PH 112: Quantum Physics and Applications

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Week-01, Lecture-1 Need for Quantum Mechanics

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Three fundamental problems

1. The question of the existence of an electromagnetic medium

2. The problem of observed differences in the electric and magnetic field between stationary and moving reference systems

   Special relativity (PH111) provided answers to these two questions.

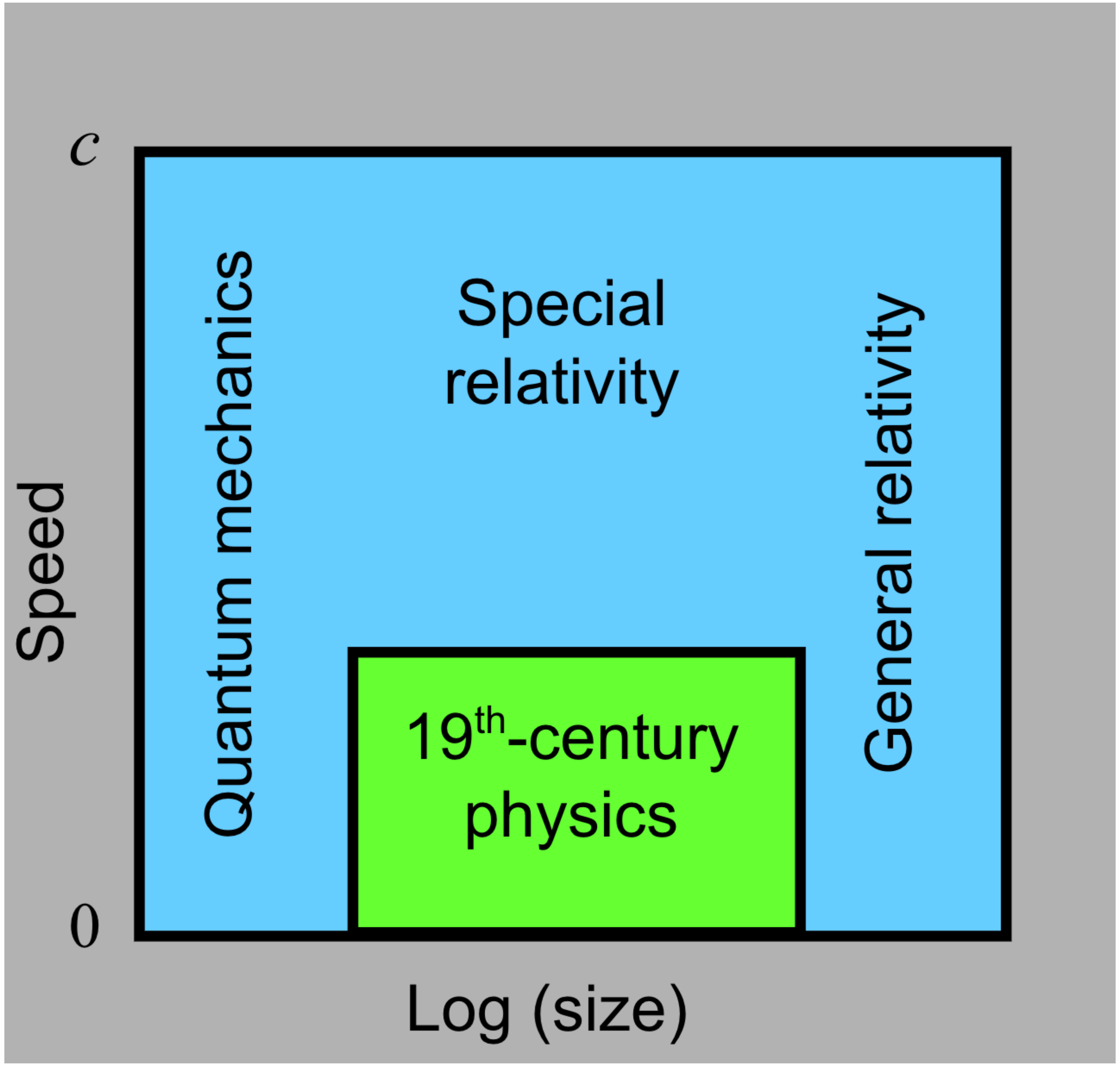
3. The failure of classical physics to explain blackbody radiation.

Topic of today's lecture

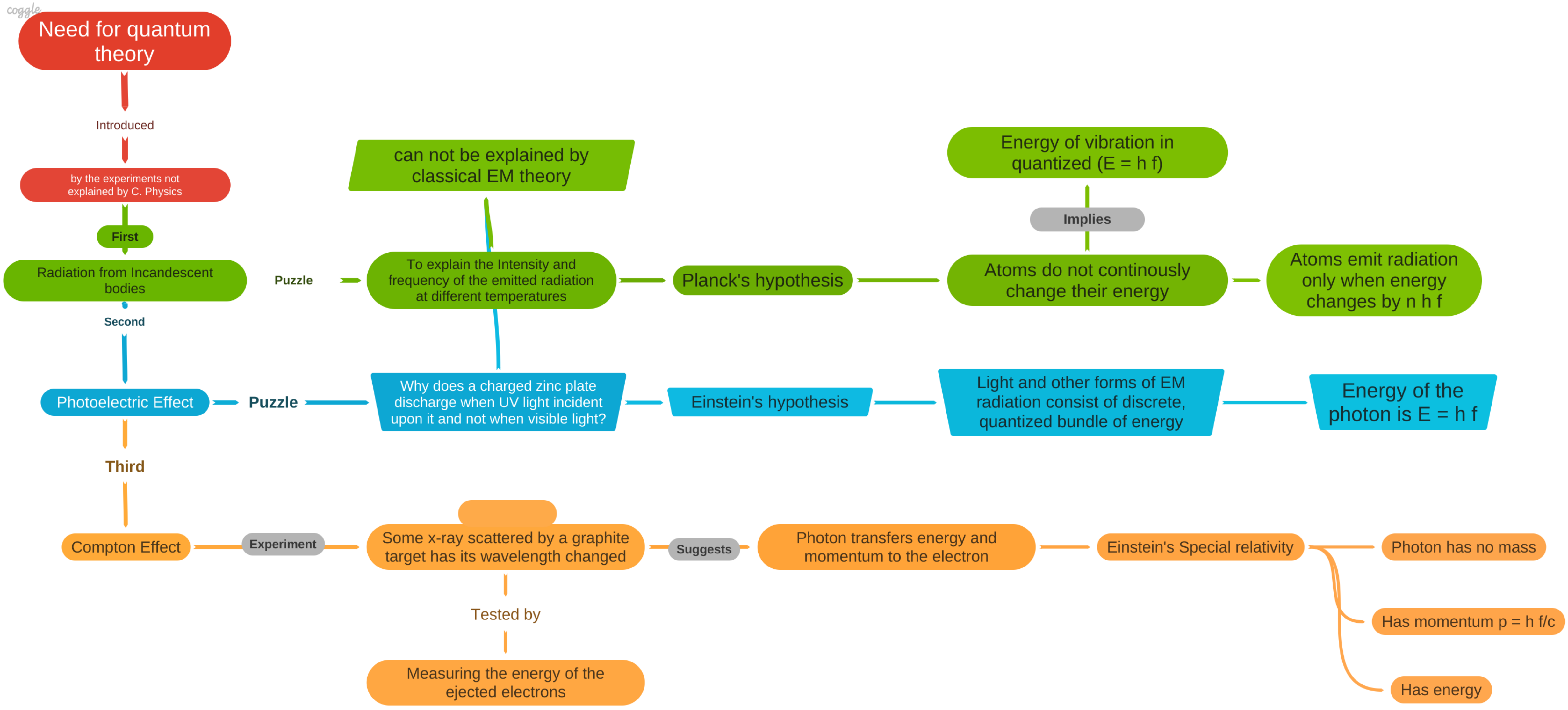
Birth of Modern Physics

- Fundamental problems and new discoveries and the many resulting complications required a revision of the fundamental physical assumptions of mechanics and atoms.

- Theory of Relativity and Quantum mechanics are the starting point of this fascinating revision.



Three experiments that C.Physics can not explain



Thermal Radiation

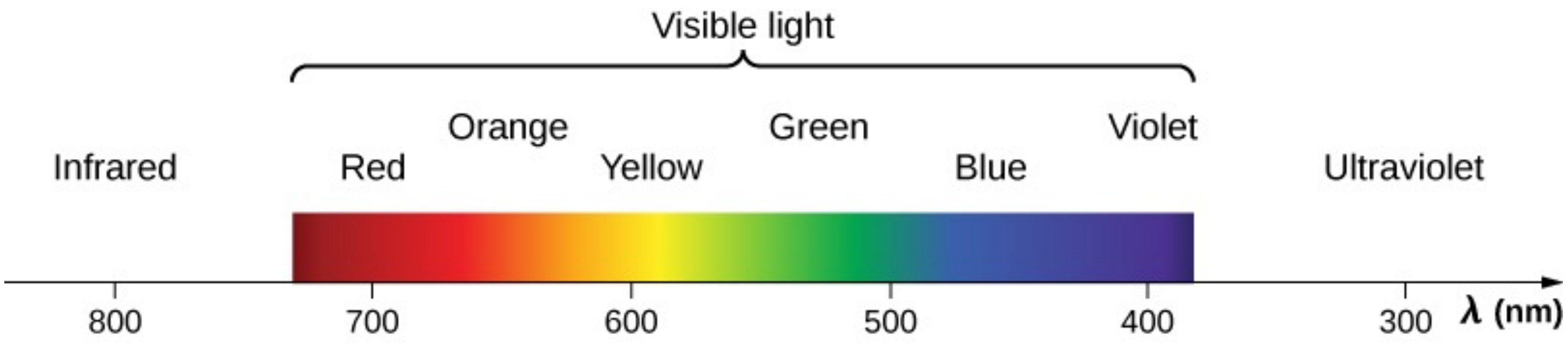
The Electromagnetic Spectrum

- All electromagnetic waves travel in a vacuum with a speed *c* given by:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \lambda f$$

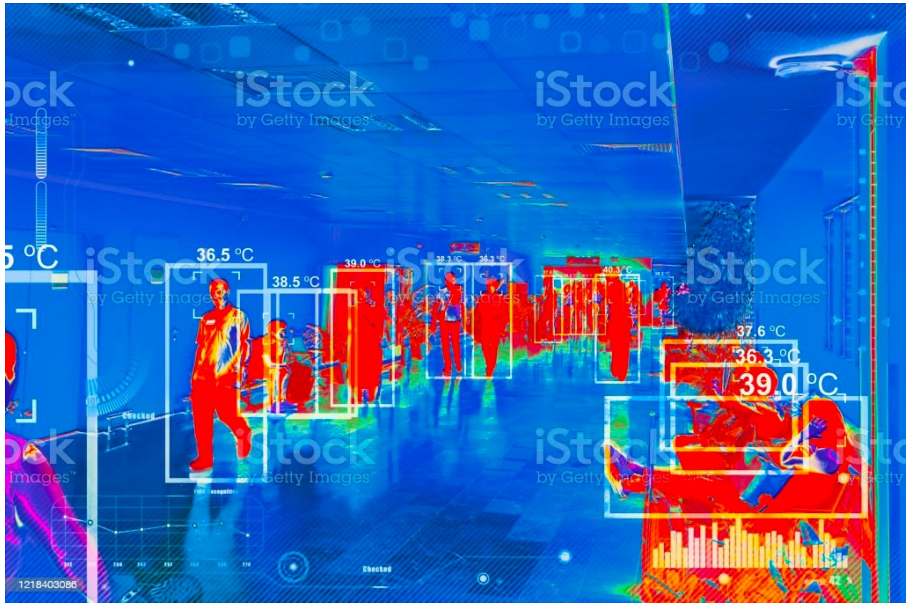
(where μ_0 and ε_0 are the respective permeability and permittivity of “free” space)

- Visible light covers only a small range of the total electromagnetic spectrum

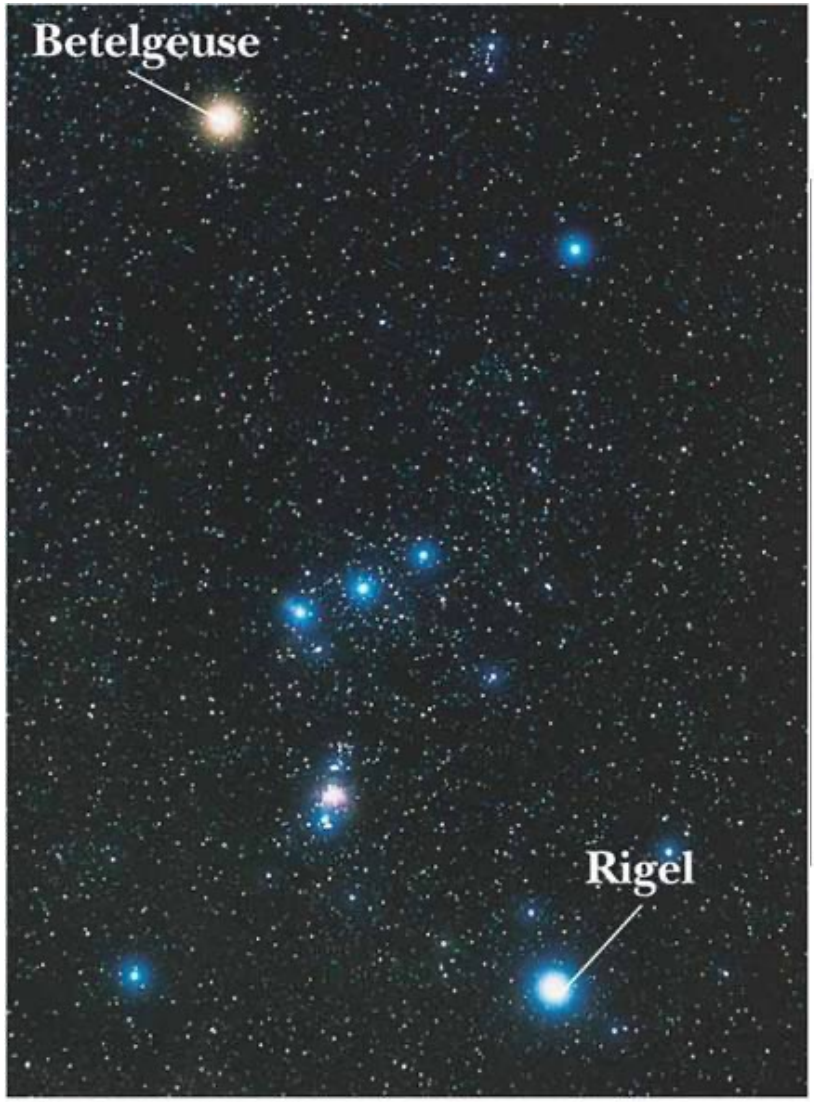


Thermal radiation

Object that is HOT (anything > 0 K is considered "hot") emits EM radiation.



Thermal radiation in the night sky



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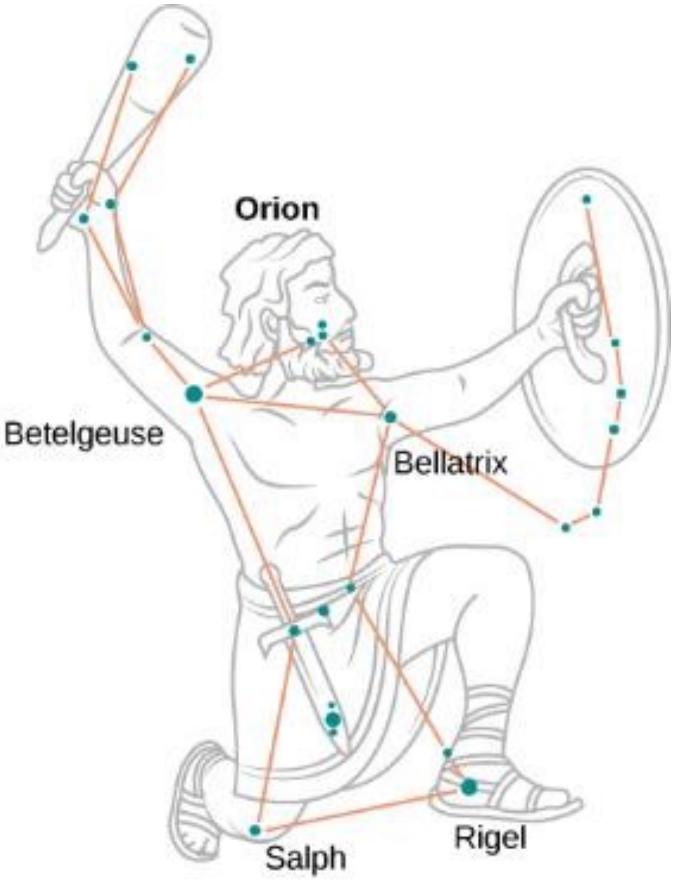
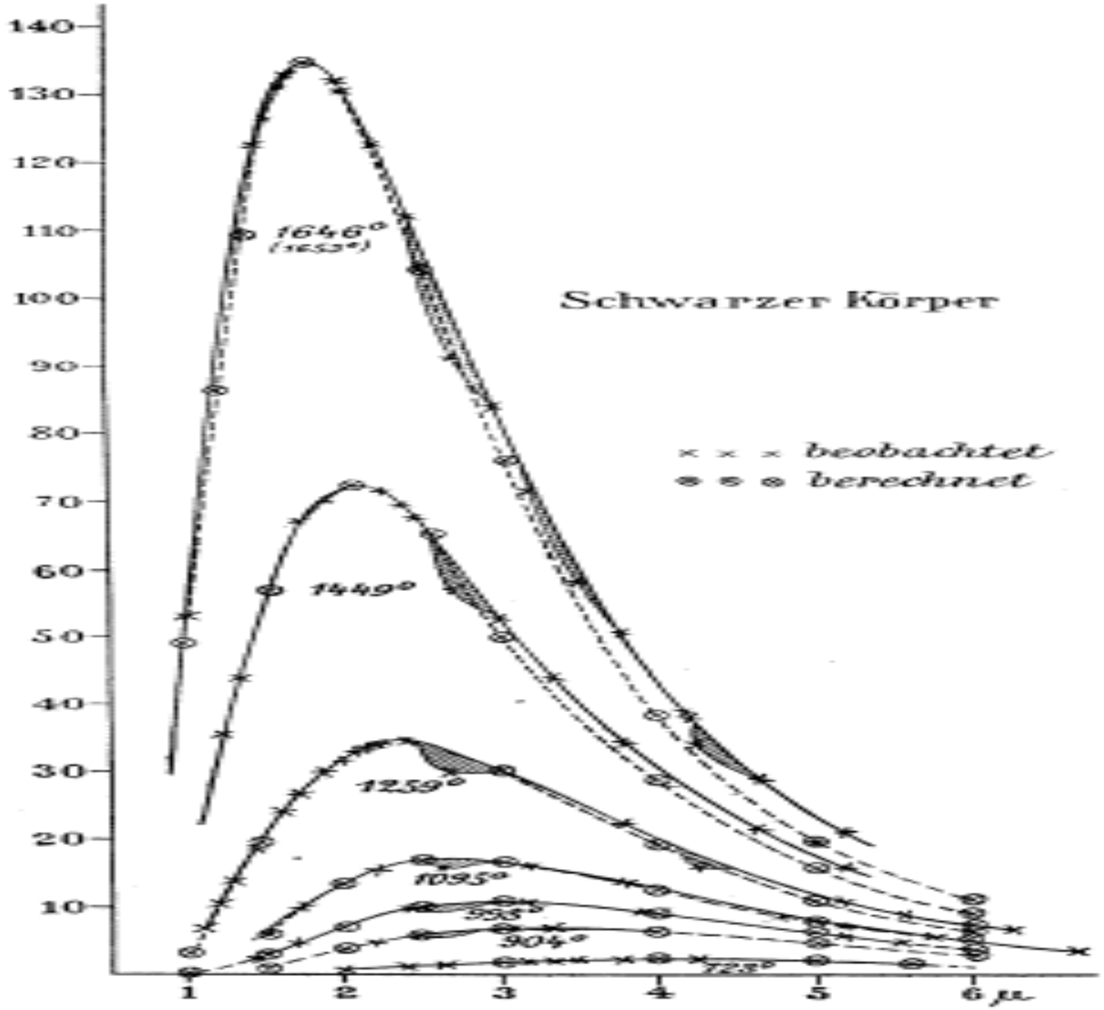


In the Orion constellation, the red star Betelgeuse, which usually takes on a yellowish tint, appears as the figure's right shoulder (in the upper left). The giant blue star on the bottom right is Rigel, which appears as the hunter's left foot. (credit: NASA)

Experimental measurement of thermal radiation



- Measurement at various temperatures by [Lummer and Pringsheim (1899).]()
- This clearly shows the distribution of intensity of the emitted radiation from a hot body at a given wavelength depends on the temperature.

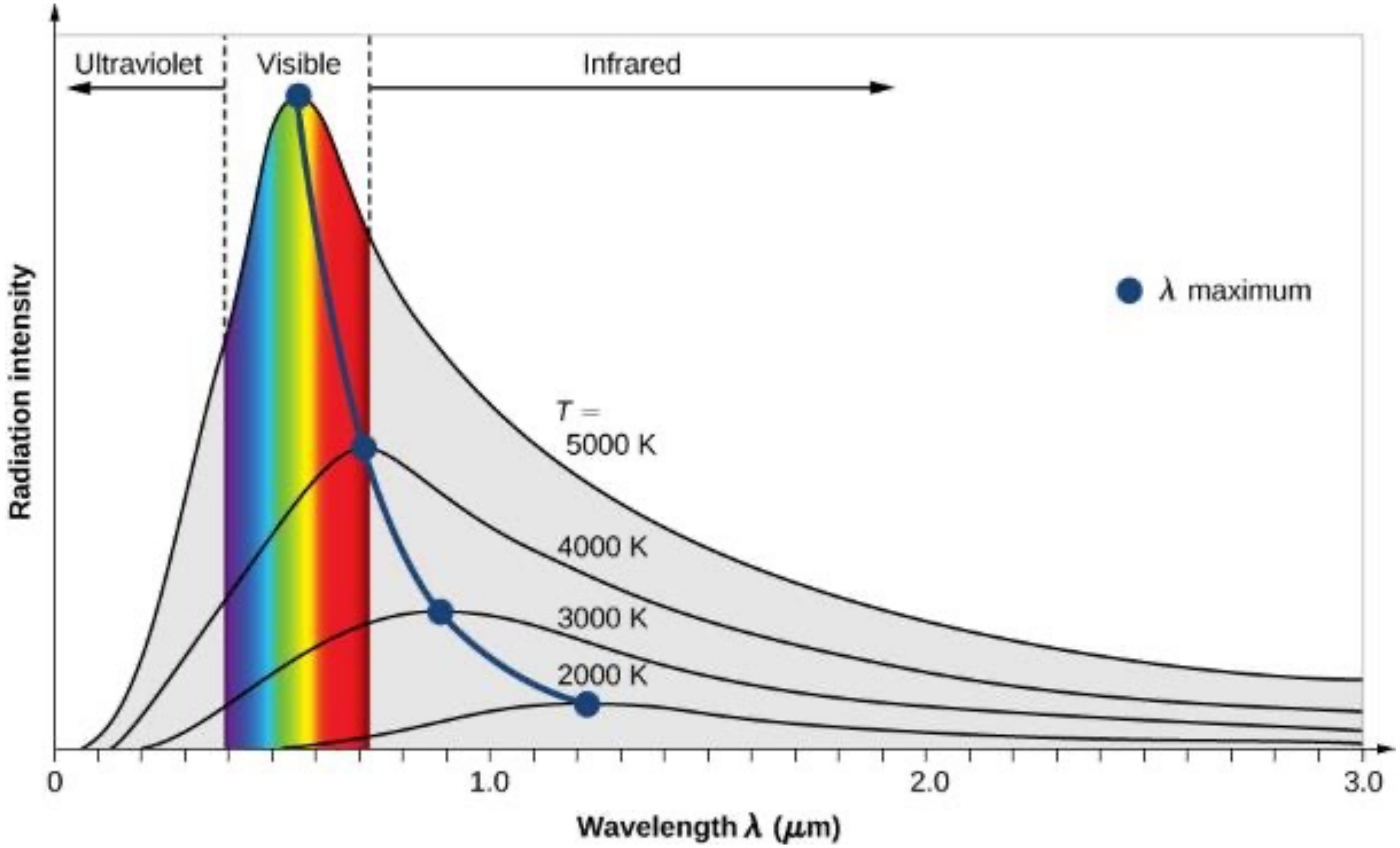
Thermal radiation: T, λ relationship

When we heat matter, it emits radiation. This is referred to as thermal radiation.

What are the properties of the observed radiation?

1. Profile of the thermal radiation depend on
   a) Temperature (*T*) and b) Surface properties of the material
2. The thermal radiation consists of a continuous distribution of wavelengths from all range of electromagnetic spectrum.
3. The energy intensities of the wavelengths differ continuously across wavelengths. At room temperature, the wavelength of the radiation is mainly in the infrared.
4. As temperature increases, the wavelength decreases.

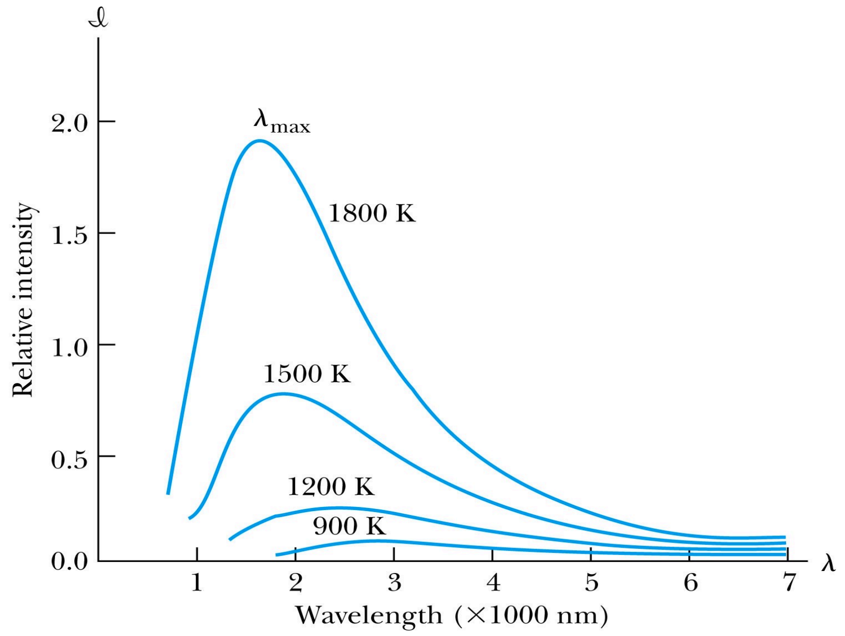
Variation of BB Radiation as a function of wavelength



Blackbody Experimental results

- Wien's displacement law: The peak of the wavelength decreases as Temperature increases.

$$\lambda_{\max} T = 2.898 \times 10^{-3} mK$$



- Stefan-Boltzmann law: The total power of the emitted radiation increases with temperature. For perfect blackbody ε = 1. (discussion below).

$$R(T) = \varepsilon\sigma T^4$$

$$\sigma = 5.6705 \times 10^{-8} W/\left(m^2 K^4\right)$$

  - Total power / area radiated increases as T^4

Early attempts to explain radiation

Attempts using classical theories

- In the early years, around 1888 – 1900, light is understood to be EM radiation

- Since hot body radiate EM radiation, hence physicists at that time naturally attempted to understand the origin of hot body in terms of classical EM theory and thermodynamics (which has been well established at that time).

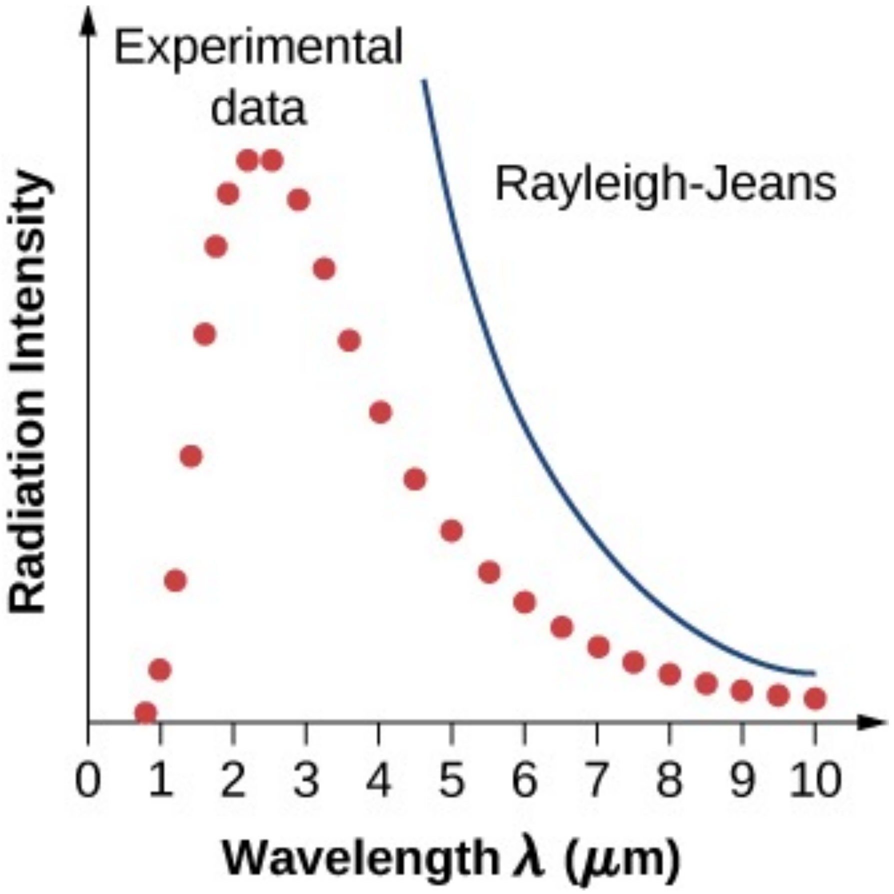
- Attempts to calculate the spectral distribution of blackbody radiation from 19th Century Physics Principles failed.

Rayleigh-Jeans Law

- The best description was given by the Rayleigh-Jeans formula

$$I(\lambda, T) = \frac{2\pi ckT}{\lambda^4}$$

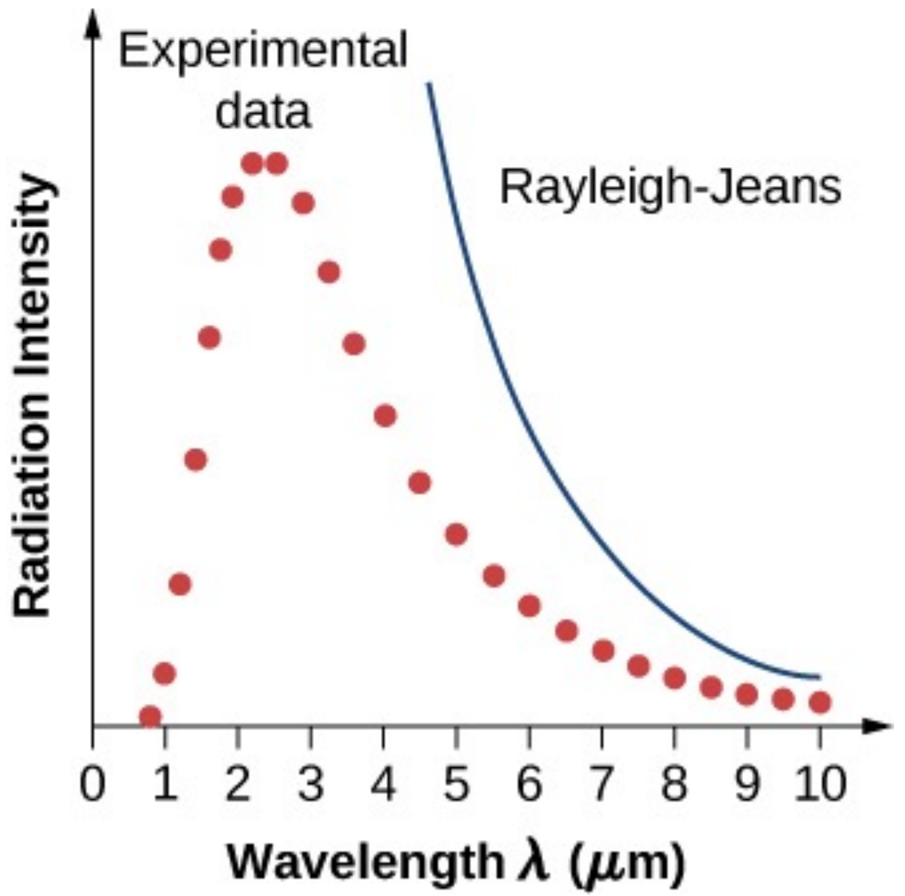
- This described the distribution at long wavelengths but increased without limit as $\lambda \to 0$.



Rayleigh-Jeans Law

Ultraviolet catastrophe

- System can have infinite energy as wavelength approaches zero!
- Suggests we have no good understanding of Physics at short wavelength.

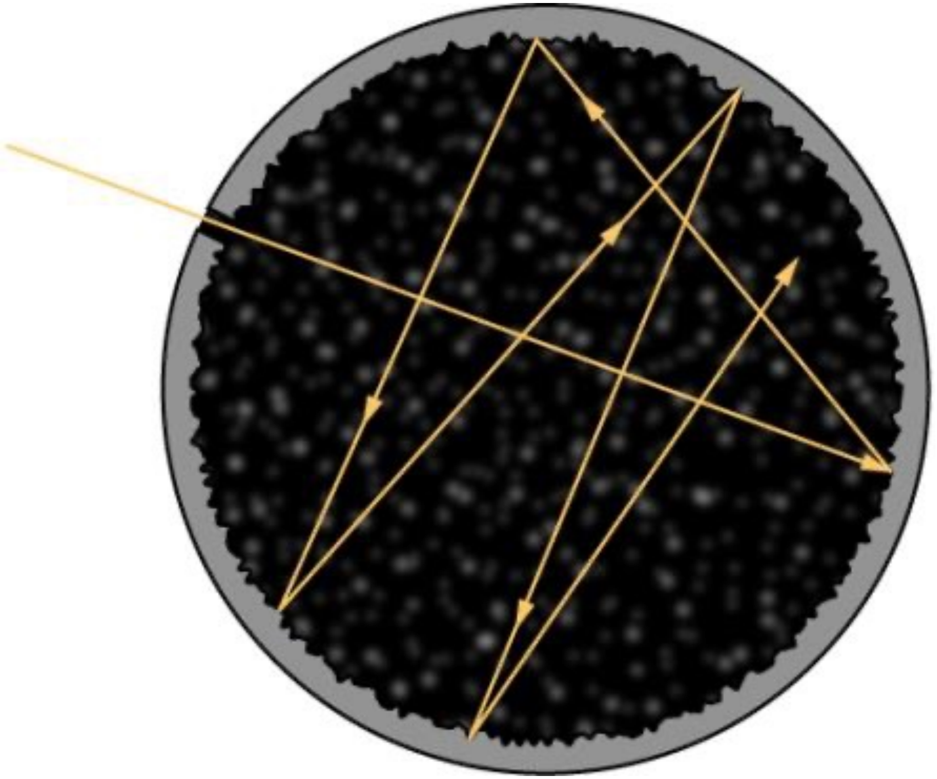


Idealized Black body

Idealized black body

- In reality the spectral distribution of intensity of radiation of a given body depends on the type of the surface.
- This renders the study of the origin of radiation by hot bodies case-dependent. (The conclusions made based on one body may not be applicable to other bodies that have different surface absorption characteristics.)
- As a strategy to overcome this non-generality, we introduce an idealized black body which, by definition, absorbs all radiation incident upon it, regardless of frequency.
- Such idealized body is universal and allows one to disregard the precise nature of whatever is radiating, since all BB behave identically
- All real surfaces could be approximate to the behavior of a black body via a parameter EMMISSIVITY ε. (ε =1 means ideally approximated, ε << 1 means poorly approximated.)

Idealized Blackbody Radiation



- This is a theoretical object that absorbs 100% of the radiation that hits it.

- It reflects no radiation and appears perfectly black. Hallow object acts as a perfect absorber. The power emitted equals the power absorbed.

- Blackbody radiation does not depend on the properties of the material. It only depends on the Temperature (*T*).

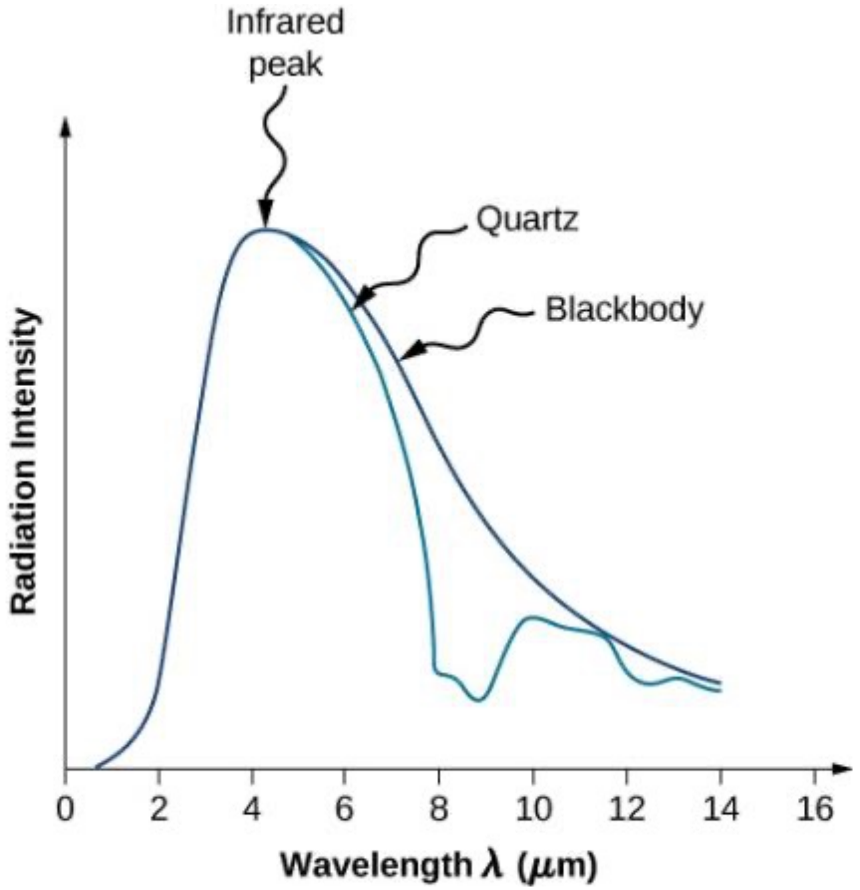
At a given temperature the black body would emit the maximum amount of energy possible for that temperature.

Idealized Blackbody Radiation

- A blackbody is a theoretical object that absorbs 100% of the radiation that hits it.
- It reflects no radiation and appears perfectly black.

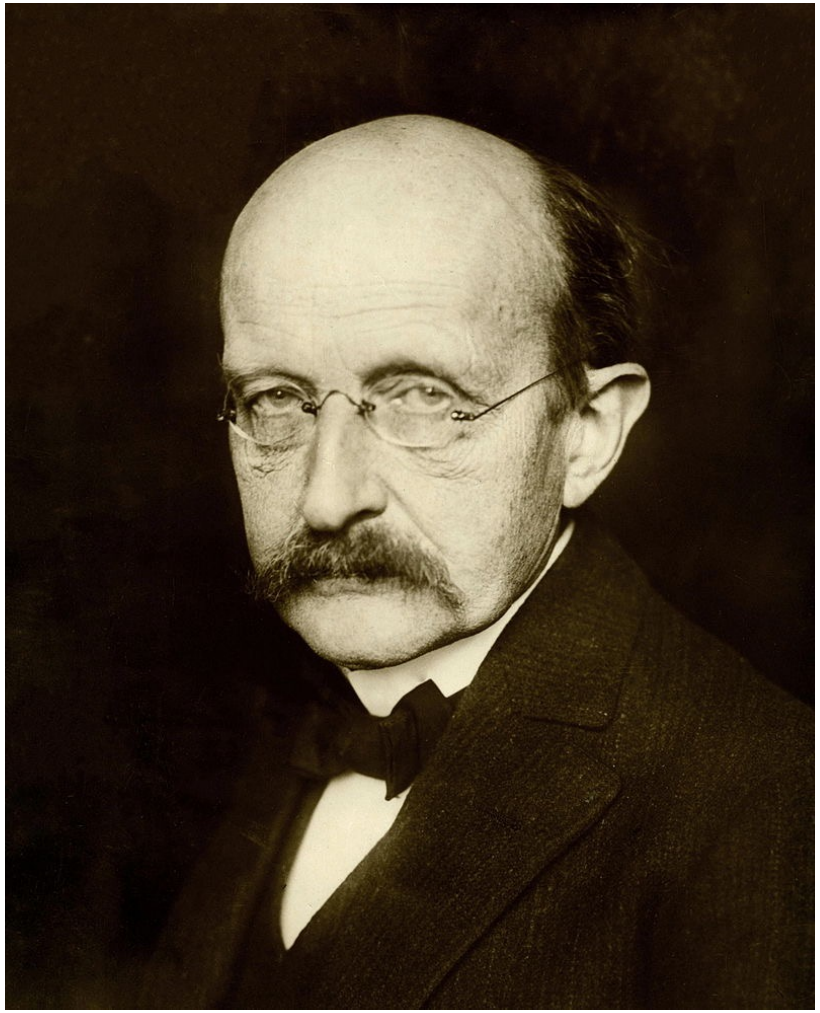
- Blackbody radiation does not depend on the properties of the material. It only depends on the Temperature (*T*).

- At a given temperature the black body would emit the maximum amount of energy possible for that temperature.



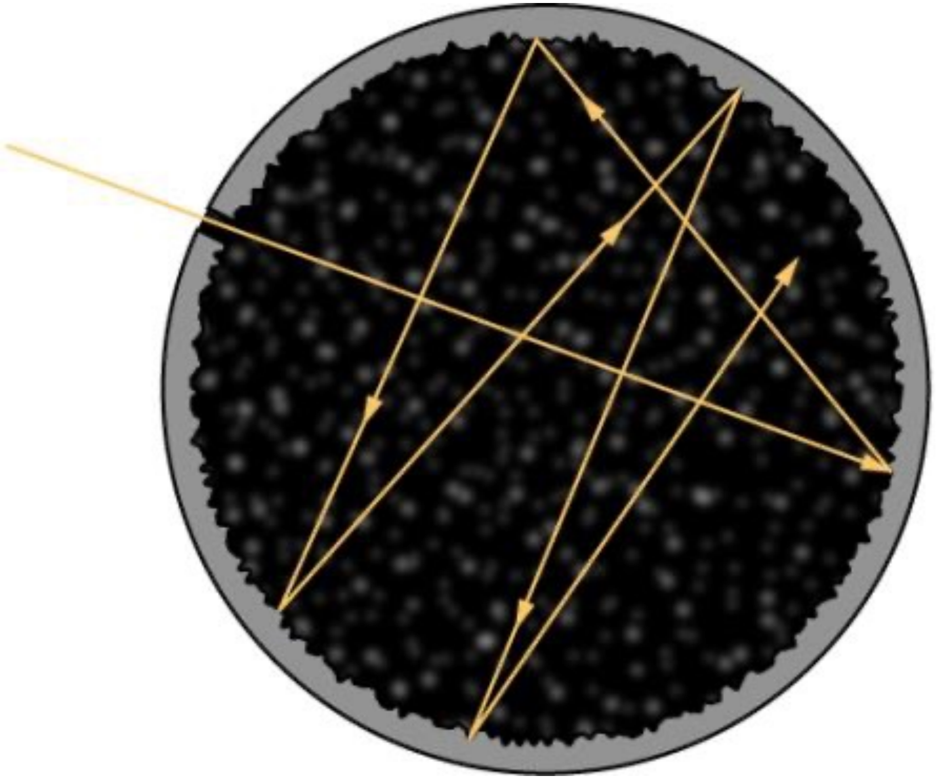
The spectrum of radiation emitted from a quartz surface (blue curve) and the idealized blackbody radiation curve (black curve) at 600 K

Planck’s proposal



Planck's theory of blackbody radiation

Planck made two modifications to classical theory



1. Electromagnetic energy can not be radiated or absorbed in any arbitrary amount, but only in discrete (quantum) amounts.

$$E_n = nhf$$

$$h = 6.6261 \times 10^{-34}\, Js$$

Planck's constant

2. The oscillators can absorb or emit energy in discrete multiples of the fundamental quantum of energy given by

$$\Delta E = hf$$

How large or small is Planck's quantum?

Ordinary Pendulum υ= 1 Hz

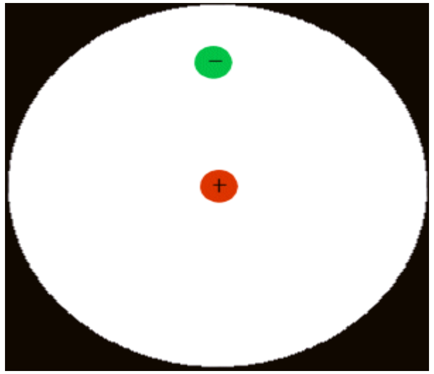
E_{quant}= $h\upsilon$ =6.6x10^{-34}Jsx1Hz

=6.6x10^{-34}J

very tiny

Electron in Hydrogen atom

$\upsilon \approx 2\text{x}10^{14}$ Hz



E_{quant}= $h\upsilon$ =(6.6x10^{-34}Js)x(2x10^{14}Hz)

=(6.6 x 2) x 10^{-34+14}J =1.3 x 10^{-19}J

about the same as the electron's KE

Classical vs *Quantum* world

In everyday life, quantum effects can be safely ignored

This is because Planck's constant is so small

At atomic & subatomic scales, quantum effects are dominant & must be considered

Laws of nature developed without consideration of quantum effects do not work for atoms

Planck’s theory of blackbody radiation

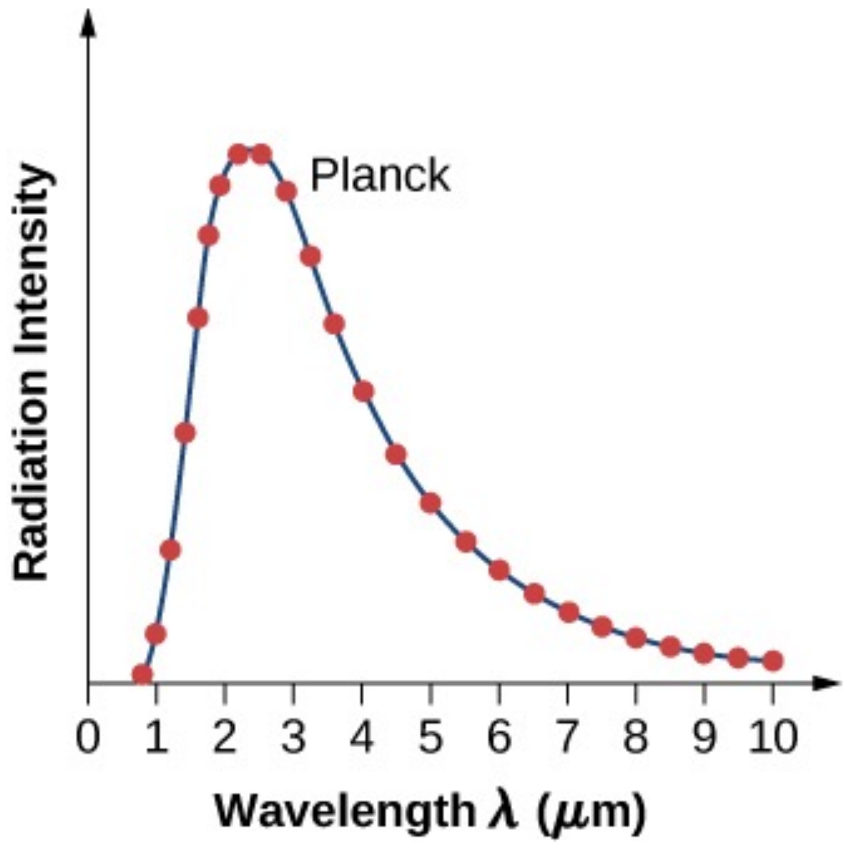
- Planck was able to calculate the correct distribution by assuming energy was quantized
- Microscopic (atomic) oscillators can only have certain discrete energies.

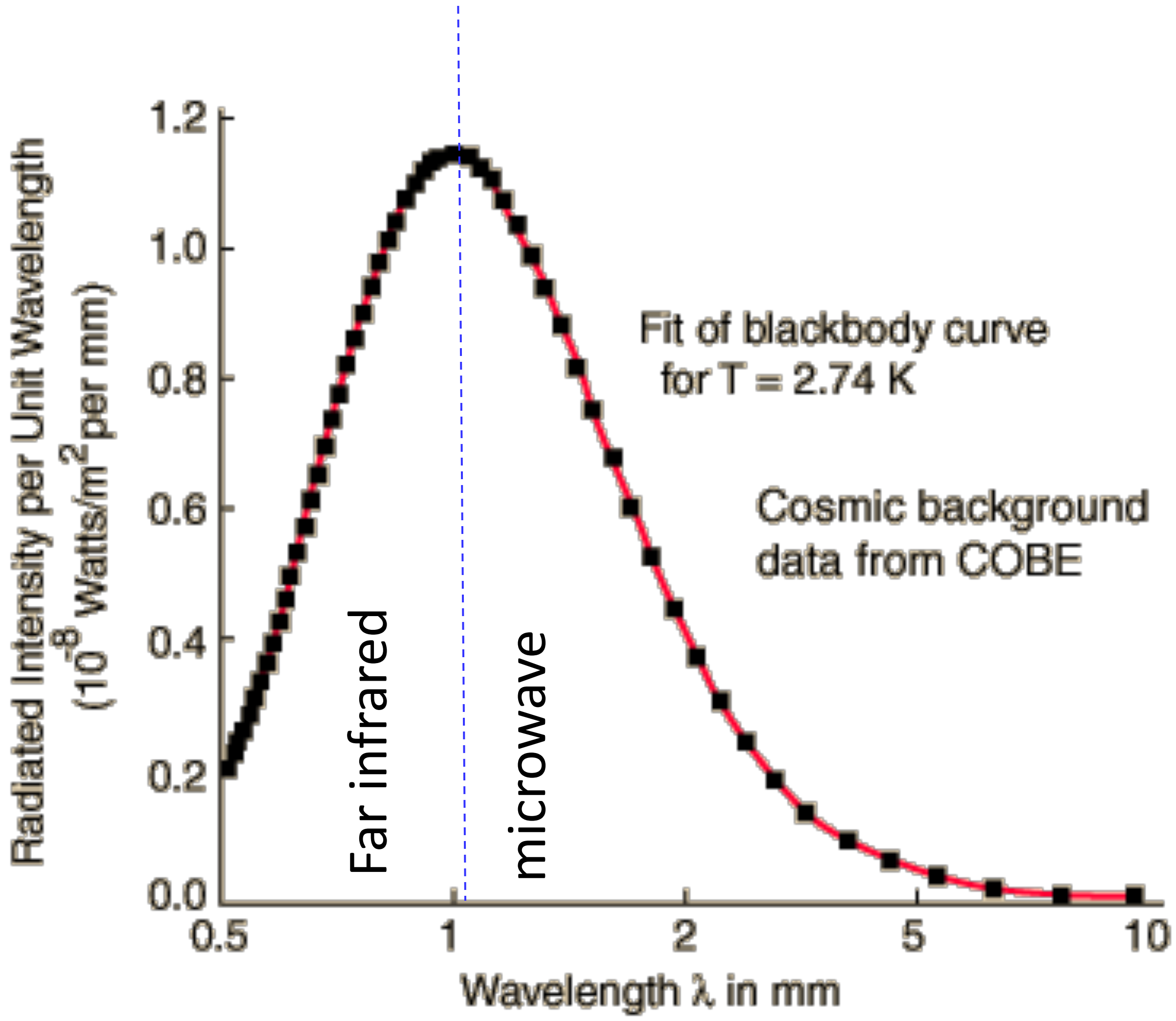
$$E_n = nhf$$

$$h = 6.6261 \times 10^{-34}\ Js$$

- The oscillators can only absorb or emit energy in multiples of $\Delta E = hf$
- Planck’s radiation law agreed with data $$I(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Planck distribution function





Planck's theoretical result (continuous curve) and the experimental blackbody radiation curve (dots).

Success of Planck Distribution function

- Planck's radiation law agreed with data

$$I(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

- It leads directly to
  - Wien's displacement law
  - Stefan Boltzmann law

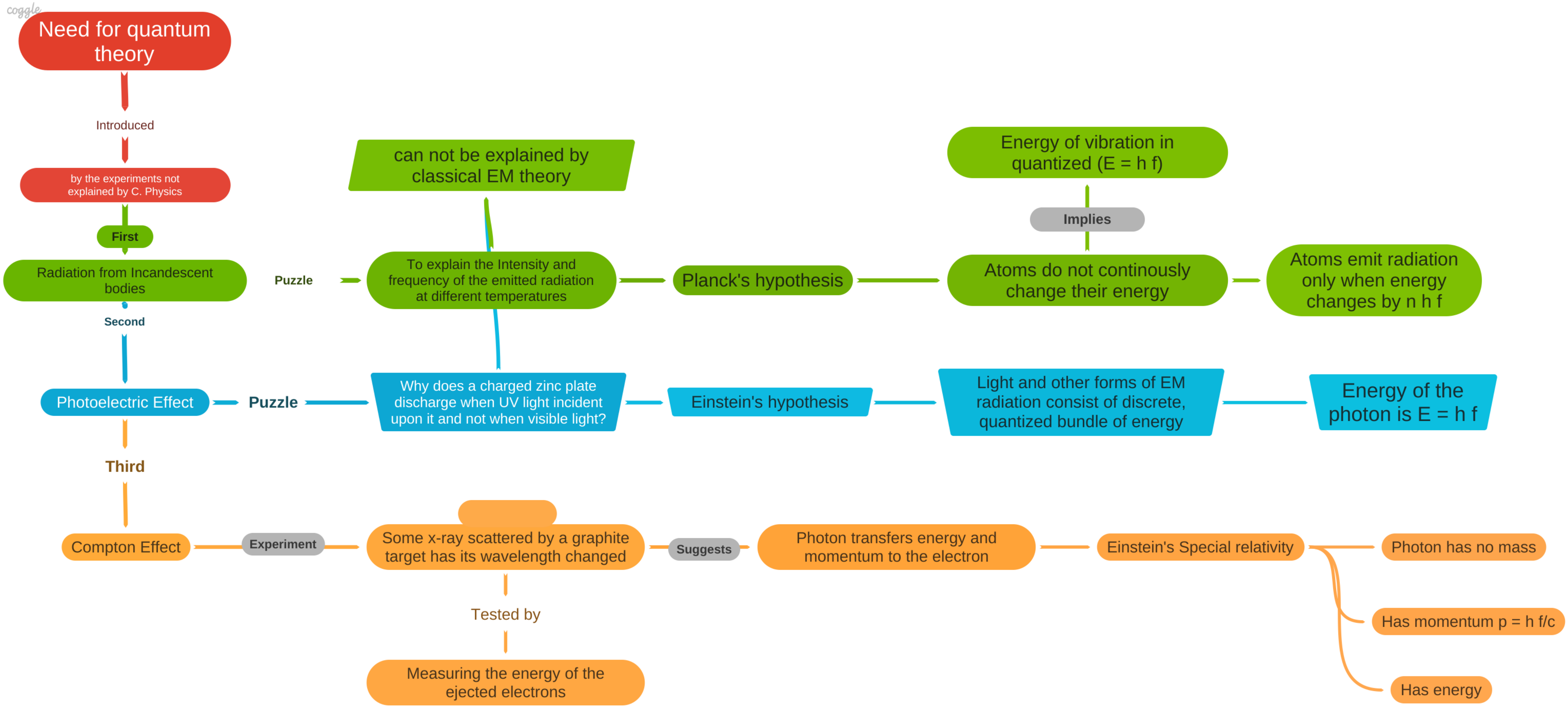
- It agrees with Rayleigh-Jeans formula for large wavelengths

Summary: Strange things not known from classical physics

- Blackbody radiation
  - Rayleigh-Jeans classical formula clearly incorrect at explaining spectrum
  - Planck: oscillators with fixed energies

- Compton scattering
  - Scattered photons have different wavelength in contrast to classical description

Three experiments that C.Physics can not explain



Recommended Reading

Black-body radiation, section 3.2 in page 68,

and section 3.3 in page 77.