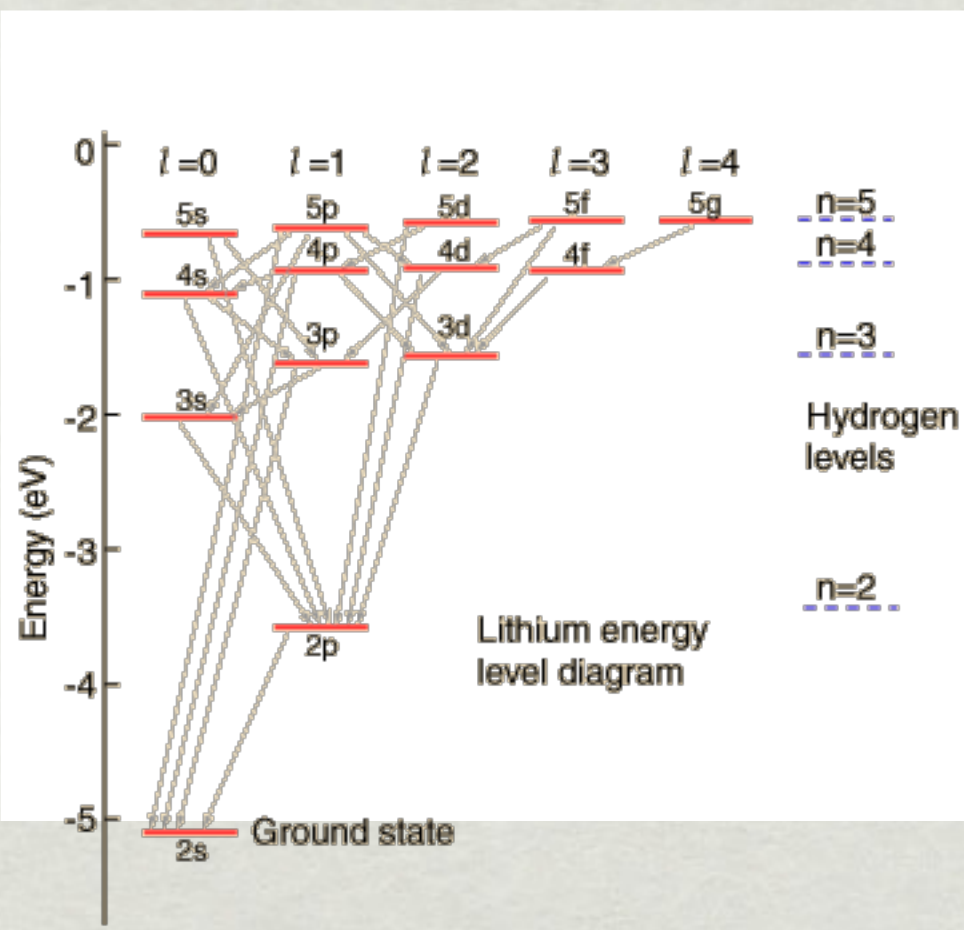
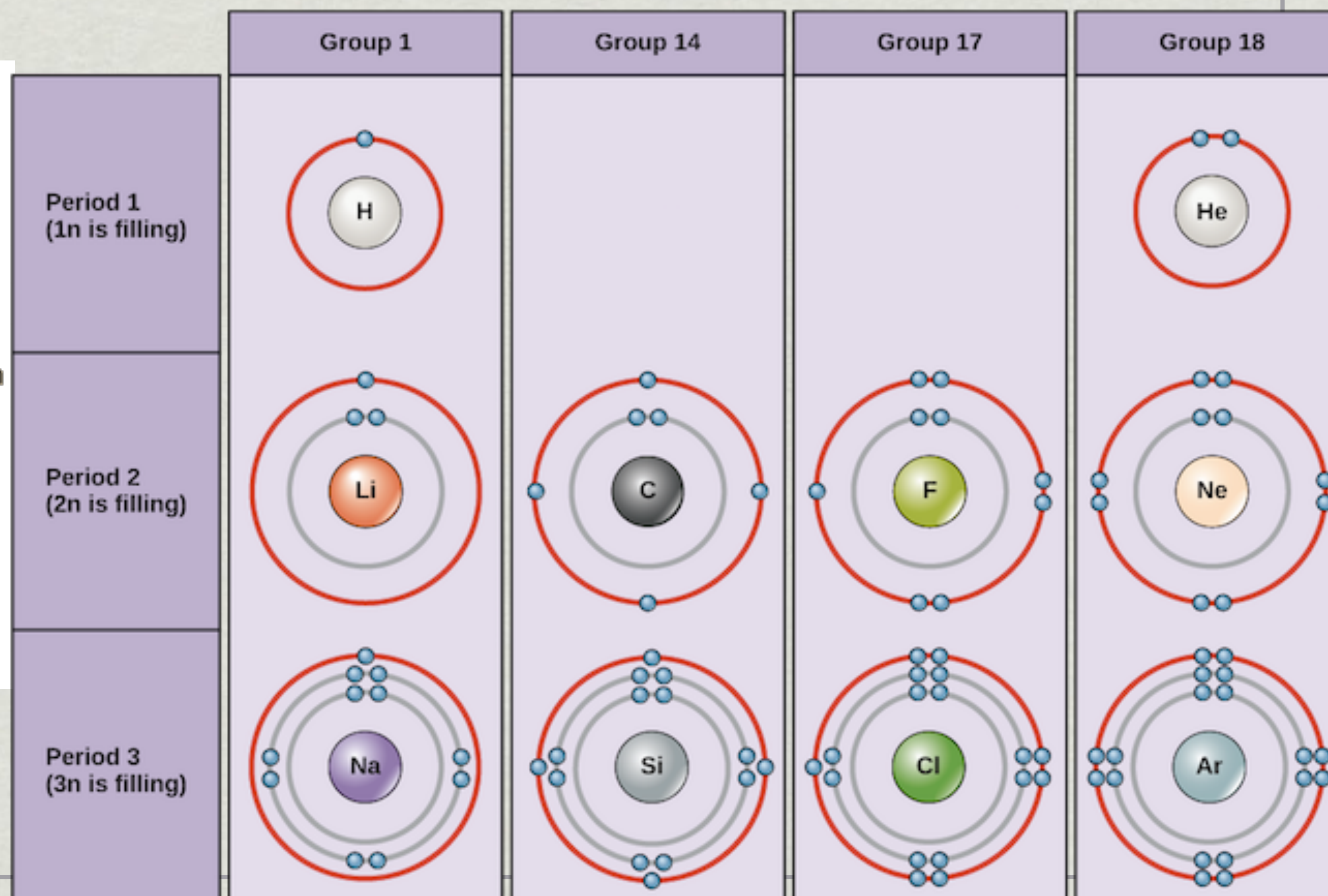
Announcements

- Midterm in-class Tuesday, February 14th
  - Content: everything through lecture 2/7, homework due 2/9 (Chapters 1,2,3,4)
  - You will get a formula sheet and all numbers you need
  - Closed book and notes
  - Bring a pencil and a non-web-enabled calculator
  - Best practice is to review the homework problems and reading assignments
- Midterm review sessions: there will be 2, TBD
- No homework due 2/16

Light and Atoms

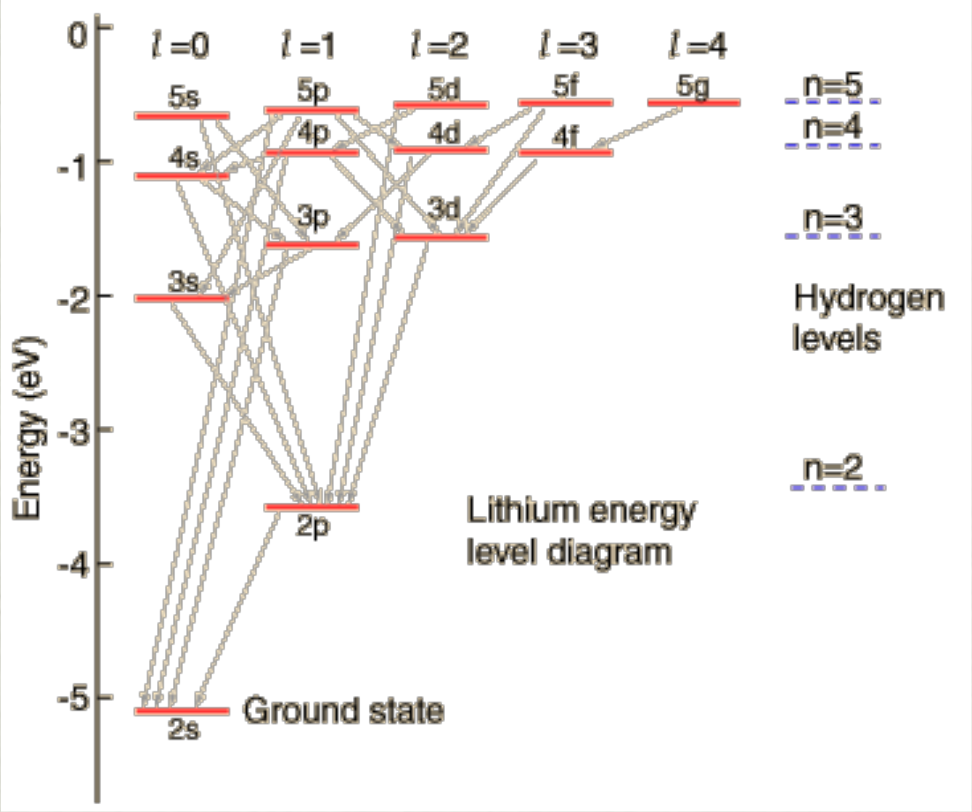
- Atoms: release and absorb photons only with certain energies
  - Different chemical elements: determined by number of protons and electrons
  - Each element has a unique set of energy levels that its electrons can occupy
  - Electrons can only move between available energy levels

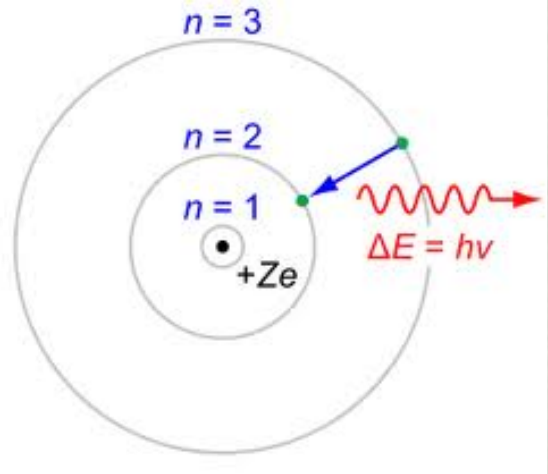




Light and Atoms

Get energy = absorb a photon, electron moves to a higher energy level
Release energy = emit a photon, electron falls to a lower energy level





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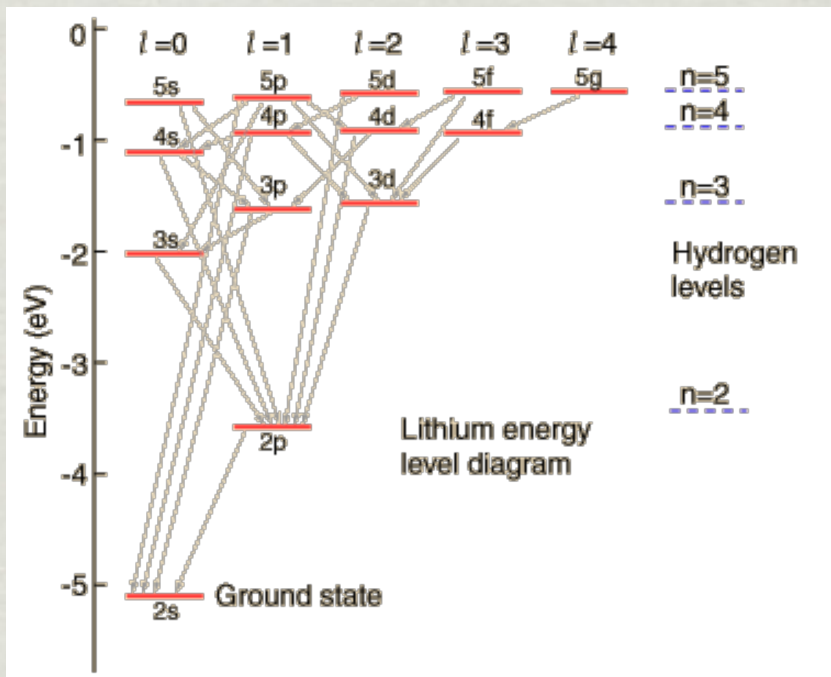
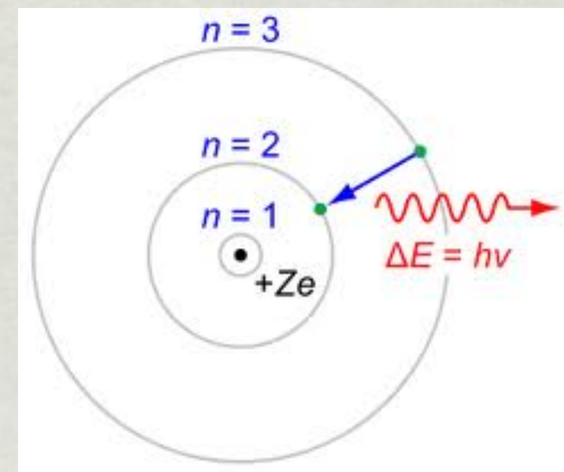


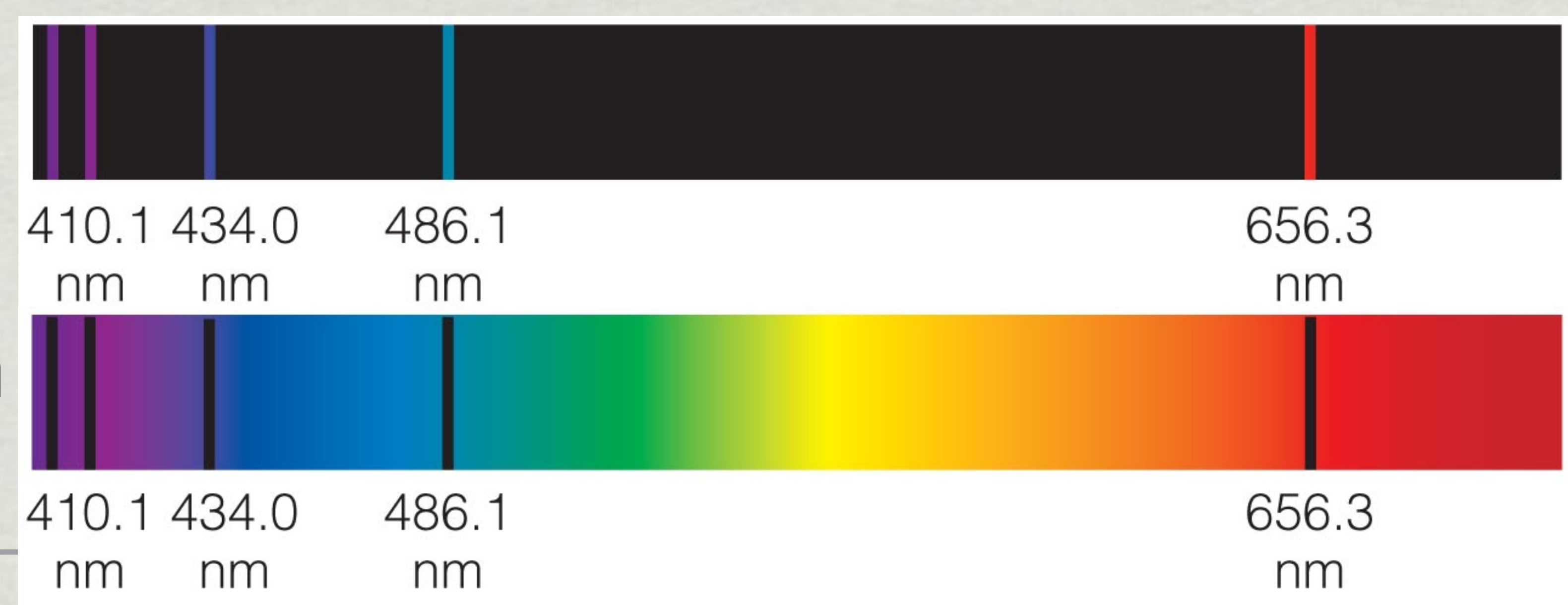


Number of photons (total amount of energy) emitted at each wavelength: a spectrum

Hydrogen Spectra:

Emission

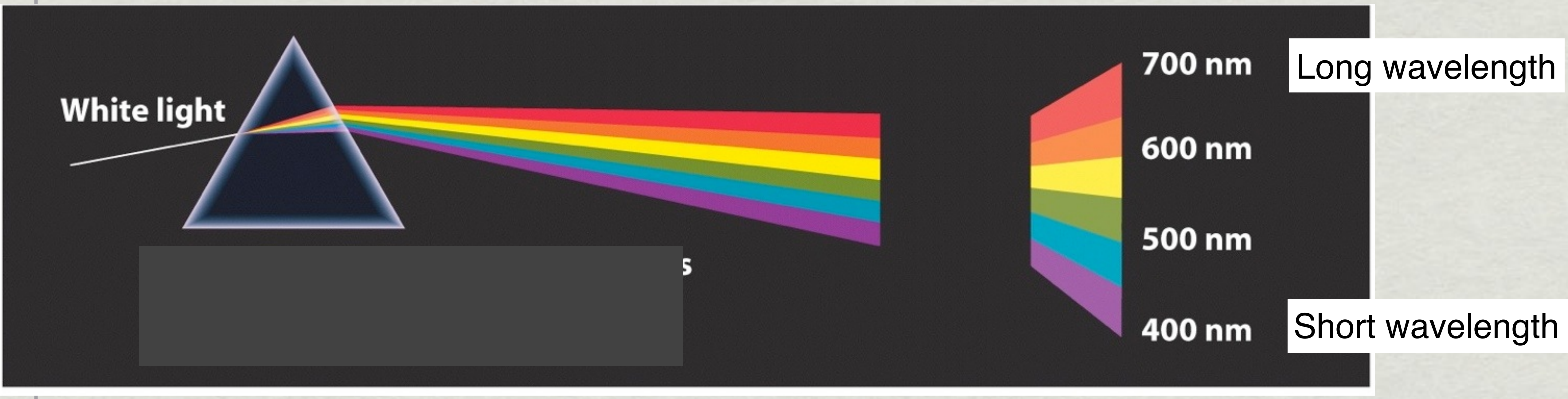
Absorption



Spectra

Prisms bend the path of photons according to their energy
White light contains a ***continuum*** of energies (wavelengths)

We see the energy of photons as the color of light
Different colors = different wavelengths of light, photons of different energies

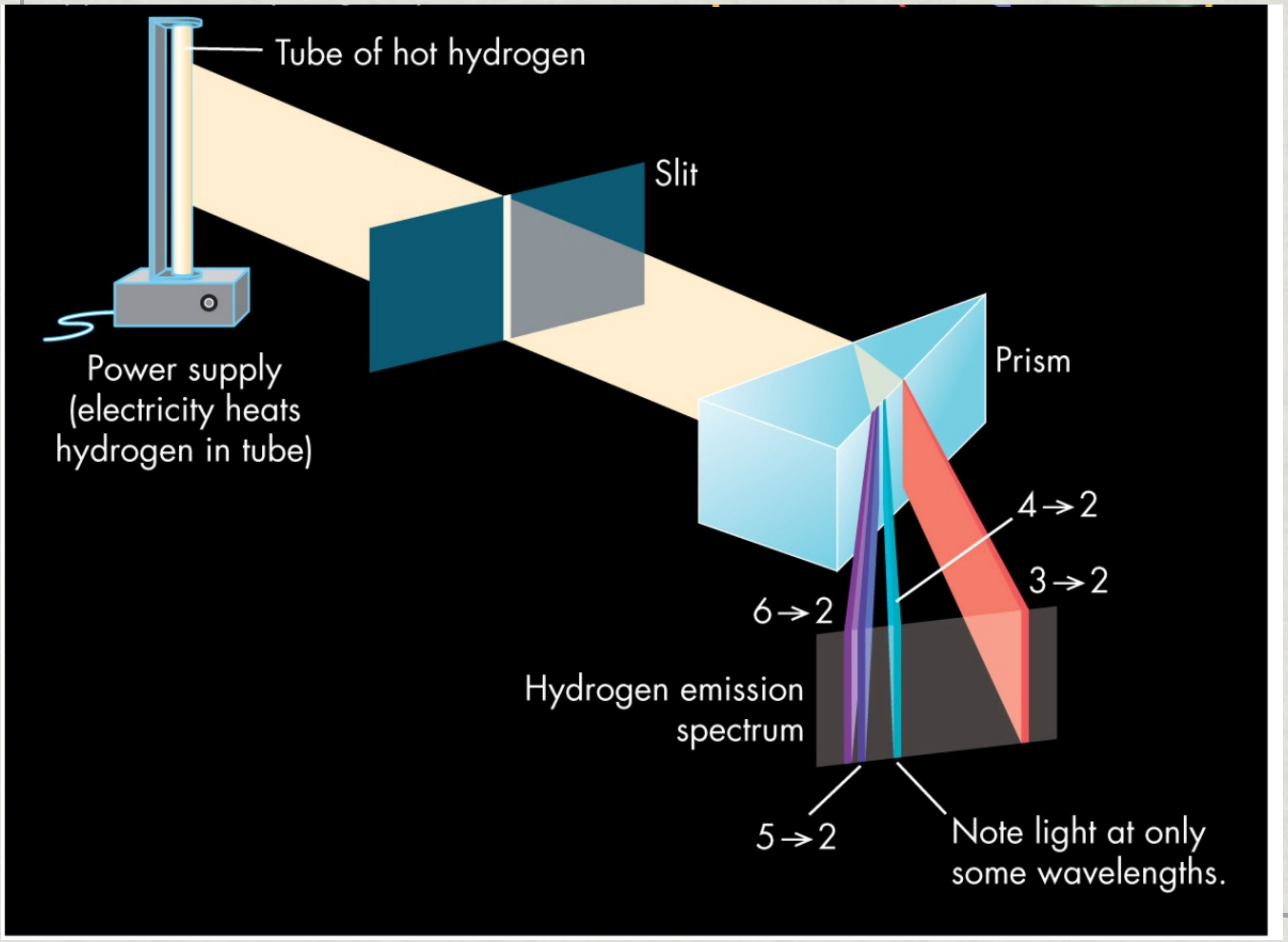


1 nm = 1×10^{-9} m = 1×10^{-6} mm

Hydrogen Spectra:

Emission

Absorption



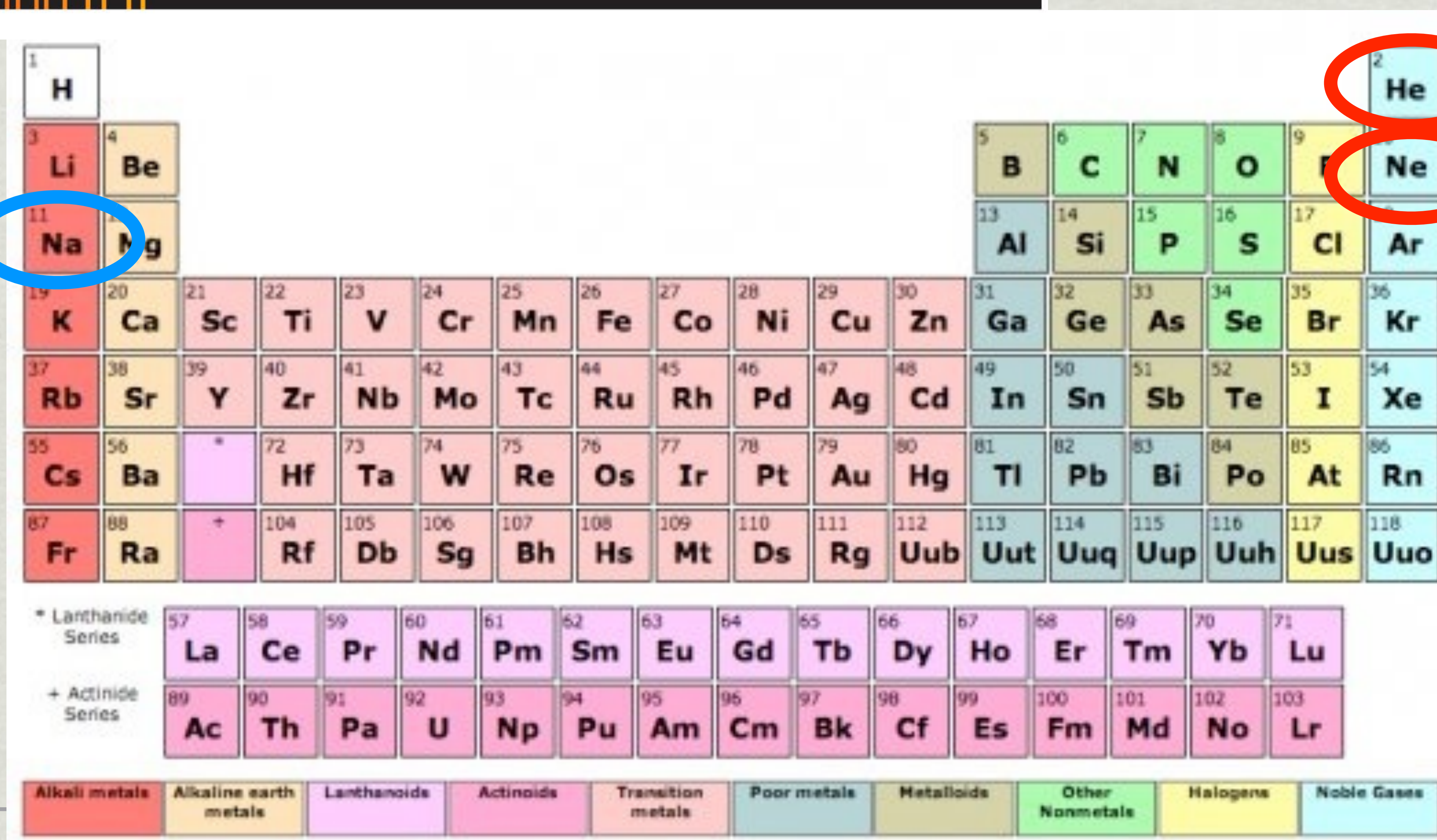
Light and Atoms

- Atoms: release and absorb photons only with certain energies
  - Different chemical elements: determined by number of protons and electrons
  - Each element has a unique set of energy levels that its electrons can occupy
  - Electrons can only move between available energy levels
  - Each element has its own fingerprint of energy

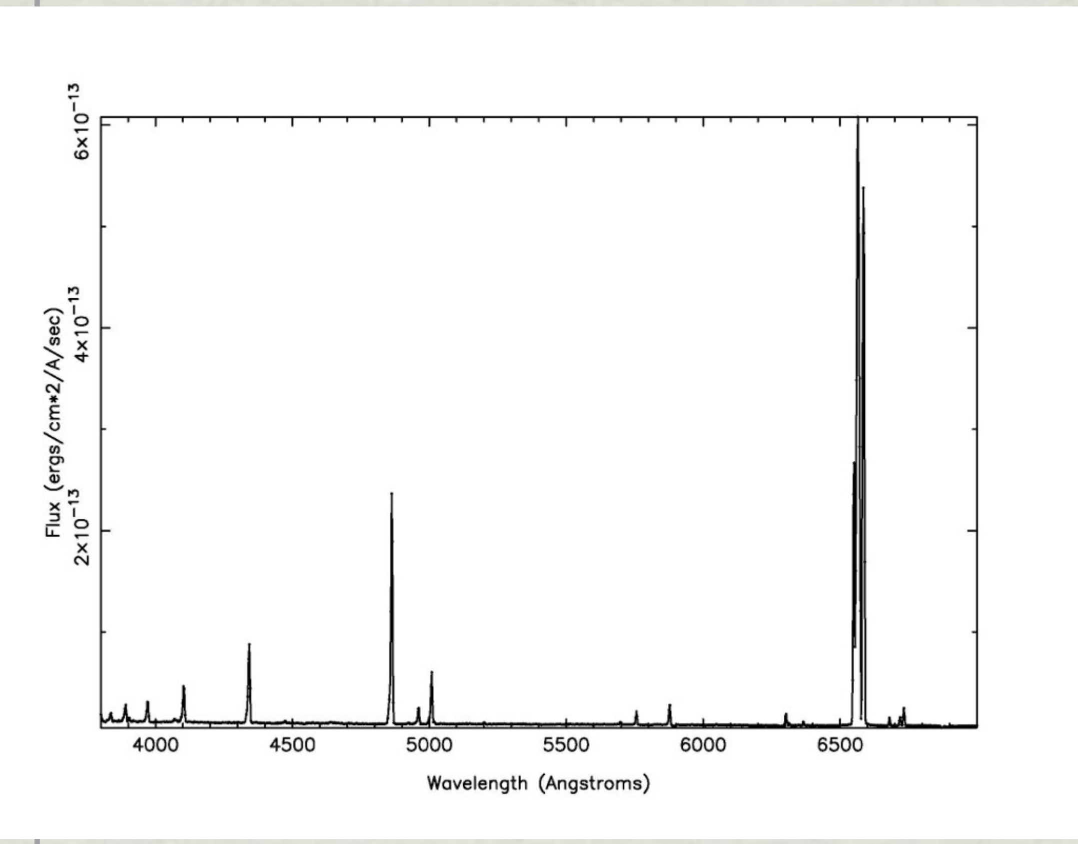
Emission spectra

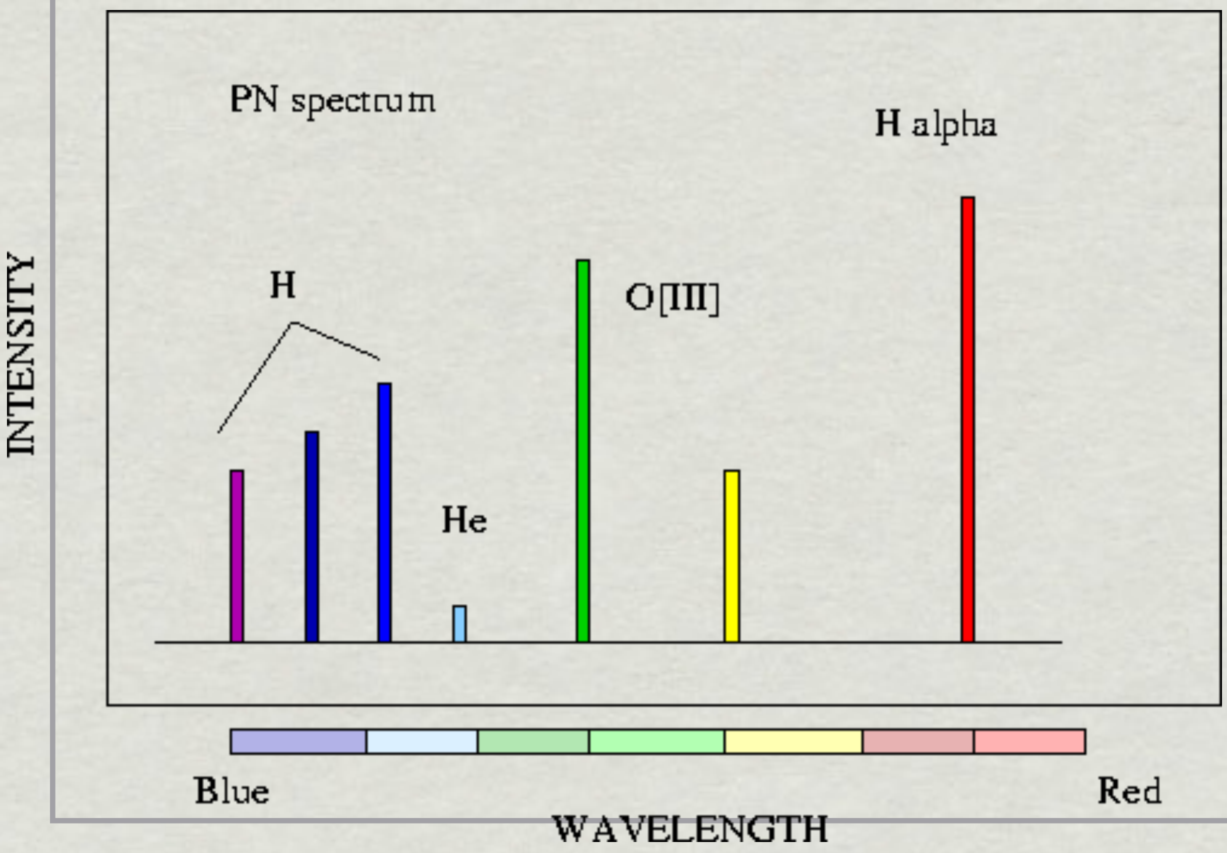
Wavelength

Emission Line “Fingerprints”



Light and Atoms: Nebula Spectrum

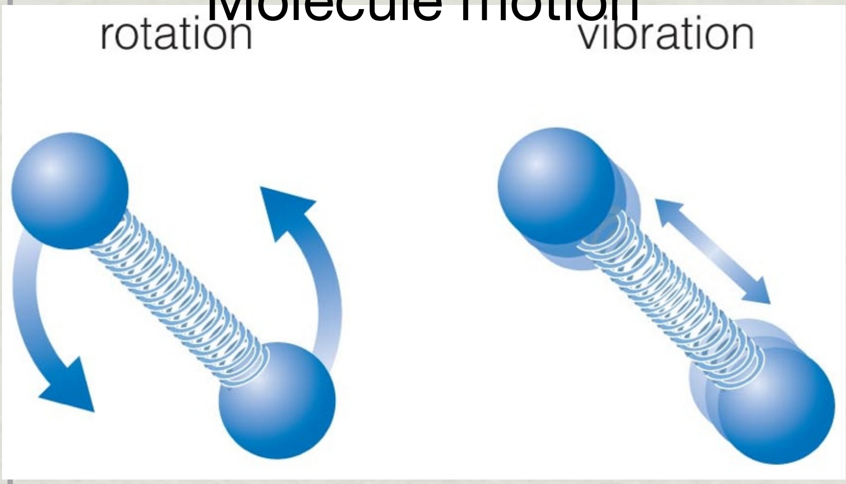




Line Emission

- Molecules: have additional energy levels because their molecules can vibrate and rotate
  - complicates their spectra: large numbers of very close vibrational and rotational levels

Molecule motion



Emission from H atoms

Emission from H_2 molecules

Wavelength

Note single lines from atoms, "Bands" of lines from molecules

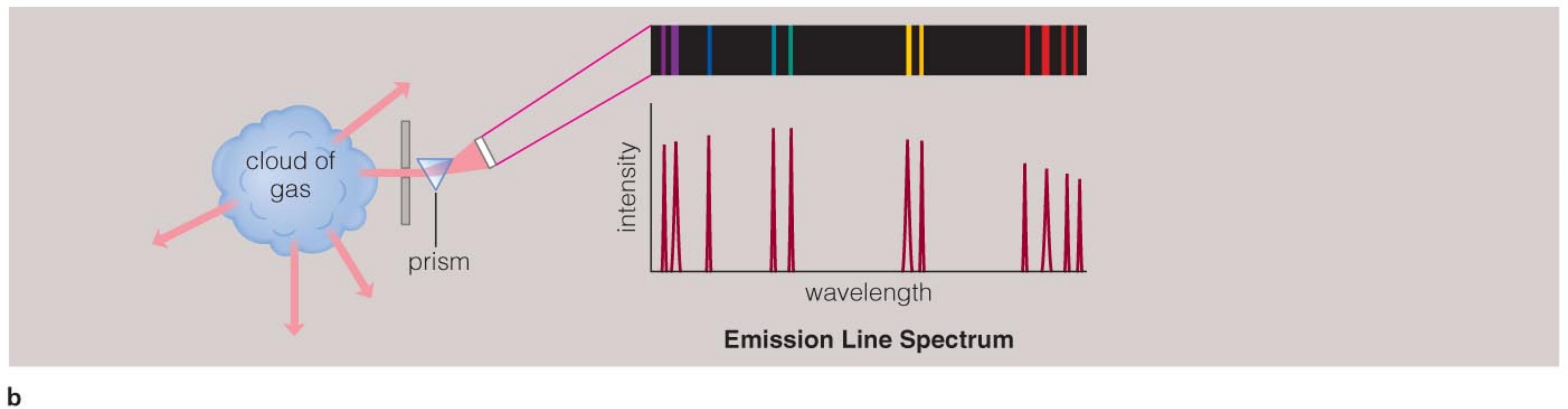
Line Emission: and Then What?

What happens to a photon after the atom or molecule releases it?

1) If the matter is transparent:

Not dense = not many other atoms around. Photons can travel freely in the blob of matter and can flow freely out

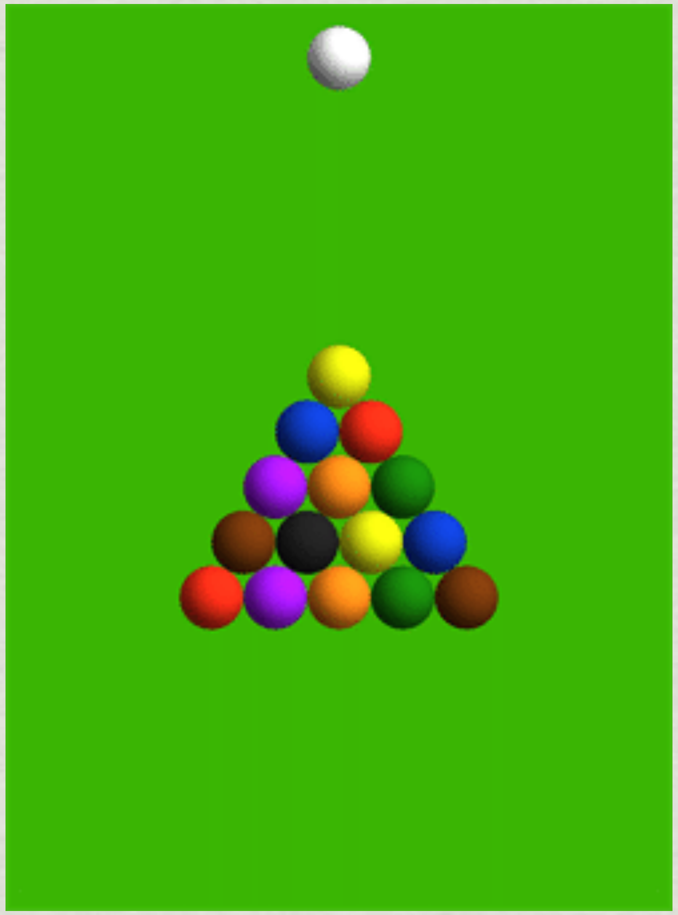
We observe: an emission line spectrum



Line Emission: and Then What?

What happens to a photon after the atom or molecule releases it?

2) If the matter the atom is in is opaque:
High density, many atoms close together.



The photons collide with each other and the atoms, like marbles shaken in a bag.

Photons share energy with the atoms.

➜ Change wavelength of photons emitted

$$\text{Photon Energy} = E = h\,\nu = \frac{h\,c}{\lambda}$$

Line Emission: and Then What?

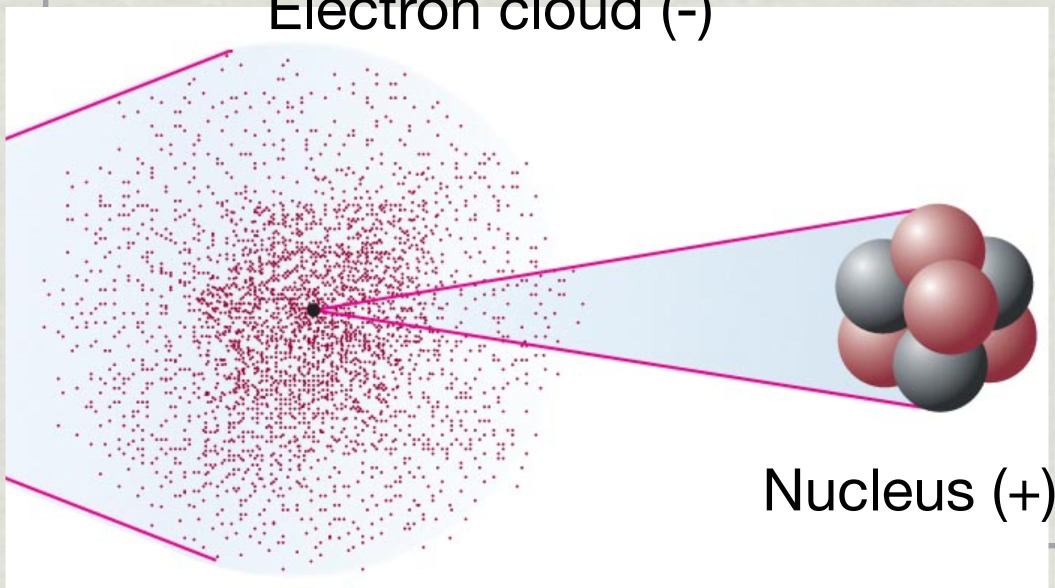
What happens to a photon after the atom or molecule releases it?

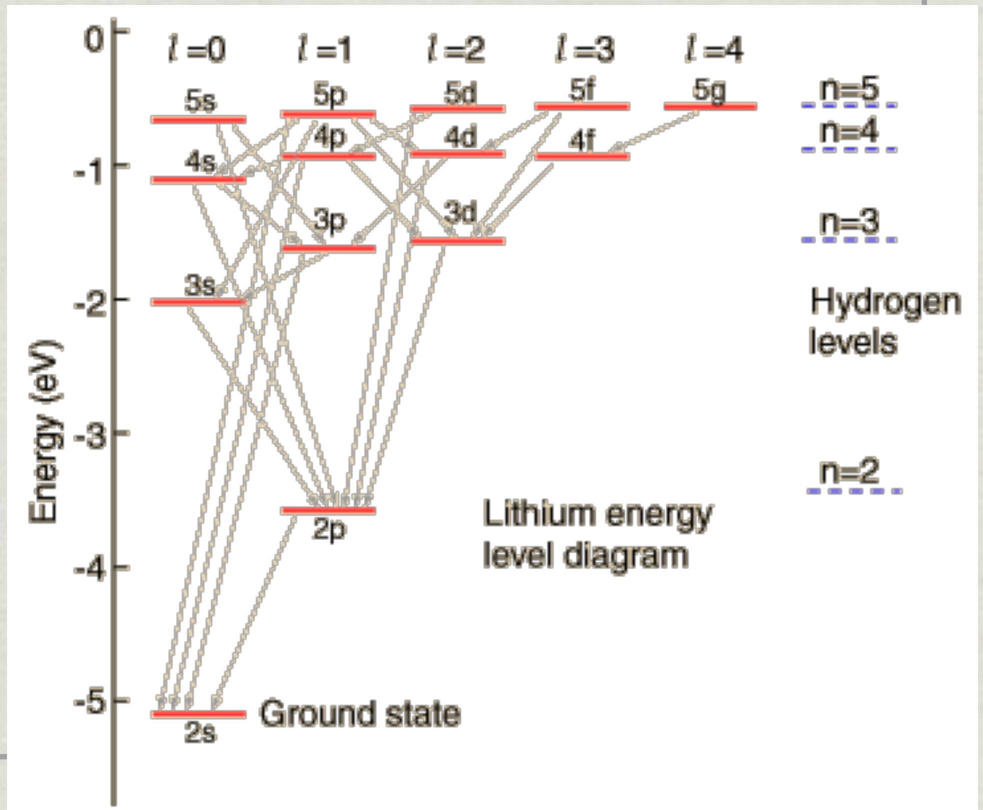
2) If the matter the atom is in is opaque:
High density, many atoms close together.

Electromagnetic force from close passes by other atom's electrons and nuclei.

Atoms change each other's energy levels.

➜ Change wavelength of photons emitted



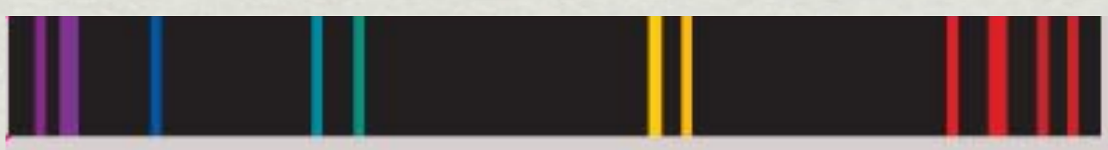


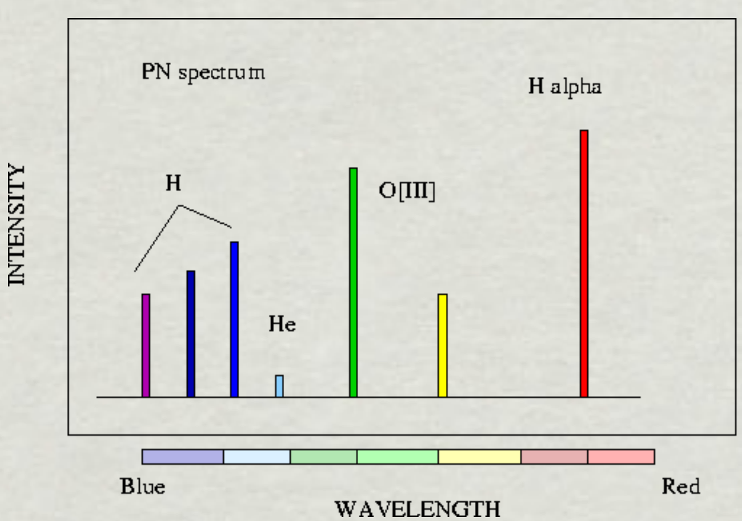
Line Emission: and Then What?

What happens to a photon after the atom or molecule releases it?

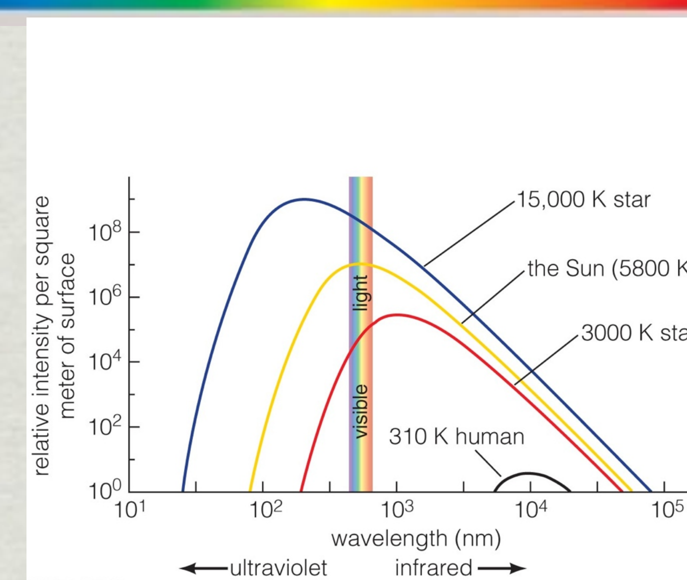
2) If the matter the atom is in is opaque:
High density, many atoms close together.

Photons start at discrete energies, become spread out over a big range of energy. Thermalized spectrum



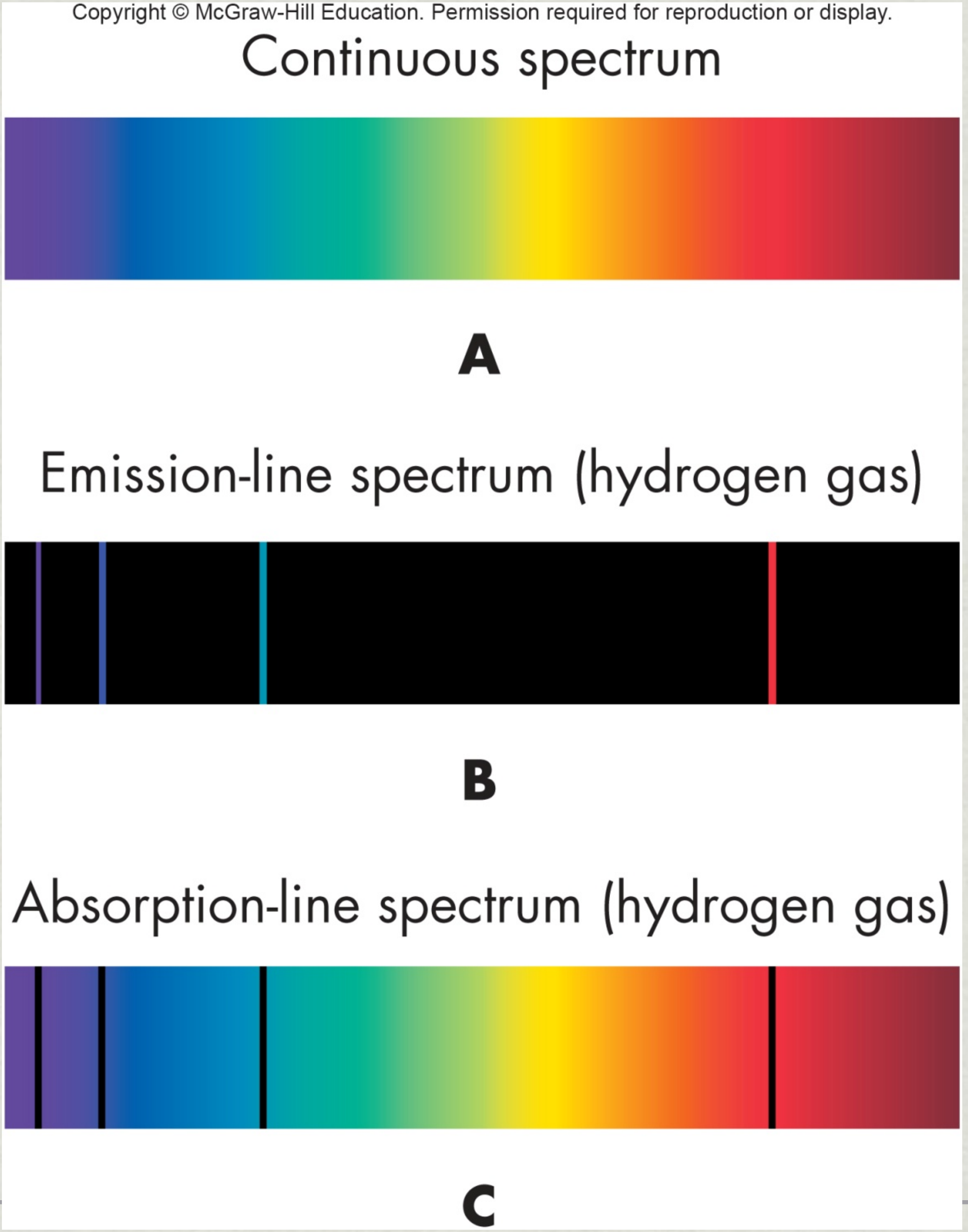


Line emission spectrum



Continuous spectrum

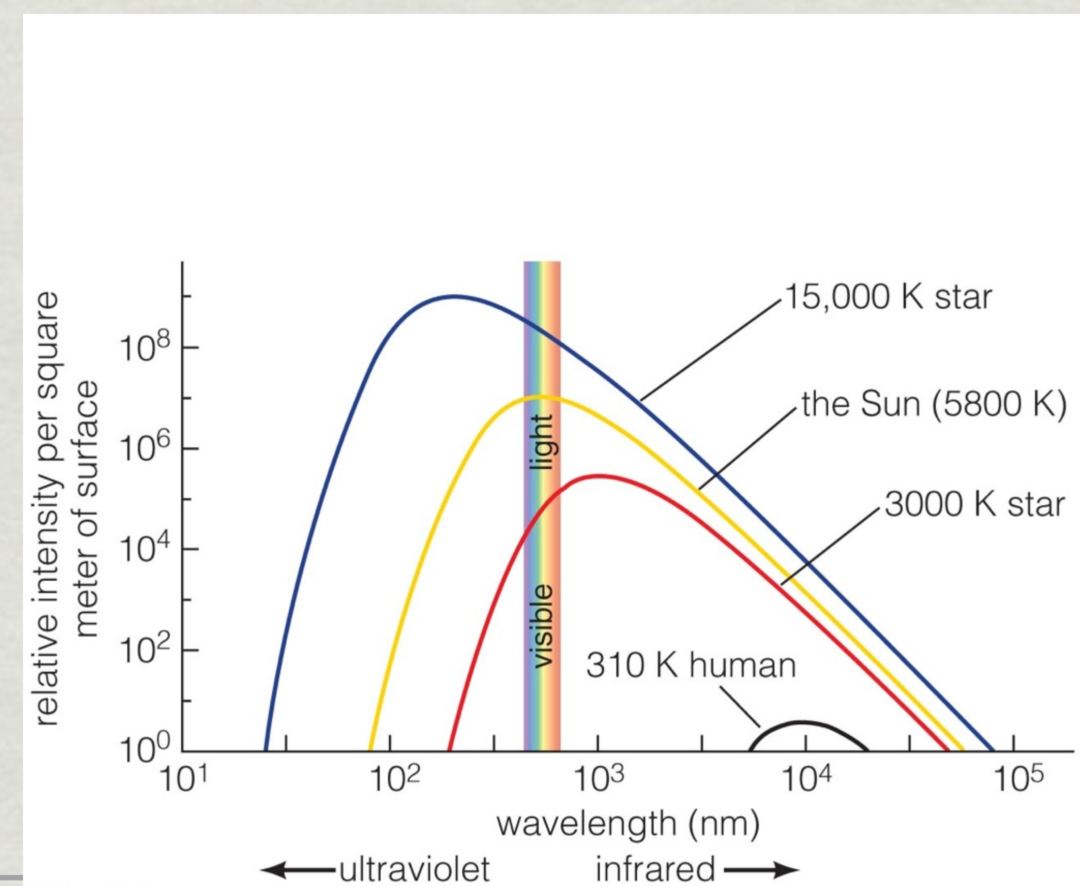
Kirchoff's Laws: Types of Spectra



Kirchoff's Laws

1) Dense, opaque objects: emit continuous spectrum, thermal emission spectrum

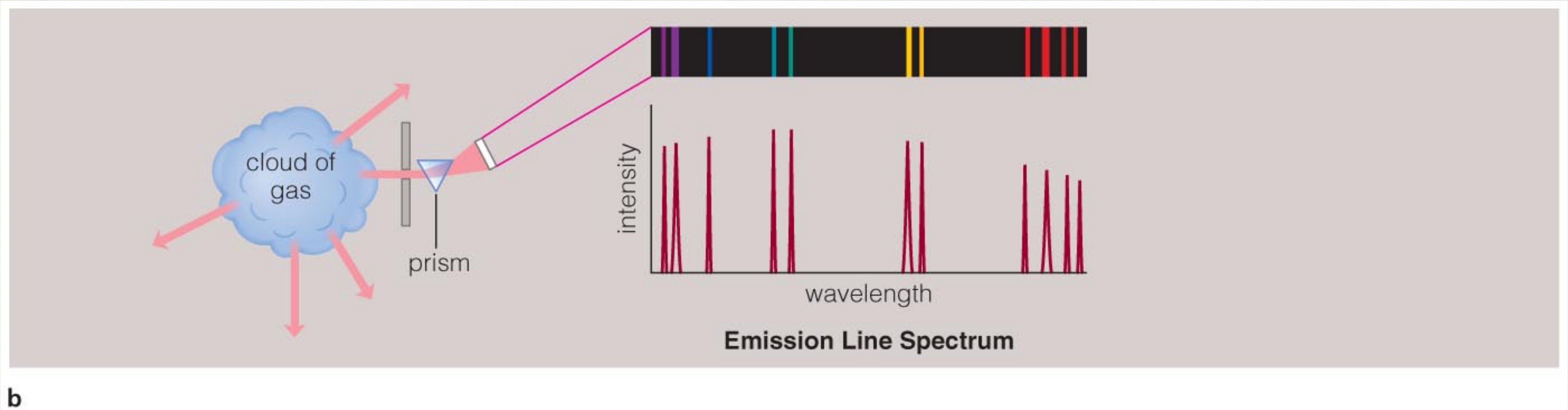
Wavelength

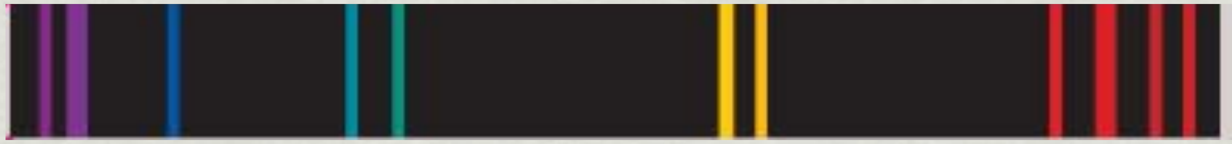


Kirchoff's Laws

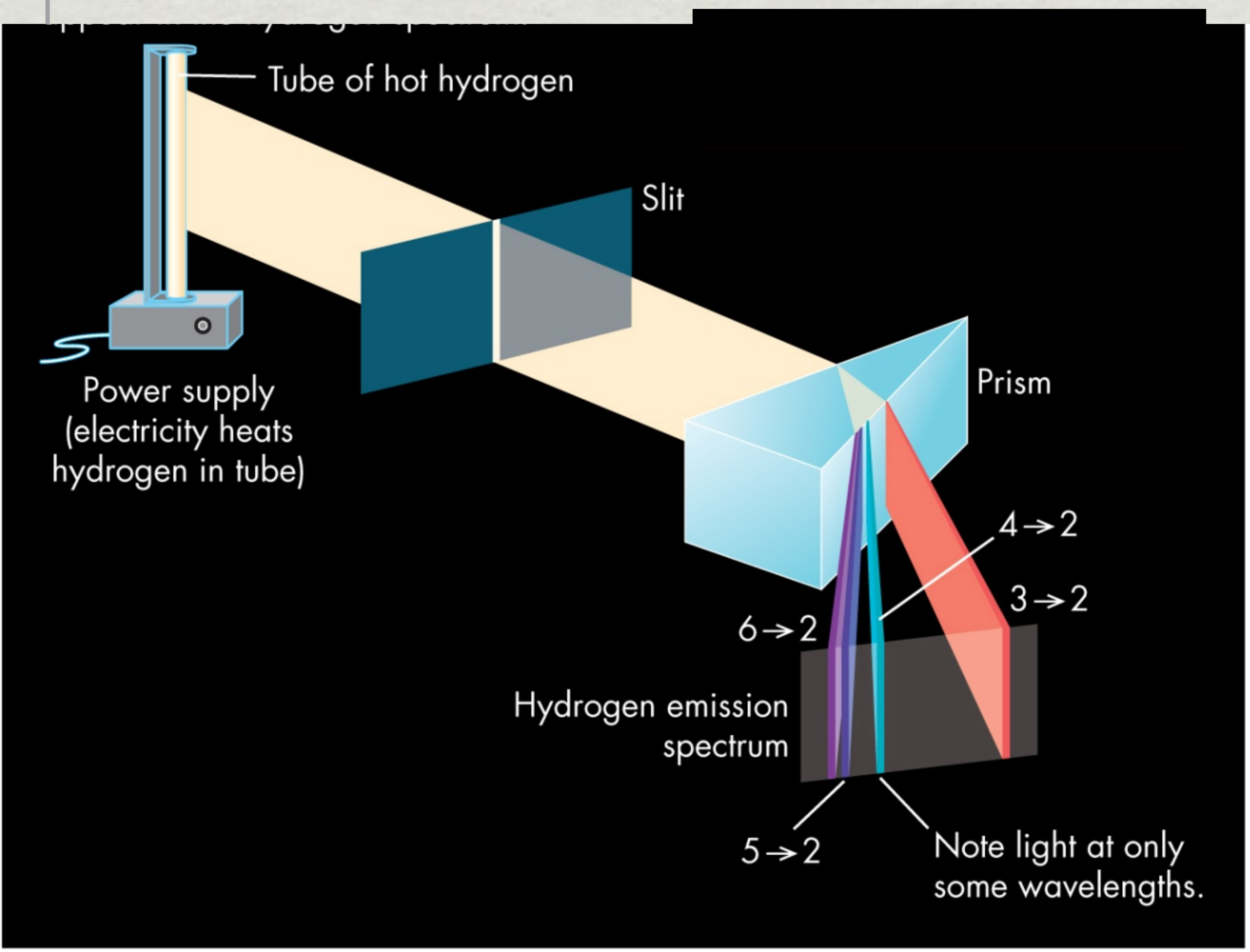
2) Transparent, low-density matter, like a cloud of gas:

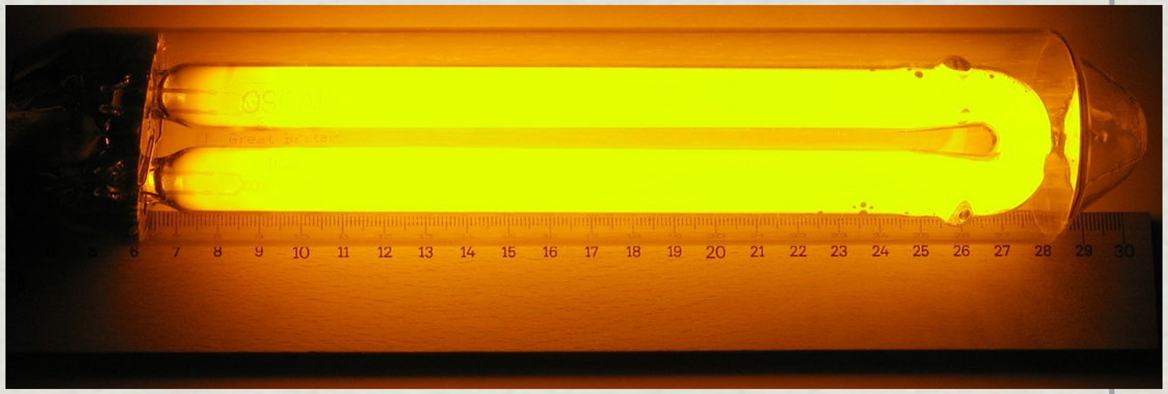
If gas is too hot to re-absorb photons: get an emission line spectrum

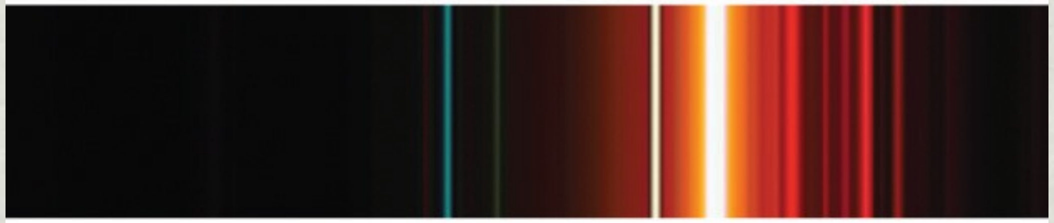




Wavelength

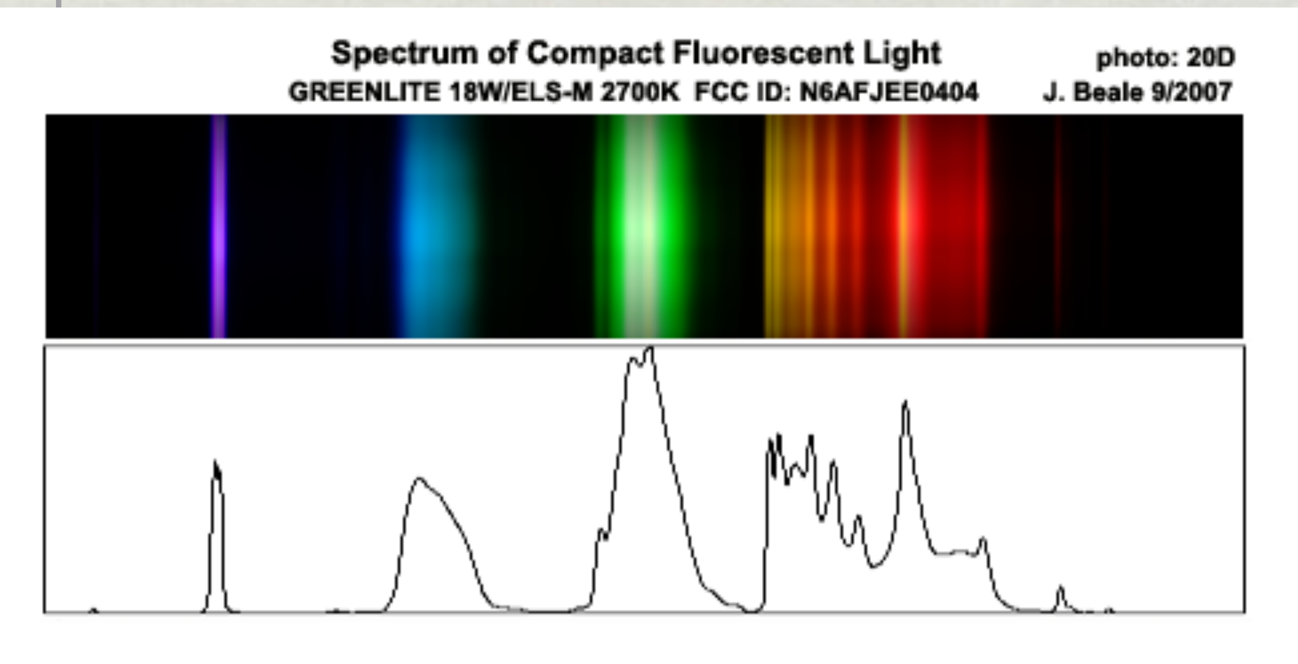


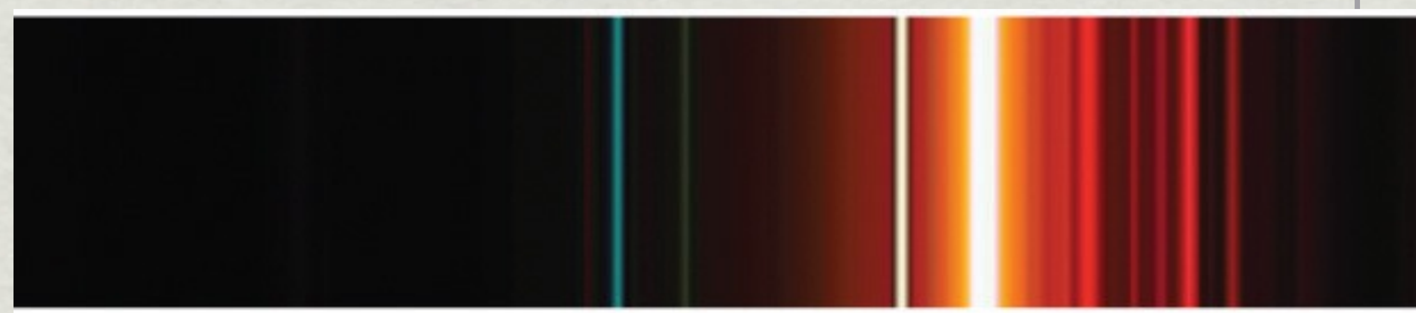




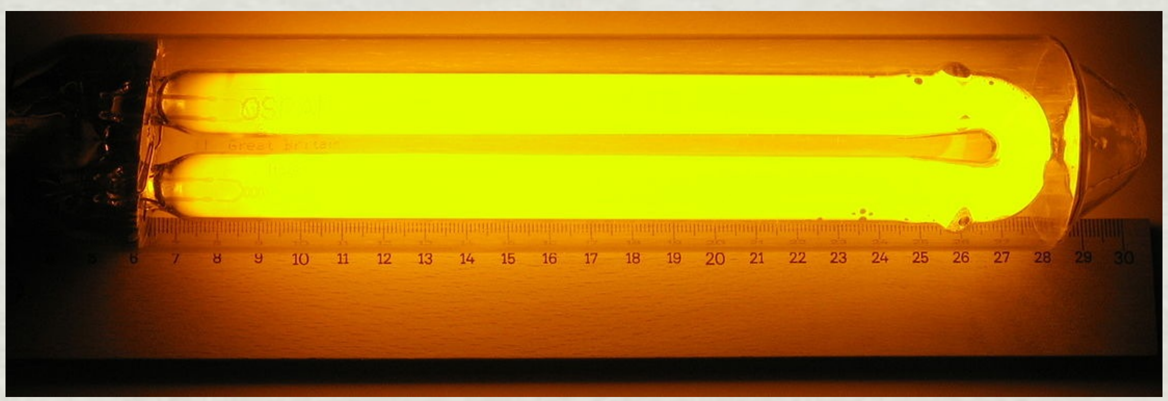
Low-pressure Na spectrum
(350-700 nm)

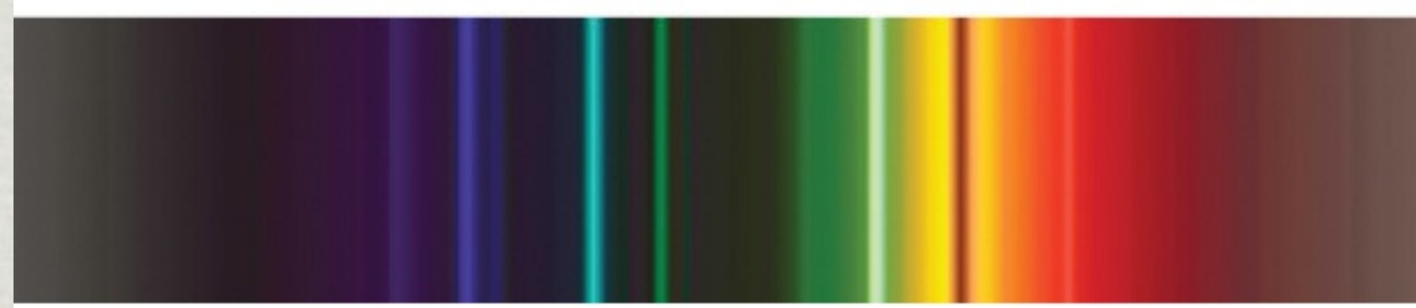
- Some everyday line emission spectra





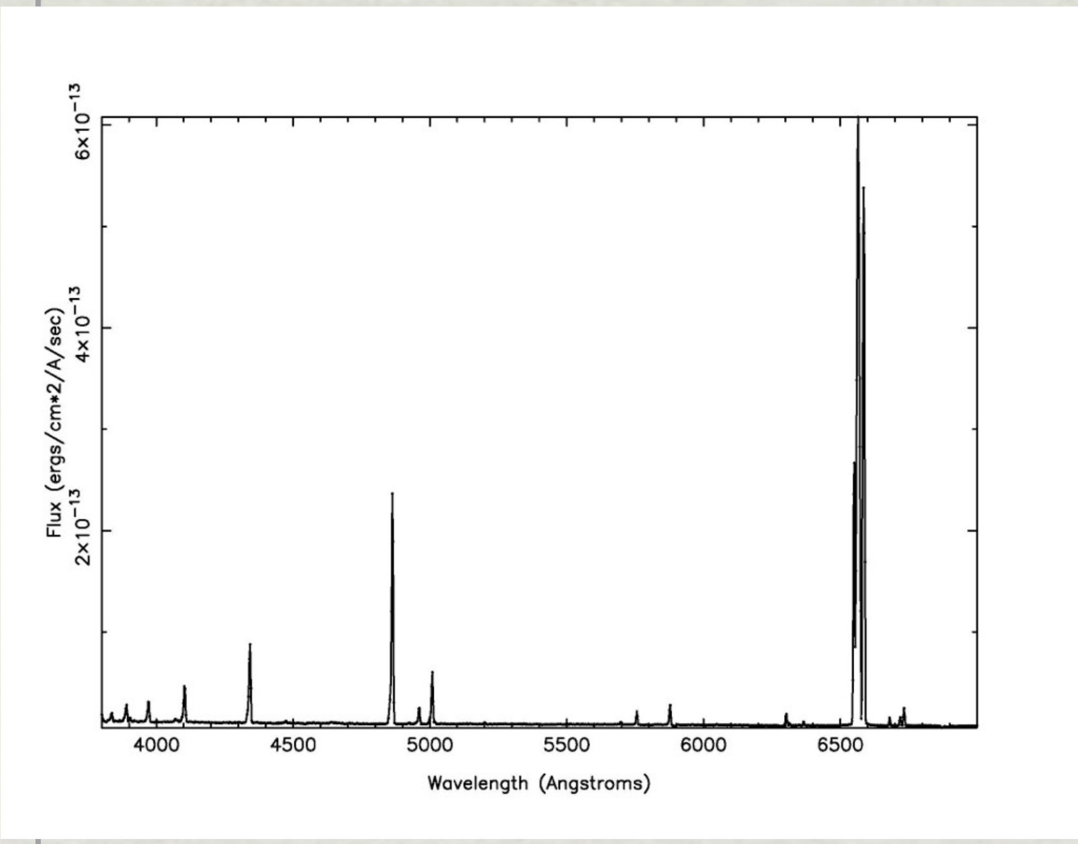
Low-pressure Na spectrum (350-700 nm)

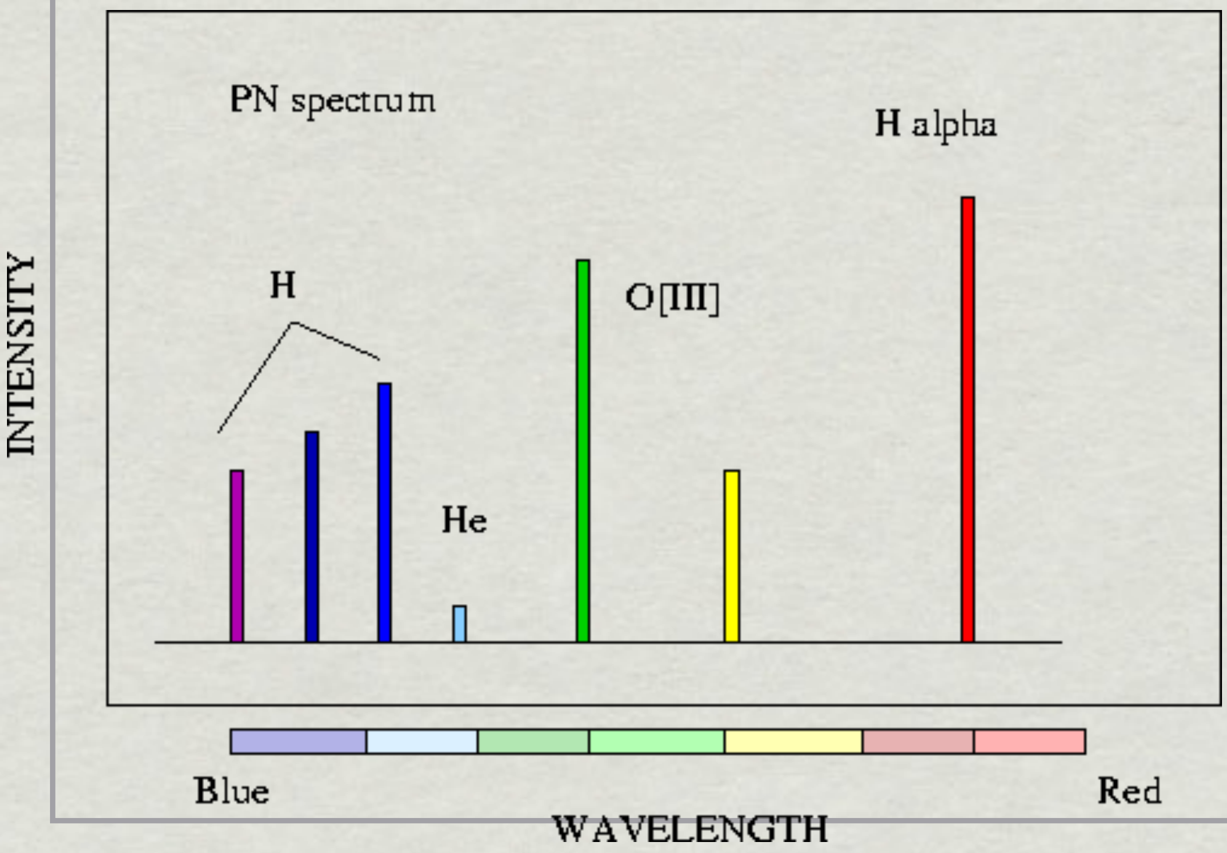




High-pressure Na spectrum (350-700 nm)

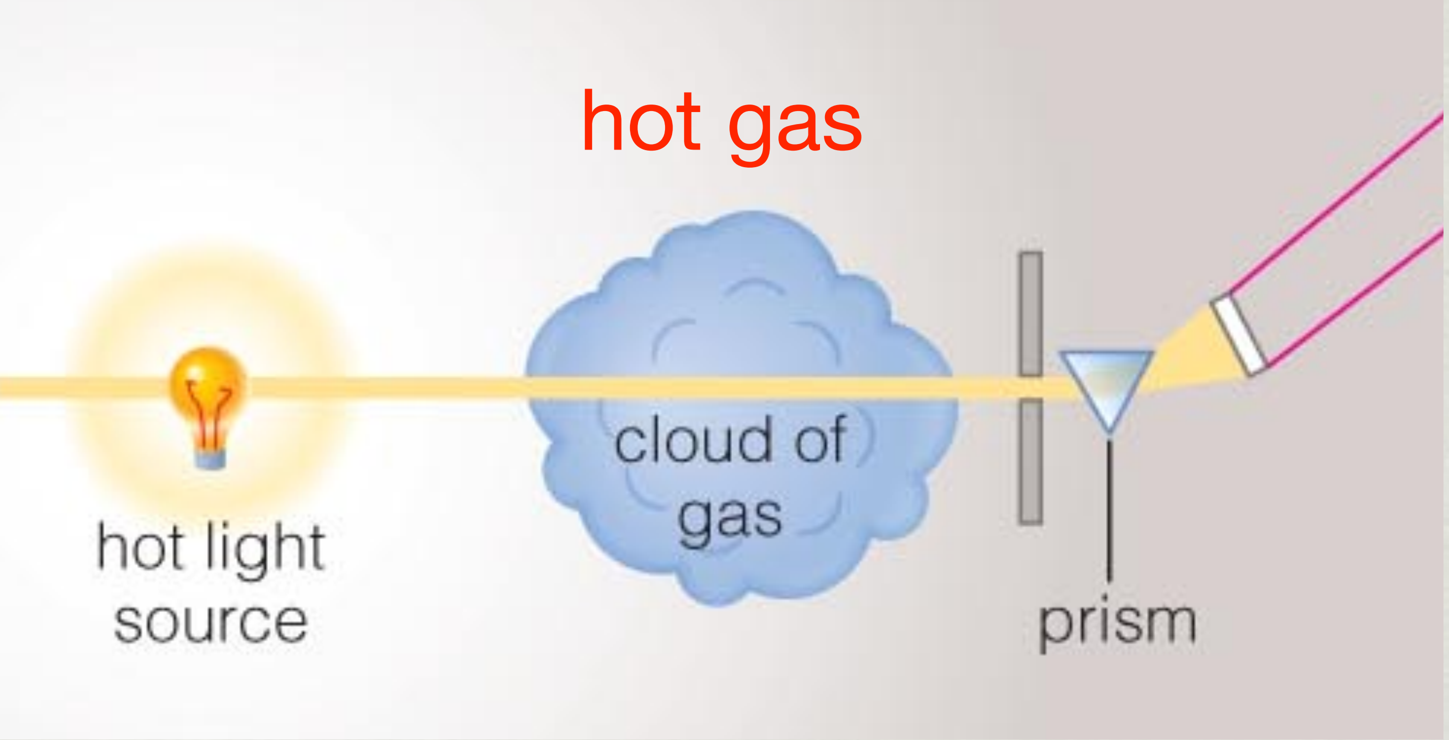
Hot, low-density gas: emission line spectrum





Kirchoff's Laws

3) Thermal emission that encounters some other matter?



A) If it is transparent matter that is also hot: gas is too hot to absorb photons. Light passes right through

(remember: transparent matter is low density)

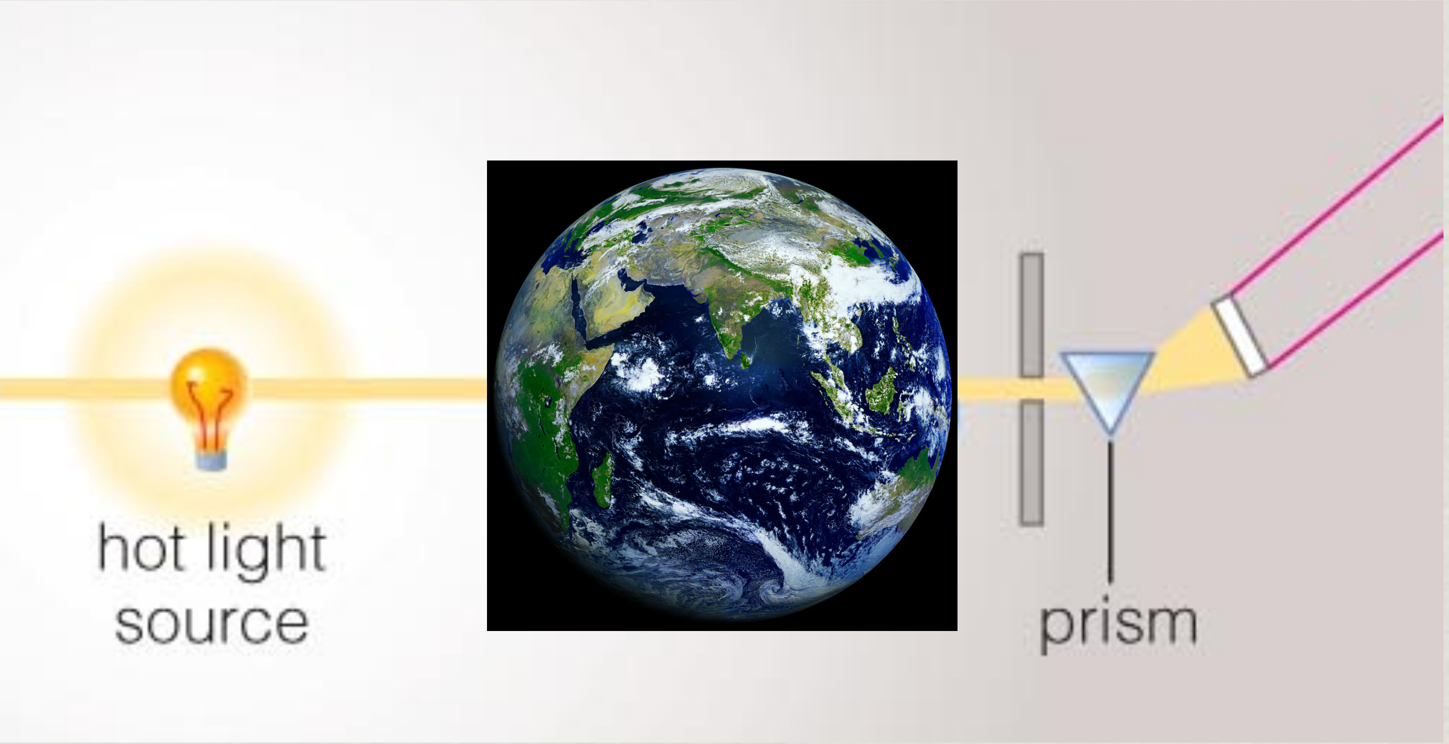
See the same thermal spectrum:

Kirchoff's Laws

3) Thermal emission that encounters some other matter?

B) If that matter is dense (opaque): emission is absorbed, energy used to heat the intervening matter

Observe: a thermal spectrum of the heated matter



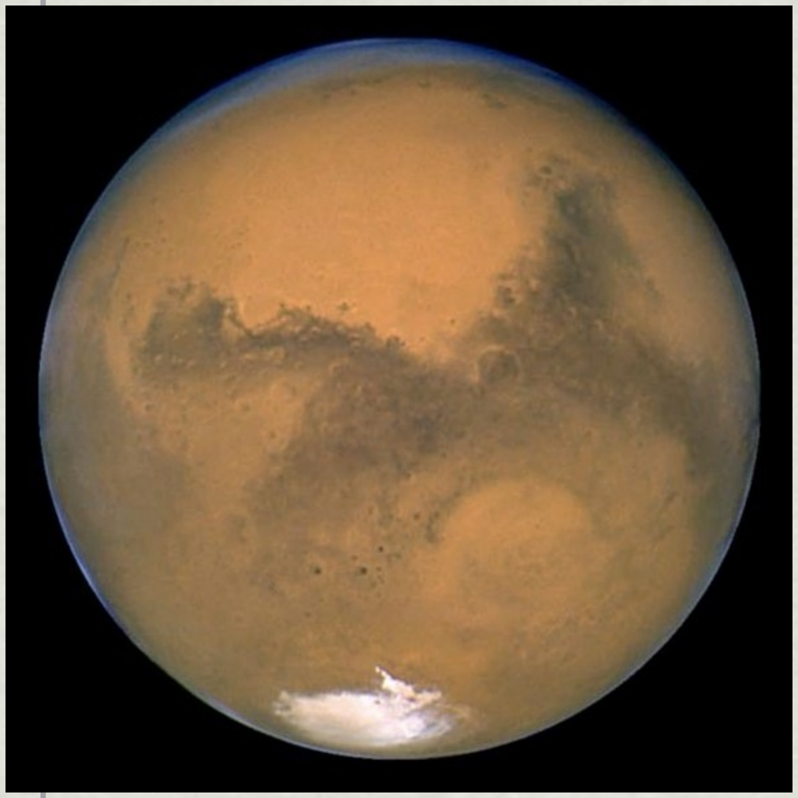
Planets, like Earth, are heated by the sun

Kirchoff's Laws

3) Thermal emission traveling through some other matter?

B) Dense, opaque matter: absorbed, thermalized

Observe thermal spectrum of the heated matter



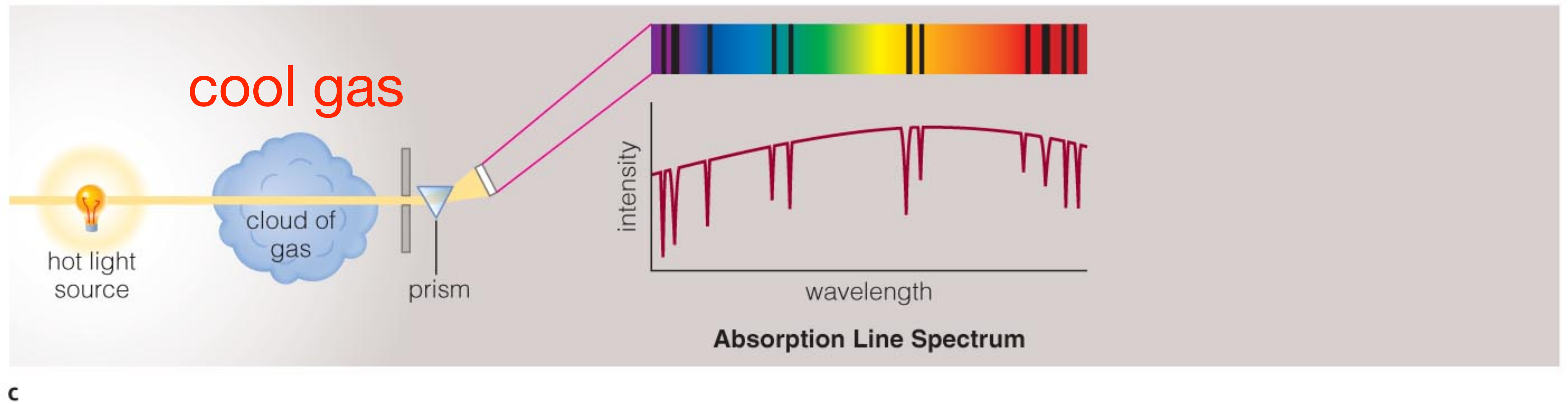
Right: Walls of a house heated by the sun.
Left: Planets, like Mars.

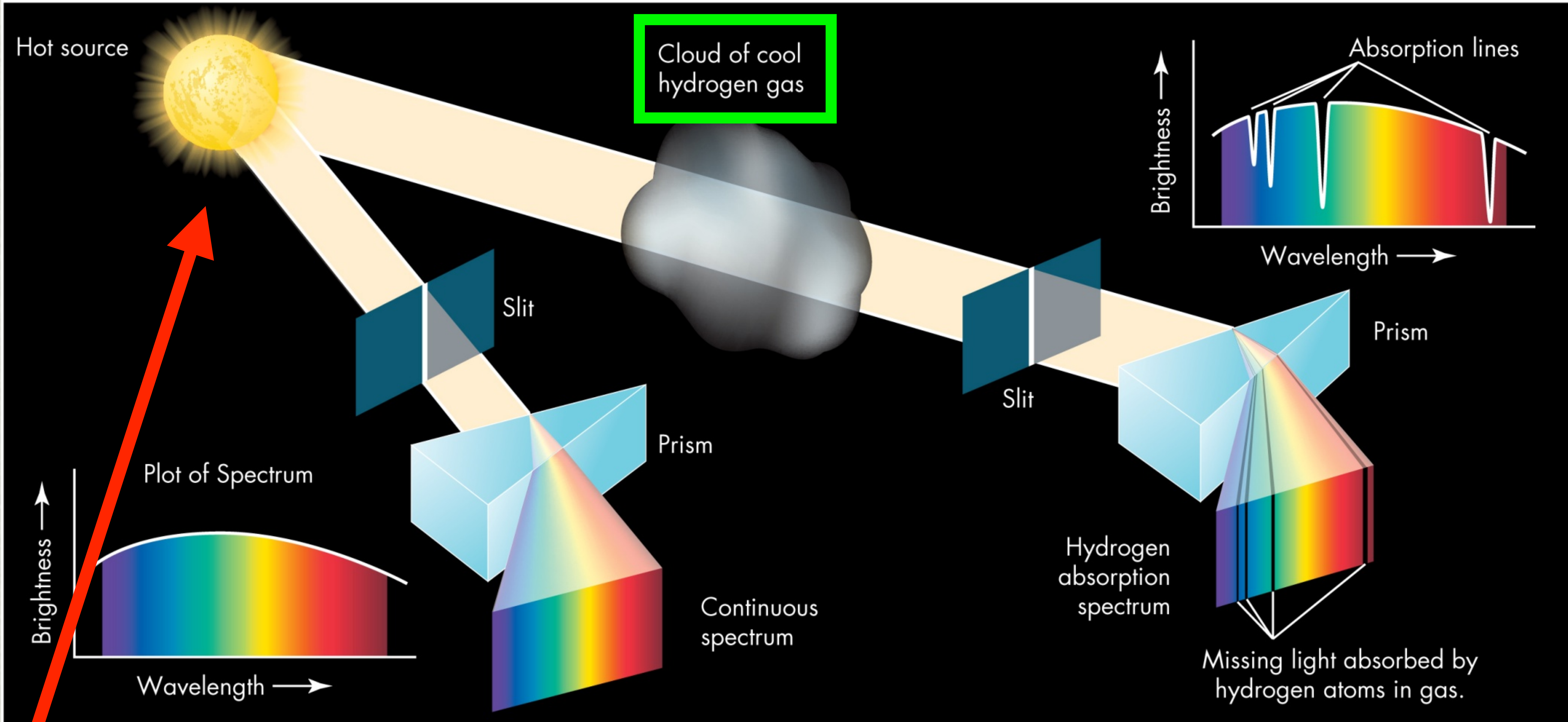
Kirchoff's Laws

3) Thermal emission traveling through some other matter?

C) Transparent, cool matter: atoms can re-absorb the light

Observe: an absorption line spectrum



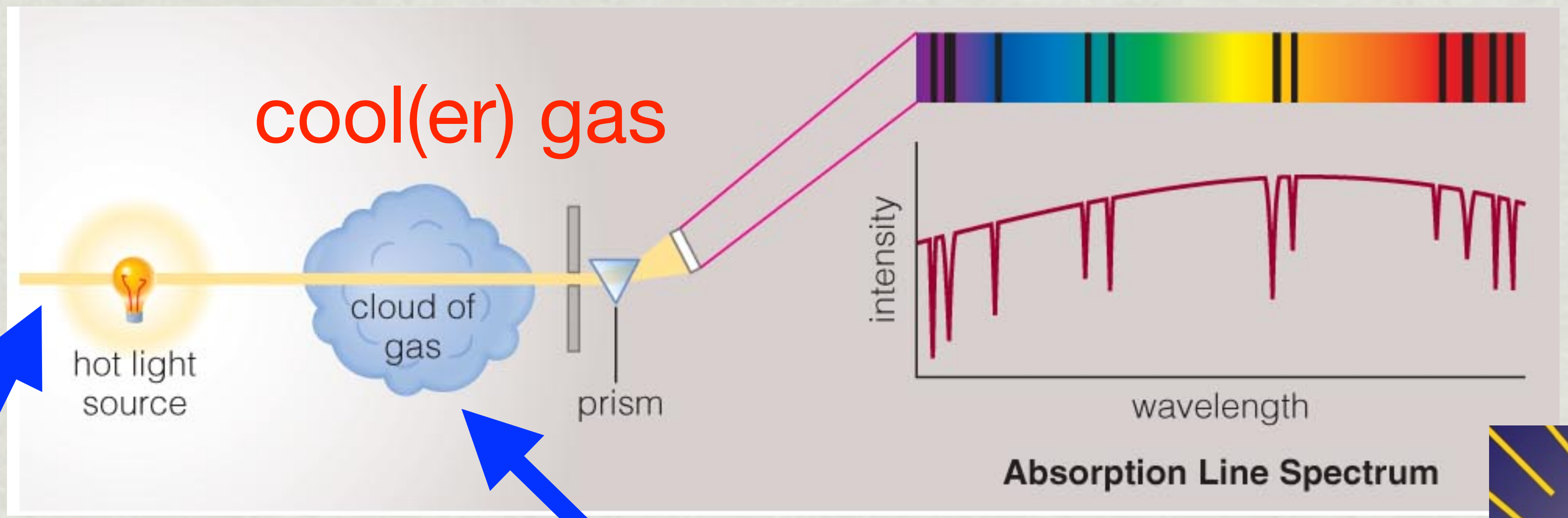


Emission from hot source in all directions, not like this (weird) image

Hydrogen absorption spectrum

Solar Spectrum

- Gas at the photosphere is cooler than the lower layers of the sun.
  - Looks like this cartoon

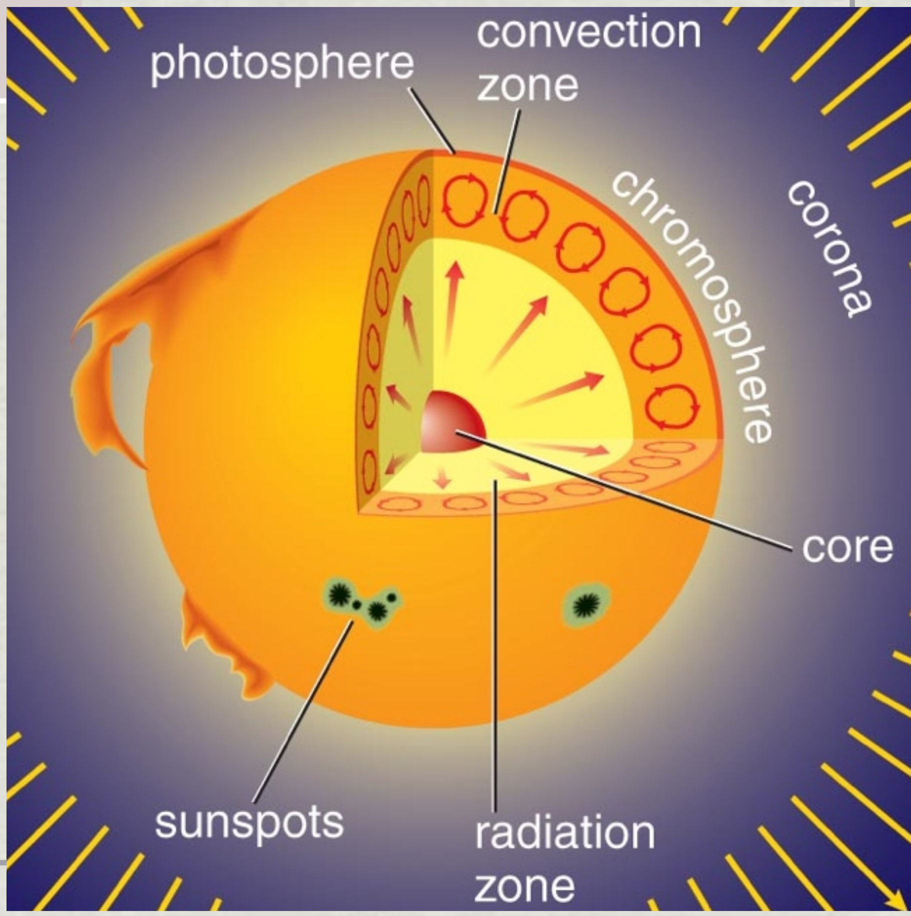


We see an absorption line spectrum from the sun

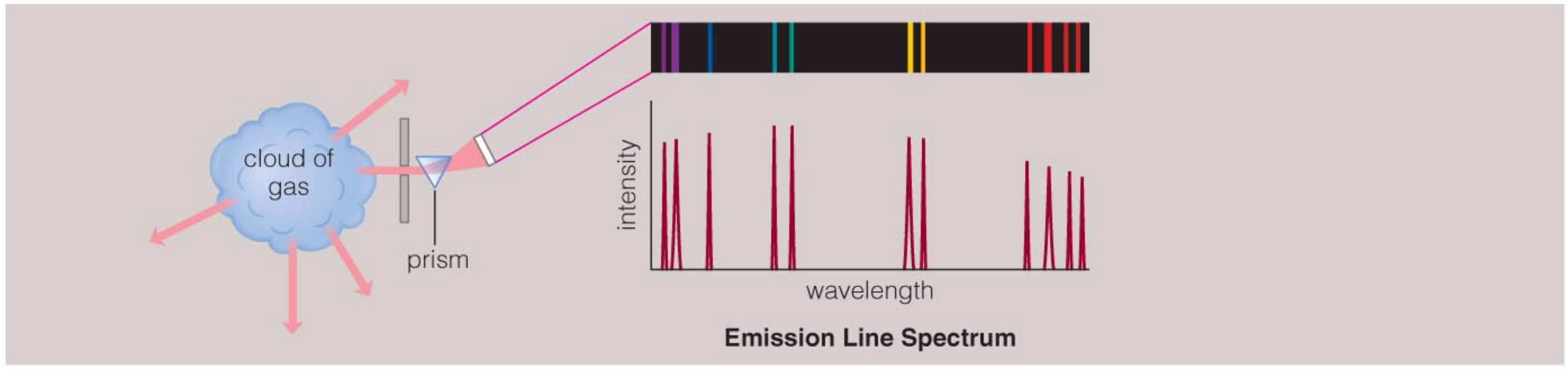
Thermal source, the inner, dense, opaque layers of the sun

Cooler gas, the photosphere

Cartoon structure of the sun →



Why do we care so much about spectra of light emitted by low-density material like clouds of gas?



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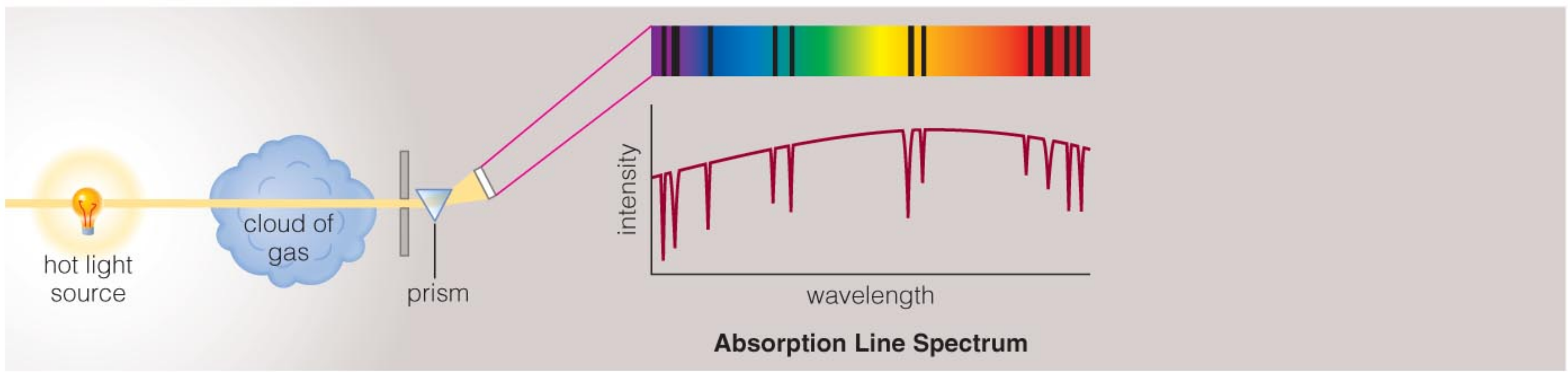

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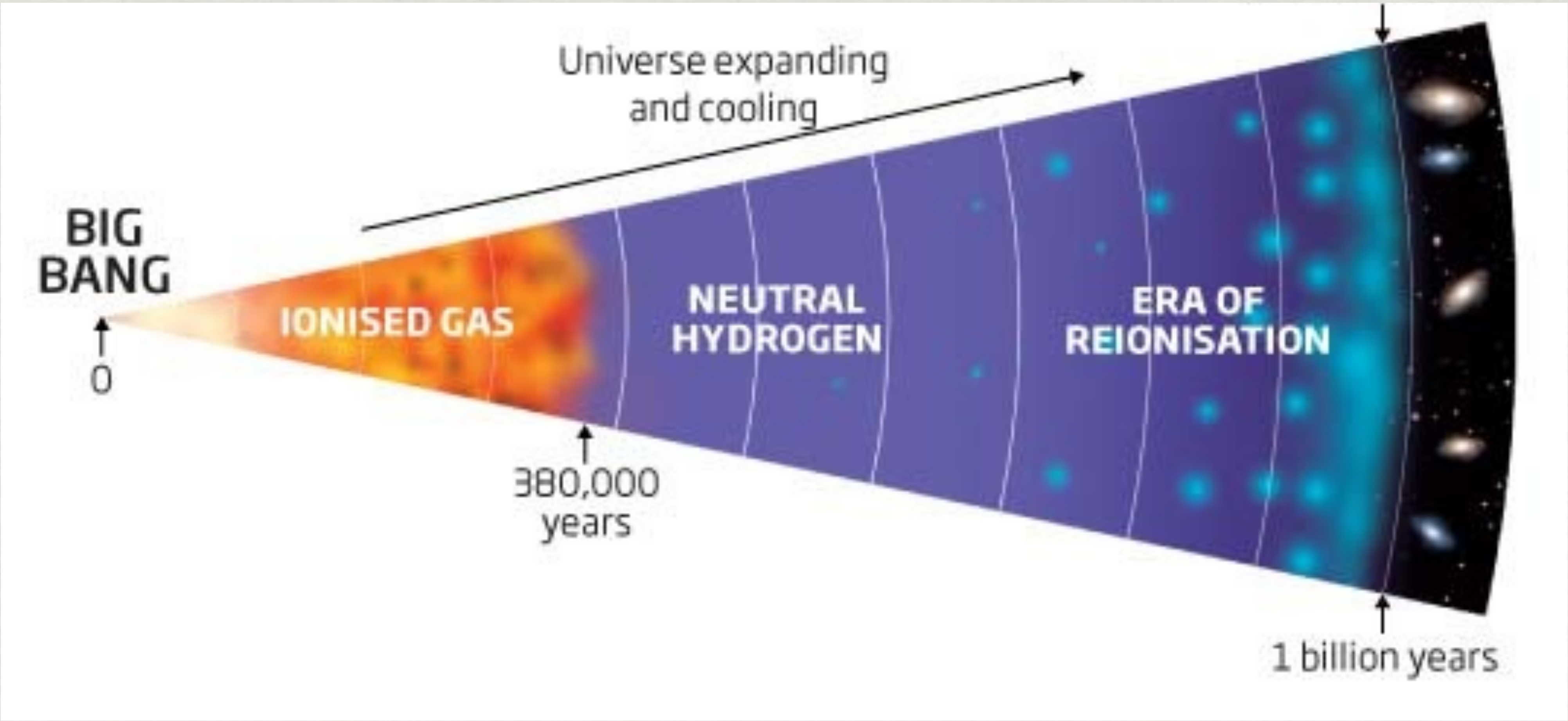
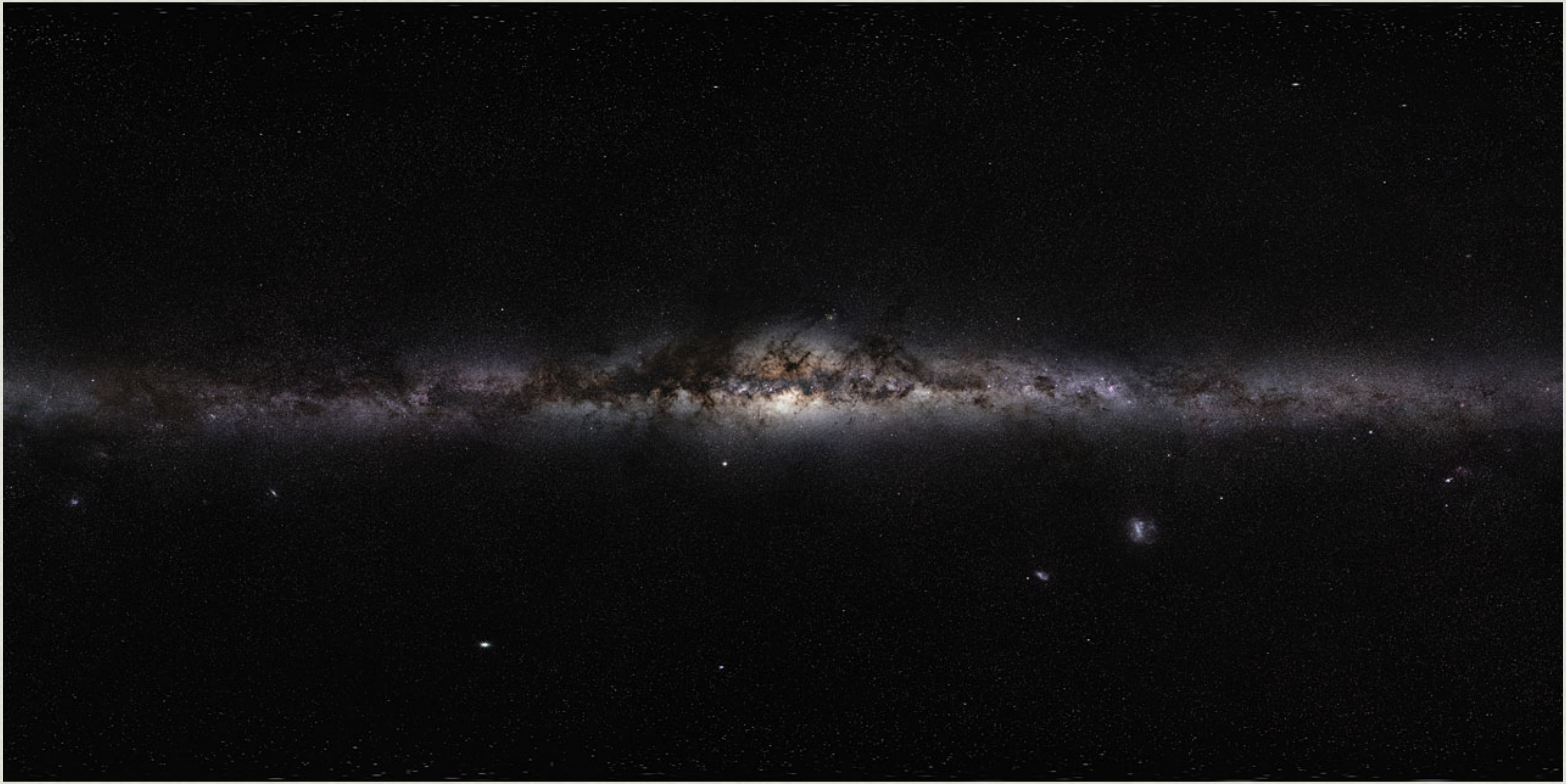
Lots of It!

From the very beginning

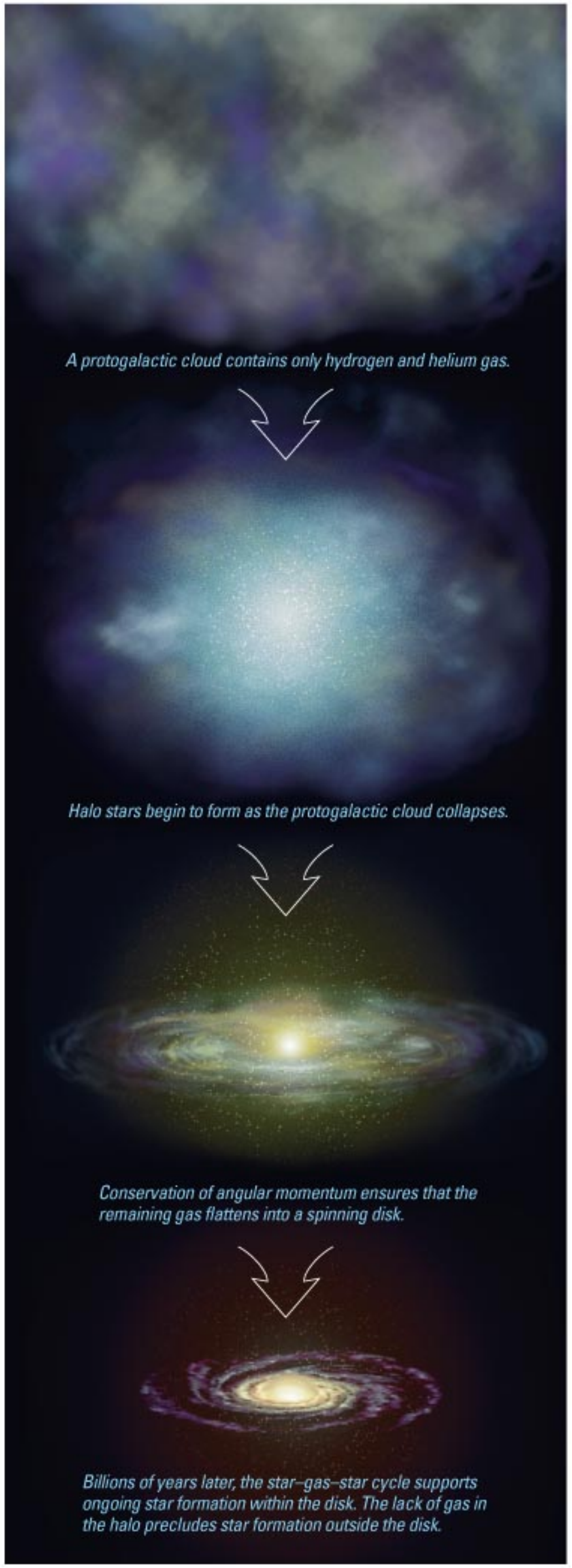


Lots of It

And in our Milky Way Galaxy



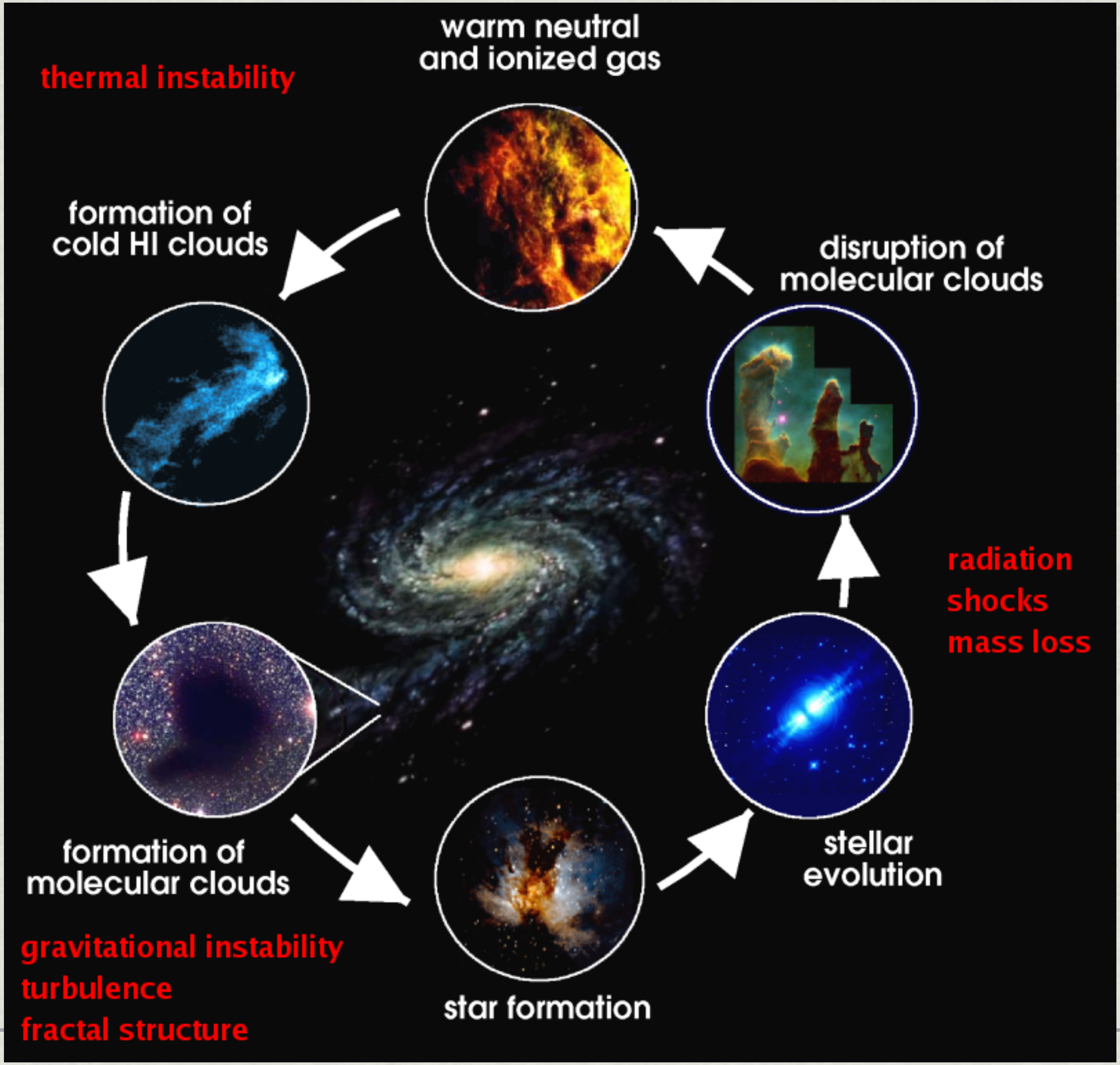
ESO, Brunier



Galaxies like ours are made from gas, which then make stars

ESO, Brunier

Stars are made from gas in galaxies, turn some H, He and other elements into all the rest of the periodic table.
Some of that processed gas is returned to the Galaxy to make more stars.



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Orion Nebula:
High energy photons (what color, blue or red?) and winds from hot, young stars heat and expand the gas.

Bubbles of hot, transparent, low-density gas that emit photons: emission spectra

Dark patches are dense, opaque regions where new stars can form: continuous spectra

Hubble Space Telescope

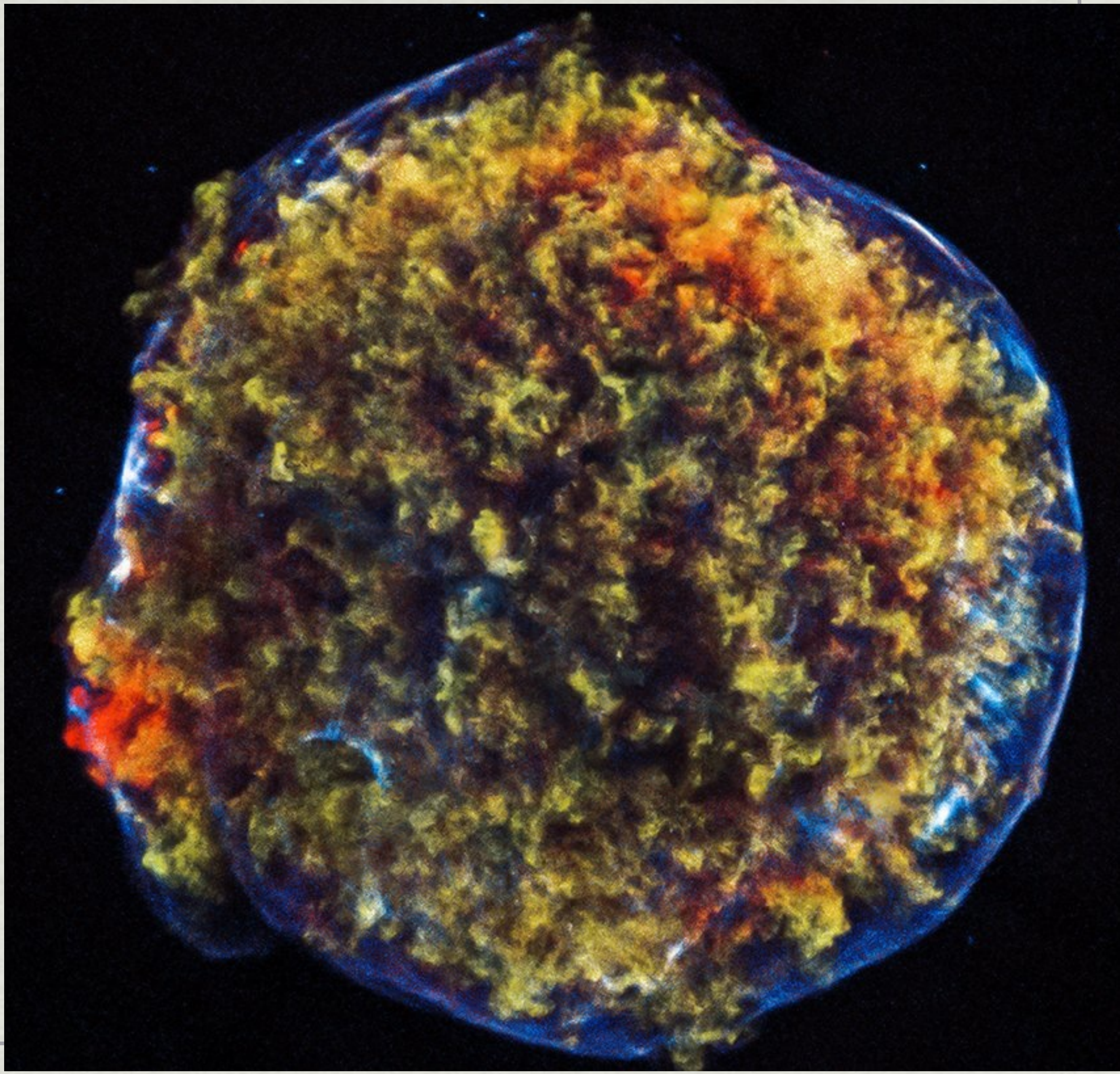
Stars are made from gas in galaxies, turn some H, He and other elements into all the rest of the periodic table.
Some of that processed gas is returned to the Galaxy to make more stars.

Tycho Supernova remnant: the outer layers of an exploded star.

Energy of the explosion heats the gas and expands it to a hot bubble of gas: emission spectrum

Light emitted from hot gas has high energy, too

This image is taken in the X-ray band



Stars are made from gas in galaxies, turn some H, He and other elements into all the rest of the periodic table.
Some of that processed gas is returned to the Galaxy to make more stars.

Helix "planetary nebula"

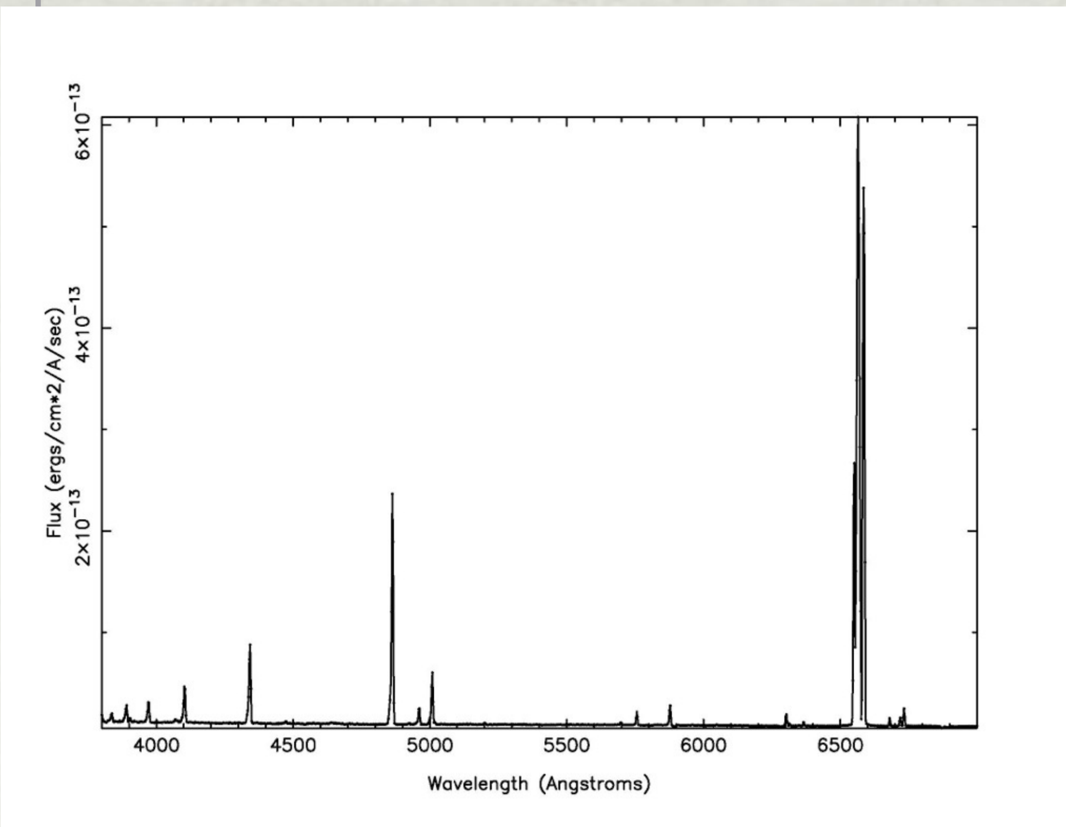
Not a planet at all, but the outer layers of a dying star.

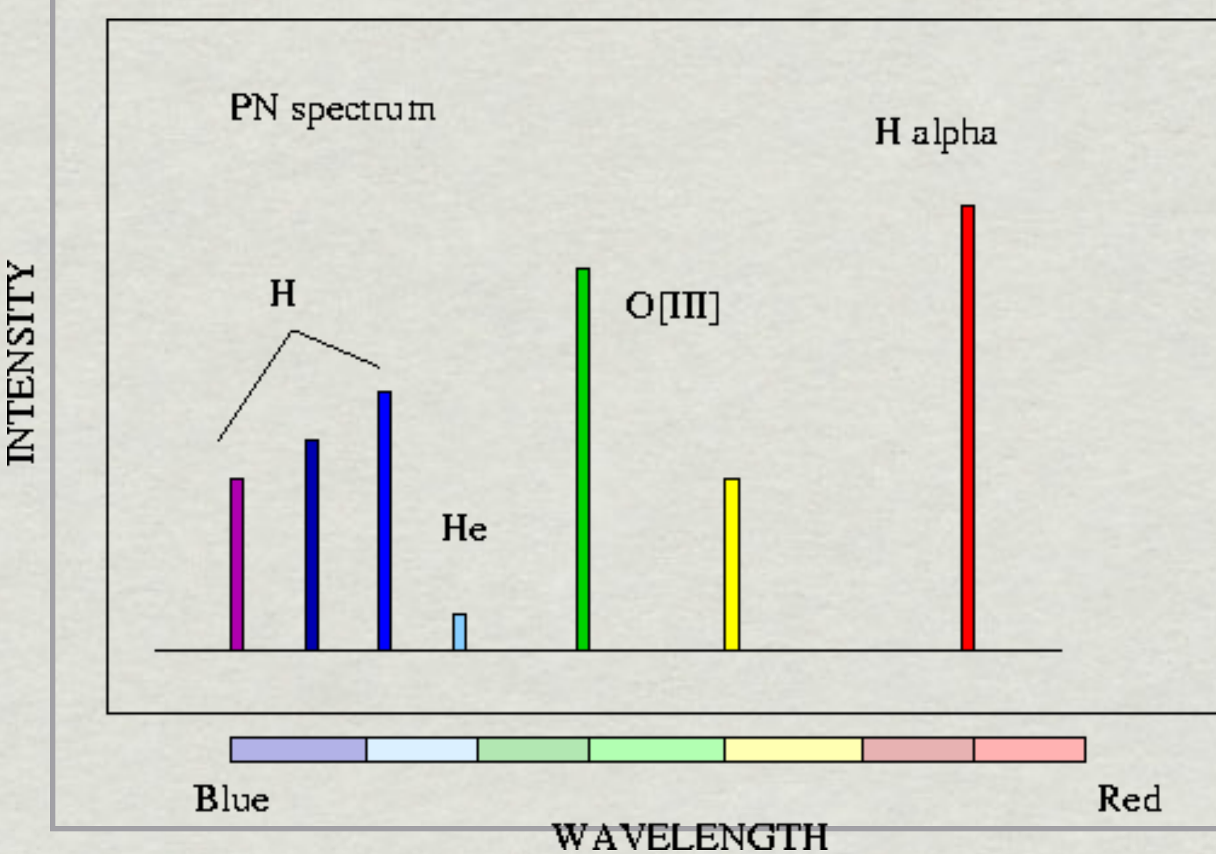
Blown off, like a super-sized solar wind.

Transparent gas heated by the hot, leftover core of the dying star.

Hubble Space Telescope

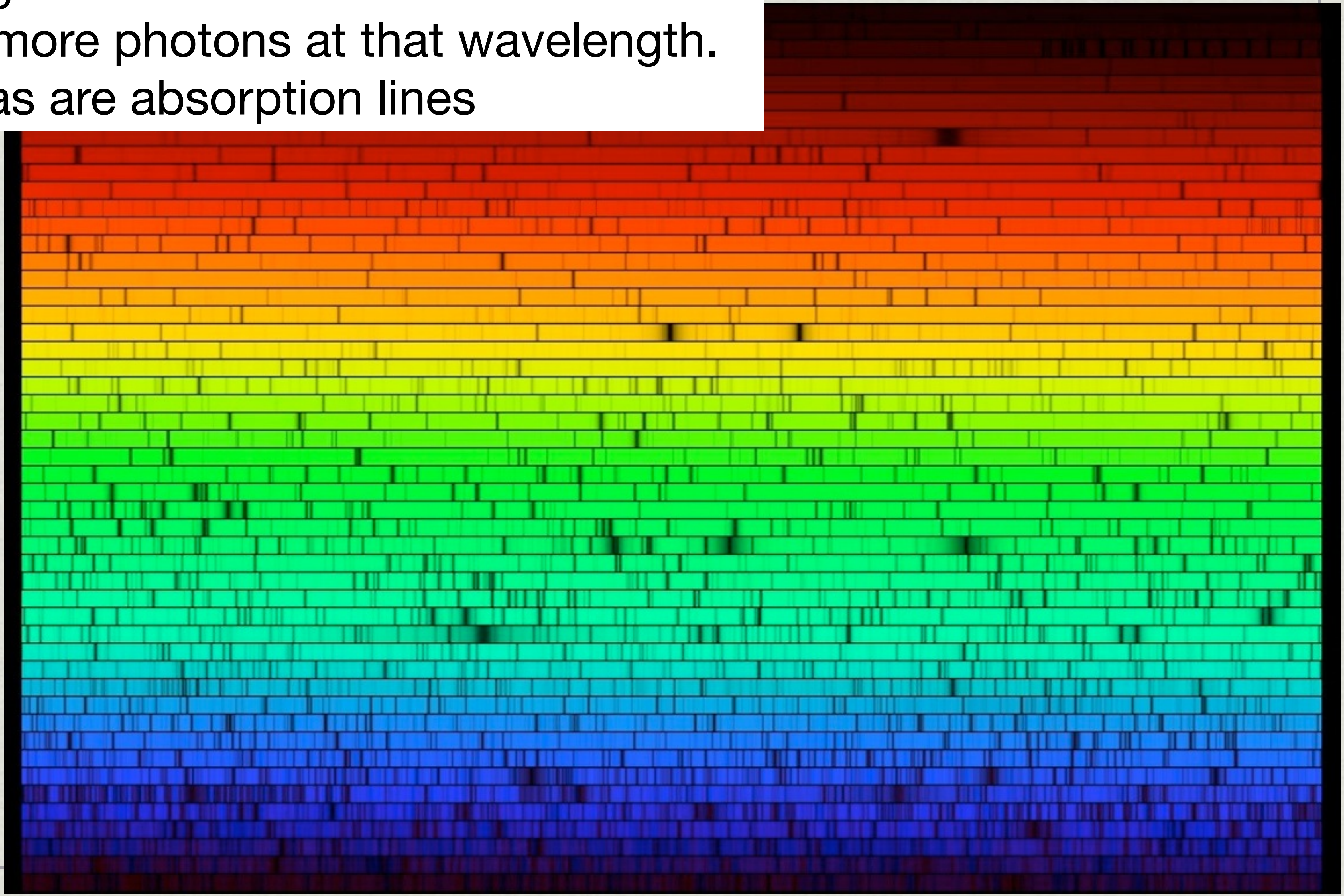
Hot, low-density gas: emission line spectrum





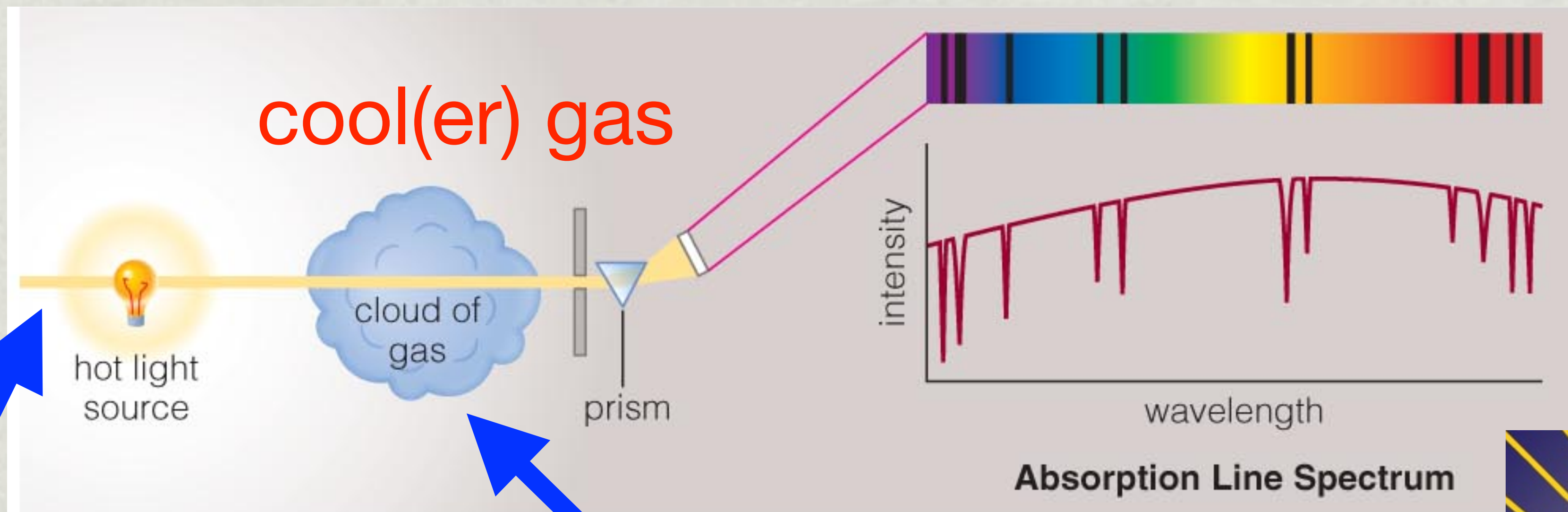
Solar Spectrum

Light from the sun dispersed, as by a prism
Wavelengths: 400 nm - 700 nm
Bright = more photons at that wavelength.
Dark areas are absorption lines



Solar Spectrum

- Gas at the photosphere is cooler than the lower layers of the sun.
  - Looks like this cartoon

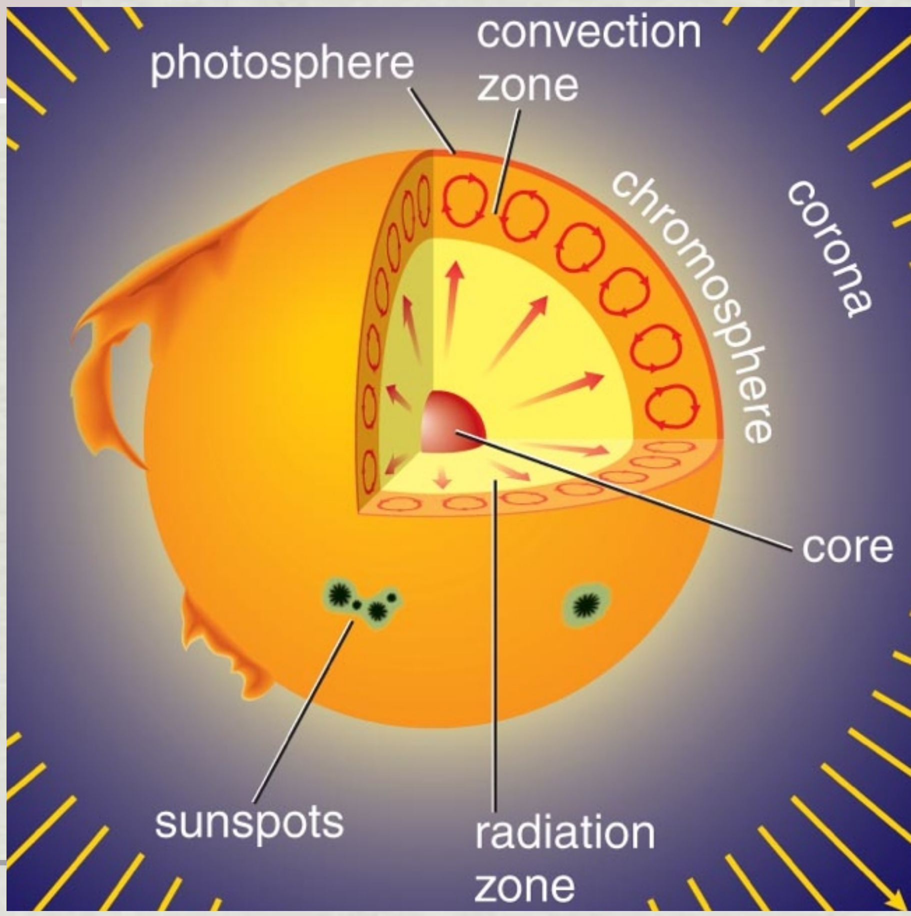


We see an absorption line spectrum from the sun

Thermal source, the inner, opaque layers of the sun

Cooler gas, the photosphere

Cartoon structure of the sun →



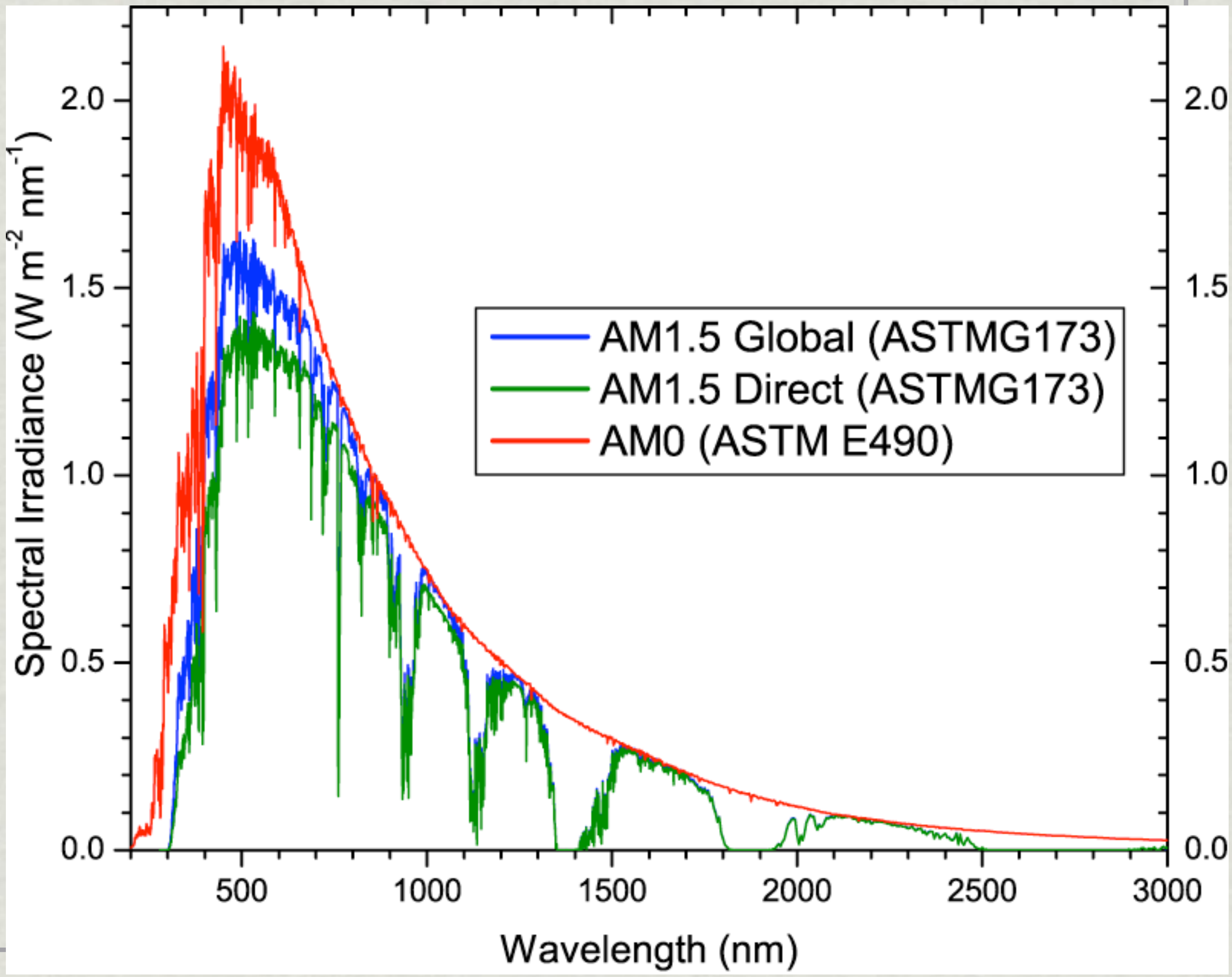
Solar Spectrum

A more compact view of the solar spectrum:

<- Wavelength ->

Very cool interactive plot of the solar spectrum:

http://bass2000.obspm.fr/solar_spect.php



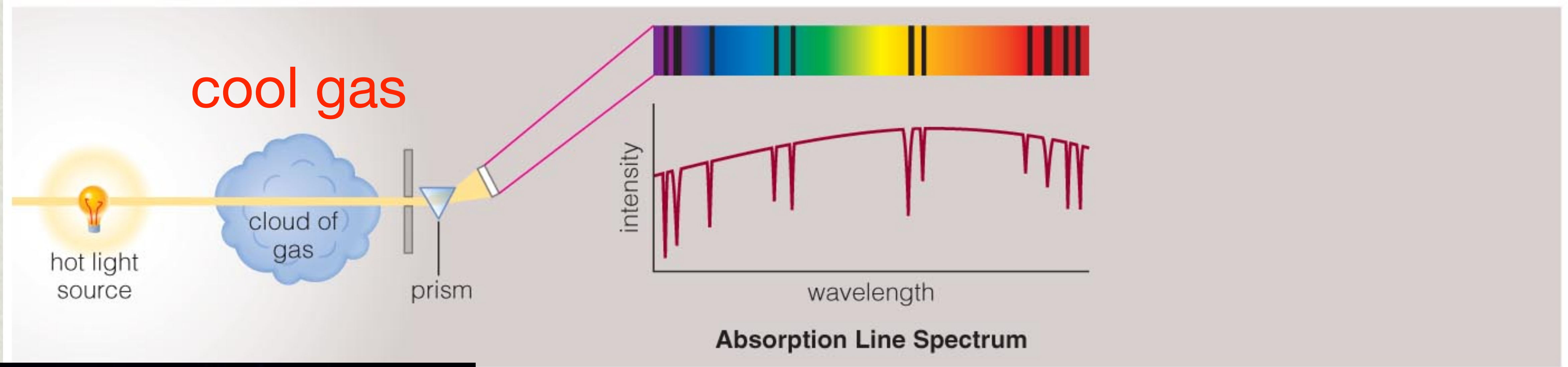
A solar spectrum showing the amount of energy at each wavelength.
A thermal spectrum with absorption lines.

Kirchoff's Laws

3) Thermal emission traveling through some other matter?

C) Transparent, cool matter: atoms can re-absorb the light

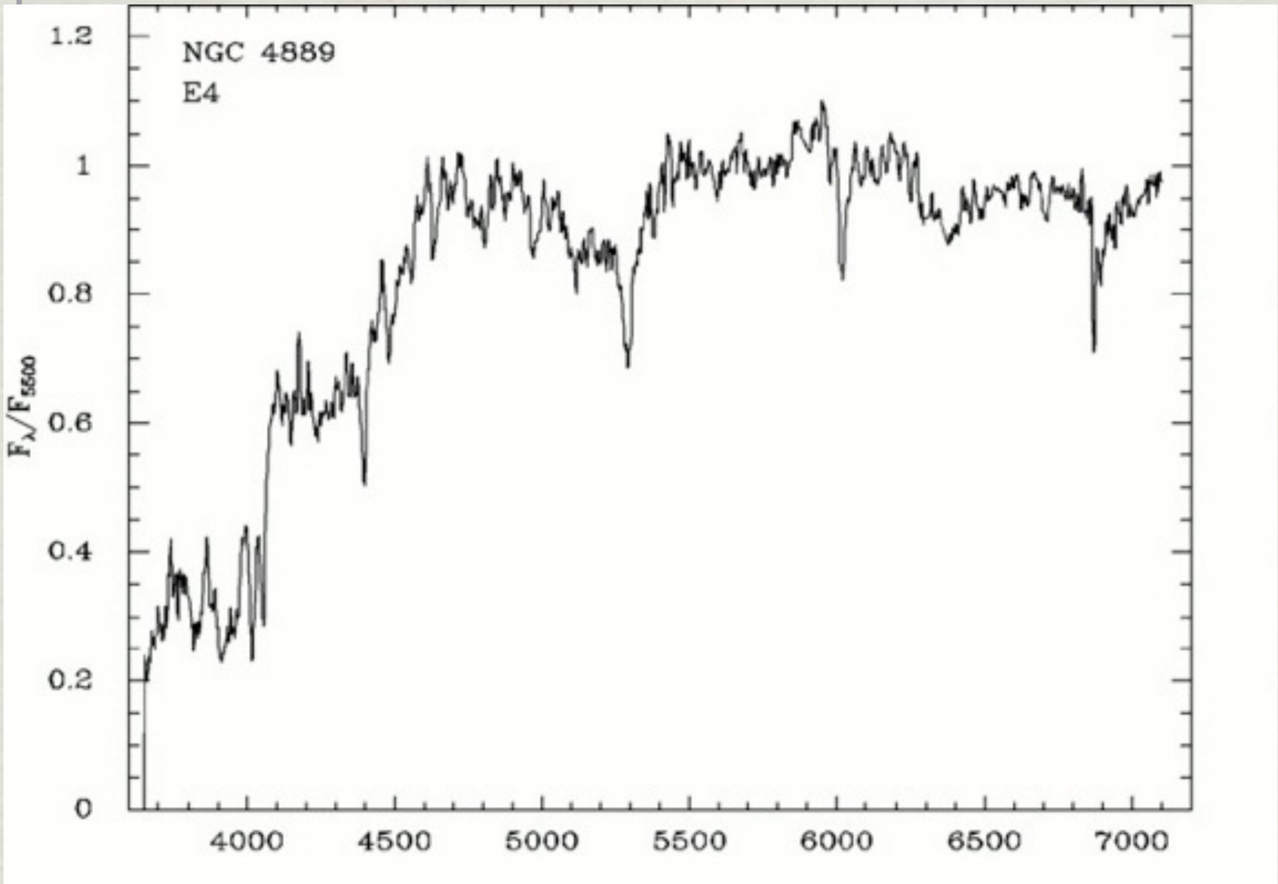
Observe: an absorption line spectrum



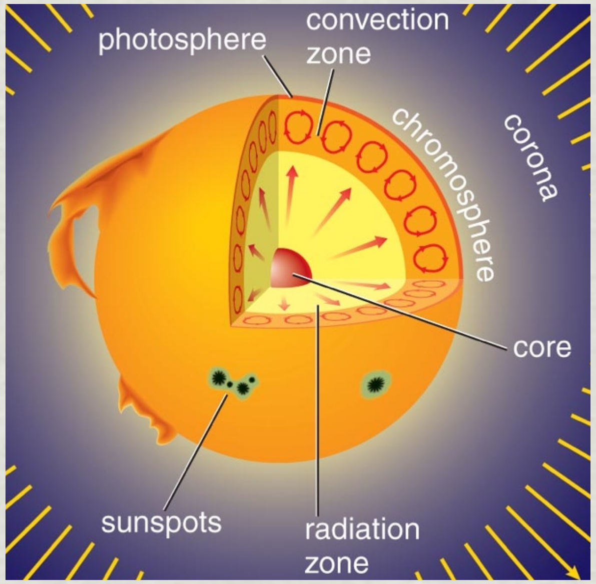
This is often the spectrum we observe from stars and galaxies (which are made of stars)

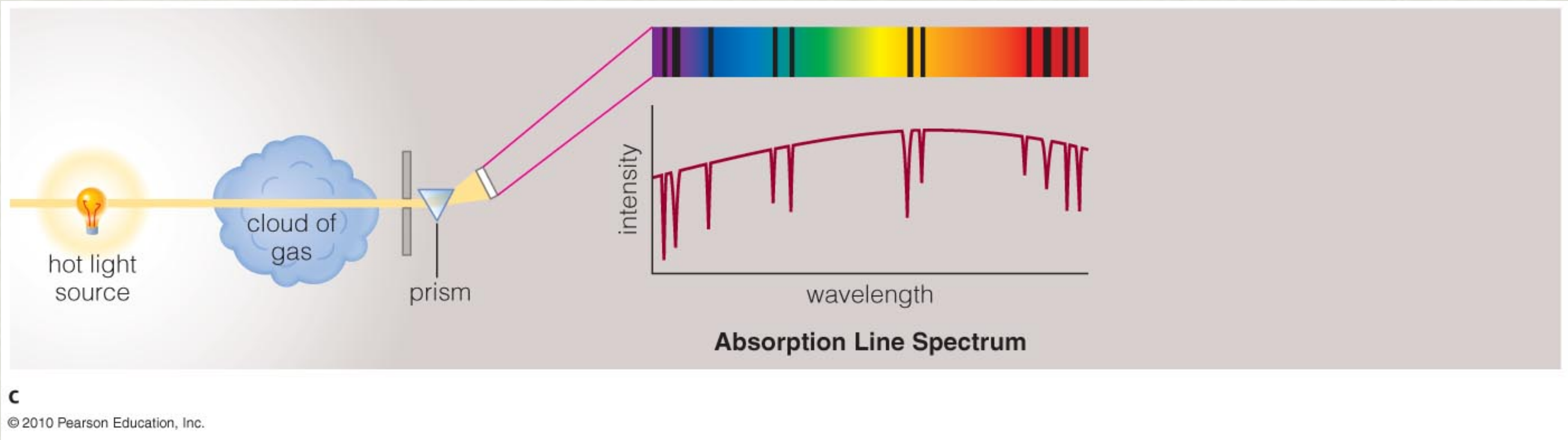
Exception: hot gas in galaxies, where stars are born or black holes live.

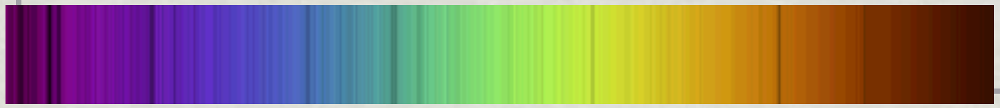
Other Kinds of Spectra: Galaxies



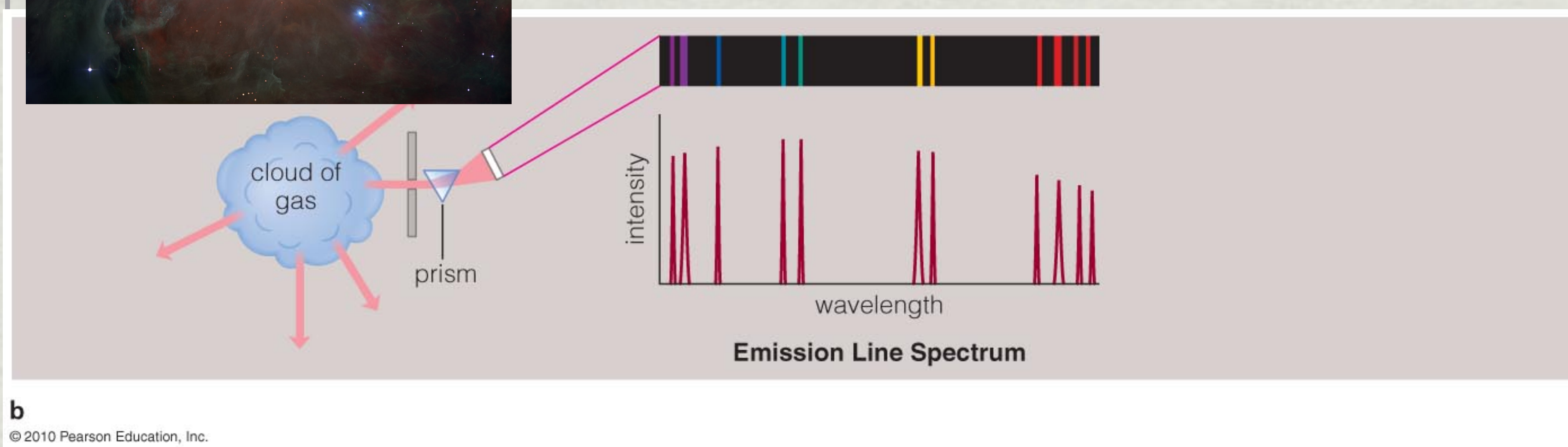
galaxy image



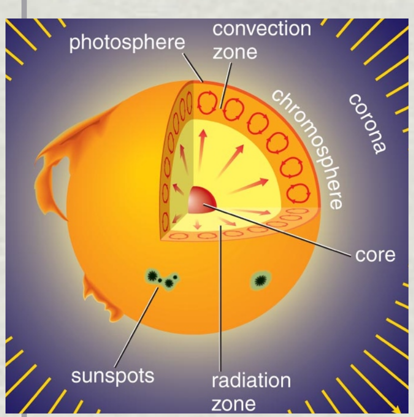


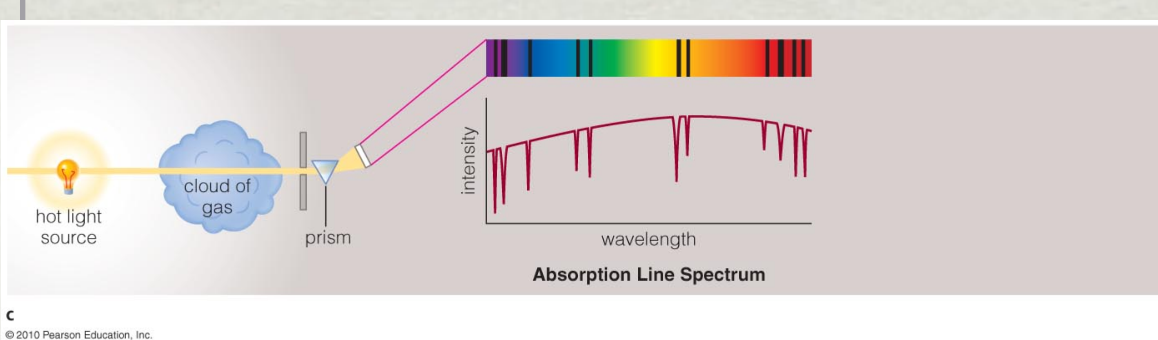


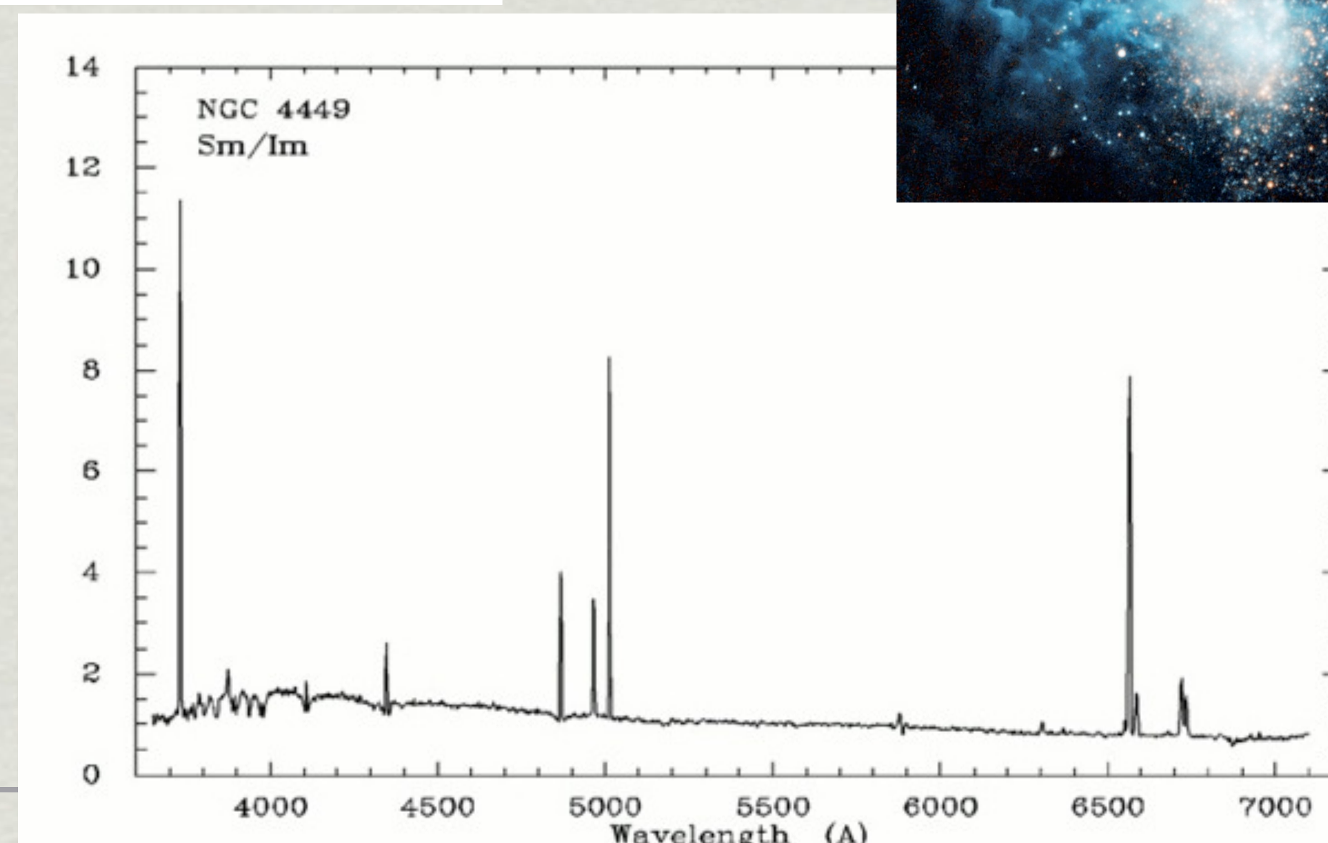
Other Kinds of Spectra: Galaxies



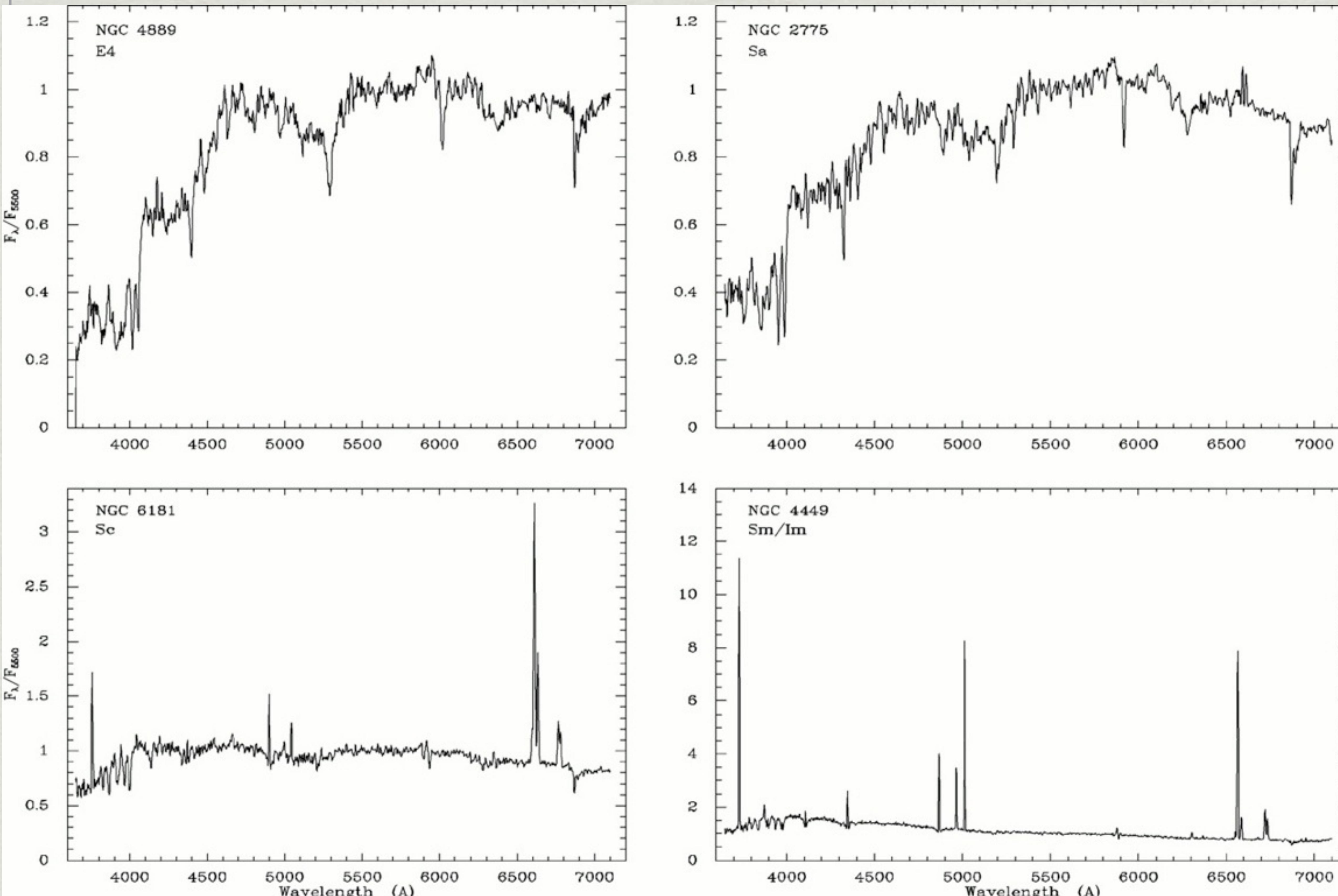
galaxy image



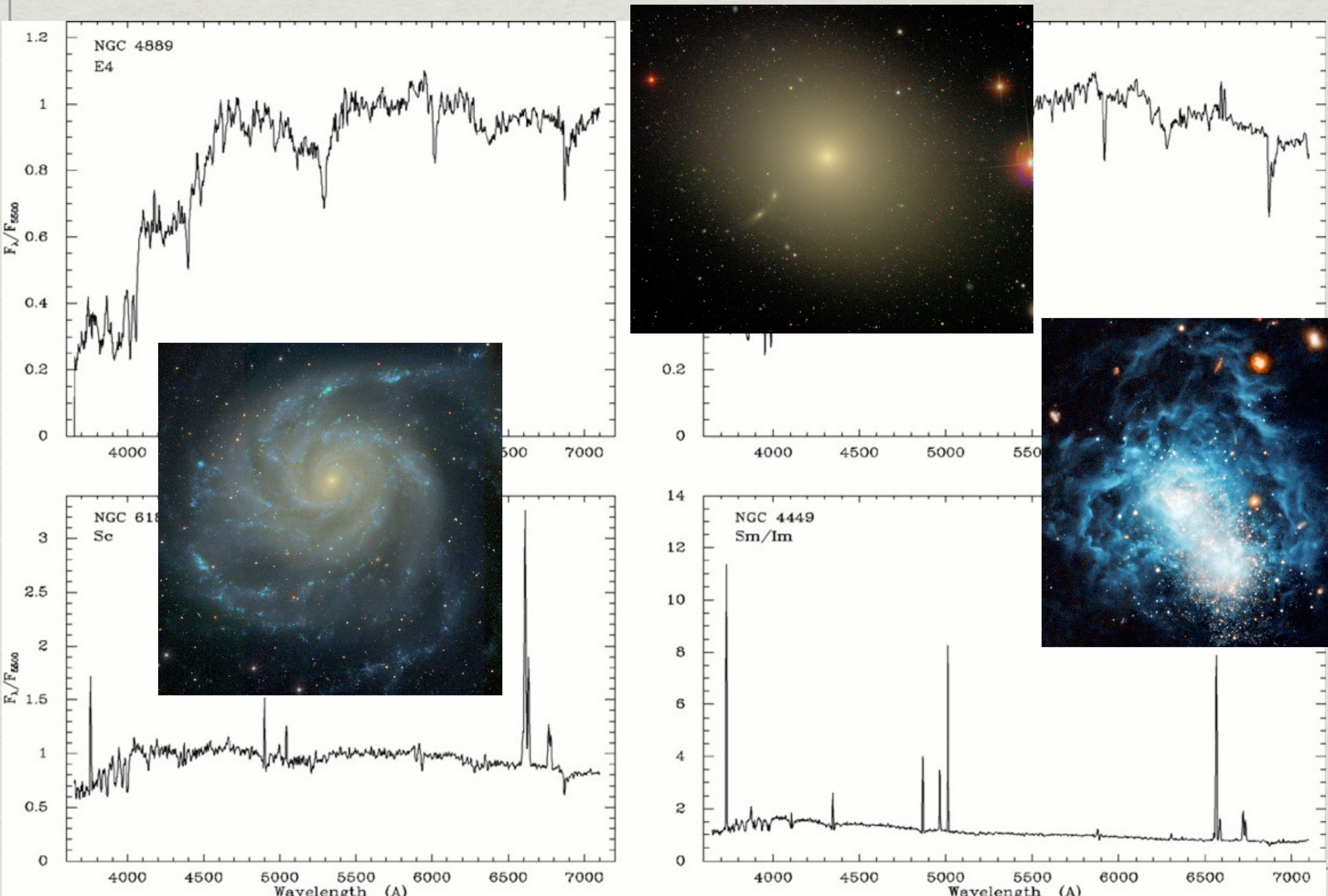




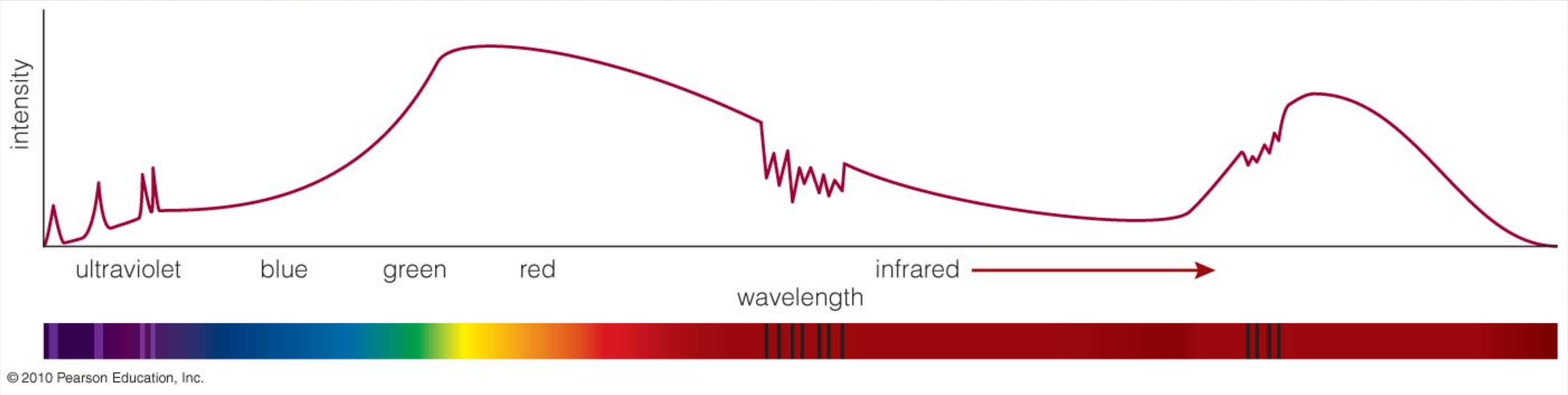
Other Kinds of Spectra: Galaxies



Other Kinds of Spectra: Galaxies

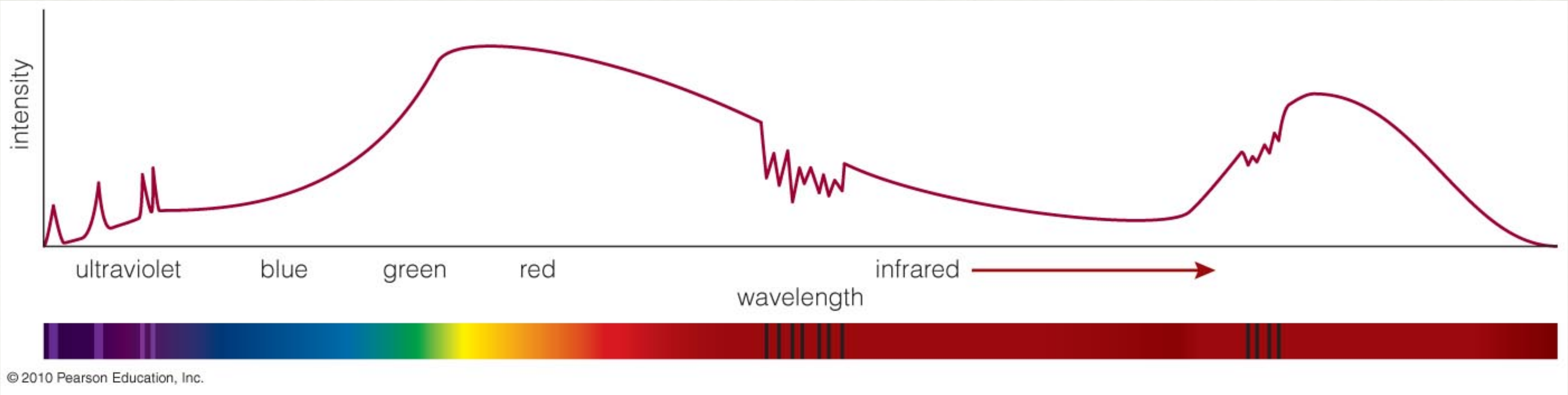


Spectra



By studying the details in a spectrum, we can learn a lot about the object that created it

Spectra

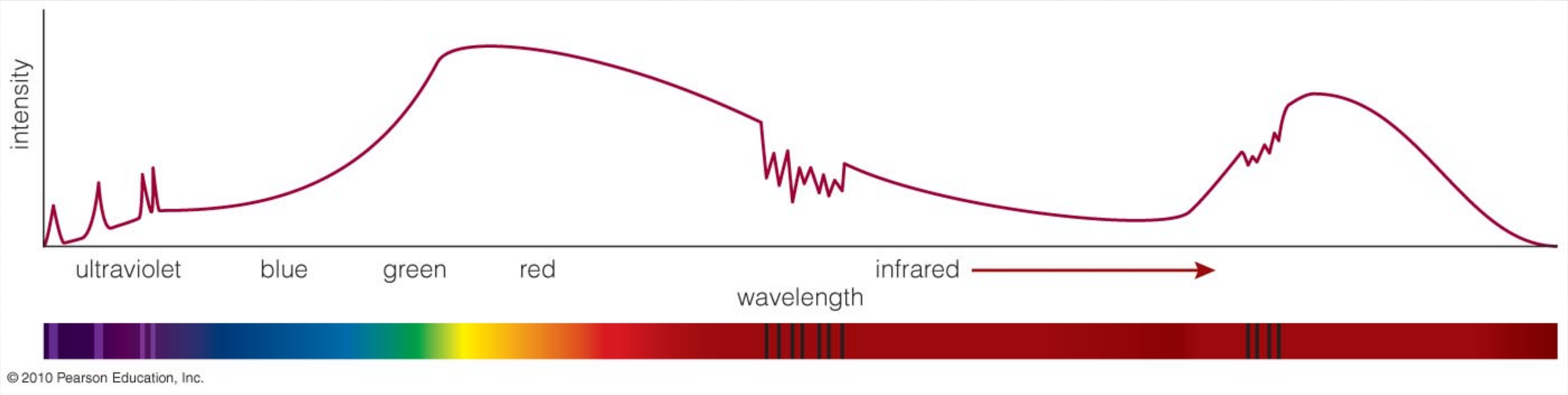


A B C D E

Which are the absorption lines?

A A
B B
C D
D A,C,D
E C,D

Spectra



A B C D E

Which are the absorption lines?

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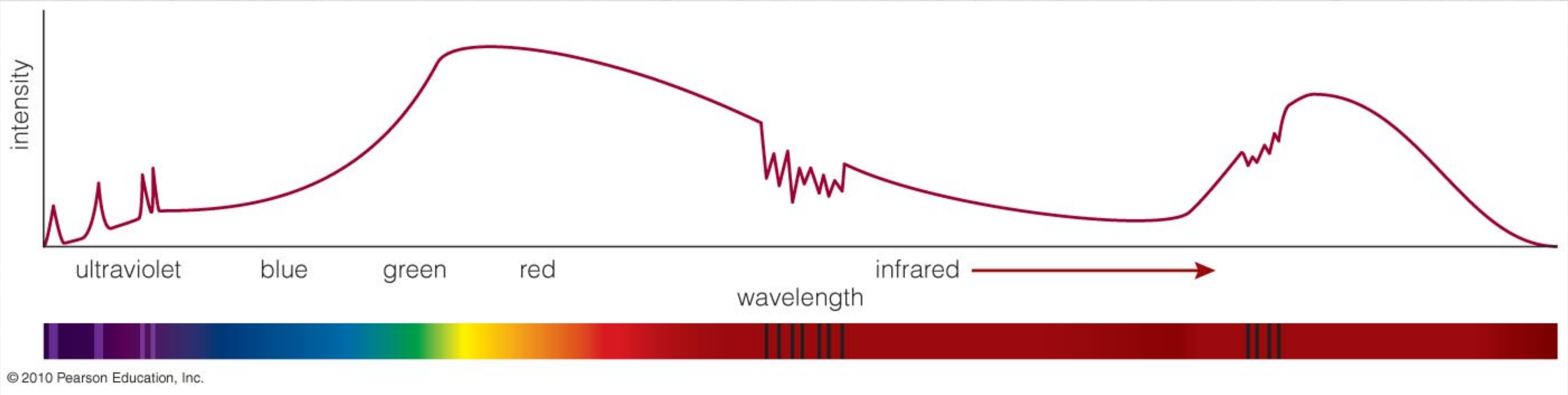
E C,D

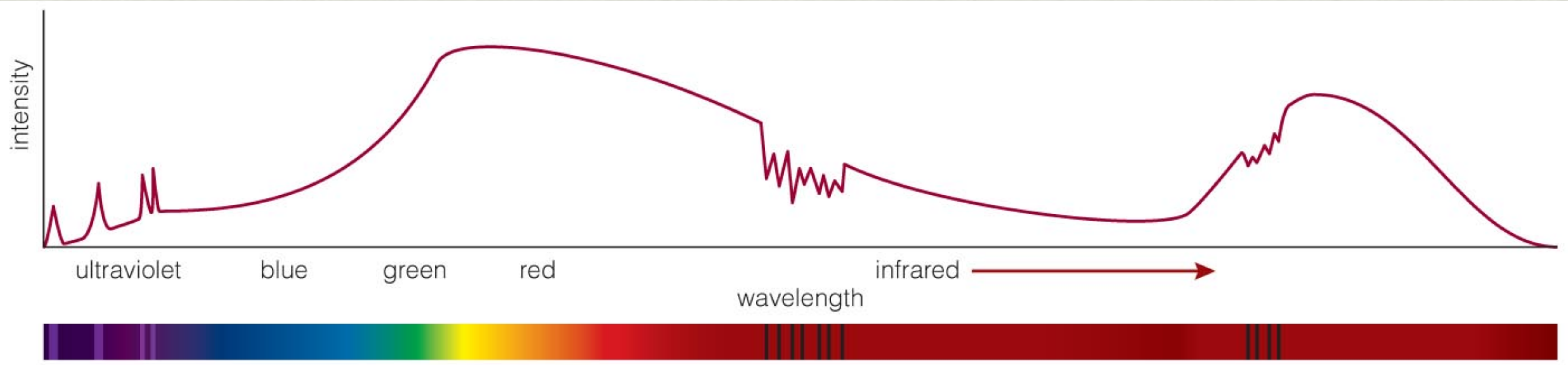
Spectra



A B C D E

Which letter labels emission lines?

Spectra

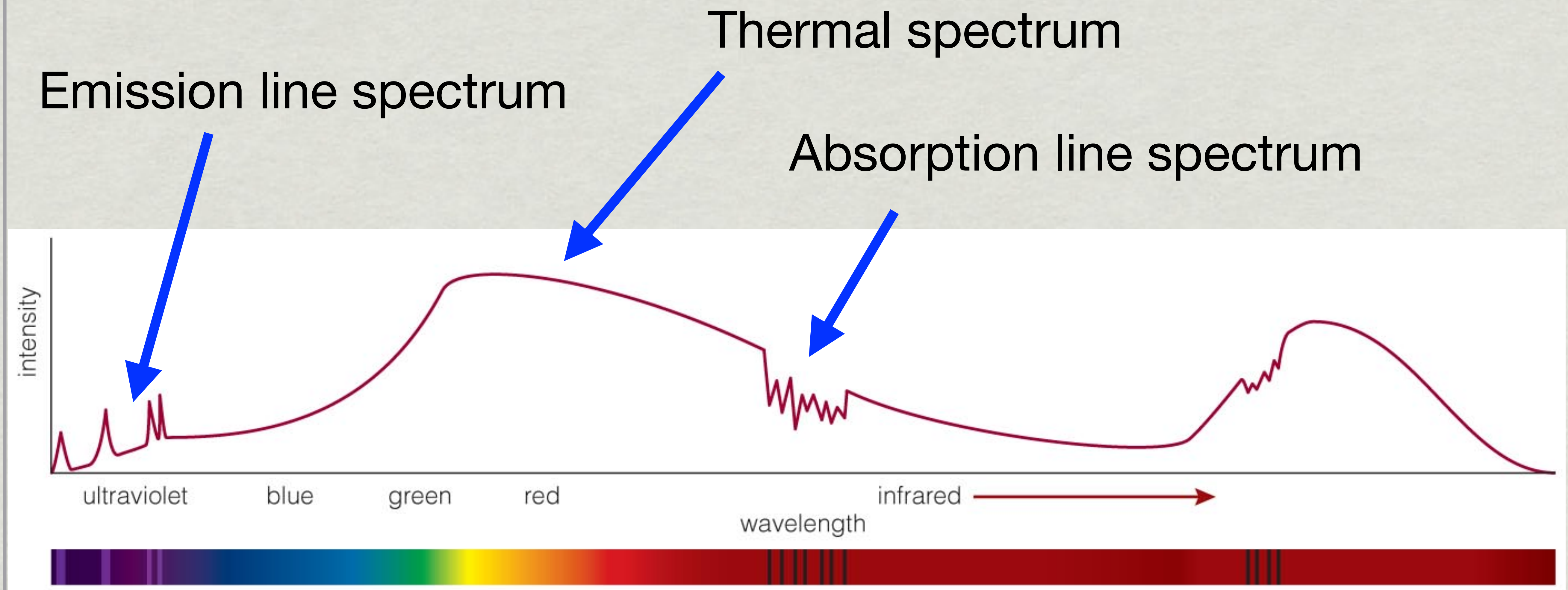


A B C D E

Which letter labels emission lines?

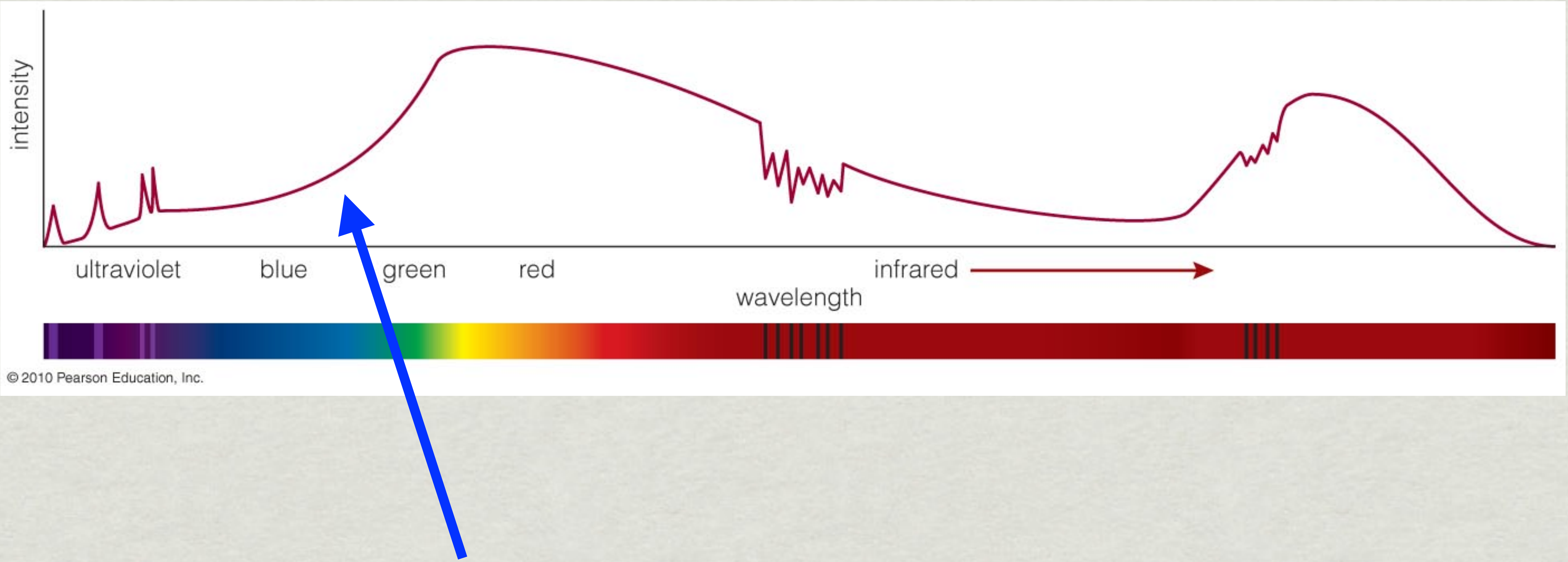
Spectra

Three types of spectra:



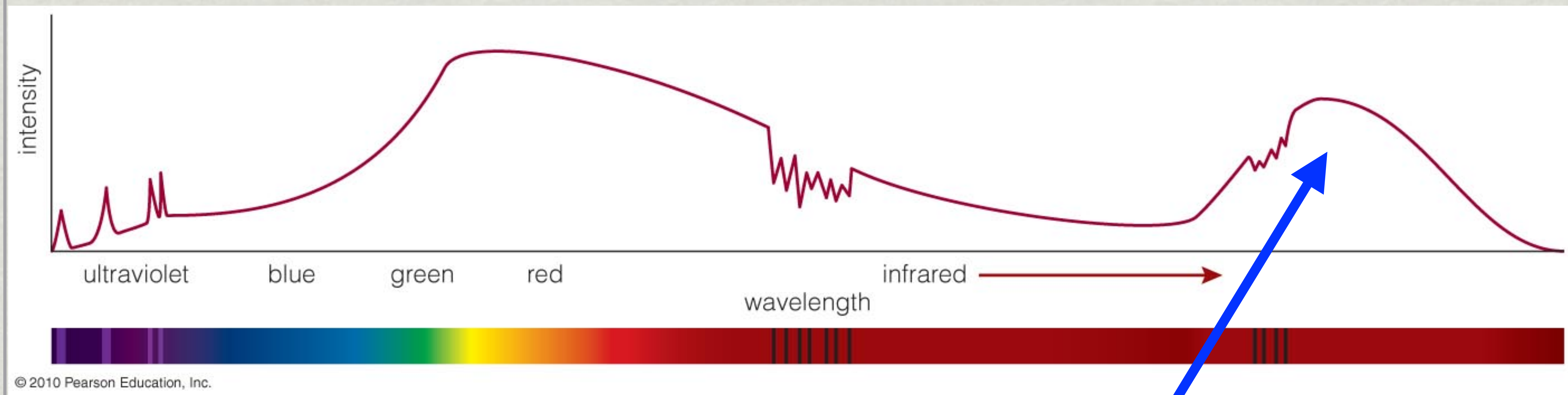
Spectra of objects we observe are usually combinations of the three basic types

What is this Object?



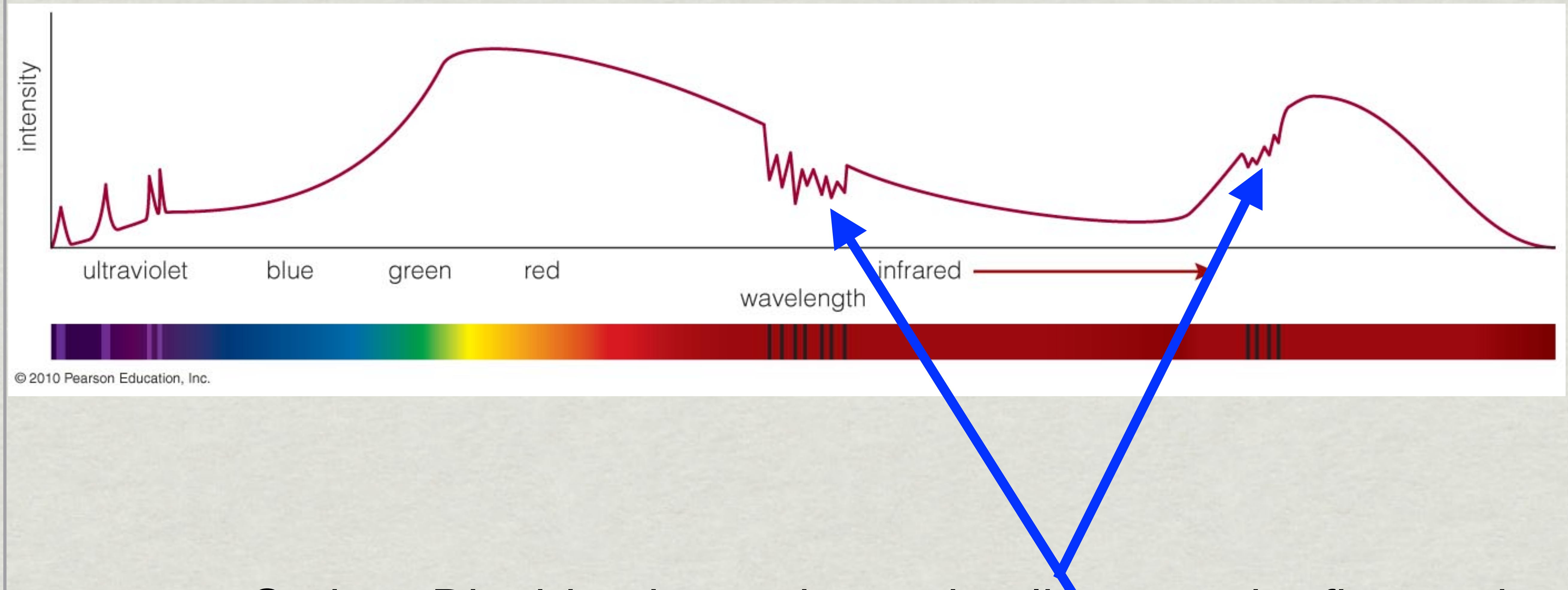
Reflected sunlight: Continuous thermal spectrum of visible light is like the sun's, except that some of the blue light is missing. It has been absorbed

What is this Object?



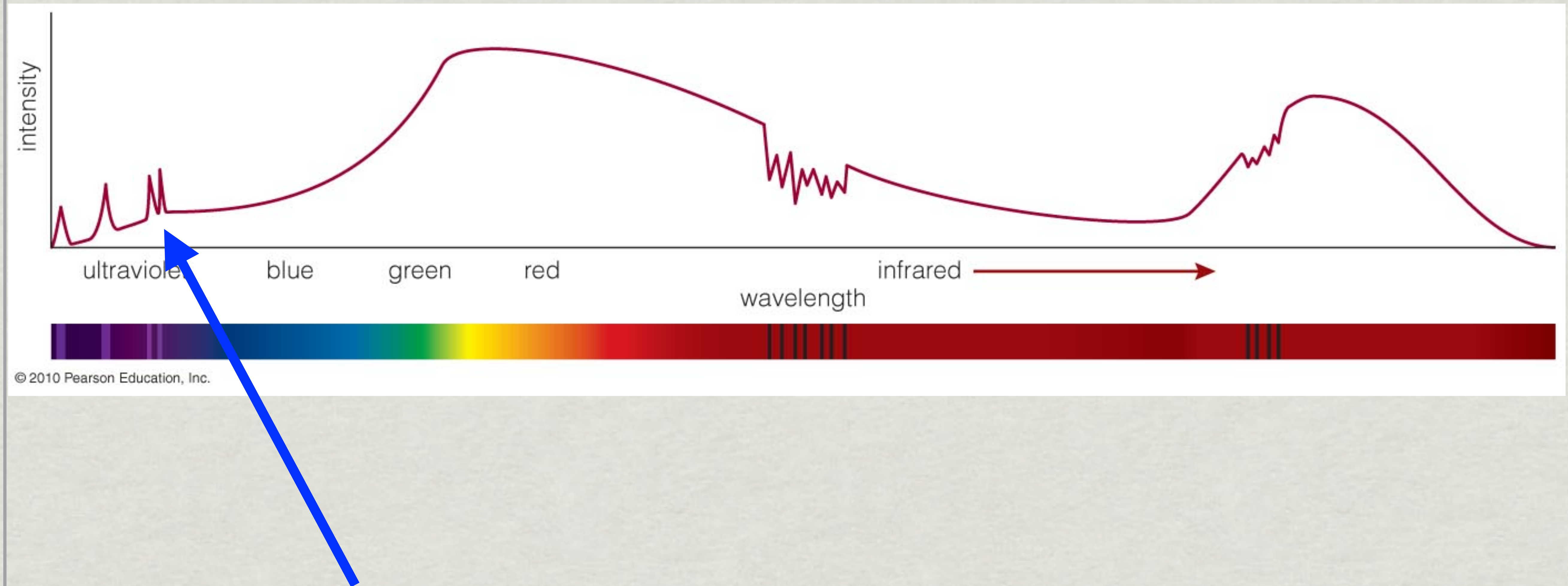
Thermal radiation: Infra-red spectrum peaks at wavelengths corresponding to a temperature of 225 K (-18 C). High density material, not very cold (by astronomy standards)

What is this Object?



Carbon Dioxide: these absorption lines are the fingerprint of cool CO_2 gas.

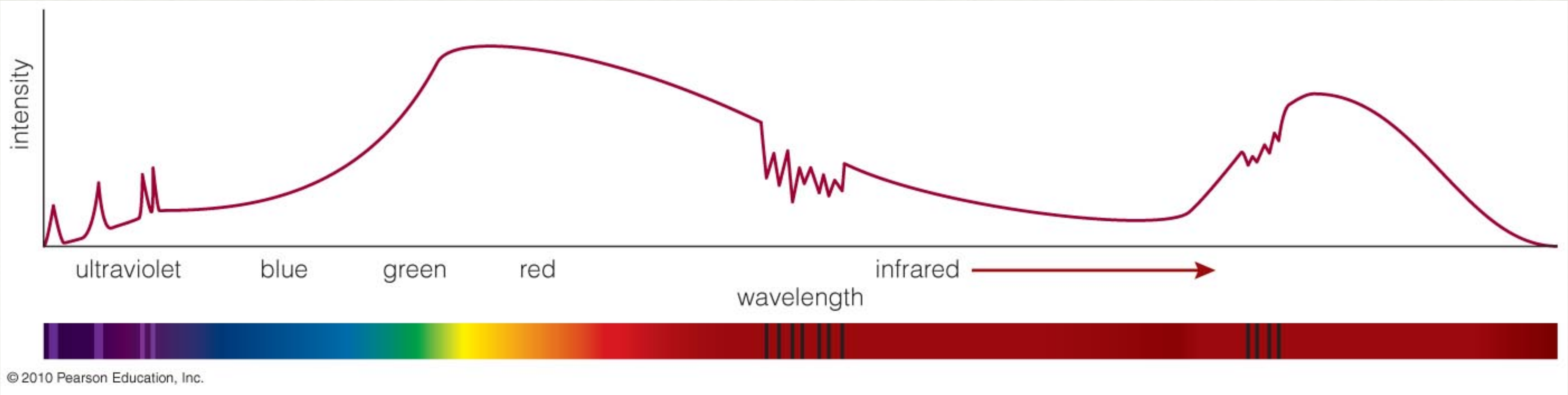
What is this Object?



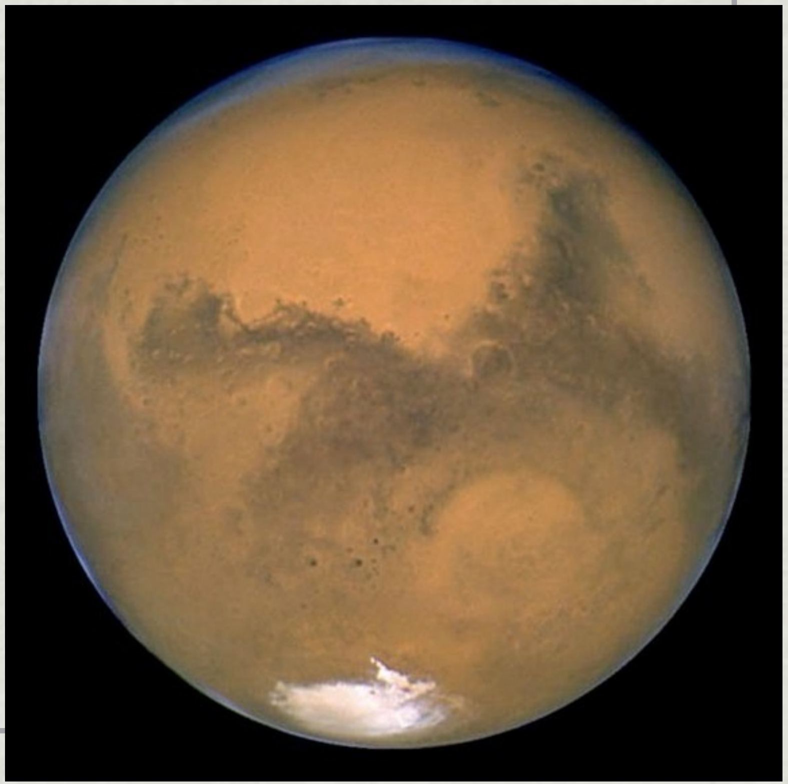
Ultra-violet emission lines: hot, low-density (transparent) gas. An atmosphere!

The atmosphere has hot gas, and cooler CO_2

What is this Object?



This is a planet around a star! In this case, Mars



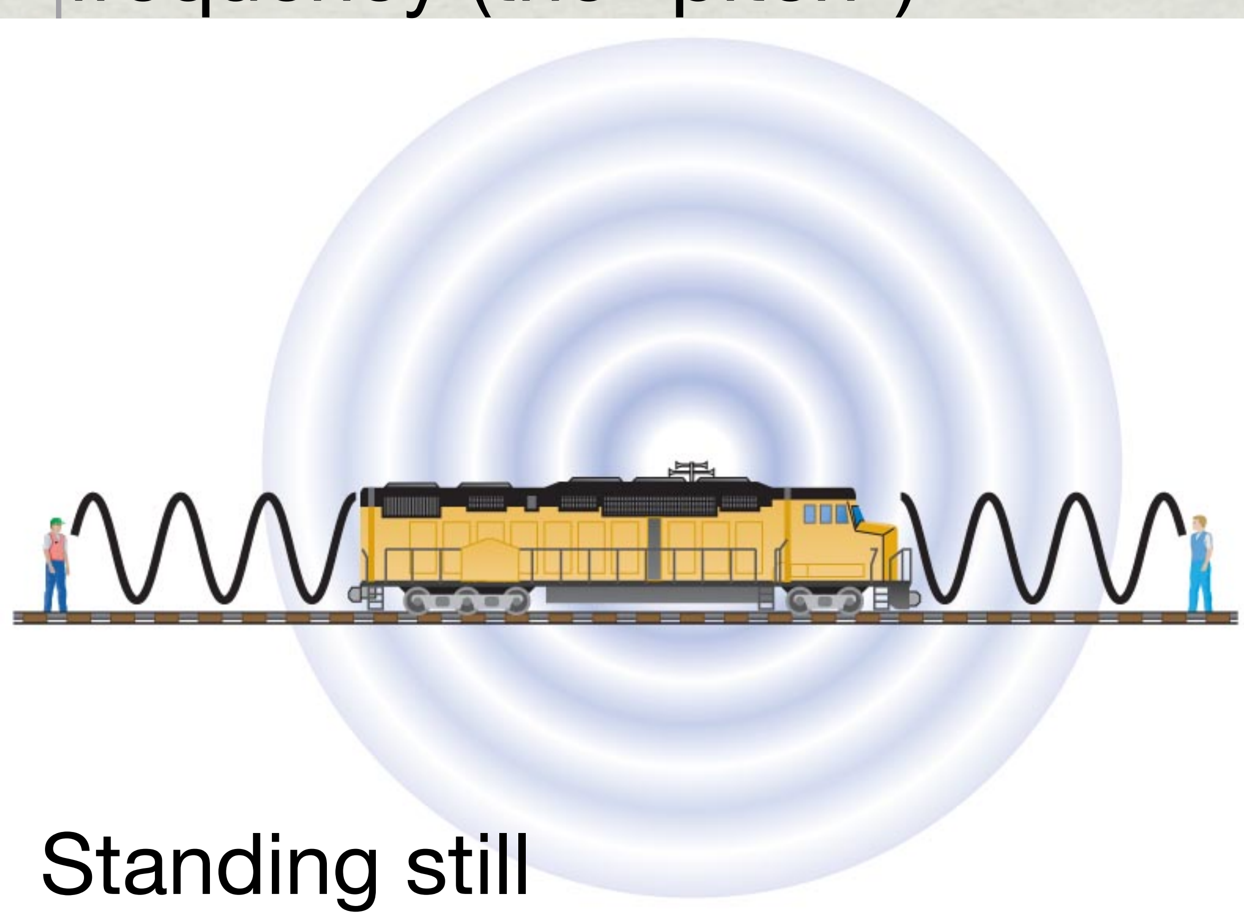
We can learn its temperature
We can learn the content and temperature and density of
its atmosphere.

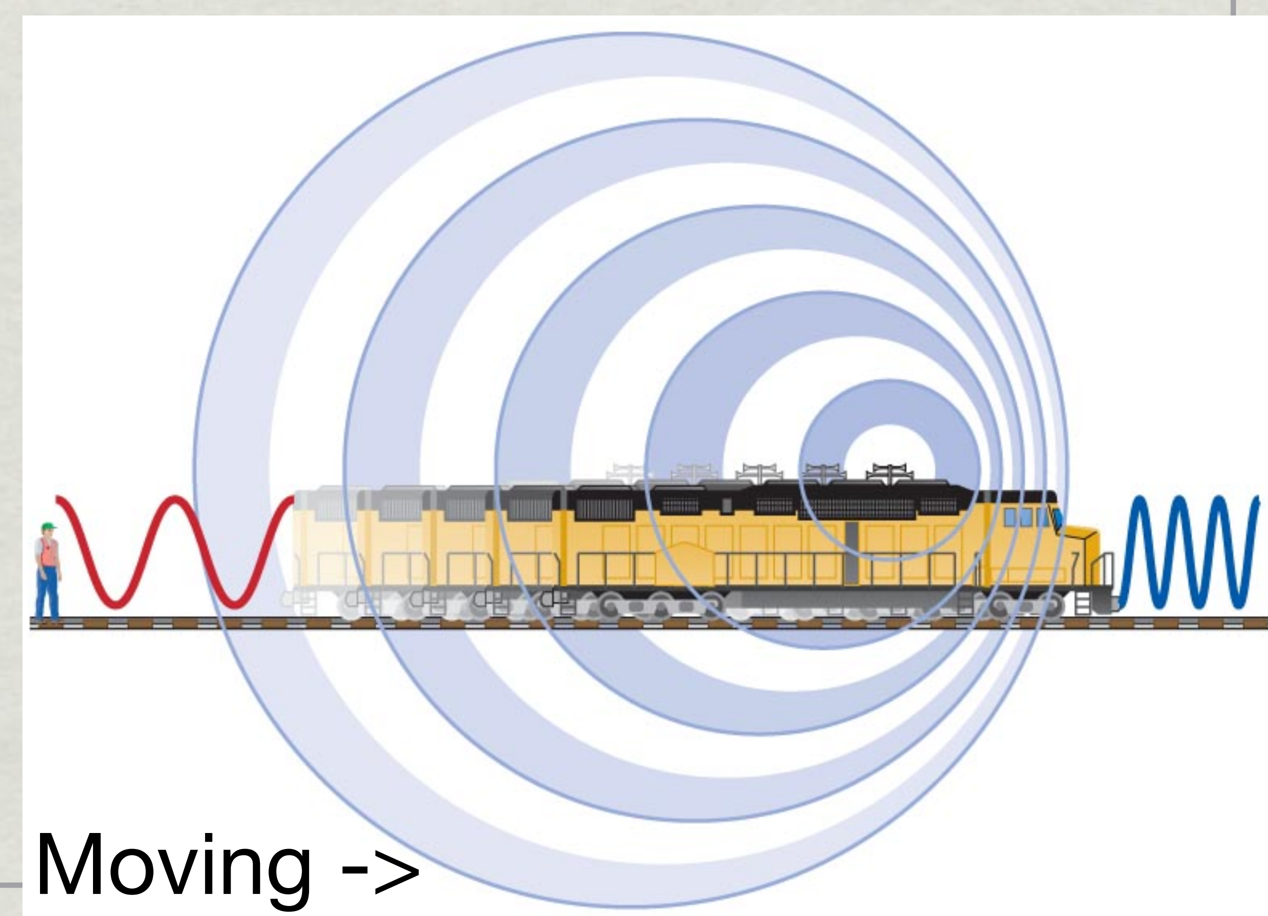
Doppler Effect

You know the Doppler Effect for sound.

If a train is standing still (at rest), its horn sounds the same (loud!) if you stand in front of it or behind it.

If the train is moving, sound waves bunch up in front and spread out behind, changing the wavelength and therefore the frequency (the “pitch”)



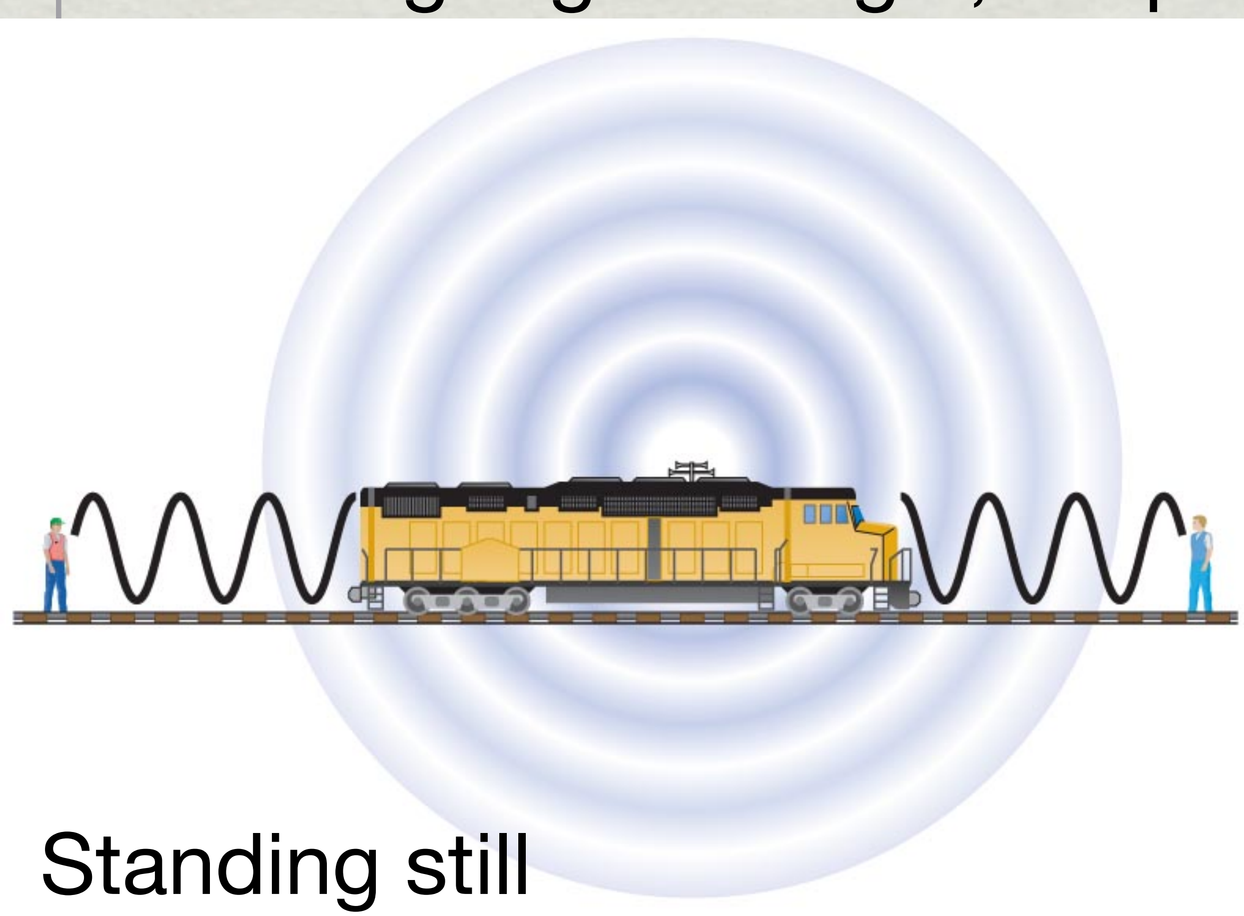


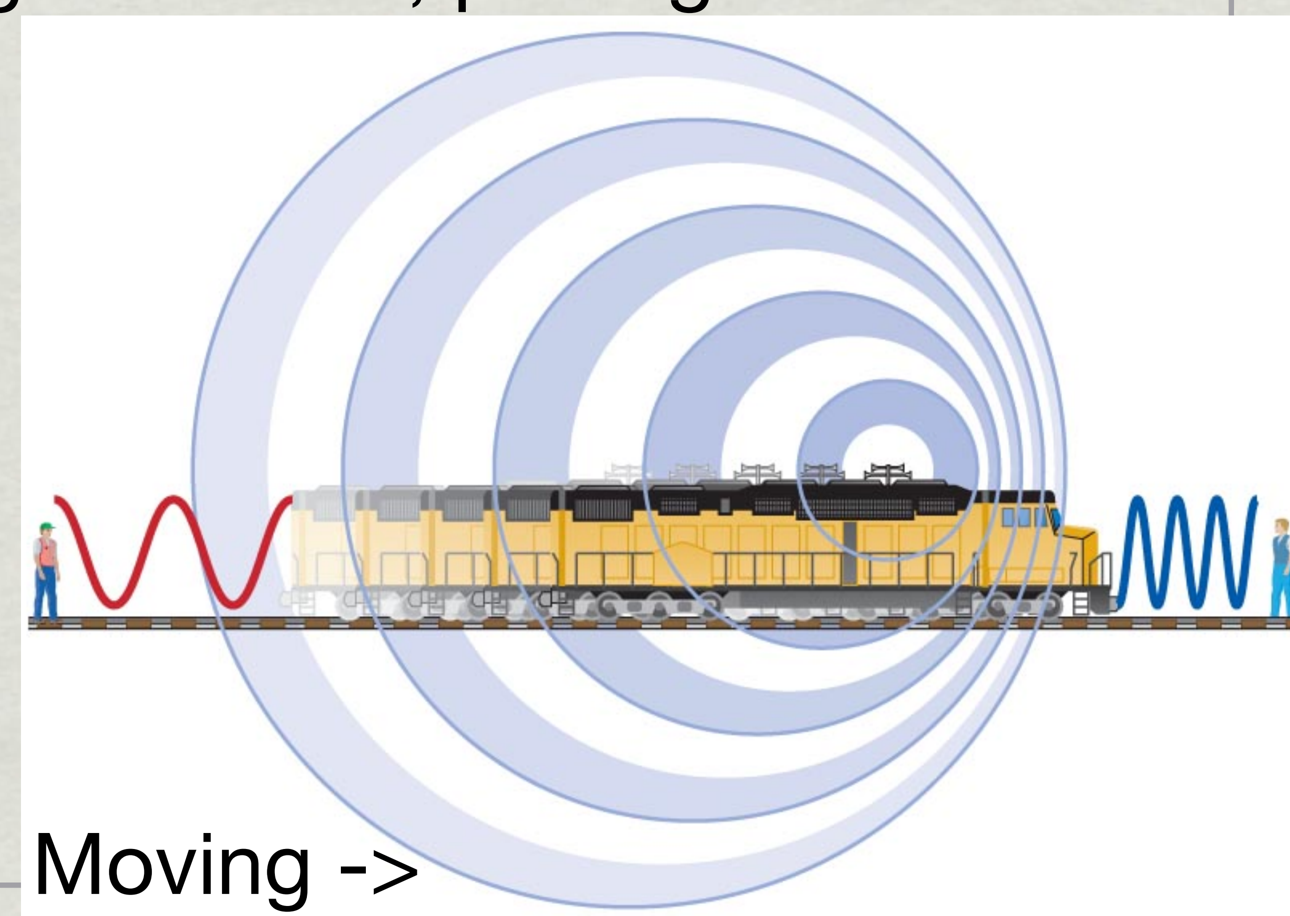
Doppler Effect

If a train is standing still (at rest), its horn sounds the same (loud!) if you stand in front of it or behind it.

Sound from an object moving toward you: peaks bunch up. Wavelength gets shorter, frequency gets faster, pitch gets higher.

For an object moving away from you, peaks stretch out. Wavelength gets longer, frequency gets slower, pitch gets lower.





Doppler Effect

The same thing happens to light.

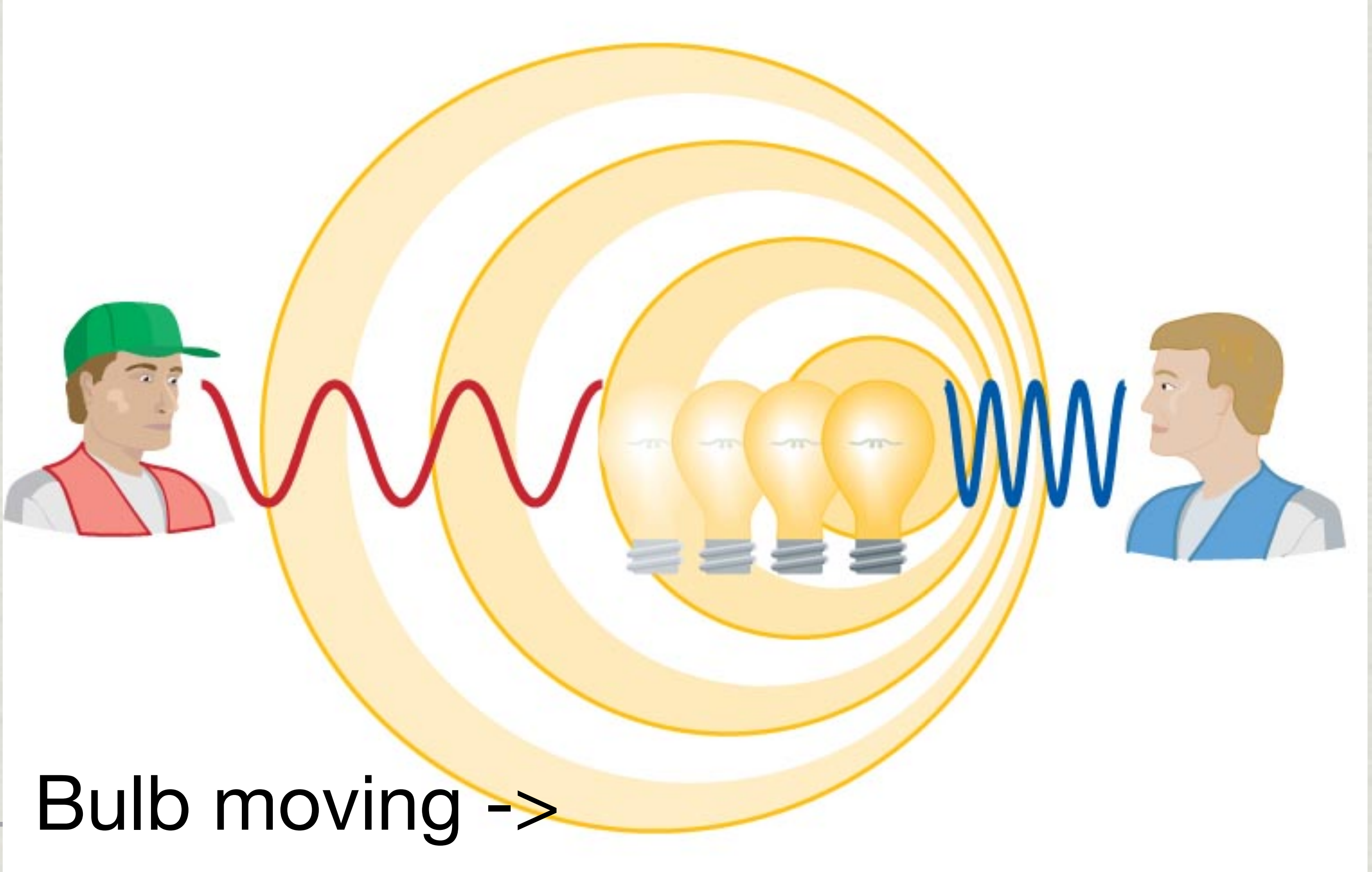
Light from an object moving toward you: peaks bunch up.
Wavelength gets shorter, frequency gets faster.

Remember: $E = h\nu = \frac{hc}{\lambda}$ So light become blue: Blue Shift

For an object moving away from you, peaks stretch out.

Wavelength gets longer, frequency gets slower.

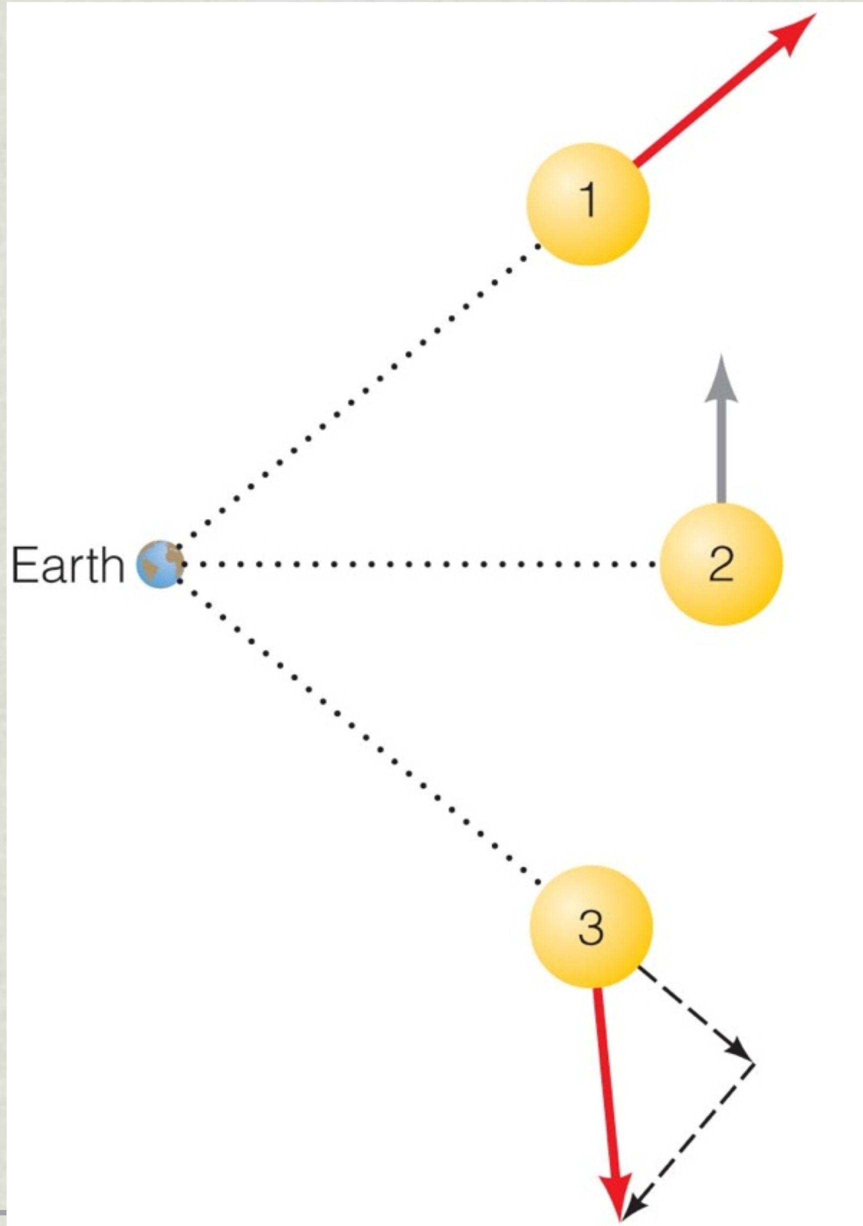
Light becomes redder: Red Shift



Doppler Effect

The amount of wavelength change you measure, red or blue, is proportional to the velocity of the light source toward you or away from you.

This is the velocity of the source along your “line of sight”



Doppler Effect

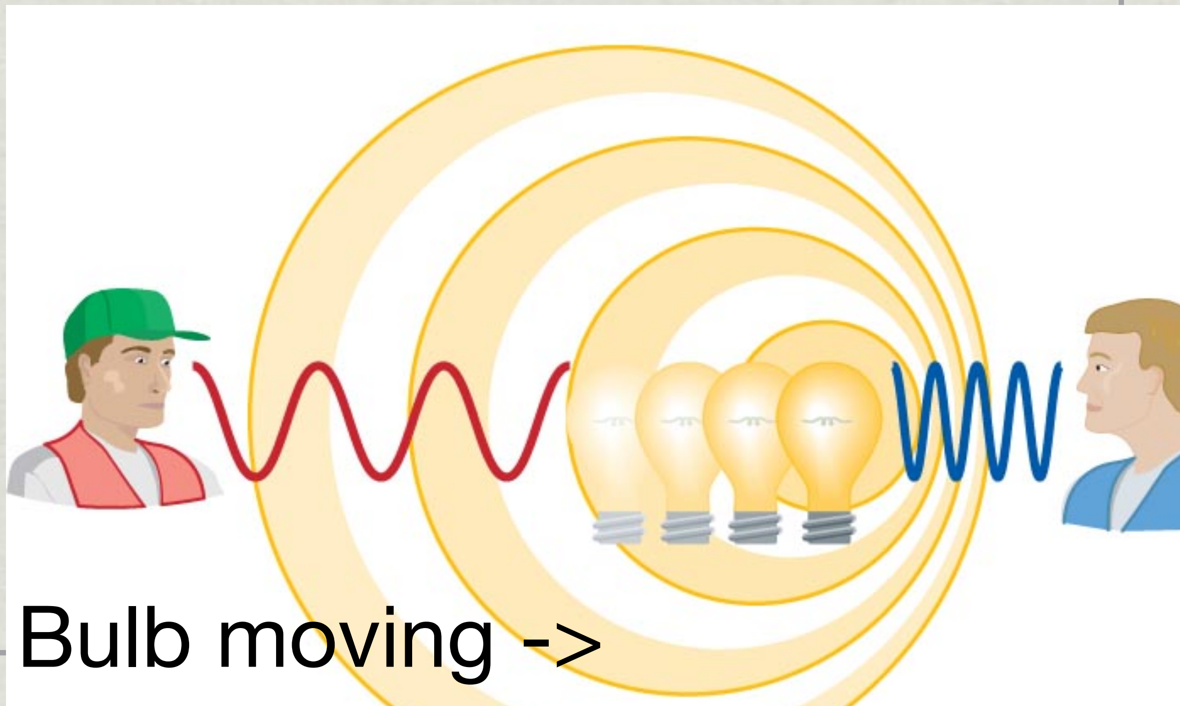
The amount of wavelength change you measure, red or blue, is proportional to the velocity of the light source toward you or away from you.

This is the velocity of the source along your "line of sight"

Doppler formula for light: $$\frac{V_{LoS}}{c} = \frac{\Delta\lambda}{\lambda_{rest}} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

$\frac{V_{LoS}}{c}$ is also called the "redshift"

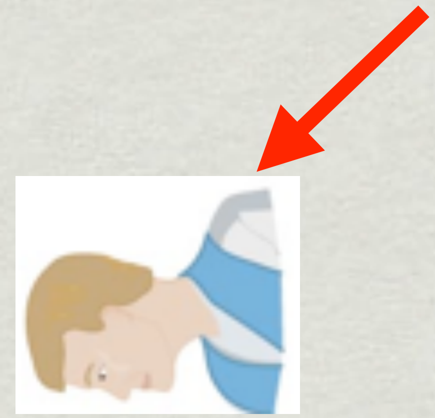
If $\lambda_{shift} > \lambda_{rest}$, $V_{LoS} > 0$ and the source is moving away from the observer



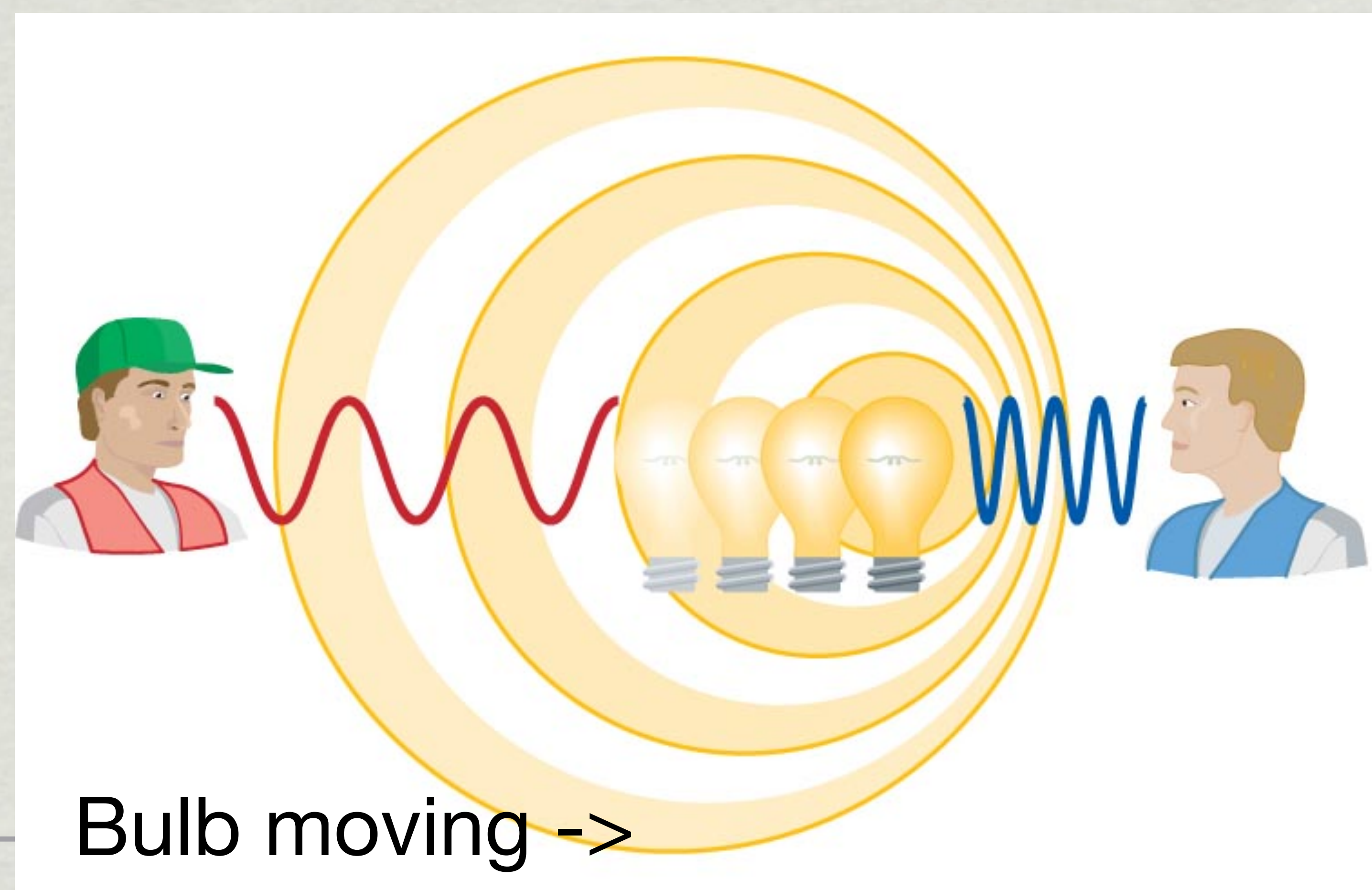
Doppler Effect

Doppler shift tells you only about the velocity along your line of sight.

Dotted: line of sight
Red and gray arrows: velocity

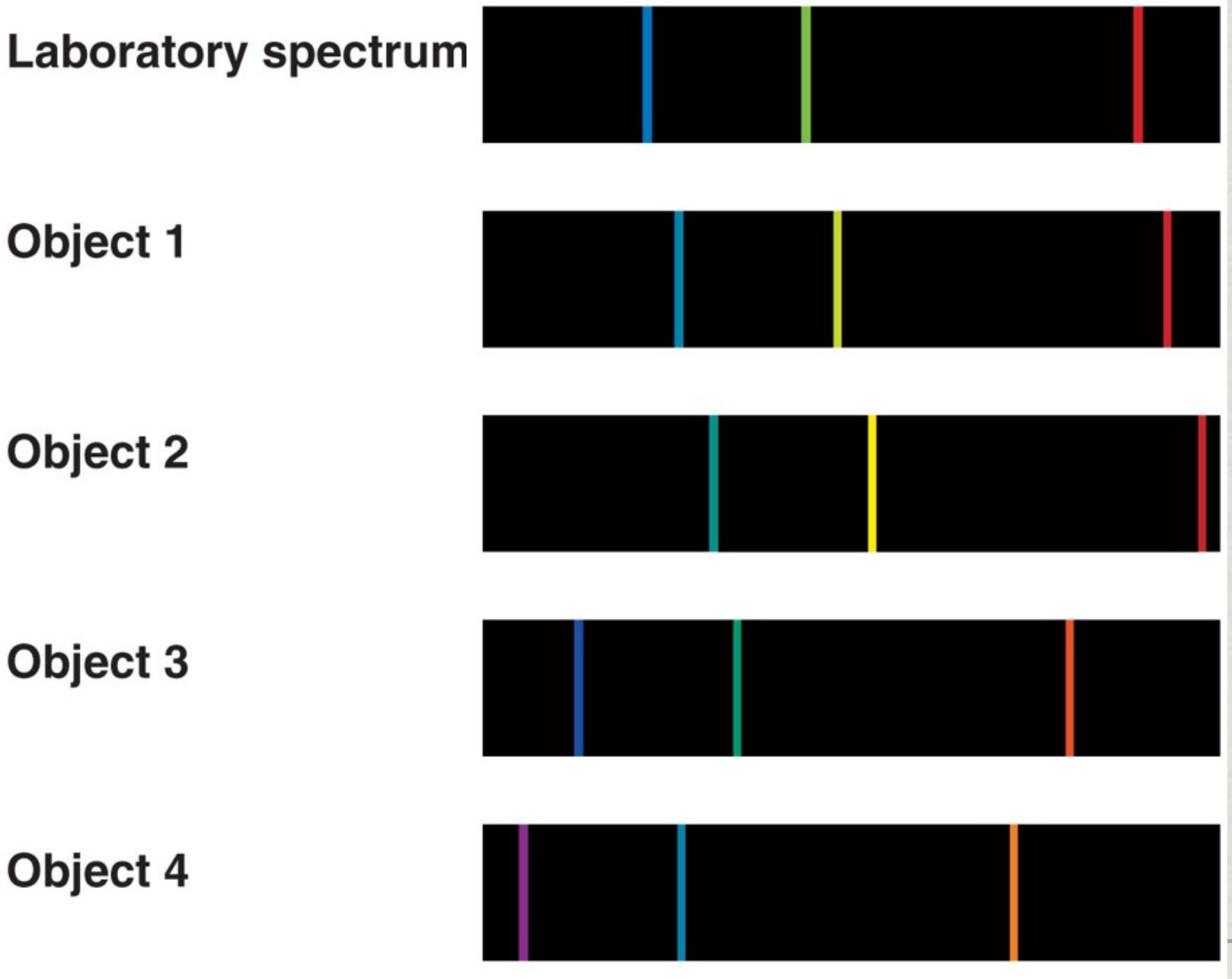


This observer doesn't see any Doppler shift: object is not moving toward or away from him.



Doppler Shift

We can measure the velocity (direction and speed) of a light source from its Doppler Shift.



Doppler Shift

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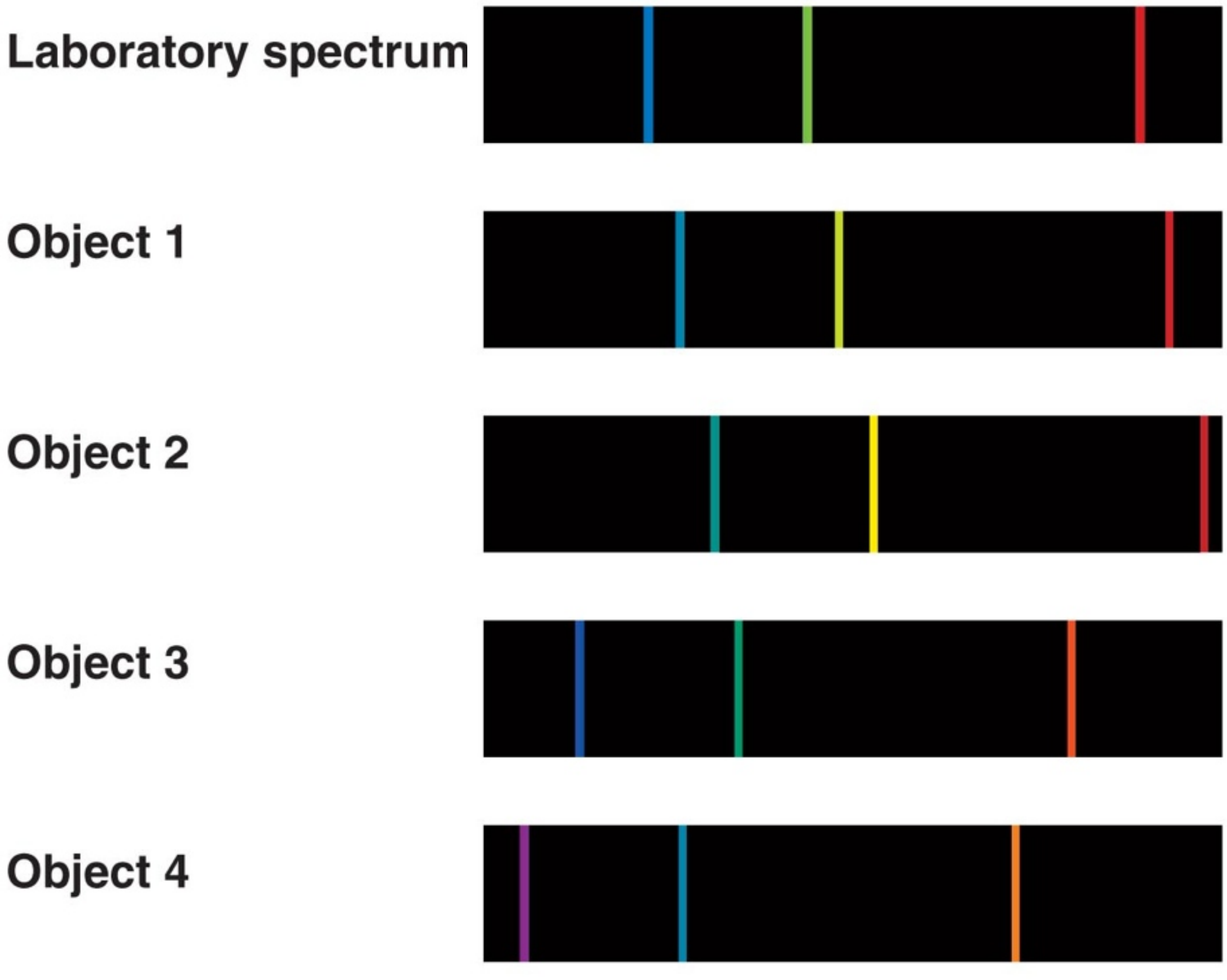


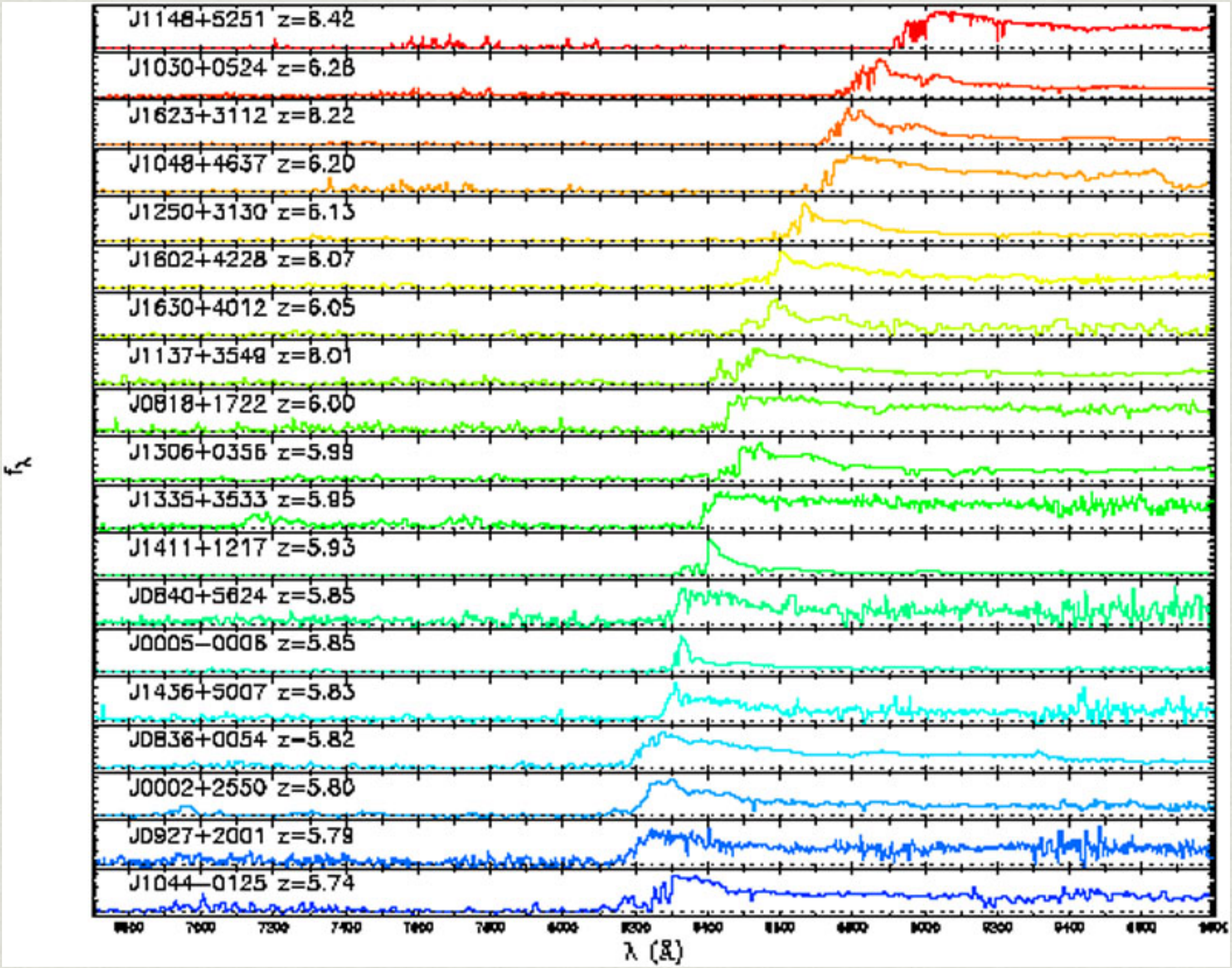
Rest

Red shift, moving away

Larger red shift, moving away faster

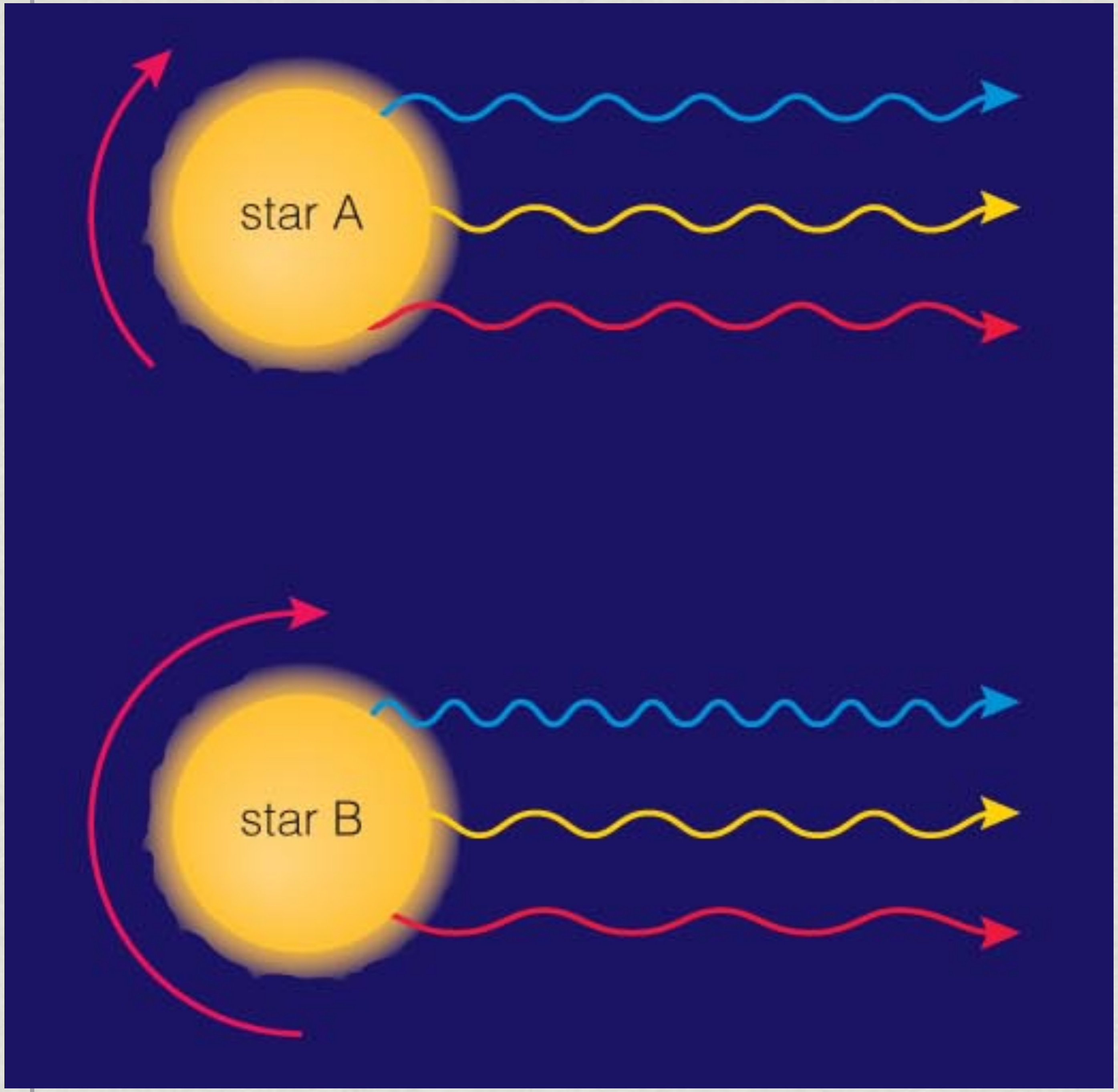
Blue shift, moving toward you

Larger blue shift, moving toward you faster



J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J1602+4228 z=6.07
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J1335+3533 z=5.95
J1411+1217 z=5.93
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
λ (Å)
f_λ

Doppler Shift



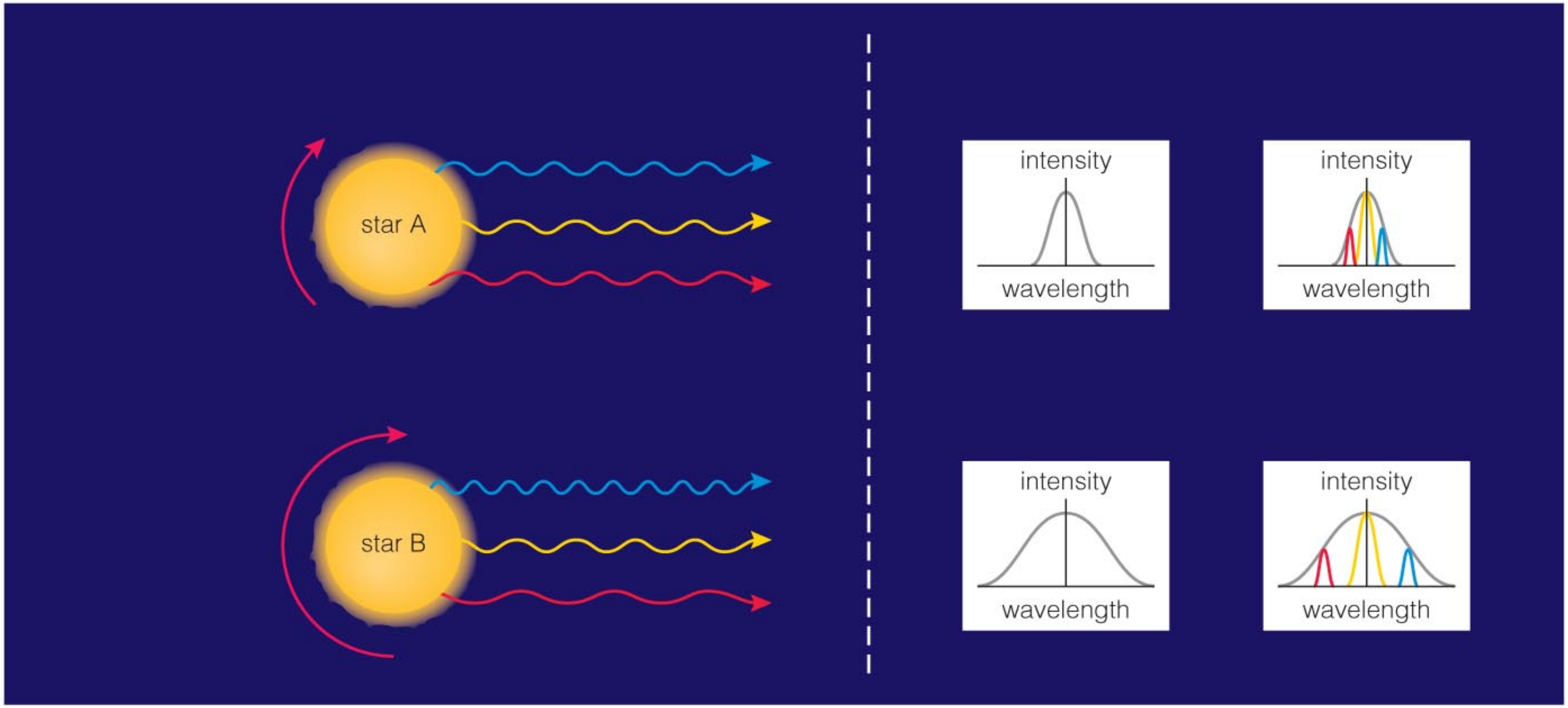
We can also measure the rotation of an object.

Light from one side is blue shifted, the other red-shifted.

Which star is rotating faster?

Doppler Shift

Spectrum of a rotating object: spectral lines get broader and spectral shape gets broader as an object rotates faster. Light is more spread out.



Measuring Masses for Planets Orbiting other Stars: Newton's Version of Kepler's 3rd Law

$$\frac{P^2}{d^3} = \frac{(2\pi)^2}{G\,(M_1+M_2)}$$

If $M_1 >> M_2$ then this can be simplified to ignore M_2

1) Measure orbital period, P, by measuring the Doppler shift of the central star $V_{Doppler,star}$ as it orbits the Center of Mass of the star +planet system

- Watch the Doppler shift change as the star moves toward and away from us on its orbit around the Center of Mass
- Measure the time it takes the Doppler shift pattern to complete a full cycle. This is the period of the planet's orbit