The basic physics of astronomical detectors

Our Eyes on the Universe

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27 February 2012

Teledyne Imaging Sensors

Detector technologies involve nearly all areas of Physics and Engineering

Detectors
(a.k.a. Imaging Sensors)

Electricity & Magnetism

Atomic Physics

Mechanics

Thermodynamics

Optics

Electronics

Solid State Physics

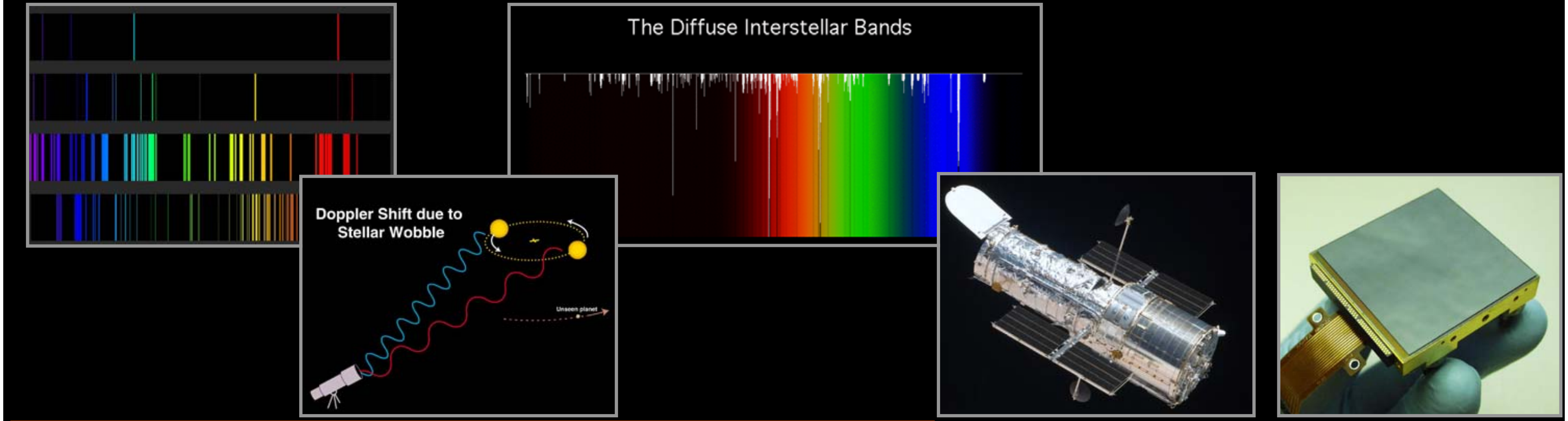
Cryogenics

Quantum Mechanics

Acoustics

Statistical Mechanics

The Generation, Propagation & Detection of Light



Emission → Propagation → Absorption → Collection → Detection

Emission

- Physics of the object under study
- Media in the path of propagation

Propagation

- Speed of light
- Doppler effect
- Expansion of the universe
- Gravitational lensing
- Atmospheric distortions

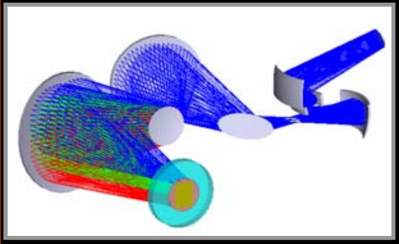
Absorption

- Intergalactic medium (IGM)
- Interstellar medium (ISM)
- Earth's atmosphere

The Physics of the Universe

Collection

- Telescopes
- Instrumentation

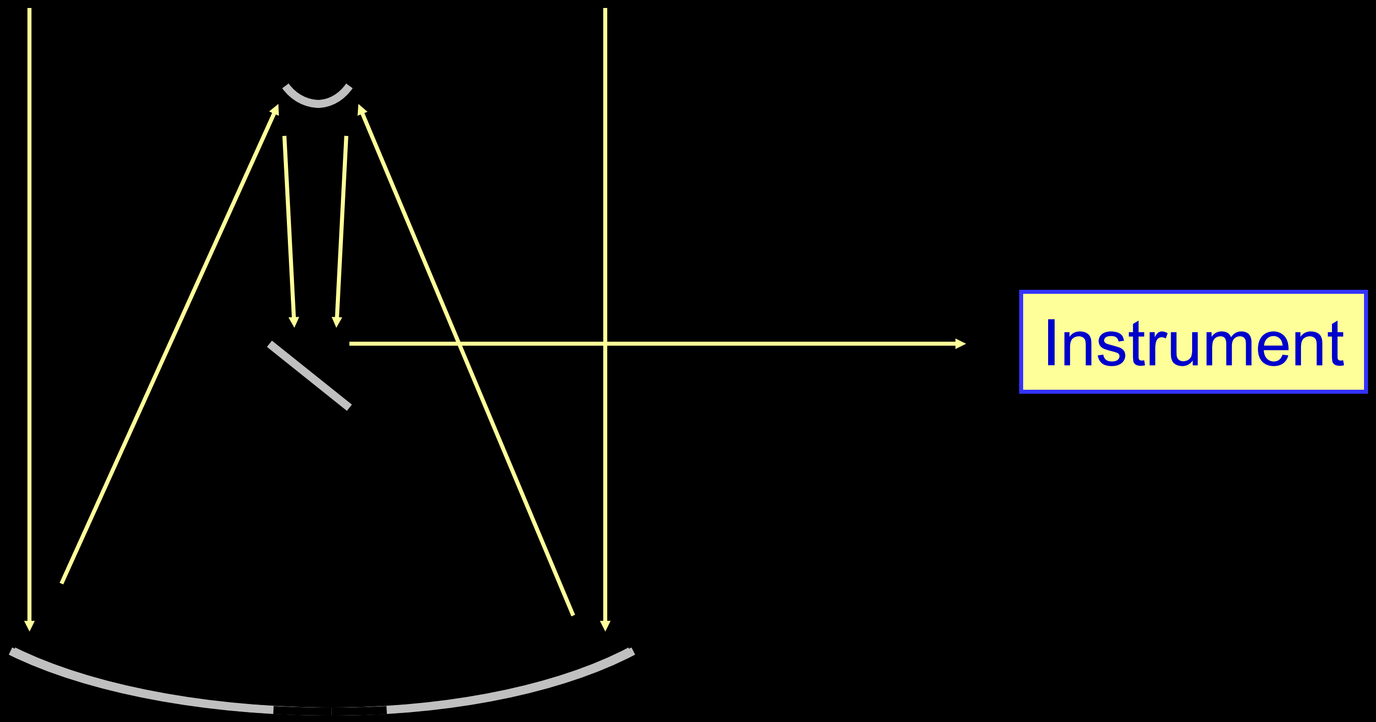


Optical and Infrared Astronomy

(0.3 to 25 μm)

Two basic parts

Telescope to collect and focus light **Instrument** to measure light



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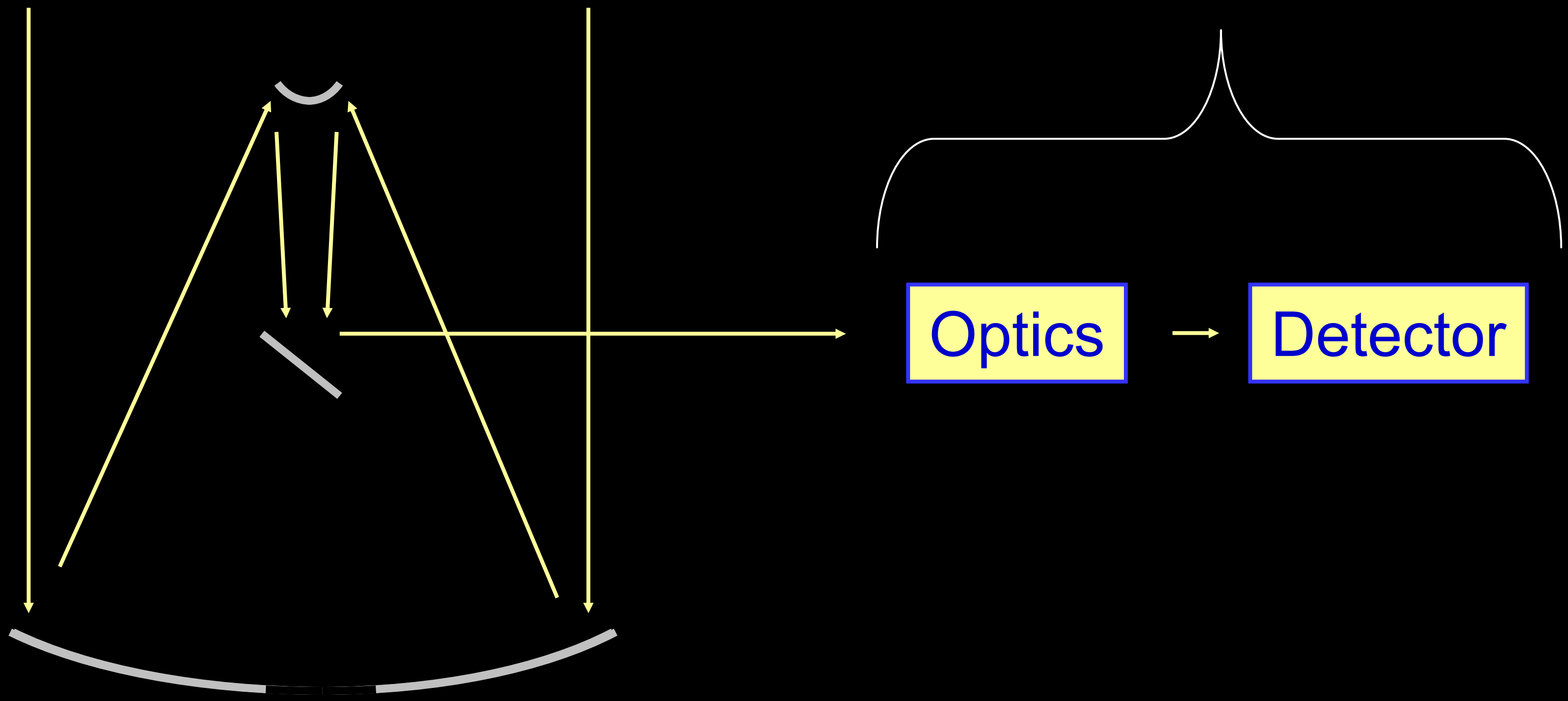
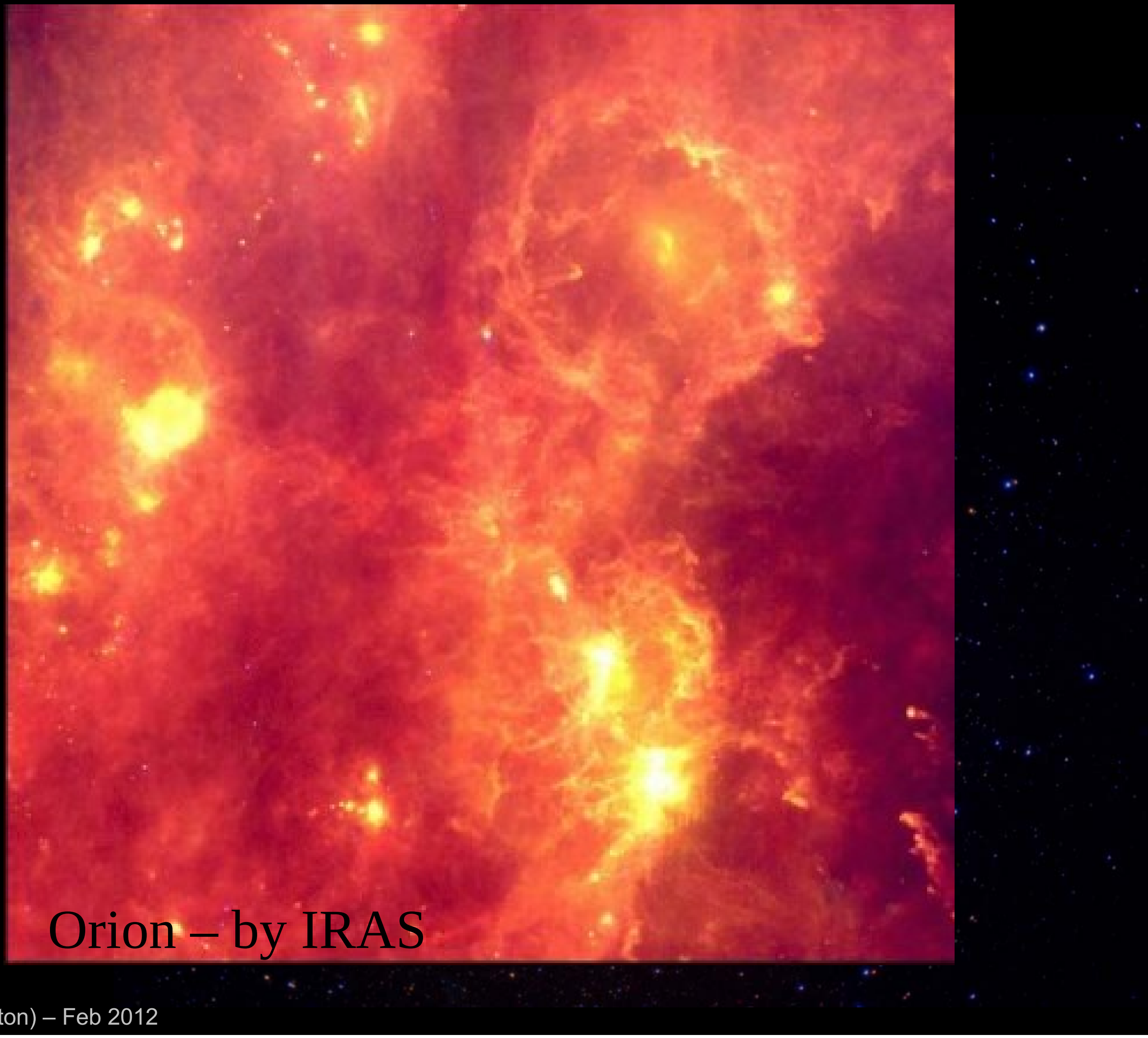


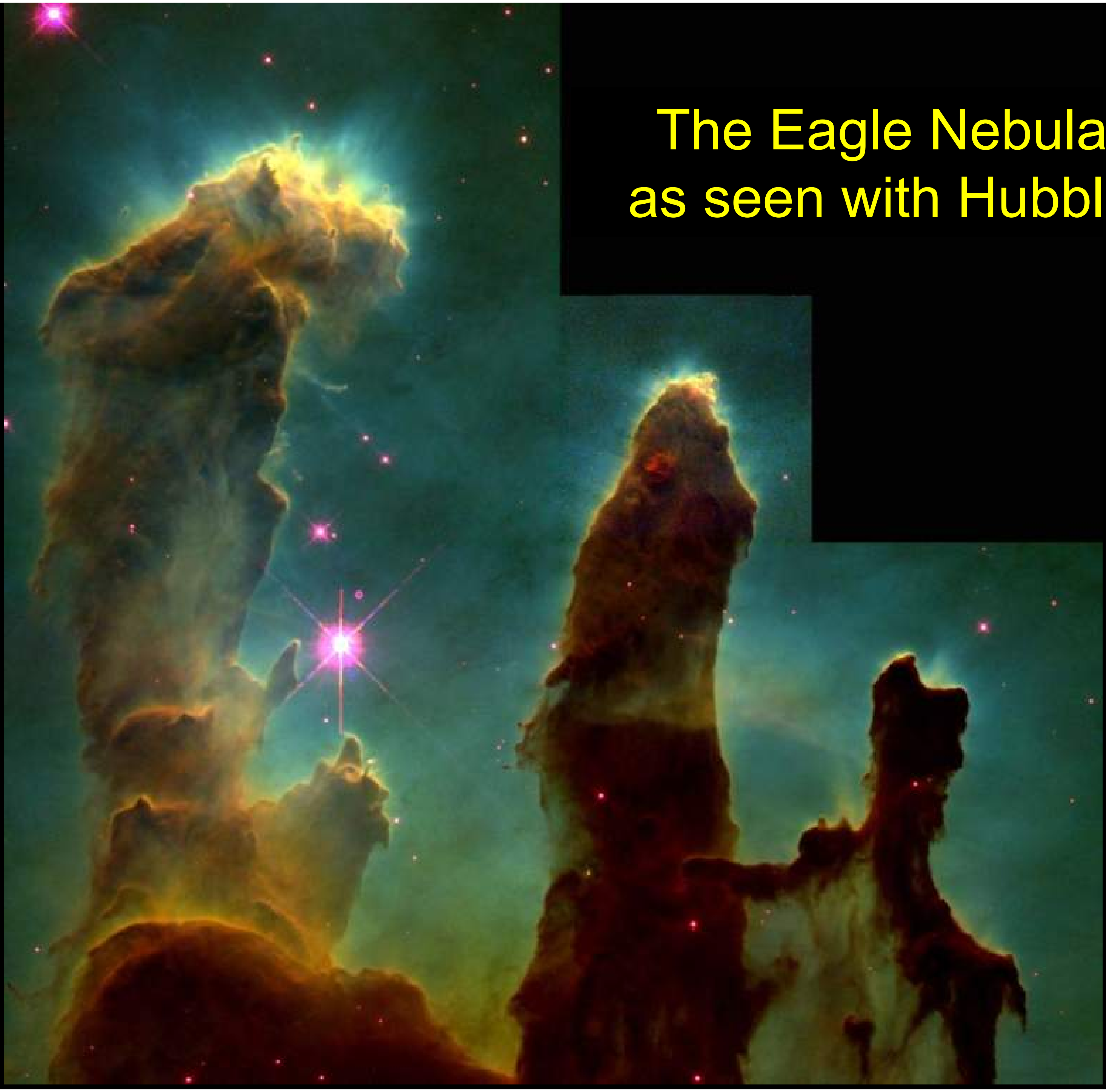
Optics → Detector

Orion – In visible and infrared light

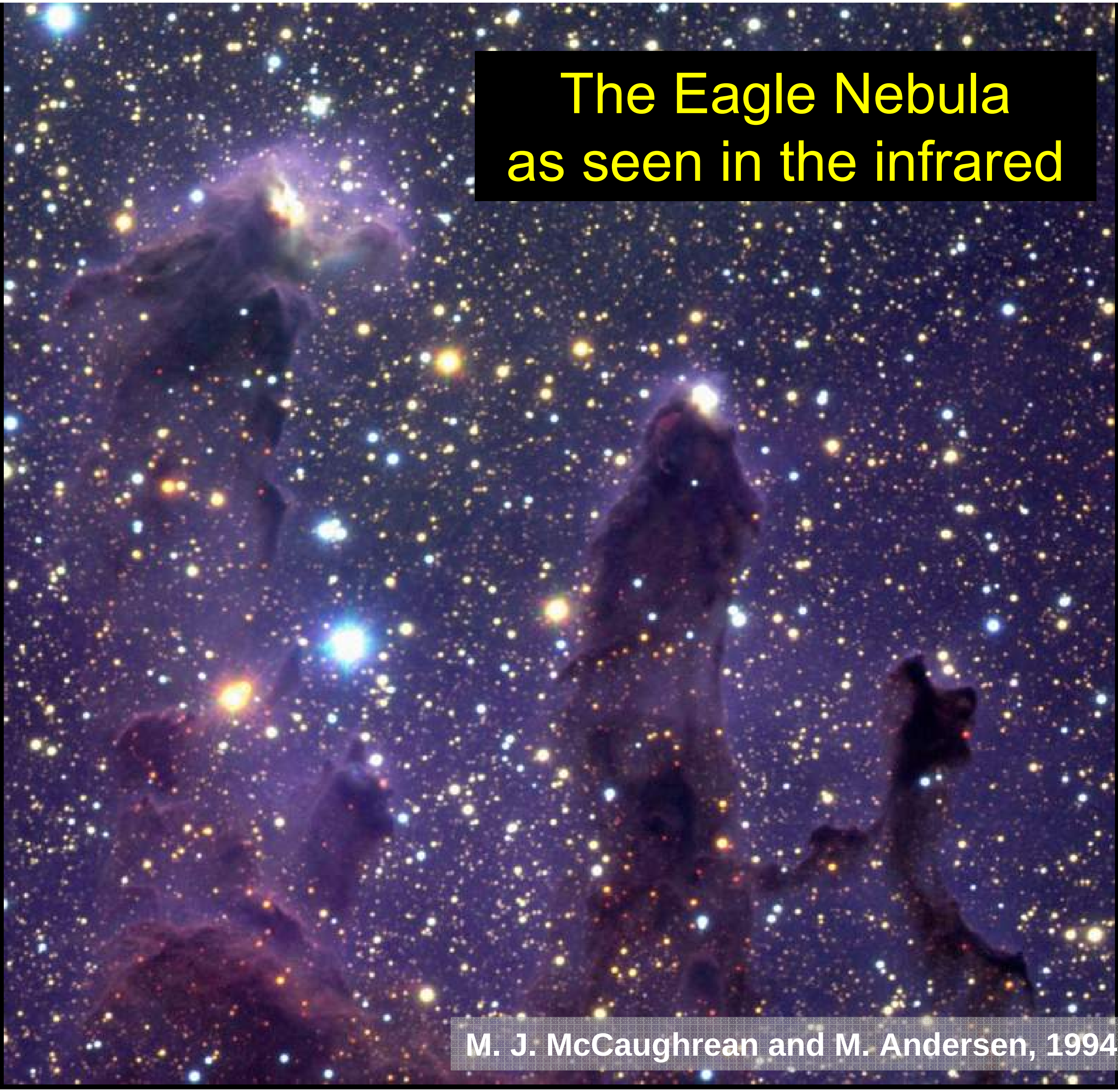


Orion – by IRAS

The Eagle Nebula as seen with Hubble

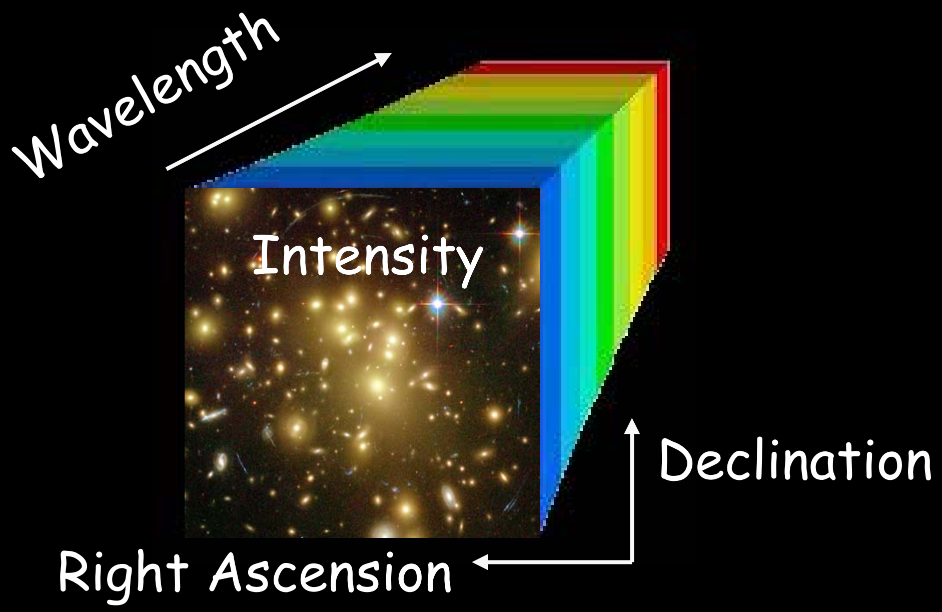


The Eagle Nebula as seen in the infrared



M. J. McCaughrean and M. Andersen, 1994

Instrument goal is to measure a 3-D data cube

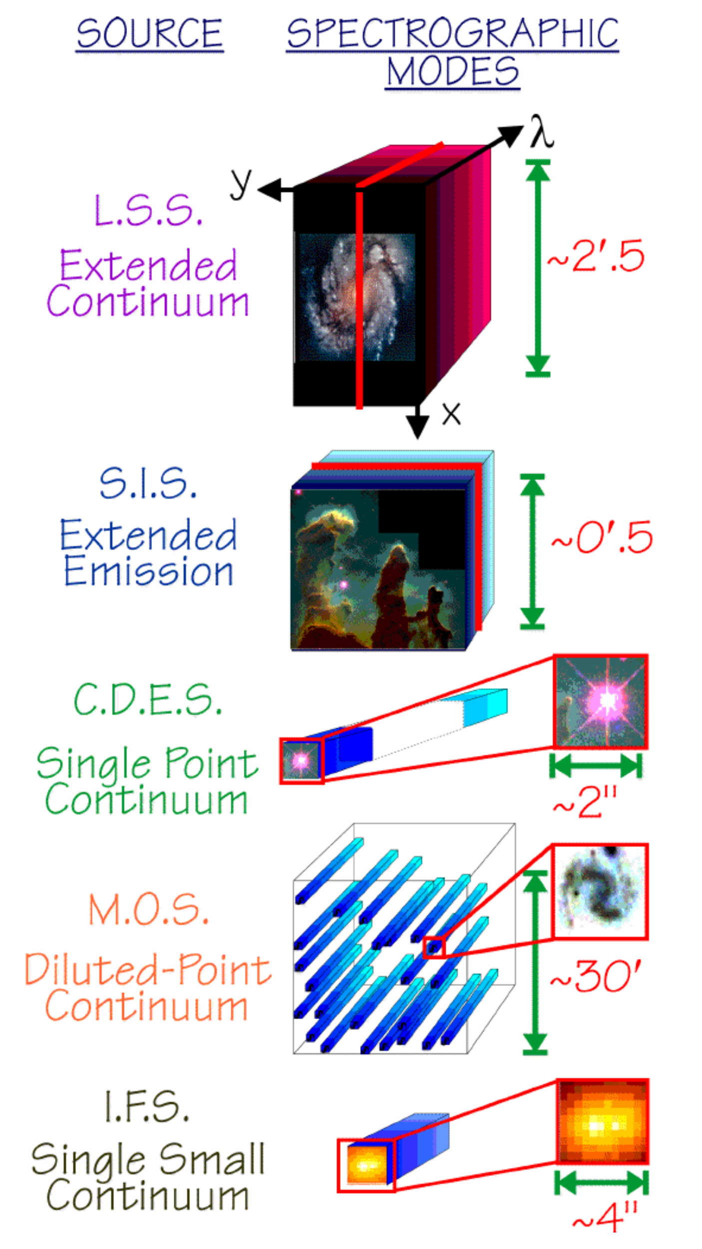


But most detectors are 2-dimensional !

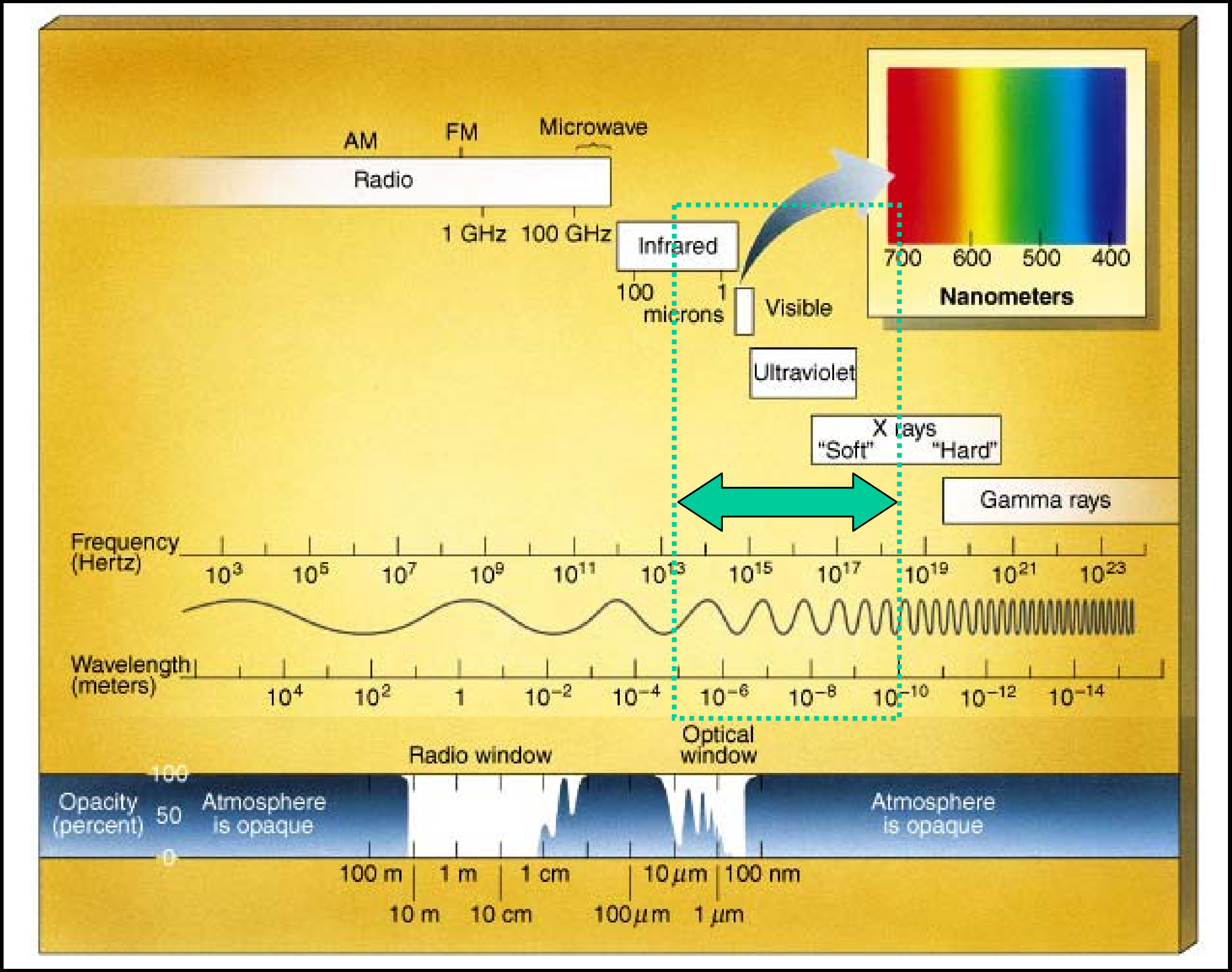
- Detectors are **BLACK & WHITE**
- Can’t measure color (exception: x-rays)
- Only measure intensity

Optics of the instrument map a portion of the 3-D data cube onto the 2-D detector

With appropriate apologies to Foveon and 3rd Gen IR

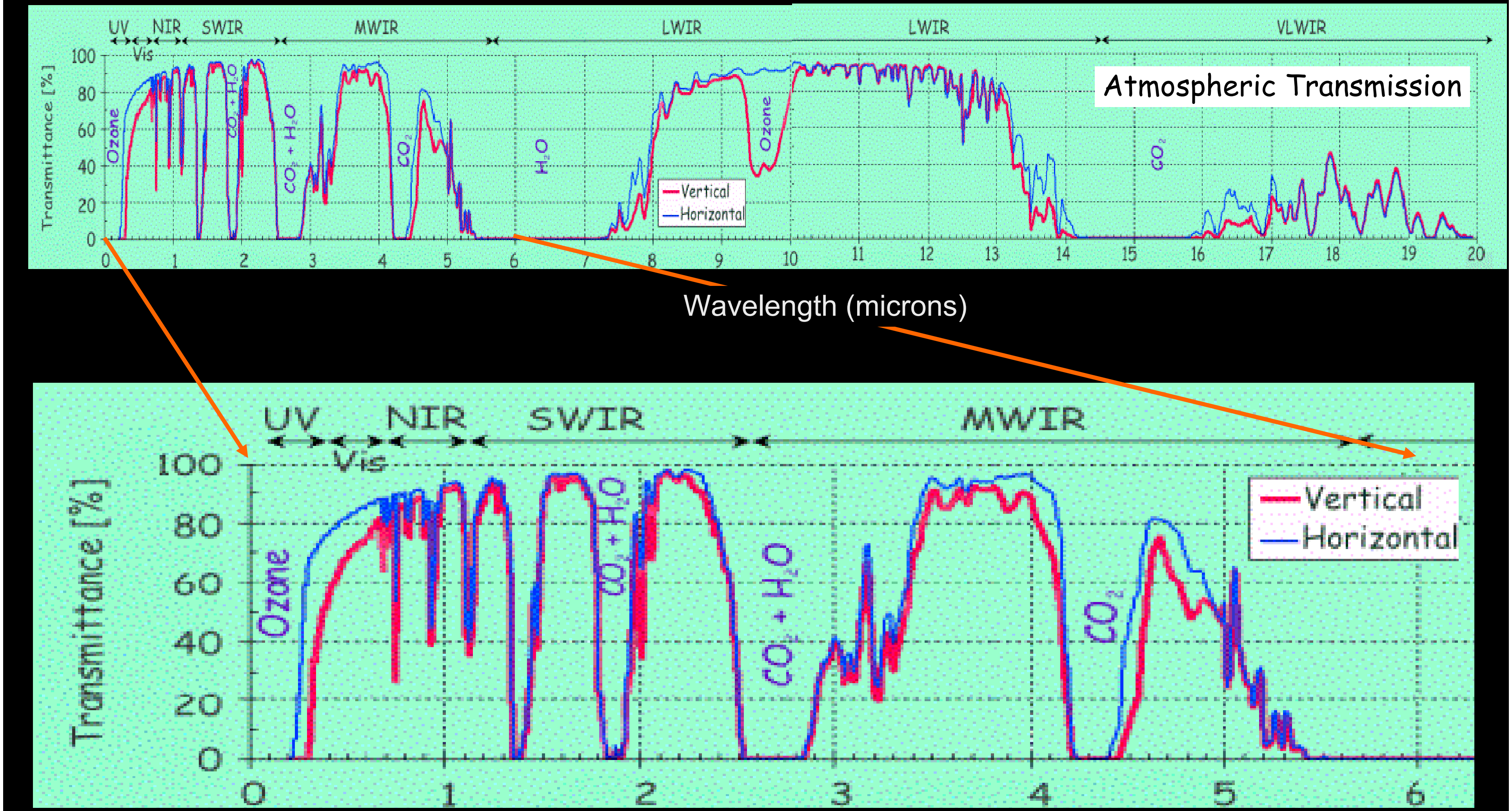


The Electromagnetic Spectrum



Atmospheric transmission

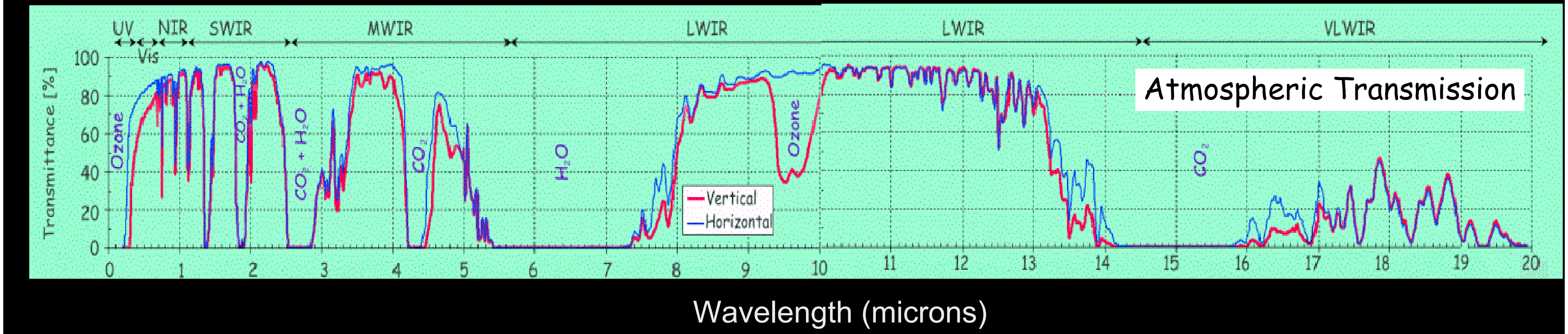
Not all of the light gets through atmosphere to ground-based telescopes



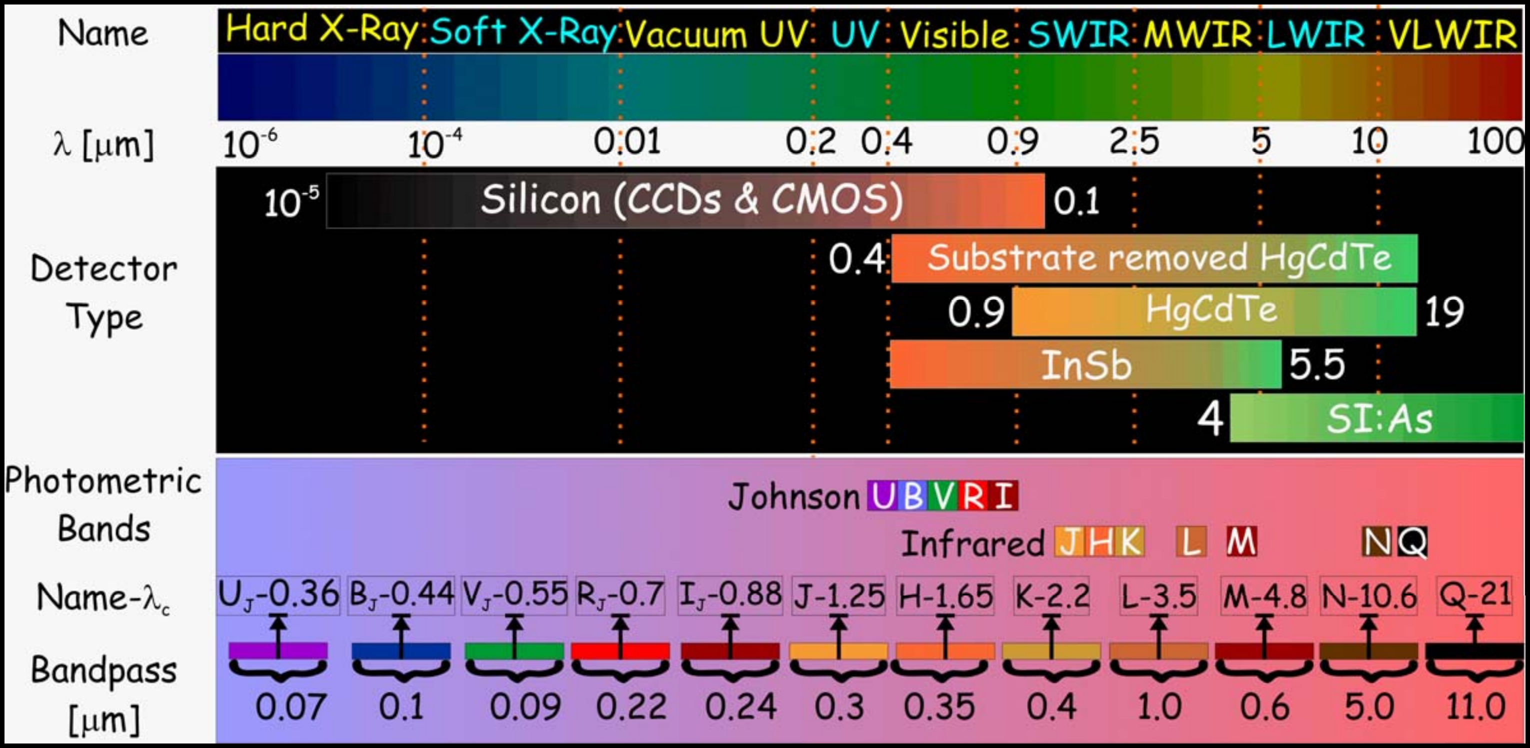
Common Astronomical Filters	J	H	K	L	M
	1.1-1.4	1.5-1.8	2.0-2.4	3.0-4.0	4.5-5.1

Spectral Bands

Defined by atmospheric transmission & detector material properties



Detector Zoology



Energy of a photon

$E = h\nu$

h = Planck constant (6.63×10^{-34} Joule•sec)

ν = frequency of light (cycles/sec) = λ/c

Wavelength (μm)	**Energy (eV)**	**Band**
0.3	4.13	UV
0.5	2.48	Vis
0.7	1.77	Vis
1.0	1.24	NIR
2.5	0.50	SWIR
5.0	0.25	MWIR
10.0	0.12	LWIR
20.0	0.06	VLWIR

Nota Bene:

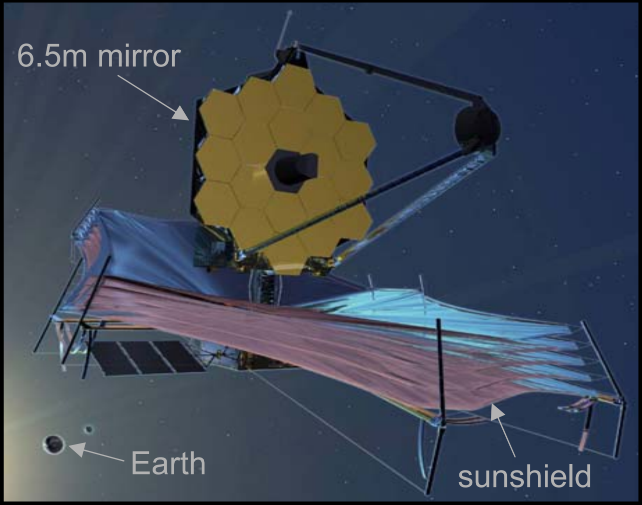
IR Industry definitions

NOT the same for astronomers !

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt potential difference.

JWST - James Webb Space Telescope

15 Teledyne 2K×2K infrared arrays on board (63 million pixels)



- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2018 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

FGS

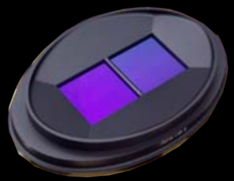
(Fine Guidance Sensors)

3 individual MWIR 2Kx2K

- Acquisition and guiding
- Images guide stars for telescope stabilization
- Canadian Space Agency

NIRSpec

(Near Infrared Spectrograph)

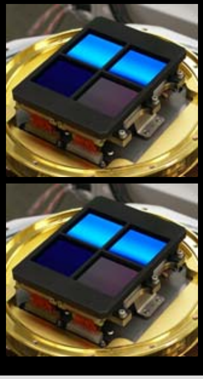


1x2 mosaic of MWIR 2Kx2K

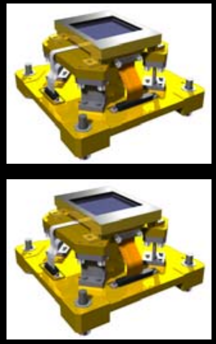
- Spectrograph
- Measures chemical composition, temperature and velocity
- European Space Agency / NASA

NIRCam

(Near Infrared Camera)



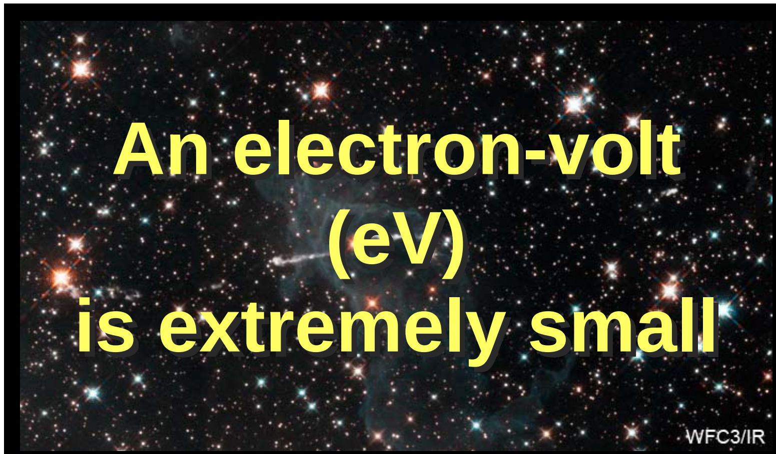
Two 2x2 mosaics of SWIR 2Kx2K



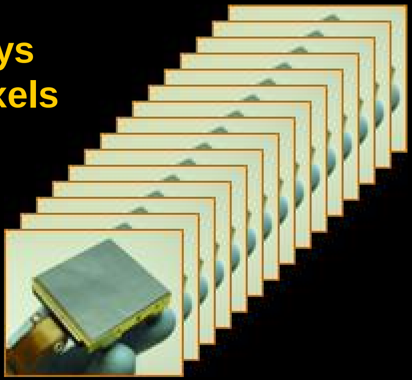
Two individual MWIR 2Kx2K

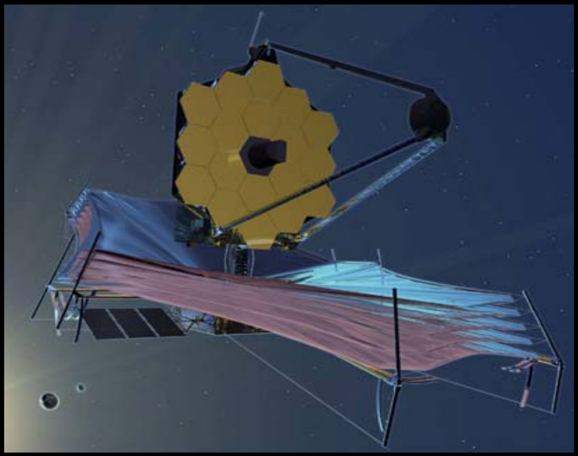
- Wide field imager
- Studies morphology of objects and structure of the universe
- U. Arizona / Lockheed Martin

An electron-volt (eV) is extremely small



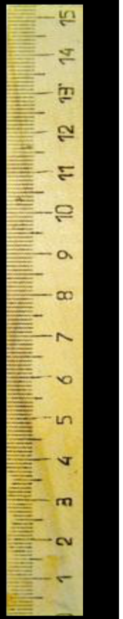
15 H2RG
2K×2K arrays
63 million pixels





- The energy of a photon is **VERY** small
  - Energy of SWIR (2.5 μm) photon is 0.5 eV
- In 5 years, JWST will take ~1 million images
  - Total # SWIR photons detected ≈ 3.6×10^{16}
  - Total energy detected ≈ 1.8×10^{16} eV
- Drop peanut M&M® candy (~2g) from height of 15 cm (~6 inches)
  - Potential energy ≈ 1.8 x 10^{16} eV

15 cm peanut M&M® drop is equal to the energy detected during 5 year operation of the James Webb Space Telescope!

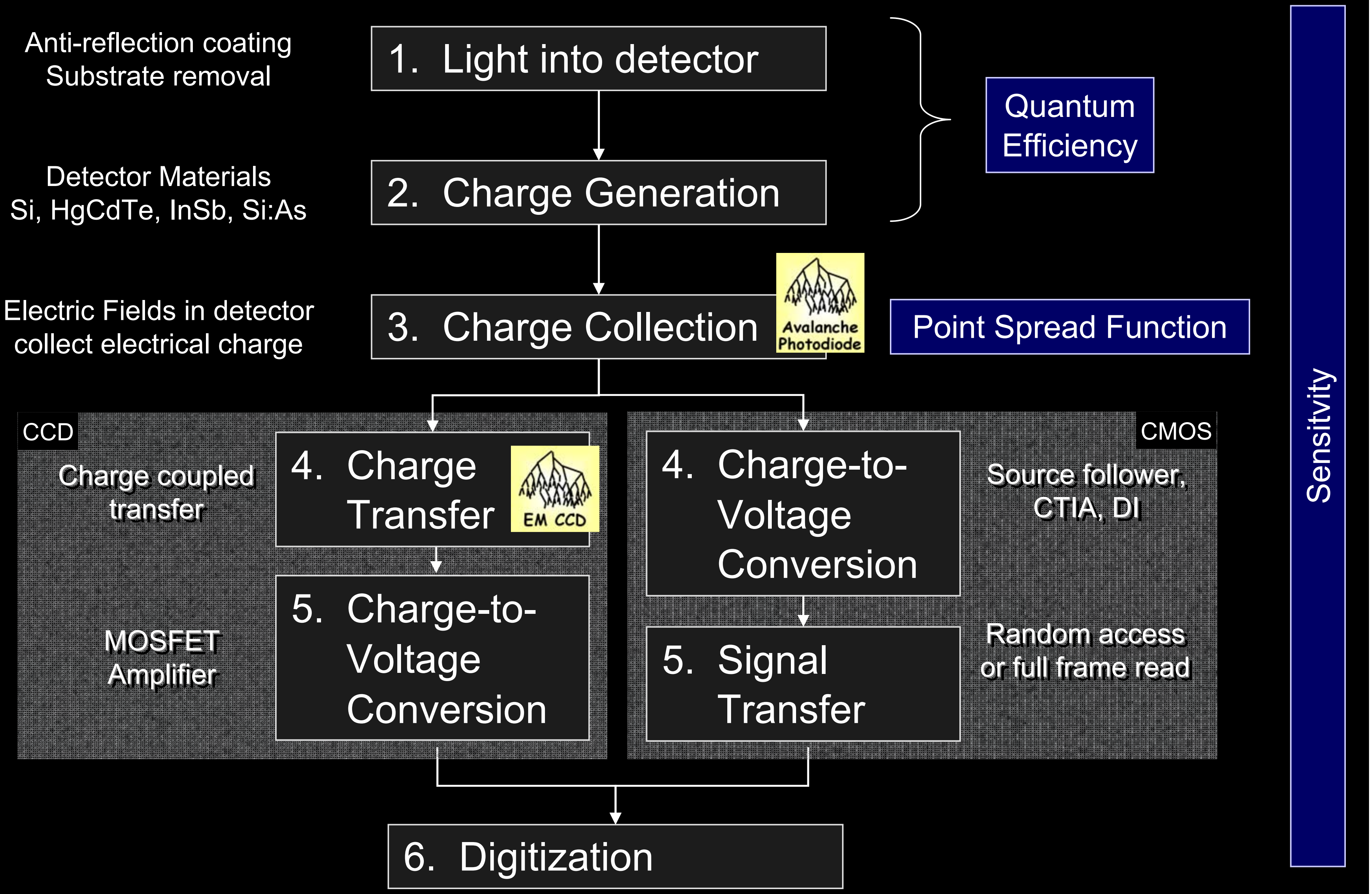


The Ideal Detector

• Detect 100% of photons	✓ Up to 98% quantum efficiency
• Each photon detected as a delta function	✓ One electron for each photon
• Large number of pixels	✓~1,400 million pixels (>10^9)
• Time tag for each photon	☒ No - framing detectors ✓ APDs & event driven readout
• Measure photon wavelength	☒ No – defined by filter ✓ Foveon, 3rd Gen IR
• Measure photon polarization	☒ No – defined by filter Can place filter on detector

Plus READOUT NOISE and other “features”

6 steps of optical / IR photon detection



Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Quantum Efficiency

Electric Fields in detector
collect electrical charge

3. Charge Collection

Point Spread Function

CCD

Charge coupled transfer

4. Charge Transfer

MOSFET Amplifier

5. Charge-to-Voltage Conversion

CMOS

4. Charge-to-Voltage Conversion

Source follower, CTIA, DI

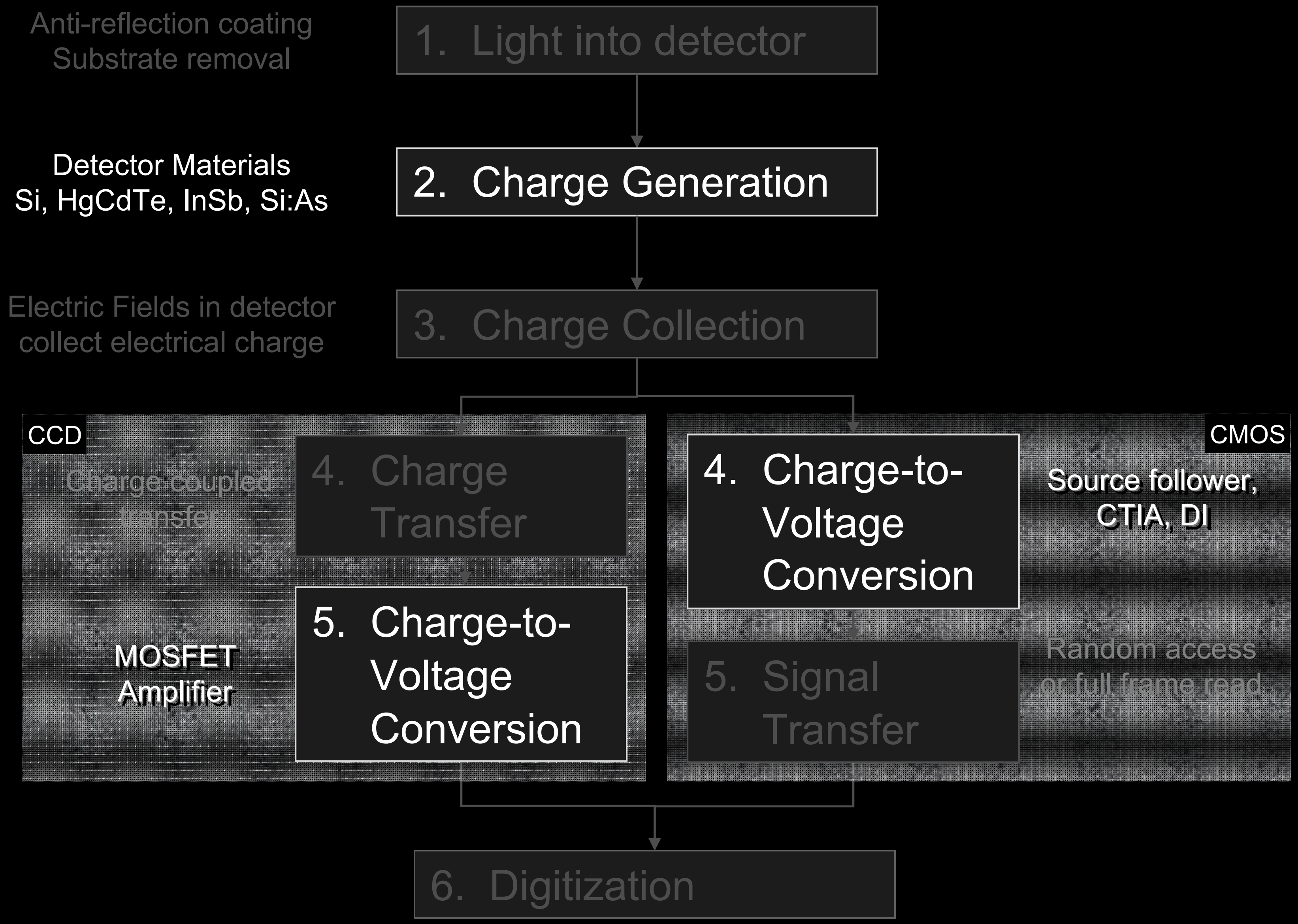
5. Signal Transfer

Random access or full frame read

6. Digitization

Sensitivity

6 steps of optical / IR photon detection



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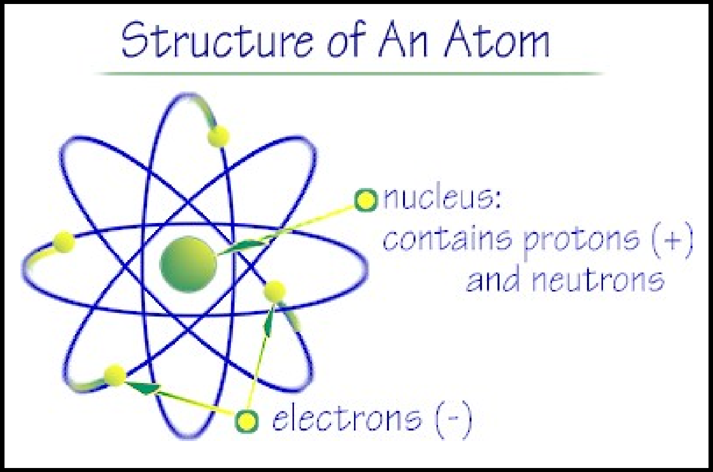
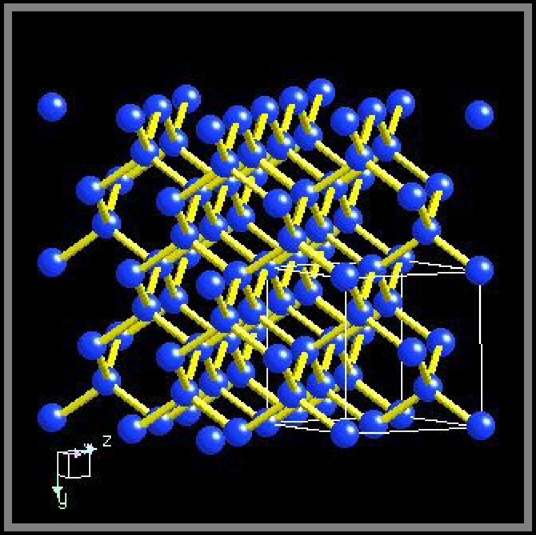
Crystals are excellent detectors of light



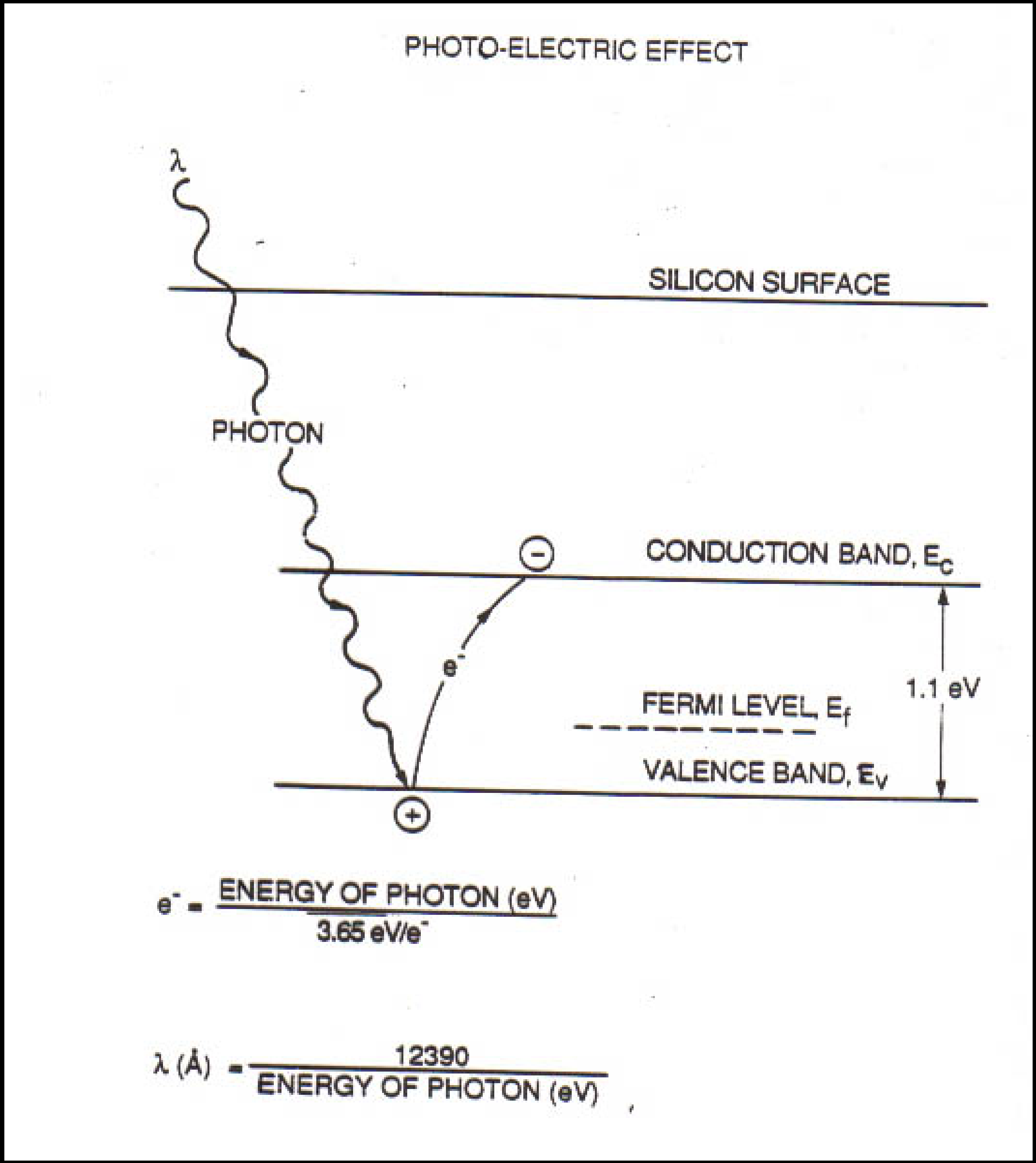
- Simple model of atom
  - Protons (+) and neutrons in the nucleus with electrons orbiting



Silicon crystal lattice

- Electrons are trapped in the crystal lattice
  - by electric field of protons
- Light energy can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an "electron-hole" pair.
- The photocharge can be collected and amplified, so that light is detected
- The light energy required to free an electron depends on the material.

Charge Generation



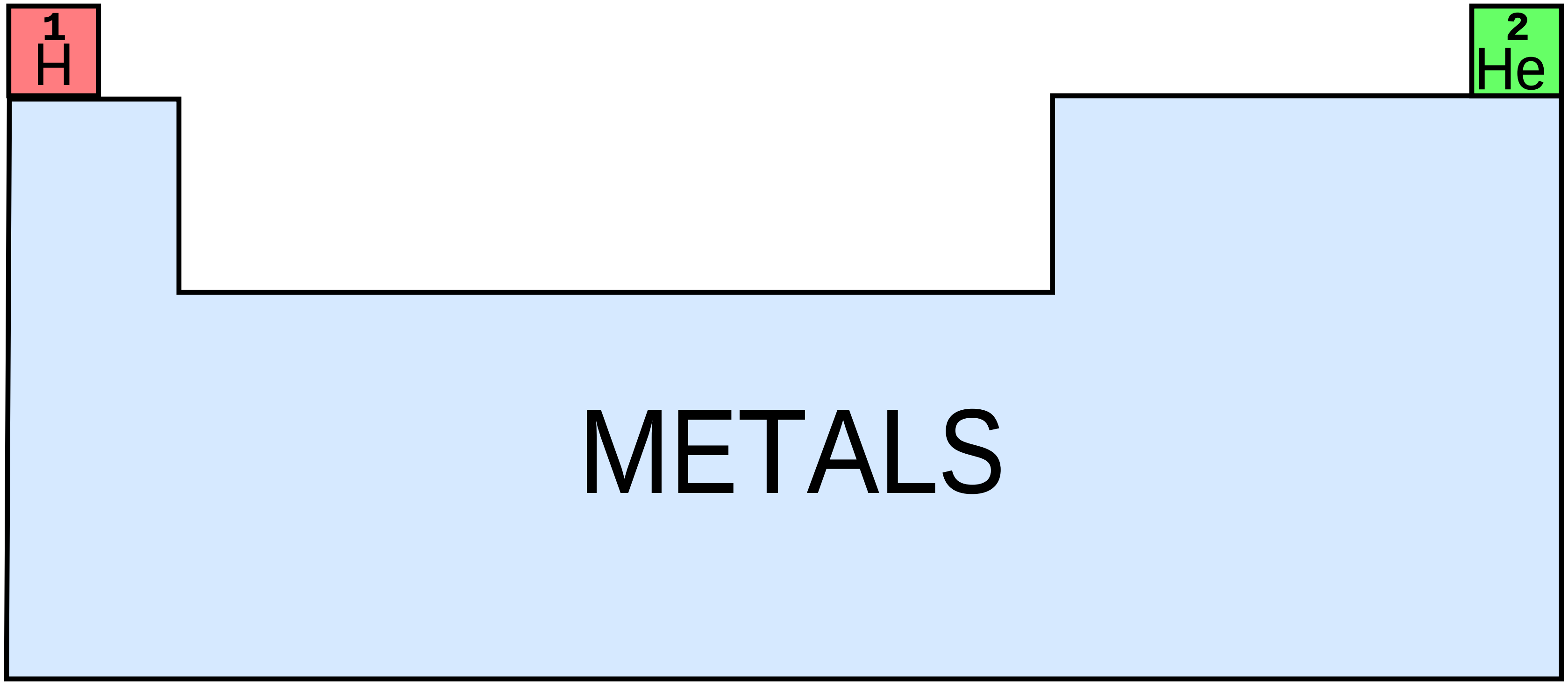
$$e^- = \frac{\text{ENERGY OF PHOTON (eV)}}{3.65\ \text{eV}/e^-}$$

$$\lambda\,(\text{Å}) = \frac{12390}{\text{ENERGY OF PHOTON (eV)}}$$

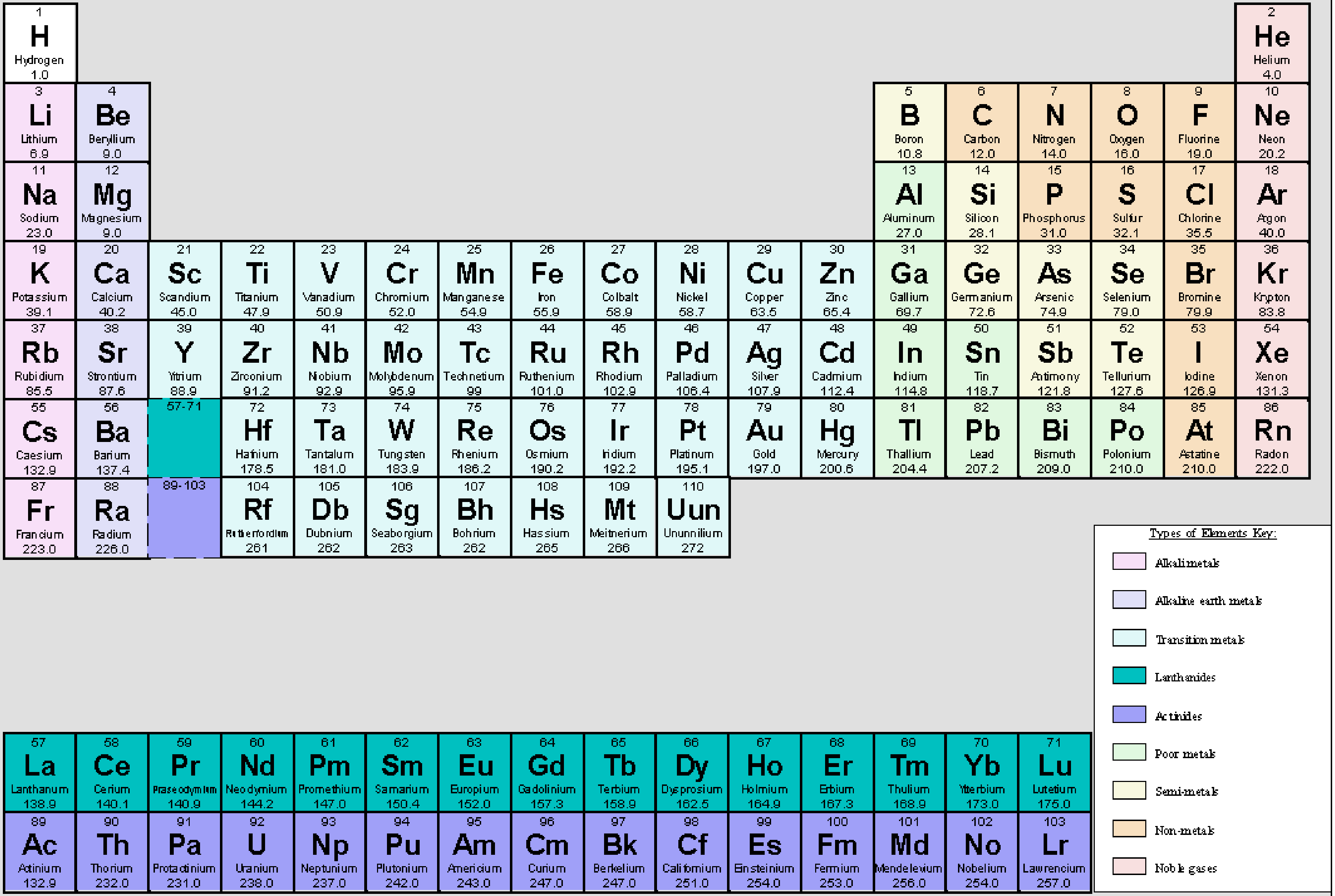
<u>Silicon CCD</u>

Similar physics for IR materials

The Astronomer's Periodic Table



Periodic Table



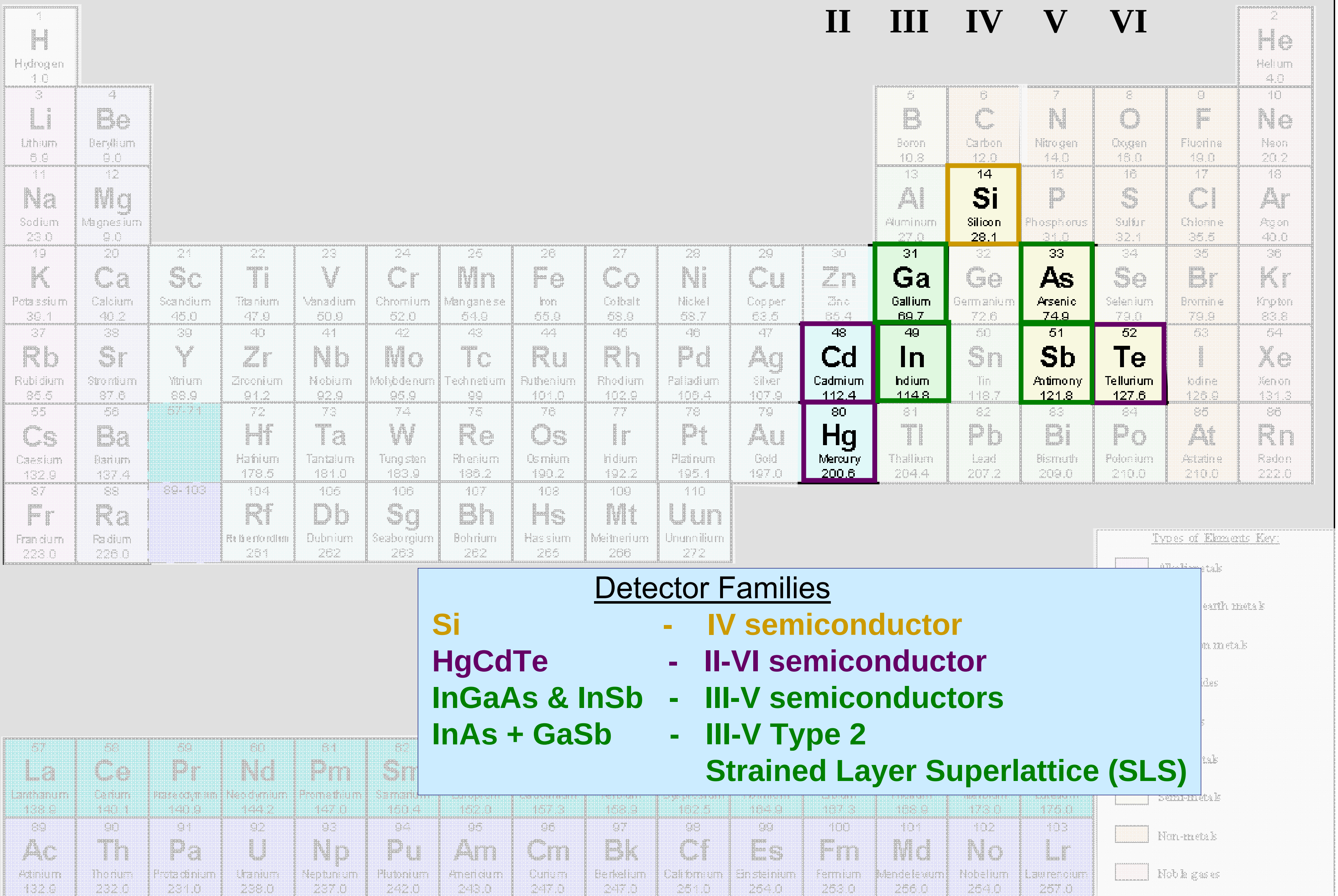
1 H Hydrogen 1.0																	2 He Helium 4.0
3 Li Lithium 6.9	4 Be Beryllium 9.0											5 B Boron 10.8	6 C Carbon 12.0	7 N Nitrogen 14.0	8 O Oxygen 16.0	9 F Fluorine 19.0	10 Ne Neon 20.2
11 Na Sodium 23.0	12 Mg Magnesium 9.0											13 Al Aluminum 27.0	14 Si Silicon 28.1	15 P Phosphorus 31.0	16 S Sulfur 32.1	17 Cl Chlorine 35.5	18 Ar Argon 40.0
19 K Potassium 39.1	20 Ca Calcium 40.2	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 55.9	27 Co Colbalt 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 101.0	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 Caesium 132.9	56 Ba Barium 137.4	57-71	72 Hf Hafnium 178.5	73 Ta Tantalum 181.0	74 W Tungsten 183.9	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	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 262	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Uun Ununnilium 272								

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium 147.0	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium 132.9	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium 237.0	94 Pu Plutonium 242.0	95 Am Americium 243.0	96 Cm Curium 247.0	97 Bk Berkelium 247.0	98 Cf Californium 251.0	99 Es Einsteinium 254.0	100 Fm Fermium 253.0	101 Md Mendelevium 256.0	102 No Nobelium 254.0	103 Lr Lawrencium 257.0

Types of Elements Key:

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

Periodic Table



Detector Families

Si - **IV semiconductor**

HgCdTe - **II-VI semiconductor**

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

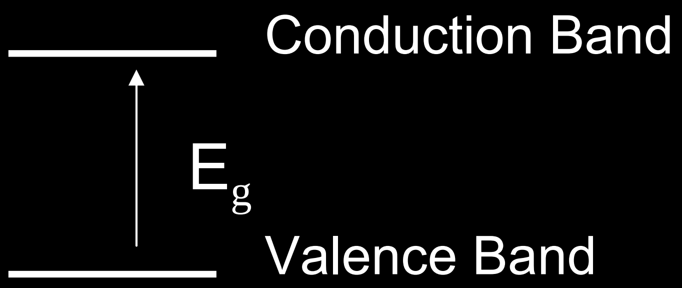
InAs + GaSb - **III-V Type 2**
Strained Layer Superlattice (SLS)

Photon Detection

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

$$h\nu > E_g$$

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



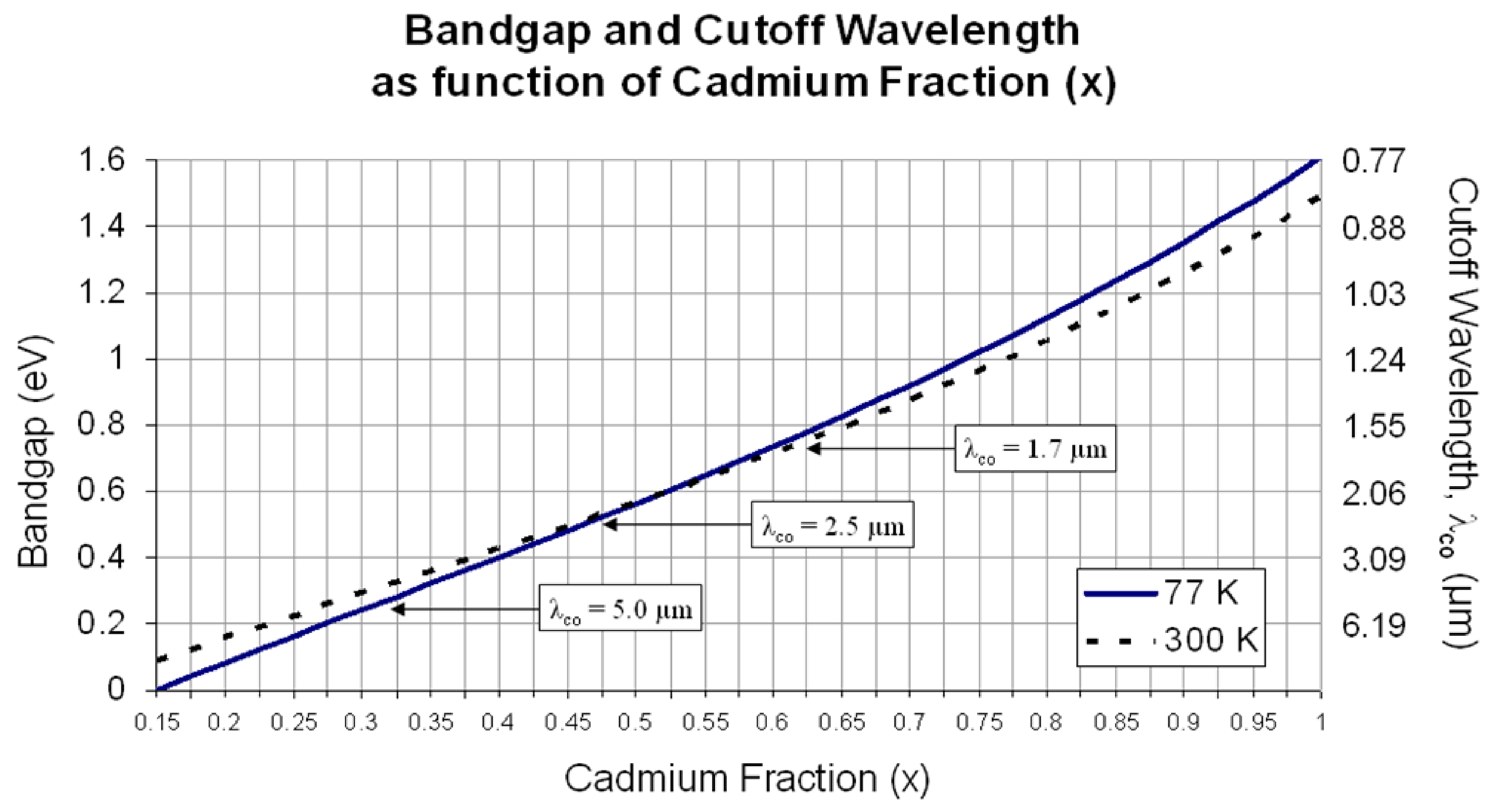
$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

Material Name	Symbol	E_g (eV)	λ_c (μm)
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 ($In_{0.53}Ga_{0.47}As$)

Tunable Wavelength: Valuable property of HgCdTe

$Hg_{1-x}Cd_xTe$ Modify ratio of Mercury and Cadmium to “tune” the bandgap energy



$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35 \times 10^{-4} T(1 - 2x)$$

G. L. Hansen, J. L. Schmidt, T. N. Casselman, J. Appl. Phys. 53(10), 1982, p. 7099

Absorption Depth

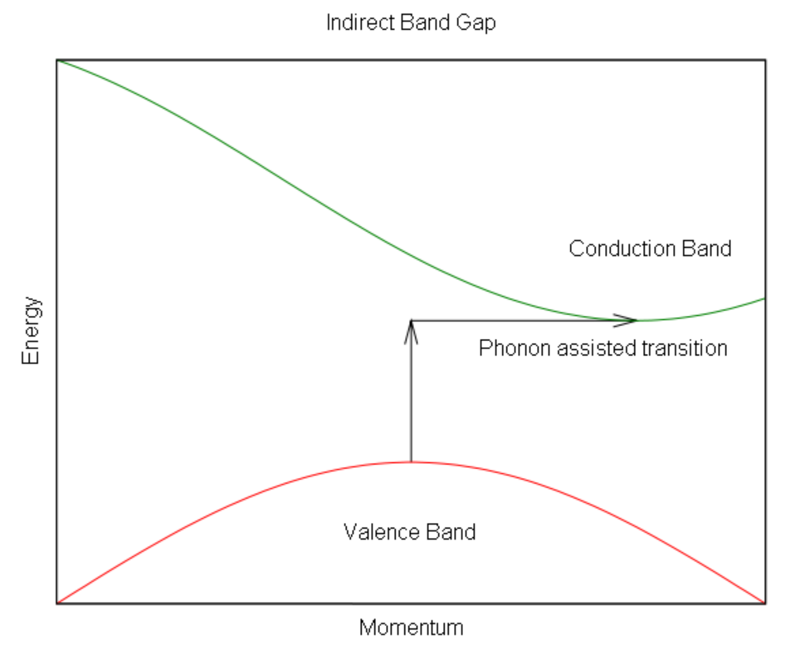
The depth of detector material that absorbs 63.2% of the radiation

(1-1/e) of the energy is absorbed

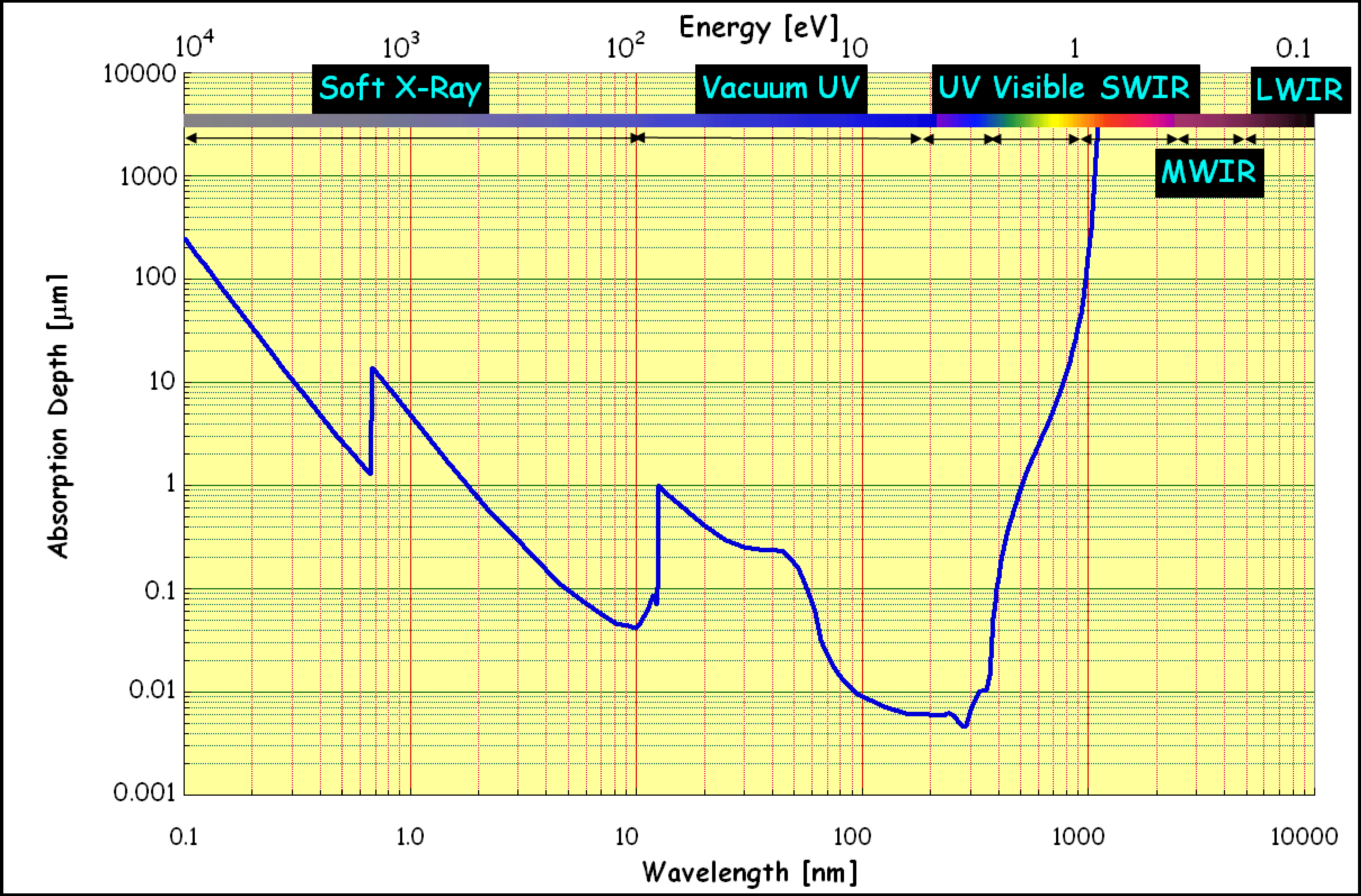
1 absorption depth(s)	63.2% of light absorbed
2	86.5%
3	95.0%
4	98.2%

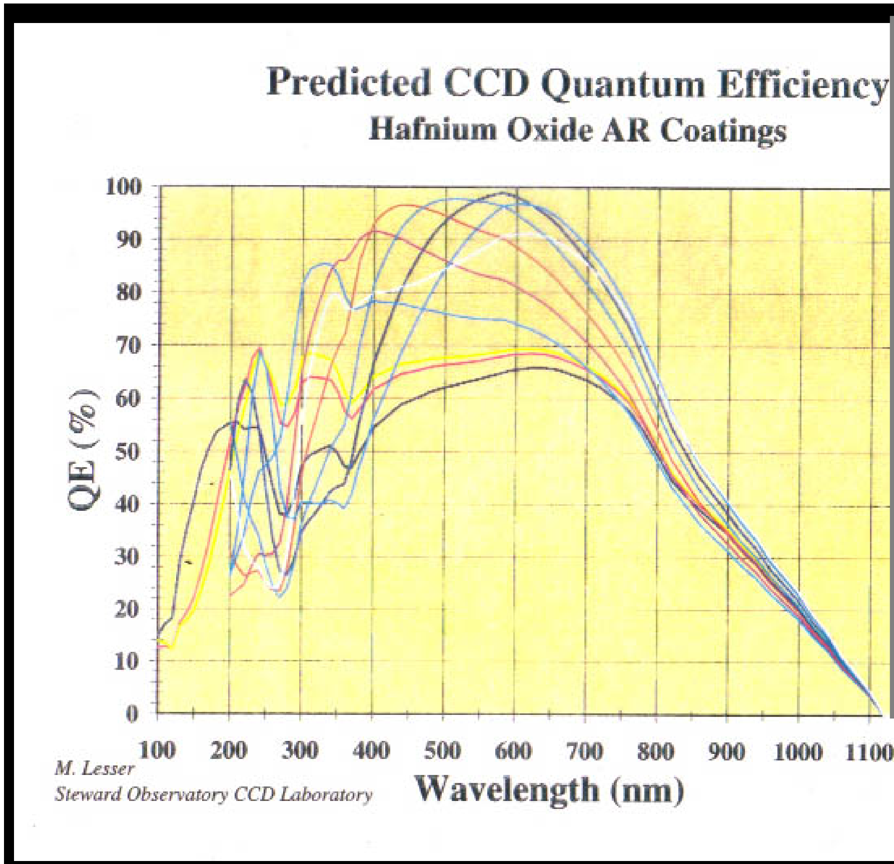
For high QE, thickness of detector material should be ≥ 3 absorption depths

Silicon is an indirect bandgap material and is a poor absorber of light as the photon energy approaches the bandgap energy. For an indirect bandgap material, both the laws of conservation of energy and momentum must be observed. To excite an electron from the valence band to the conduction band, silicon must simultaneously absorb a photon and a phonon that compensates for the missing momentum vector.



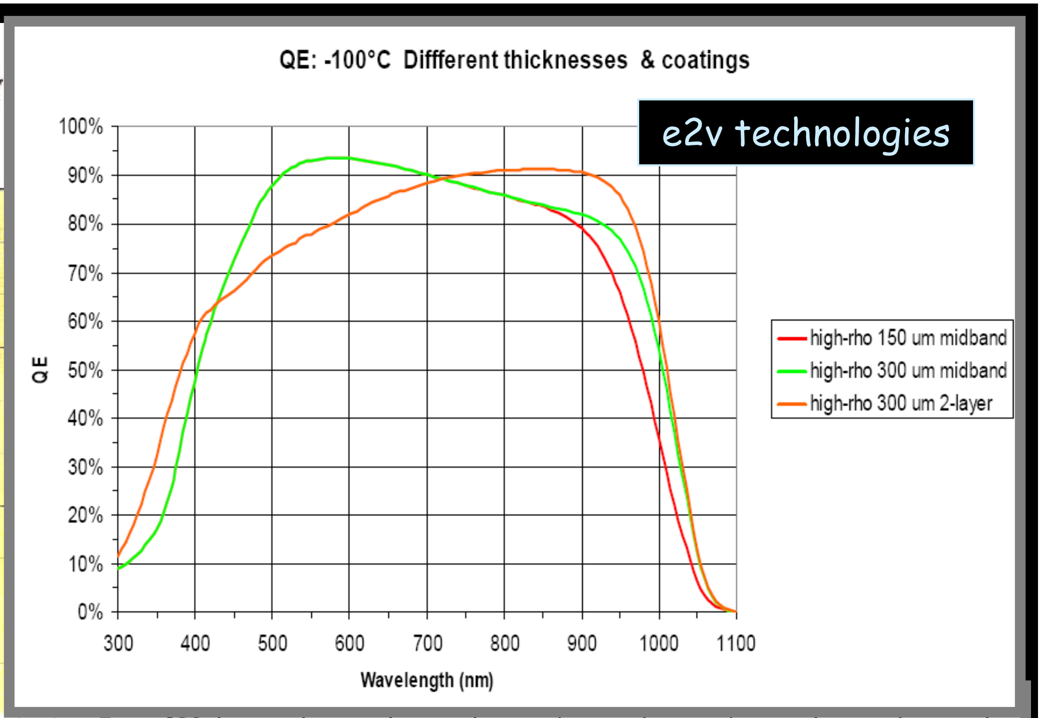
Absorption Depth of Light in Silicon



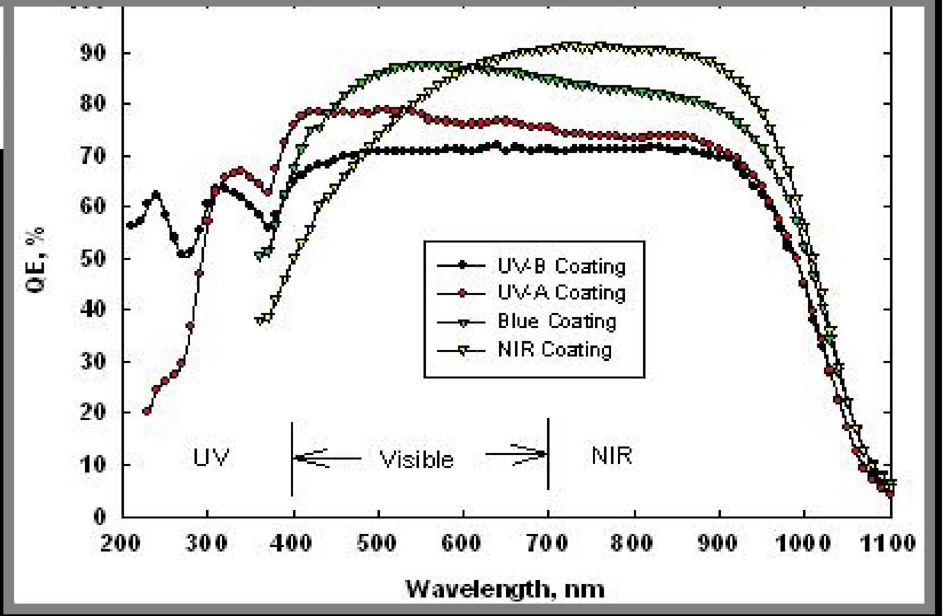


Quarter wave HfO_2 AR Coating

Mike Lesser, U. Arizona



e2v technologies

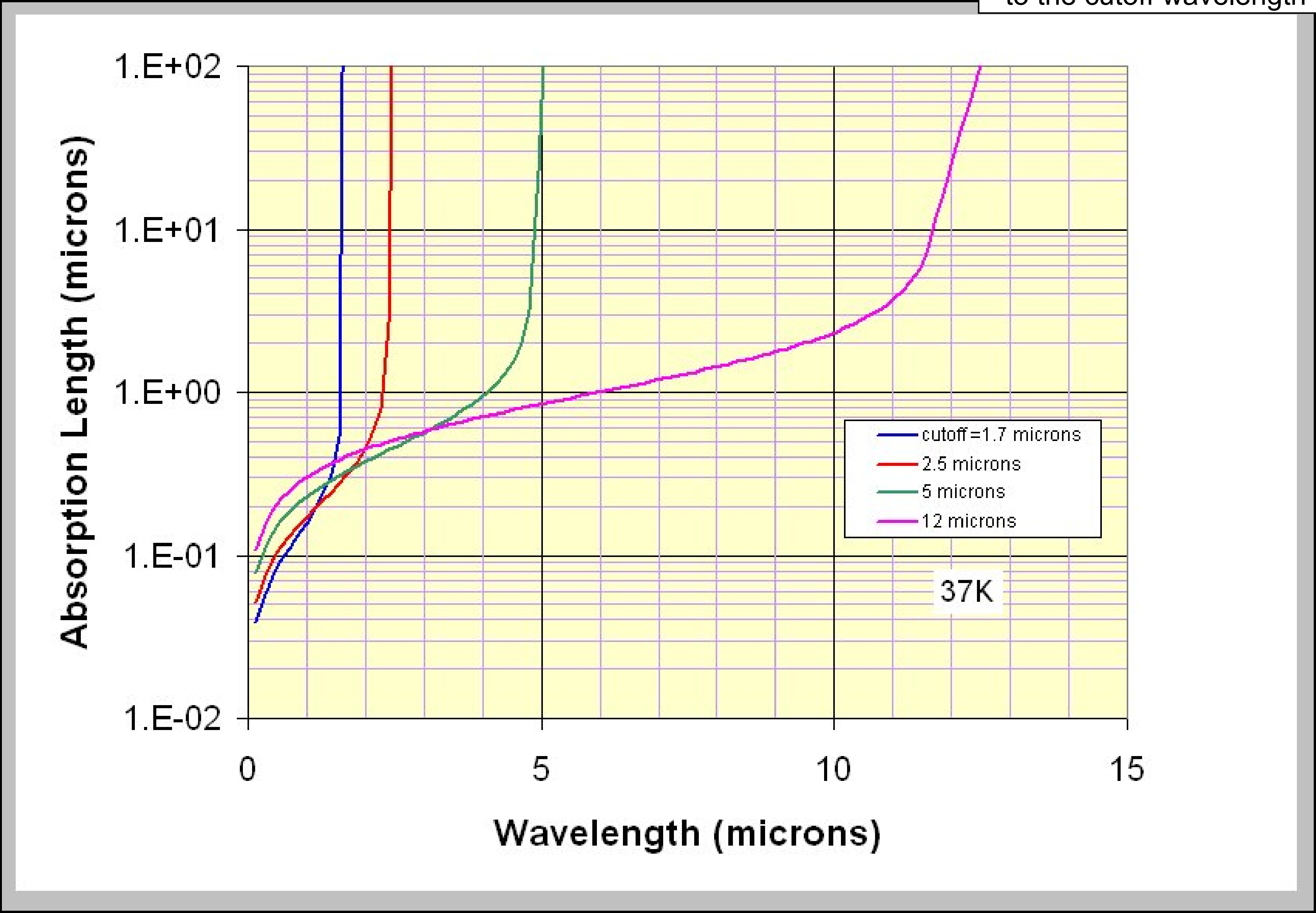


Teledyne Imaging Sensors

Absorption Depth of HgCdTe

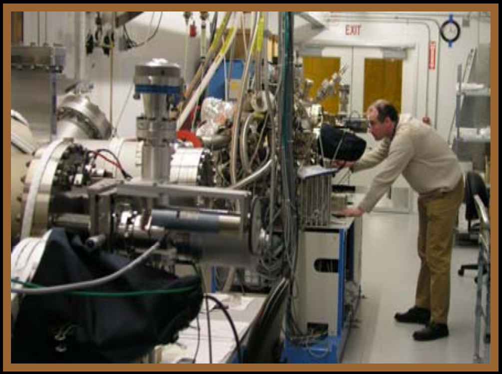
Rule of Thumb

Thickness of HgCdTe layer needs to be about equal to the cutoff wavelength



MBE produces highest quality HgCdTe

- Older version of HgCdTe growth is Liquid Phase Epitaxy (LPE)
- Molecular Beam Epitaxy (MBE)
  - Enables very accurate deposition ⇒ “bandgap engineering”
  - HgCdTe grown on CdZnTe wafers

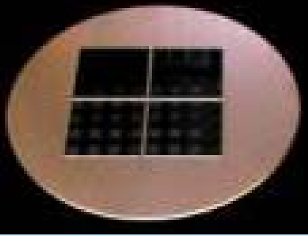


RIBER 3-in MBE Systems

3 inch diameter
platen allows
growth on one
6x6 cm
substrate

More than 8000 HgCdTe
wafers grown to date

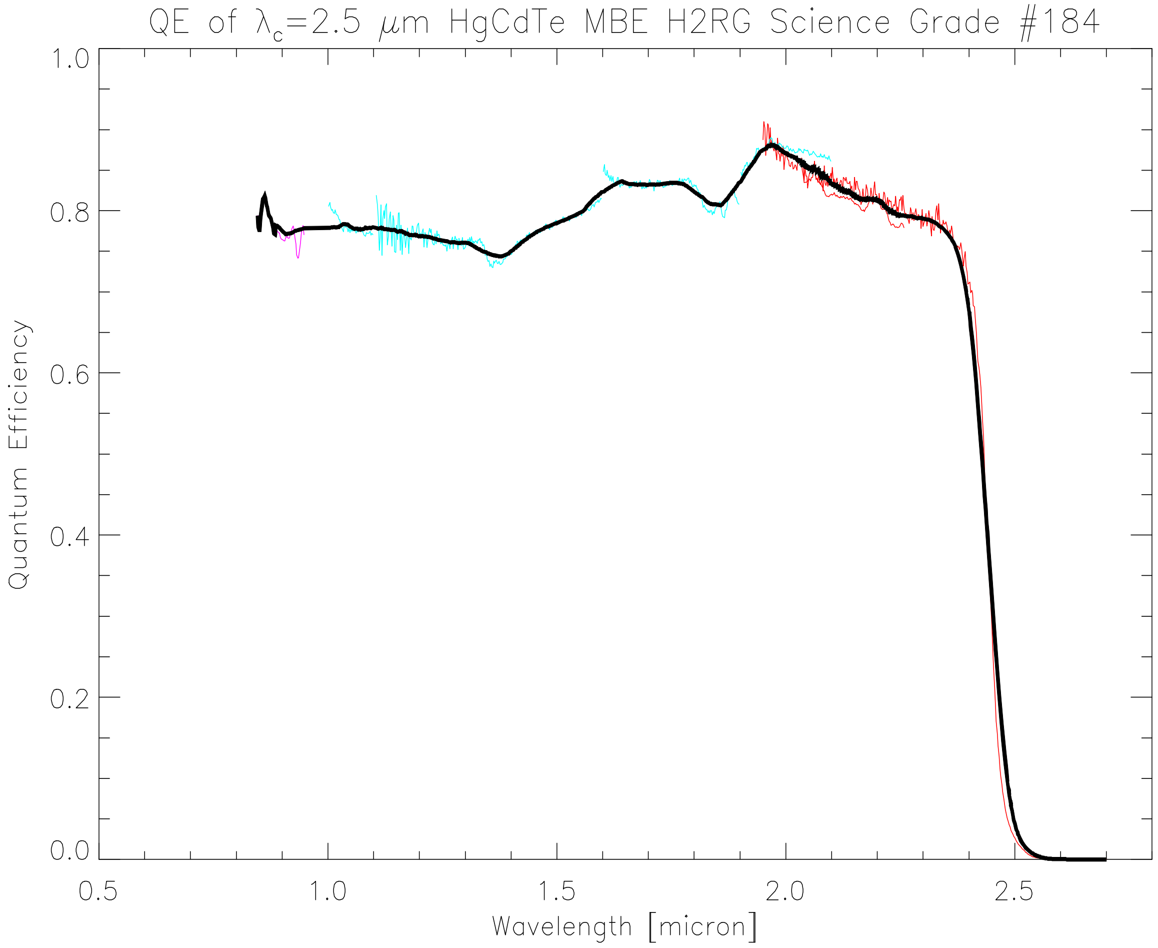
RIBER 10-in MBE 49 System



10 inch diameter
platen allows
simultaneous growth
on four 6x6 cm
substrates

Teledyne Imaging Sensors

High Quantum Efficiency Visible – Infrared Measured by the European Southern Observatory



Data: Courtesy of ESO, KMOS project

Quantum Yield: One photoelectron for every detected photon

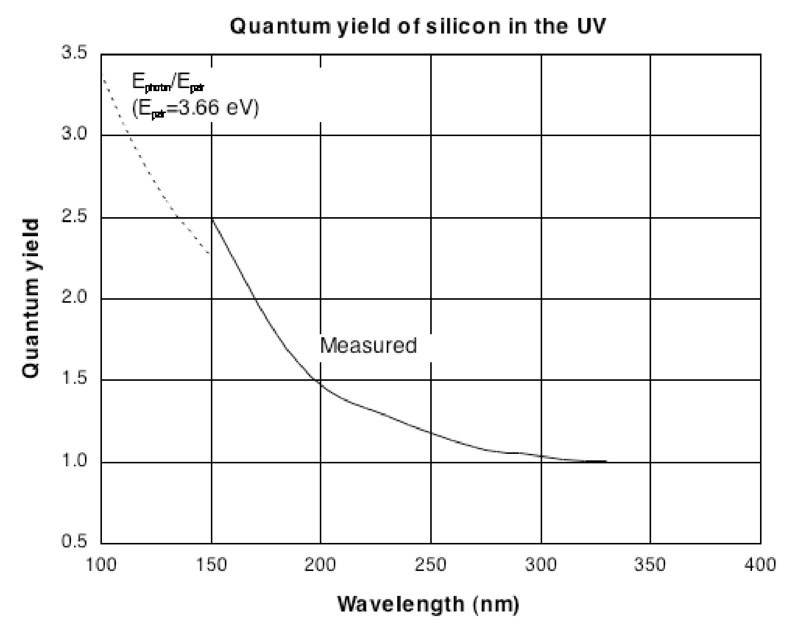
…for most wavelengths of interest to ground-based astronomy

Silicon

For wavelengths that are 30% to 100% of the cutoff wavelength, there will a single electron-hole pair created for every detected photon.

For shorter wavelengths (higher energies), there is an increasing probability of producing multiple electron-hole pairs.

For silicon, this effect commences at ~30% of the cutoff wavelength (λ < 330 nm).



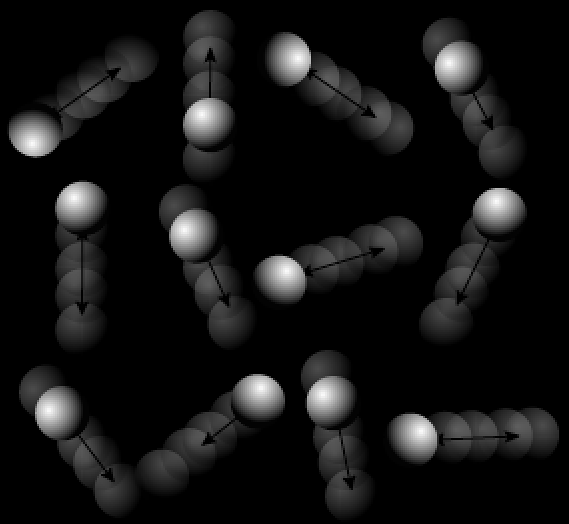
Data from Barry Burke, MIT Lincoln Laboratory

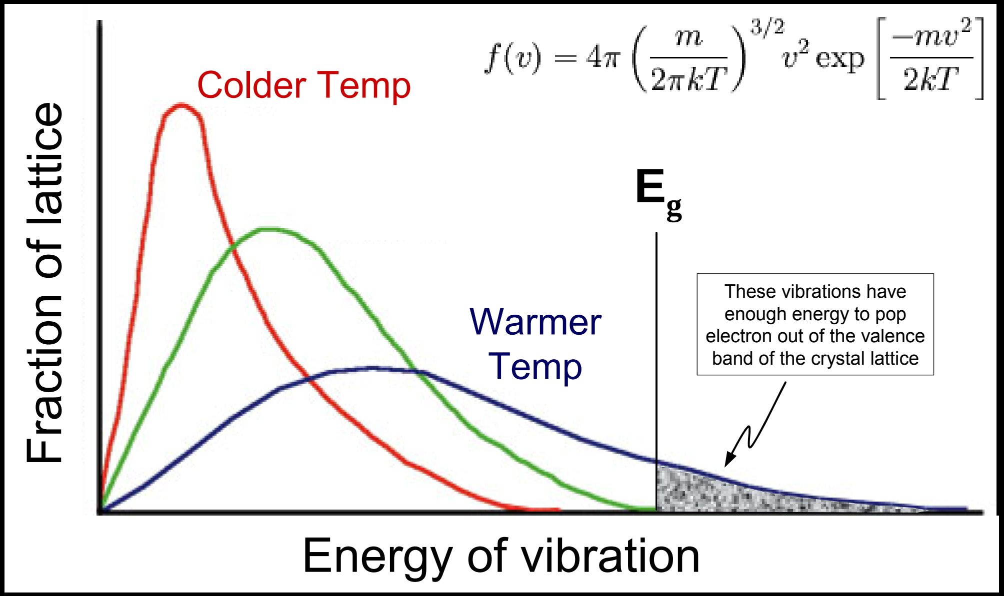
HgCdTe

- Limited data from HgCdTe detectors shows that quantum yield is not significant at 800 nm for a 5400 nm cutoff detector (11% of cutoff wavelength).
- The quantum yield of HgCdTe is still being investigated.

Dark Current

Undesirable byproduct of light detecting materials

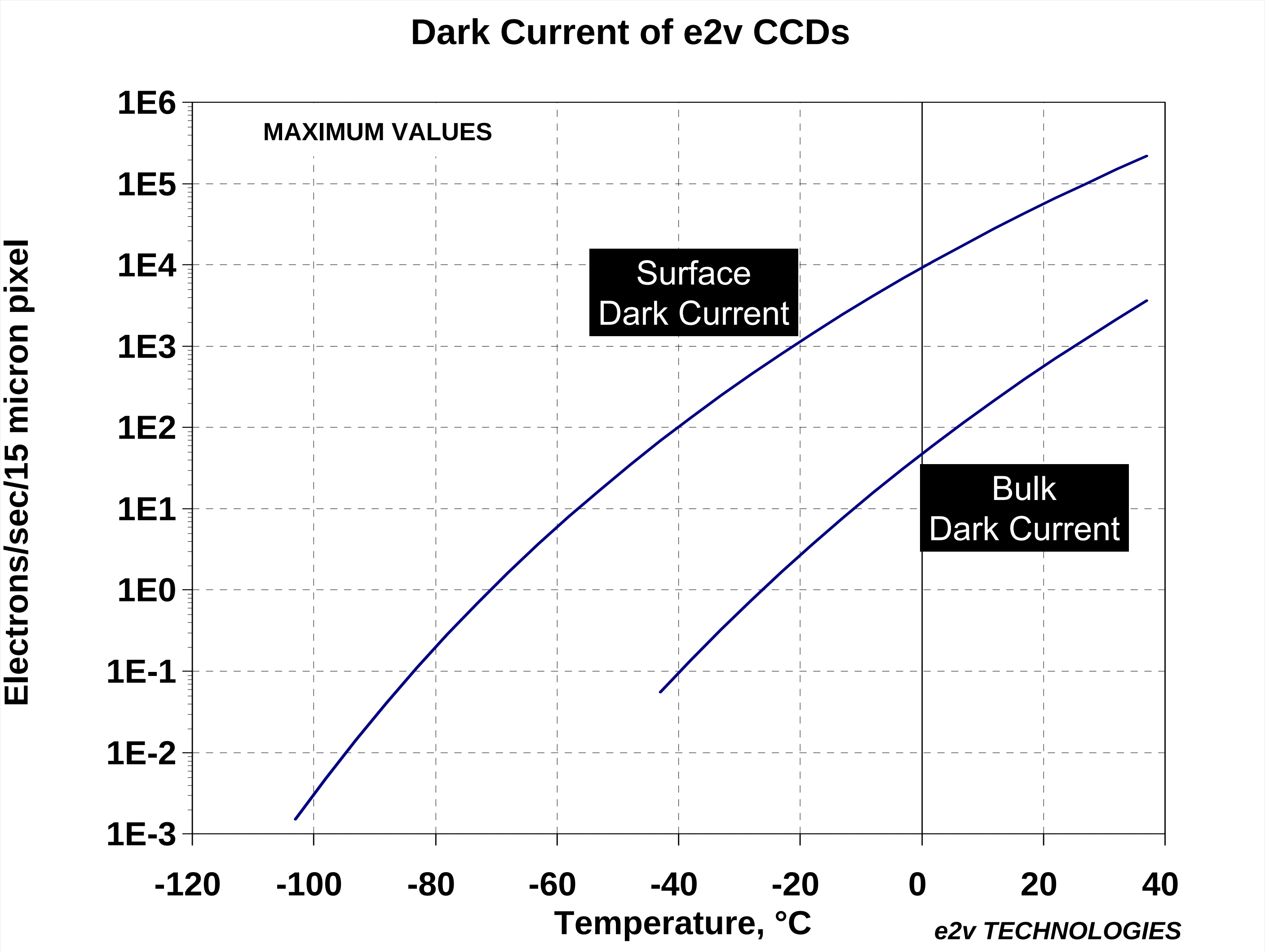




These vibrations have enough energy to pop electron out of the valence band of the crystal lattice

- The vibration of particles (includes crystal lattice phonons, electrons and holes) has energies described by the Maxwell-Boltzmann distribution. Above absolute zero, some vibration energies may be larger than the bandgap energy, and will cause electron transitions from valence to conduction band.
- Need to cool detectors to limit the flow of electrons due to temperature, i.e. the **dark current** that exists in the absence of light.
- The smaller the bandgap, the colder the required temperature to limit dark current below other noise sources (e.g. readout noise)

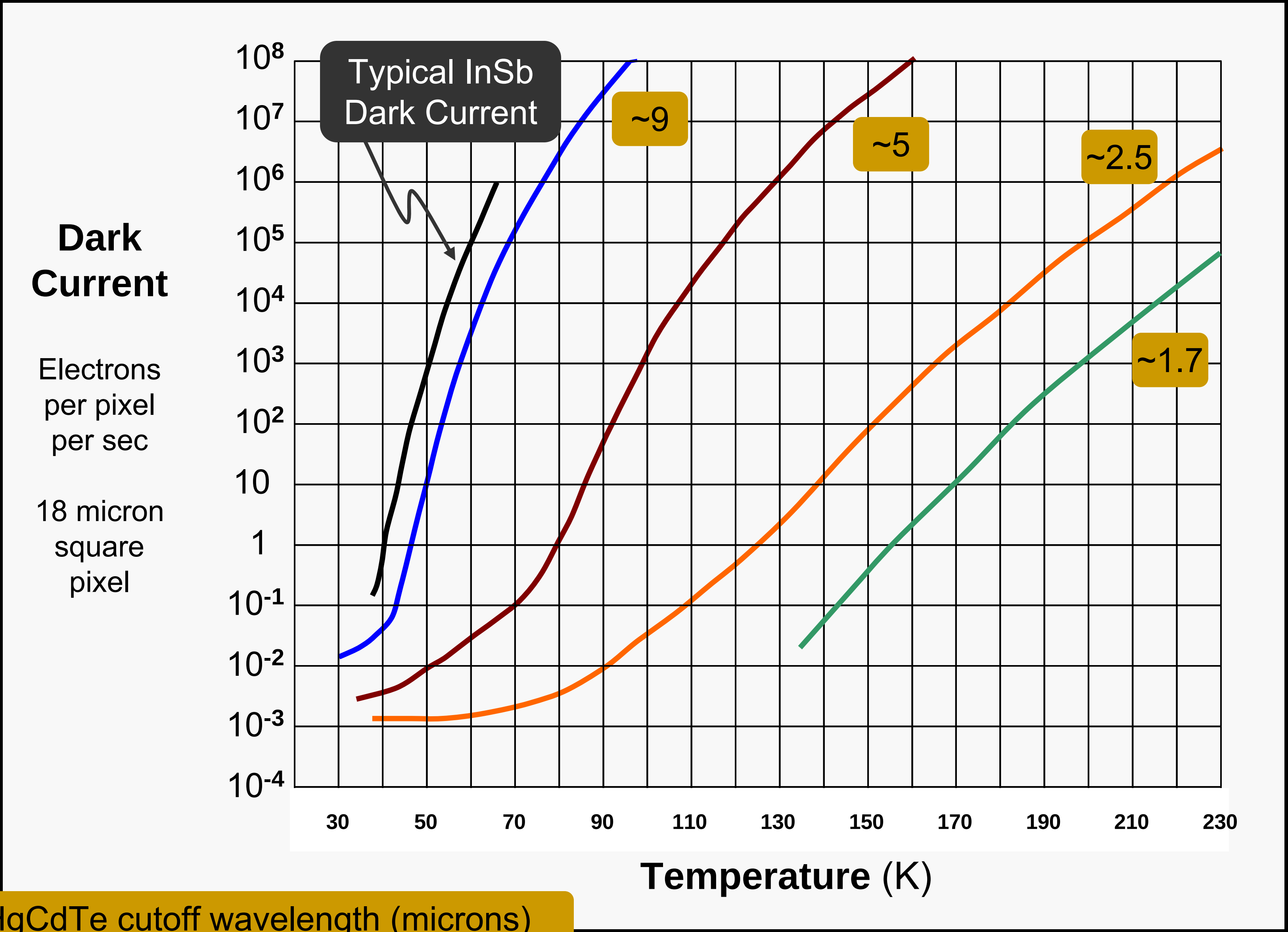
Dark Current of Silicon-based Detectors



In silicon, dark current usually dominated by surface defects

e2v technologies

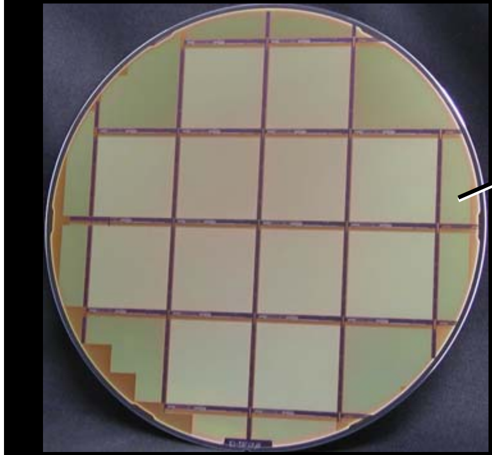
Dark Current of HgCdTe Detectors

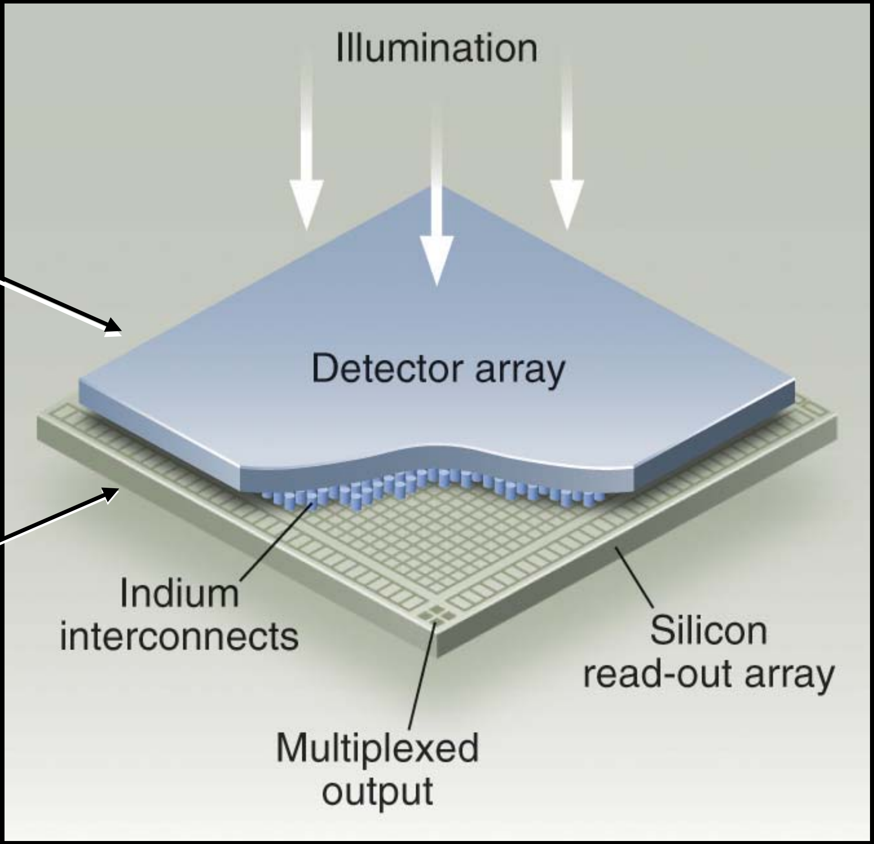


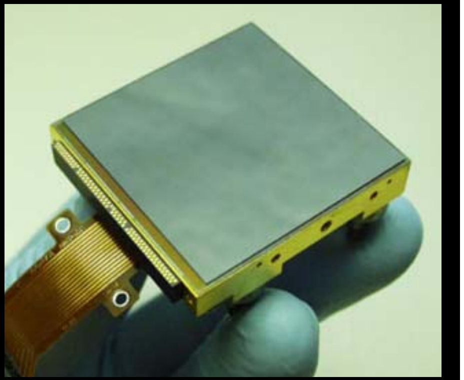
HgCdTe cutoff wavelength (microns)

Teledyne Imaging Sensors

Hybrid CMOS Infrared Imaging Sensors



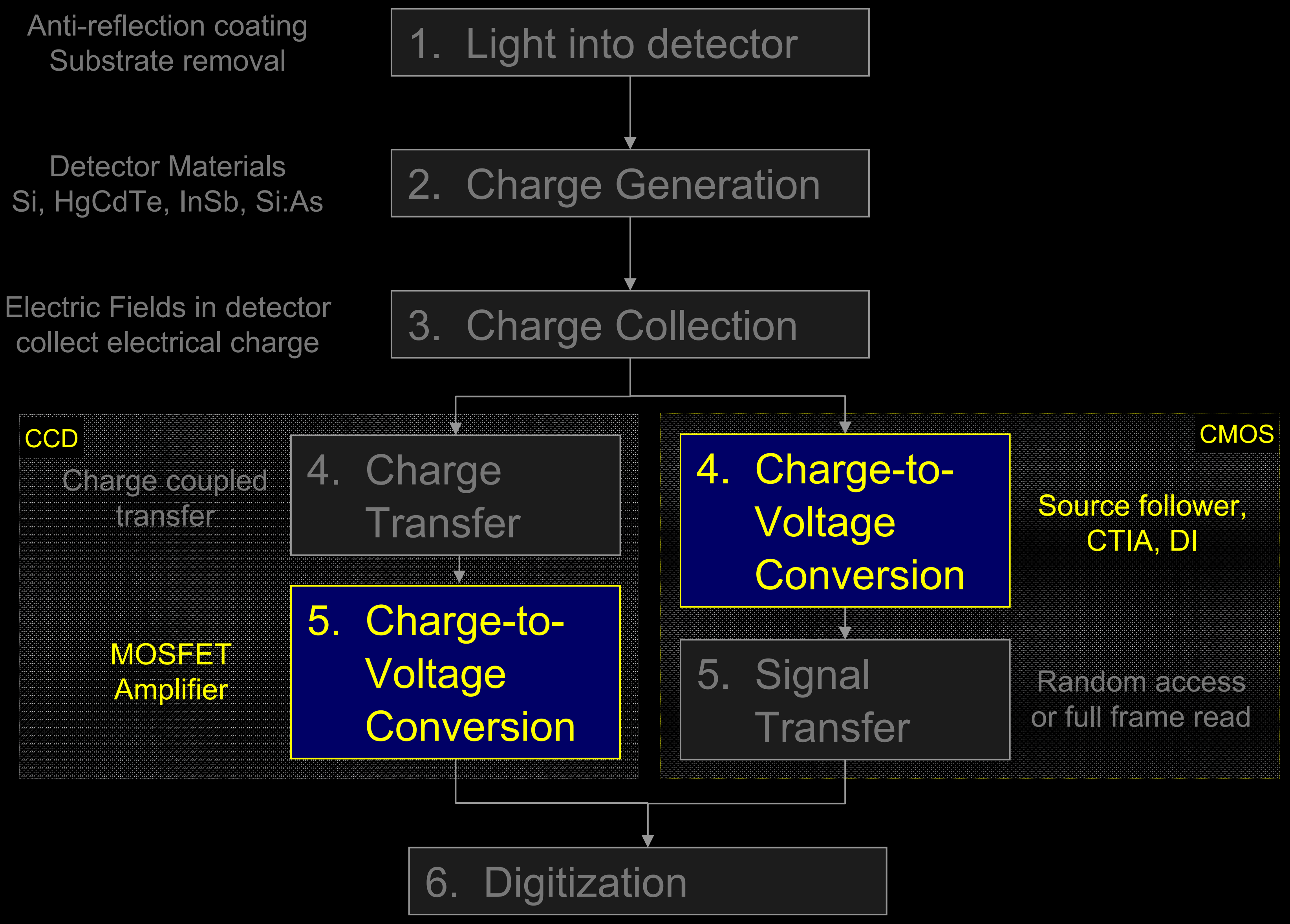




Three Key Technologies

- Growth and processing of the HgCdTe detector layer
- Design and fabrication of the CMOS readout integrated circuit (ROIC)
- Hybridization of the detector layer to the CMOS ROIC

6 steps of optical / IR photon detection



Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Electric Fields in detector
collect electrical charge

3. Charge Collection

CCD

Charge coupled
transfer

4. Charge Transfer

MOSFET
Amplifier

5. Charge-to-Voltage Conversion

CMOS

4. Charge-to-Voltage Conversion

Source follower,
CTIA, DI

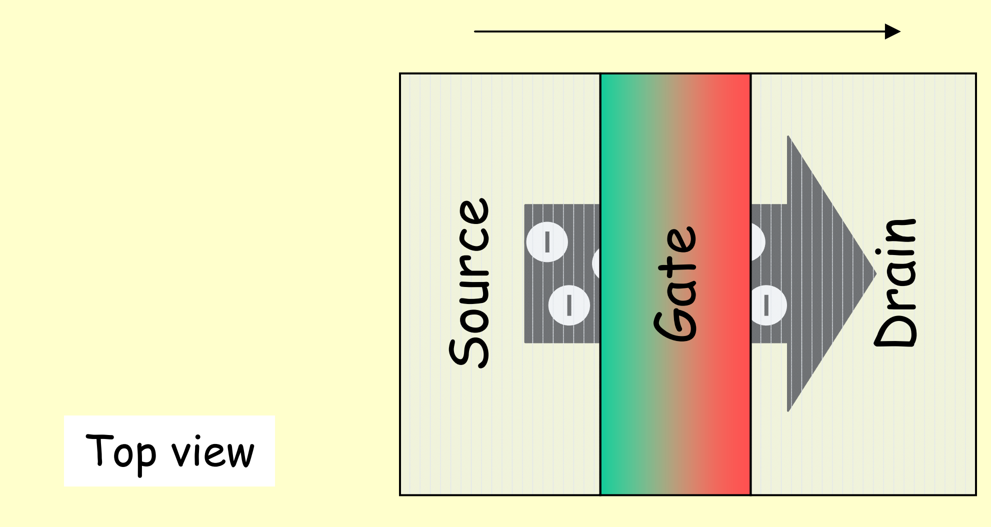
5. Signal Transfer

Random access
or full frame read

6. Digitization

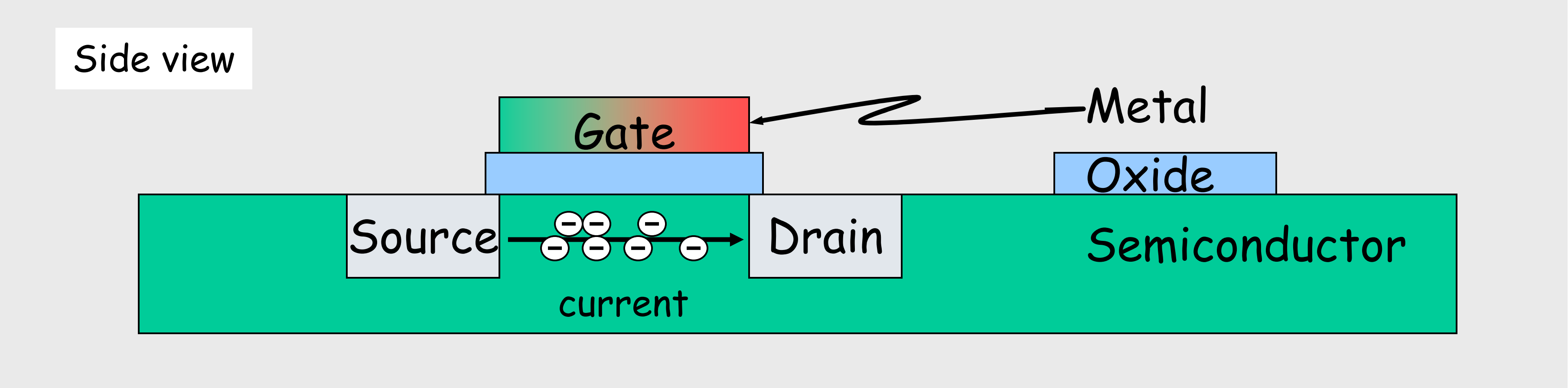
MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor



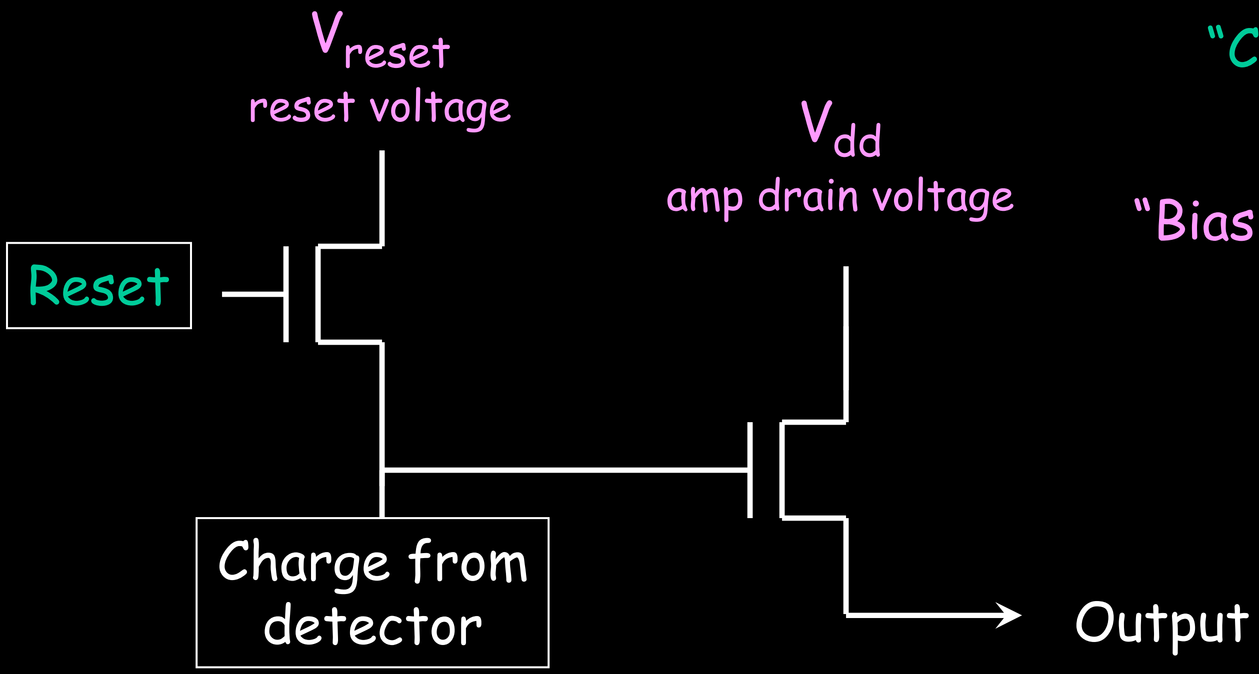
Turn on the MOSFET and current flows from source to drain

Add charge to gate & the current flow changes since the effect of the field of the charge will reduce the current



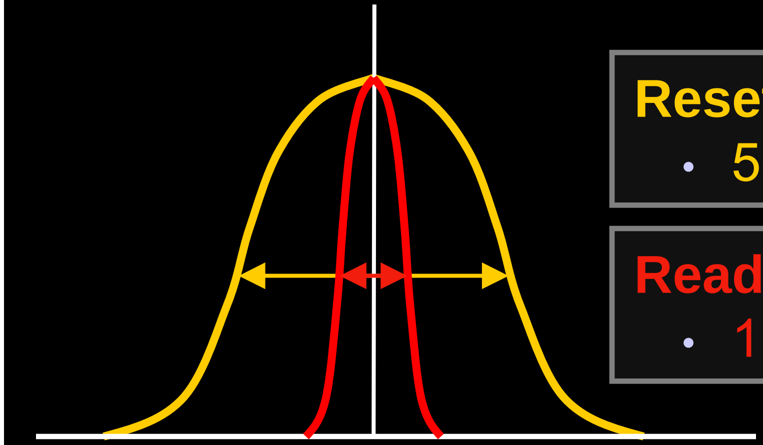
Fluctuations in current flow produce “readout noise”
Fluctuations in reset level on gate produces “reset noise”

MOSFET Amplifier Noise



"Clock" (green)

"Bias voltage" (purple)



Reset Noise

- 50 to 100 e- rms

Read Noise

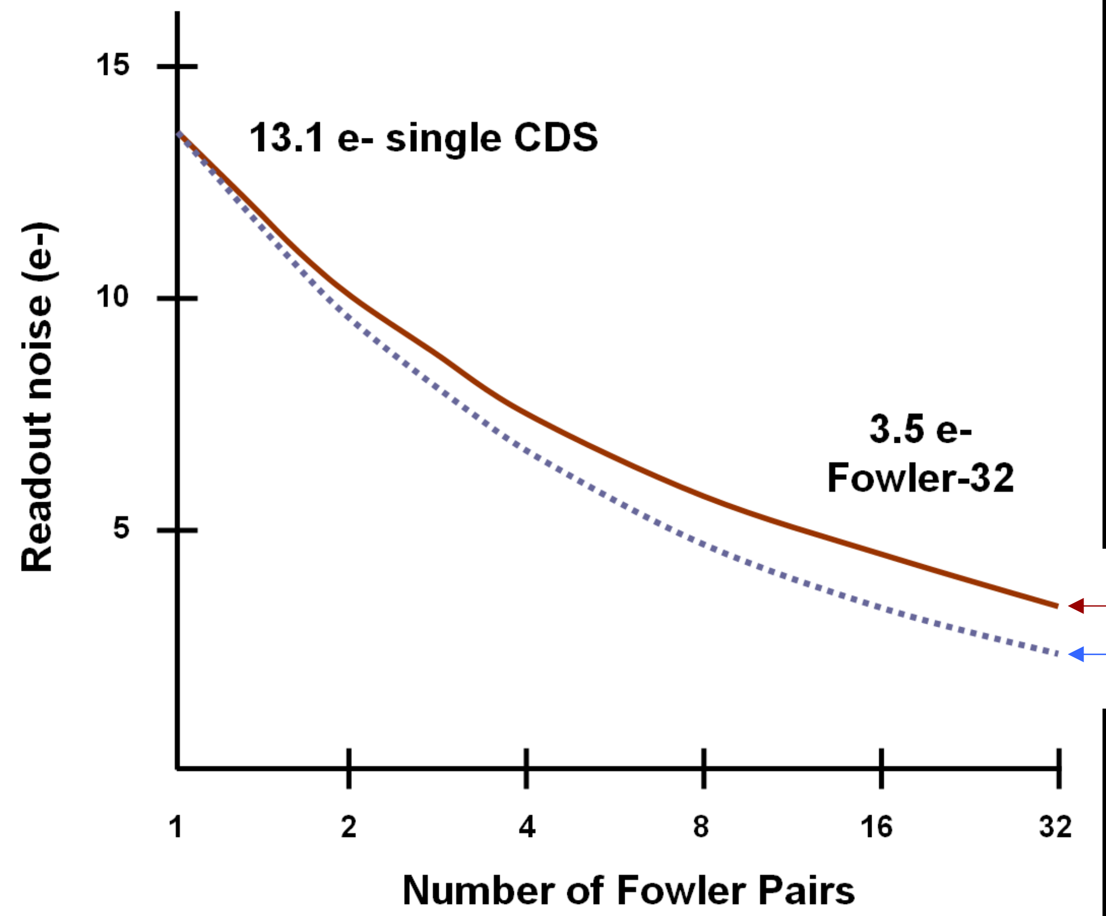
- 1.5 to 10 e- rms

Correlated Double Sample (CDS)

- Reset
- Read
- Put charge on gate
- Read

Example of Noise vs Number of Fowler Samples

Non-destructive readout enables reduction of noise from multiple samples

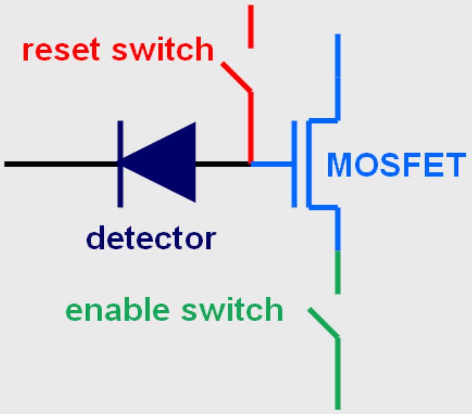


← Measured

← Simple Theory (no 1/f noise)

H2RG array
2.5 micron cutoff
Temperature = 77K

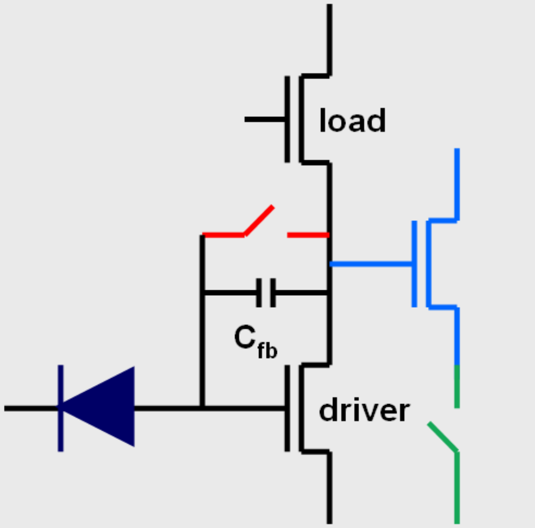
CMOS Pixel Amplifier Types



Source follower
(SF)

- Integration on detector node
- Low power & compact
  (3 FETs / pixel)
- Ideal for small pixels & low flux
- Poor performance for high flux

- Full Well: ~100,000 electrons
- Readout Noise: <15 e-

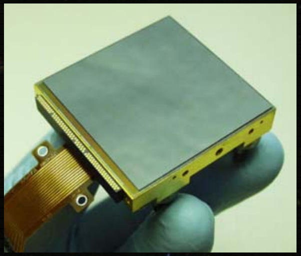


Capactive TransImpedance Amplifier (CTIA)

- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SF for low flux
- Worse performance than DI for high flux
- Full Well: ~1 to 10 million e-
- Readout Noise: <50 e-

HgCdTe Sensors for Astronomy

State-of-the-art



Teledyne H2RG 2K×2K

Raytheon VIRGO 2K×2K

Teledyne H4RG-15 4K×4K

- Large format
  - 2048×2048 pixels is standard
  - 4096×4096 pixels is in development
- Quantum efficiency
  - 70-90% over wide bandpass; UV through infrared
- Noise
  - Dark current can be made negligible with cooling
  - Readout noise as low as 2-3 electrons with multiple sampling
  - Dynamic range (full well / total noise) of ~10,000 for the best sensors

- What astronomers want to be improved in HgCdTe sensors

– Latency / Persistence:	0.1% degrades science
– Operability:	95% to 99% specs set by cost
– LWIR Producibility:	LWIR more difficult, with lower yield
– High speed, low noise:	500 Hz frame rate, 128^2, 3 e- noise
– Cost:	IR detectors are ~10× visible CCDs

Thank you for your attention

Teledyne

Enabling humankind to understand the Universe and our place in it