Example:

$$\lambda_c = 1200\,\text{nm}, \quad NA = 0.12$$

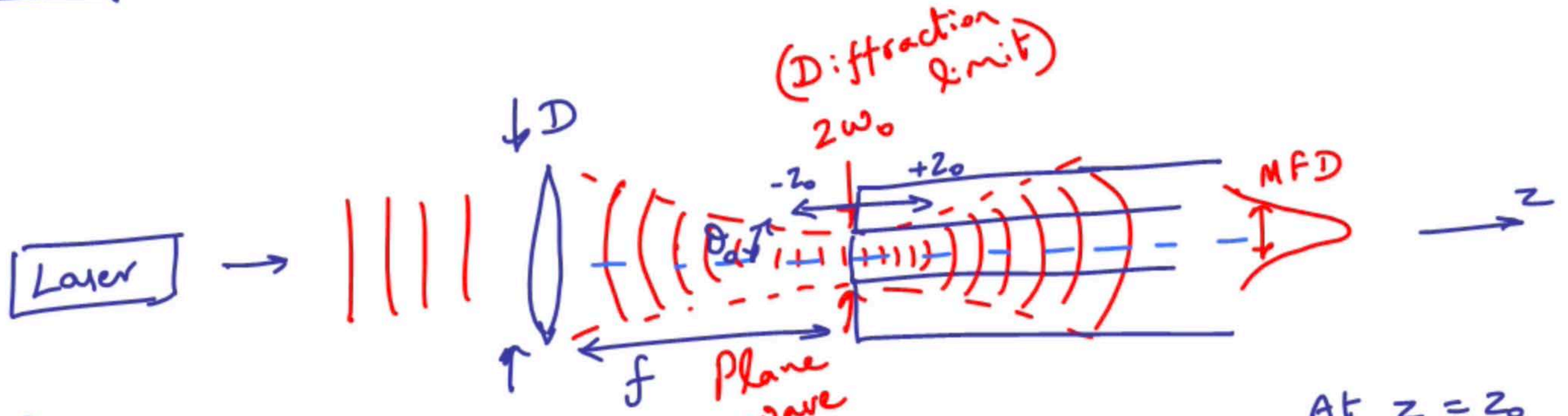
$$\downarrow$$

$$V = 2.405 = \frac{2\pi a}{\lambda} \times NA \quad \Rightarrow \quad 2a \simeq \underline{\underline{8\ \mu m}}$$

$$V_{1.5\mu m} = V_{1.2\mu m} \times \frac{1.2\times10^{-6}}{1.5\times10^{-6}} = 2.405 \times \frac{4}{5} = \underline{\underline{1.92}} \quad \text{(single mode)}$$

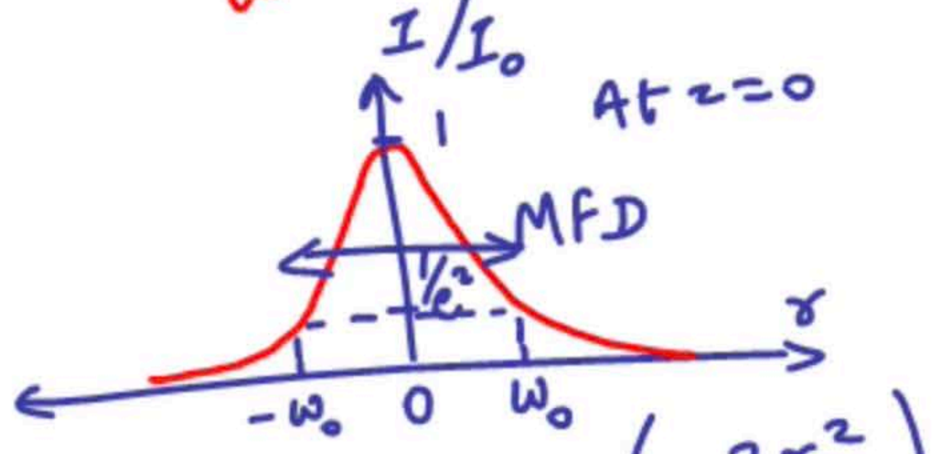
$$V_{0.65\mu m} = 2.405 \times \frac{1.2\times10^{-6}}{0.65\times10^{-6}} = \underline{\underline{4.44}} \quad \text{(slightly multimode)}$$

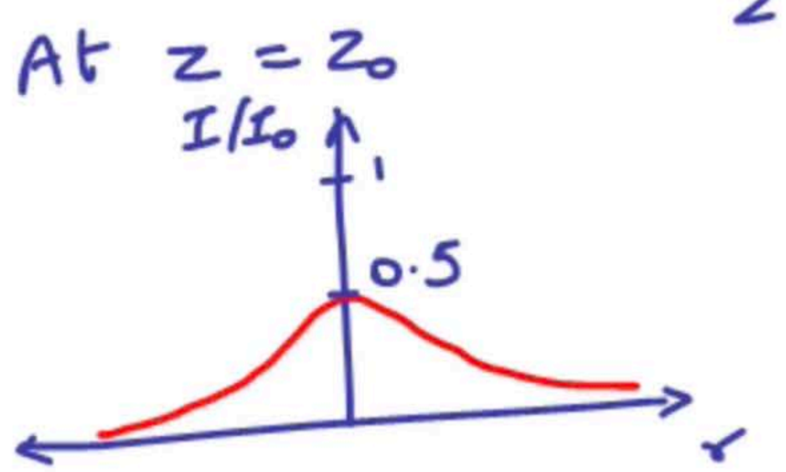
Coupling light into optical fiber:



Gaussian Beam

$2z_0 \rightarrow$ Rayleigh range





$$I = I_0 \exp\left(-\frac{2r^2}{w_0^2}\right)$$

Spot radius, $w_0 = \dfrac{\lambda}{\pi\theta_0} = 2\cdot\dfrac{\lambda f}{\pi D}$

$$\theta_0 = \frac{D/2}{f}$$

Spot diameter, $\boxed{2w_0 = 4\cdot\dfrac{\lambda f}{\pi D}}$

Learning Outcome: Identify the fundamental principles of photon optics & quantify photon properties

$$\nabla \cdot \vec{D} = \rho_v$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{H} = \vec{J}_c + \frac{\partial \vec{D}}{\partial t}$$

$$\vec{D} = \epsilon \vec{E}$$
$$\vec{B} = \mu \vec{H}$$

* Light as electromagnetic waves

- satisfy Maxwell's equ.

- represented by wave equ.

$$\nabla^2 \vec{E} + k^2 \vec{E} = 0 \qquad \nabla^2 \vec{H} + k^2 \vec{H} = 0$$

For a plane EM wave propagating in +z direction

$$\vec{E} = \left(\hat{a}_x E_x + \hat{a}_y E_y e^{j\phi}\right) e^{-jkz}$$

If $\phi = 0 \Rightarrow$ linear polarization

If $\phi = \pm \pi/2 \Rightarrow$ circular polarization
$E_x = E_y$

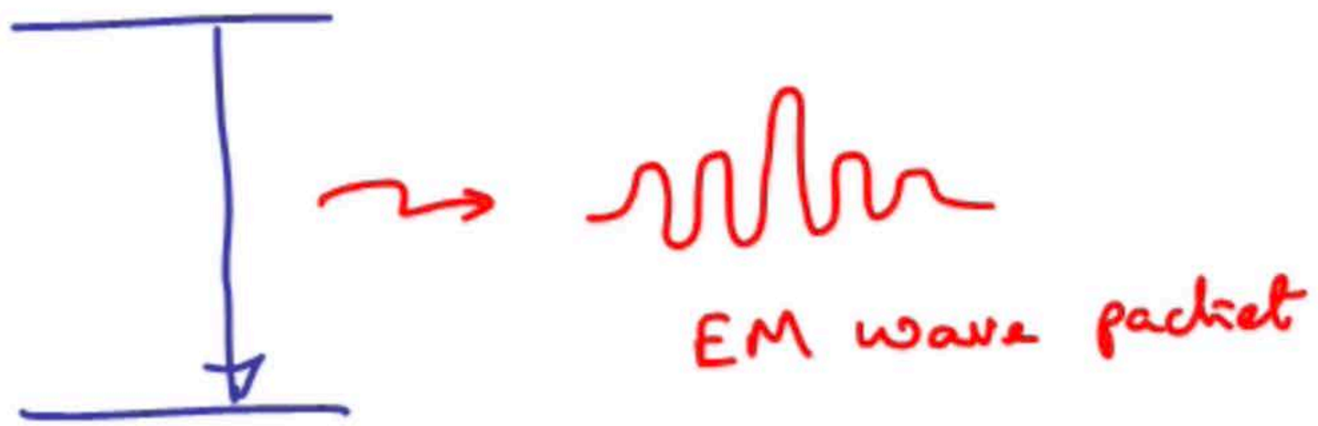
Any other $\Rightarrow$ Elliptical polarization

* For a given structure, only specific field configurations are allowed

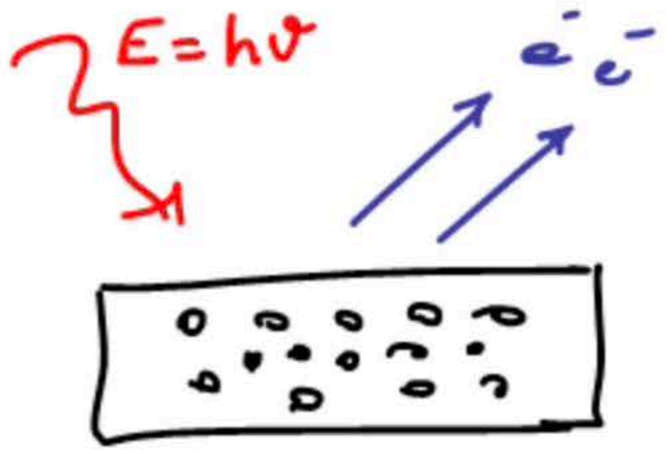
$\Rightarrow$ Eigenmodes or Modes of the structure

Photon Optics:

* Planck, 1900 → black-body radiation
  → quantized wave packets



* Einstein, 1905 → $E = h\nu$
  - Planck's const.
  - Frequency

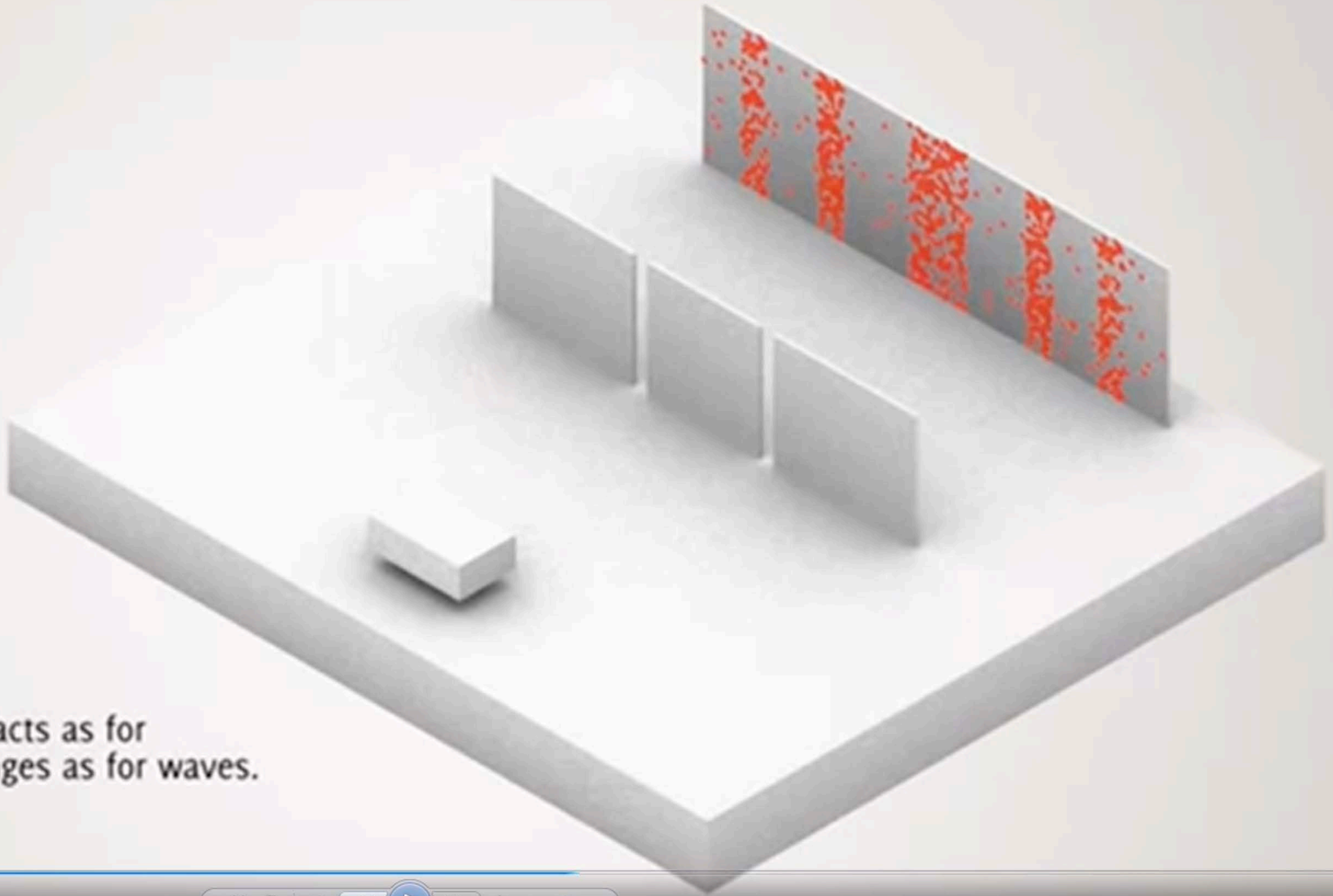


Photoelectric emission

WAVE
PARTICLE DUALITY

- particle
- wave
- quantum object
- add an observer

At the end, one observes impacts as for particles, and interference fringes as for waves.



01:07

Photon Optics:

* Planck, 1900 → black-body radiation

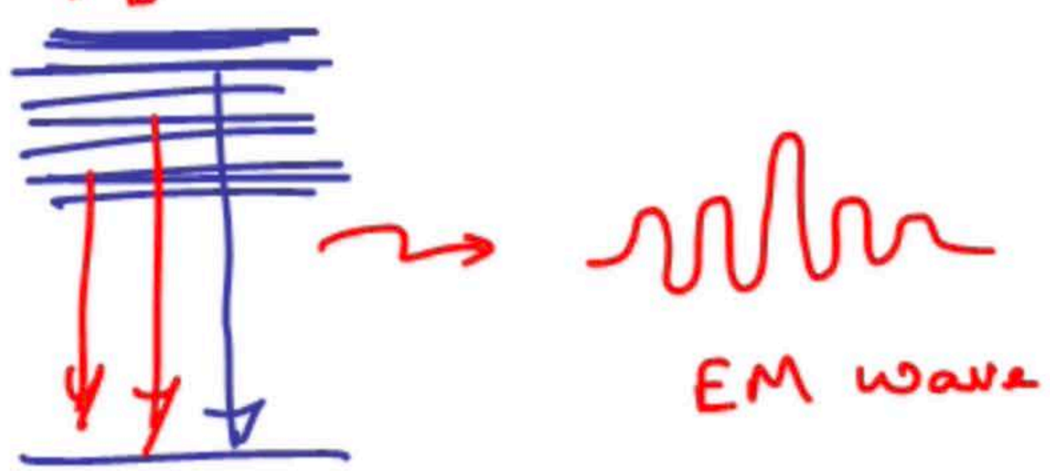
→ quantized wave packets

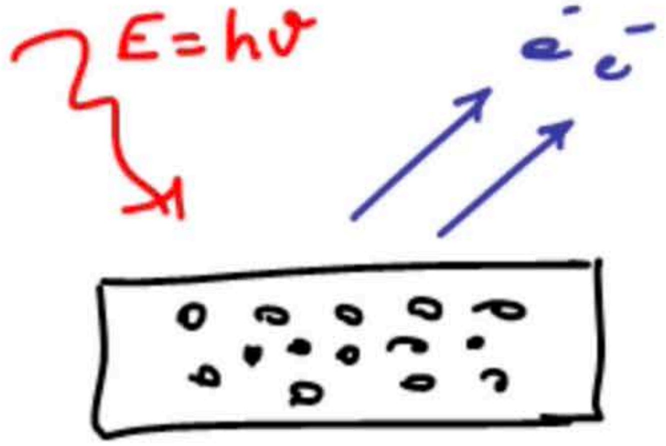
* Einstein, 1905 → $E = h\nu$

h: Planck's const.

ν: Frequency

Exhibits Wave-particle duality





Photoelectric emission

Photon Optics

$$E = h\nu = \frac{hc}{\lambda}$$

$h = 6.63 \times 10^{-34}$ J-s

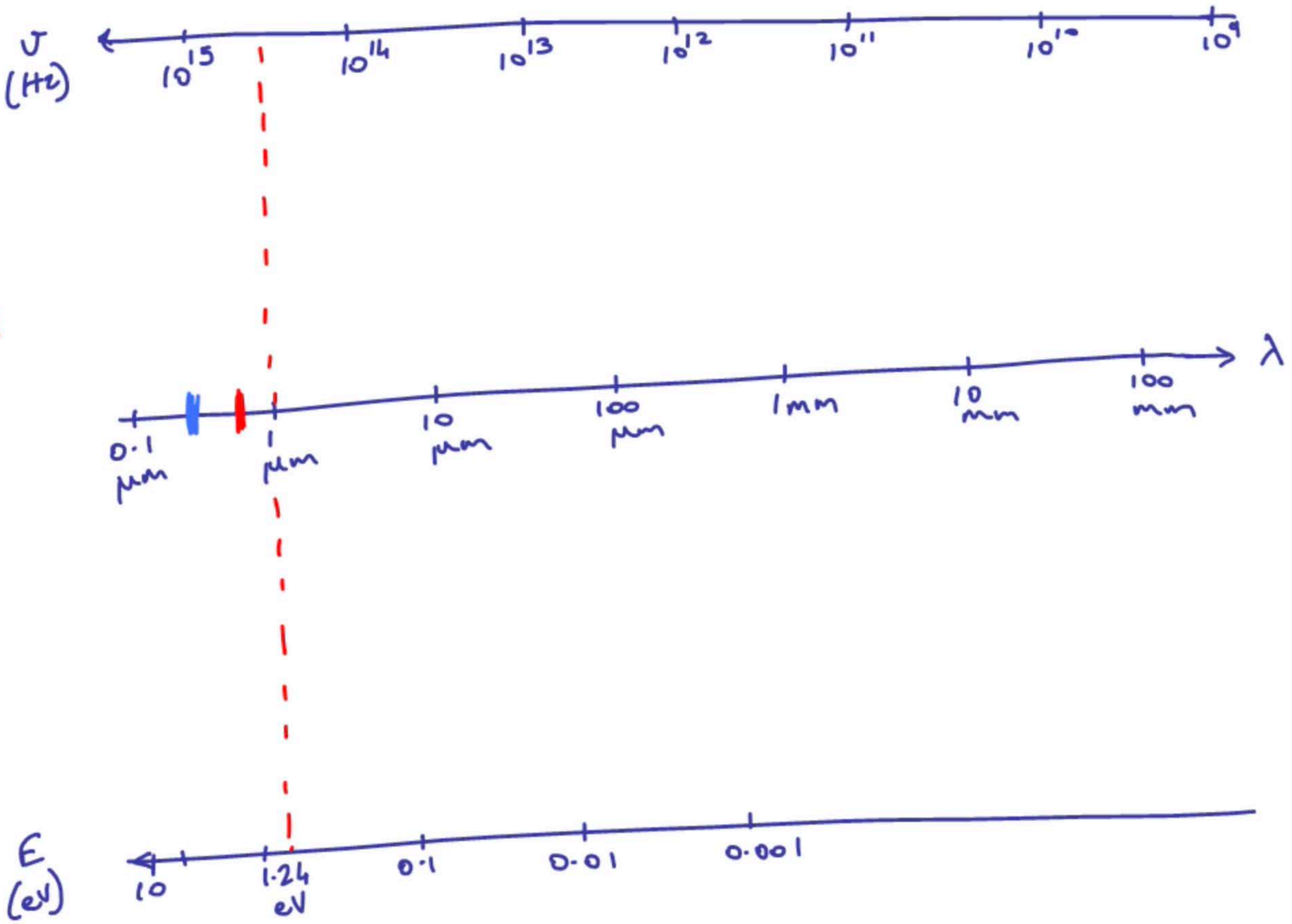
$c = 3 \times 10^{8}$ m/s

$1 \text{eV} = 1.602 \times 10^{-19}$ J

Wavelength (μm), $\lambda = \dfrac{1.24}{E(\text{eV})}$

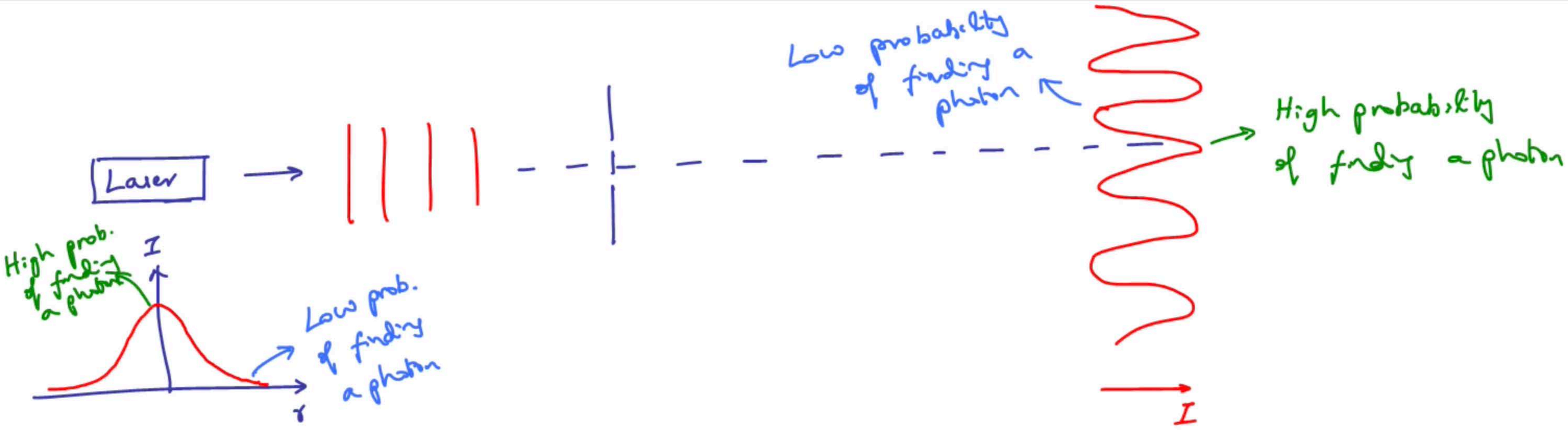
Photons have zero rest mass

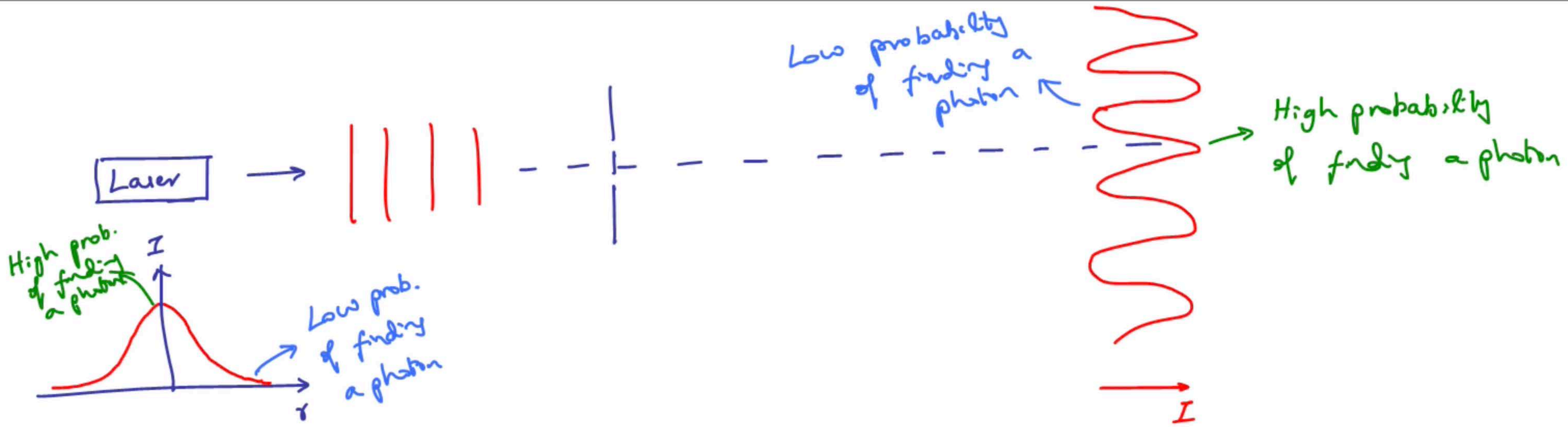
Photon momentum, $p = \dfrac{E}{c} = \dfrac{h}{\lambda} = \hbar k$ $\quad \hbar = h/2\pi$

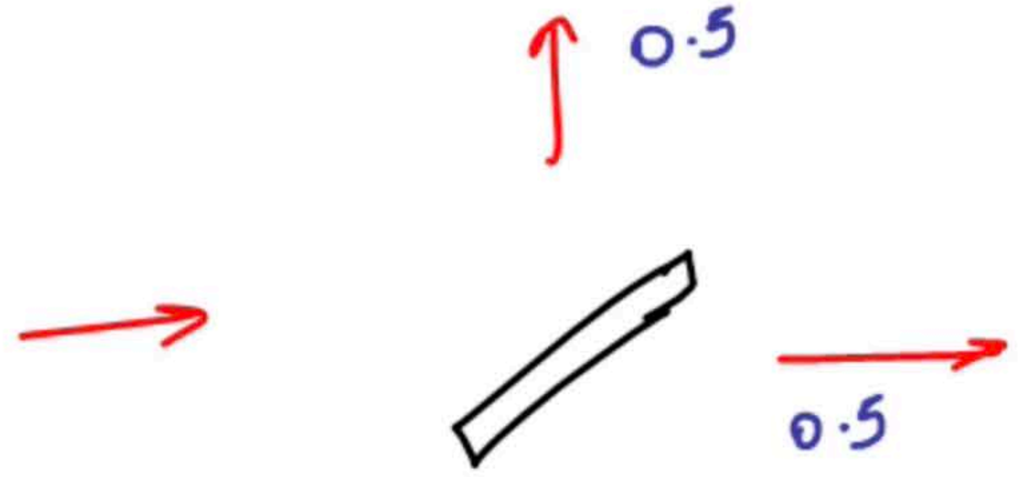


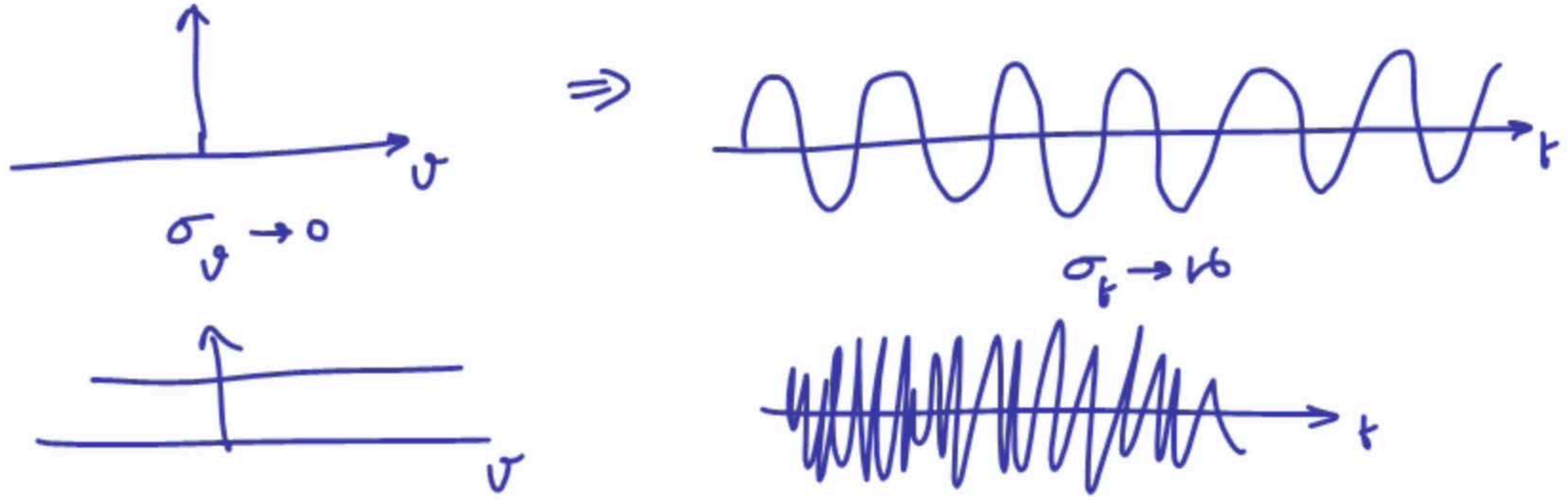
Photon probability

$$p(r)\, dA \propto I(r)\, dA$$


Laser
Low probability of finding a photon
High probability of finding a photon
I
High prob. of finding a photon
Low prob. of finding a photon
r







Photon uncertainty

$$\boxed{\sigma_E \cdot \sigma_t \geq \frac{\hbar}{2}}$$