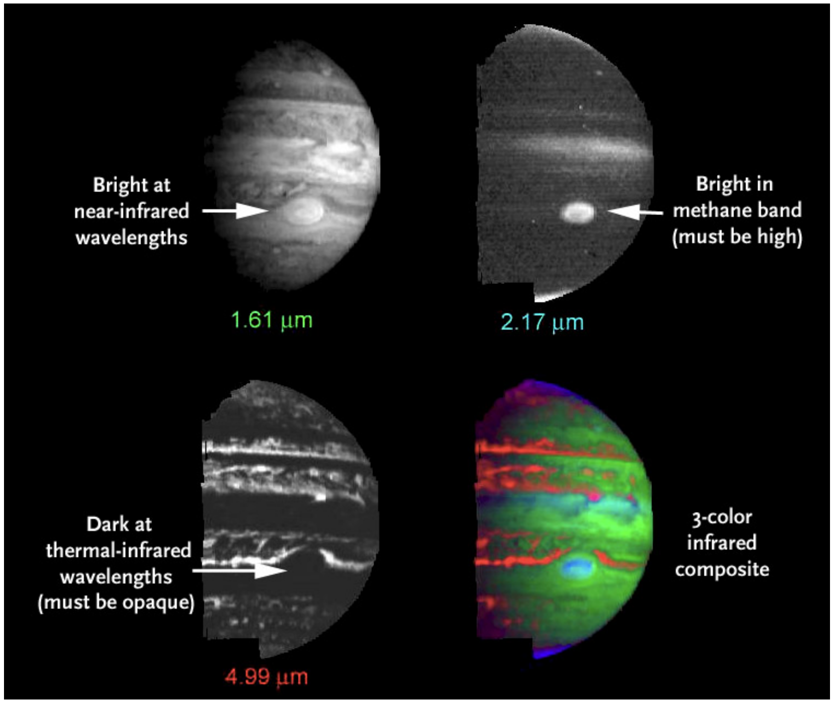
[09] Light and Matter (9/26/17)

Upcoming Items

1. Homework #4 due now.
2. Midterm #1 on Tuesday, October 10. Ch. 1–6.
3. Read Ch. 5.4 by next class and do the self-study quizzes



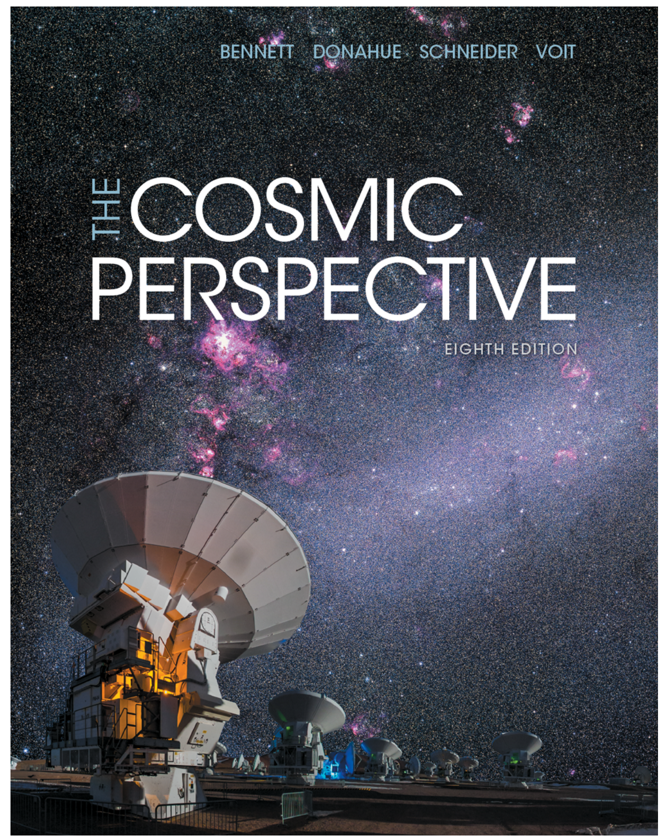
Galileo spacecraft images of Jupiter

LEARNING GOALS

Chapters 5.1–5.3

For this class, you should be able to…

- … *use the wave and particle properties of light to relate wavelength, frequency, and energy of electromagnetic radiation, and calculate these values.*
- … *understand blackbody radiation*
- … *understand the basics of how light interacts*

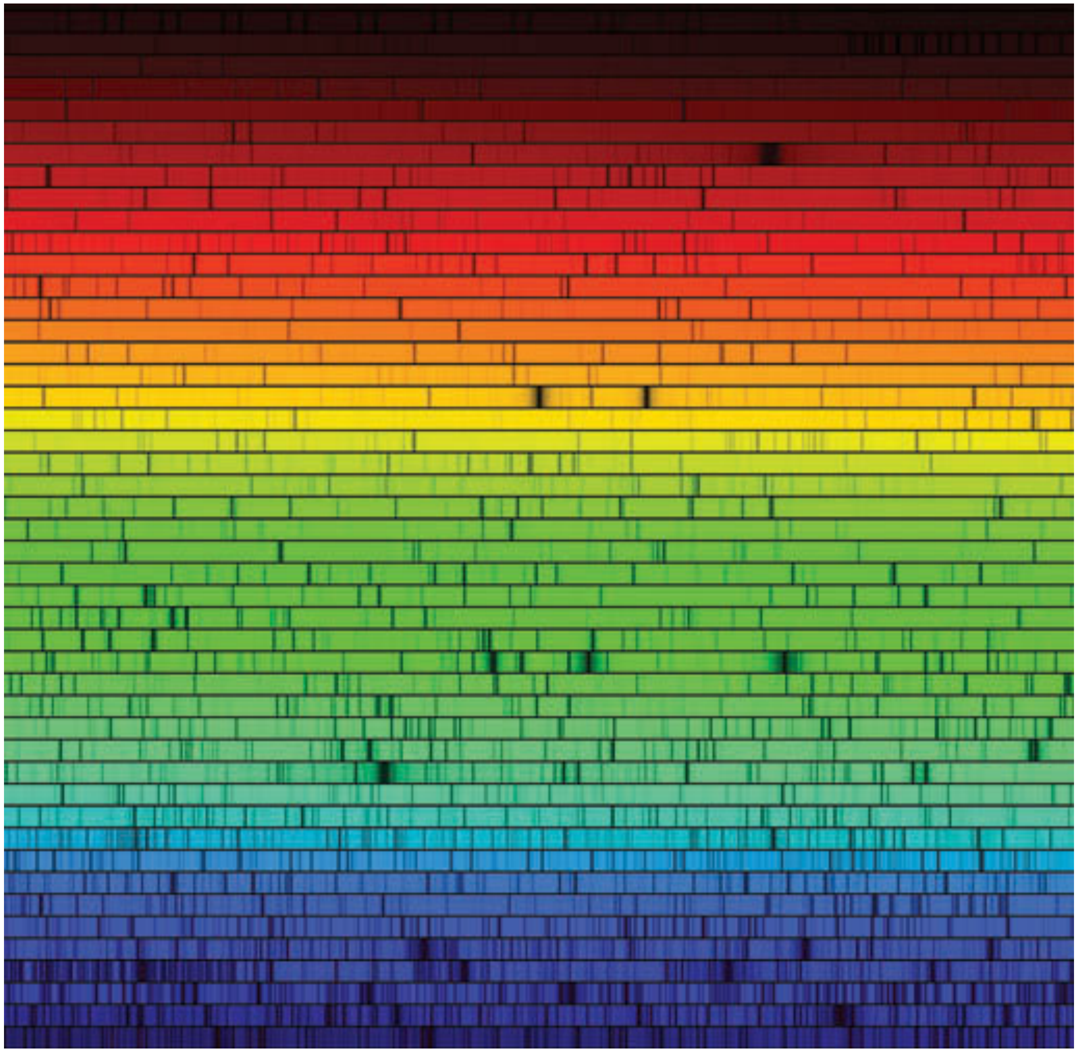


Any astro questions?

Reminder: Midterm 1 in Two Weeks!

- In class, regular time (11-12:15), regular classroom; Oct 10
- Closed-book, closed-notes, you must bring a calculator
  I will provide a formula sheet, and will post on Oct 3
- Exam will be on all material in the class through and including next Tuesday's (Oct 3) lecture
  Thus Chapters 1-6 in the book, all slides, homework, discussion, ...
- Anything is fair game; what I have put on my slides is what I consider to be the most important content, but content beyond that is possible as well
- I ***strongly*** recommend that you prepare in advance; talk to the tutors, not just right before HW is due ☺
- Currently planning a review on October 9; *completely* driven by your questions (TA will not prepare *any* review slides)

What is this? What features do you see?



Why light?

- Why is light the main way we know about the universe?

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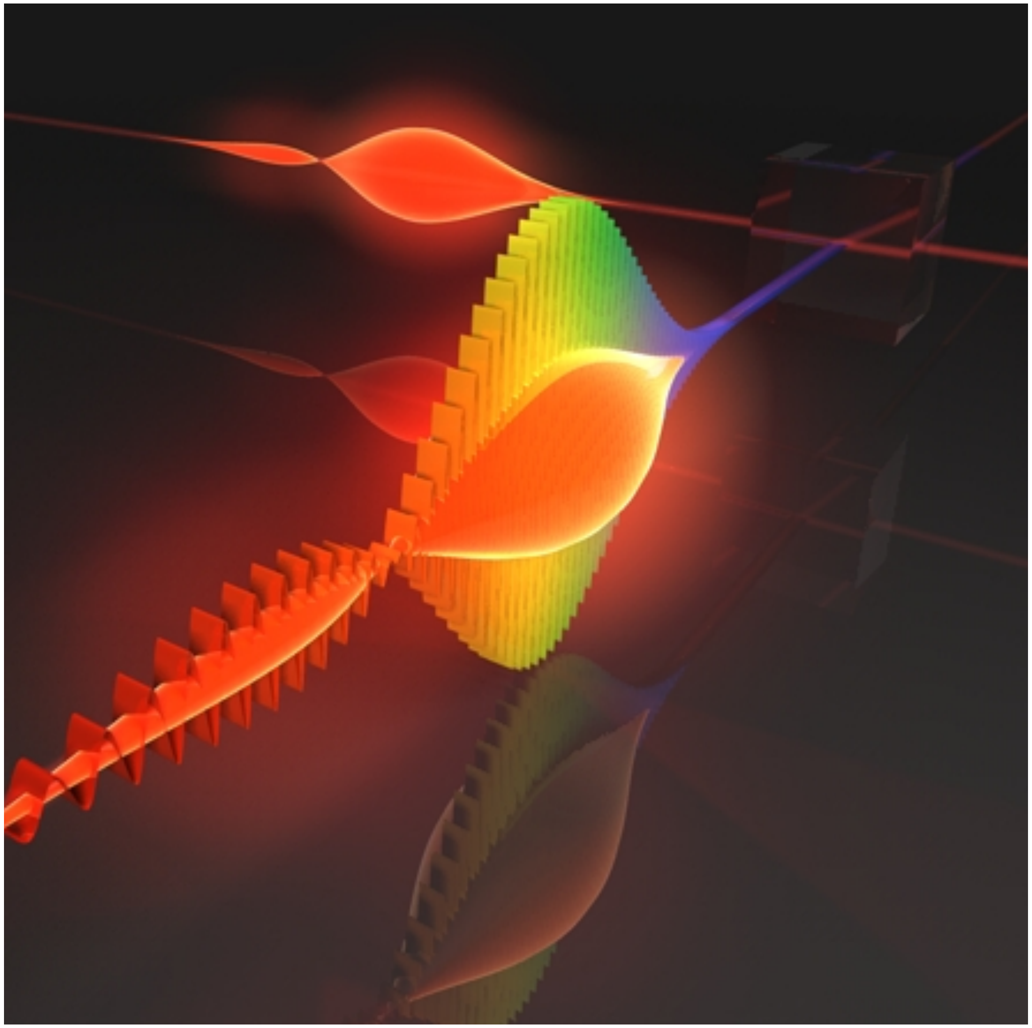
- Why is light the main way we know about the universe?
  Travels fast; oddly, at the speed of light ☺
  Almost everything makes light
  Not too easily blocked...
  ...but can be detected relatively straightforwardly

Light is Made Out of Photons

- “Particles” of light
- What properties do photons have?



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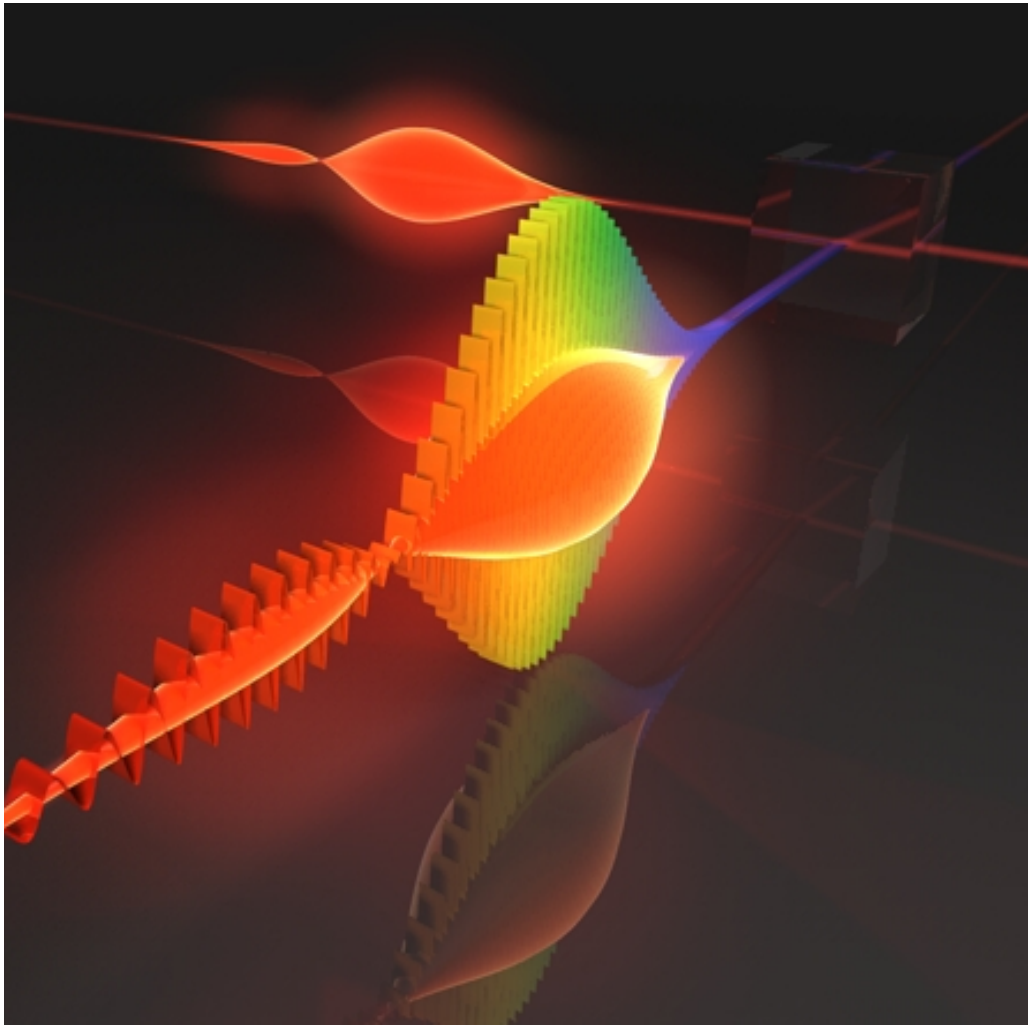
Light is Made Out of Photons

- “Particles” of light
- What properties do photons have?
  Energy
  Linear momentum
  Angular momentum



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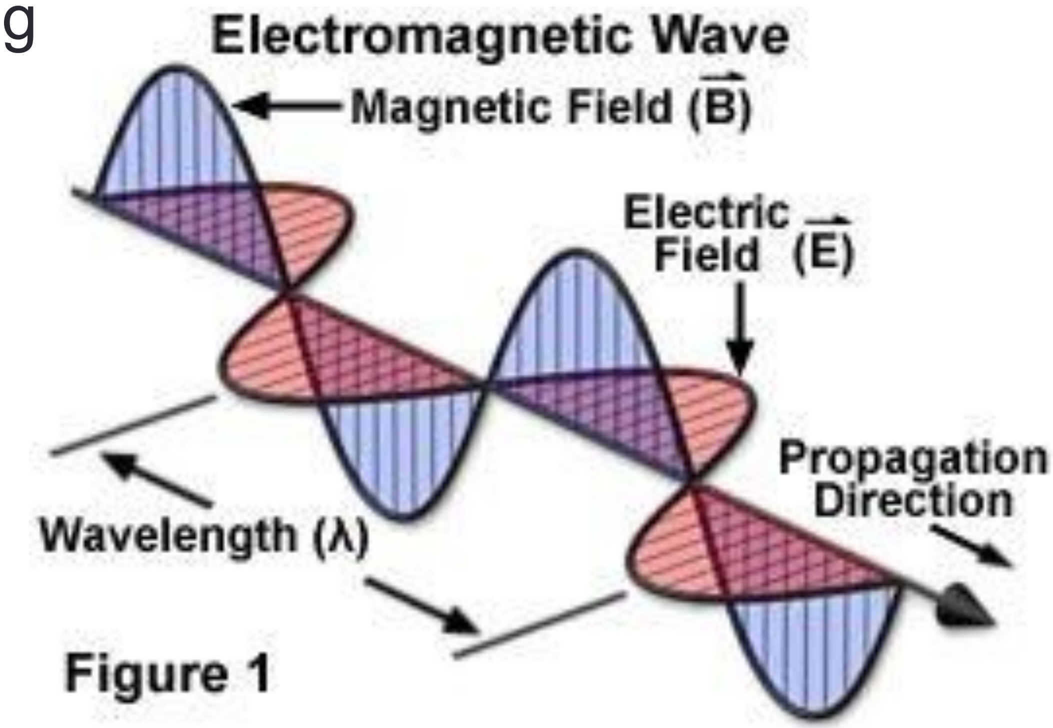
The Properties of Individual Photons

- Energy
  $E=h\nu$, where $h=6.626\times10^{-34}$ kg m^2 s^{-1} is Planck's const and ν is the frequency
  Can also write $E=hc/\lambda$, where λ=wavelength, c=speed of light
- Linear momentum
  $p=E/c$, or $E=pc$; can go in any direction
  Photons can bounce off things and deliver force!
  Light has wavelike, and particle-like, properties: QM!
- Angular momentum
  Magnitude per photon is $h/2\pi$
  Thus each photon, individually, has circular polarization
  Many photons in a wave can combine for linear polarization

Photons in a Vacuum

- Electromagnetic waves
- That is, they are propagating waves of electric and magnetic fields.
- In a *vacuum*, photons of all wavelengths travel at the same speed
  But not in a medium! E.g., a prism works because photons of different wavelengths move at different speeds



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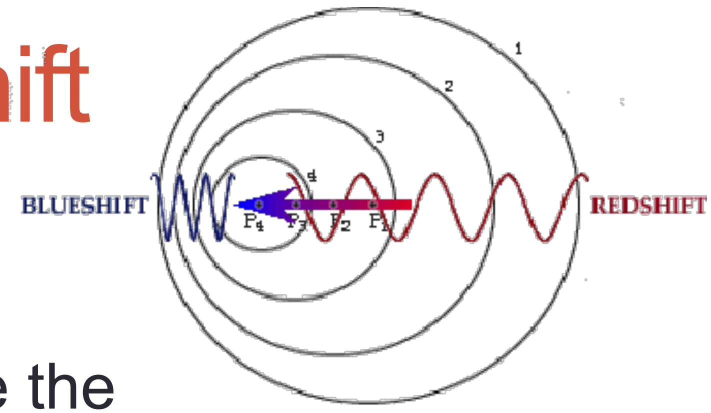
To reinforce that point: which of the following wavelengths of light will move slowest in vacuum?

A. Radio waves
B. Infrared light
C. Optical light
D. Gamma rays
E. All the wavelengths move at the same speed in vacuum

For discussion: what if we ask “which of the following wavelengths of light will move slowest in interstellar space?” Is the answer necessarily the same?

A. Radio waves
B. Infrared light
C. Optical light
D. Gamma rays
E. All the wavelengths move at the same speed

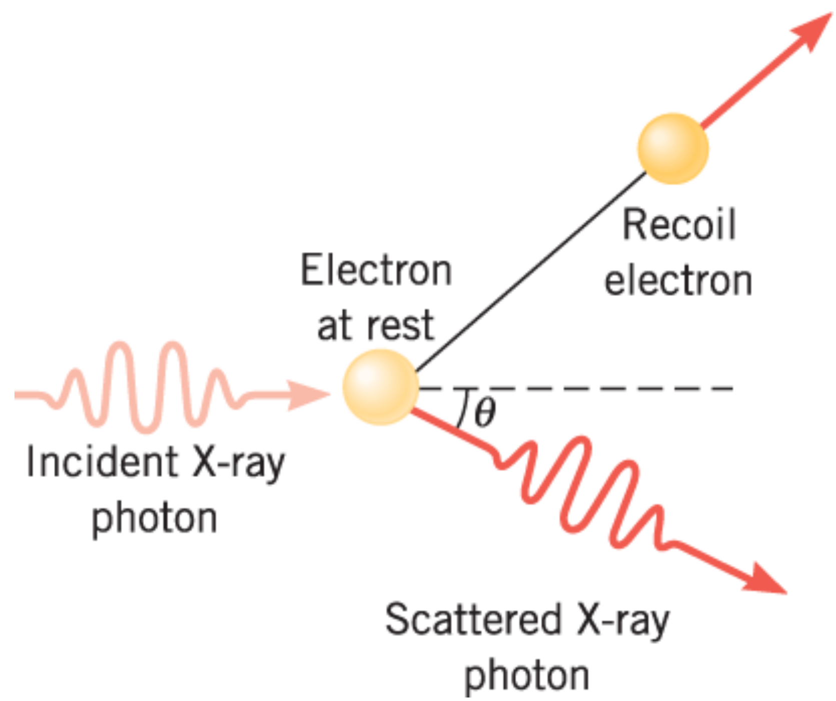
Doppler Shift



- Even though light all travels at the same speed, if the source moves away from you then you will observe the photon to be longer-wavelength (redder) than if the source is not moving with respect to you
  Wave-like property
- Similarly, motion toward you means shorter wavelength
  Called, respectively, redshift and blueshift
- Similar effects can happen due to strong gravitational fields ("gravitational redshift") and cosmological expansion ("cosmological redshift")
- If you knew the wavelength the photon had in its rest frame, what, therefore, could you learn?

The Life of a Photon: Scattering

- Still being agnostic about how the photon came to be...
- A photon can “bounce” off of, say, an electron
  Particle-like property
- Question: if the electron was initially at rest, and after the scattering the electron is now moving, what has happened to the energy of the photon?



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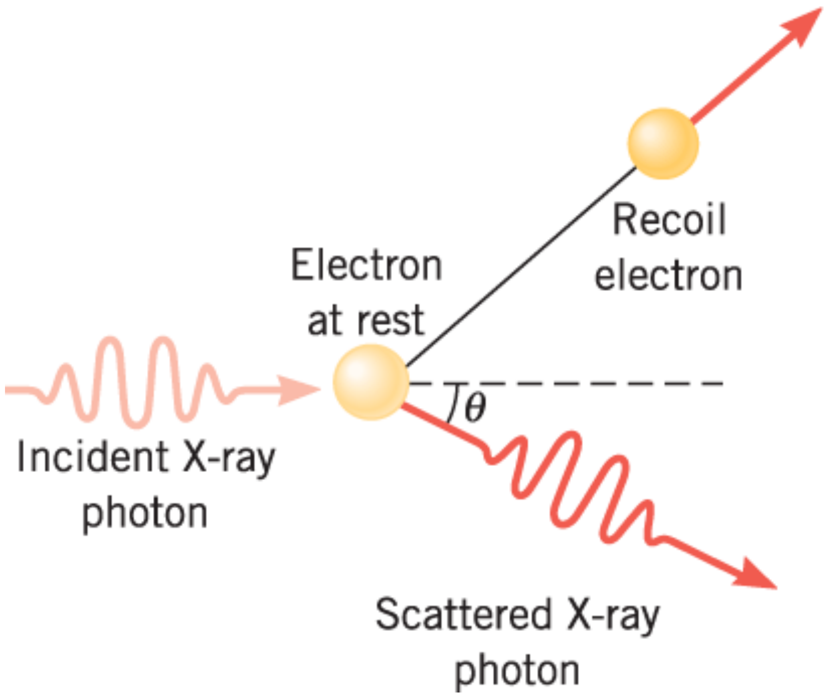
- Question: if a bright source has a scattering medium in front of it, will it seem brighter, dimmer, or unchanged to you?



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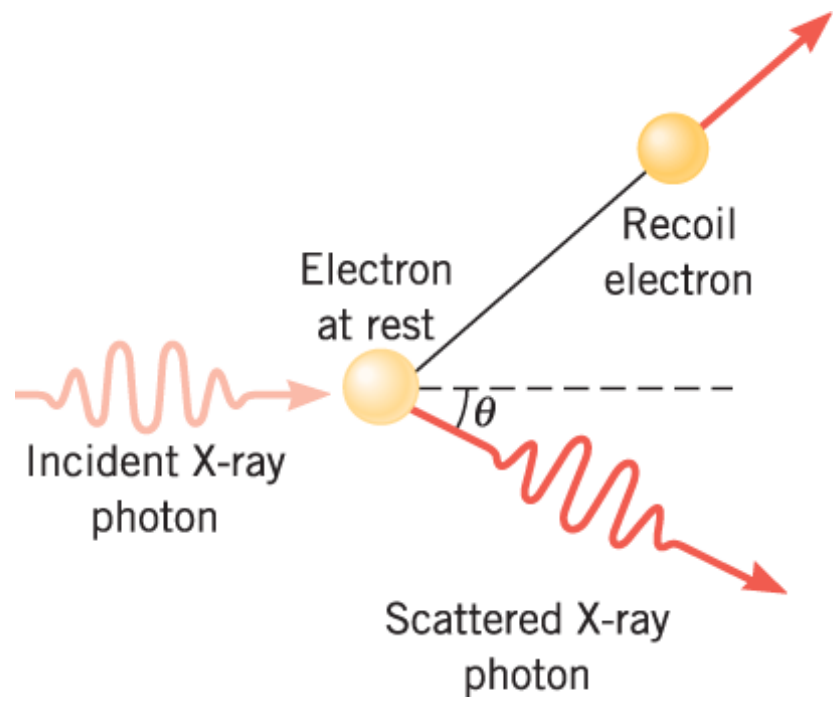
The Life of a Photon: Scattering

- Still being agnostic about how the photon came to be...
- A photon can "bounce" off of, say, an electron
- Question: if a bright source has a scattering medium in front of it, will it seem brighter, dimmer, or unchanged to you?
- Dust can also scatter photons



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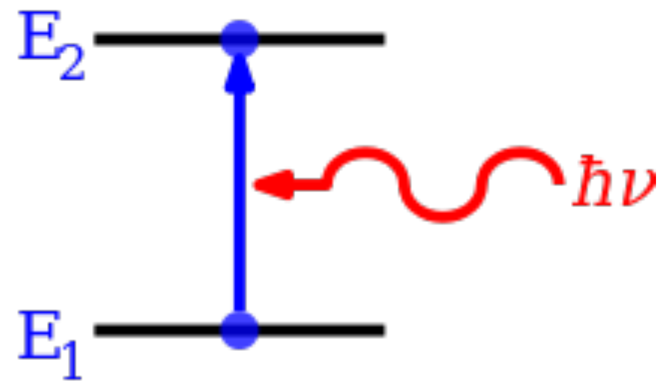
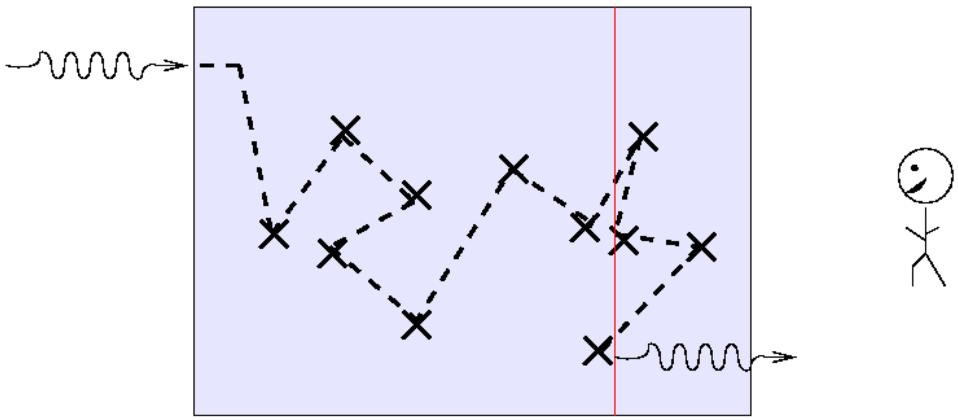
The Life of a Photon: Absorption

- In some cases, a photon can be "eaten", so that it is actually gone
  Called absorption
- Energy conservation means that the energy in the photon must now reside somewhere in the system that absorbed the photon
  In the schematic at right, this means that the system has gone from a lower energy state E_1 to a higher energy state E_2



Wikipedia

Optical Depth



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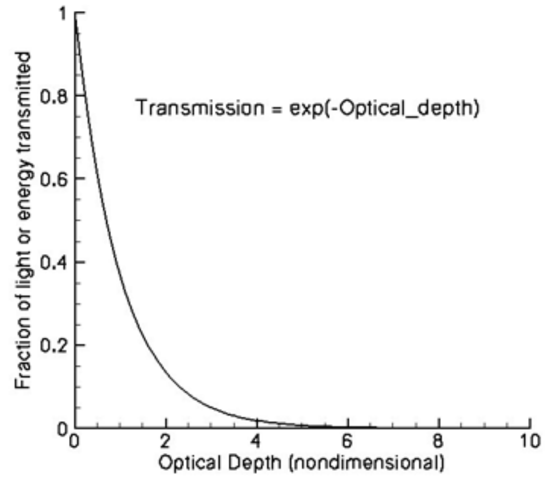

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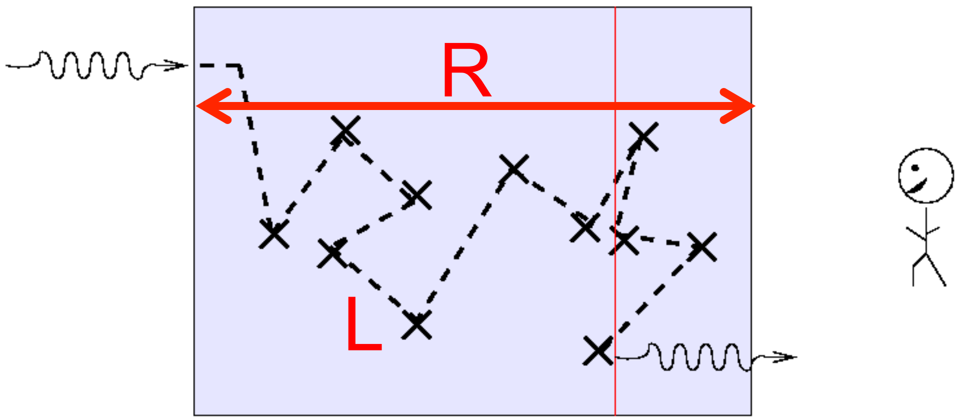
- So *now* can we learn how photons are made?

Optical Depth



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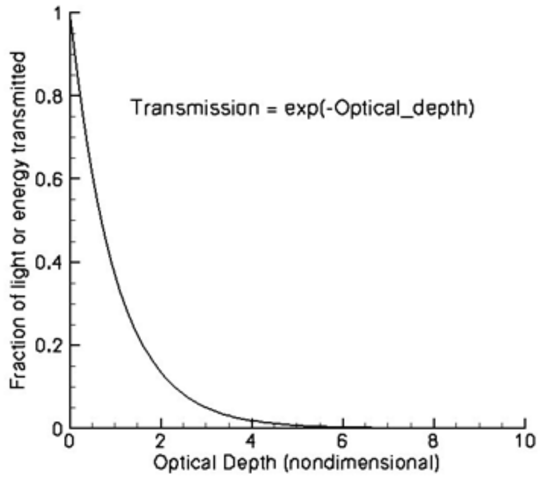

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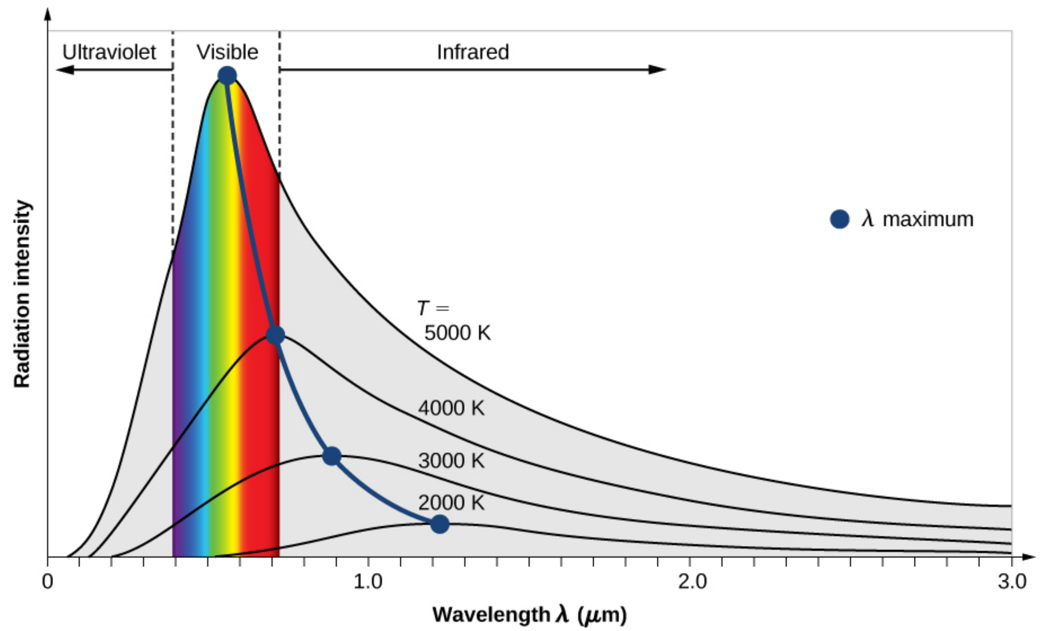
- So *now* can we learn how photons are made?
  No! Hold your horses...
- First, optical depth (τ). If the typical distance traveled by a photon (its "mean free path") is L, and the distance through the material is R, then the optical depth is defined as τ=R/L.
- τ<<1 => "optically thin"; τ>>1 => "optically thick"
- A fraction $e^{-\tau}$ of photons get through without interacting

Blackbody Radiation

- What radiation do we expect in equilibrium?
- Here "equilibrium" means that all process and their inverses (e.g., absorption and emission) are in balance. Requires $\tau >> 1$. Why is that?
- In this perfect situation, the spectrum depends only on temperature
  Spectrum=energy per area per time at different frequencies
- What astronomical sources might approximate this?



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What features do you notice about these curves?

Blackbody Spectrum, Take 1

- An early derivation suggested that the energy per area per time per frequency for blackbody radiation should go as $B_\nu(T)=8\pi\nu^2kT/c^3$ where ν is the frequency, T is the temperature, k is the Boltzmann constant, and c is the speed of light
- Is there any problem with this?

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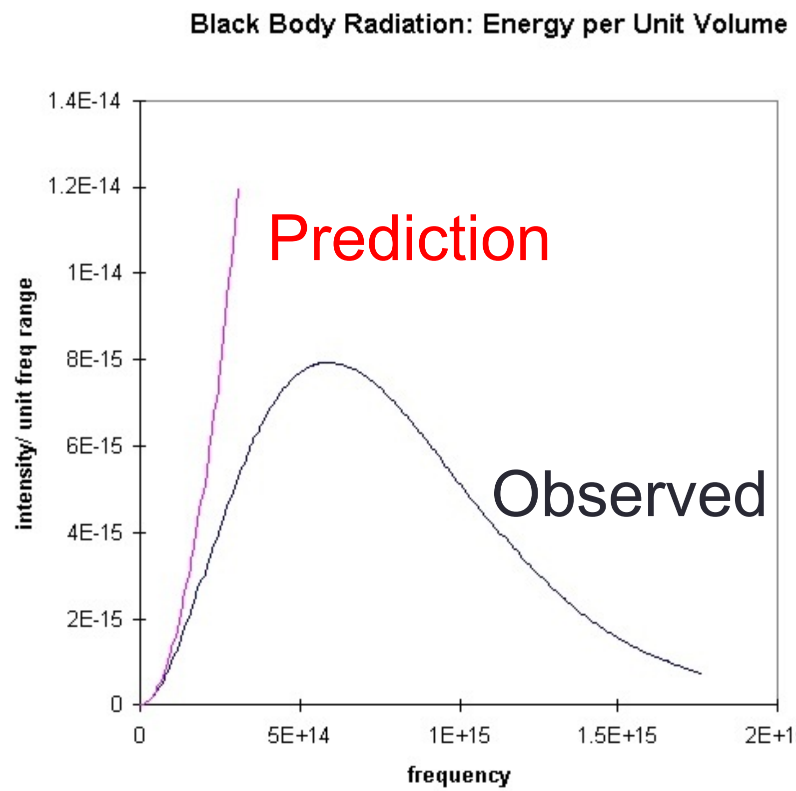
  $B_\nu(T)=8\pi\nu^2kT/c^3$
  where ν is the frequency, T is the temperature, k is the Boltzmann constant, and c is the speed of light
- Is there any problem with this?
  Ultraviolet catastrophe!



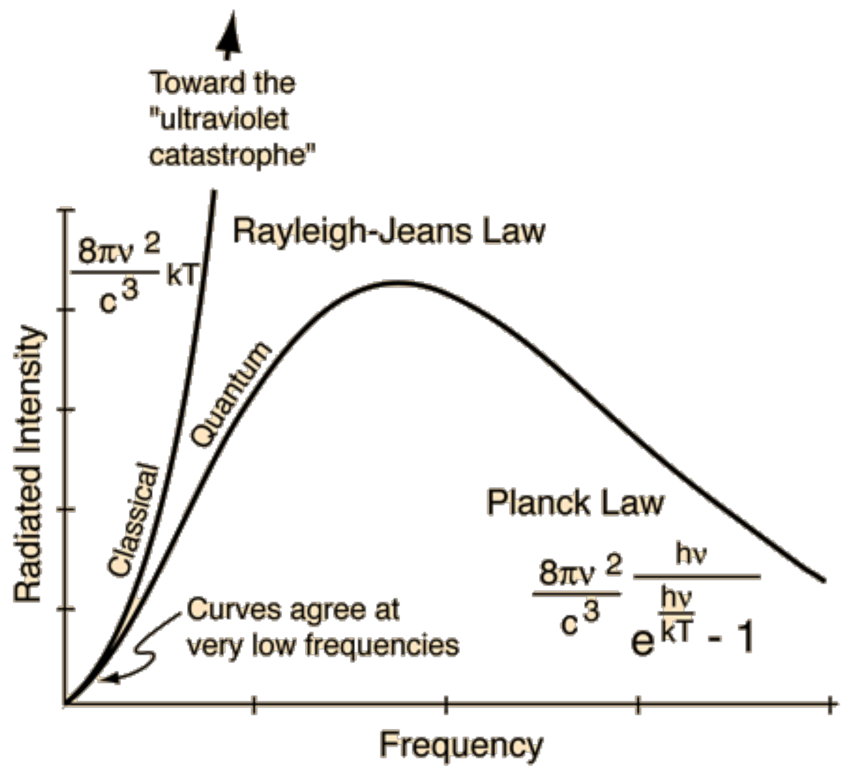
https://thecuriousastronomer.files.wordpress.com/2013/10/20131021-145512.jpg

Blackbody Spectrum, Take 2

- Brilliant idea by Max Planck: light is quantized
  i.e., for a given frequency, can't chop light up indefinitely
- Using this hypothesis:

$$B_\nu(T) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1}$$

- Works incredibly well!
- Let's look at some of the properties of the formula



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h=Planck's constant; fundamental to QM!
$h=6.626\times10^{-34}$ m^2 kg s^{-1}

Low Frequency Limit

- Our formula again: $$B_\nu(T) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1}$$
- Suppose the frequency is low, in the sense that $h\nu \ll kT$. Does the formula simplify?
- Using calculus we can show that if $x \ll 1$, $e^x \sim 1+x+\ldots$ Thus $e^{h\nu/kT}-1 \sim 1+h\nu/kT-1=h\nu/kT$
- Simplifying, we get that in this limit $B_\nu(T) \sim 8\pi\nu^2kT/c^3$
- This is the classical formula; tellingly, h does not appear
- This is called the Rayleigh-Jeans limit
- Very useful for radio astronomy, where the frequency ν is extremely low and thus the approximation applies

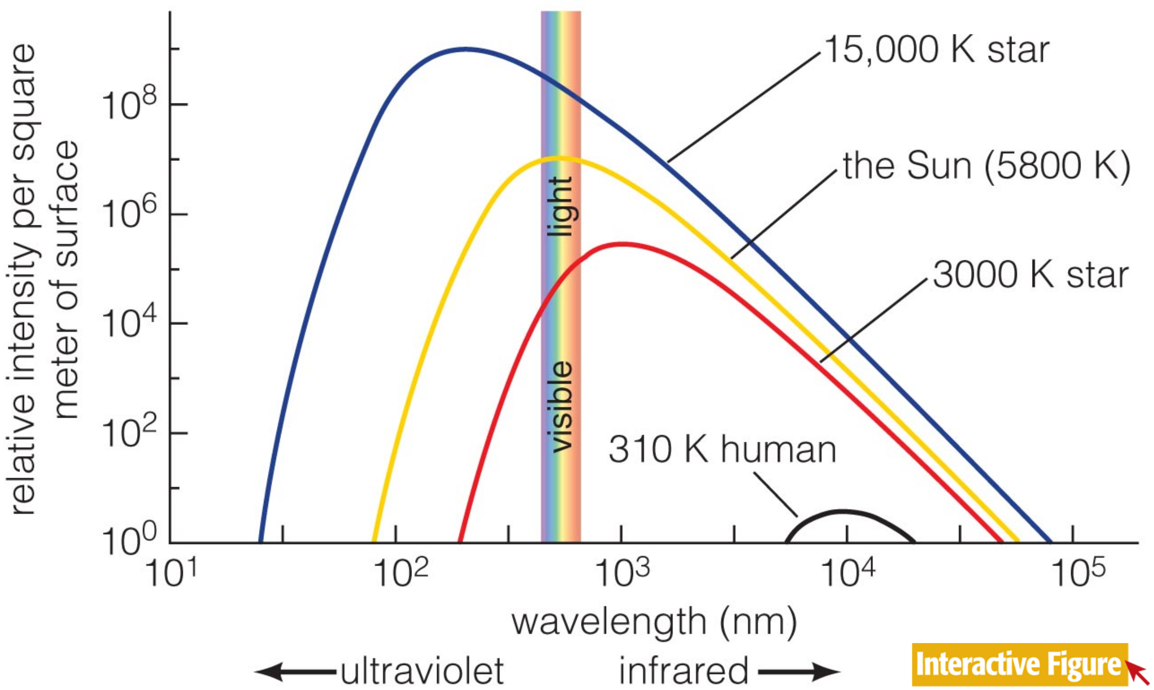
High Frequency Limit

- Our formula: $$B_\nu(T) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1}$$
- Suppose now that the frequency is high: $h\nu >> kT$.
- Then $e^{h\nu/kT} >> 1$, so we can neglect the "-1" in denom
- Simplifying, we therefore get that in this limit $B_\nu(T) \sim (8\pi h\nu^3/c^3)e^{-h\nu/kT}$
- Now h *does* appear; sign that quantum mechanics matters!
- No "ultraviolet catastrophe" here. Spectrum drops rapidly.
- This is called the Wien limit
- Useful for the high energy tails of distributions

Properties of Blackbody Radiation

- Hotter objects emit more light at ***all*** frequencies *per unit area*.
- Hotter objects emit photons with a *higher average energy*.
- Peak energy of a blackbody spectrum is proportional to kT
- Total integrated flux (energy/area/time) proportional to T^4

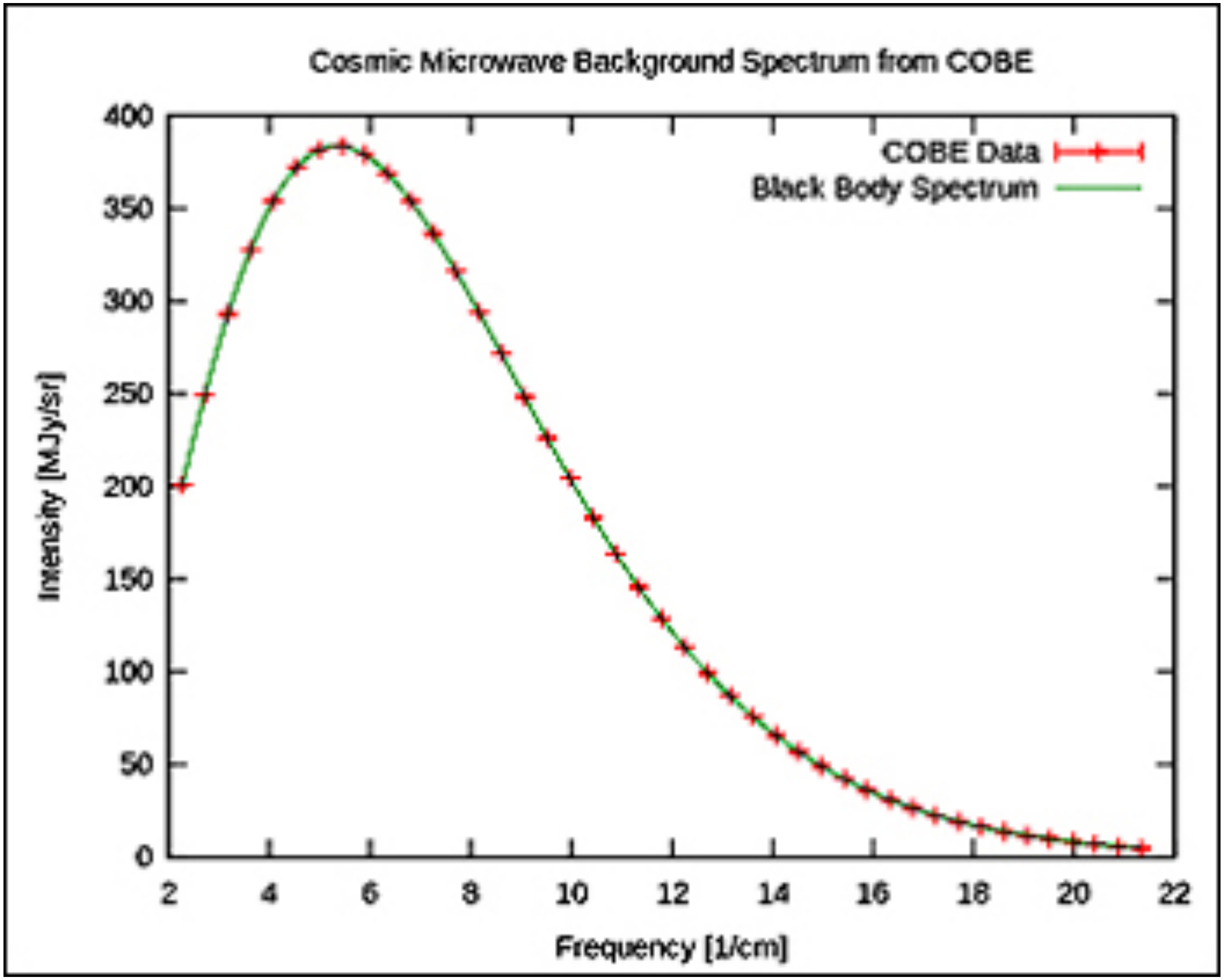
Notice log scale…



Why Spend Time on Blackbodies?

- Seems like this is just one, specific, spectrum, so why focus on it?
- Answer: this is the unique spectrum you get when everything is in equilibrium (i.e., plenty of time for many scatterings, absorptions, emissions, etc.)
- Nothing is a perfect blackbody, and many things are very far from a blackbody, but a surprising number of astronomical objects are pretty close (e.g., many stars)

Cosmic Microwave Background: BB!



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