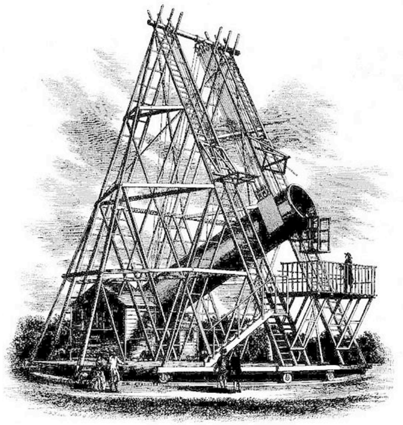
Imagers and Detectors

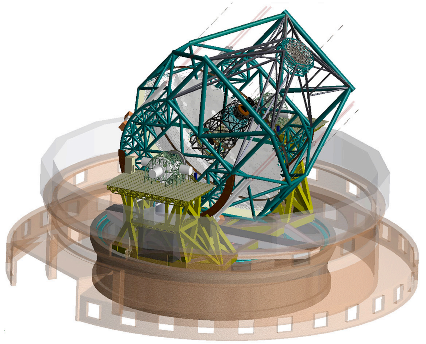
ATI 2014 Lecture 09
Keller and Kenworthy

Accurately recording what you see

Looking at the sky without recording it is just tourism!



Herschel 1789



E-ELT (2026)

Observations

Astronomical observations are:

Expensive

Impossible to repeat in a controlled way

An OBSERVATION is a permanent record of what is seen at the focal plane of a telescope.

The Atmosphere

Recap: The Atmosphere

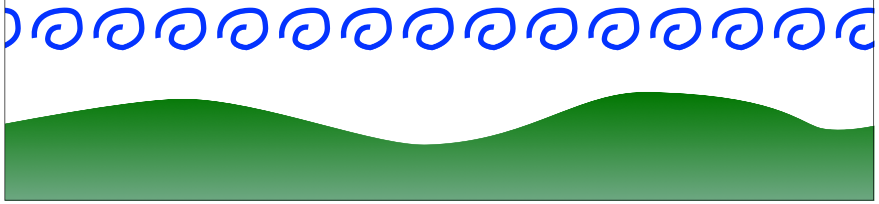
Atmosphere is modeled with:

An outer and inner scale length, and a power spectrum of index fluctuations between them

Thin layers of frozen turbulence at 2 to 5 different altitudes

Described with three parameters:

$$r_0, \tau_0 \text{ and } \theta_0$$

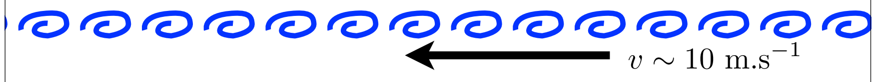


Fried length r_0

$$r_0 \propto \lambda^{6/5}$$

Equal to diameter of 1rad² error variance in phase

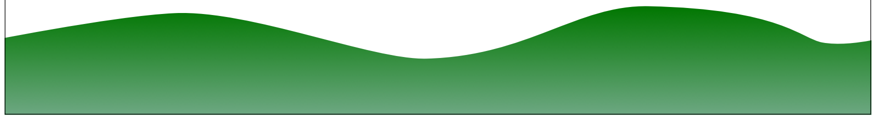
$$r_0 \sim 10 - 20cm$$



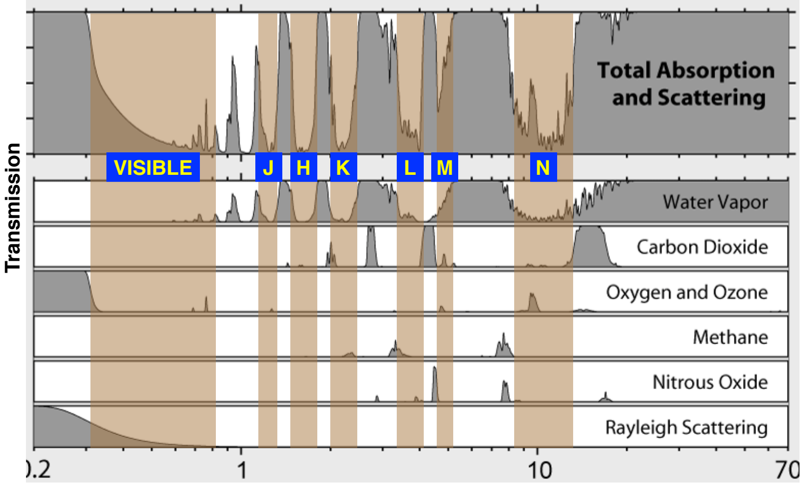
$$v \sim 10 \text{ m.s}^{-1}$$

Atmospheric time constant $\tau_0 = 0.31 \frac{r_0}{v}$

$$\tau_0 \sim 1 - 10 \text{ ms}$$

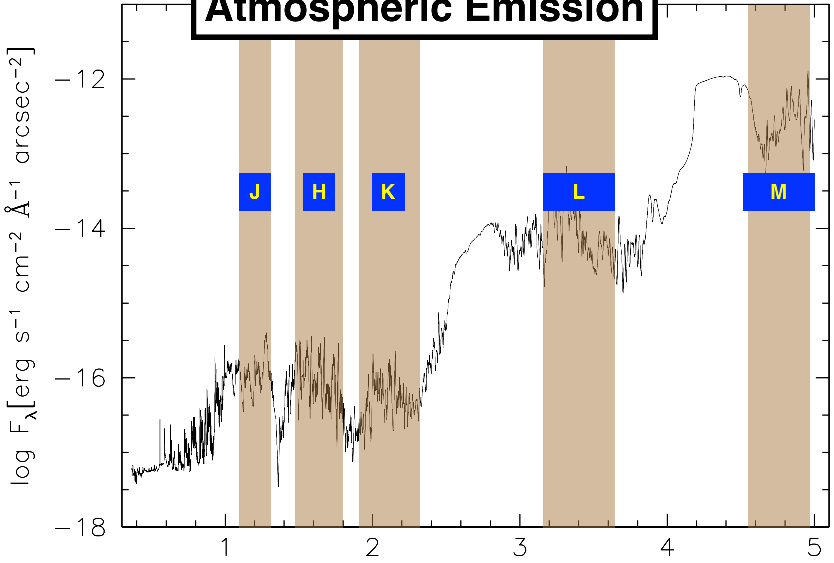


Atmospheric Transmission



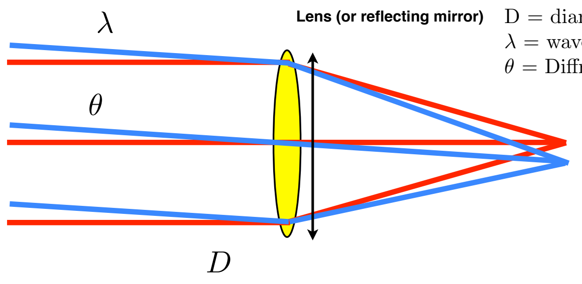
Source: HITRAN model Wikipedia

Atmospheric Emission



Source: Gemini Exposure Time Calc

Angular Resolution

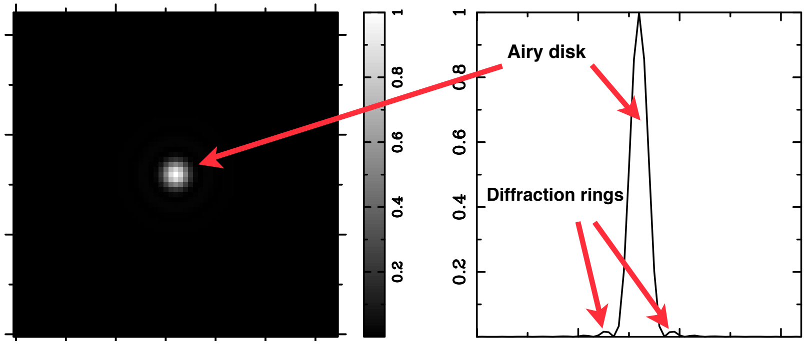


D = diameter (m)
λ = wavelength of light (m)
θ = Diffraction limit (arcsec)

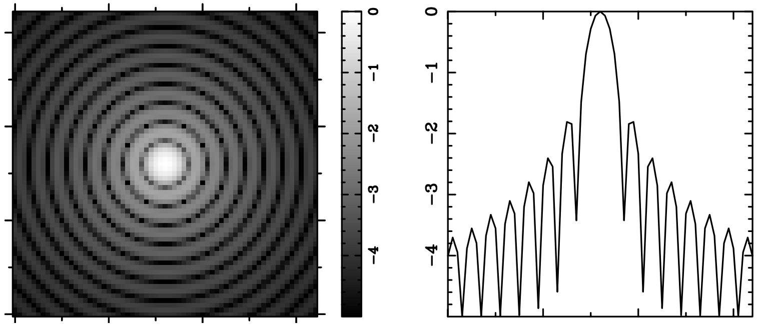
$$\theta = 1.22\lambda/D = 206265 \times \lambda/D \text{ arcsec}$$

Full Width at Half Maximum (FWHM) and Airy Disk

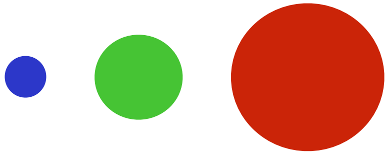
Imaging a point source with a telescope shows a diffraction pattern due to finite size of telescope aperture and wavelike nature of light



FWHM and Airy Disk (logarithmic)



$$\mathrm{FWHM} = 1.22\frac{\lambda}{D}$$

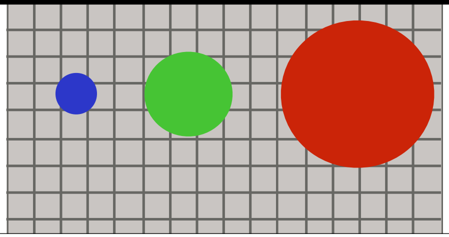


The Goldilocks Detector

There is an OPTIMUM pixel scale for a given wavelength

From Shannon and Nyquist Sampling theorem: $\sim 2.5\mathrm{pix}/\mathrm{FWHM}$

Most AO imagers have a plate scale that matches 2.5 pixels FWHM at the shortest wavelength



< 2 : undersampled

> 4 : oversampled

Astronomers want as much spatial resolution as possible

Diffraction limited by the telescope's primary mirror: $\approx \frac{\lambda}{D_{tel}}$

for the Hubble Space Telescope

$$\approx \frac{0.5\mu m}{2.4m} = 0.2\mu rad$$

$$\approx 43 \text{ milliarcsec}$$

Hubble Space Telescope Credit: NASA

The atmosphere limits diffraction limited imaging

Diffraction limited by the turbulent atmosphere: $\approx \frac{\lambda}{r_0}$

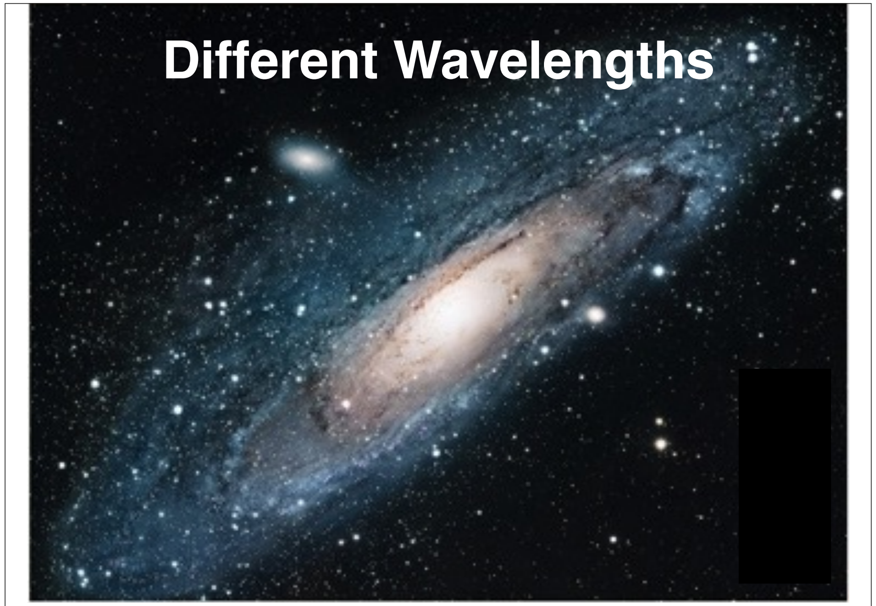
Typically for professional observatories:

$$\approx \frac{0.5\,\mu m}{10\,cm} = 5\mu rad$$

$$\approx 1 \text{ arcsec}$$

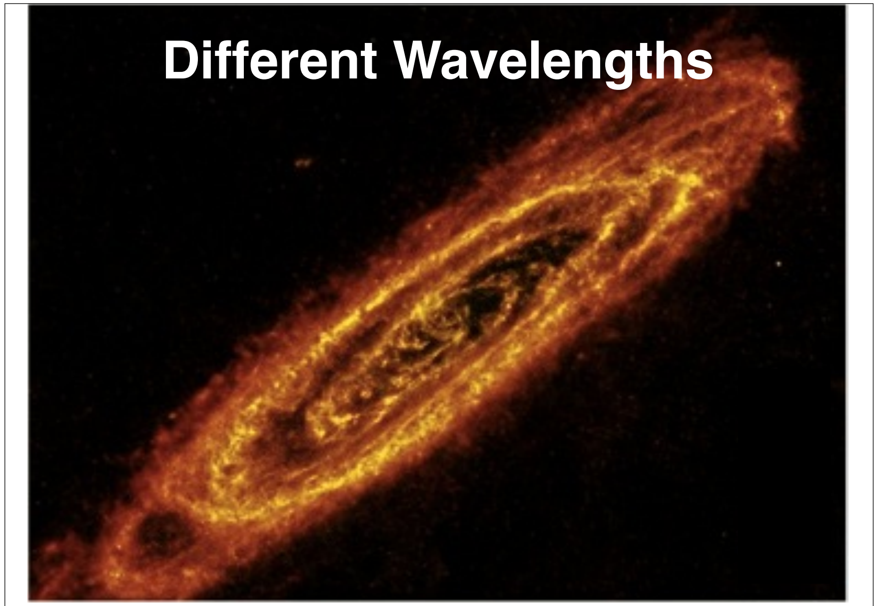
Imagers

Different Wavelengths

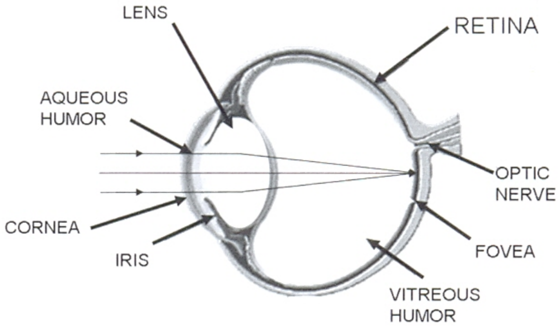


[redacted]

Different Wavelengths



The Human Eye

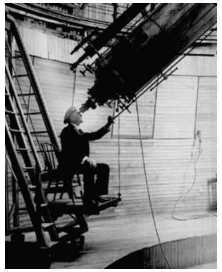


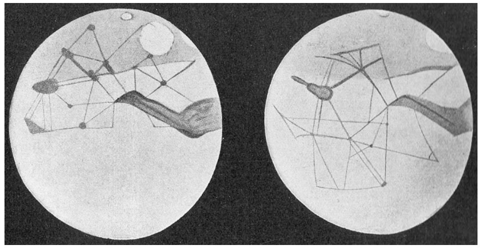
Theoretical: $\theta \sim \lambda/D \sim 0.5\mu m/7mm \sim 14''$

In practice: $\theta \sim 1$ arcminute

The Eye's Computer

Percival Lowell





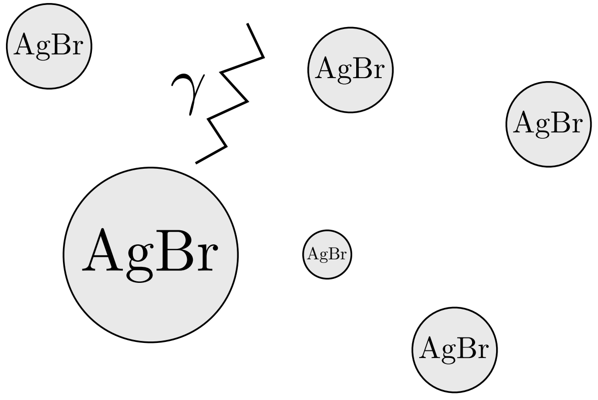
Canals on Mars!!!

The Eye's Computer

Photographic Plates

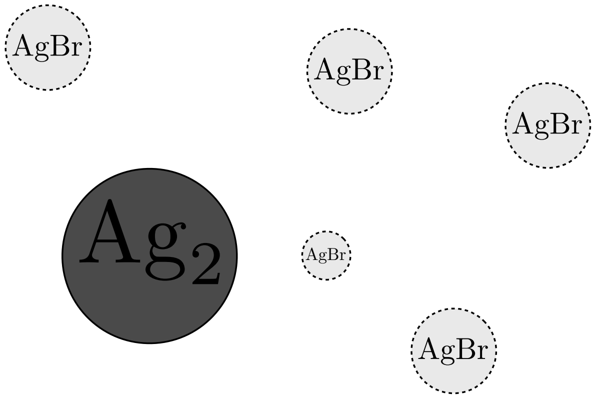
Photographic Plate Principle

Expose grains of slightly soluble Silver Halide salts to light:



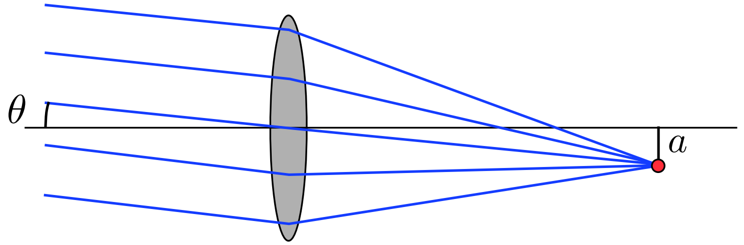
Photographic Plate Principle

Chemical fixing - remove stray ions and develop ALL silver in a grain:



The plate scale

Simple lens with diameter D and focal length f



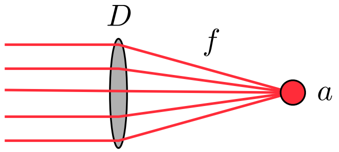
Arcseconds / mm

$$\text{Plate Scale} = \frac{\theta}{a} = \frac{206}{f}$$

metres

NOTE! Plate scale does NOT depend on diameter D, only the focal length

Take a seeing limited telescope and double it in size



Focal length doubled - focal ratio kept constant

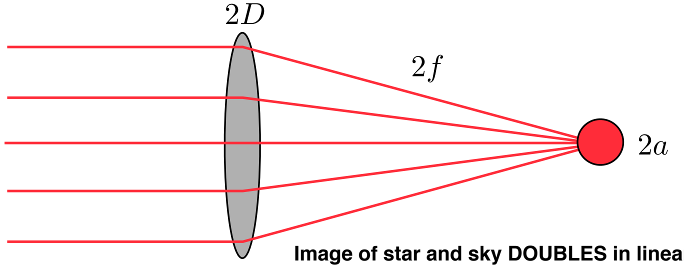
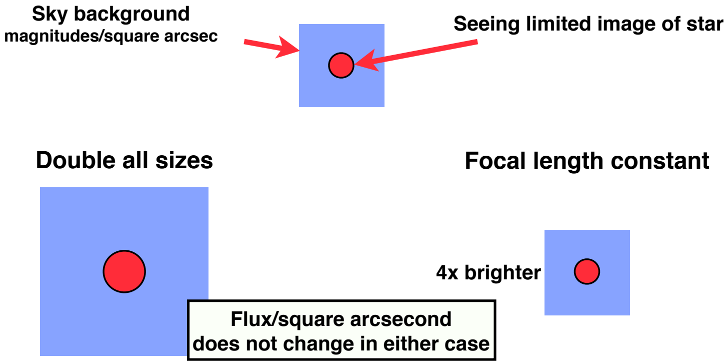


Image of star and sky DOUBLES in linear size

Seeing limited telescope sensitivity

$$\text{Signal to noise} = \frac{S}{N} \propto D^2$$



Sky background
magnitudes/square arcsec

Seeing limited image of star

Double all sizes

Focal length constant

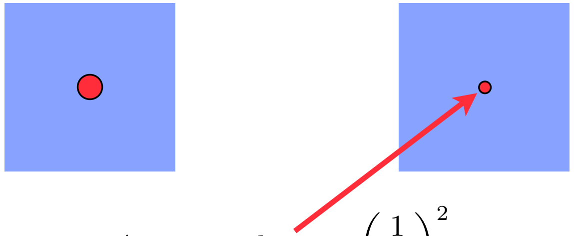
4x brighter

Flux/square arcsecond
does not change in either case

Diffraction limited telescope sensitivity

Diffraction limited star image is
SMALLER than seeing star image

Doubling the diameter



$$A_{PSF} = \pi d_{PSF} \propto \left(\frac{1}{D}\right)^2$$

Area DECREASES for the PSF, so the noise contribution goes down

$$\text{Signal to noise} = \frac{S}{N} \propto D^4$$

Plate scales for Prime and Cass

Effective focal lengths for Naysmith and Cassegrain foci are:
f/10 to f/40

For Coude, f/100 to f/200 not unusual, so ONLY ONE OBJECT

Prime Focus Correctors

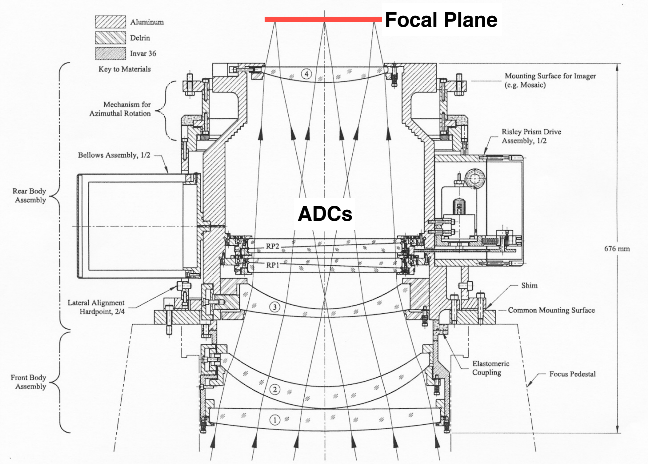


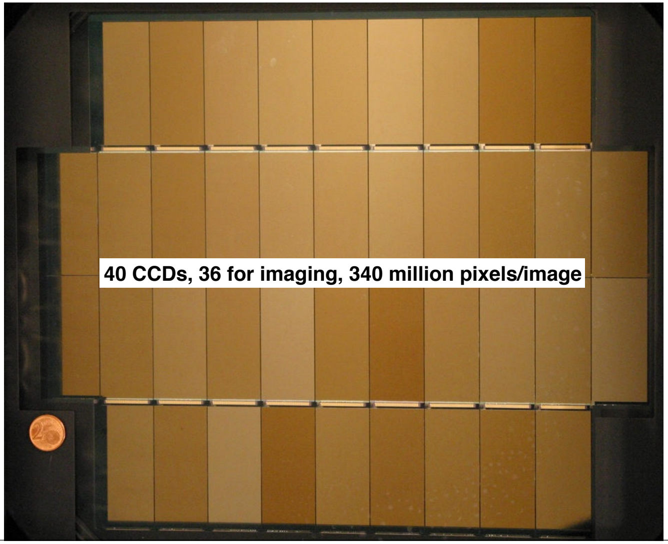
Figure 2. The opto-mechanical assembly for the new 4-m prime focus corrector. Elements #1, #2, #3, and #4 are SiO_2. The ADC materials comprising RP1 and RP2 are UBK7 (rear) and LLF6 (front), where "rear" is closer to the detector.

4m Mayall telescope on Kitt Peak

http://www-kpno.kpno.noao.edu/glaspey/mayall_params.html

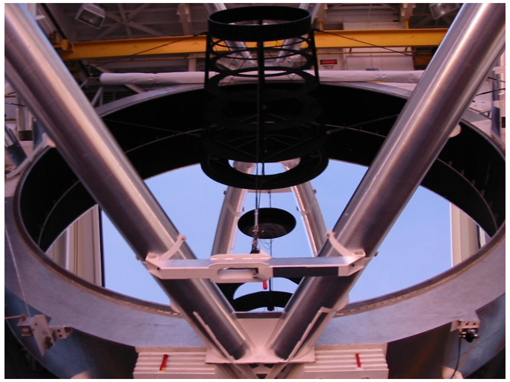
Prime Focus Imagers

Ground based imaging - MEGACAM at CFHT



40 CCDs, 36 for imaging, 340 million pixels/image

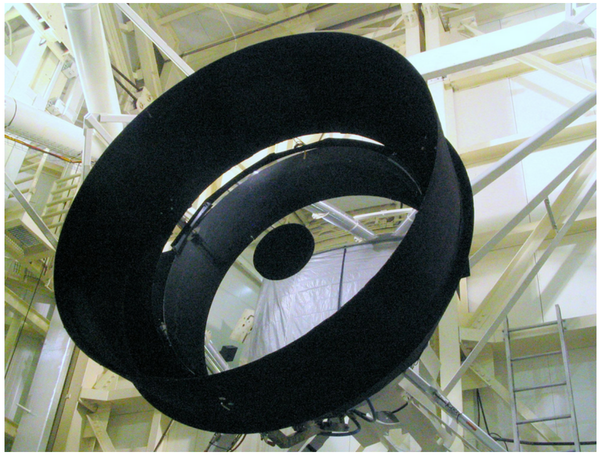
Wide Field Imagers



Telescope baffling above Cassegrain at MMTO 6.5m telescope

https://www.cfa.harvard.edu/~mlacasse/

Wide Field Imagers



Telescope baffling for f/5 mirror at MMTO 6.5m telescope

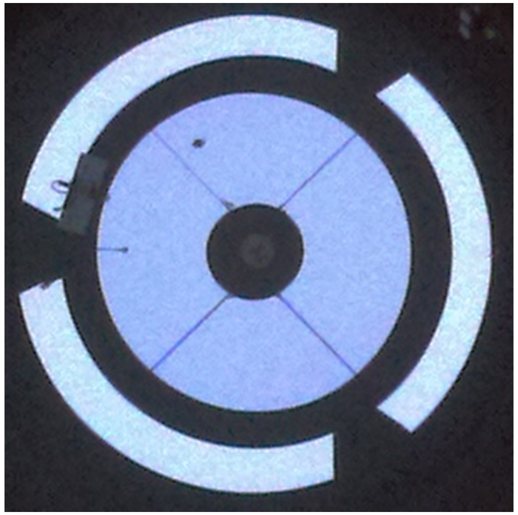
https://www.cfa.harvard.edu/~mlacasse/

Wide Field Imagers

Internal reflections from a Schmidt camera

http://www.robertreeves.com/repair1.htm

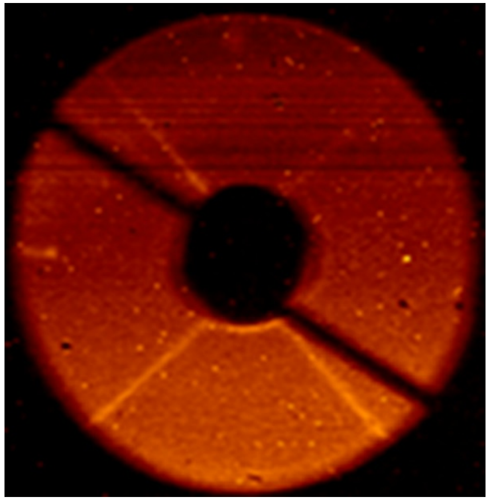
Visible Pupil image



https://visao.as.arizona.edu/simulations/magao-pupils-and-fourier-optics/

Kate Morzinski

Infrared 3.4 micron Pupil image

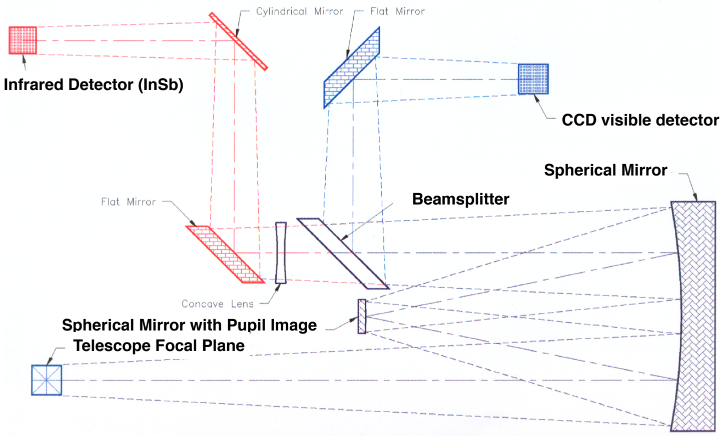


https://visao.as.arizona.edu/simulations/magao-pupils-and-fourier-optics/

Kate Morzinski

Offner Relay

Used to make cold stops in IR cameras



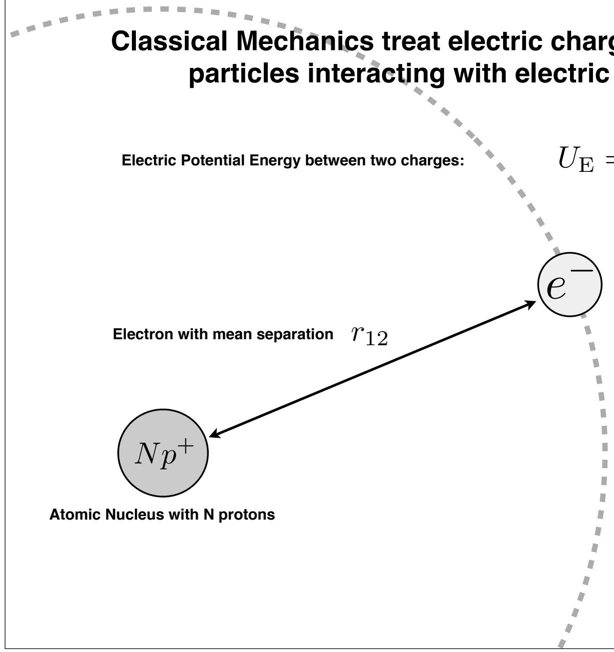
http://www.astronomy.ohio-state.edu/~depoy/research/instrumentation/andicam/andicam.html

Photodetectors

Classical Mechanics treat electric charges as point particles interacting with electric fields

Electric Potential Energy between two charges:

$$U_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}}$$

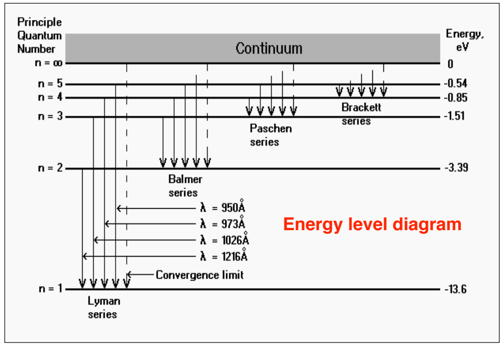


Electron with mean separation r_{12}

Atomic Nucleus with N protons

Electrons can absorb or emit photons and change to a different allowed orbital

e.g. the Hydrogen atom with one electron



Energy level diagram

$$m = 2 \text{ to } n = 3, 4, 5, 6$$

Photons of only specific energies can be absorbed or emitted

In the **BOHR MODEL**, the orbital angular momentum of the electron is **quantized** in units of $\hbar$

$$p_\theta = n\hbar$$

...where $n = 1, 2, 3, \ldots$

The QM properties of electrons lead to atomic lines and semiconductor bands

Multiple electrons around a positively charged nucleus have four quantum numbers:

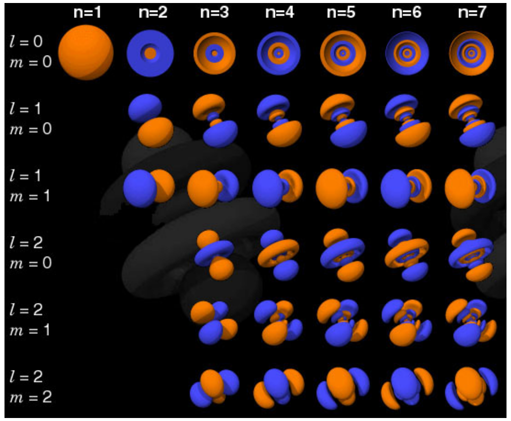
$$n, l, m_l, m_s$$

Only **ONE FERMION** can have one set of quantum numbers!

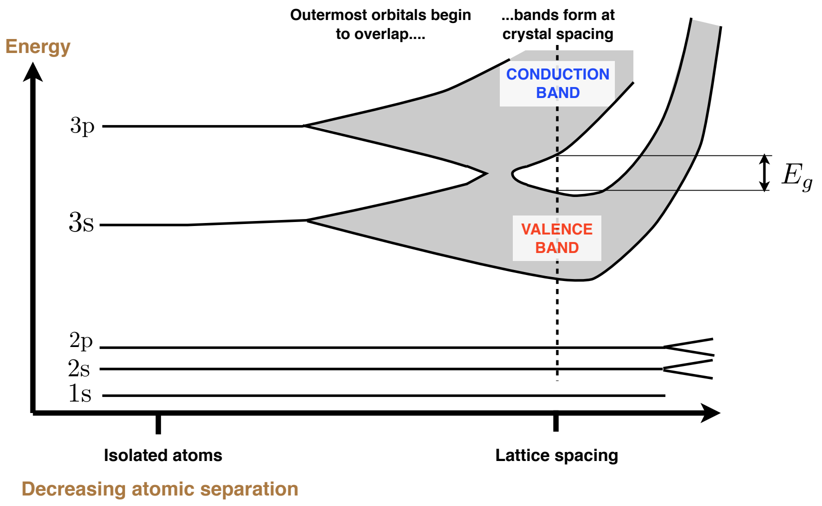
Electrons (and other particles) are described with Schrodinger's Wave Equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \hat{H}\Psi(x,t)$$

Electrons are described by probability clouds called **ORBITALS** with specific energies.



Atomic orbitals overlap in a crystal to form electronic bands



Outermost orbitals begin to overlap....

...bands form at crystal spacing

Energy

CONDUCTION BAND

VALENCE BAND

3p

3s

2p

2s

1s

E_g

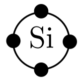
Isolated atoms

Lattice spacing

Decreasing atomic separation

Incomplete orbitals provide electrons for bonding

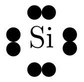
Silicon and Germanium have 4 electrons in their outermost (n=2) orbital:



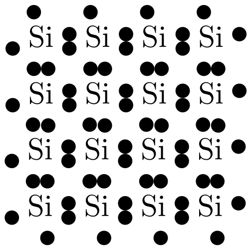
d = 0.230 nm

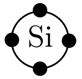
(In the Periodic Table these are GROUP IV elements)

Energetically they want to have 8 electrons to form a stable configuration:

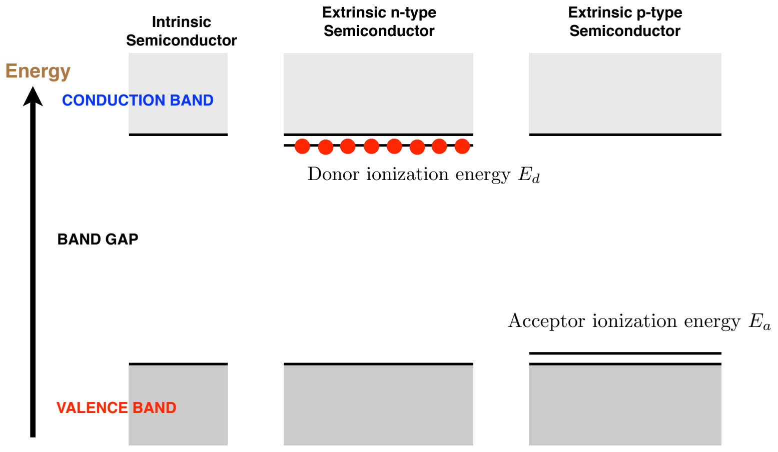


Forming a crystal sharing electrons with other Si atoms forms a stable LATTICE:





Energy Band Diagram for Donors and Acceptors



Intrinsic Semiconductor

Extrinsic n-type Semiconductor

Extrinsic p-type Semiconductor

Energy

CONDUCTION BAND

Donor ionization energy E_d

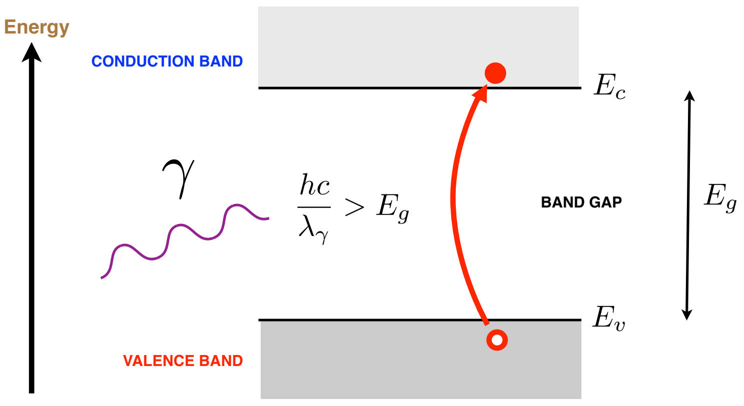
BAND GAP

Acceptor ionization energy E_a

VALENCE BAND

$$T = 0K$$

Energy Band Diagram



Energy

CONDUCTION BAND

E_c

γ

$$\frac{hc}{\lambda_\gamma} > E_g$$

BAND GAP

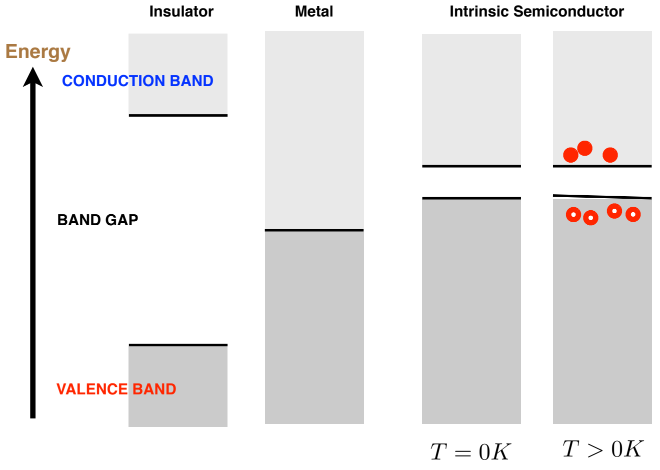
E_g

E_v

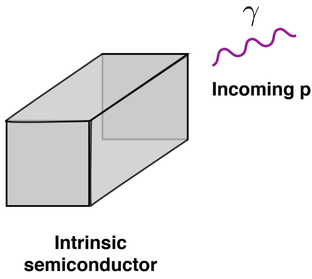
VALENCE BAND

Electrons can also be THERMALLY excited

Energy Band Diagram



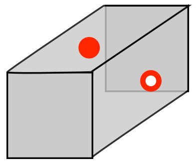
Photon Detectors respond directly to individual photons



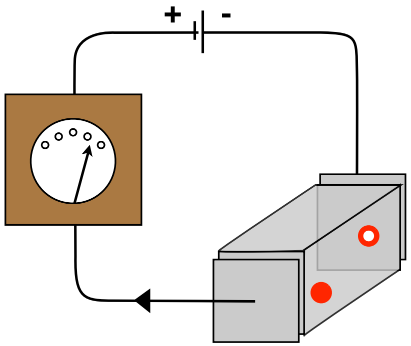
Incoming photon with energy greater than bandgap energy:

$$E_\gamma = \frac{hc}{\lambda} > E_{bandgap}$$

...is converted into releasing an electron and a hole....



Charge carriers move out of semiconductor and register as a signal

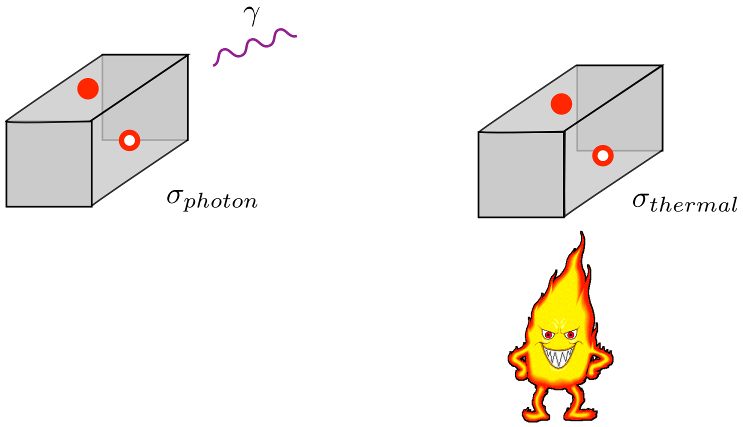


Applying an electric field causes electric charges to move in the material and register a signal as an electric current

---

Charge carriers are generated with both photons and thermal excitation

We measure the electrical conductivity!

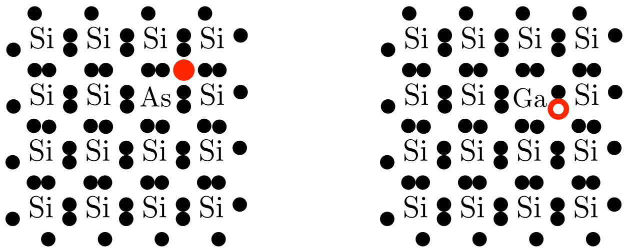


Dopants in Silicon

We can dope a pure silicon crystal with small amounts of Group V or Group III elements

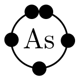
Adding a Group V element introduces conduction electrons and creates n-type silicon, called a donor.

Adding a Group III element introduces an electron hole and creates p-type silicon, called an acceptor.



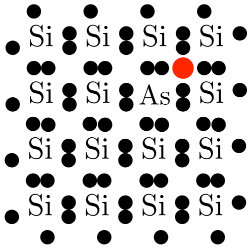
Pure semiconductors are INTRINSIC, doped semiconductors are EXTRINSIC

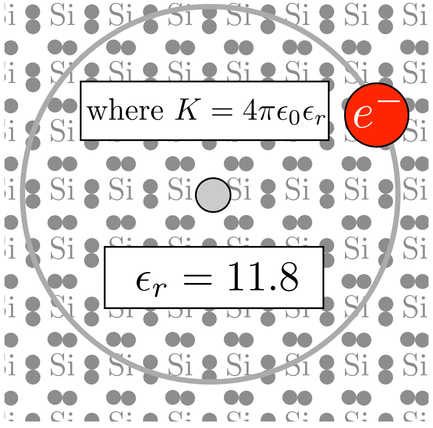
Why is a donor easily ionised?



As atom looks "hydrogen-like" with covalent bonds shielding large nuclear charge:

$$E_{bohr} = \frac{mq^4}{2K^2\hbar^2}$$



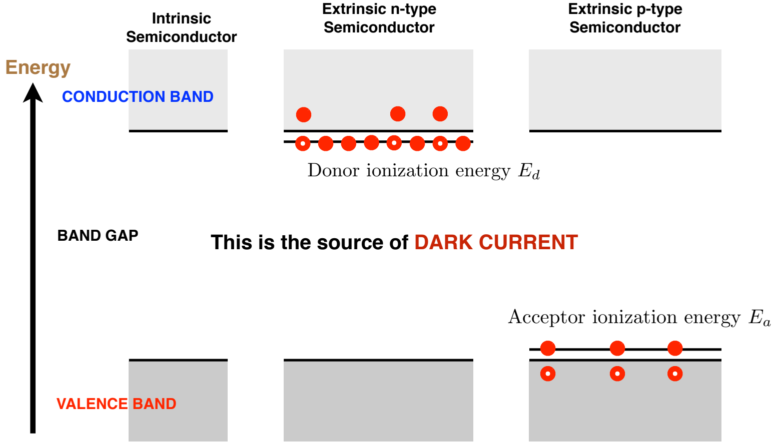


$$\text{where } K = 4\pi\epsilon_0\epsilon_r$$

$$\epsilon_r = 11.8$$

Electron is REALLY easy to ionise!

Energy Band Diagram for Donors and Acceptors

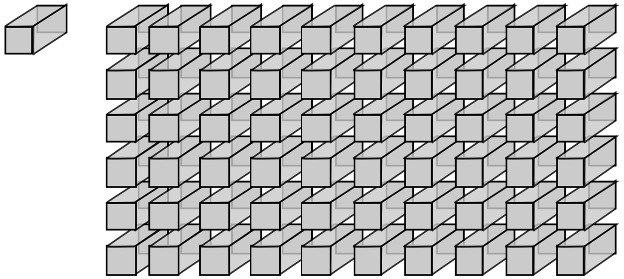


This is the source of DARK CURRENT

$$T > 0K$$

Detector Arrays

Arrays formed from individual photoconductors



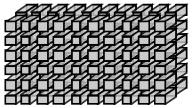
+ Readout Electronics

= Detector Array

Two types of arrays in the Optical/IR

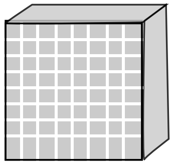
IR Arrays

$(1\mu m - 40\mu m)$



Charge Coupled Devices (CCDs)

$(0.1nm - 1\mu m)$



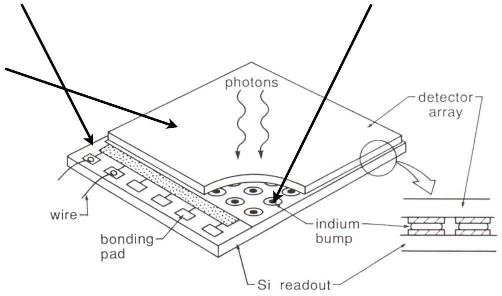
+ directly access individual pixels

- complex and expensive

+ monolithic structure built in Si wafer

- charge transfer inefficiencies

Production of IR Arrays



Make a grid of readout amplifiers in Silicon

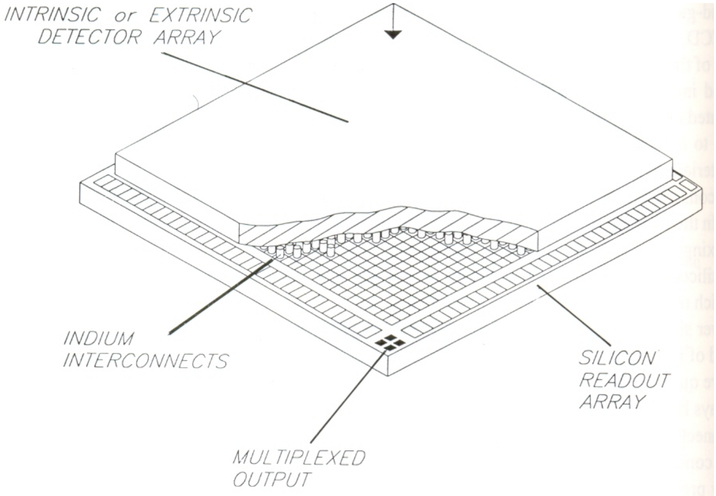
Make a matching image of detector pixels

Deposit Indium bumps on both sides

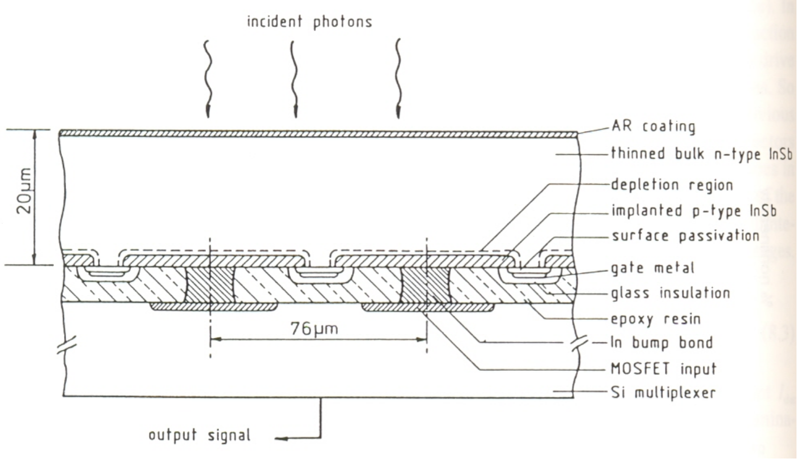
Squeeze them together to make a hybrid array

Why Indium? It's a soft metal and will still be ductile at cryogenic temperatures!

Production of IR Arrays

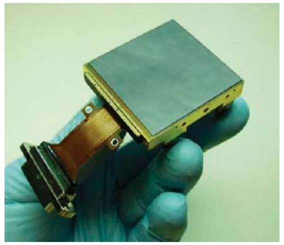


Detailed Bonding Structure of IR Array

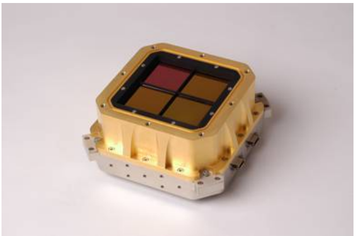


The Teledyne 2k x 2k Hawaii-2RG detector

Parameter	Specification
Detector technology	HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5MHz (continuously adjustable)
Total pixels	2048 x 2048
Pixel pitch	18 μm
Fill factor	≥ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3μm
Operating temperature	≥ 30K
Quantum efficiency (array mean)	≥ 65%
Charge storage capacity	≥ 100,000e^-
Pixel operability	≥ 95%
Dark current (array mean)	≤ 0.1 e^-/sec (77K, 2.5 μm)
Read noise (array mean)	≤ 15 e^- CDS @ 100 kHz
Power dissipation	≤ 4 mW @ 100 kHz



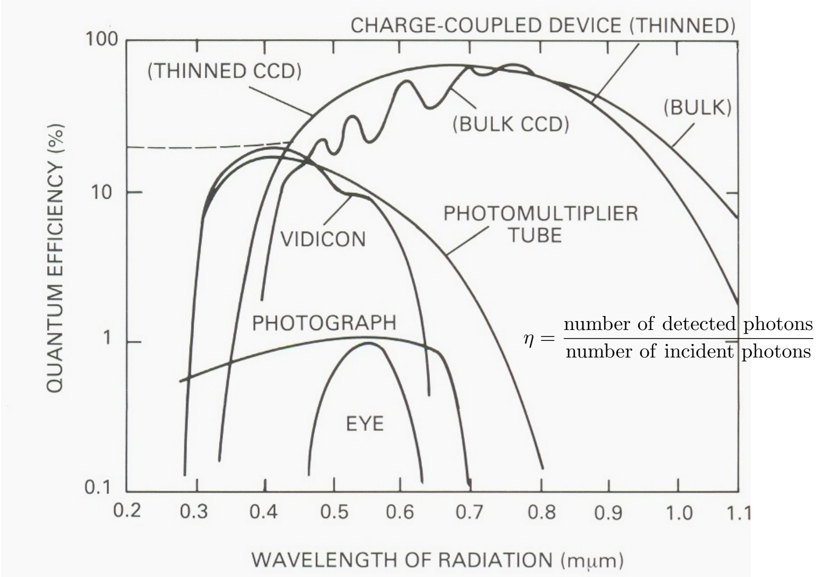
Can also be combined to a 2x2 mosaic



Some Performance Aspects of Detectors

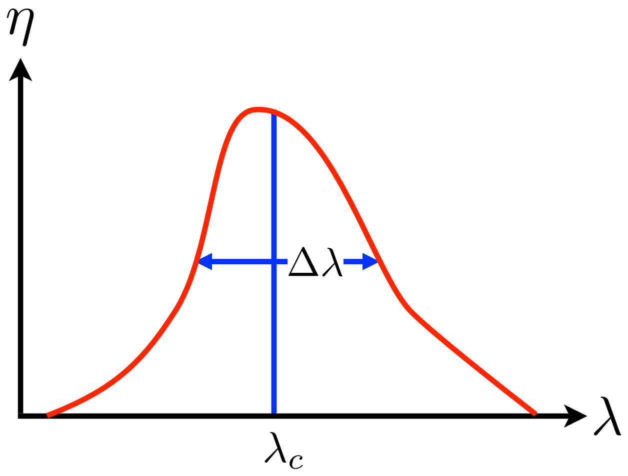
- Spectral response and bandwidth
- Linearity / saturation
- Dynamic range
- Quantum efficiency
- Noise
- Geometric properties
- Time response
- Polarization
- Operational aspects

Spectral Response and Bandwidth



$$\eta = \frac{\text{number of detected photons}}{\text{number of incident photons}}$$

Spectral Response and Bandwidth



Linearity and Dynamic Range

http://www.luckymanpress.com

Commercial cameras: 8 to 12 bits $10^{2.4}$ to $10^{3.6}$

Astronomical cameras: 16 bits ++ $10^{4.2}$

Noise

Most important: $\boxed{\sigma = \frac{Signal}{Noise}}$ measured as (S+B)-mean{B}

Total noise = $\sqrt{\sum (N_i)^2}$ if statist. independent

Most relevant noise sources:

Photon noise follows Poisson statistics: $P(m) = \frac{e^{-n} n^m}{m!}$

(= probability to detect m photons in a given time interval where, on average, n photons $S/N = \sqrt{n}$)

G-R noise: statistics of the generated and recombined holes and electrons, related to the Poisson statistics of the incoming photons.

Johnson, kTC or reset noise: thermodynamic noise due to the thermal motion of the charge carriers.

1/f noise (increased noise at low frequencies) due to bad electrical contacts, temperature fluctuations, surface effects (damage), crystal defects, JFETs, …

Noise

$\boxed{\sigma = \frac{Signal}{Noise}}$

Signal: (S + B) - mean(B)

Noise: can be added as $\sqrt{\sum (N_i)^2}$

Photon noise follows Poisson statistics:

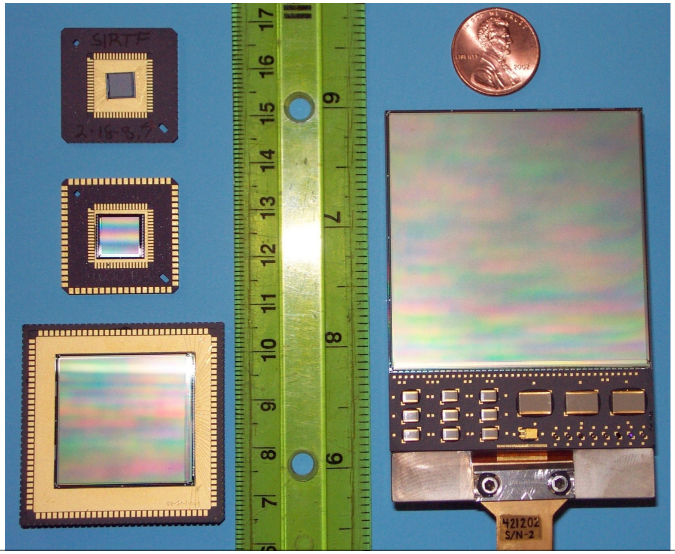
$$P(m) = \frac{e^{-n} n^m}{m!} \qquad S/N = \sqrt{n}$$

where P(m) the probability to detect m photons over a time interval and where the mean rate of photons is n

Geometrical Properties

Geometrical dimension and pixel number x × y

4 Generations of Raytheon Infrared Detectors



Calibrating a CCD image

For each SCIENCE image S (exposure time t_s)

Subtract off a BIAS image B to remove ADC offset (zero time integration)

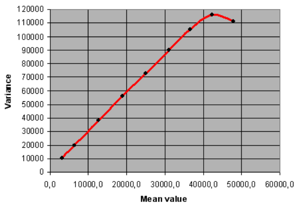
Subtract off a DARK image D to remove dark current offset (exposure time t_d)

Divide by a FLAT FIELD image F to remove gain variations (exposure time t_f)

$$S' = \frac{S - \frac{t_S}{t_D}(D - B) - B}{F - \frac{t_F}{t_D}(D - B) - B}$$

- $F - \frac{t_F}{t_D}(D - B) - B$ often normalized such that mean of S' = mean of S

Gain, Read Noise, Saturation limit



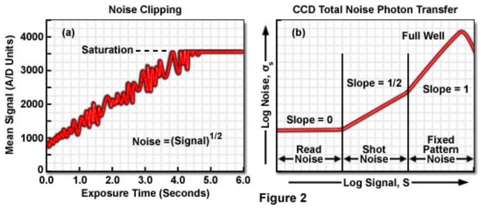


Figure 2

- gain (G) between arbitrary digital units (ADU, A) and number of photo-electrons (e): $A = G \cdot e$
- noise in e is given by $\sigma_e^2 = e$
- and therefore $\sigma_A^2 = G^2\sigma_e^2 = G^2 e$
- gain G determined from $G = \frac{\sigma_A^2}{A}$

Typical Array Artifacts

Thermal Mismatch damages the Indium contacts

Thermal mismatch is a problem when cooling a hybrid array down

Differential thermal contraction between photosensitive material and silicon readout wafer:

$\alpha_{Si} \sim 2.6 \times 10^{-6}$ $\alpha_{HgCdTe} \sim 5 \times 10^{-6}$

$$\frac{\Delta L}{L_0} = \alpha_L \Delta T$$

$$\Delta L_{mis} = L_0(\alpha_{HgCdTe} - \alpha_{Si})\Delta T = 36.9mm \times 2.4 \times 10^{-6} \times 200K = 17\mu m$$

...so, for a 2K by 2K array, we have a mismatch of about 1 pixel
the Indium bumps break, and we get dead pixels

Dead / Hot / Rogue Pixels

Dead Pixel: a defective pixel that delivers no signal and cannot be used

Hot Pixel: Highly elevated signal and noise level. It usually remains "hot" but may deliver limited information

Rogue Pixel: Has very high dark current and/or abnormal photon responsivity (similar to a hot pixel) but may be "healed" with annealing or other techniques

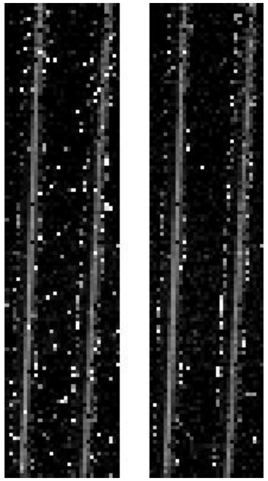
Mitigate with:

Assign it 'NaN' in your data reduction

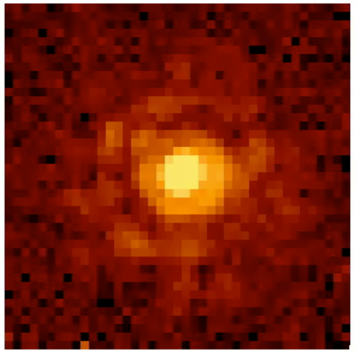
Interpolate from nearest neighbour values

subtract off an off-source image

reduce bias voltage



Dead / Hot / Rogue Pixels



An InSb detector working at 5 microns showing flickering pixels in an animation - read out every 1/10 of a second

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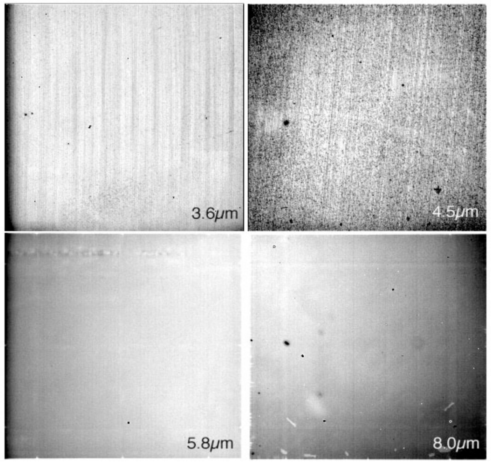
Pixel-to-pixel Variations

PROBLEM:
Fixed pattern noise - a combination of offsets, dark current variations and response variations

Significant patterns can occur on small and large scales

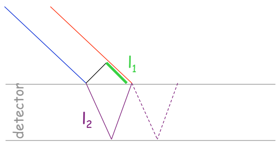
Here are examples for IRAC, a camera on the Spitzer Space Telescope

SOLUTION:
Look at an evenly illuminated source - this makes a "flat field" image that you can divide into your science images



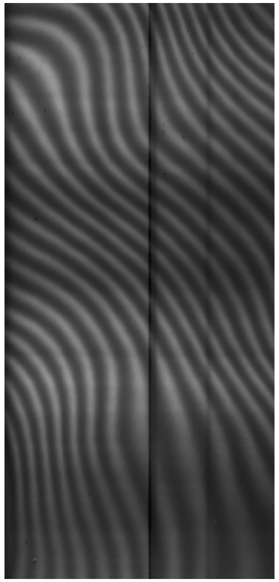
Fringes

PROBLEM:
Photons reflect off the back of the detector and interfere with the incoming light



If the phase difference between l_1 and $n \cdot l_2$ is an even multiple of π constructive interference occurs. If an odd multiple destructive interference occurs

Most prominent in spectrographs where the monochromatic wavelength varies across the array and the conditions for constructive/destructive interference are locally met



Multiple simultaneous amplifier readouts lead to "crosstalk"

PROBLEM:
The signal from a strongly illuminated pixel can couple into an adjacent amplifier readout board and appear as a "ghost" image

The negative (white) images in the upper right quadrant correspond to the black star images in the lower left quadrant