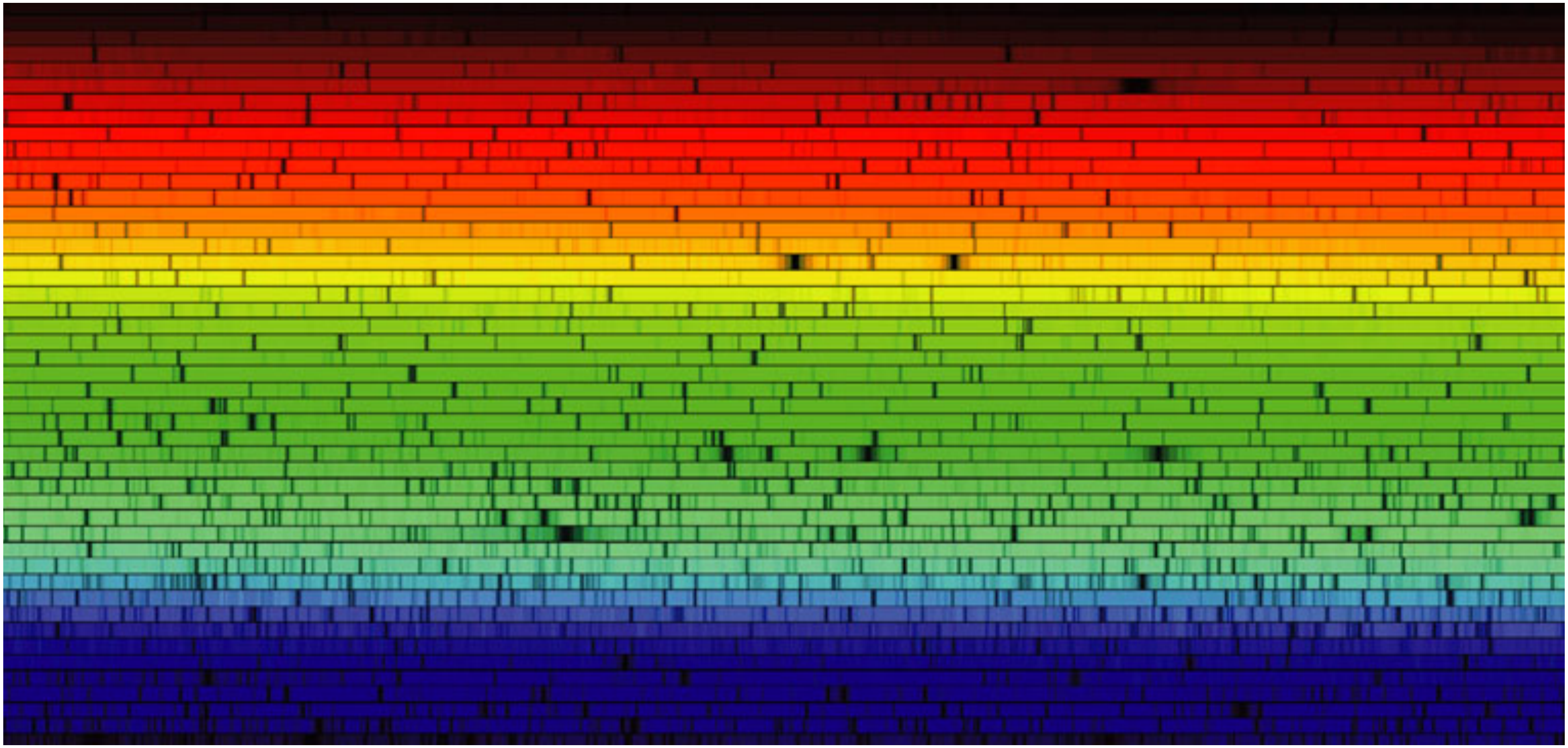
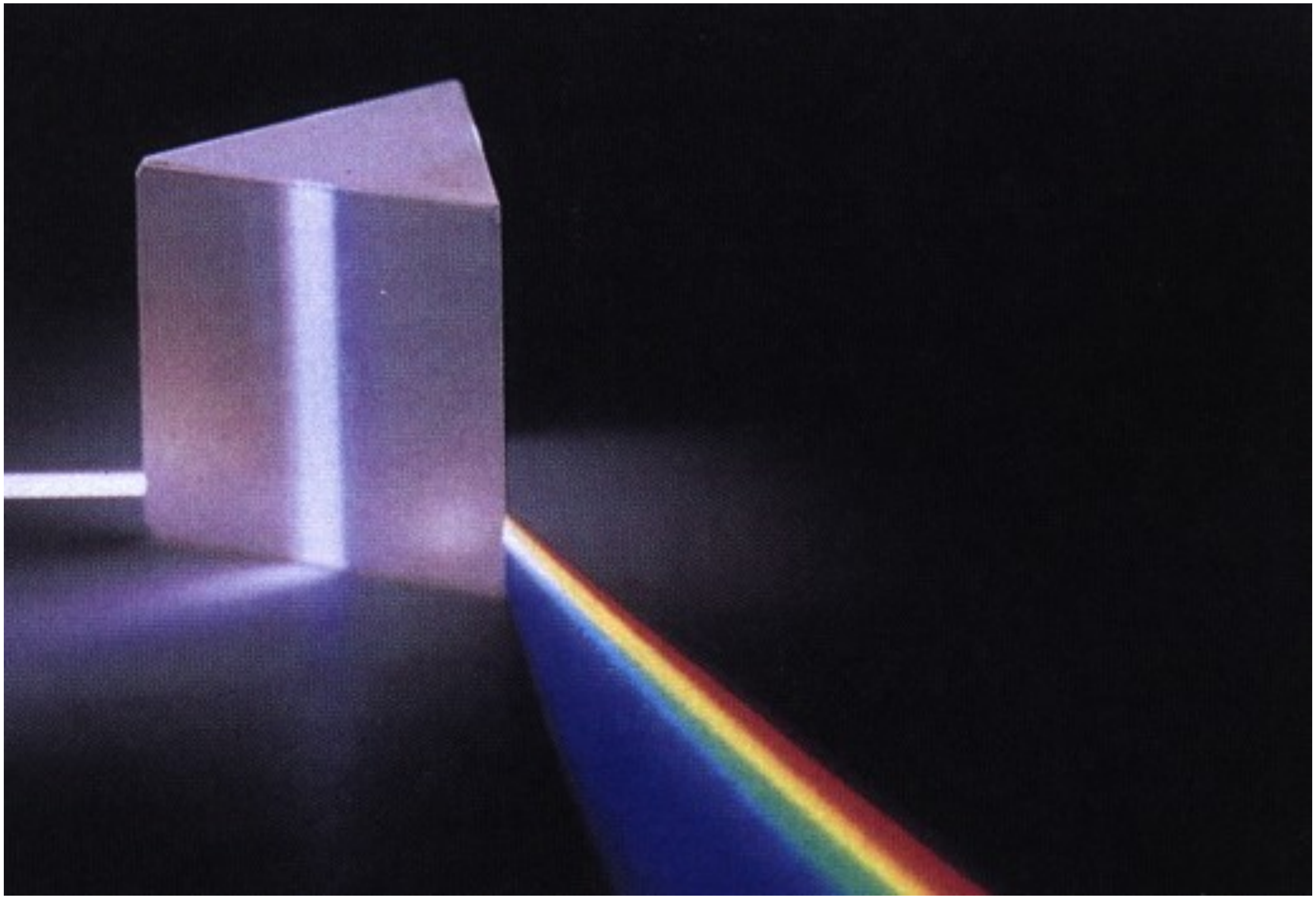
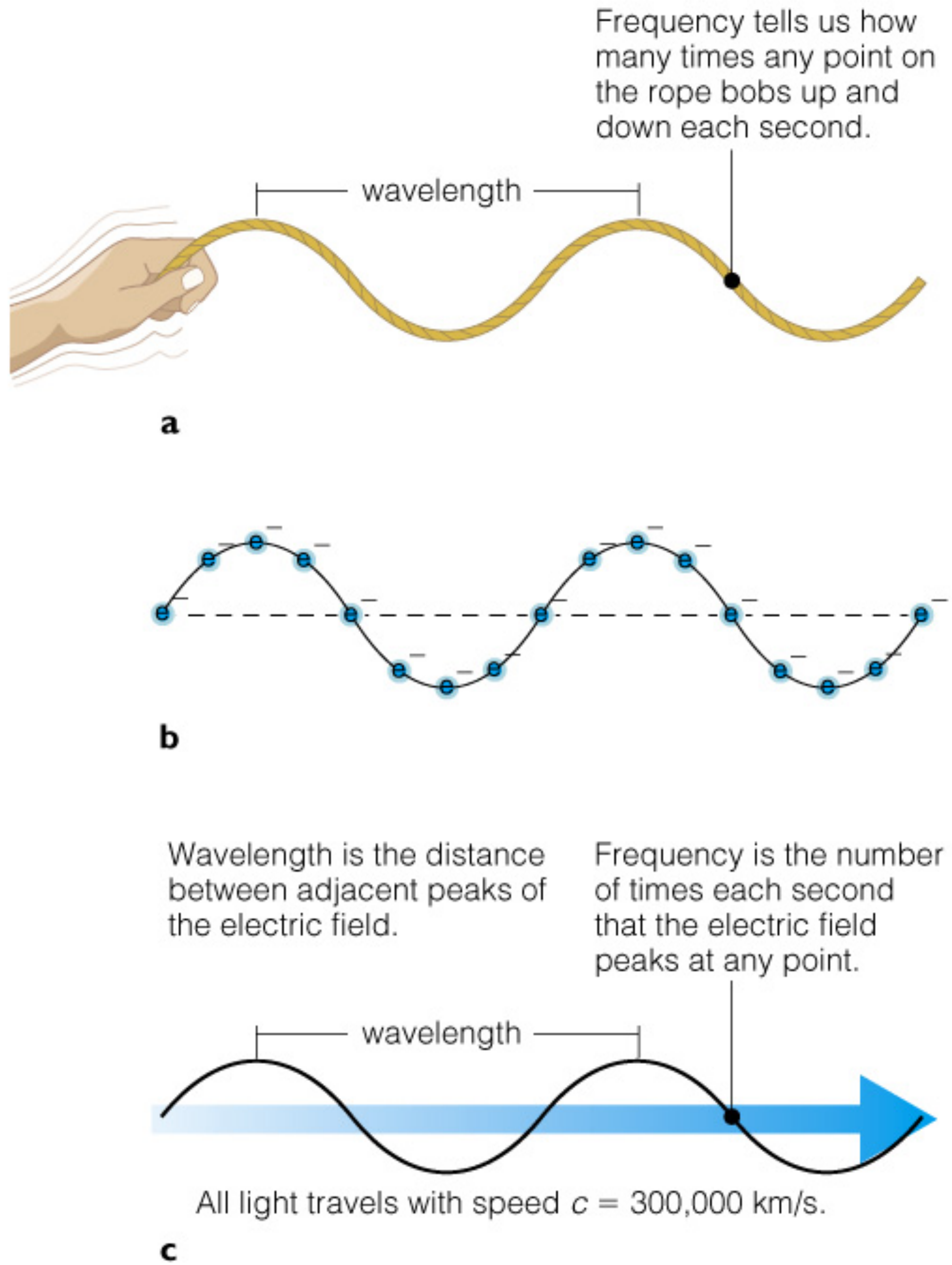
Radiation, Matter and Energy

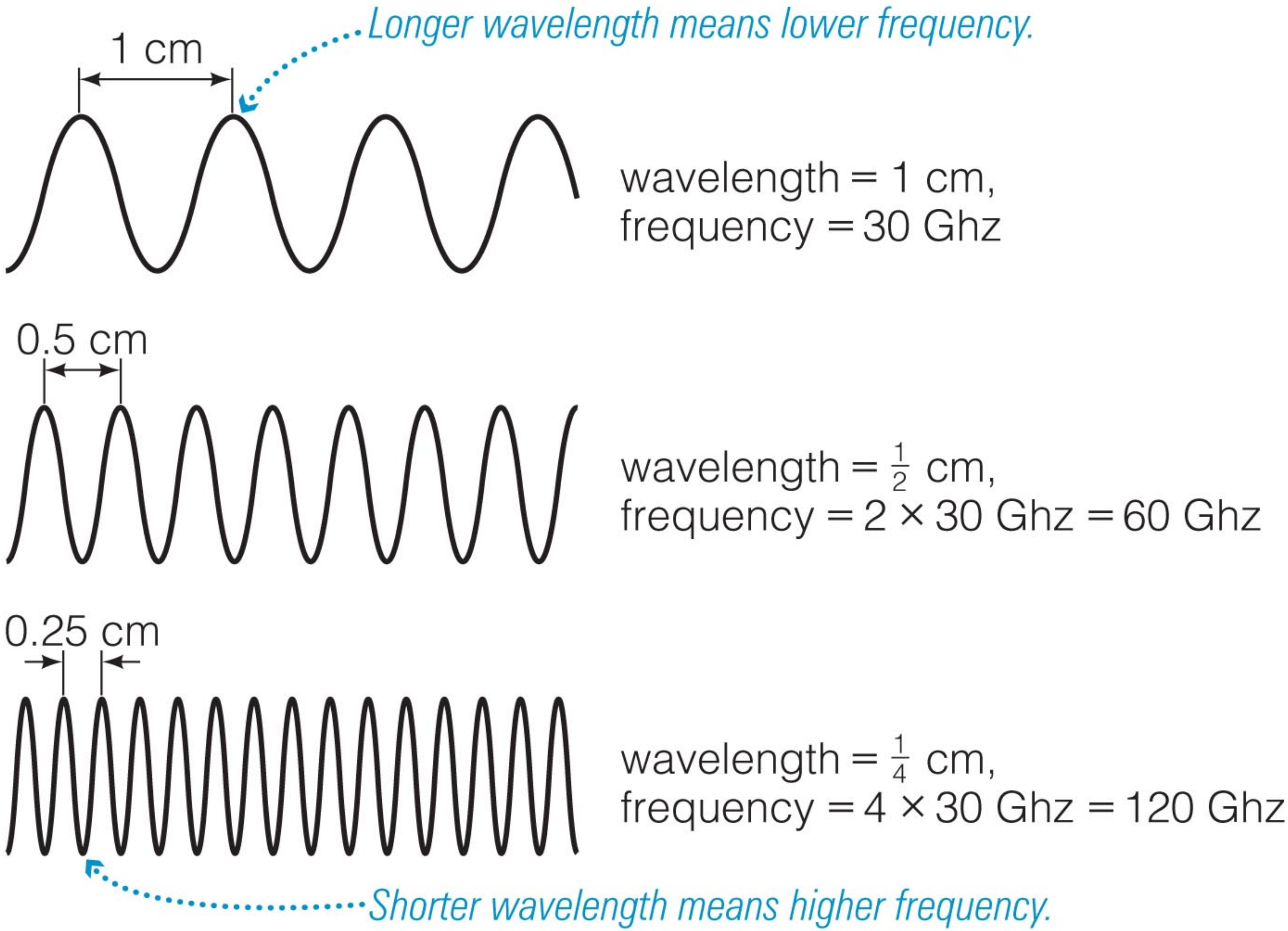


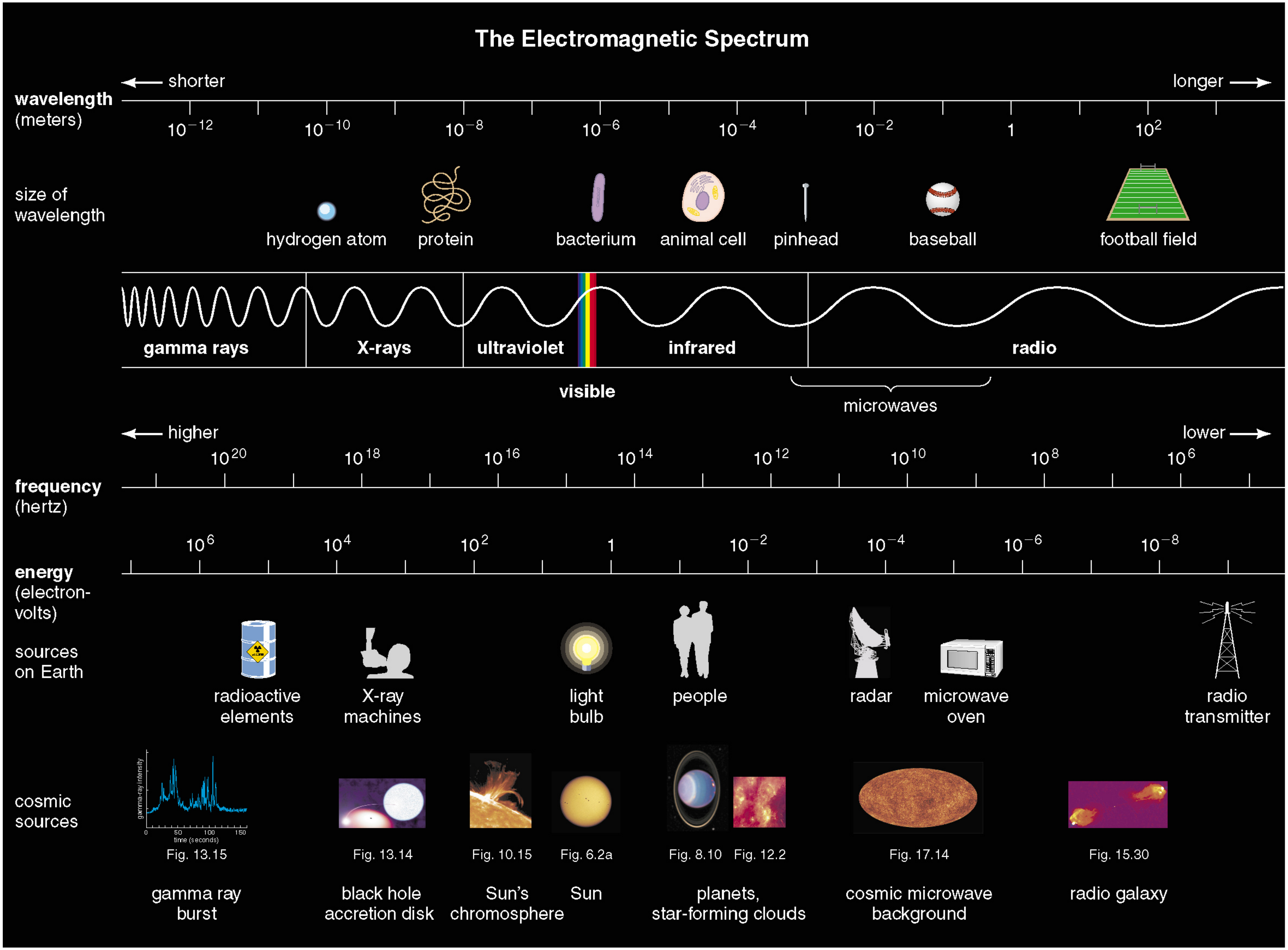
What is light?



Light is an
electromagnetic wave




Longer wavelength means lower frequency.
1 cm
wavelength = 1 cm,
frequency = 30 Ghz
0.5 cm
wavelength = $\frac{1}{2}$ cm,
frequency = 2 × 30 Ghz = 60 Ghz
0.25 cm
wavelength = $\frac{1}{4}$ cm,
frequency = 4 × 30 Ghz = 120 Ghz
Shorter wavelength means higher frequency.


The Electromagnetic Spectrum
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
gamma rays
X-rays
ultraviolet
infrared
radio
visible
microwaves
higher
lower
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
frequency
(hertz)
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
energy
(electron-
volts)
sources
on Earth
radioactive
elements
X-ray
machines
light
bulb
people
radar
microwave
oven
radio
transmitter
cosmic
sources
Fig. 13.15
gamma ray
burst
Fig. 13.14
black hole
accretion disk
Fig. 10.15
Sun's
chromosphere
Fig. 6.2a
Sun
Fig. 8.10
Fig. 12.2
planets,
star-forming clouds
Fig. 17.14
cosmic microwave
background
Fig. 15.30
radio galaxy

Light is also a particle

Photons: “pieces” of light, each with precise wavelength, frequency, and energy. Think of photons as tiny bullets

Energy is proportional to frequency

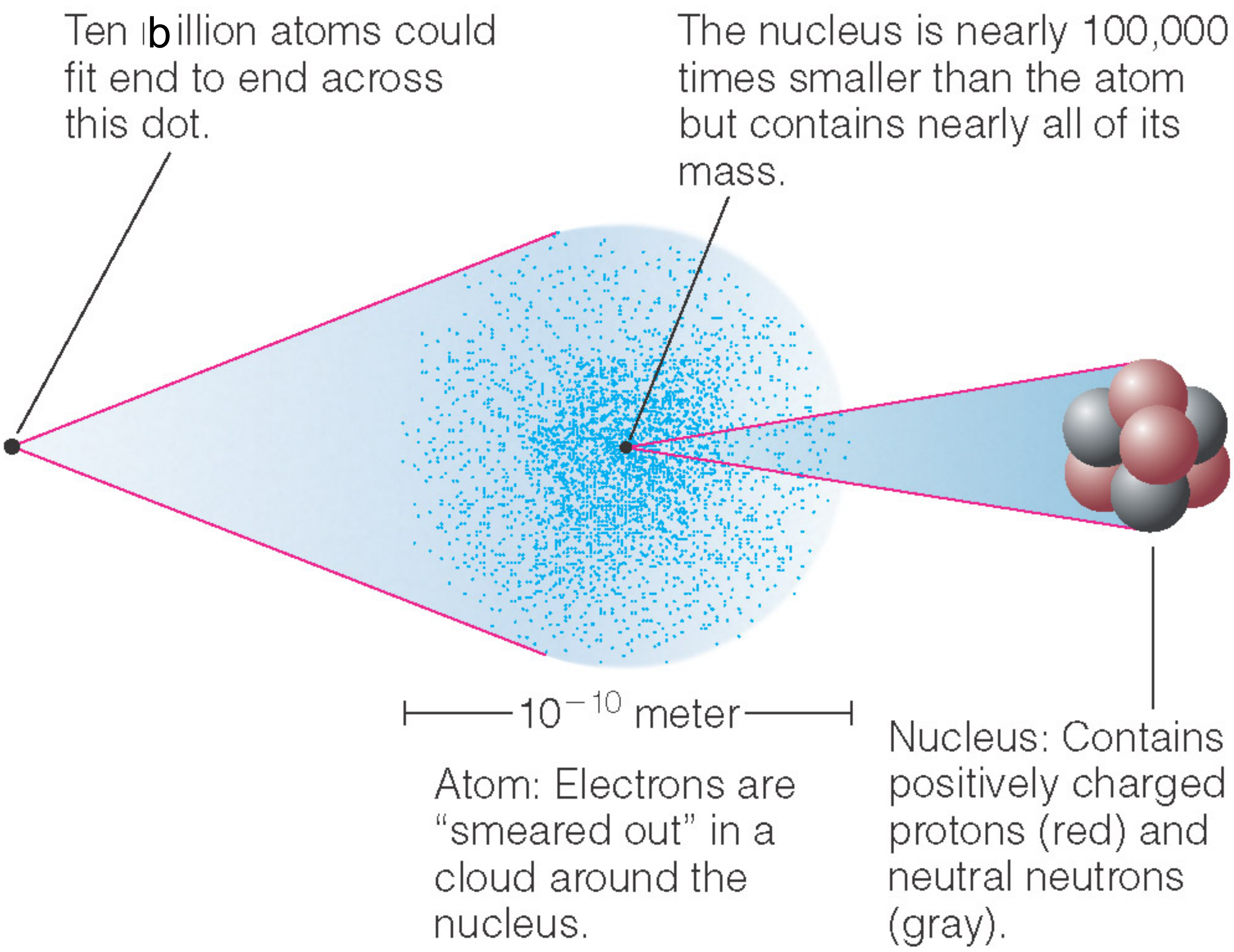
Within the visible spectrum, **blue light** has higher energy than **red light**

Within the electromagnetic spectrum, X-rays have the highest energy, followed by UV, visible light, IR, and radio

Remember: *Light is just one form of electromagnetic wave of energy, the kind we can detect with our eyes.*

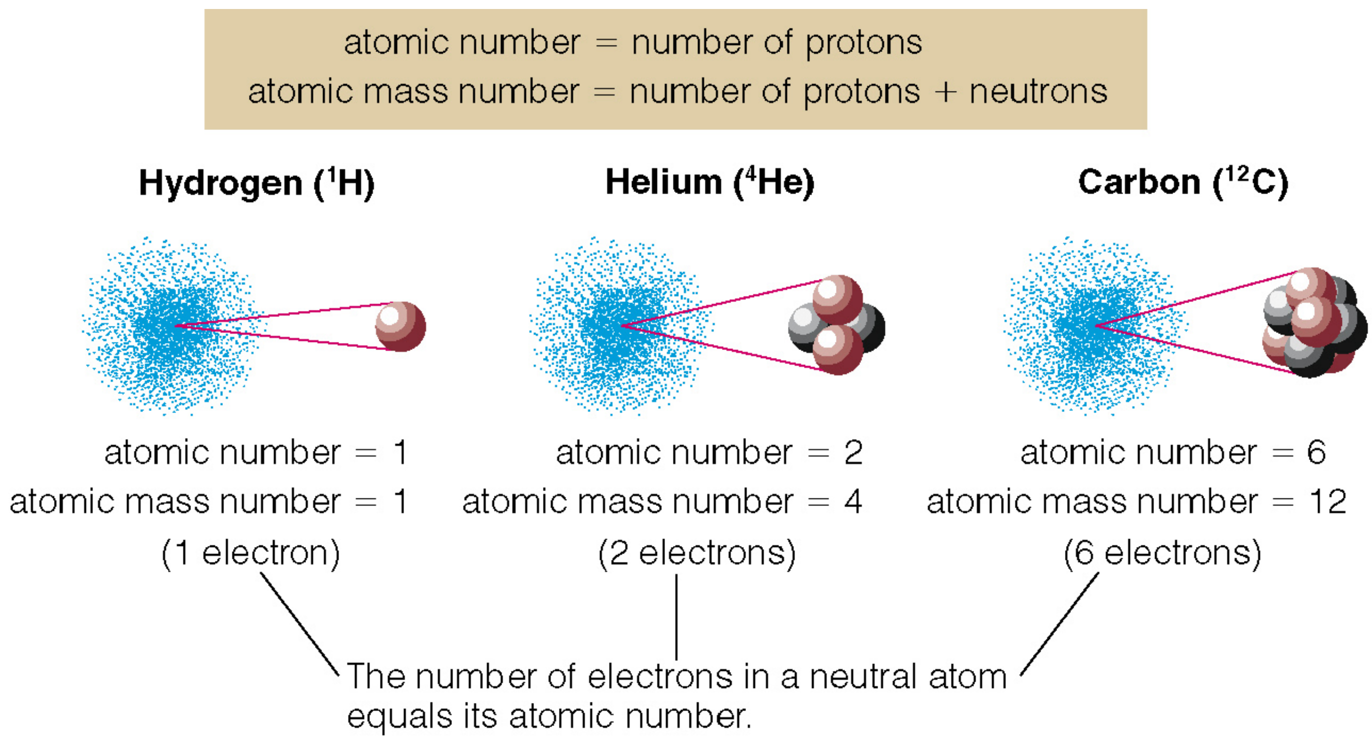
What is matter?

Atomic structure:



Atomic Terminology

- Atomic Number = # of protons in nucleus
- Atomic Mass Number = # of protons + neutrons



Atoms organized on Periodic Table

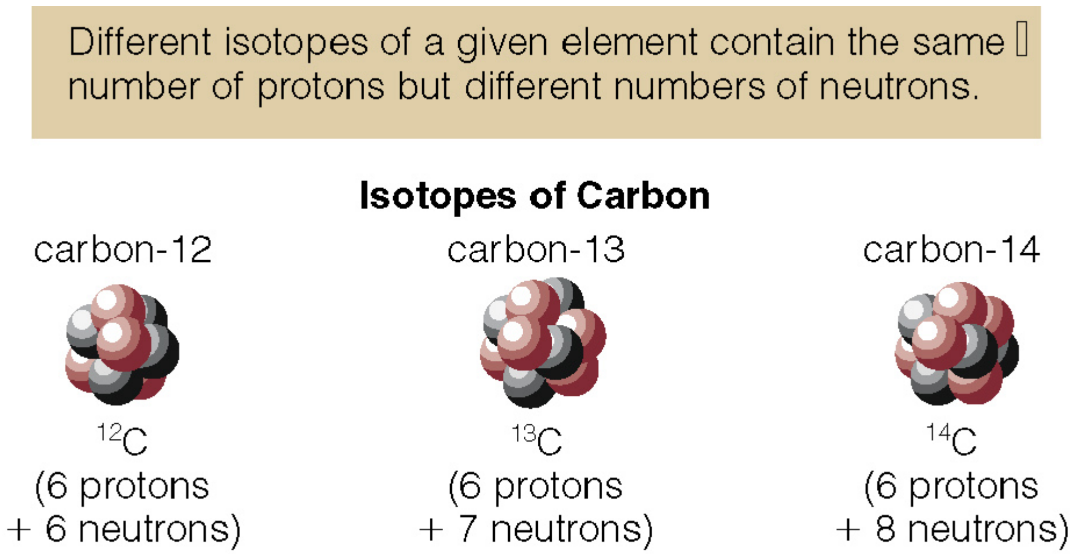
- Atomic Number = # of protons in nucleus

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* * Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

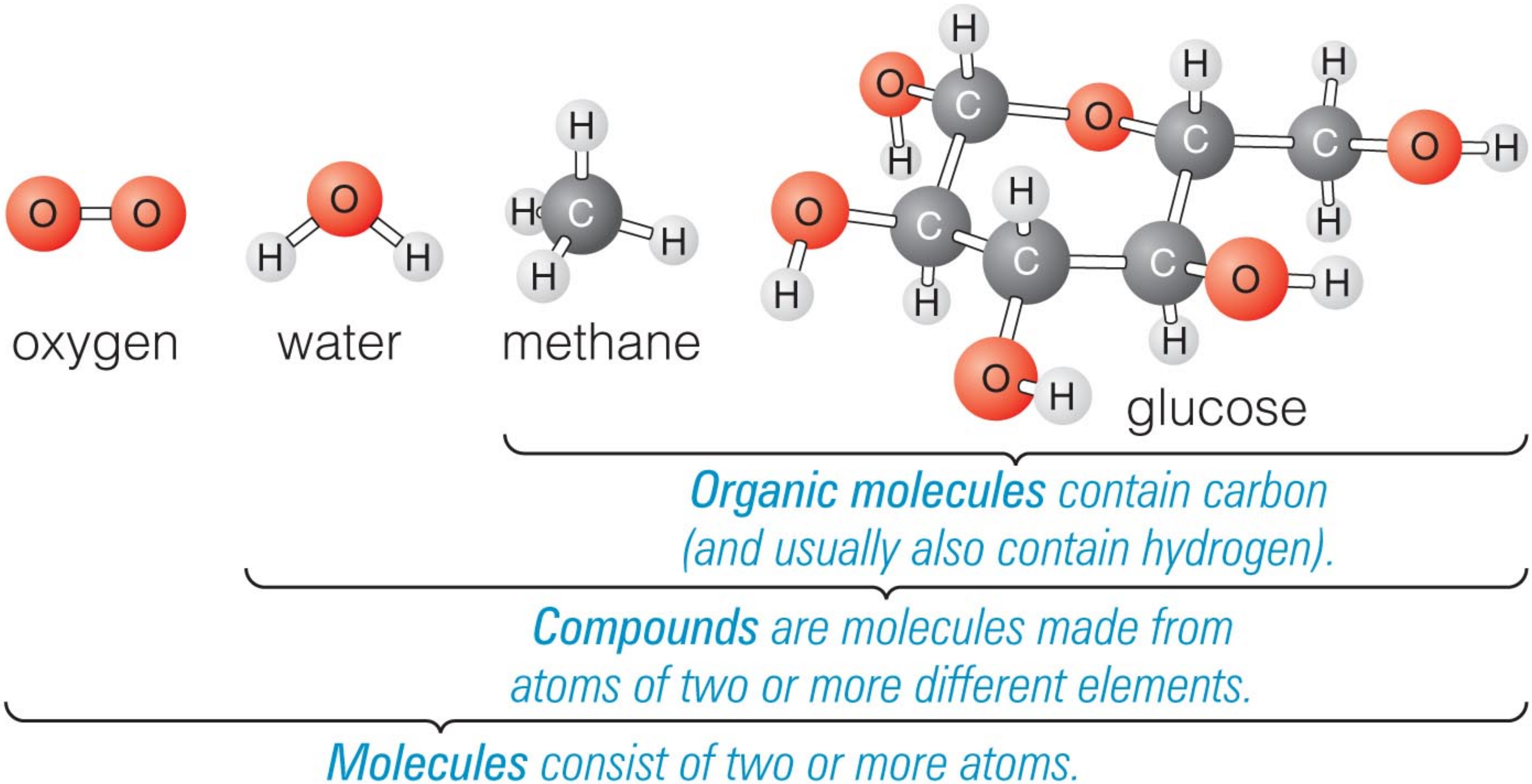
Atomic Terminology

- Isotope: same # of protons but different # of neutrons. (^{4}He, ^{3}He)



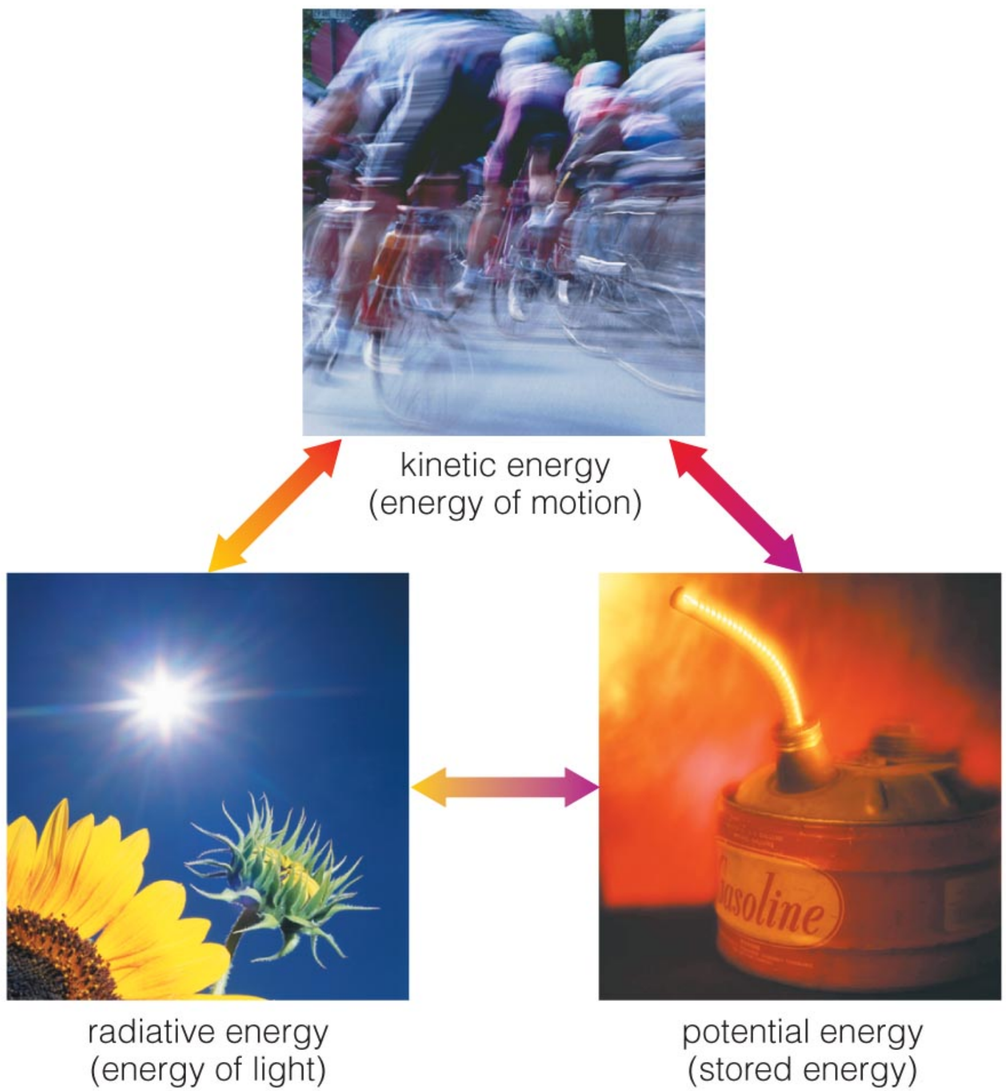
Atomic Terminology

- Molecules: consist of two or more atoms (H_2O, CO_2)



What is energy?

Energy can be converted from one form to another.



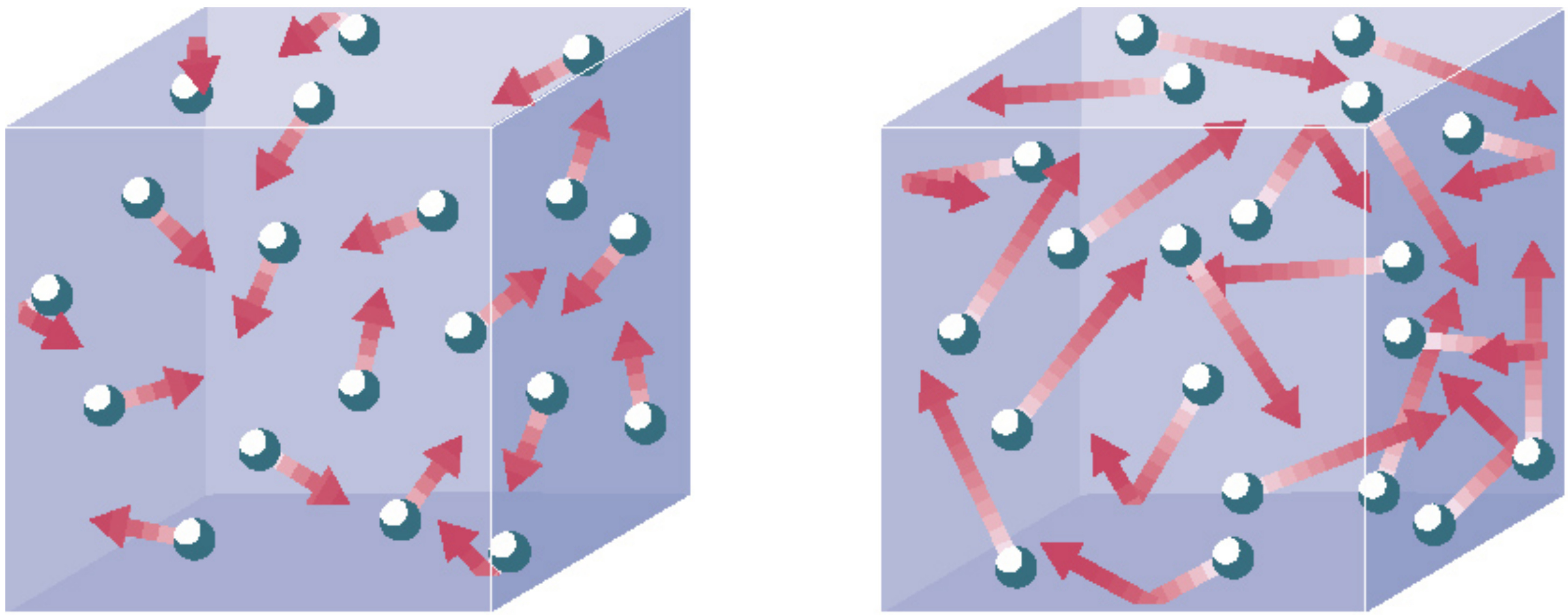
Energy is a very broad concept, basically it's anything that can make matter move or change

Energy changes forms but is not created or destroyed: this is a law of physics

Life mostly uses light energy (the Sun) and potential (chemical) energy from molecules

In all matter, anywhere in the universe, atoms and molecules in constant, microscopic motion

Temperature is a measure of the *average* kinetic energy of the many particles in a substance.



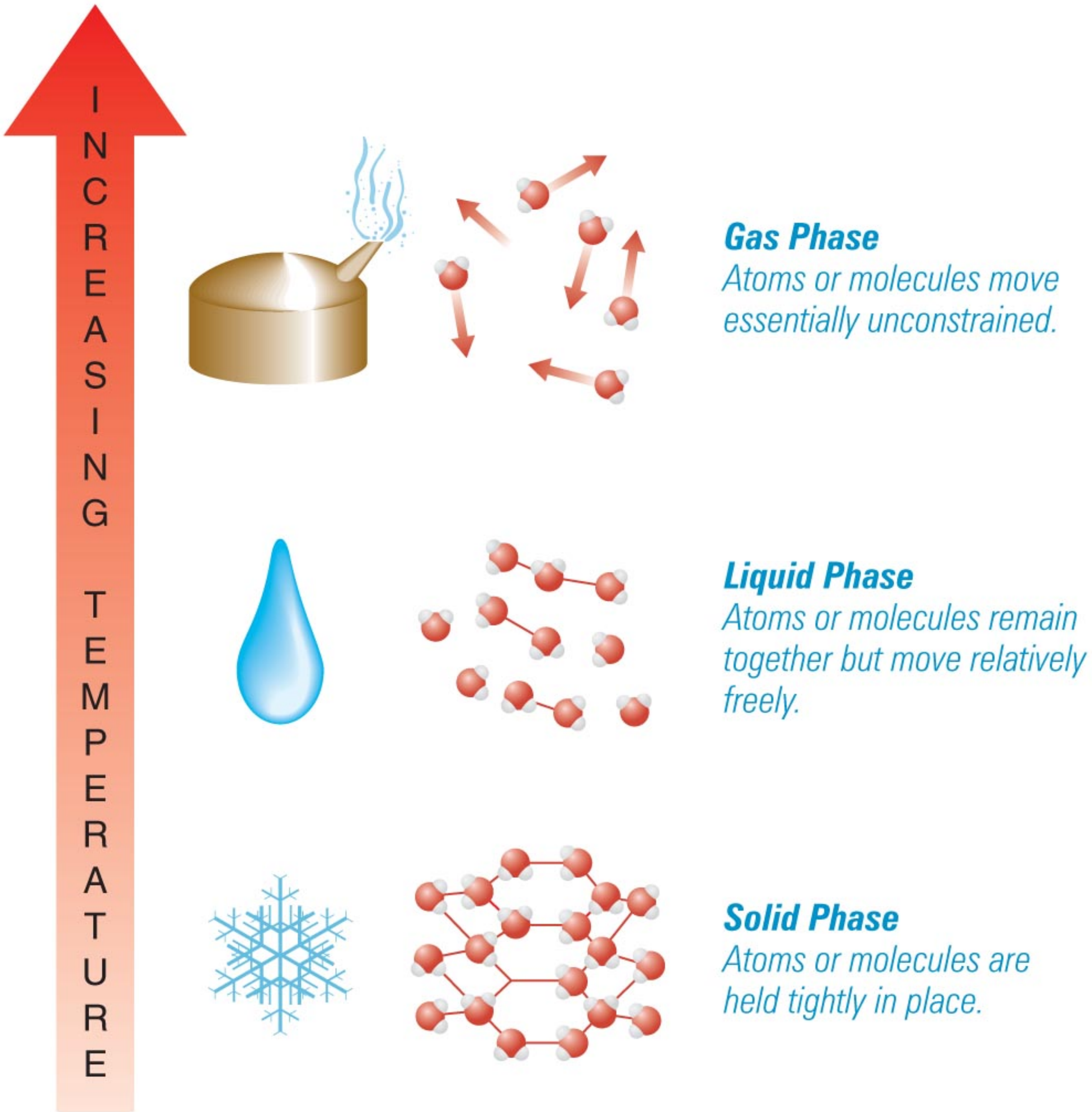
Longer arrows mean higher average speed.

All atoms and molecules in the universe are in constant microscopic motion or vibration:

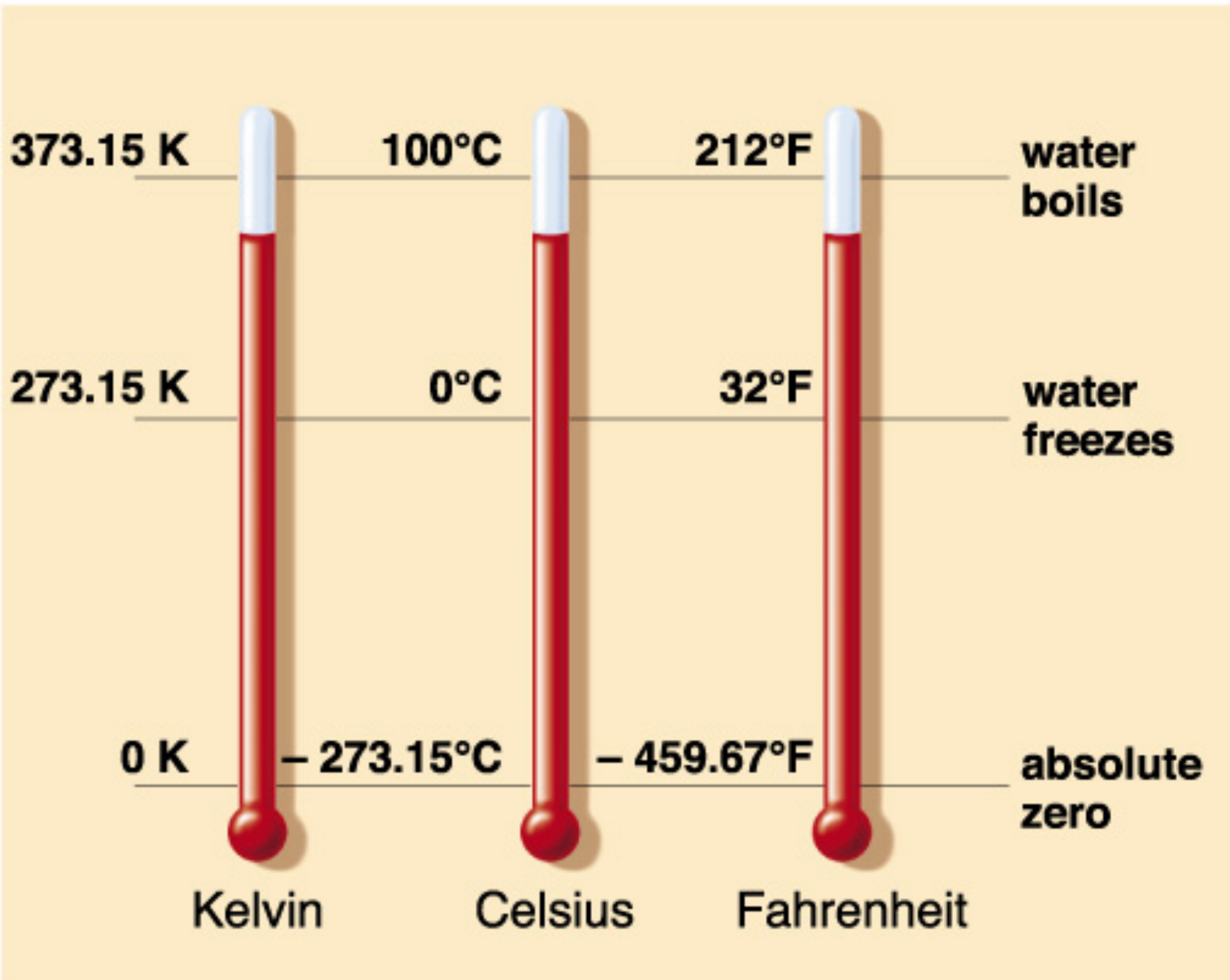
Thermal energy

As a result, every substance emits a smooth spectrum of radiation, mostly at invisible infrared wavelengths:

Thermal radiation



Temperature Scales



Stars are thousands of degrees

Terrestrial planets

Outer gas Planets

Most of the universe

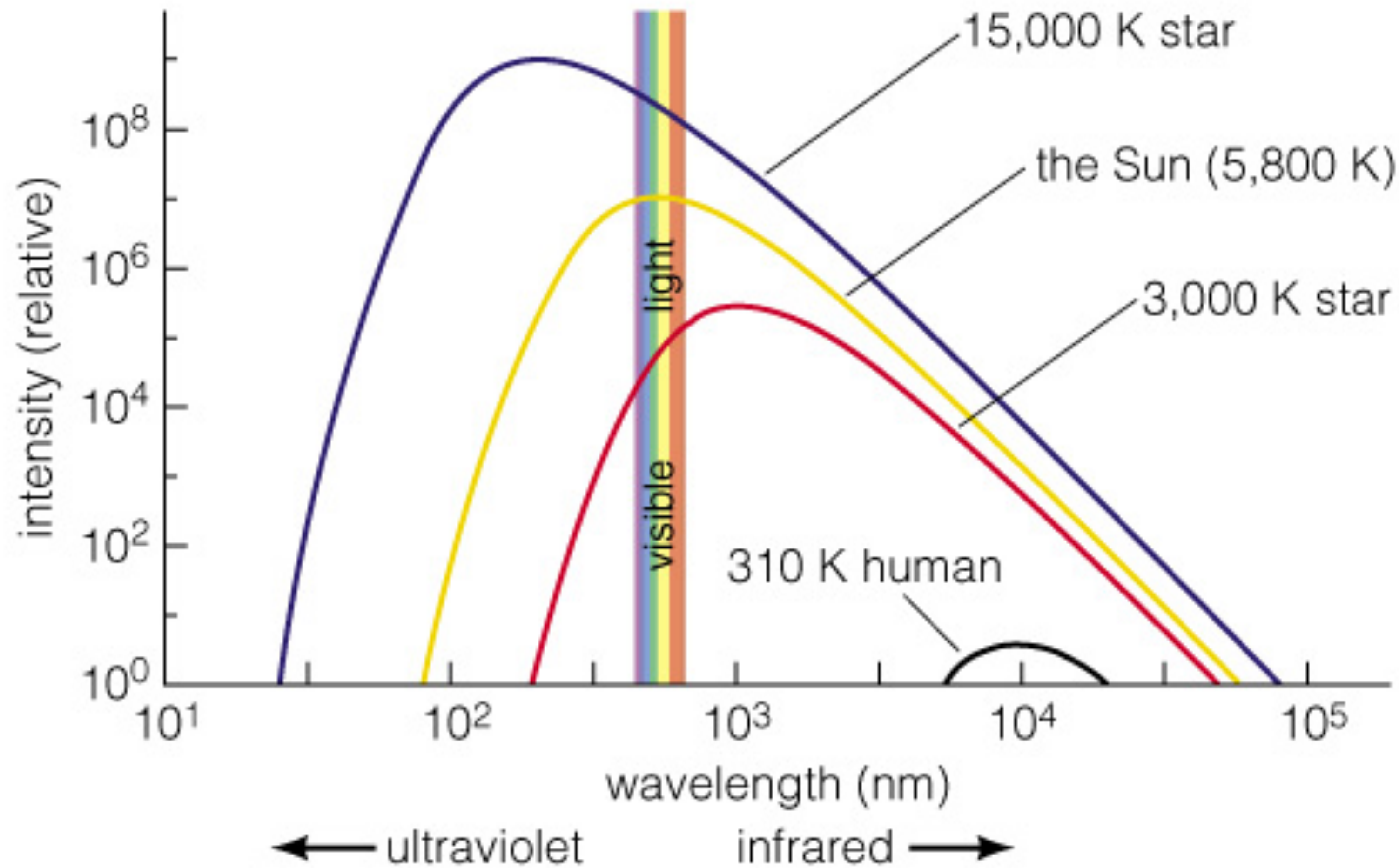
How does light tell us the temperatures of planets and stars?

Thermal Radiation

- Nearly all large or dense objects emit thermal radiation, including stars, planets, you, me…
- Thermal radiation has a smooth and broad spectrum, like the Sun's rainbow of color
- An object's thermal radiation spectrum depends on only one property: its **temperature**

Two Properties of Thermal Radiation:

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.



How do light and matter interact?

- Emission
- Absorption
- Transmission
- Reflection or Scattering

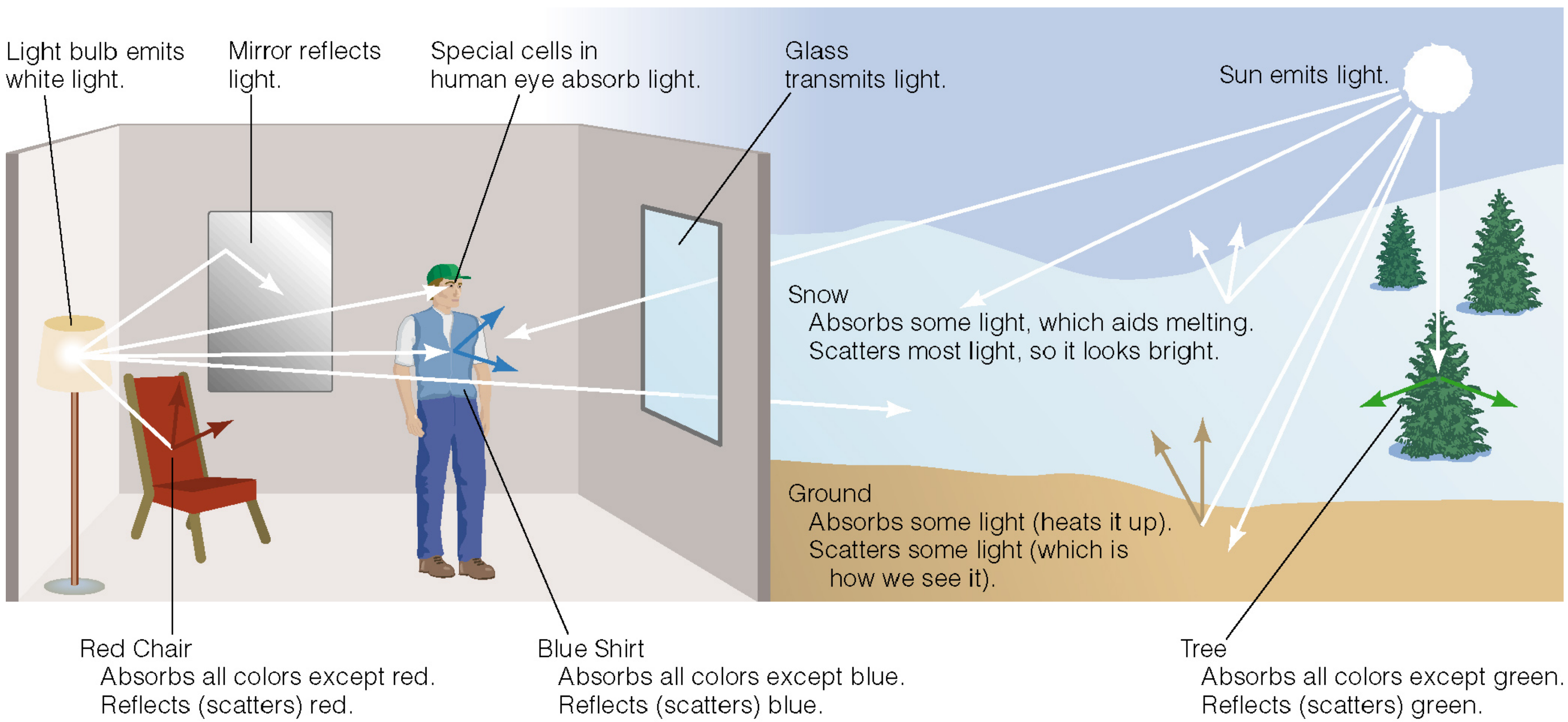
} Everything we know about the universe is a result of these effects

Terminology:

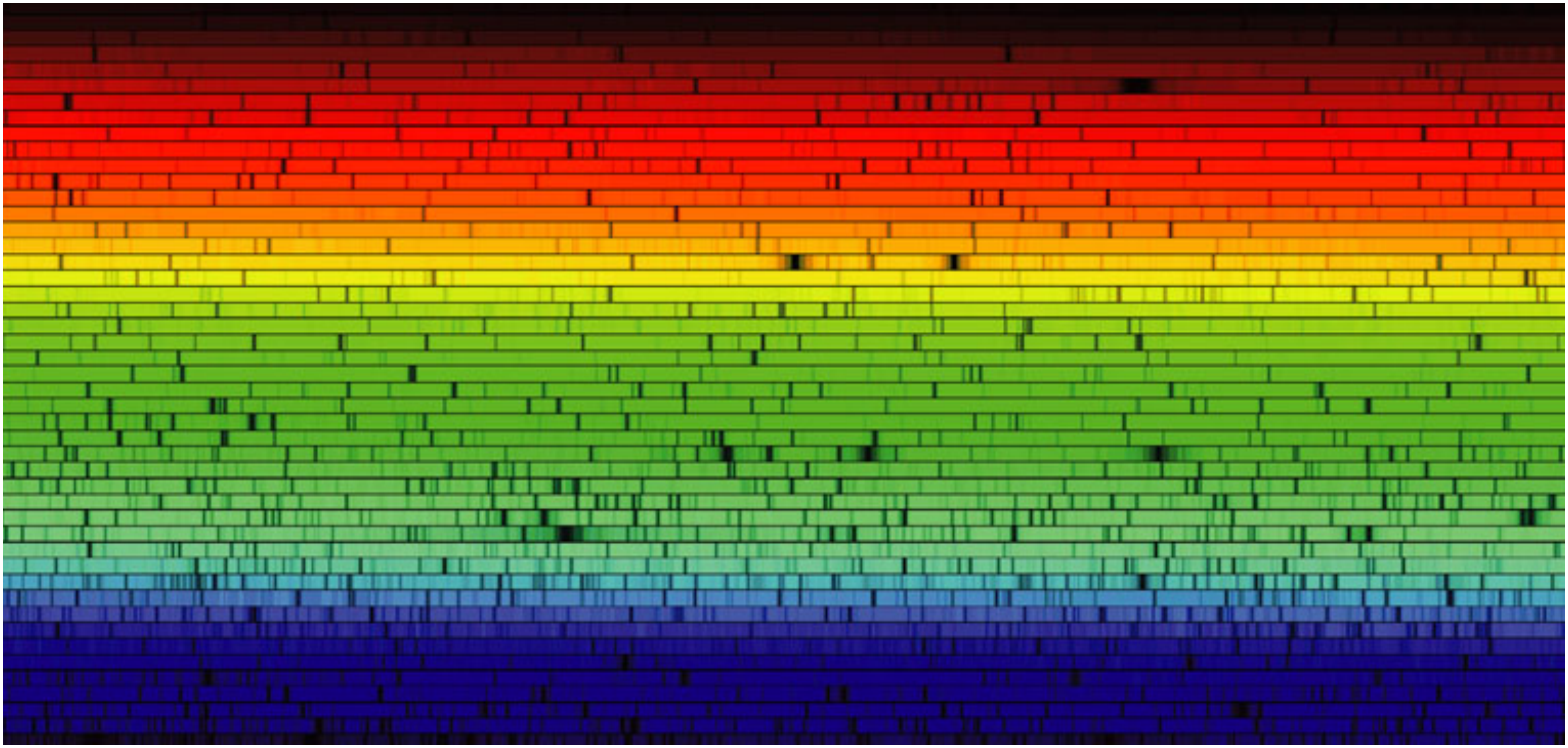
- Transparent: transmits light
- Opaque: blocks (absorbs) light

Interactions of light and matter

Applied to a distant object like a planet, this can give us important physical information ➡ remote sensing



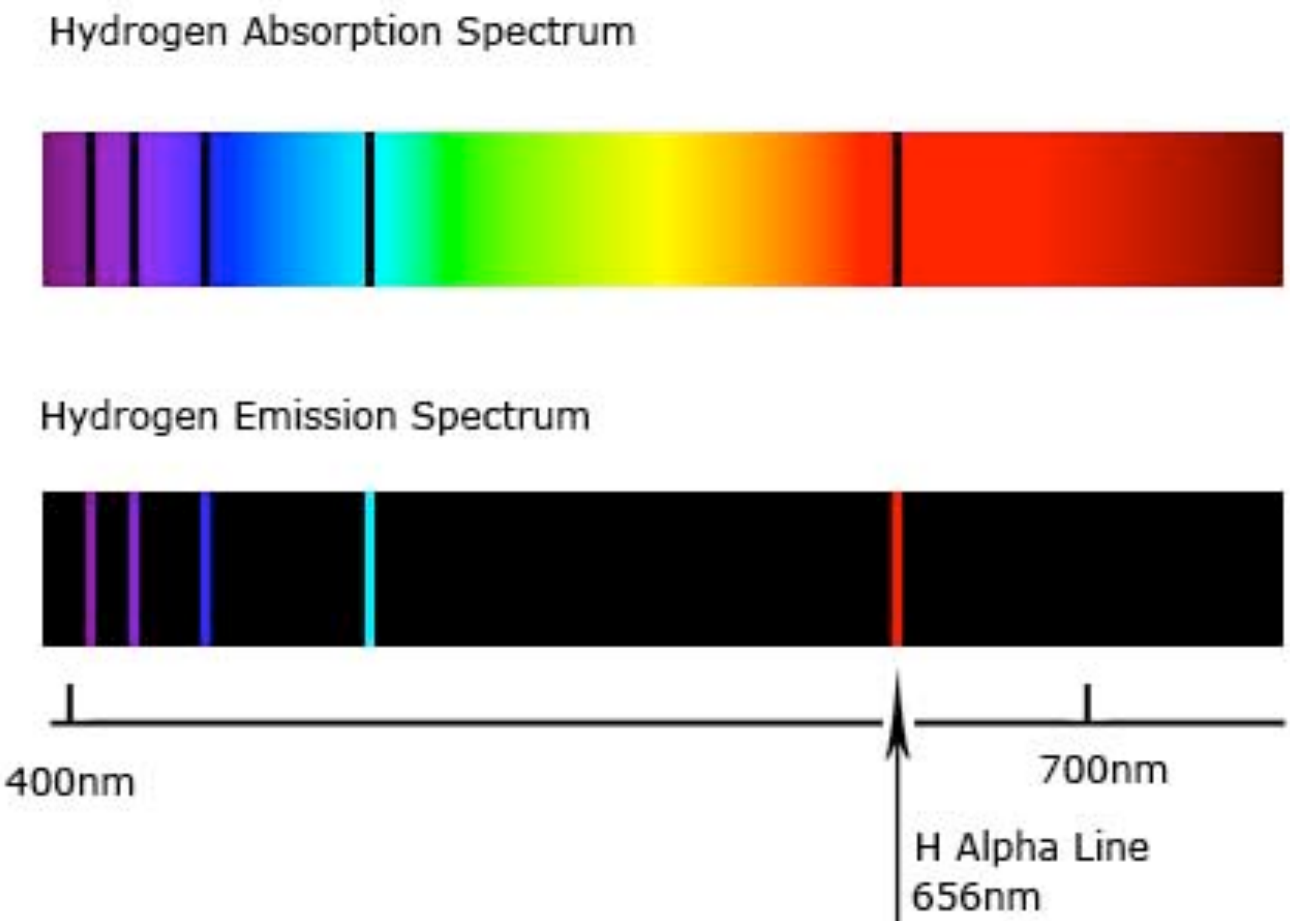
Example: the Sun's Spectrum



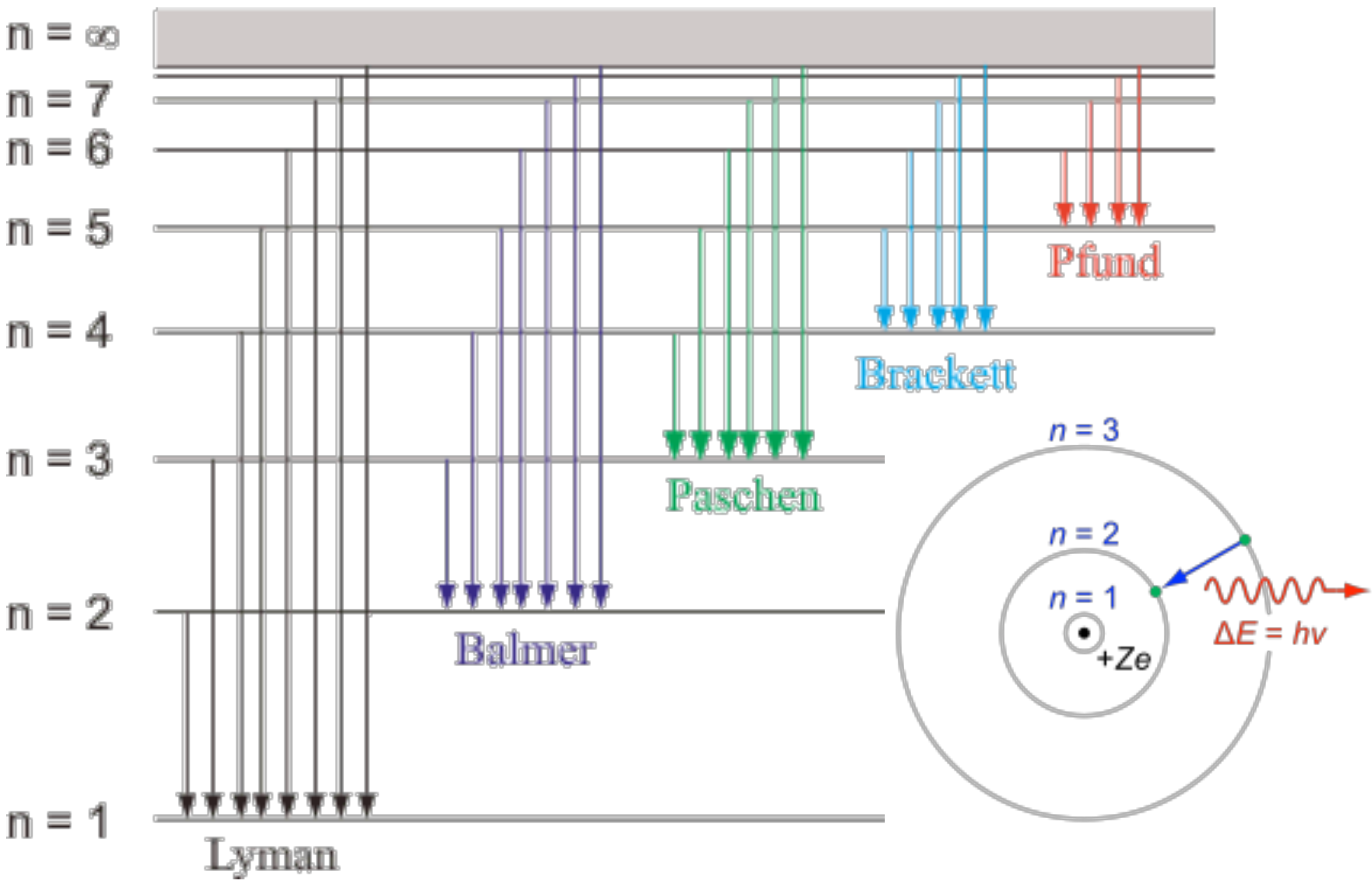
Chemical Fingerprints

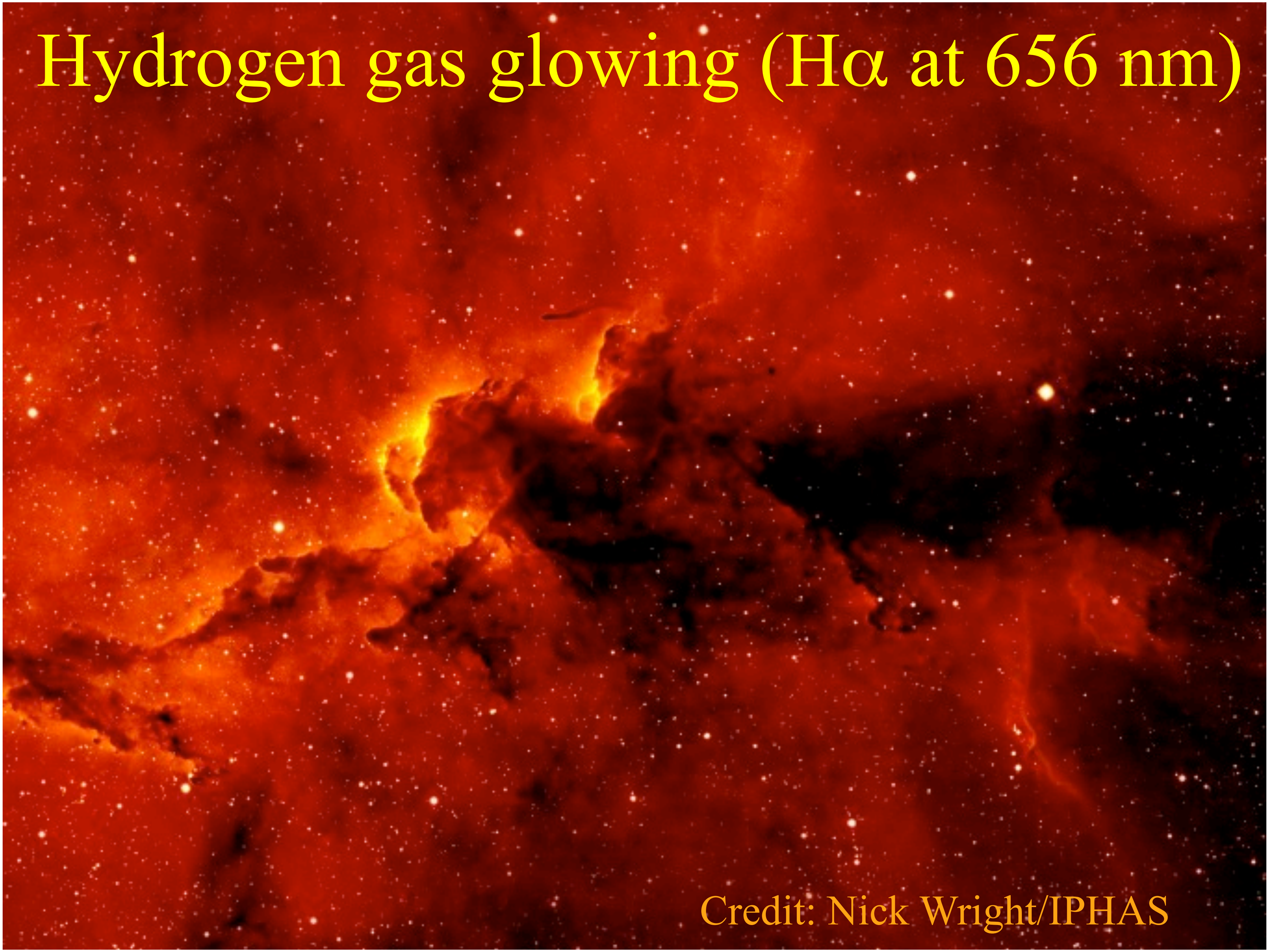
- Every atom, ion, and molecule has a unique spectral "fingerprint"
- We can identify the chemicals in gas by their fingerprints in the spectrum.
- With additional physics, we can figure out abundances of the chemicals, and often the temperature, pressure, and much more.

Example: Hydrogen Spectrum

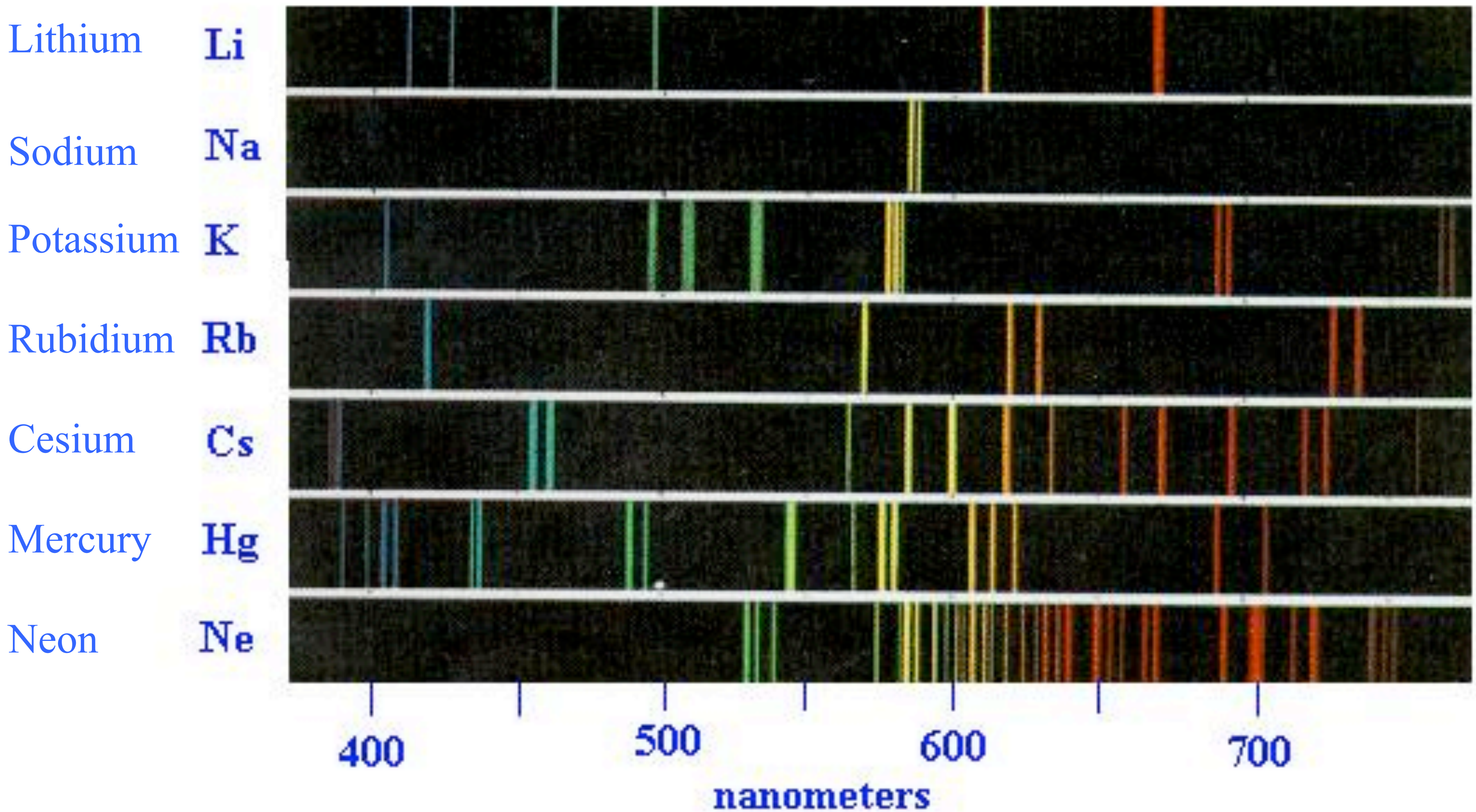


Hydrogen ***Electronic*** Energy Levels




Hydrogen gas glowing (Hα at 656 nm)
Credit: Nick Wright/IPHAS

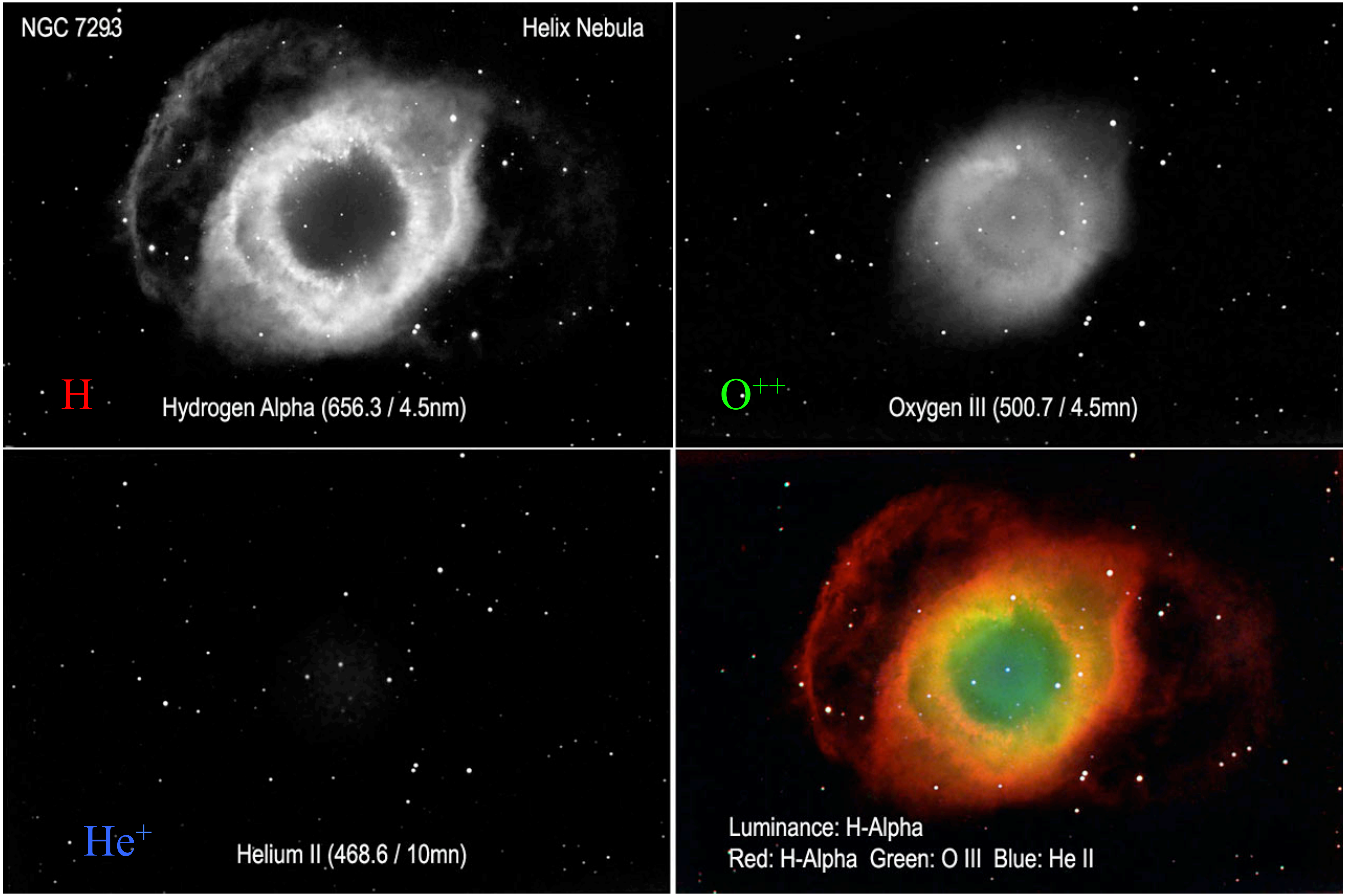
Example: More Elements…



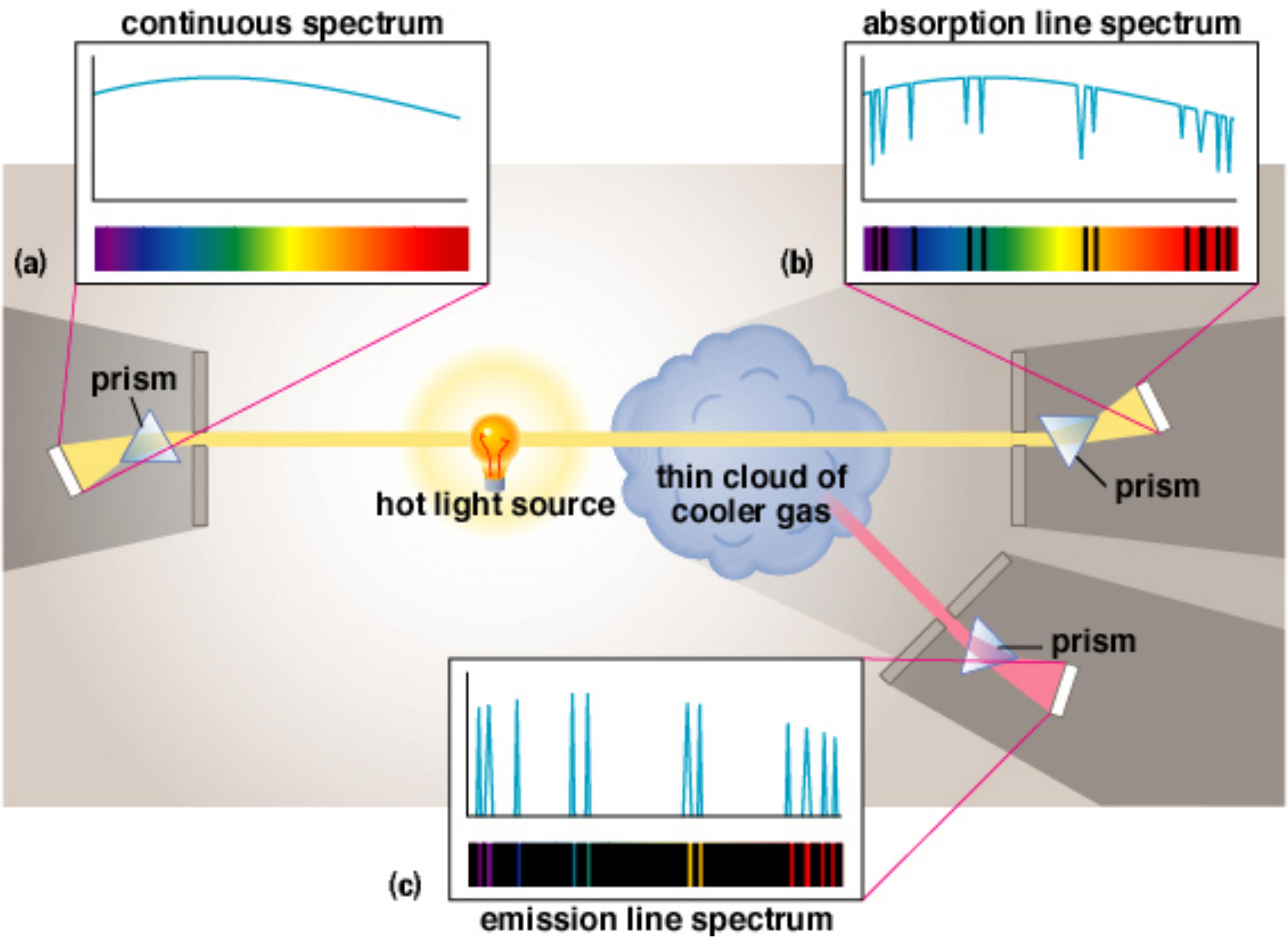
Sodium gas glowing (yellow light)

Look at previous slide to see why it is yellow…

We can even see ionized elements!



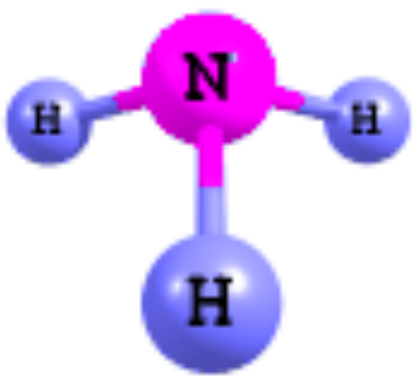
What types of light spectra can we observe?



We also see molecules in space

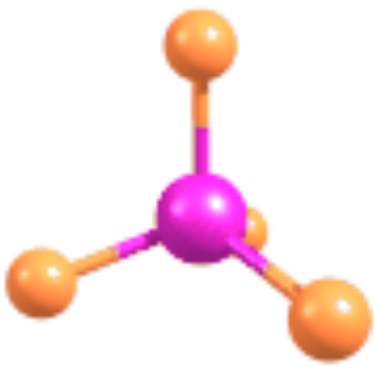
In addition to electronic transitions, molecules can also vibrate and rotate. These transitions are at lower energy and thus occur in the infrared to radio wavelengths.

Vibration



Vibrations are quantized

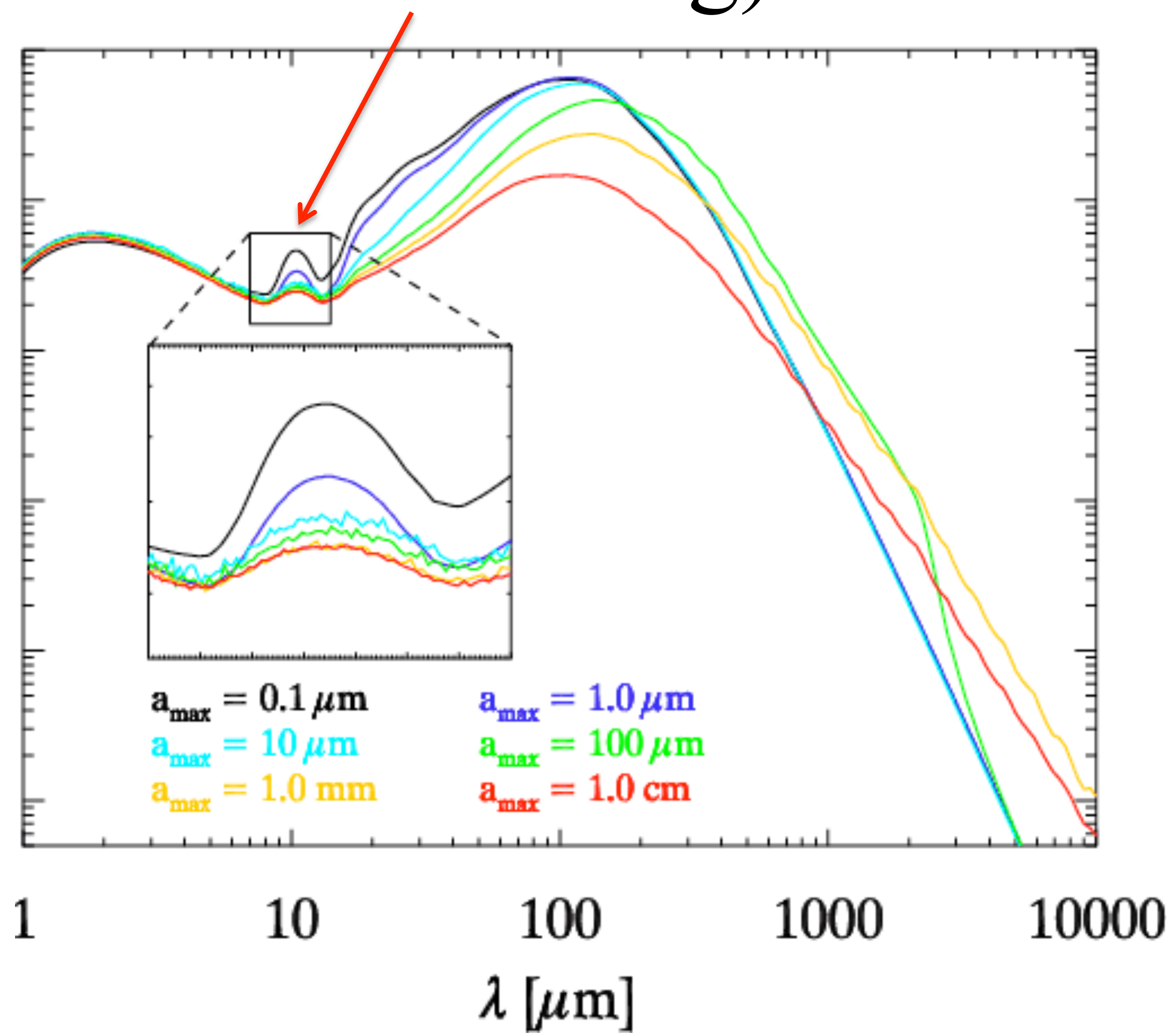
Rotation



Rotations are also quantized

Obscuring Dust Cloud … what is it made of ??

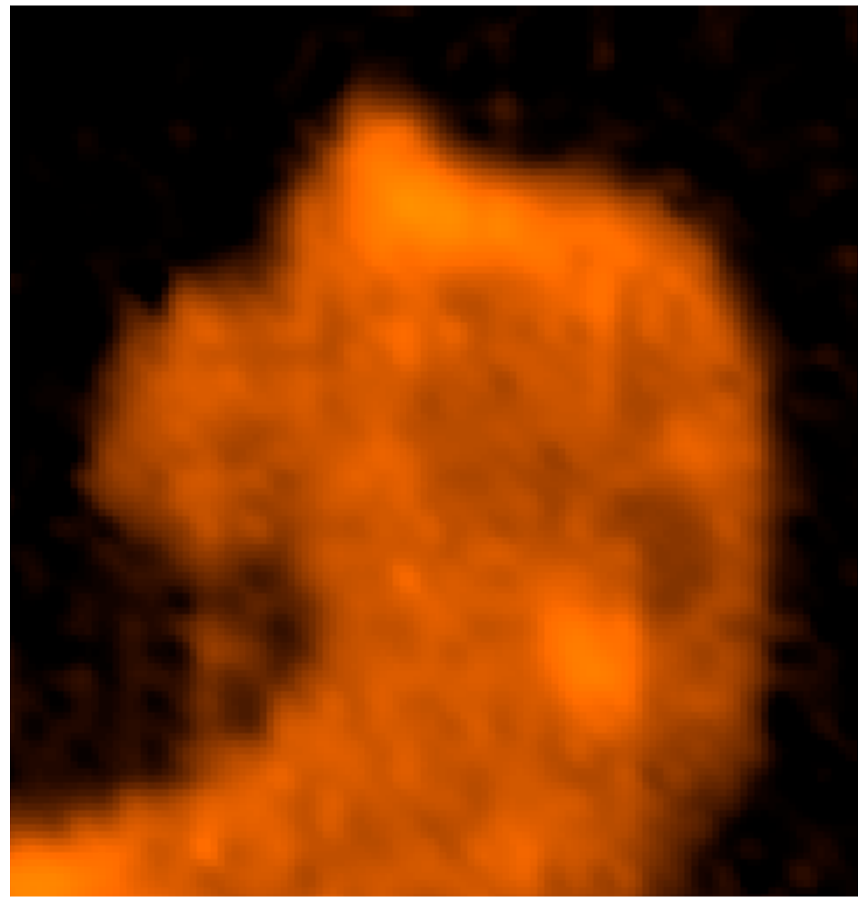
Dust is made primarily of Silicates (Si-O bonds vibrating)



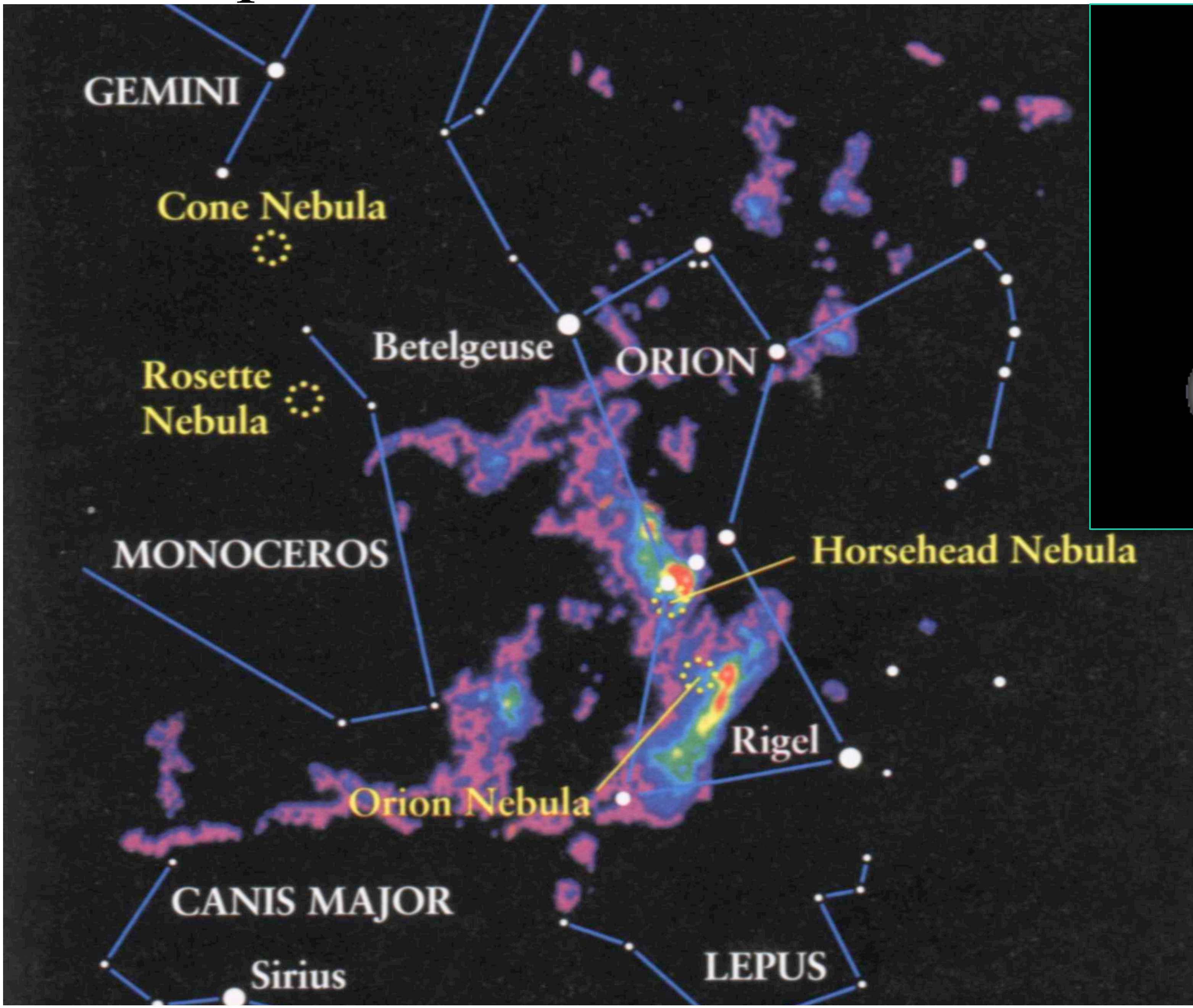
Example: Rotational Transitions

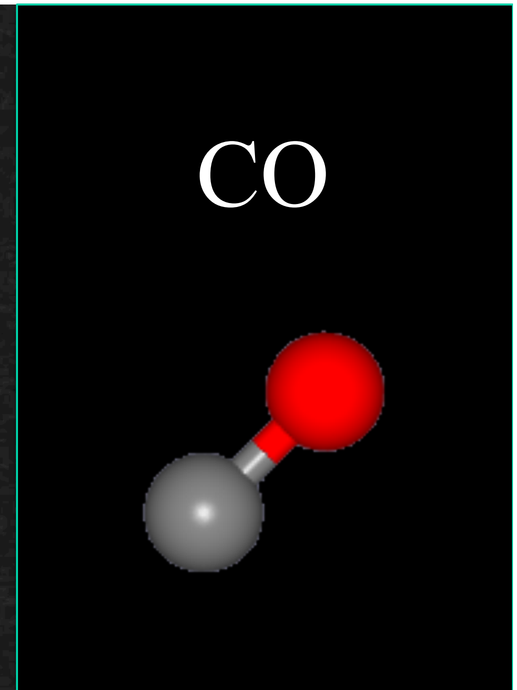
Optical Image

Carbon Monoxide molecules



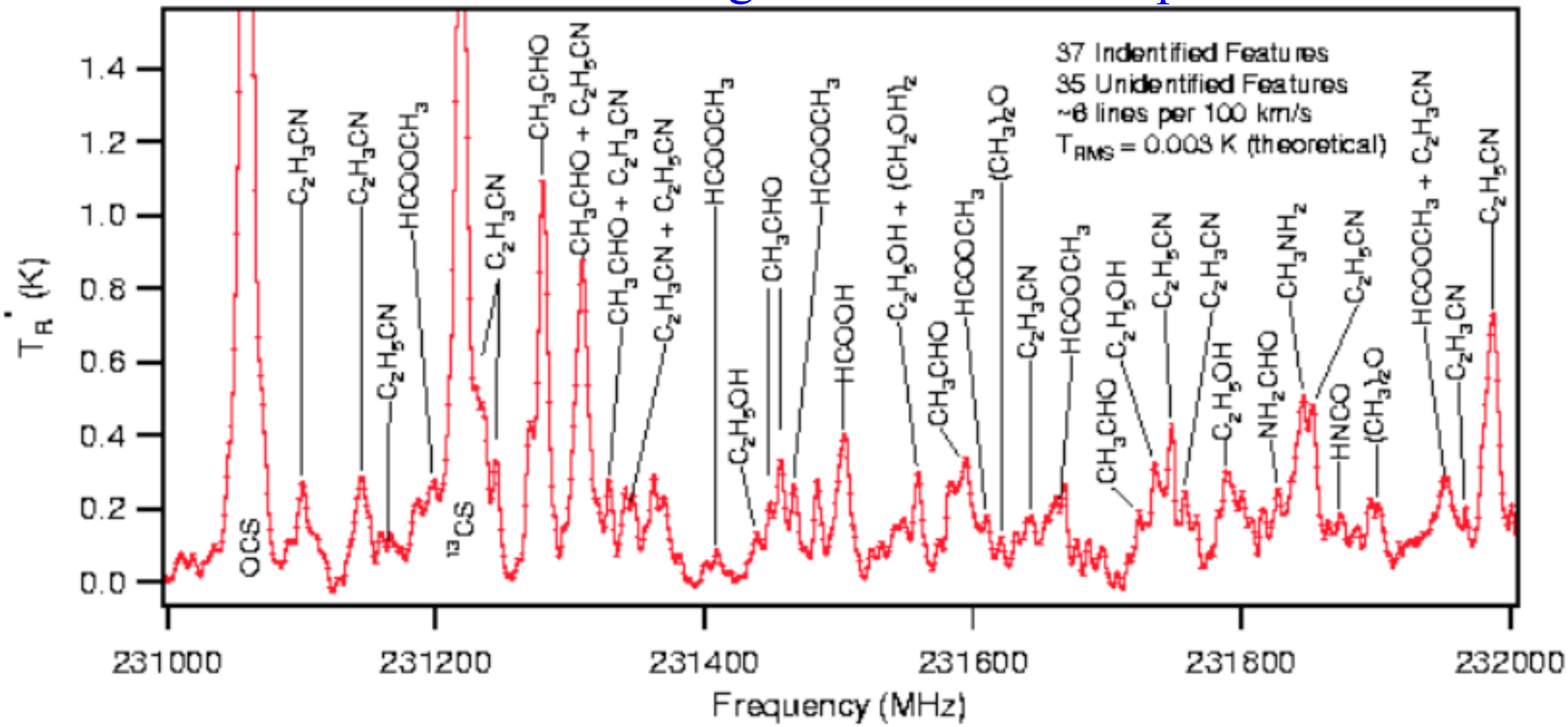
Example: Carbon Monoxide towards Orion





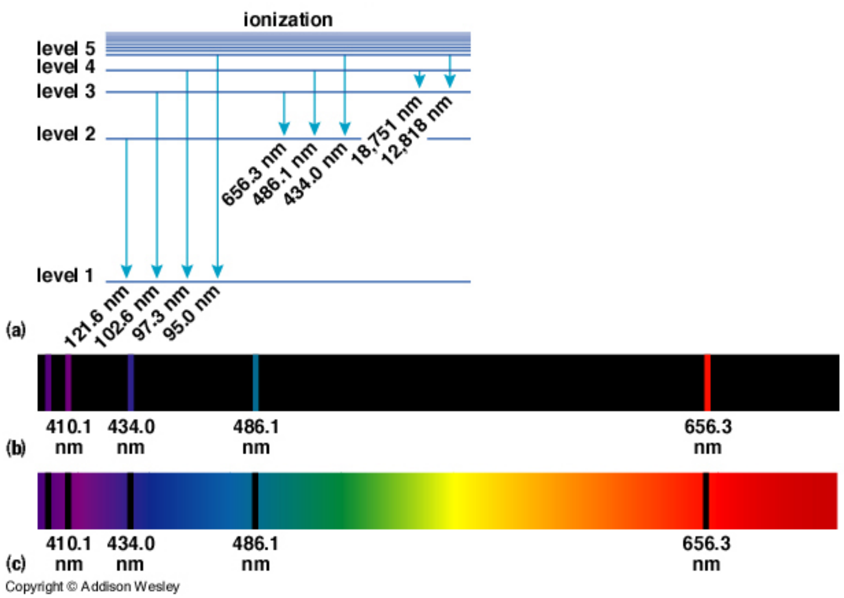
Rotational Transitions in Radio Spectrum

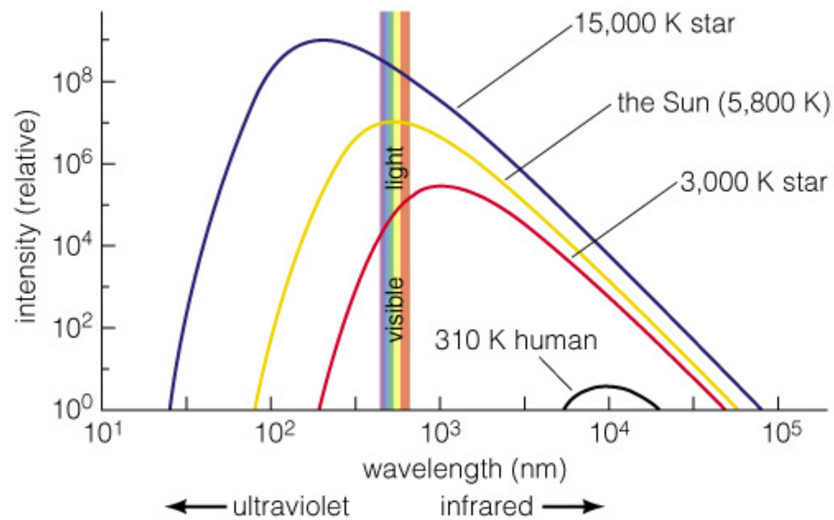
Detections of organic molecules in space!



Wavelength ~ 1mm. The frequency of this observations is ~2000x higher than FM radio

Two Fundamentally Different Spectral Mechanisms





Spectral lines:

- narrow, sharp features
- pattern unique to each element
- gives chemical composition
- emission (hot, diffuse gas)
- absorption (cool, diffuse gas)

Thermal radiation:

- broad, smooth continuum
- peak emission gives temperature
- higher temp, shorter wavelength
- no information on composition
- everything emits thermally