# Detectors

**RIT Course Number 1051-465**
**Lecture Single Element Detectors**

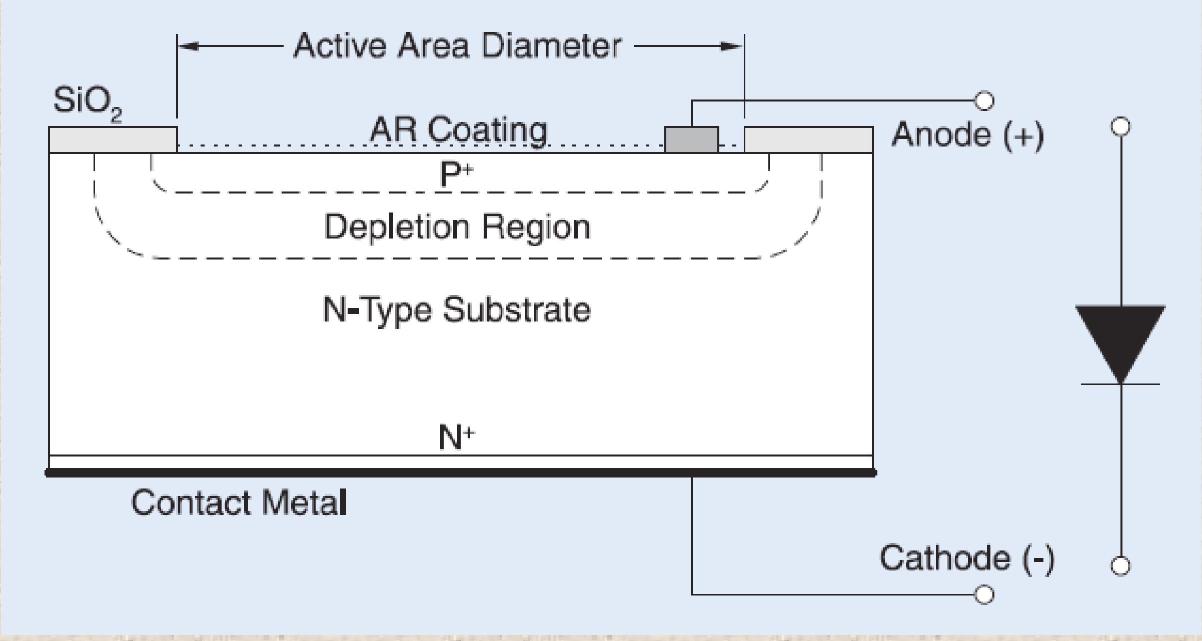
# Aims for this lecture

- review common single element detectors
  - photodiode
  - bolometer
  - photomultiplier tube
- learn a broader range of semiconductor materials
- demonstrate early use in Galactic center research

# **Photodiode**

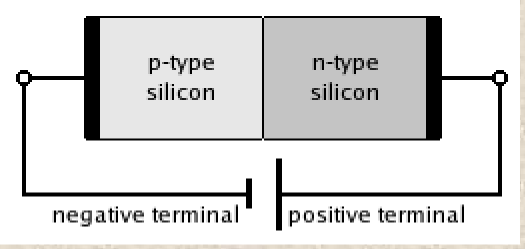
# Definition of Photodiode

- A photodiode is a diode that responds to light. It differs from a regular diode primarily in construction, i.e. it must have a mechanism for coupling to light.
- A photodiode generates current as a function of the intensity of absorbed light.
- Photodiodes can be used as light measuring devices or energy conversion devices.



# Photodiode Principles of Operation

- A pn junction is reverse biased in order to enhance the width of the depletion region, and thereby reduce the capacitance. Recall that:




$$C = \frac{\kappa \varepsilon_0 A}{d}, \text{ where}$$

$\kappa$ = dielectric constant,

$\varepsilon_0$ = permittivity of free space,

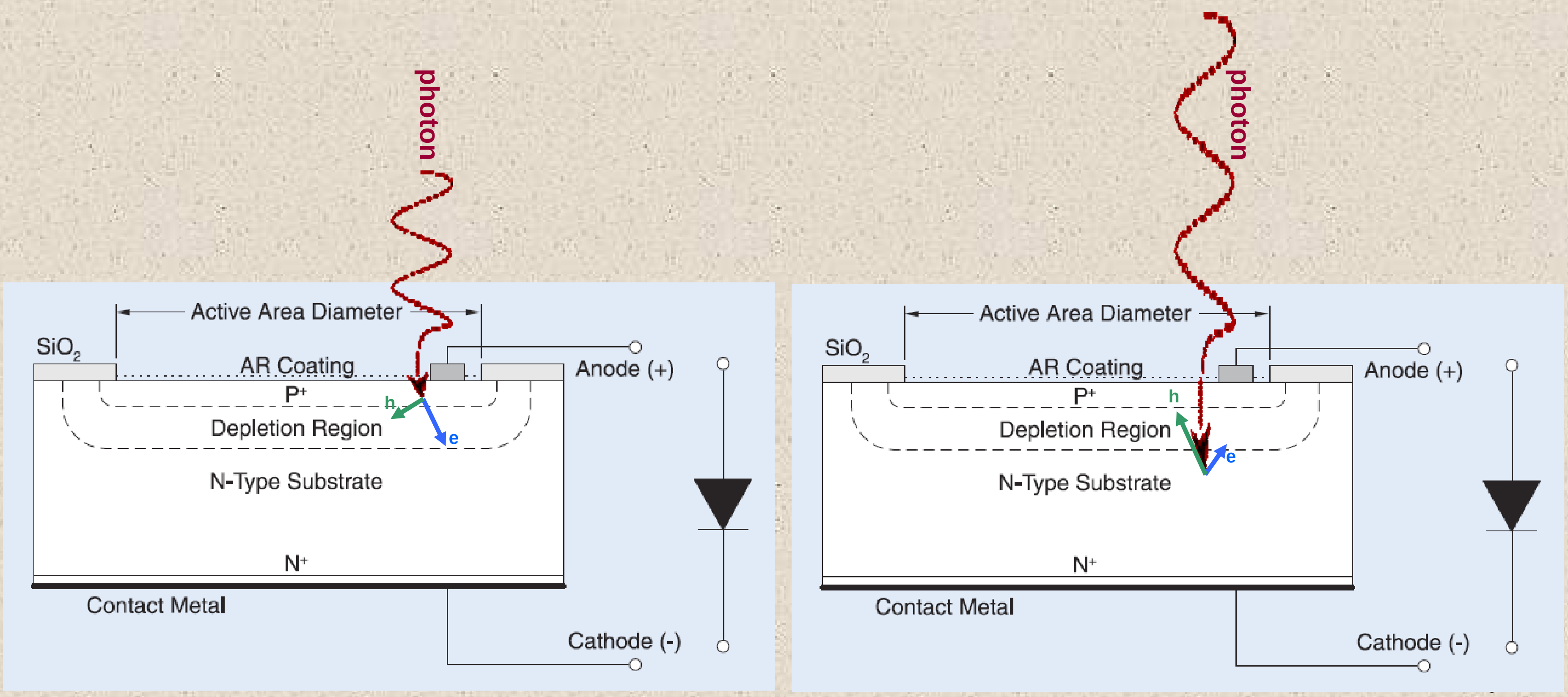
A = area of capacitor, and

d = distance between plates of capacitor.

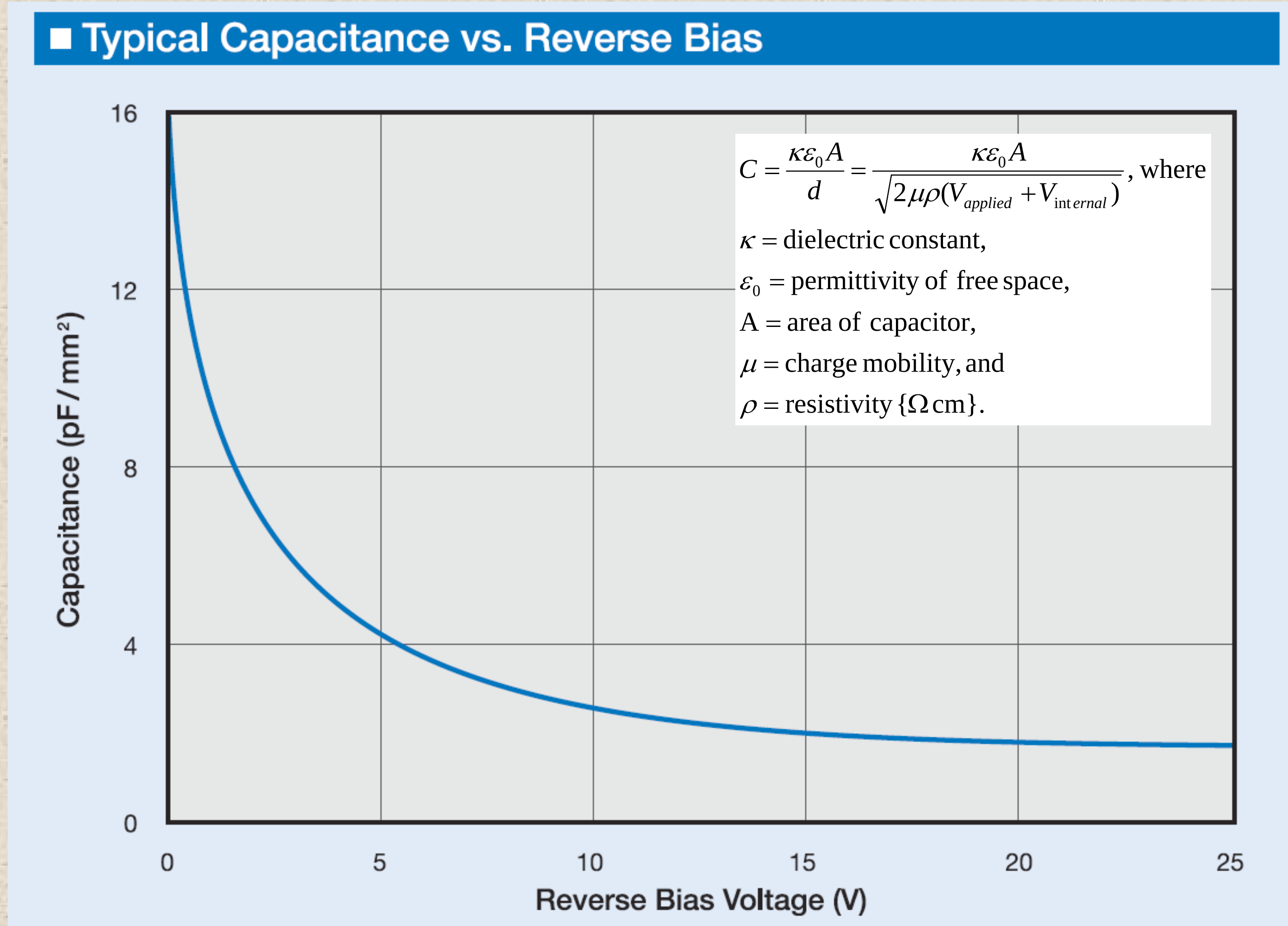
- Photons of sufficient energy ($E > E_{bandgap}$) are absorbed and generate photogenerated electron-hole pairs.
- The charge flows across the depletion region and recombines, thereby reducing the voltage difference across the depletion region by a small amount.
- The reduction in voltage can be sensed as an indication that light has been absorbed.

# Photon Absorption in Photodiode

- A photon will be absorbed at a depth that depends on its wavelength.
- As long as the absorption is near enough to the depletion region, the photogenerated charge (eh pair) will contribute electrons to the n-side and holes to the p-side.



# C vs. Reverse Bias



# Penetration Depth

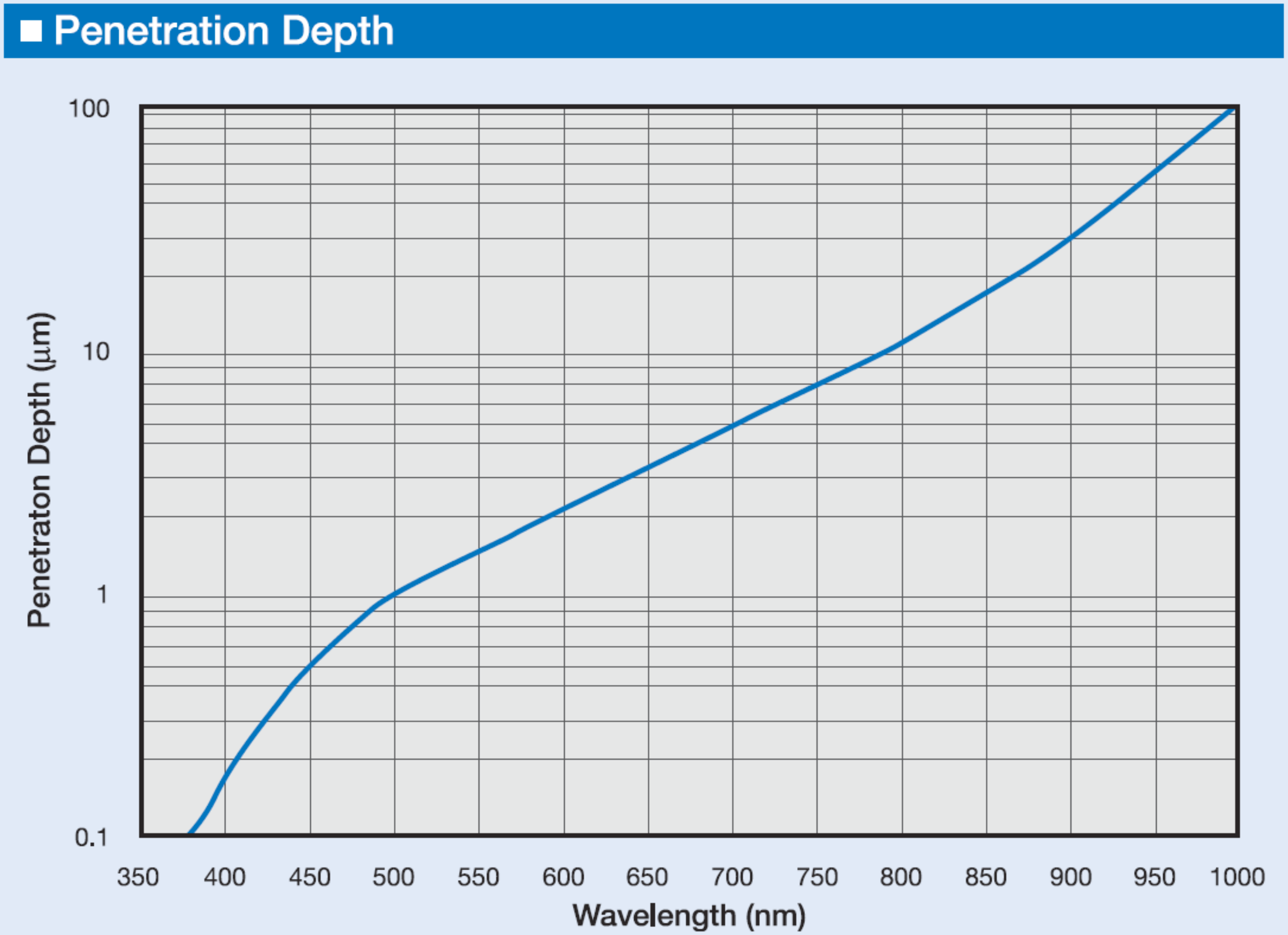
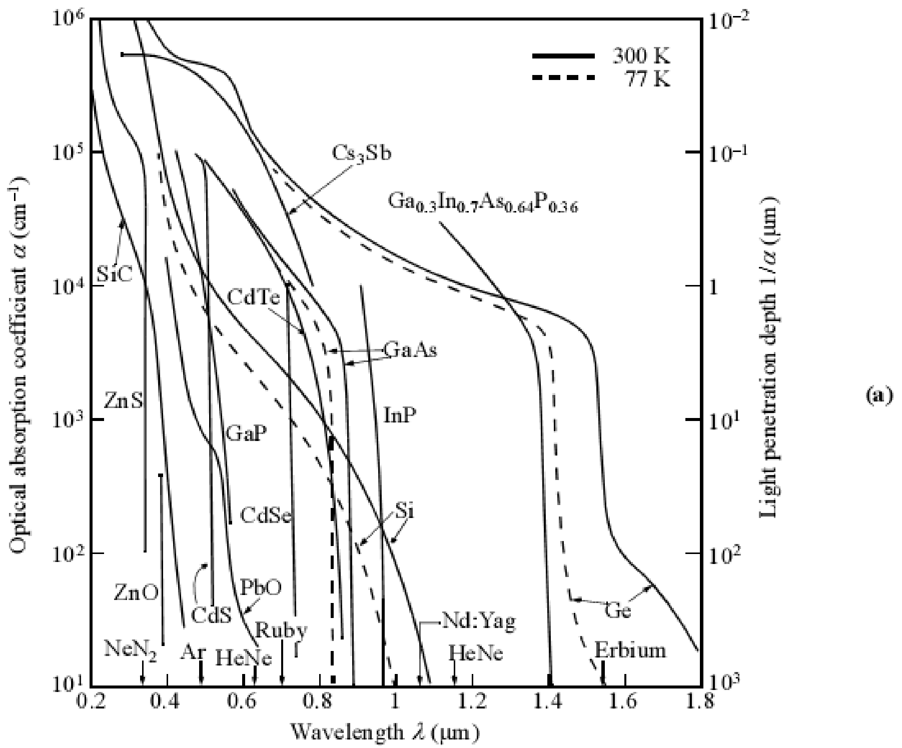
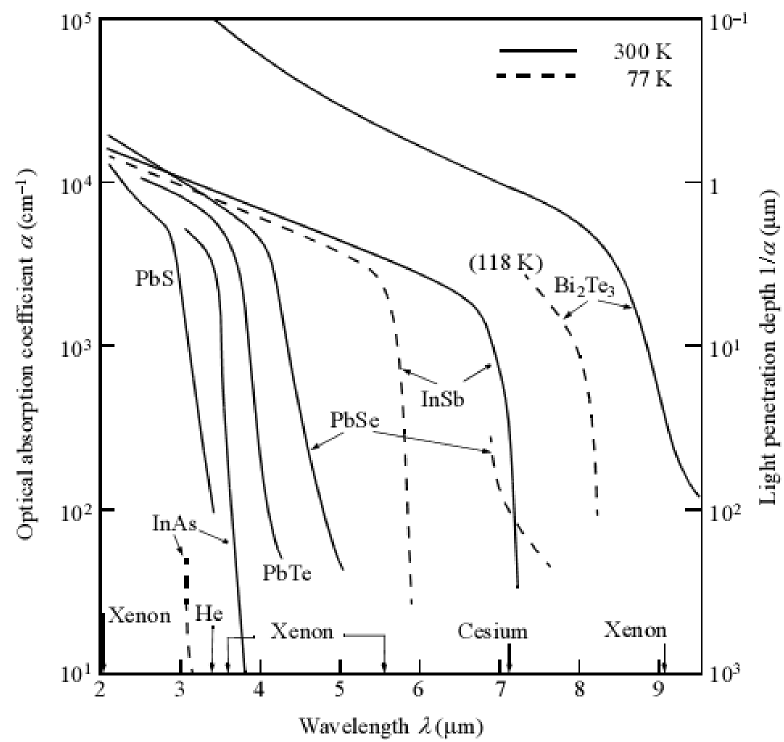



Figure 2. Penetration depth (1/e) of light into silicon substrate for various wavelengths.

# Material Absorption/penetration Depths




$$I(x) = I_0 e^{-\alpha x}, \text{ where}$$

$\mathrm{I(x)} =$ intensity at depth x,

$\mathrm{I_0} =$ initial intensity,

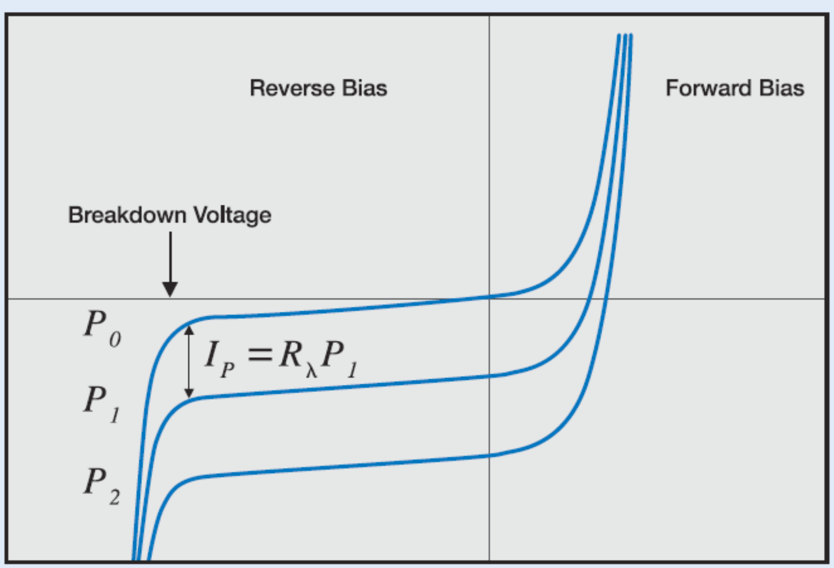
$\alpha =$ absorption coefficient $\{\mathrm{cm^{-1}}\}$,

$\mathrm{x} =$ depth $\{\mathrm{cm}\}$.

# Conduction in Photodiode

- If the pn junction is not biased, then the extra photogenerated charge will induce a current. Note that there is no extra charge with which to recombine because there is no reverse bias.
- The photogenerated current can be used to drive a load, thereby converting light into electrical power.
- This mode of operation defines photovoltaic devices that are often used to convert solar energy into electricity.

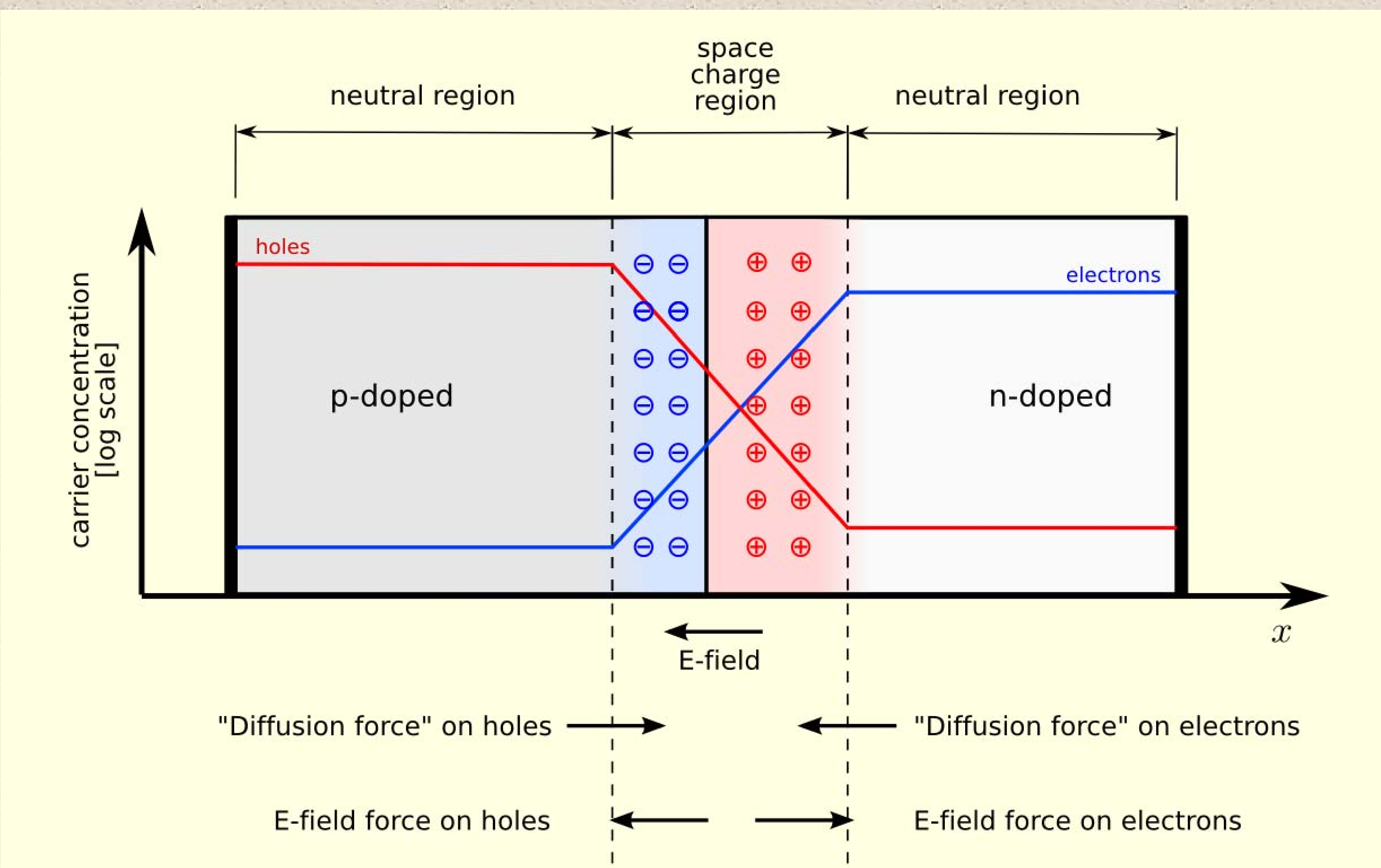
■ Photodetector I-V Curves



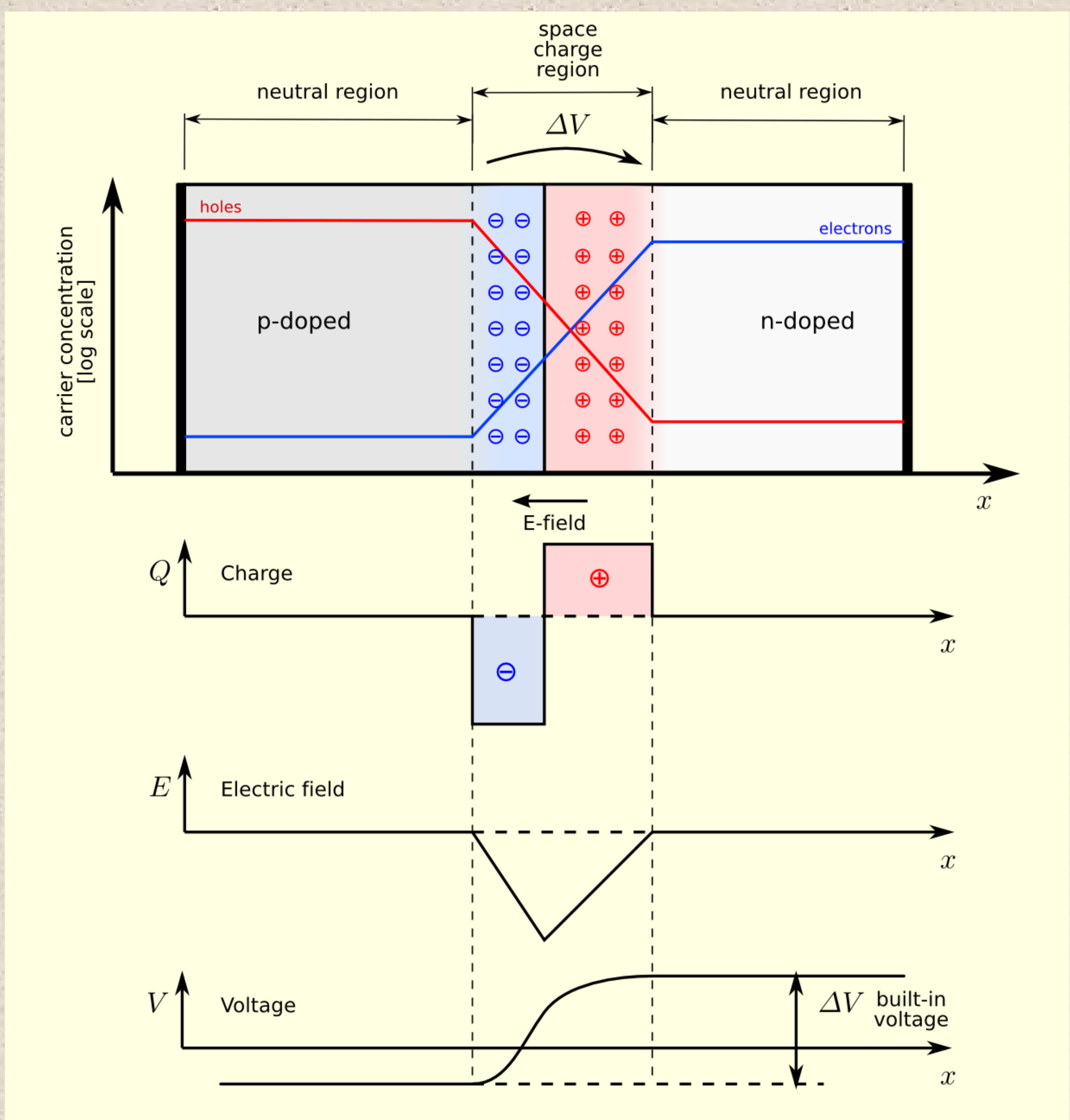

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent ($I_P$). Thus:

$$I_{TOTAL} = I_{SAT}\,(e^{\frac{qV_A}{k_B T}} - 1) - I_P \qquad (8)$$

# Review of pn Junction



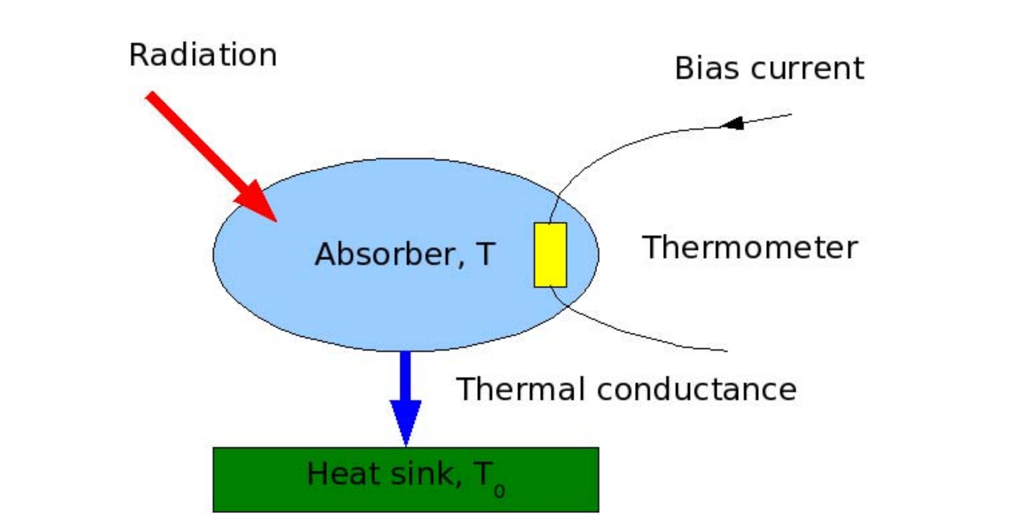
# Q, E, V, in pn Junction



# Bolometers

# Definition of Bolometer

- A bolometer is a device that changes temperature when it absorbs the energy of a particle.
- In light detection, a bolometer changes temperature when photons are absorbed.
- This temperature change is usually sensed by measuring a resultant change in electrical resistance in a thermometer that is thermally coupled to the bolometer.
- The bolometer was invented by Astronomer Samuel P. Langley in ~1880.



# Bolometer Principles of Operation

- A photon has energy h$\nu$.
- This energy is absorbed and produces a change in temperature that depends on the heat capacity of the material.
- A small heat capacity will induce a larger temperature change.
- Low fluxes correspond to relatively small changes in temperature, resistance, and thus voltage; therefore, thermal noise needs to be minimized through cooling.

$$\Delta E = C\Delta T,$$

$$\Delta T = \frac{1}{C}\Delta E, \text{ where,}$$

$$C = mc,$$

$\Delta\text{E}$ = change in energy,

$\Delta\text{T}$ = change in temperature,

C = heat capacity of absorber,

c = specific heat capacity of absorber, and

m = mass of absorber.

# Bolometer Thermal Time Constant

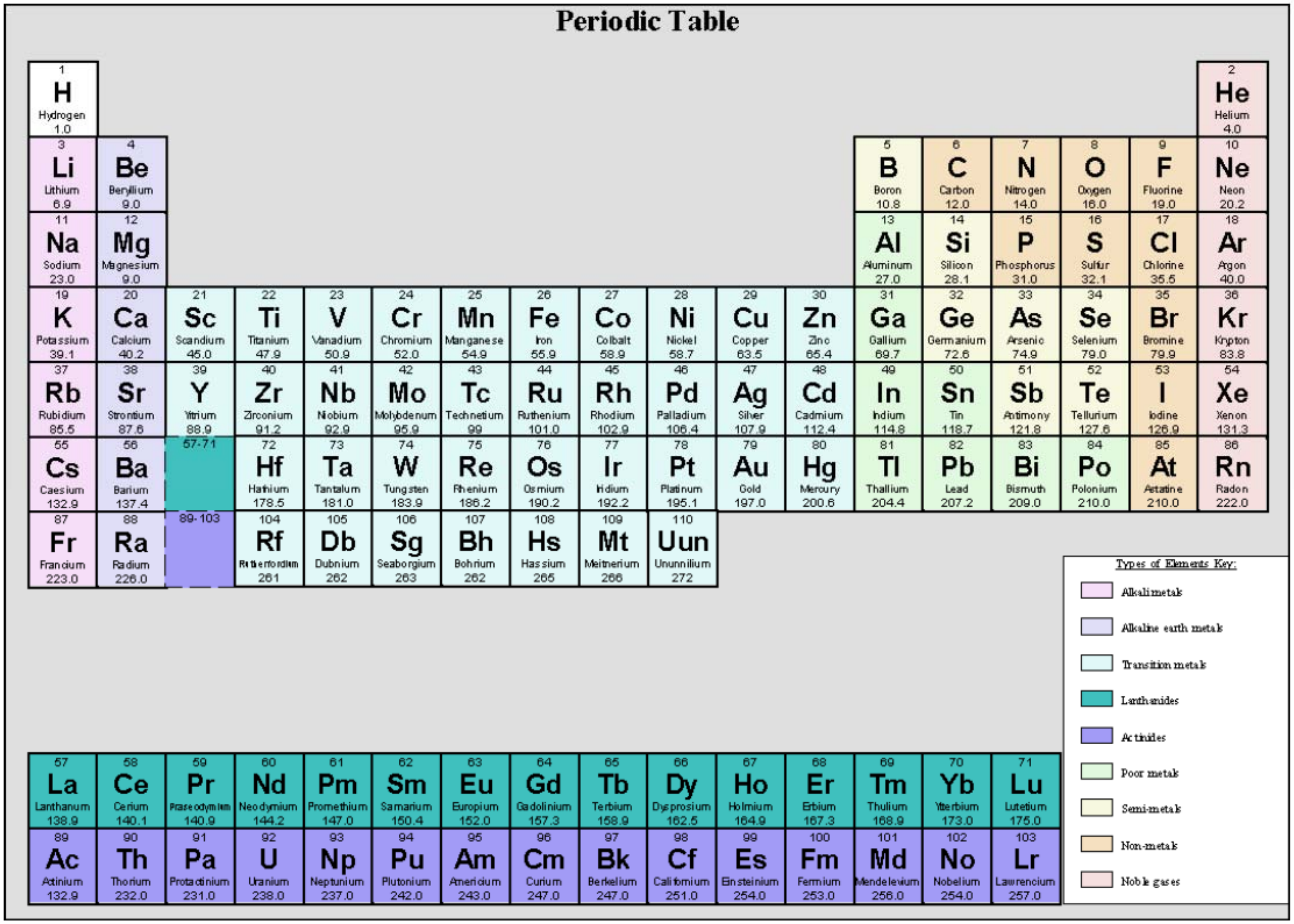
- As each photon is absorbed, the temperature of the bolometer temporarily increases.
- The bolometer cools down at a rate that depends on the thermal conductance of its connection to a nearby thermal bath (heat sink).
- Typically, some small amount of bias power is injected into the bolometer to elevate the temperature ($T_1$) slightly above that of the heat sink ($T_0$).

$$\text{thermal conductance} \equiv G = \frac{P_{bias}}{T_1},$$

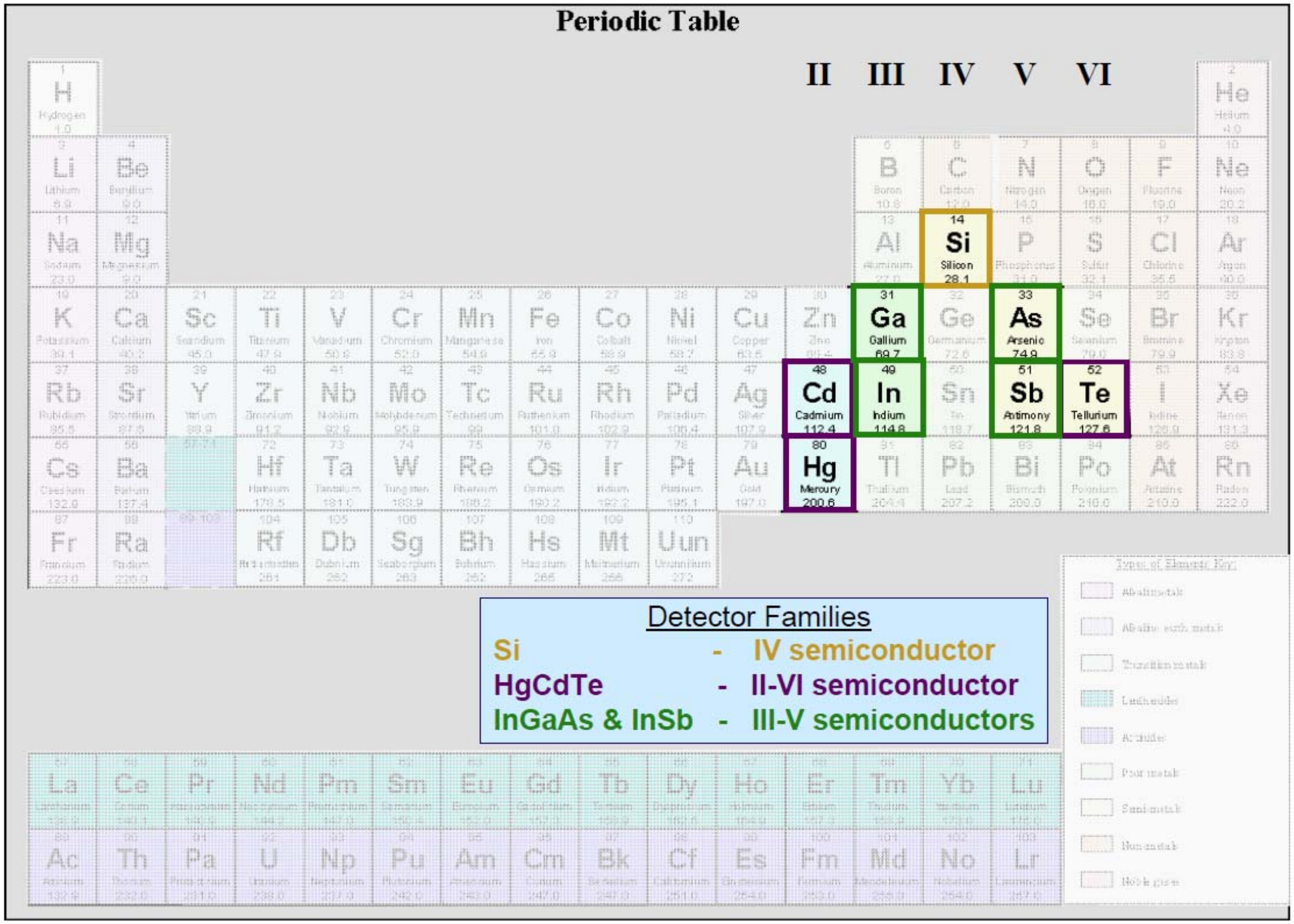
$$\tau = \frac{C}{G}.$$

- Thermal time constant is a function of thermal conductance and heat capacity.
- Note that this time constant could become important for high speed operation.

# Periodic Table



# Periodic Table and Detector Material



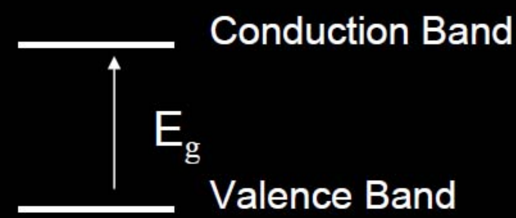
# Band Gaps

## Photon Detection

For an electron to be excited from the valence band to the conduction band

$$h\nu > E_g$$

h = Planck constant ($6.6310^{-34}$ Joule•sec)
$\nu$ = frequency of light (cycles/sec) = $\lambda/c$
$E_g$ = energy gap of material (electron-volts)




$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

| Material Name | Symbol | $E_g$ (eV) | $\lambda_c$ ($\mu$m) |
|---|---|---|---|
| Silicon | Si | 1.12 | 1.1 |
| Indium-Gallium-Arsenide | InGaAs | 0.73 – 0.48 | 1.68* – 2.6 |
| Mer-Cad-Tel | HgCdTe | 1.00 – 0.07 | 1.24 – 18 |
| Indium Antimonide | InSb | 0.23 | 5.5 |
| Arsenic doped Silicon | Si:As | 0.05 | 25 |

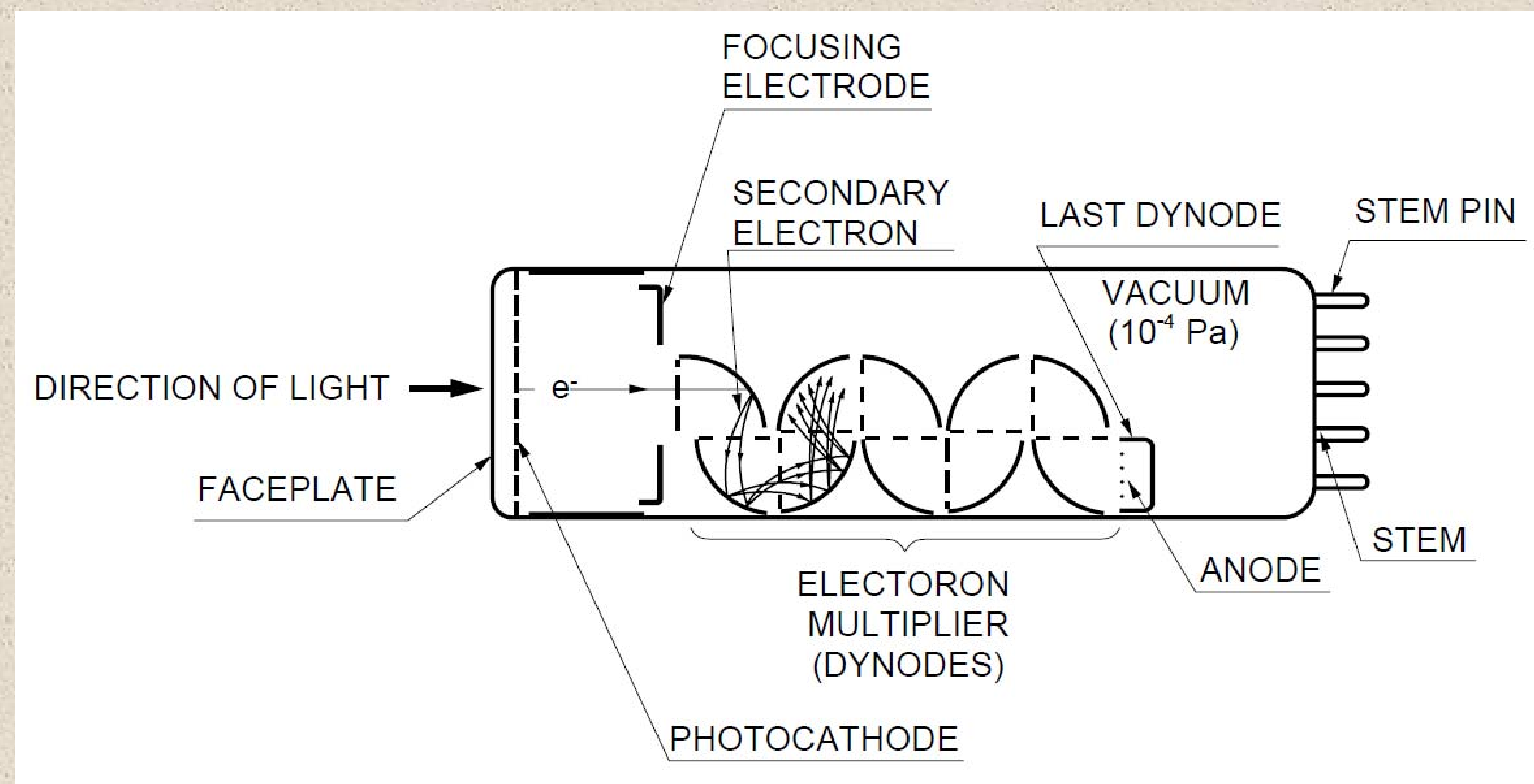
*Lattice matched InGaAs ($In_{0.53}Ga_{0.47}As$)

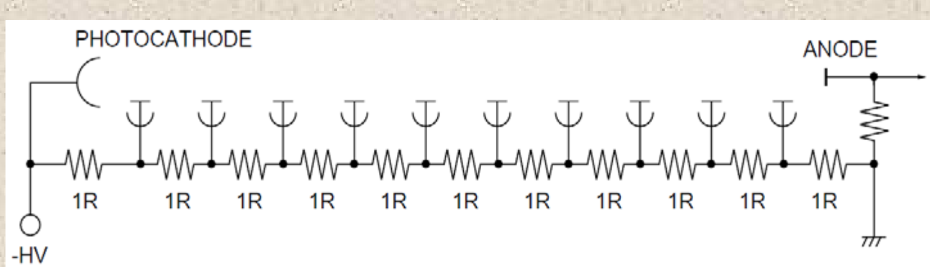
# Photo-multiplier Tubes

# Photo-multiplier Tubes (PMTs)

- PMTs convert individual photons into relatively large packets of charge through an avalanche process that relies upon the photoelectric effect.
- The incoming photon must have sufficient energy to generate charge with energy that exceeds the “work function,” i.e. enough energy to be able to leave the material. This is called the “photoelectric effect.”
- Semiconductors are usually used for the absorbing material, as they are less reflective than conductors.
- PMTs have only one element, i.e. they are not imagers.
- PMTs offer high sensitivity and fast response times (a few ns).

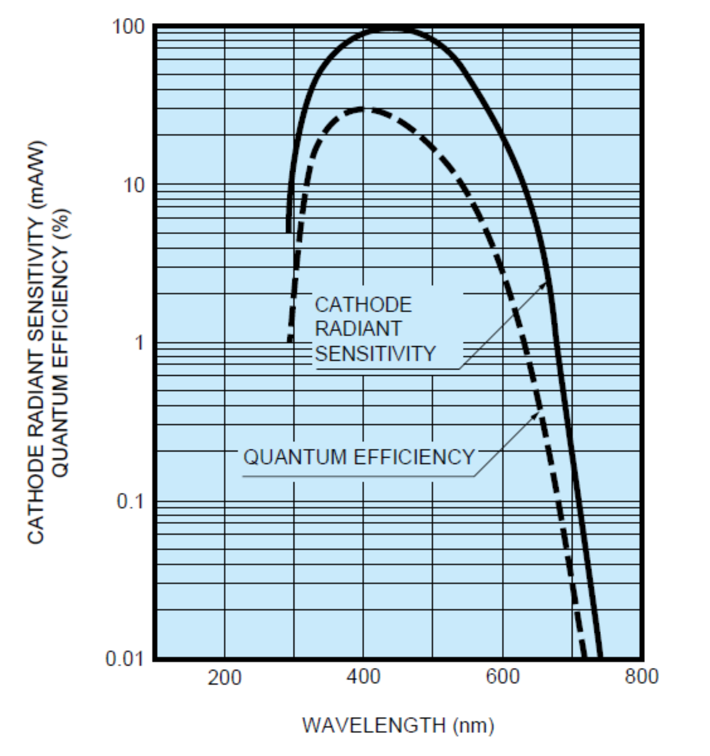
# PMT Cross-section and Schematic

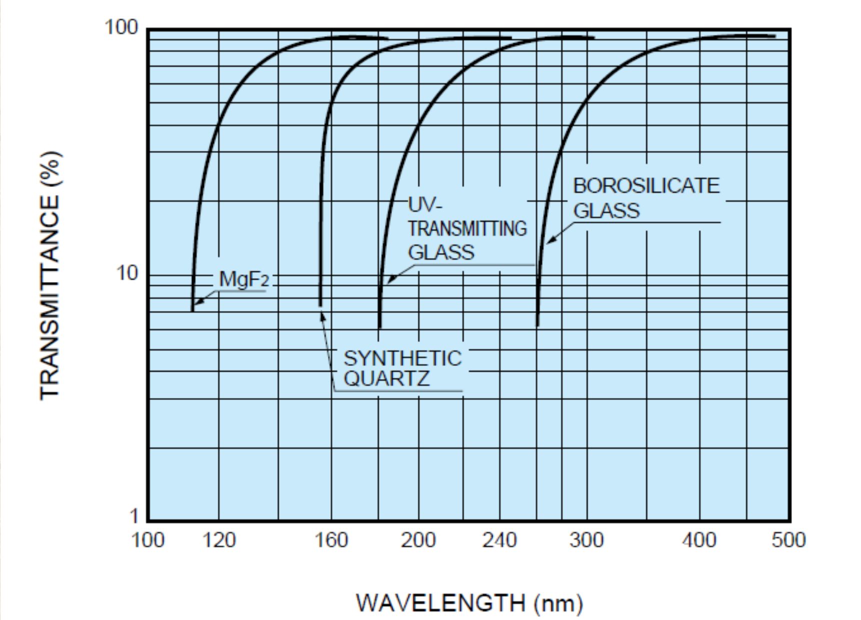


# PMT Response

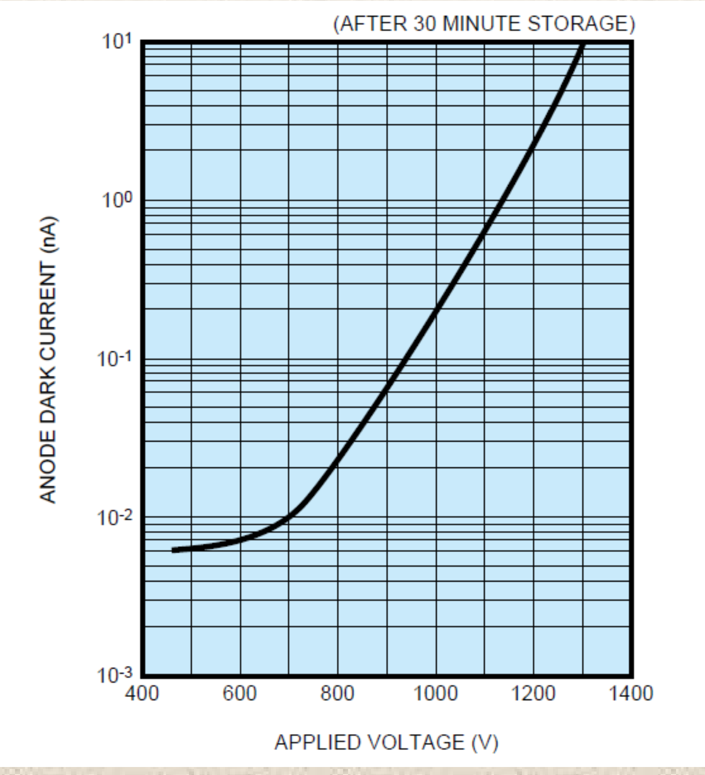
- PMT response is dependent on quantum efficiency of photocathode material and transmission of window.

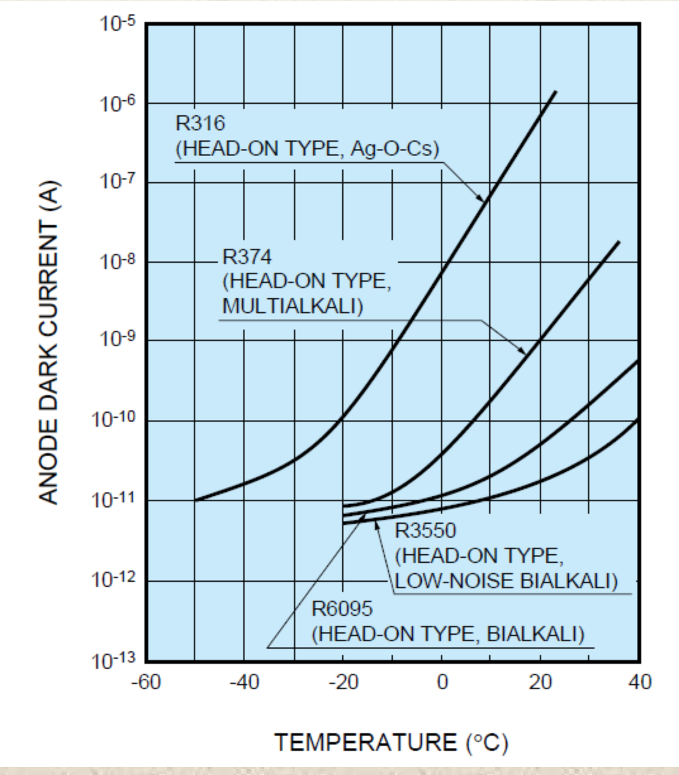


# PMT Dark Current

- PMT dark current is a function of cathode voltage and temperature.



# PMT Sensitivity

- PMT sensitivity is often expressed as the minimum source flux to generate a signal that has at least SNR=1. This is sometimes called the "equivalent noise input" (ENI).

$$ENI = \frac{\sqrt{2q \cdot Idb \cdot \mu \cdot \Delta f}}{S} \quad \text{(watts or lumens)}$$

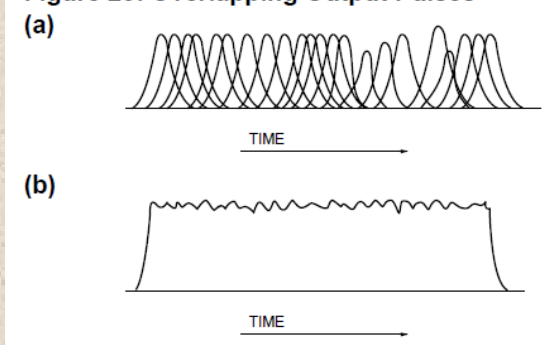
where

- $q$ = electronic charge ($1.60 \times 10^{-19}$ coul.)
- $Idb$ = anode dark current in amperes after 30-minute storage in darkness
- $\mu$ = current amplification
- $\Delta f$ = bandwidth of the system in hertz (usually 1 hertz)
- $S$ = anode radiant sensitivity in amperes per watt at the wavelength of interest or anode luminous sensitivity in amperes per lumen

# PMTs and Single Photon Counting

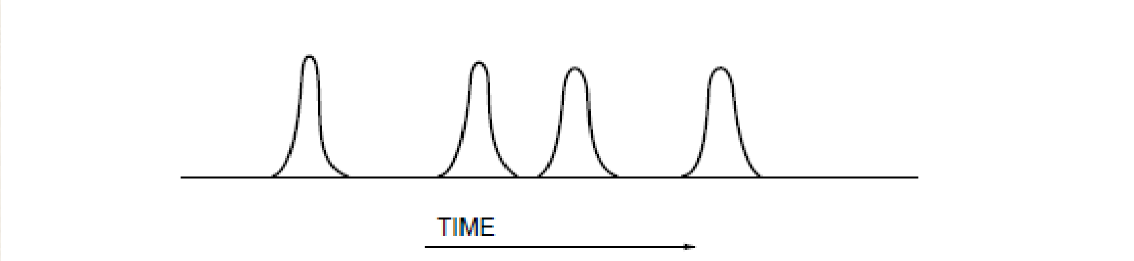
- In a typical application, the individual charge packets are indistinguishable, and the PMT generates a steady "direct current" (DC) level.

Figure 25: Overlapping Output Pulses




- In low light conditions, each individual charge packet can be discerned. This enables photon counting and zero read noise.

Figure 26: Discrete Output Pulses (Single Photon Event)



# PMTs and High Energy Detection

- It is possible to use a PMT to effectively detect high energy photons by using scintillator material.
- The scintillator absorbs the high energy photon and subsequently emits photons of lower energy that are in the energy range of detection by the PMT.
- This configuration can be used to measure energy.

**Figure 29: Diagram of Scintillation Detector**

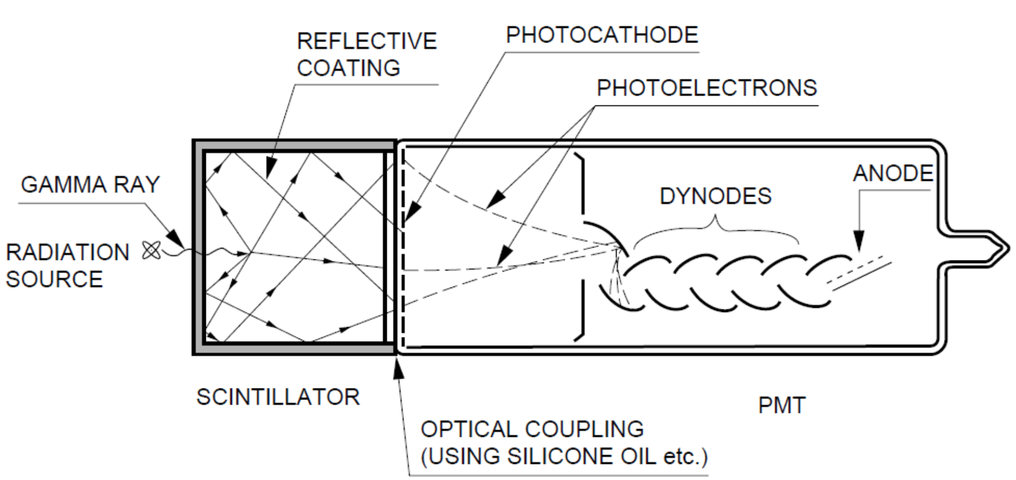
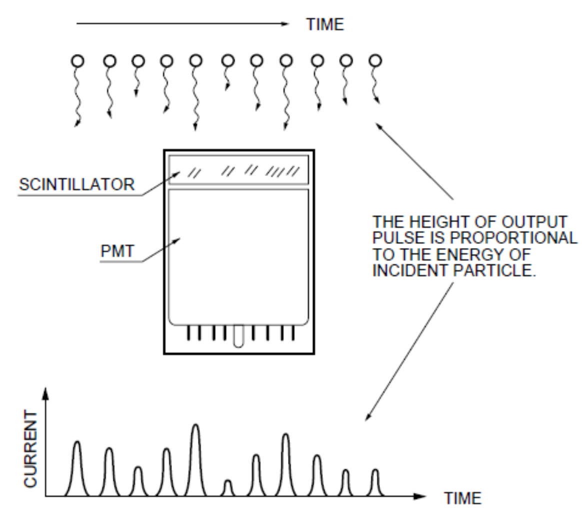
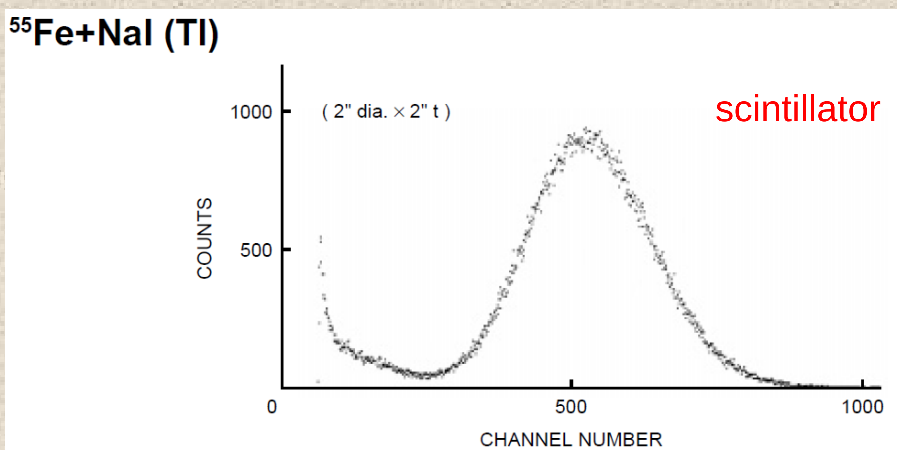


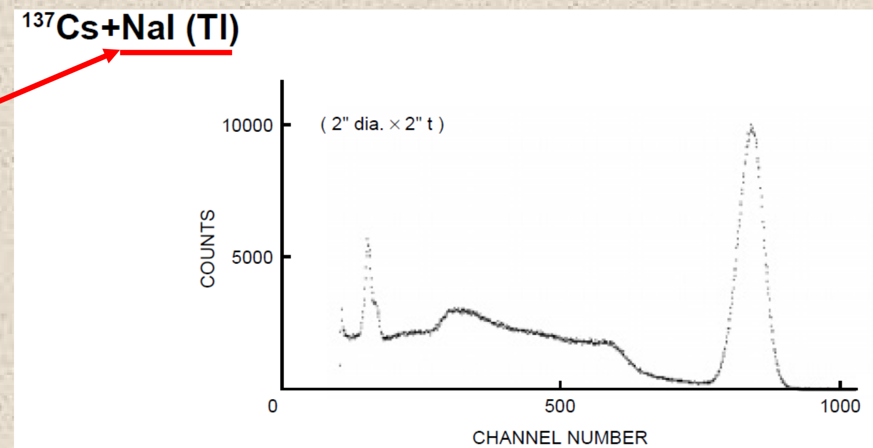

**Figure 30: Incident Particles and PMT Output**

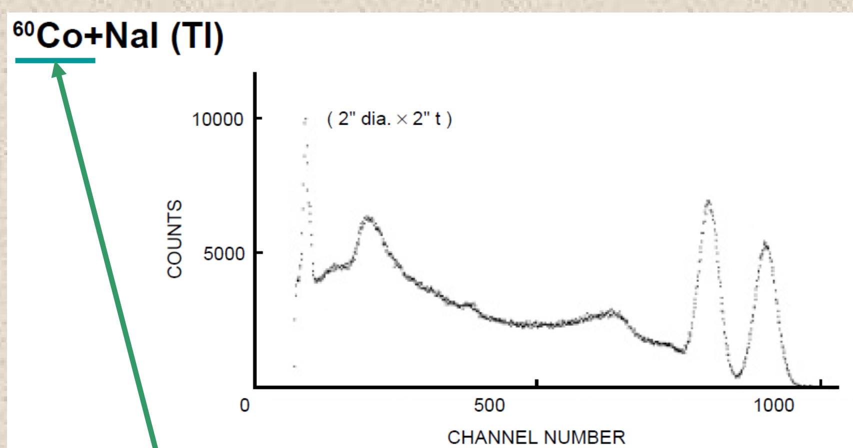


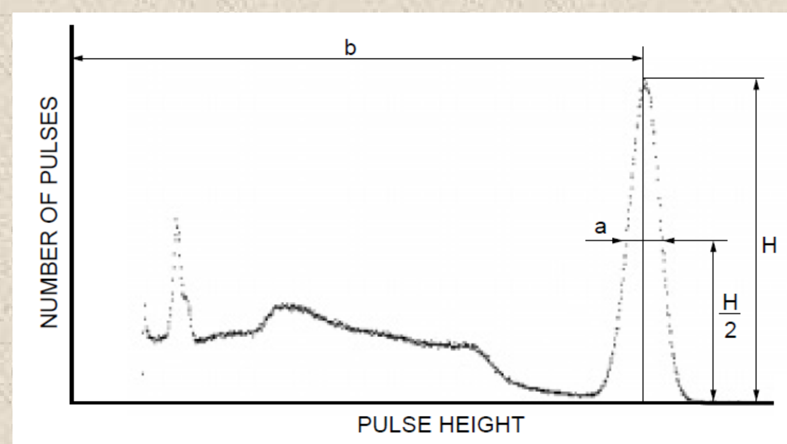
# PMTs and Energy Resolution

- Scintillator material will emit a number of photons that is proportional to the input energy of the high energy photon.




radioactive material

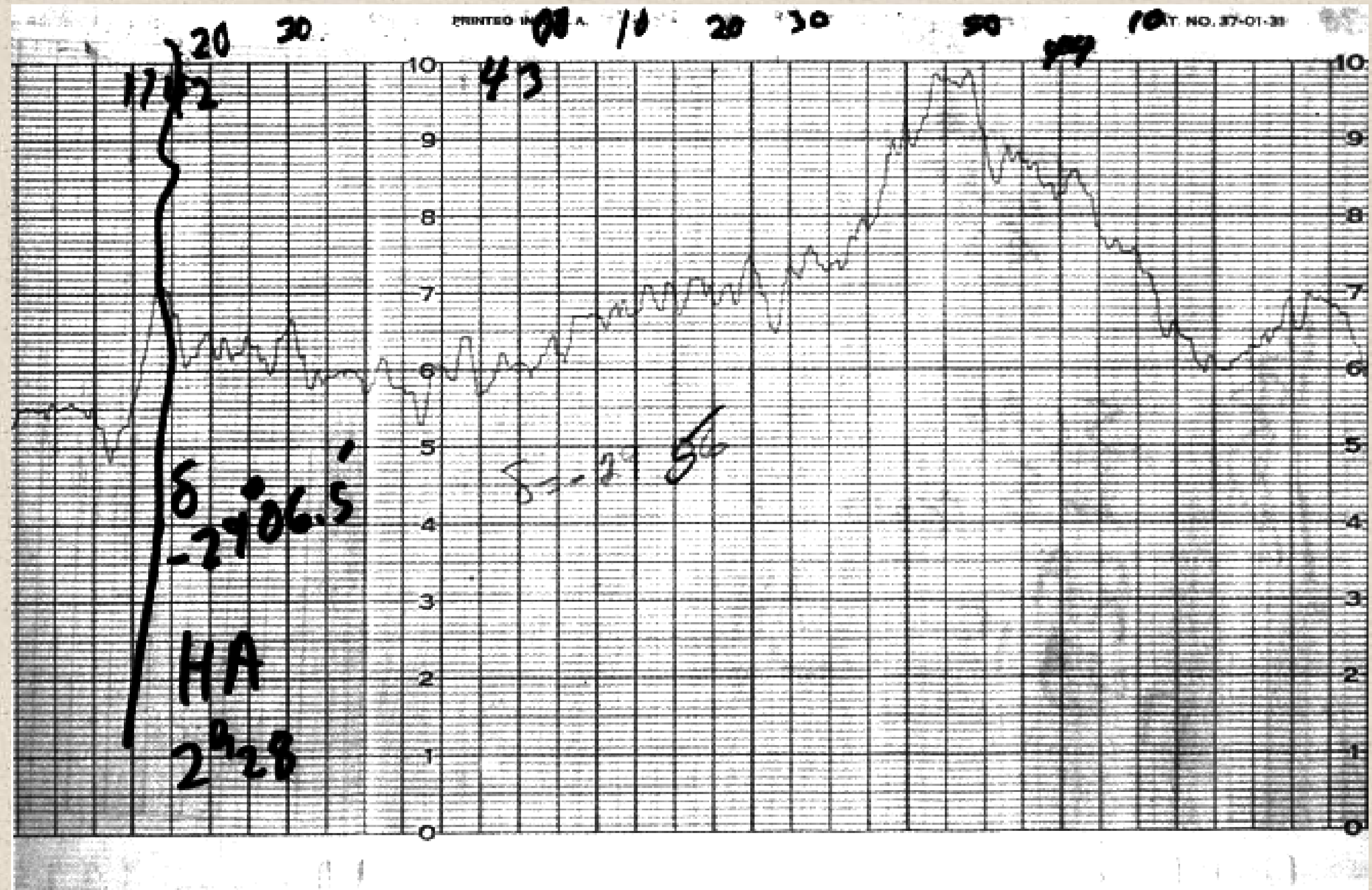
# PMTs Examples (Hamamatsu)

es

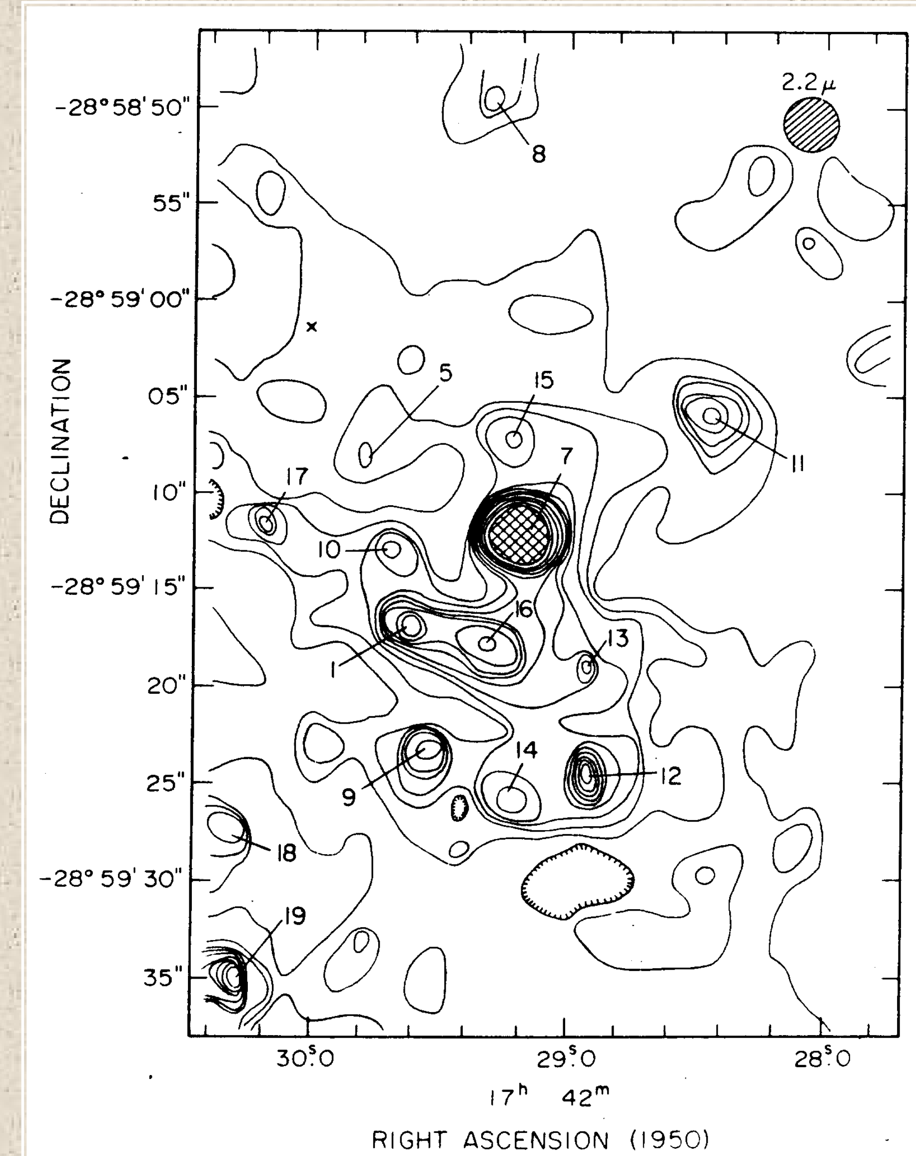
| Part Number | Type | Size mm | Min λ nm | Max λ nm | Peak Sens. nm | Window | Gain | Dark Current after 30 min. nA | Rise Time ns | Multi Anode |
|---|---|---|---|---|---|---|---|---|---|---|
| R10699 | Side on | 28 | | 450 | | UV Glass | 1.3 X $10^7$ | 2 | 2.2 | |
| H10744 | Assembly | | | 240 | | Sapphire | 1.0 x $10^7$ | | 2.5 | |
| R9880U-210 New | Head on | 16 | | | 380 | Borosilicate | 2.0E+05 | 10 | 0.57 | N |
| R9880U-110 | Head on | 16 | 300 | 650 | 330 | Borosilicate | 4.0E+06 | 1 | 0.57 | N |
| R9779 | Head on | 51 | | | | Borosilicate Glass | 5.0 x $10^5$ | 15 | 1.8 | N |
| R9647 | Head on | 28 | 300 | 650 | 420 | Borosilicate Glass | 6.3 x $10^5$ | 1 | 3.4 | N |
| R9420-100 New | Head on | 38 | | | 350 | Borosilicate | 2.5E+05 | 100 | 1.6 | N |
| R9220 | Side on | 28 | 185 | 900 | 450 | UV Glass | 1.0E+07 | 10 | 2.2 | N |
| R9110 | Side on | 28 | 185 | 900 | 450 | UV Glass | 1.9E+07 | 5 | 2.2 | N |
| R8900U-100-M4 New | Head on | 30 | | | 350 | Borosilicate | 1.0E+05 | 20 | 1.4 | Y |
| R8900U-100-C12 New | Head on | 30 | | | 350 | Borosilicate | 6.5E+05 | 20 | 2.2 | Y |
| R8900U-100 New | Head on | 30 | | | 350 | Borosilicate | 1.0E+05 | 20 | 1.8 | N |
| R8900U-00-C12 | Square | | 300 | 650 | 420 | Borosilicate glass | 0.7 x $10^6$ | 2 | 2.2 | Y |
| R8900-100-M16 New | Head on | 30 | | | 350 | Borosilicate | 1.0E+05 | 8/ch | 1.3 | Y |
| R8900-00-C12 | Square | | 300 | 650 | 420 | Borosilicate glass | 0.7 x $10^6$ | 2 | 2.2 | Y |
| R8619 | Head on | 25 | 300 | 650 | 420 | Borosilicate | 2.0E+06 | 2 | 2.6 | N |
| R8487 | Side on | 28 | 115 | 195 | 130 | MgF2 | 3.9E+06 | 0.1 | 2.2 | N |
| R8486 | Side on | 28 | 115 | 320 | 200 | MgF2 | 1.0E+07 | 1 | 2.2 | N |
| R7899-01 | Head on | 25 | 300 | 650 | 420 | Borosilicate | 2.0E+06 | 2 | 1.6 | N |

# Applications

# The Galactic Center: Discovery Strip Chart

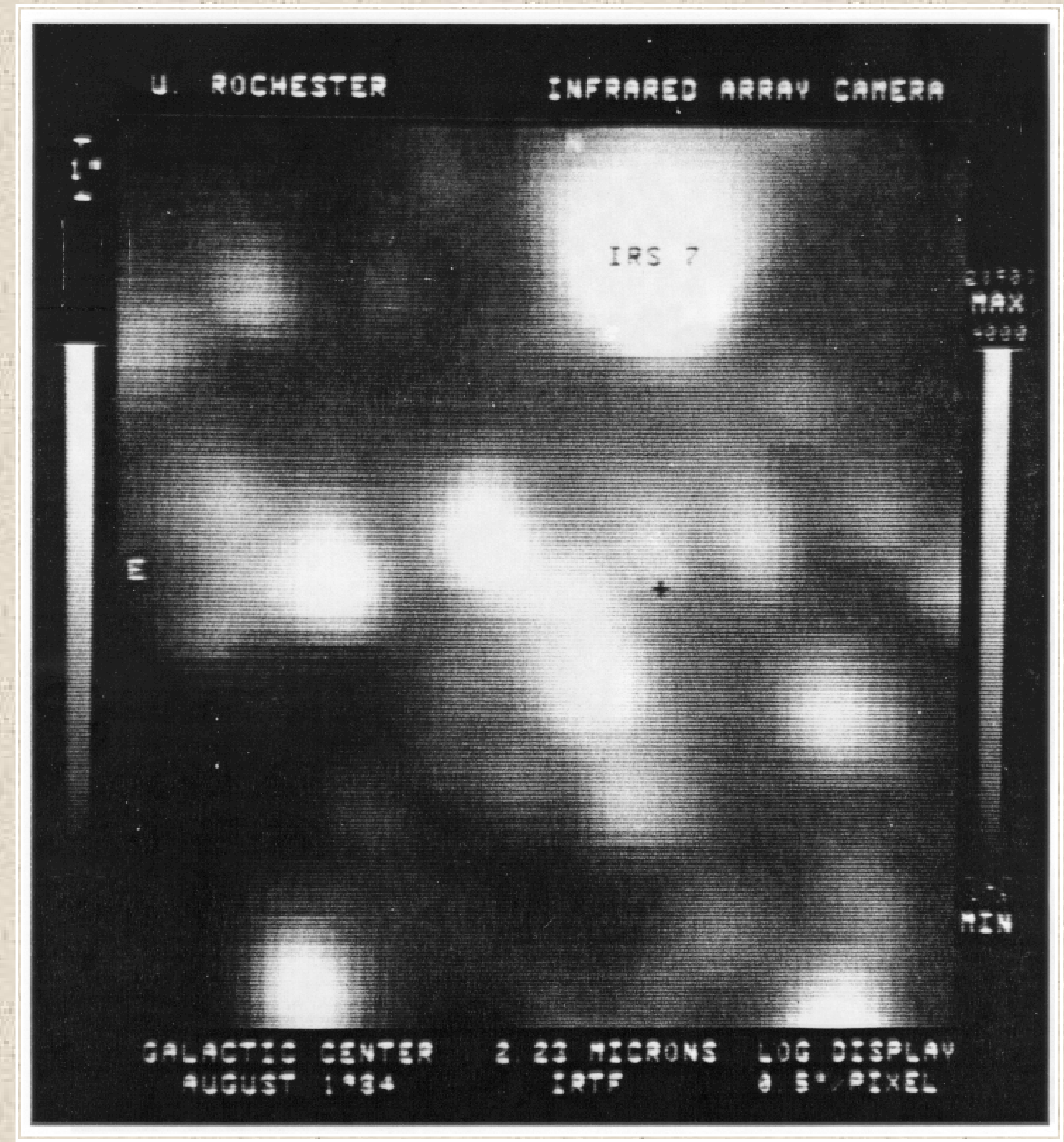


# The Galactic Center: PbS Bolometer



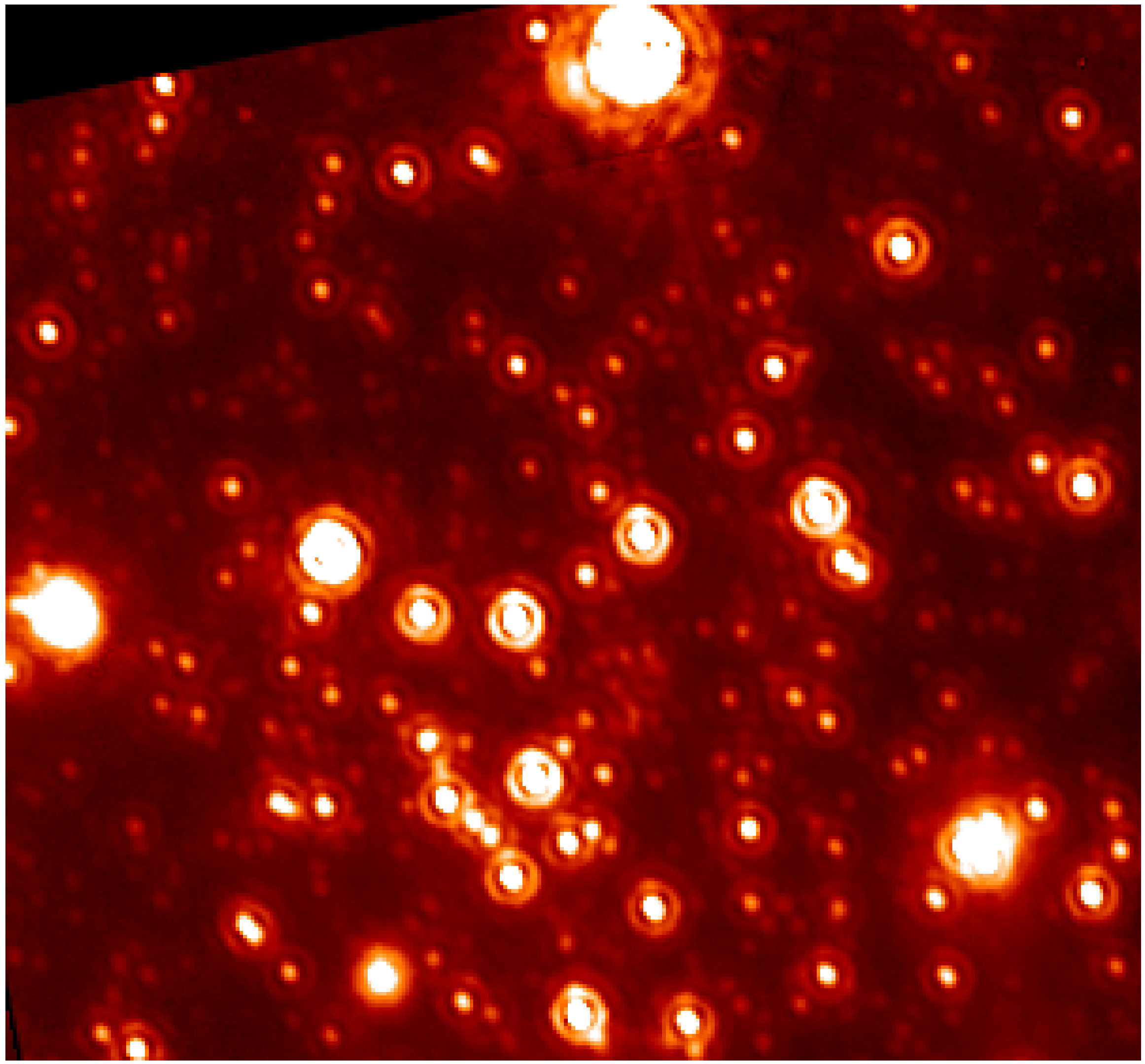

Becklin and Neugebauer, 1975

# The Galactic Center: InSb Photodiode Array



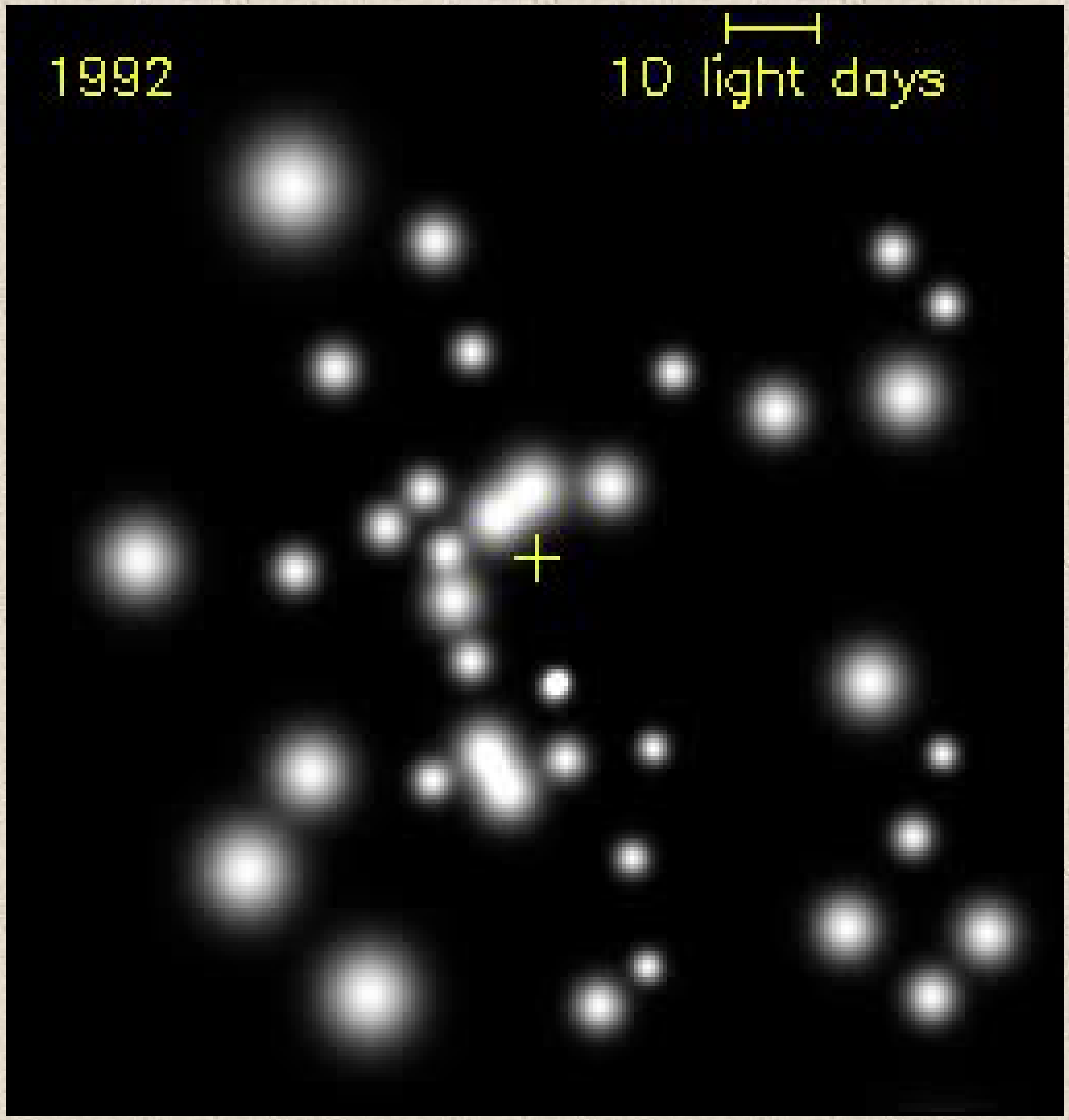

Forrest et al., 1986

# The Galactic Center: HgCdTe Photodiode Array



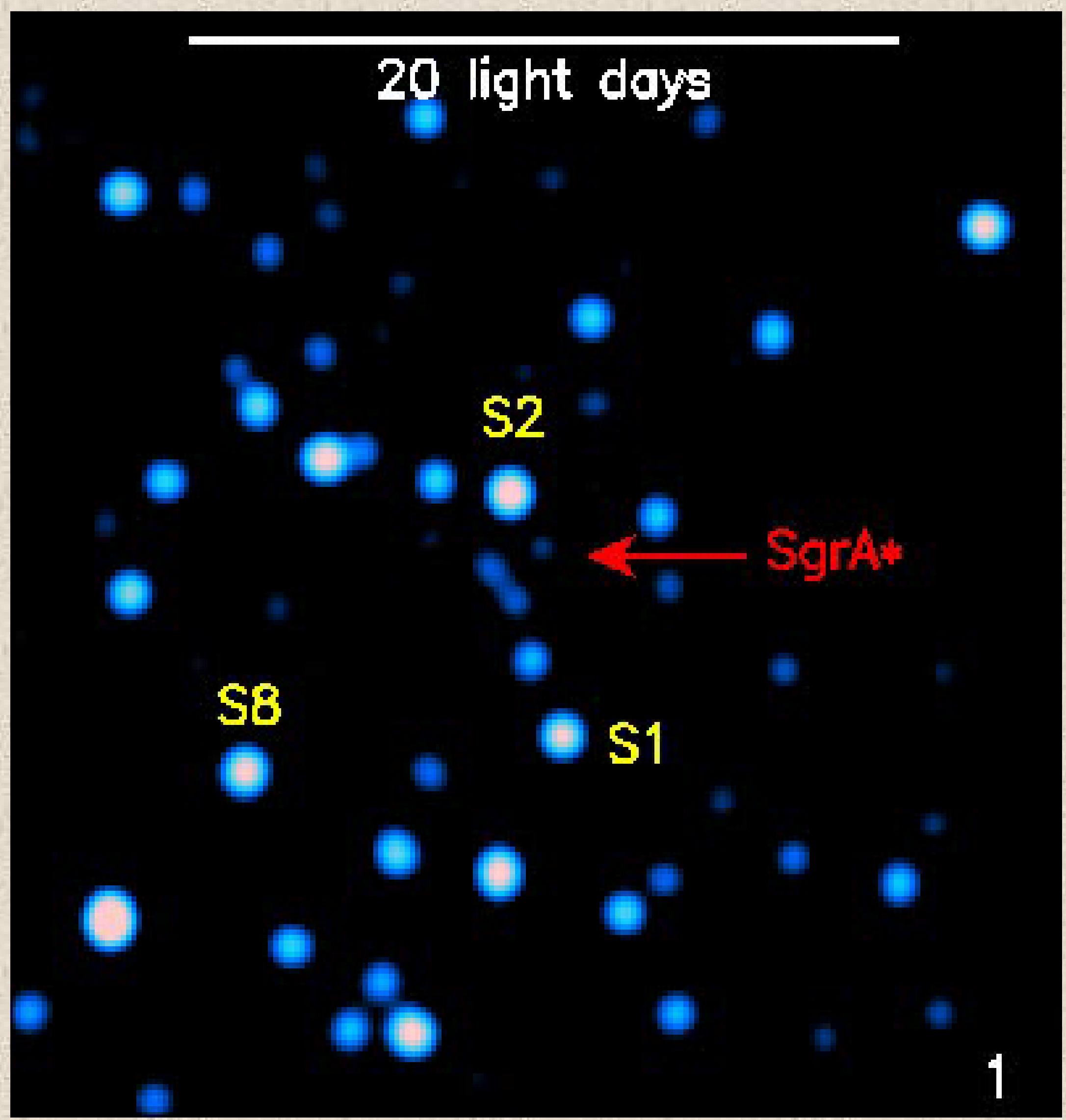
Rigaut et al., 1998

# The Galactic Center: Evidence of Black Hole




Zeroing in on a Massive Black Hole…

# The Galactic Center: Black Hole




Infrared Flares and Black Hole Feeding

# The 25 Year "Evolution" of the Galactic Center…

- Our basic understanding of key areas in astronomy is clearly a function of current technology
- What took us perhaps 25 years to achieve before, may only take ~10 years with the rapid acceleration of technology available to astronomers
- Advancements in science detectors have made this all possible…