Light and Matter (Chapter 5)

Light

The section on matter in Chapter 5 was discussed earlier

Based on part of Chapter 5

- This material will be useful for understanding Chapters 6, 10, 11, 12, 13, and 14 on “Telescopes”, “Planetary Atmospheres”, “Jovian planet systems”, “Remnants of ice and rock”, “Extrasolar planets”, and “The Sun: Our Star”
- Chapter 4 on “Momentum, energy, and matter” will be useful for understanding this chapter

Goals for Learning

- How do light and matter interact?
- Does light behave like a wave or a particle?
- How do energy levels affect the light emitted or absorbed by atoms?
- What is thermal radiation? (next class)
- What is the Doppler shift? (next class)

Universe = Matter and Energy

- Matter = stuff, things, objects
- Energy = kinetic, radiative, potential
  - kinetic = energy of moving stuff
  - potential = energy stored within stuff
  - radiative = energy that has no connection to stuff

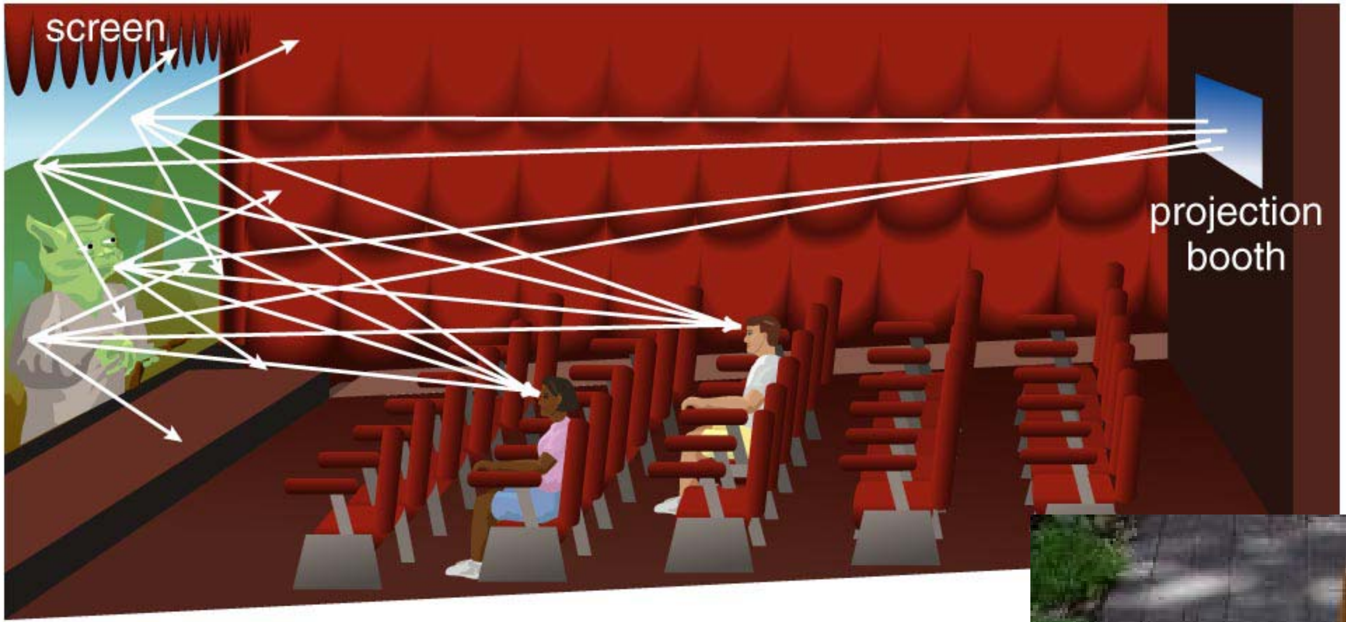
- Light carries radiative energy, light is radiative energy

How do light and matter interact?

- Light bulb
- Window
- Table
- Laser
- Clothes
- Ocean
- Air

How do light and matter interact?

- Emission. The filament of a light-bulb emits light.
- Absorption. A brick wall absorbs light.
- Transmission. Glass in a window allows light to pass through undisturbed.
- Reflection/Scattering. Light can bounce off things, changing its direction
  - Scattering. Light bounces off in all directions
  - Reflection. Light bounces off in one direction

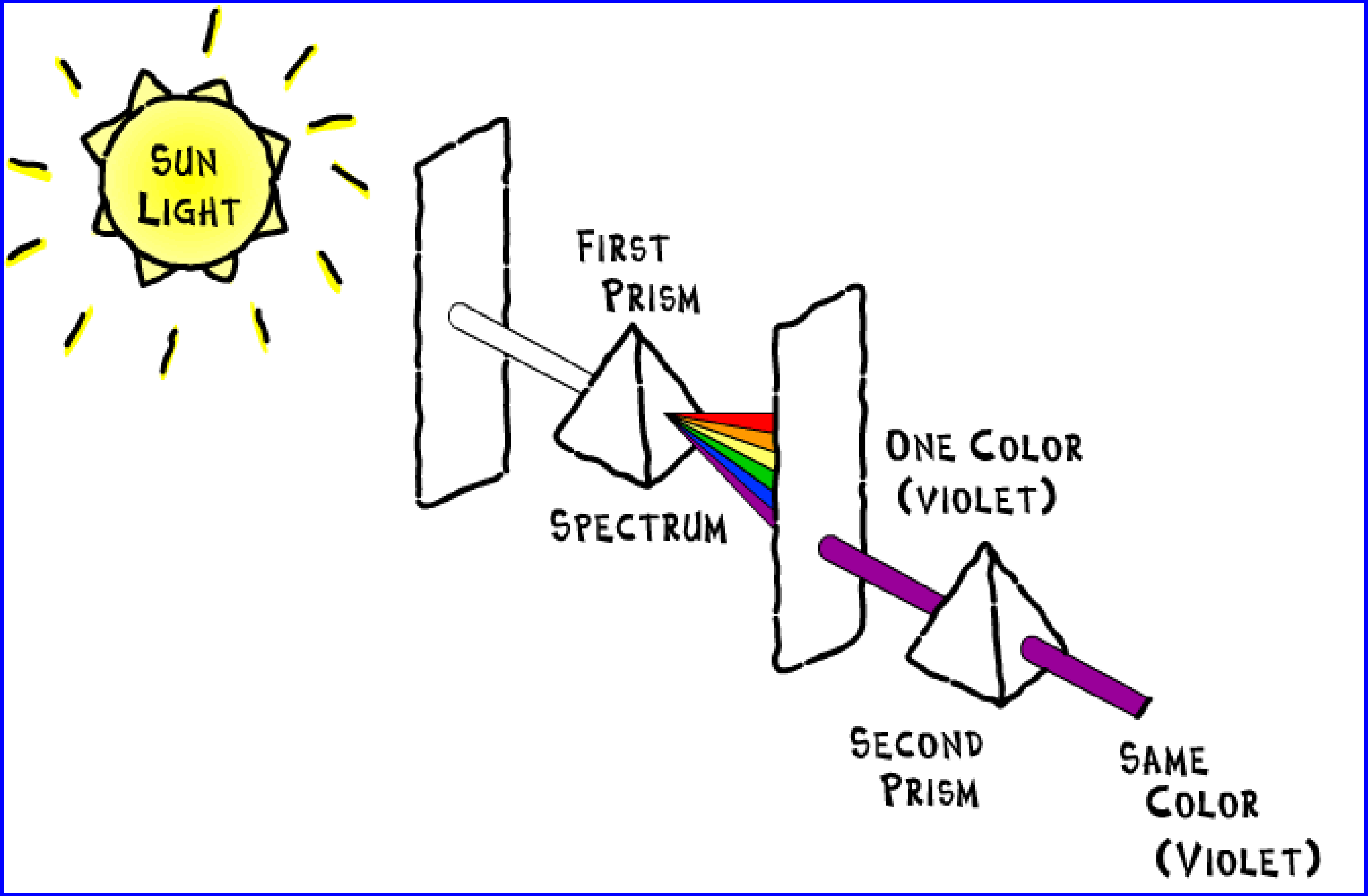


Scattering

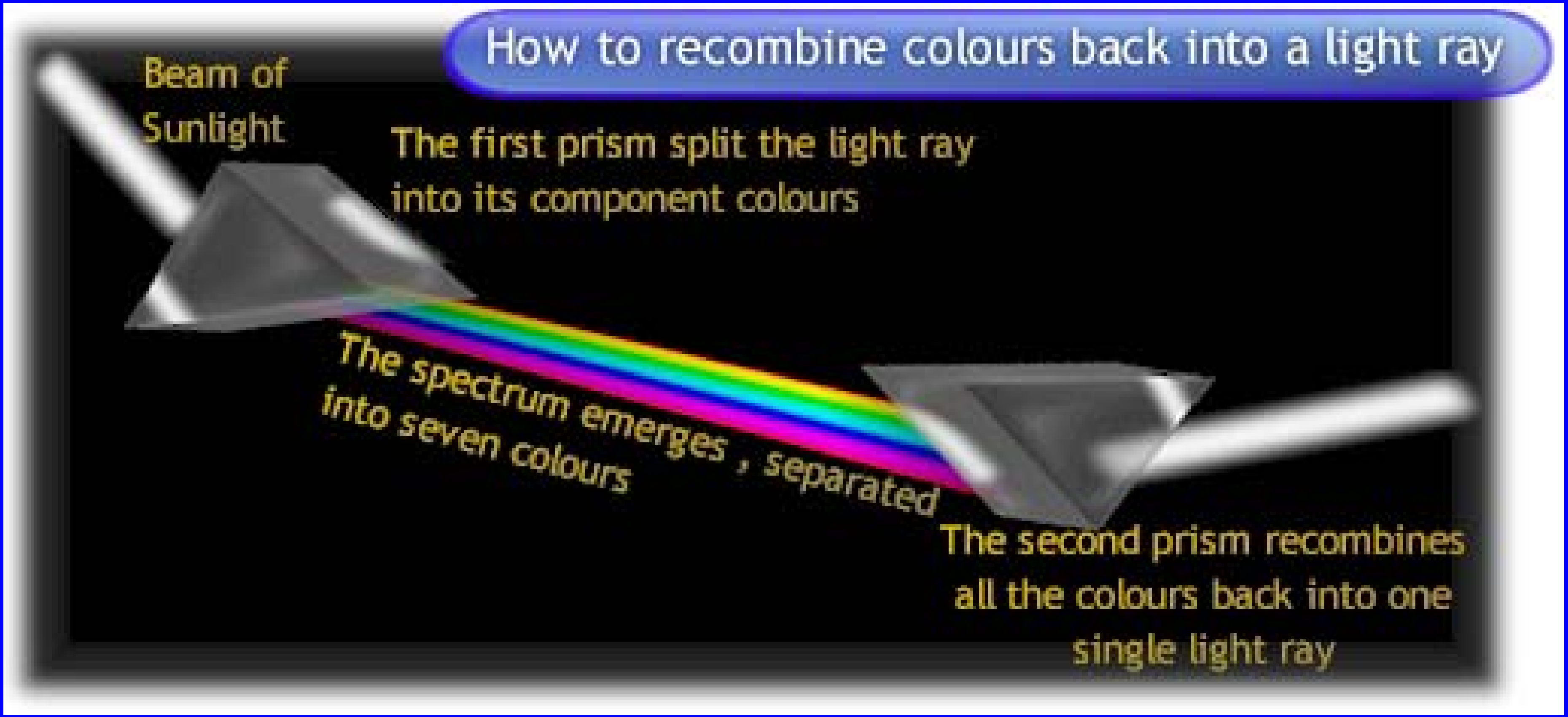
Reflection

Colour

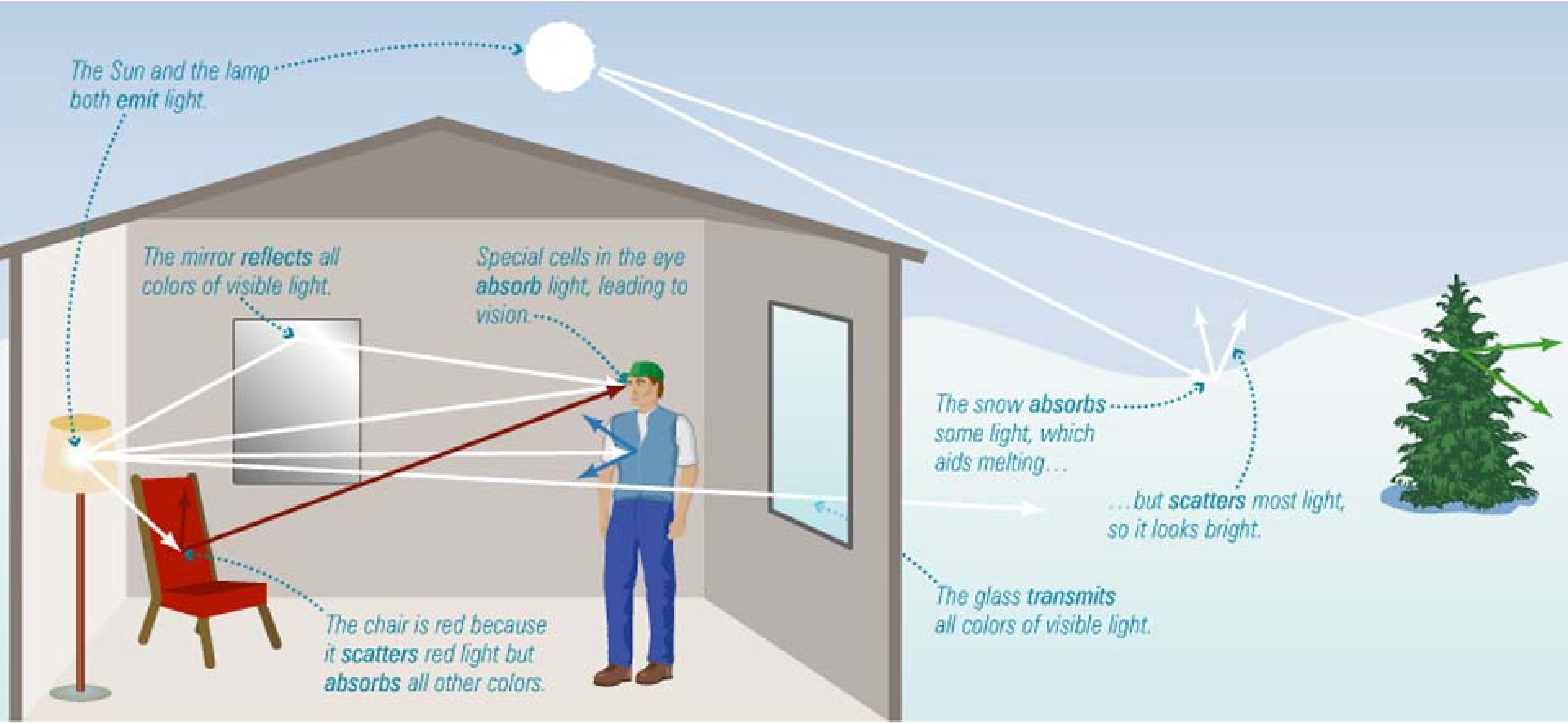
- A single beam of light can be split into a rainbow of colours



Colour is a property of light, not of the prism



What makes red light different from green light?
Answer coming soon



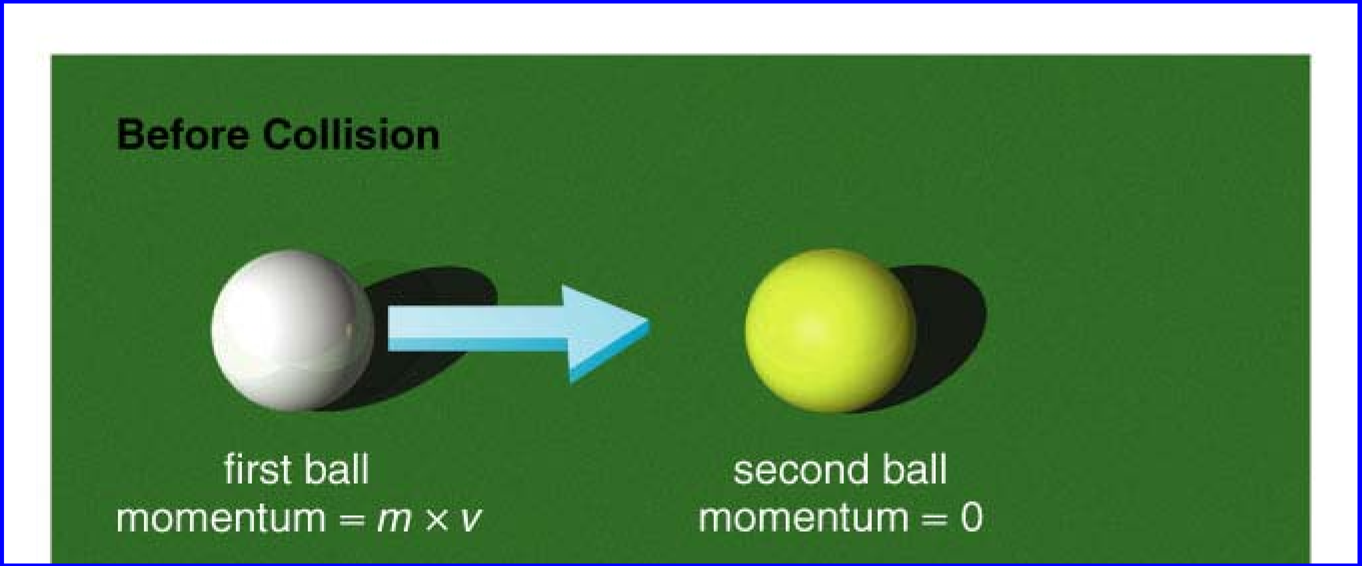
What does a red piece of glass do to red light? to green light?
What does a green tree do to green light? to red light?

What is light?

- All matter is made of particles. Particles have a mass and a size, you can picture them easily
- Light is different.
  - Light has some properties of a wave
  - Light has some properties of a particle

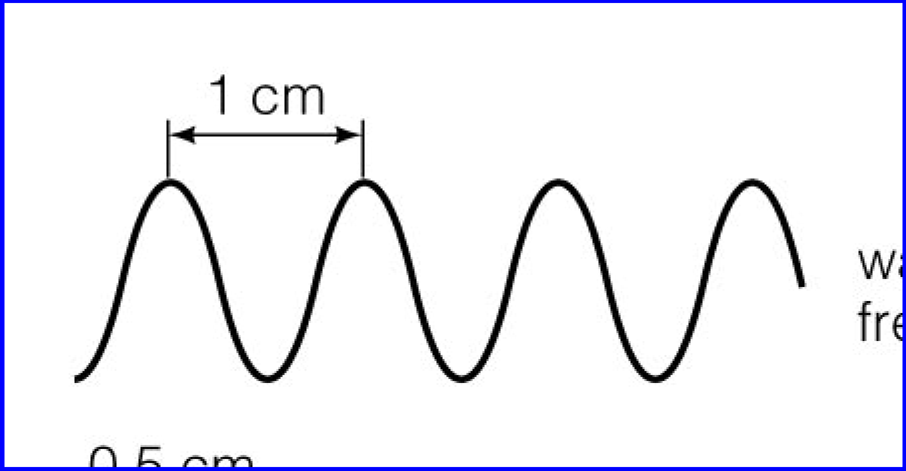
What are Particles?

- Particles have well-defined positions
- You can have one, two, or three particles; you can't have 1.5 particles
- Particles have boundaries or edges



What are Waves?

- Waves are patterns
- Waves don't have fixed boundaries/edges
- Wave don't come in "packages", so you can't count 1, 2, or 3 waves
- Waves have a wavelength, frequency, and speed



Animation of a wave in Windows Media Player

Light = Wave and Particle

- Light comes in isolated packages called photons
  - Each package has a wavelength, frequency, and speed
- You don’t get half-photons

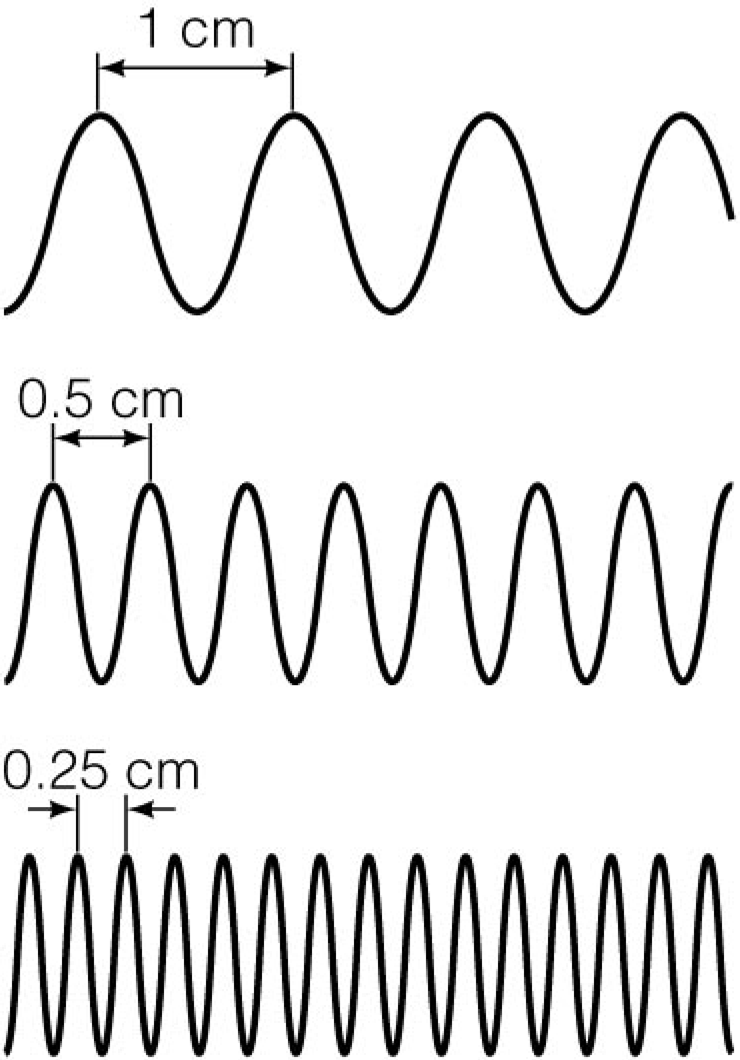
- What is waving up and down as a package of light travels past?
  - Tiny electric forces that can exist even in empty space

- Sound waves can’t travel without air molecules, water waves can’t travel without water molecules, but light doesn’t need any molecules

Speed of Light

- Speed = Wavelength x Frequency
  m/s m 1/s or Hz
- All light travels with the same speed, often called $c = 3 \times 10^8$ m/s

- Long wavelength, small frequency
- Short wavelength, large frequency



wavelength = 1 cm,
frequency = 30 Ghz

wavelength = $\frac{1}{2}$ cm,
frequency = 2 × 30 Ghz = 60 Ghz

wavelength = $\frac{1}{4}$ cm,
frequency = 4 × 30 Ghz = 120 Ghz

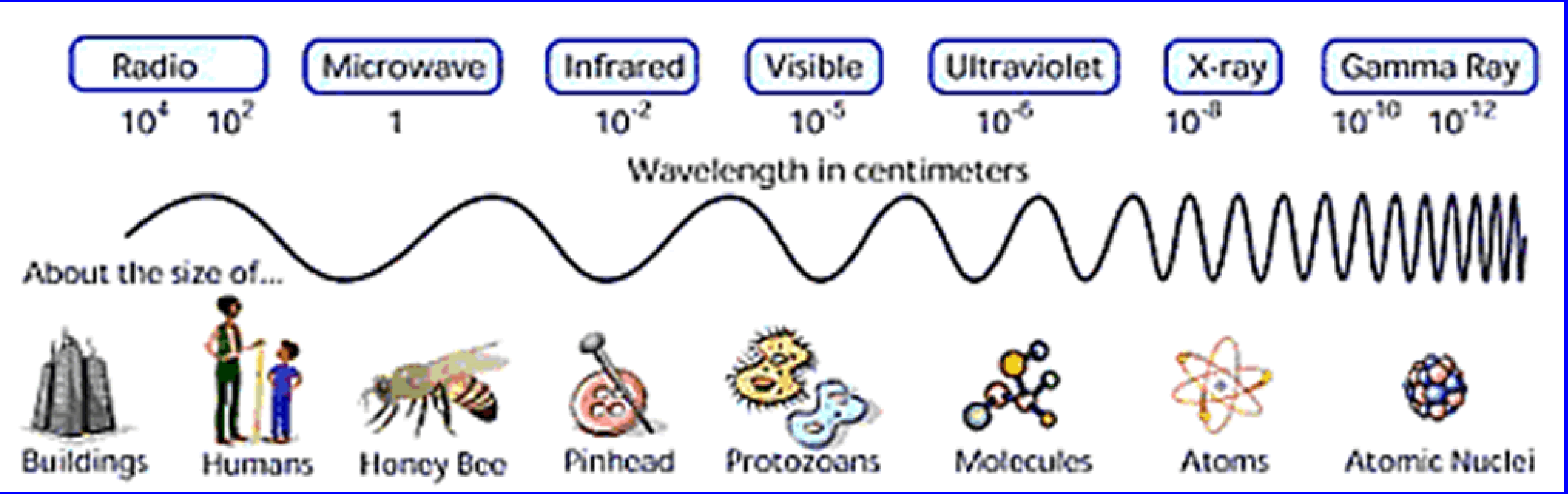
Red and Green Light

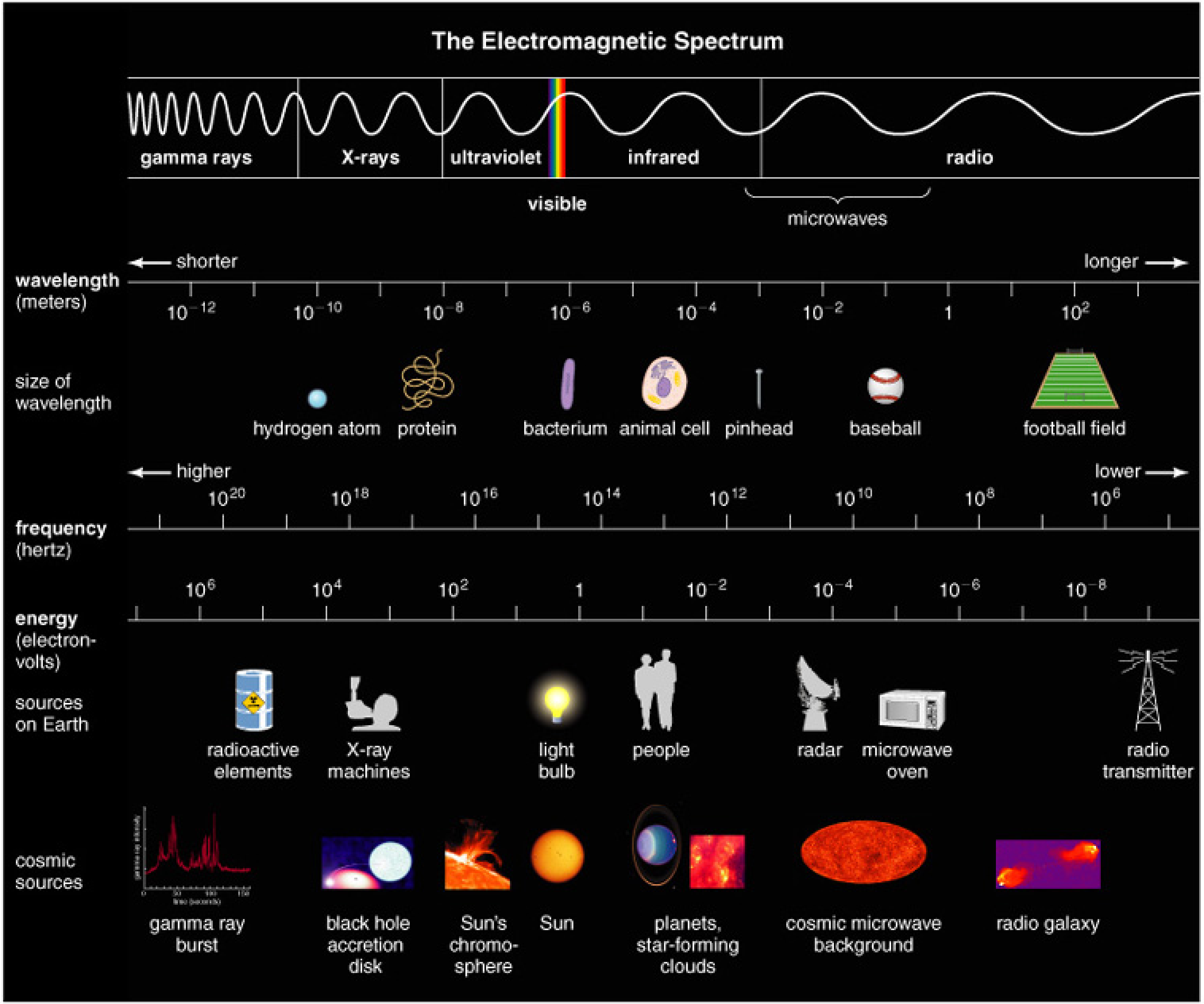
- These different colours have different frequencies and different wavelengths

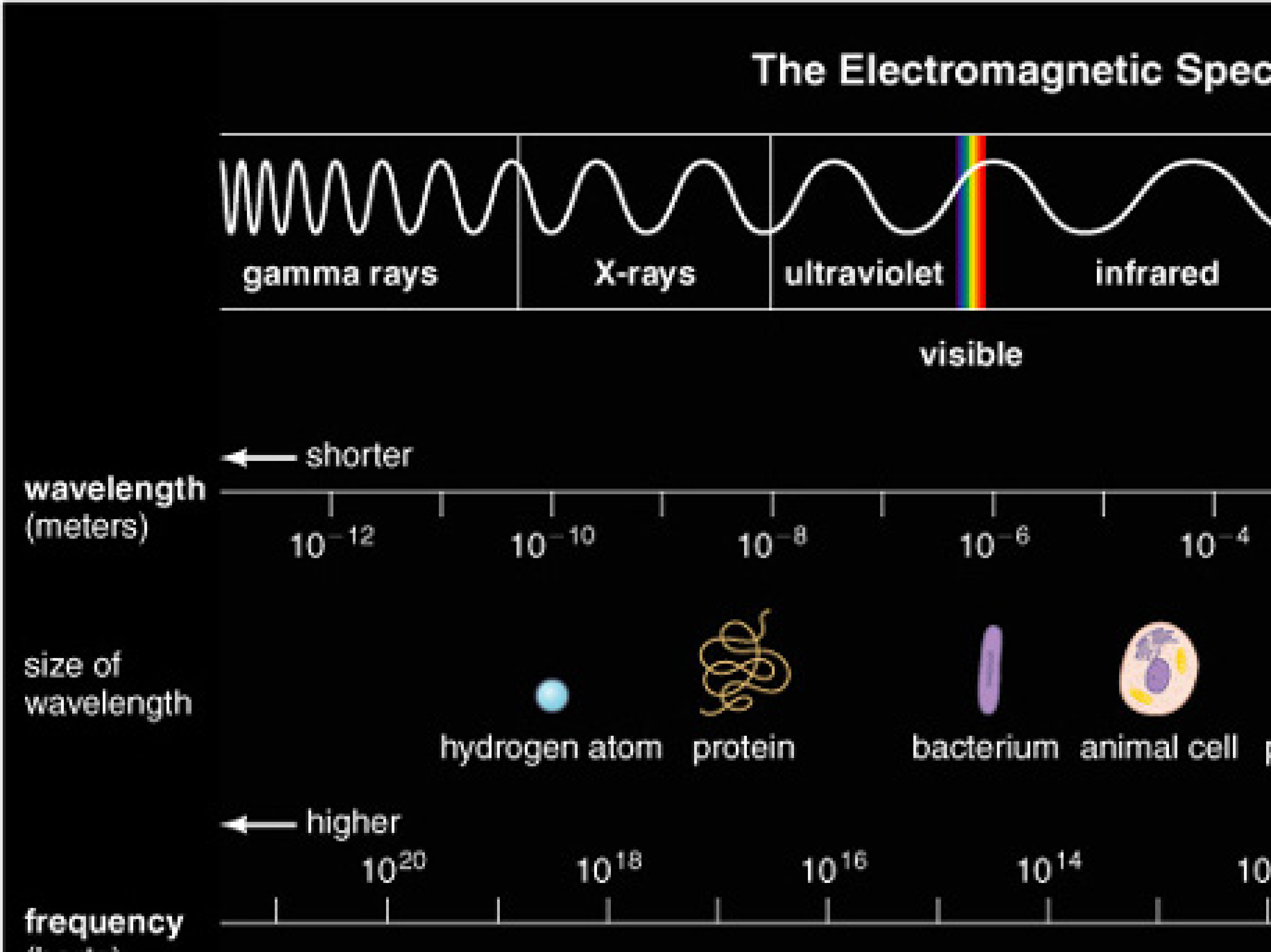
What lies beyond the red and purple edges of this rainbow?

Beyond the Rainbow

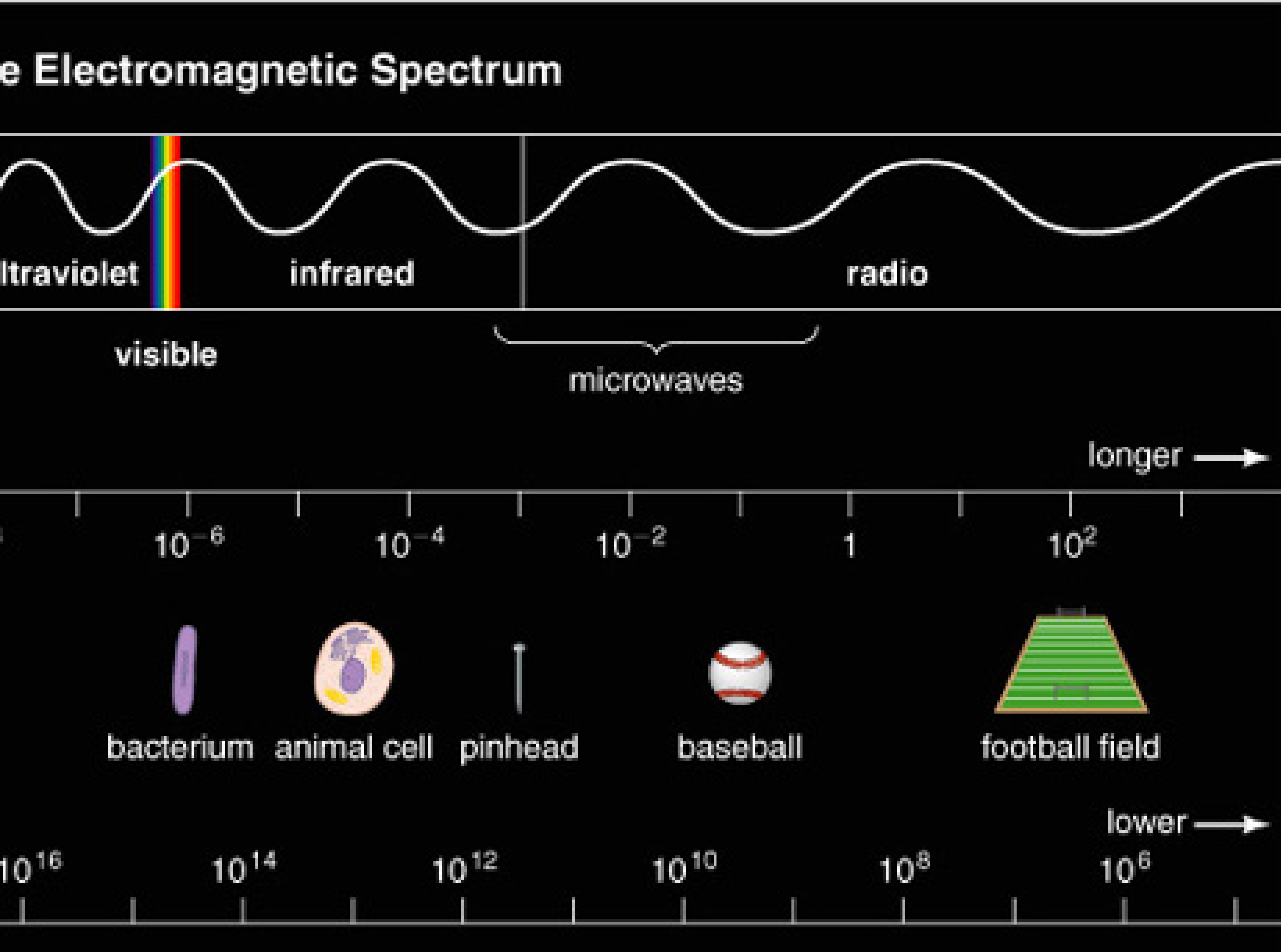
- Red light = 700 nm, violet = 400 nm
- Does nature only create light with wavelengths in this range?
- Or do our eyes only see light with wavelengths in this range?

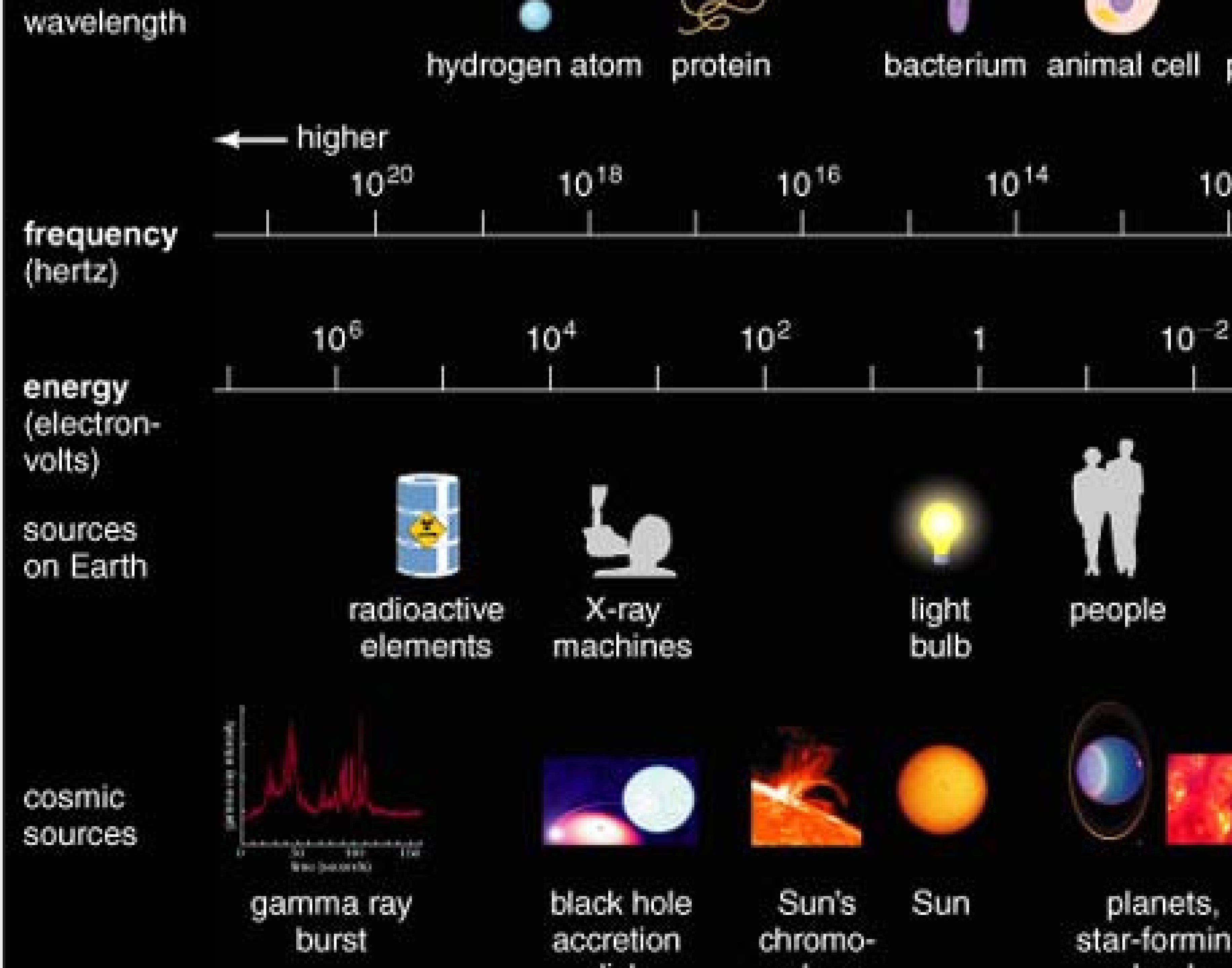

Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^{4} 10^{2}
1
10^{-2}
10^{-5}
10^{-6}
10^{-8}
10^{-10} 10^{-12}
Wavelength in centimeters
About the size of...
Buildings
Humans
Honey Bee
Pinhead
Protozoans
Molecules
Atoms
Atomic Nuclei


The Electromagnetic Spectrum
gamma rays
X-rays
ultraviolet
visible
infrared
radio
microwaves
shorter
longer
wavelength (meters)
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
size of wavelength
hydrogen atom
protein
bacterium
animal cell
pinhead
baseball
football field
higher
lower
frequency (hertz)
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
energy (electron-volts)
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
sources on Earth
radioactive elements
X-ray machines
light bulb
people
radar
microwave oven
radio transmitter
cosmic sources
gamma ray burst
black hole accretion disk
Sun's chromo-sphere
Sun
planets, star-forming clouds
cosmic microwave background
radio galaxy

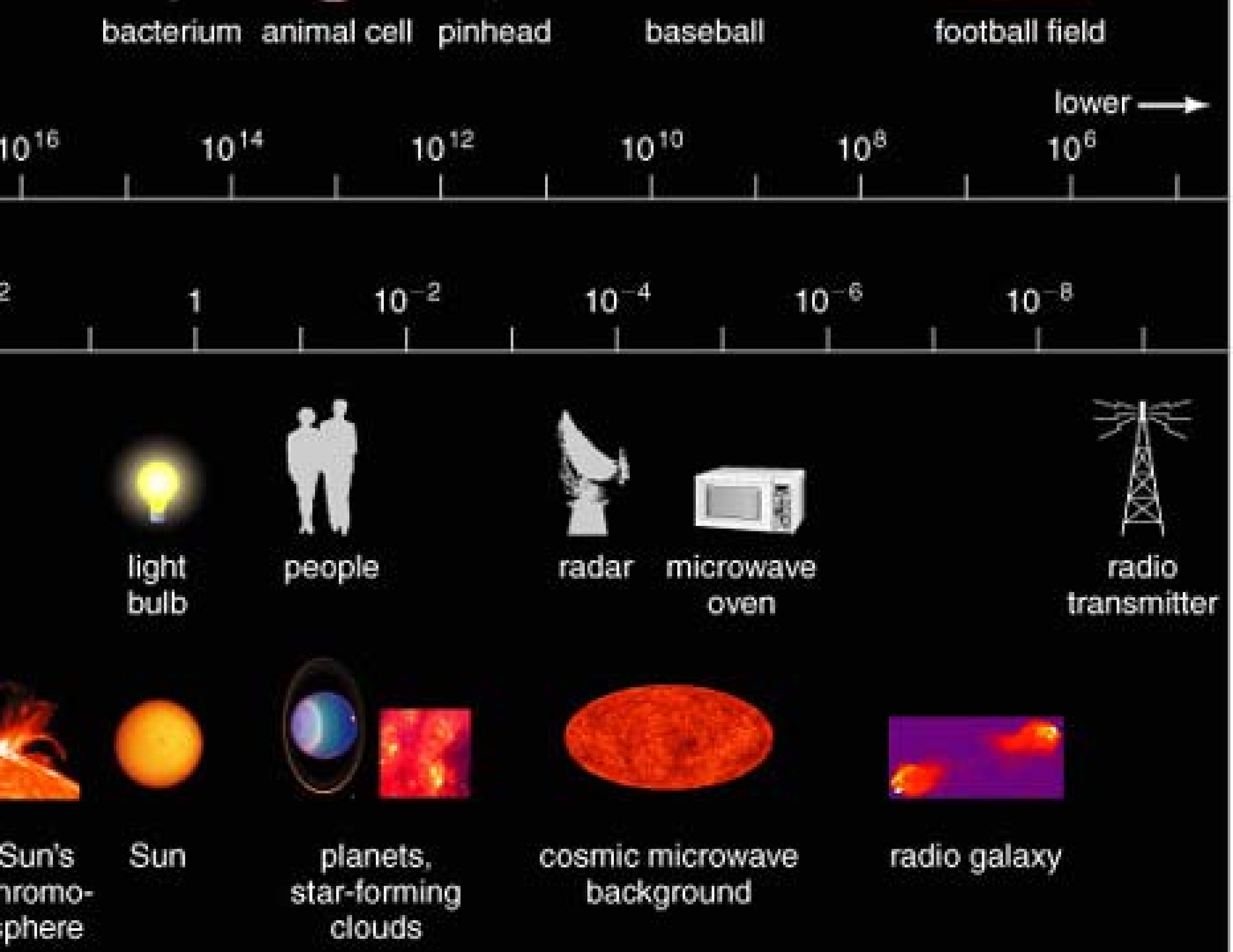


The Electromagnetic Spec
gamma rays
X-rays
ultraviolet
infrared
visible
shorter
wavelength
(meters)
10⁻¹²
10⁻¹⁰
10⁻⁸
10⁻⁶
10⁻⁴
size of
wavelength
hydrogen atom
protein
bacterium
animal cell
higher
10²⁰
10¹⁸
10¹⁶
10¹⁴
frequency


e Electromagnetic Spectrum
ltraviolet
infrared
radio
visible
microwaves
longer
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
bacterium
animal cell
pinhead
baseball
football field
lower
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}



wavelength
hydrogen atom
protein
bacterium
animal cell
← higher
10^20
10^18
10^16
10^14
frequency (hertz)
10^6
10^4
10^2
1
10^-2
energy (electron-volts)
sources on Earth
radioactive elements
X-ray machines
light bulb
people
cosmic sources
gamma ray burst
black hole accretion
Sun's chromo-
Sun
planets,



bacterium
animal cell
pinhead
baseball
football field
lower
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
light bulb
people
radar
microwave oven
radio transmitter
Sun
planets, star-forming clouds
cosmic microwave background
radio galaxy

Energy of Light

- Each package of light, or photon, has energy E = h x f
- h = Planck's constant = 6.63 x 10^{-34} J s
- Units of h are J s or J / Hz

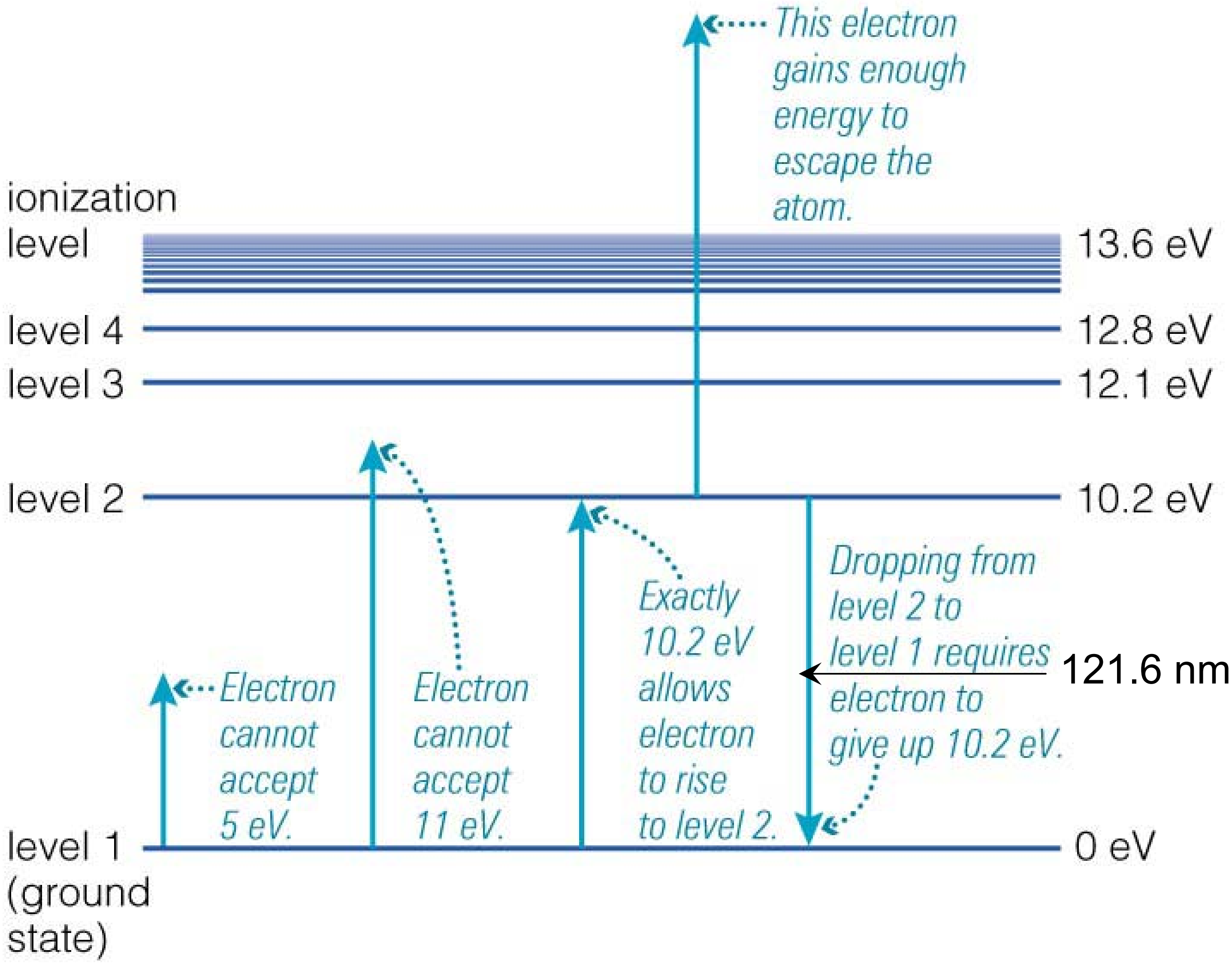
- 100 low energy photons are not the same as 1 high energy photon

How do light and matter interact?

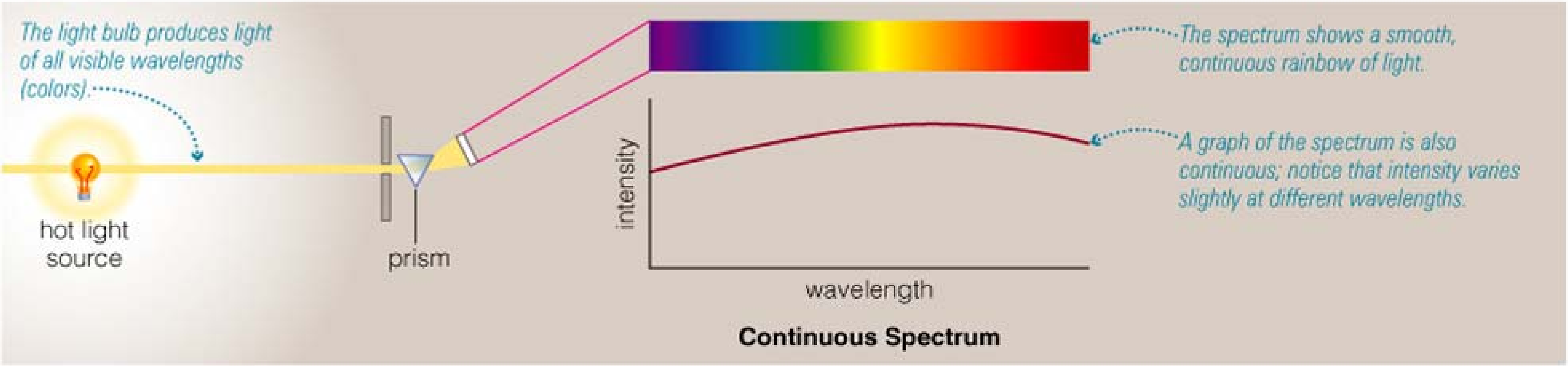
- Brick wall and visible/radio waves
- Skin and UV/visible light
- Flesh/bone and X-rays

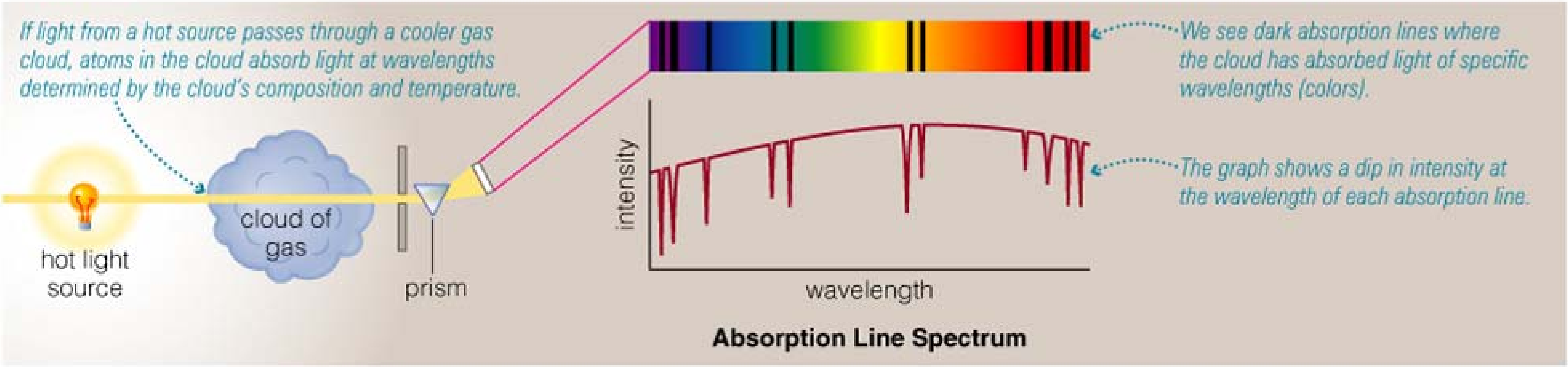
- Does a light-bulb emit gamma rays? visible light? radio waves?

- Absorption, emission, transmission, reflection/scattering

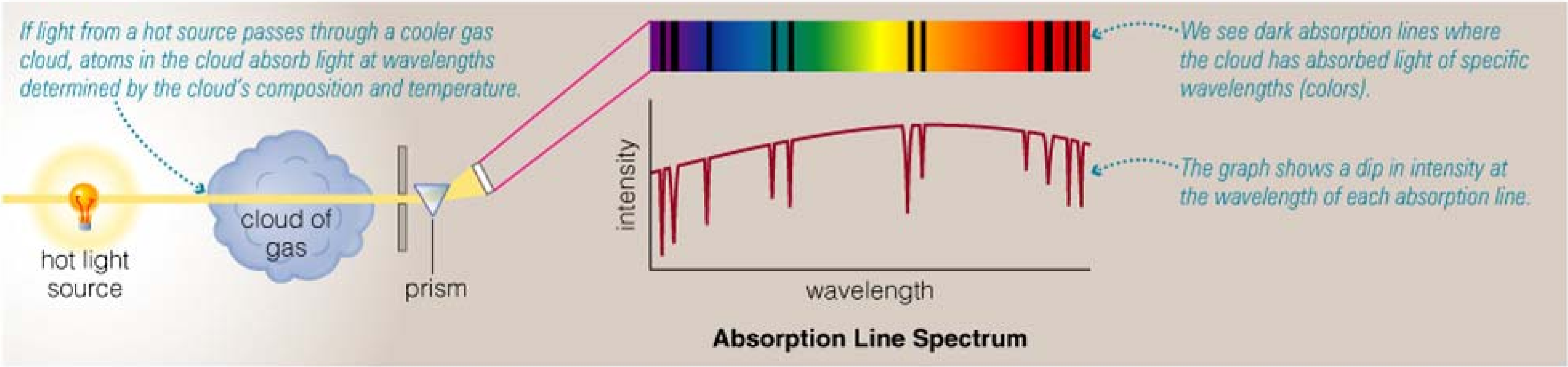


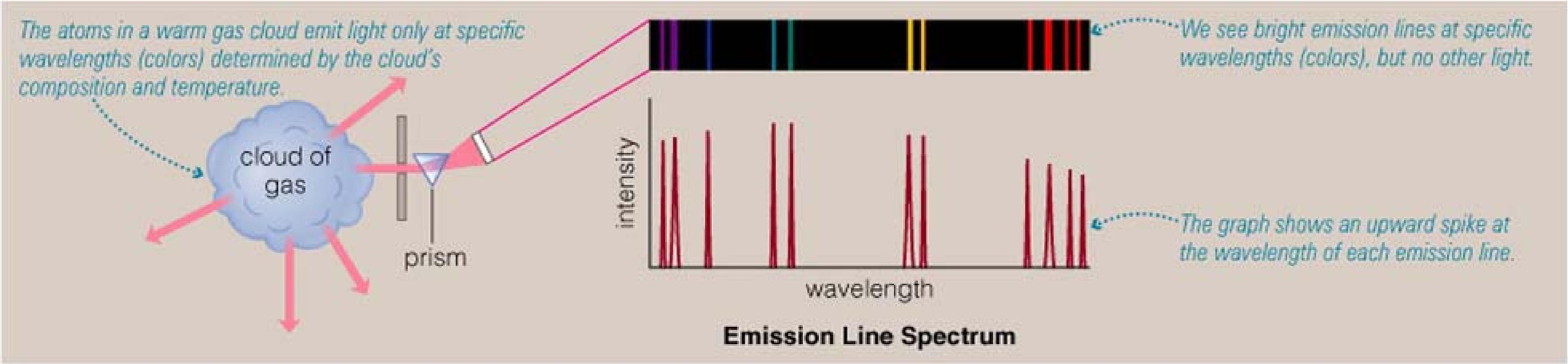
What if we shine light of all wavelengths on hydrogen atoms?





Interactive Figure 5.14

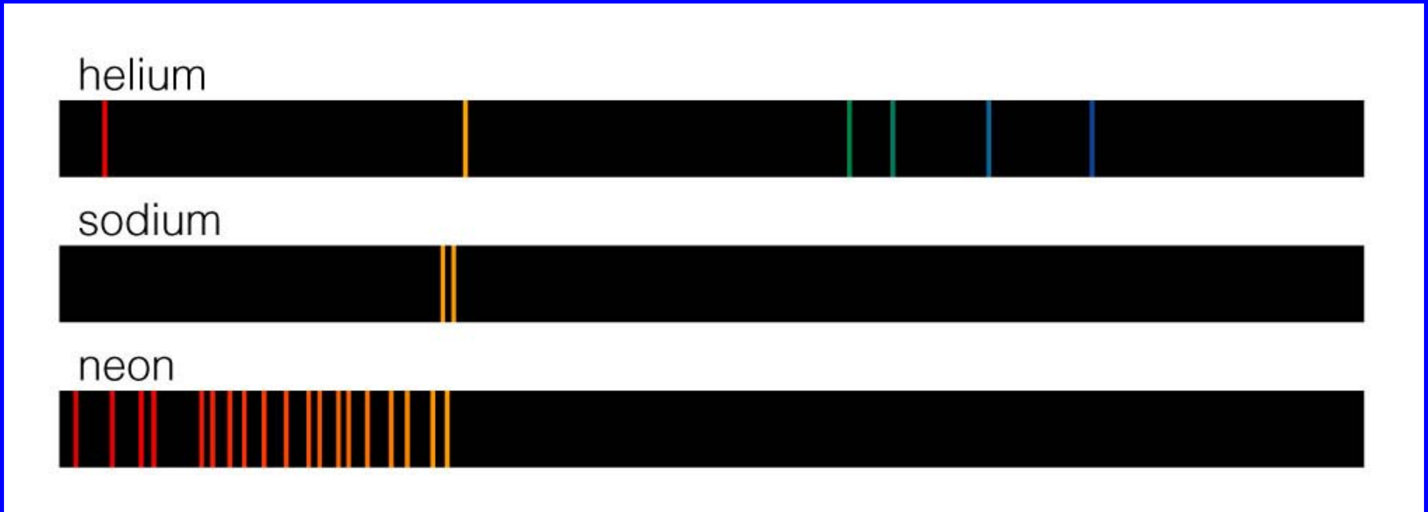




A spectrum is like a fingerprint

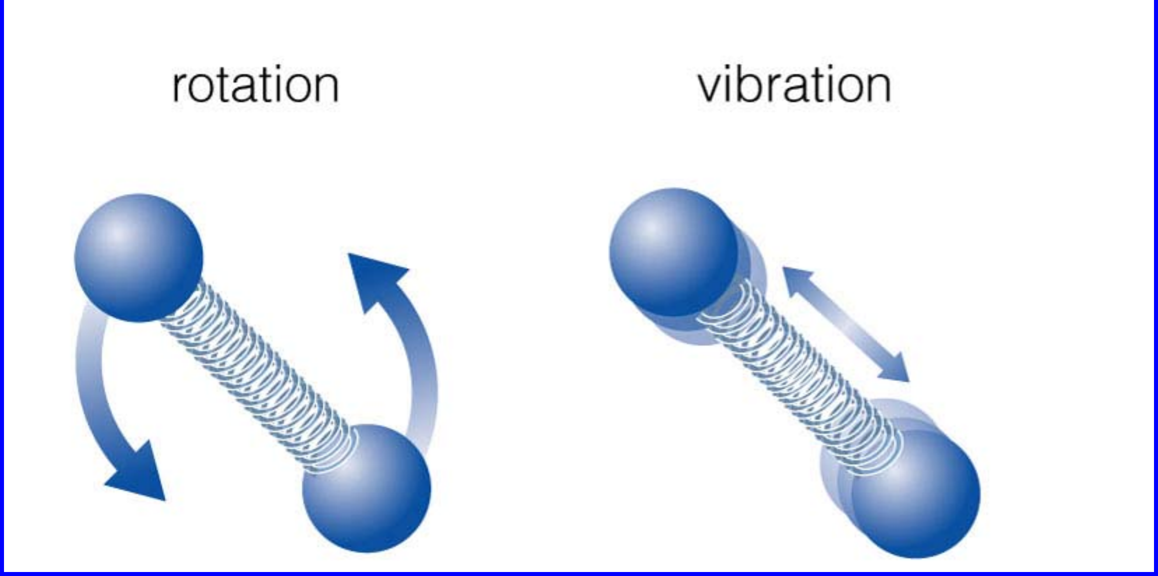
Emission and Absorption Spectra

- Fewer electrons, fewer lines on a spectrum
- Changing the energy levels of electrons often corresponds to visible or UV light
- A unique fingerprint for a gas
- What about a mixture of gases?



Spectrum for Molecules

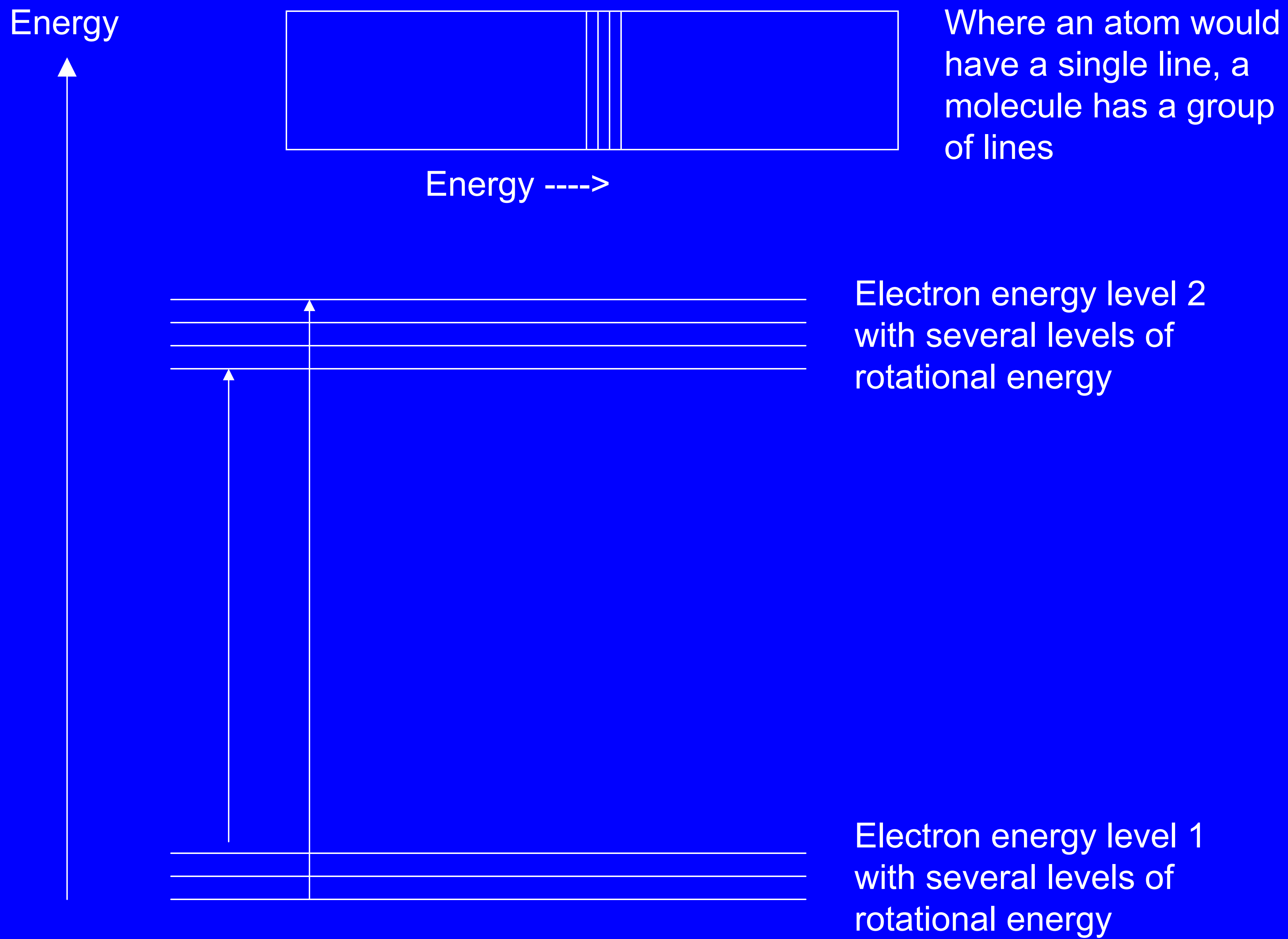
- Atoms can store energy in the potential energy of their electrons
- So do molecules, but they can also store energy associated with vibration or rotation



Spectrum for Molecules

- The energy of rotation or vibration is also quantized in fixed levels, but steps between levels are smaller that steps between electron energy levels

- Can absorb low-energy photons (IR). Change rotation/vibration state of molecule without changing electron energy level


Energy
Energy ---->
Where an atom would have a single line, a molecule has a group of lines
Electron energy level 2 with several levels of rotational energy
Electron energy level 1 with several levels of rotational energy

Goals for Learning

- How do light and matter interact?
- Does light behave like a wave or a particle?
- How do energy levels affect the light emitted or absorbed by atoms?
- What is thermal radiation? (next class)
- What is the Doppler shift? (next class)

Goals for Learning

- How do light and matter interact?
  - Emission
  - Absorption
  - Transmission
  - Reflection/Scattering

Goals for Learning

- Does light behave like a wave or a particle?
  - Yes, light does behave like a wave or a particle
  - Light comes in isolated packages called photons. Each package has a wavelength, frequency, and speed.
  - Electric forces fluctuate like the water level on a disturbed pond as light propagates, which gives light some of the properties of a wave

Goals for Learning

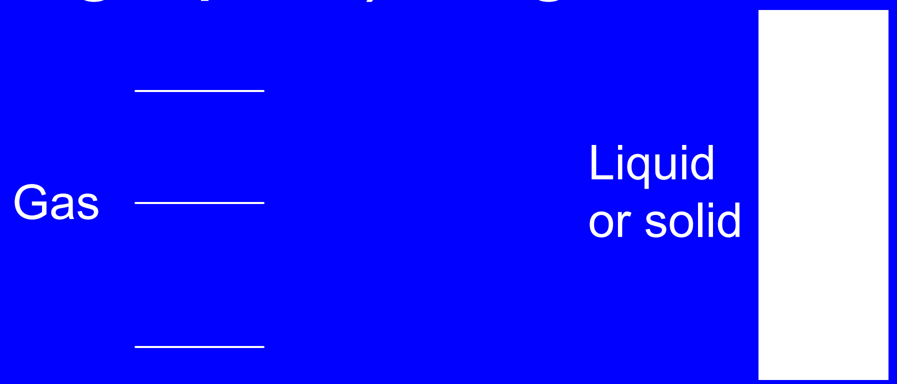
- How do energy levels affect the light emitted or absorbed by atoms?
  - Atoms can only absorb a photon if the photon's energy matches the difference between two energy levels in the atom
  - Atoms only emit photons whose energy matches the difference between two energy levels in the atom

Goals for Learning

- How do light and matter interact?
- Does light behave like a wave or a particle?
- How do energy levels affect the light emitted or absorbed by atoms?
- What is thermal radiation? (next class)
- What is the Doppler shift? (next class)

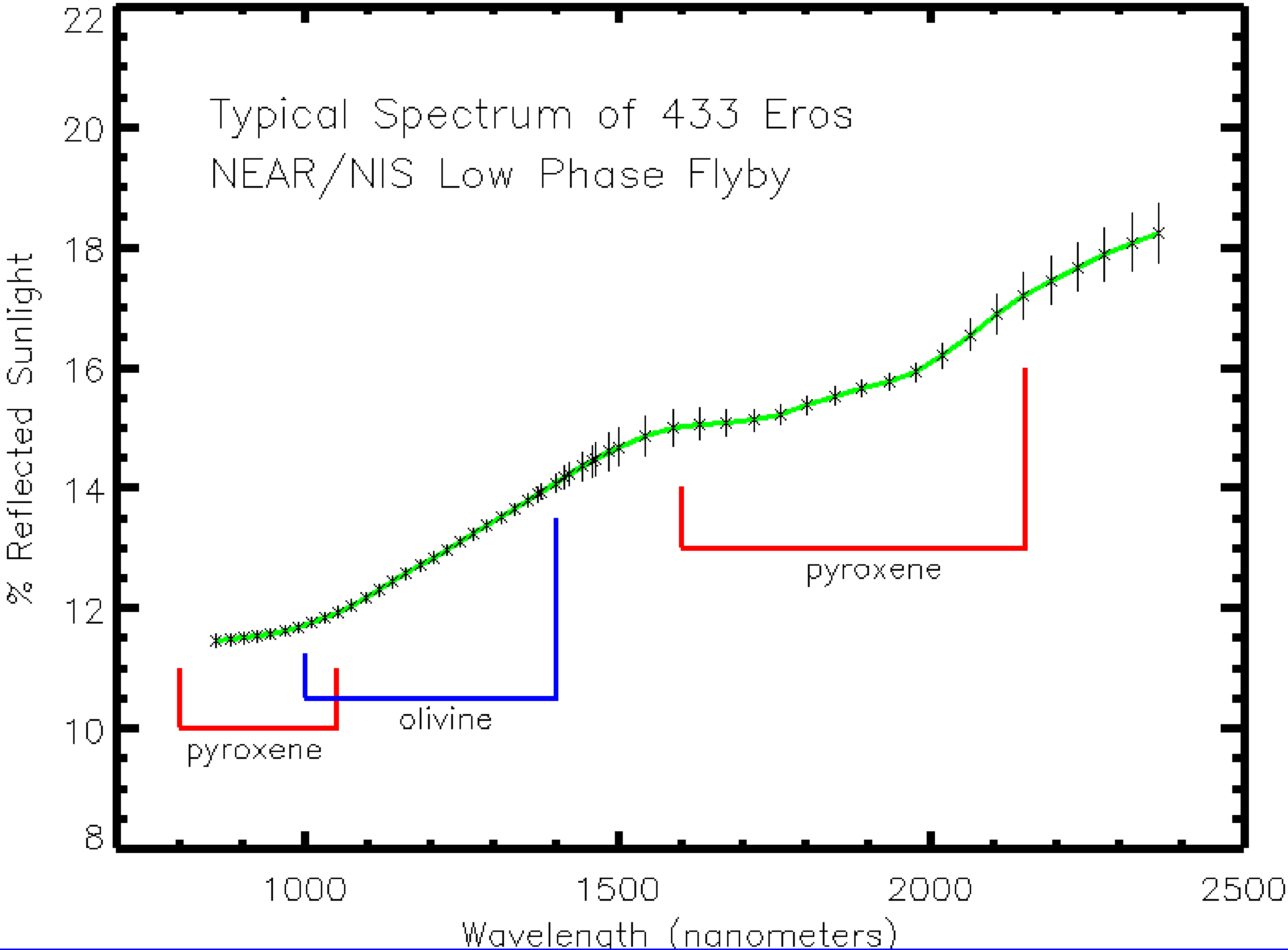
Liquids and Solids

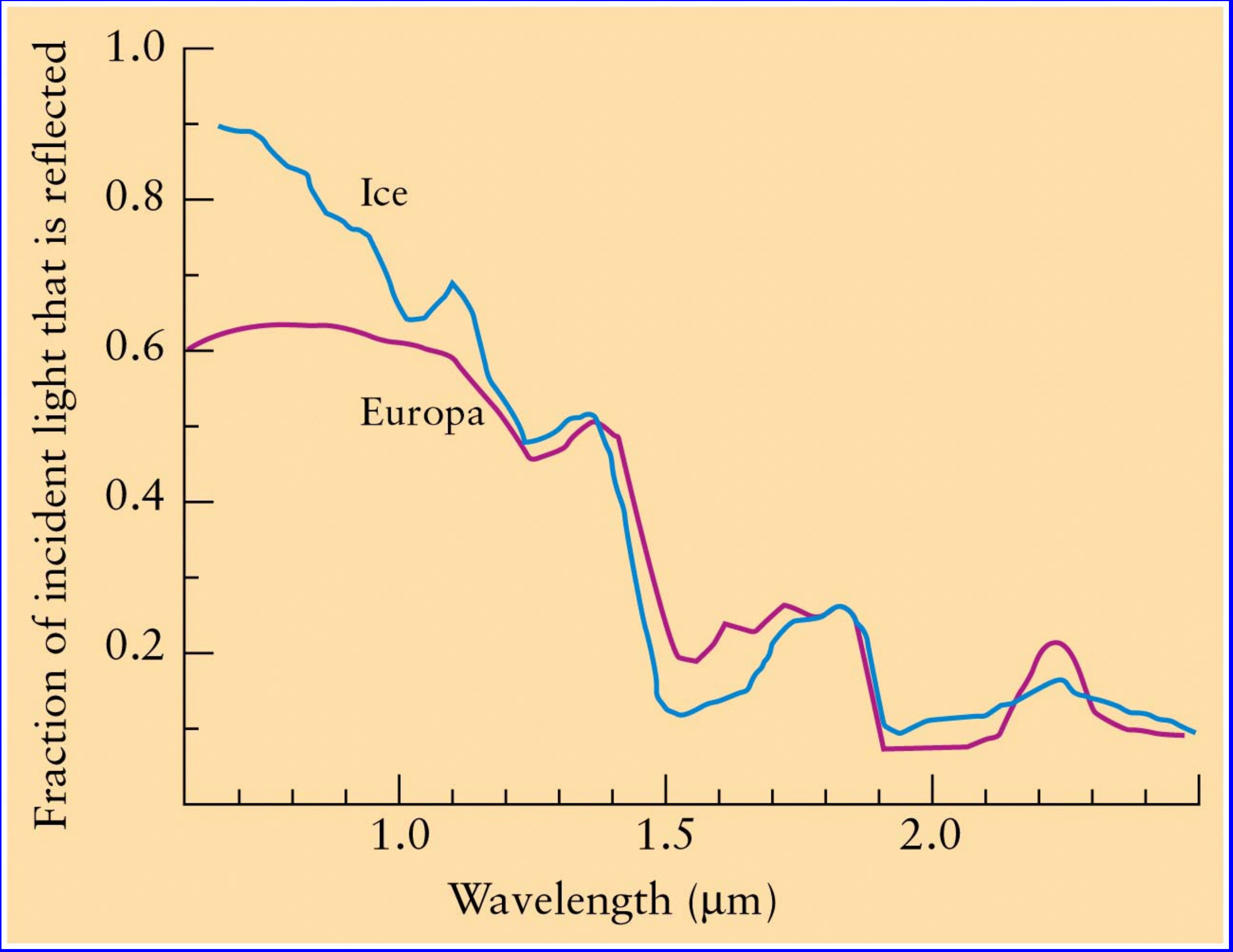
- Atoms don't interact in gases, but they interact a lot in liquids and solids.
- When atoms interact, their energy levels get distorted and spread out
- Liquids and solids don't have as distinctive spectra (fingerprint) as gases do



More Liquids and Solids

- Photons passing through a gas have very few interactions with the atoms in the gas
- Photons passing through a liquid/solid interact with lots of atoms as they bounce around
  - The interactions become more complex
- Reflectance spectrum, not emission or absorption spectrum, is most common for liquids and solids


Typical Spectrum of 433 Eros
NEAR/NIS Low Phase Flyby
% Reflected Sunlight
Wavelength (nanometers)
8
10
12
14
16
18
20
22
1000
1500
2000
2500
pyroxene
olivine
pyroxene



Fraction of incident light that is reflected
1.0
0.8
0.6
0.4
0.2
Ice
Europa
1.0
1.5
2.0
Wavelength (μm)

Spectrum -> Composition

- Spectra of moons, asteroids, and planets are the main way scientists determine what minerals are present on their surface
- Interpreting spectra is not easy or certain. Arguments are common.

Spectra summary (so far)

- Emission and absorption spectra are useful for gases (atmospheres). Features are narrow lines for atoms, wider bands for molecules.
- Reflectance spectra are useful for liquids/solids (surfaces). Less sunlight is reflected at wavelengths where the minerals in the surface absorb lots of light. Features are very broad, almost shapeless bands

What wavelength?

- Visible/UV = electron energy levels in atoms, useful for gases
- Infrared/microwave = rotation/vibration of molecules, useful for solid surfaces

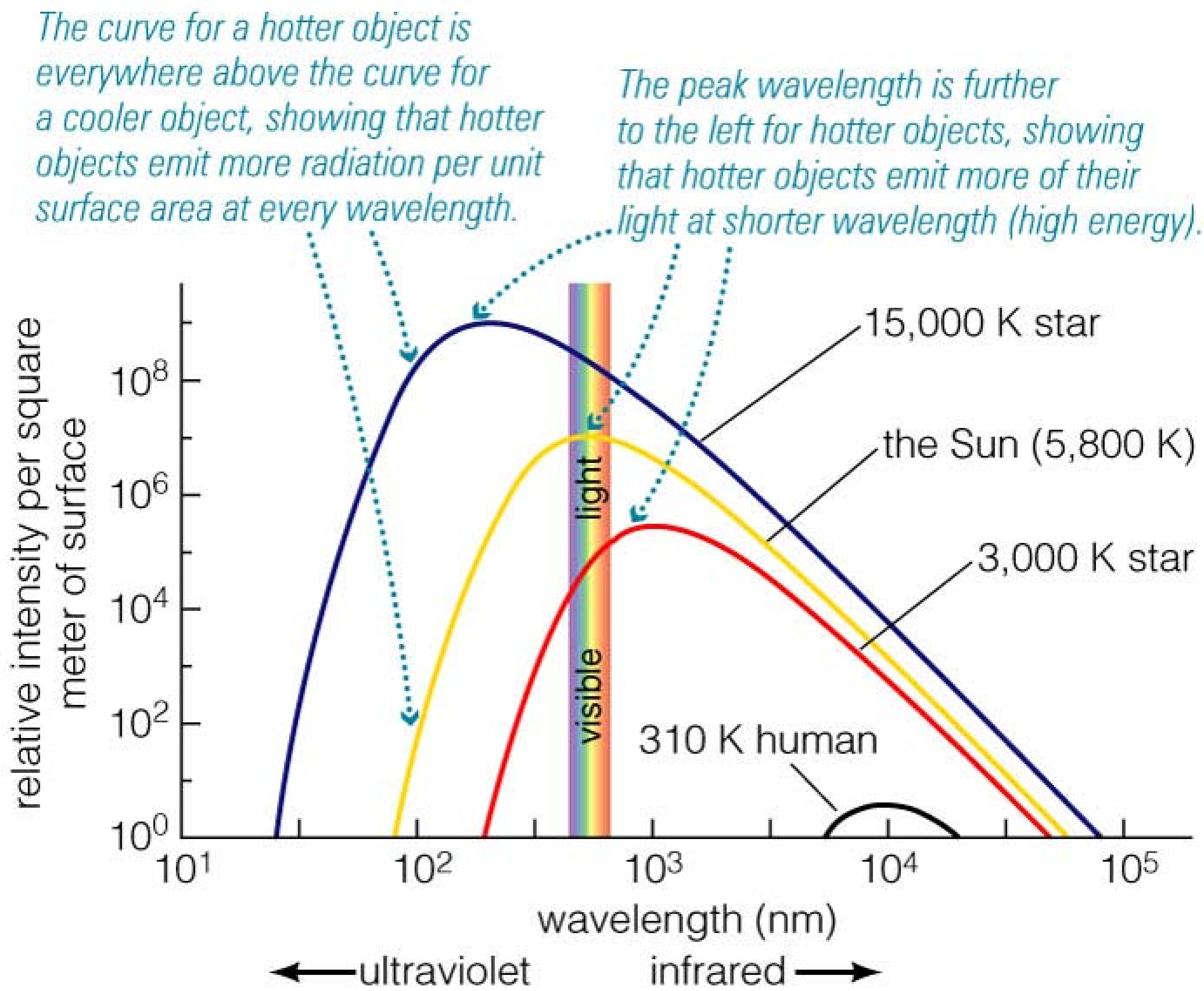
Thermal radiation

- Hot things emit light at a range of wavelengths
- This emission doesn’t have narrow lines, bands, or anything like that

- This is a different topic from the absorption and later re-emission of light that we’ve just been talking about

Thermal Radiation

- Photons end up with energies controlled by the thermal motions of atoms in the gas/liquid/solid
- This emission spectrum has a smooth, continuous shape that is fixed by the temperature. The spectrum depends only on temperature, nothing else
- Interactive Fig 5.19



Black body spectrum

First Law of Thermal Radiation

- Total power (all wavelengths) emitted per unit area = σT^4
- σ = Stefan-Boltzmann constant = 5.67×10^{-8} W / (m^2 K^4)
- Temperature must be in Kelvin

- A hot object emits more power at any wavelength than a cool object does at the same wavelength

Second Law of Thermal Radiation

- Thermal emission spectra have a hump, or a peak, corresponding to the wavelength at which the most power is emitted.
- This wavelength is called λ_{max}
- λ_{max} = 3 mm / (T in Kelvin)

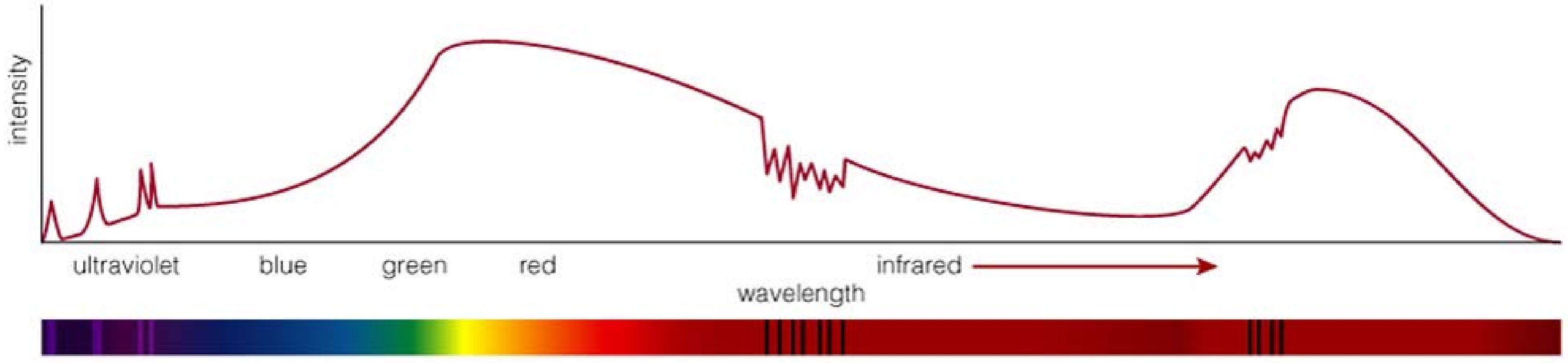
Star Colours

- Cool star, 3000K, looks red
- Sun, 5800 K, looks white
- Hot star, 15000 K, looks blue

- Humans, 300 K, λ_{max} = 0.01 mm, don't emit any visible light
- But humans do emit infra-red light (night-vision goggles)

A real spectrum

- What is the light source? Sun
- Light goes from Sun, through planet's atmosphere to surface, back through planet's atmosphere, then through Earth's atmosphere to reach us
- This gets messy



The spectrum of Mars

UV lines are due to a hot upper atmosphere
The bulge at visible wavelengths is due to reflection of light from the Sun
(Sun = 5800 K thermal emission)
Mars reflects more red light than blue light, so it looks red

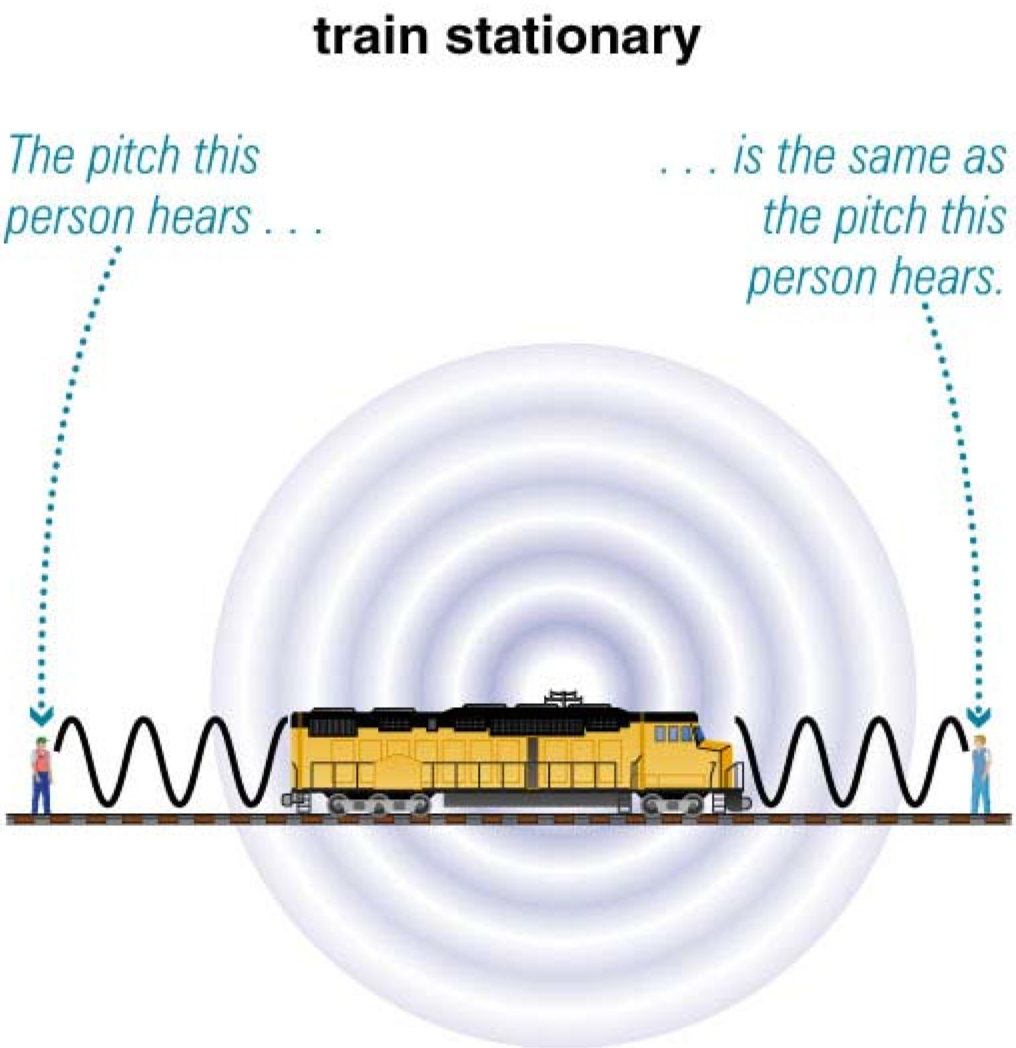
Carbon dioxide in the atmosphere causes absorption of infrared photons

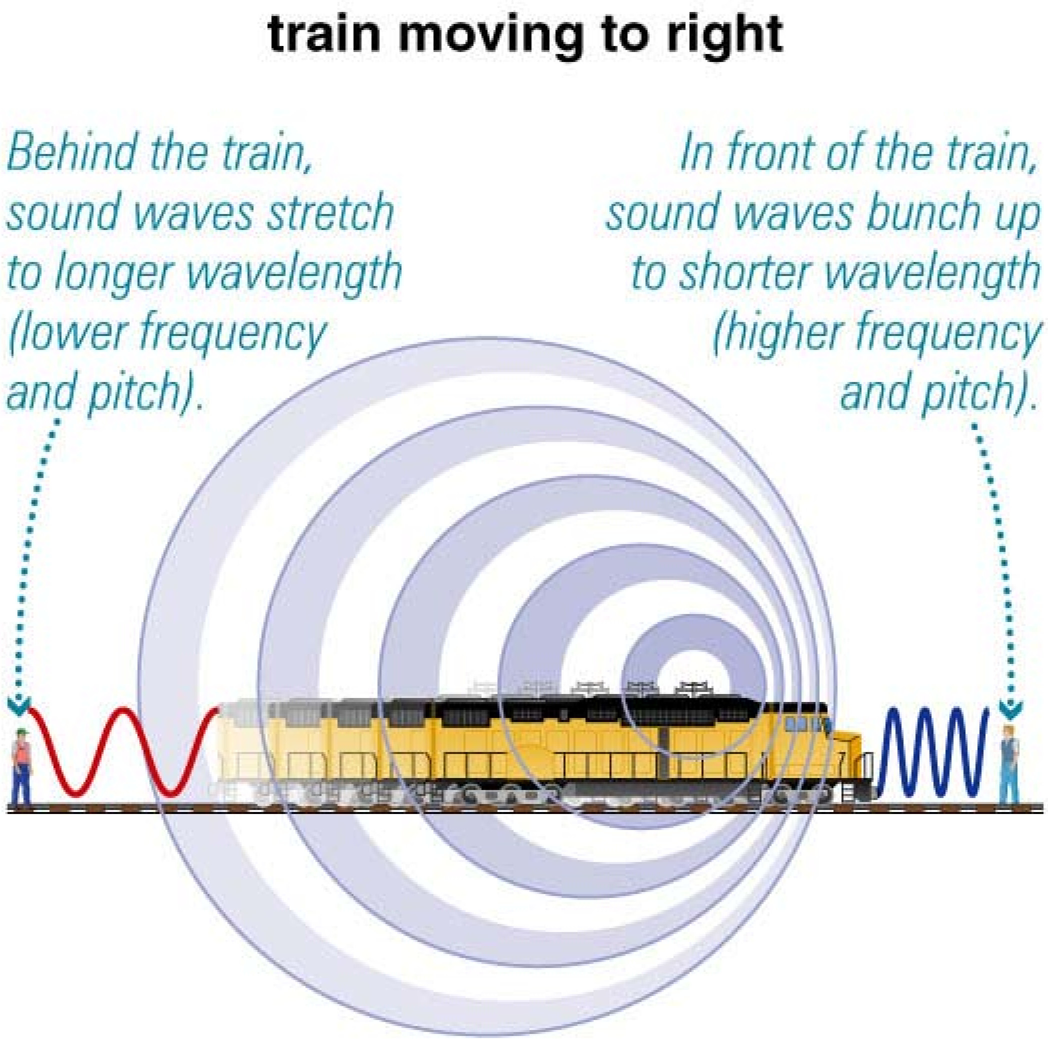
Mars emits thermal emission in the infrared (225 K) causing the second bulge

Doppler Shift

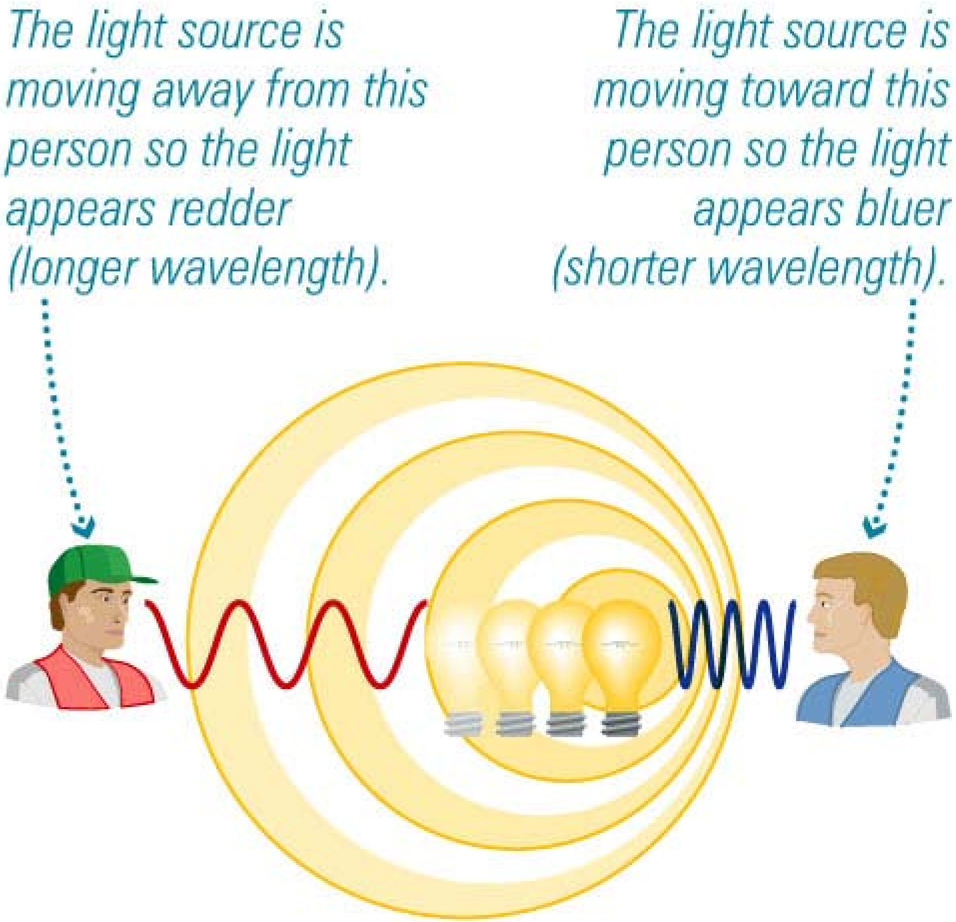
- Light is affected by motion of the object emitting the light
- Its wavelength (and frequency) change, but not its speed

- First an example with sound


train stationary
The pitch this person hears . . .
. . . is the same as the pitch this person hears.


train moving to right
Behind the train, sound waves stretch to longer wavelength (lower frequency and pitch).
In front of the train, sound waves bunch up to shorter wavelength (higher frequency and pitch).

light source moving to right



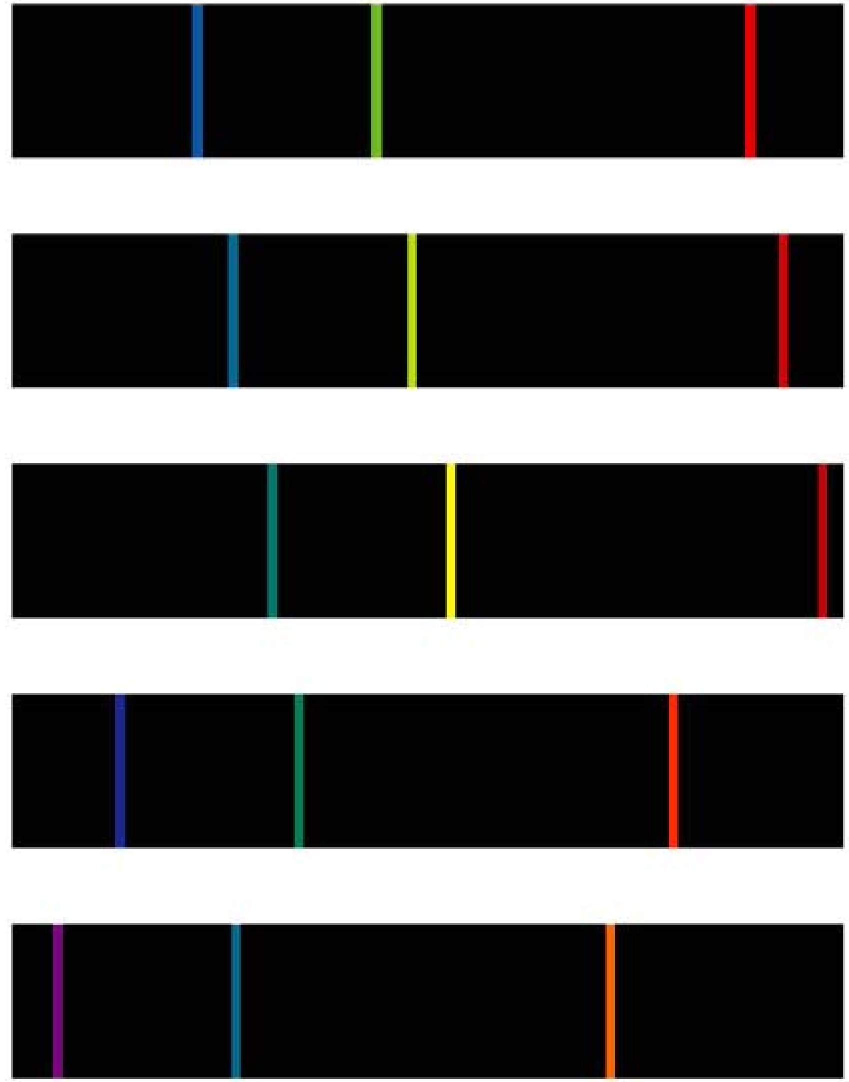
Laboratory spectrum
Lines at rest wavelengths.

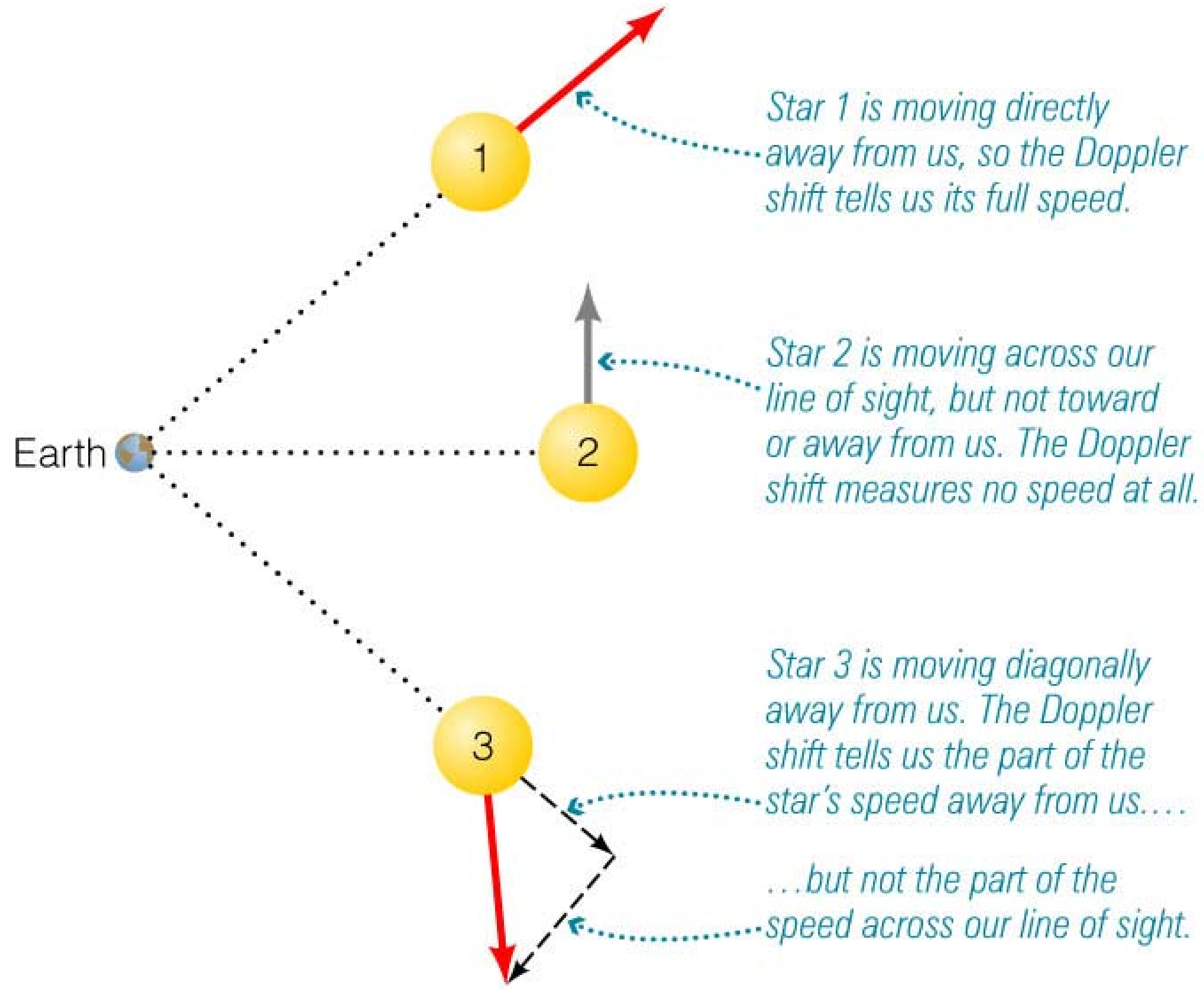
Object 1 *Lines redshifted: Object moving away from us.*

Object 2 *Greater redshift: Object moving away faster than Object 1.*

Object 3 *Lines blueshifted: Object moving toward us.*

Object 4 *Greater blueshift: Object moving toward us faster than Object 3.*





Star 1 is moving directly away from us, so the Doppler shift tells us its full speed.
Star 2 is moving across our line of sight, but not toward or away from us. The Doppler shift measures no speed at all.
Earth
1
2
3
Star 3 is moving diagonally away from us. The Doppler shift tells us the part of the star's speed away from us....
...but not the part of the speed across our line of sight.

Doppler Shift

- $v / c = (\lambda_{shifted} - \lambda_{rest}) / \lambda_{rest}$
- v = speed of emitting object
- c = speed of light
- λ_{rest} = usual wavelength of this spectral line
- $\lambda_{shifted}$ = shifted wavelength of this spectral line

Doppler Shift

- Doppler shift tells astronomers how other stars are approaching the Sun or moving away from the Sun
- Also reveals the rotation of other stars and planets

Goals for Learning

- What is thermal radiation?
- What is the Doppler shift?

Goals for Learning

- What is thermal radiation?
  - The motion of molecules leads to emission over a broad range of wavelengths
  - This emission depends only on the object's temperature
  - λ_{max} = 3 mm / (T in Kelvin)

Goals for Learning

- What is the Doppler shift?
  - The wavelength and frequency of light change if the object emitting the light is moving
  - $v / c = (\lambda_{shifted} - \lambda_{rest}) / \lambda_{rest}$

- http://upload.wikimedia.org/wikipedia/en/6/6a/Mirror.jpeg
- http://teachart.msu.edu/pila/images/newton.gif
- http://library.thinkquest.org/C001377/prism_combine.jpg
- http://nssdc.gsfc.nasa.gov/planetary/image/near_eros_spectrum.gif
- http://homepage.smc.edu/balm_simon/IMAGES/astro%201b/solar_system_intro/europa_spectrum.jpg