

Nano-Photonics

Lecture 4.X Where does light come from?

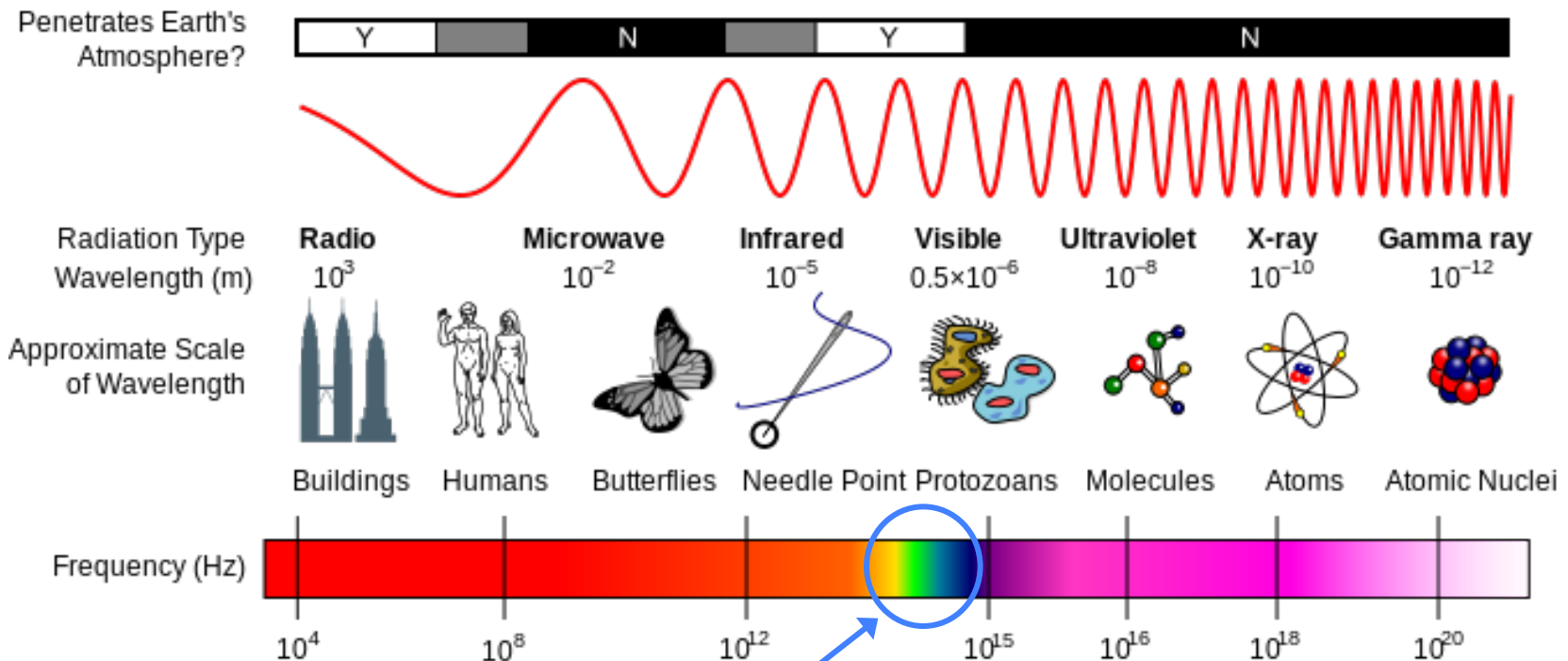
2 μm

Reminder: the spectrum

Light waves are characterized by wavelength.

The Electromagnetic Spectrum

Source: Wikimedia Commons



Visible light is here. Its wavelength is between 400 and 700 nm.

Accelerating charges emit light

This is the origin of essentially every photon in the universe.

- Linearly accelerating charge

See the java applet here:

<http://www.cco.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html>

- Vibrating electrons or nuclei of an atom or molecule
- Synchrotron radiation—light emitted by charged particles deflected by a magnetic field
- Bremsstrahlung ("Braking radiation")—light emitted when charged particles collide with other charged particles

Which motions of molecules are the ones that matter?

Core (tightly bound) electrons vibrate in their motion around nuclei

$\nu \sim 10^{18} - 10^{20}$ cycles per second.

Valence (not so tightly bound) electrons vibrate in their motion around nuclei

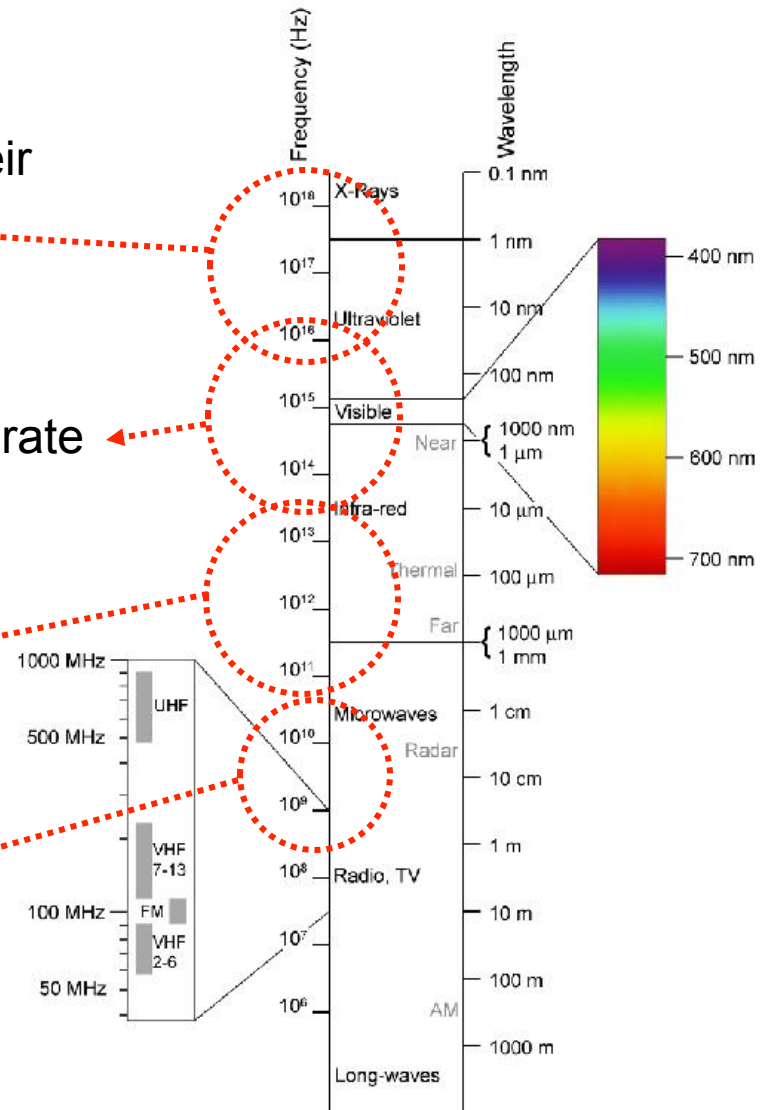
$\nu \sim 10^{14} - 10^{17}$ cycles per second.

Nuclei in molecules vibrate with respect to each other

$\nu \sim 10^{11} - 10^{13}$ cycles per second.

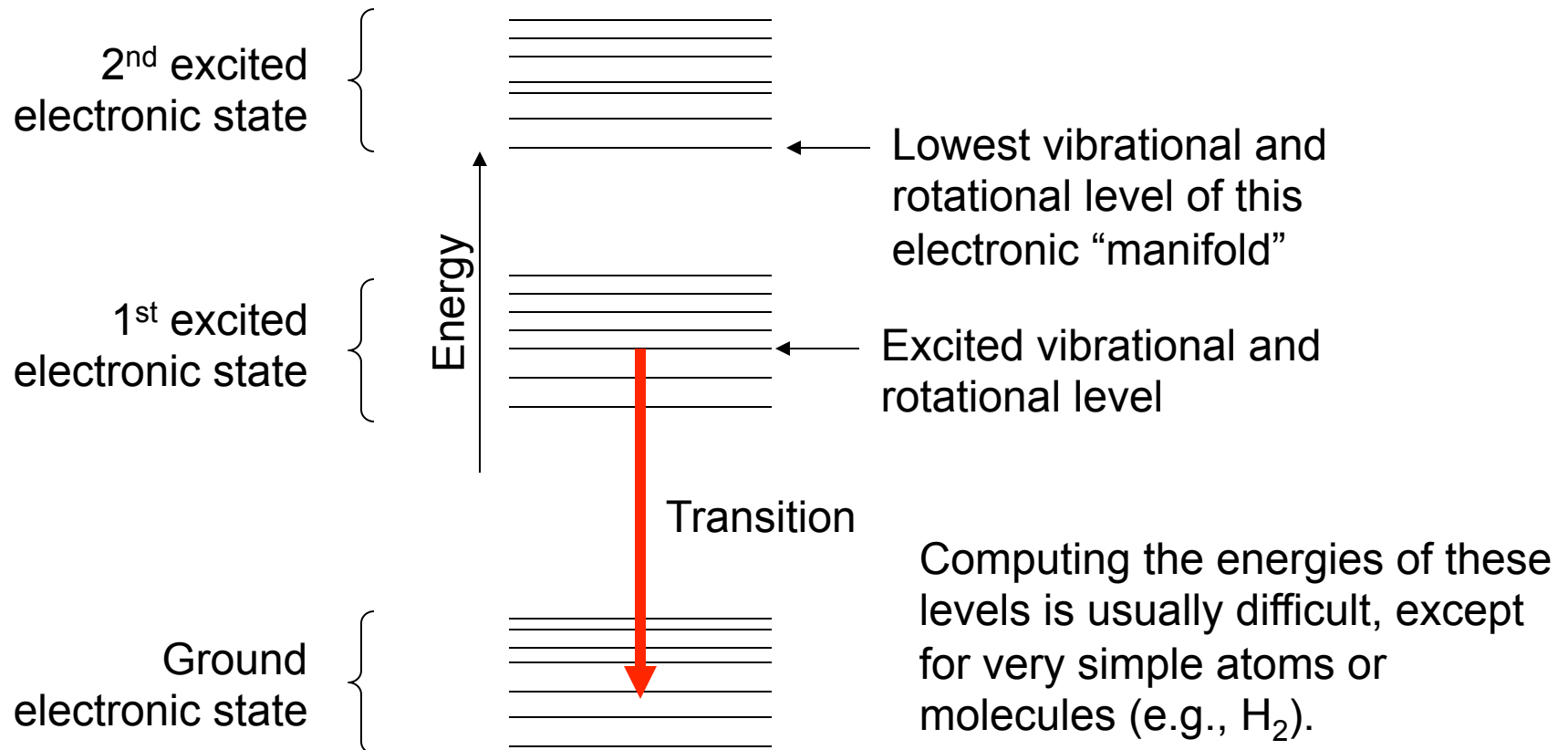
Molecules rotate

$\nu \sim 10^9 - 10^{10}$ cycles per second.

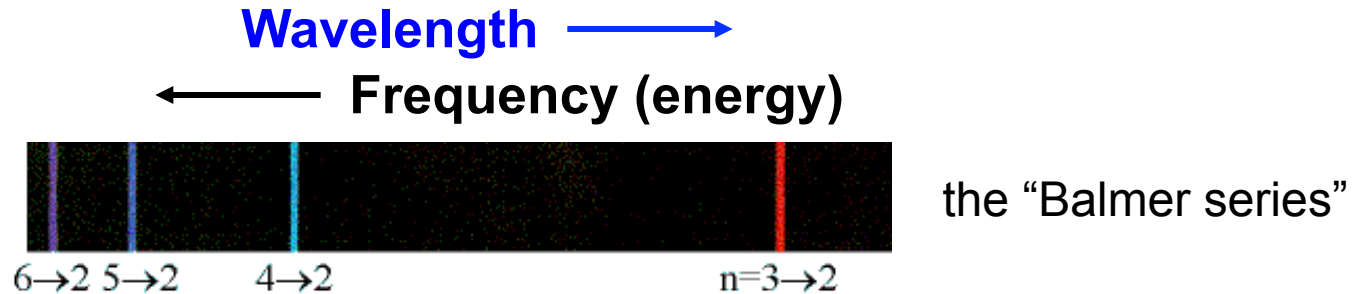


The quantum version

Energy levels for a typical molecule:



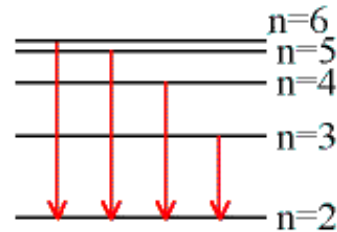
Different atoms emit light at different frequencies



Source: Wikimedia commons

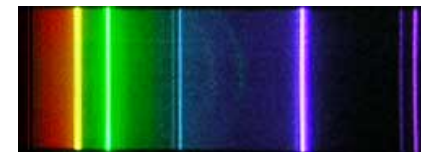


Johann Balmer
(1825 - 1898)

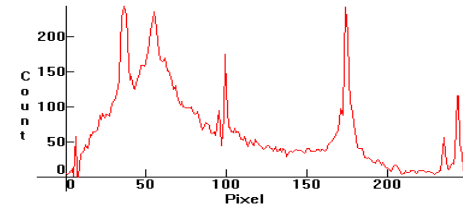


This is the emission spectrum from hydrogen. It is simple because hydrogen has only one electron.

n=1 (Ground State)



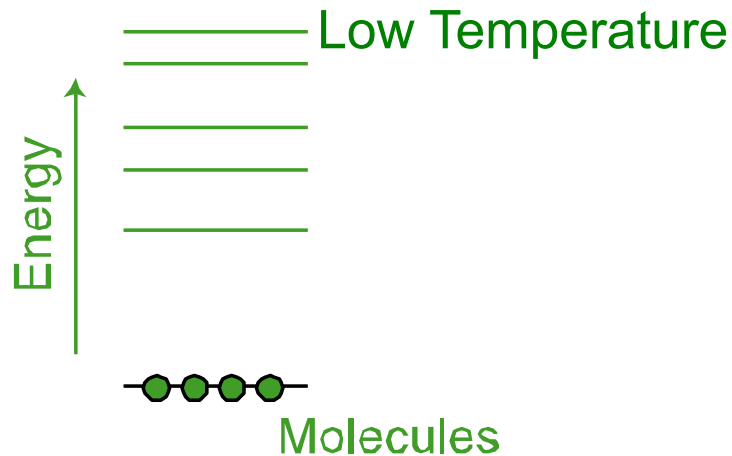
mercury vapor



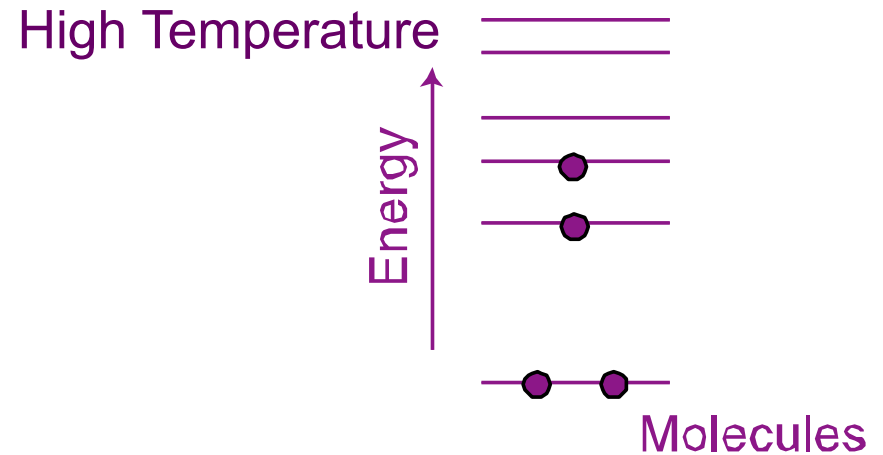
Bigger atoms have much more complex spectra, because they are more complex objects. Molecules are even more complex.

For population of energy levels, temperature matters

In the absence of collisions, molecules tend to remain in the lowest energy state available.



Collisions can knock a molecule into a higher-energy state. The higher the temperature, the more this happens.

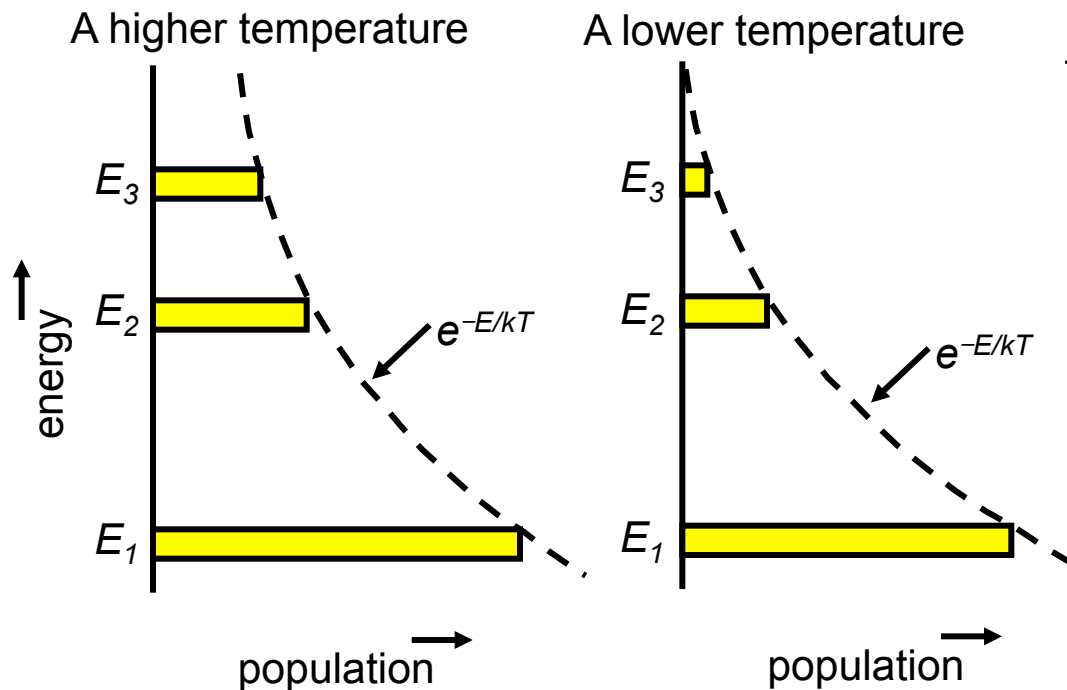


Boltzmann figured this out

In equilibrium at a temperature T , the ratio of the populations of any two states (call them number 1 and number 2) is given by:

$$\frac{N_2}{N_1} = \exp \left[- (E_2 - E_1) / k_B T \right]$$

As T goes up, higher lying energy levels become more populated.



Ludwig Boltzmann
(1844 - 1906)



Source: Wikimedia commons

How do we describe the light emitted by hot things?

If we understand how temperature affects the population of states, can we use this to describe the light emitted by hot objects? This was one of the key challenges facing physics in the 1890's.



Warning: for this topic, temperature is in Kelvins, not F or C!

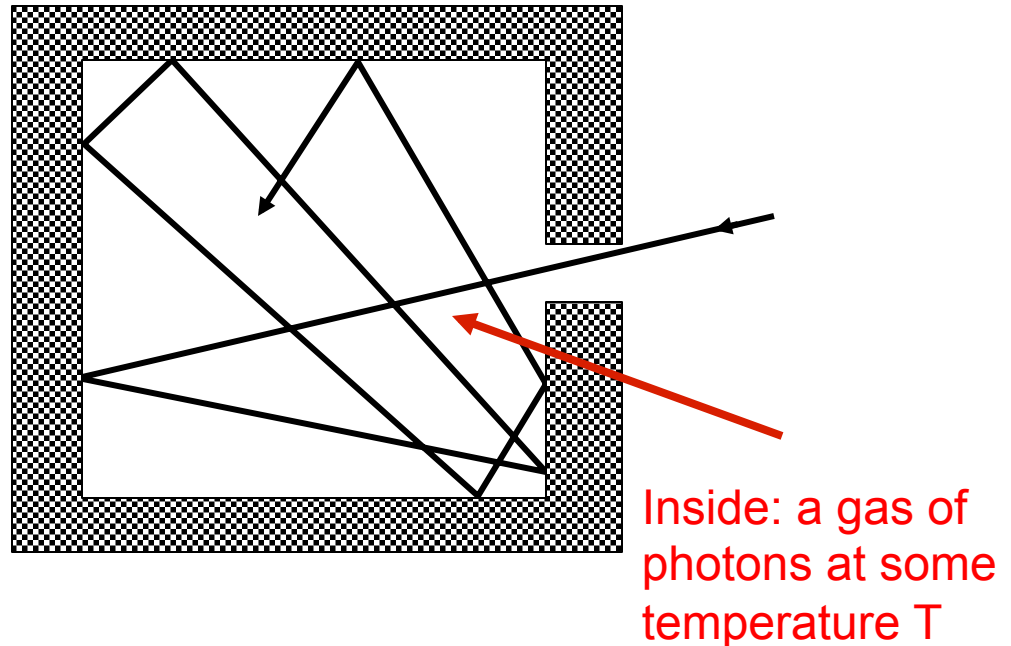
Blackbody radiation

Blackbody radiation is the radiation emitted from a hot body ($T > 0 \text{ K}$). It's anything but black!

It results from a balance between the absorption and emission of light by the atoms which comprise the object, at a given temperature.

Imagine a box, the inside of which is completely black.

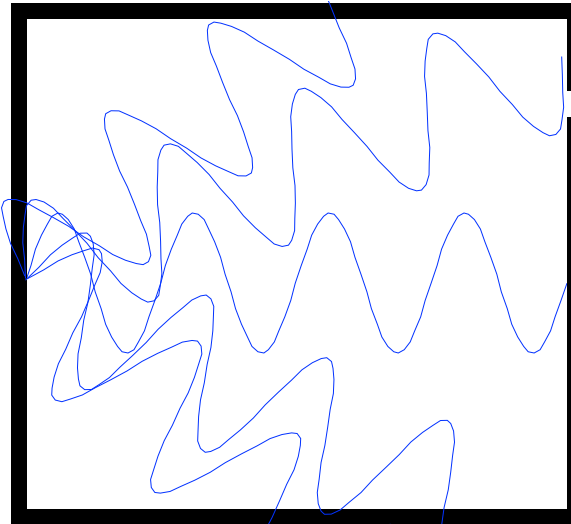
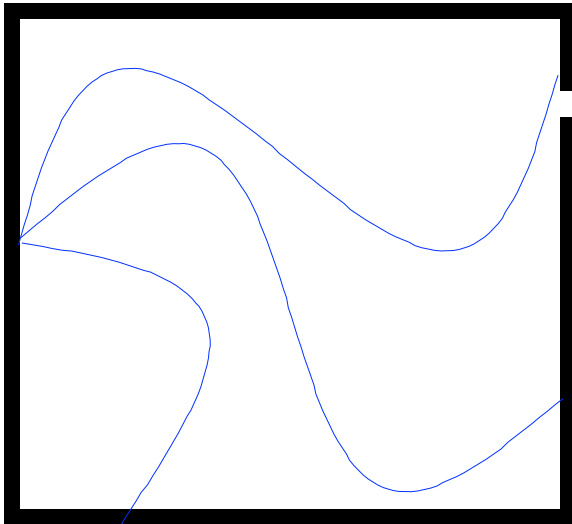
Consider the radiation emitted from the small hole.



The classical physics approach

Lord Rayleigh figured out how to count the electromagnetic modes inside a box.

Basically, the result follows from requiring that the electric field must be zero at the internal surfaces of the box.

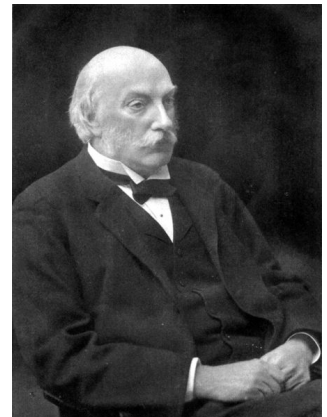


Number of modes per unit frequency interval per unit volume $\sim \nu^2$

For higher frequencies, you can fit more modes into the box.

And the energy per mode is $k_B T$. (this is another consequence of Boltzmann's work, known as the "equipartition theorem")

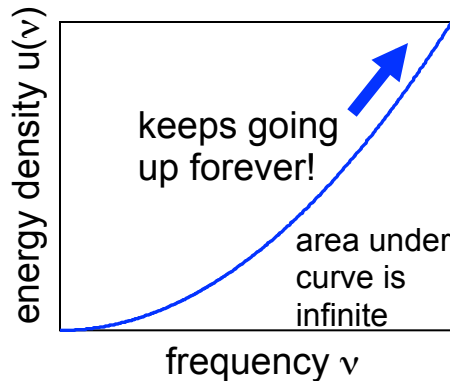
John William Strutt,
3rd Baron Rayleigh
(1842 - 1919)



Wikimedia commons

The Rayleigh-Jeans law (circa 1900)

energy density of a radiation field: $u(\nu) = \frac{8\pi \nu^2 kT}{c^3}$



Total energy radiated from a black body:
infinity

The "ultraviolet catastrophe"

Rayleigh (and others) knew this was wrong. They thought that it merely showed the inadequacy of the idea of equipartition (i.e., that each mode should have the same average energy).

But something even more profound was going on...

The ideas

- Accelerating charges emit light
- The color of light emitted by atoms and molecules depends on their level spacing
- Classical physics cannot explain why there is less light at high frequencies

Nano-Photonics

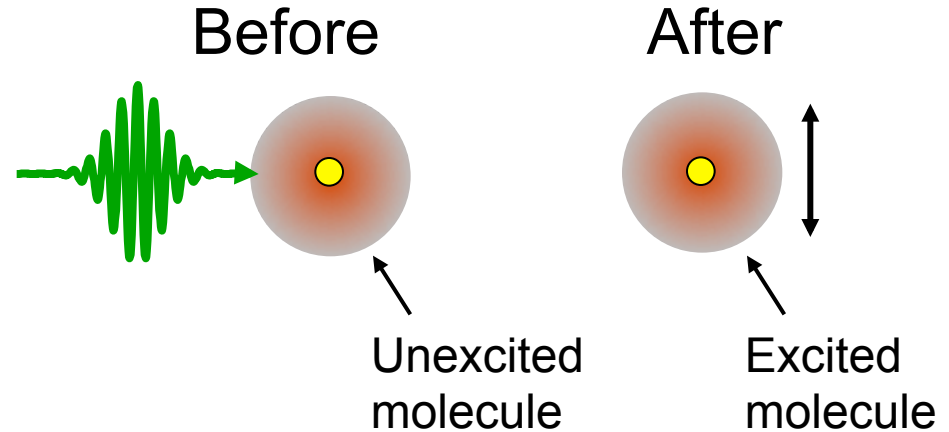
Lecture 4.Y Light-matter interactions and blackbody radiation

2 μm

Light-atom interactions

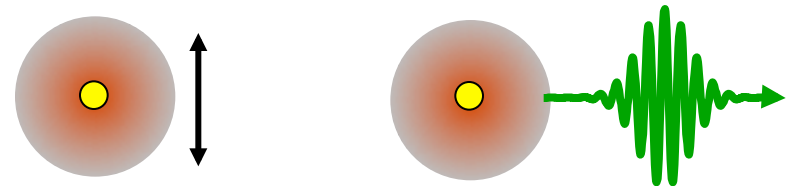
Absorption

- Promotes molecule to a higher energy state
- Decreases the number of photons in the world by one



Spontaneous Emission

- Molecule drops from a high energy state to a lower energy state
- Increases the number of photons in the world by one



The quantum version of these pictures:



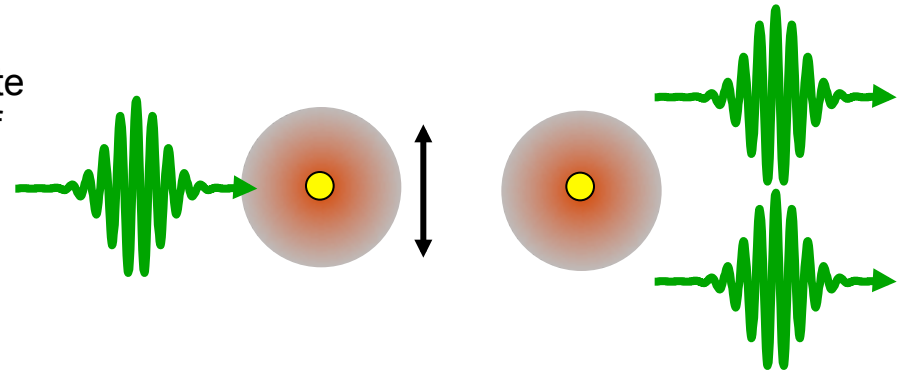
A NEW light-atom interaction

Absorption and spontaneous emission were the only two known to classical physics.

In 1916, Einstein postulated the existence of a third mechanism:

Stimulated Emission

- Molecule drops from a high energy state to a lower state
- The presence of one photon stimulates the emission of a second one
- This process has an analog in classical physics, but it was only developed after the fact – really, it only makes sense with quantum mechanics.



This turns out to be the key to understanding blackbody radiation.

It is also the basis upon which lasers work.

Einstein A and B coefficients

Einstein considered the various transition rates between molecular states (say, 1 and 2) involving light of energy density u :

$$\text{Absorption rate} = B_{12} N_1 u$$

$$\text{Spontaneous emission rate} = A N_2$$

$$\text{Stimulated emission rate} = B_{21} N_2 u$$

In equilibrium, the rate of upward transitions equals the rate of downward transitions:

$$B_{12} N_1 u = A N_2 + B_{21} N_2 u$$

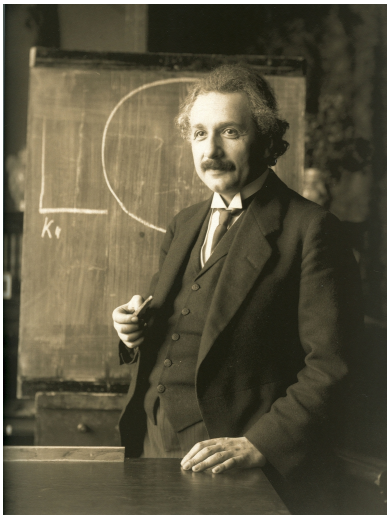
using the
Boltzmann result

Rearranging:

$$(B_{12} u) / (A + B_{21} u) = N_2 / N_1 = \exp[-\Delta E / k_B T]$$

Einstein A and B coefficients II

Wikimedia commons



Einstein in 1921

We can solve this expression for the energy density:

$$(B_{12} u) / (A + B_{21} u) = \exp[-\Delta E/k_B T]$$

Rearrange to: $B_{12} u \exp[+\Delta E/k_B T] = A + B_{21} u$

or:
$$u = \frac{A/B_{21}}{\frac{B_{12}}{B_{21}} \exp[\Delta E / k_B T] - 1}$$

For blackbody radiation, we would expect that $u(\nu)$ should be infinite in the limit that $T = \infty$. But, as $T \rightarrow \infty$, we notice that $\exp[\Delta E/k_B T] \rightarrow 1$

So: $B_{12} = B_{21} \equiv B \quad \leftarrow \text{Coeff. up} = \text{coeff. down!}$

Einstein A and B coefficients III

We can eliminate*
the ratio A/B to find:

$$u(\nu) = \frac{[8\pi h\nu^3 / c^3]}{\{\exp[h\nu / k_B T] - 1\}}$$

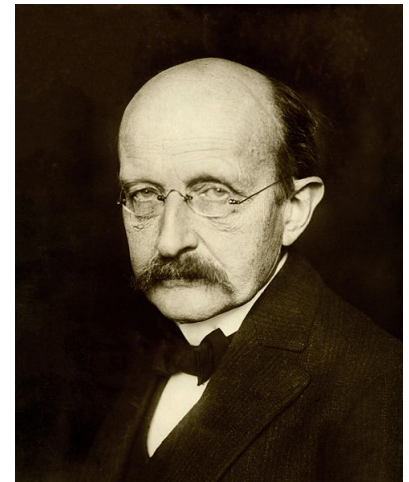
(we have used $\Delta E = h\nu$)

* We require that this expression has to be the same as the Rayleigh-Jeans law in the limit of very low frequencies. This allows us to determine the value of A/B as shown.

Einstein was delighted to realize that this was the result that Max Planck had 'guessed' to explain black-body radiation in the 1890's.

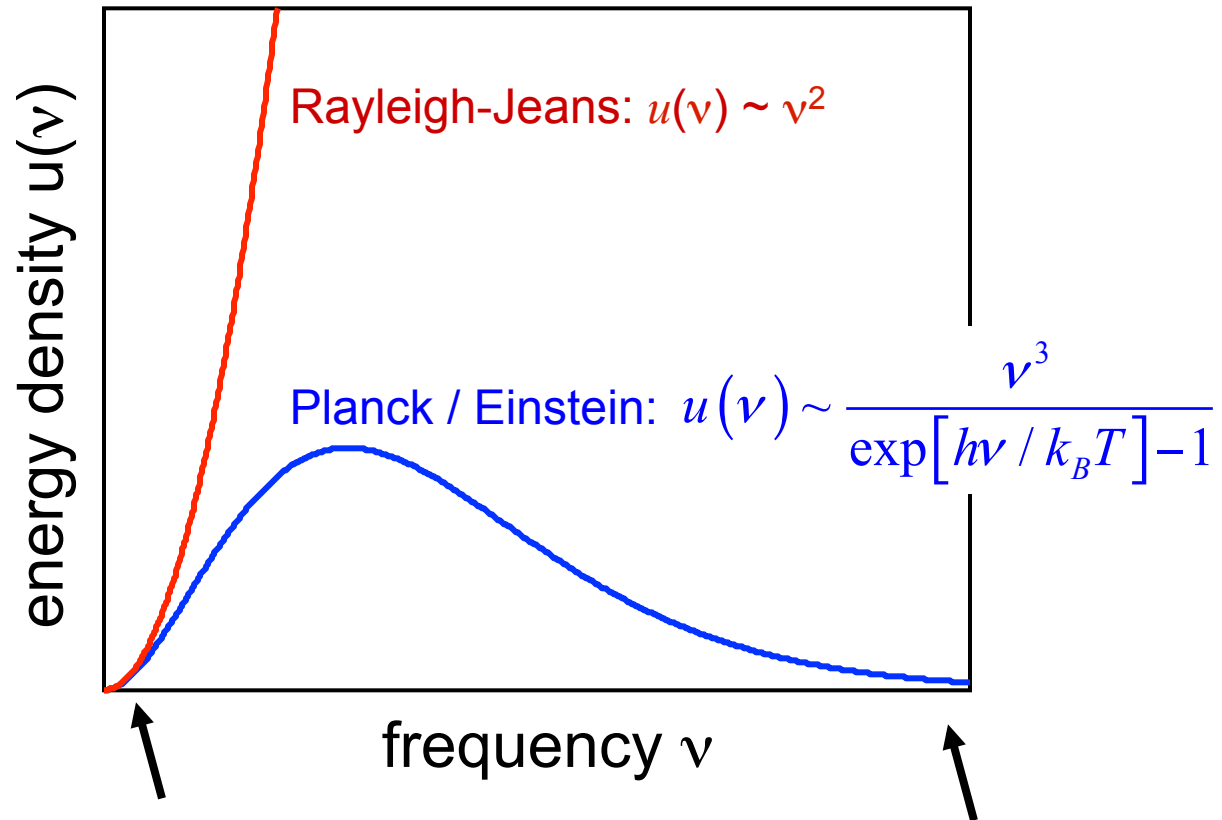
Einstein's derivation put Planck's postulate of energy quanta on a firm theoretical footing, for the first time.

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Max Planck in 1933

Ultraviolet catastrophe: solved



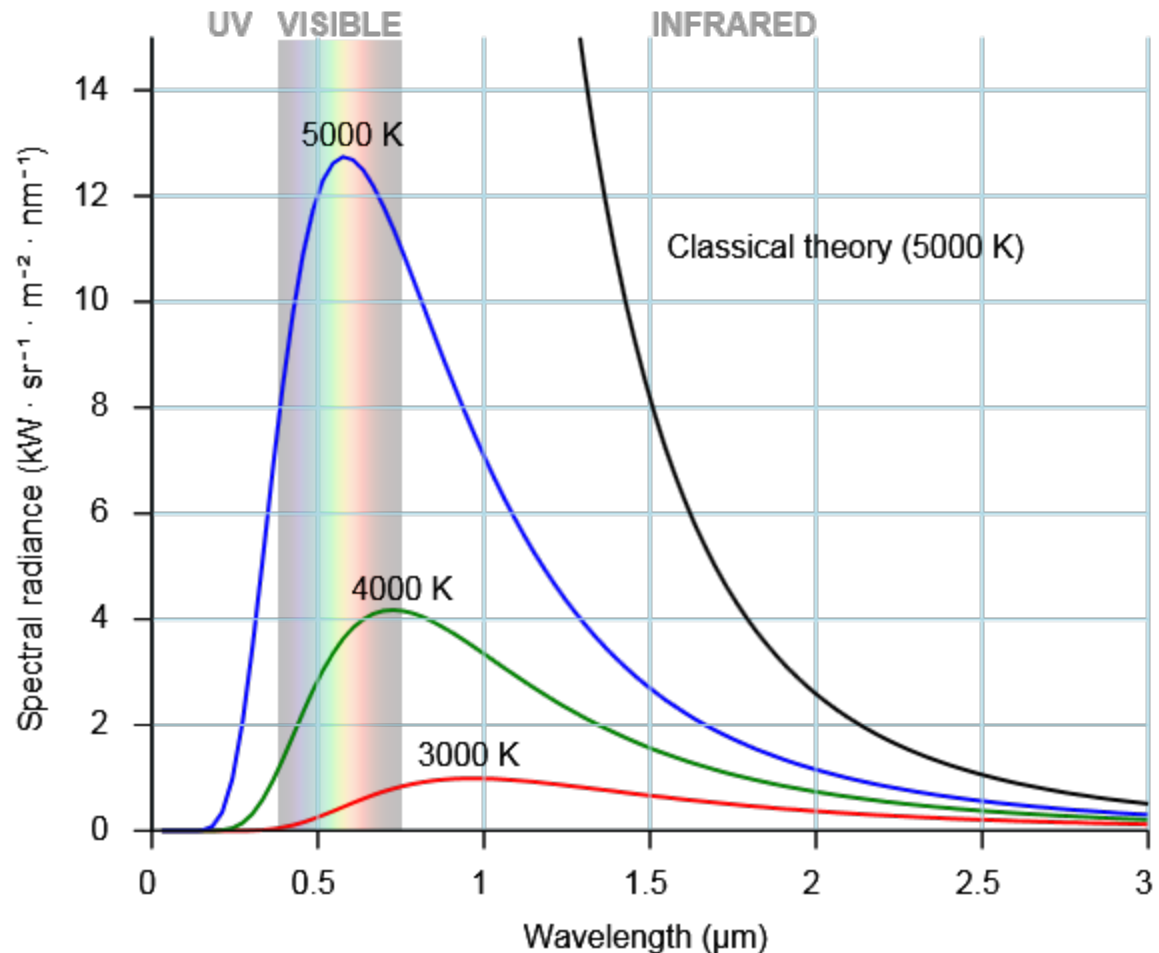
At low frequencies, the two results are basically equivalent.

At high frequencies, Einstein's result goes back down to zero, so the integral of $u(\nu)$ is finite.

Blackbody radiation

The higher the temperature, the more the emission and the shorter the average wavelength.

So “blue hot” is hotter than “red hot”.

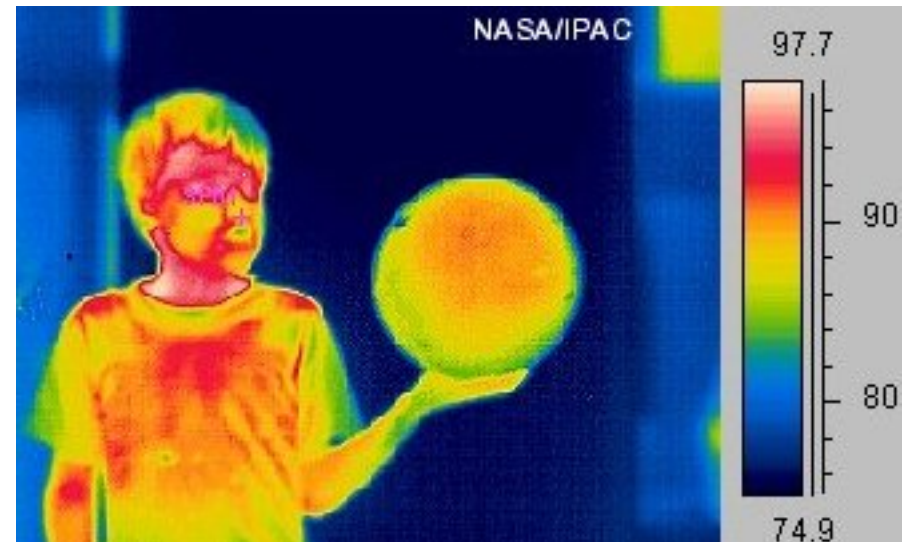


You are a blackbody

Thermal imaging uses a camera that is sensitive in the mid-infrared, which is where the blackbody radiation spectrum peaks for objects that are near room temperature.

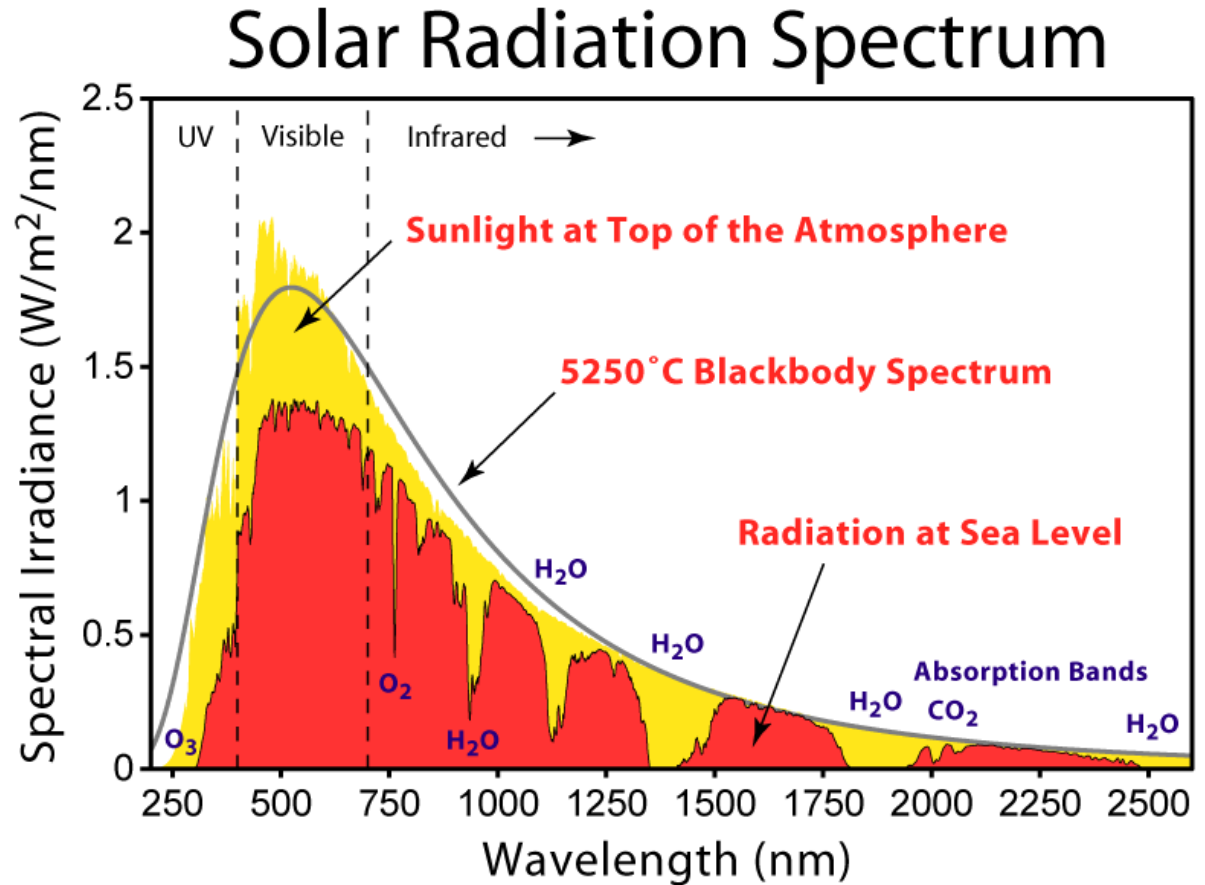
You glow at a wavelength of about 10 microns.

thermal image of a boy holding a basketball before and after bouncing it.



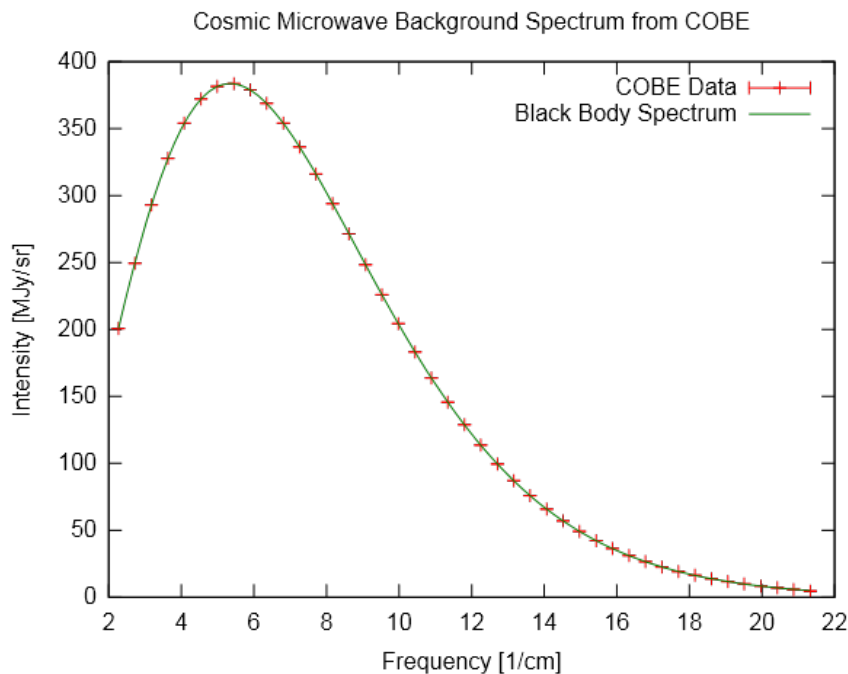
The sun is a blackbody

When measured at sea level, one sees absorption lines due to molecules in the atmosphere.



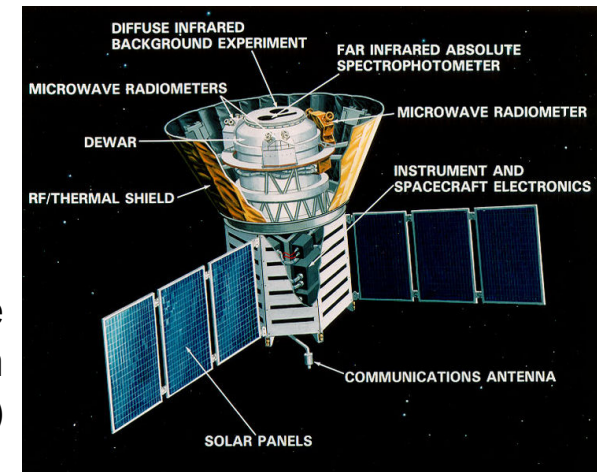
So is the universe

As an object cools slowly, the radiation it emits retains the blackbody spectrum. But the peak shifts to lower and lower frequencies.



The 2.7° cosmic microwave background is blackbody radiation left over from the Big Bang!

COBE satellite
(launched in
1989)



The ideas

- Stimulated emission: quantum mechanic's addition to the list of ways atoms and photons can interact
- The Einstein-Planck result solves the ultraviolet catastrophe
- Blackbody radiation: everywhere!