Wave-particle duality of light

Light as a wave $\vec{E} = \vec{E}_0 \cos(kx - \omega t + \varphi)$

Wave properties
frequency ω, phase φ
wave vector $\vec{k}$ (propagation direction)
amplitude $|\vec{E}_0|$, intensity (energy flow)
$I = \frac{c\varepsilon_0}{2} |E_0|^2$

Polarization $\vec{E}_0 / |\vec{E}_0|$

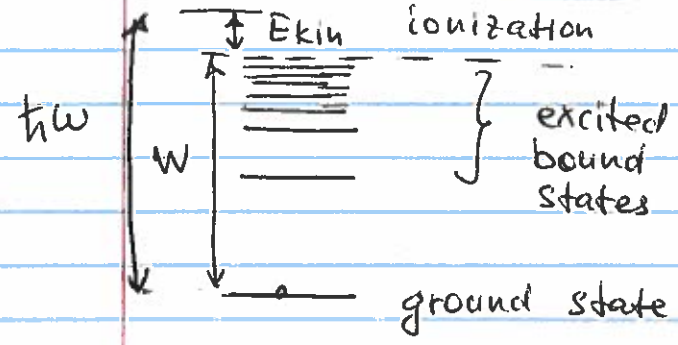
What parameters we use to describe the motion of a particle

position
velocity $\vec{v}$ or momentum $m\vec{v}$
~~etc~~ (kinetic) energy

Light propagates as a wave, but gets detected as a particle, in quantized bunches of energy

Single photon energy $\hbar\omega$
Single photon momentum $\hbar\vec{k}$

Many photon / light detectors are based on photoelectric effect:
A bound electron absorbs a photon, and it gives it enough energy to break the bond and become free



W - amount of energy electron needs to escape (generally called "work function")

Electron ~~gained~~ $\hbar\omega = W + E_{kin}$
Kinetic energy of the released photons

$E_{kin} = \hbar\omega - W$ depends of light freqiuency, not intensity

Einstein received his Nobel prize for explaining of the photoelectric effect as confirmation quantum theory

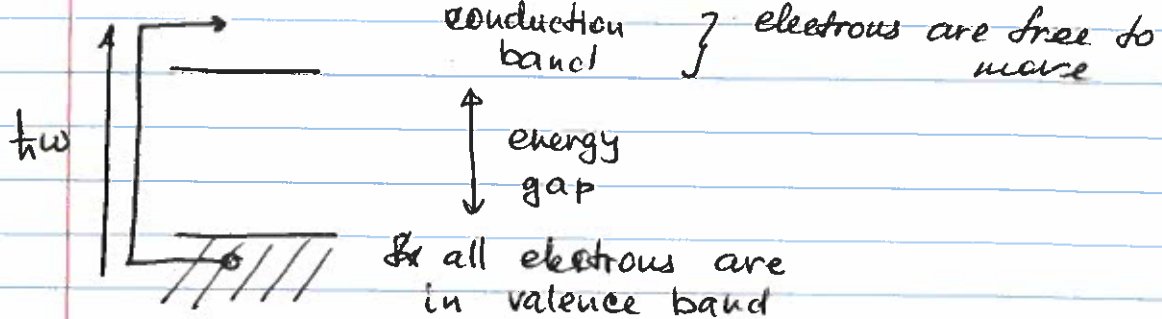
N photons/s → W electrons/s (ideally)

Electric current $I = N \cdot e$
proportional to the number of ~~electrons~~ photons

Quantum efficiency (QE) $= \frac{\#\text{ of emitted electrons}}{\#\text{ of incoming photons}}$

"classical" photodetectors

Photodiodes (semiconductor materials)



A photon, when absorbed, promotes an electron in a conduction band, producing electric current proportional to the # of photons
Different materials have different bandgap and work for different spectral region

Silicon : visible (0.4-0.9 μm) high QE
In-doped silicone : visible + near UV (0.2-0.8 μm)
Germanium : near-IR (1-2 μm)

Many photons produce many electrons, and we can use conventional electronics to measure the photocurrent and convert it into the light power/intensity/energy

Energy of one green photon ($\lambda = 500nm$)

$$E = \frac{2\pi\hbar c}{\lambda} \approx 4 \cdot 10^{-19} J$$

A weak laser pointer $1mW = 10^{-3}\frac{J}{s} = 2.5 \cdot 10^{15}\frac{photons}{sec}$

Single-photon detectors

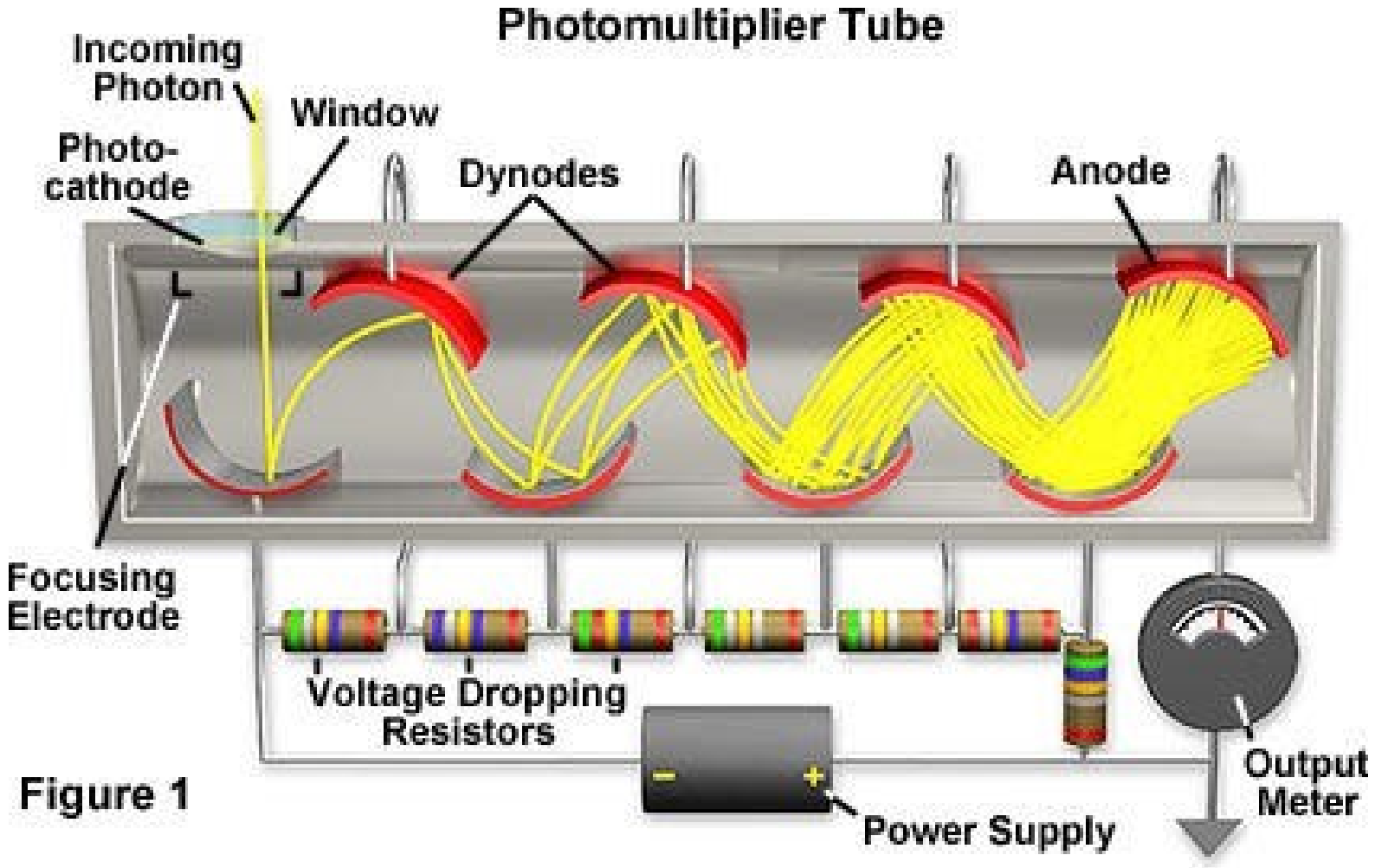
Main challenge - dark noise, there will be some thermally-induced electrons even in the absence of light. That is why most single-photon detectors or cameras are cooled, often to very low temperatures

Photomultipliers / Avalanch photodetectors

One photon produces an electron that kicks off an avalanch, producing a sizable voltage spike that can be measured using standard equipment.

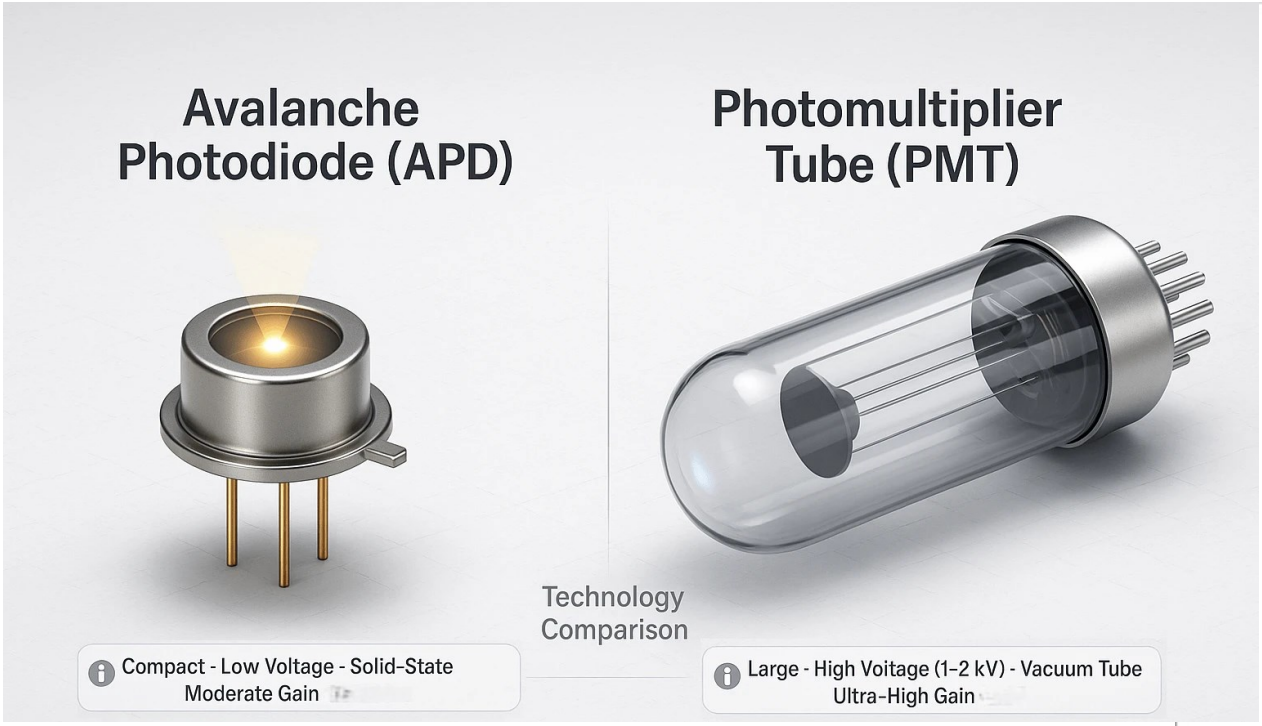
Draw backs - low quantum efficiency
- ~~tang~~ unpredictable amplitude of the final pulse - lack of # of photon information.

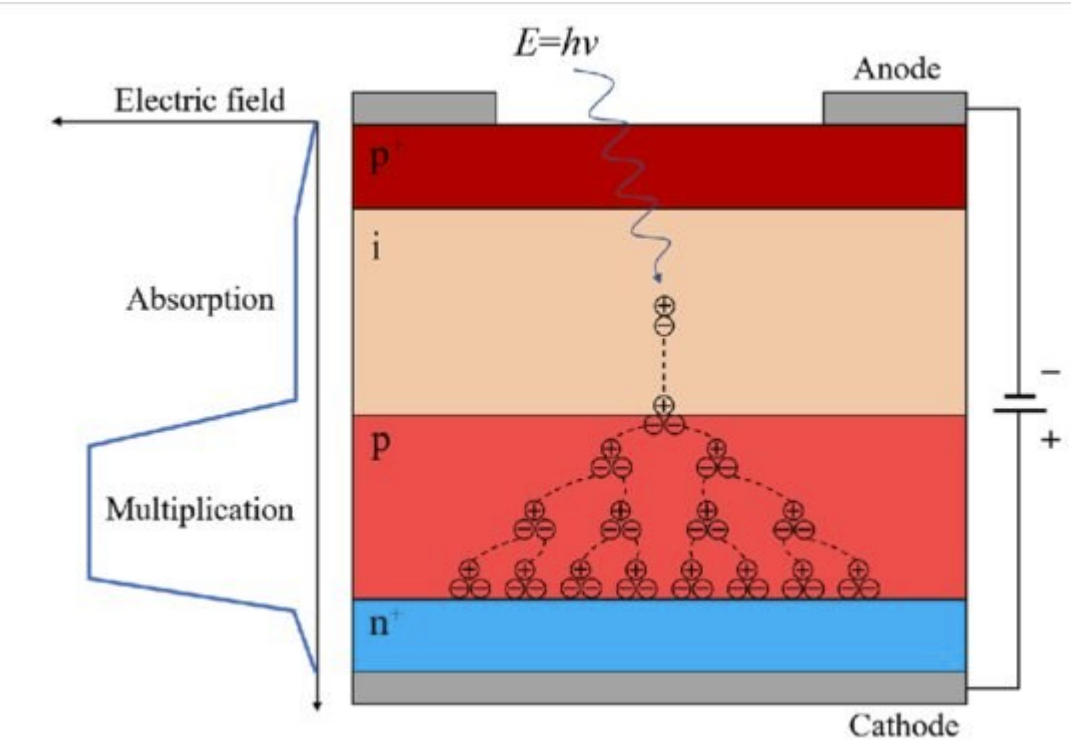
Traditional single-photon detectors: PMT



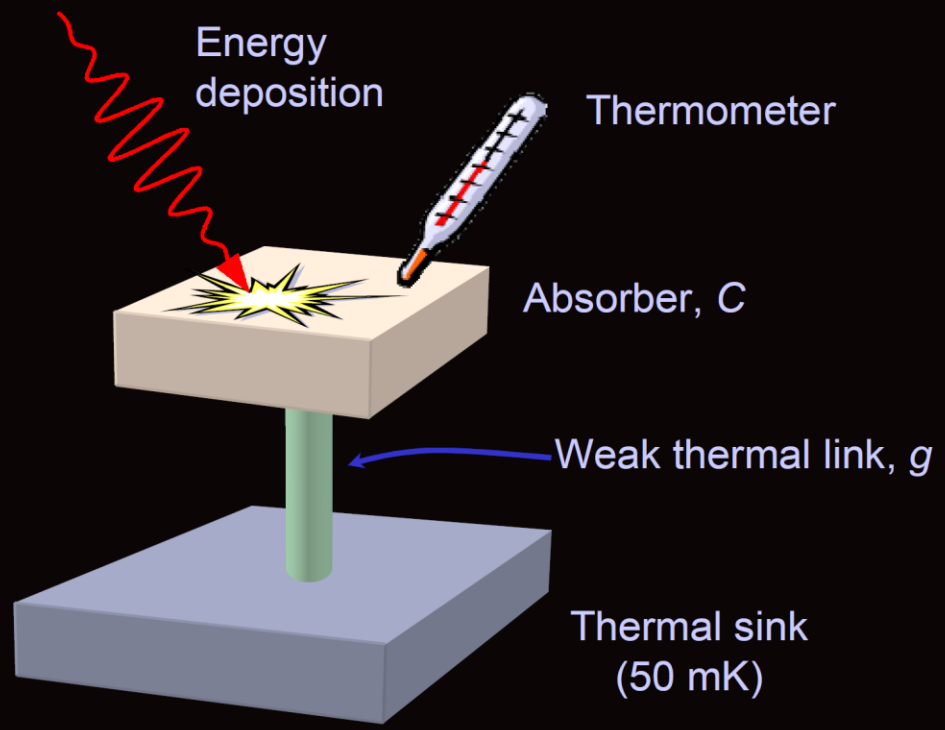
https://evidentscientific.com/en/microscope-resource/knowledge-hub/digitalimaging/concepts/photomultipliers

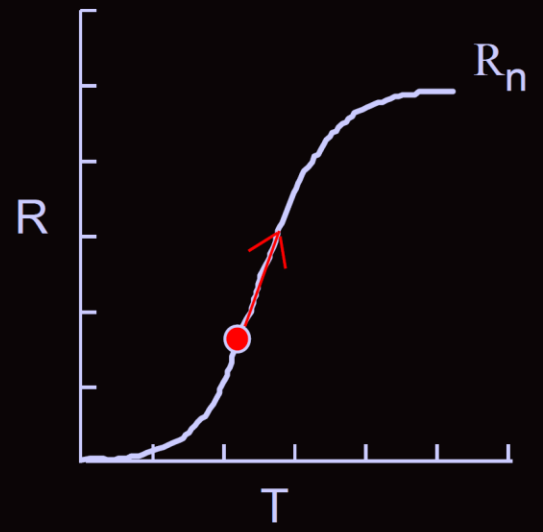
Traditional single-photon detectors: APD





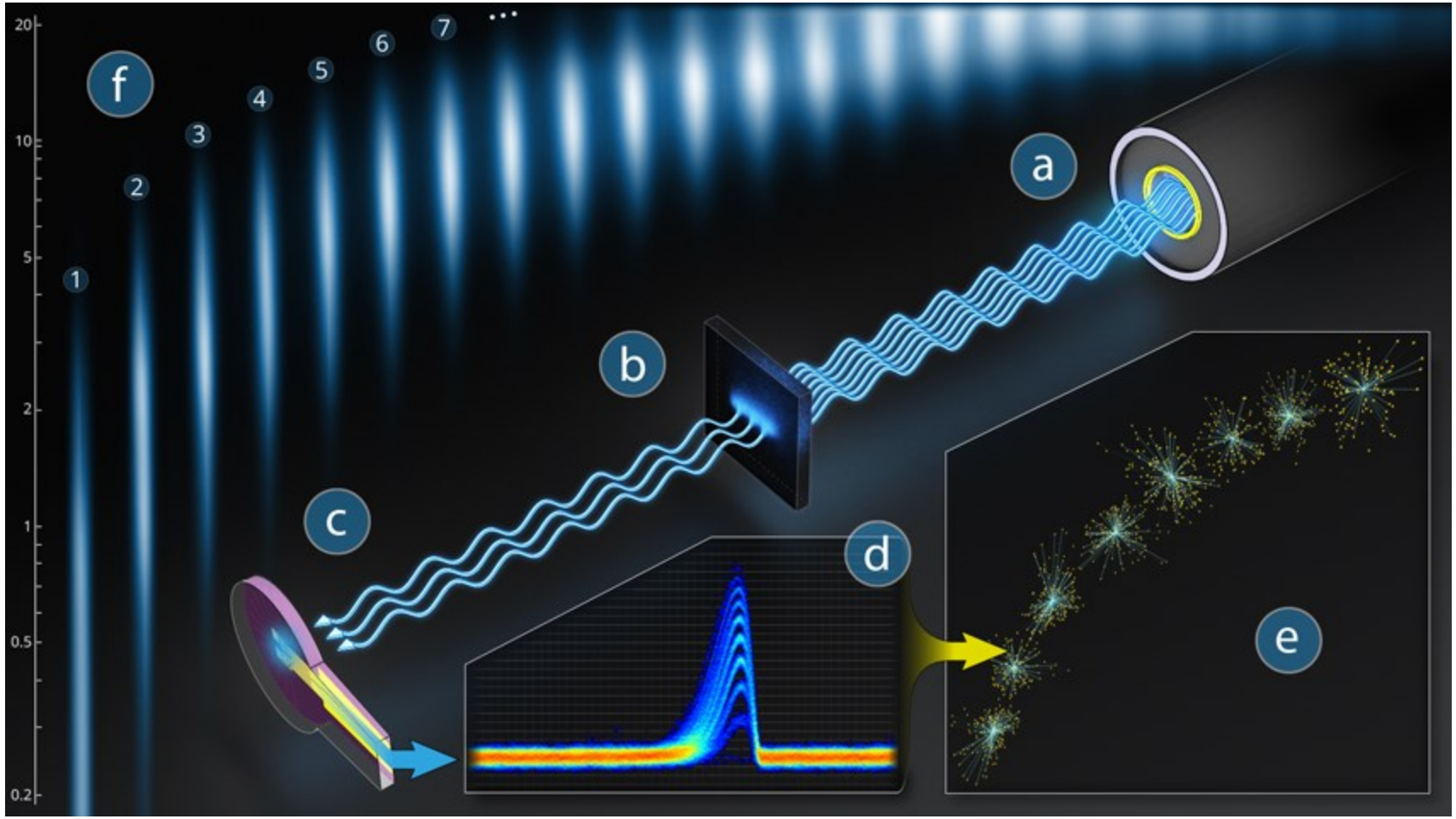
Transition Edge Sensor (TES)





- Calorimetric detection of UV/optical/IR photons:
- Temperatures are ~100 mK to ensure low noise and high sensitivity.
- Absorber and thermometer are the same (superconducting W thin film)
- Microfabrication techniques

Transition edge sensor (TES)



Light from a pulsed laser (a) is directed through a variable attenuator (b) onto a transition edge sensor device (c). The resulting signal (d) is analyzed with a statistical clustering algorithm (e) which returns a nominal photon number (f).

Transition edge sensor (TES)

