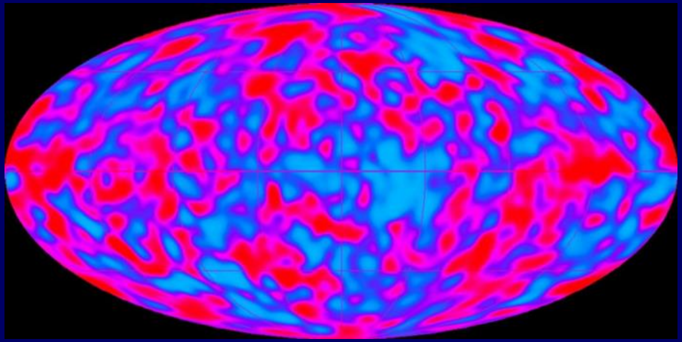
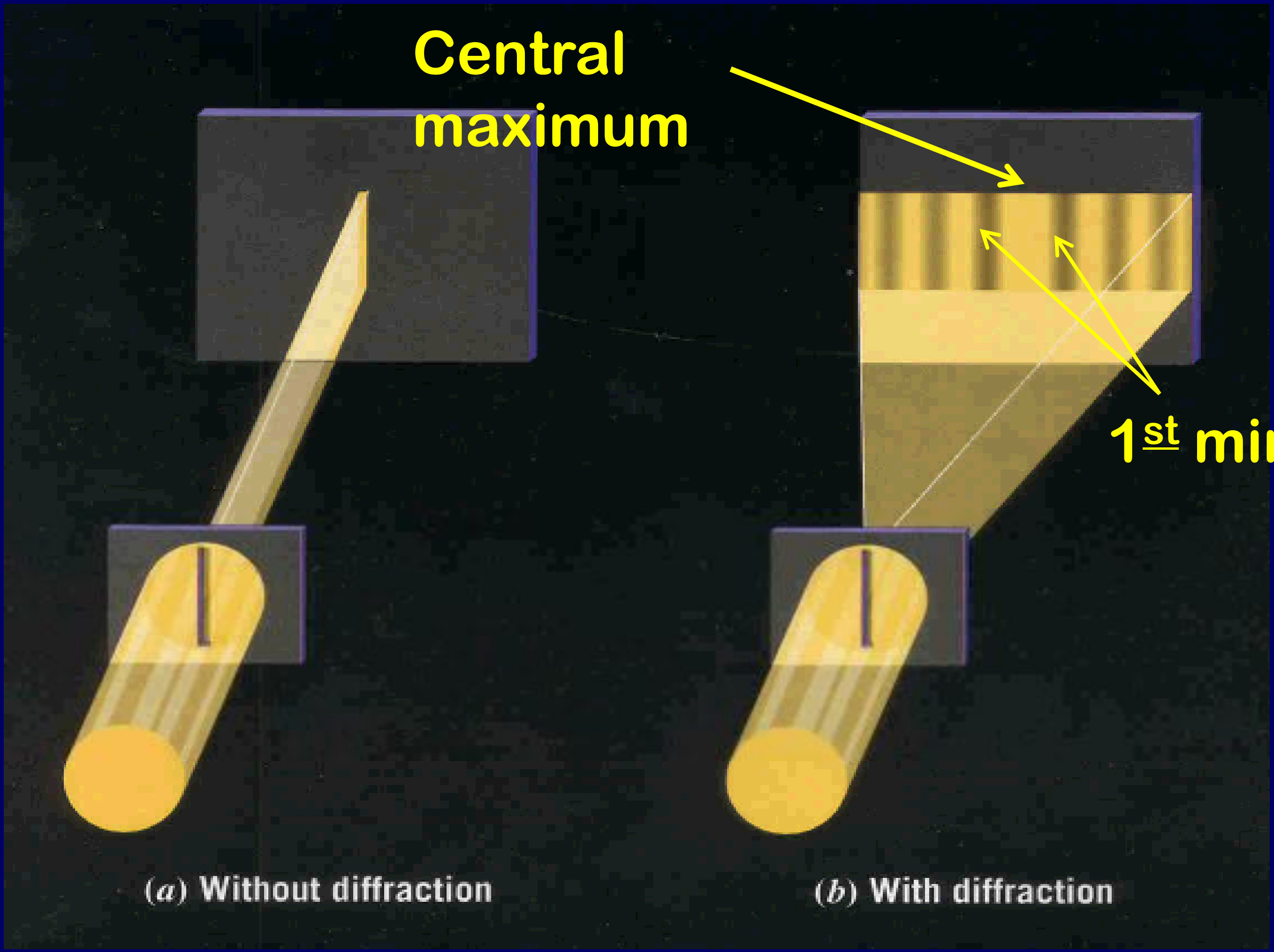
Physics 102: Lecture 22

Single Slit Diffraction
and Resolving Power

Quantum Mechanics:
Blackbody Radiation &
Photoelectric Effect

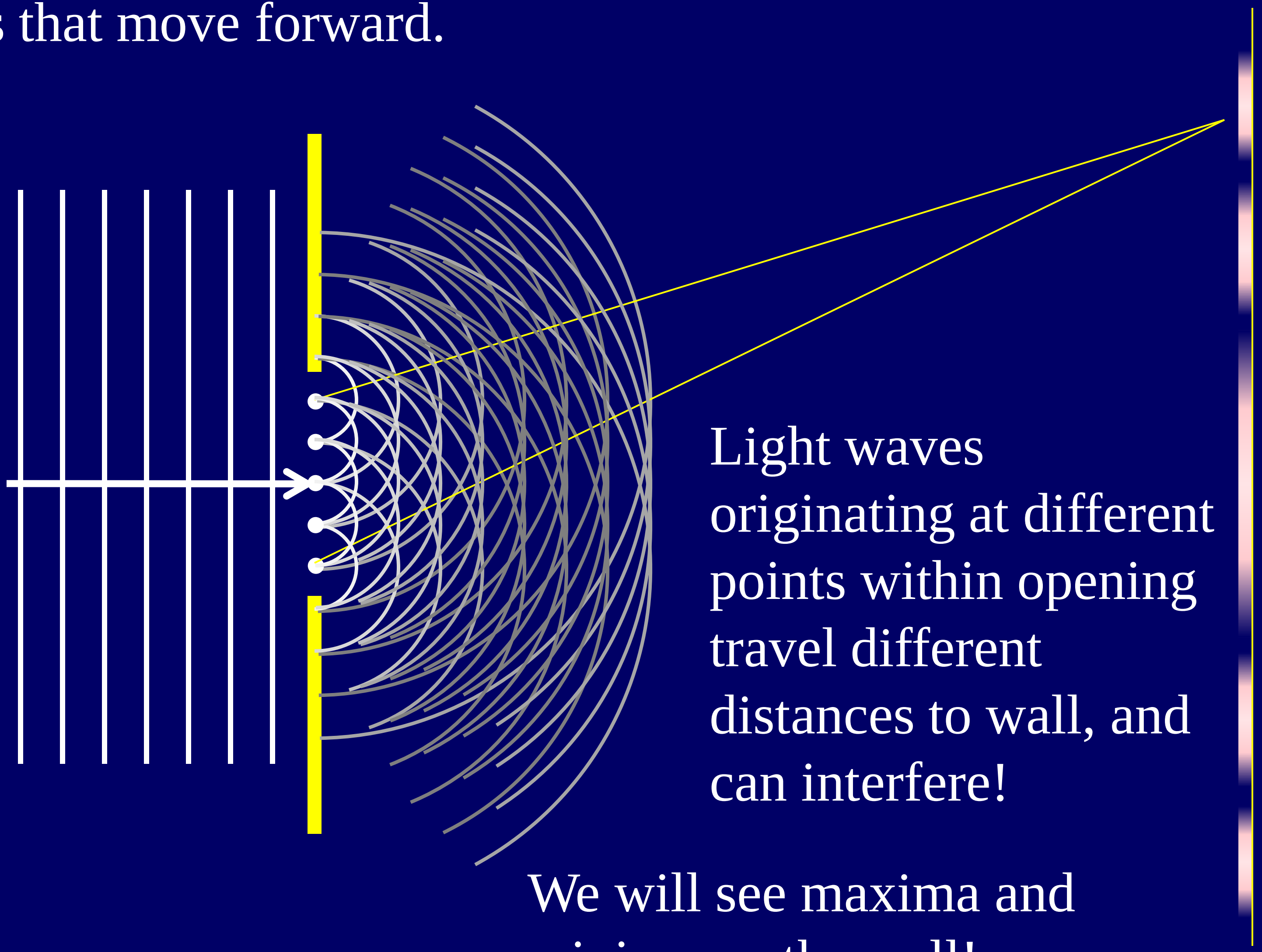


Recall last time: single-slit diffraction!



Diffraction/Huygens' principle

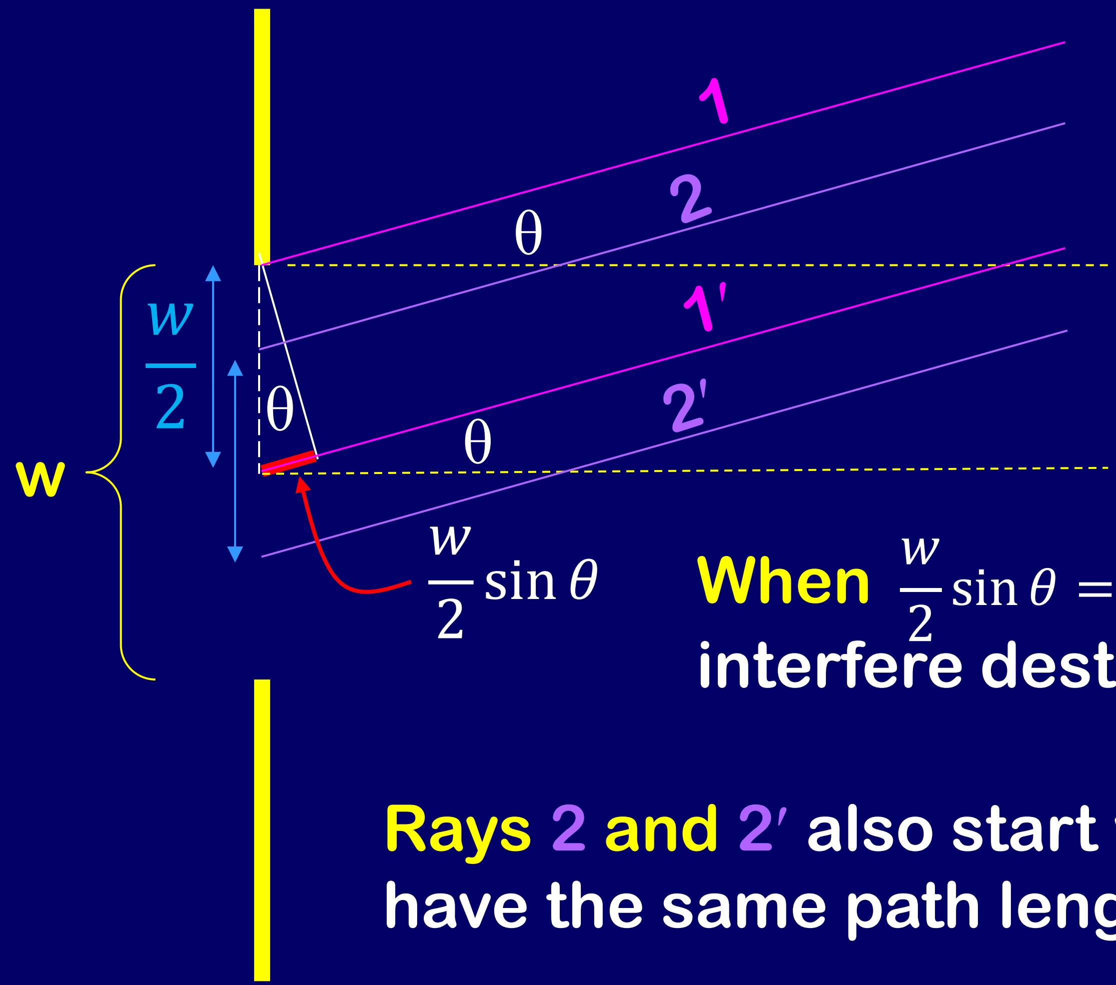
Huygens: Every point on a wave front acts as a source of tiny wavelets that move forward.



Light waves originating at different points within opening travel different distances to wall, and can interfere!

We will see maxima and minima on the wall!

Single Slit Diffraction



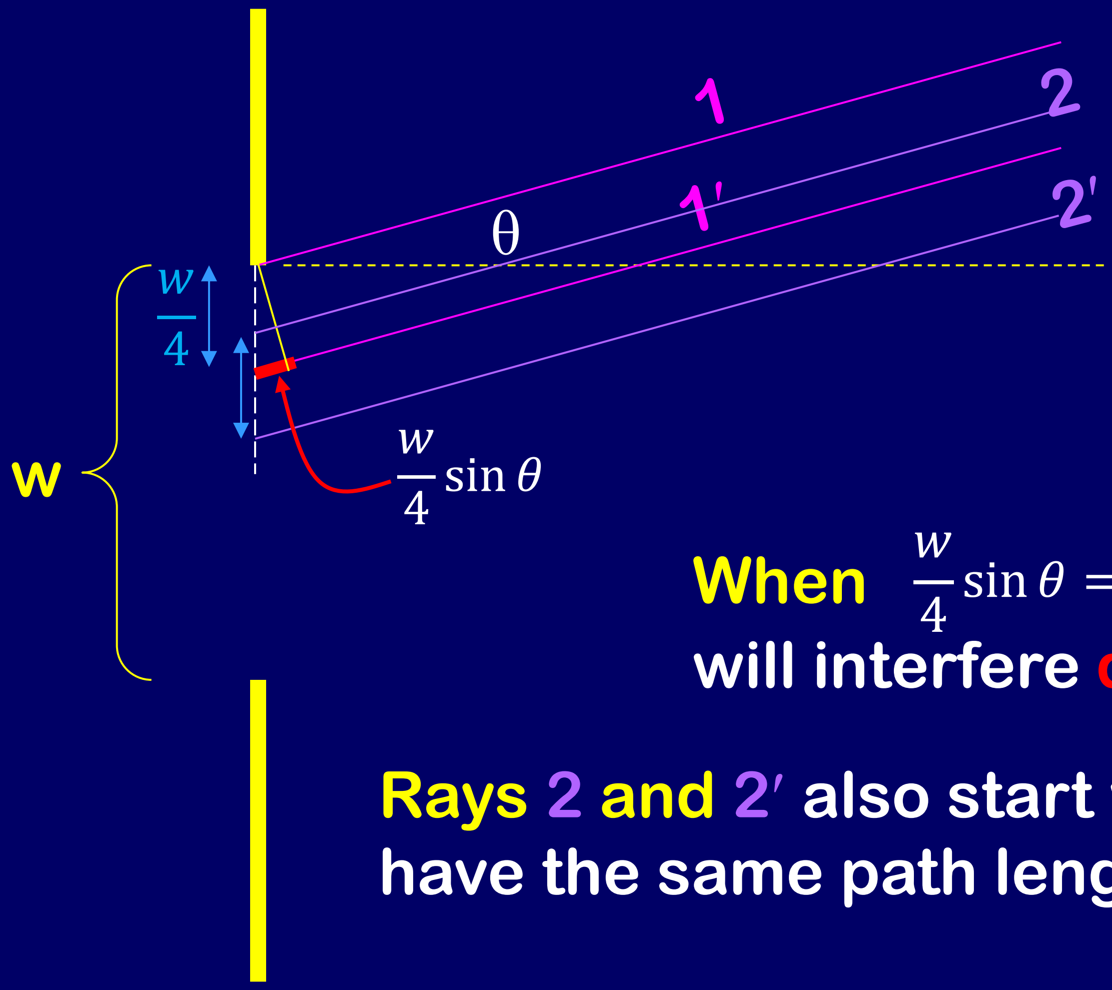
When $\frac{w}{2}\sin\theta = \frac{\lambda}{2}$ **rays 1 and 1′ interfere destructively.**

Rays 2 and 2′ also start w/2 apart and have the same path length difference.

Under this condition, every ray originating in top half of slit interferes destructively with the corresponding ray originating in bottom half.

1st minimum at $\sin\theta = \lambda/w$

Single Slit Diffraction



When $\frac{w}{4}\sin\theta = \frac{\lambda}{2}$ rays 1 and 1′ will interfere destructively.

Rays 2 and 2′ also start w/4 apart and have the same path length difference.

Under this condition, every ray originating in top quarter of slit interferes destructively with the corresponding ray originating in second quarter.

2nd minimum at $\sin\theta = 2\lambda/w$

Single Slit Diffraction Summary

Condition for halves of slit to destructively interfere

$$\sin\theta = \frac{\lambda}{w}$$

Condition for quarters of slit to destructively interfere

$$\sin\theta = 2\frac{\lambda}{w}$$

Condition for sixths of slit to destructively interfere

$$\sin\theta = 3\frac{\lambda}{w}$$

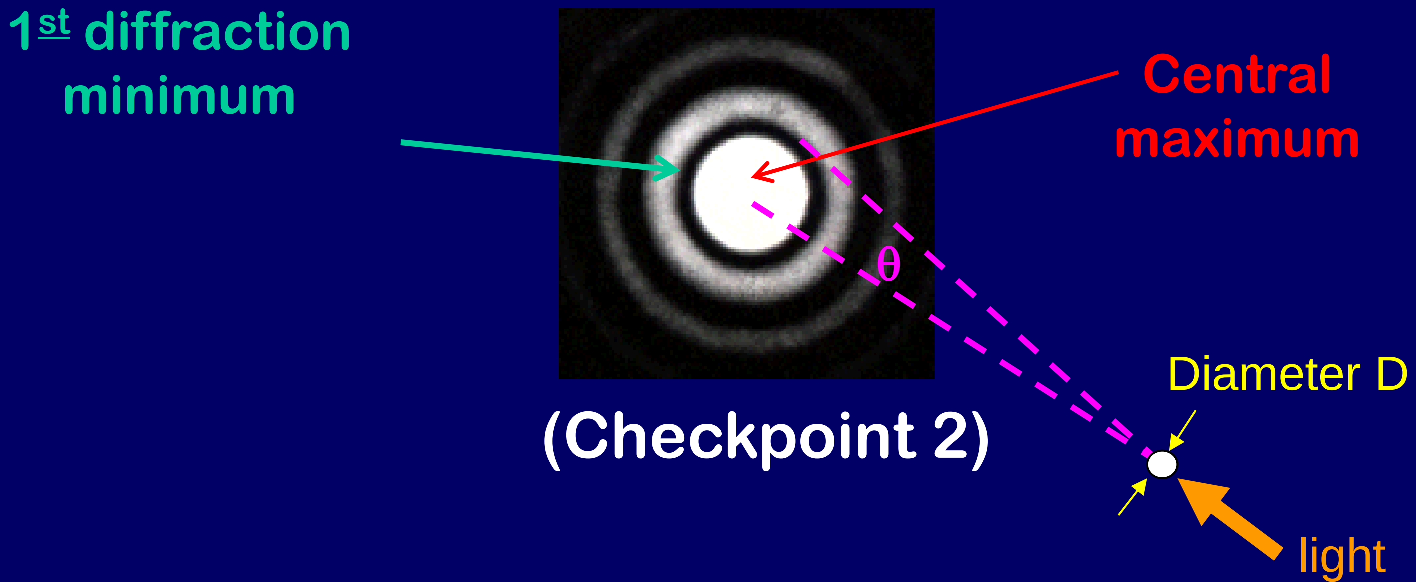
All together… $\sin\theta = m\frac{\lambda}{w}$ **(m = ±1, ±2, ±3, …)**

THIS FORMULA LOCATES MINIMA!!

Narrower slit => broader pattern (Checkpoint 1)

Note: interference only occurs when w > λ

Diffraction from Circular Aperture

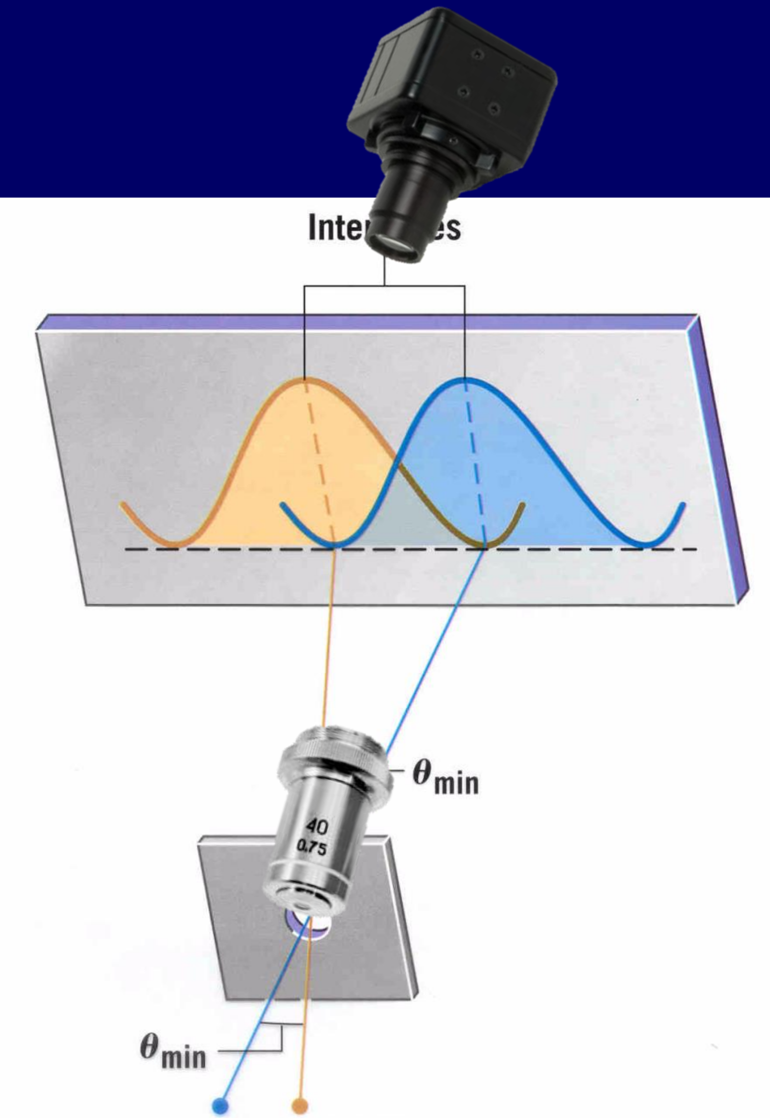


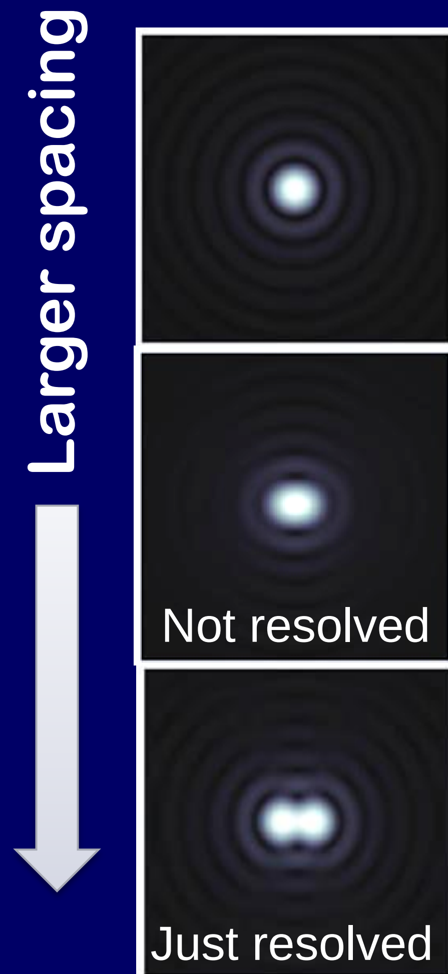
(Checkpoint 2)

Maxima and minima will be a series of **bright** and **dark** rings on screen

First diffraction minimum is at $\sin\theta = 1.22\dfrac{\lambda}{D}$

Demo: Resolving Power





Two objects are just resolved when the maximum of one diffraction pattern is at the minimum of the other.

These objects are *just* resolved

Resolving Power

To see two objects distinctly, need $\theta_{objects} > \theta_{min}$

$\theta_{objects}$ is angle between objects measured at aperture:

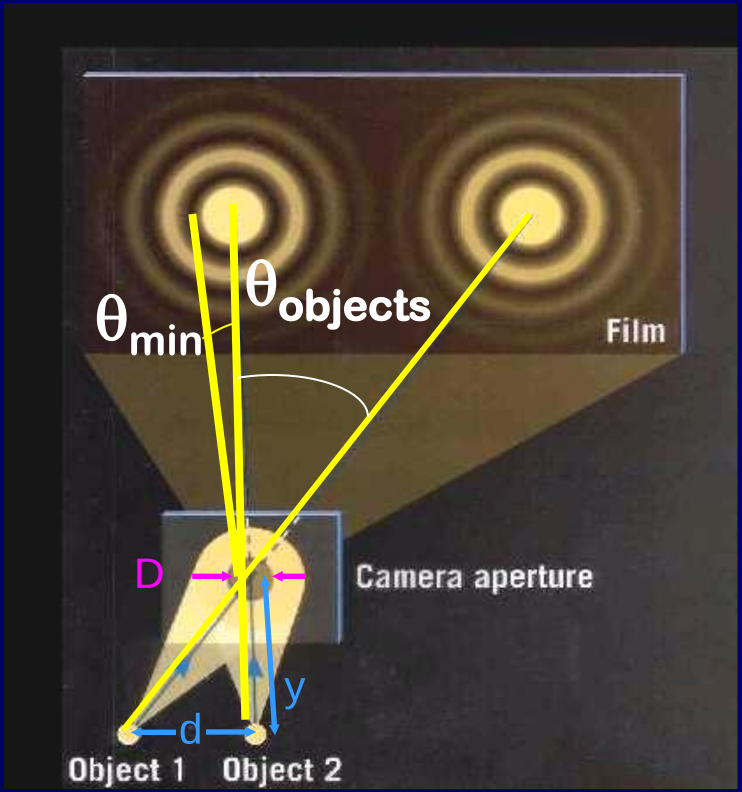
$$\boxed{\theta_{objects} \approx \tan^{-1}(d/y)}$$

$$\boxed{\theta_{objects} \approx d/y}$$ (if d much smaller than y and θ in radians)

θ_{min} is minimum angular separation that aperture can resolve:

$$\boxed{\sin\theta_{min} \approx \theta_{min} = 1.22\ \lambda/D}$$

$d = 1.22\lambda y/D$ **Just resolved!**



Improve resolution by increasing D or decreasing λ

ACT: Resolving Power

$$\boxed{\sin\theta_{min} \approx \theta_{min} = 1.22\ \lambda/D}$$

How does the maximum resolving power of your eye change when the brightness of the room is decreased?

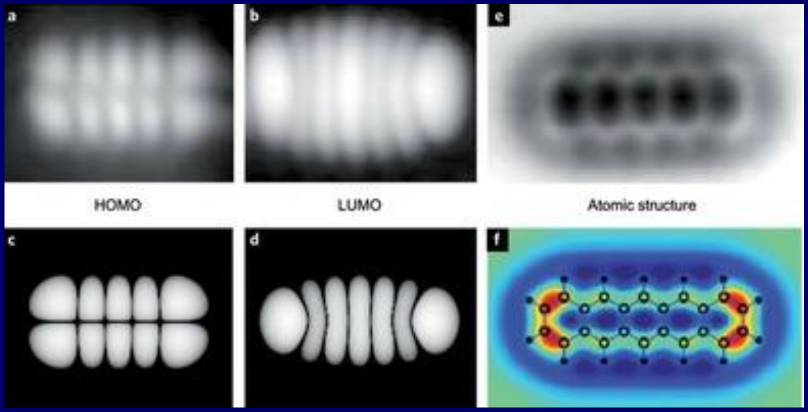
1) Increases **2) Constant** **3) Decreases**

When the light is low, your pupil dilates (D can increase by factor of 10!) Other effects (density of rods/ganglia, limited field of view, etc.) tend to limit this effect.

Checkpoint 3

Quantum Mechanics

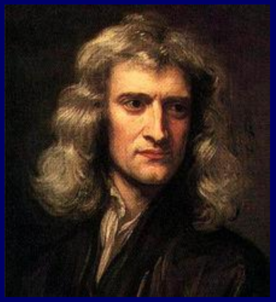
- At very small sizes the world is VERY different!
  - Energy can be discrete
  - Processes are probabilistic
  - Particles are in many places at the same time
  - Looking at something changes how it behaves

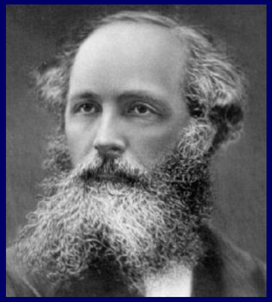


Measured & predicted electron distributions around pentacene!

State of Late 19th Century Physics

- Two great theories "Classical physics"
  - Newton's laws of mechanics, including gravity
  - Maxwell's theory of electricity & magnetism, including propagation of electromagnetic waves





- But…some unsettling experimental results calls into question these theories
  - The quantum revolution
  - Einstein and relativity

Three Early Indications of Problems with Classical Physics

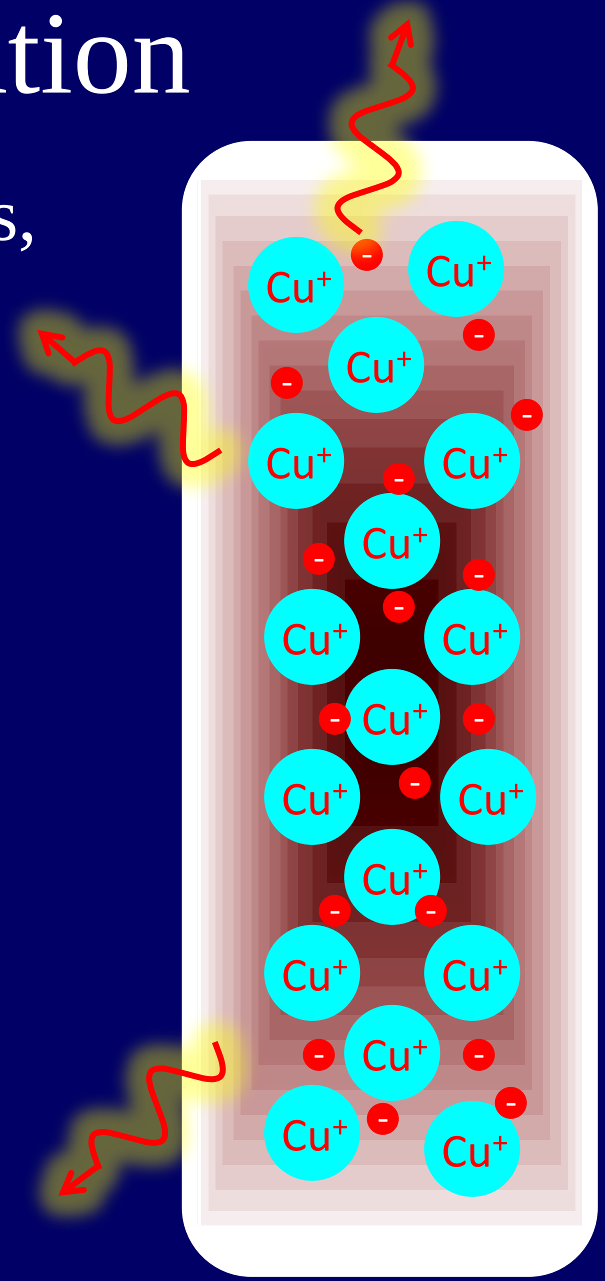
- Blackbody radiation
- Photoelectric effect

Today

- Wave-particle duality **Next Lecture**

Blackbody Radiation

Hot objects glow (toaster coils, light bulbs, the sun).

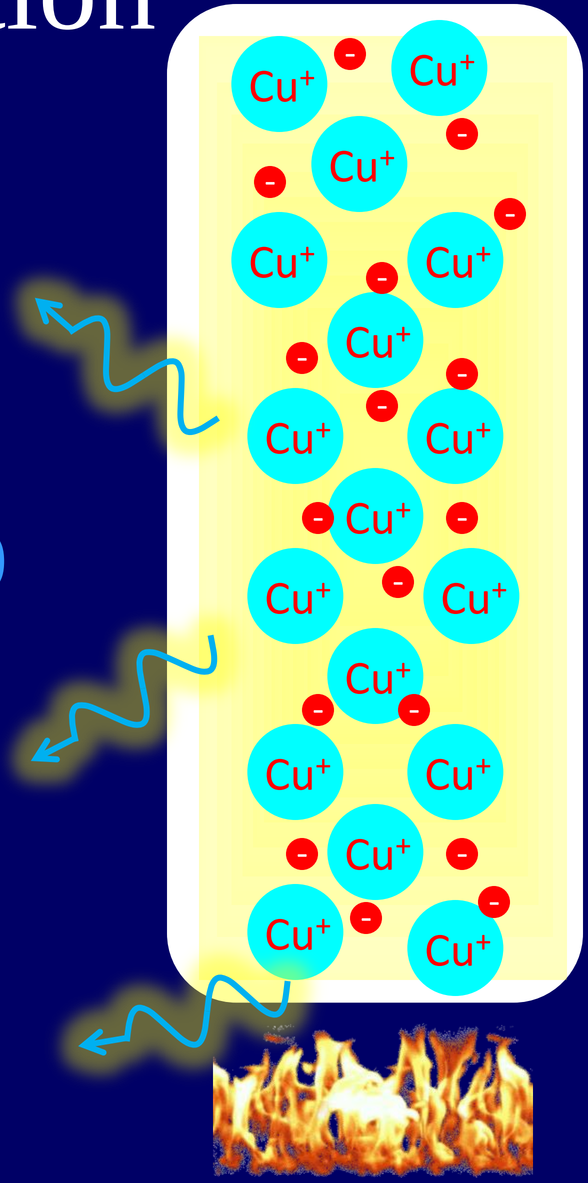


Blackbody Radiation

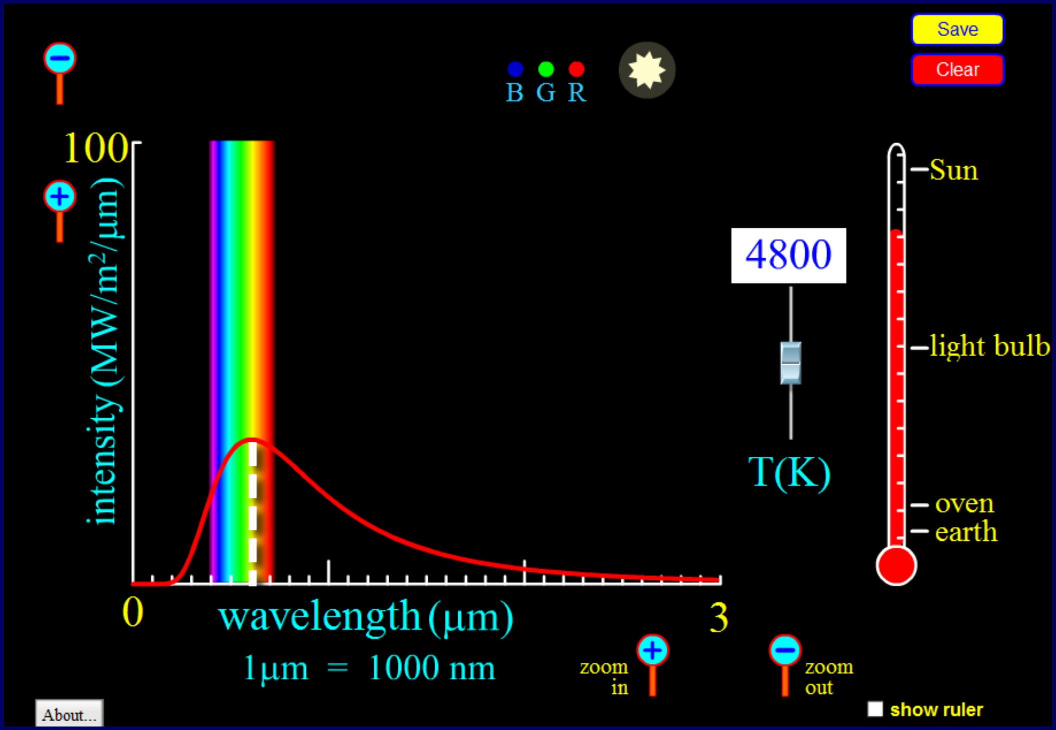
Hot objects glow (toaster coils, light bulbs, the sun).

As the temperature increases the color shifts from Red (700 nm) to Blue (400 nm)

The classical physics prediction was completely wrong! (It said that an infinite amount of energy should be radiated by an object at finite temperature)



Blackbody Radiation Spectrum



http://phet.colorado.edu/sims/blackbody-spectrum/blackbody-spectrum_en.html

Higher temperature: peak intensity at shorter λ

Wien's Displacement Law:

$$\lambda_{max} T = 2.898\text{x}10^{-3}\ \text{m}\cdot\text{K}$$

λ_{max}**: wavelength for peak intensity**

Blackbody Radiation: First evidence for Q.M.

Max Planck found he could explain these curves if he assumed that electromagnetic energy was radiated in discrete chunks, rather than continuously.

The "quantum" of electromagnetic energy is called the photon.

Energy carried by a single photon is

$$E = hf = hc/\lambda$$

Planck's constant: $h = 6.626 \times 10^{-34}$ Joule sec

Checkpoint 5

A series of light bulbs are colored red, yellow, and blue. Which bulb emits photons with the most energy?

Blue! **Lowest wavelength is highest energy.**

$$E = hf = hc/\lambda$$

The least energy?

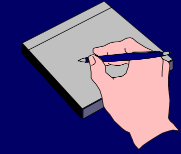
Red! **Highest wavelength is lowest energy.**

Which is hotter?

(1) stove burner glowing red

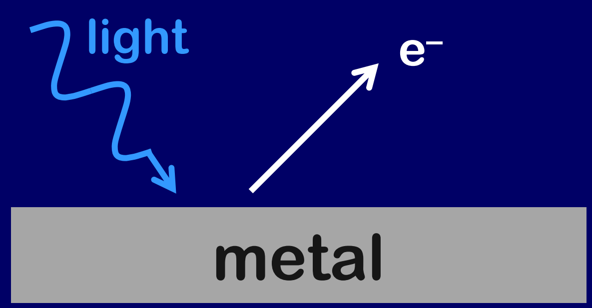
(2) stove burner glowing orange

Hotter stove emits higher-energy photons (lower wavelength = orange)



Photoelectric Effect

- Light shining on a metal can “knock” electrons out of atoms.
- Light must provide energy to overcome Coulomb attraction of electron to nucleus
- Light Intensity gives power/area (i.e. Watts/m^2)
  - Recall: Power = Energy/time (i.e. Joules/sec.)

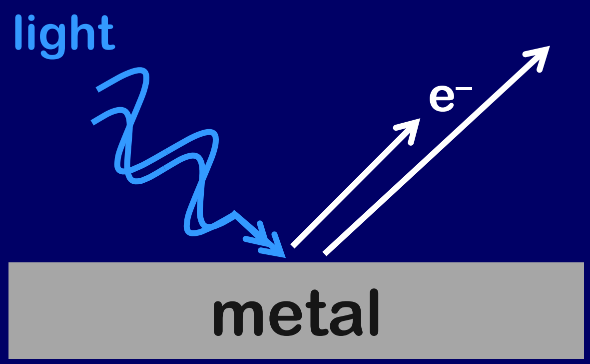


Photoelectric Effect: Light Intensity

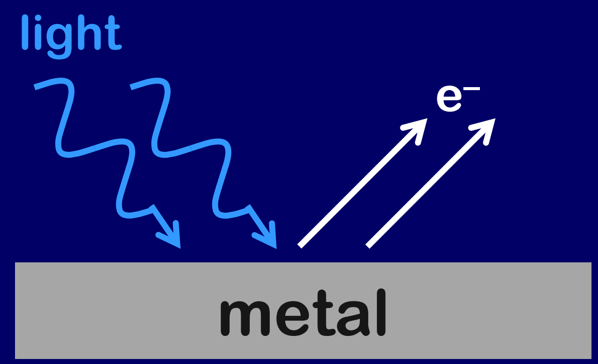
When the brightness is increased…

Rate of electron emission increases

Maximum kinetic energy of electrons unchanged



Classical



Quantum

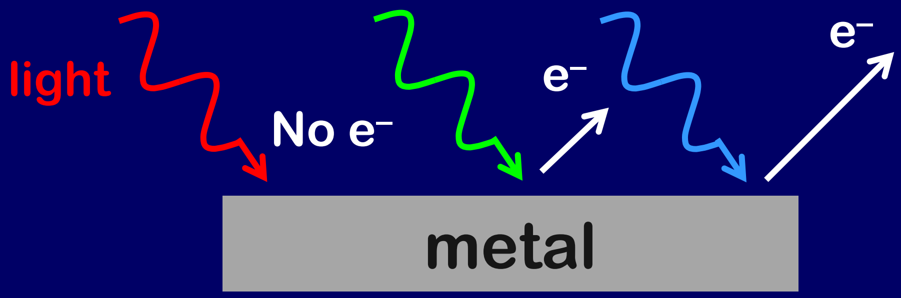
Checkpoint 4

Photoelectric Effect: Light Frequency

When the frequency of the light is changed…

Emission rate unchanged, but…
electron emission only for $f > f_{min}$

Maximum electron KE increases



Photoelectric Effect Summary

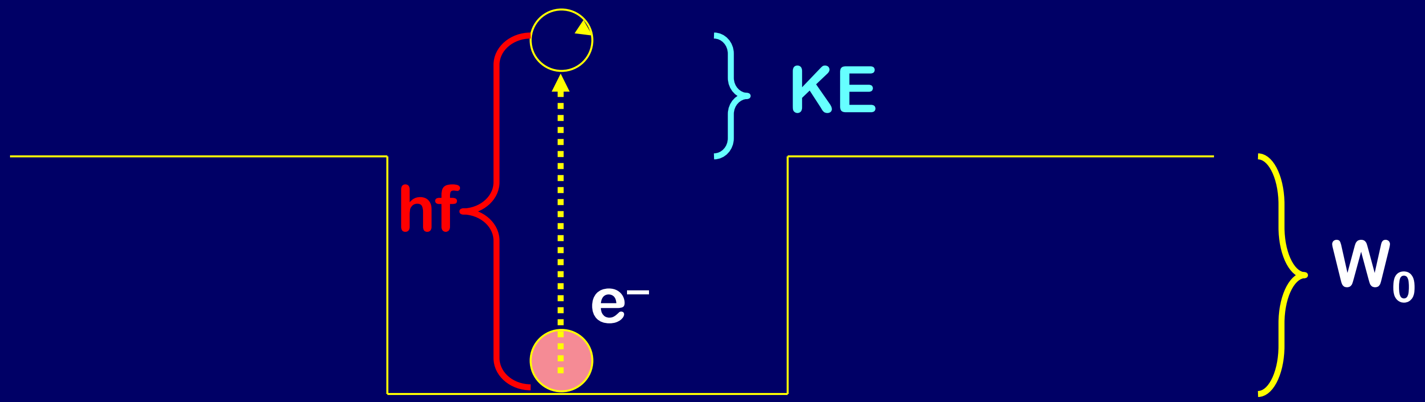
- Each metal has "Work Function" (W_0) which is the minimum energy needed to free electron from atom.
- Light comes in packets called Photons

$$\boxed{E = h\,f}$$

$h = 6.626 \times 10^{-34}$ Joule sec

- Maximum kinetic energy of released electrons

$$\boxed{K.E. = hf - W_0}$$



ACT: Photon

A red and green laser each emit 2.5mW. Which one produces more photons/second?

1) Red   2) Green   3) Same

$$\text{power} = \frac{\text{energy}}{\text{time}} = \frac{\#\,\text{photons}}{\text{time}} \frac{\text{energy}}{\text{photon}}$$

Red light has less energy/photon so if they both have the same total power, red has to have more photons/time!

Quantum Physics and the Wave-Particle Duality

I. Is Light a Wave or a Particle?

- Wave
  - Electric and Magnetic fields act like waves
  - Superposition: Interference and Diffraction

- Particle
  - Photons (blackbody radiation)
  - Collision with electrons in photo-electric effect

BOTH Particle AND Wave Behavior