

# *Week 3*

# Light & Matter

1. Electromagnetic waves & photons
2. Spectroscopy and atoms
3. Particles, nuclei, and fusion

REMINDER: **Midterm #1** is next week on Monday, September 23.

# Today's Topics

Monday, September 16, 2019 (Week 3, lecture 8) – Chapter 5.

1. Electromagnetic waves
2. Electromagnetic spectrum
3. Blackbody radiation
4. Photons

# Speed of Light

The speed of light in **vacuum** is always  $c = 3.0 \times 10^8$  m/s.  
= 300,000 km/s

**It's an experimental fact** but also very counter-intuitive.

# Speed of Light

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 $= 300,000 \text{ km/s}$

**It's an experimental fact** but also very counter-intuitive.

The speed of light does NOT depend on the observer:

- **If observer A is at rest** and measures the speed of light in their laser pointer, then they will measure  $c = 3.0 \times 10^8 \text{ m/s}$ .
- **If observer B is moving at 290,000 km/s**, then they will measure the speed of light of observer A's laser pointer to be  $c = 3.0 \times 10^8 \text{ m/s}$ .

# Speed of Light in Matter

The speed of light *in matter is slower* than in vacuum

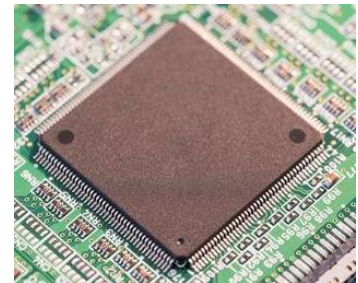
Speed of light in **air** = 99.97% of  $c$

Speed of light in **water** = 75% of  $c$

Speed of light in **glass** = 67% of  $c$

Speed of light in **diamond** = 41% of  $c$

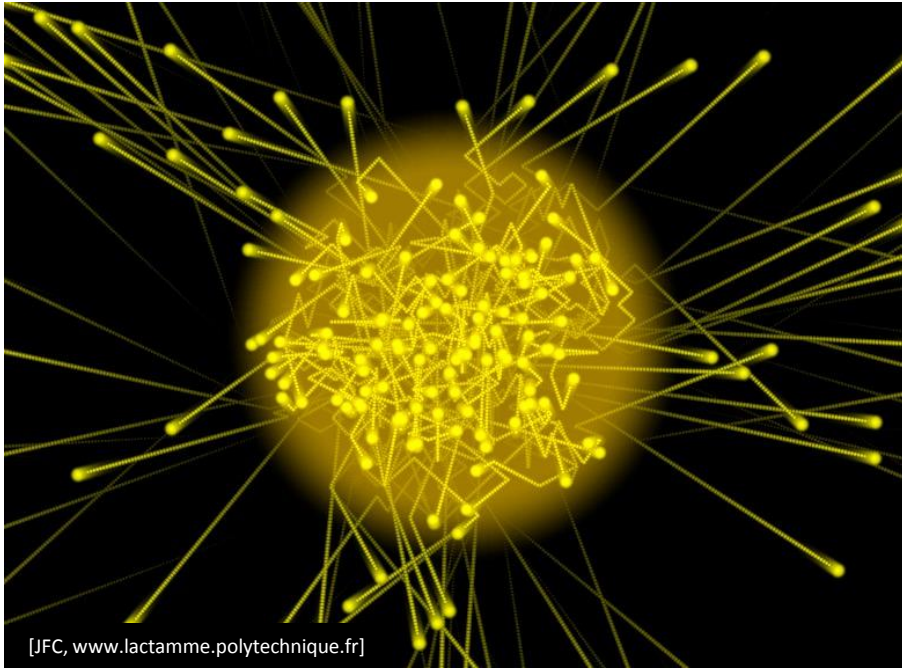
Speed of light in **silicon**  $\approx$  25% of  $c$



[123RF.com]

Note: In engineered atomic gases, light can be brought  $\sim 10$  m/s and even stopped.  
(Novikova Lab at W&M)

# Light: Particle or Wave?



# Electromagnetic Waves

**James Clerk Maxwell** (1831-1879) worked on electricity and magnetism:

- They are different facets of the **same phenomenon**.
- Light is a wave of **electric** & **magnetic fields**.



[OpenStax]

James Clerk Maxwell

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[OpenStax]

James Clerk Maxwell

oscillating electric field



oscillating magnetic field



oscillating electric field

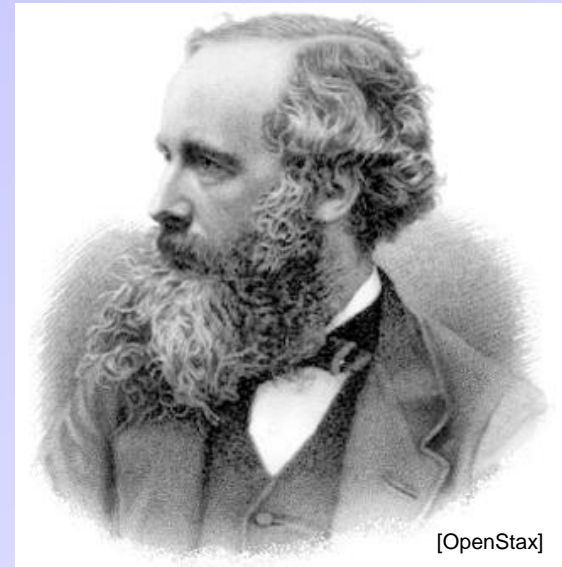




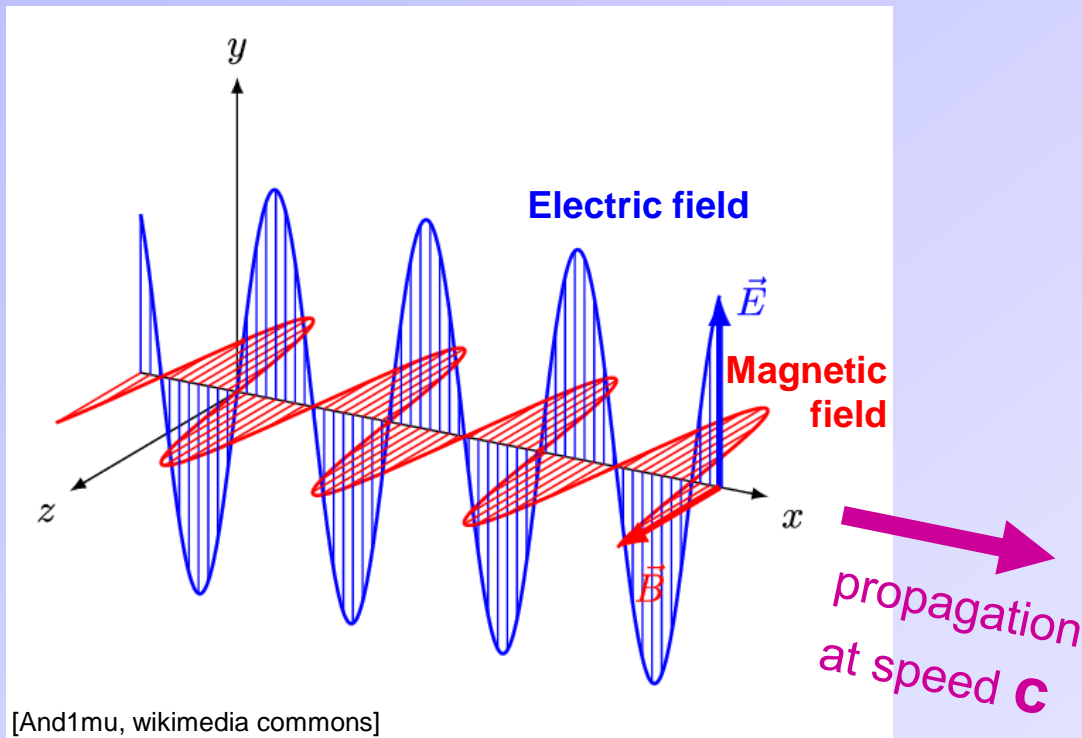
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James Clerk Maxwell



oscillating electric field



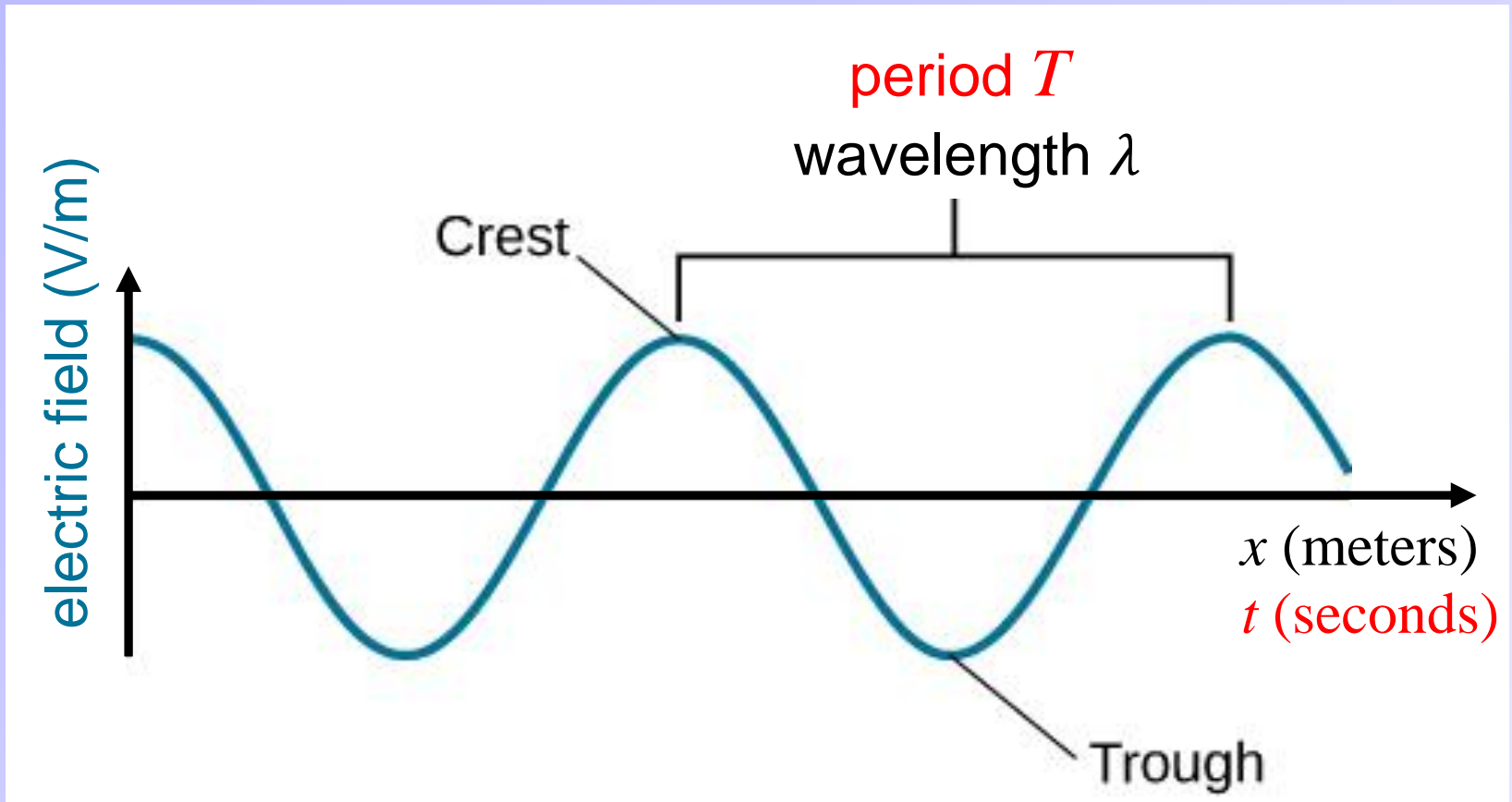
oscillating magnetic field



oscillating electric field

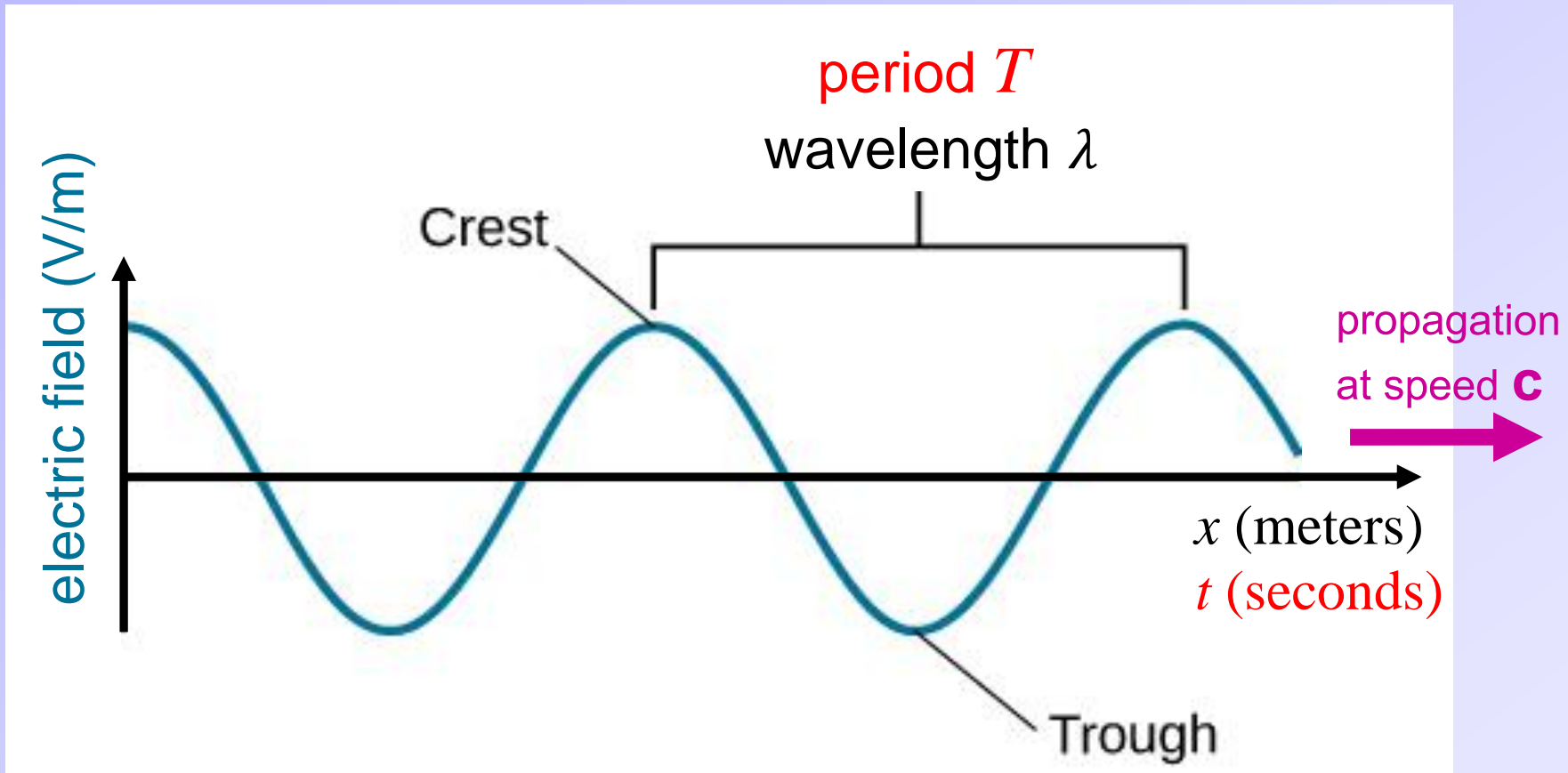


# Wave Properties



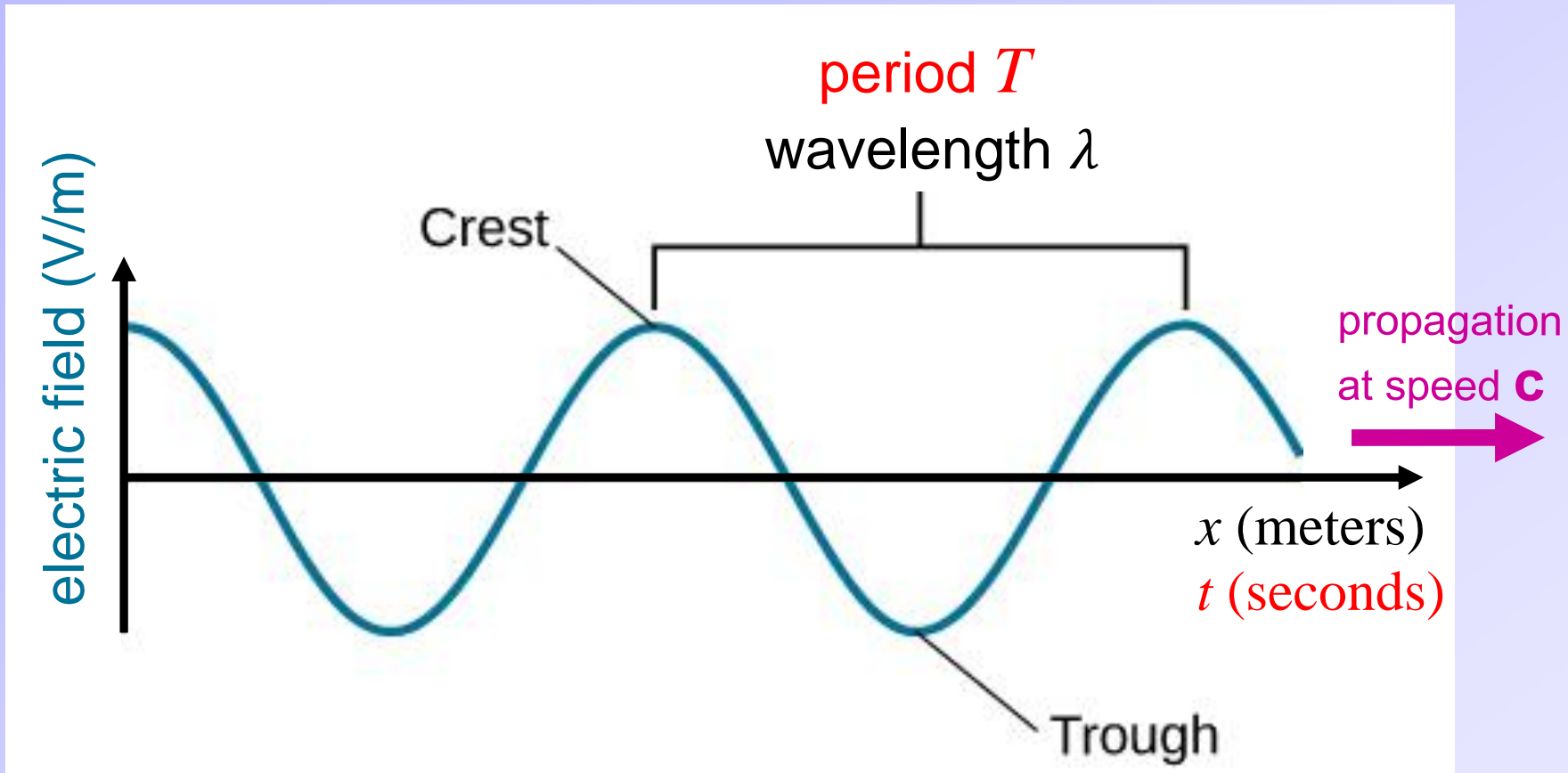
Frequency:  $f = \frac{1}{T} = \text{oscillations per second}$

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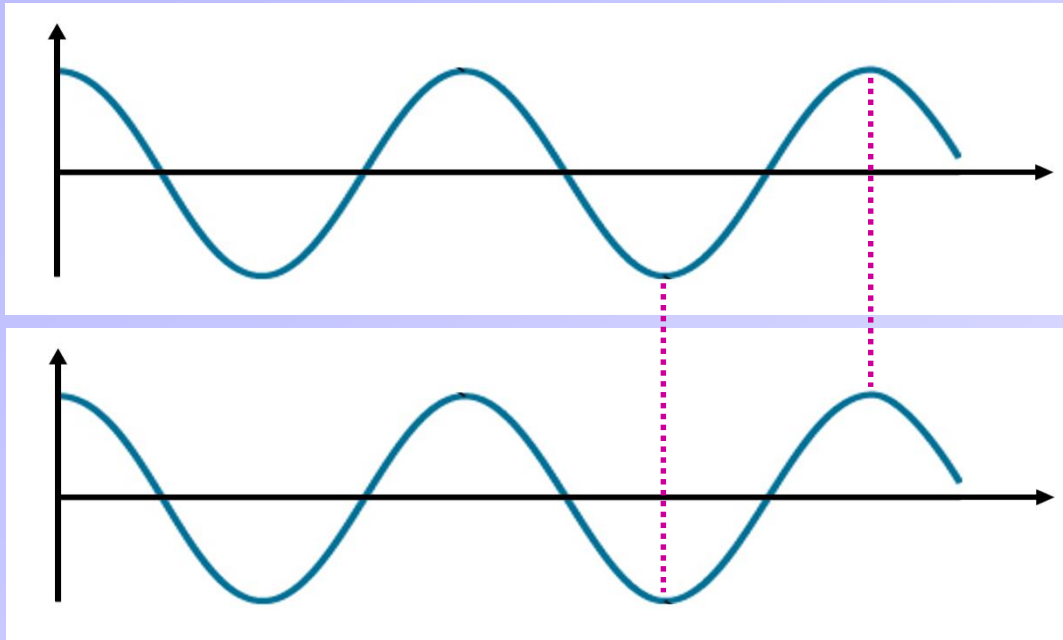


Frequency:  $f = \frac{1}{T}$  = oscillations per second

Traveling wave formula:  $\lambda f = c$

# Wave Addition: Constructive Interference

+

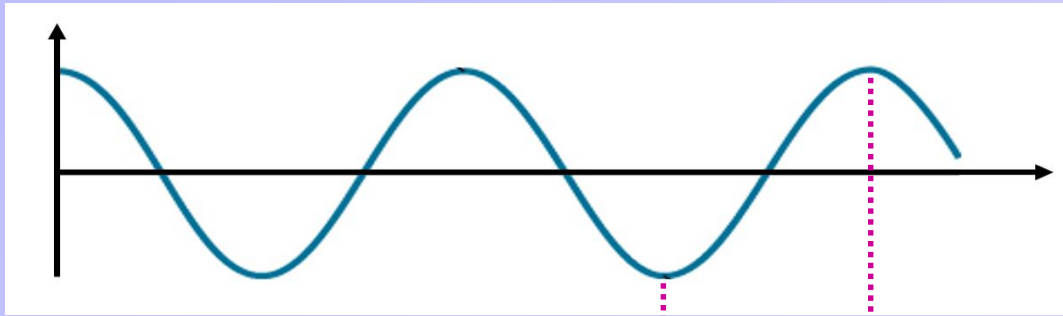


Troughs are in sync

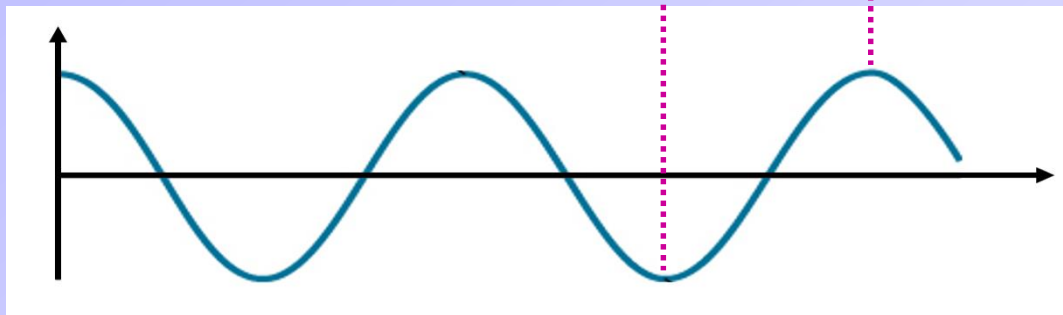
Crests are in sync

# Wave Addition: Constructive Interference

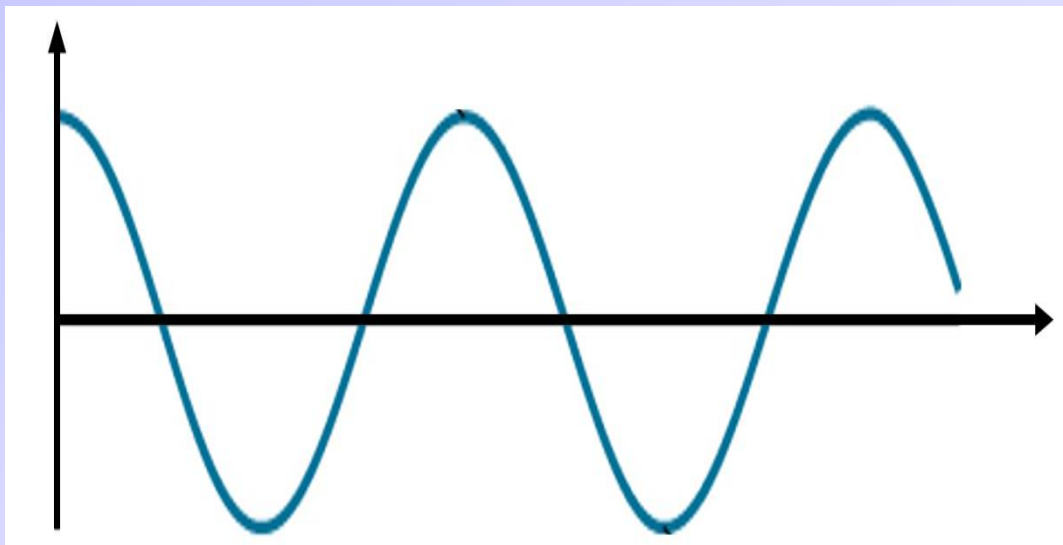
+



Troughs are in sync



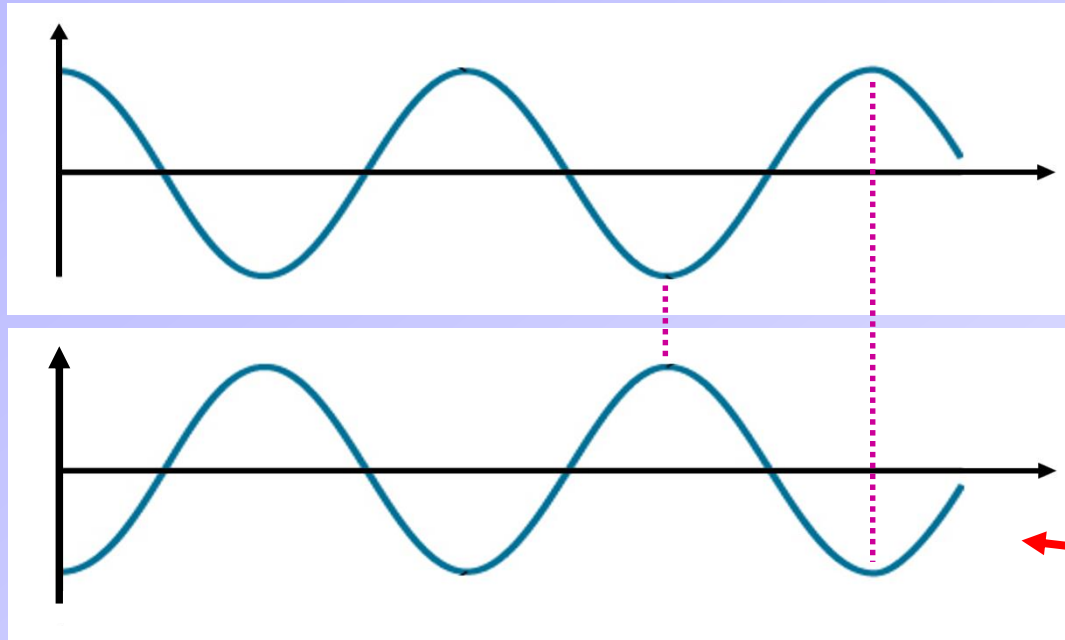
Crests are in sync



amplitude  
doubles

# Wave Addition: Destructive Interference

+

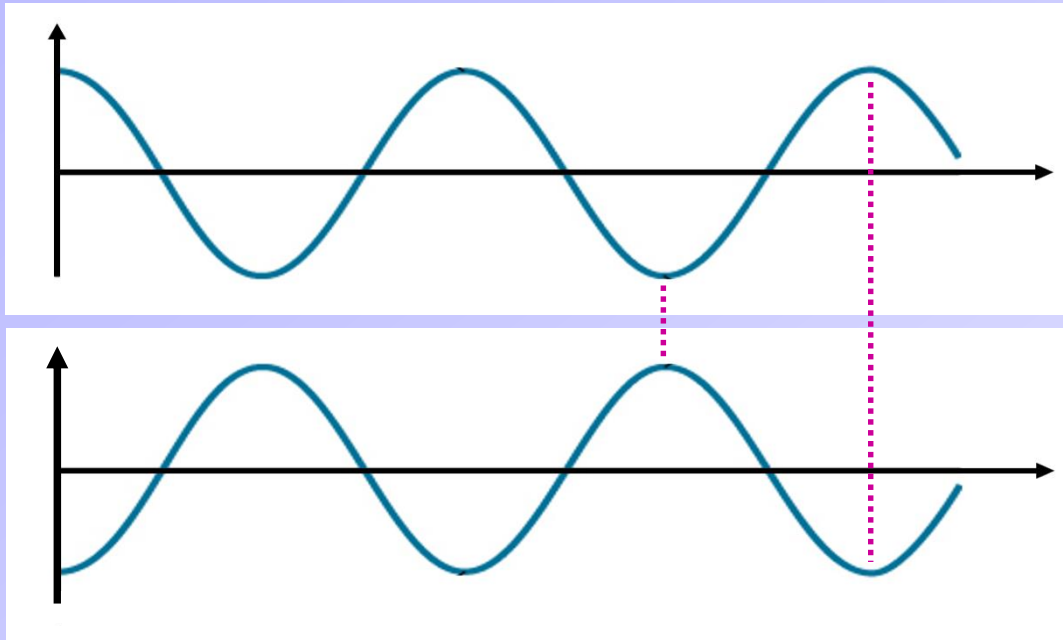


Troughs & crests  
are exactly  
out of sync

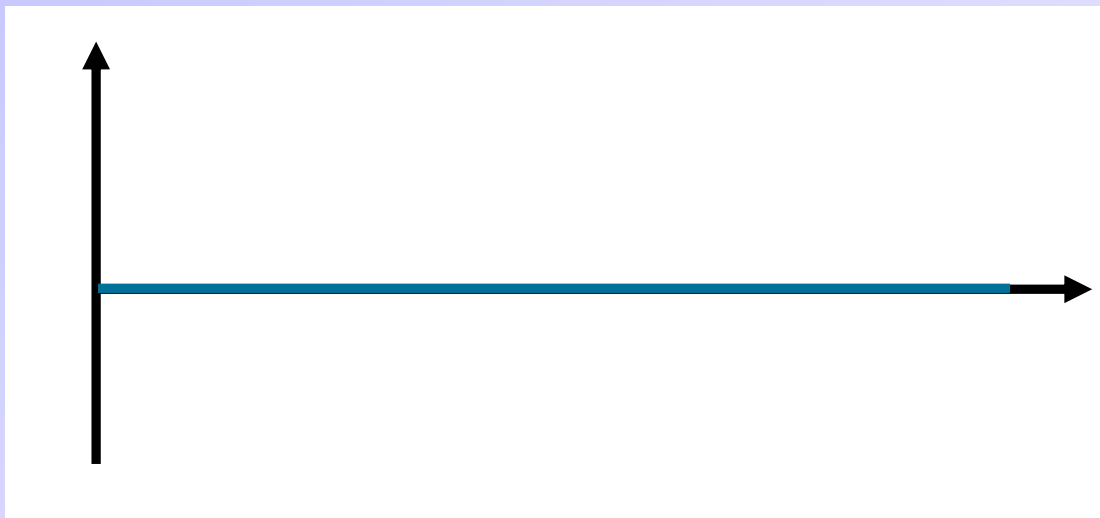
← wave shifted by 180°

# Wave Addition: Destructive Interference

+



Troughs & crests  
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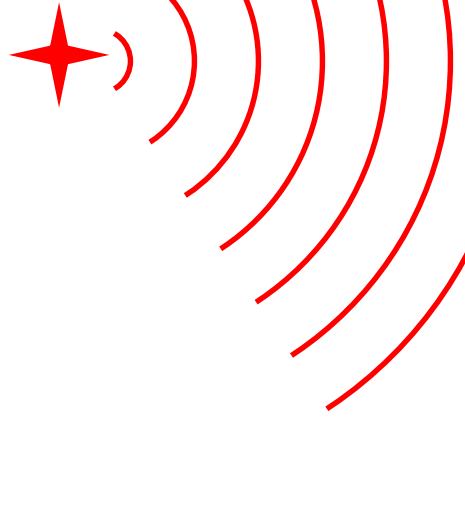


amplitude  
goes to zero  
(wave disappears)



# Interference Experiment

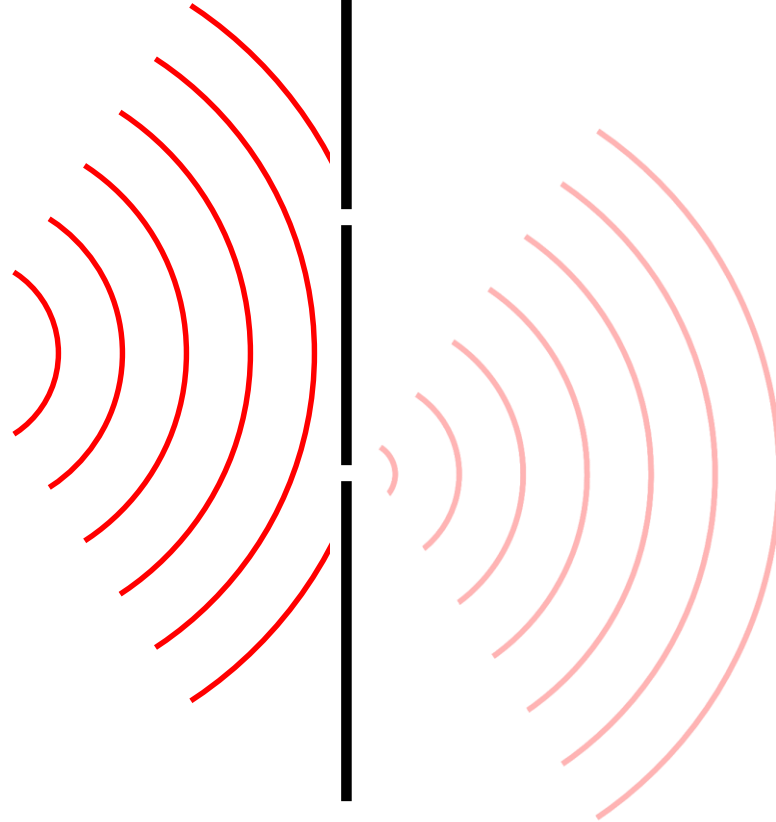
LASER  
source



Screen

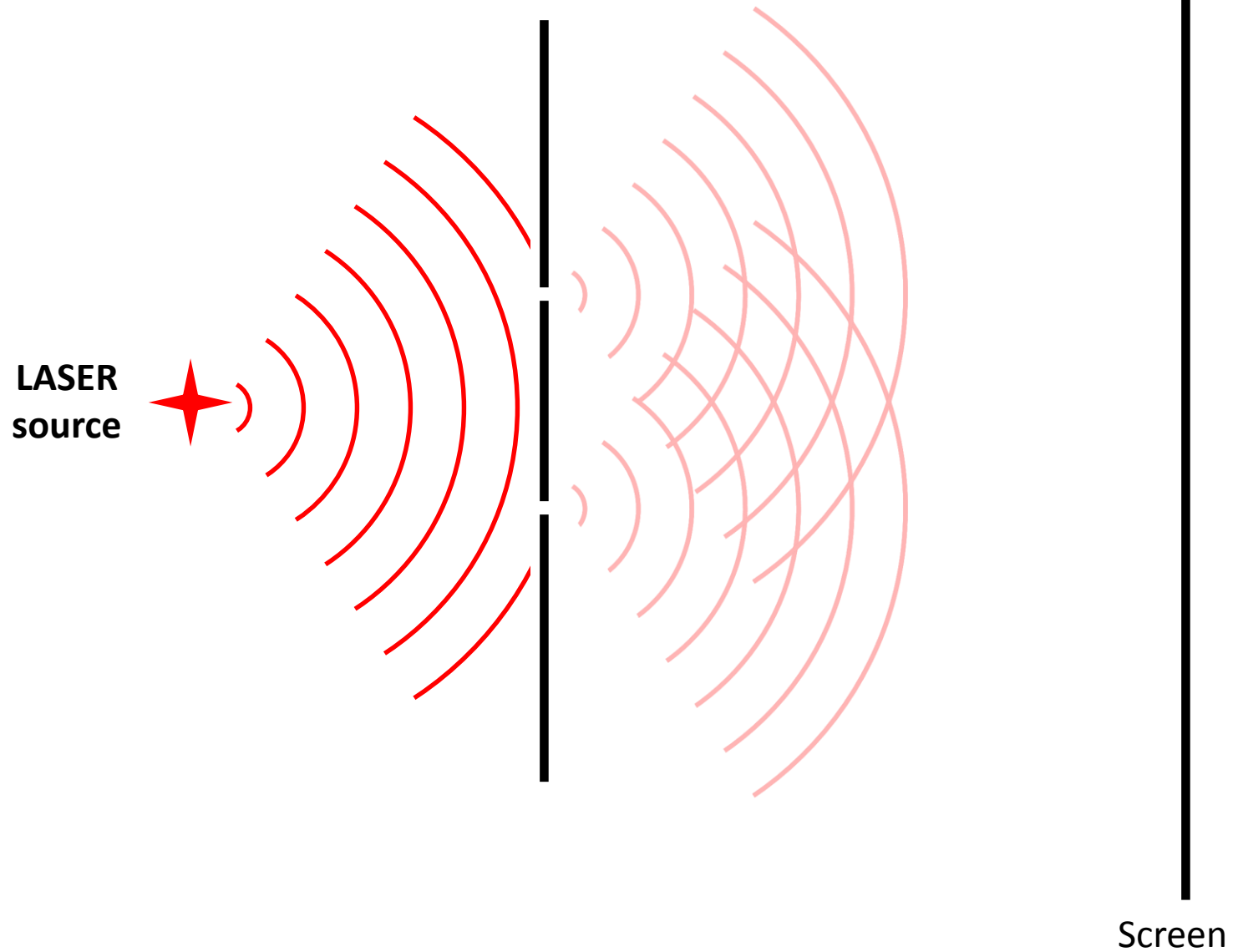
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LASER  
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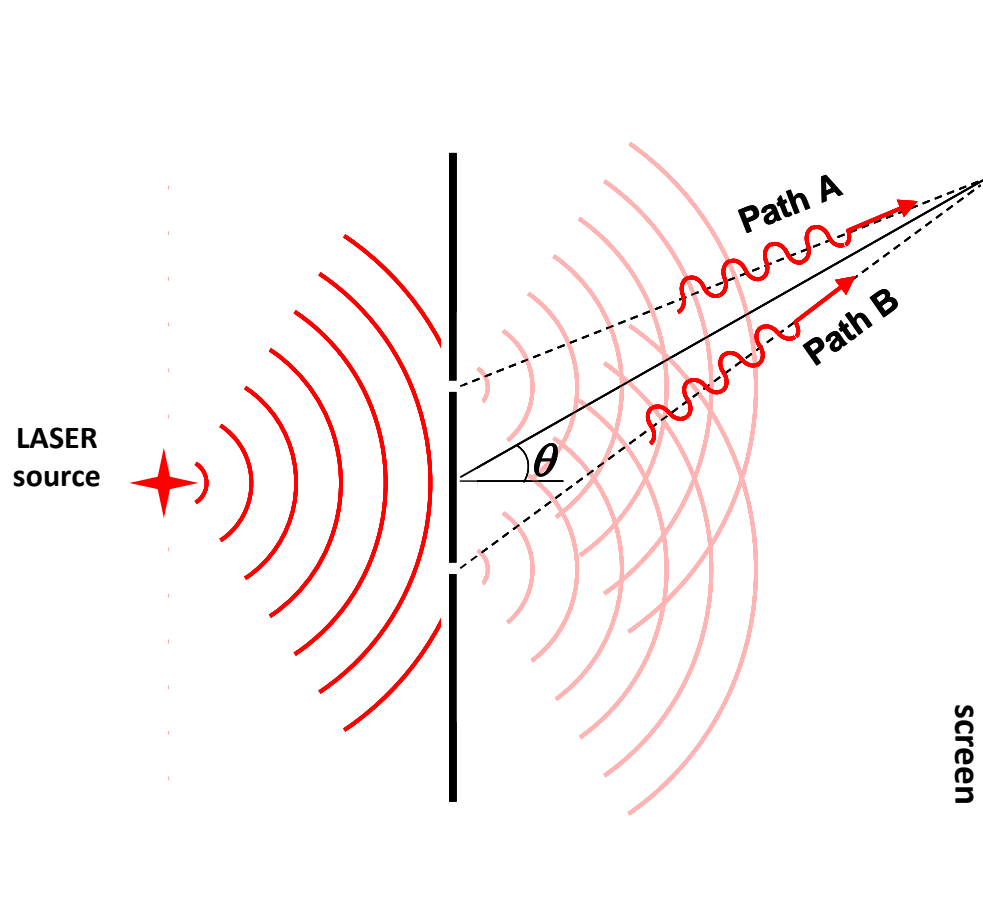


Screen

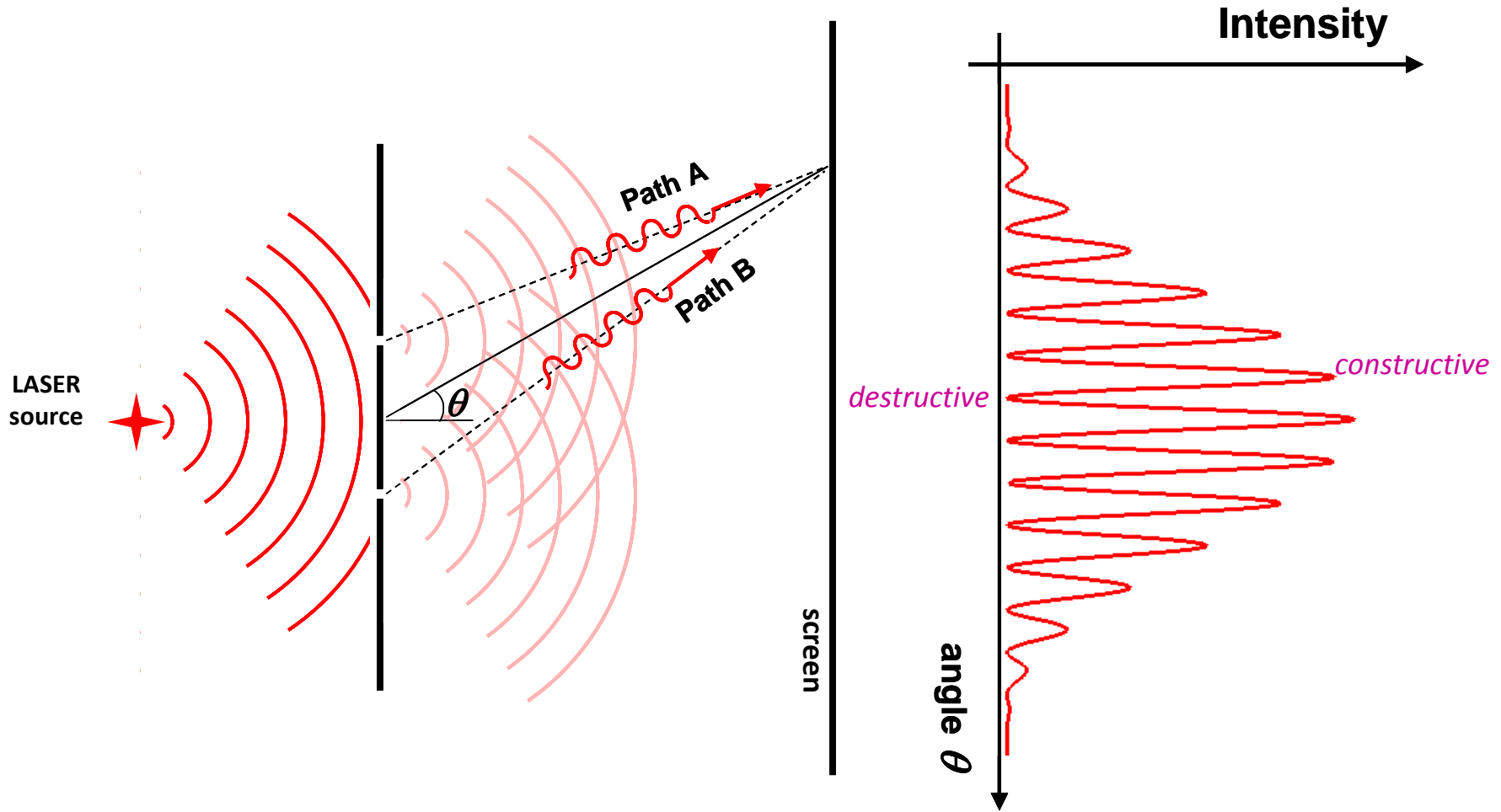
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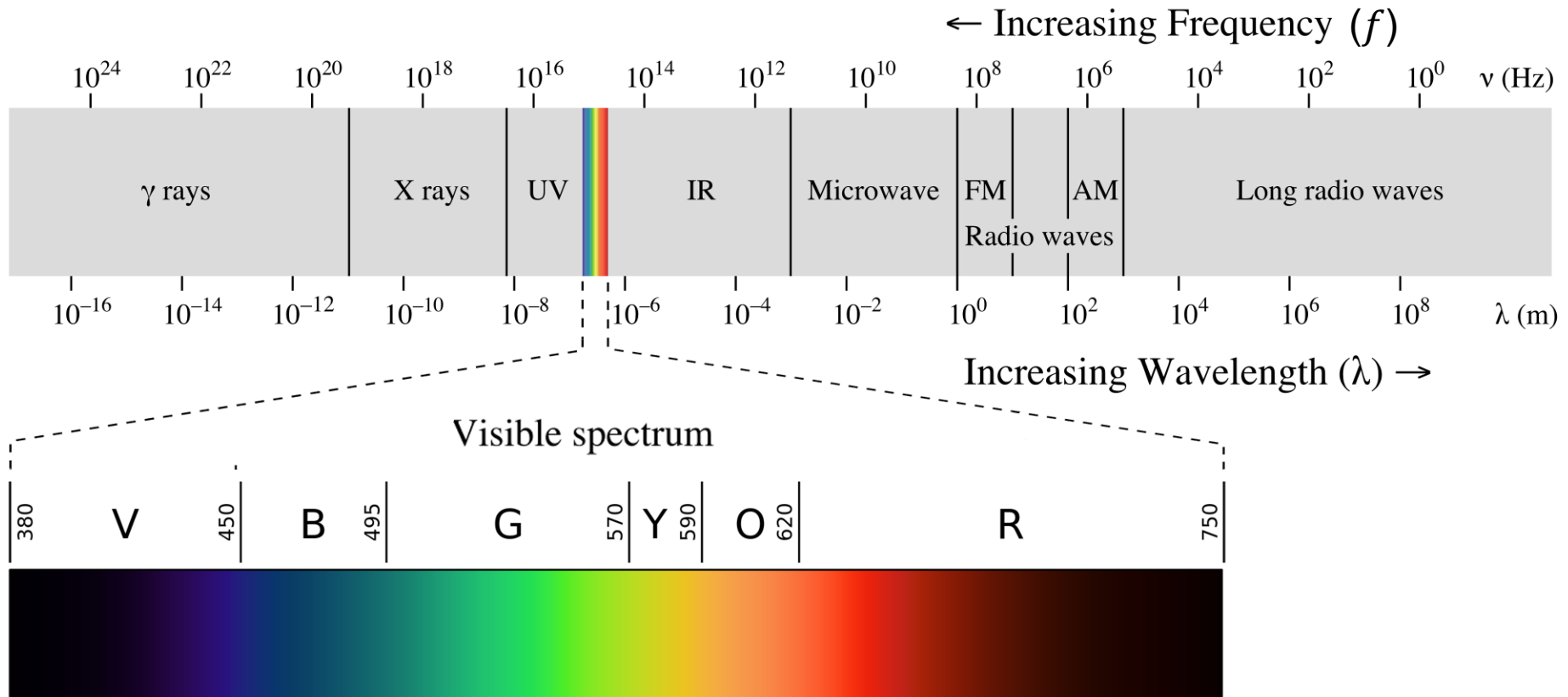
[Young's double slit experiment, by Thomas Young (1773-1829) in 1801-1803.]

# Electromagnetic Spectrum

- Visible light represents only a small portion of electromagnetic waves.
- Electromagnetic waves cover over 25 orders of magnitude in frequency & wavelength.

# Electromagnetic Spectrum

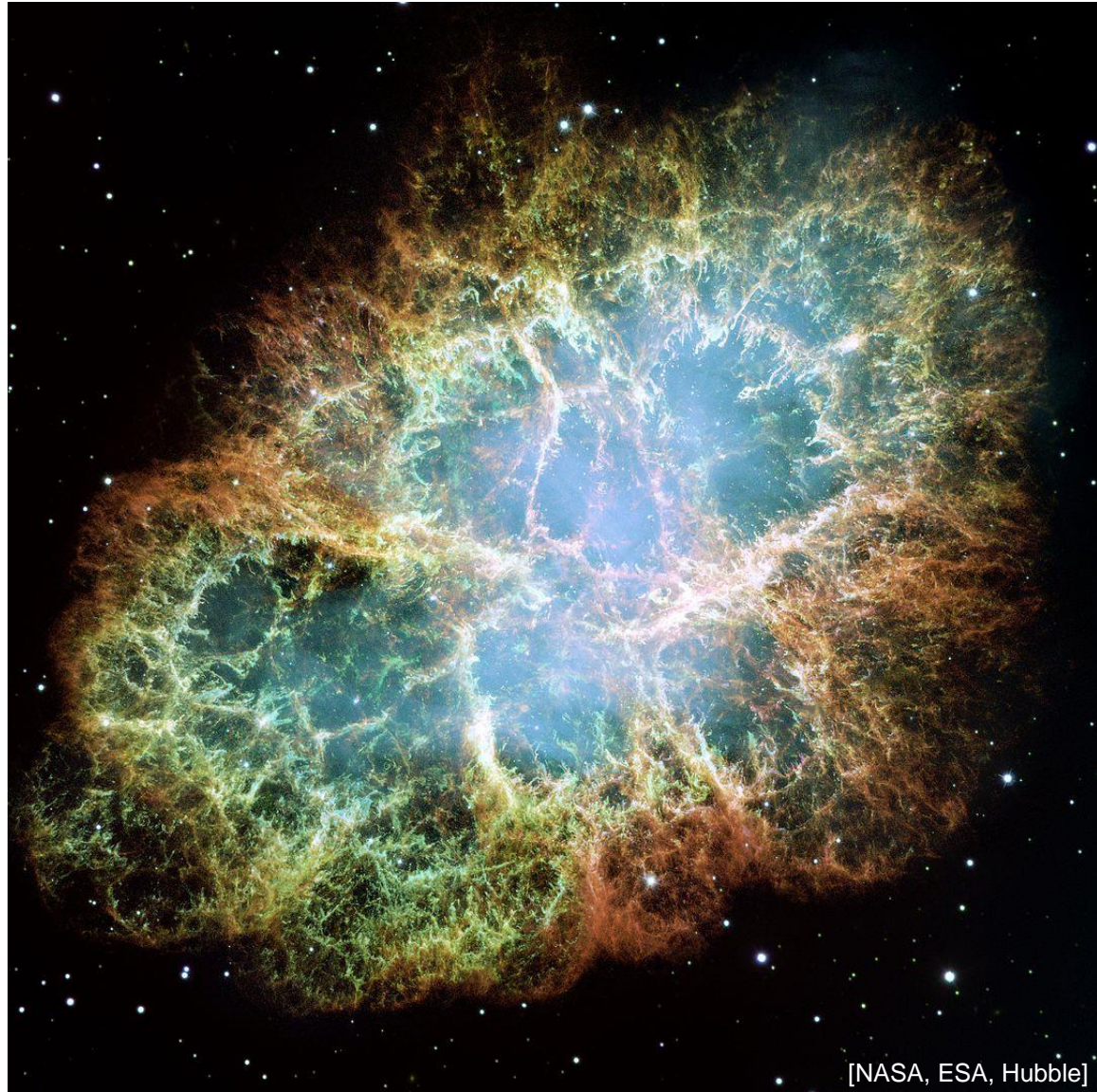
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# Astronomers use all Wavelengths

## Crab Nebula (M1)

- Exploding star remnant (supernova).
- Recorded by Chinese astronomers and others (1054 AD).
- Located at about 6500 ly in our galaxy (Taurus constellation).
- This composite image is by the Hubble Space Telescope (visible light).



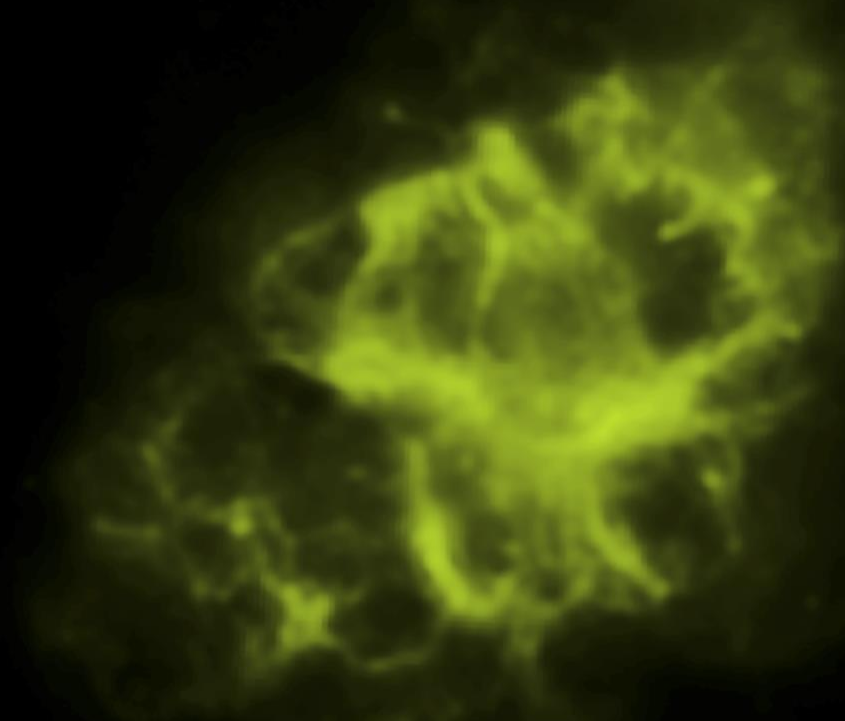


# Crab Nebula with Radio-Waves



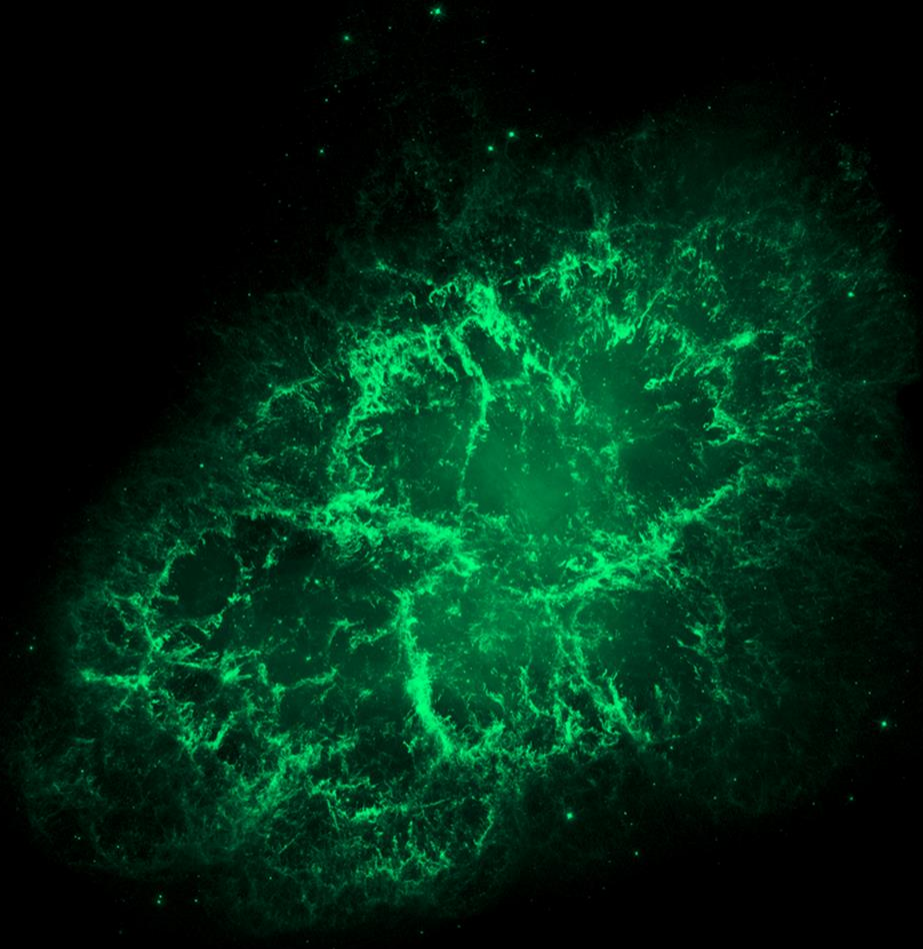
Radio (Very Large Array)

# Crab Nebula with Infrared Light



Infrared (Spitzer)

# Crab Nebula with Visible Light



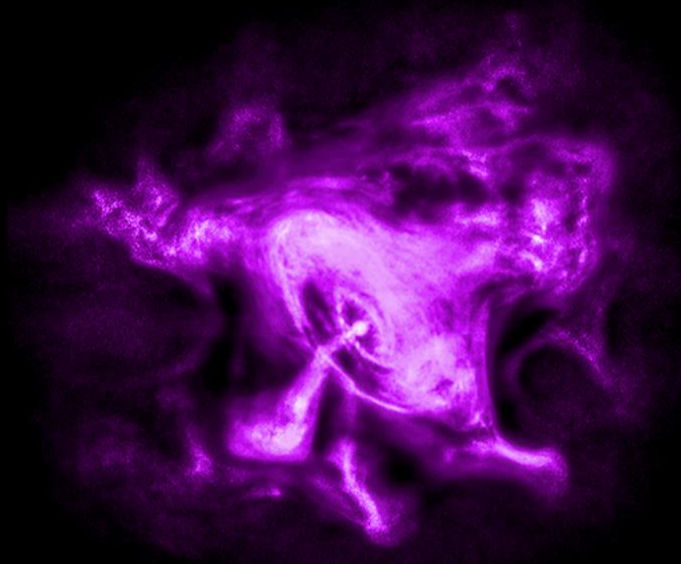
Optical (Hubble)

# Crab Nebula with Ultraviolet Light



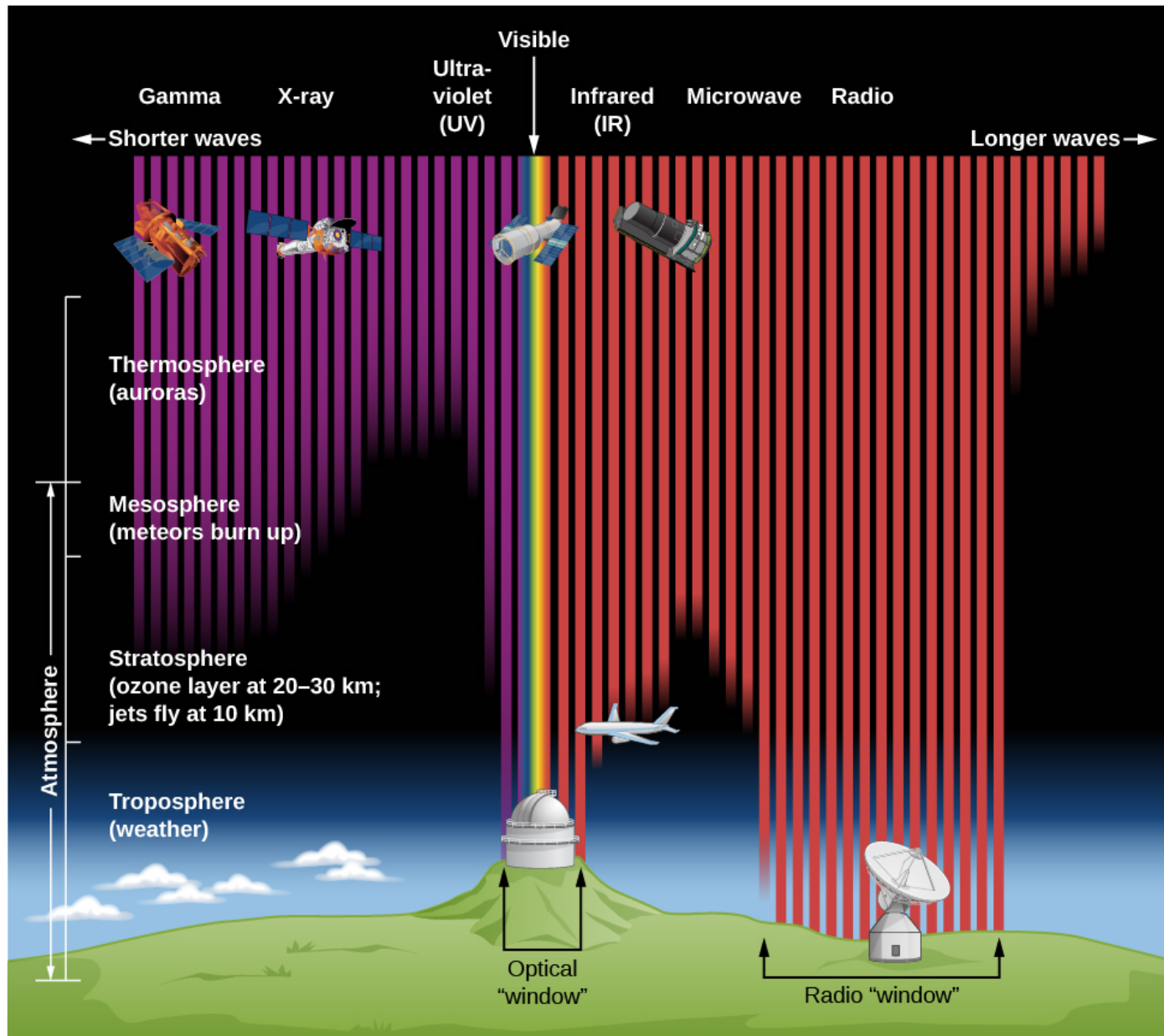
UltraViolet (XMM-Newton)

# Crab Nebula with X-Rays



X-ray (Chandra)

# Absorption by Earth's Atmosphere



# Thermal Light Sources

## Blackbody Radiation

- The oldest and simplest way to make light is by **heating** something up (filament, gas, wood, etc).
- **Hotter = brighter**, colder = dimmer.
- **Hotter = white-blue**, **colder = dim red**.
- Color of thermal source → temperature.

**Blackbody** (definition): An object that does not reflect light. All light emitted by its surface is due to heat.

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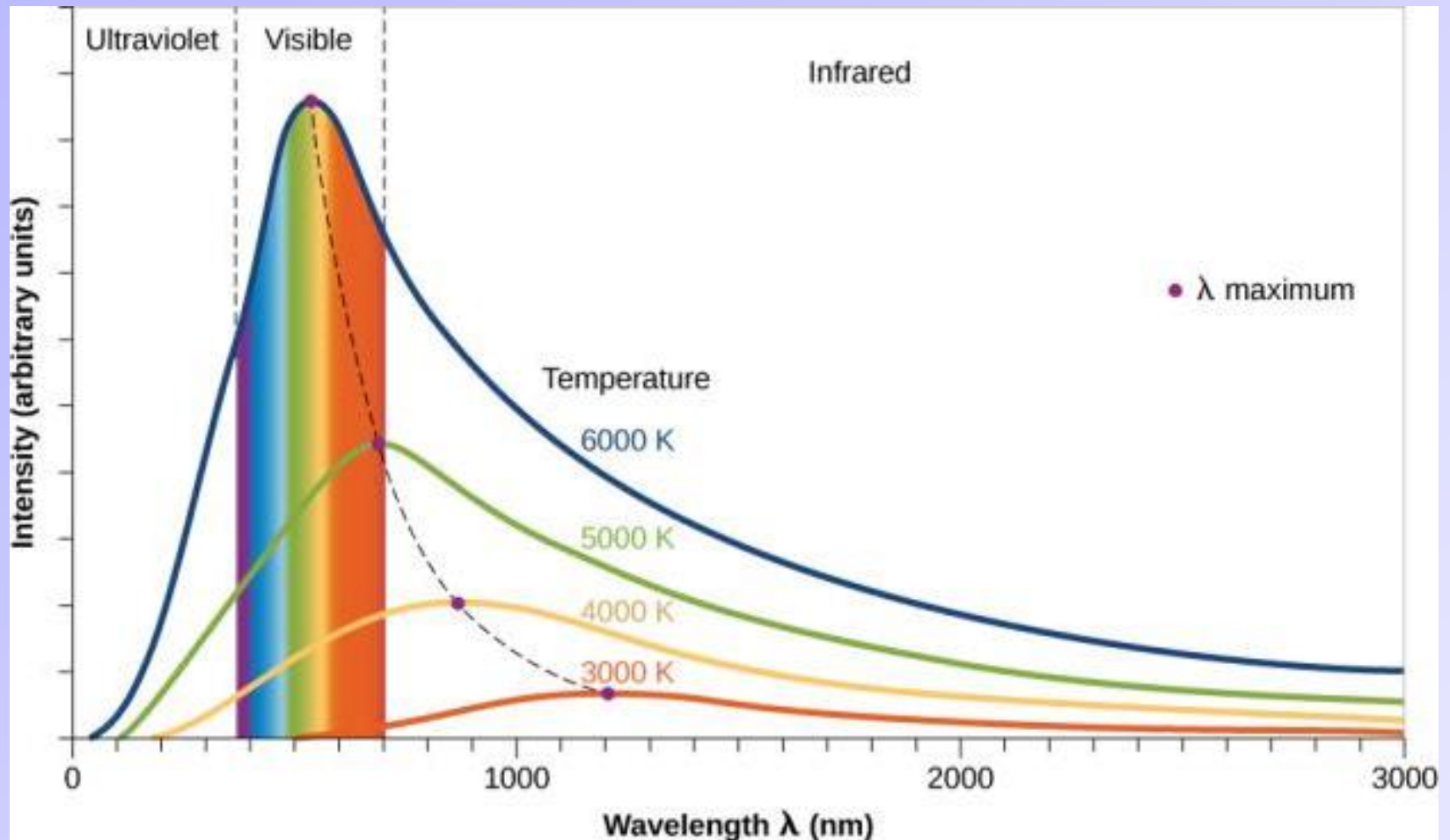


*incandescent lightbulb*

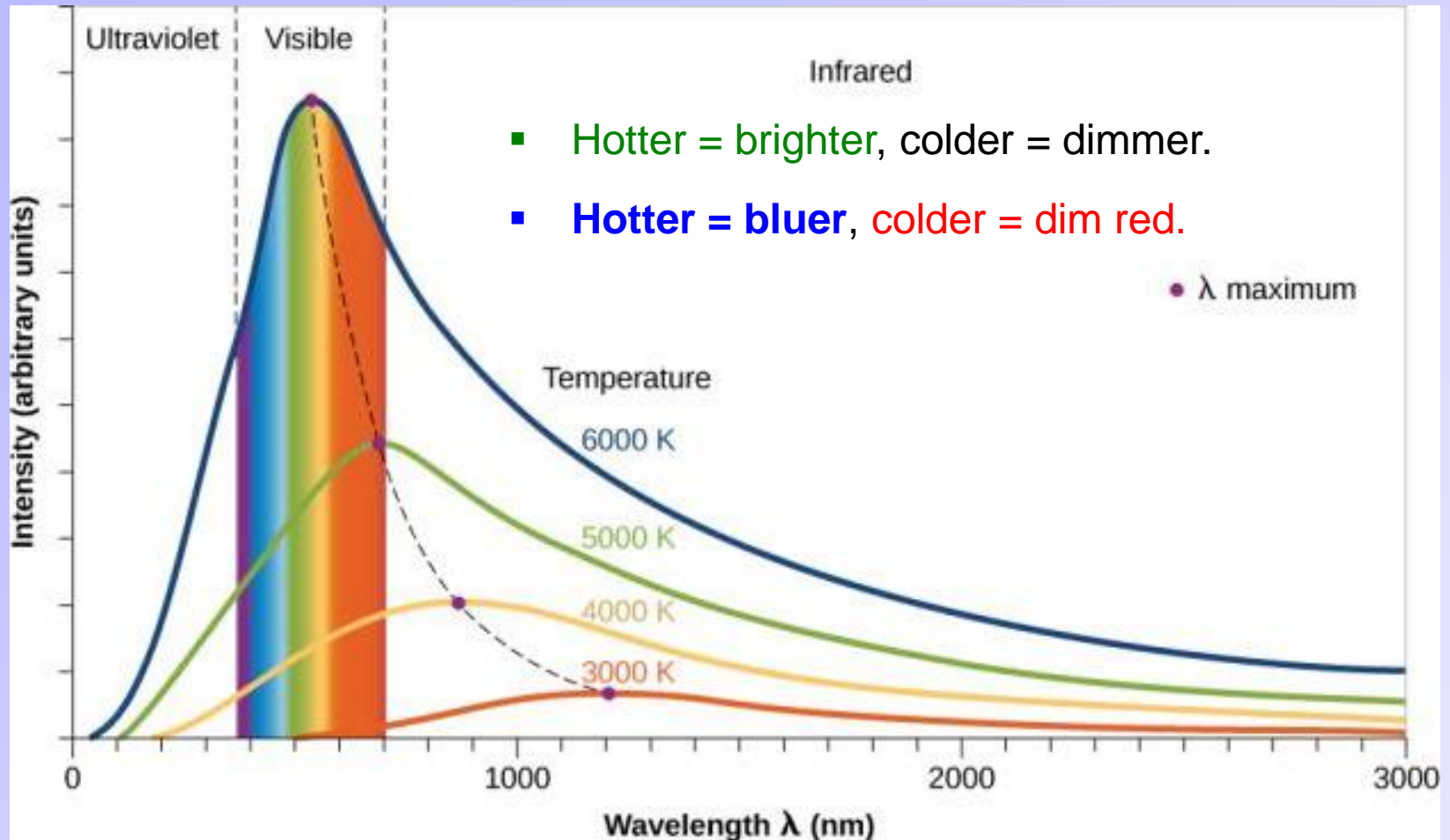
**Blackbody** (definition): An object that does not reflect light. All light emitted by its surface is due to heat.

↑  
Ideal thermal source of light

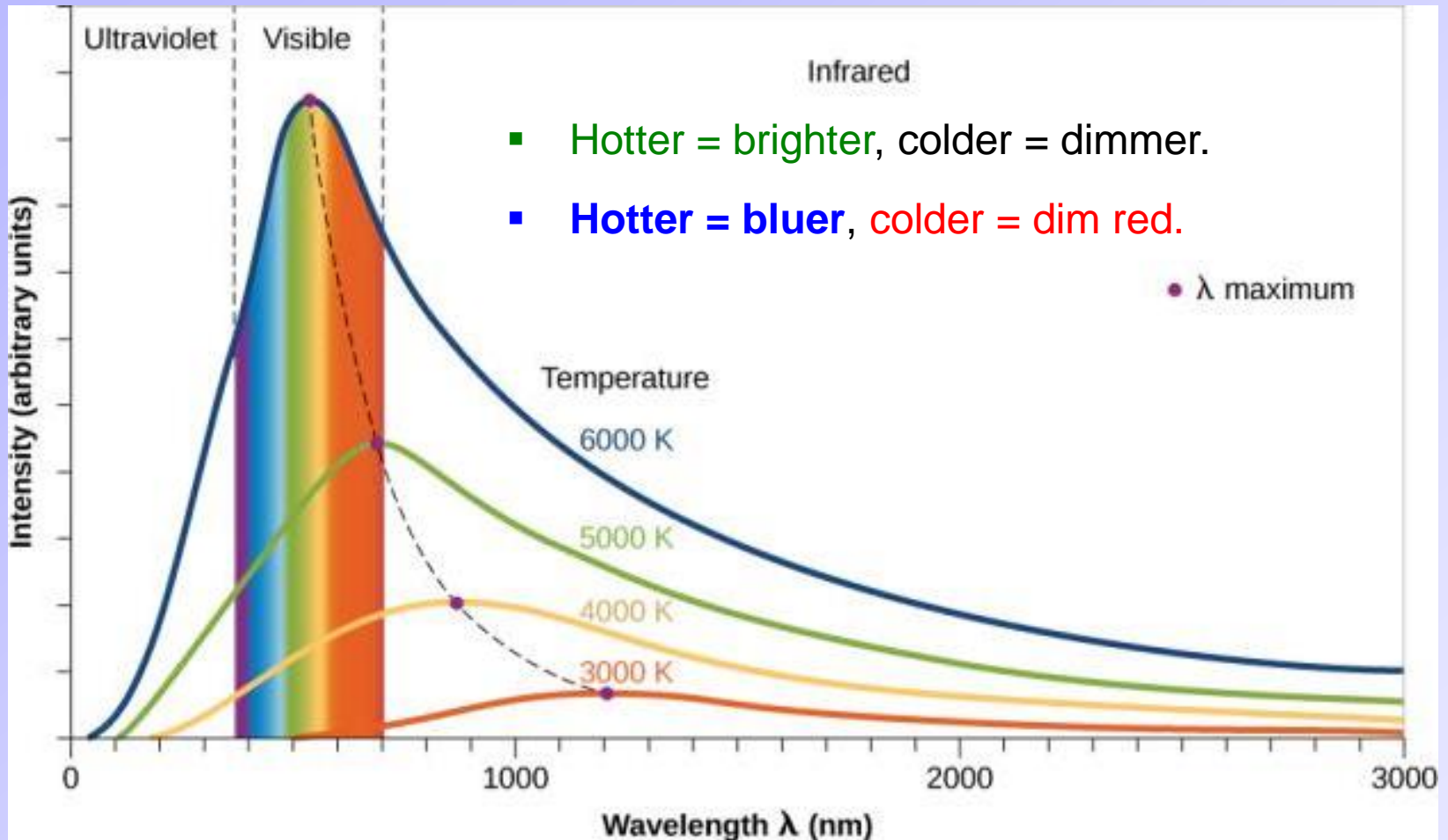
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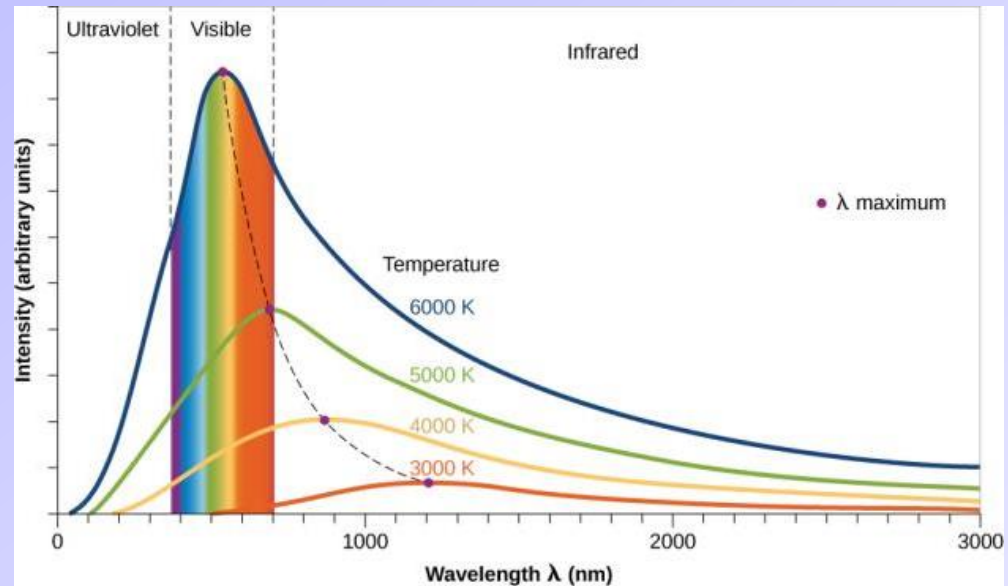


Wien's Law:  $\lambda_{\text{max}} = \frac{2.9 \times 10^6}{T}$

nm  $\lambda_{\text{max}}$  degrees Kelvin  $T$

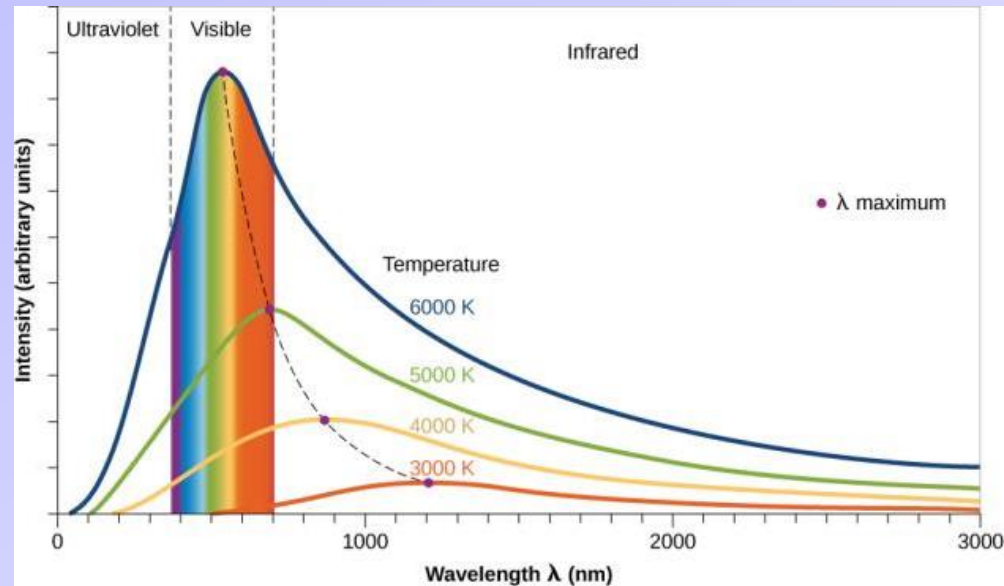
# Blackbody Radiation (2)

- Total output power (per unit area)  
= area under the curve  
= Luminosity (L)
- Power = Energy per time
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**Stefan-Boltzman Law:**

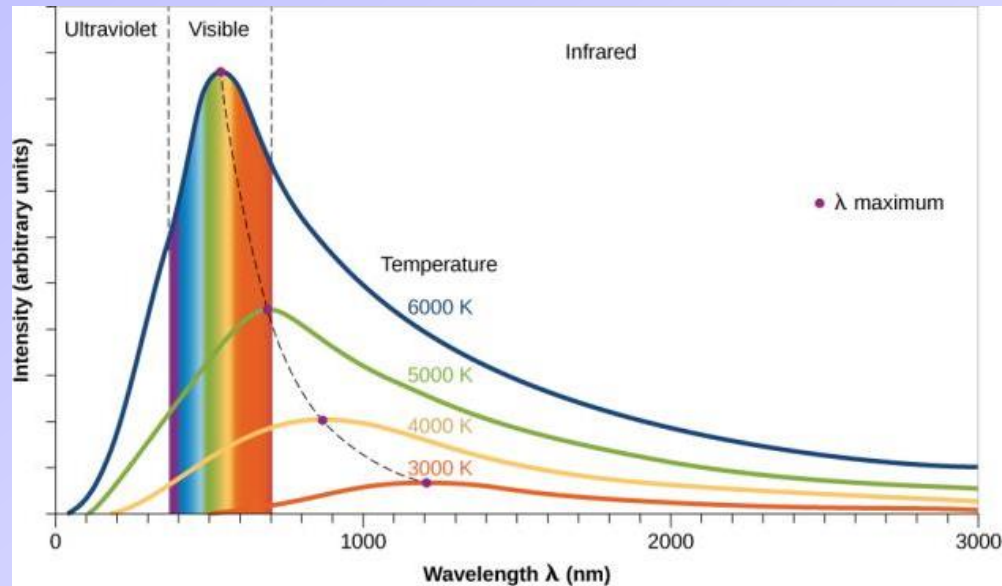
$$L = \sigma T^4$$

*Stefan-Boltzman constant:*

$$\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4}$$

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**Stefan-Boltzman Law:**

$$L = \sigma T^4$$

Increasing temperature,  
increases output power a lot

*Stefan-Boltzman constant:*

$$\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4}$$

# Light is also a particle: the Photon

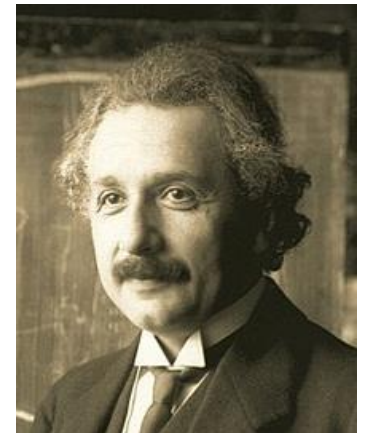
- **Max Planck** (1858-1947) figured out that light also behaves as a **particle** using **blackbody radiation**.
- Albert Einstein (1879-1955) also figured out that light behaves as a **particle** based on the **photo-electric effect**.
- Light particle = photon = packet of EM energy

- Energy =  $hf$  ( $f$  is the frequency)  
 $h$  = Planck's constant =  $6.626 \times 10^{-34}$  J·s

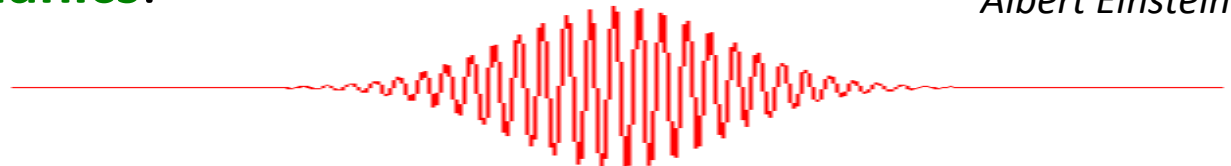
- Discovery of the photon helped initiate **Quantum Mechanics**.



Max Planck

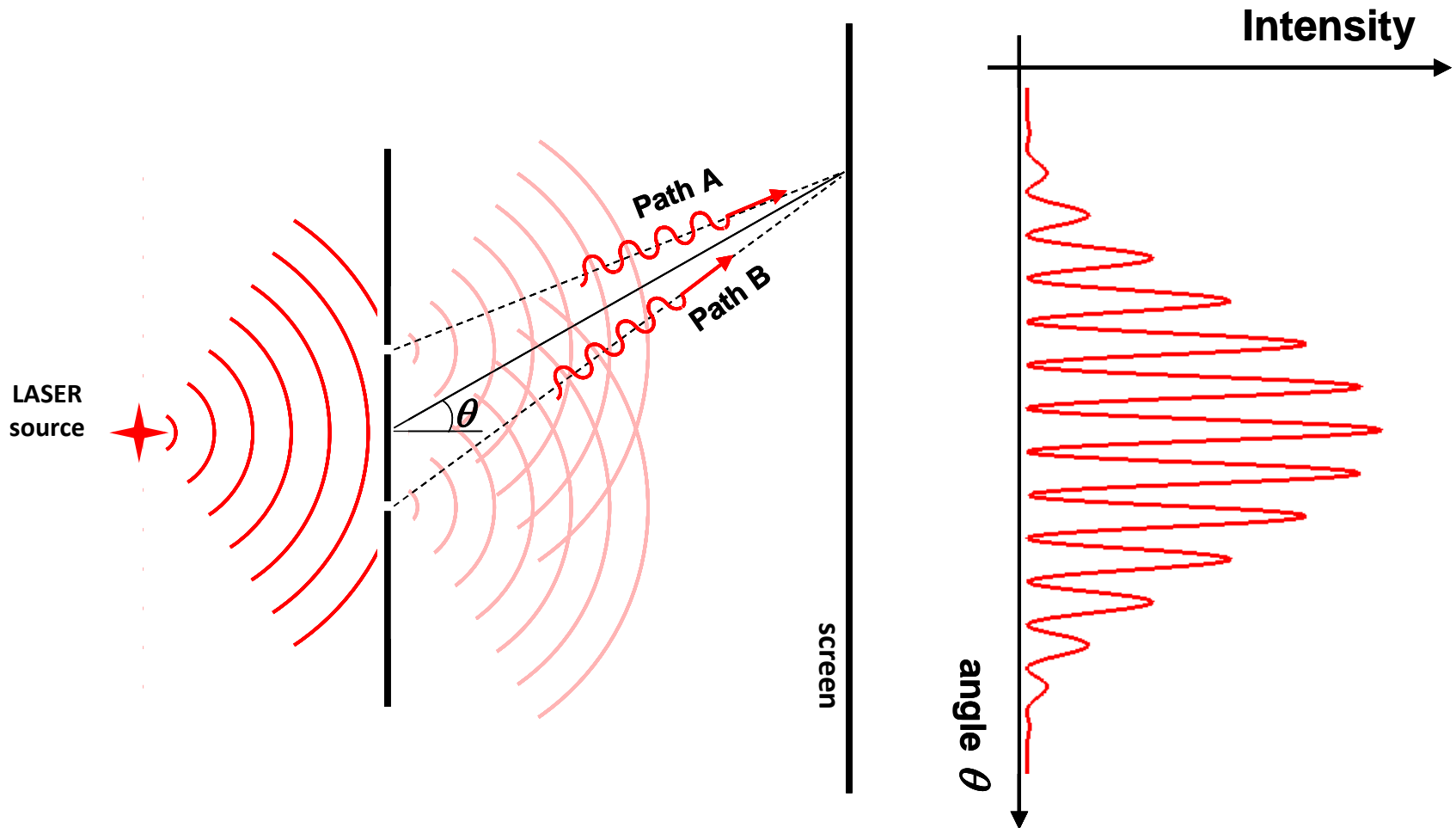


Albert Einstein

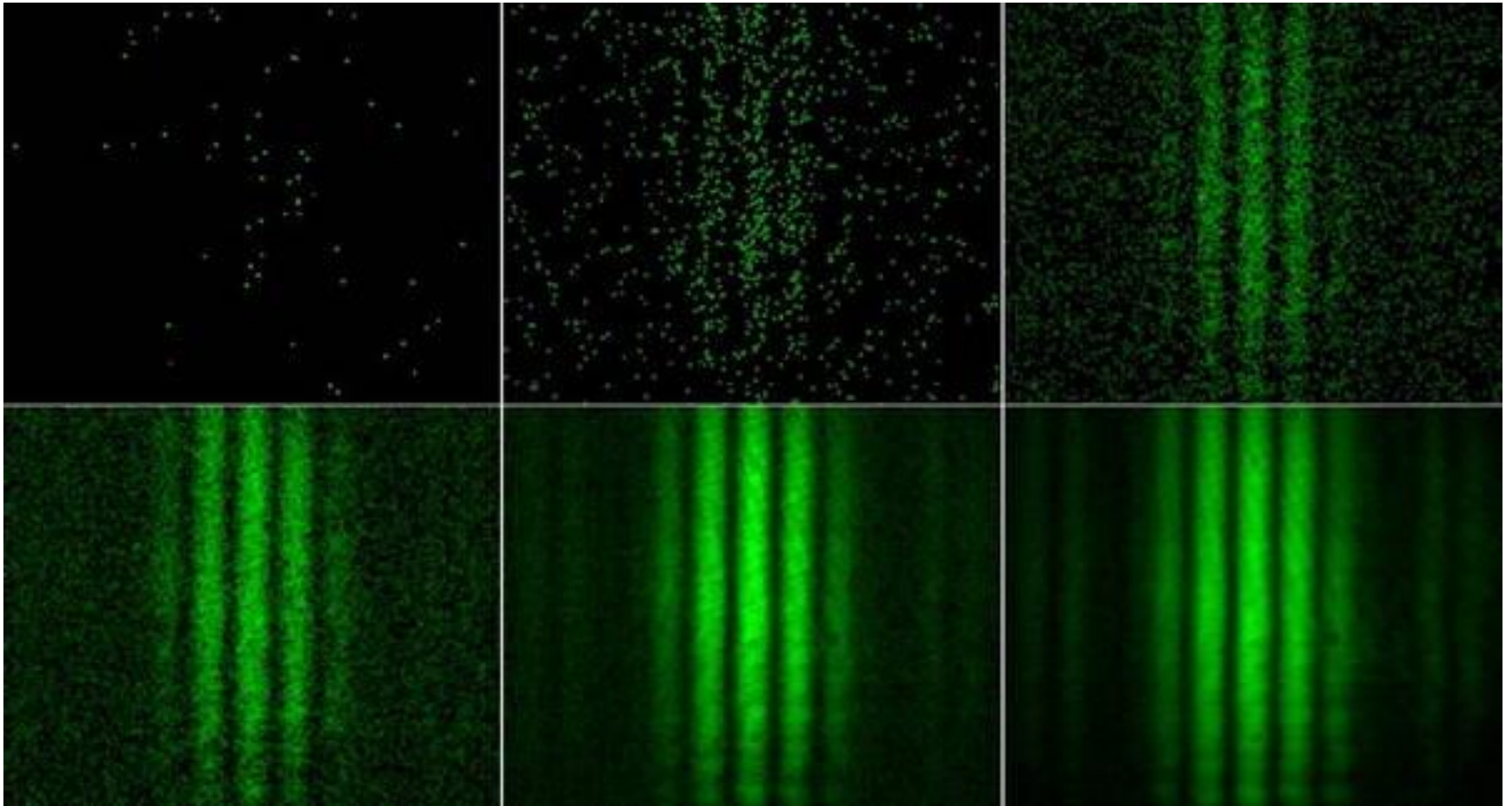




# Repeat Interference Experiment one photon at a time



# Repeat Interference Experiment one photon at a time



[A. L. Weiss and T. L. Dimitrova, Swiss Physics Society, 2009.]

LIGHT IS A

WAVE!