Announcements

April 11

Quiz 1 on April 18: Sections are operating this week

Clickers seem to be magically associating with students in all but a few cases

I have permission codes

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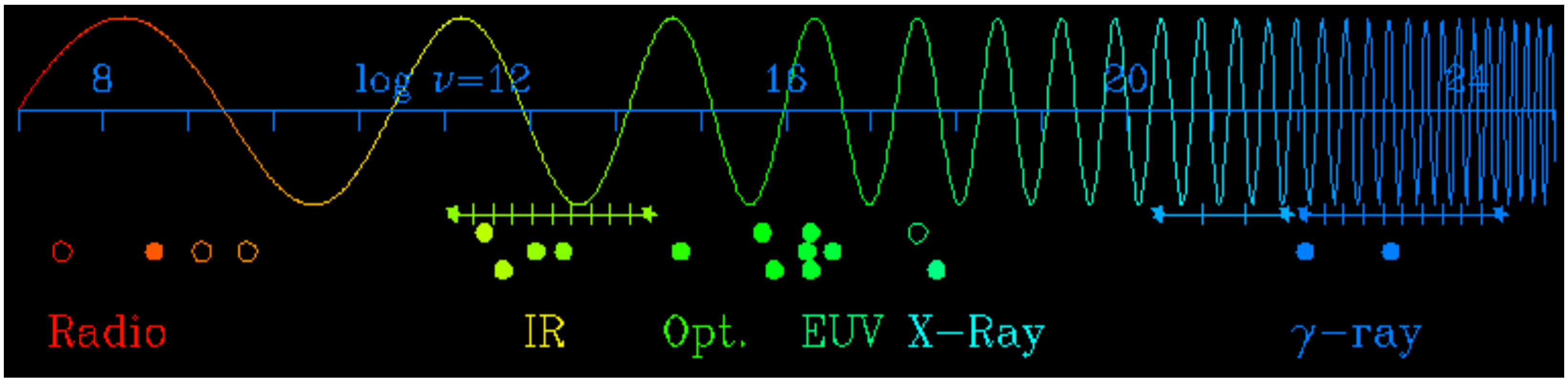
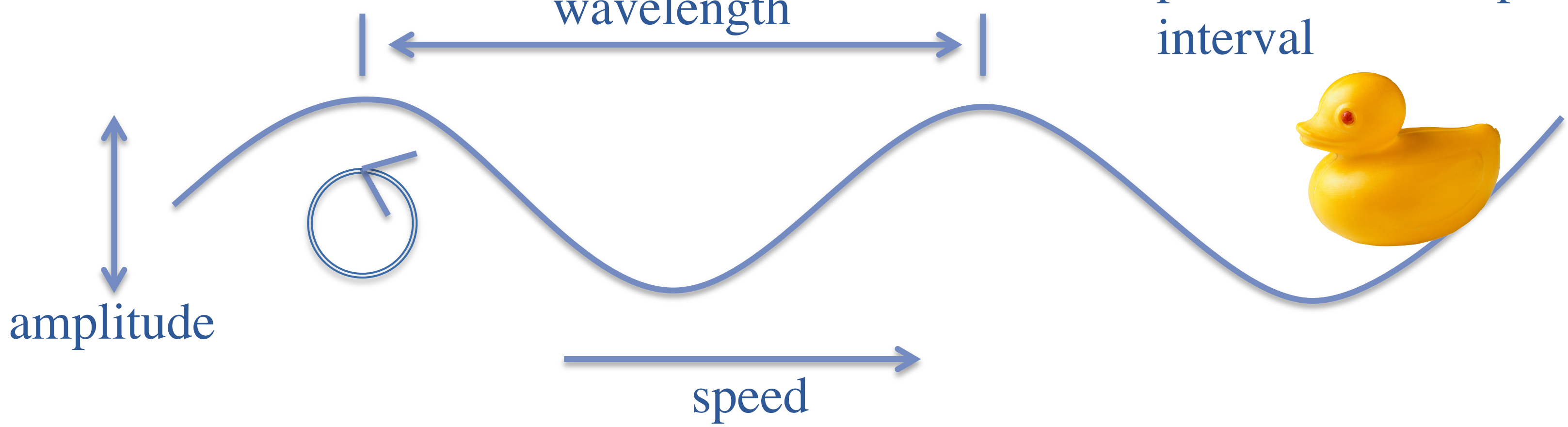
Let there be Electromagnetic Radiation



Light, radio waves, x-rays, ultra-violet radiation are all forms of a type of wave composed of oscillating electric and magnetic fields

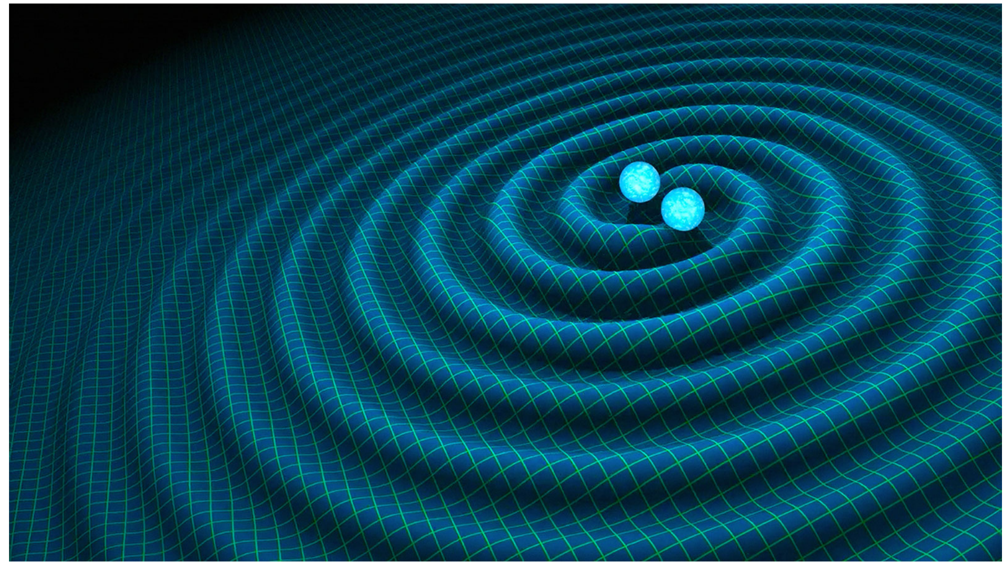
Waves

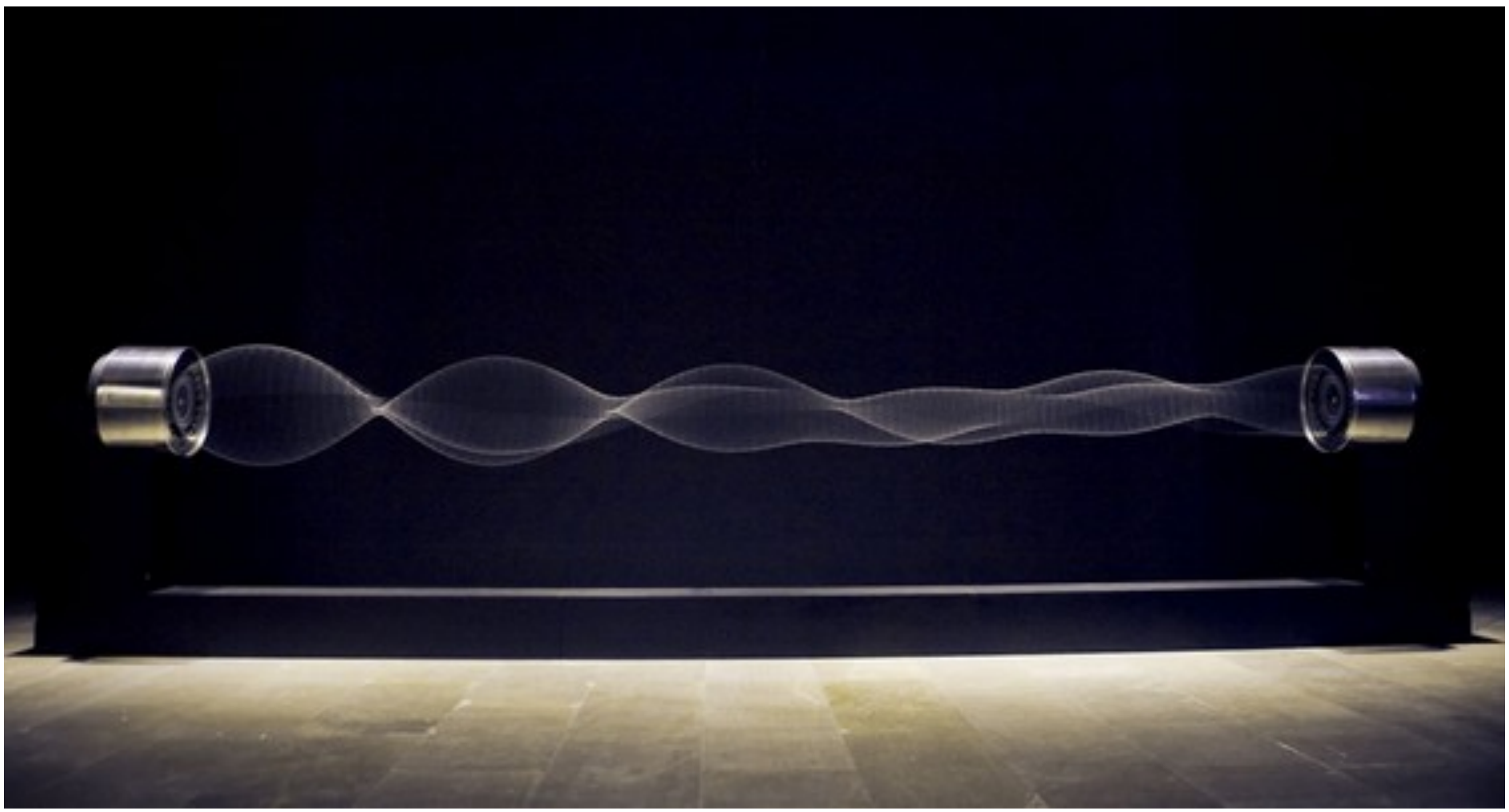
f = # of times a wave crest passed the duck per time interval



Water waves. They are characterized by their amplitude (height) and three related quantities: wavelength (λ), frequency (f) and speed (s)

$$s = f \times \lambda \quad \text{and} \quad \lambda = s/f$$

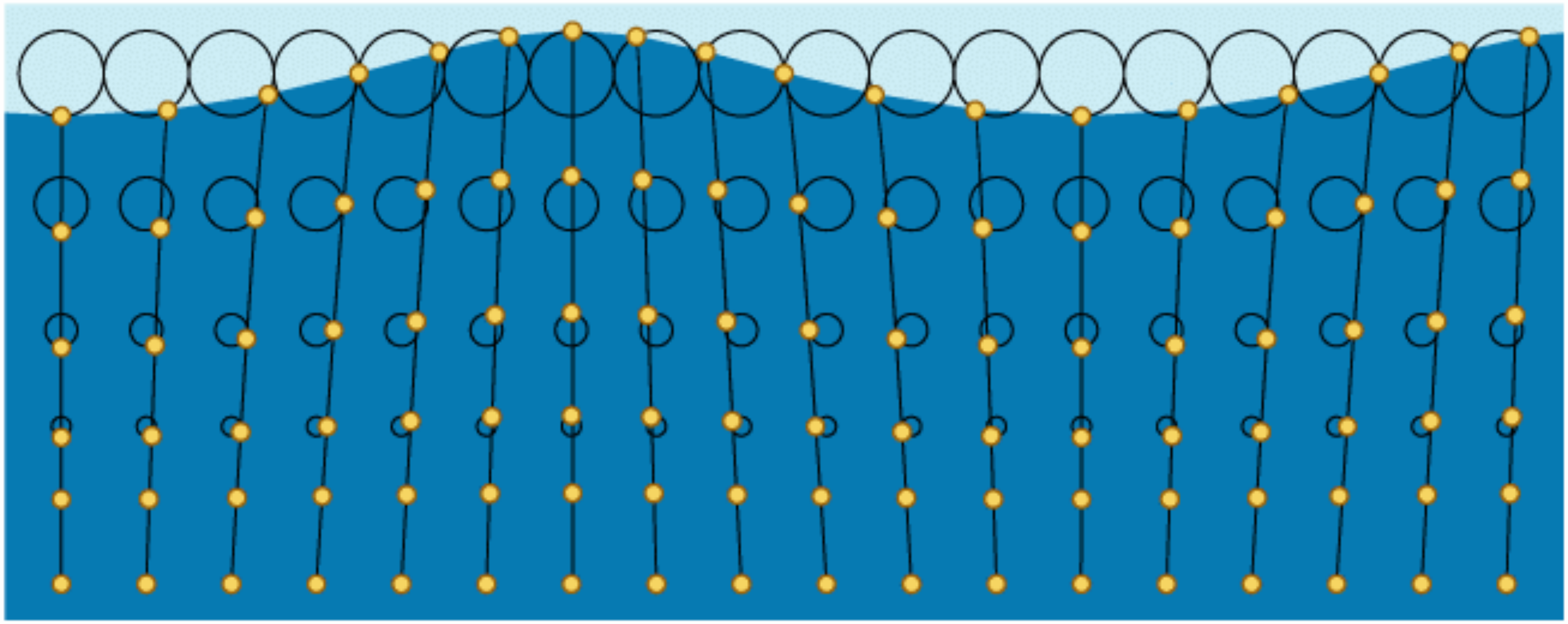




- Wavelength has units of distance
- Frequency, the number of times the boat goes up and down per unit time, has units of 1/time, e.g. 1/second.
- Speed has units of distance/time.

Q. What moves at the wave speed?

ENERGY

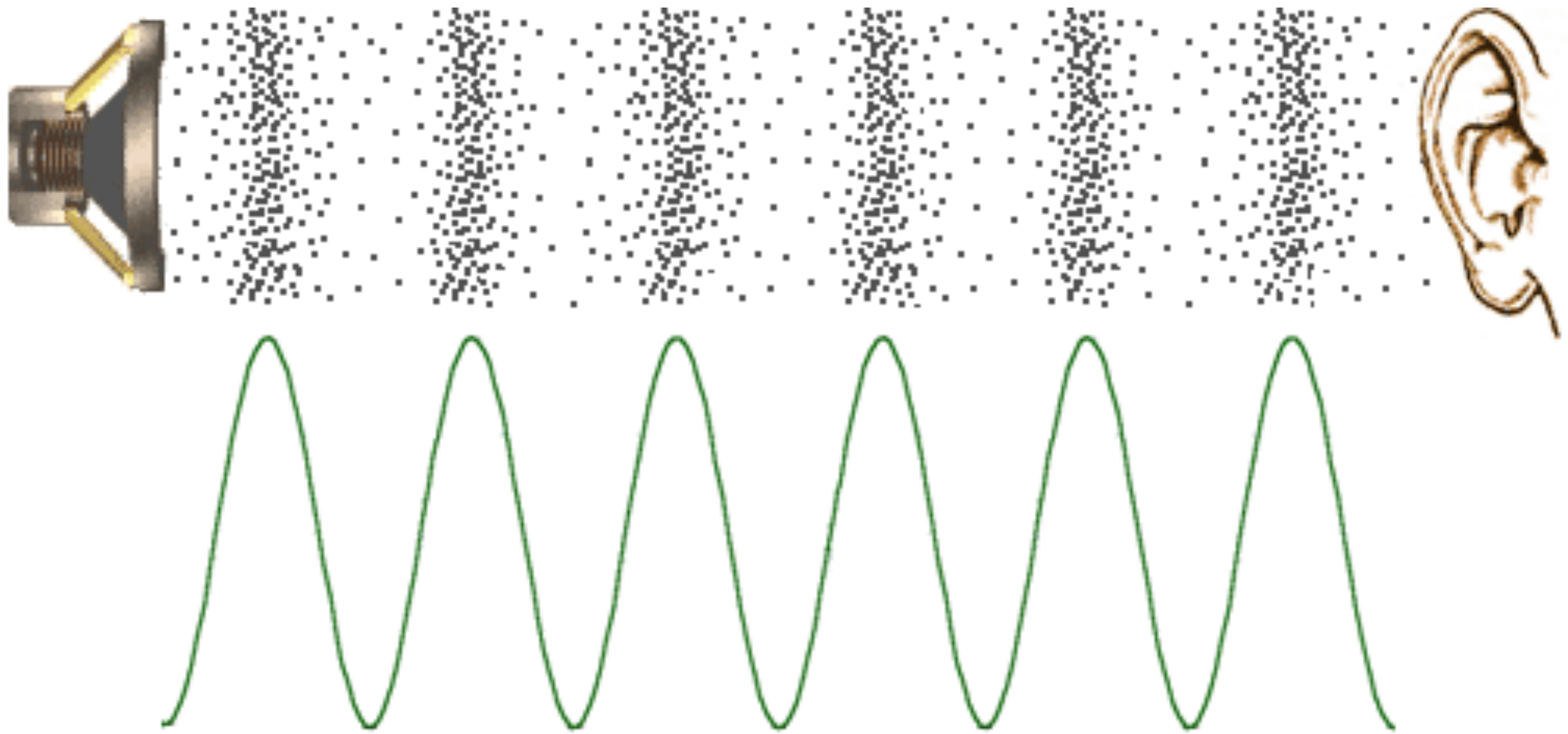


The medium supporting the wave does not move (much), the wave travels through the medium

Other waves

- There are other kinds of waves. Ocean waves are sometimes called `gravity' waves.
- Sound waves are density/pressure waves

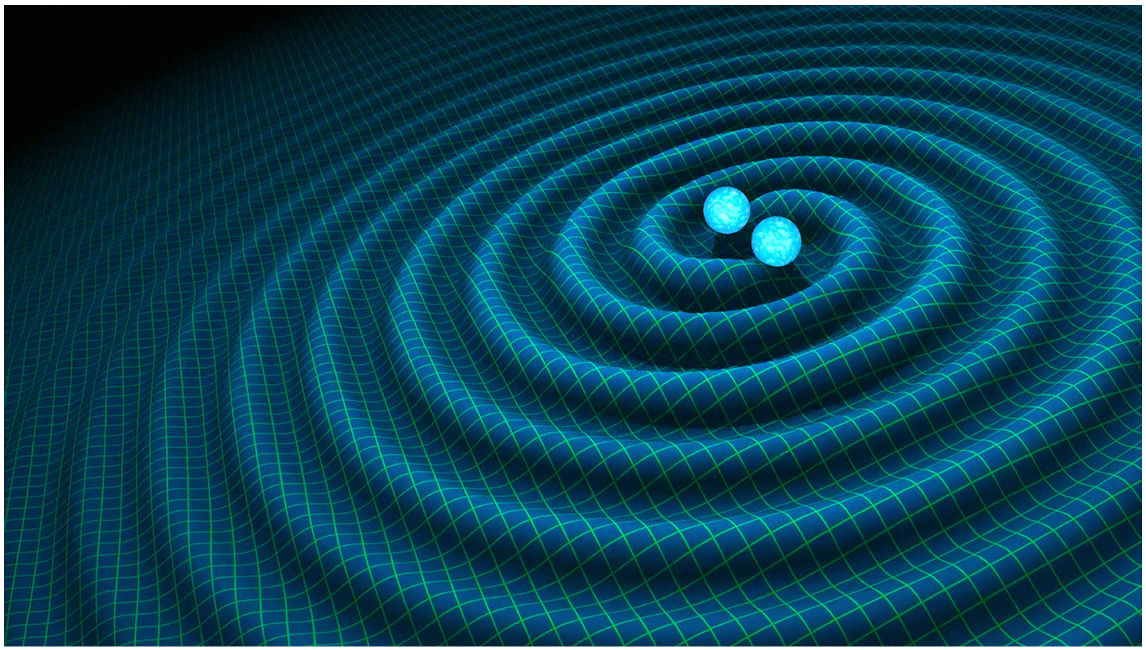
Sound Waves



Sound waves

- Sound waves only travel at 1000 ft/sec in air. This is the basis of the old thunderstorm trick.
  - The light from lightning travels at the speed of light (it arrives almost instantaneously).
  - Thunder is a pressure wave triggered by the rapid expansion of the heated air near the lightning bolt. This travels at the speed of sound in air.
- So, for every second delay between seeing the lightning and hearing the thunder, the storm is 1000ft away (5280 feet/mile)

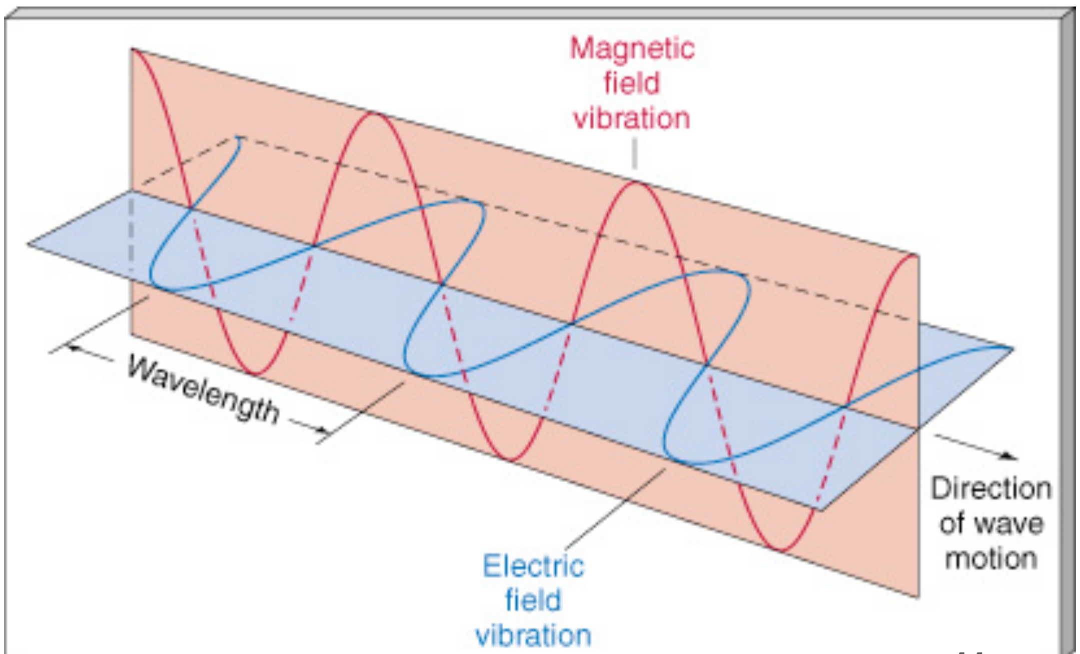
Gravitational Waves



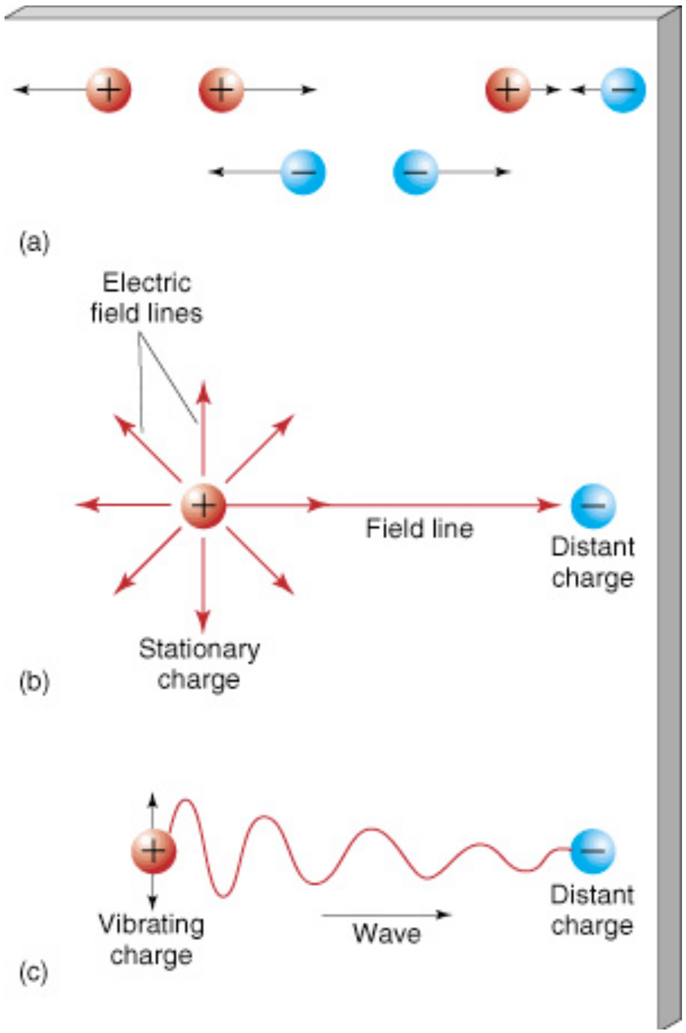
In 2016, for the first time we made the direct detection of "gravitational waves" which are spatial and temporal distortions in the space-time fabric of the Universe

E-M Radiation

- Light is a type of wave composed of oscillating electric and magnetic fields propagating through space.



E-M radiation



- This diagram is not quite right, but gives you the idea.
- Any charged particle has a radial electric field extending to infinity. If the charge moves, the center of the field has changed.
- This information propagates outward as a `kink' in the field lines. This changing electric field induces a changing magnetic field.

It's the Law

- The varying electric and magnetic fields move outward at the speed of light.
- In a vacuum, this speed is:

$$c = 300{,}000 \text{ kilometers/second}$$

$$c = 3 \times 10^5 \text{km/s} = 180{,}000 \text{ miles/second}$$

Lookback Time

- Because of the finite speed of light, we see all objects with a time delay.
- The Sun we see as it was 8.3 minutes in the past.
- The nearest big galaxy, the Andromeda galaxy is two million light years away -- we see it as it appeared two million years ago.

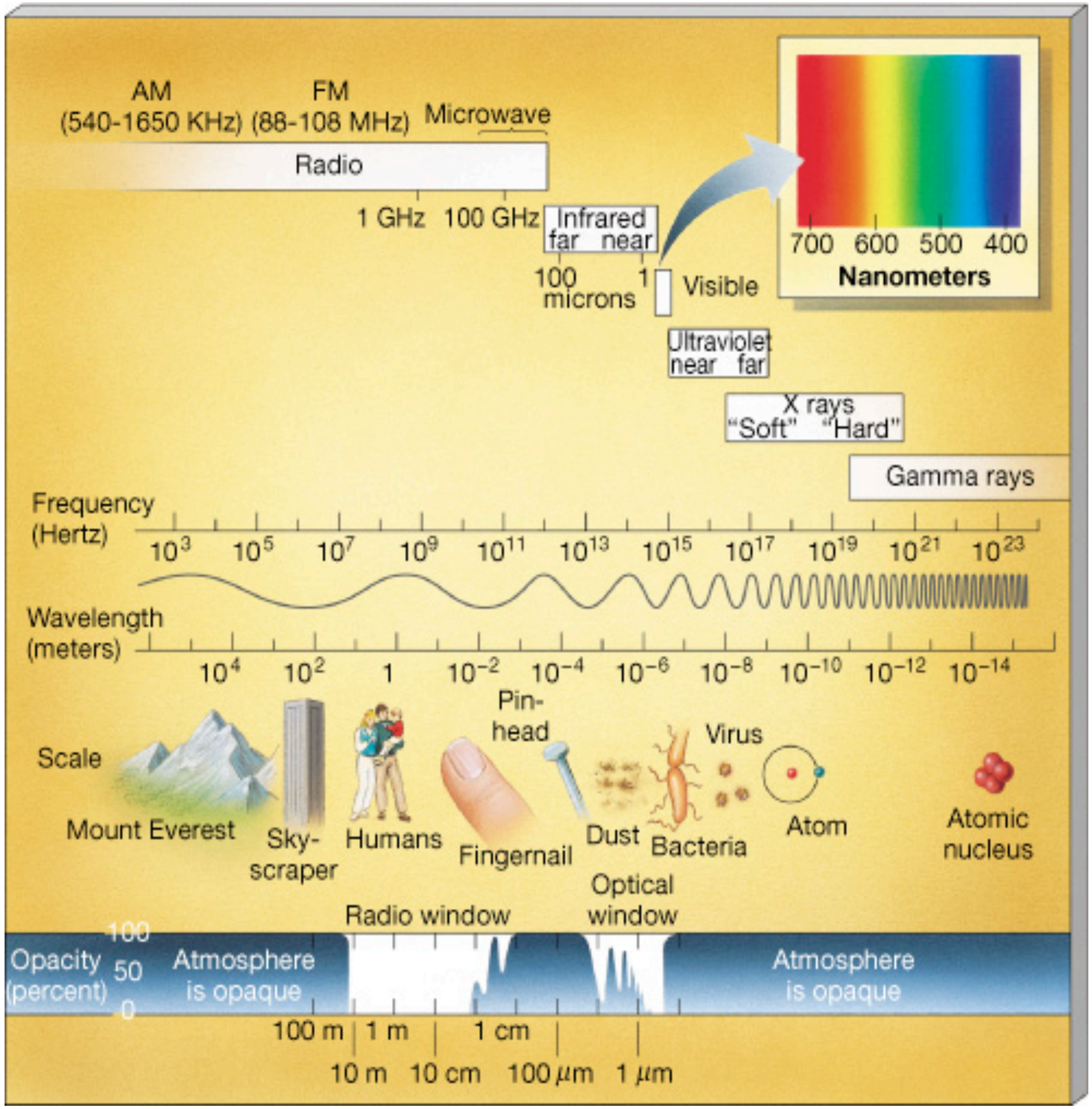
Lookback Times

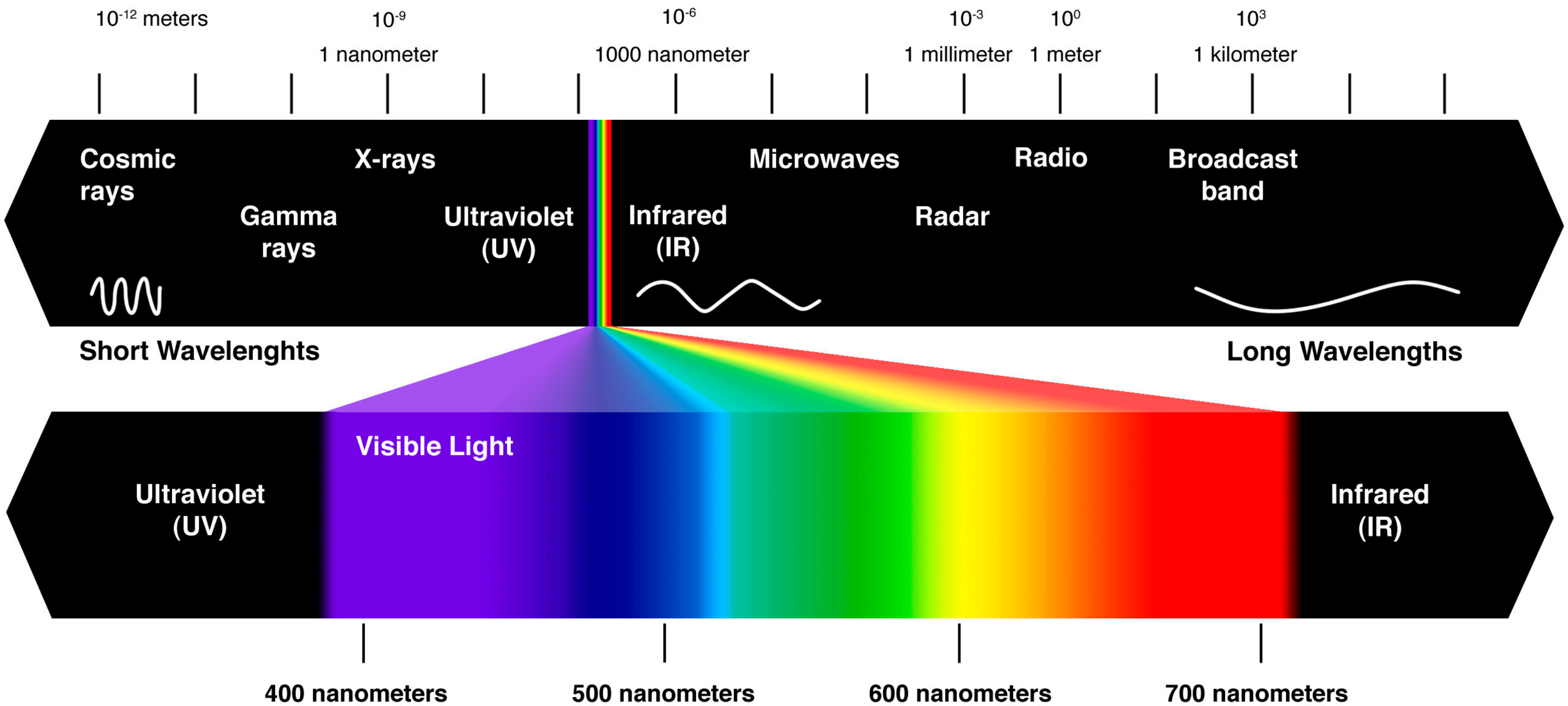
In the Hubble Ultra Deep Field, some of the objects have lookback times > 12 billion LY. This provides an opportunity to view the Universe at different times in its evolution (!)

E-M Radiation

- Light is only one form of E-M radiation. There are different names for E-M radiation with different wavelength (or frequency).

X-rays
Ultraviolet
Microwaves
Infrared
Radio


AM
(540-1650 KHz)
FM
(88-108 MHz)
Microwave
Radio
1 GHz
100 GHz
Infrared
far near
100 microns
1
Visible
700 600 500 400
Nanometers
Ultraviolet
near far
X rays
"Soft" "Hard"
Gamma rays
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23}
Wavelength (meters)
10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14}
Scale
Mount Everest
Sky-scraper
Humans
Fingernail
Pin-head
Dust
Bacteria
Virus
Atom
Atomic nucleus
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Atmosphere is opaque
100 m
1 m
1 cm
10 m
10 cm
100 µm
1 µm



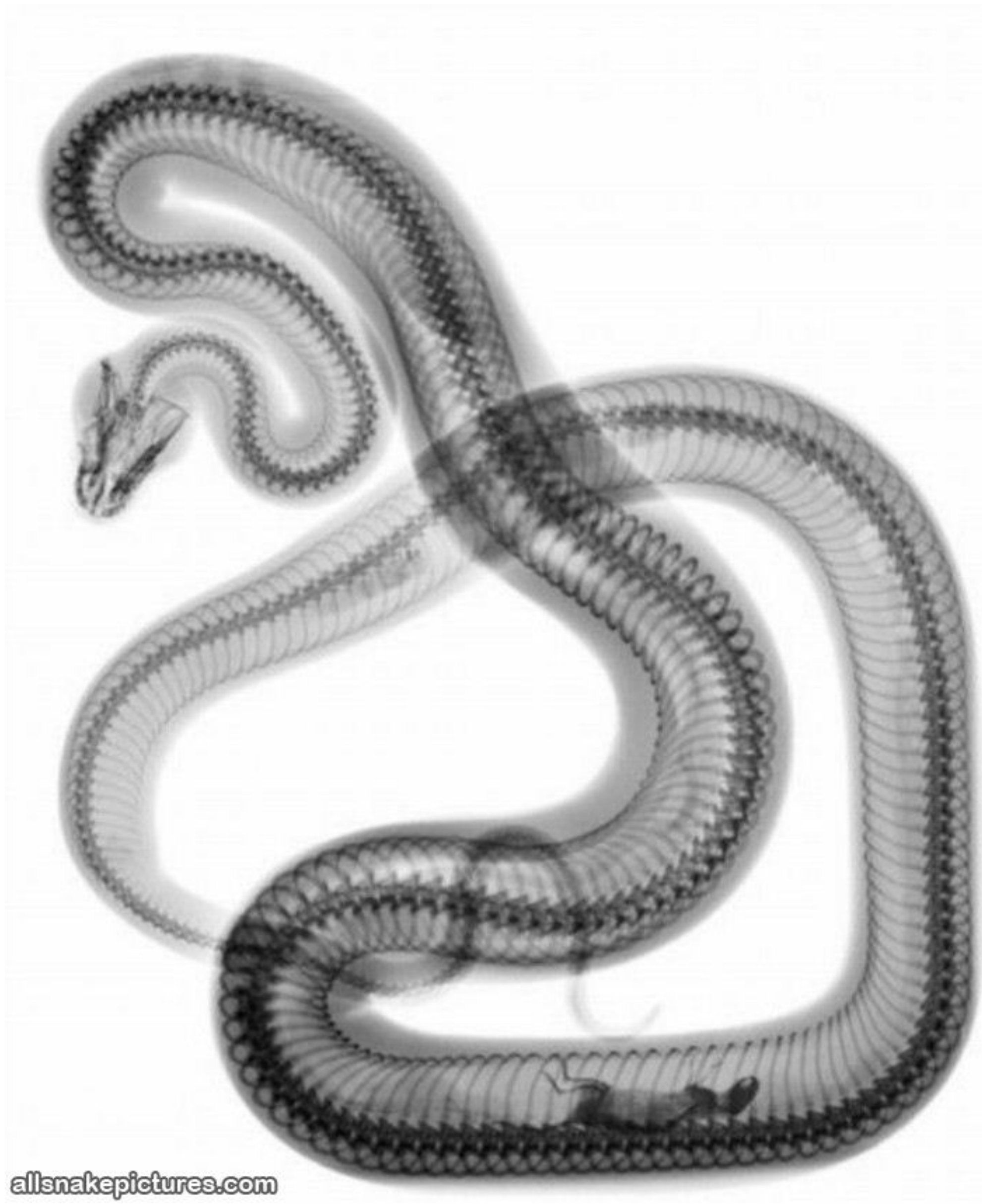
Wavelength increases, frequency decreases, energy decreases

E-M Radiation (EMR)

- EMR with wavelength= 10^{-7} m can be detected by cells in the retina of your eye.
- EMR between 0.5 meters and 1000 meters is used to transmit radio and television signals.
- EMR with wavelength ~10^{-3}m (*microwaves*) is absorbed by water molecules (i.e. the energy of the EMR is transferred to the water molecules, they heat up and your burrito in the microwave oven gets warm).

More EM Radiation

- EMR with wavelength ~10^{-5}m (*infrared*) can be sensed with your skin (but not eyes)
- EMR with wavelength ~10^{-8}m (*ultraviolet*) activates pigments in your skin which causes you to tan (and triggers skin cancer).
- EMR with wavelength ~10^{-9}m (*X-rays*) can penetrate flesh but not bones.


allsnakepictures.com

Q. What is the wavelength of 810 Kilohertz on your AM dial?

\`kilo' > 1000; \`hertz' > 1/second

$$\lambda = \frac{c}{f} = \frac{3 \times 10^5}{810{,}000} \frac{\text{km}/\cancel{\text{sec}}}{1/\cancel{\text{sec}}} = 0.37\text{km} = 1214\text{ft}$$

More Waves: Energy

- Radio wave, light, Infrared radiation, UV and X-rays are all E-M radiation and travel at the speed of light .
- They differ in ***wavelength*** and ***frequency.***
- Each wavelength of E-M radiation also has a unique Energy given by:

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

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

- *h* is called `Planck's constant. For a given wavelength or frequency of E-M radiation this is the `unit' energy. This is not the same as the intensity of the radiation, put rather it is the energy of a single `***photon'*** of a given wavelength

- h=6.626068 x 10^{-34}Joules·sec (=m^2kg/s)

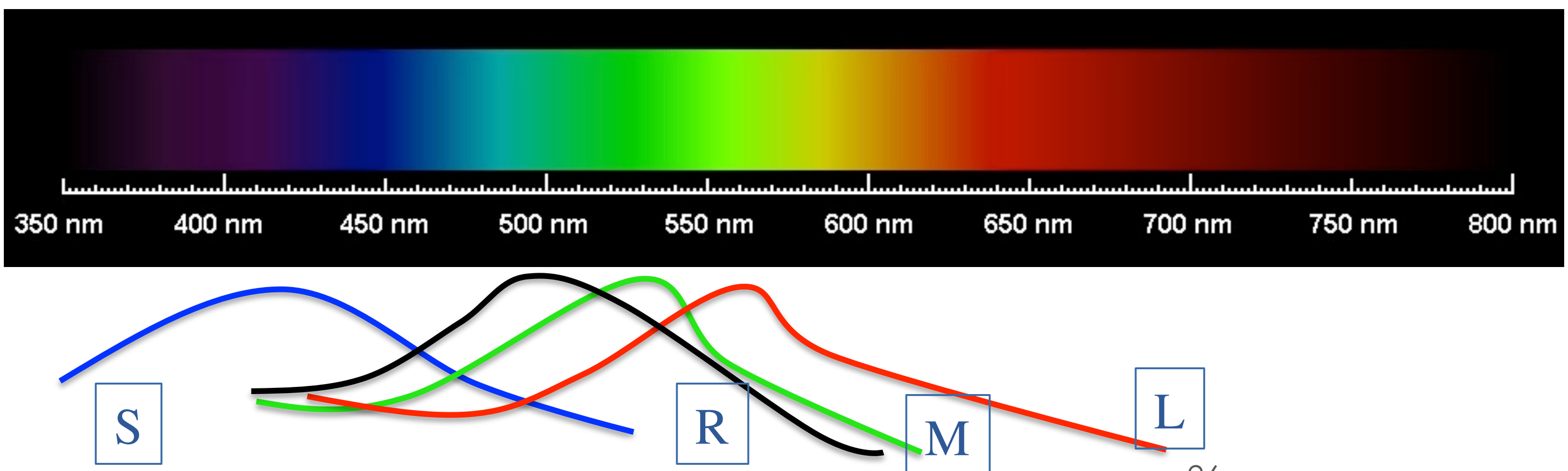
Photons

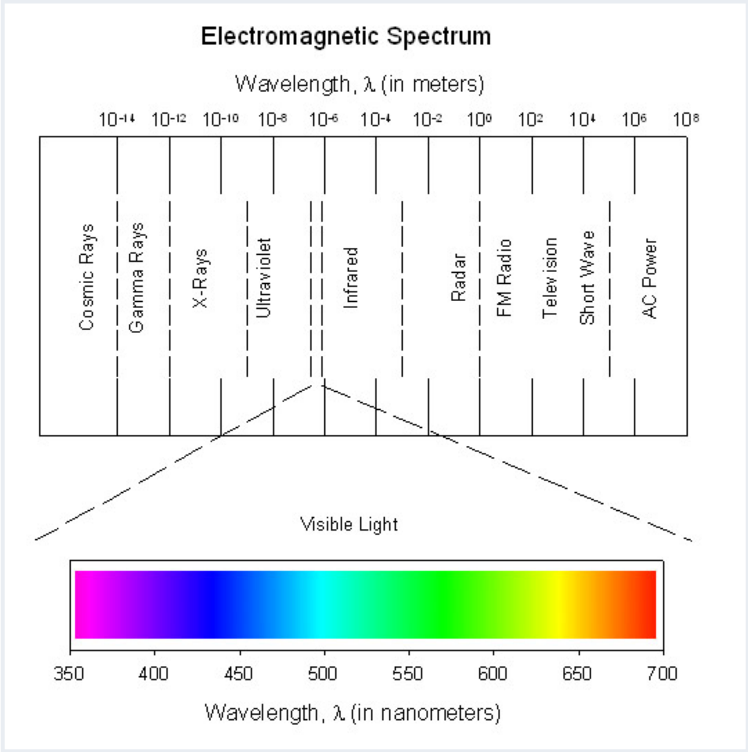
- The photon model of E-M radiation is different than the wave model.
- A photon is like a tiny E-M bullet with characteristic wavelength, frequency and energy.
- Both models are right and this is the source of many discussions on the wave-particle duality of light.

Visible Light: Details

The shortest wavelength of E-M Radiation our eyes can sense is 3.5×10^{-7} meters (350 nm) which is interpreted by our brain as blue light. The longest wavelength our eyes are sensitive to is 700nm -- this is interpreted as red light

Visible continuous spectrum

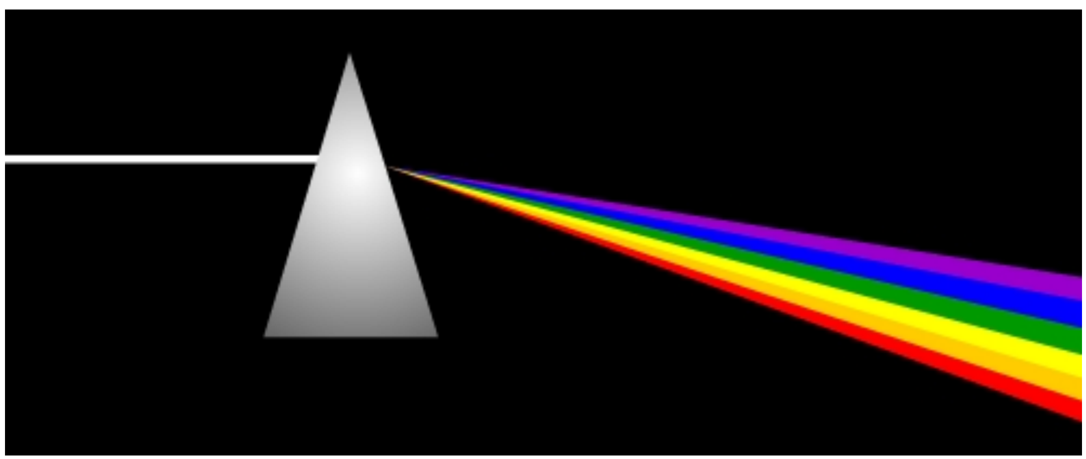




- Note that the visible part of the spectrum is only a small fraction of the E-M spectrum.
- If a source emits all the wavelengths of the visible part of the E-M spectrum, our brain interprets this as <u>white light</u>.

White Light

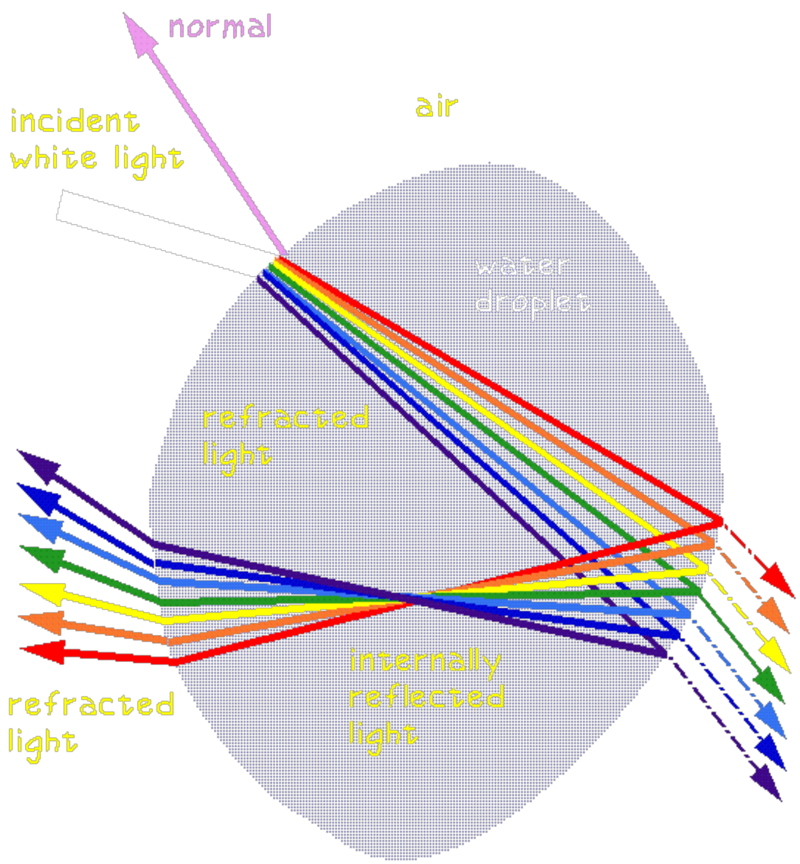
This can be demonstrated in many ways. Newton used a prism and wrote out the first discussion of light, colors and waves.



White Light

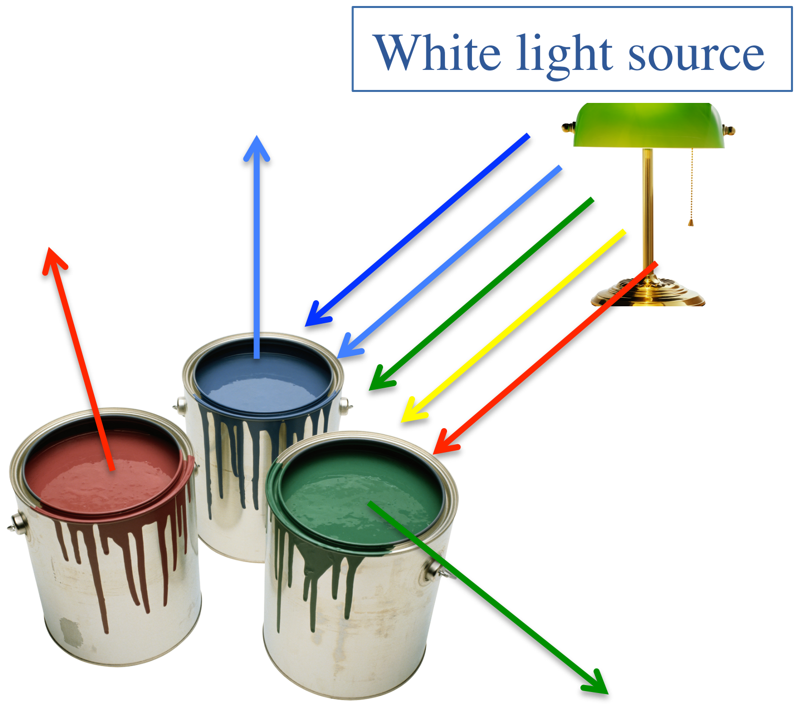
Nature provides a beautiful means of dispersing white light into its constituent colors.

Rainbows



Rainbows are caused when sunlight enters raindrops and reflect off the back surface. Different wavelengths of light travels at different velocity in the drop and are bent different amounts and therefor separated on the sky

Double rainbows occur for two reflections in the raindrops (note the reversed order of the colors).



Red (blue, green) paint absorbs all color except red (blue, green) which it reflects

- Most colors we see are in reflected light. The different colored objects in the room are reflecting come components of the white light and absorbing the rest.
- Black shirt absorbs all wavelengths
- Blue reflects blue wavelengths, absorbs the rest -- a blue shirt demonstrates that white light contains blue light.

Clicker Quiz

Q. What wavelengths are reflected by a white shirt?

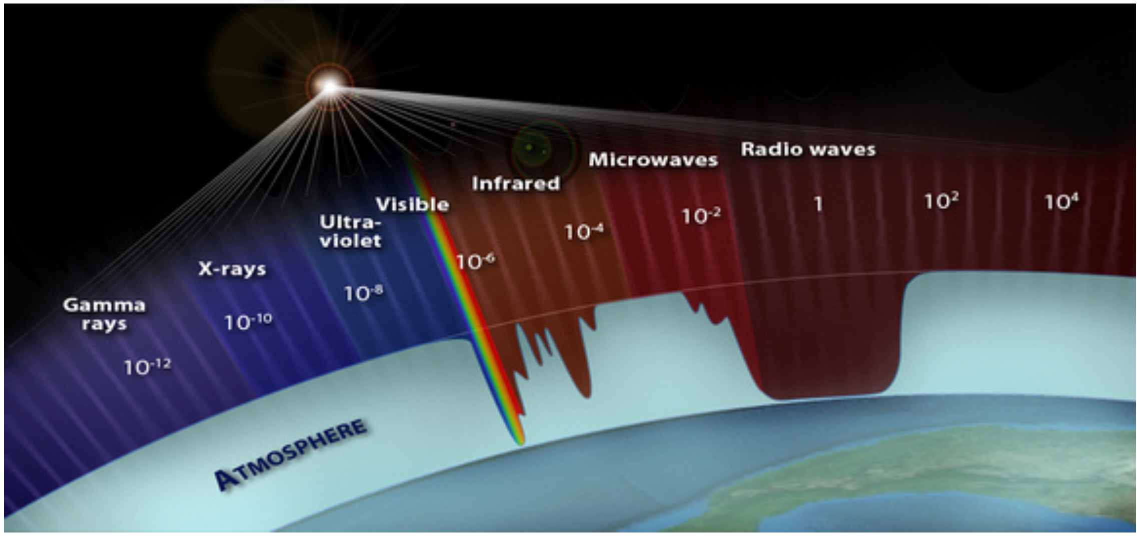
A. All wavelengths of visible light
B. “white” light with a wavelength just shorter than blue light
C. Only wavelengths between green light and the ultraviolet
D. It depends on the temperature of the white shirt

Clicker quiz

Q. What color is a yellow banana slug illuminated with blue light?

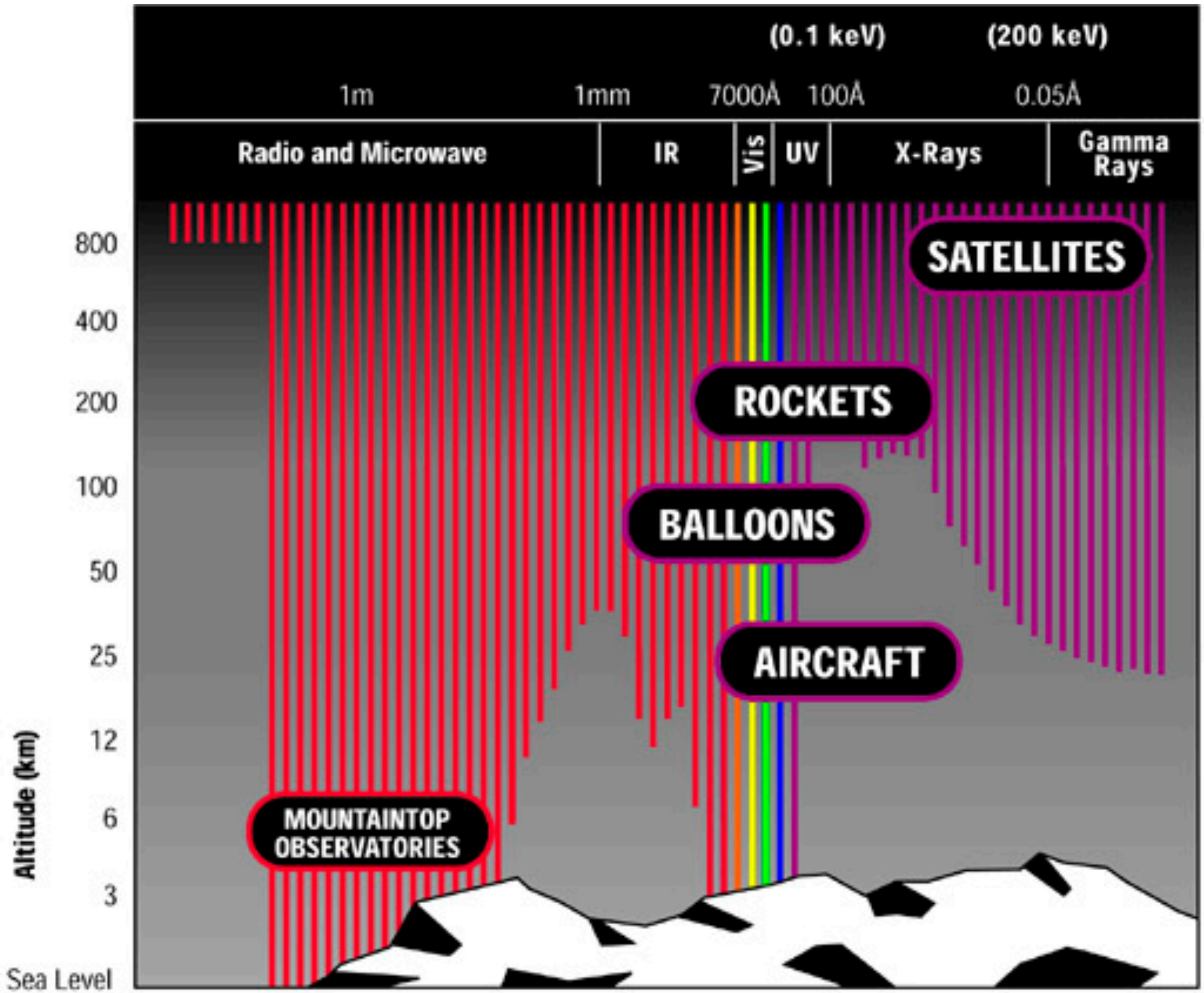
A. Black
B. Yellow
C. Blue
D. Green (yellow combined with blue)

Atmospheric Windows



- The atmosphere only passes certain `spectral windows' (either way).
- The atmosphere is transparent to visible light (do you think it is a coincidence that our eyes are sensitive to visible light?), some parts of the radio and some parts of the Infrared.

- Fortunately, the atmosphere is opaque to UV, X-rays and gamma rays. All are harmful to humans and other animals and plants.
- The Infrared between 10 and a few 100 microns is also absorbed by the atmosphere.
- To make observations of the Universe at these wavelengths requires going into space. Satellites, rockets and balloons all provide platforms.


(0.1 keV)
(200 keV)
1m
1mm
7000Å
100Å
0.05Å
Radio and Microwave
IR
Vis
UV
X-Rays
Gamma Rays
SATELLITES
ROCKETS
BALLOONS
AIRCRAFT
MOUNTAINTOP OBSERVATORIES
Altitude (km)
800
400
200
100
50
25
12
6
3
Sea Level

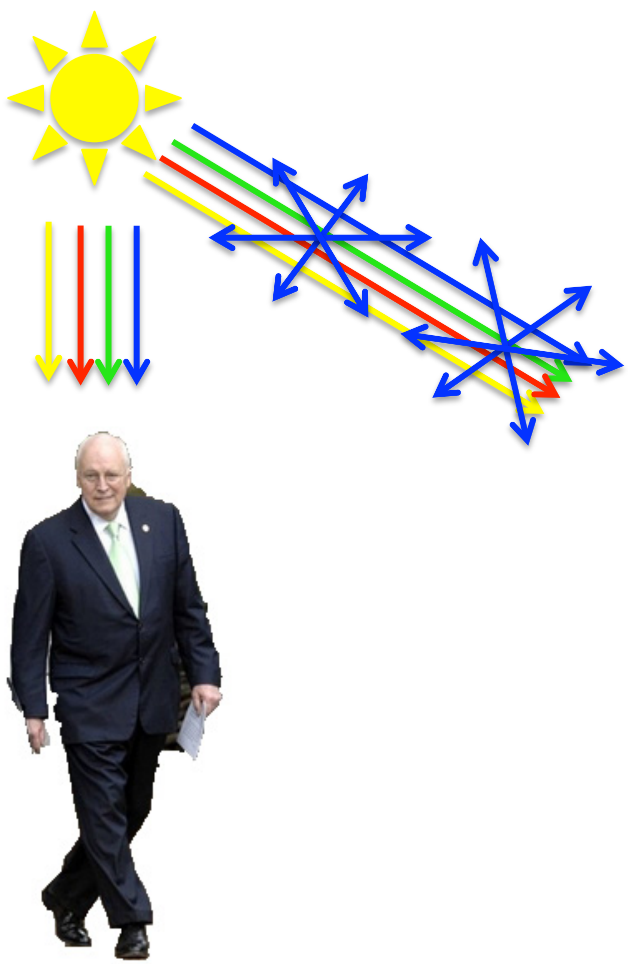
Sidetrip: Why is the Sky Blue?

- When you look *at* the Sun, it appears yellow-white.

- When you look into the sky AWAY from the Sun, the sky *should* appear black as there is no light source.

So, why is it blue?

Blue Sky cont.



- The reason the sky is blue is that molecules and small particles in the upper atmosphere scatter blue photons more efficiently than red ones.
- When you look *away* from the Sun, you see blue light that has bounced off the upper atmosphere into your line of sight.

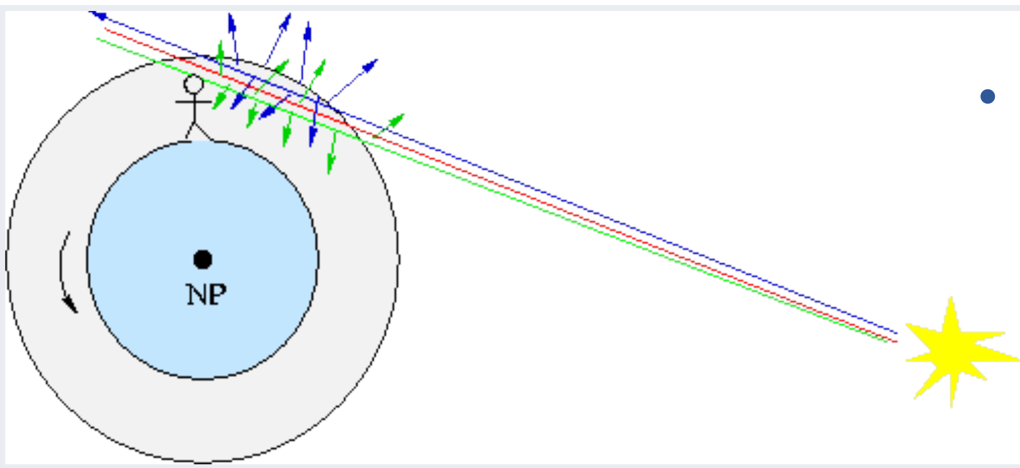
Q. What color is the sky (away from the Sun) as seen by an astronaut on the Space Shuttle?

BLACK

Q. What color is the sky (away from the Sun) as seen from the surface of the Moon?

BLACK

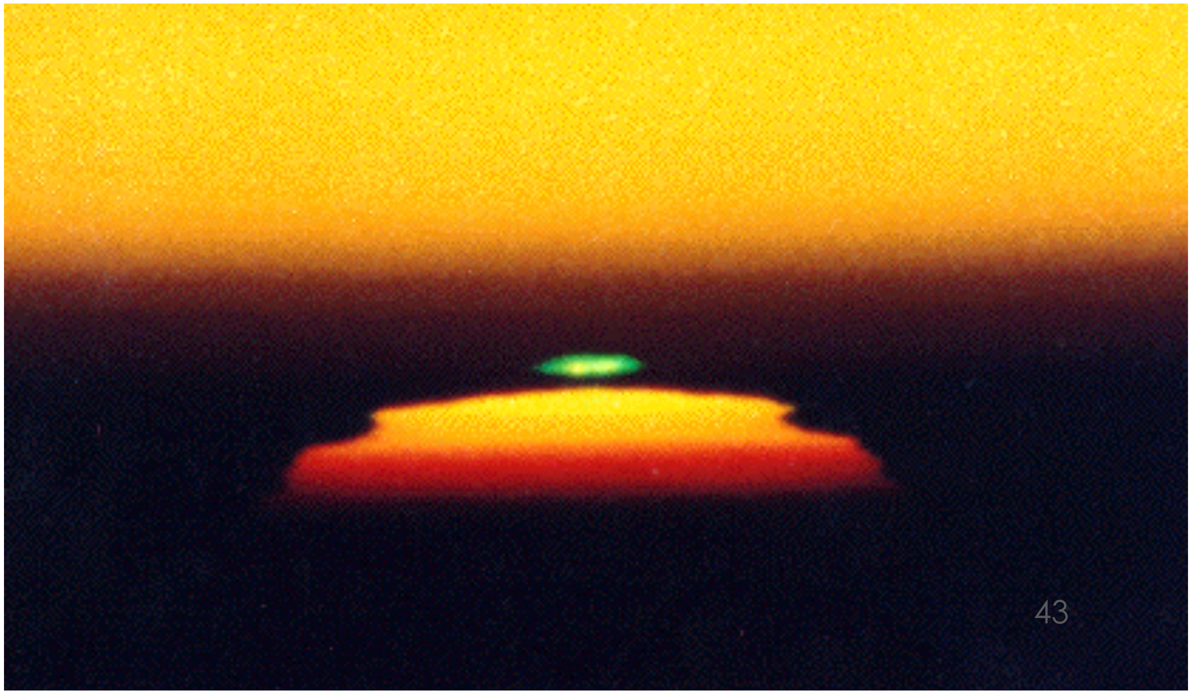
Sidetrip: Why is the Sun red at sunset?

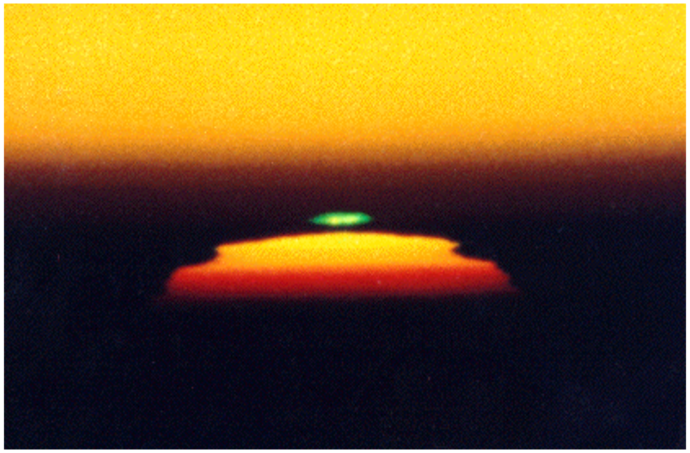


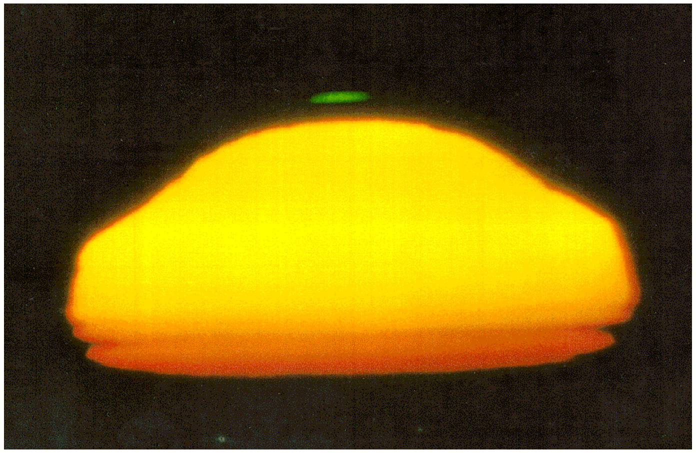
- For the same reason the sky is blue - scattering of blue photons.
- The long path length through the atmosphere when the Sun is low means there are more molecules and particles to scatter out all the blue light leaving only red.

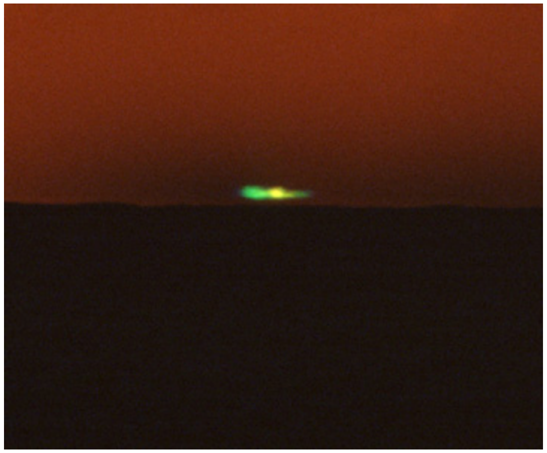
The Green Flash

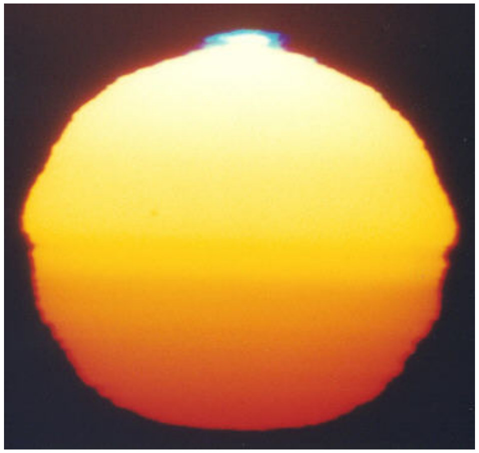
- One more interesting sidelight occurs because the atmosphere acts like a prism. Red light is less bent than green light which is less bent than blue light. The image of the Sun in these different colors is therefore separated. When the Sun is low on the horizon, the red Sun sets first, then the green Sun. By then, all the blue light is scattered out so there is no `blue' flash.











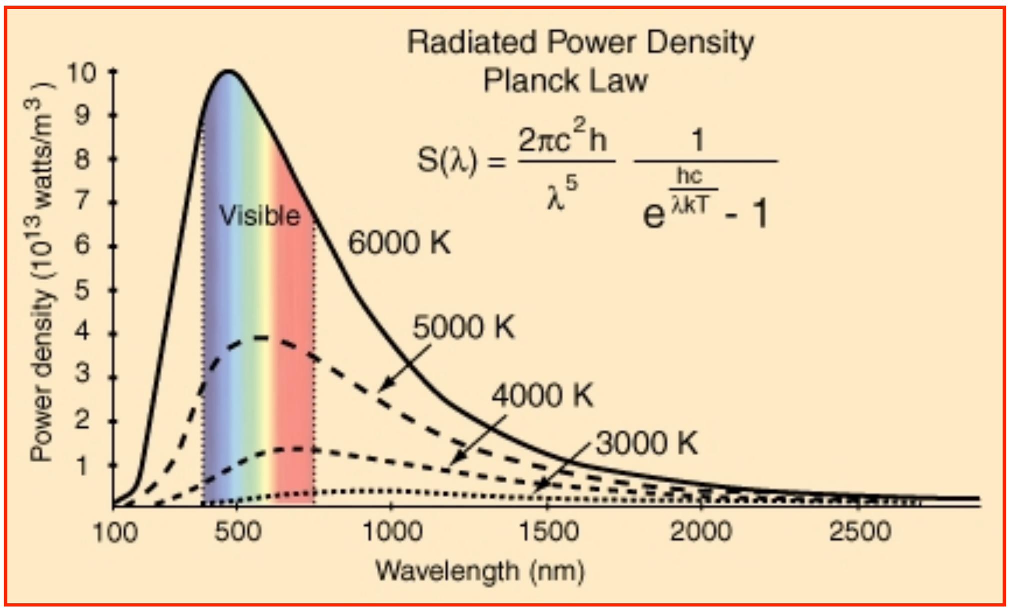
How is E-M Radiation Produced?

1. Accelerate charged particle back and forth like they do at the radio station.
2. All solids or liquids with temperature above *Absolute Zero* emit E-M radiation.
   - Absolute zero is the temperature at which all motion (on an atomic level) ceases.
   - $0K = -459^{\circ}F = -273^{\circ}C$

Continuous or Planck Radiation

If the intensity of E-M radiation at each wavelength for a non-absolute-zero solid or liquid is plotted, this is called a `*spectrum*' .

Intensity



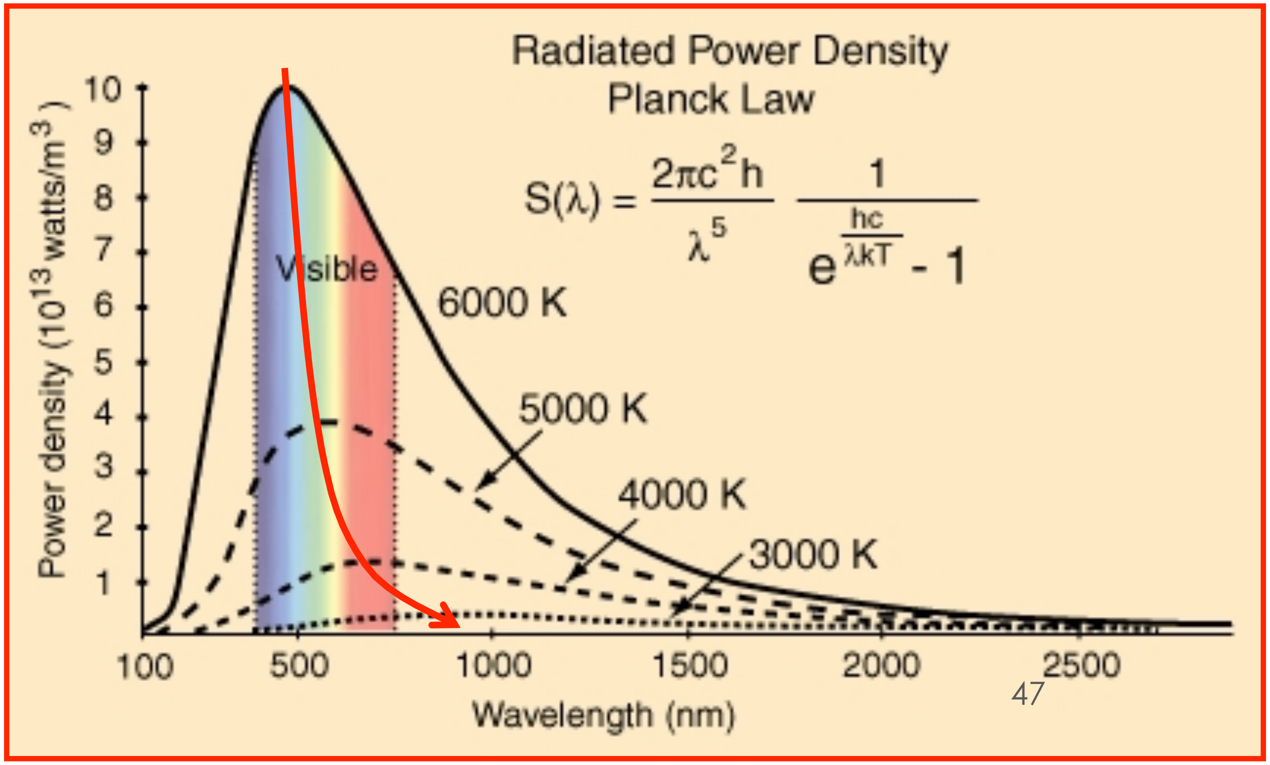
Wavelength

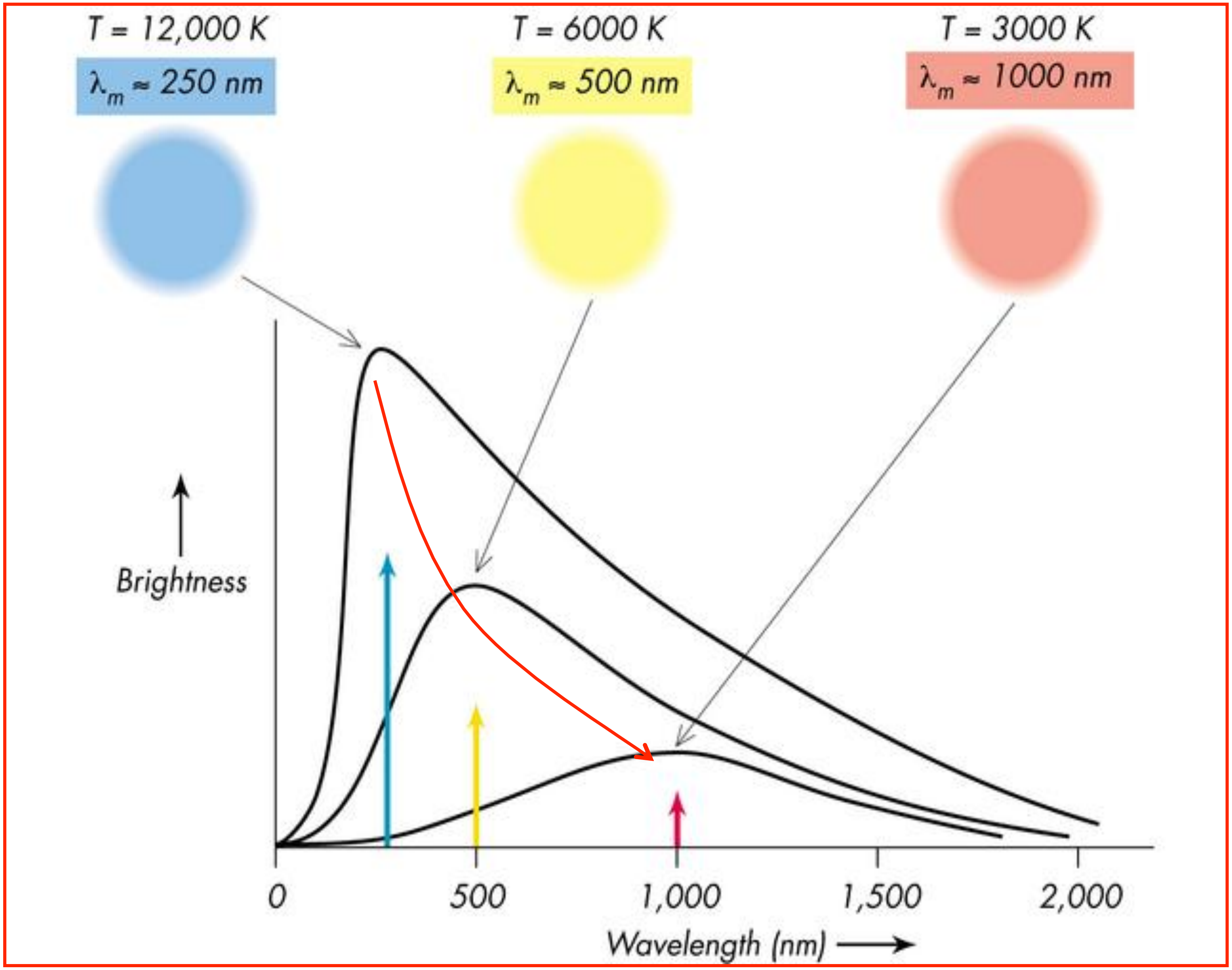
Continuous Spectra

For a given object, as the temperature goes up:

(1) The intensity of radiation at all wavelengths increases

(2) The peak of the intensity curve moves to shorter wavelengths




T = 12,000 K
λm ≈ 250 nm
T = 6000 K
λm ≈ 500 nm
T = 3000 K
λm ≈ 1000 nm
Brightness
0
500
1,000
1,500
2,000
Wavelength (nm)

Wien's Law

- The way the peak of the Planck spectrum changes with temperature is quantified by *Wien's Law*.

$$T(K) = \frac{0.29}{\lambda_{\max}(cm)}$$

- This is very powerful!

Wien's Law

Take a spectrum of the Sun and you discover that the peak in the spectrum is at about 5500 angstroms = 5.5 x 10^{-5}cm. Use Wien's Law to get the surface temperature of the Sun:

$$T(K) = \frac{0.29}{5.5 \times 10^{-5}} = 5200K$$

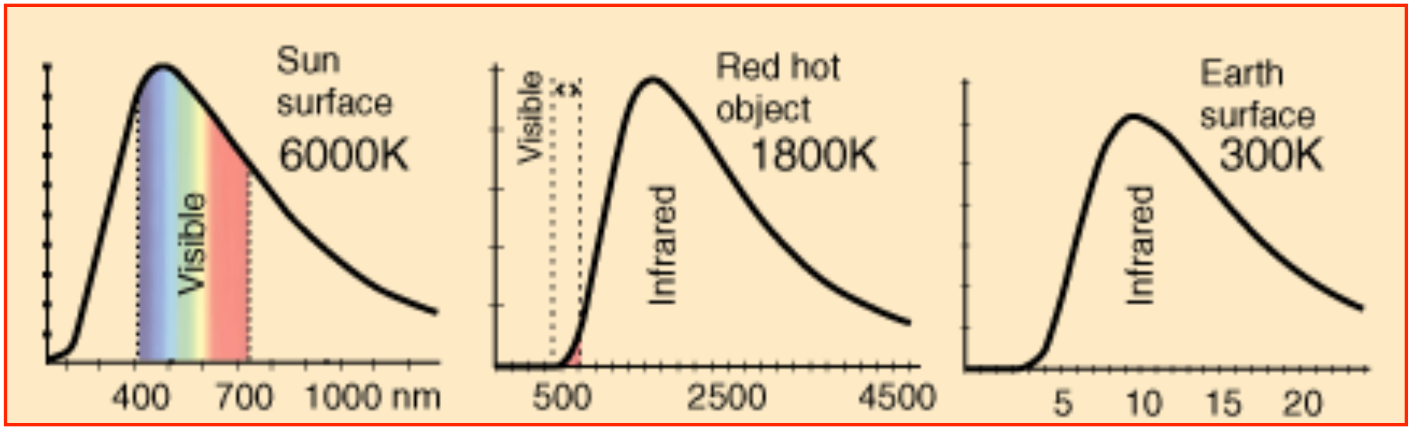
Radiation from Humans

- Note that the radiation we are using to see one another is *reflected* from the lights in the room.
- Human temperature is about 300K, so the peak radiation is:

$$\lambda_{\max}(cm) = \frac{0.29}{T(K)} = 9.8 \times 10^{-4}(cm)$$

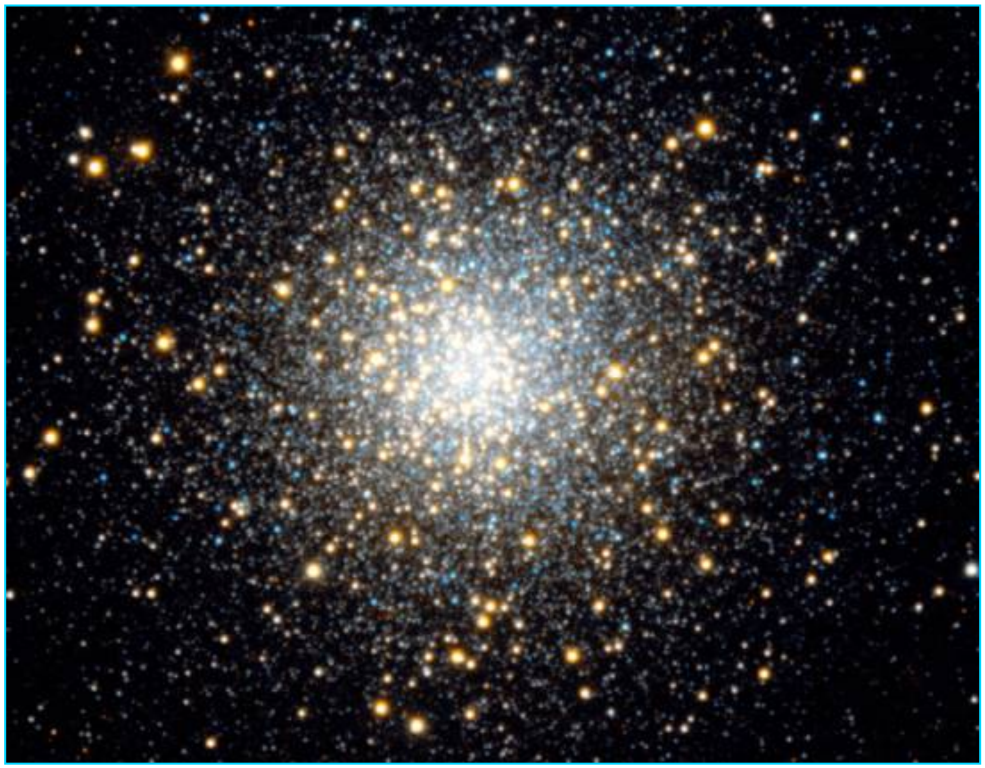
- This is in the infrared.

Red hot vs white hot



- Think about the stove element. When its temperature is <800K, it emits IR radiation.
- By ~1300K, it emits more IR radiation and is emitting enough radiation at shorter wavelengths to just start to glow red.

Colors and Temperature

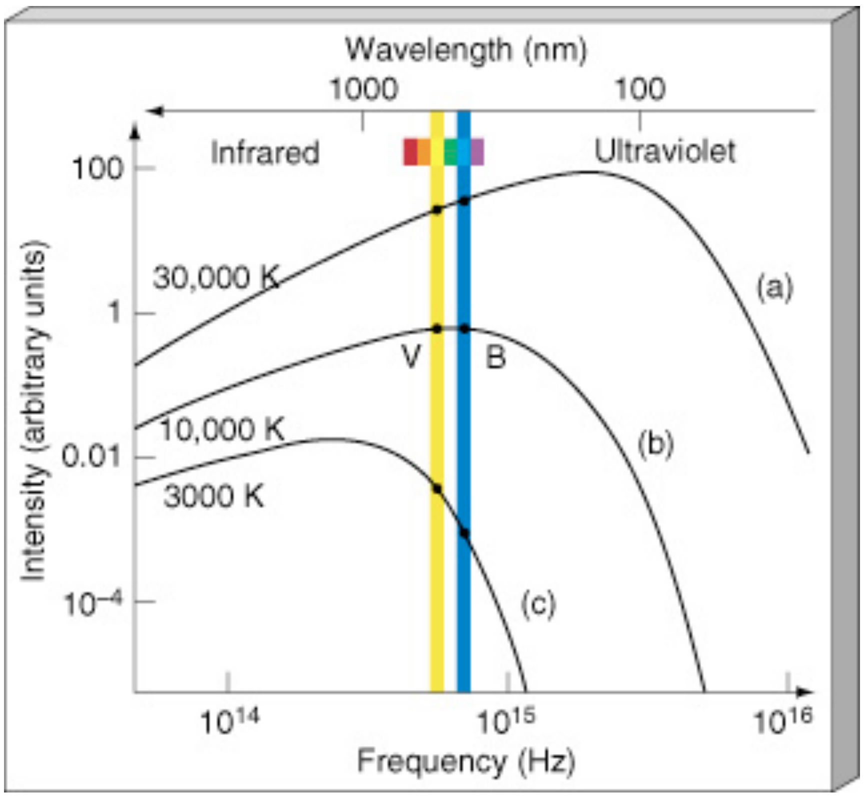


Simply glancing at this globular cluster you can see that there are stars with a range of temperature.

Colors and Stellar Temperatures

- Ultra-cheap trick: ``That star looks a little redder than the Sun, so it's surface temperature must be less than 5200k"
- Cheap Trick: Disperse the light from a star (take a spectrum), find λ_{max} and use Wien's Law
- One of the two ways it's done in practice: measure colors

Photometric Colors

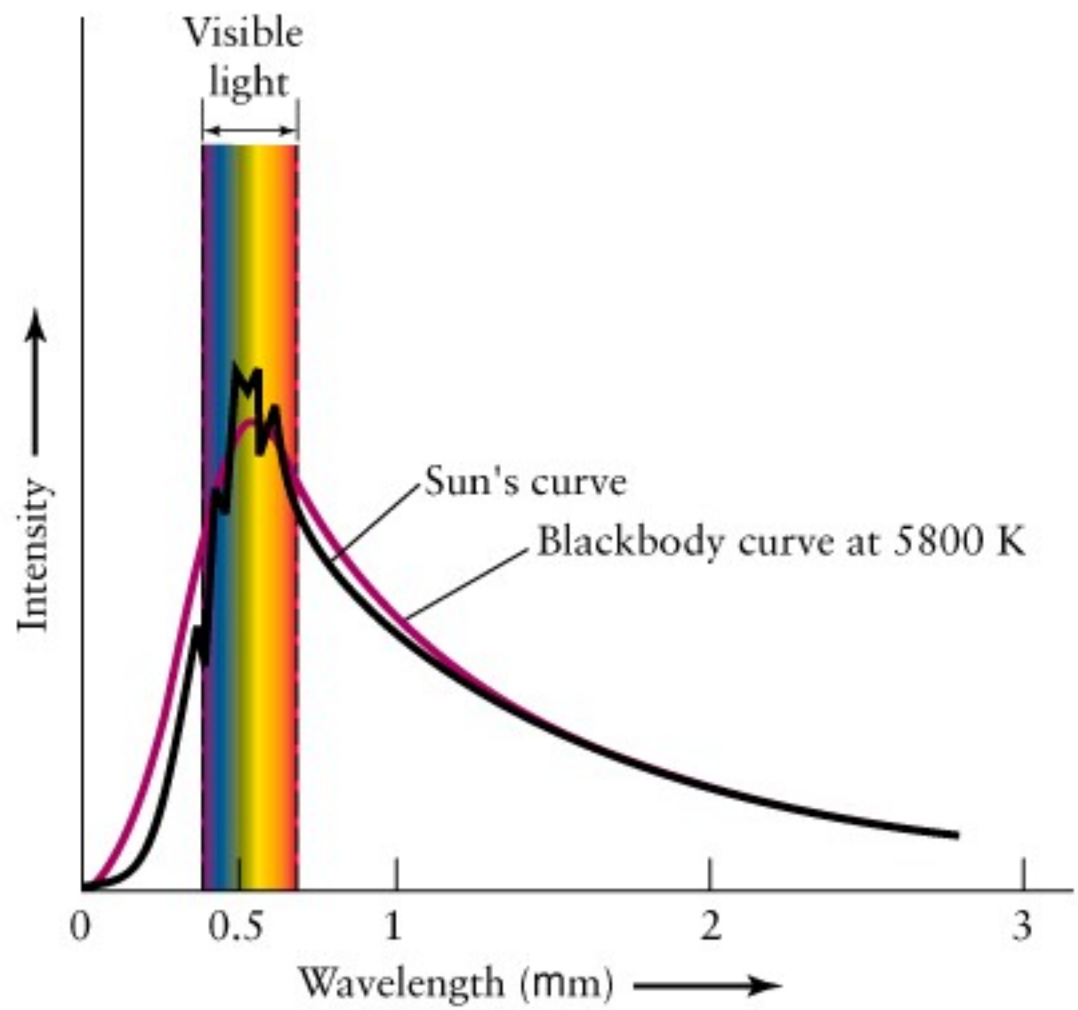


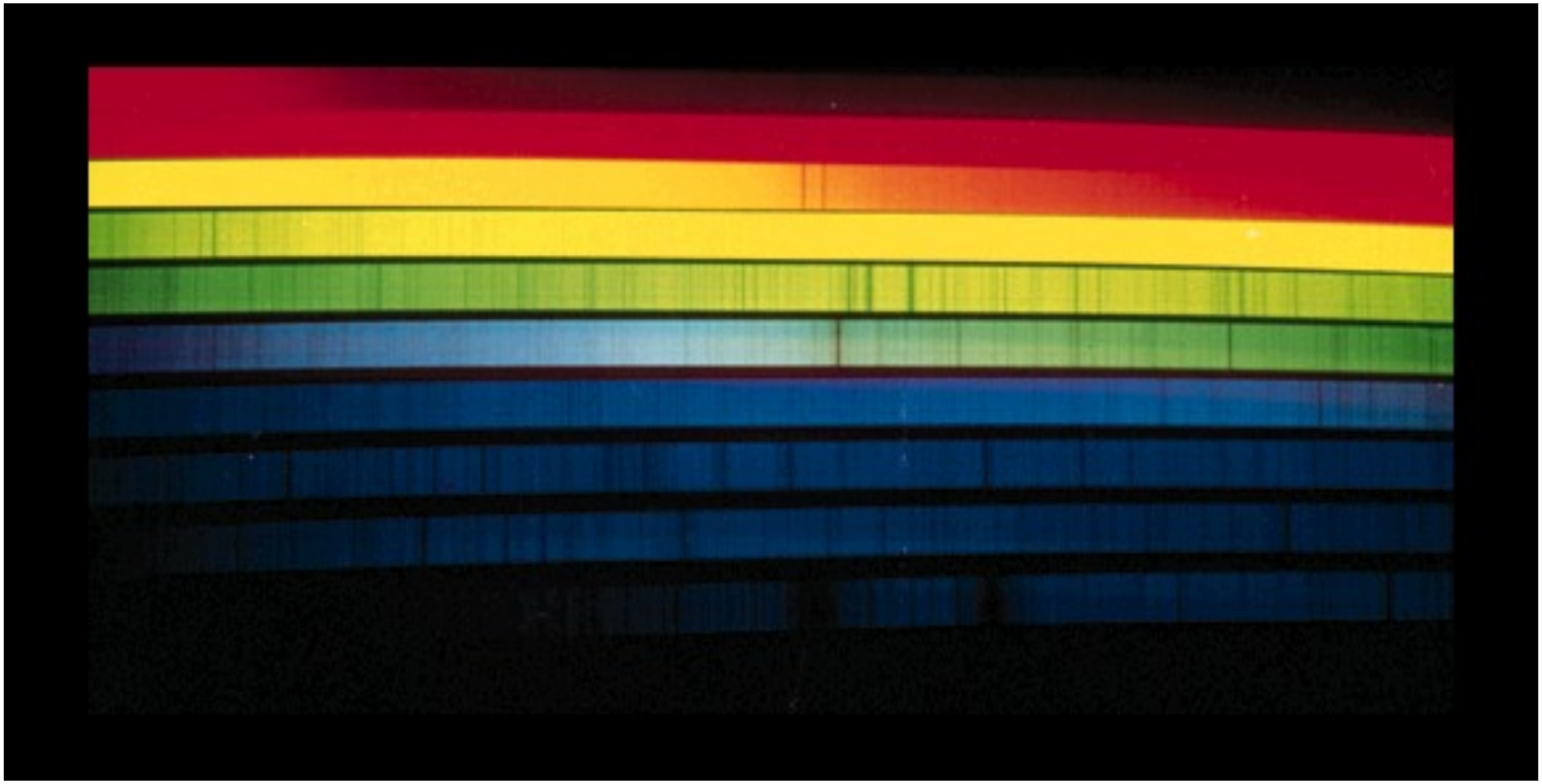
For Planck spectra the ratio of the light in two different color filters unambiguously give the temperature of the radiating object.

Stellar Colors

- To the extent that stellar spectra look like Planck spectra (spectra of solid objects), accurately measured colors can give quantitative stellar temperatures.
- What do stellar spectra look like?
- Back in the 1800's, spectra of the Sun showed that it was similar to a Planck spectrum, but there was missing light at certain wavelengths -- `absorption spectra'

Stellar Spectra



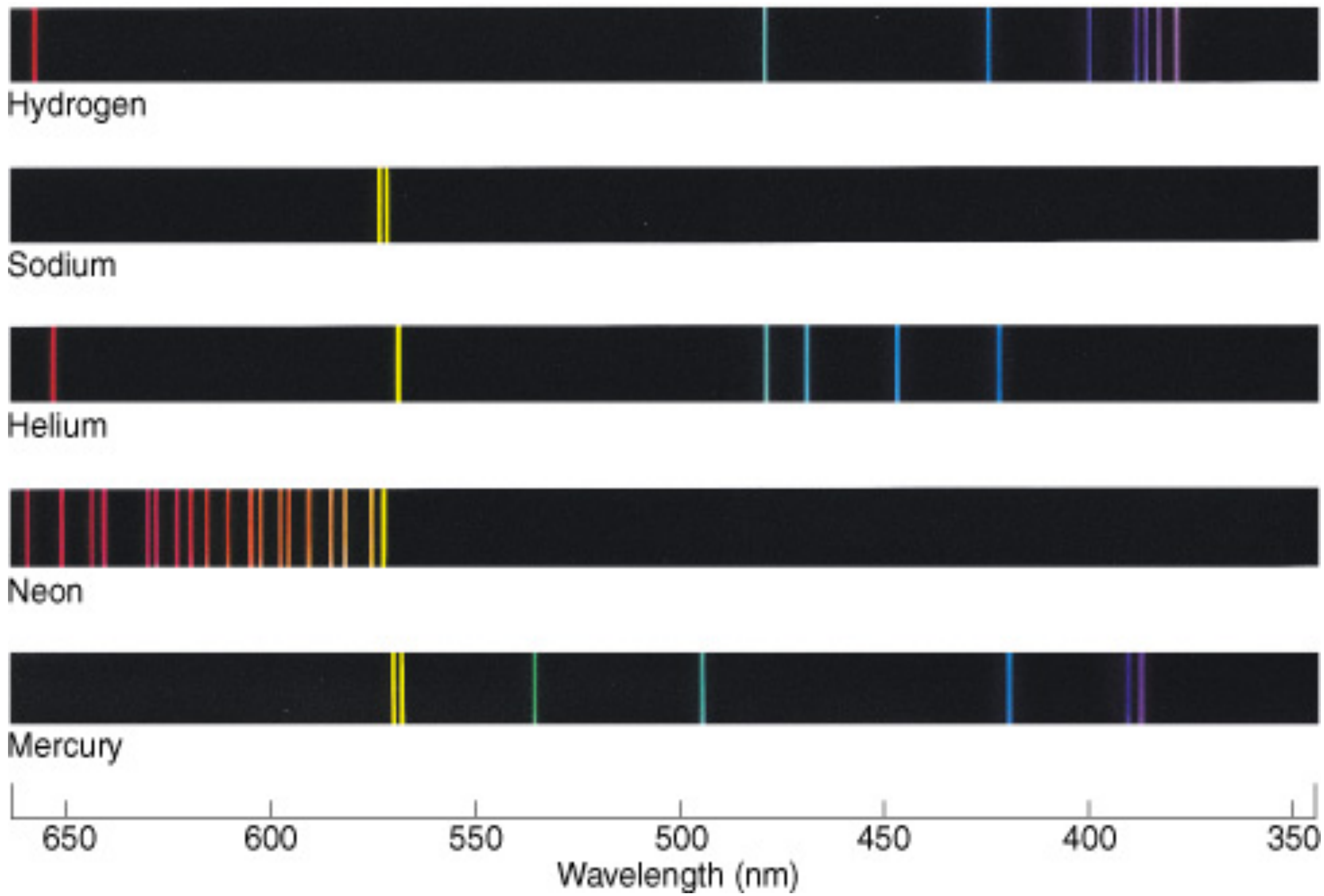


Because the spectra of stars are pretty close to being Planck Curves, stellar colors can be used to measure stellar temperatures. The process is:

1. Use computer models of spectra generated for stars of different temperature and calibrate a color-temperature relation
2. Measure the brightness of a star through two filters and compare the ratio of red to blue light

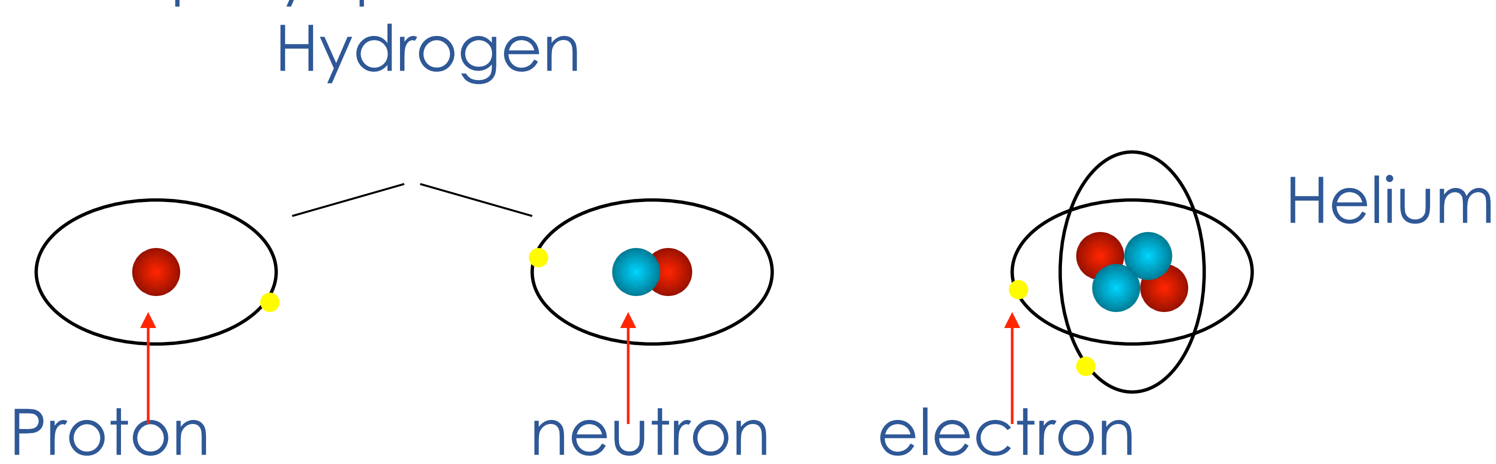
Absorption and Emission Lines

- The wavelengths with missing light in stellar spectra turned out to be very interesting and important.
- When chemists heated gases to the point where they (the gases) began to glow, the resulting spectra were not continuous, but had light at discrete wavelengths that matched the wavelengths of missing light in stellar spectra.
- *Different elements had different sets of emission/absorption lines!*


Hydrogen
Sodium
Helium
Neon
Mercury
650
600
550
500
450
400
350
Wavelength (nm)

Light and Atoms

- The understanding of spectral lines had to await the development of Atomic Physics.
- What makes an *element*?
  - The number of protons in the nucleus of an atom uniquely specifies the element.



Elements

- Hydrogen has one proton-- $^{1}H_{1}$
- Hydrogen with a neutron is a `heavy' isotope of hydrogen called deuterium -- $^{2}H_{1}$
- Add a second proton and you have the next element in the Periodic Table -- Helium

$$2p^{+} + 1n^{\circ} = {}^{3}He_{2}$$

total # of nucleons   # of protons

Q. How many neutrons in $^{238}U_{92}$?

$p^+ + n^0 = 238$ and there are 92 protons.
So, must have $238 - 92 = 146$ neutrons.

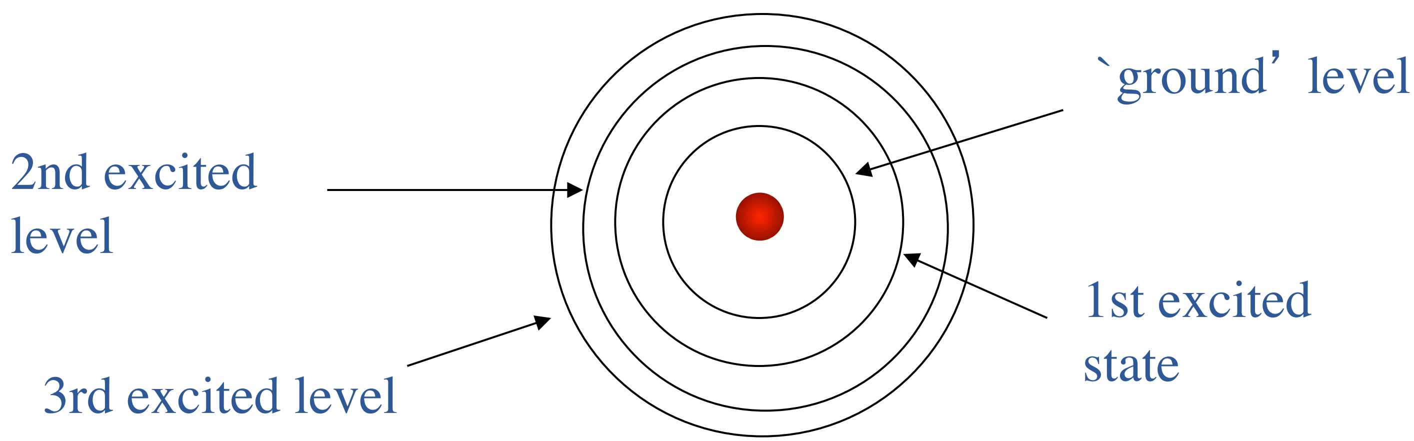
Atoms and Spectra

- What does this have to do with spectral lines?
- Lots of clever experiments in the early 1900s demonstrated:

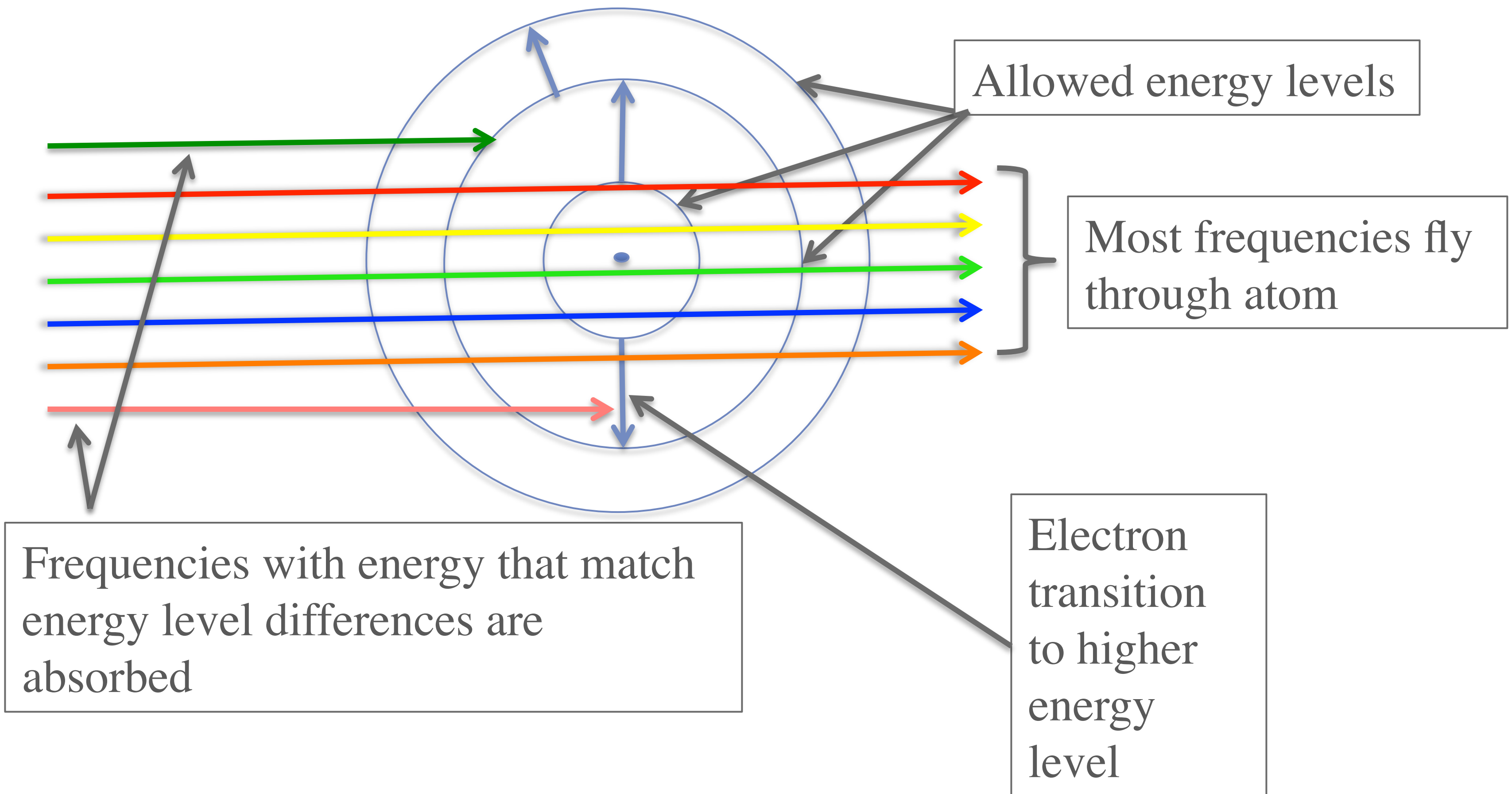
1. Light can be modeled as a stream of `quanta' called photons. Each photon carries and energy $E=hf$ where h is Planck's constant and f is the frequency of light. (sometimes f is called ν)

Hydrogen Schematic: 4 lowest energy levels

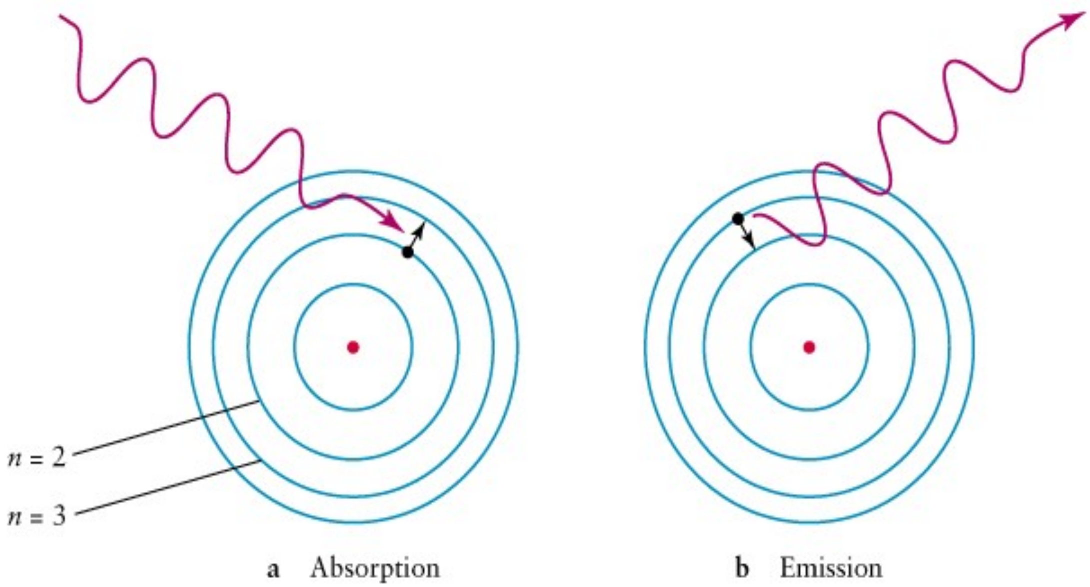
2. Atoms have a crazy structure in which only certain orbits are "allowed" for the electrons. Atomic orbits and energy levels are said to be *quantized*.

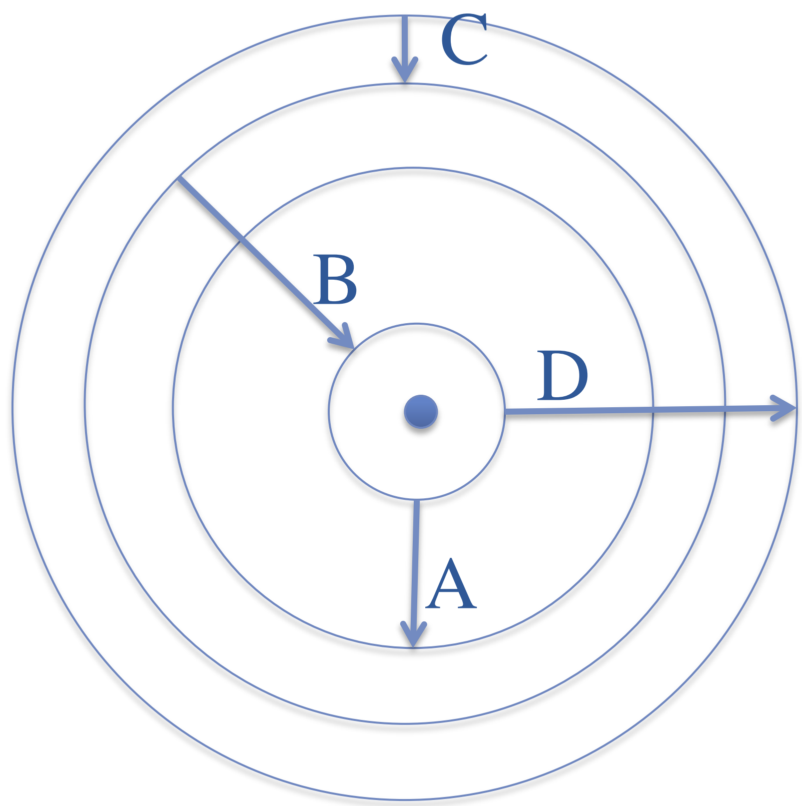


- Now, fire photons with a range of energy, frequency and wavelength at an atom and the majority of them go right through the atom.
- *But, a photon with energy equal to an energy level difference between two allowed states in the atom will be absorbed, boosting the e- into the higher level.*

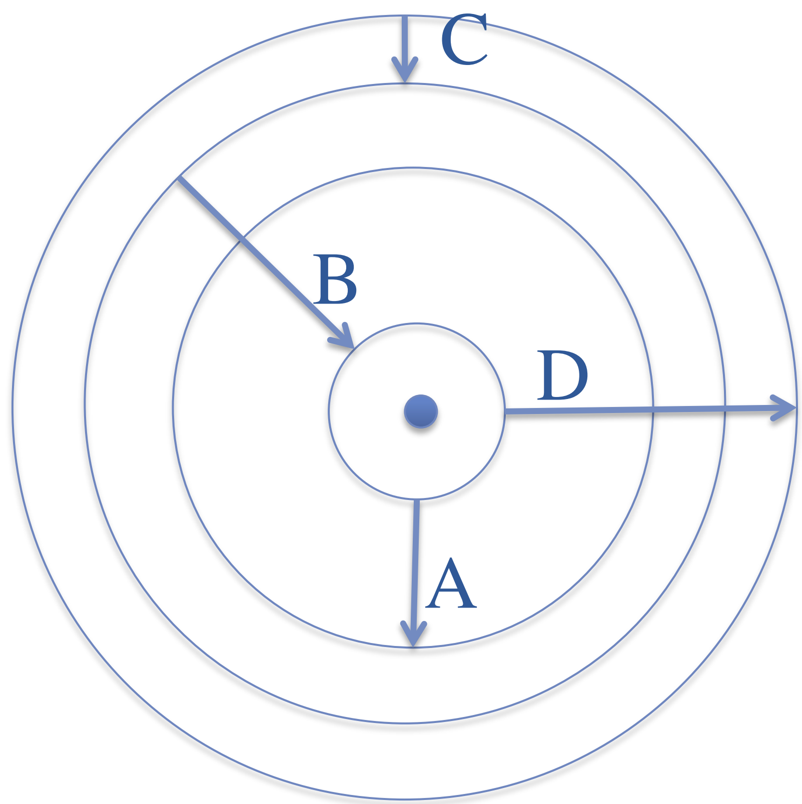


- One of Nature's favorite rules is that systems always seek the lowest available energy state.
- This means that atoms with electrons in excited levels will rapidly `de-excite' and spit out a photon to conserve energy.





Q. Which transition(s) correspond to ABSORPTIONS of photons? A, B, C, D (clicker quiz)



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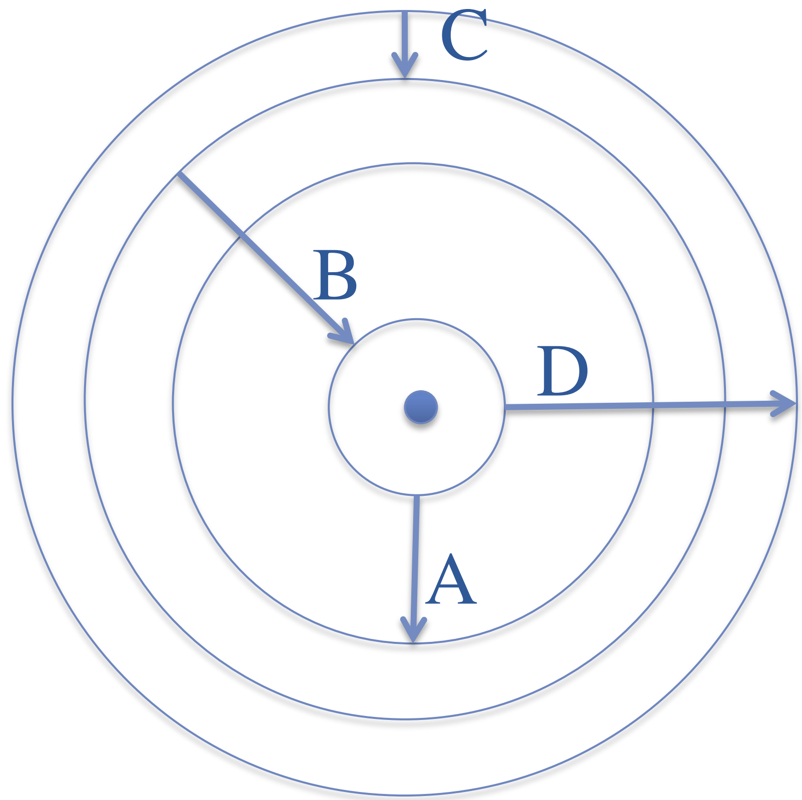
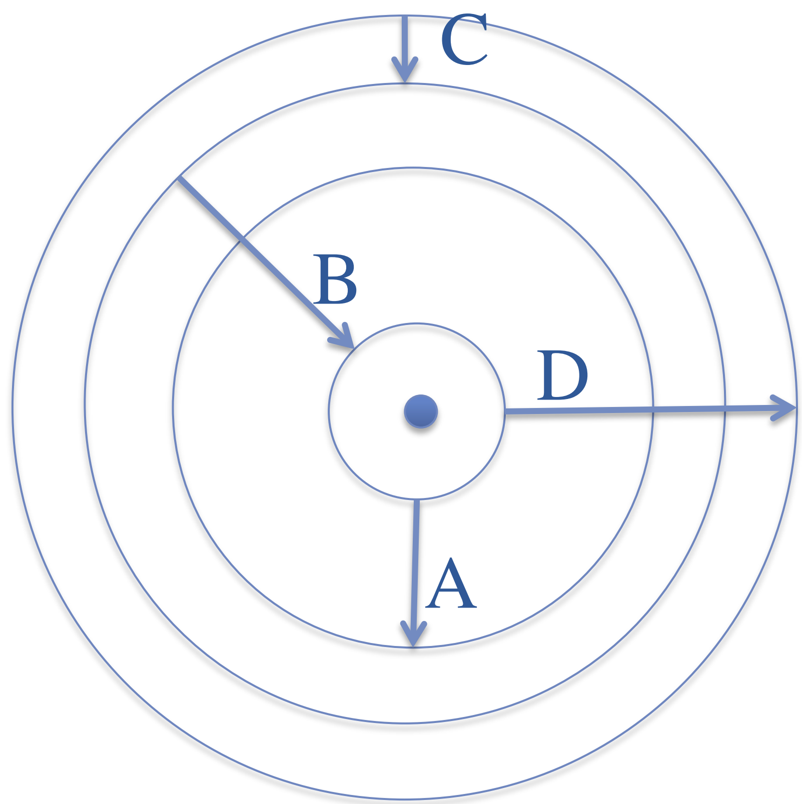
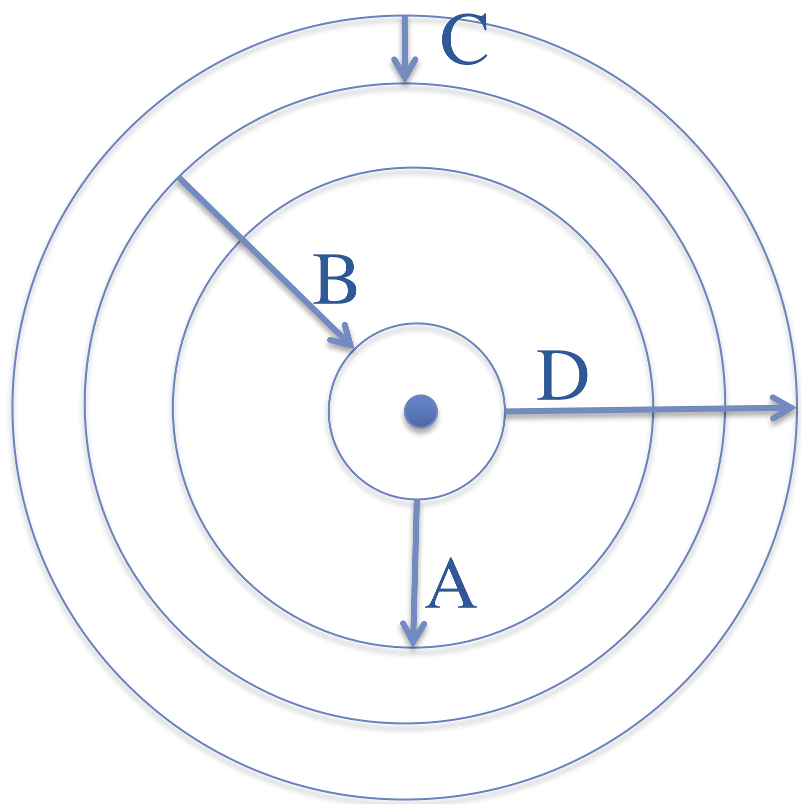


Q. Which transition(s) correspond to the highest energy photon EMITTED? A, B, C, D

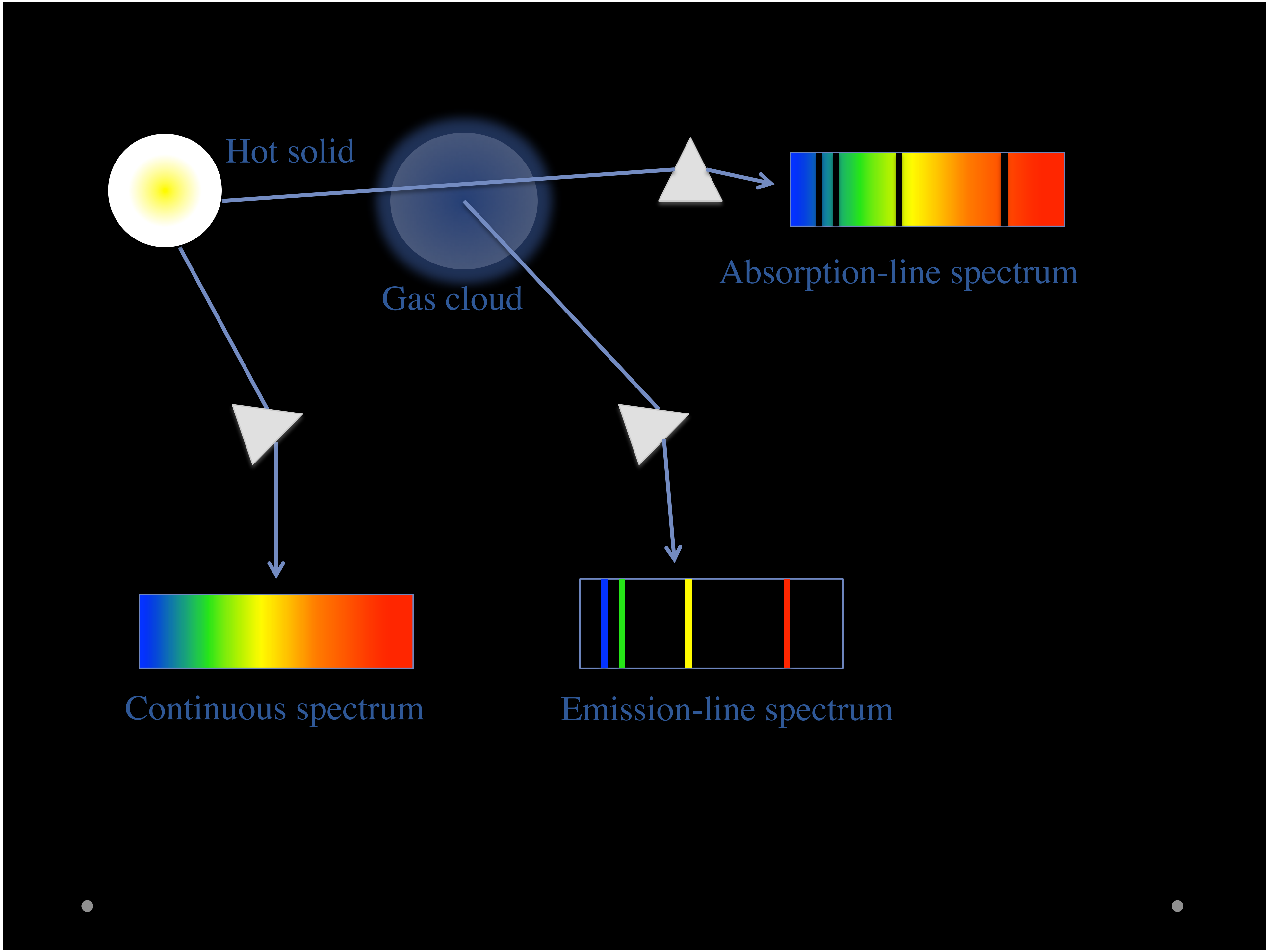


Q. Which transition(s) correspond to the highest energy photon EMITTED? A, **B**, C, D



Q. Which transition(s) correspond to the longest wavelength photon EMITTED?

C


Hot solid
Gas cloud
Absorption-line spectrum
Continuous spectrum
Emission-line spectrum

Next topic: The Solar System