

ASTR 1P02

Brock University

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Lecture 13: Properties of stars

We will learn about...

- Brown dwarfs.
- Stellar masses and their relation to luminosity.
- The Hertzsprung–Russell (H-R) diagram.
- Luminosity classes.
- Various types of stars.
- Measuring distances to the stars.
- And more...

Stellar masses

- Stars have a very wide range of masses.
- Usually, we measure stellar masses (masses of stars) in units of **solar mass** (the mass of our Sun):
$$M_{\odot} \approx 2 \times 10^{30} \text{ kg}$$
- The smallest-mass stars have a mass of $\sim M_{\odot}/12$. Below that mass, nuclear fusion of protons into helium to produce light cannot happen.

Stellar masses

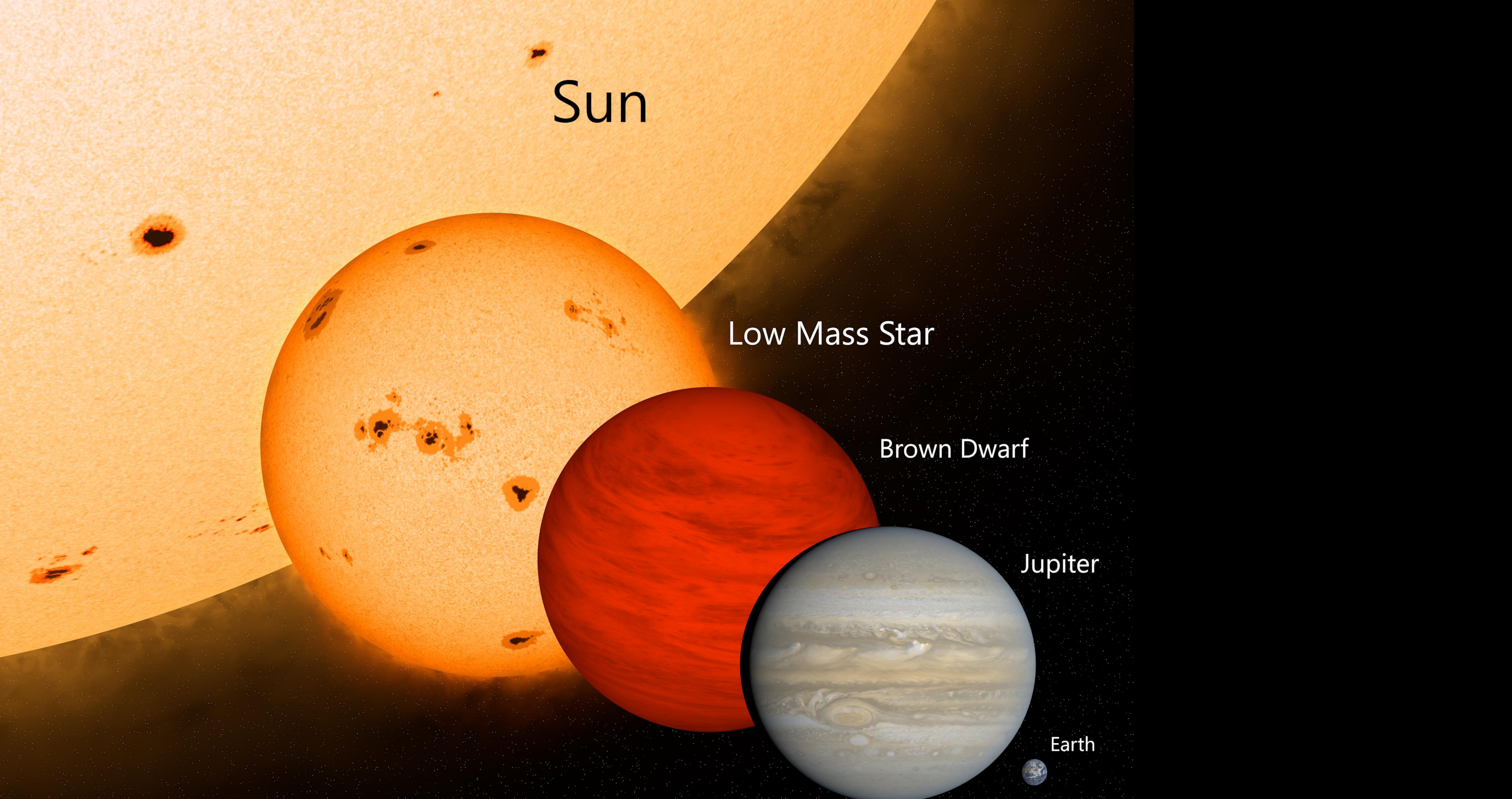
- Remember that **deuterium**, or hydrogen-2, is an isotope of hydrogen with 1 proton and 1 neutron.
- Objects with masses of $\sim M_{\odot}/80$ to $M_{\odot}/12$ cannot fuse protons like stars do, but they can fuse deuterium.
 - Deuterium fusion is the 2nd stage of the proton-proton chain.
- These objects are called **brown dwarfs**.
 - However, they are not necessarily brown; the warmest can be orange or red, and the coldest can appear magenta or black.
- Brown dwarfs are also known as **failed stars** because they “failed” to achieve proton fusion.

Stellar masses

- The **mass of Jupiter** is $M_J \approx 2 \times 10^{27}$ kg. So Jupiter is $\sim 1,000$ times less massive than the Sun.

$$1 M_{\odot} \approx 1,000 M_J$$

- Brown dwarfs have masses between ~ 13 to $80 M_J$. They are less massive than stars, but more massive than planets.
- Planets do not generate their own light by nuclear reactions. Brown dwarfs do, but only very little light.



Sun

Low Mass Star

Brown Dwarf

Jupiter

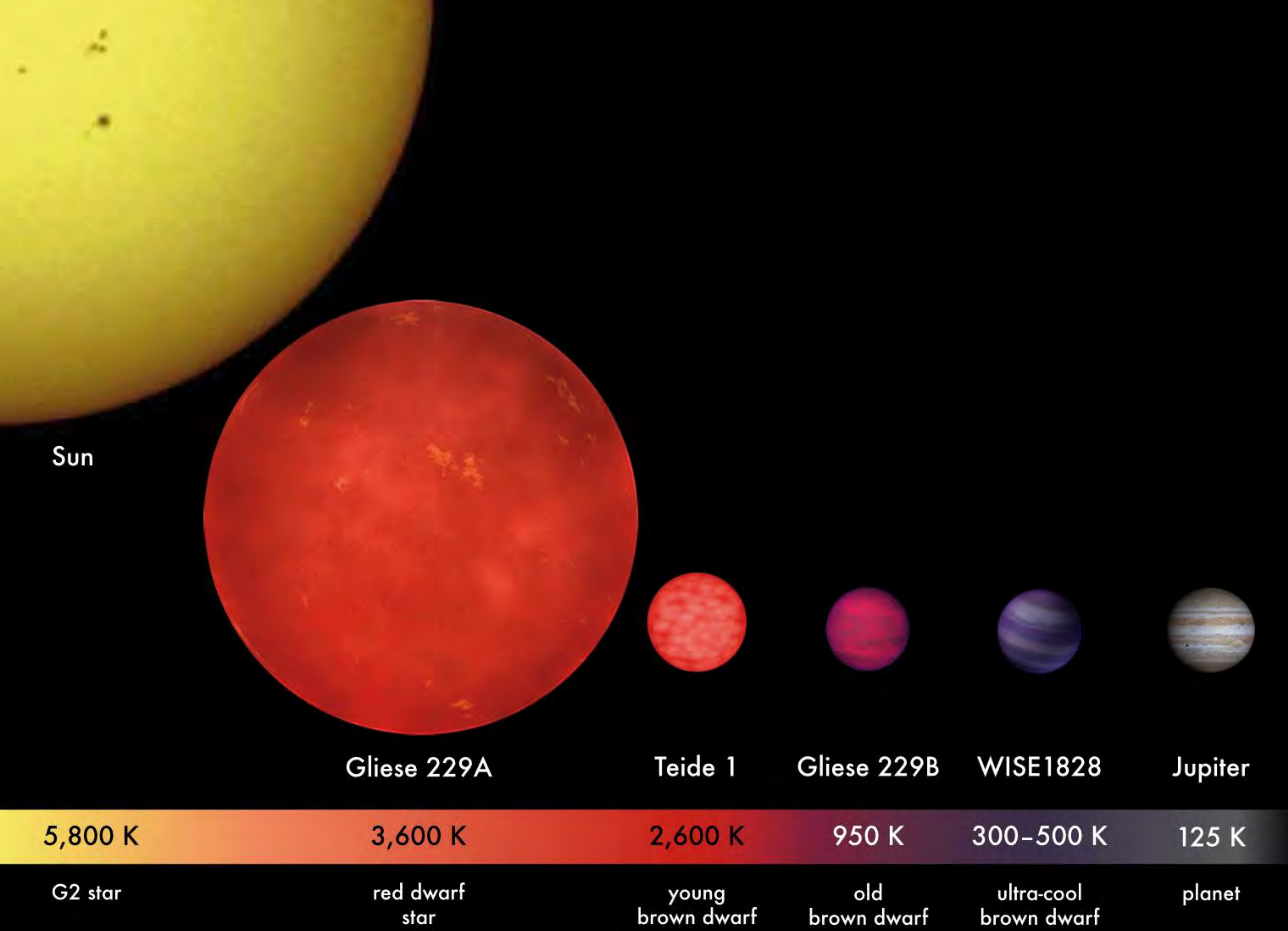
Earth

Comparison of stars, brown dwarfs, and planets. Brown dwarfs are only slightly larger than Jupiter, but they are up to 80 times more massive, which means they have much higher density.

Credits: Planetkid32 (Wikipedia)

Stellar masses

- Recall the spectral classes for stars, which are, from hottest to coldest: O, B, A, F, G, K, and M.
- The hottest brown dwarfs are of class M, but colder brown dwarfs belong to additional spectral classes: L, T, and Y.
- These dwarfs are so cold that most of their light is in the infrared spectrum.
 - Remember, infrared has a lower frequency compared to red, and thus corresponds to lower energy and colder temperatures.



Comparison of stars, brown dwarfs, and planets, showing temperatures and colors.

Credits: Planetkid32 (Wikipedia)

Stellar masses

- More massive stars are also more luminous.
- The luminosity L and mass M of a star are related by the equation
$$L \sim M^4$$
- So if the mass increases by a factor of 2, the luminosity increases by a factor of $2^4 = 16$.
 - The exponent 4 works for stars with masses between 0.4 and $2 M_{\odot}$. For other mass ranges, the exponent will be different, but the general rule that luminosity increases with mass is true for all stars.

Simulation

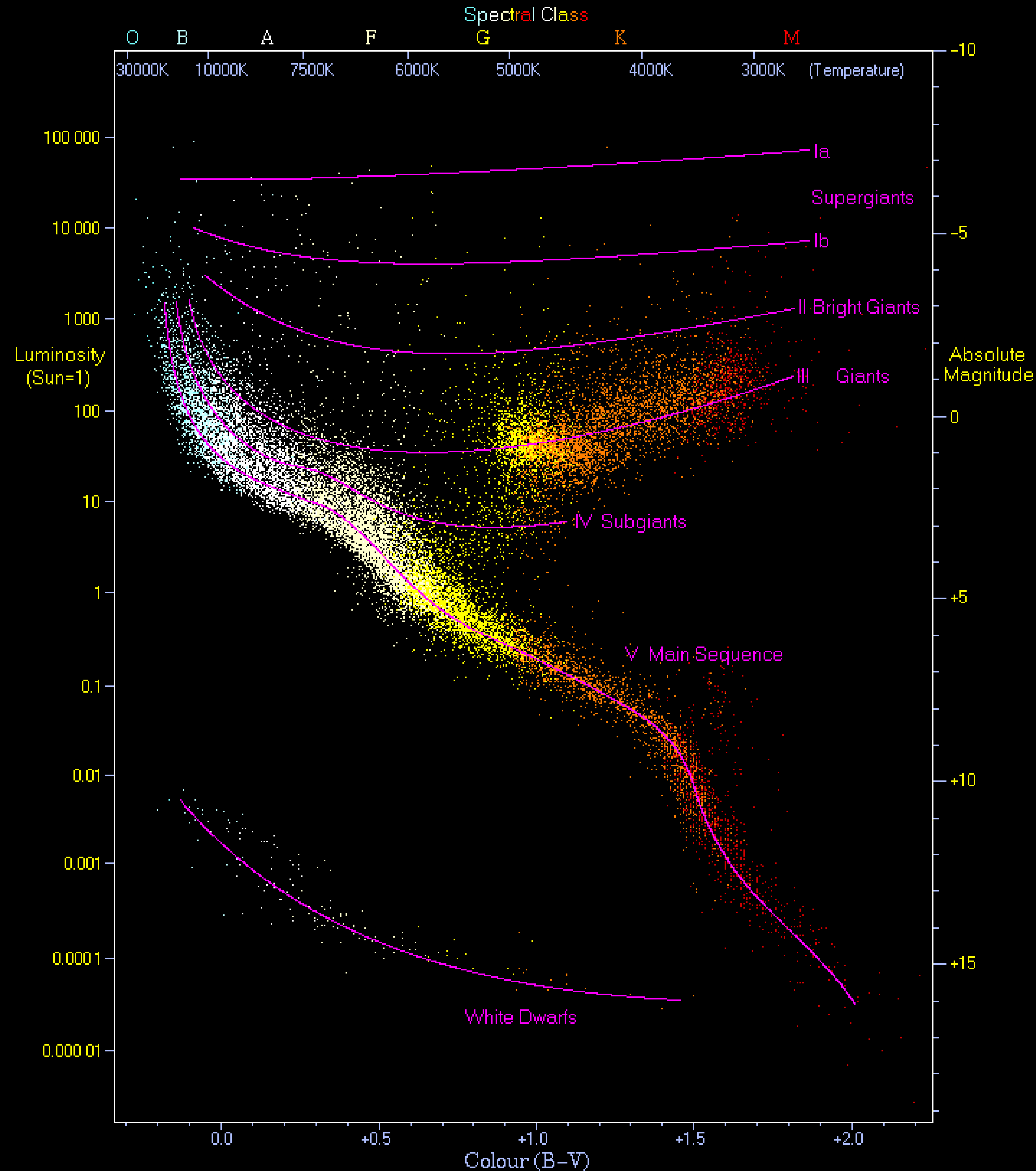
- The following simulation calculates the luminosity, as well as temperature, color, and other properties of stars, as a function of mass.
- It can be found at this URL:

<https://applets.kcvs.ca/StarMaker/starmaker.html>

H-R diagrams

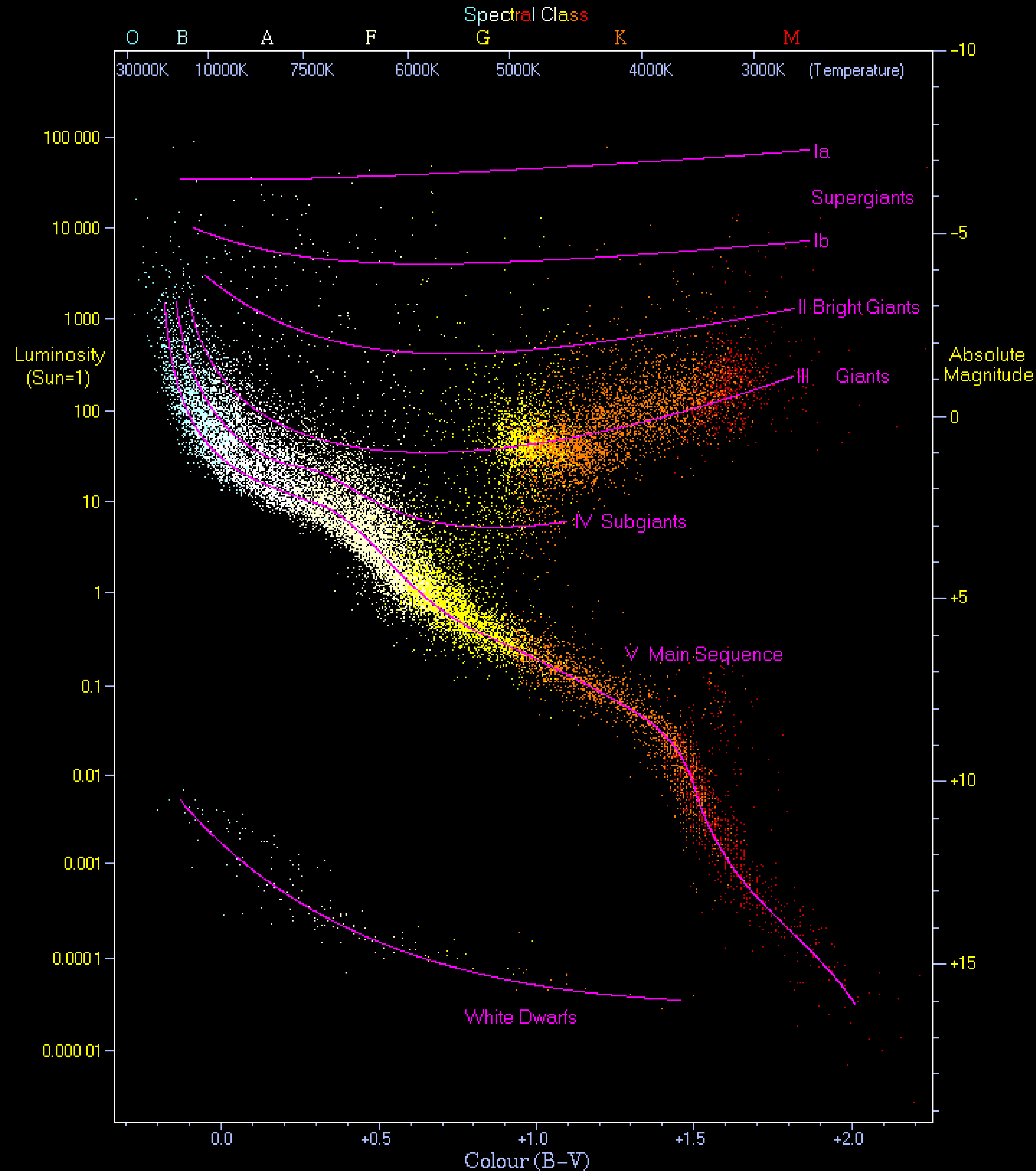
- The **Hertzsprung–Russell (H-R) diagram** is a plot of stars according to two defining properties:
 - Horizontal axis: temperature (or spectral class). Hotter temperatures are to the left.
 - Vertical axis: luminosity (or absolute magnitude). Brighter luminosity is toward the top.
- H-R diagrams are very important in astronomy, because when stars are plotted on this diagram, we notice some interesting relationships and patterns.

- Clearly, the stars are not distributed randomly. They cluster into several main regions.
- Most stars are along the **main sequence**, the diagonal from the upper left (bright and hot) to the lower right (dim and cold).
- For stars on the main sequence, hotter temperature means more luminosity.



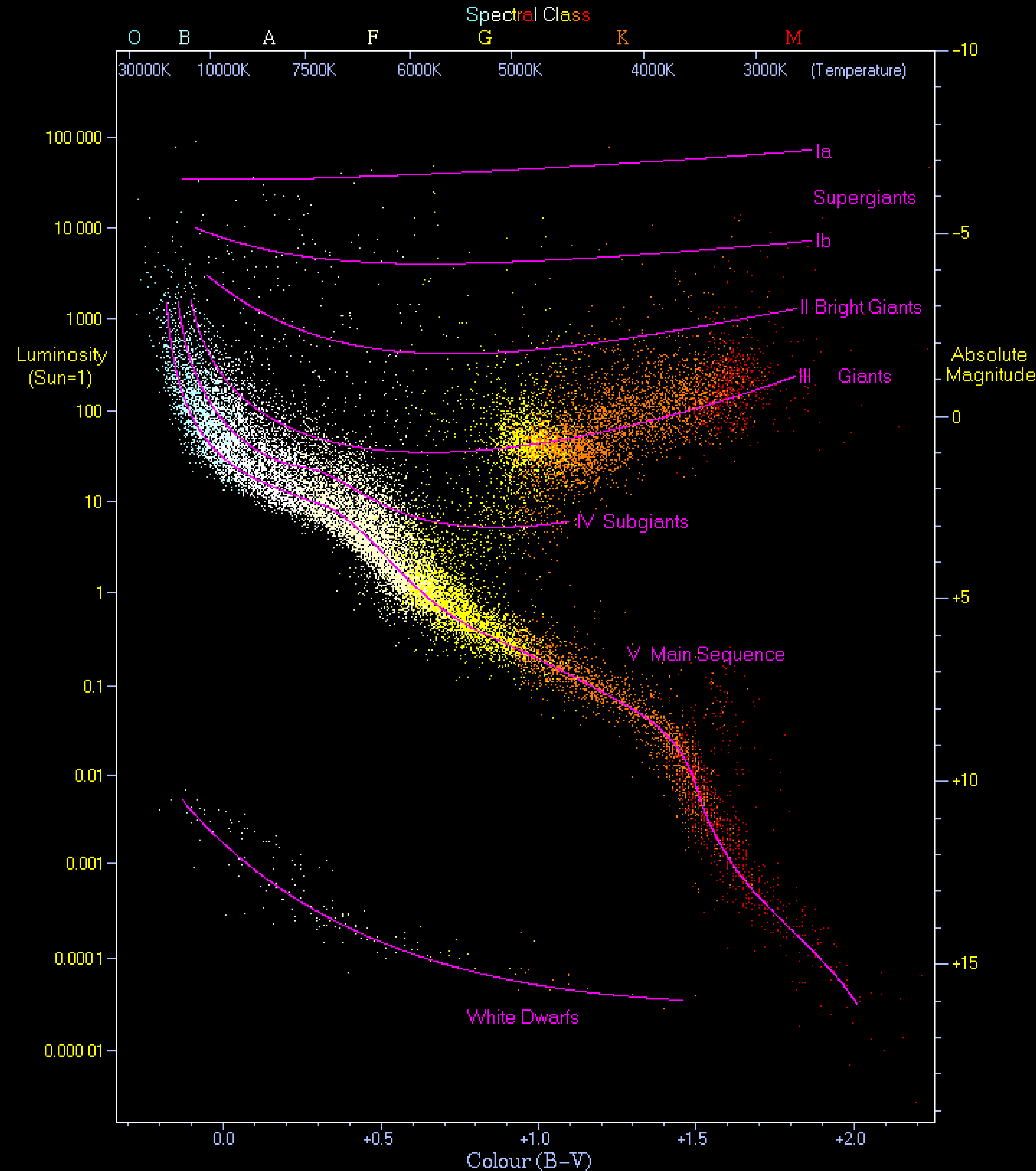
A Hertzsprung-Russell diagram with 23,000 stars.
Credits: Richard Powell

- On the upper right we find various types of **giants**.
- Giants have low temperature but high luminosity.
- The energy they emit per square meter of surface area is small, due to their low temperature.
- So for these stars to have luminosity equivalent to very hot main-sequence stars, their total surface area must be huge.
- Therefore, giants are much larger than main-sequence stars.



A Hertzsprung-Russell diagram with 23,000 stars.
Credits: Richard Powell

- On the bottom left we find a few **white dwarfs**.
- White dwarfs have high temperature but low luminosity.
- By the same logic as for giants, white dwarfs must be very small, so they don't emit too much light despite their very high temperatures.

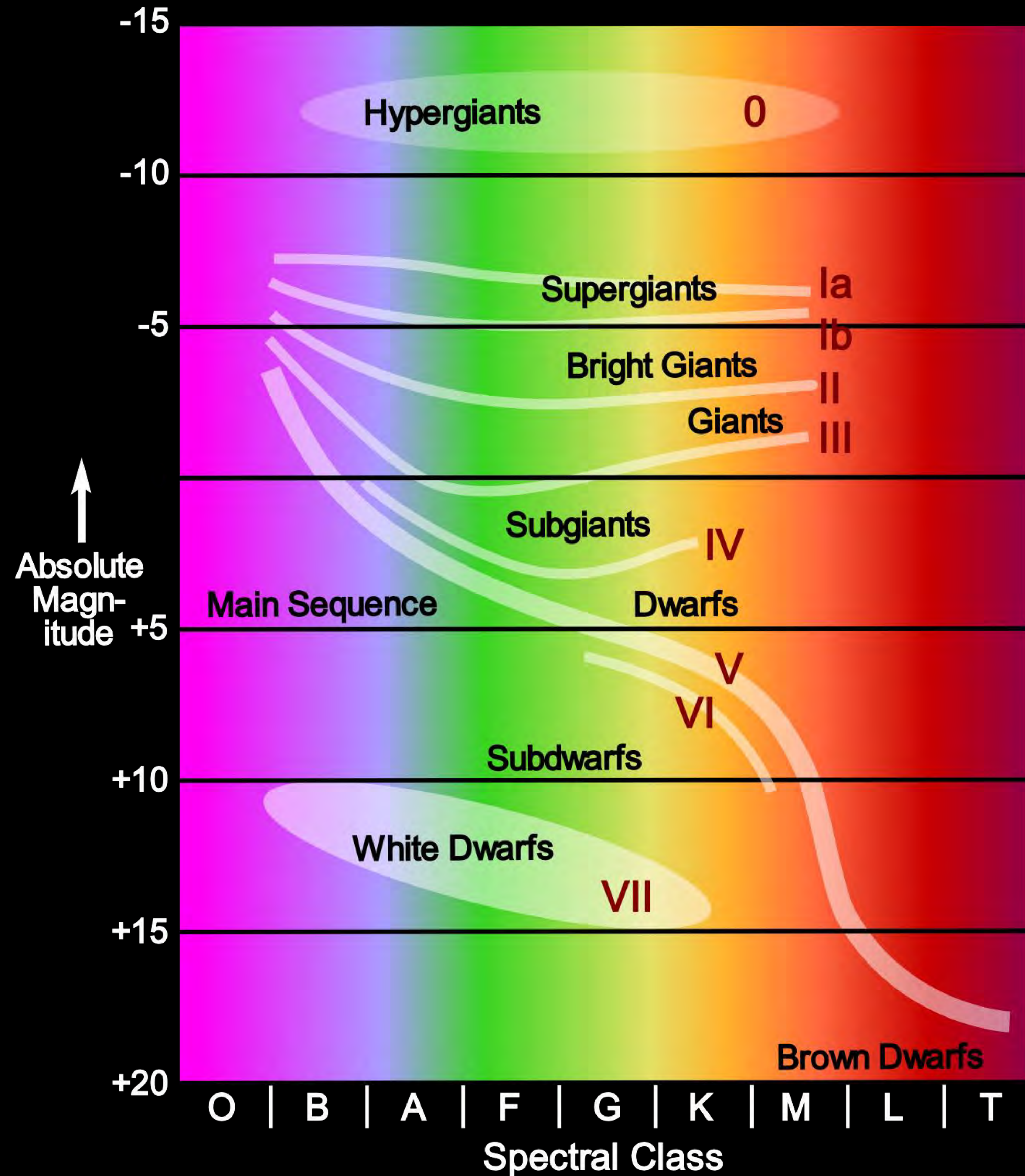


A Hertzsprung-Russell diagram with 23,000 stars.
Credits: Richard Powell

- We can classify stars on the diagram into **luminosity classes**:

- 0 or Ia⁺: **hypergiants** (extremely luminous supergiants)
- Ia: more luminous **supergiants**
- Ib: less luminous supergiants
- II: **bright giants** (between normal giants and supergiants)
- III: normal **giants**
- IV: **subgiants** (less bright than giants)
- V: **main sequence stars** (sometimes confusingly called “dwarfs”)
- VI: **subdwarfs** (less luminous than main sequence stars)
- VII: **white dwarfs**

- We write the luminosity class next to the spectral class, e.g. B2V is a main-sequence B2.



H-R diagrams

- Main sequence stars are sometimes called “dwarfs”. This is confusing because they’re not necessarily smaller than giants, and brown or white dwarfs are not on the main sequence.
- Dwarfs are categorized by color, but this definition is not very consistent; different sources define them differently.
- **Red dwarfs:** class MV, can also include cold KV and hot LV.
 - The dimmest, smallest, and coldest main sequence stars; also the most common type of star.
 - Temperature: $\sim 2,000\text{-}3,900$ K, mass: $\sim 0.07\text{-}0.6 M_{\odot}$.
 - Example: Proxima Centauri (M5.5V).



Proxima Centauri, false-color image. It is the closest star to the Sun. Note the 4 diffraction spikes, distinctive of photos from the Hubble Space Telescope.

Credits: ESA / Hubble & NASA

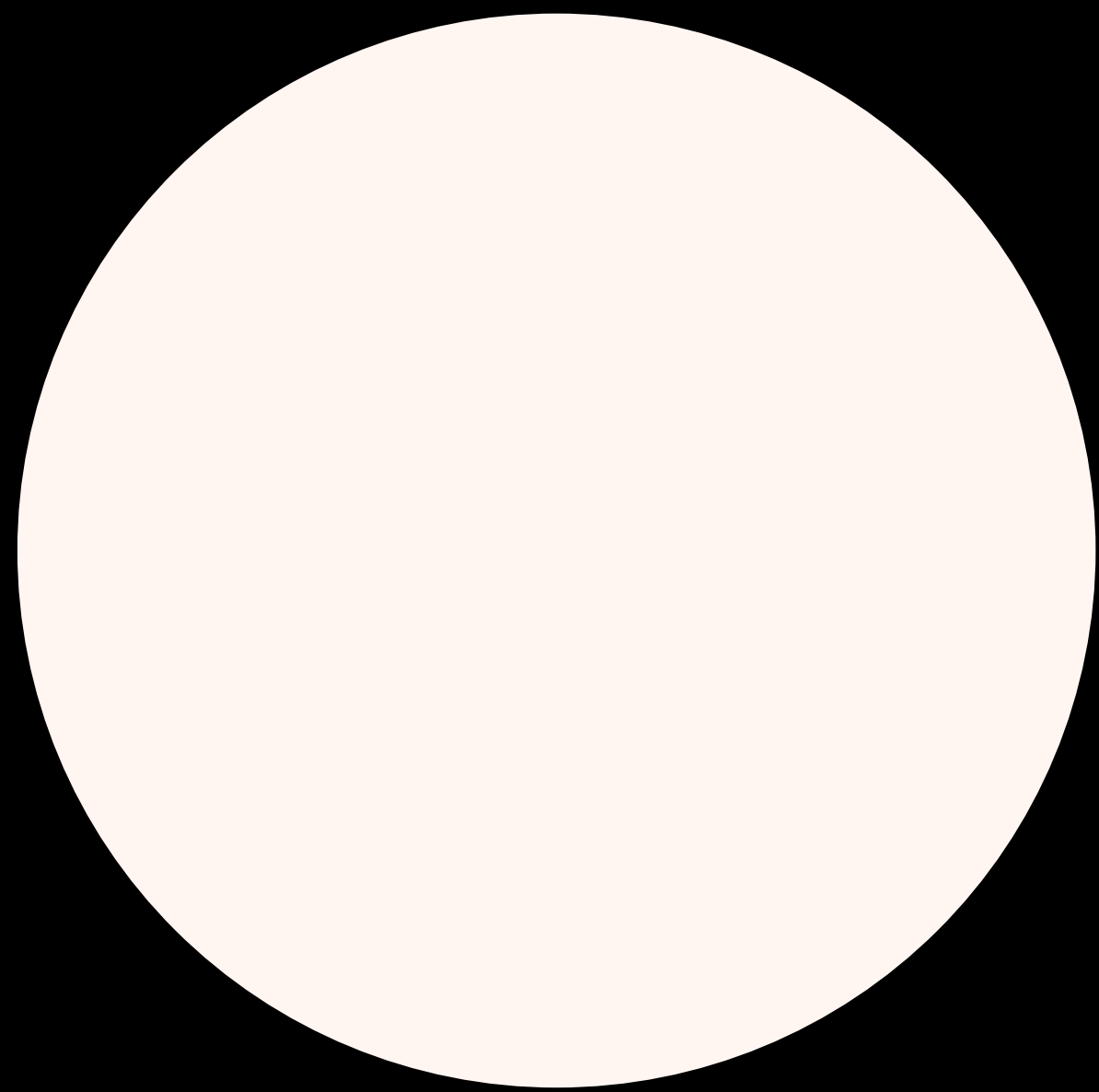
H-R diagrams

- **Orange dwarfs:** class KV.
 - Temperature: $\sim 3,900\text{-}5,300$ K, mass: $\sim 0.6\text{-}0.9 M_{\odot}$.
 - Example: Alpha Centauri B (K1V).
- **Yellow dwarfs:** class GV.
 - Temperature: $\sim 5,300\text{-}6,000$ K, mass: $\sim 0.9\text{-}1.1 M_{\odot}$.
 - Examples: The Sun (G2V), Alpha Centauri A (G2V).
 - Not really yellow; most GV stars, including the Sun, are actually white.

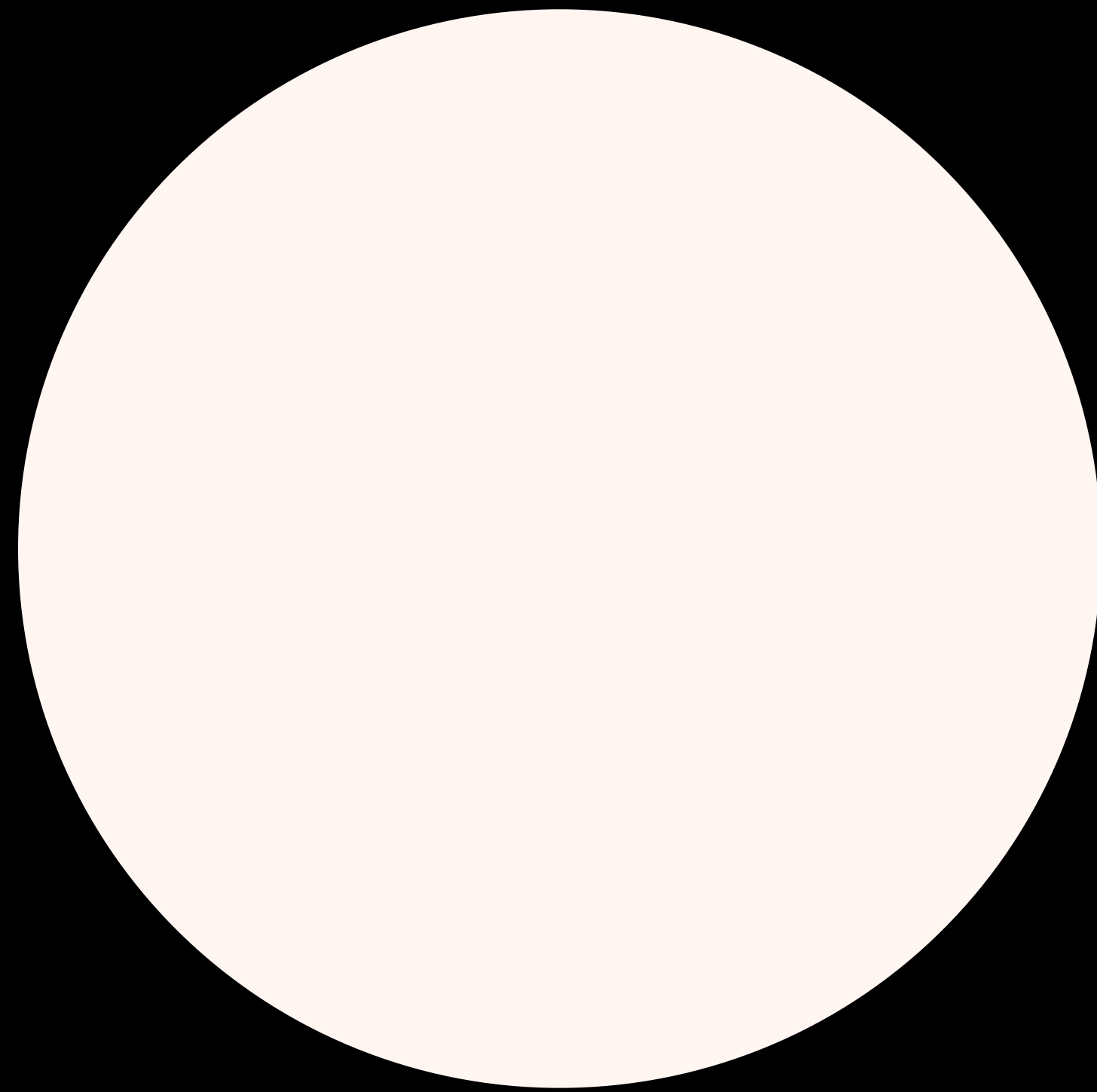


Alpha Centauri A (left) and B (right), a binary system. Together with Proxima Centauri (a.k.a. Alpha Centauri C), they form a triple star system.

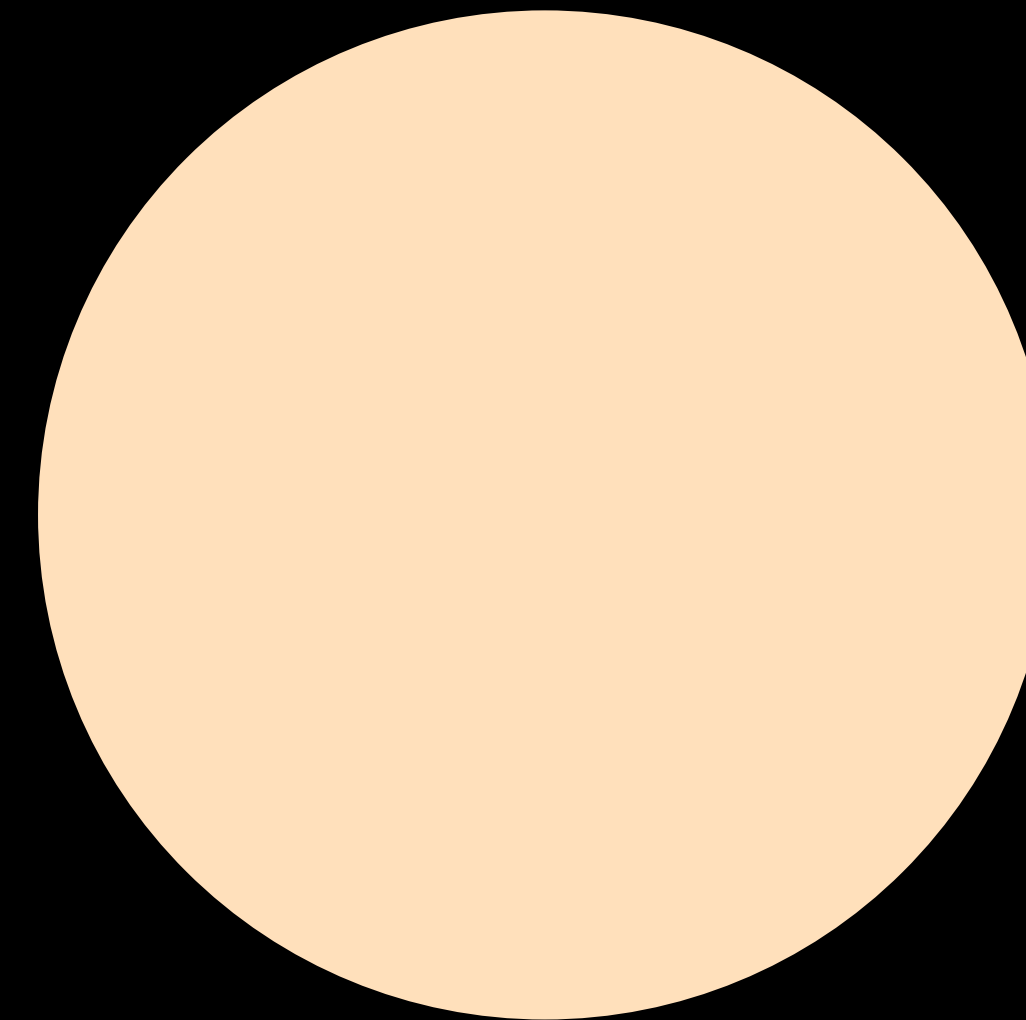
Credits: ESA / Hubble & NASA



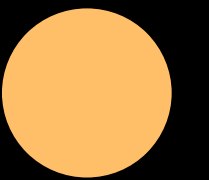
Sun



α Centauri A



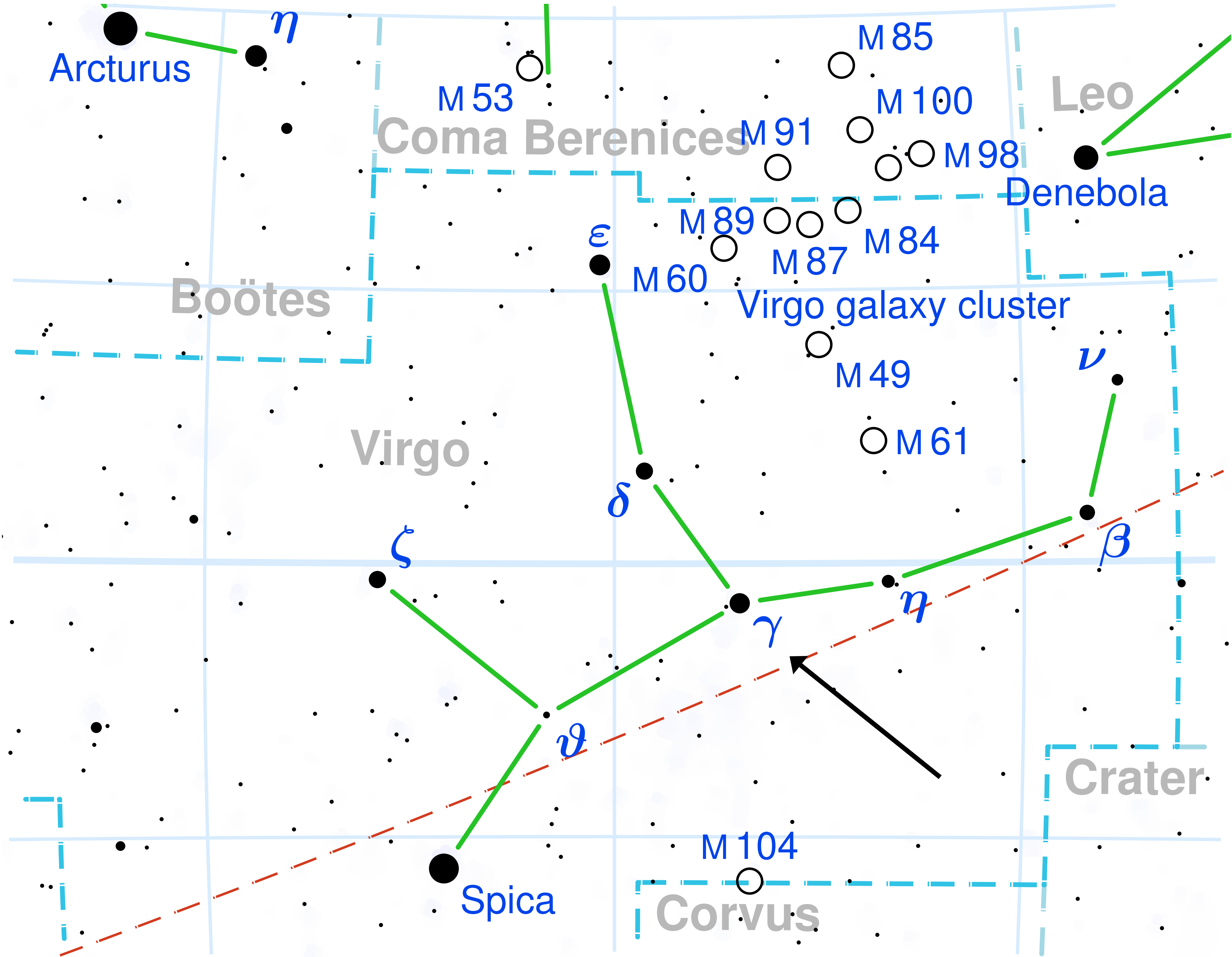
α Centauri B



Proxima

H-R diagrams

- **Yellow-white dwarfs:** class FV.
 - Temperature: $\sim 6,000\text{-}7,600$ K, mass: $\sim 1.1\text{-}1.4 M_{\odot}$.
 - Examples: Gamma Virginis A and B (F0V)
- **A dwarfs:** class AV.
 - Temperature: $\sim 7,600\text{-}10,000$ K, mass: $\sim 1.4\text{-}2.1 M_{\odot}$.
 - Example: Vega (A0V).



When a star's name contains a Greek letter and a constellation name, typically it is one of the main stars in the constellation. Here, Gamma (γ) Virginis is shown in the Virgo constellation.

Credits: Torsten Bronger

H-R diagrams

- The hottest main sequence stars are not usually called “dwarfs”, because they are larger than the colder main sequence stars.
- However, they are still not as large as giants.
- **B-type main-sequence stars:** class BV.
 - Temperature: $\sim 10,000\text{-}30,000$ K, mass: $\sim 2.1\text{-}16 M_{\odot}$.
 - Example: Algol A (B8V).
- **O-type main-sequence stars:** class OV.
 - Temperature: $\sim 30,000\text{-}50,000$ K, mass: $\sim 16\text{-}90 M_{\odot}$.
 - Example: 10 Lacertae (O9V).

H-R diagrams

- Giants are also divided into several color/temperature categories.
- **Red giants:** giants with the coldest temperatures.
 - Spectral classes K and M, sometimes also G.
 - Example: Arcturus (K1.5III).
- **Yellow giants:** giants with intermediate temperatures.
 - Spectral classes G, F, and sometimes also A.
 - Example: Sigma Octantis (F0IV).
- **Blue giants:** giants with the hottest temperatures.
 - Spectral classes O, B, and sometimes also A.
 - Example: Alcyone (B5III).

H-R diagrams

- We estimate that:
 - ~90% of stars are on the main sequence.
 - ~10% are white dwarfs.
 - Less than ~1% are giants.
- It turns out that the different categories correspond to different stages in the lifetime of a star.
- Stars are created when clouds of dust collapse under their own gravity (we will learn more about this later).
- They then spend 90% of their lives in the main sequence.
- Giants and white dwarfs represent later life stages of stars.

Simulation

- We will explore the H-R diagram using a simulation.
- It can be found at this URL:

http://astronomy.nmsu.edu/geas/labs/hrde/hrd_explorer.html

Video

- To get an idea of the huge range of sizes of stars, we will watch a video comparing the sizes of celestial bodies, from dwarf planets, though different types of stars, to galaxies, to the whole universe.
- We already saw this video in the beginning of ASTR 1P01, but now we are better equipped to understand what we're seeing.
- The video is available at this URL:

<https://youtu.be/i93Z7zljQ7I>

Video

- Objects in the video smaller than stars:
 - Ceres: dwarf planet
 - The Moon
 - Callisto: moon of Jupiter
 - Mercury
 - Mars
 - Venus
 - Earth
 - Kepler 22b: exoplanet
 - Neptune
 - Uranus
 - Saturn
 - Jupiter

Video

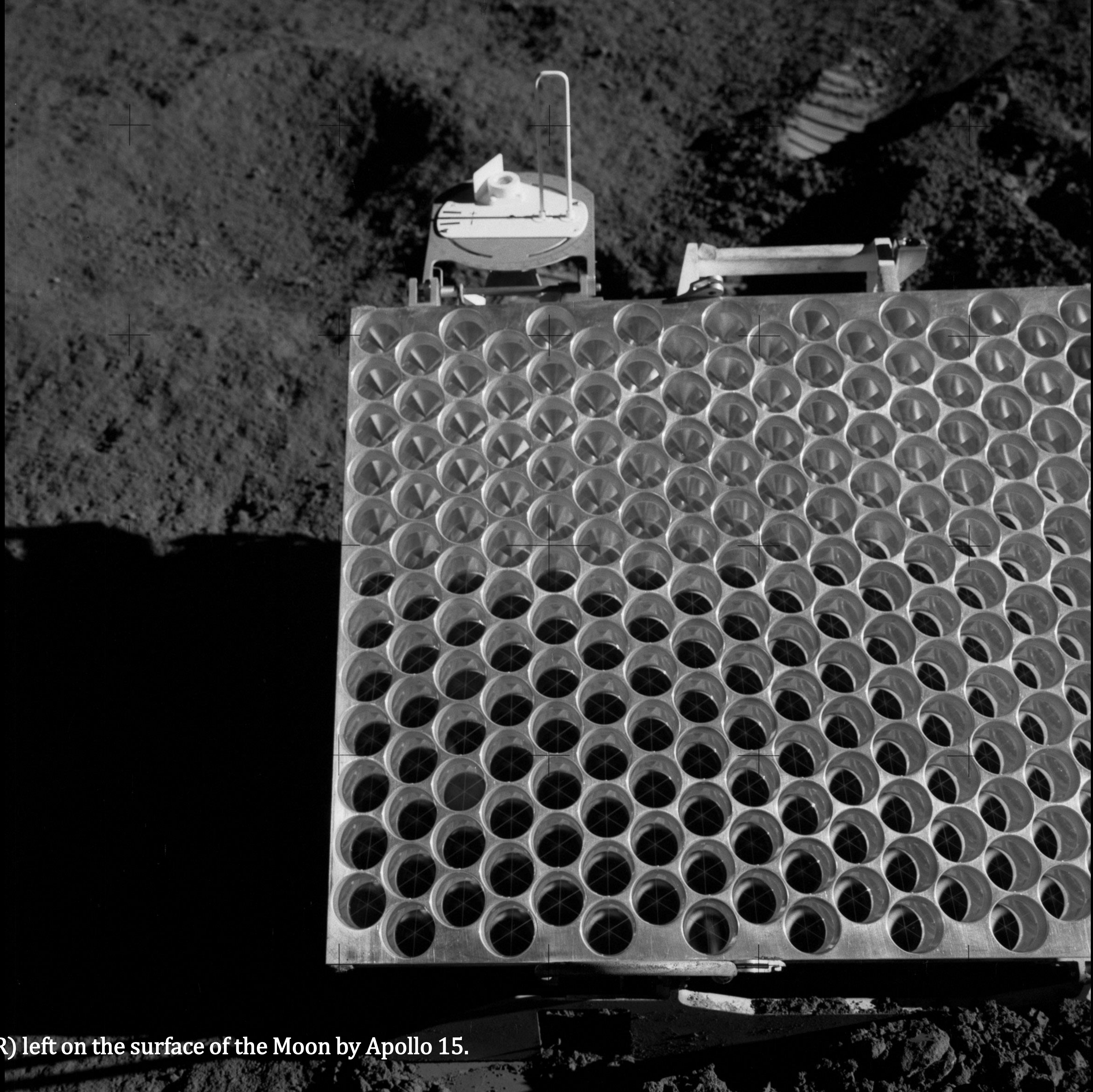
- Stars in the video and their classifications:
 - Proxima Centauri (sen-TOR-eye): M5.5V (red dwarf)
 - The Sun: G2V (yellow dwarf)
 - Sirius A: A0V (A dwarf)
 - Vega: A0V (A dwarf)
 - Arcturus: K1.5III (red giant)
 - Rigel: B8Ia (blue supergiant)
 - Betelgeuse: M1Ia (red supergiant)
 - VY Canis Majoris (CAN-iss muh-JOR-iss): M4Ia⁺ (red hypergiant)
 - UY Scuti (SCOOT-eye): M2Ia⁺ (red hypergiant)

Video

- Larger objects in the video (we will learn more about them later):
 - NGC 1277: supermassive black hole at the center of a galaxy
 - TON 618: larger supermassive black hole
 - Cat's Eye Nebula: huge cloud of gas and dust
 - Helix Nebula
 - Orion Nebula
 - Omega Centauri: globular cluster, a spherical-shaped cluster of ~ 10 million stars
 - Small Magellanic Cloud: dwarf galaxy near the Milky Way
 - The Milky Way
 - IC 1101: giant galaxy
 - Bootes Void: an enormous, almost empty region of space with very few galaxies
 - The Universe: at least the observable part; the entire universe may be infinite

Celestial distances

- Distances to objects close to us can be measured directly.
- For example, we can measure the distance to the Moon ($\sim 384,000$ km) by reflecting a laser beam off it, up to a 1 mm accuracy!
- Since we know the speed of light ($\sim 300,000$ km/s), we can determine the distance by measuring how long it takes the laser beam to get back to us.
- There are currently 5 **retroreflectors** (devices which reflect light) on the Moon, placed there by the **Apollo** and **Luna** missions between 1969 and 1973.



The Lunar Ranging Retro Reflector (LRRR) left on the surface of the Moon by Apollo 15.

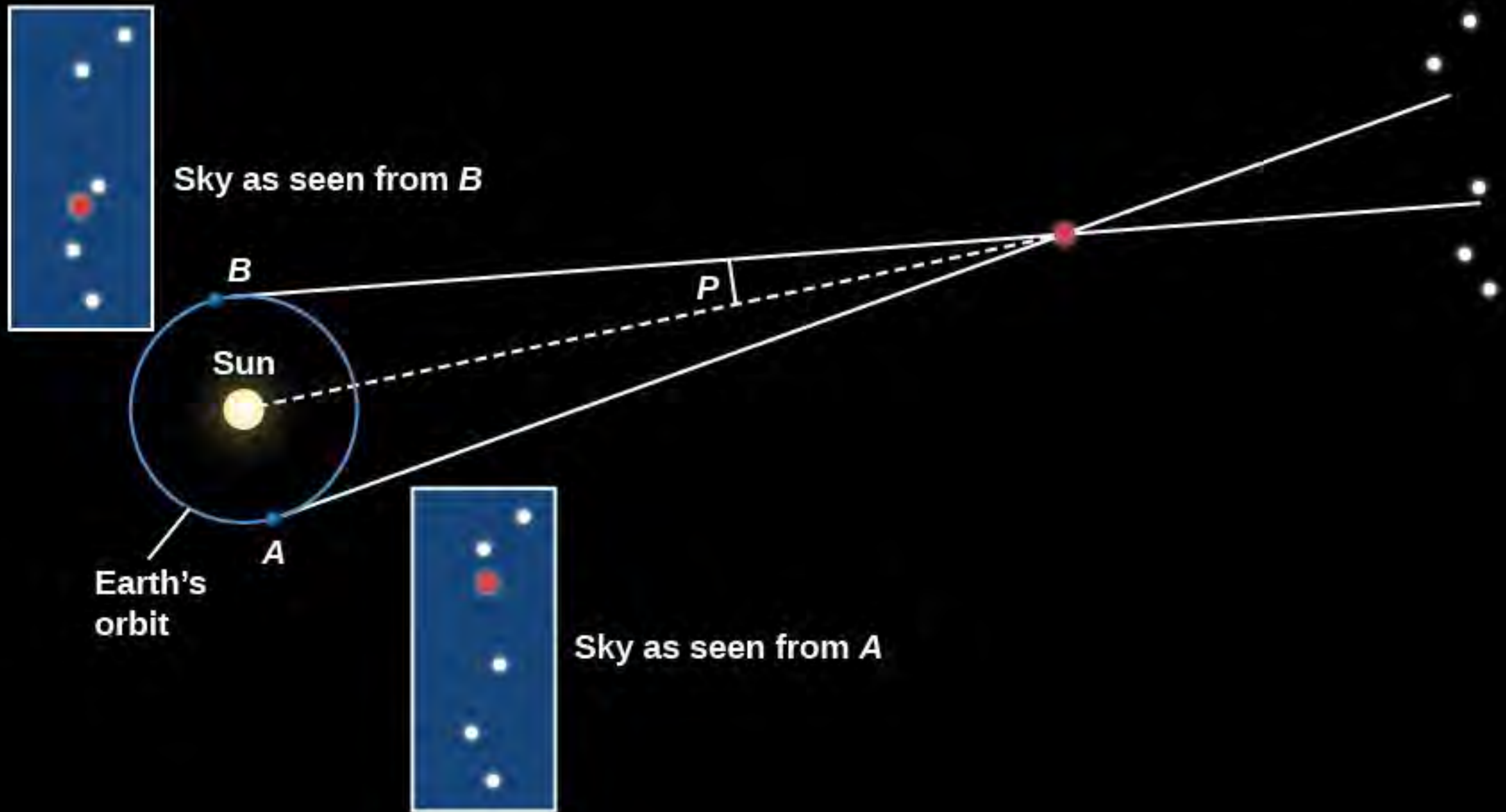
Credits: Dave Scott, NASA



The locations of the lunar retroreflectors left by Apollo (A) and Luna (L) missions.
Credits: NASA

Celestial distances

- Stars are so far away that even light takes many years to travel the distance. So we cannot measure the distance to stars directly.
- Instead, there are some indirect methods.
- One such method is **stellar parallax**, which we learned about in lecture 3 of ASTR 1P01.
- By observing how a star moves with respect to farther away stars (which do not move as much), we can estimate the distance to the star with simple trigonometry.



Stellar parallax. Note that the parallax angle P is actually half the total parallax angle, because we like to have a baseline of 1 AU, which is half the diameter of the Earth's orbit.

Credits: OpenStax Astronomy

Celestial distances

- Recall there are 3,600 **arcseconds** in an angle of 1 degree.
- The parallax of a star is measured in the sky in arcseconds (the entire sky is 360°).
- A star with a parallax of 1 arcsecond is located ~ 3.26 light-years or $\sim 3.09 \times 10^{13}$ kilometers away.
- This distance is called a **parsec** (parallax of 1 second), symbol **pc**.
- A star with a smaller parallax angle is farther away. The basic formula is:

$$\text{distance in parsecs} = \frac{1}{\text{parallax in arcseconds}}$$

Pop quiz

$$\text{distance in parsecs} = \frac{1}{\text{parallax in arcseconds}}$$

- You observed that a star has a parallax angle of 0.5 arcseconds. What is the distance to the star?

A: 5 parsecs

B: 0.5 parsecs

C: 2 parsecs

Pop quiz

- The correct answer is:

C: 2 parsecs

$$\frac{1}{0.5 \text{ arcseconds}} = 2 \text{ parsecs}$$

Celestial distances

- Let us summarize the units commonly used in astronomy to measure distances:
 - **Meter:** Defined using the speed of light as the distance light travels in $\sim 1/300,000,000$ of a second, denoted m.
 - Often, we use units of kilometer ($1 \text{ km} = 1,000 \text{ m}$).
 - **Light-year:** The distance that light travels in a year, denoted ly.
 - **Parsec:** The distance to a star with a parallax of 1 arcsecond, denoted pc.
- $1 \text{ ly} \approx 0.31 \text{ pc} \approx 9.46 \text{ trillion km}$.
- $1 \text{ pc} \approx 3.26 \text{ ly} \approx 30.9 \text{ trillion km}$.

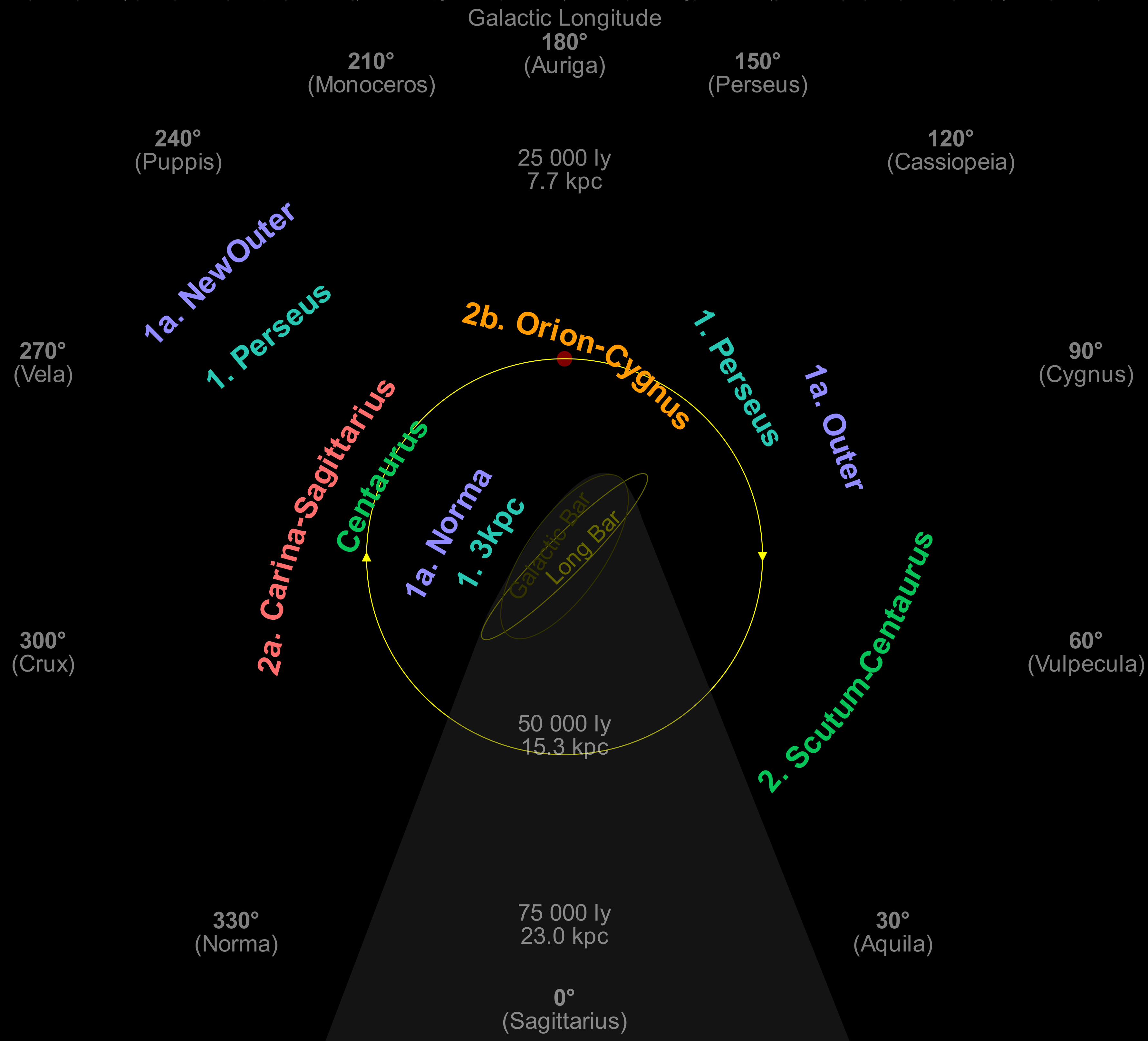
Simulation

- This simulation shows the effects of stellar parallax for stars at different distances.
- It can be found at this URL:

<https://www.compadre.org/osp/EJSS/3571/9.htm>

Celestial distances

- In stellar parallax, we measure how a star moves with respect to farther stars that don't appear to move. So stellar parallax only works for stars that are relatively close to us.
- The European Space Agency's **Gaia space observatory** is currently (until 2025) measuring parallaxes of stars up to 30,000 ly away.
- The Milky Way has a radius of $\sim 87,000$ ly. The Sun is located $\sim 27,000$ ly from the center of the galaxy.
- This means that many stars in the galaxy are too far away to measure their distance using stellar parallax, and it definitely cannot be used to measure distances to other galaxies.



Artist's conception of the Milky Way galaxy.
 Credits: NASA/JPL-Caltech/ESO/R. Hurt

Celestial distances

- Remember the **inverse-square law** of light: brightness decreases with the square of the distance.
- If all stars had the same luminosity, the farther ones would look dimmer and the closer ones would look brighter, so we could use the inverse-square law to calculate distances.
- However, this is not the case; as we have seen from the H-R diagram, stars have a huge range of luminosities.

Celestial distances

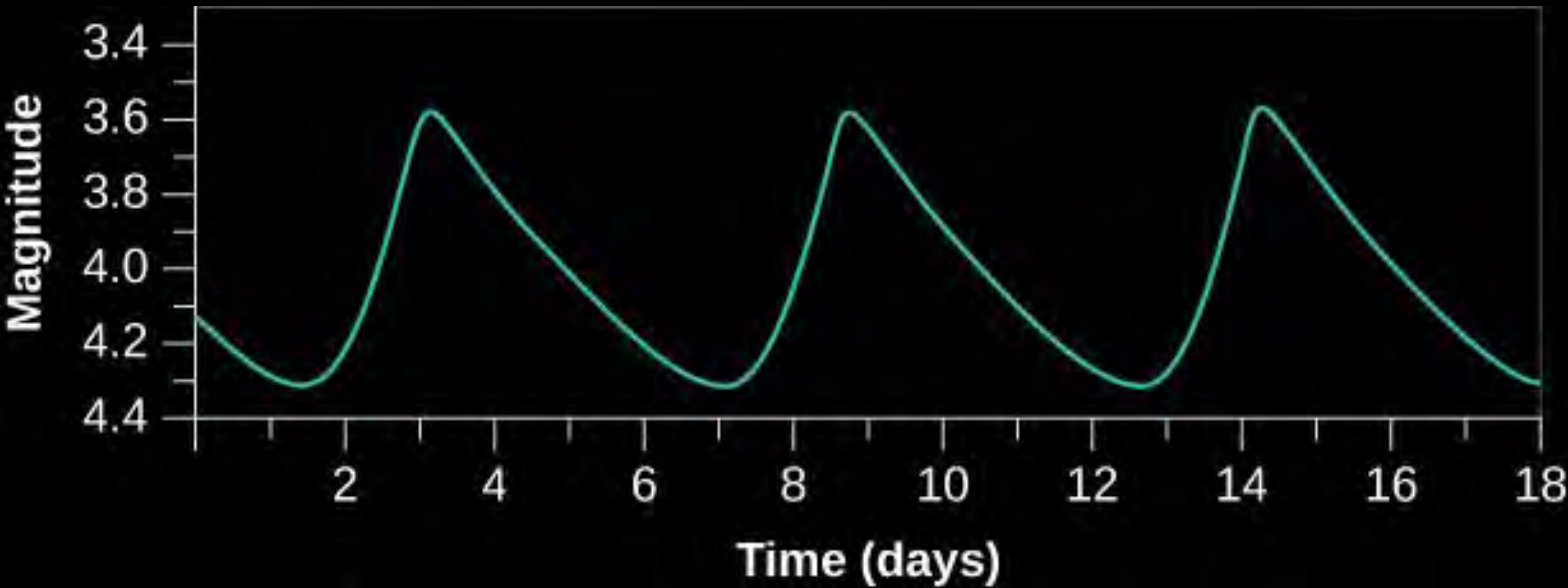
- If we knew that a specific type of stars always have the same luminosity, then we could compare the apparent brightness of different stars of the same type to find the distances to them.
- These types of stars are referred to as “**standard candles**”.
- One example of standard candles are **variable stars**. These are stars with brightness that varies over time.

Celestial distances

- Some variable stars are **pulsating stars**, which expand and contract periodically.
- This pulsation can be detected using the **Doppler effect**, because the lines in the spectrum undergo blueshift when the star expands (its surface moves towards us) and redshift when it contracts.
- Both the temperature and brightness vary as the star pulsates.

Celestial distances

- One type of pulsating stars are called **cepheid (SEH-fee-uhd) variables**, named after the first known star of this type, **Delta Cephei (SEF-ee-eye)**.
- Cepheid variables (a.k.a. cepheids) are yellow bright giants and supergiants of spectral class F6-K2 with masses of $\sim 4-20 M_{\odot}$.
- They have luminosities of $\sim 100-1,000 L_{\odot}$ which vary over periods of $\sim 3-50$ days.



A plot of the luminosity of the cepheid variable star Delta Cephei over time. This is called a **light curve**.

Credits: OpenStax Astronomy

Celestial distances

- Many cepheids were discovered in the **Large Magellanic Cloud** and **Small Magellanic Cloud**, two satellite galaxies of the Milky Way.
- Because they are in a different galaxy, we can assume that they are all roughly the same distance from us.
 - For example: The Small Magellanic Cloud is $\sim 204,000$ ly away. At this distance, a difference of a few thousand ly between stars is negligible.
 - Analogy: Any person in Vancouver is $\sim 3,400$ km away from St. Catharines even though not all of them are at the same place within Vancouver.

Celestial distances

- Since all the stars in each of the Magellanic Clouds are roughly the same distance away, their apparent brightness (as seen by us) is directly related to their luminosity (the actual brightness).
- In 1908, **Henrietta Leavitt** discovered the **period-luminosity relationship** by comparing the periods and luminosities of different stars in the Magellanic Clouds.
- The periods and average luminosities of cepheids turn out to be related: the longer the period, the greater the luminosity.

Celestial distances

- This means that if we know the period (which is easy to measure), we can calculate the luminosity.
- Then we can compare it with the apparent brightness and use the inverse-square law to calculate the distance.
- This discovery allows us to use the cepheids as standard candles, both in our galaxy and in other galaxies.

Celestial distances

- Another important group of variable stars are the **RR Lyrae variables**, named after the star RR Lyrae (LYE-ree).
- They are much more common than cepheids, but much less luminous, so they are harder to see. They also have shorter periods of ~ 7 -24 hours.
- Different RR Lyrae variables seen in the same star cluster are observed to have the same apparent brightness.
- Stars in the same cluster are roughly the same distance from us, so all RR Lyrae variables must have the same luminosity, ~ 40 -50 L_{\odot} .
- Therefore, they can also be used as standard candles.

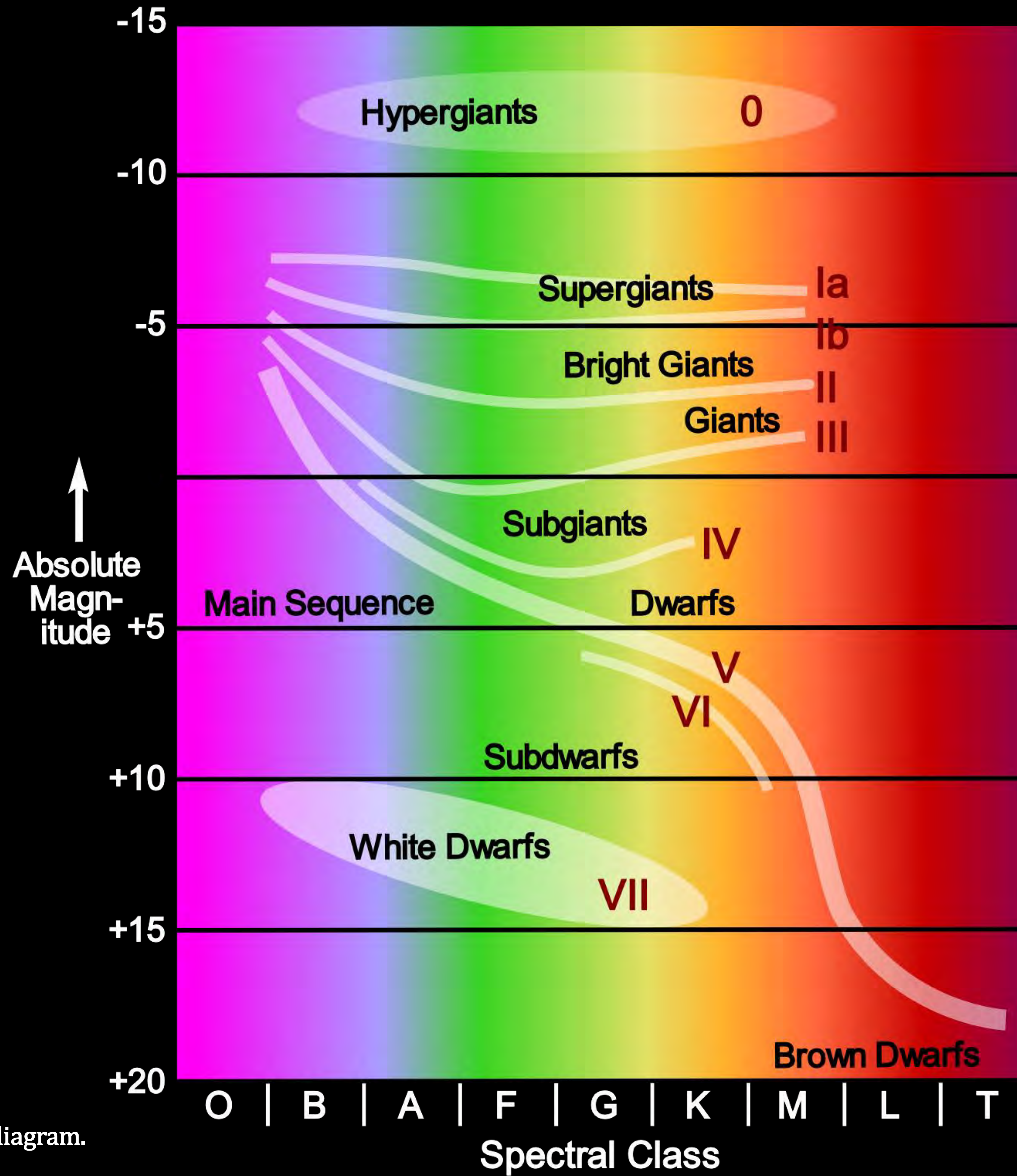
Video

- The following video, from the European Southern Observatory, shows the central region of the Milky Way galaxy.
- Several variable stars are marked with circles. Note that they brighten and fade in regular intervals.
- At the end, the video zooms in and two RR Lyrae variables are marked with red circles. Note that they are much fainter.
- The video can be found at this URL:

<https://www.eso.org/public/videos/eso1636a/>

Celestial distances

- Another way to estimate the luminosity of a star is using the H-R diagram. This is important, because most stars are not variable.
- Remember: luminosity is the vertical axis in the H-R diagram, temperature (or spectral class) is the horizontal axis.
- To place a star on the diagram, we look at its spectrum. This allows us to determine its spectral class (O, B, A, F, G, K, M, L, T, Y) and luminosity class (I, II, III, IV, V, etc.).
- Using this information, we can place the star on the diagram and read its luminosity from its vertical position.



Luminosity classes on the Hertzsprung–Russell diagram.
Credits: Rursus (Wikipedia)

Celestial distances

- We have seen different methods to measure distances to stars.
- Stellar parallax is the most precise method, because it does not rely on any assumptions about luminosity.
- However, it can only be used for stars that are close enough to see the parallax, up to $\sim 30,000$ ly.
- We can use stellar parallax to measure distance to nearby stars and determine the true luminosity of standard candles using the inverse-square law.
- When we see the same standard candles farther away, we can do the opposite: use the luminosity and inverse-square law to calculate the distance.

Celestial distances

- This is called the **cosmic distance ladder**. Each step of the ladder provides information (such as luminosity of standard candles) that can be used to **calibrate** the higher steps.
- Here is a rough summary of the ranges of the methods we covered:
 - Stellar parallax: up to $\sim 30,000$ ly (when the Gaia mission is complete).
 - RR Lyrae variables: up to $\sim 300,000$ ly.
 - H-R diagram: up to $\sim 1,200,000$ ly.
 - Cepheid variables: up to $\sim 60,000,000$ ly.

Celestial distances

- Until the 1920s, people thought the Milky Way galaxy was all there is. They didn't know that other galaxies existed.
- The **Andromeda galaxy** was known as the "Andromeda nebula" and was thought to be a nebula, that is, a cloud of gas and dust.
- In 1925, Edwin Hubble used Cepheid variables to measure the distance to Andromeda, which is $\sim 2,500,000$ ly.
- This is farther away than any star in the Milky Way, so it proved that Andromeda is indeed a separate galaxy and not a nebula within our own galaxy.



Andromeda Galaxy
Credits: David (Deddy) Dayag

Celestial distances

- The distance to the farthest known galaxies, at the edge of the observable universe, is $\sim 93,000,000,000$ ly.
- To measure the distances to faraway galaxies, beyond $\sim 60,000,000$ ly, the methods we learned are not sufficient. We will learn other methods later.

Conclusions

- In this lecture we learned about different types of stars, their classification, and how to measure distances to them.
- We saw that stars come in many varieties, with a huge range of masses, sizes, luminosities, and colors.
- Reading: OpenStax Astronomy, chapters 18-19.
- Exercises: Practice questions will be posted on Teams. Additional questions are available in the textbook, at the end of each chapter.
- **This Wednesday there will be a practice session for the test!**