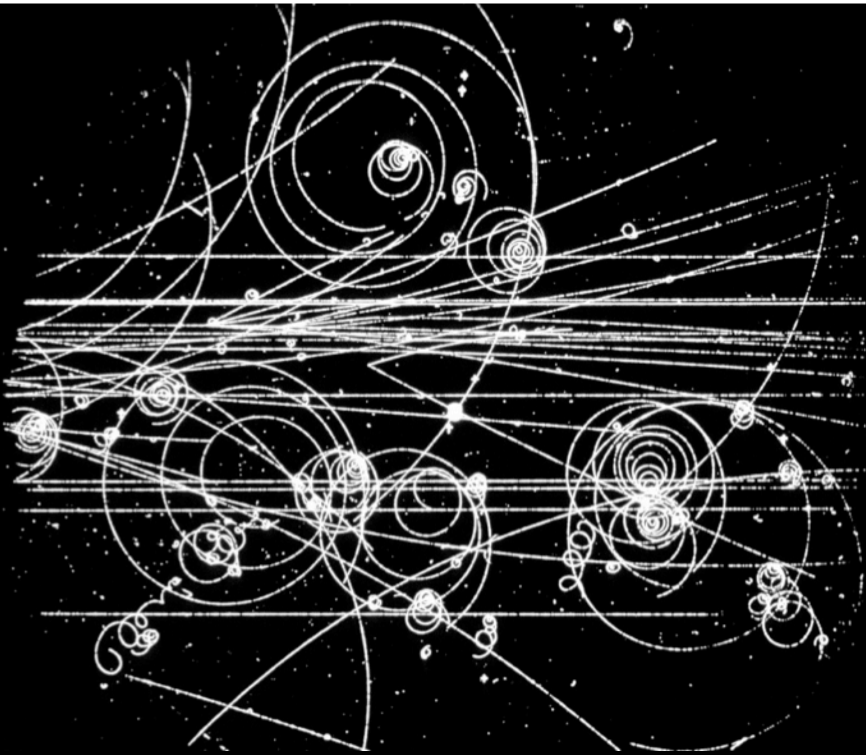
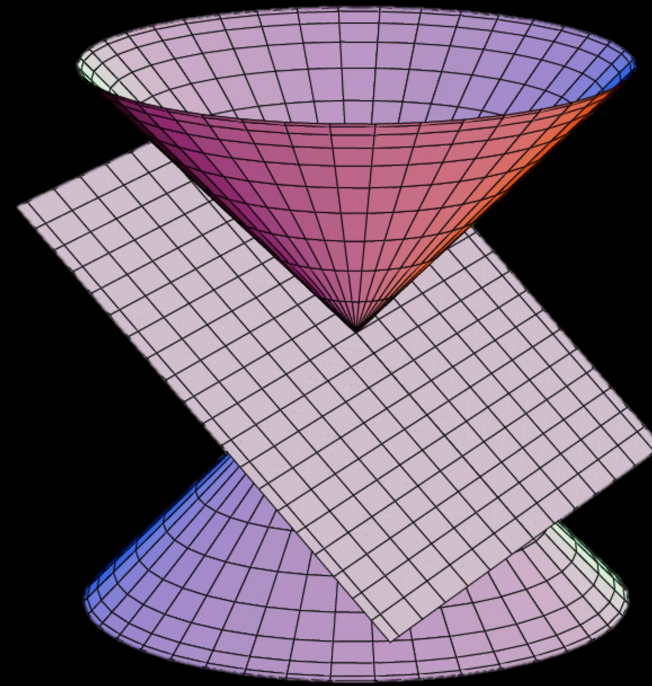




Modern Physics (Phys. IV): 2704

Professor Jasper Halekas
Van Allen 70
MWF 12:30-1:20 Lecture

Announcements

- Wednesday is Midterm 1 in class
  - Midterm 1 covers Ch. 1-4 (lecture through Friday)
  - Bring an 8.5" x 11" (one side) equation sheet
  - You are allowed a calculator

  - Note: Course exams are intended to be difficult, with mean of ~60-65%

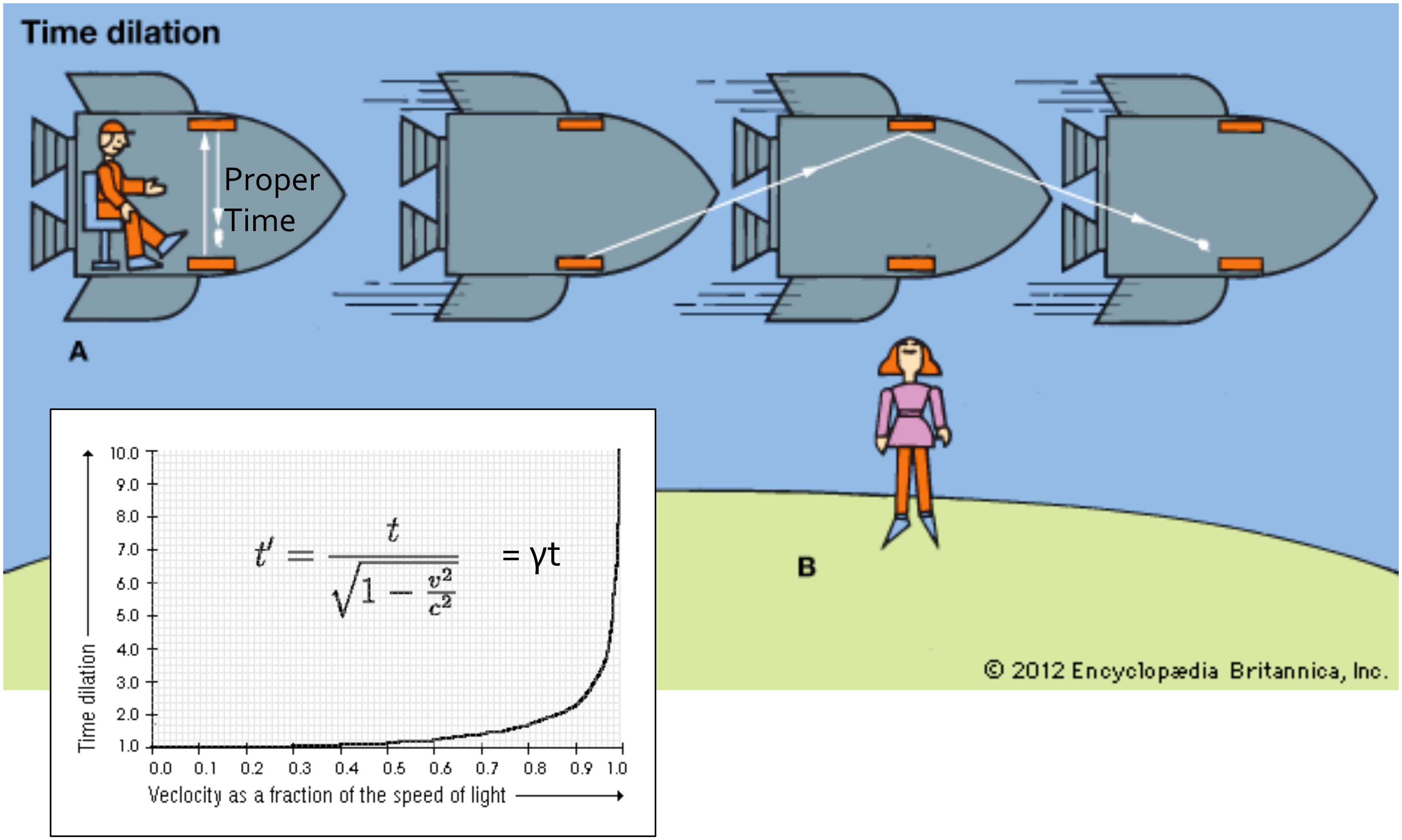
- No labs or homework this week

From Innocuous Assumptions, Strange (but True) Theories Grow

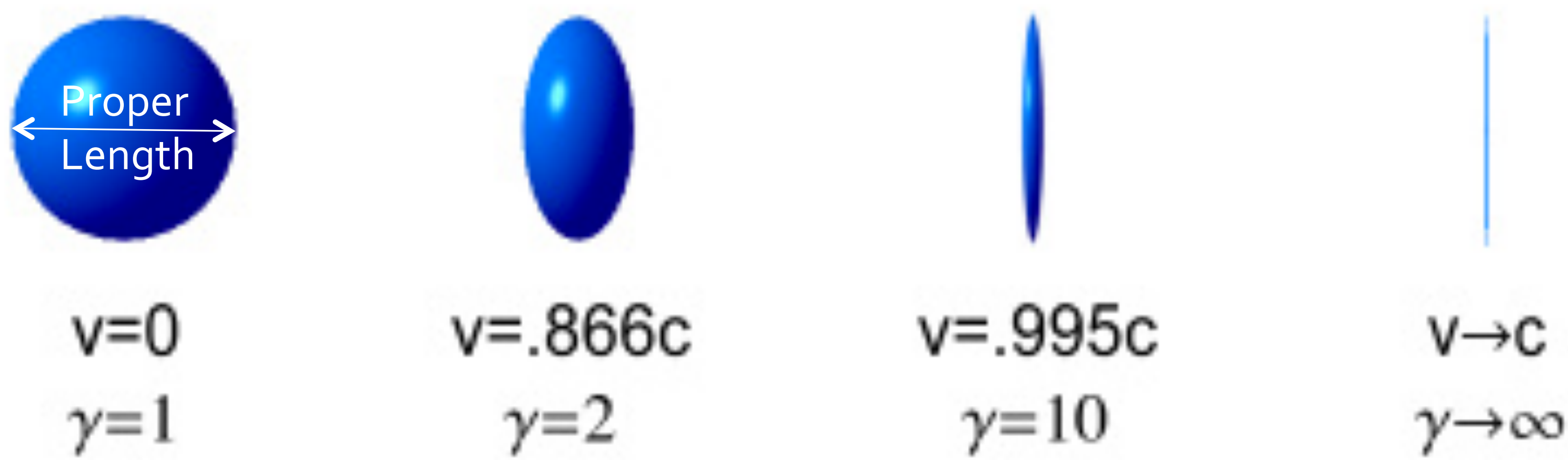
- *1. The Principle of Relativity*
  - The laws of physics are the same in all inertial frames of reference.

- *2. The Constancy of Speed of Light in Vacuum*
  - The speed of light in vacuum has the same value c in all inertial frames of reference.

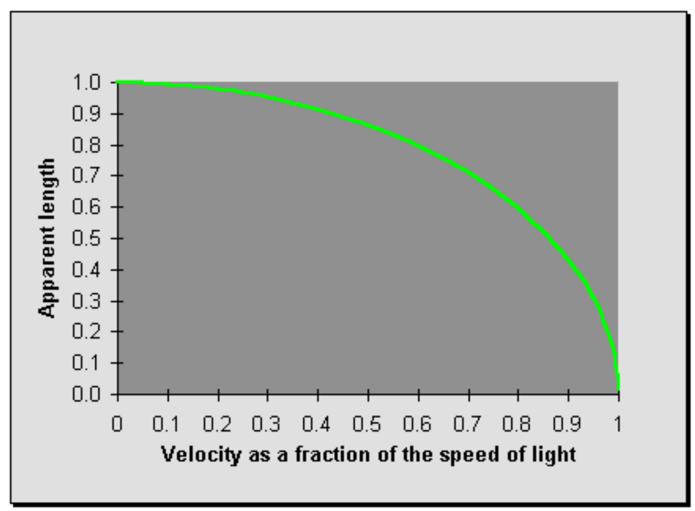
Time Dilation



Length Contraction



$$\Delta L' = \Delta L\sqrt{1-\frac{v^2}{c^2}} = \Delta L/\gamma$$



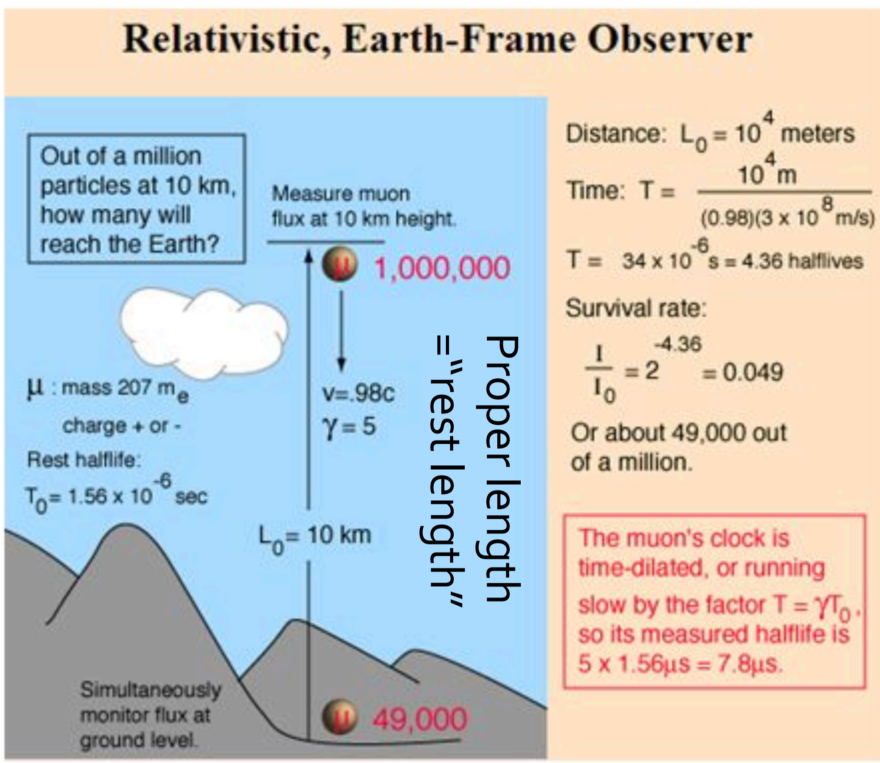
Concept Check

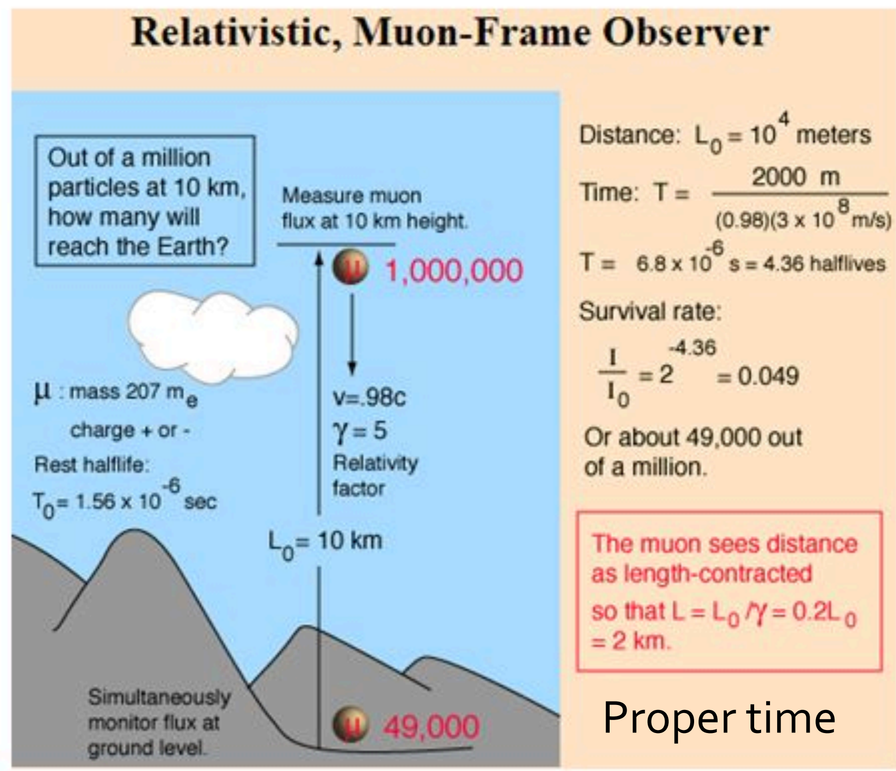
- Do the proper time and the proper length have to be in the same frame?

A. Yes
B. No

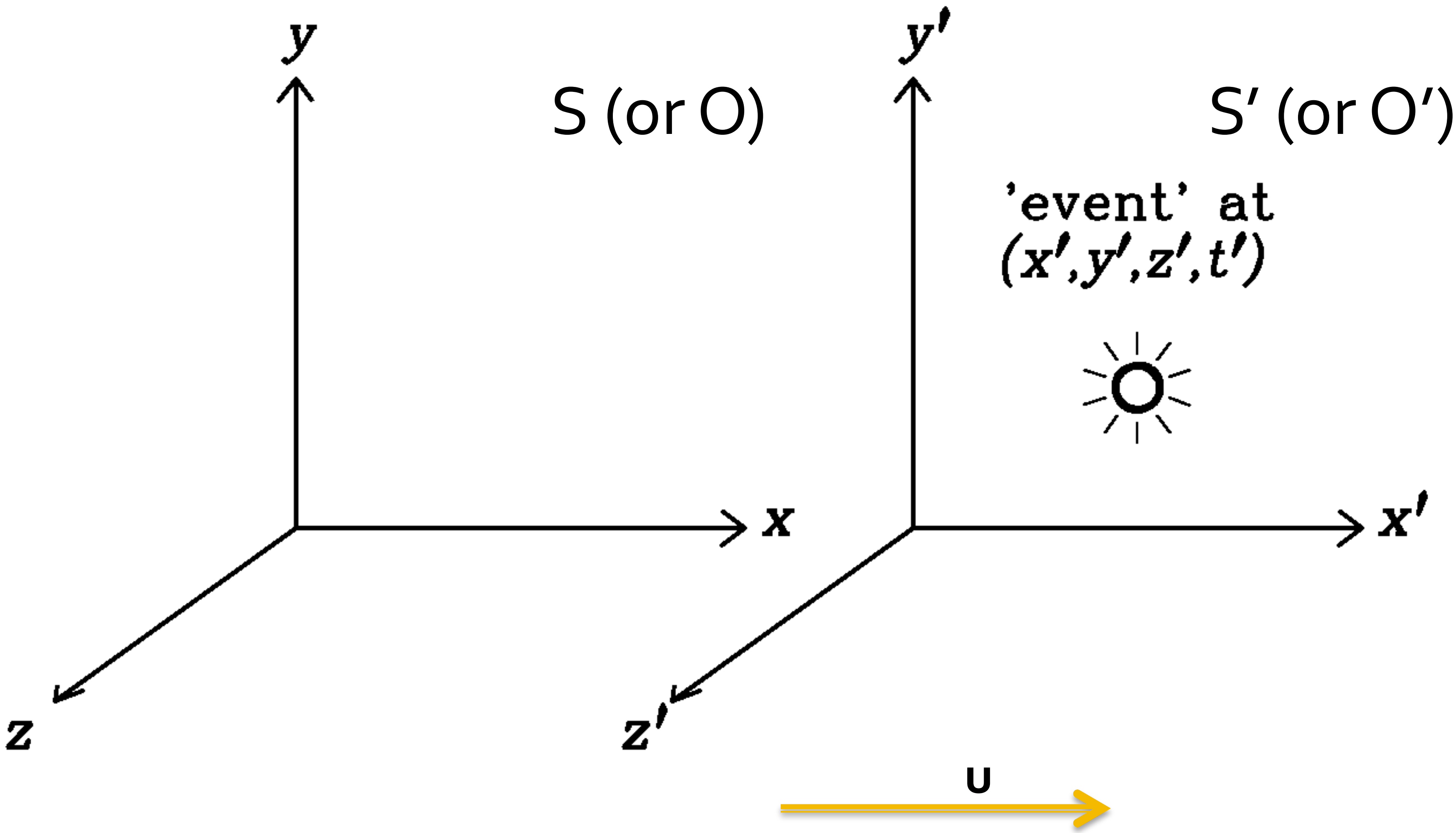
Concept Check

- Do the proper time and the proper length have to be in the same frame? No





Lorentz Transformation



Lorentz Transformation

Lorentz Transformation, and inverse Lorentz transformation:

From *O* to *O'*, i.e.,
x, y, z, t* → *x', y', z', t'

$$x' = \frac{x - ut}{\sqrt{1 - u^2/c^2}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t - (u/c^2)x}{\sqrt{1 - u^2/c^2}}$$

From *O'* to *O*, i.e.,
x', y', z', t'* → *x, y, z, t

$$x = \frac{x' + ut'}{\sqrt{1 - u^2/c^2}}$$

$$y = y'$$

$$z = z'$$

$$t = \frac{t' + (u/c^2)x'}{\sqrt{1 - u^2/c^2}}$$

Lorentz Transformation of Velocity

Classical:

$$v'_x = v_x - u$$

$$v'_y = v_y$$

$$v'_z = v_z$$

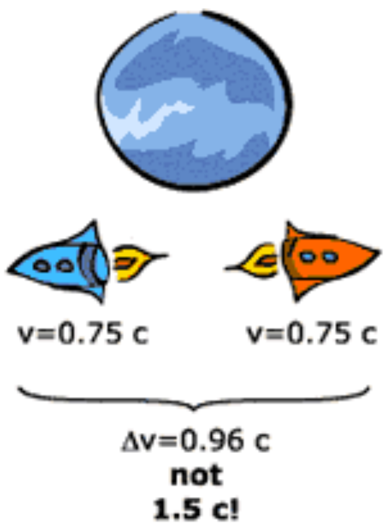
Relativistic:

$$v'_x = \frac{v_x - u}{1 - v_x u / c^2}$$

$$v'_y = \frac{v_y}{\gamma\left(1 - v_x u / c^2\right)}$$

$$v'_z = \frac{v_z}{\gamma\left(1 - v_x u / c^2\right)}$$

Relativistic Velocity Addition



Relativistic Addition of Velocities

Galilean Transformation

$$V_{AB} = \frac{V_{AC} + V_{CB}}{1 + \frac{(V_{AC})(V_{CB})}{c^2}}$$

Lorentz Factor

Relativistic Doppler Shift

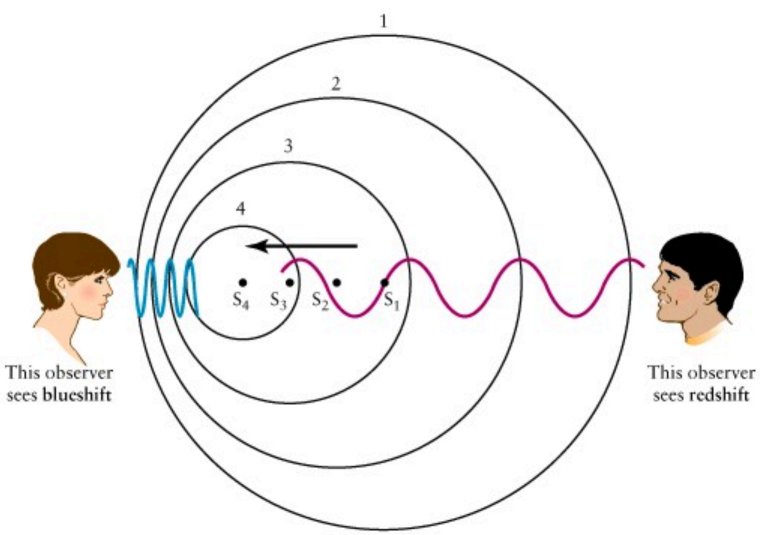
Doppler effect for light

$$\nu_{observed} = \left[\frac{\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v}{c}}\right]\nu_{source}$$

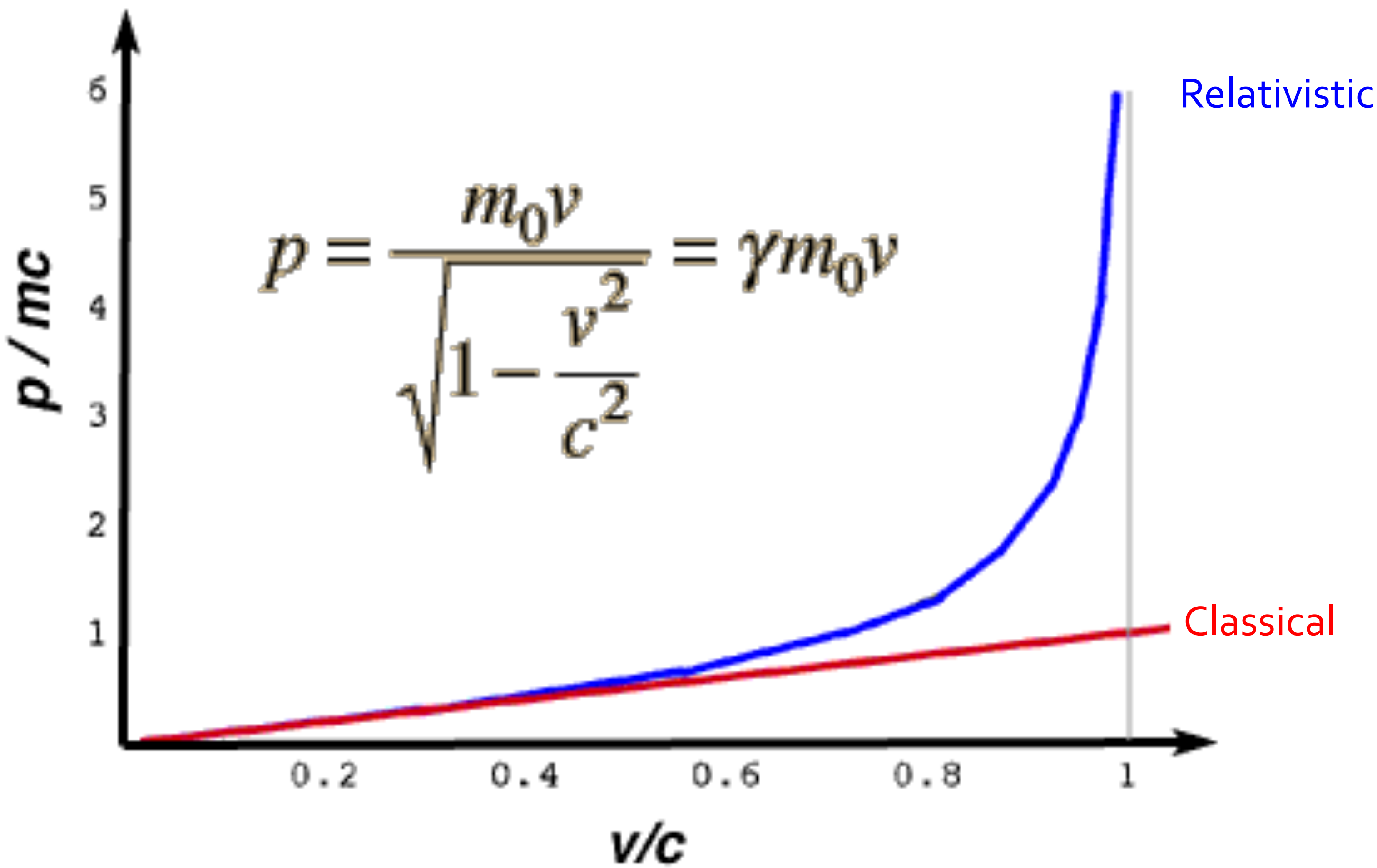
which can be rearranged to the form

$$\nu_{observed} = \nu_{source}\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$

$$\lambda_{observed} = \lambda_{source}\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}$$

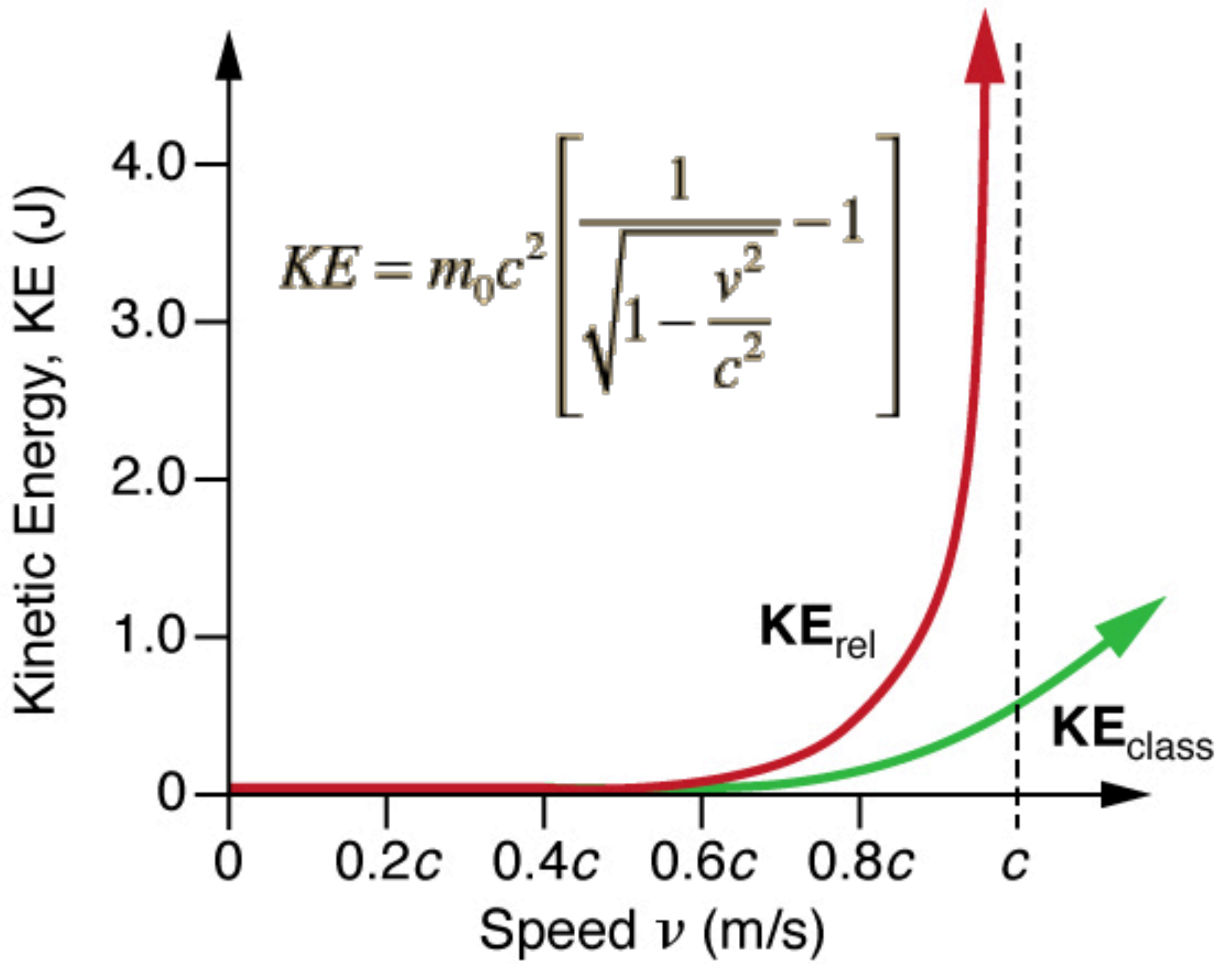


Relativistic Momentum



$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_0 v$$

Relativistic Kinetic Energy

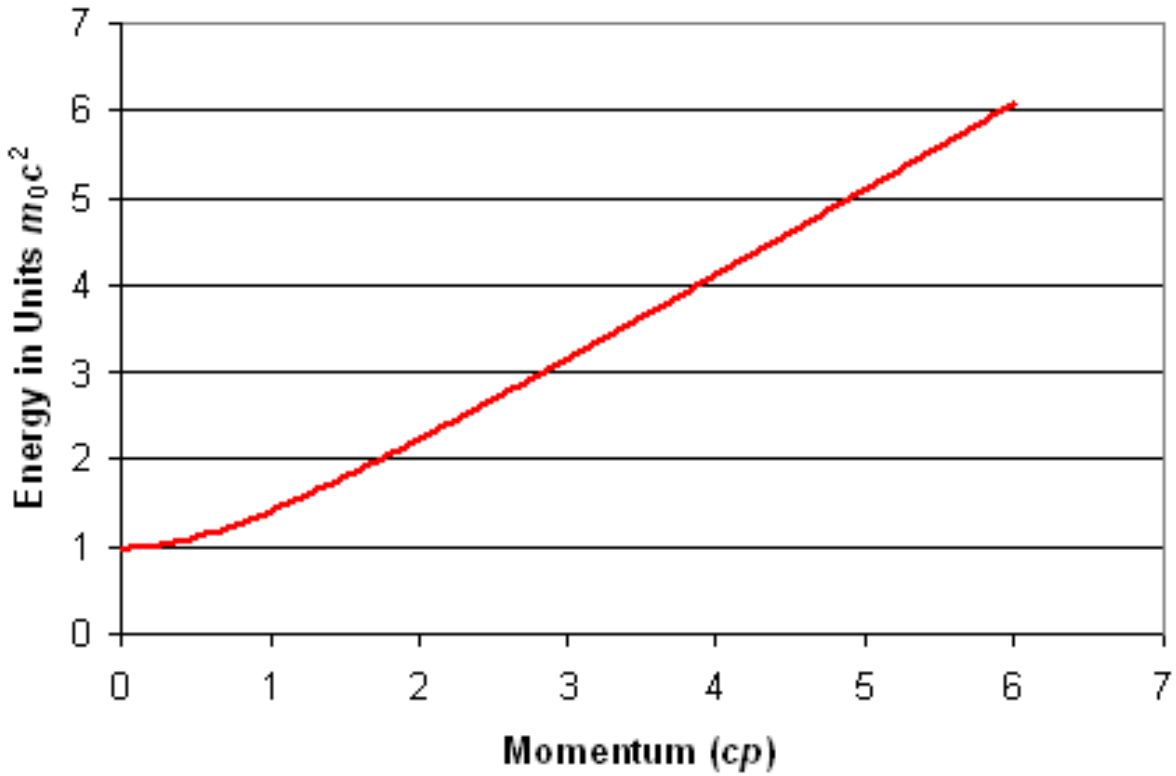


Relativistic Total Energy

$$\begin{aligned}\text{total energy E} &= \text{rest energy } + \text{KE} \\ &= (mc^2) \quad + \quad (\gamma - 1)\, mc^2 \\ &= \gamma mc^2\end{aligned}$$

Energy-Momentum Relationship

$$E^2 = p^2c^2 + m^2c^4$$

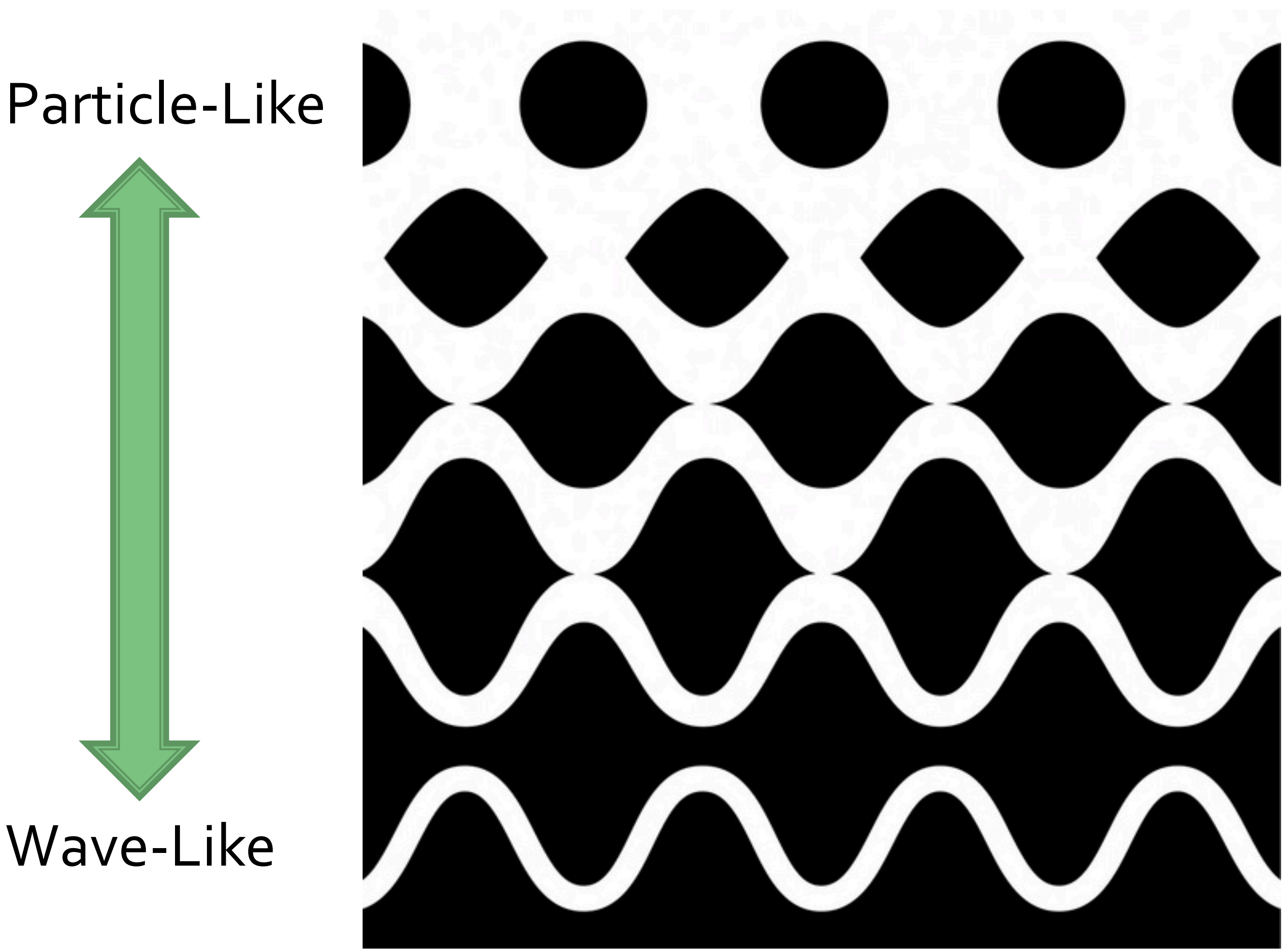


Conservation Laws

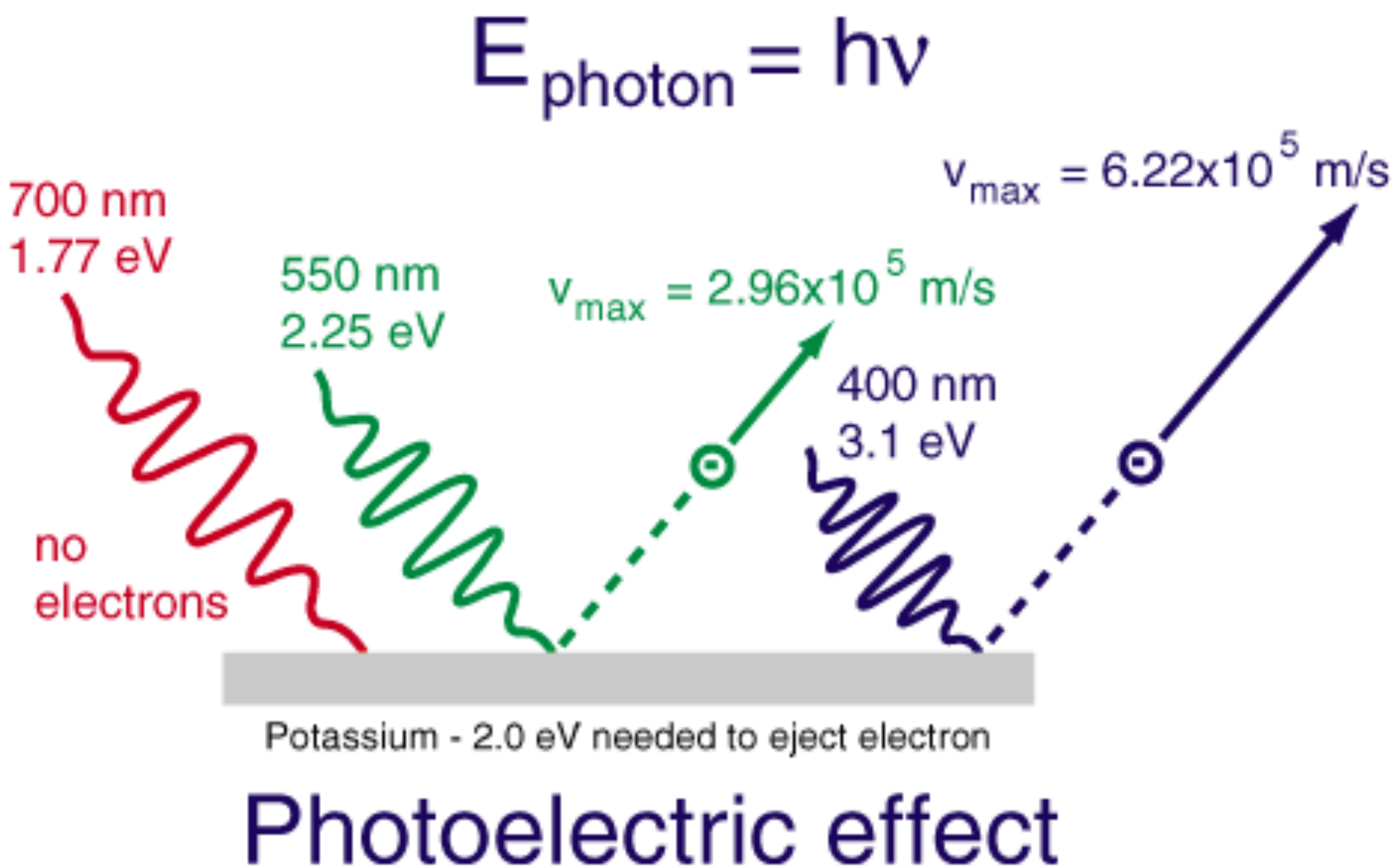
- Total (relativistic) energy is always conserved in any isolated system
  - But, kinetic energy and rest energy can be transformed from one to the other

- Total (relativistic) momentum is always conserved in any isolated system

Wave-Particle Duality

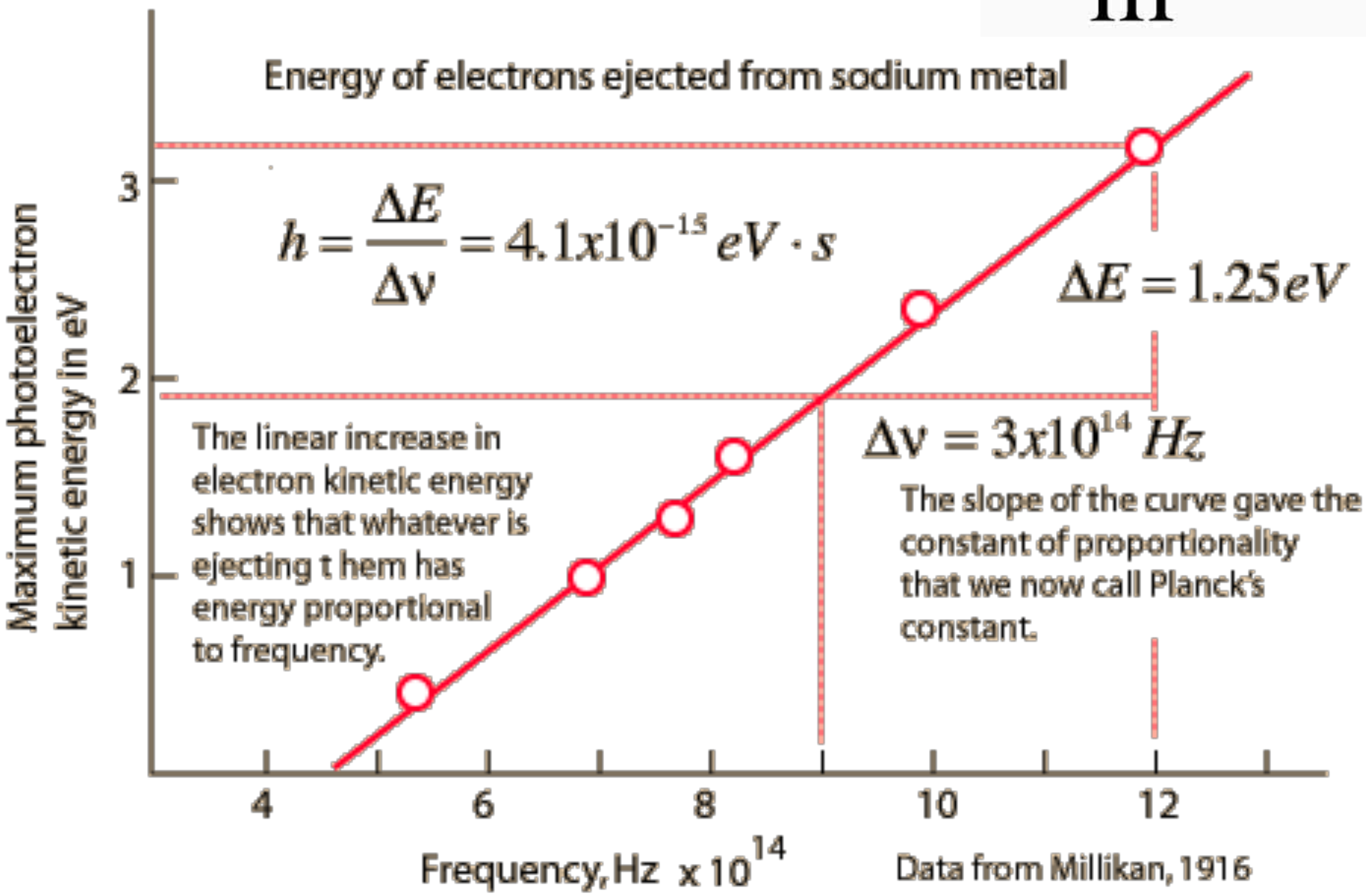


Photoelectric Effect

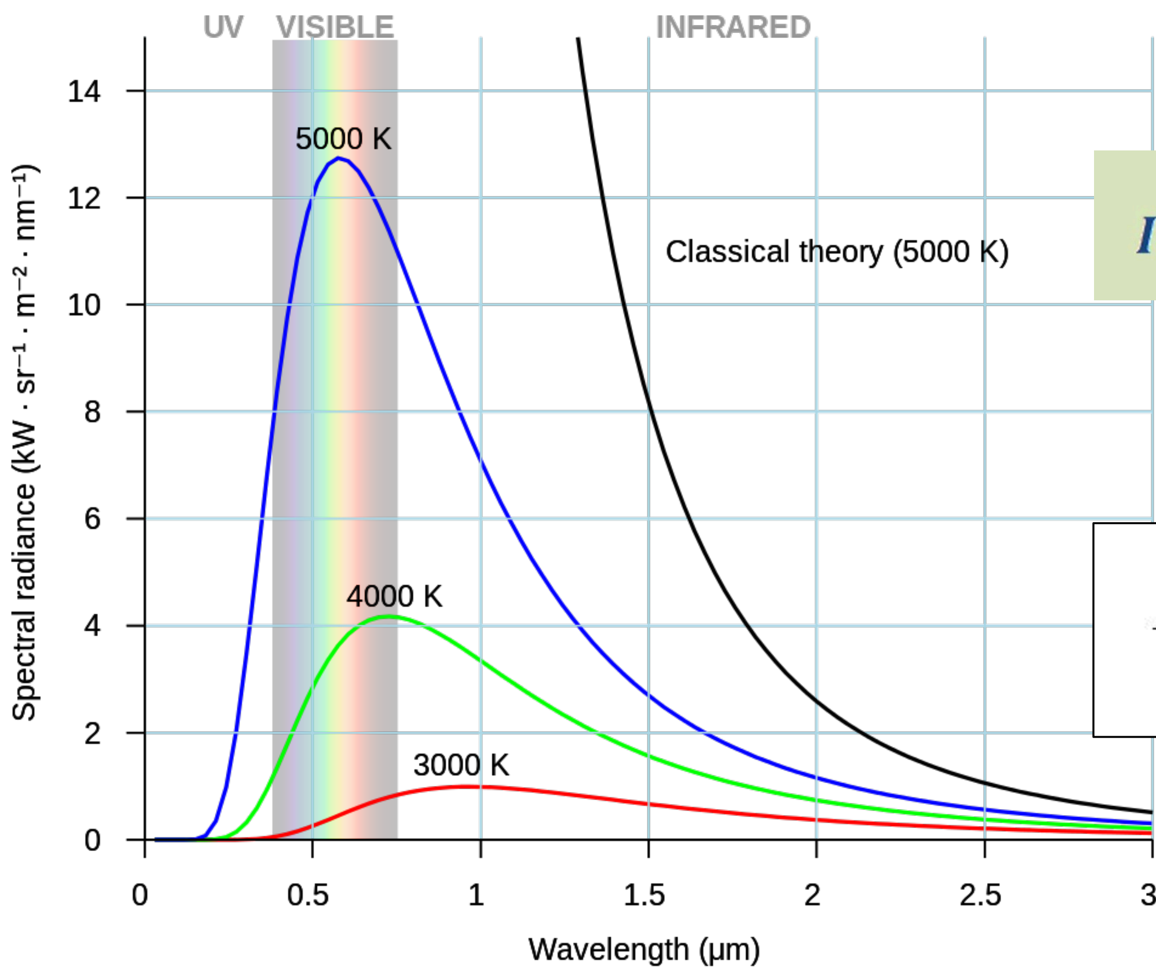


Photoelectric Effect

$$K_m = h\nu - \phi$$



Blackbody Radiation



$$I\left(\lambda, T\right) = \frac{2\pi . cK_bT}{\lambda^4}$$

$$I\left(\lambda,T\right) = \frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda k_B T} - 1\right)}$$

Particle-Like Properties of Light

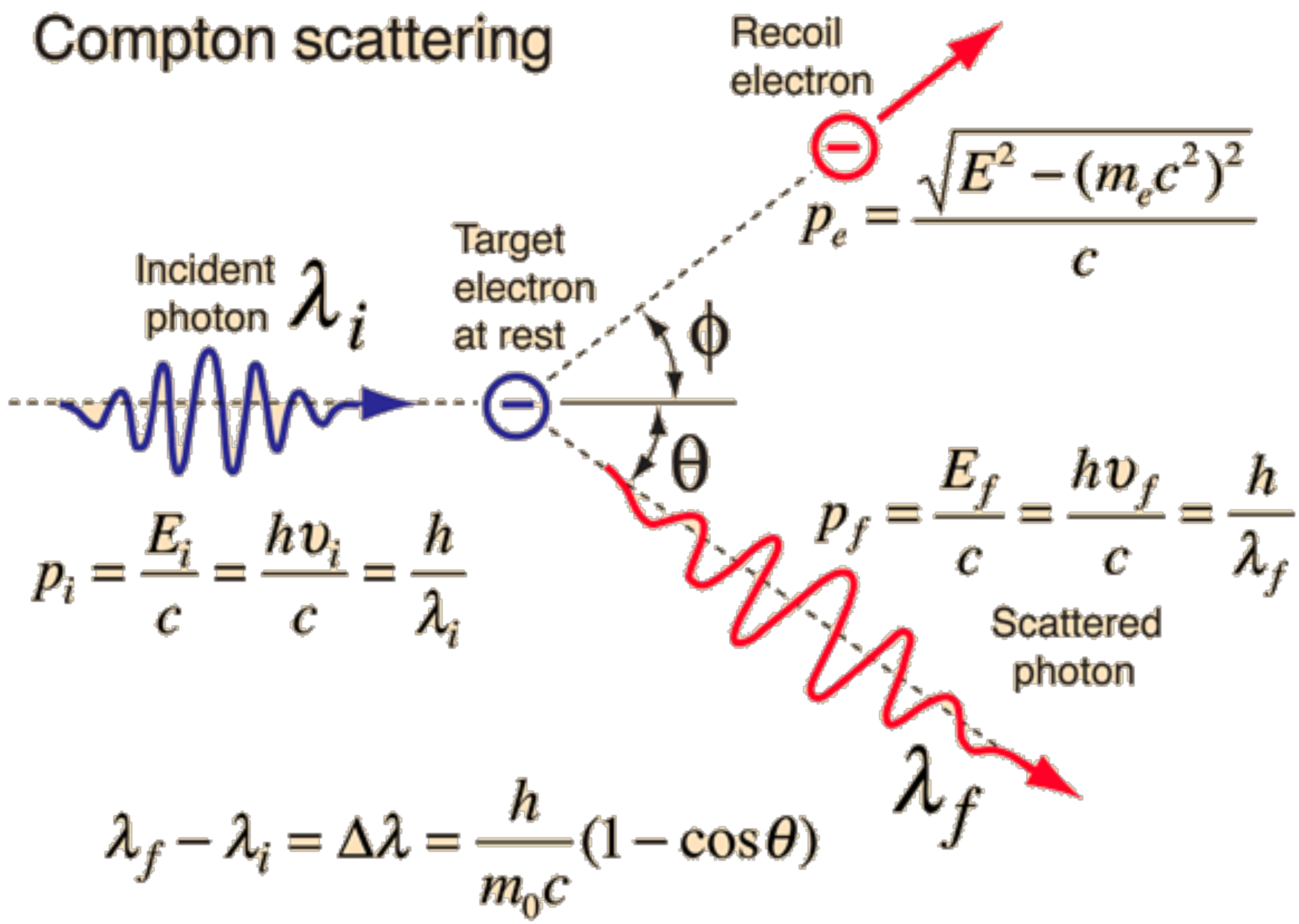
$$E = h\nu = h\frac{c}{\lambda}$$ = 1240 eV / λ(nm)

$$E^2 = \cancel{(mc^2)^2} + p^2c^2 \Rightarrow \boxed{p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}}$$

Alternatively:

$$\boxed{p = \frac{h}{2\pi}\frac{2\pi}{\lambda} = \hbar k}$$

Compton Scattering



Concept Check

- The Compton wavelength is $\lambda_c = h/(m_e c)$, and the energy of a photon is $E = hc/\lambda$. What is the energy of a photon with a wavelength $\lambda=\lambda_c$?

A. $E = m_e c^2$
B. $E = m_e/c$
C. $E = h^2/m_e$
D. Impossible to determine

Concept Check

- The Compton wavelength is $\lambda_c = h/(m_e\, c)$, and the energy of a photon is $E = hc/\lambda$. What is the energy of a photon with a wavelength $\lambda=\lambda_c$?

A. $E = m_e\, c^2$
B. $E = m_e/c$
C. $E = h^2/m_e$
D. Impossible to determine

Note:

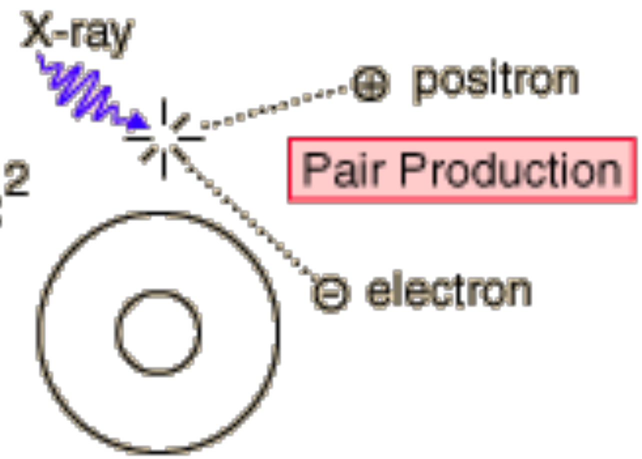
$m_e c^2$ = 511 keV
or ~500,000 eV

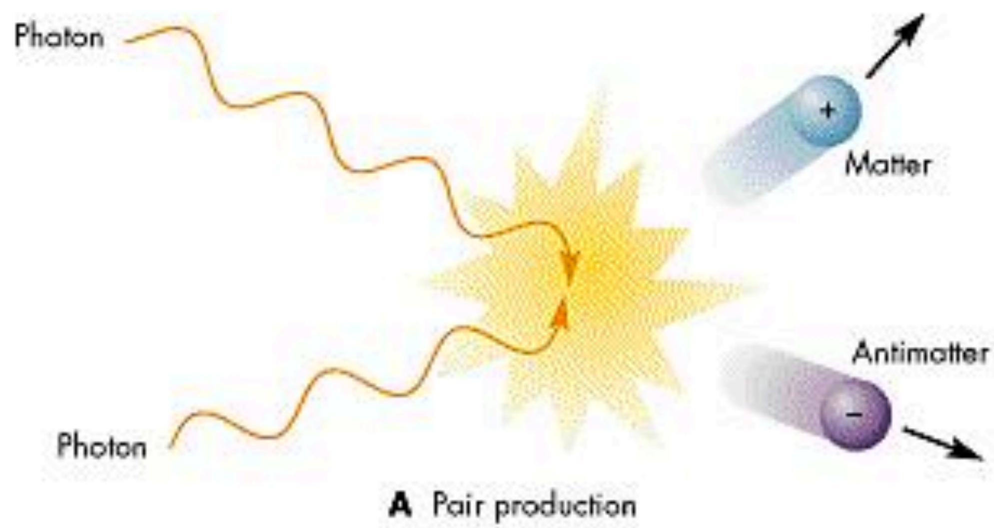
λ_c = 0.0024 nm

hc/λ = 1240 eV-nm/(λ in nm)

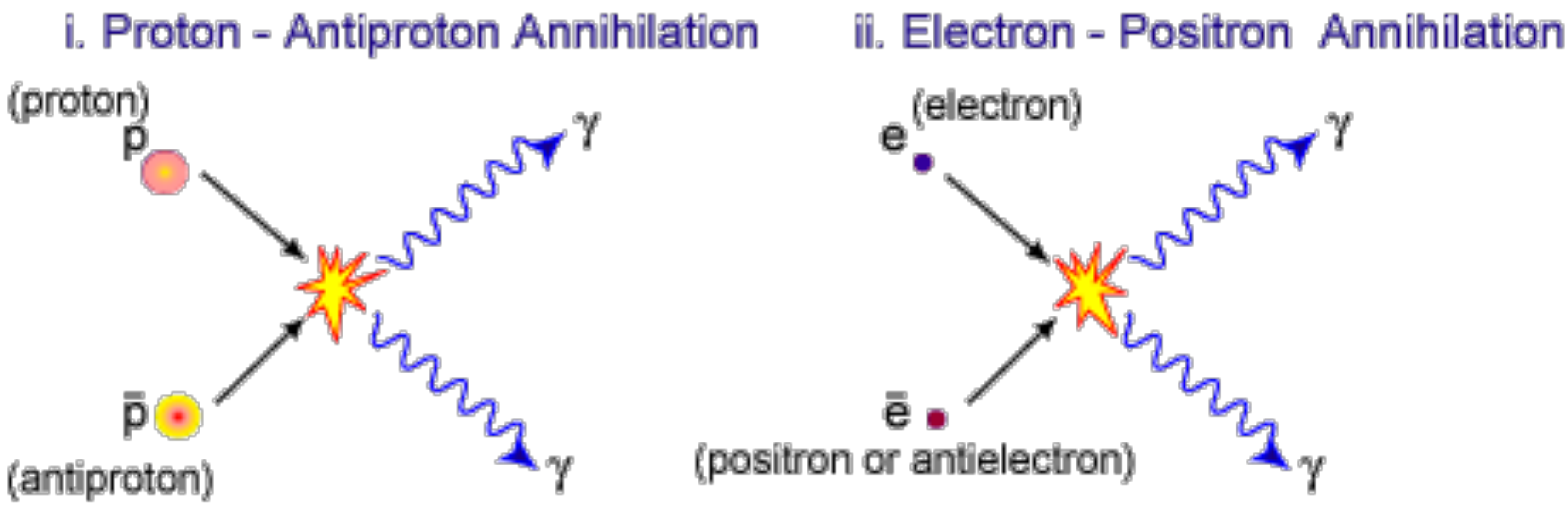
Pair Production

$$E_{threshold} = 2m_0c^2$$



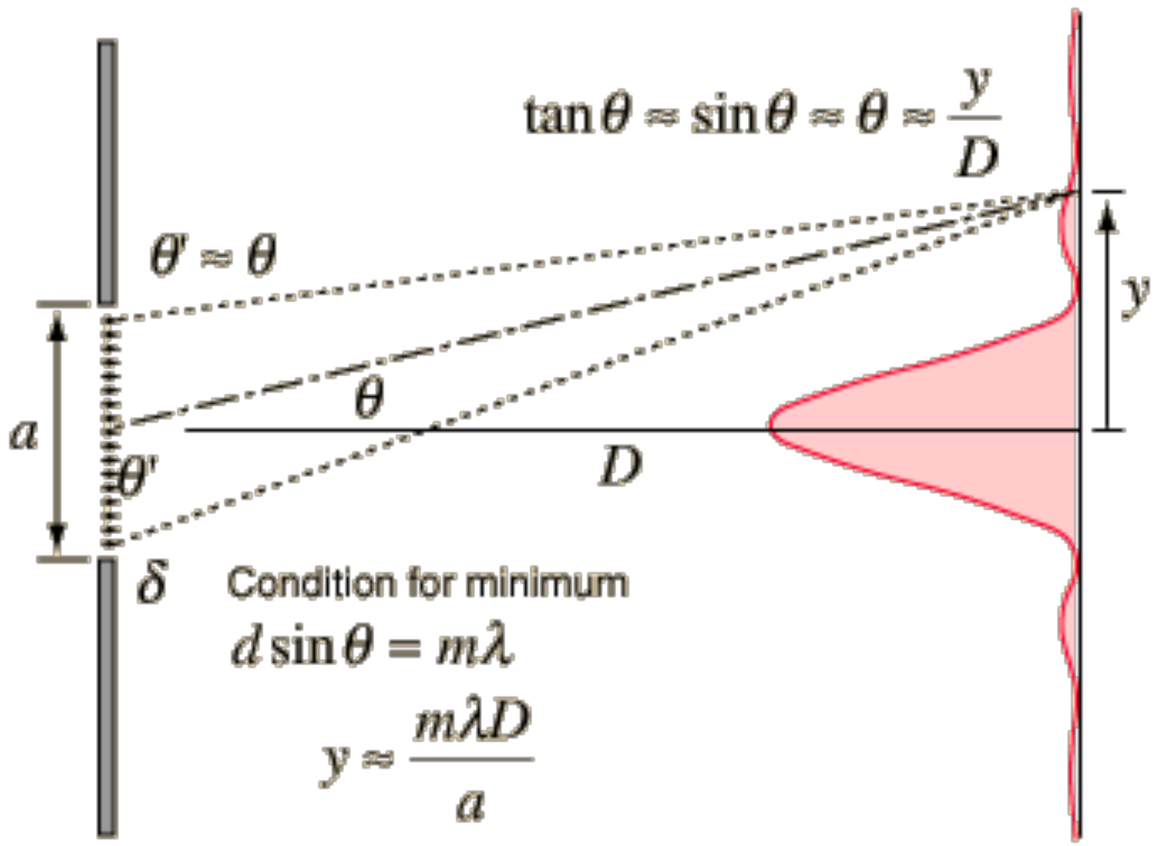


Pair Annihilation

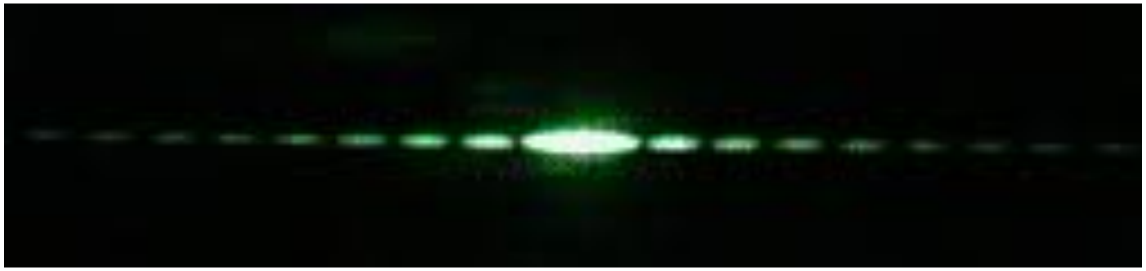


In each case the particle and its antiparticle annihilate each other, releasing a pair of high-energy gamma photons

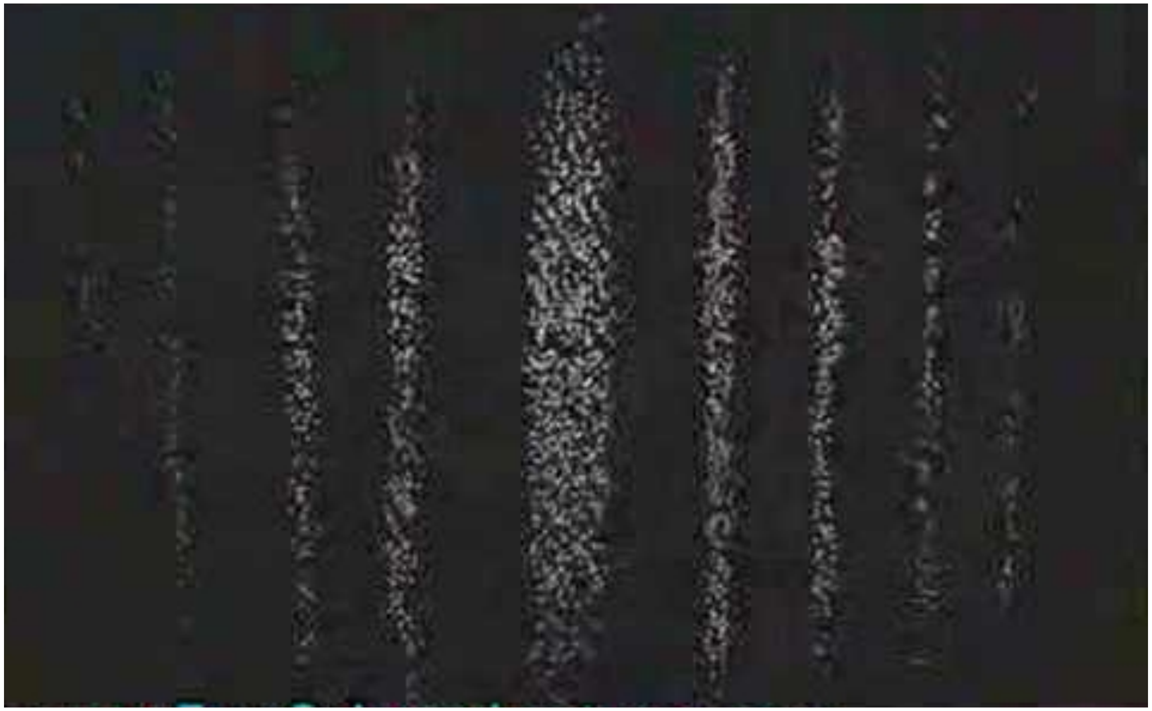
Diffraction



Diffraction: Photons vs. Electrons

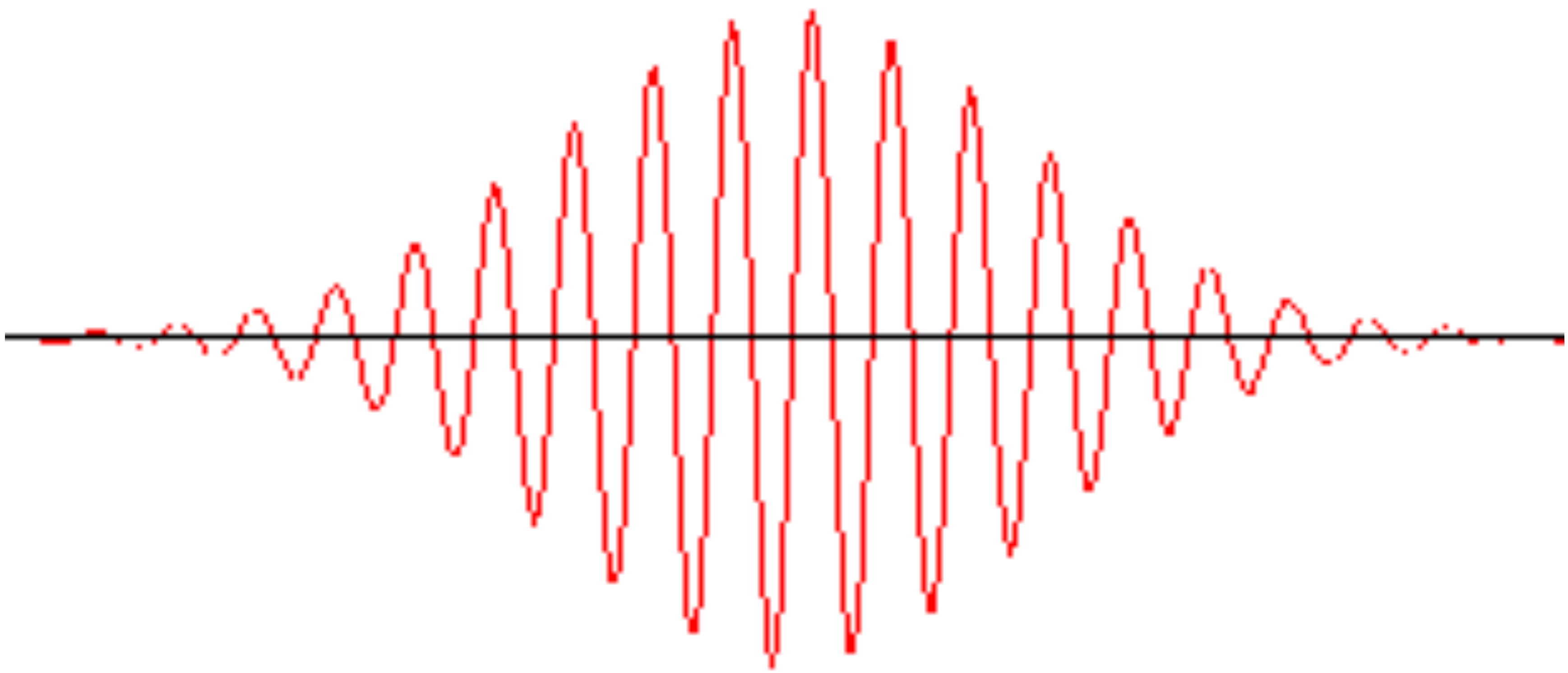


Photons



Electrons

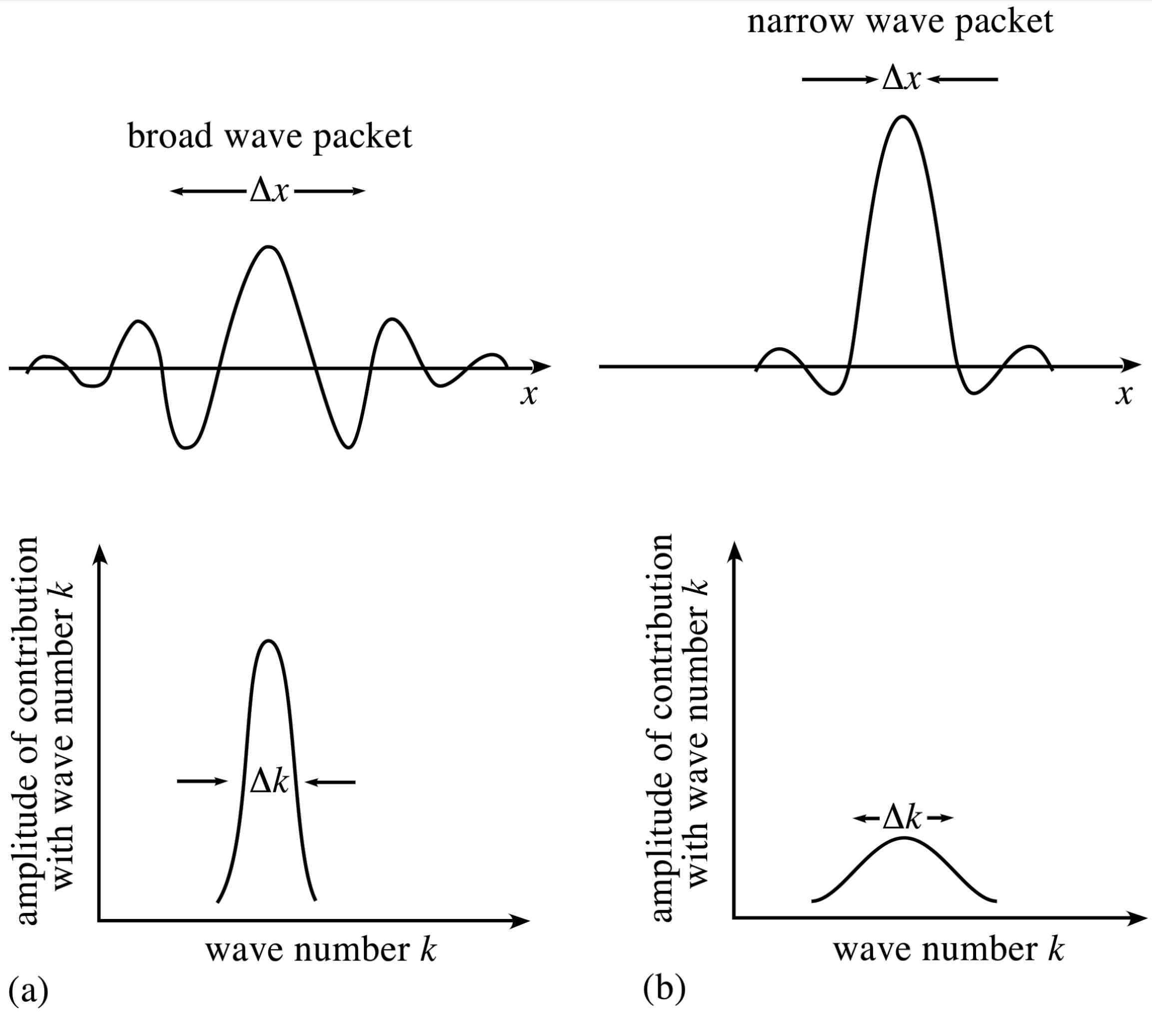
A particle is… a wave packet?



Heisenberg Uncertainty Principle

$$\Delta p \, \Delta x \geq \frac{1}{2} \hbar$$

$$\Delta E \, \Delta t \geq \frac{1}{2} \hbar$$



Concept Check

- If you measure the energy of an unstable particle, in which case would your energy measurement have more uncertainty?

A. A long-lived particle
B. A short-lived particle
C. The lifetime doesn't matter

Concept Check

- If you measure the energy of an unstable particle, in which case would your energy measurement have more uncertainty?

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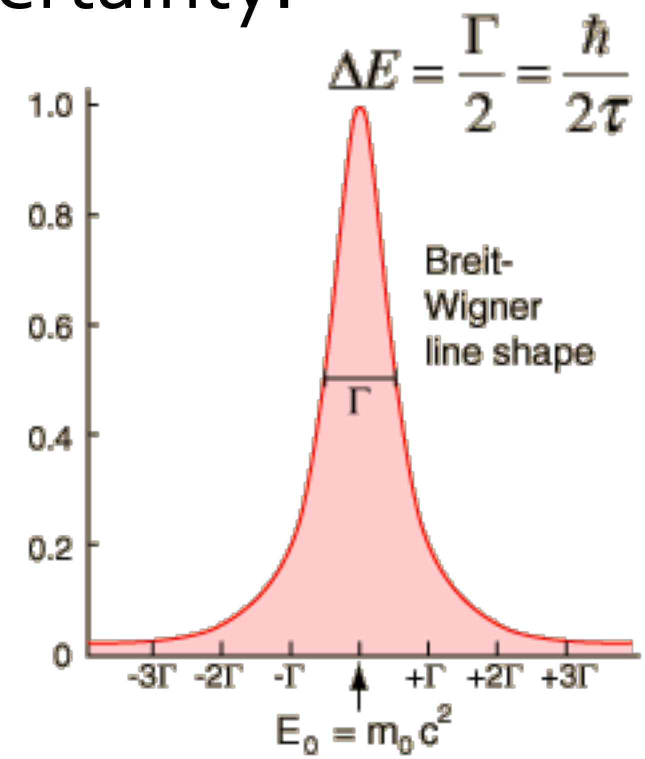

Phase and Group Velocity

Group velocity: $v_g = d\omega/dk$ = "Particle Velocity"

Phase velocity: $v_p = \frac{\omega}{k} = \lambda f$