ASTR 1P02
Brock University
Prof. Barak Shoshany

Lecture 12: Starlight

We will learn about…

- How star brightness is measured.
- Light and the electromagnetic spectrum.
- What the colors of the stars mean.
- What we can learn about stars by analyzing their light.

A long-exposure photo showing stars moving around the south celestial pole. Each circle is the path of an individual star across the sky. Note the different colors of the stars.
Credits: ESO/A.Santerne

Star brightness

- Let’s start by reviewing some units.
- The standard unit of energy is called joule (J).
  - 1 J is the energy required to accelerate a 1 kg mass at 1 m/s^2 over a distance of 1 m.
- Power is energy per unit time, and is measured in watt (W).
  - 1 W $=$ 1 J/s (1 joule per second).
  - A 100 W lightbulb consumes 100 J every second.

Star brightness

- The luminosity of a star is the total amount of energy it emits per second in the form of light.
  - We can also measure the luminosity of other astronomical objects, like galaxies.
- Luminosity is measured in watts.
- The Sun's luminosity is $L_\odot = 3.828 \times 10^{26}$ W (a.k.a. solar luminosity).
  - The symbol $\odot$ in astronomy represents the Sun.
  - For example, $M_\odot \approx 2.0 \times 10^{30}$ kg is the Sun's mass and $R_\odot \approx 7.0 \times 10^{8}$ m is its radius.

Star brightness

- It's convenient to measure the luminosity of stars and other astronomical objects in terms of $L_{\odot}$.
- For example, BAT99-98, a star in the Large Magellanic Cloud, is one of the most luminous stars known, at $\sim$5,000,000 $L_{\odot}$.
- On the other hand, 2MASS J0523-1403, a very faint star, has a luminosity of only $\sim$0.0001 $L_{\odot}$.

Star brightness

- The apparent magnitude of a star measures how bright it is as observed from Earth.
- It depends on several factors:
  1. The star's luminosity.
  2. The star's distance from Earth, since light dims with distance.
  3. Interstellar dust along the line of sight from Earth to the star, since it can block some of the light.
- The star's luminosity is an objective property of the star, while its apparent magnitude is subjective; it will be different when observed from different planets.

Star brightness

- When a star emits light, it is emitted in all directions.
- The light that we see on Earth is just the portion of light that happened to be emitted in our direction. We never see all the light from the star.
- Also, as light gets farther away from the star, it spreads out over a larger area.
- The farther we are from the star, the less of its total light we see.

Star brightness

- The brightness of light decreases based on an inverse-square law.
- This is because light is emitted from the star in the shape of a sphere that increases in radius as the light moves away.
- The surface area of a sphere with radius r is $A = 4\pi r^2$.
- The area increases as the radius increases, but the total amount of light in the sphere always stays the same.
- The light spreads out over the entire area. So there is less and less light per unit area as the radius increases.
- This means that the brightness of light is inversely proportional to the square of the radius.

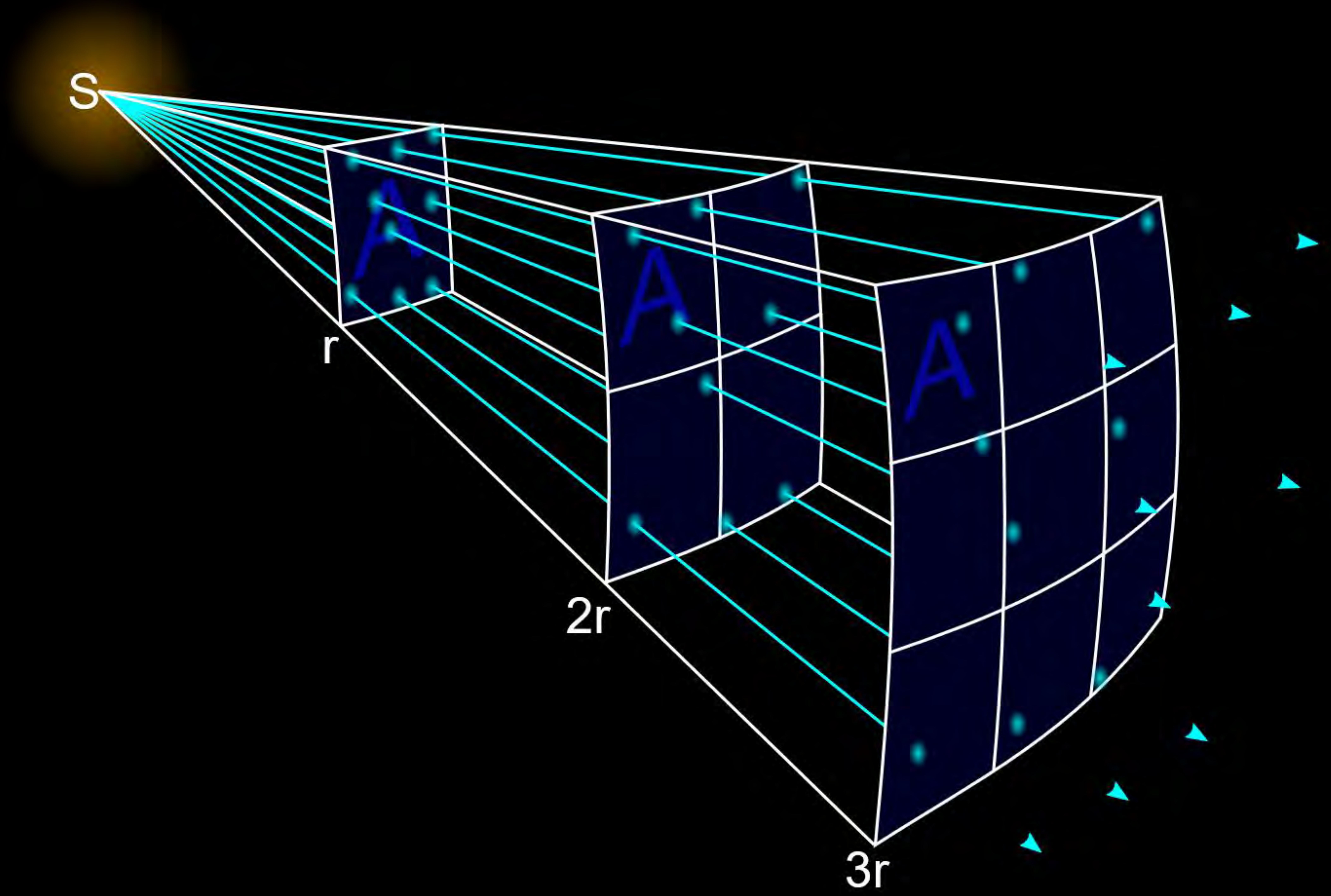


Illustration of the inverse square law. As the light gets farther away from the source, it spreads over a larger area, so the amount of light per unit area decreases as the square of the distance.
Credits: Borb (Wikipedia)

Video

- This video explains the inverse square law for light.
- It is taken from the video at this URL:

  https://youtu.be/2FMx2GDqMo4
- However, we will only watch from around 1:02 to 2:20.

Class demonstration

- I will demonstrate the inverse square law of light experimentally, using a flashlight and measuring tape.

Star brightness

- We can see an example of the inverse square law of light in the solar system.
- The distance from the Sun to Earth is 1 AU $\approx$ 150,000,000 km.
- The distance from the Sun to Neptune is $\sim$30 AU.
  - So Neptune is $\sim$30 times farther away. This means that the Sun is $\sim 30^2 = 900$ times less bright on Neptune compared to Earth.
- On the other hand, Mercury is $\sim$0.4 AU from the Sun.
  - So Mercury is $\sim$2.5 times closer. This means that the Sun is $\sim 2.5^2 = 6.25$ times brighter on Mercury compared to Earth.

Pop quiz

- A star is located 10 ly away from Earth. How bright will the same star look to aliens living on a planet 30 ly away from the star?

A: 3 times less bright

B: 9 times more bright

C: 9 times less bright

Pop quiz

- The correct answer is:

C: 9 times less bright

- The alien planet is 3 times farther from the star compared to Earth, so it is $3^2 = 9$ times less bright.

Pop quiz

- A star is located 10 ly away from Earth. How bright will the same star look to aliens living on a planet 5 ly away from the star?

A: 2 times less bright

B: 4 times more bright

C: 5 times less bright

Pop quiz

- The correct answer is:

B: 4 times more bright

- The planet is 2 times closer to the star compared to Earth, so it is $2^2 = 4$ times brighter.

Star brightness

- Apparent magnitude is measured using the magnitude scale.
- The brighter an object is in the sky, the lower its apparent magnitude on this scale.
  - This is for historical reasons.
  - It also means the brightest objects have negative magnitudes, because negative numbers are lower than positive numbers on the scale.

Star brightness

Some apparent magnitudes as seen from Earth, from brightest to dimmest:

- The Sun: −26.8
- Full Moon: −12.7
- Venus: −4.1
- Jupiter: −2.2
- Sirius (brightest star): −1.5
- Vega: +0.03
- Betelgeuse: +0.5
- Bellatrix: +1.6
- Polaris: +2.0
- Mintaka: +2.2
- Andromeda Galaxy: +3.4
- Vesta (asteroid): +5.2
- Neptune: +7.8
- Proxima Centauri (closest star): +11
- Charon (moon of Pluto): +15.6
- Fenrir (tiny moon of Saturn): +25

Star brightness

Apparent magnitude can tell us about the visibility of the object:

- Under −25: So bright it’s painful to look at.
- Under −4: Visible to the naked eye during the day.
- Under −2.5: Visible during the day when the Sun is very low in the sky.
- Under +3.5: Visible to the naked eye at night from an urban neighborhood.
- Under +6.5: Visible to the naked eye under very good visibility conditions.
- Under +9.5: Visible using binoculars.
- Under +27.7: Visible to the Subaru Telescope in Hawaii (10-day exposure).
- Under +31.5: Visible to the Hubble Space Telescope (23-day exposure).
- Under +34: Visible to the James Webb Space Telescope.

Star brightness

- The absolute magnitude of an object is defined as the apparent magnitude it would have if viewed from a distance of 32.6 light-years without any dimming due to interstellar dust.
- Therefore, absolute magnitude is objective, like luminosity. It doesn't depend on how the star is viewed from Earth.
- For example:
  - Betelgeuse has an apparent magnitude of +0.5 as seen from Earth, but an absolute magnitude of −5.85.
  - Vega has an apparent magnitude of +0.03 and an absolute magnitude of +0.58. So Vega looks to us brighter then Betelgeuse (lower apparent magnitude) but is actually much less bright (higher absolute magnitude).

Simulation

- I will show how to use Stellarium to find the magnitudes of different objects in the sky.
- This software is available for free at this URL:

https://stellarium.org/

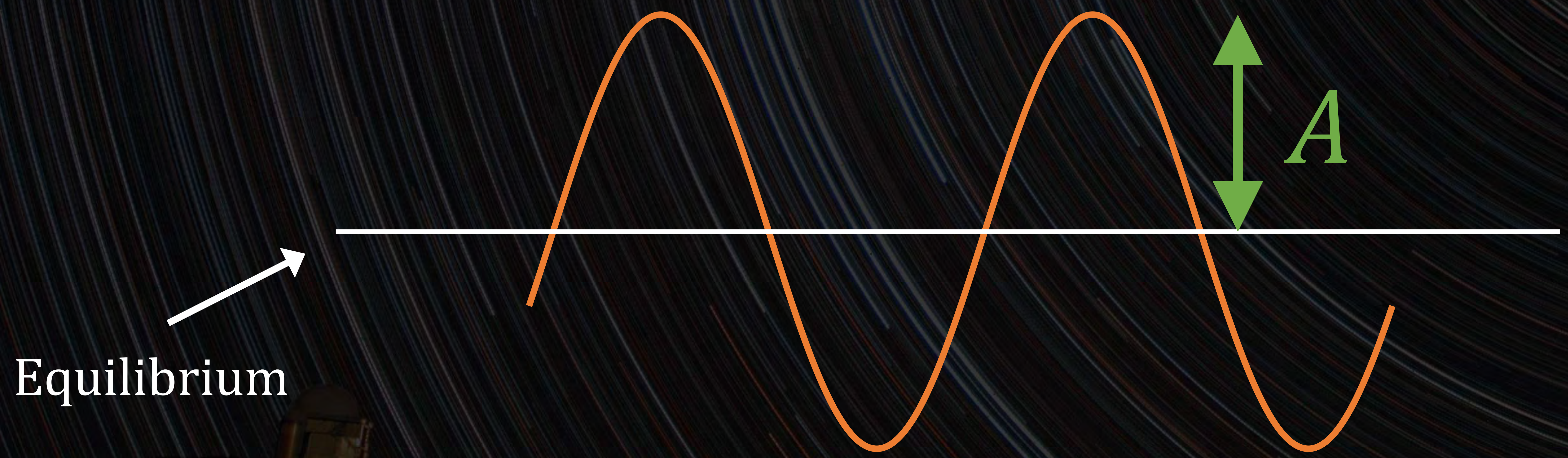
Light as a wave

- Light can be described in two ways:
  1. As an electromagnetic wave made of electric and magnetic fields.
  2. As a collection of massless elementary particles called photons.
- The two definitions seem contradictory. How can something be both a continuous wave and a discrete particle?
- This is called wave-particle duality and is an important concept in quantum mechanics.
  - The contradiction is resolved by understanding that “wave” and “particle” are classical concepts that do not apply to the quantum world. They are familiar ways in which we can interpret what we see, but light really is something else that doesn’t have a familiar classical description.

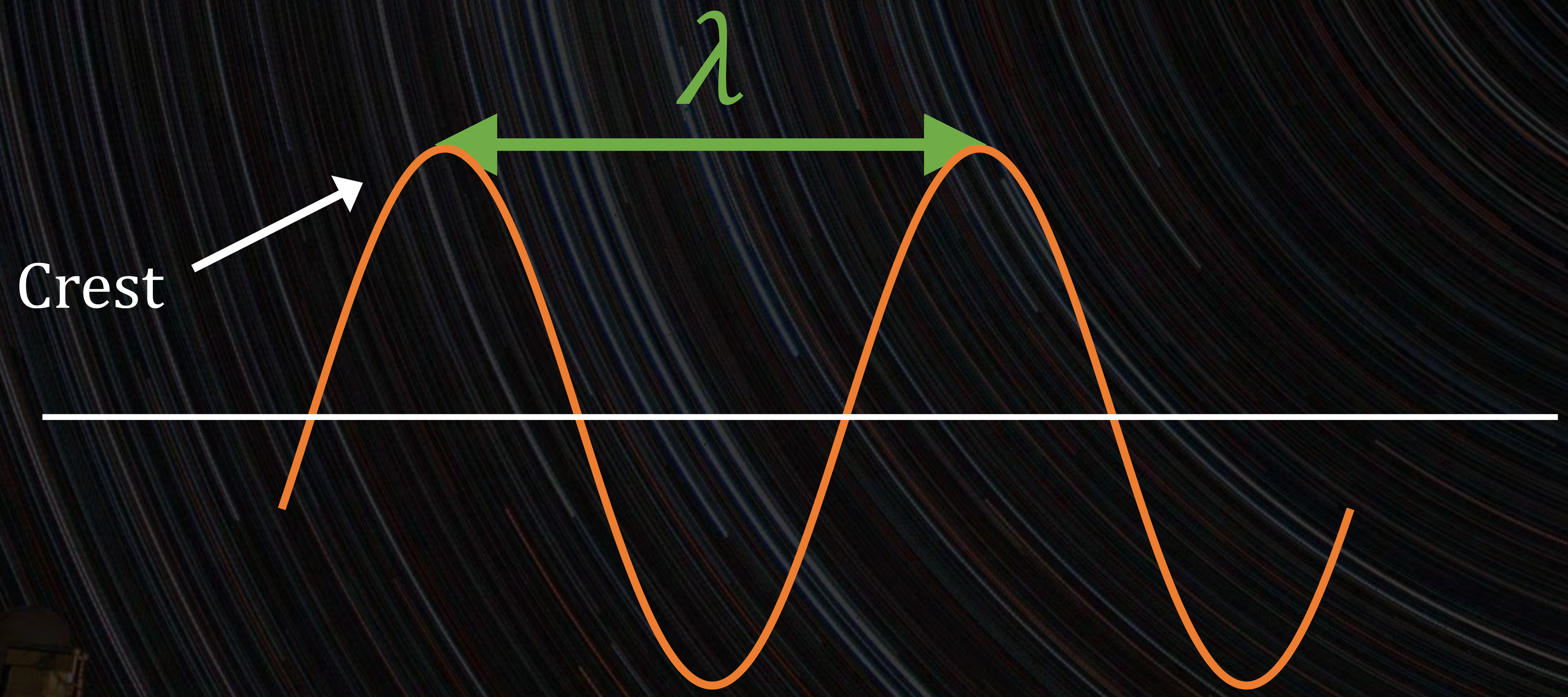
Light as a wave

- A wave is a regular disturbance propagating in space.
- "Disturbance" means a change in some physical quantity compared to its equilibrium.
  - For example: in water waves, the disturbance is the change in the height of the water, above or below sea level, which is the equilibrium.
- "Regular" means it's not random, but has an organized structure, often repeating itself many times.
  - For example: a sound wave for a specific musical note repeats the same pattern over and over until the note stops.
- "Propagating" means it's moving in some direction in space.
  - There are also standing waves, which look like they're not moving.

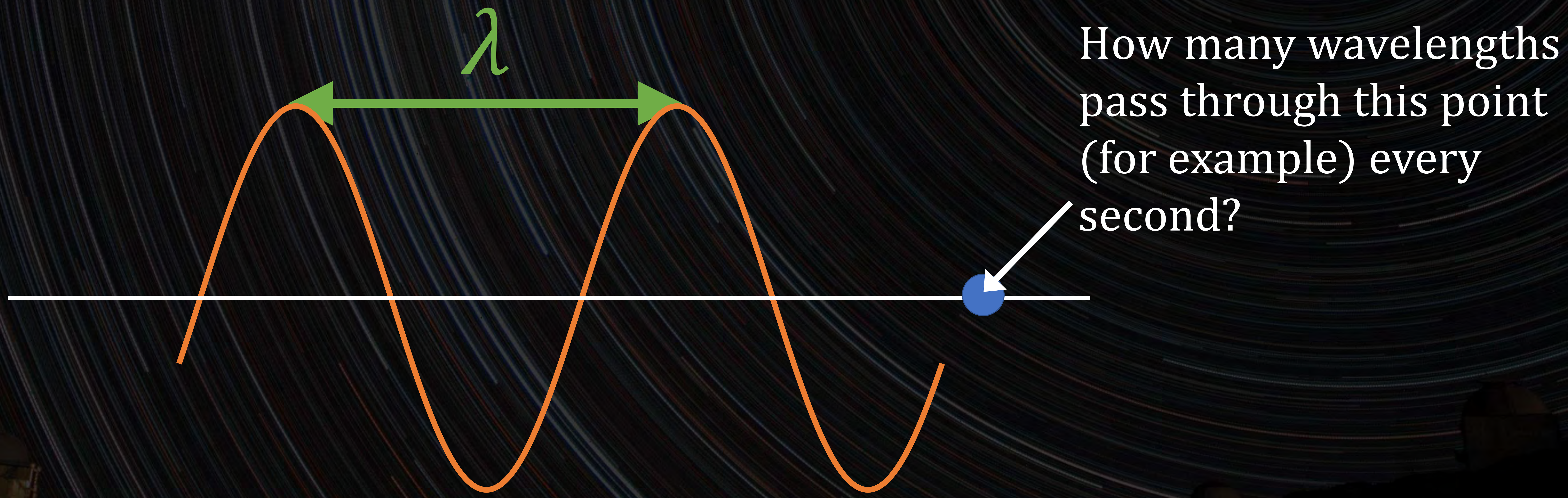
- Let's introduce some basic properties of waves.
- **Amplitude**, denoted by A, is the maximum displacement of the wave from equilibrium.
- It measures how strong the disturbance is.
- For example: a sound wave with larger amplitude will be louder.



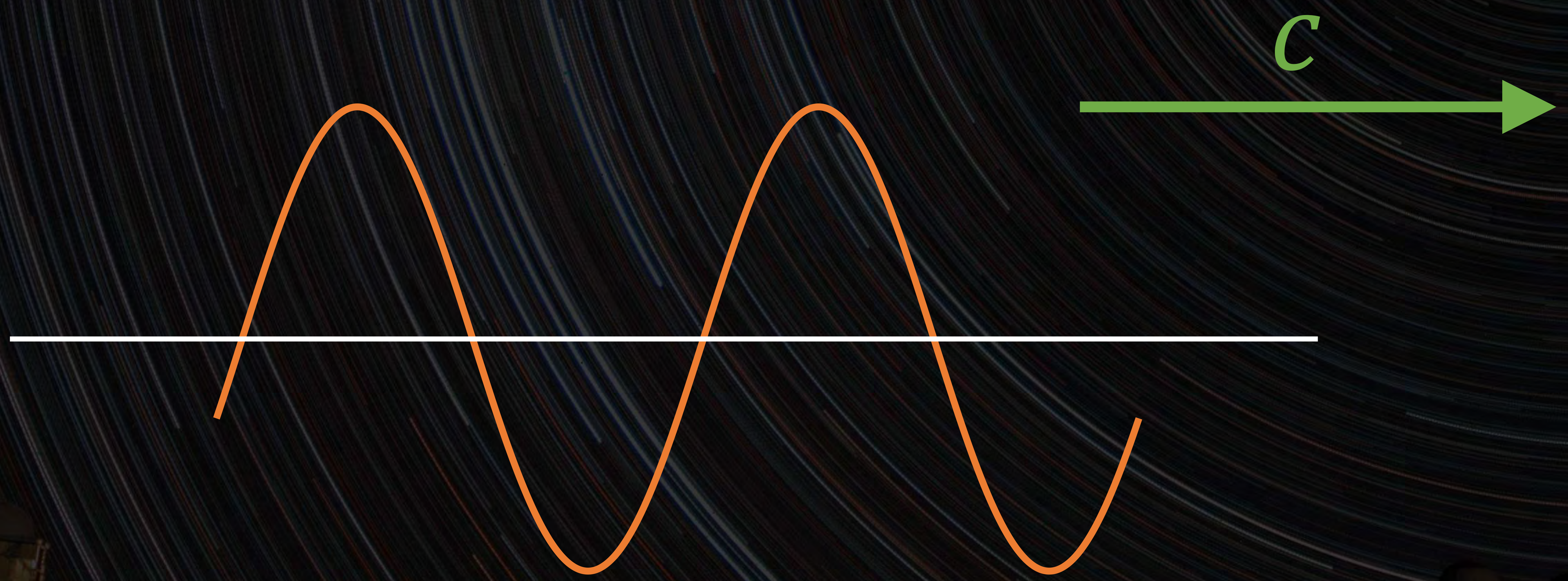
- Wavelength , denoted by λ (the Greek letter lambda), is the distance between two crests (peaks) of the wave.
- It is measured in meters.



- Frequency, denoted by f, is the number of wavelengths passing through a point in space each second.
- Measured in hertz (Hz): 1 Hz = 1 wavelength per second.
- For a sound wave, higher frequency means higher pitch.
- For light, higher frequency means more energy (as we will see).



- Speed, denoted by c, measures how fast the wave travels in space.
- For example, the speed of a wave on a guitar string depends on its tension. If we tighten the string, the wave will move faster.
- But waves of light (in vacuum) always travel at the same speed, the speed of light: $c \approx 3 \times 10^8$ m/s.



Light as a wave

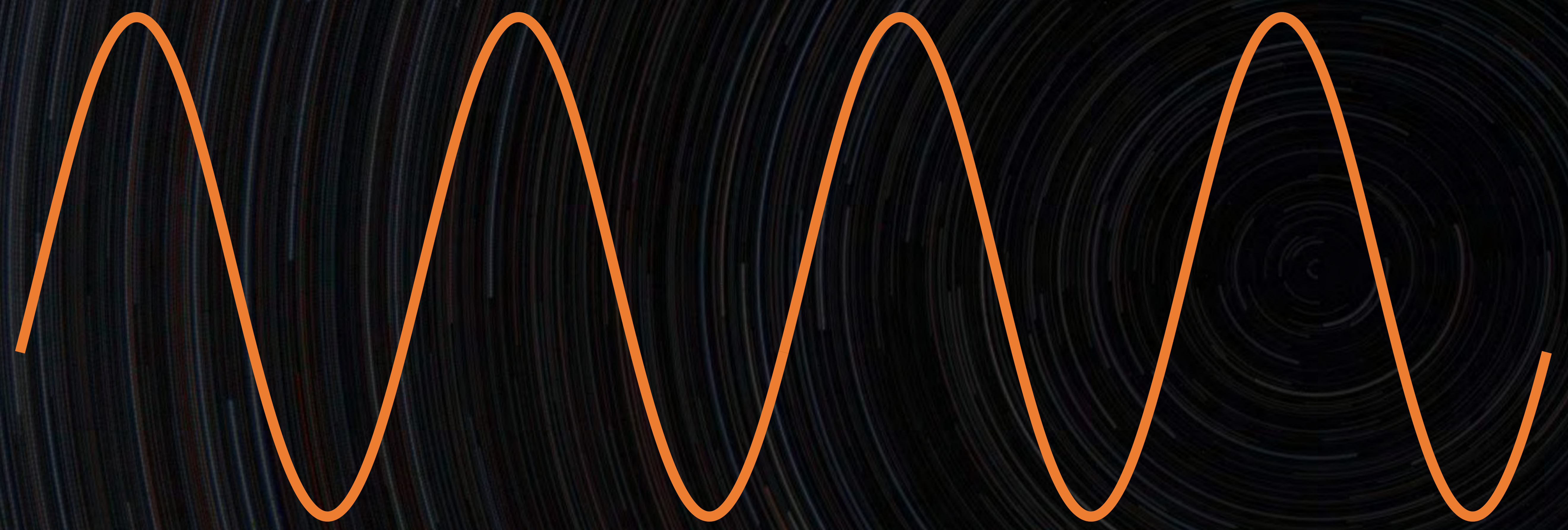
- The speed, wavelength, and frequency of a wave are related by

$$c = \lambda f \quad \text{or} \quad \lambda = \frac{c}{f} \quad \text{or} \quad f = \frac{c}{\lambda}$$

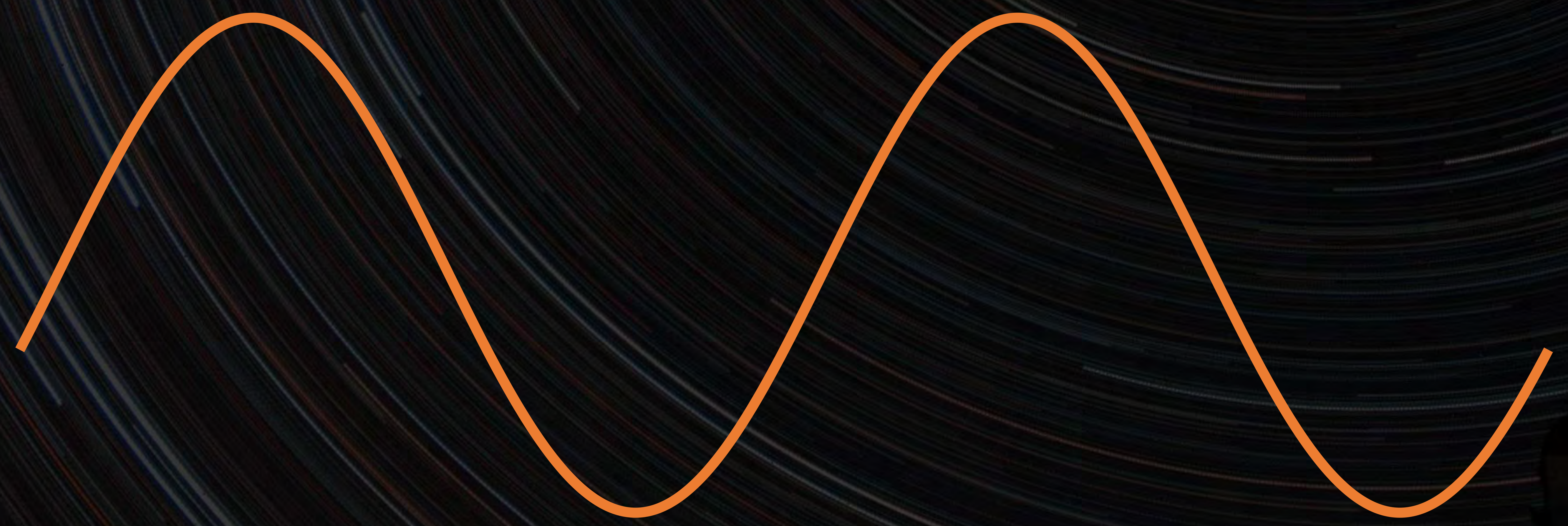
- This is because f is the number of wavelengths λ per second, so $c = \lambda f$ is the total distance traveled per second.
- For example:
  - $\lambda = 1$ meter.
  - $f = 5$ wavelengths (of 1 meter) pass through a point in space per second.
  - So $c = 5$ meters per second.

Since $\lambda = c/f$, wavelength and frequency are inversely proportional:

High frequency
Short wavelength



Low frequency
Long wavelength



Simulation

- I will demonstrate the properties of waves using an online simulation.
- The simulation can be found at this URL:

  https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html

- Hint: Choose "oscillate" on the top left and "no end" on the top right. Tension determines the speed.

Video

- In this video, the 6 strings of an acoustic guitar are filmed up close, and we can see the waves generated by different notes as the strings are plucked.
- Pitch is proportional to frequency. Notes with higher pitch have higher frequency and shorter wavelength.
- Amplitude is proportional to volume. When the notes die out, the amplitude decreases.
- The video is available at this URL

https://youtu.be/tFw8FzeDjIE

Light as a wave

- The electromagnetic field is composed of both electric and magnetic fields.
- In a light wave, the propagating disturbance is in the electromagnetic field, and the equilibrium is when there is no field.
- There is an interesting interaction between the electric and magnetic fields that makes this possible (but we won't learn about that here).

An illustration of an electromagnetic wave moving to the right, showing that the electric field E and the magnetic field B both oscillate together, but in perpendicular directions.
Credits: SuperManu (Wikipedia)

Star colors

- Light has a wavelength and a frequency because it's a wave.
- But we said that light is also a particle – it's made of photons.
- From quantum mechanics, we know that the energy of a photon is proportional to its frequency:

$$E = hf = \frac{hc}{\lambda}$$

  - $h \approx 4.1 \times 10^{-15}$ eV/Hz is called Planck's constant.
  - Note that energy, like frequency, is inversely proportional to wavelength.
- This makes sense. The higher the frequency, the faster the wave oscillates (moves up and down), so it has more kinetic energy.

Star colors

- The wavelength and frequency of light determine its color.
- Visible light is the range that the human eye can see:
  - Wavelength: ~380-750 nm (nanometers, a billionth of a meter)
  - Frequency: ~400-790 THz (terahertz, a trillion hertz)
- Light in only one of these frequencies is called monochromatic and the colors it corresponds to are called spectral colors.
  - These are the colors of the rainbow.
- There are also non-spectral (or extra-spectral) colors that can only be obtained by combining two or more wavelengths.
  - Example: magenta is a mix of red and blue wavelengths.

The spectral colors

Color	Wavelength (nm)	Frequency (THz)	Photon energy (eV)
Violet	380–450	670–790	2.75–3.26
Blue	450–485	620–670	2.56–2.75
Cyan	485–500	600–620	2.48–2.56
Green	500–565	530–600	2.19–2.48
Yellow	565–590	510–530	2.10–2.19
Orange	590–625	480–510	1.98–2.10
Red	625–750	400–480	1.65–1.98

Star colors

- The spectrum of light, called the electromagnetic spectrum, contains much more than just visible light!
- The spectrum includes, from lowest to highest frequency:
  - Radio waves (lowest frequency / longest wavelength)
  - Microwaves
  - Infrared (infra = “below”, because it has frequency below visible light)
  - Visible light (red = lowest frequency, violet = highest frequency)
  - Ultraviolet (ultra = “above”)
  - X-rays
  - Gamma rays (highest frequency / shortest wavelength)

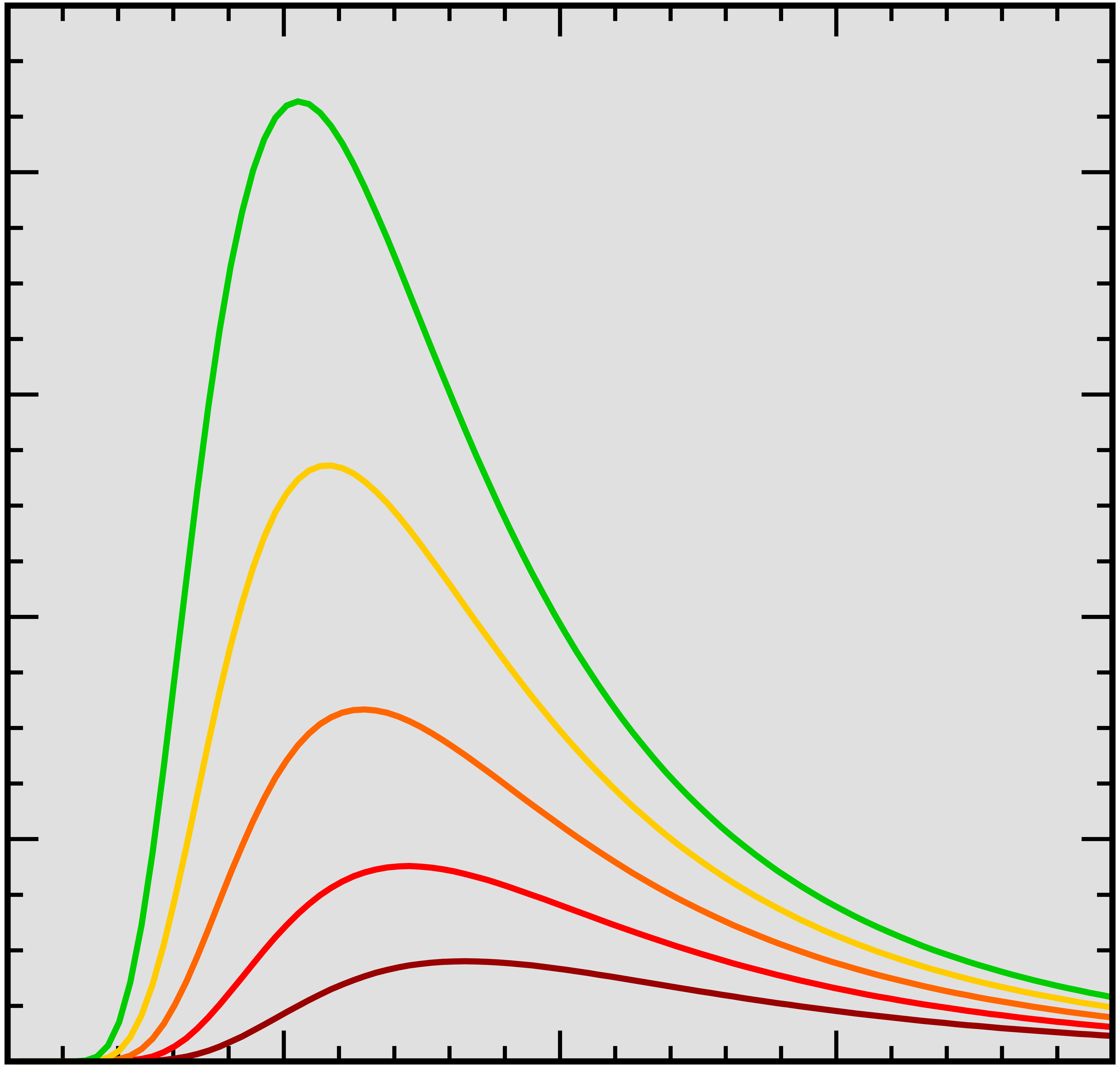
The electromagnetic spectrum.
Credits: NASA/Wikipedia

Star colors

- A black body is an idealized body that absorbs all incoming electromagnetic radiation.
- Quantum mechanics predicts that a black body emits radiation called black body radiation.
- This radiation is emitted in all wavelengths, but the peak wavelength λ_{peak} is determined according to Wien's displacement law: (pronounced "vin")

$$\lambda_{\text{peak}} = \frac{b}{T}$$

  - $b \approx 2.9 \times 10^{-3}\ \text{m} \cdot \text{K}$ is a constant of proportionality.



Wien’s displacement law.
Credits: 4C (Wikipedia)

Star colors

- From $\lambda_{\text{peak}} = b/T$ we see that the wavelength is inversely proportional to temperature.
- This means the frequency is proportional to temperature.
- This makes sense. The frequency of light is proportional to the photon energy, so light emitted at hotter temperatures (more thermal energy) should have a higher frequency.
- Stars are not perfect black bodies, but their radiation spectrum is well approximated by black body radiation.

The electromagnetic spectrum, including corresponding temperatures.
Credits: NASA/Wikipedia

Star colors

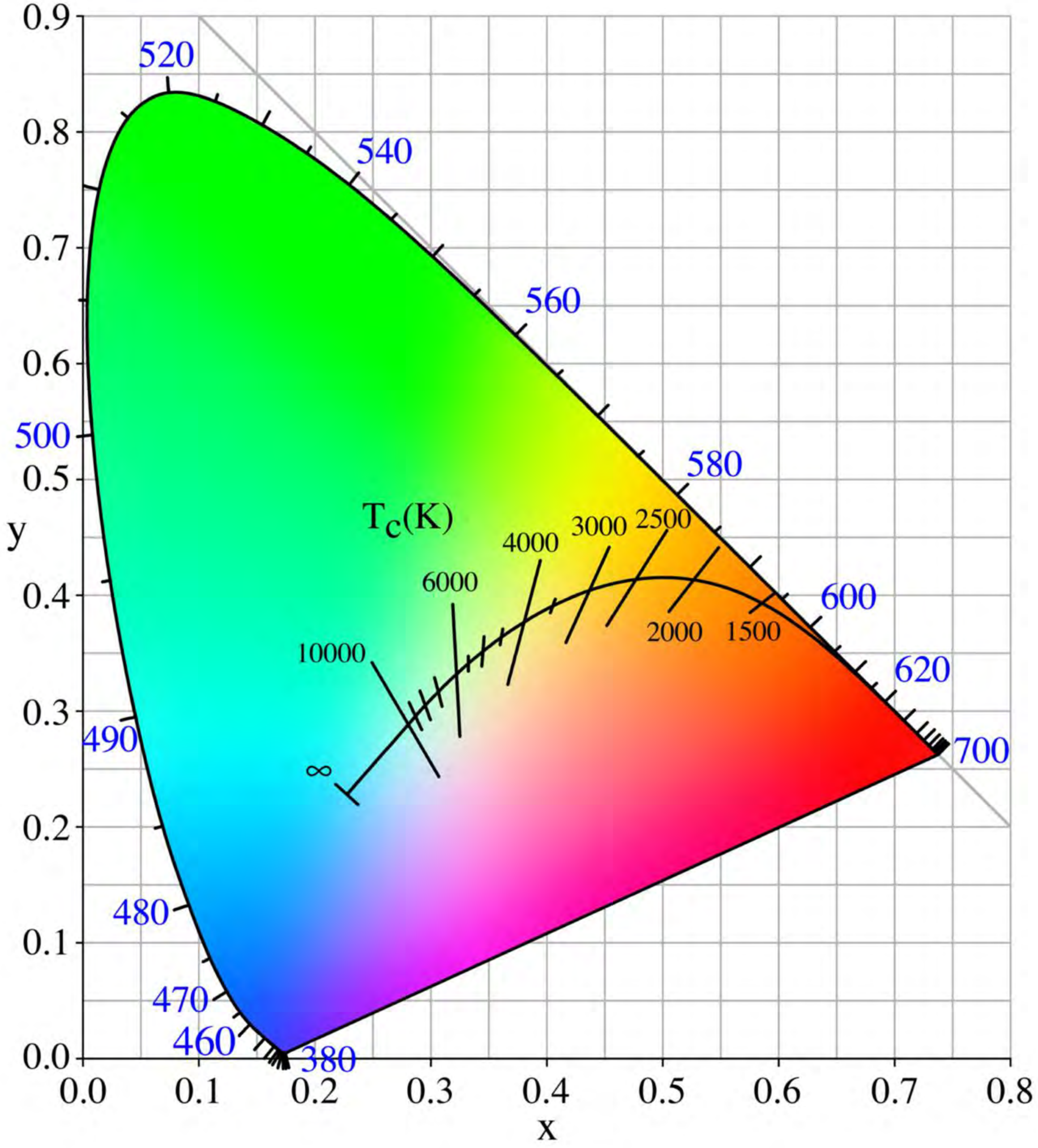
- Now we understand why different stars have different colors: the color depends on the temperature of the star's photosphere.
- Red has the lowest frequency = lowest temperatures: ~3,000 K.
- Blue has the highest frequency = highest temperatures: ~25,000 K.
- Note that this is the opposite of the colors on water taps! When it comes to stars, red is cold and blue is hot, and not the other way around.

Star colors

- Violet has a higher frequency than blue. Why are the hottest star not violet?
- It turns out that black-body radiation never looks violet. It also never looks green.
- It starts at red at low temperatures, then passes through orange, yellow, white, and ends up at blue at the highest temperatures.
- This “path” it makes through the color palette is called the Planckian locus or black body locus.

The numbers on the black path are temperatures in kelvins.

The blue numbers are wavelengths in nanometers.



The Planckian locus.
Credits: PAR (Wikipedia)

The colors corresponding to different temperatures of black-body radiation.
Credits: Bhutajata (Wikipedia)

It is convenient to denote the color of a lightbulb in kelvins. Confusingly, colder temperatures create light we interpret as “warm” and hotter temperatures create “cool” light.
Credits: Yerocus (Wikipedia)

Star colors

- By observing the color of a star, we can estimate its temperature.
- For example:
  - Betelgeuse is a red star and its temperature is estimated at 3,600 K.
  - Bellatrix is a blue star and its temperature is estimated at 21,800 K.
- Our Sun is a white star and its temperature is ~5,778 K.
  - White light includes roughly equal amounts of light from the entire visible spectrum.
  - This is exactly why we evolved to see the visible spectrum: it’s the spectrum of light that our Sun emits the most of.
  - Aliens living near a blue or red star will probably evolve to see different parts of the electromagnetic spectrum.

True color image of the Sun in visible light.
Credits: Matúš Motlo

Star colors

- When light from the Sun passes through the atmosphere, it undergoes Rayleigh scattering.
- Some of the light scatters off particles in the atmosphere. It collides with them and changes its direction, so it doesn't reach us directly.
- Shorter (blue) wavelengths are scattered more than longer (red) wavelengths.
- So the blue light scatters, and we see it coming from all over the sky, which is why the sky appears blue.
- Meanwhile, longer wavelengths are not scattered, so they reach us directly, which is why the Sun appears yellow, red, and/or orange.

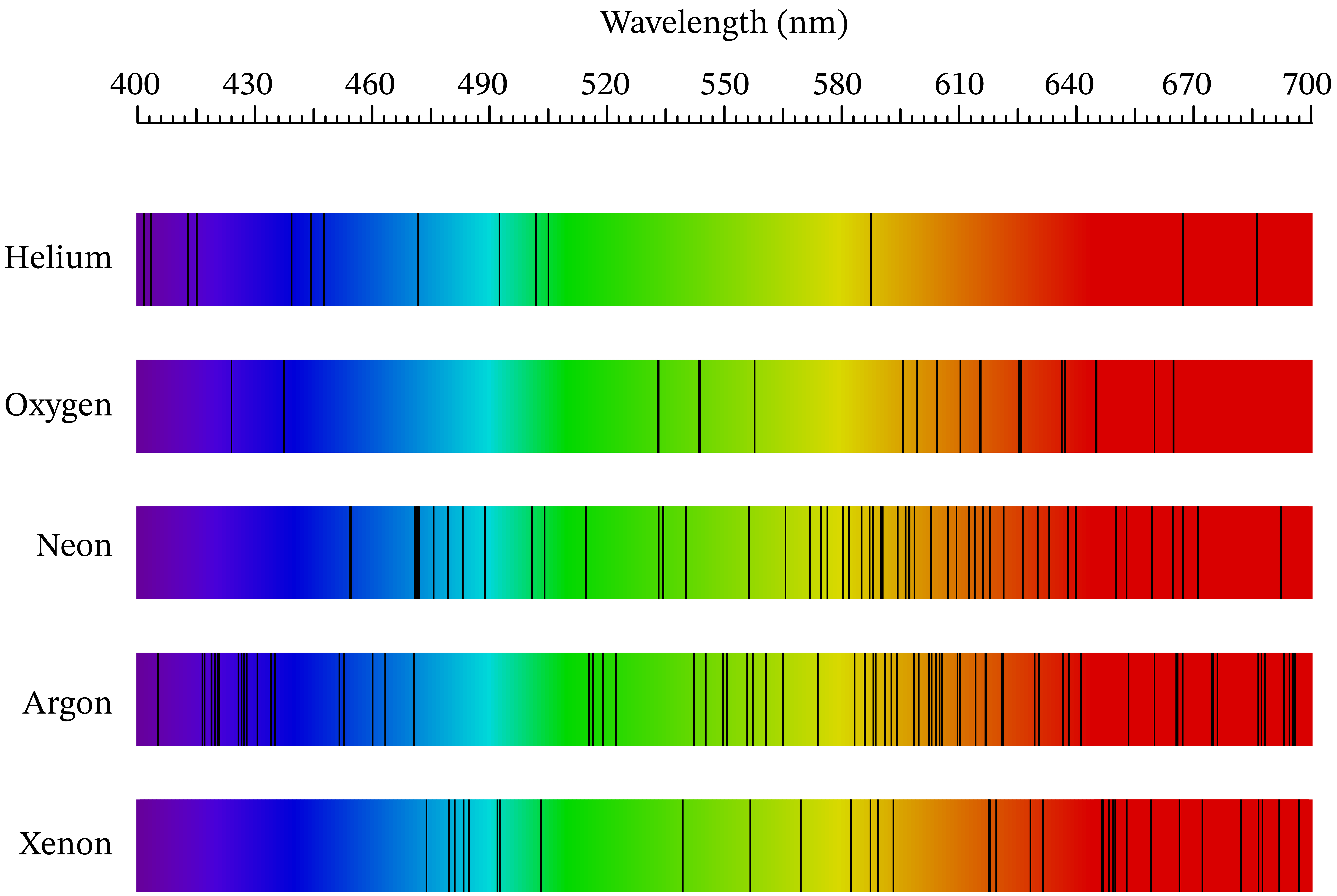
Simulation

- I will demonstrate how a star's spectrum and peak wavelength depends on its temperature.
- The simulation can be found at this URL:

https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html

Spectroscopy

- When light shines through a gas, some of the frequencies of the light get absorbed by it.
- If we examine the spectrum of the light, we will find dark absorption lines at those specific frequencies.
- The type of atoms or molecules the light passes through determines which frequencies will be absorbed.
- If we know which gases correspond to which absorption lines, we can identify them in the spectra of stars.



Absorption lines of some different gases.
Credits: Nagwa

Fraunhofer lines, the absorption lines in the spectrum of the Sun, which can be used to determine its chemical composition.
Credits: Wikipedia

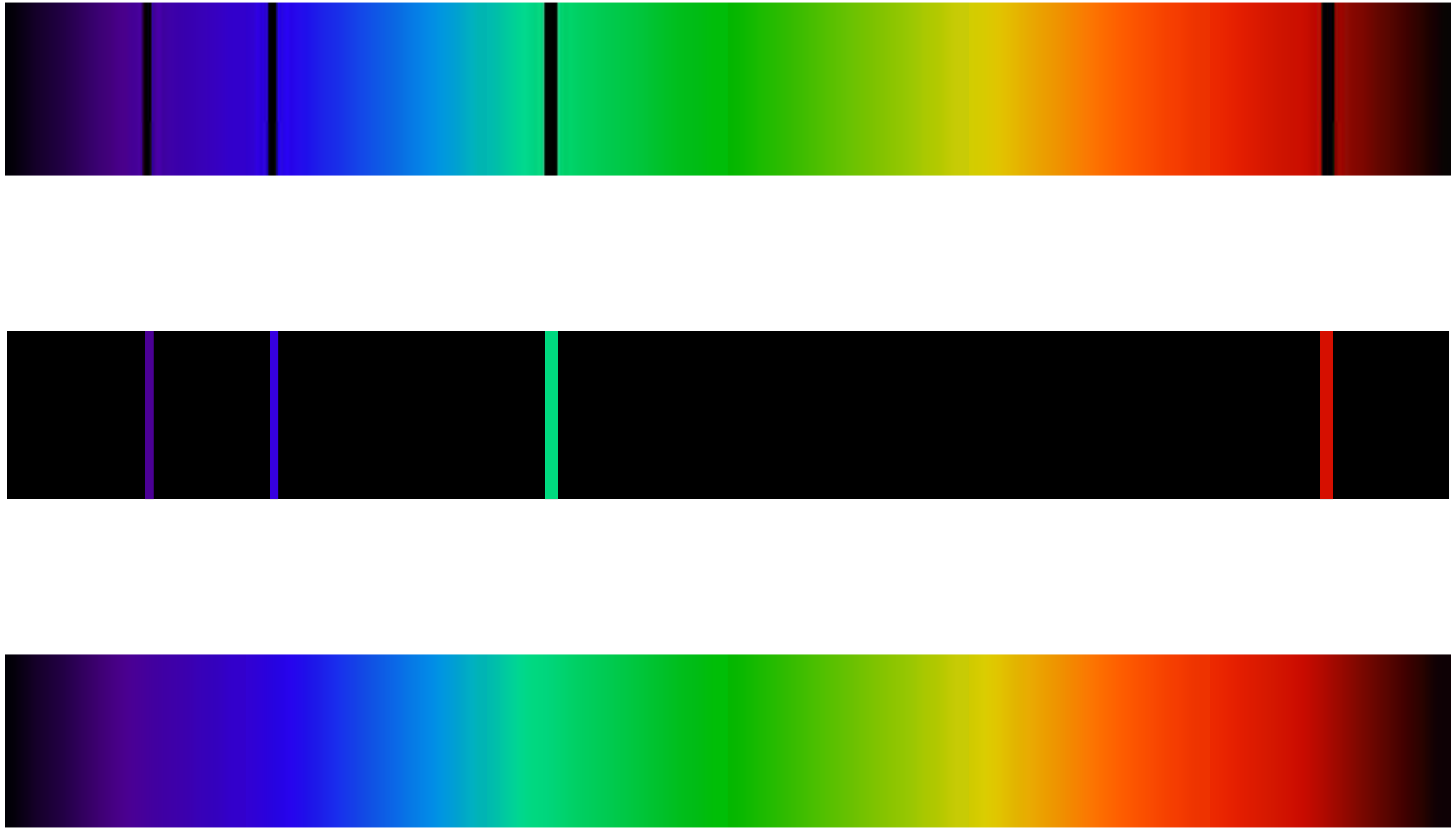
Spectroscopy

- Something similar happens when we heat a gas. It emits light at frequencies that depend on the atoms and molecules in the gas.
- If we examine the spectrum of the light, we will find bright emission lines at those specific frequencies.
- The emission lines are at the same frequencies as the absorption lines.
- Shining a light through a gas will absorb the frequencies, and the gas on its own, when heated, will emit the same frequencies.

Absorption spectrum

Emission spectrum

Both together



Absorption and emission lines complement each other.
Credits: Stkl (Wikipedia)

Simulation

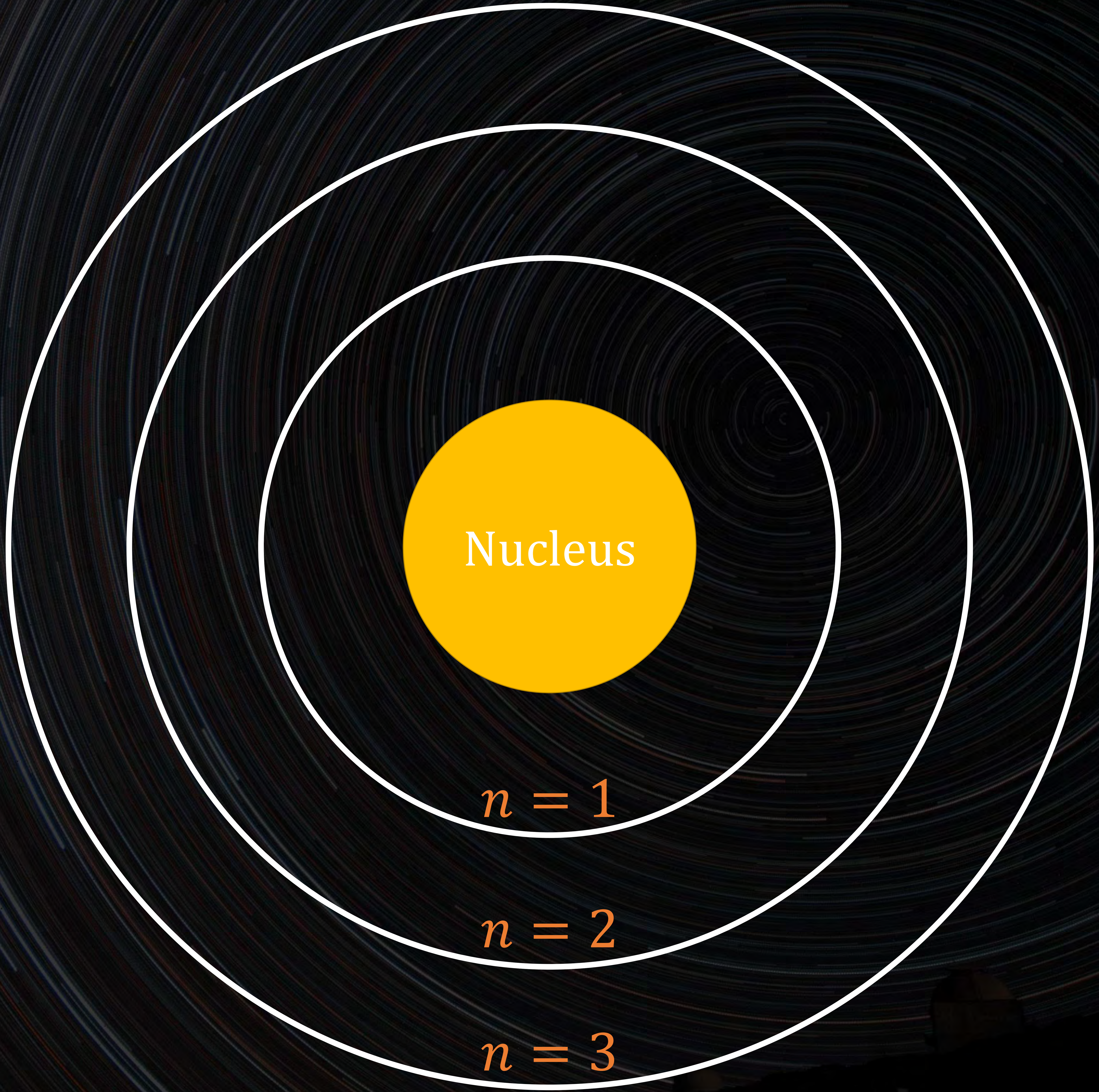
- I will show a simulation of how absorption and emission lines combine together when different elements are present.
- The simulation is available at this URL:

  https://foothillastrosims.github.io/Spectroscopy-Demonstrator/

Spectroscopy

- But what causes these spectral lines to appear?
- We can explain them using a simplified model of the atom known as the Bohr model.
- Note that this model is not accurate, but it is a good approximation for simple atoms.
    - The correct model (as far as we know) is that of atomic orbitals, where each electron's position is described by a quantum mechanical probability distribution or "electron cloud", but it is much more complicated.

- In the Bohr model, electrons orbit around the nucleus in discrete orbits, and cannot be anywhere except in one of these orbits.
- The orbits are denoted by integers $n = 1,2,3, \ldots$
- The lowest orbit, with $n = 1$, is the closest to the nucleus. It is called the ground state.
- Orbits with $n > 1$ are called excited states.



Spectroscopy

- Each orbit has an energy level associated with it.
- When an electron moves to an orbit closer to the nucleus (n decreases), it emits a photon with energy:

$$E = Rhc\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

  - R is called the Rydberg constant.
  - h is the Planck constant.
  - c is the speed of light.
  - n_i is the initial orbit.
  - n_f is the final orbit, where $n_f < n_i$.

Spectroscopy

- An electron can also move to an orbit farther away from the nucleus (n increases) by absorbing a photon that collides with it.
- But this can only happen if the photon has the exact energy required by the formula. Otherwise, the photon does not interact with the electron.
- This is the exact opposite of photon emission. The electron emits a photon when it moves to a lower orbit n, and moves to a higher orbit n when it absorbs a photon.
- The absorbed and emitted photon energies are the same if the electron moves up or down between the same two orbits n_i and n_f.

Spectroscopy

- Remember that for a photon, the energy, wavelength, and frequency are related:

$$E = hf = \frac{hc}{\lambda}$$

- So if we know E, we can calculate λ:

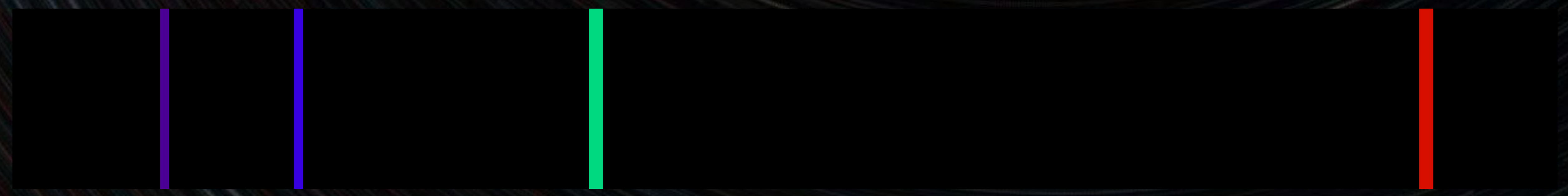
$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

  - This is called the Rydberg formula. It was known experimentally (by measuring spectral lines) in 1888, before Bohr formulated his model in 1913, but the Bohr model provided a theoretical explanation for the formula, and a derivation of the constant R.

Spectroscopy

- Absorption lines occur because photons of the appropriate wavelengths are absorbed, and their energy is used to excite electrons to higher energy levels.

- Emission lines occur because electrons are excited to higher energy levels by heat, and when they fall to lower levels, they emit photons with the corresponding wavelengths.



Simulation

- I will demonstrate how photons are absorbed and emitted when electrons move between energy levels in the hydrogen atom.
- We will also see that when a photon has more energy than the maximum energy level, the atom is ionized (loses an electron).
- The simulation can be found at this URL:

  https://foothill.edu/astronomy/astrosims/hydrogen-atom/

Spectral classes

- Most stars are composed of the same chemical elements as the Sun.
- So you would expect all stars to have the exact same absorption lines in their spectra, because the lines are determined by the chemical elements.
- But it turns out that things are not that simple, and the spectral lines also depend on the temperature of the star.

Spectral classes

- If a star is very hot, the heat provides enough energy to ionize most of its hydrogen atoms.
- The absorption lines are created by photons that excite the electrons. But in an ionized hydrogen atom there are no electrons, so there are no absorption lines.
- If the star is very cold, most hydrogen atoms are in the ground state.
- It takes a lot of energy to excite an electron from the ground state, so this excitation seldom happens in a very cold star.

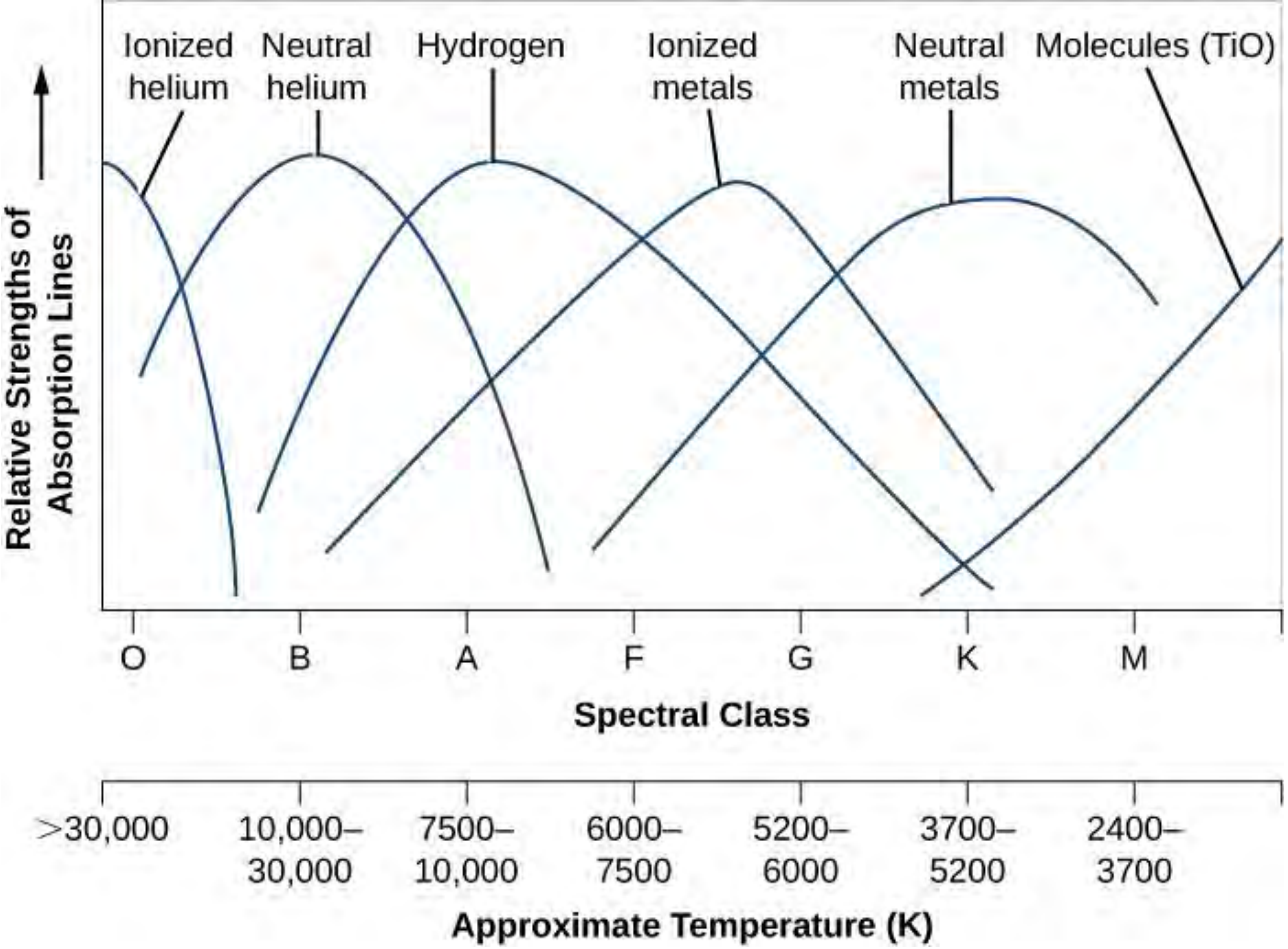
Spectral classes

- Therefore, very cold and very hot stars have weak or missing hydrogen spectral lines.
- The hydrogen lines are stronger in stars that have intermediate temperatures, and strongest around 10,000 K.
- Similarly, other chemical elements also have temperatures for which their absorption lines are the strongest.

Spectral classes

- This means we can use the spectral lines of a star to determine its temperature.
- Stars are therefore divided into spectral classes that correspond to their surface temperatures.
- From hottest to coldest, the spectral classes are: O, B, A, F, G, K, M.
  - Why these letters? Like in most cases where the notation doesn't make sense, it's for historical reasons.
  - Mnemonic: "Oh Barak, An F Grade Kills Me!"
- There are also newer spectral classes for stars cooler than class M that were discovered more recently: L, T, and Y.

Illustration of stars of different spectral classes, from hottest (left) to coldest (right). Note also how hotter stars are larger (and more massive).
Credits: Wikipedia



Absorption lines in stars of different spectral classes. Note that in astronomy "metal" means any element heavier than helium, for historical reasons.
Credits: OpenStax Astronomy

Spectral classes

- For each class, we also add a number from 0 to 9, where 0 is the hottest and 9 is the coldest within that specific class.
- For example:
  - Remember, from hot to cold: O, B, A, F, G, K, M.
  - An O star is hotter than a B star.
  - A B2 star is hotter than a B7 star, but colder than an O5 star.
- Our Sun is a G2 star.

Actual spectra of stars with different spectral classes.
Credits: Modification of work by NOAO/AURA/NSF

Spectral classes

- As we will learn later, stars come in a huge range of sizes.
- Very large stars are called giants. Smaller stars are called dwarfs.
- Because they're so large, their atoms are spread out more, so they have lower density and pressure.
- This means less collisions between atoms, and therefore narrower spectral lines.
- If two stars have the same temperature but different sizes, they will have similar spectral lines, but the larger star will have narrower lines.

Spectral lines for a dwarf and a giant with similar temperatures. The dwarf has broad spectral lines and the giant has narrow spectral lines.
Credits: Wikipedia

The Doppler effect

- When a car passes by you while it sounds its horn, the pitch of the horn will change. The reason for that is called the Doppler effect.
- The car is emitting a sound wave with constant pitch.
- However, when it moves toward you, the wave will “compress”, the wavelength will decrease, and the frequency/pitch will increase.
- The opposite effect happens when it moves away from you. The wave will “expand”, the wavelength will increase, and the frequency/pitch will decrease.

Video

- We will watch a video with several animations explaining the Doppler effect.
- The video can be found at this URL:

https://youtu.be/ffg4TOpXZyg

The Doppler effect

- When a star is moving away from us, the wavelength of the light will increase and the frequency will decrease.
- Since red corresponds to lower frequency than other colors, we say that the light is redshifted.
- When a star is moving toward us, the wavelength of the light will decrease and the frequency will increase.
- Since blue corresponds to higher frequency than (most) other colors, we say that the light is blueshifted.
- This is referred to as a Doppler shift.

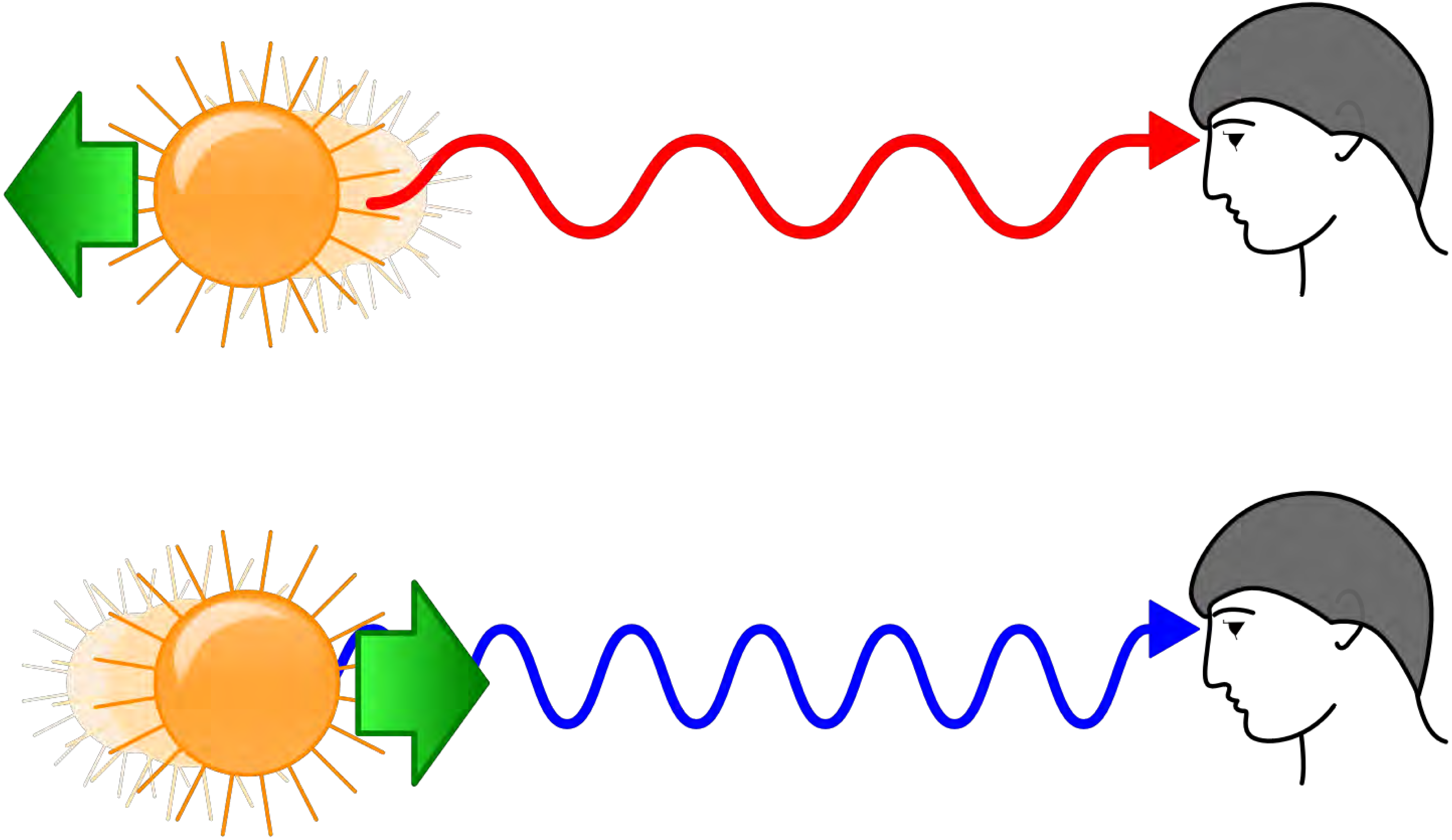


Illustration of redshift and blueshift.
Credits: Aleš Tošovský

The Doppler effect

- If we look at the spectrum of a star, we will see the lines in its entire spectrum either redshifted or blueshifted.
- This way, we can determine whether the star is moving towards or away from us.
- This type of movement, along the line of sight between us and the star, is called radial velocity.

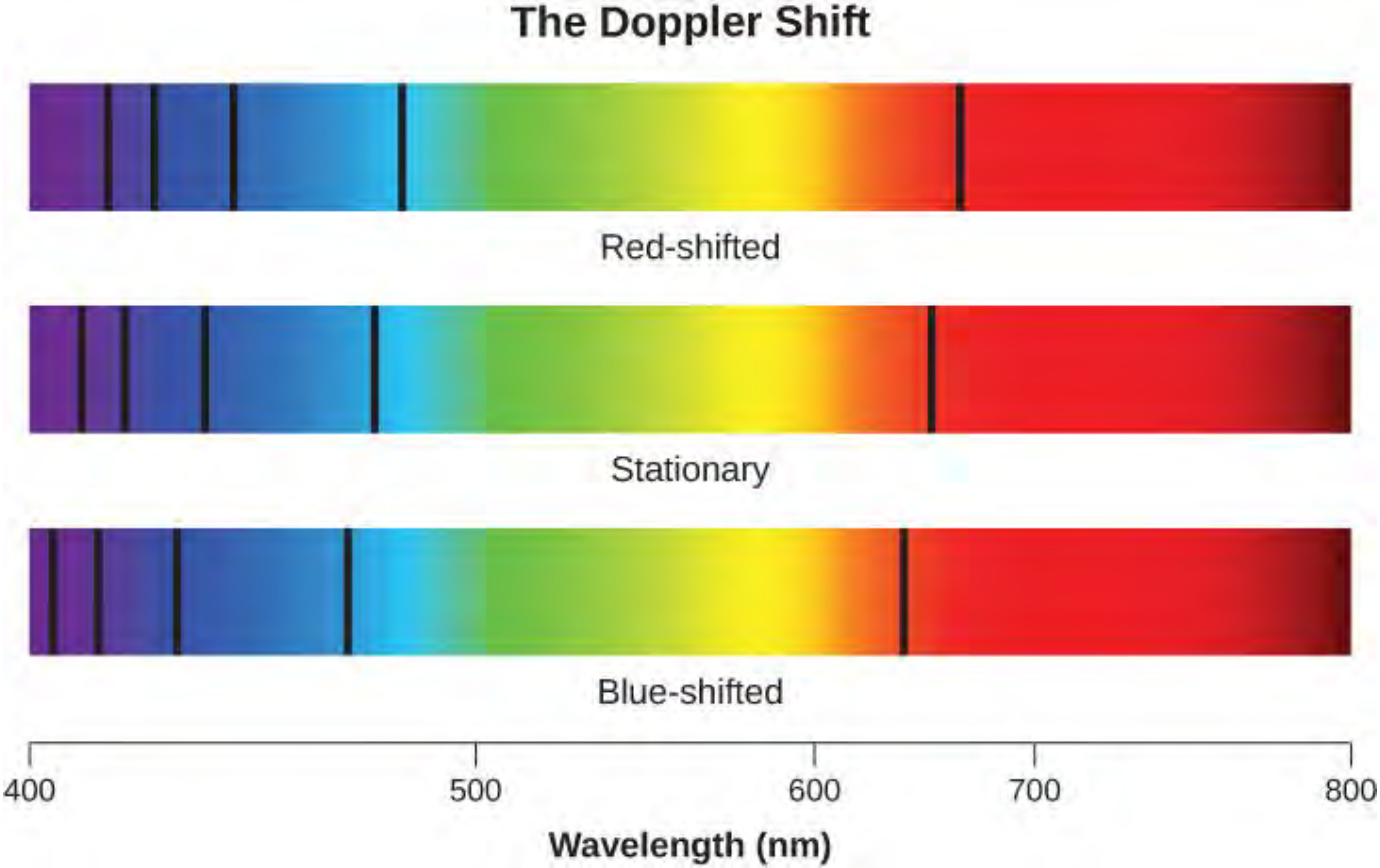
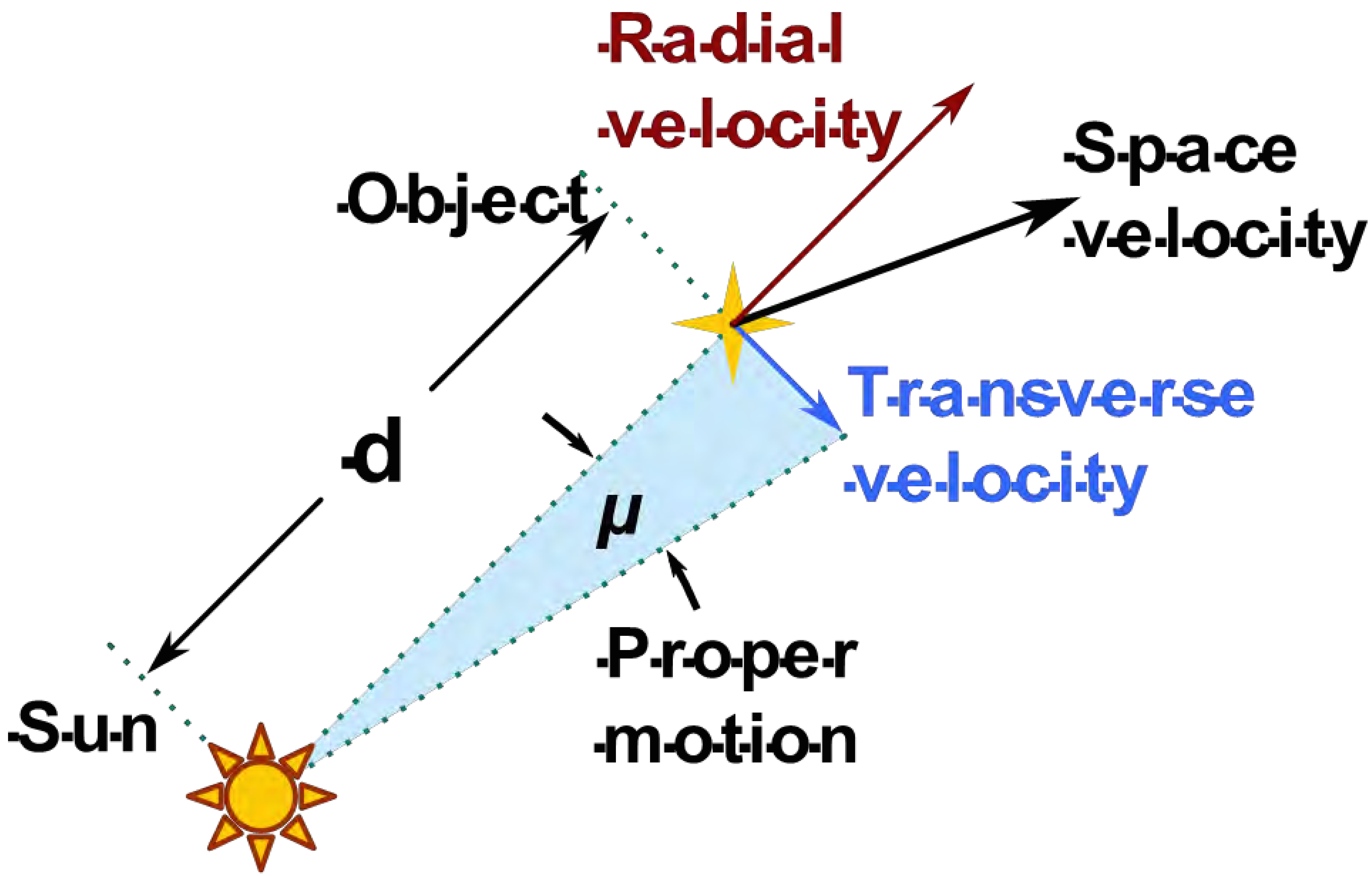


Illustration of Doppler-shifted spectral lines for 3 stars: moving away from us (top), not moving relative to us (middle), and moving toward us (bottom).
Credits: OpenStax Astronomy

The Doppler effect

- We are not special! Stars in the galaxy don’t move only toward or away from us, they also move in other directions.
- The motion of a star across the sky is called proper motion.
- Doppler shift can tell us about the radial velocity of the star (along the line of sight).
- Observations of proper motion tell us about the transverse velocity of the star (perpendicular to the line of sight).
- If we also know the distance to the star, this information allows us to calculate its space velocity, i.e. its actual velocity in space.



The relationship between radial, transverse, and space velocity of a star.
Credits: Brews ohare / CheChe (Wikipedia)

Proper motion of the binary star system 61 Cygni in the sky between 2012 and 2020.
Credits: IndividusObservantis (Wikipedia), GIF available here: https://en.wikipedia.org/wiki/File:61_Cygni_Proper_Motion.gif

Reconstructed orbits of stars moving in and out of our galaxy. These are space velocities, not radial velocities; the stars are not moving specifically away from or towards Earth.
Credits: ESA (artist's impression and composition); Marchetti et al 2018 (star positions and trajectories); NASA/ESA/Hubble (background galaxies)

The Doppler effect

- We can also use the Doppler effect to measure a star’s rotation.
- Depending on the rotation axis and direction, one side of the star is moving toward us, and the opposite side is moving away from us.
- The star is just a point, so we cannot measure the light from each side separately.
- However, the spectral lines from one side will be redshifted, and the lines from the other side will be blueshifted.
- So in total, we will see the lines broadening. The amount of broadening tells us the rotation speed of the star.

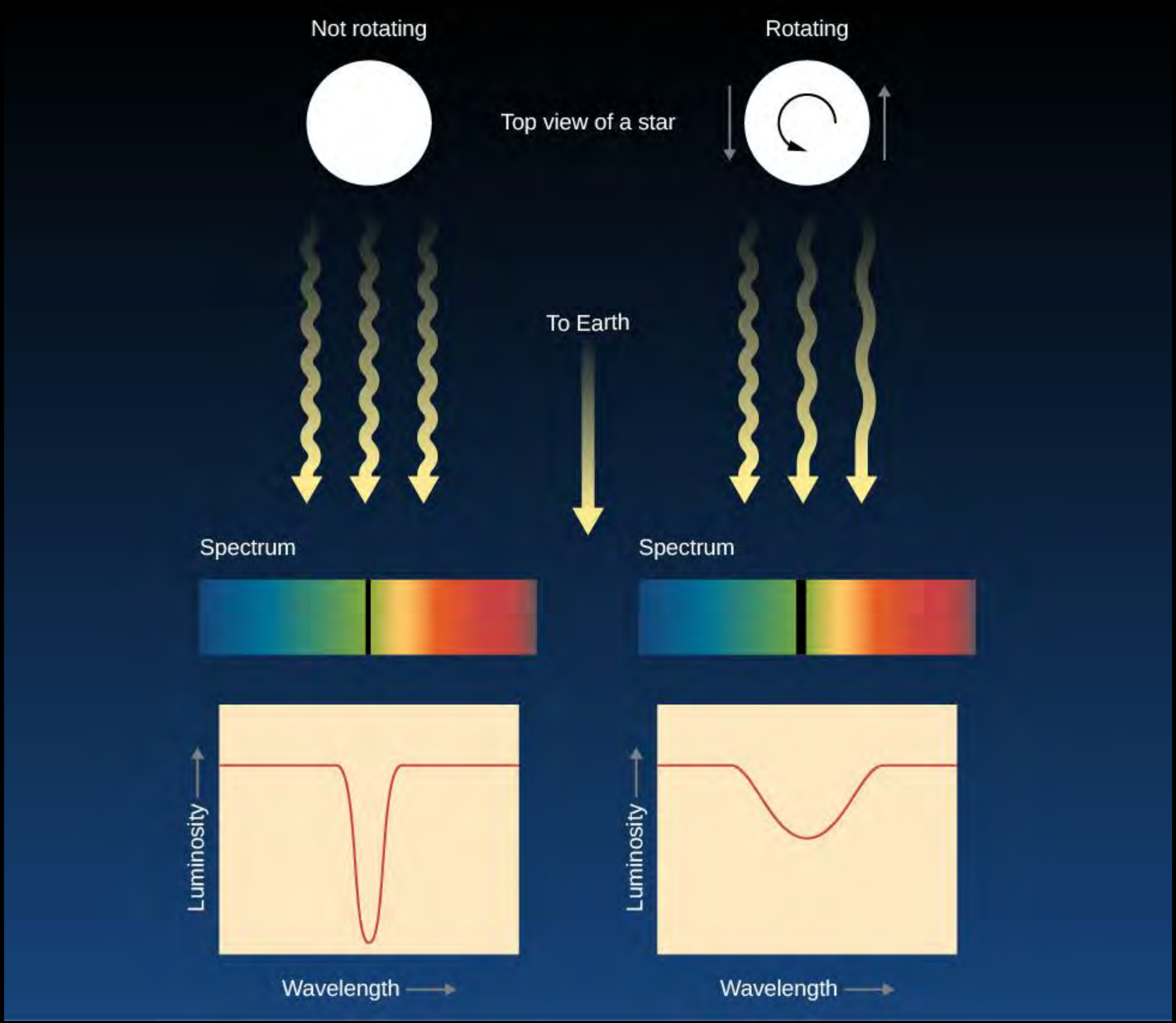


Illustration of line broadening.
Credits: OpenStax Astronomy

Conclusions

- In this lecture we learned how to use properties of light, such as brightness, color, and spectral lines, to learn about the star that produced the light.
- The properties of light (and waves in general) that we learned about will continue to be useful later.

- Reading: OpenStax Astronomy, chapter 17.
- Exercises: Practice questions will be posted on Teams.