Astro 7: Chapter 5 – Matter & Light

- The Atom and its components
- The 4 phases of matter
- Light – traveling electromagnetic waves, quantized as “photons”
- The two ways to create photons.
- Atoms vs molecules – absorption lines from atoms, but absorption bands from molecules, and relation to climate and greenhouse effect
- The thermal radiation laws
- Molecules and absorption

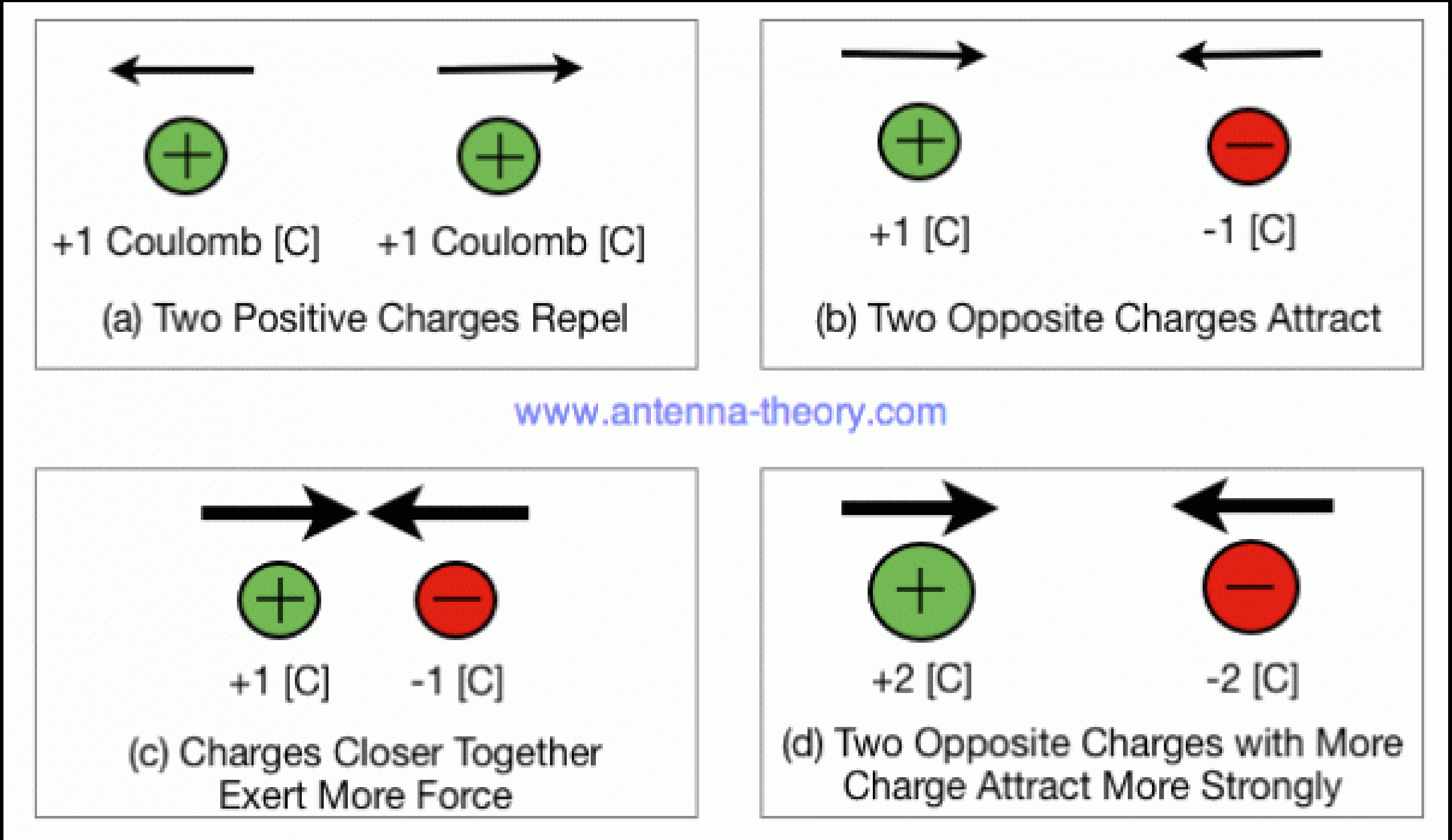
The Three Stable Particles Making up Most Ordinary Matter

- Proton: Mass = 1 AMU, charge= +1
- Neutron: Mass = 1 AMU, charge = 0
- Electron: Mass = 1/1860 AMU, charge = -1

Mass and Charge

- In classical physics, mass has an associated force: ***Gravity***
- Another quality possessed by elementary particles is ***charge***. Comes in two flavors; positive and negative. Likes repel, and opposites attract.
- The associated force is called ***Electromagnetism***

Opposites Attract, Likes Repel

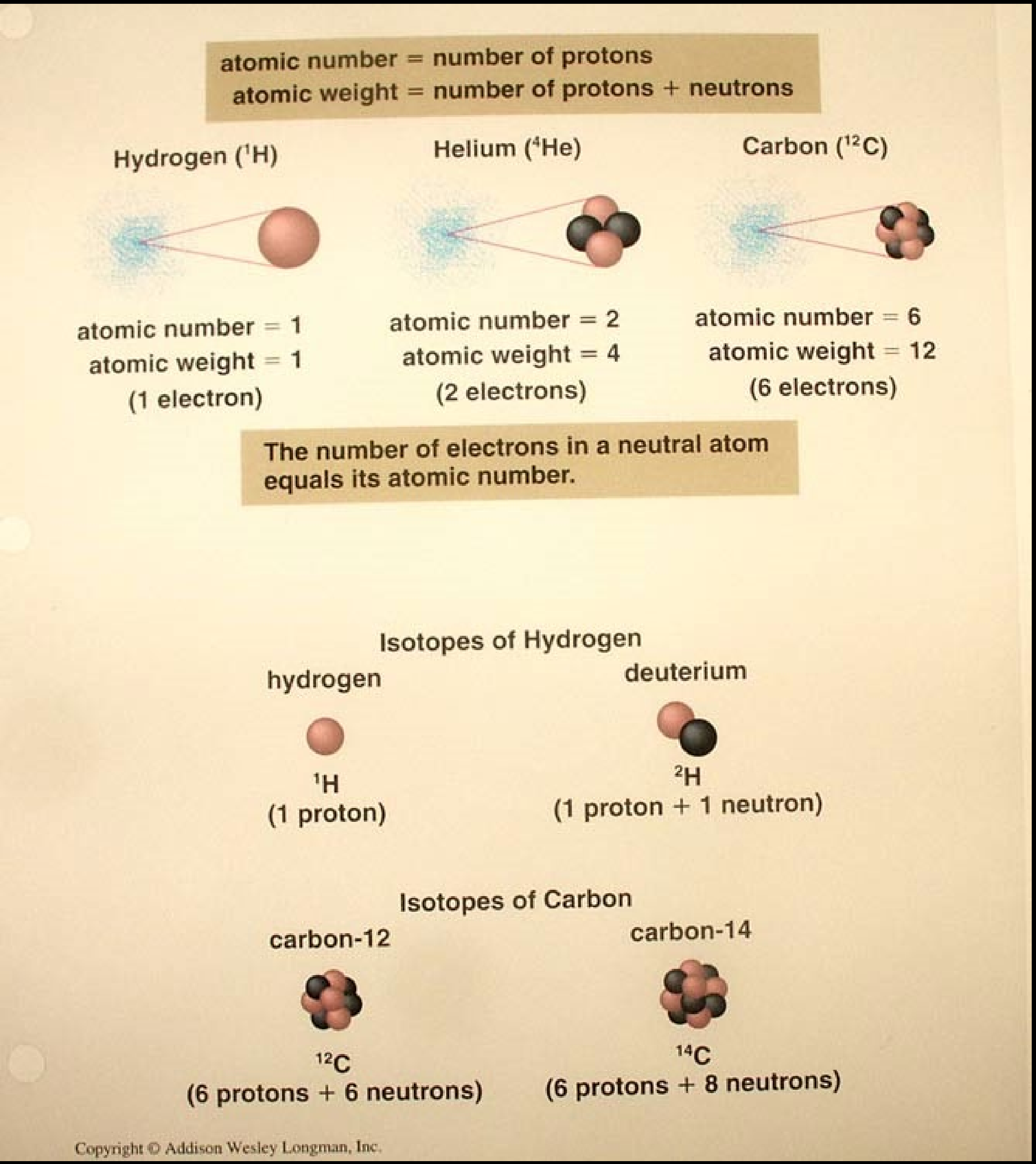


An Atom is Made Up of..

- A nucleus of protons (+ charge) and neutrons (zero charge).
- A “cloud” of electrons surrounding the nucleus; as many electrons as there are protons.
- Electron energies are *quantized* – they can only take on certain discrete values. This is the realm of **Quantum Mechanics**, and your intuition will need a heavy dose of new thinking! (see chapter S4 for the curious, but not required for Astro 7)

Different Electron Number Means Different Chemistry, so We Give Different Names…

- ***Hydrogen*** – 1 proton. ~90% of all atoms are hydrogen
- ***Helium*** – 2 protons – most other atoms are helium
- ***Lithium*** – 3 protons
- ***Beryllium*** – 4 protons
- ***Boron*** – 5 protons
- ***Carbon*** – 6 protons
- Etc, up to ***Uranium*** – 92 protons



atomic number = number of protons
atomic weight = number of protons + neutrons

Hydrogen (^{1}H)

atomic number = 1
atomic weight = 1
(1 electron)

Helium (^{4}He)

atomic number = 2
atomic weight = 4
(2 electrons)

Carbon (^{12}C)

atomic number = 6
atomic weight = 12
(6 electrons)

The number of electrons in a neutral atom equals its atomic number.

Isotopes of Hydrogen

hydrogen
^{1}H
(1 proton)

deuterium
^{2}H
(1 proton + 1 neutron)

Isotopes of Carbon

carbon-12
^{12}C
(6 protons + 6 neutrons)

carbon-14
^{14}C
(6 protons + 8 neutrons)

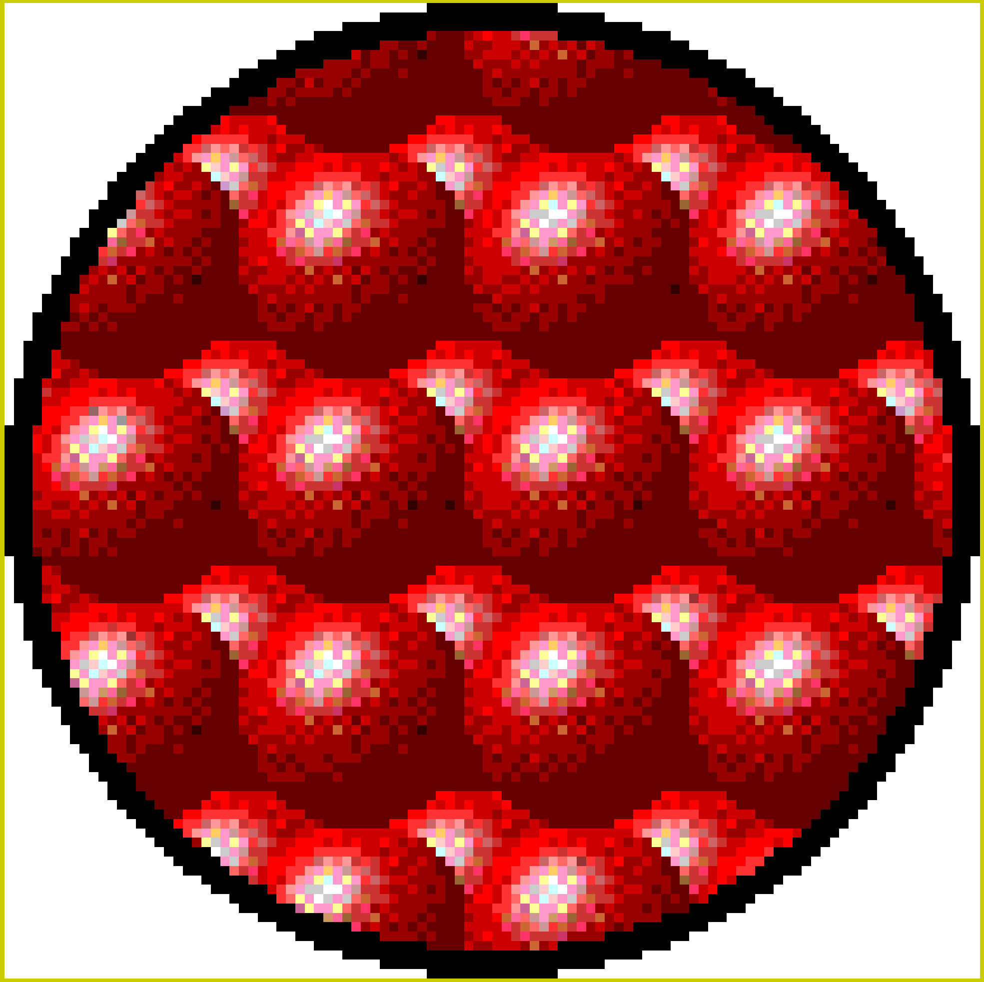
Different Isotopes of an Atom = Different numbers of neutrons. Doesn't affect the chemical bonds since neutrons have no net charge. Different isotopes CAN have different chemical reaction rates because of their different mass and hence different behavior at a give temperature. <u>This makes isotope ratios a good proxy for temperature.</u> More on that later

The 4 Phases of Matter

1. Solid

- Atoms are “elbow-to-elbow” and keep their relative positions, but can still vibrate.
- The material is *incompressible.* If you squeeze it, it won’t get smaller.

A Solid: The Atoms keep their same neighbors and just jiggle around (but not locked together like this over-simple .gif)



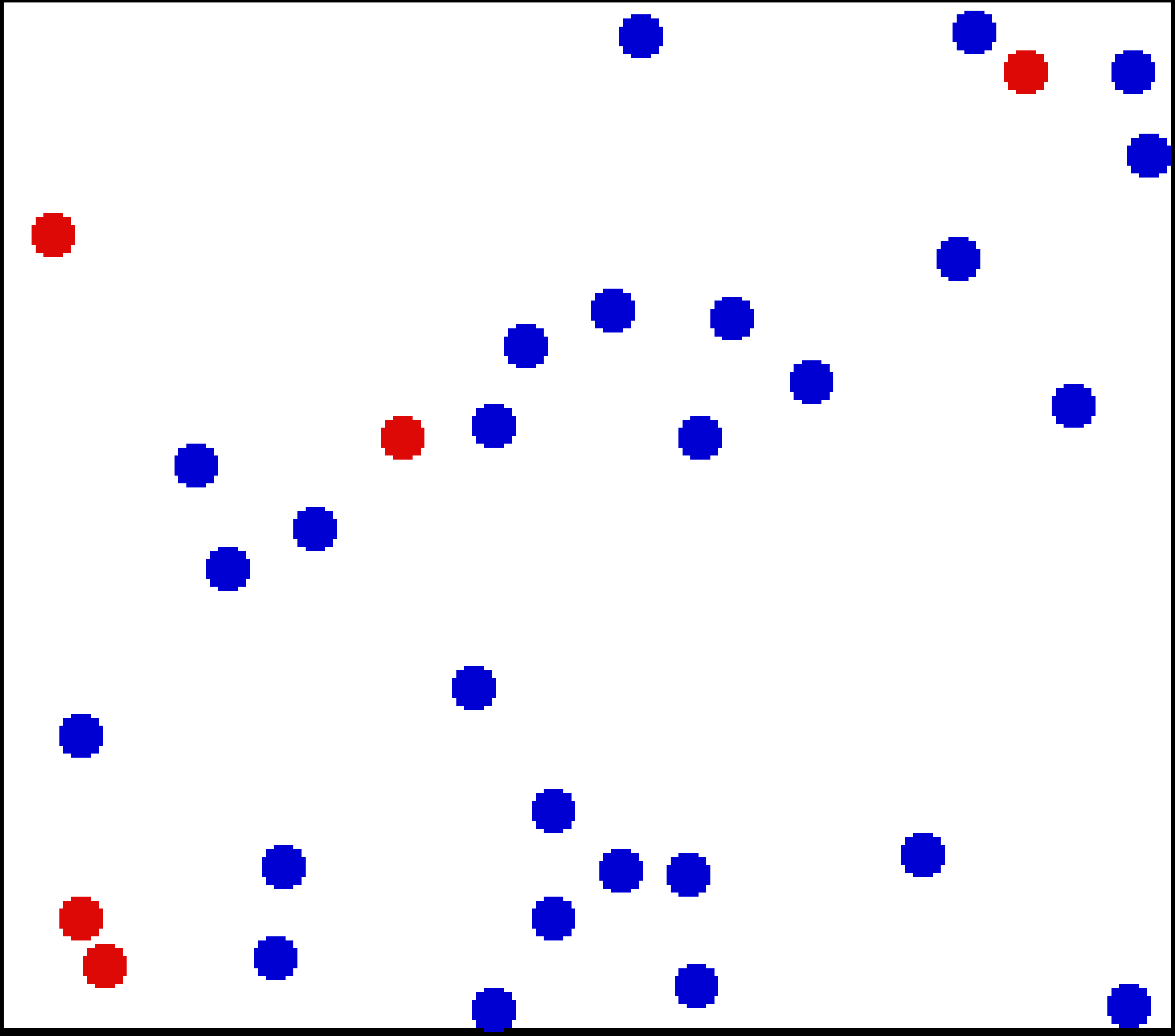
2. Liquid

- Atoms are still “elbow-to-elbow”, but now there’s enough energy to keep the atoms from keeping their same neighbors, and they mill around square-dance fashion.
- The material is still *incompressible*, but now it can flow.

3. Gas

- Atoms now have enough energy to keep from “sticking” at all.
- The atoms (or molecules) now are caroming off each other like balls on a pool table.
- With empty space around each atom, the material is now *compressible*.

Atoms (or molecules) in a Gas



4. Plasma = Ionized Gas

- At high temp, atoms hit each other so violently they knock electrons off the atoms and keep them knocked off. Each atom now called an “ion” and is positively charged. Negatively charged electrons also bouncing around.
- Charged – so feels the EM force, and in an EM field, behaves in a complex way compared to an ordinary (neutral) gas (more on EM fields later).
- Very roughly, the field locks together with the ionized gas; on a larger scale, they move around together. Unlike a neutral gas, which hardly notices if it’s in a magnetic field.
- Otherwise, it still is like a gas (compressible, empty space around each ion)
- (An atom can sometimes have one too many electrons too; that’s also an ion. Classic example is the H^- ion).

Most atmospheres are almost entirely neutral gas, not ionized

Now Let’s See How Light Is Produced…

- To do that, we first need to get a feel for how charges “feel” each other, and the nature of the electromagnetic field

The Field Paradigm

- A charge sets up an **Electromagnetic Field** around itself, permeating all of space, and this field acts directly on other objects.
- It is the FIELD which has reality, has energy, and yet it itself has no mass.
- (Surprising, perhaps - things can physically exist and yet have no mass)
- The force felt at a location has an *strength*, and a *direction*, so therefore it is a *vector field*

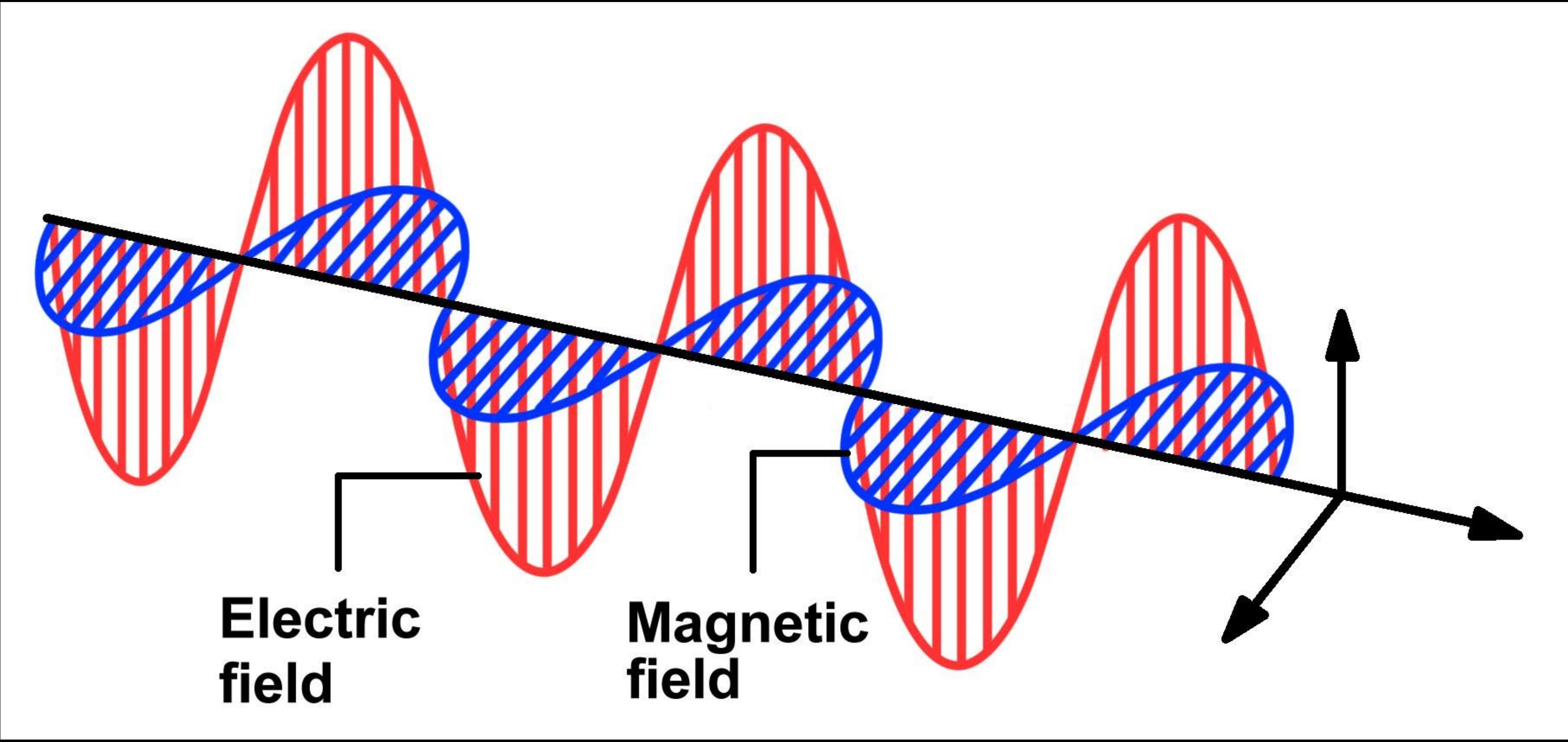
A Changing ***Electric*** field Creates a ***Magnetic*** field…

- Accelerate a charge, you wiggle the associated field, and this wiggle moves outward at the speed of light. 300,000 km/sec
- But this changing electric field creates a magnetic field, and a changing magnetic field creates an electric field
- **And a moving electro-magnetic field is… LIGHT!**

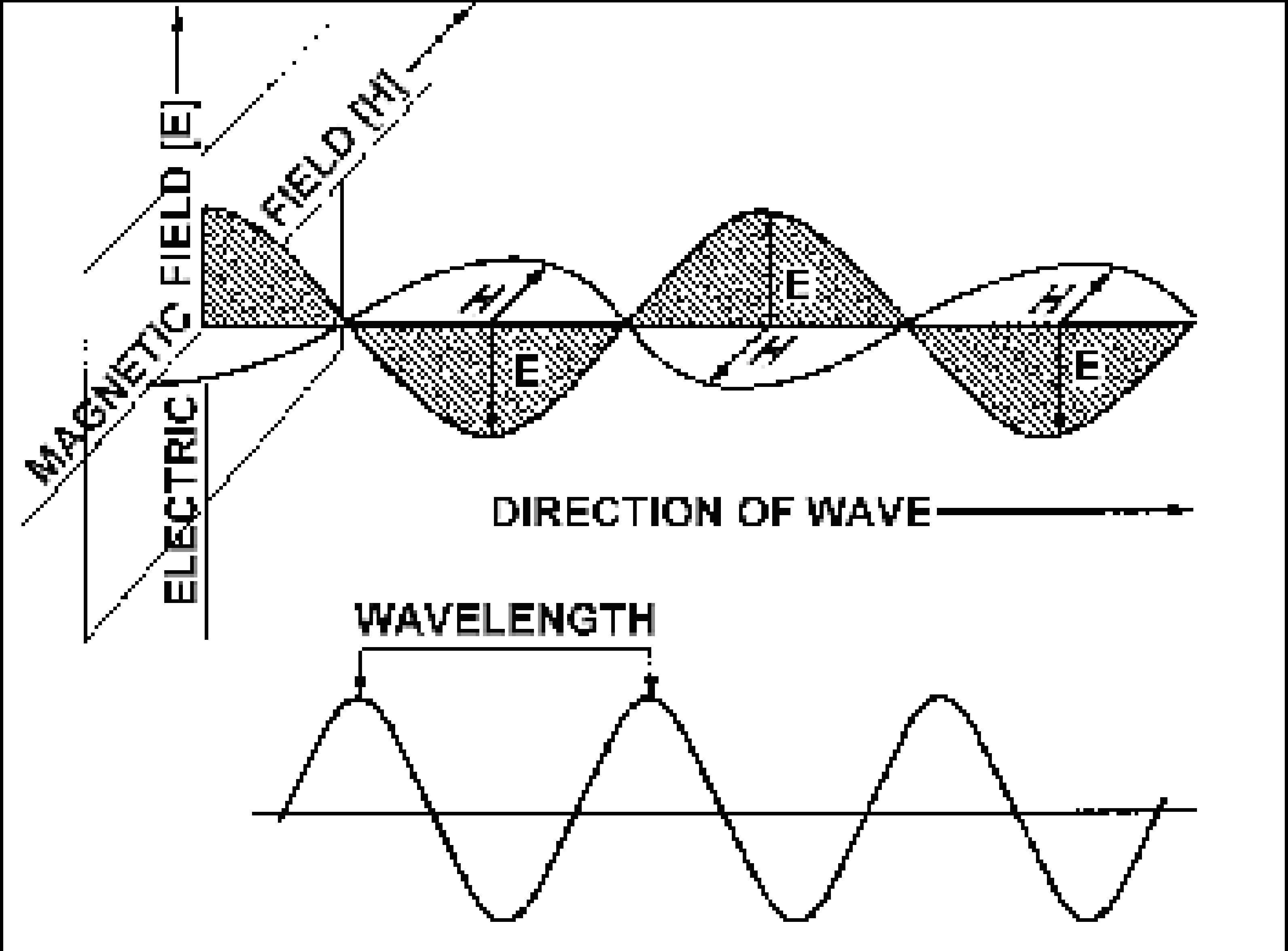
EM Field Waves: Quantized, as Photons

- These field changes are not quite like water waves; they’re quantized into individual little bundles of energy possessing wave-like and particle-like characteristics.
- They are… ***photons***
- How to picture a photon?....

Light: A Travelling EM Wave



A Photon: A Travelling Oscillating Electric and Magnetic Field



The Energy of a Photon…

All photons travel at the same **speed** no matter who's observing them.

Does it feel in your intuition like shorter wavelength photons should have **more energy?**

Or **less energy?**

…than longer wavelength photons?

The Energy of a Photon…

- Your intuition is (I expect) correct! …
- **More rapidly oscillating** waves have **more energy**
- Said another way; higher ***frequency*** (how many wave crests arrive per second) corresponds to more photon energy
- And so, **shorter wavelength corresponds to higher frequency and higher photon energy**

Nature is Simple Here

- She's decided to go with the simplest mathematical expression which embodies these two correct intuitions
- $E = hc/\lambda$, where λ is the wavelength of the wave, and **c** is the speed of light and ***h*** is Planck's Constant
- (The fact that $h=6.626 \times 10^{-27}$ ***erg-seconds, or*** 6.626×10^{-34} ***joule-seconds***) is so very tiny, is telling us that quantum mechanics is, pretty much, only obvious at very tiny size scales)
- ***For this class, you only need to remember: higher frequency photons = shorter wavelength photons = higher energy***

The Two Ways to Produce Photons…

- 1. Accelerate a charge, as we just showed.
- 2. Transitions within atoms or molecules between allowed energy levels (or “orbitals”) in an atom
- Let’s look at the first way first…., and its most important consequence: **Thermal Radiation**

Stars are Pretty Much Near Perfect Thermal Radiators

- That means virtually all the light that comes from their surface is by the “thermal mechanism”.
- “Thermal radiation” is light which follows the patterns imposed by the thermal mechanism)

Thermal Radiation

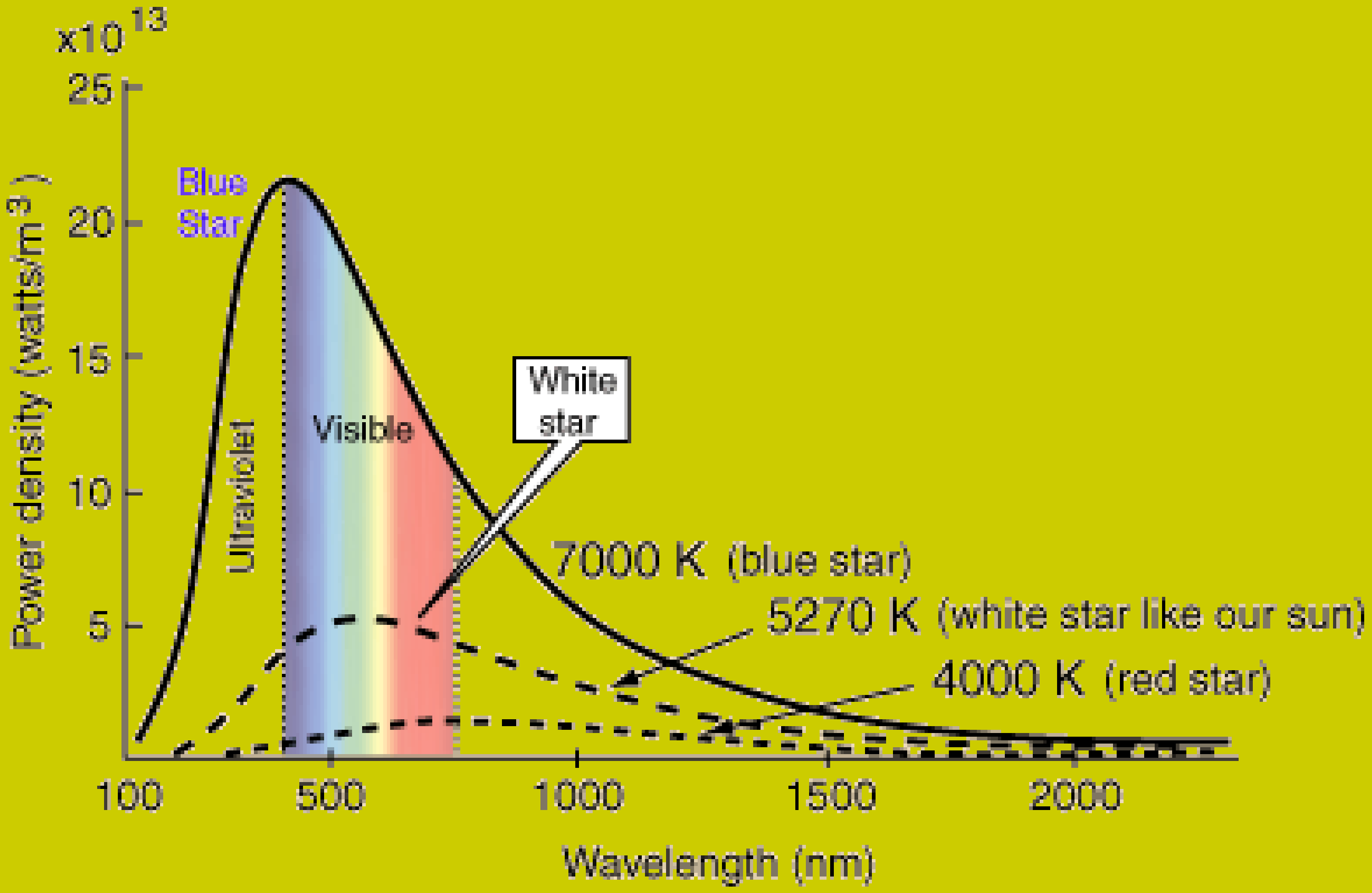
- Imagine atoms and molecules in a solid, vibrating against each other, or in a fluid colliding against each other.
- This deforms their electron clouds, since electrons repel each other. This deformation is a form of “acceleration of a charge” - one of the two ways photons are produced.
- **And so… Light is produced by all objects that are not at absolute zero temperature.**
- This light bouncing around will exchange energy with the particles so that the particles and photons come to have the same energy and same temperature.

- In this way, in a typical gas of huge numbers of atoms, there will be huge numbers of photons produced every second
- Emerging light will have a “grade curve” distribution of photon energy.
- This is called a **“Thermal” spectrum.**
- **You’ll hear me use an older but still popular term which means exactly the same thing – “Blackbody” spectrum.**

What is a Spectrum?

- Light (photons) emerge by the billions from objects, usually with a wide range of wavelengths
- A graph of how much energy is emitted at each wavelength is called the object’s “spectrum”.

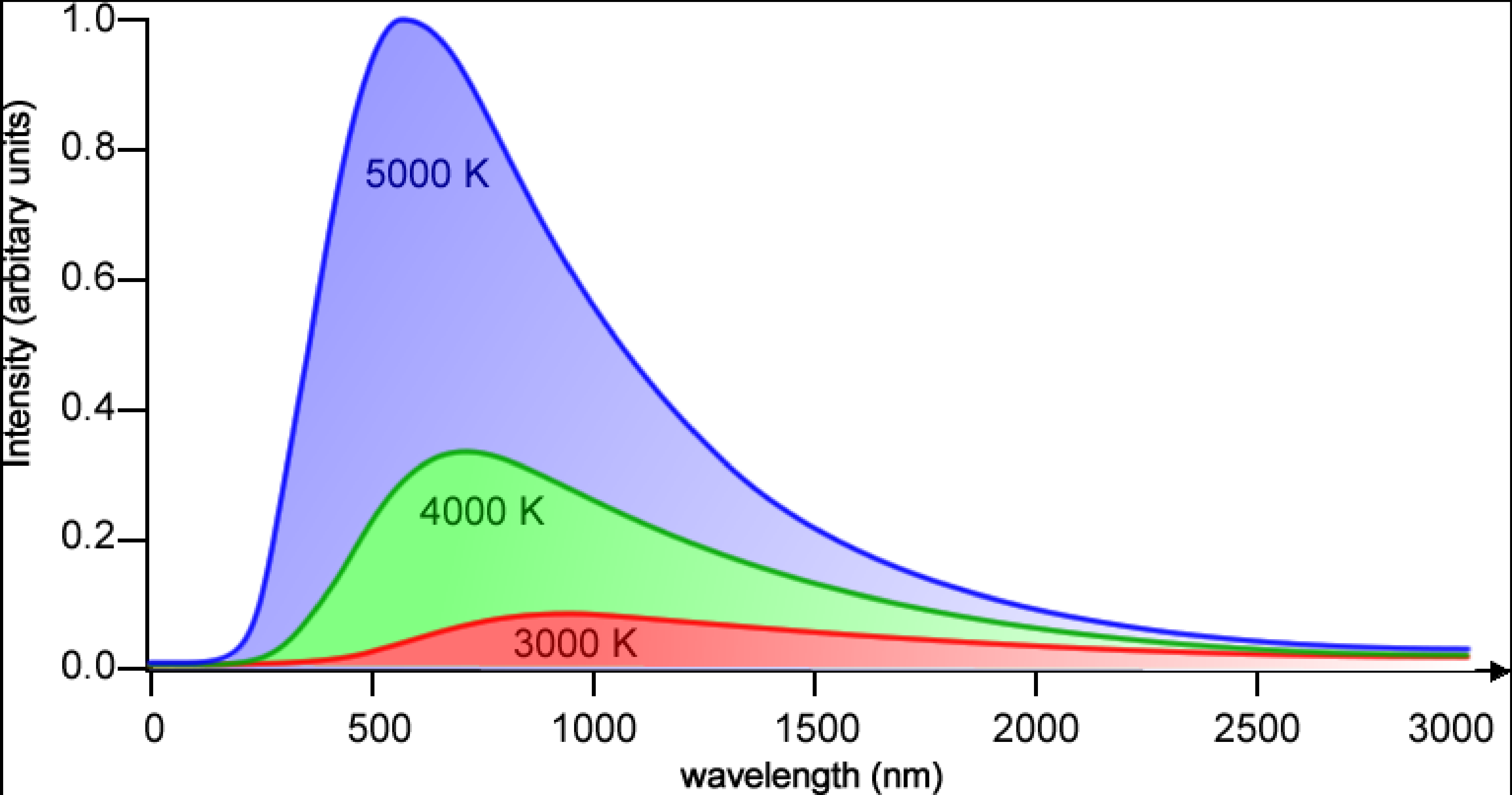
Hotter objects are both “Bluer” and “Brighter”. That’s a condensation of the two Thermal Radiation Laws



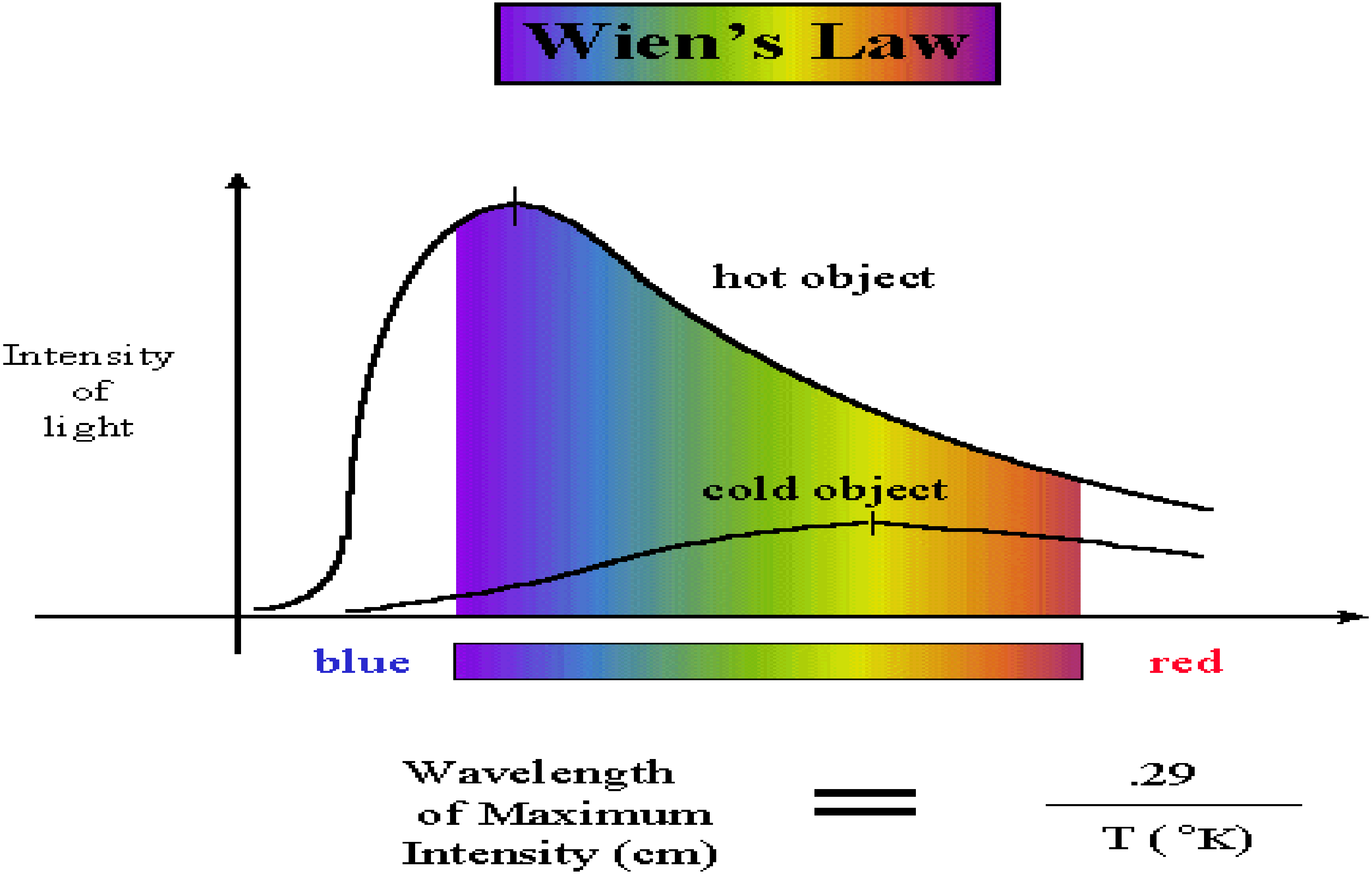
The Two Laws of Thermal Radiation

- **Wien's Law:** the wavelength of the maximum intensity is inversely proportional to the temperature. ***Higher temperature -> shorter wavelength for most of the light.***
- **Stefan-Boltzmann Law:** The luminosity per unit area from a thermal radiator is proportional to the temperature to the 4th power. ***Hotter objects are MUCH brighter.***
- Here's what they mean…

The luminosity is the area under these curves. Notice that hotter objects are MUCH more luminous: to the 4th power of the temperature

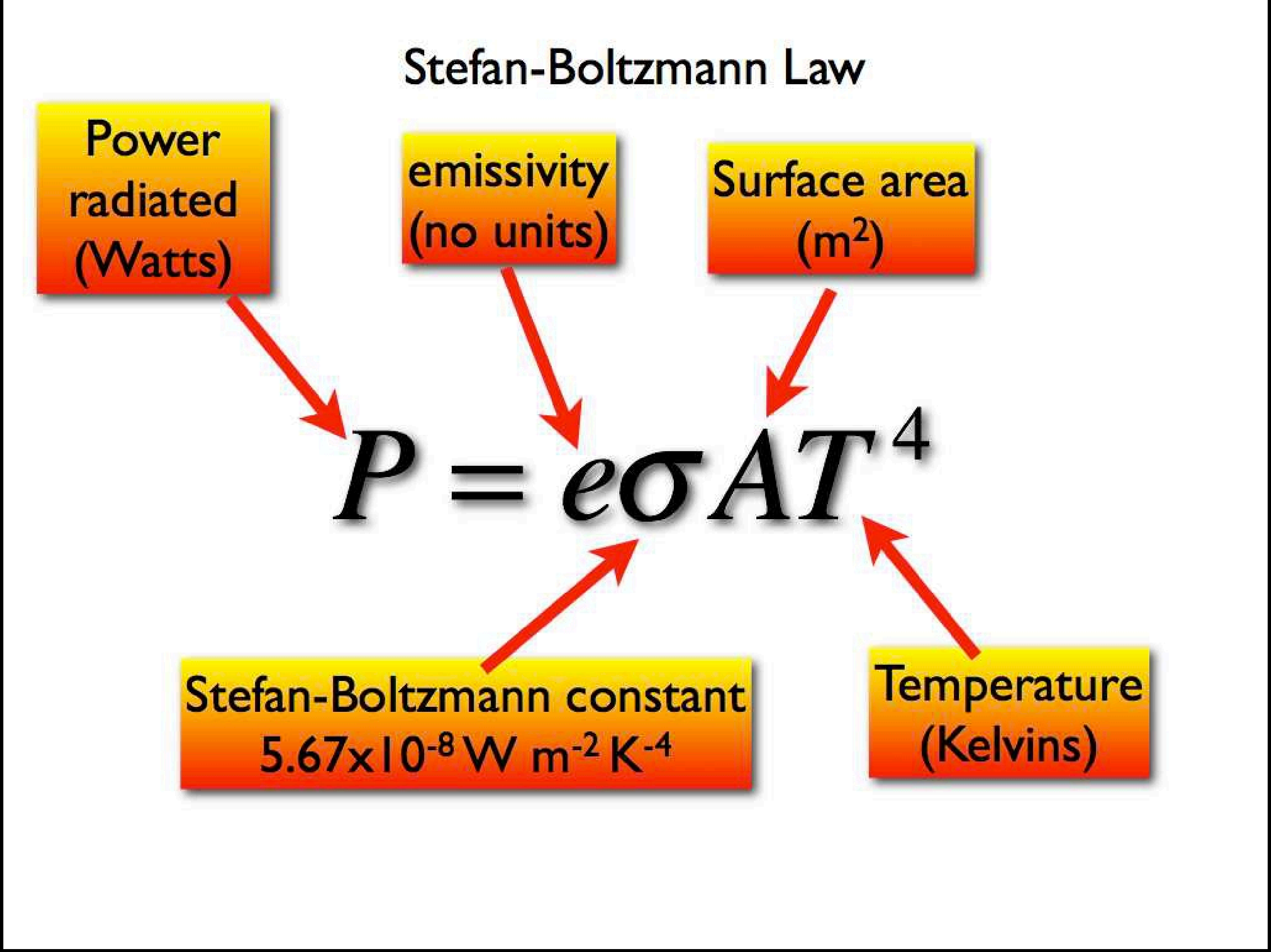


Eyeballs have built-in wavelength detectors; we perceive different wavelengths as having different <u>color</u>.



$$\text{Wavelength of Maximum Intensity (cm)} = \frac{.29}{T\ (^\circ K)}$$

Stefan-Boltzmann Law: Power (called Luminosity in Astronomy), goes as Temperature to the 4th power



Stefan-Boltzmann Law

Power radiated (Watts)

emissivity (no units)

Surface area (m^2)

$$P = e\sigma A T^4$$

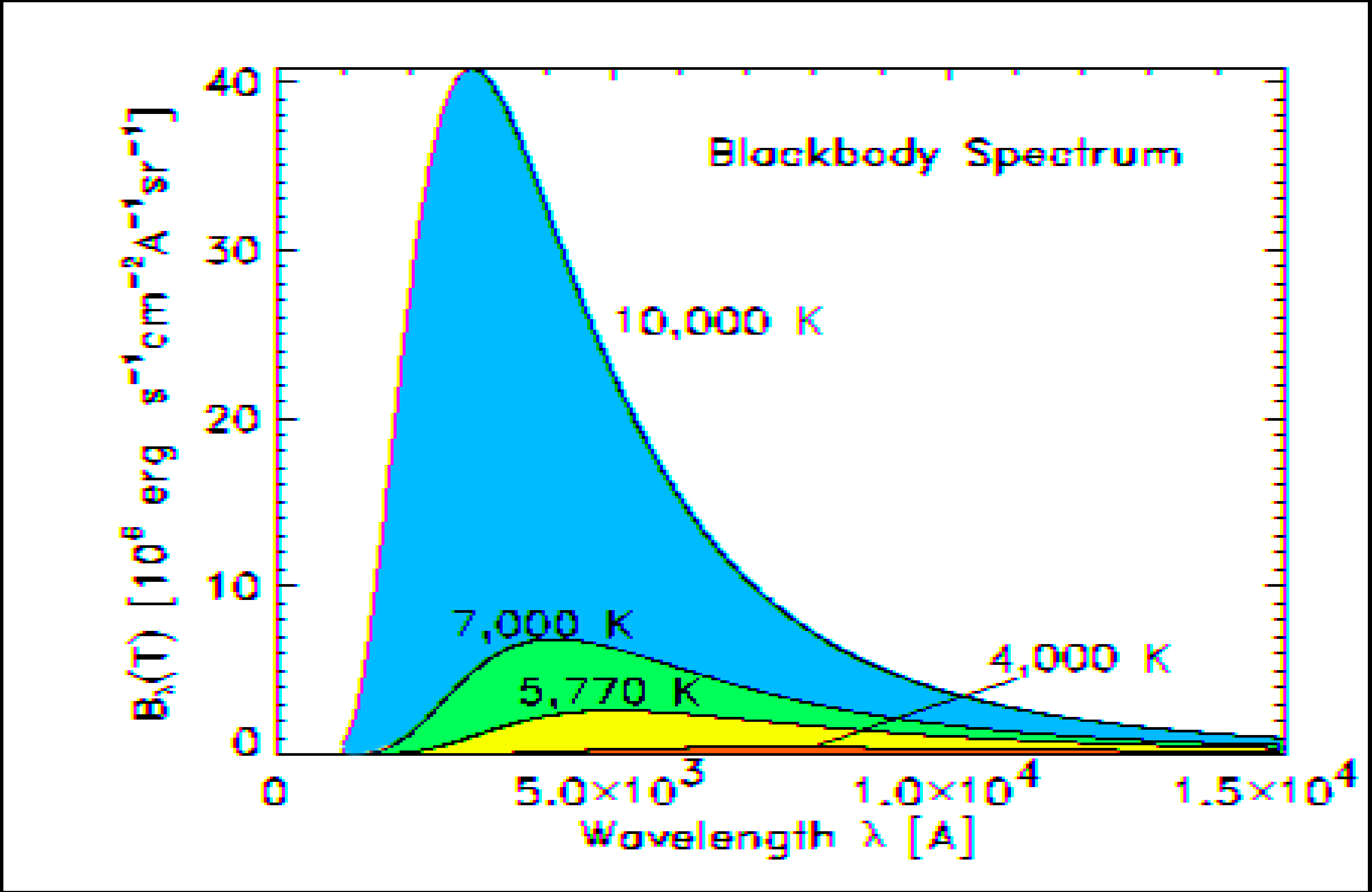
Stefan-Boltzmann constant $5.67\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$

Temperature (Kelvins)

Emissivity e

- e=1 if the object perfectly absorbs all light that falls on it, like fuzzy black sweaters. It reflects nothing, all emitted light is thermal.
- e=0 if perfectly reflective, like a shiny Christmas tree ornament. Their surfaces reflect light both from the inside trying to get out, and outside light bouncing off the surface. They don't cool efficiently, and therefore cool only slowly.
- **Atmospheres, planet surfaces, all are somewhere between 0<e<1**

Wein’s Law and the Stefan-Boltzmann Law: Hotter Stars are BLUER and BRIGHTER



Thermal Radiators: What temperature goes with what peak wavelength?

- Billions of Kelvins: **Gamma rays**
- Millions of Kelvins: **X-rays**
- 10’s-100’s thousands Kelvins: **Ultra-Violet**
- Few thousand Kelvins: **visible light**
- Few hundred Kelvins: **Infrared (like planets, atmospheres). Earth; 288K**
- A Few Kelvin: **Microwaves**
- Radio waves are produced non-thermally, nothing natural in the universe is colder than a few K, because of the left over heat of the Big Bang

The Second Way to Produce Photons…

- #2. Transitions between the allowed energy levels in an atom, or vibrational energy levels in a molecule

How Do Transitions Work?

- **Absorption** – an electron can be bumped to a higher “orbit” if a photon hits the atom and it has *exactly* the same energy as the energy difference between the two orbitals. The photon will be gone and the atom now in an “excited state”, with the electron in a higher energy level. A collision with a particle can do the same thing.
- **Emission** – an electron will fall down to a lower orbital if it is available, giving off the energy difference between the orbitals as a photon, or sometimes through collision

Spectral Line series for Hydrogen (don’t memorize this!)

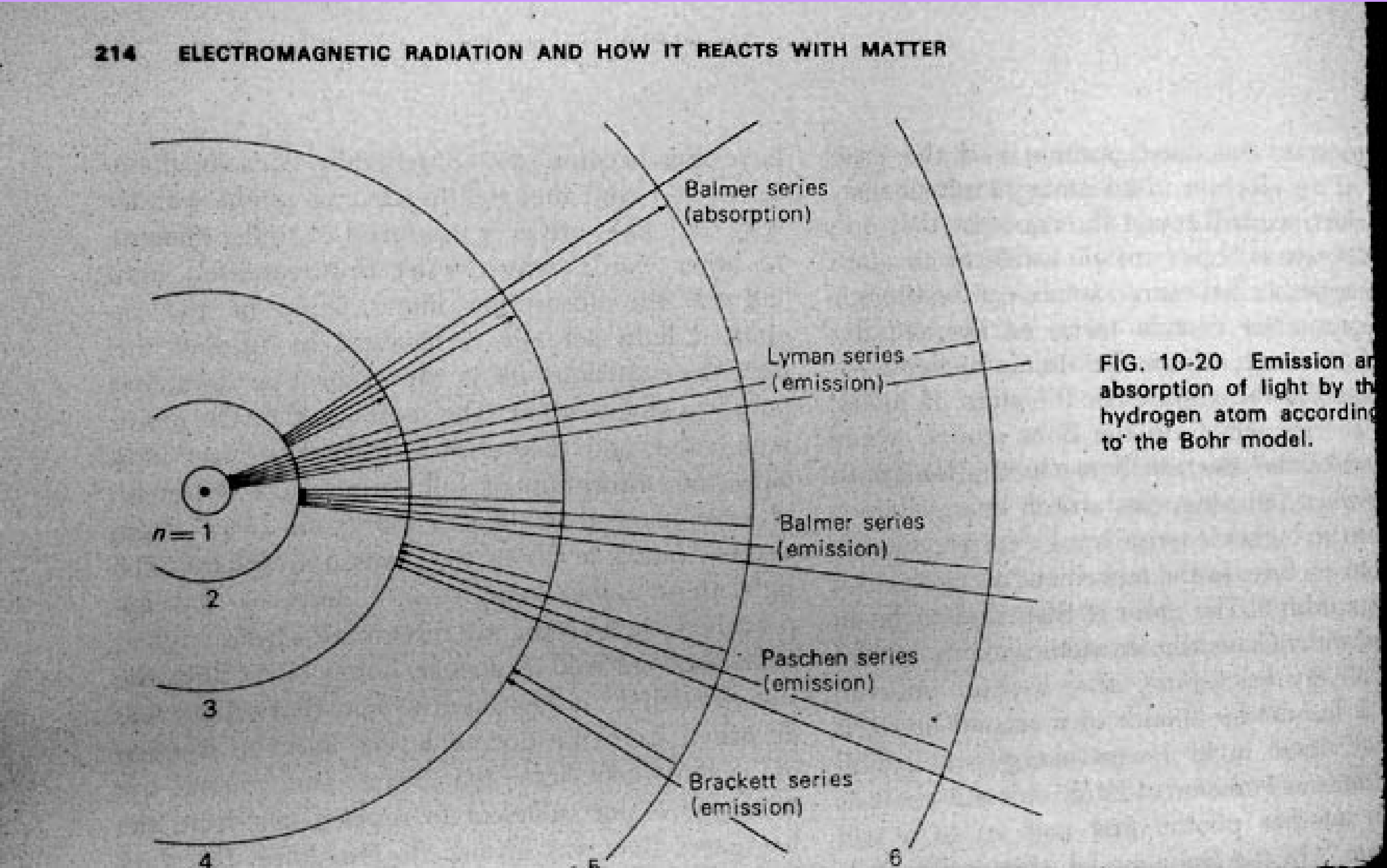


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FIG. 10-20 Emission an absorption of light by th hydrogen atom accordin to the Bohr model.

Collisions and Excitations

- A collision can also excite an atom (orbital transitions) or molecules (vibrational modes), and the two colliding atoms or molecules will now rebound with less speed and hence less kinetic energy (the energy difference has gone into those internal excitations), and thus the temperature of the gas where this happens goes down.

If this happens in a dense atmosphere…

- …then the excited molecule, when it de-excites, sends out another photon which is likely trapped by doing the same process before it gets very far.
- But if it happens in a very low-density atmosphere, the photon released has a high probability of escaping, and hence it makes a net loss of energy from the atmosphere. Temperature goes down.
- As we'll see later, this is why rising CO2 causes **rising** temperature in the dense troposphere where we live, but **falling** temperatures in the high stratosphere – a key prediction (verified) of human-caused global warming by CO2.

Types of Spectra…

- *Emission spectrum* – a spectrum dominated by emission lines. **Clouds of gas** with hot stars shining on them from the side produce this kind of spectrum. **Not so relevant for a Climate class.**
- *Absorption spectrum* – a smooth continuous range of wavelengths, but certain wavelengths have less energy than surrounding wavelengths and so appear dark by contrast. **Stars** usually have this kind of spectrum. Absorption especially by molecules IS relevant for climate!
- *Thermal spectrum* – a spectrum produced by an object purely because of its temperature. Must be denser than typical interstellar gas in order to be a thermal radiator. Examples: incandescent light bulb. Approximate thermal radiators - stars, planets . This is pretty much what we get from the sun, so is climate relevant.

An Absorption spectrum, and associated graph of the light intensity *vs.* wavelength. Narrow down-spikes of less light than the underlying continuum of light

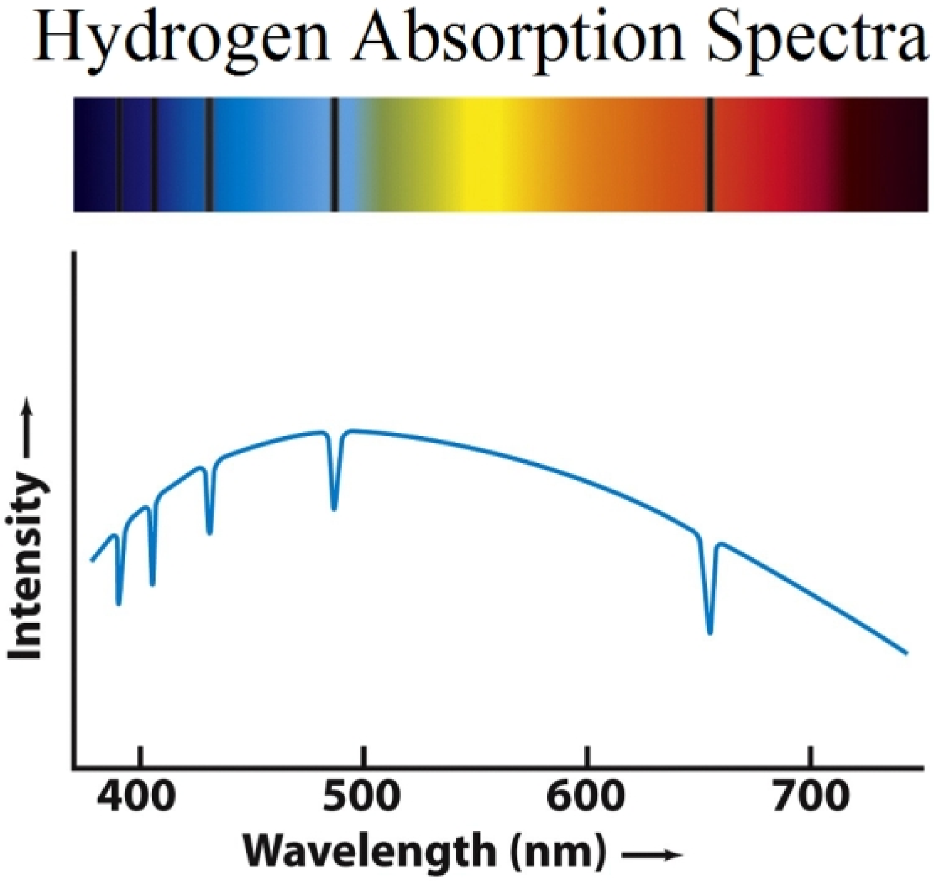

Figure 4-8ab
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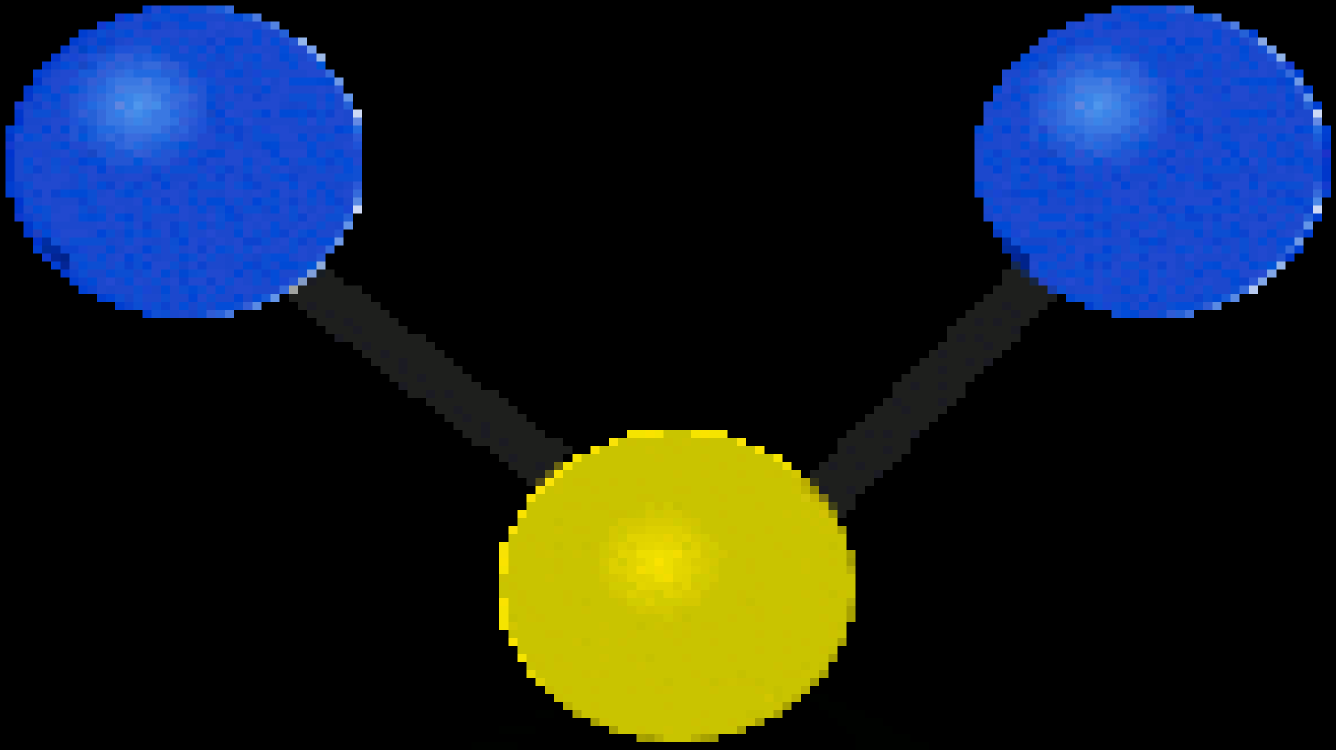
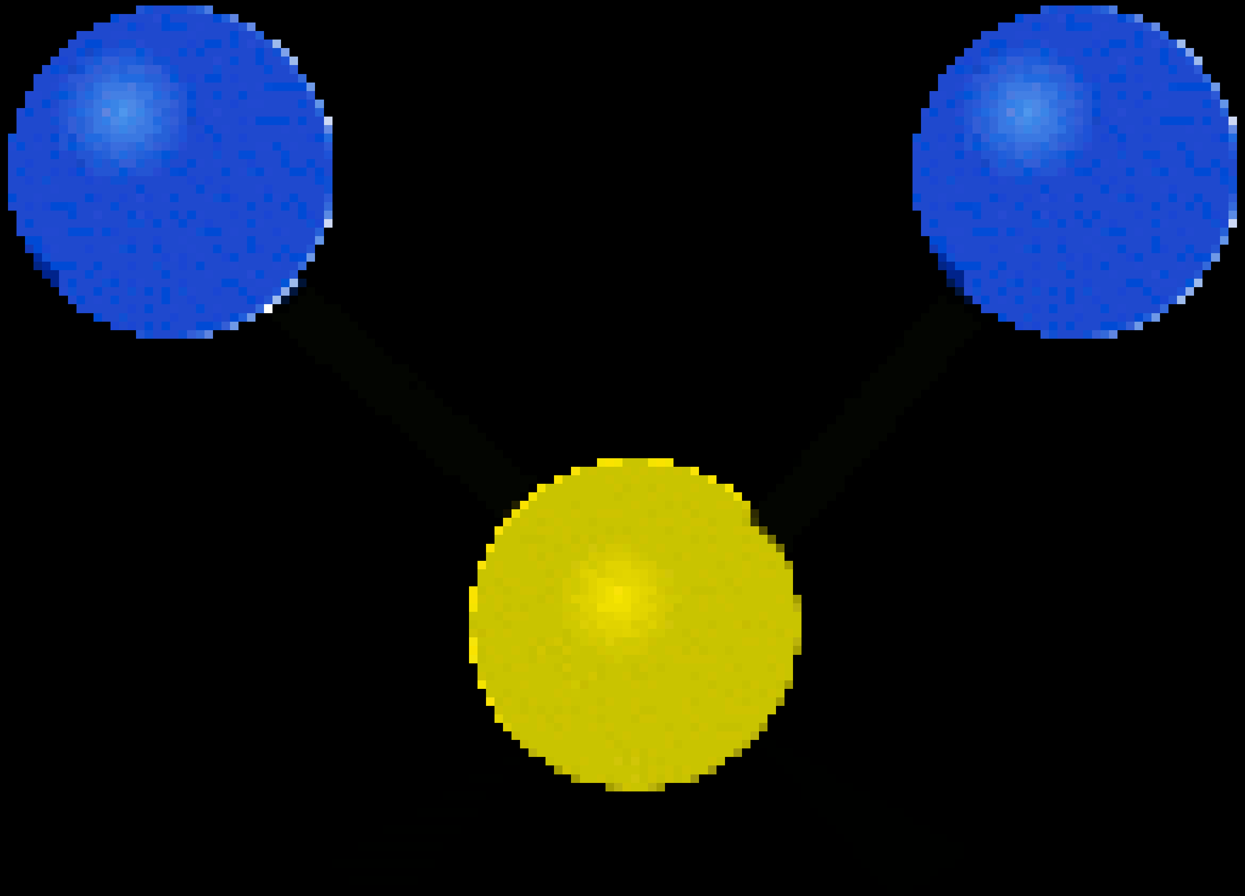
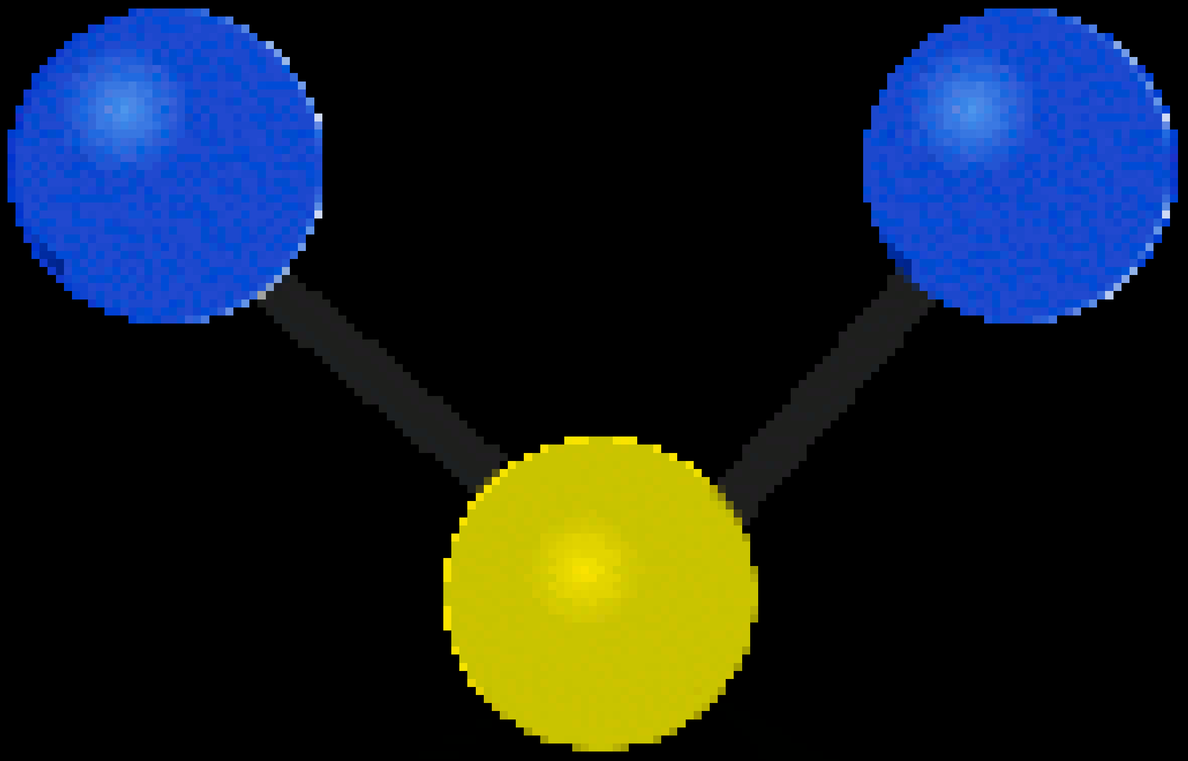
Absorption by Molecules

- Molecules have additional “degrees of freedom” (or modes) which can be excited by collisions or absorbing photons.
- These modes are…
- Vibration or rotation for molecules with 2 or more atoms
- And more complex motions for more complex molecules
- To see a few of the **vibration modes of CO2**, check this link.
- **An important consequence is: The more atoms in a molecule, the stronger it is as a greenhouse gas.**







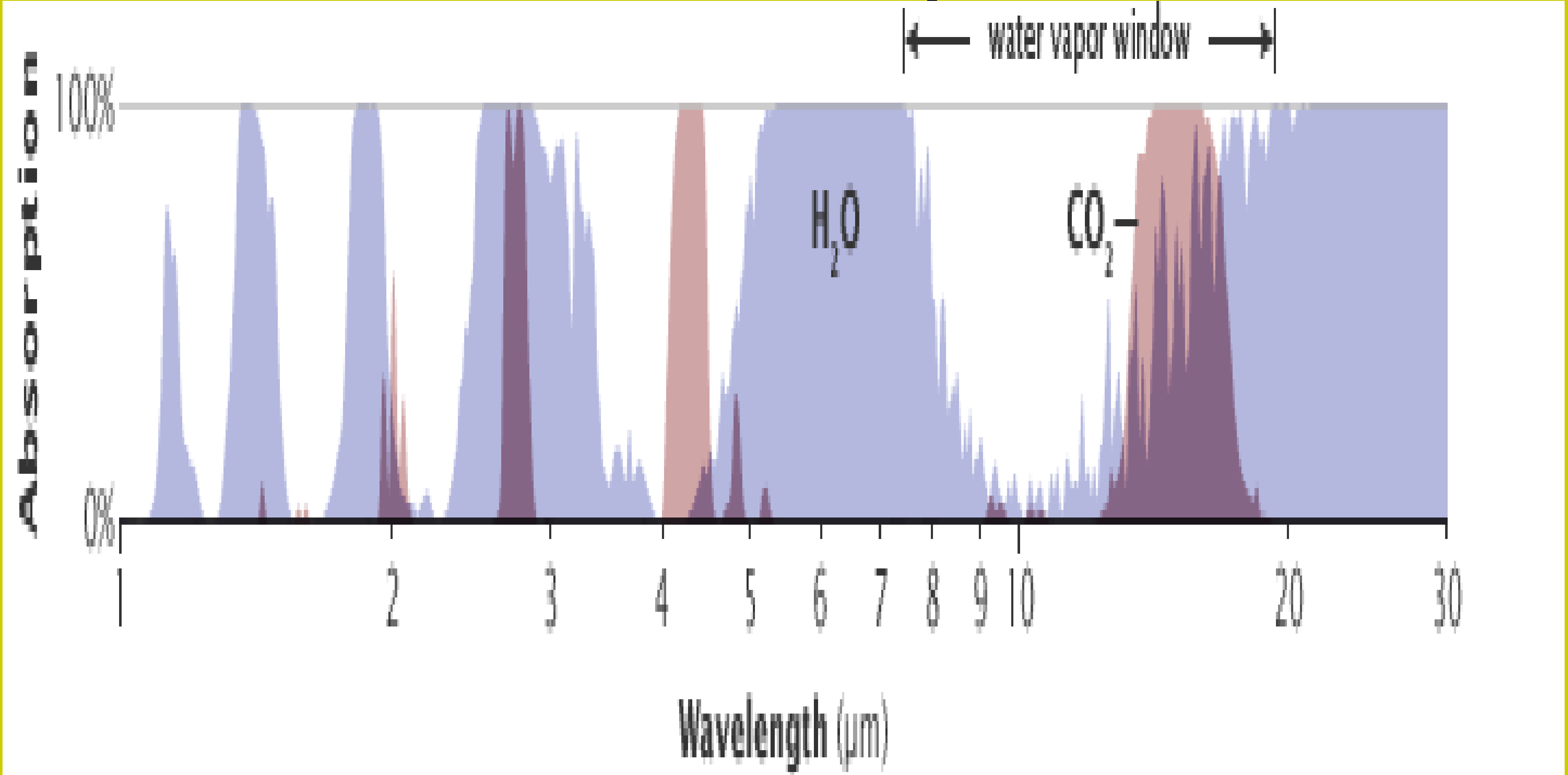
These Internal Excitations Are Ways that Molecules can Soak Up Energy Which Individual Atoms Cannot

- If you add heat to a gas of molecules, some of the heat goes into exciting these internal vibratons,
- and this part does **not** go into the kinetic energy of the molecule as a whole – and that means - it does not go into raising its temperature.
- This is a major reason why water H_2O can absorb a lot of heat energy without raising its temperature much; a good deal of the energy goes into those hidden internal vibrations.
- **This will be critical in understanding the ocean / atmosphere connection and how crucial the ocean is to understanding climate.**

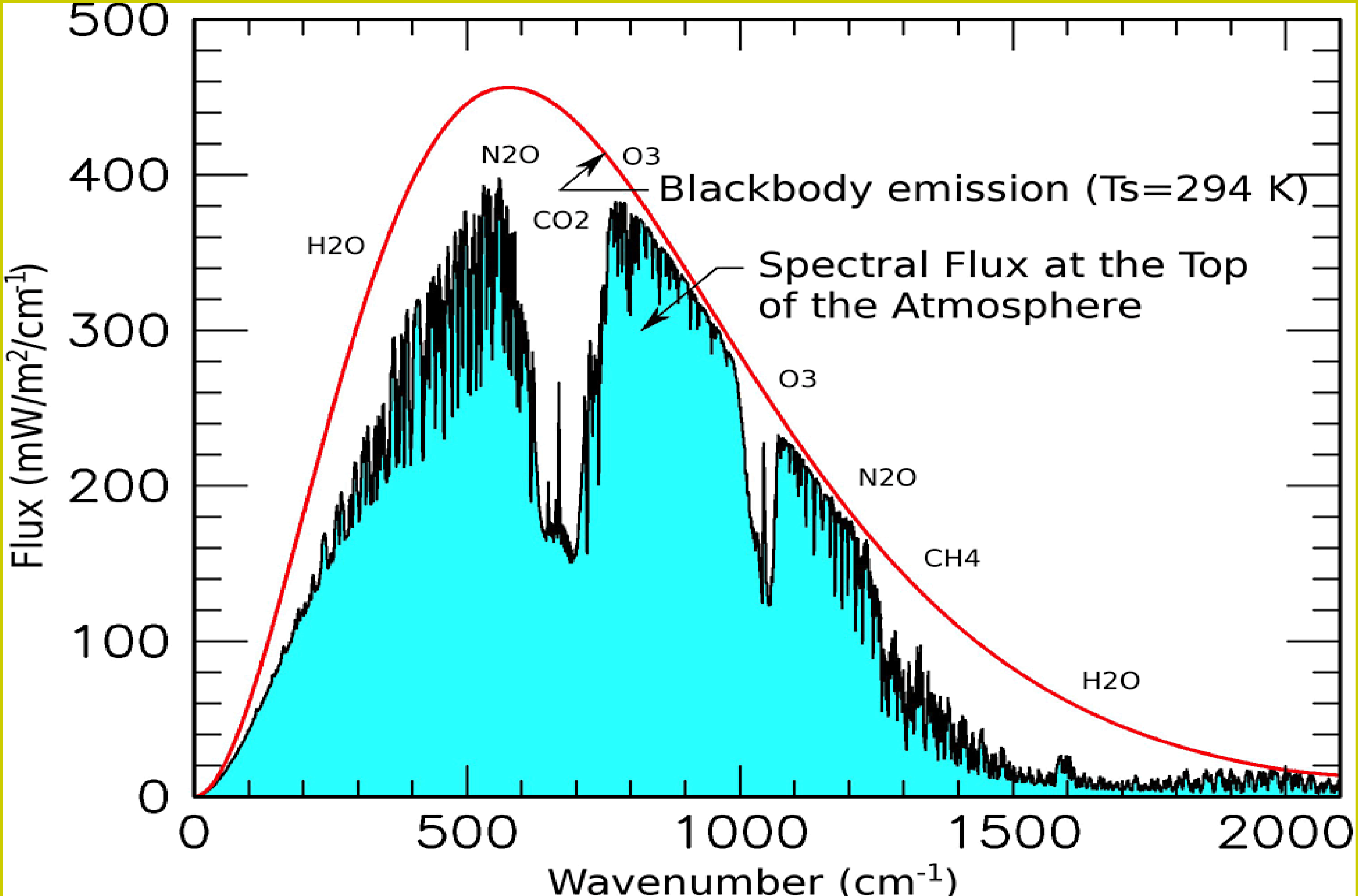
These excited states, just like for atoms, are quantized

- Individual atoms' electron transitions make very narrow **lines** of absorption and emission. But molecular vibration transitions take out much bigger **bands** of light.
- **Molecules take out large swaths of passing light – essential for understanding the Greenhouse Effect**

Unlike atoms, molecules have vibrational modes, can absorb across big fat “bands” of wavelength. That makes them effective inhibitors of out-going long wave (IR) radiation from planets



Wide molecular absorption bands in Earth's atmosphere



For Planetary Climate…

- Where and how wide the lines are affects climate greatly, as it makes the atmosphere more or less opaque at key wavelength ranges.
- Water vapor is thelargest absorber of our outgoing IR radiation. But it is rising CO2 which controls temperatures, because water will condense and rain out if it gets too large. CO2 will not.
- It is our steep rise in CO2 which is allowing rising humidity and water vapor absorption of out going IR. Without that rising CO2, water vapor humidity could not rise.

Astro 7: Chap 5 – Light and Matter Key Ideas

- Photons = quanta of EM field energy.
- Photon energy; short wavelength=high energy
- Know the names of the different wavelength bands (IR, radio, etc) and the correct order
- Know the two ways to produce photons (accelerate a charge, or transitions in atoms or molecules)
- Know the two ways to excite an atom or molecule (collisions, and photon absorption)
- Molecules have addition quantum degrees of freedom: vibration, rotation, and more complex motions for molecules of 3 or more atoms. Such transitions mostly in the Infrared.
- Molecular absorption lines are much broader than for individual atoms. We call them instead "absorption BANDS"
- Different ISOTOPES of an atom have different numbers of neutrons in nucleus
- Ionized atom = ion = has one or more electrons knocked off
- Temperature measures the average kinetic energy per particle
- Emission spectra *vs.* absorption spectra – know which situation gives which
- Emission of photon when electron falls to lower orbital. For absorption, run that movie in reverse.
- Absorption ONLY happens if the photon has exactly the right energy to lift electron to an allowed orbit, or ionizes it altogether.