitted from such a body would be made to return towards it, by its own proper gravity"

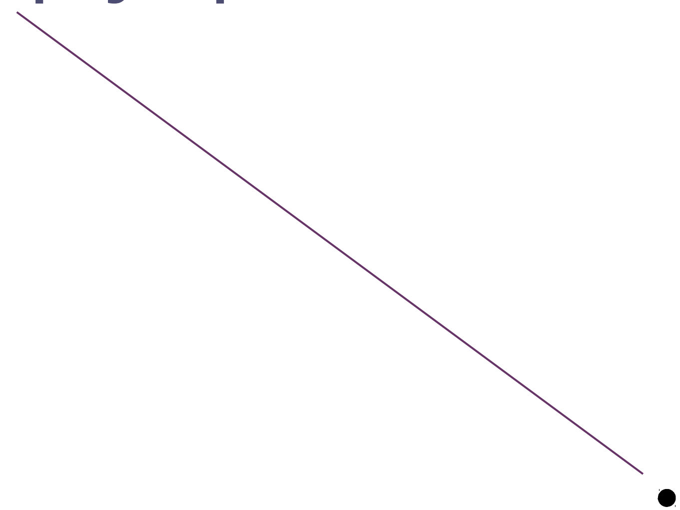
vis inertiae = inertia

John Michell — contemplating the existence of black stars.

Pierre Simon Laplace, 1799

"Proof of the theorem, that the attractive force of a heavenly body could be so large, that light could not flow out of it."

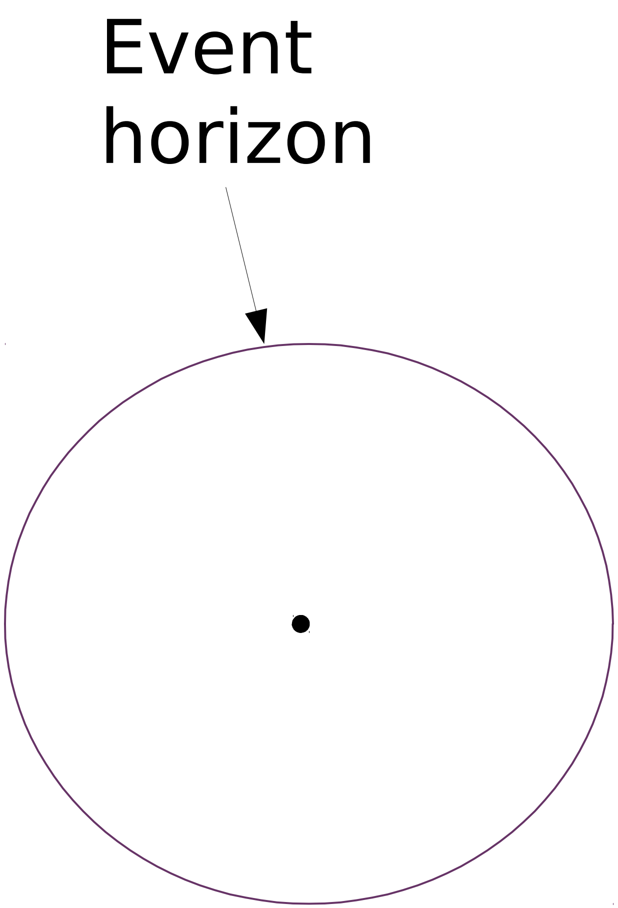
The matter collapses to a speck, surrounded by empty space.



Near the speck the gravitational field is so intense that the escape velocity is greater than the speed of light, the upper limit on speed in our universe. Because nothing can travel faster than this, nothing can escape.

The region from which nothing can escape is the ***black hole***. Its boundary is called an ***event horizon*** because no one outside can see events that occur inside:

You can't see anything inside the event horizon.



BLACK HOLES

- A black hole is a region of space from which nothing can escape to the outside

- The boundary of a black hole is called the event horizon because no events occurring beyond the horizon can be seen from the outside.

- After a star has collapsed to within the event horizon, it continues to collapse to a tiny speck – actually a point of infinite density called a singularity.

How big is the event horizon?
It depends on the mass of the black hole

- If the Sun collapsed to a black hole, its event horizon would have a radius of about 3 km

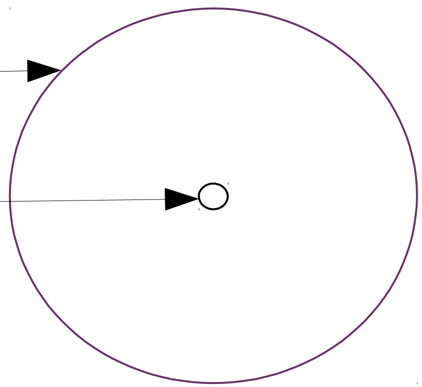
This is why the planets would continue to orbit as usual; they are very, very far beyond where the event horizon would be

- The Earth would have an event horizon of about 9 mm, the size of a peanut

What happens if you fall into a black hole?

There are two places in a black hole that are special:

- Event horizon
- Speck in the center (singularity)



There is nothing actually at the event horizon – if you cross it you might not even notice. But your doom is sealed at this point: there is nothing you can do to escape.

The singularity is a point of infinite density – you are destroyed here.

What happens if you fall into a black hole?

But in fact, since you aren't a tiny speck, you probably won't survive even as far as the event horizon. The force of gravity is so strong, and changing so fast as you get closer and closer to the black hole, that it is much stronger on your feet than it is on your head. A gravitational forces that changes across the length of an object is called a **tidal force**, and in the case of a black hole, it will pull you apart.

What happens if you fall into a black hole?

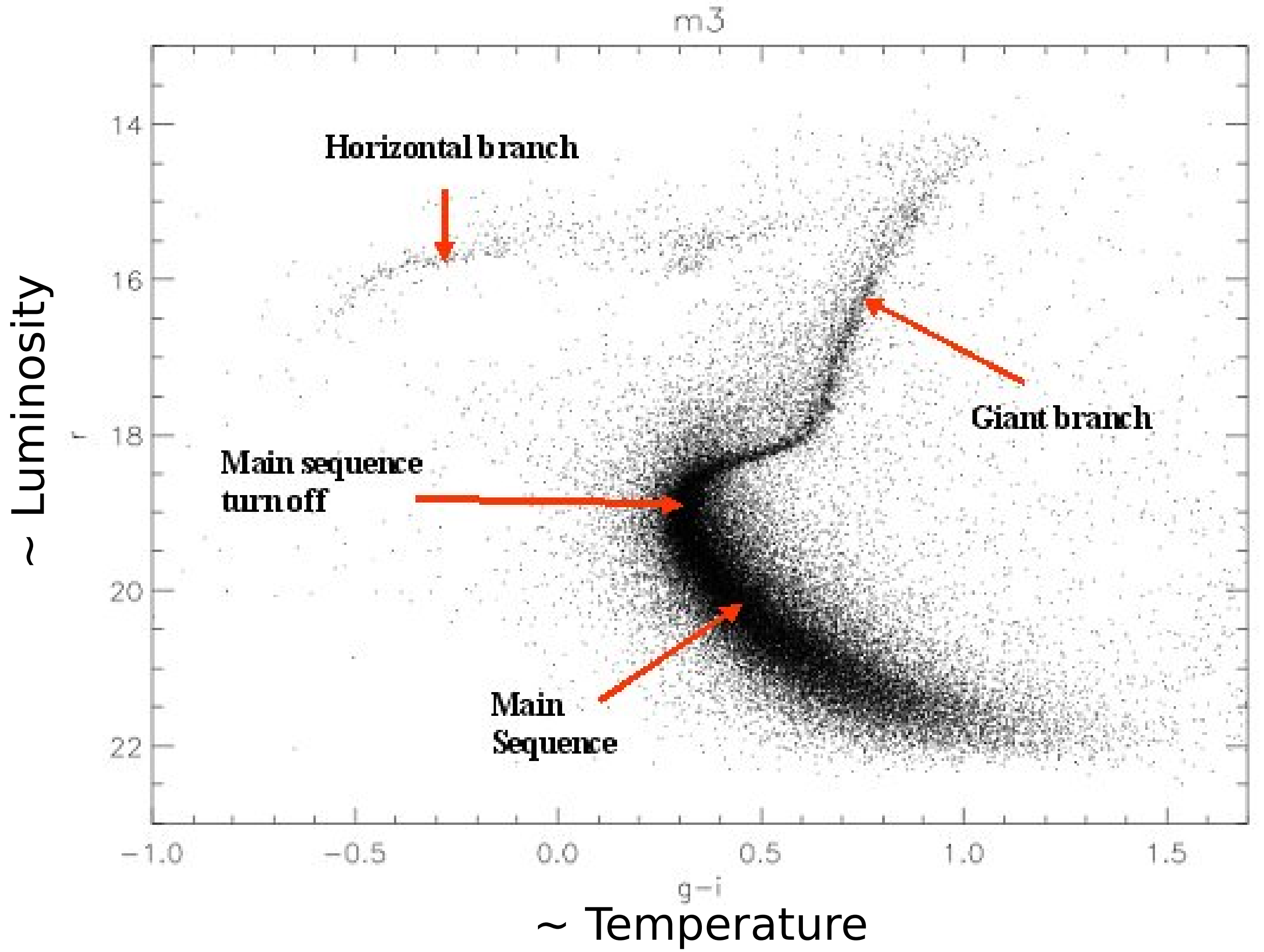
This process is called **spaghettification**, since anything falling into a black hole will be stretched out like a piece of spaghetti!

Rest of Chapter 12

Estimating the ages of star clusters from the Hertzsprung-Russell Diagram

The Ages of Star Clusters

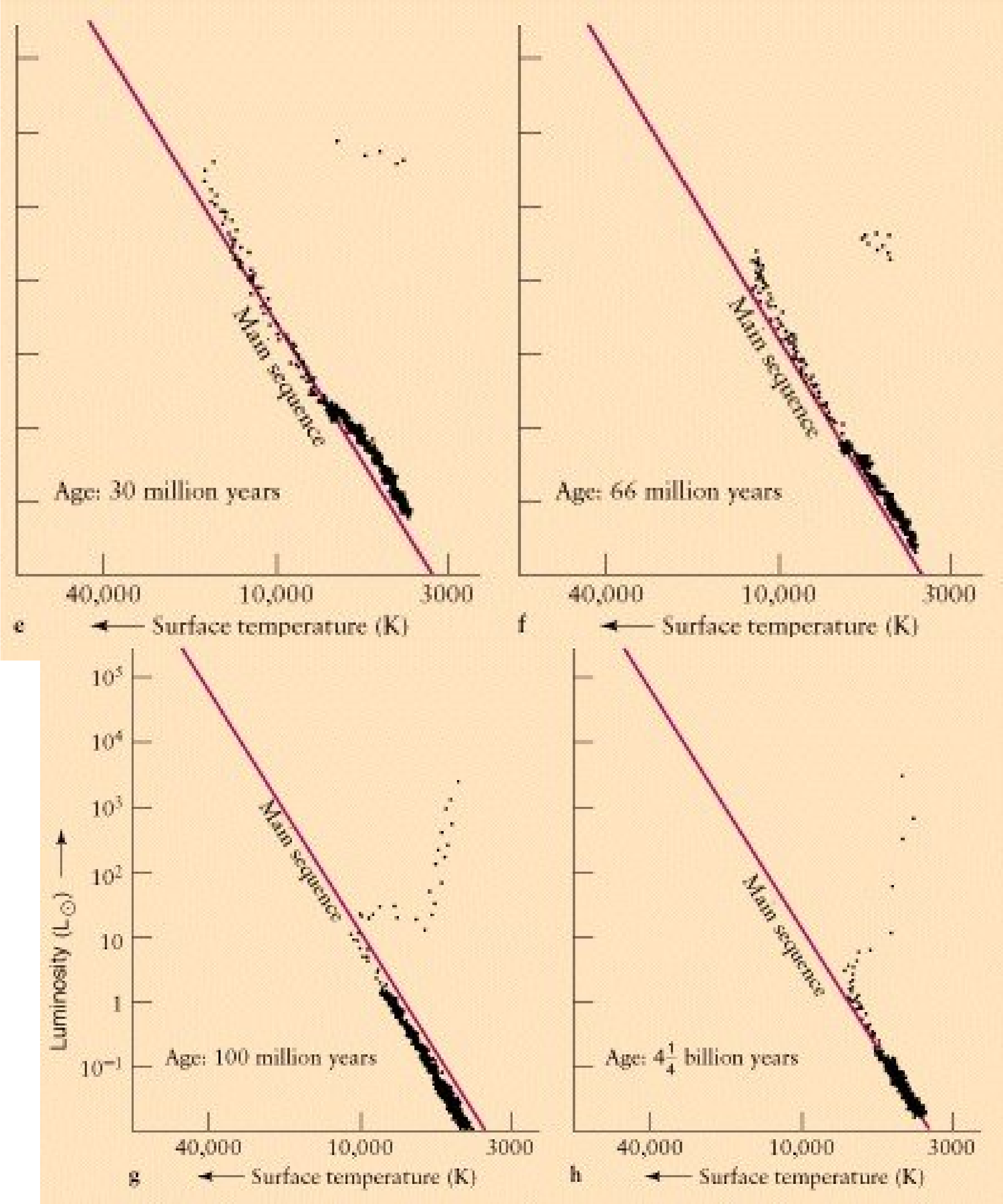
- The more massive a star is, the more quickly it evolves.
- One can find the age of a cluster of stars by observing which stars have left the main sequence
- In the **youngest clusters even the most massive stars (O and B) are still on the main sequence**
- In the **oldest clusters, stars with mass as small as the Sun’s (spectral types O, B, A, F, G) have evolved to red giants**

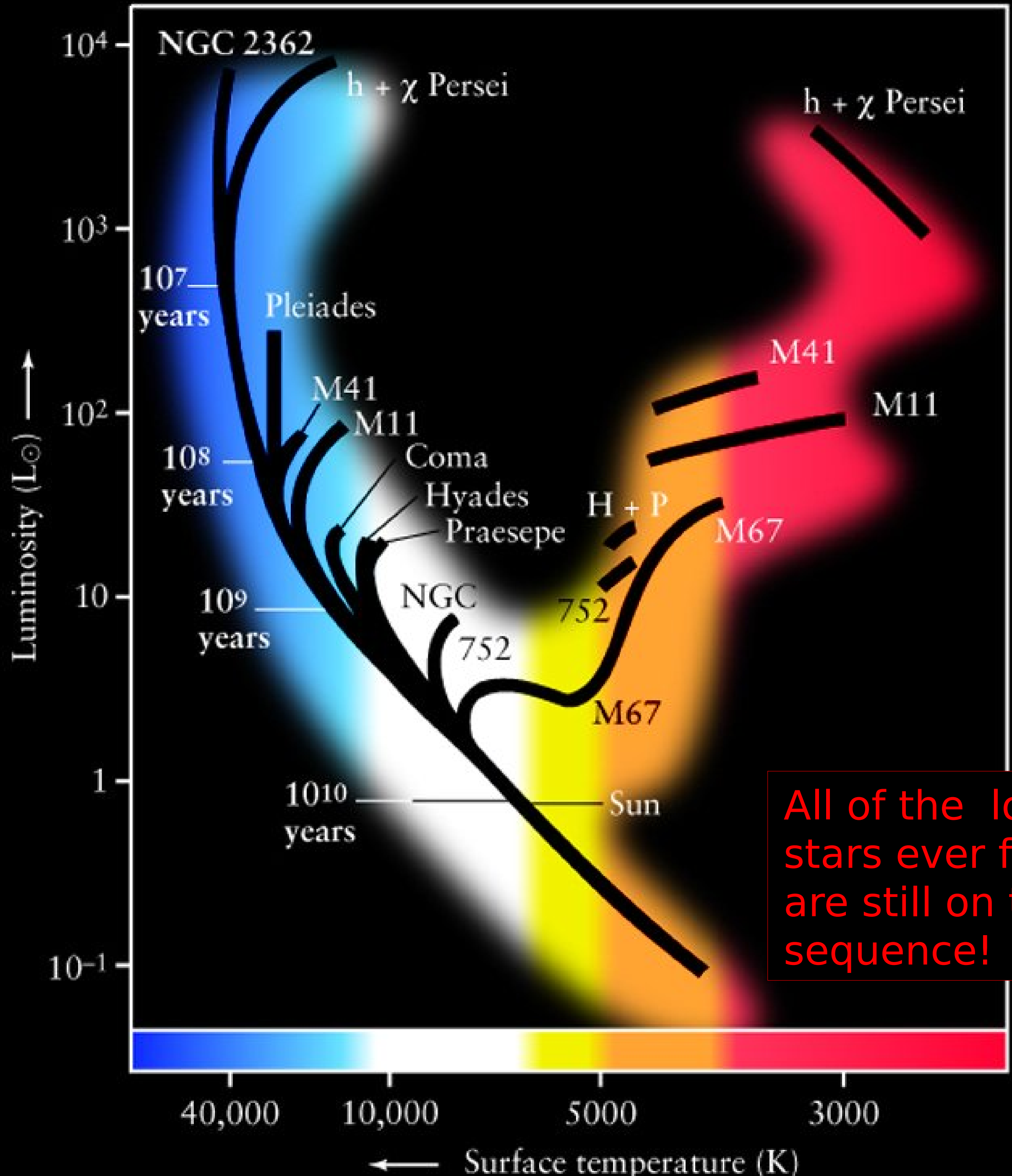


- Find a star cluster, plot all the stars on an H-R diagram
- Find the point where stars leave the main sequence: **main sequence turnoff**
- The age of the cluster is the main sequence lifetime of a star with the mass of the stars that have just left main sequence

Younger clusters

Older clusters

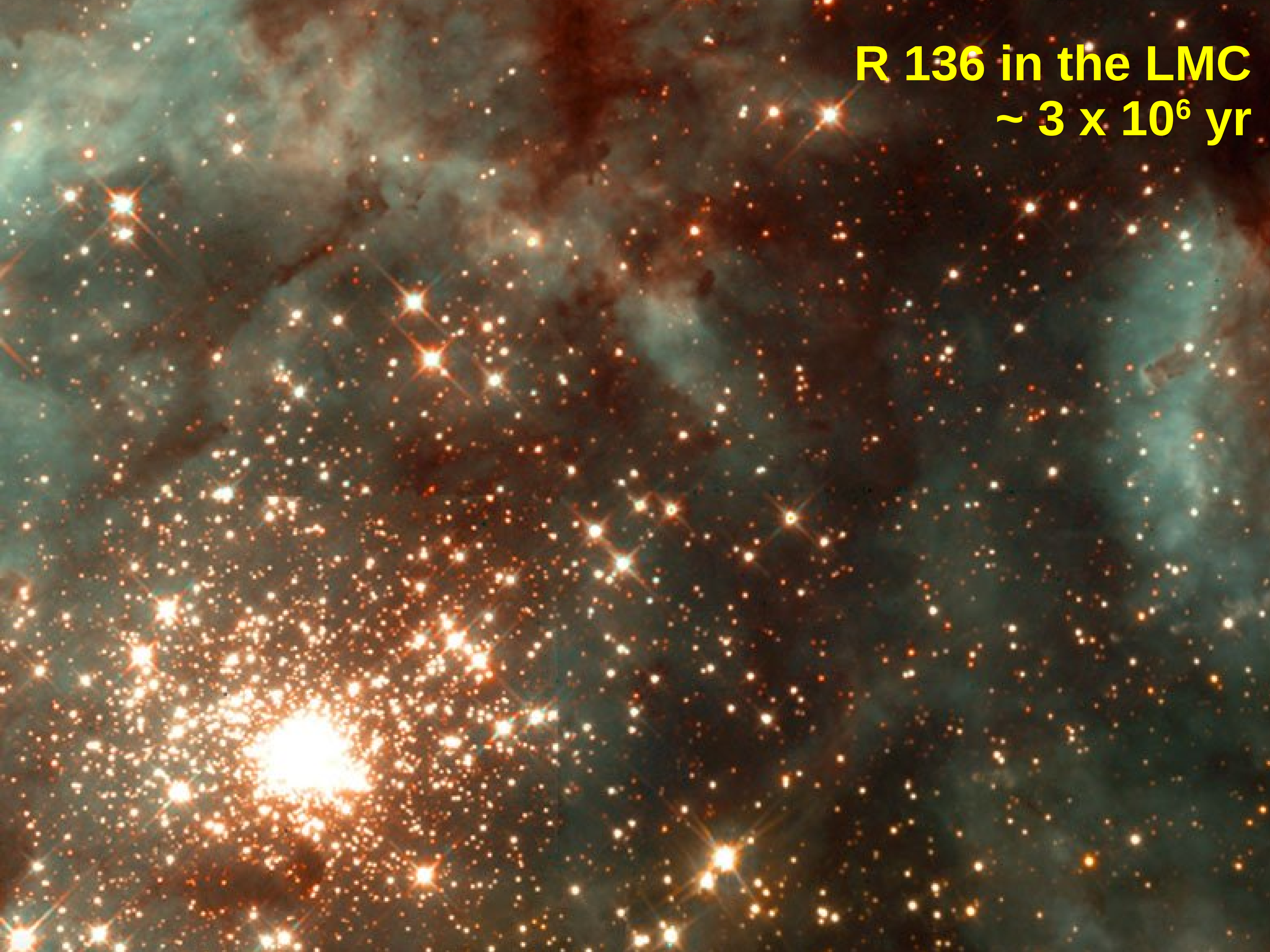




All of the low mass stars ever formed are still on the main sequence!

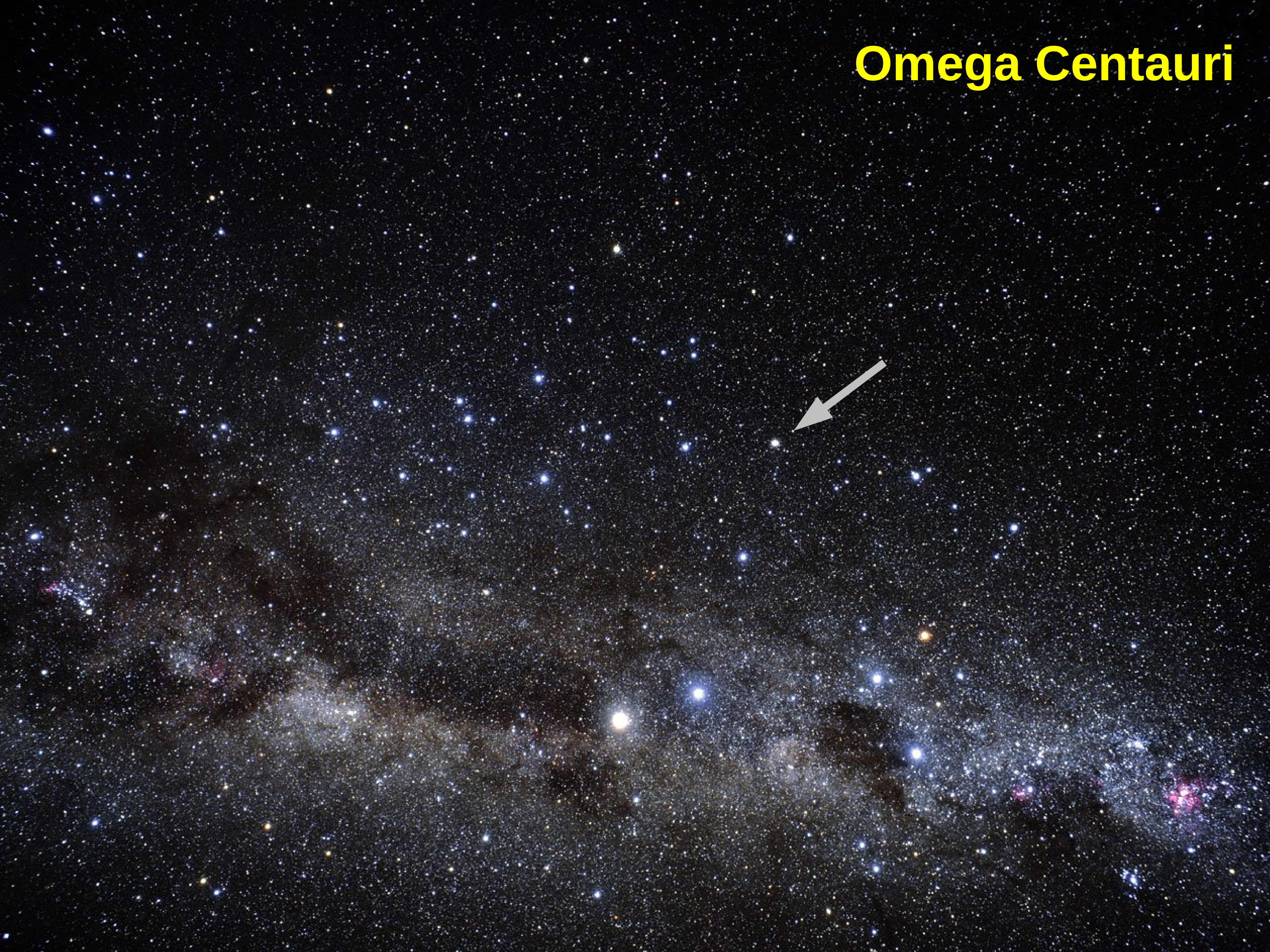

The Orion nebula


The Rosetta nebula

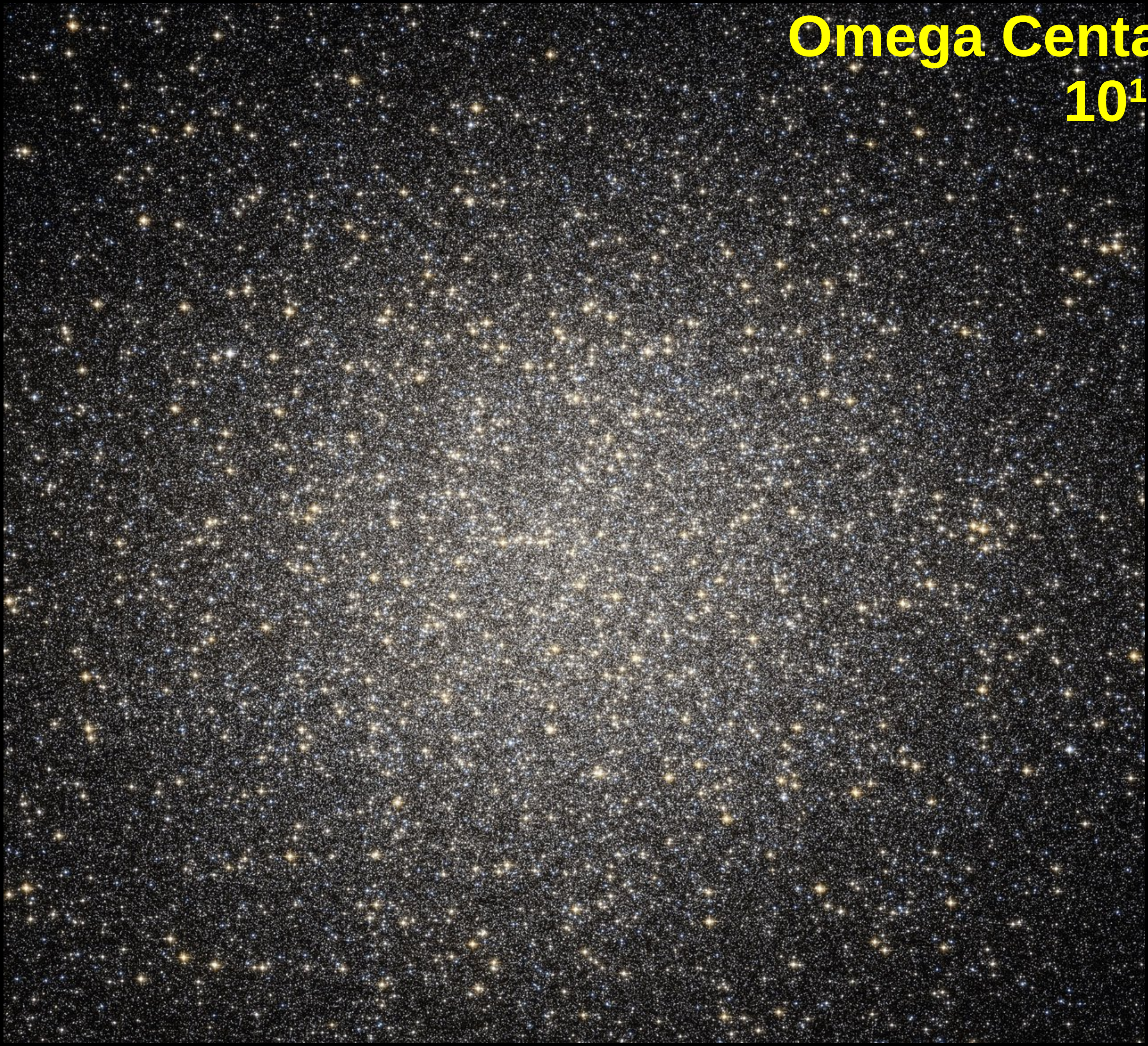

R 136 in the LMC
~ 3 x 10^6 yr


H and Chi Perseus
1 x10^7 yr
Credit & Copyright: Roth Ritter (Dark Atmospheres)

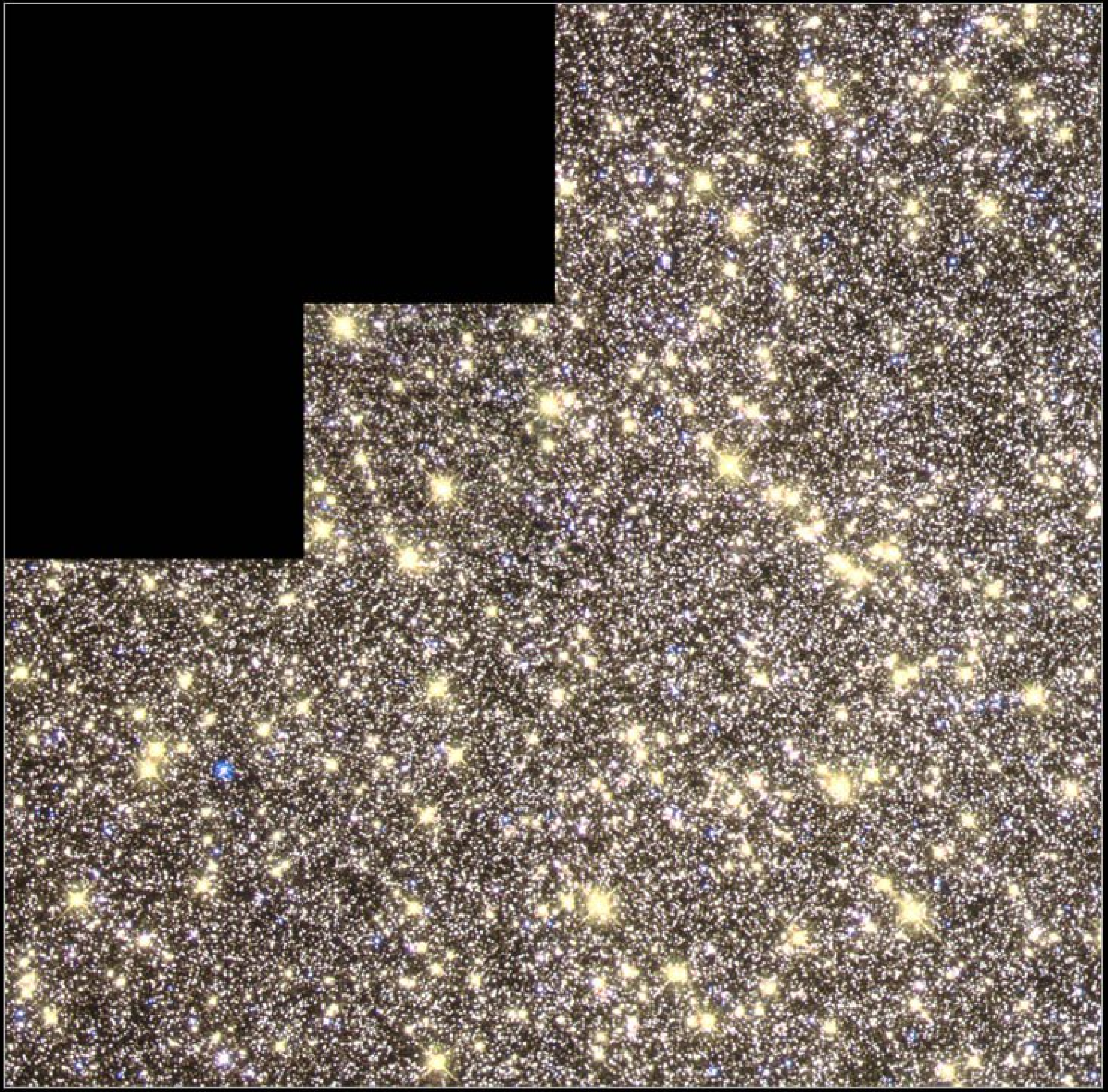

Pleiades
4 x 10⁸ yr


Omega Centauri

Omega Centauri
10^{10} yr

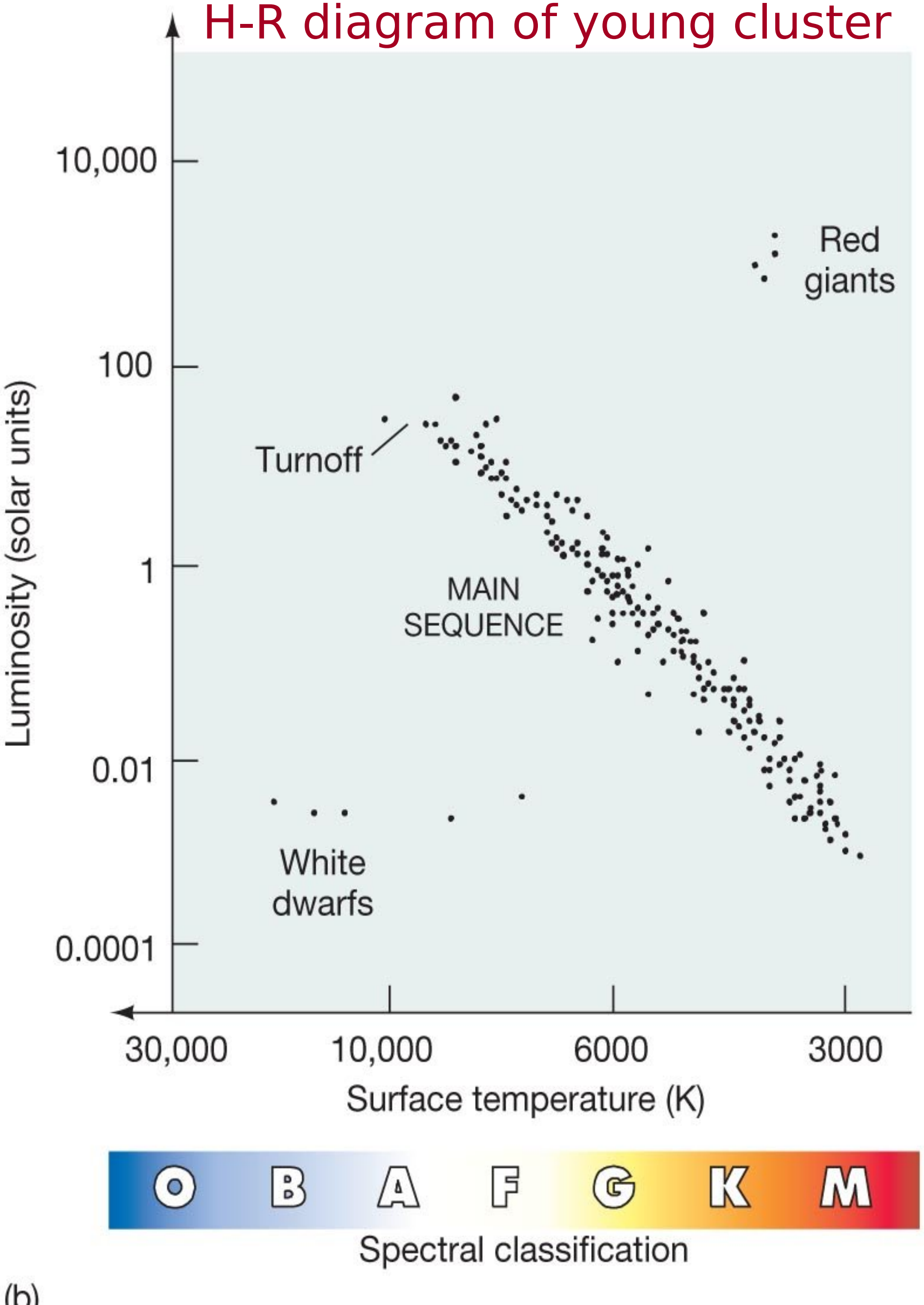


Globular Cluster Omega Centauri

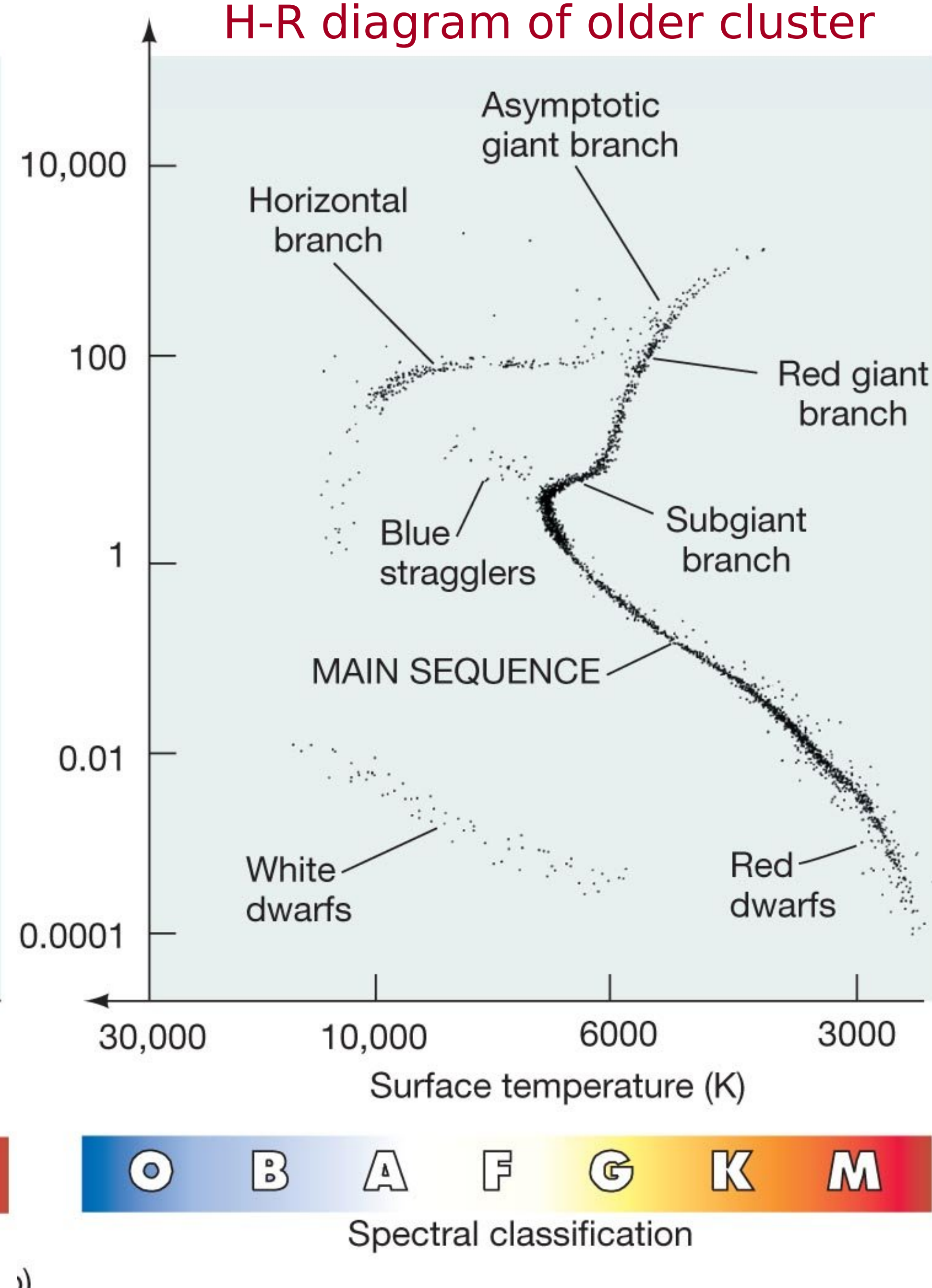


Hubble
Heritage

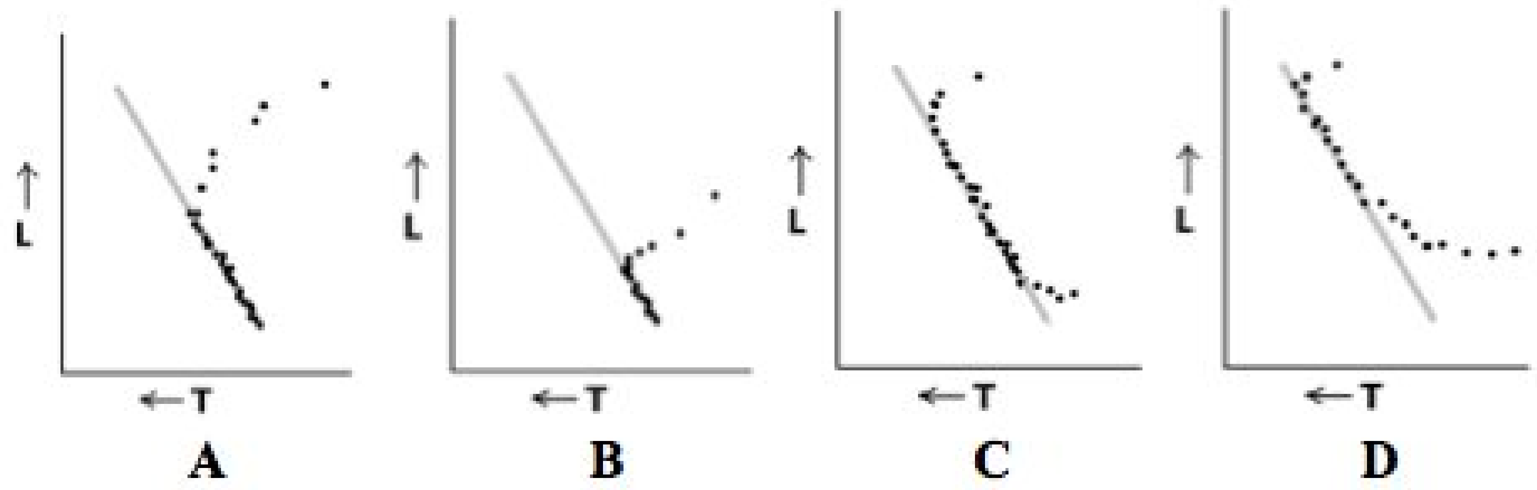
H-R diagram of young cluster



H-R diagram of older cluster



This figure shows H-R diagrams for four star clusters. Which one is the oldest?



A A

C C

B B

D D

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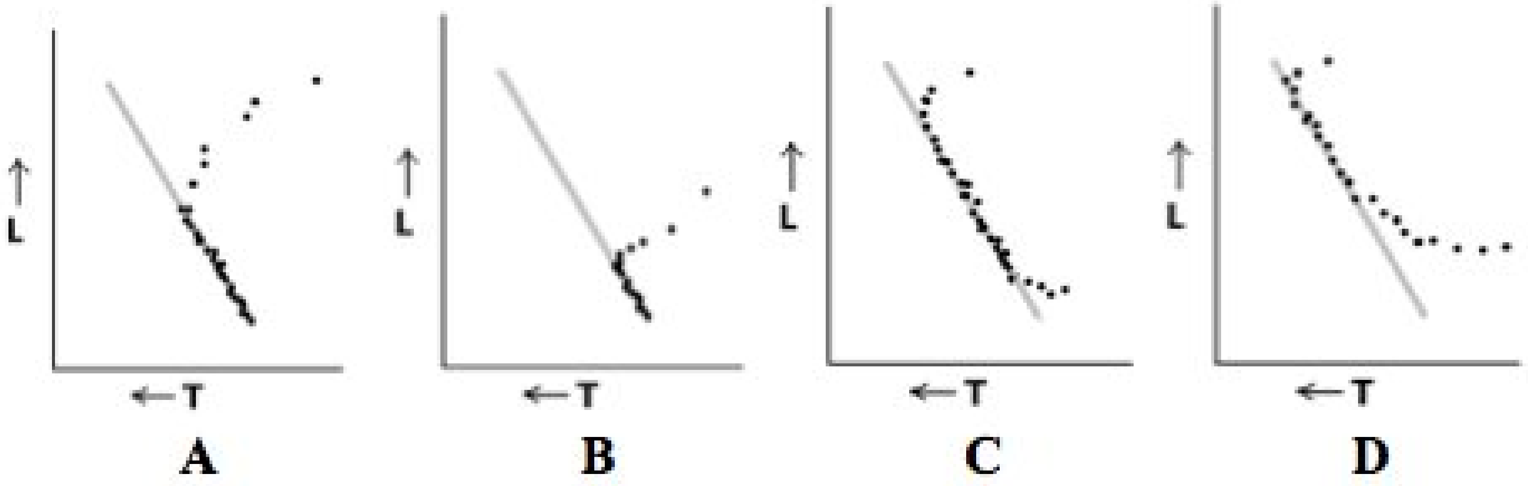

A A

C C

B B

D D

Outlook

- Read Chapter 13 – More details on neutron stars and black holes than we talked about in class
- Coming Up:
  Chapter 4-8: Solar System, Planets
- Midterm: October 29
  covers Chapters 3 (Telescopes) and 9-12 (Sun, Stars, Interstellar Medium, Stellar Evolution)
- After midterm: Extrasolar Planets and planetary highlights, Galaxies and Cosmology