

# Detectors

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

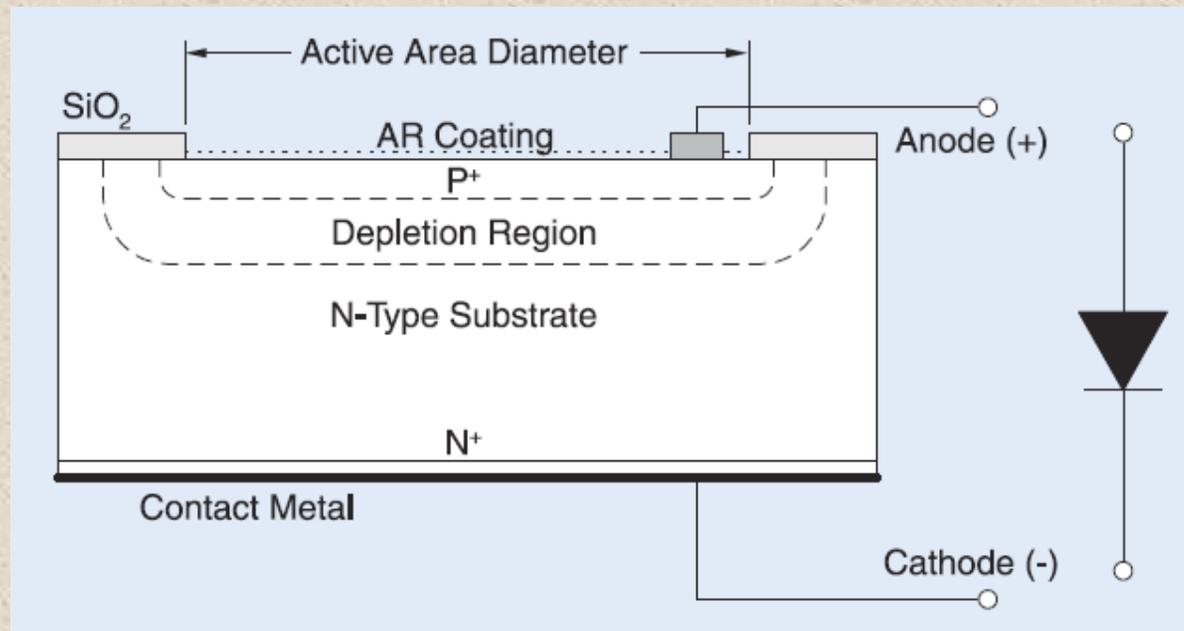
# Aims for this lecture

- 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:

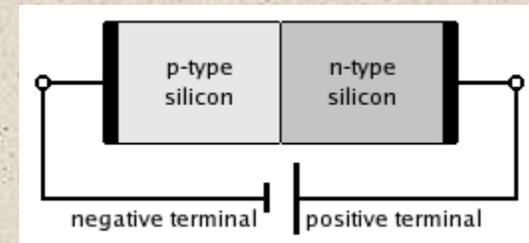
$$C = \frac{\kappa\epsilon_0 A}{d}, \text{ where}$$

$\kappa$  = dielectric constant,

$\epsilon_0$  = permittivity of free space,

$A$  = area of capacitor, and

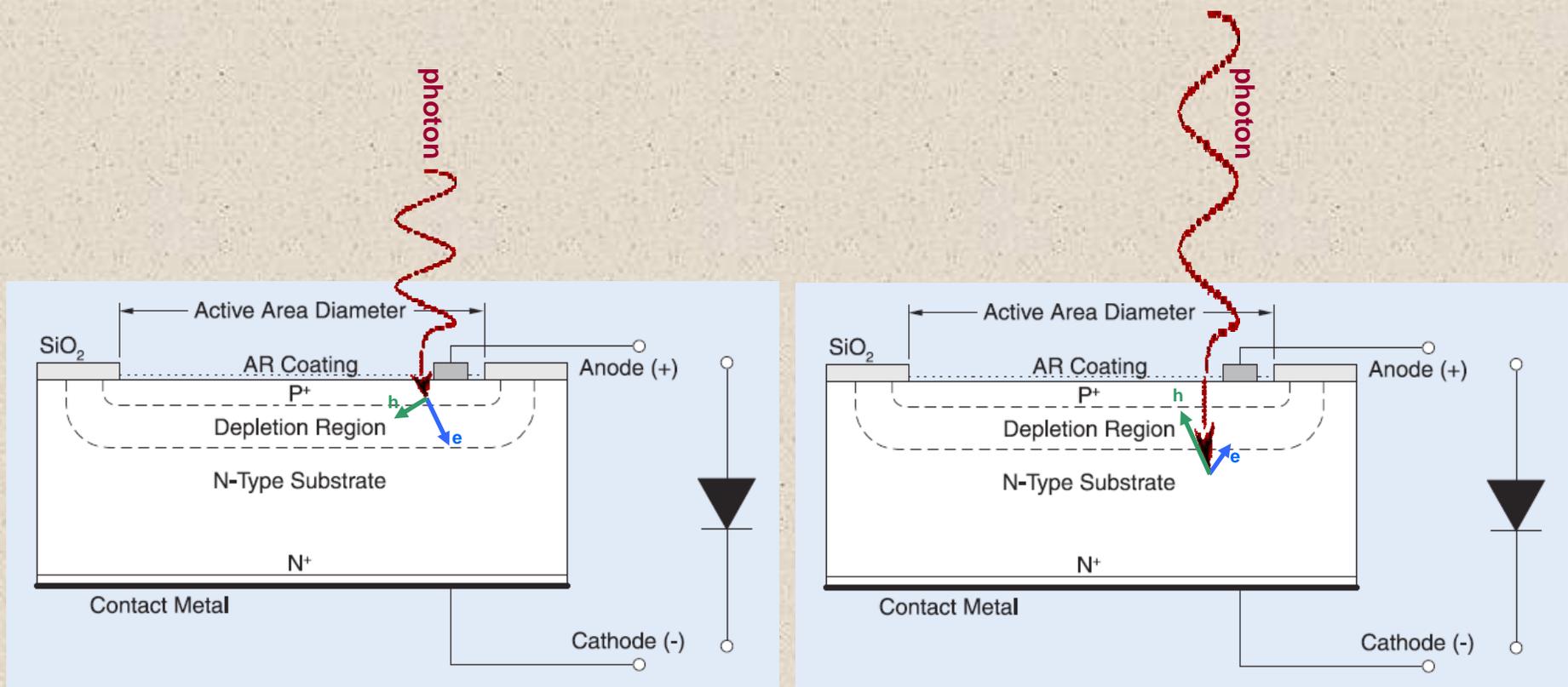
$d$  = distance between plates of capacitor.



- Photons of sufficient energy ( $E > E_{\text{bandgap}}$ ) 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.

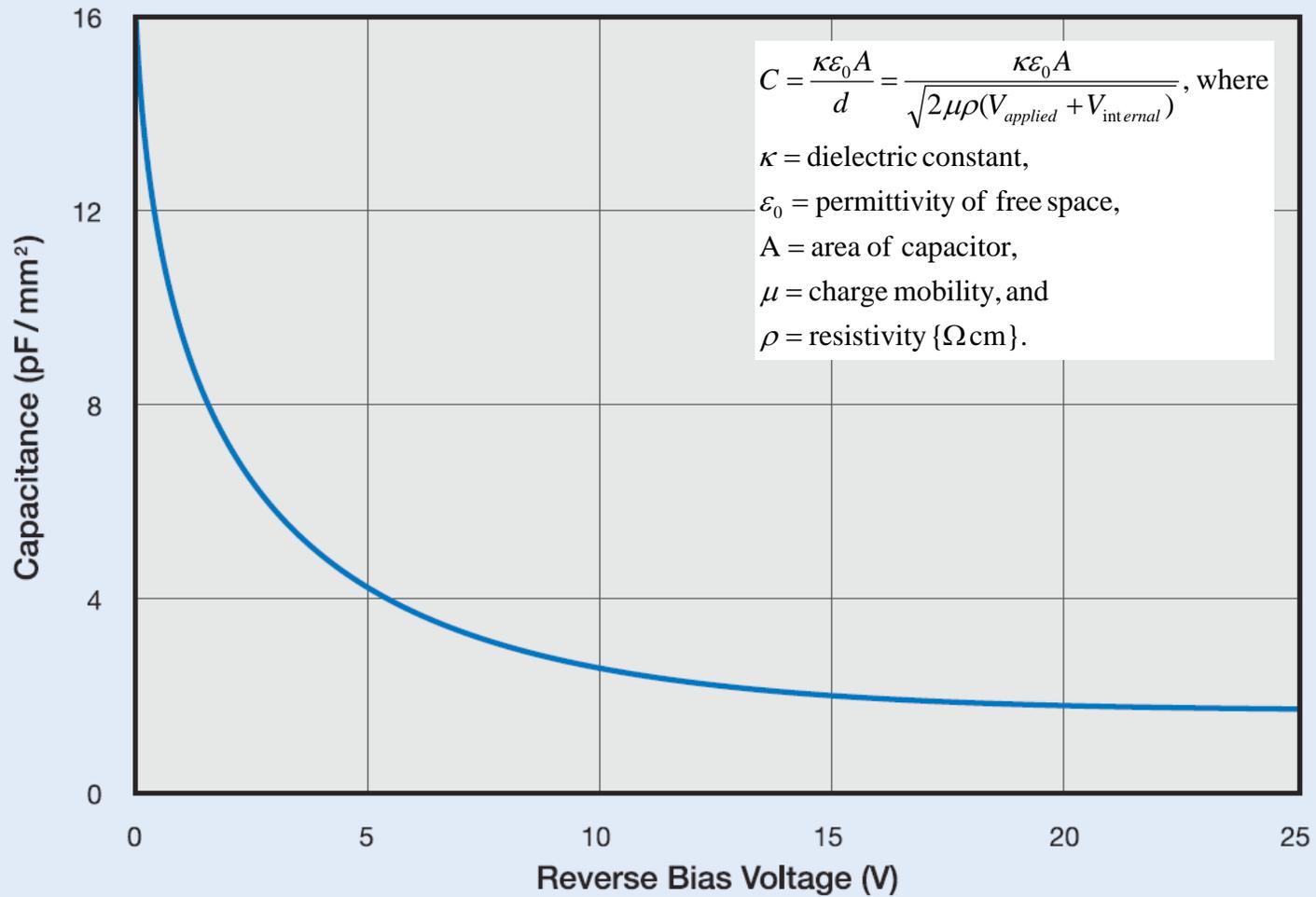
# Photon Absorption in Photodiode

- 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

## ■ Typical Capacitance vs. Reverse Bias



# Penetration Depth

## ■ Penetration Depth

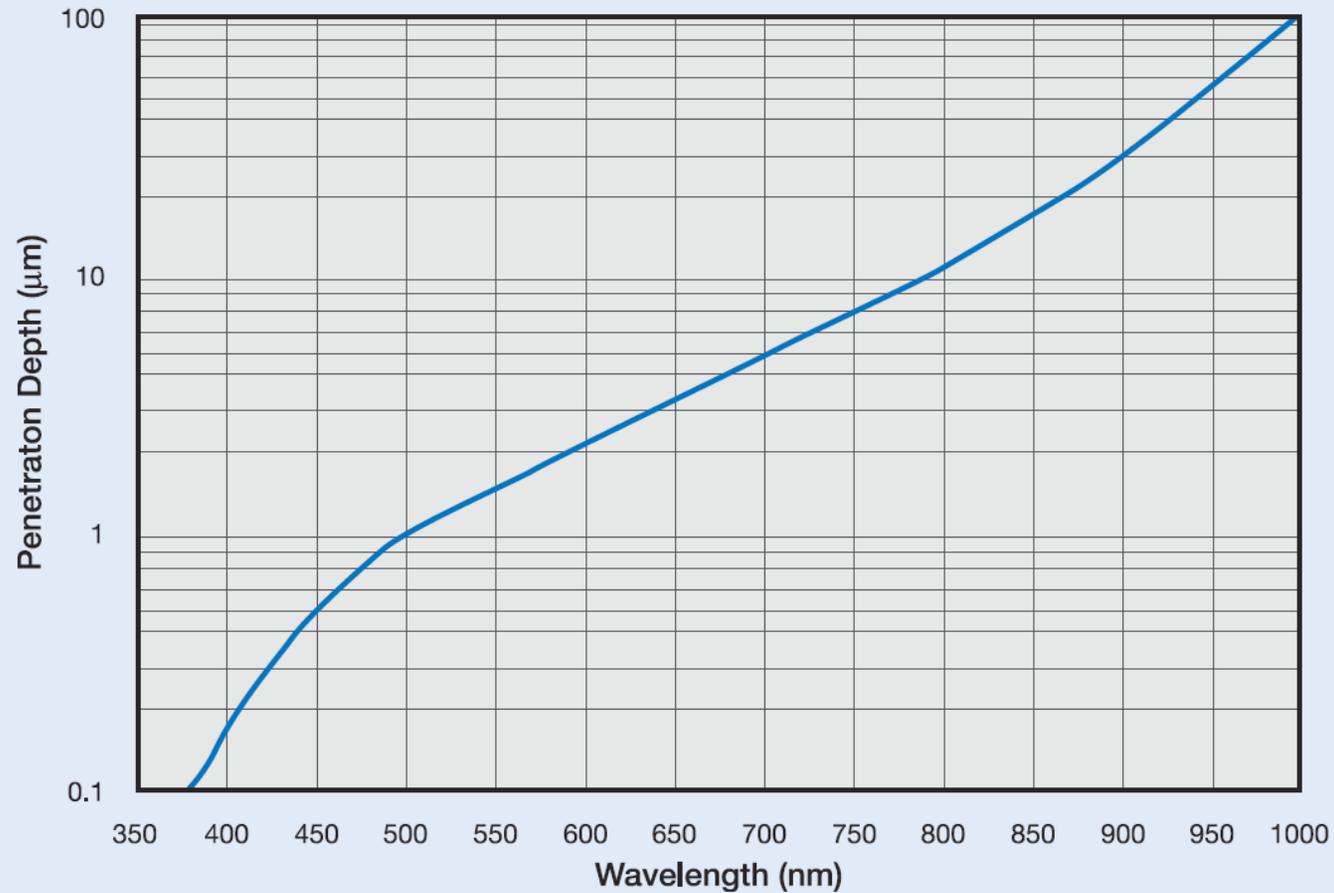
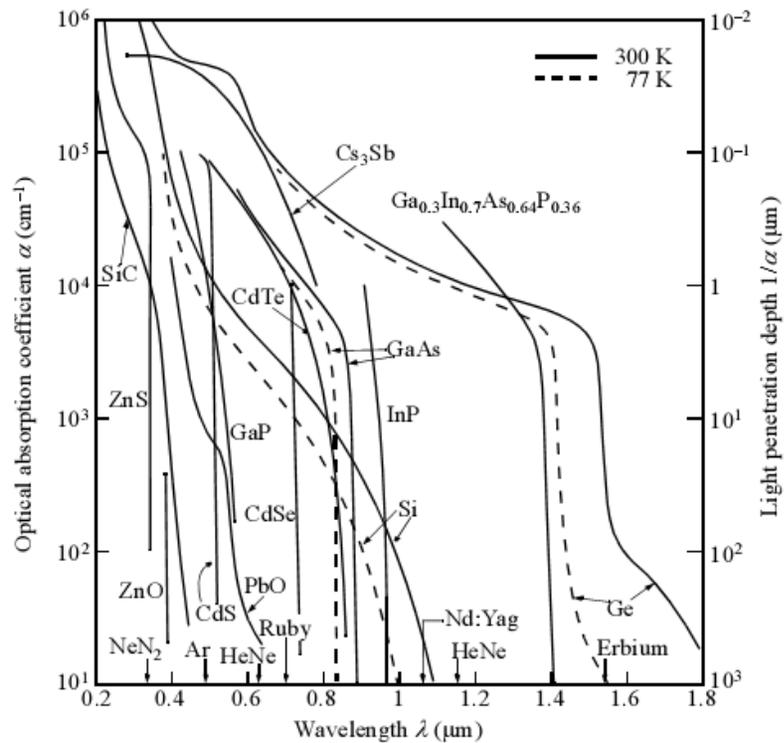
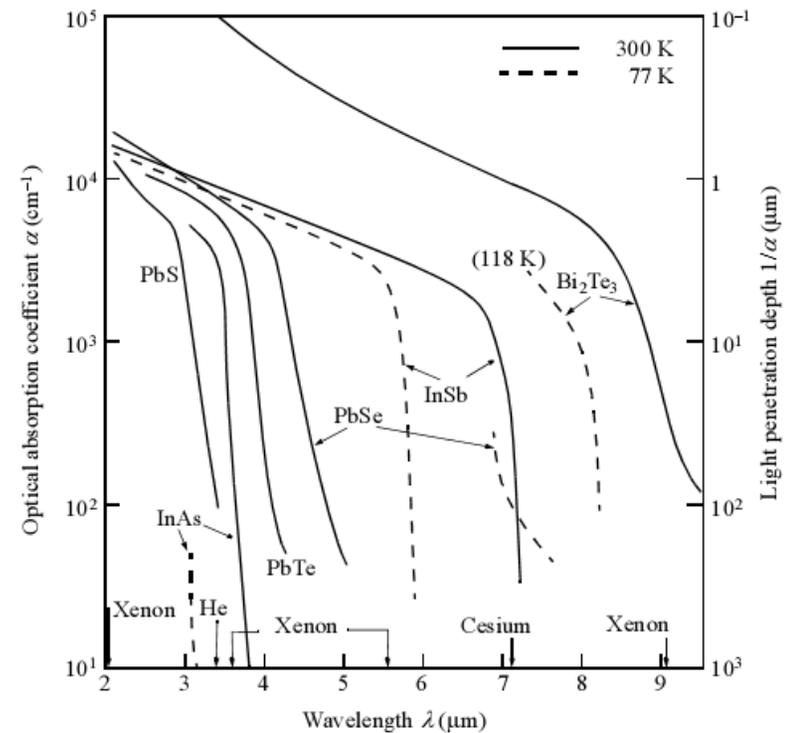


Figure 2. Penetration depth (1/e) of light into silicon substrate for various wavelengths.

# Material Absorption/penetration Depths



(a)



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

$I(x)$  = intensity at depth  $x$ ,

$I_0$  = initial intensity,

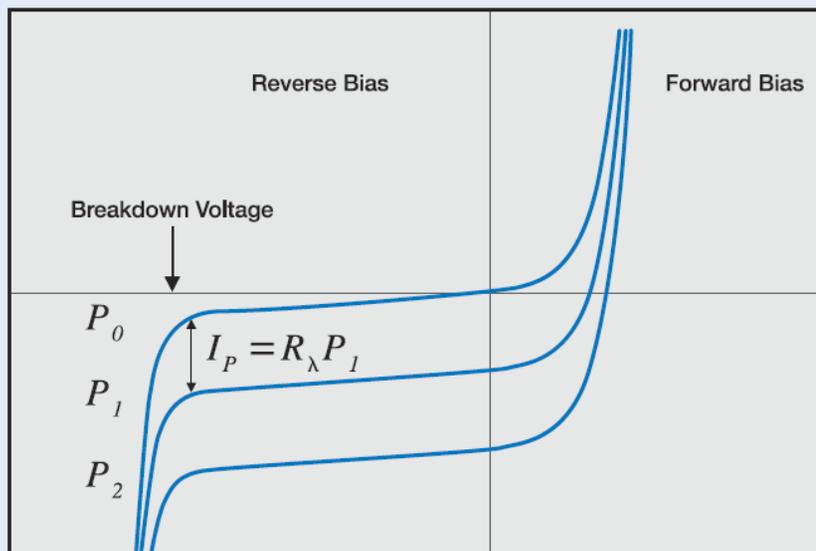
$\alpha$  = absorption coefficient {cm<sup>-1</sup>} ,

$x$  = depth {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.

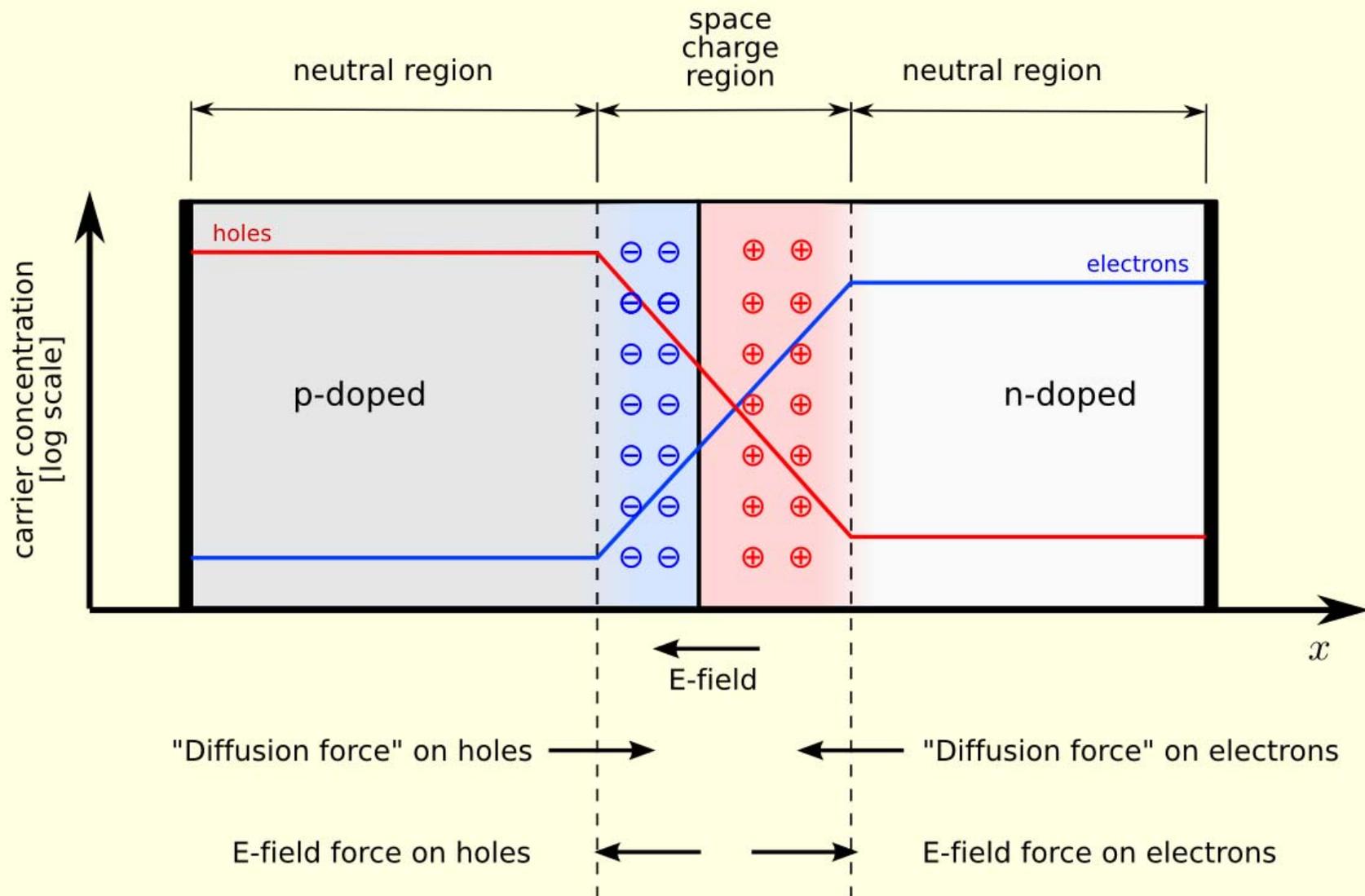
■ Photodetector I-V Curves



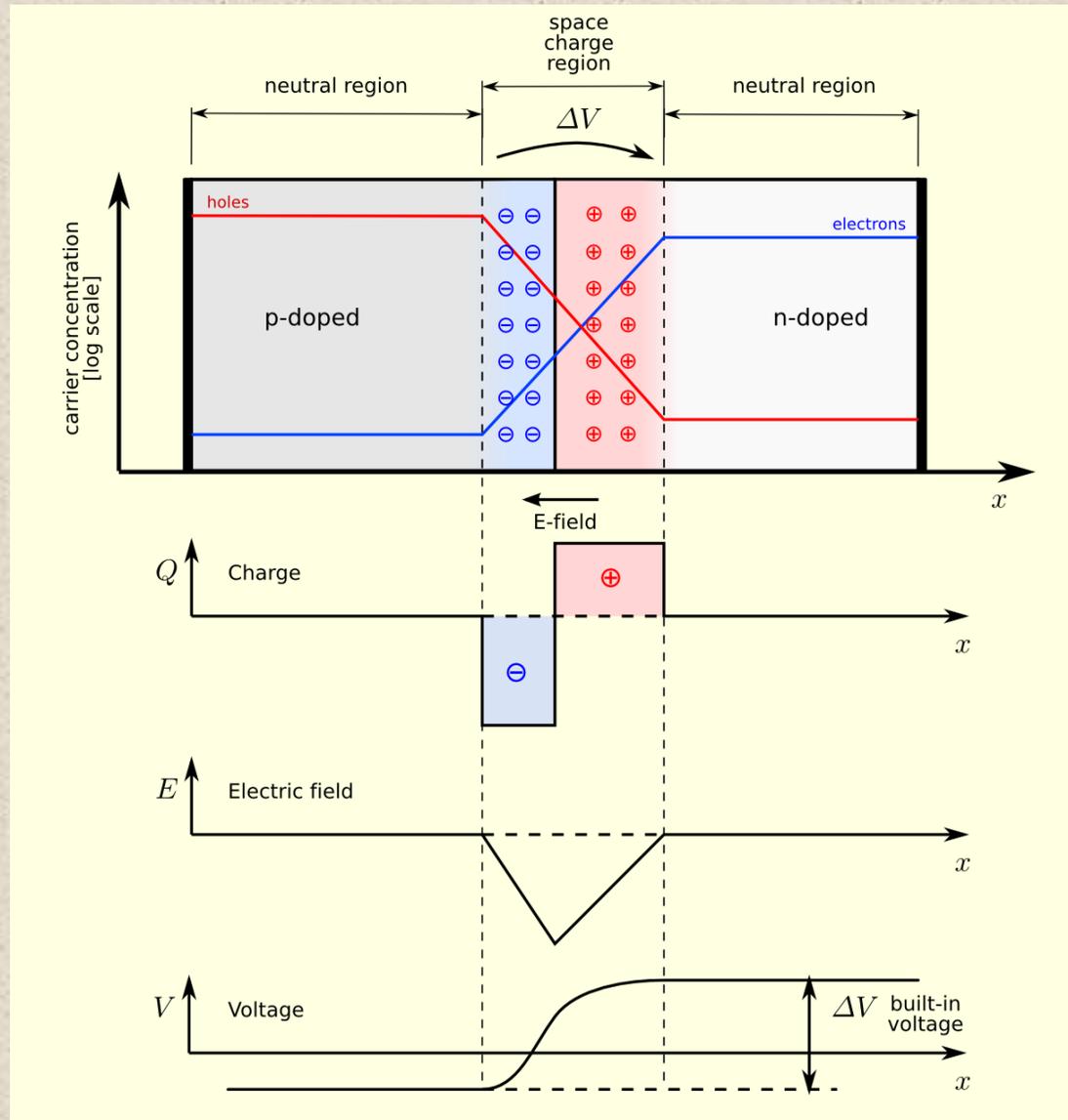
Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent ( $I_P$ ). Thus:

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

# Review of pn Junction



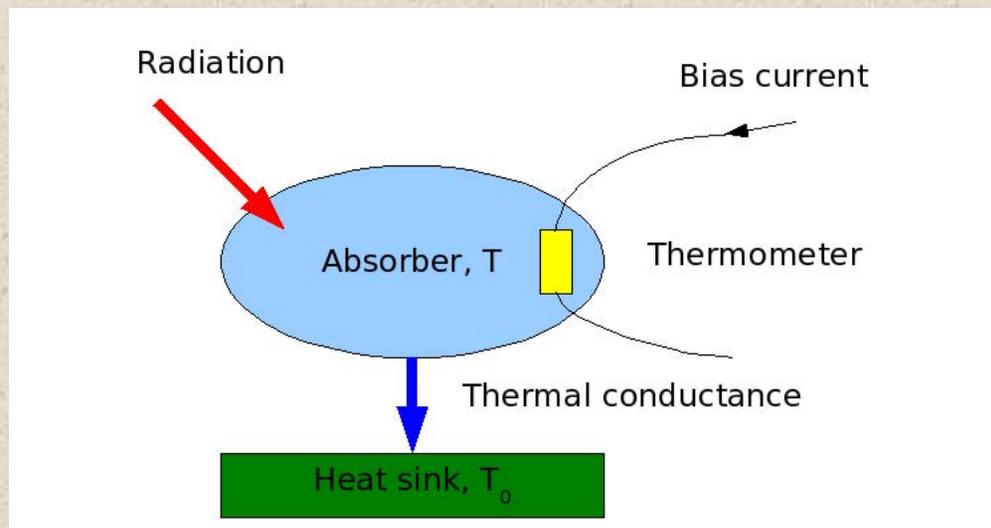
# Q, E, V, in pn Junction



# 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.

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

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

$$C = mc,$$

$\Delta E$  = change in energy,

$\Delta T$  = 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 ( $T_0$ ).

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

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

- 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**

1 <b>H</b> Hydrogen 1.0																	2 <b>He</b> Helium 4.0
3 <b>Li</b> Lithium 6.9	4 <b>Be</b> Beryllium 9.0											5 <b>B</b> Boron 10.8	6 <b>C</b> Carbon 12.0	7 <b>N</b> Nitrogen 14.0	8 <b>O</b> Oxygen 16.0	9 <b>F</b> Fluorine 19.0	10 <b>Ne</b> Neon 20.2
11 <b>Na</b> Sodium 23.0	12 <b>Mg</b> Magnesium 9.0											13 <b>Al</b> Aluminum 27.0	14 <b>Si</b> Silicon 28.1	15 <b>P</b> Phosphorus 31.0	16 <b>S</b> Sulfur 32.1	17 <b>Cl</b> Chlorine 35.5	18 <b>Ar</b> Argon 40.0
19 <b>K</b> Potassium 39.1	20 <b>Ca</b> Calcium 40.2	21 <b>Sc</b> Scandium 45.0	22 <b>Ti</b> Titanium 47.9	23 <b>V</b> Vanadium 50.9	24 <b>Cr</b> Chromium 52.0	25 <b>Mn</b> Manganese 54.9	26 <b>Fe</b> Iron 55.9	27 <b>Co</b> Cobalt 58.9	28 <b>Ni</b> Nickel 58.7	29 <b>Cu</b> Copper 63.5	30 <b>Zn</b> Zinc 65.4	31 <b>Ga</b> Gallium 69.7	32 <b>Ge</b> Germanium 72.6	33 <b>As</b> Arsenic 74.9	34 <b>Se</b> Selenium 79.0	35 <b>Br</b> Bromine 79.9	36 <b>Kr</b> Krypton 83.8
37 <b>Rb</b> Rubidium 85.5	38 <b>Sr</b> Strontium 87.6	39 <b>Y</b> Yttrium 88.9	40 <b>Zr</b> Zirconium 91.2	41 <b>Nb</b> Niobium 92.9	42 <b>Mo</b> Molybdenum 95.9	43 <b>Tc</b> Technetium 99	44 <b>Ru</b> Ruthenium 101.0	45 <b>Rh</b> Rhodium 102.9	46 <b>Pd</b> Palladium 106.4	47 <b>Ag</b> Silver 107.9	48 <b>Cd</b> Cadmium 112.4	49 <b>In</b> Indium 114.8	50 <b>Sn</b> Tin 118.7	51 <b>Sb</b> Antimony 121.8	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.9	54 <b>Xe</b> Xenon 131.3
55 <b>Cs</b> Caesium 132.9	56 <b>Ba</b> Barium 137.4	57-71 <b>Lanthanides</b>	72 <b>Hf</b> Hafnium 178.5	73 <b>Ta</b> Tantalum 181.0	74 <b>W</b> Tungsten 183.9	75 <b>Re</b> Rhenium 186.2	76 <b>Os</b> Osmium 190.2	77 <b>Ir</b> Iridium 192.2	78 <b>Pt</b> Platinum 195.1	79 <b>Au</b> Gold 197.0	80 <b>Hg</b> Mercury 200.6	81 <b>Tl</b> Thallium 204.4	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 209.0	84 <b>Po</b> Polonium 210.0	85 <b>At</b> Astatine 210.0	86 <b>Rn</b> Radon 222.0
87 <b>Fr</b> Francium 223.0	88 <b>Ra</b> Radium 226.0	89-103 <b>Actinides</b>	104 <b>Rf</b> Rutherfordium 261	105 <b>Db</b> Dubnium 262	106 <b>Sg</b> Seaborgium 263	107 <b>Bh</b> Bohrium 262	108 <b>Hs</b> Hassium 265	109 <b>Mt</b> Meitnerium 266	110 <b>Uun</b> Ununnilium 272								
57 <b>La</b> Lanthanum 138.9	58 <b>Ce</b> Cerium 140.1	59 <b>Pr</b> Praseodymium 140.9	60 <b>Nd</b> Neodymium 144.2	61 <b>Pm</b> Promethium 147.0	62 <b>Sm</b> Samarium 150.4	63 <b>Eu</b> Europium 152.0	64 <b>Gd</b> Gadolinium 157.3	65 <b>Tb</b> Terbium 158.9	66 <b>Dy</b> Dysprosium 162.5	67 <b>Ho</b> Holmium 164.9	68 <b>Er</b> Erbium 167.3	69 <b>Tm</b> Thulium 168.9	70 <b>Yb</b> Ytterbium 173.0	71 <b>Lu</b> Lutetium 175.0			
89 <b>Ac</b> Actinium 132.9	90 <b>Th</b> Thorium 232.0	91 <b>Pa</b> Protactinium 231.0	92 <b>U</b> Uranium 238.0	93 <b>Np</b> Neptunium 237.0	94 <b>Pu</b> Plutonium 242.0	95 <b>Am</b> Americium 243.0	96 <b>Cm</b> Curium 247.0	97 <b>Bk</b> Berkelium 247.0	98 <b>Cf</b> Californium 251.0	99 <b>Es</b> Einsteinium 254.0	100 <b>Fm</b> Fermium 253.0	101 <b>Md</b> Mendelevium 256.0	102 <b>No</b> Nobelium 254.0	103 <b>Lr</b> Lawrencium 257.0			

**Types of Elements Key:**

- Alkali metal
- Alkaline earth metal
- Transition metal
- Lanthanides
- Actinides
- Poor metal
- Semi-metal
- Non-metal
- Noble gases

# Periodic Table and Detector Material

**Periodic Table**

										II III IV V VI																
1 H Hydrogen 1.0																		2 He Helium 4.0								
3 Li Lithium 6.9	4 Be Beryllium 9.0																		5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2		
11 Na Sodium 23.0	12 Mg Magnesium 24.3																		13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0		
19 K Potassium 39.1	20 Ca Calcium 40.1	21 Sc Scandium 45.0	22 Ti Titanium 47.9	23 V Vanadium 50.9	24 Cr Chromium 52.0	25 Mn Manganese 54.9	26 Fe Iron 55.8	27 Co Cobalt 58.9	28 Ni Nickel 58.7	29 Cu Copper 63.5	30 Zn Zinc 65.4	31 Ga Gallium 69.7	32 Ge Germanium 72.6	33 As Arsenic 74.9	34 Se Selenium 79.0	35 Br Bromine 79.9	36 Kr Krypton 83.8									
37 Rb Rubidium 85.5	38 Sr Strontium 87.6	39 Y Yttrium 88.9	40 Zr Zirconium 91.2	41 Nb Niobium 92.9	42 Mo Molybdenum 95.9	43 Tc Technetium 99	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3									
55 Cs Cesium 132.9	56 Ba Barium 137.4	57-71 Lanthanides	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium 210.0	85 At Astatine 210.0	86 Rn Radon 222.0									
87 Fr Francium 223.0	88 Ra Radium 226.0	89-103 Actinides	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununium 272																	

**Detector Families**

**Si** - IV semiconductor

**HgCdTe** - II-VI semiconductor

**InGaAs & InSb** - III-V semiconductors

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu															
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr															

Legend of Element Type

- Alkali metal
- Alkali earth metal
- Transition metal
- Lanthanides
- Actinides
- Poor metal
- Semi metal
- Non metal
- Noble gas

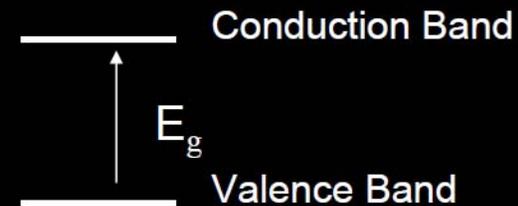
# Band Gaps

## Photon Detection

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

$$h\nu > E_g$$

$h$  = Planck constant ( $6.63 \cdot 10^{-34}$  Joule $\cdot$ 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)	$\lambda_c$ ( $\mu\text{m}$ )
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 ( $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ )

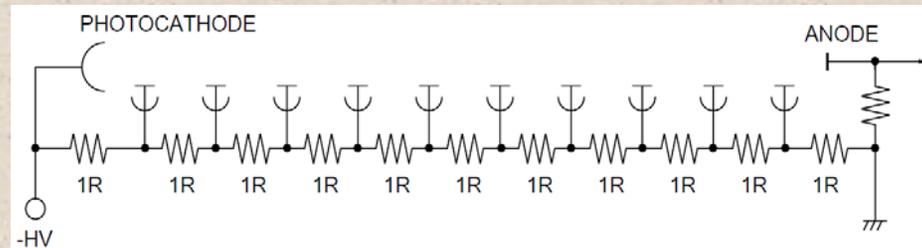
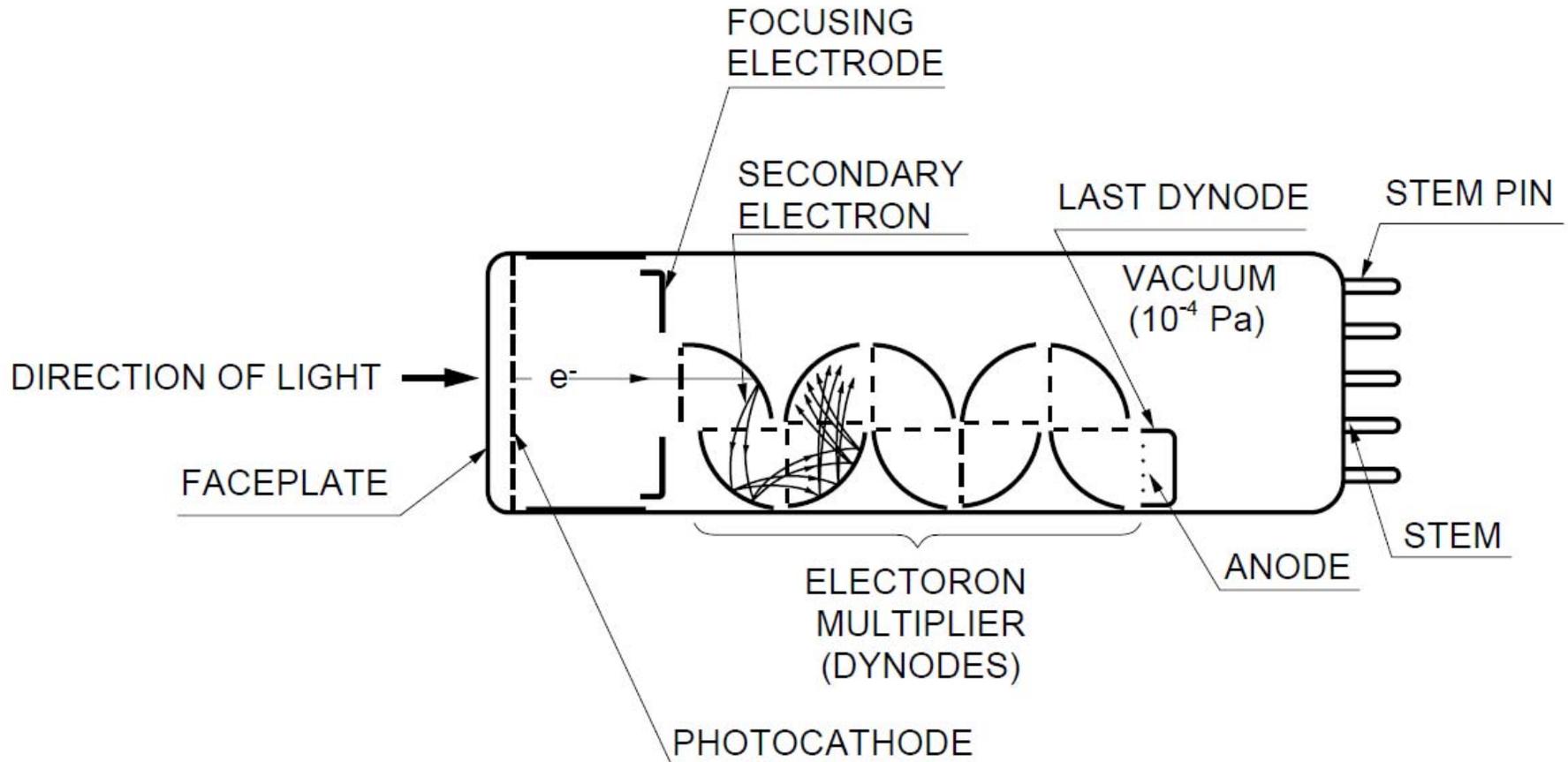


# Photo-multiplier Tubes

# Photo-multiplier Tubes (PMTs)

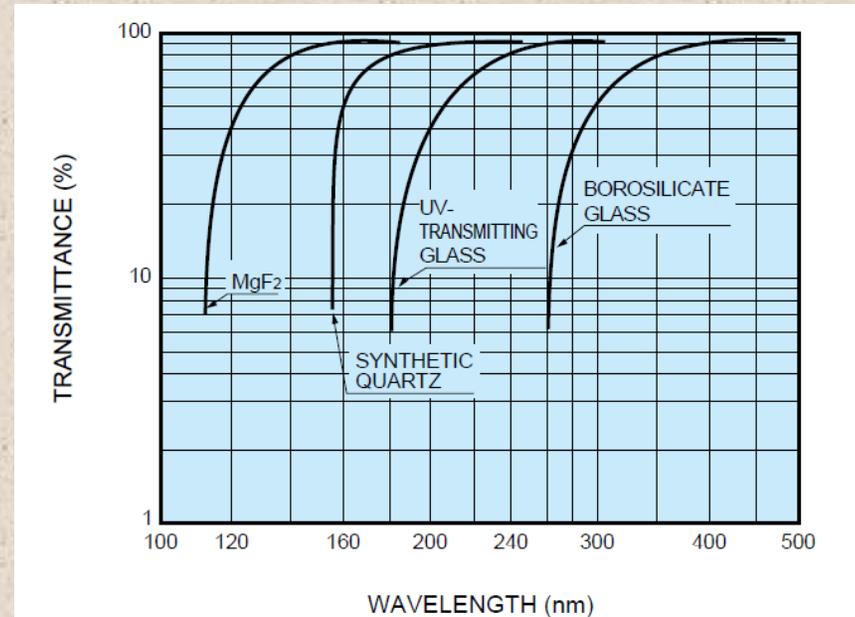
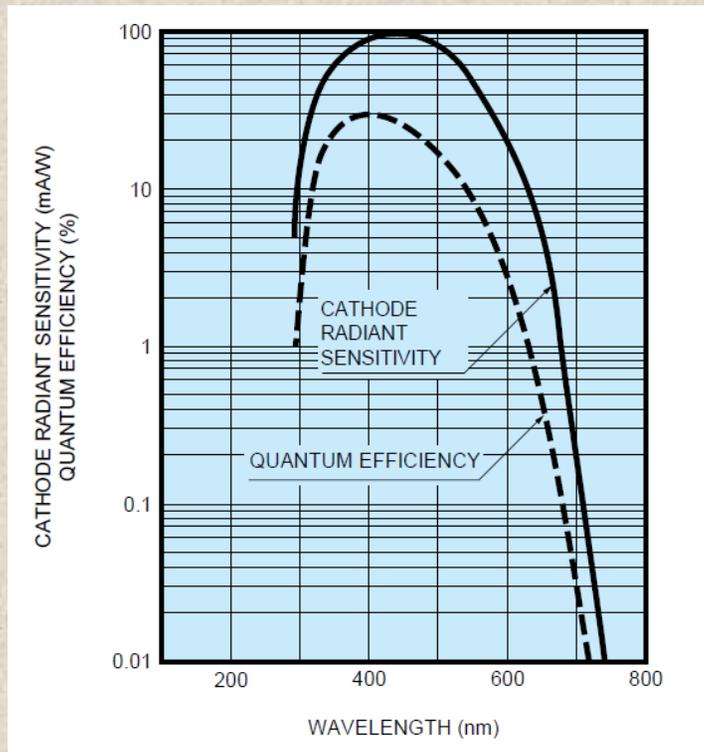
- PMTs convert individual photons into relatively large packets of charge through an avalanche process that relies upon the photoelectric effect.
- The incoming photon must have sufficient energy to generate charge with energy that exceeds the “work function,” i.e. enough energy to be able to leave the 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



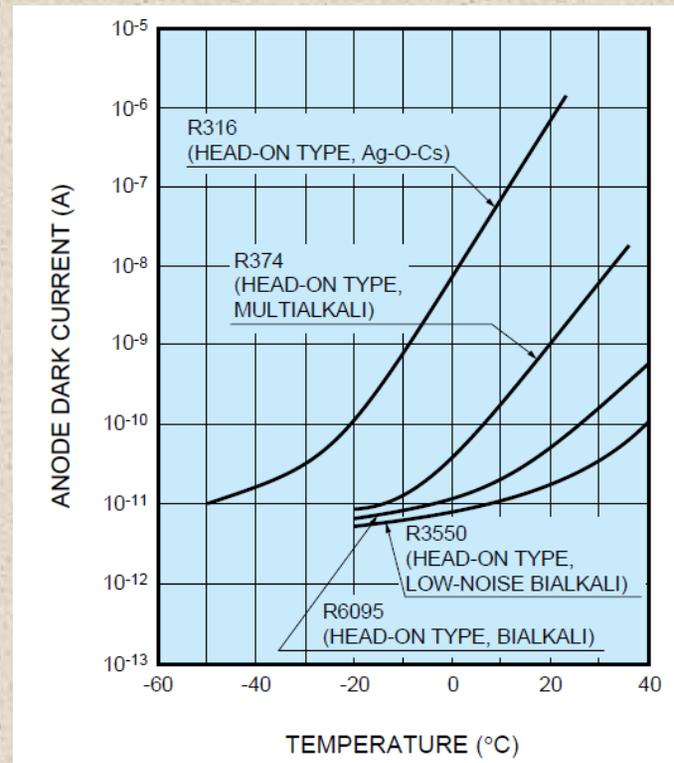
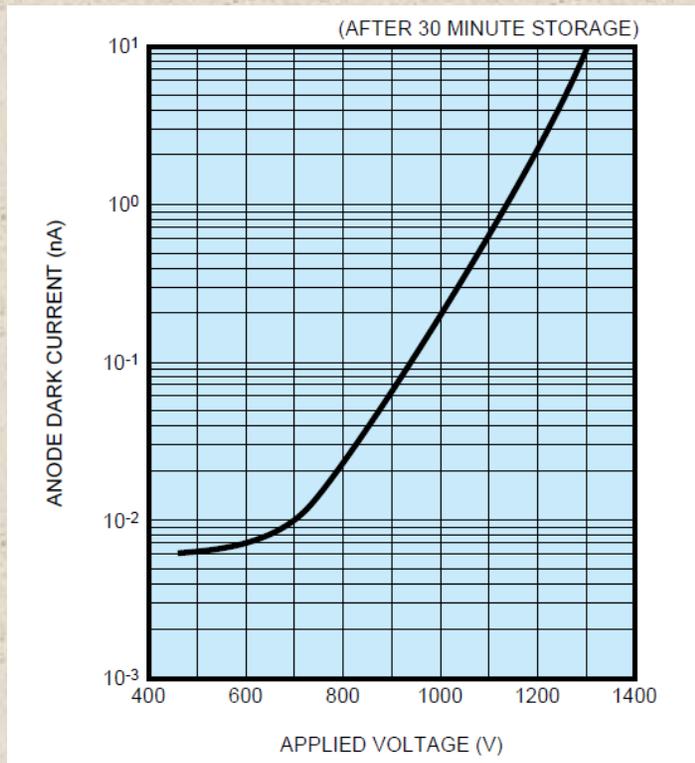
# PMT Response

- 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).

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

where

q = electronic charge ( $1.60 \times 10^{-19}$  coul.)

I<sub>db</sub> = anode dark current in amperes after 30-minute storage in darkness

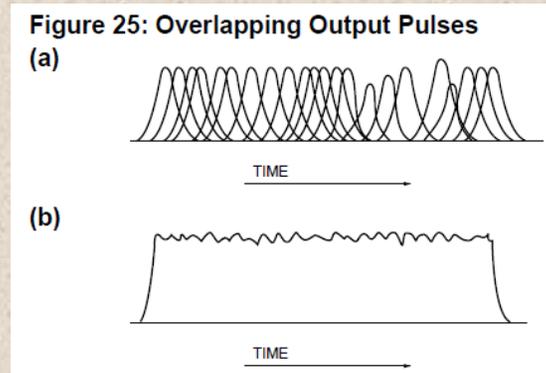
μ = current amplification

Δf = 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

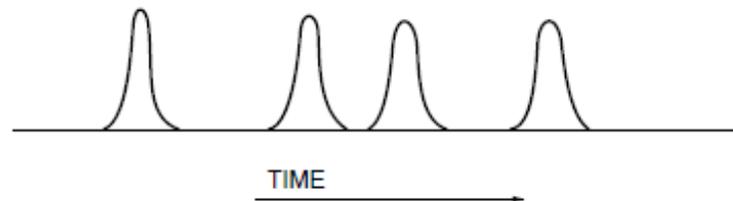
# PMTs and Single Photon Counting

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



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

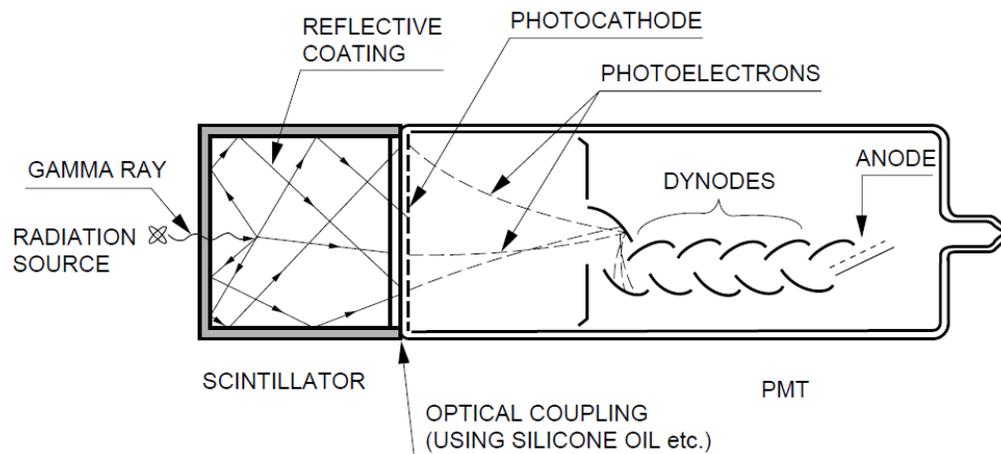
**Figure 26: Discrete Output Pulses (Single Photon Event)**



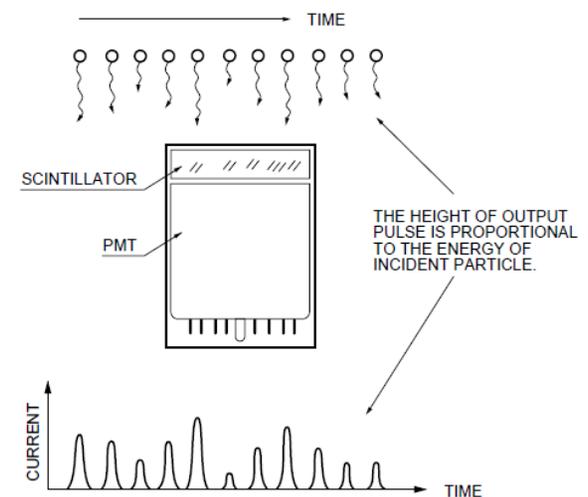
# PMTs and High Energy Detection

- 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**

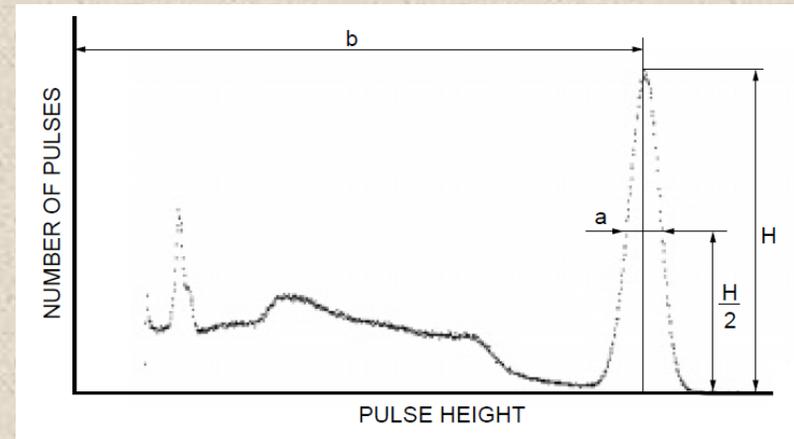
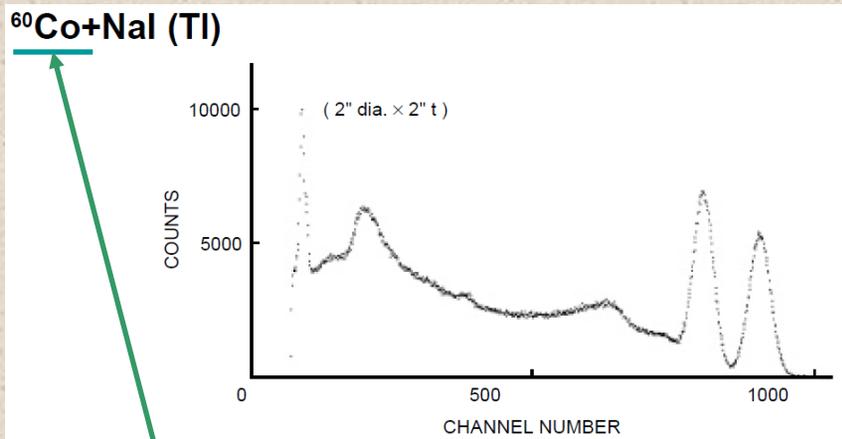
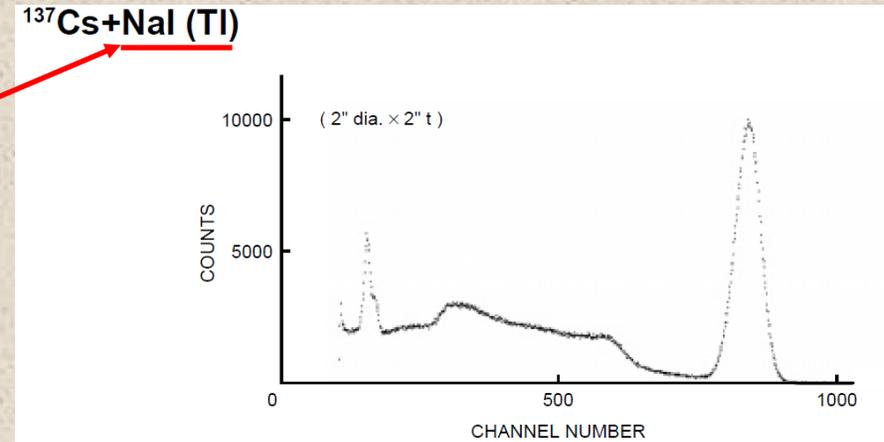
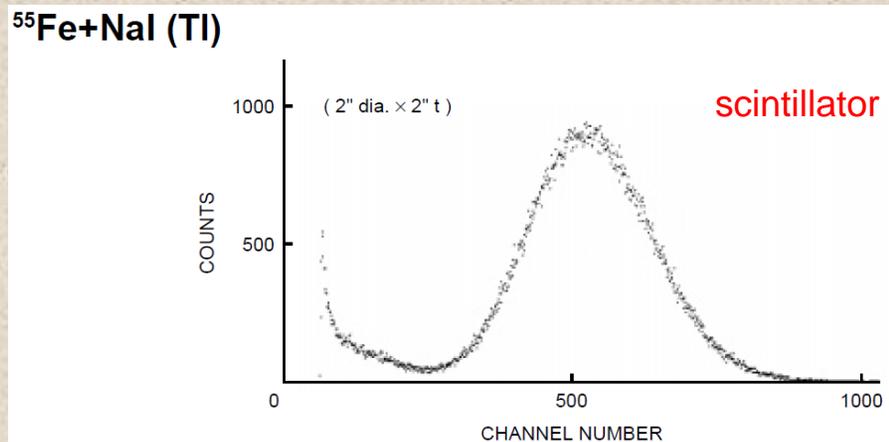


**Figure 30: Incident Particles and PMT Output**



# PMTs and Energy Resolution

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



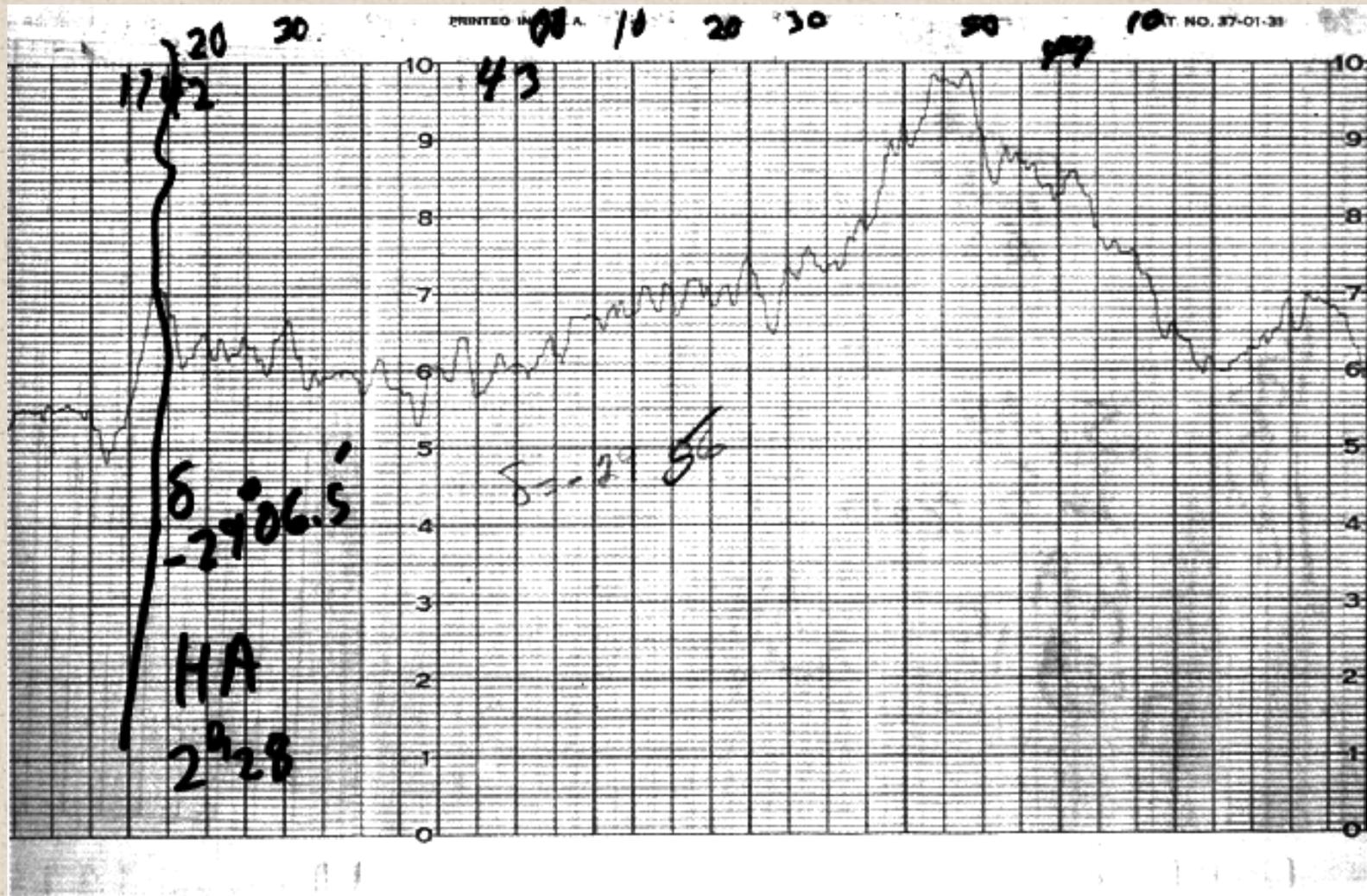
# PMTs Examples (Hamamatsu)

es

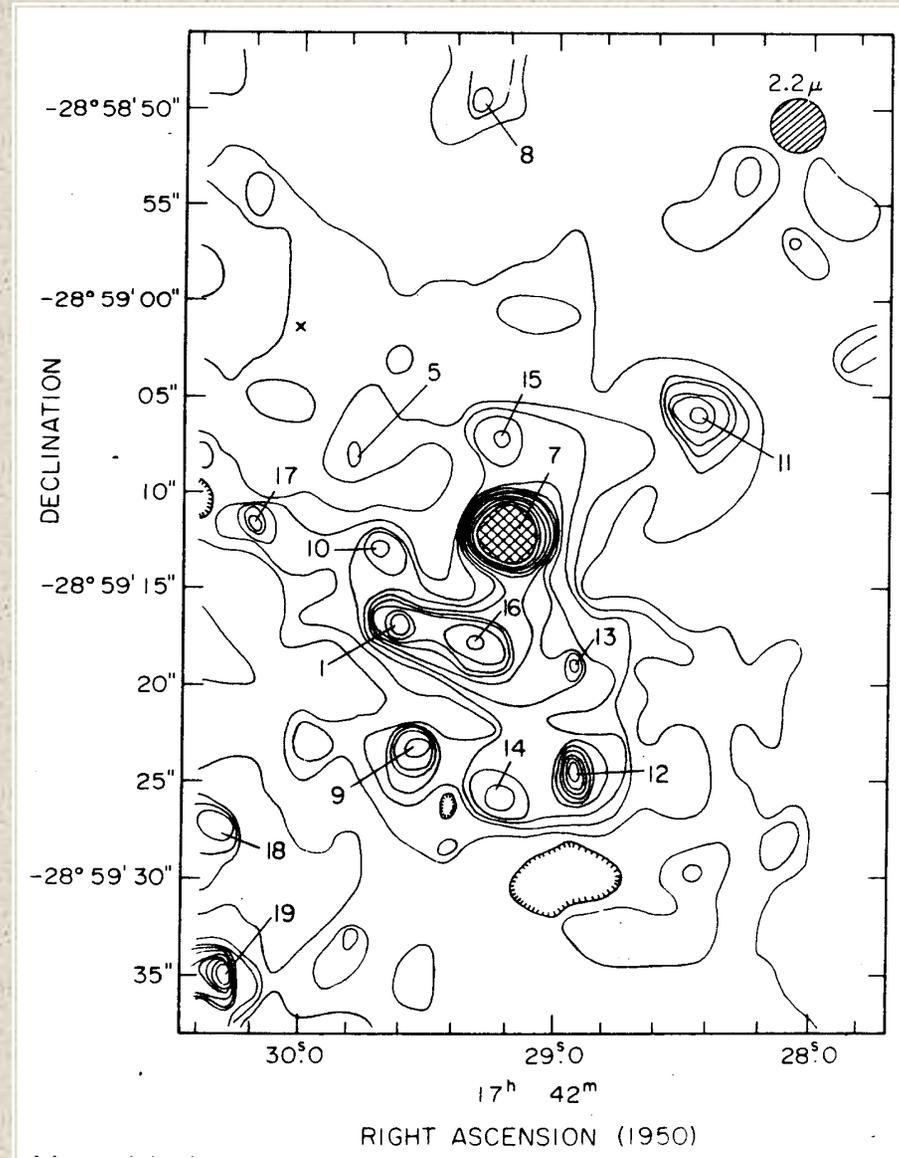
Part Number	Type	Size mm	Min $\lambda$ nm	Max $\lambda$ nm	Peak Sens. nm	Window	Gain	Dark Current after 30 min. nA	Rise Time ns	Multi Anode
<b>R10699</b>	Side on	28		450		UV Glass	1.3 X 10 <sup>7</sup>	2	2.2	
<b>H10744</b>	Assembly			240		Sapphire	1.0 x 10 <sup>7</sup>		2.5	
<b>R9880U-210</b> <small>Now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

# Applications

# The Galactic Center: Discovery Strip Chart

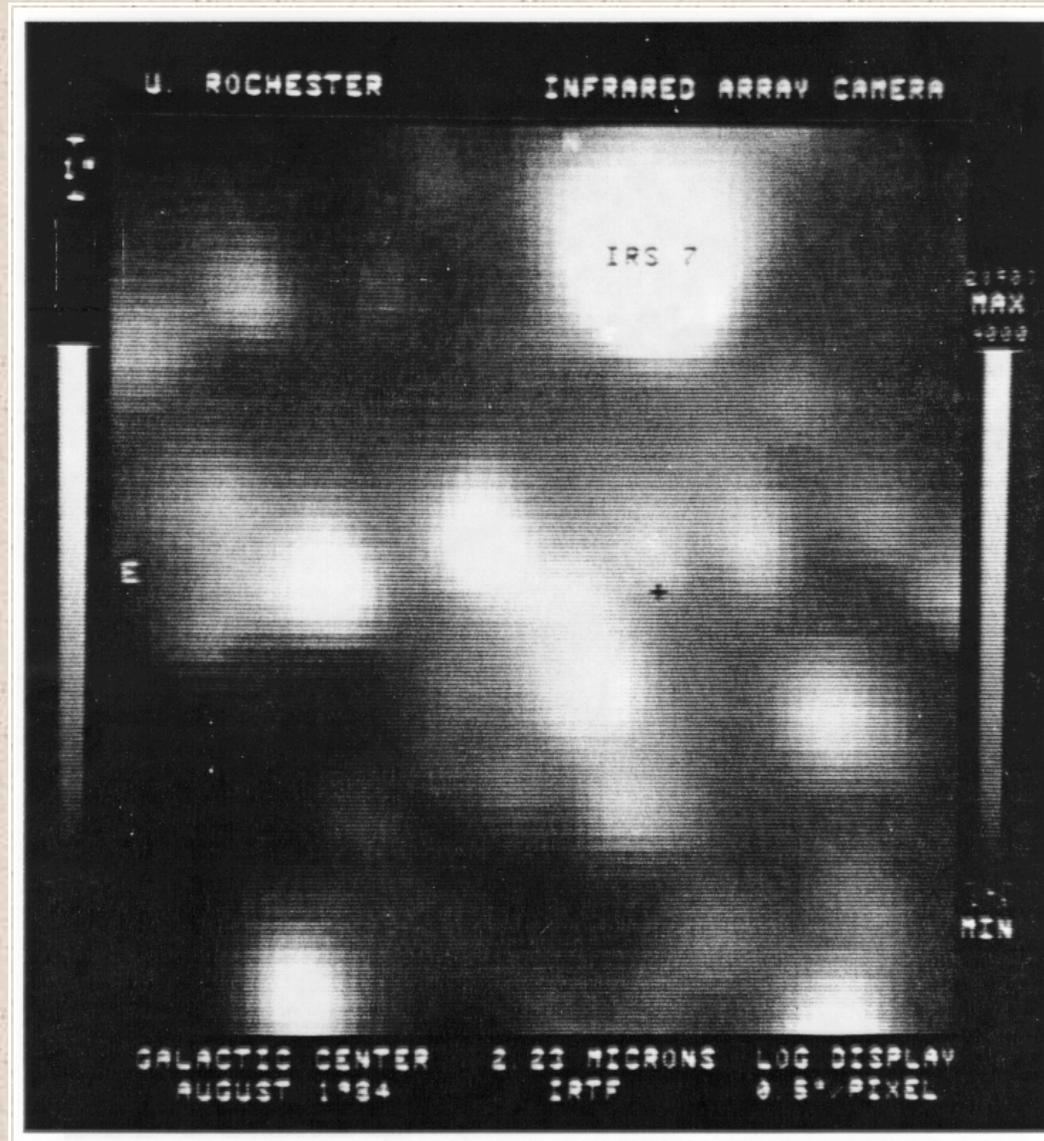


# The Galactic Center: PbS Bolometer



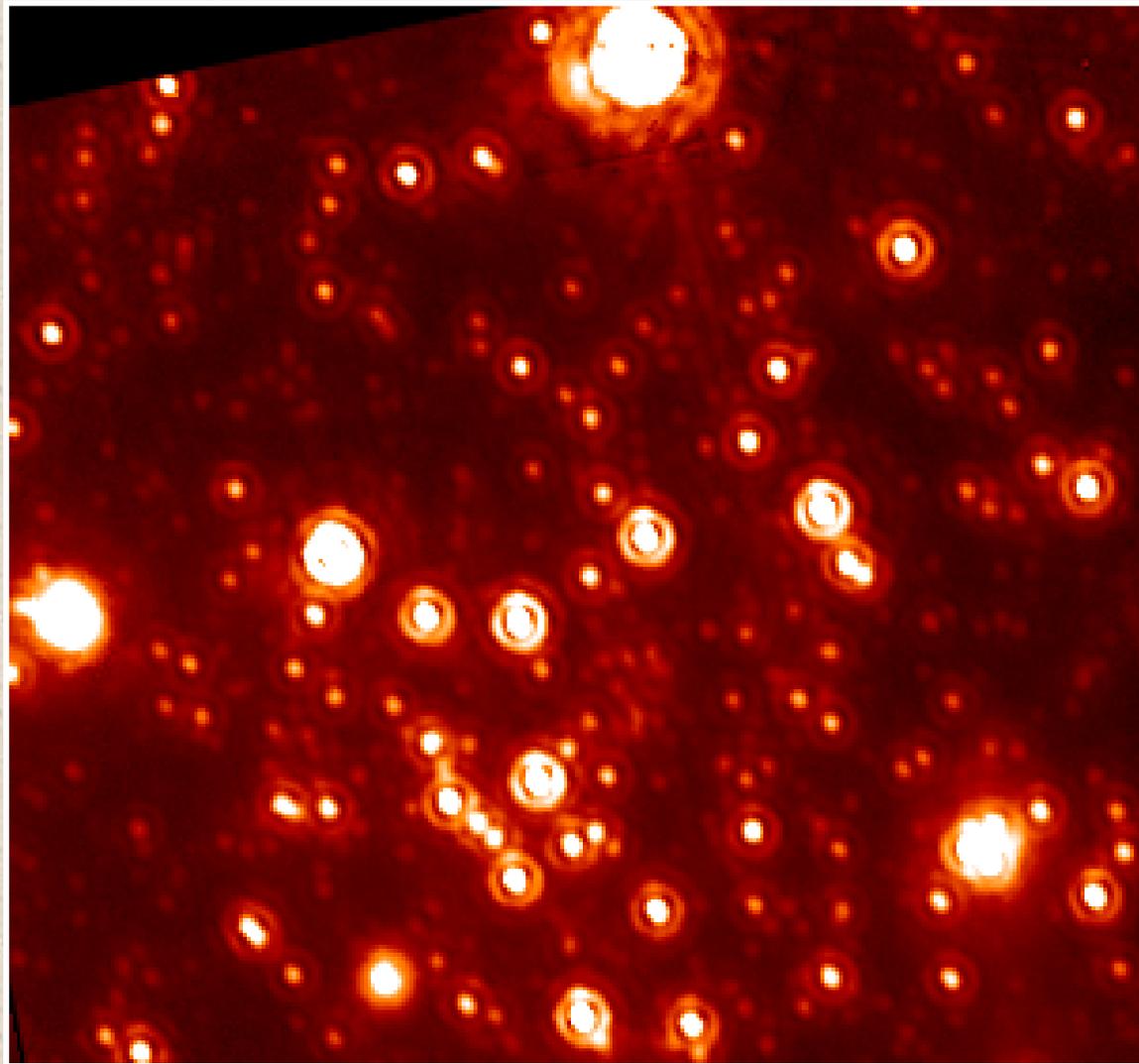
Becklin and Neugebauer, 1975

# The Galactic Center: InSb Photodiode Array



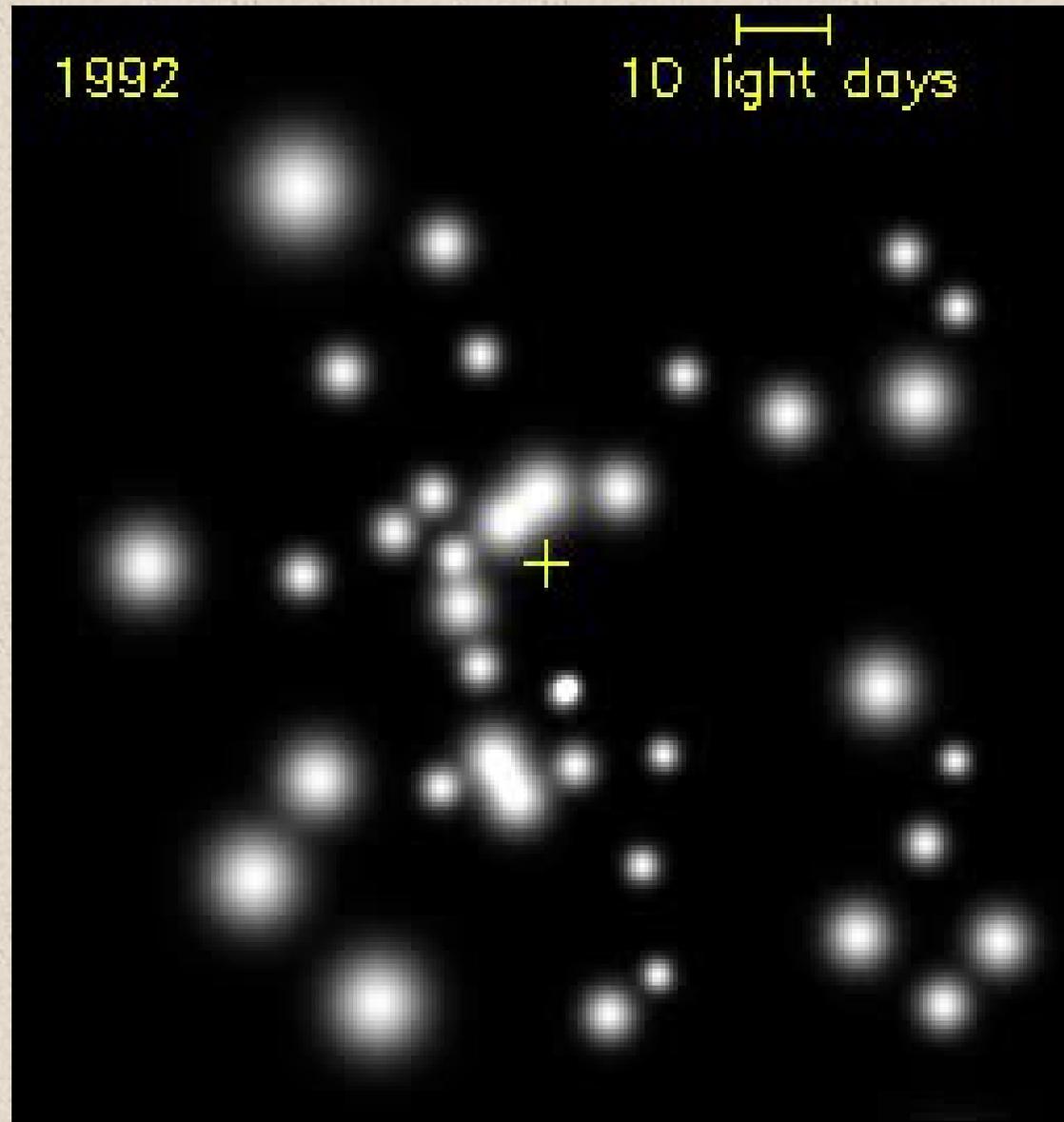
Forrest et al., 1986

# The Galactic Center: HgCdTe Photodiode Array



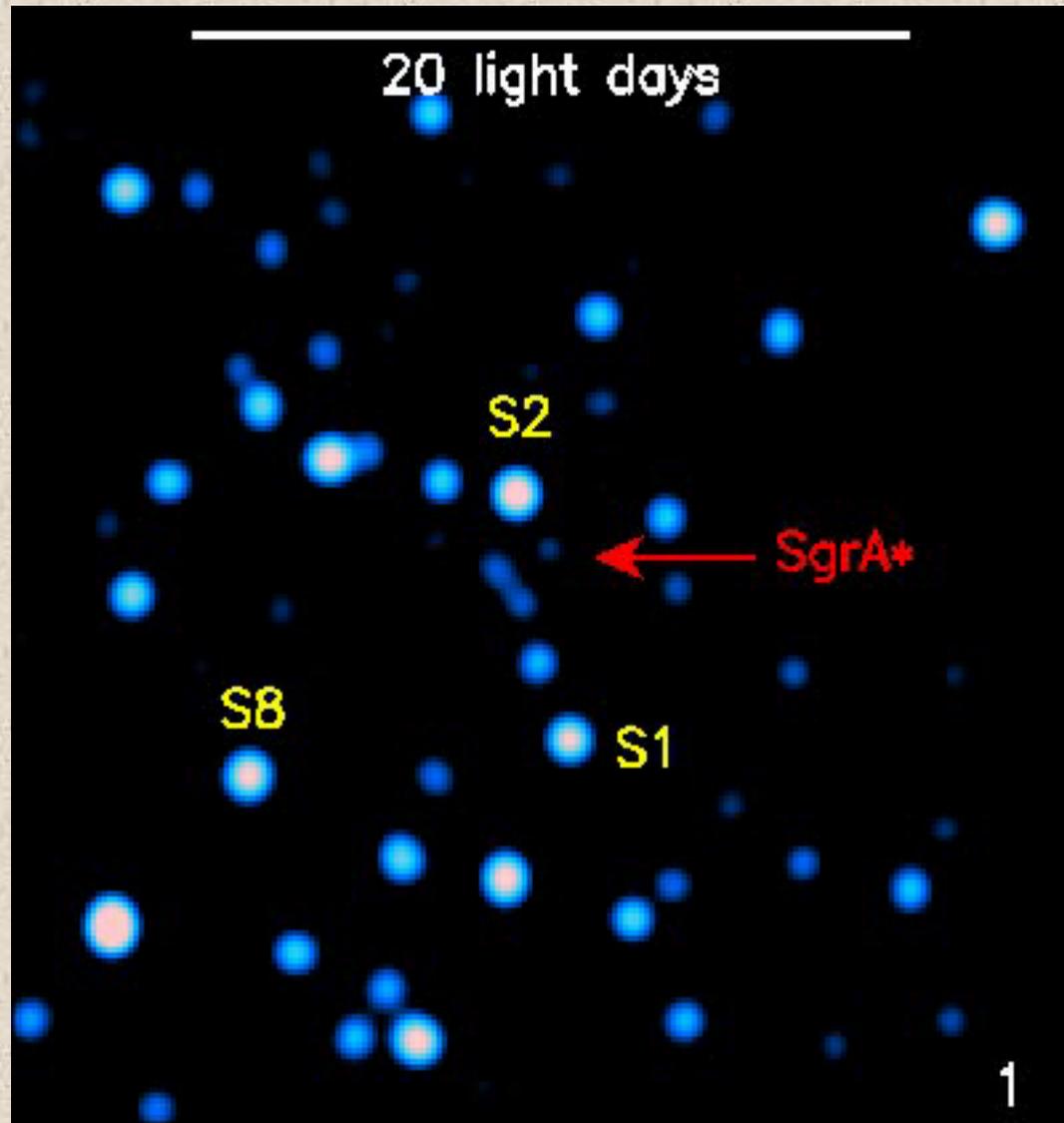
Rigaut et al., 1998

# 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...

