Imagers and Detectors

ATI 2017 Lecture 9

M. Kenworthy // Leiden Observatory

Observations

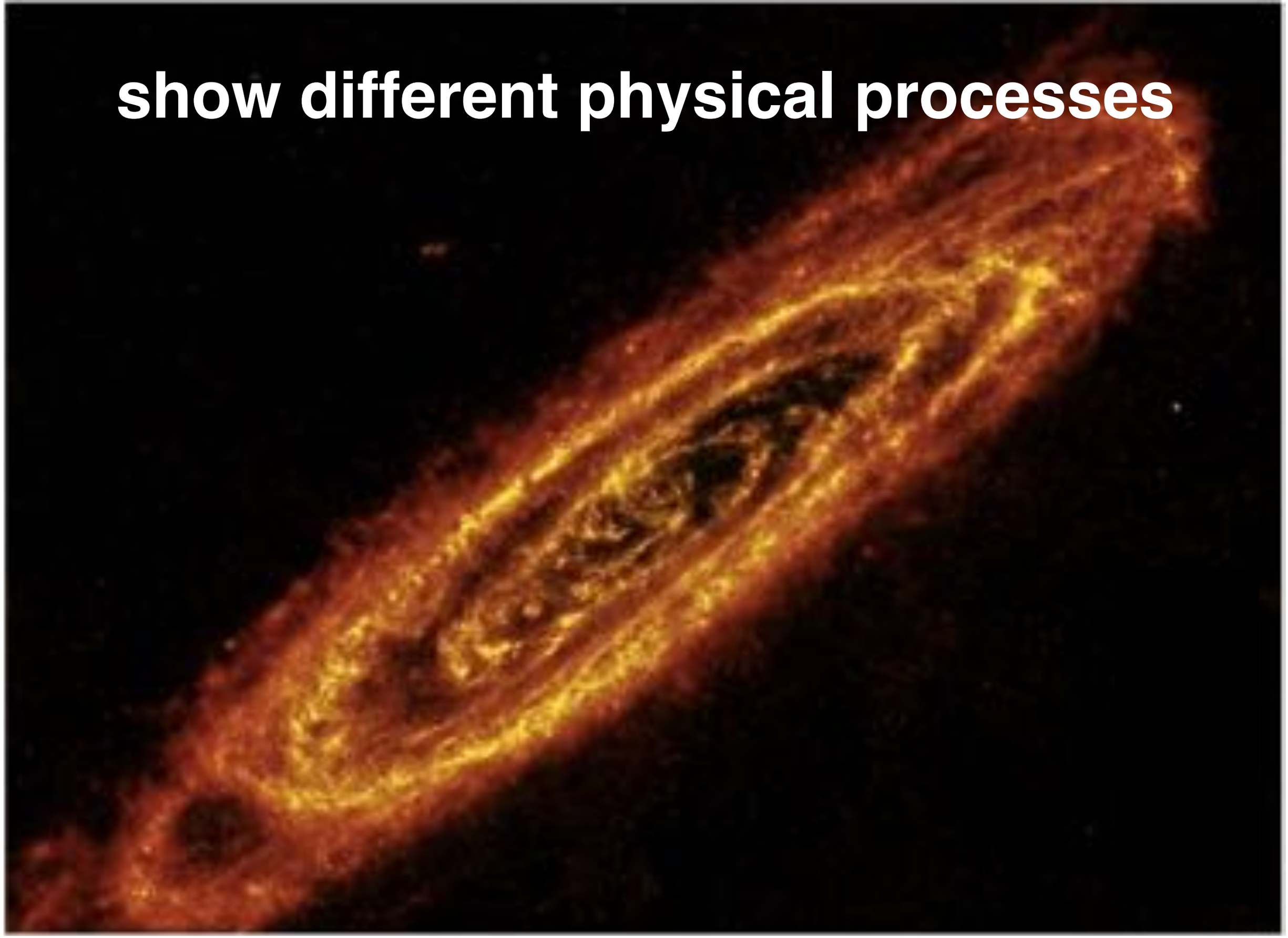
Astronomical observations are:

Expensive

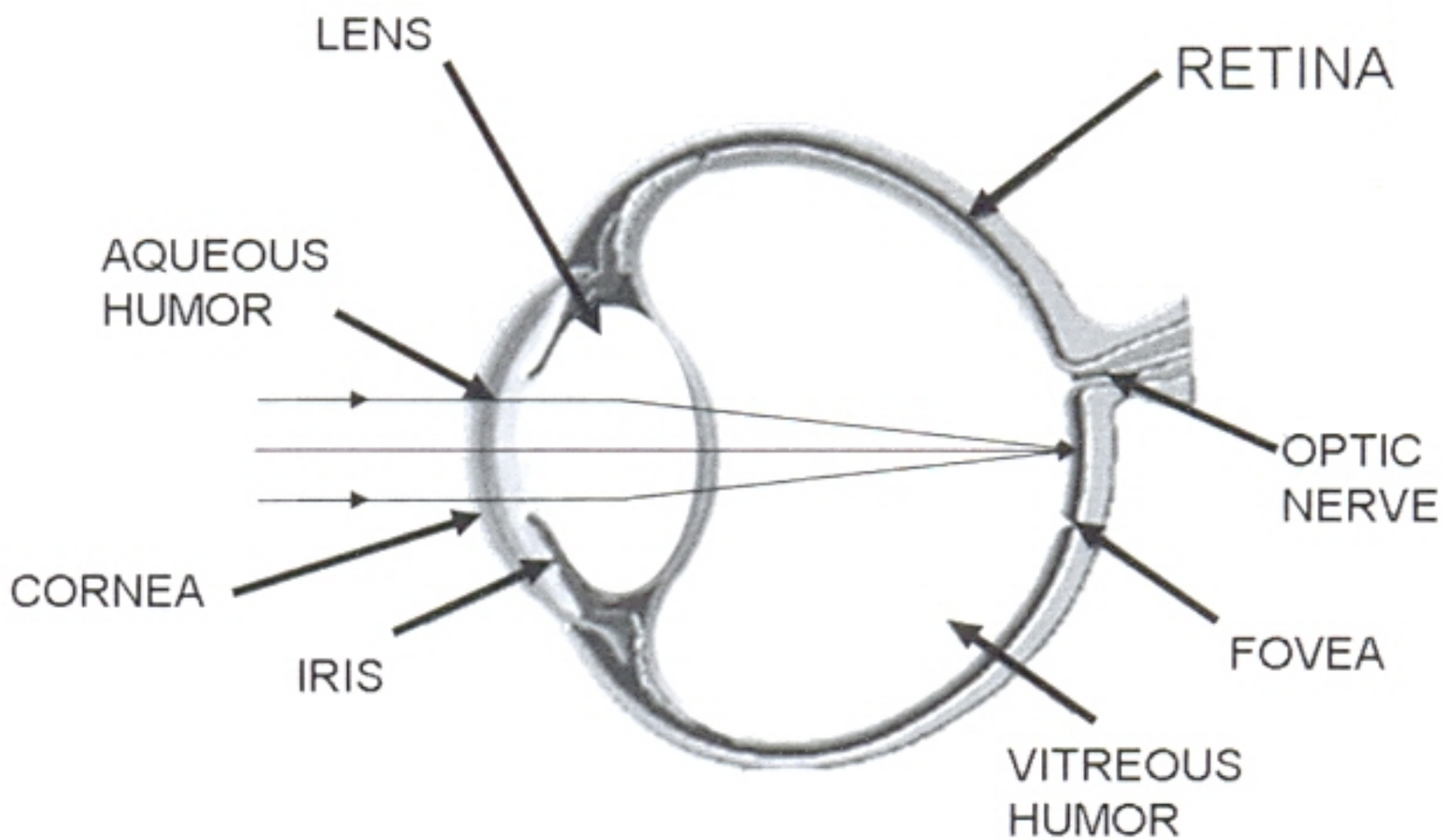
Impossible to repeat in a controlled way

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

Different Wavelengths…


show different physical processes

The Human Eye

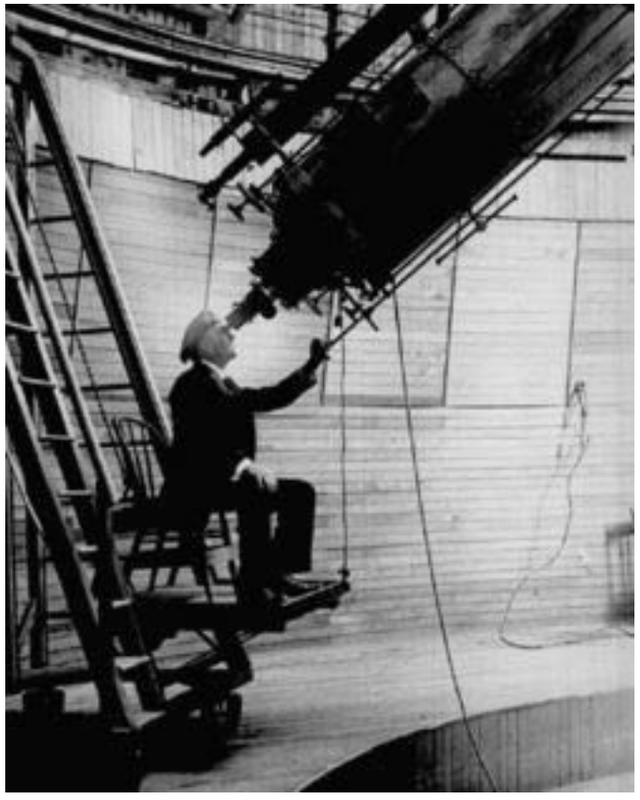


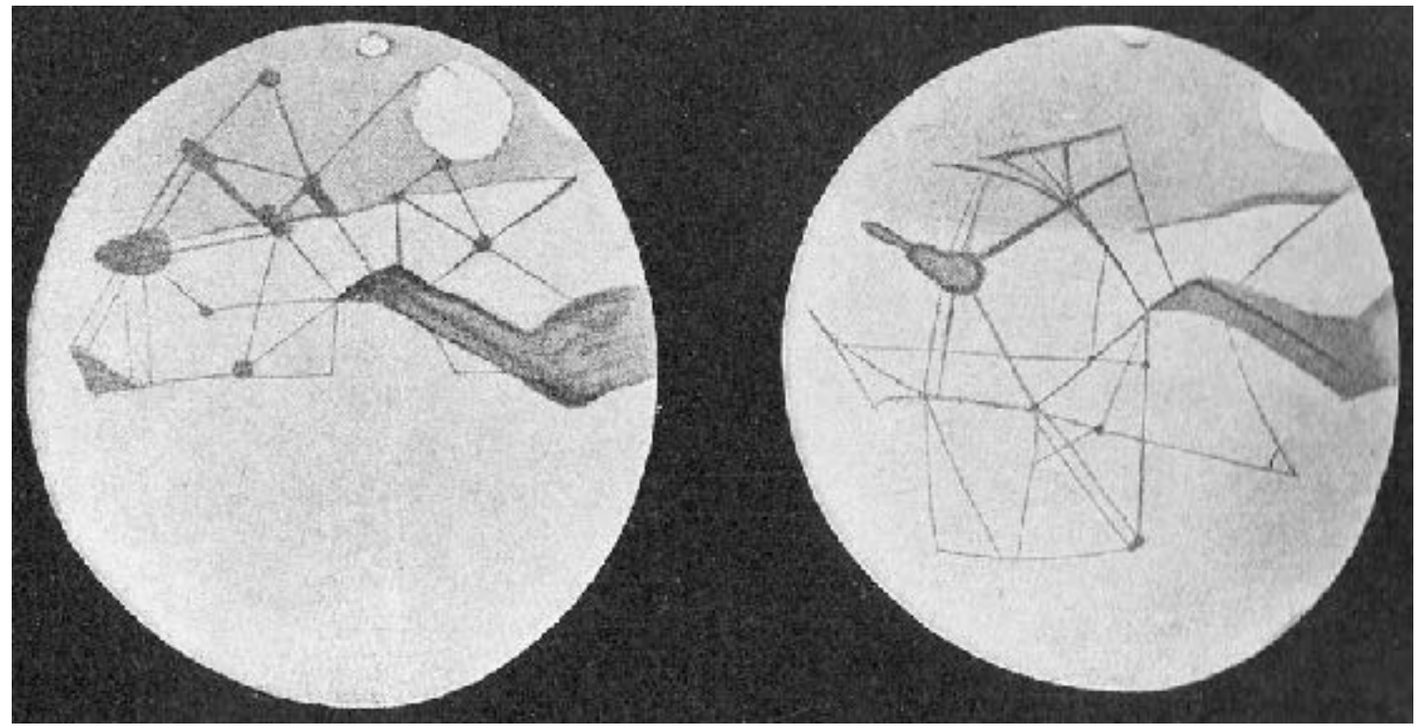
Theoretical: $\theta \sim \lambda/D \sim 0.5\mu m/7mm \sim 14''$

In practice: $\theta \sim 1$ arcminute

The Eye’s Computer

Percival Lowell

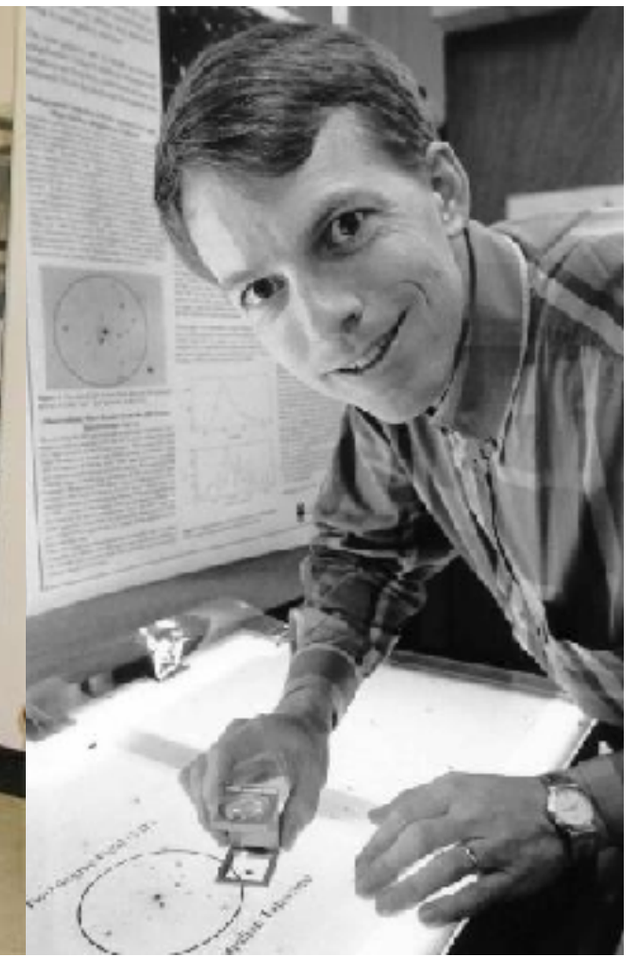




Seeing canals on Mars

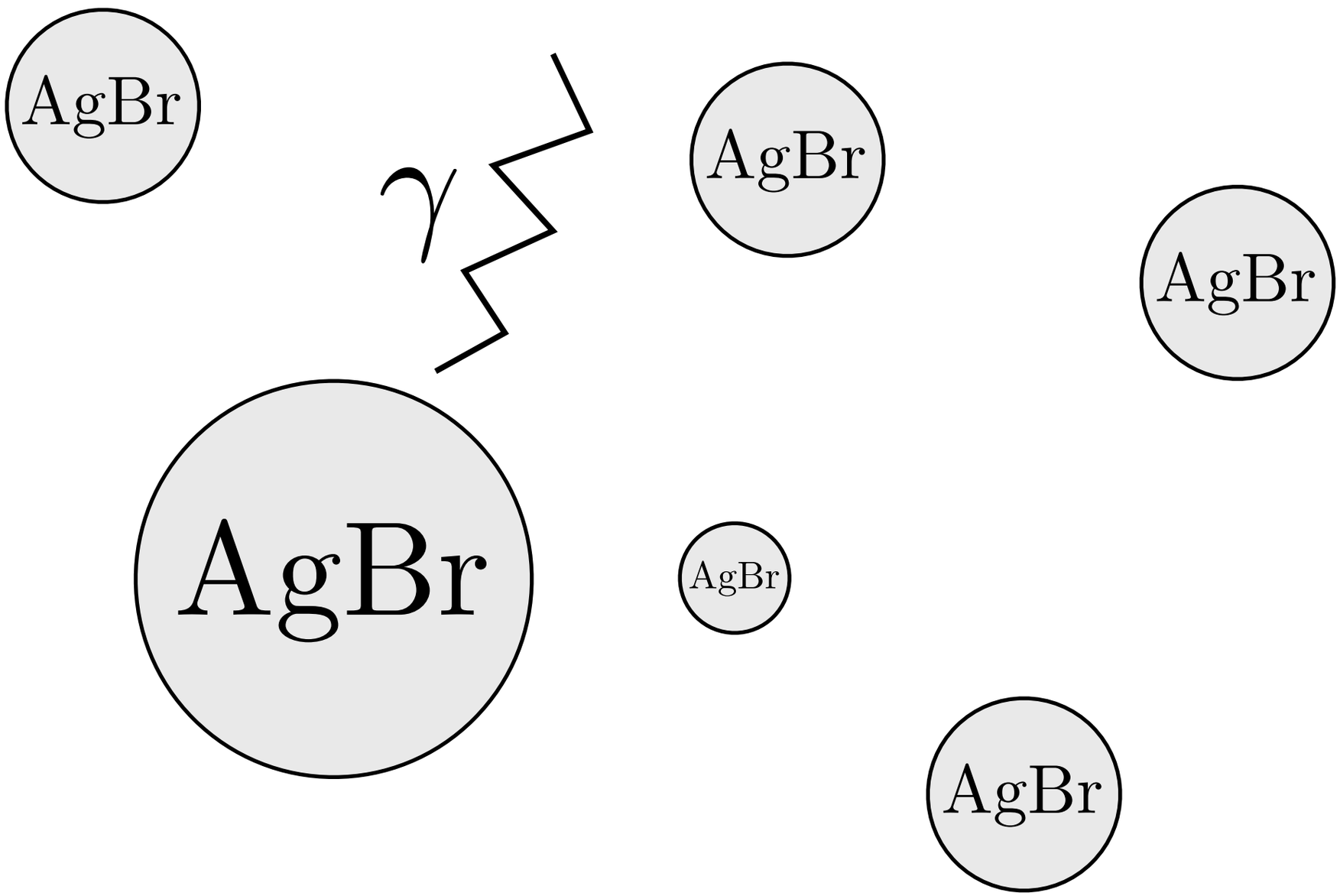
The Eye’s Computer

Photographic Plates



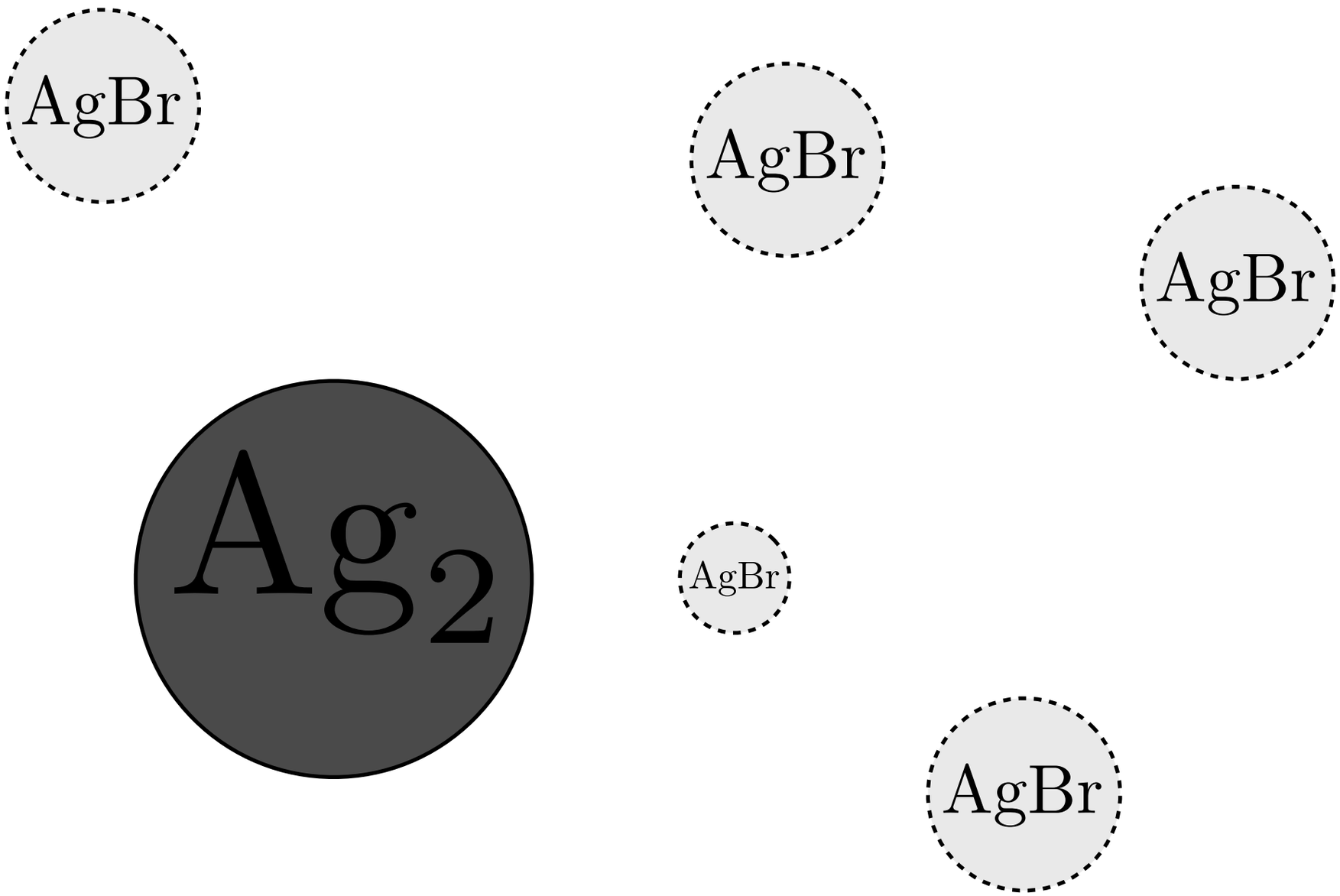
Photographic Plate Principle

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:

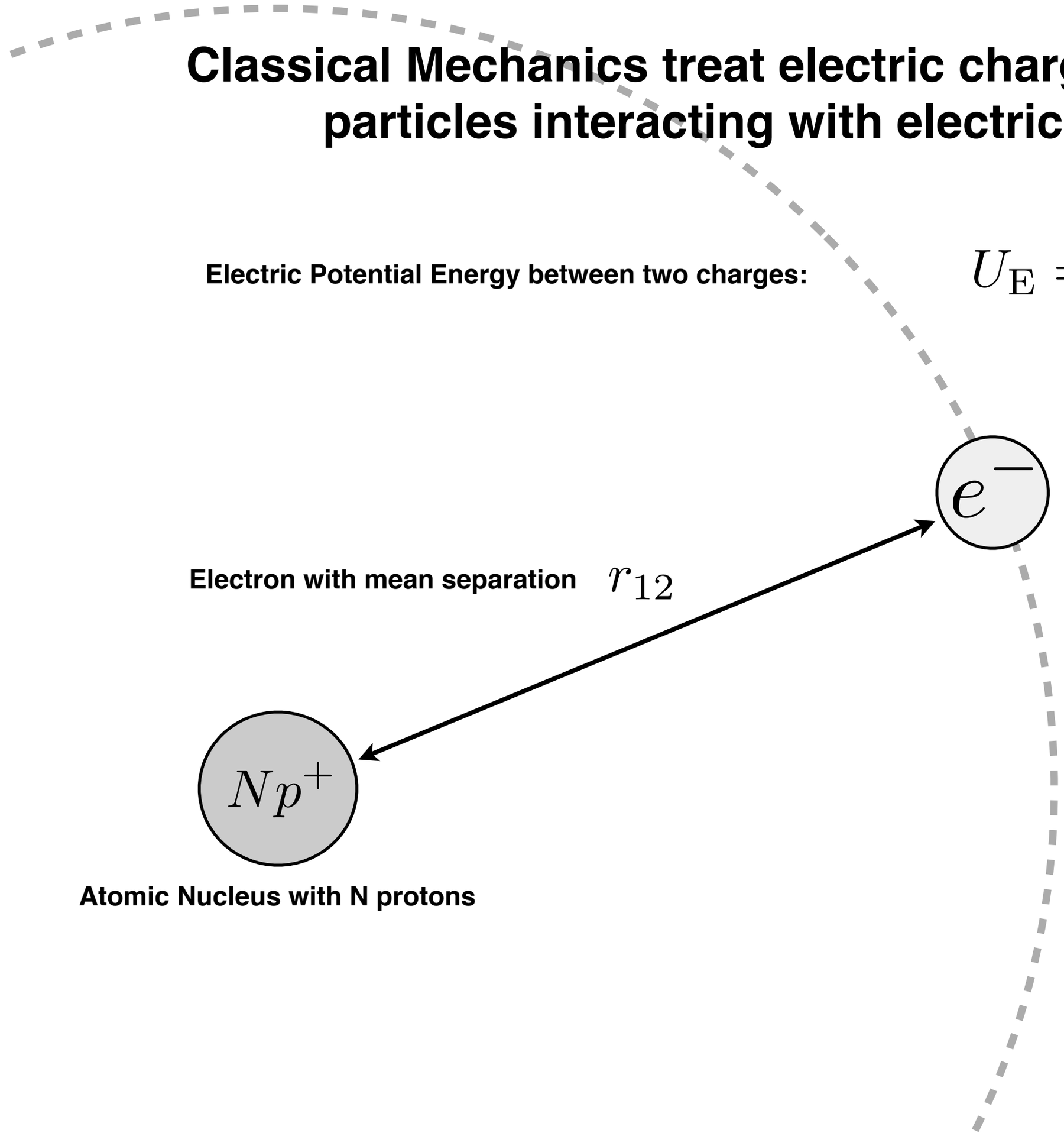


Photodetectors

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

Electric Potential Energy between two charges:

$$U_{\mathrm{E}} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}}$$



Quantum Mechanics

Particles in an energy potential V(x) are described by the Schrödinger wave equation and the wavefunction psi(x,t):

$$\frac{-\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V(x)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

"Kinetic energy" **"Potential energy"** **"Total energy"**

$$\psi(x,t) = u(x)e^{-iEt/\hbar}$$

probabilities not certainty

The square of the wave function gives the relative probability of finding the particle in a small region:

$$P(x,t) = \psi^* \psi$$

After you've observed the particle in a specific place, put that in as the new wave function and run the equation forwards again

(this is the bit which makes many people unhappy)

remove time dependency

Many problems are simplified to steady state
(particles in a box, no energy added or removed)

$$\frac{-\hbar^2}{2m}\frac{\partial^2 u(x)}{\partial x^2} + V(x)u(x) = E\ u(x)$$

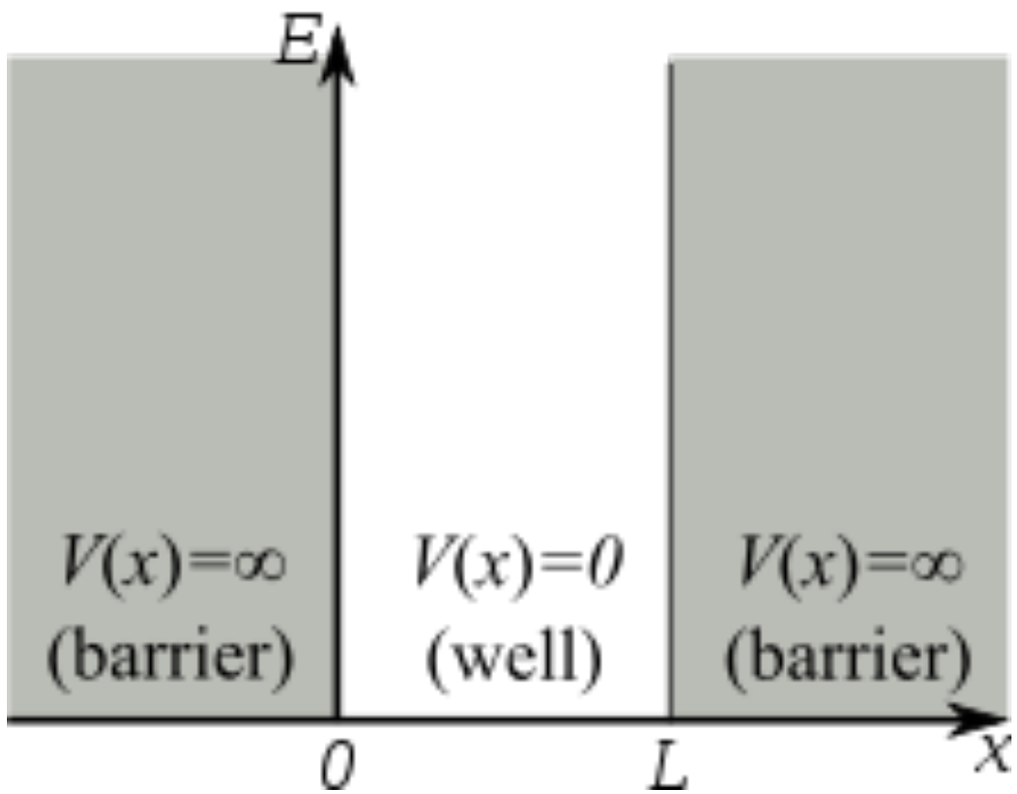
This is the Time Independent Schrödinger Equation

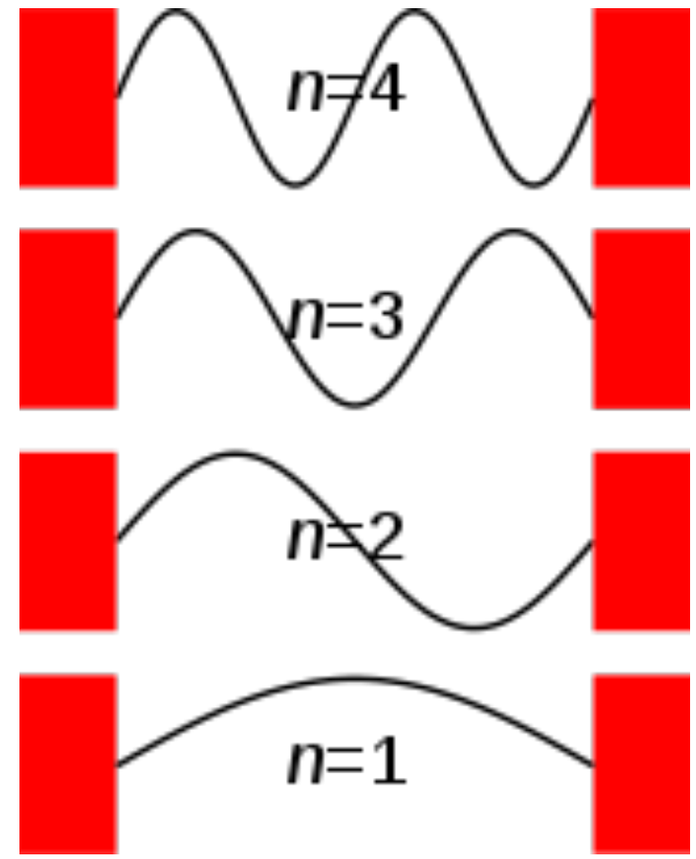
$$\psi(x,t) = u(x)e^{-iEt/\hbar}$$

The full equation with the time dependency separated

particle in a 1-D box

Infinite walled box of size L has many wave function solutions:





The four lowest wave function solutions

source: wikipedia/Particle_in_a_box

particle in a 1-D box

The wave function:

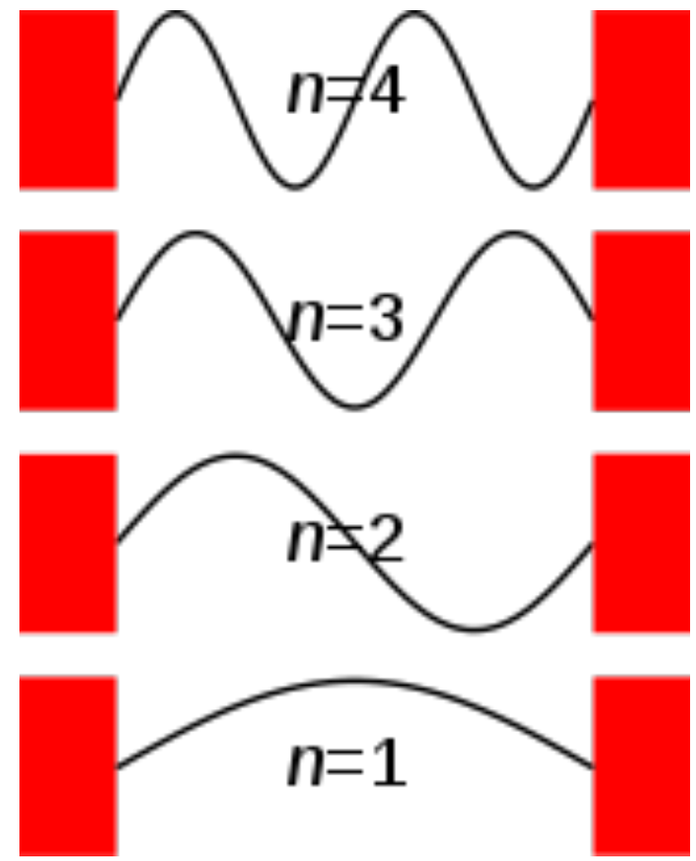
$$\psi_n(x,t) = \left\{ A \sin\left(k_n \left(x - x_c + \frac{L}{2}\right)\right) \mathrm{e}^{-i\omega_n t} \right.$$

…where:

$$k_n = \frac{n\pi}{L}$$

….and the ENERGY in state n is:

$$E_n = \hbar\omega_n = \frac{n^2\pi^2\hbar^2}{2mL^2}$$



The four lowest wave function solutions

source: wikipedia/Particle_in_a_box

particle energy is quantised

The wave function:

$$\psi_n(x,t) = \begin{cases} A\sin\left(k_n\left(x - x_c + \frac{L}{2}\right)\right)\mathrm{e}^{-i\omega_n t} \end{cases}$$

…where:

$$k_n = \frac{n\pi}{L}$$

….and the ENERGY in state n is:

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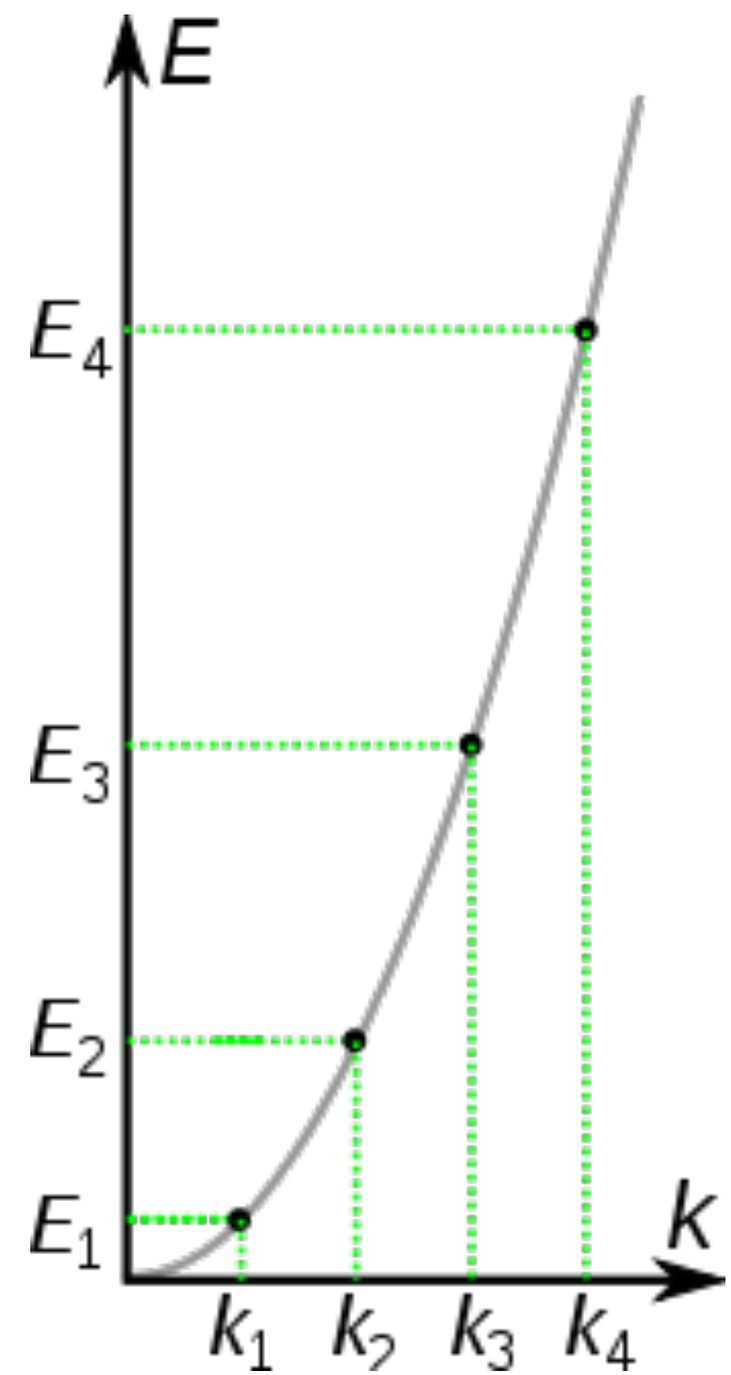


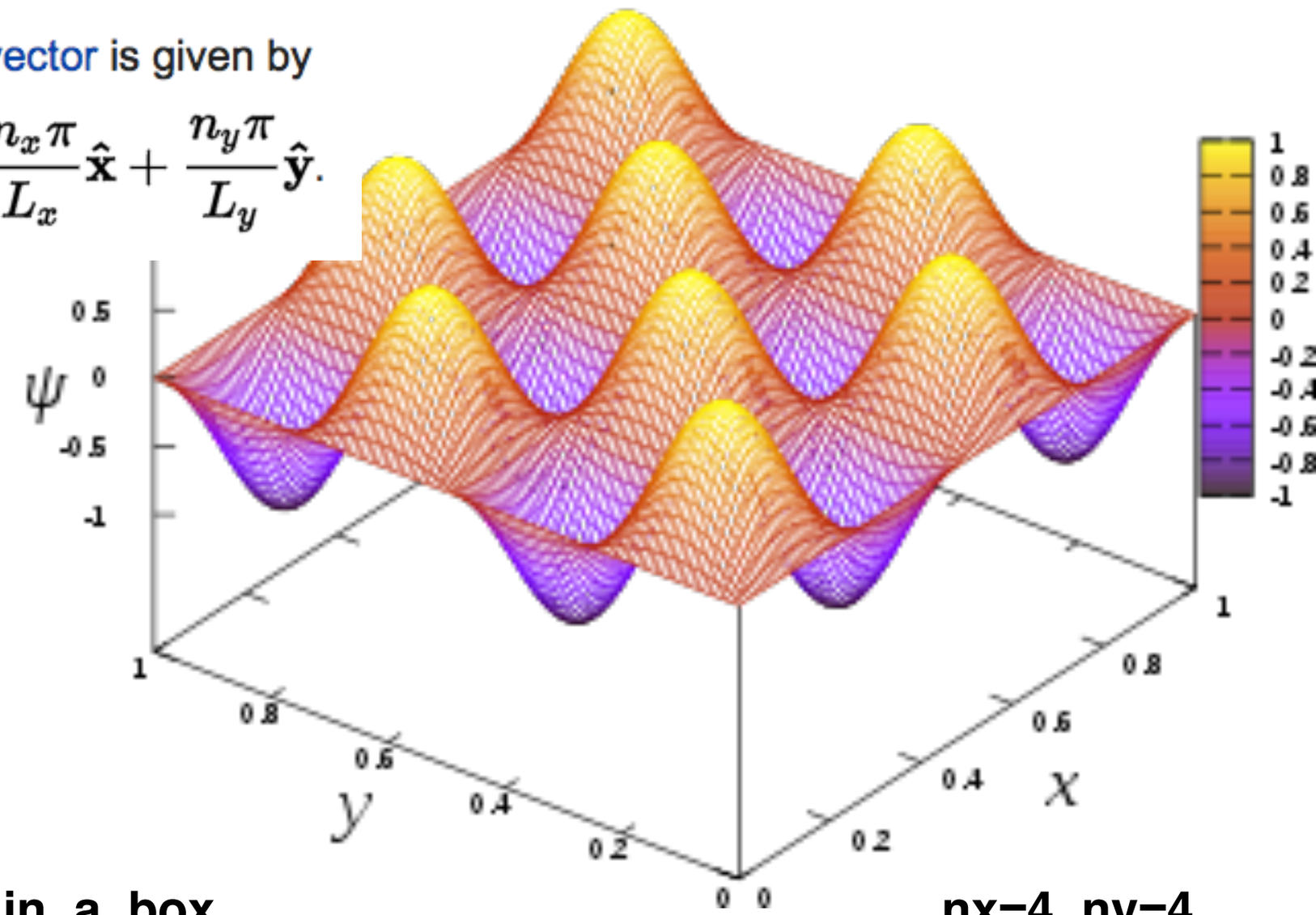
2D version has two quantum numbers

$$\psi_{n_x,n_y} = \psi_{n_x}(x,t,L_x)\psi_{n_y}(y,t,L_y),$$

$$E_{n_x,n_y} = \frac{\hbar^2 k_{n_x,n_y}^2}{2m},$$

where the two-dimensional wavevector is given by

$$\mathbf{k}_{\mathbf{n_x},\mathbf{n_y}} = k_{n_x}\hat{\mathbf{x}} + k_{n_y}\hat{\mathbf{y}} = \frac{n_x\pi}{L_x}\hat{\mathbf{x}} + \frac{n_y\pi}{L_y}\hat{\mathbf{y}}.$$

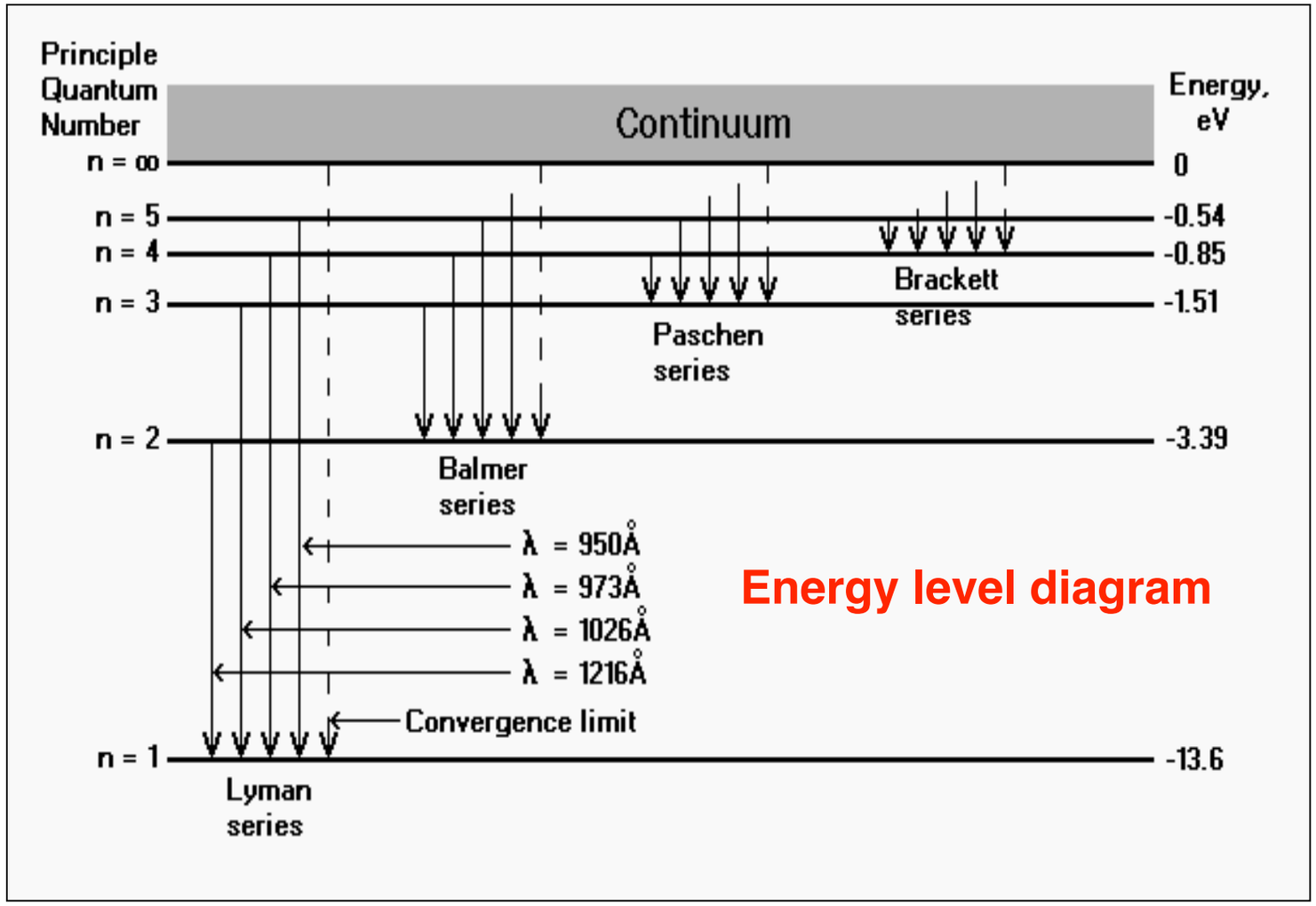


source: wikipedia/Particle_in_a_box

nx=4, ny=4

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

e.g. the Hydrogen atom with one electron



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

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

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

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

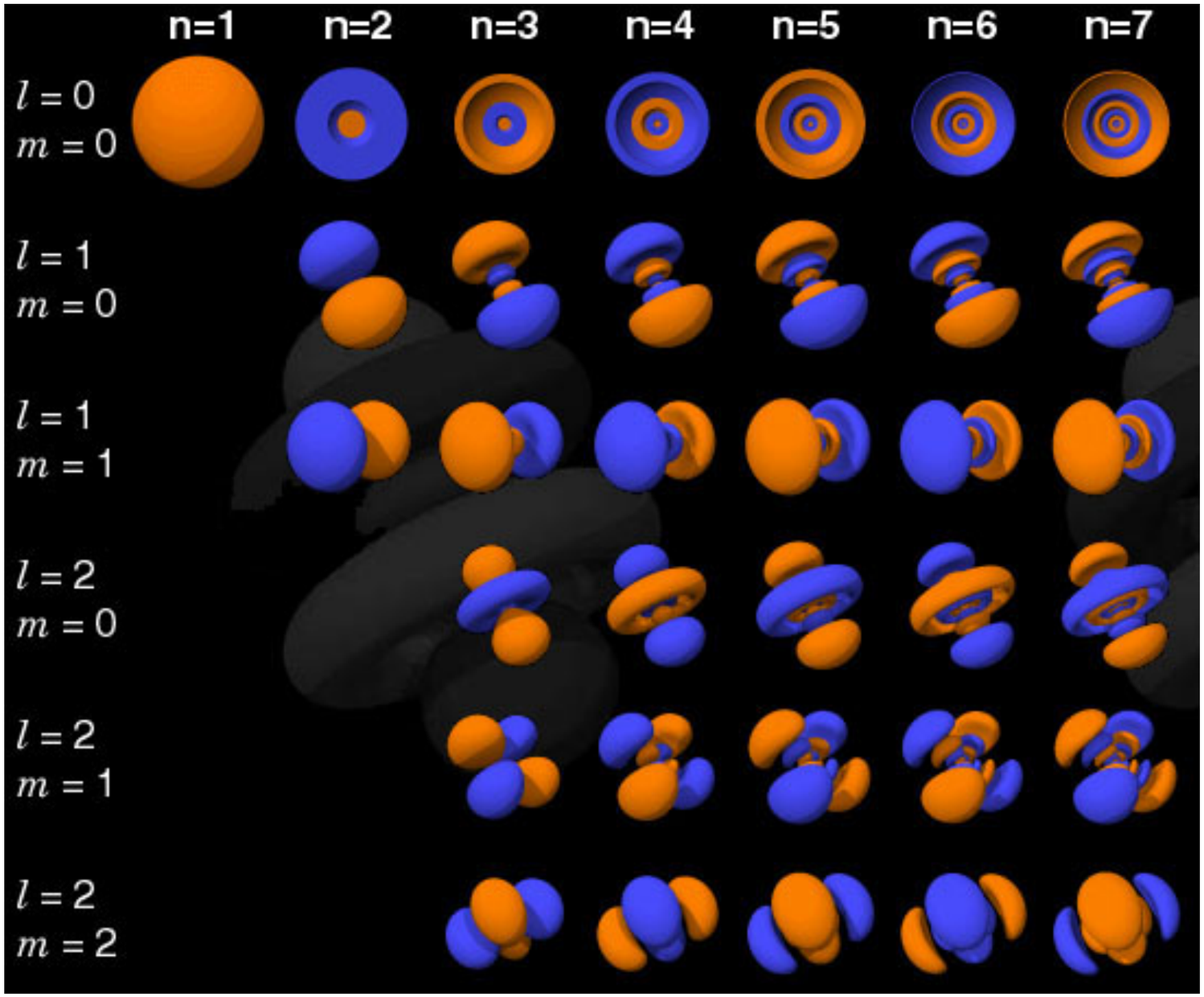
$$n, l, m_l, m_s$$

Only ONE FERMION can have one set of quantum numbers!

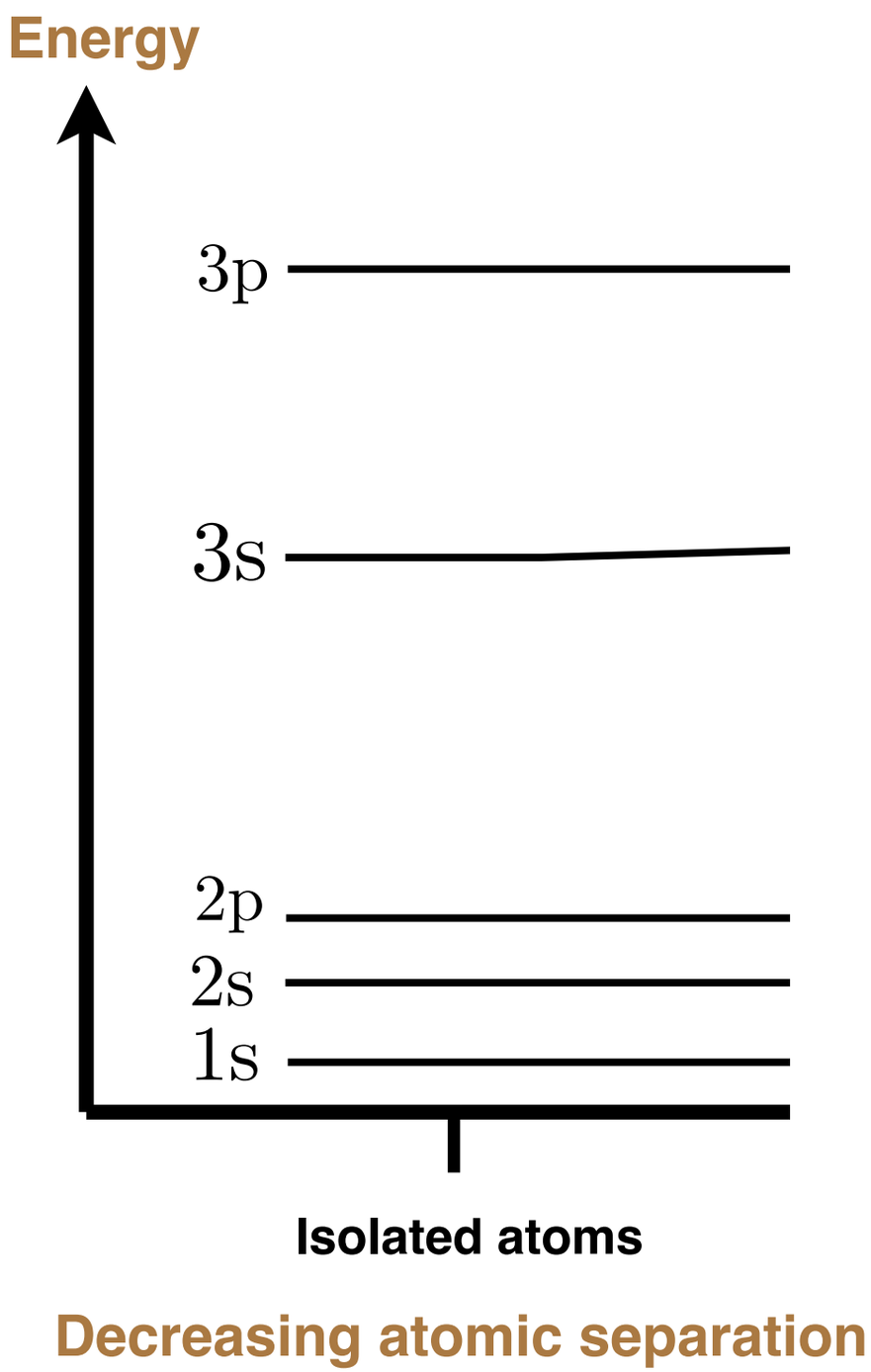
Electrons (and other particles) are described with Schrodinger's Wave Equation:

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

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



Atomic orbitals overlap in a crystal to form electronic bands



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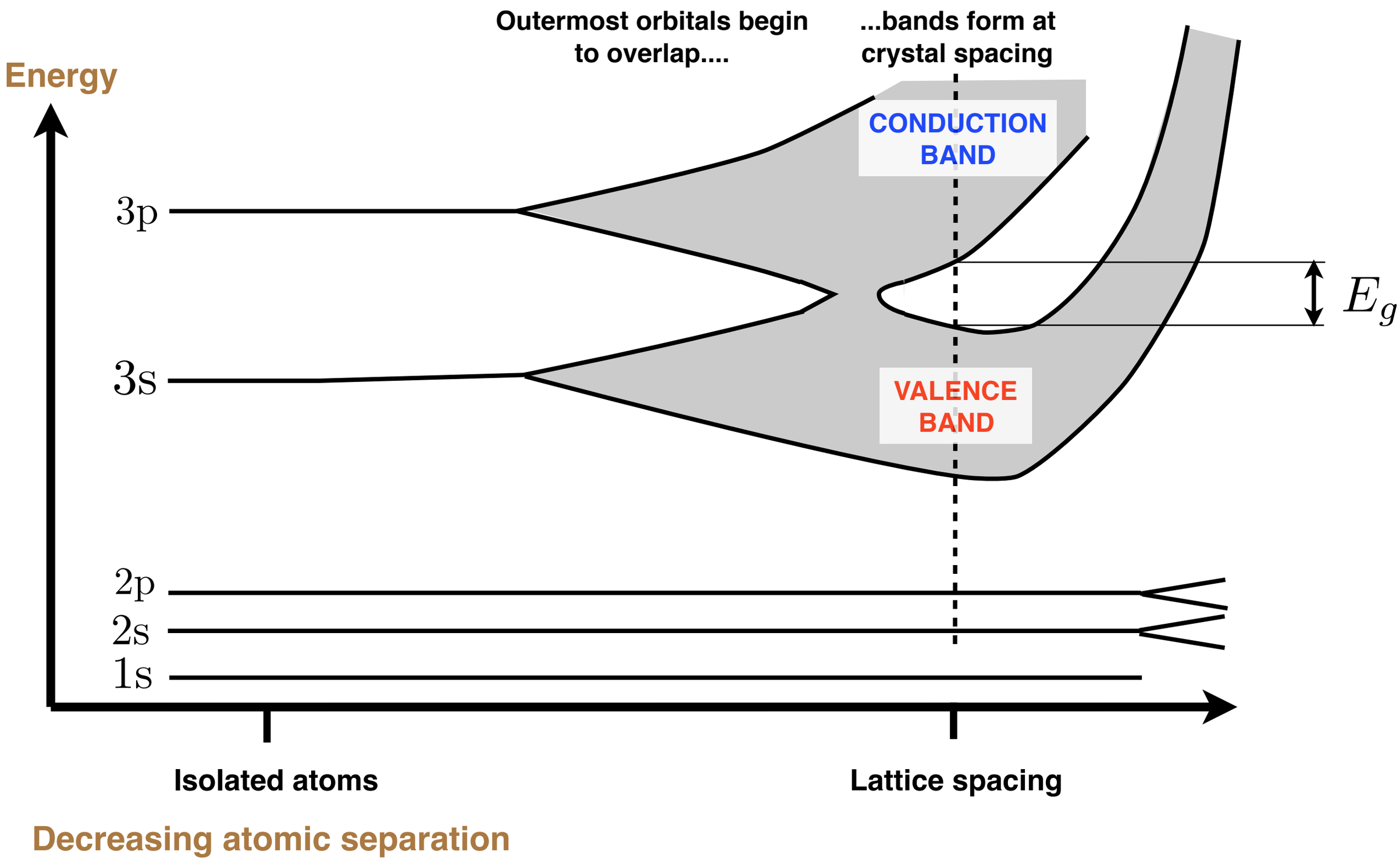
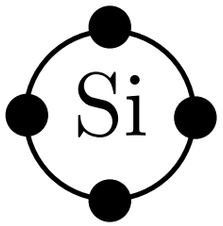


Incomplete orbitals provide electrons for bonding

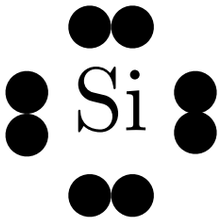
Silicon and Germanium have 4 electrons in their outermost (n=2) orbital:



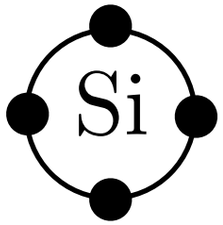
$$d = 0.230 \text{ nm}$$

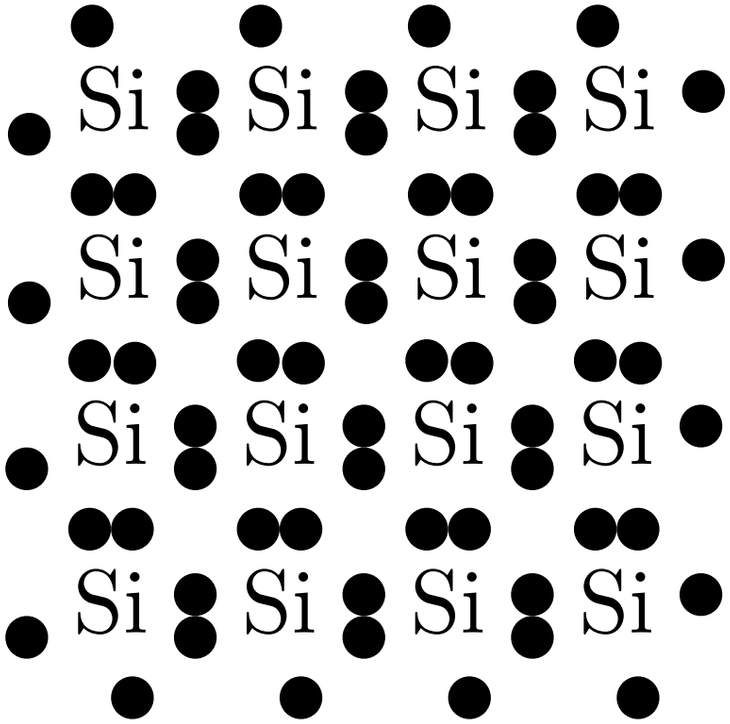
(In the Periodic Table these are GROUP IV elements)

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

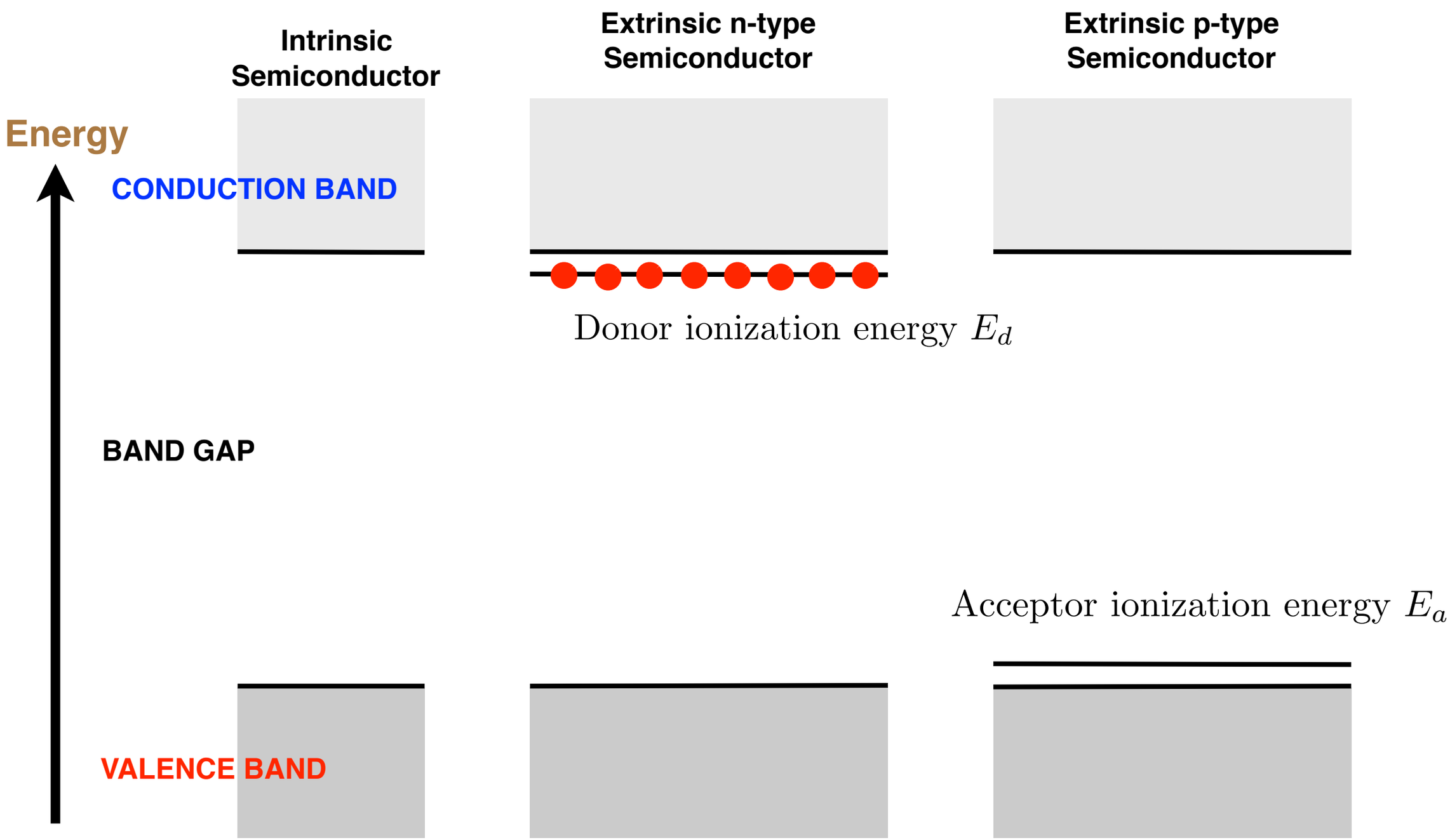


Forming a crystal sharing electrons with other Si atoms forms a stable LATTICE:



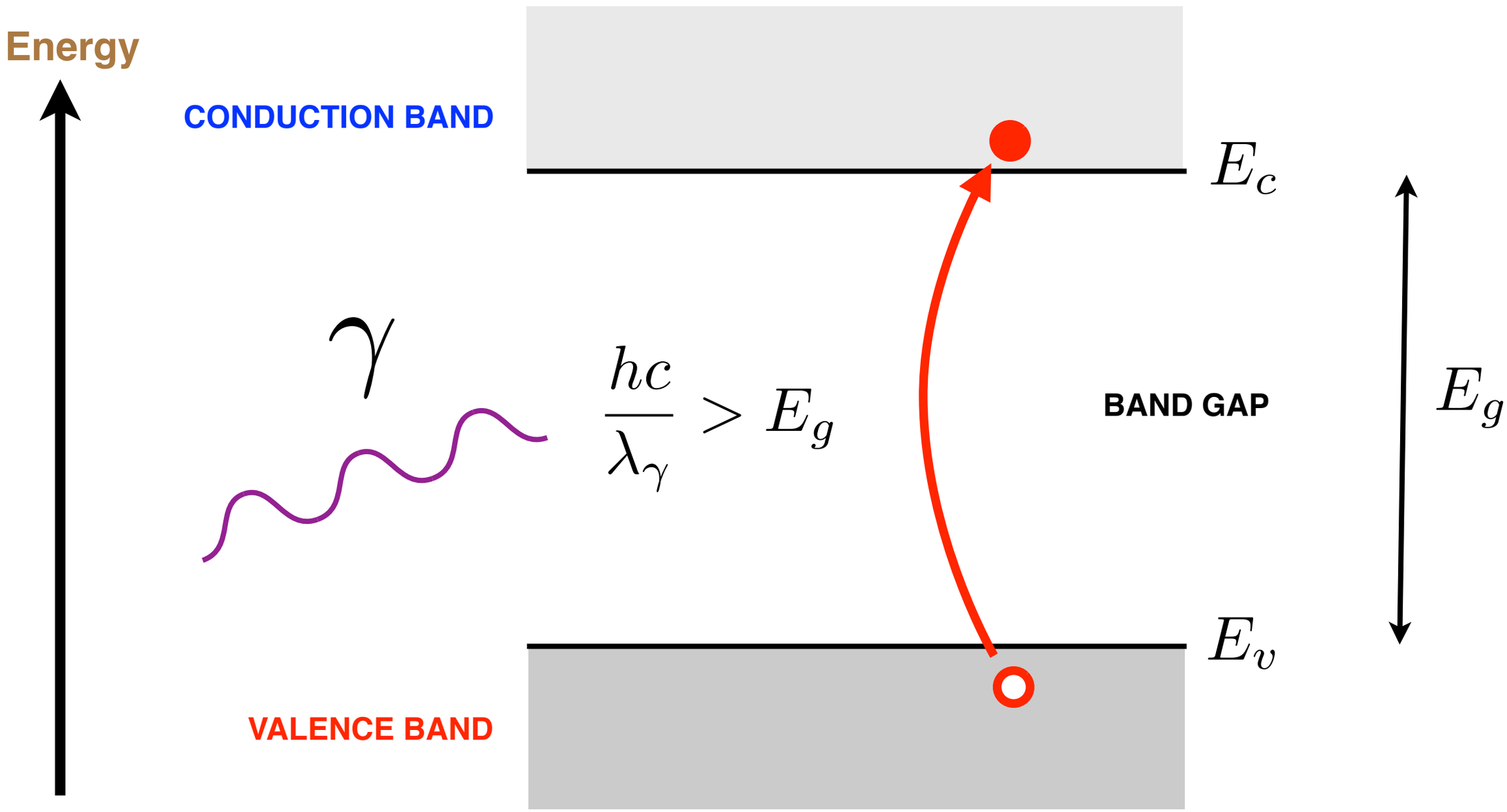


Energy Band Diagram for Donors and Acceptors



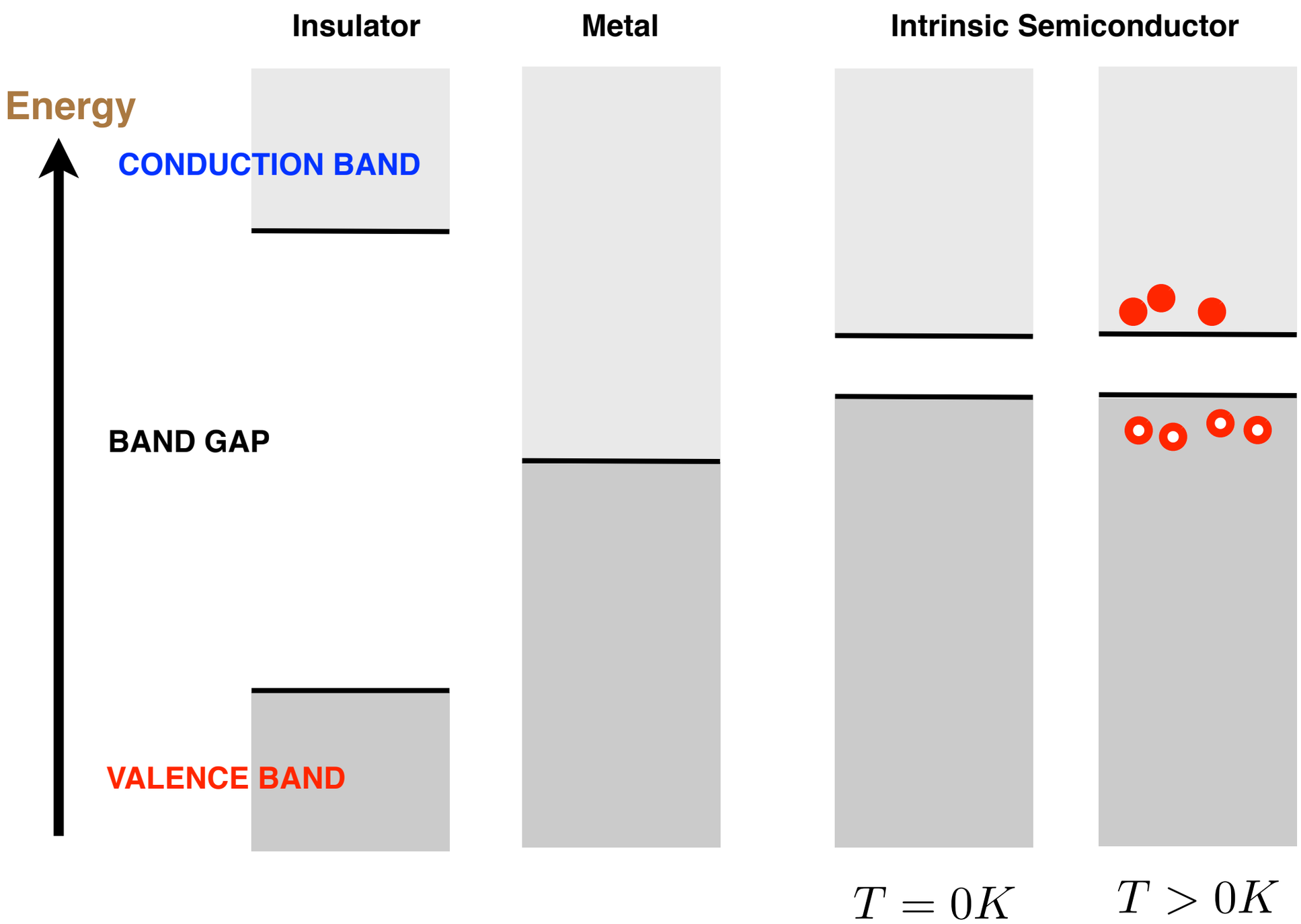
$$T = 0K$$

Energy Band Diagram

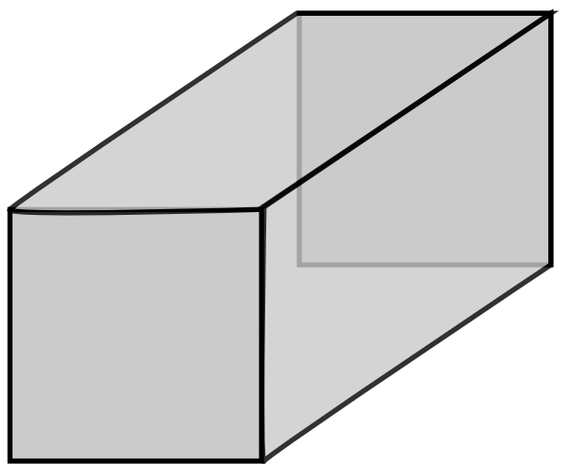


Electrons can also be THERMALLY excited

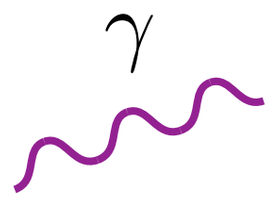
Energy Band Diagram



Photon Detectors respond directly to individual photons



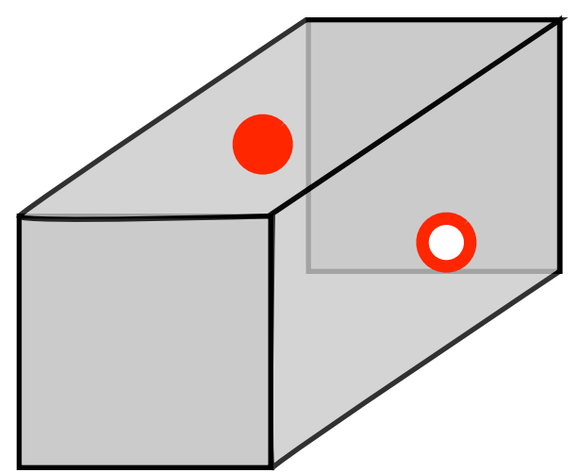
Intrinsic semiconductor



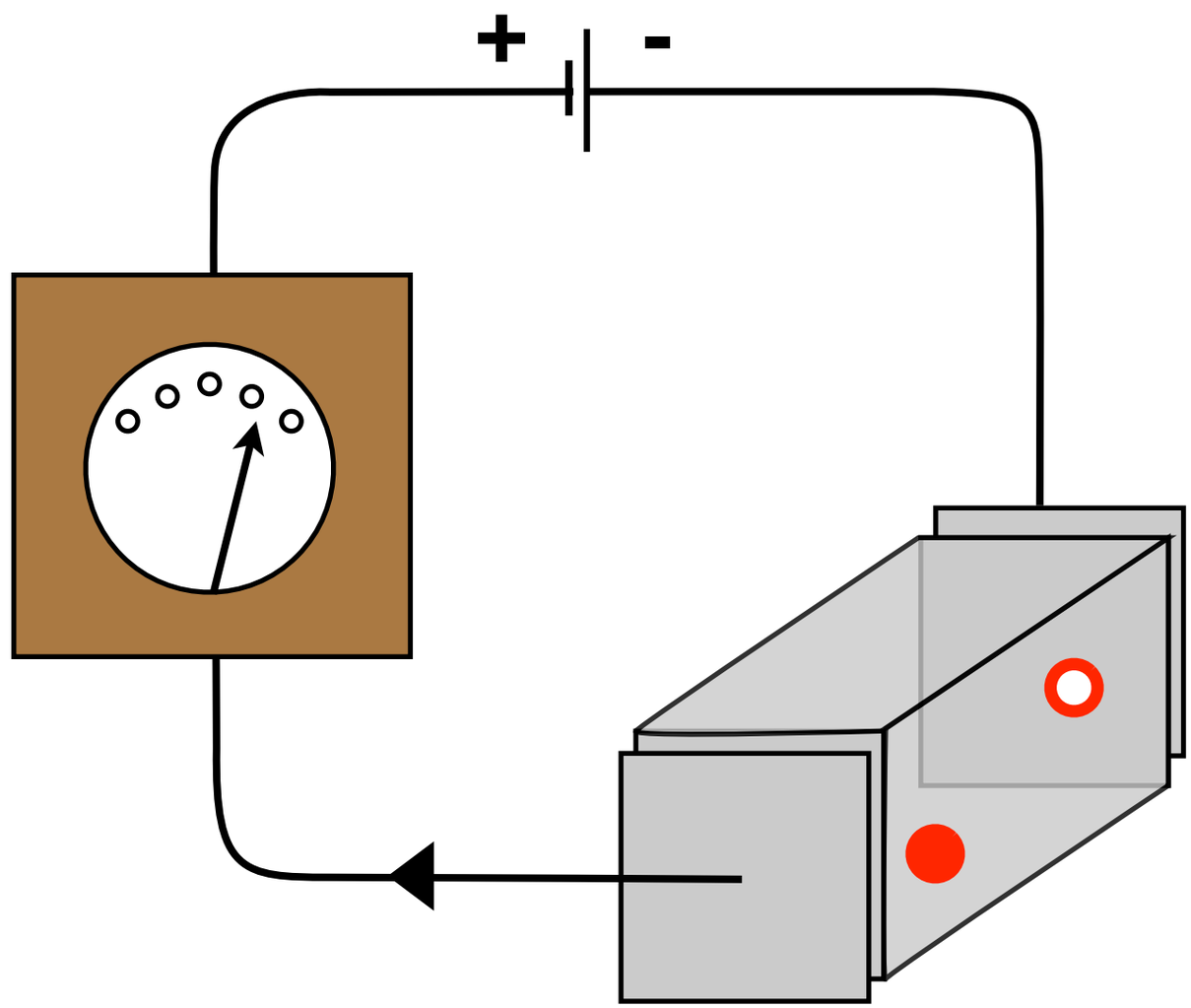
Incoming photon with energy greater than bandgap energy:

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

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



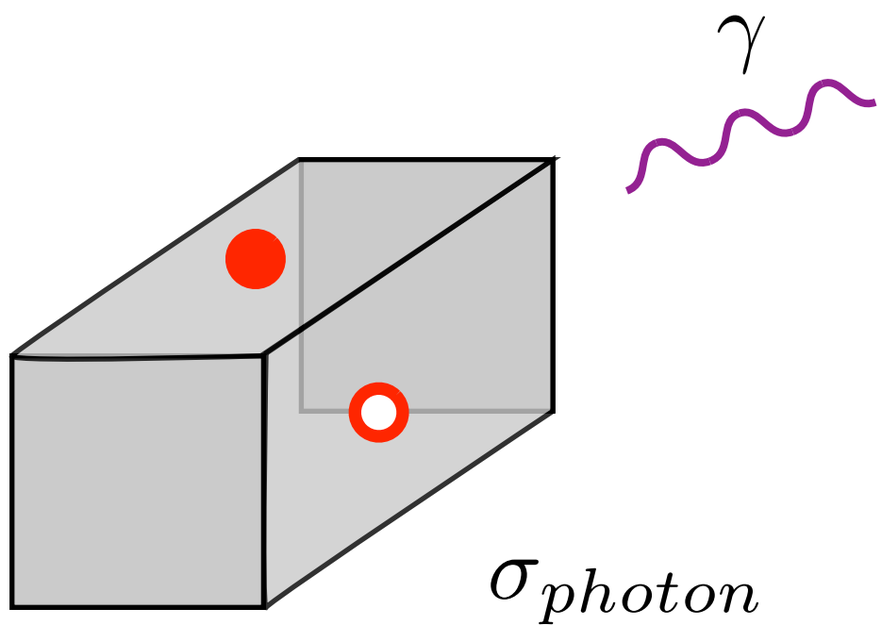
Charge carriers move out of semiconductor and register as a signal



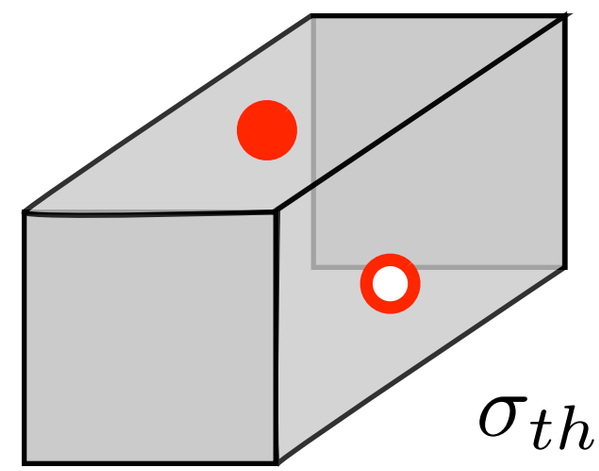
Applying an electric field causes electric charges to move in the material and register a signal as an electric current

Charge carriers are generated with both photons and thermal excitation

We measure the electrical conductivity!



σ_{photon}

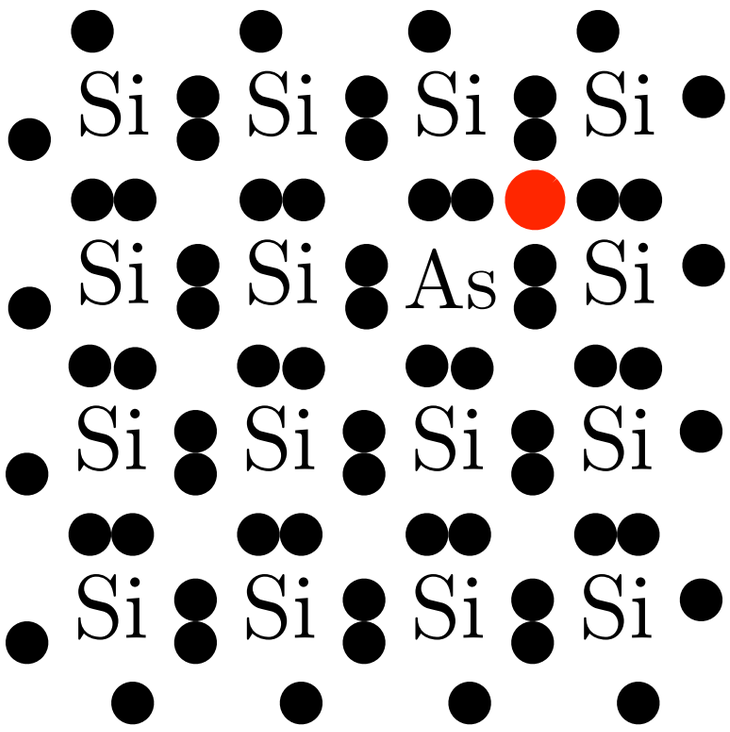


$\sigma_{thermal}$

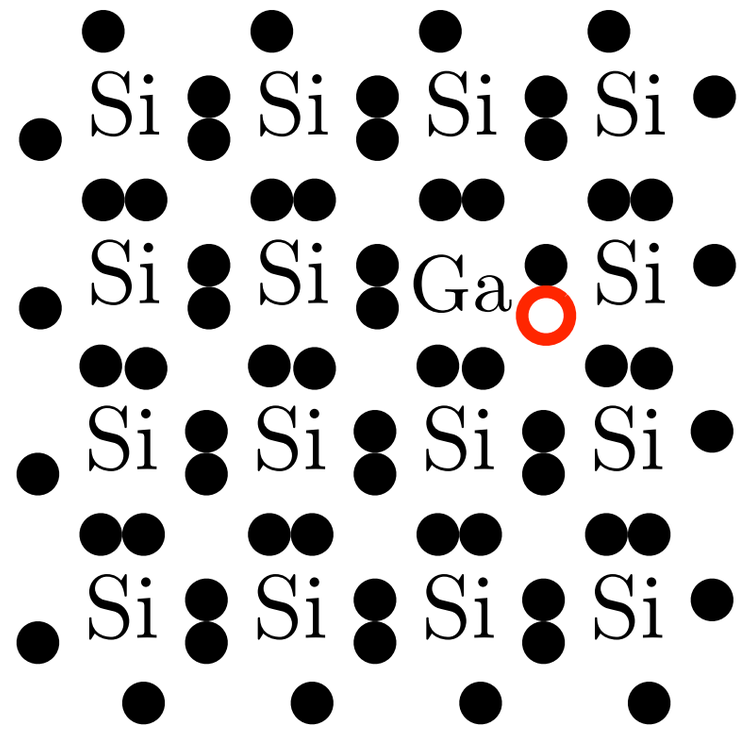
Dopants in Silicon

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.

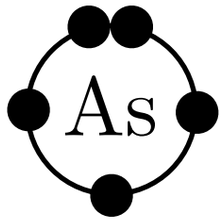


Adding a Group III element introduces an electron hole and creates p-type silicon, called an acceptor.



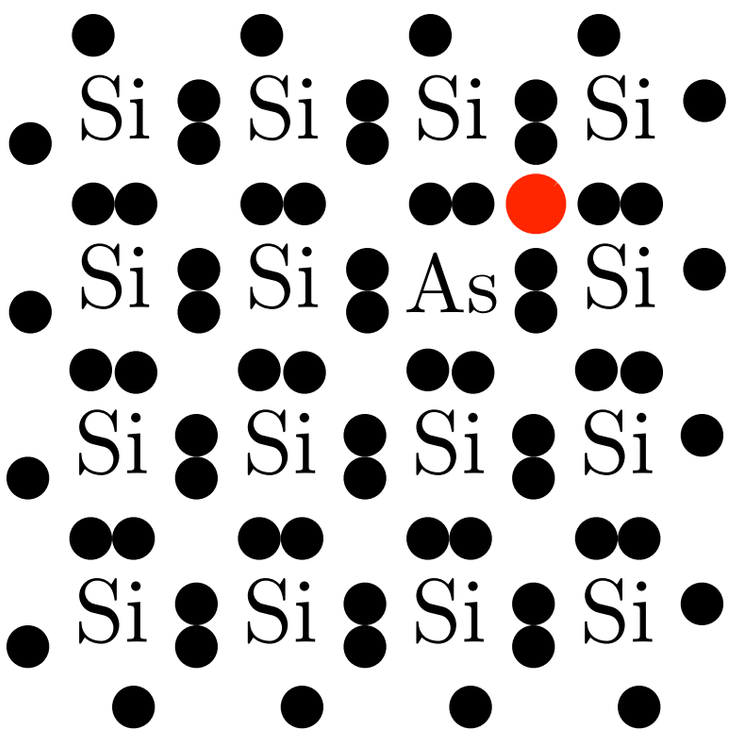
Pure semiconductors are INTRINSIC, doped semiconductors are EXTRINSIC

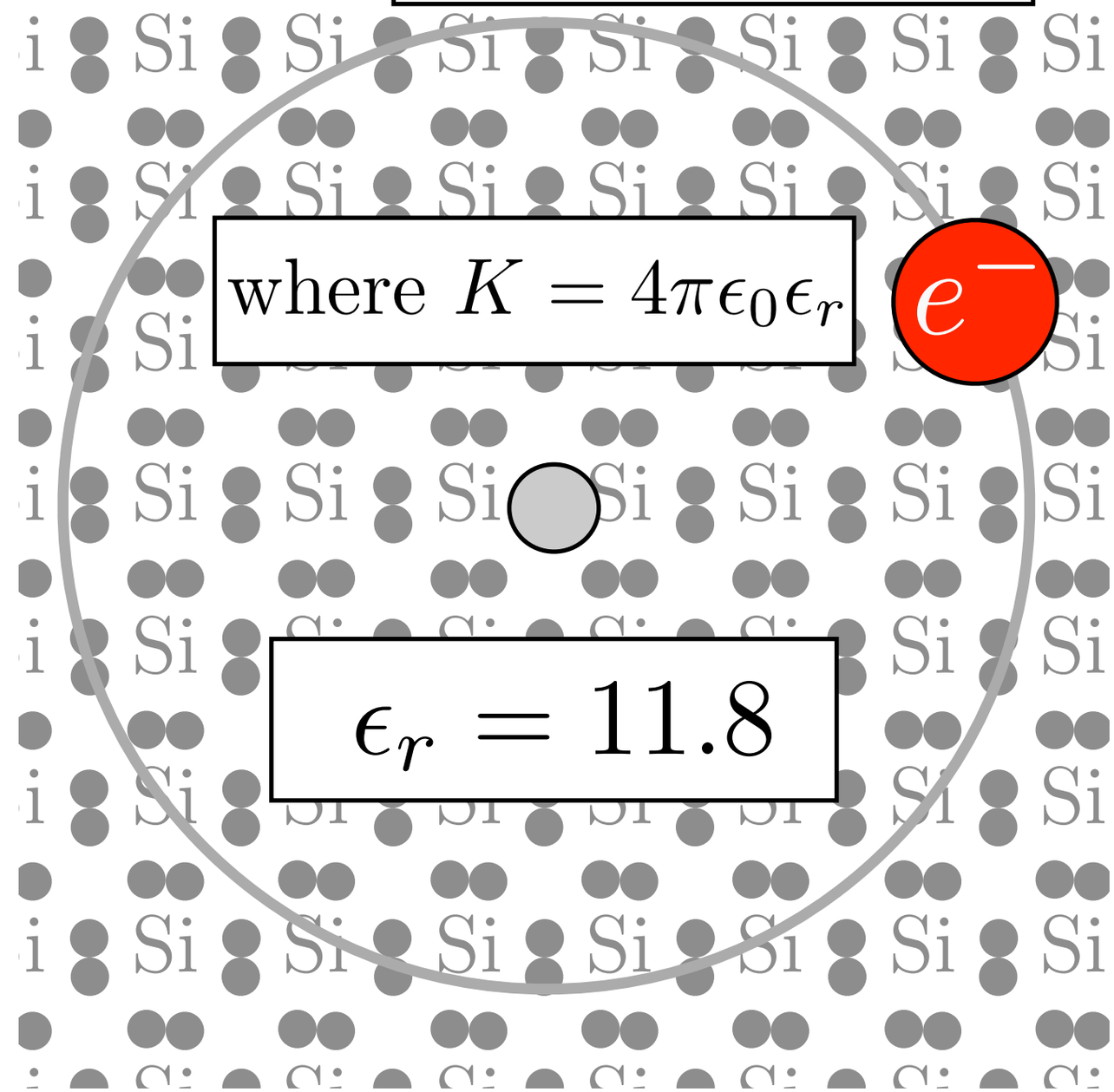
Why is a donor easily ionised?



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

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



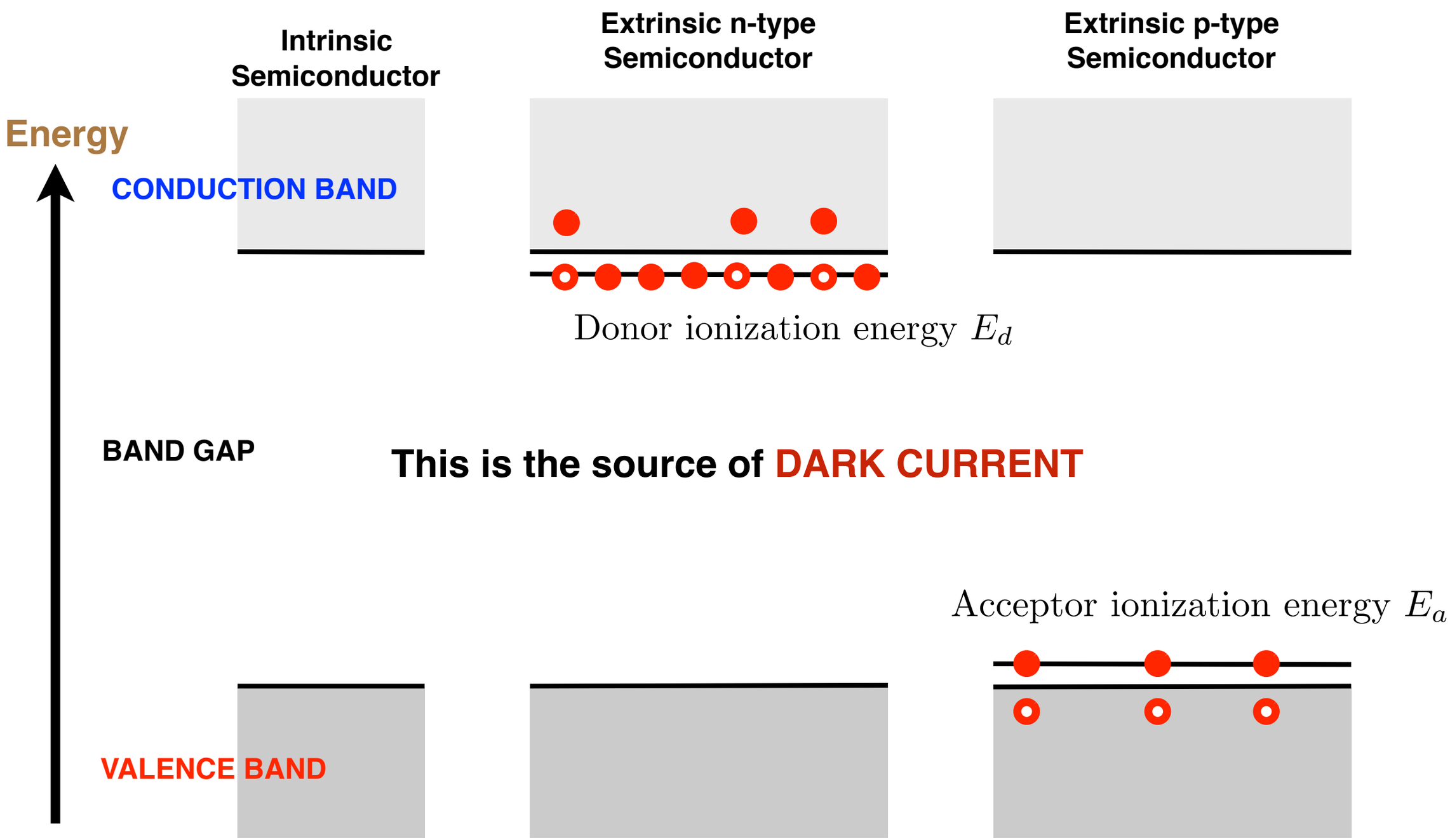


where $K = 4\pi\epsilon_0\epsilon_r$

$\epsilon_r = 11.8$

Electron is REALLY easy to ionise!

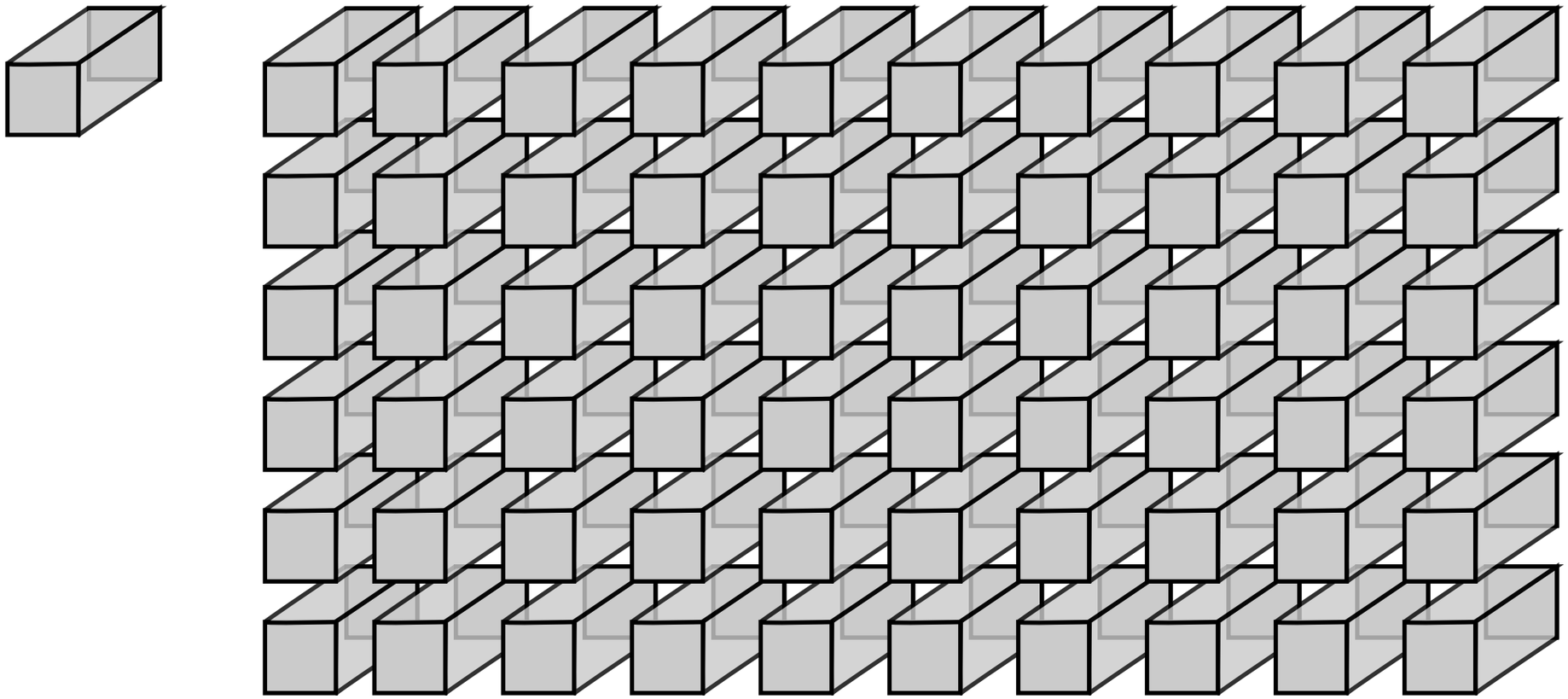
Energy Band Diagram for Donors and Acceptors



$$T > 0K$$

Detector Arrays

Arrays formed from individual photoconductors



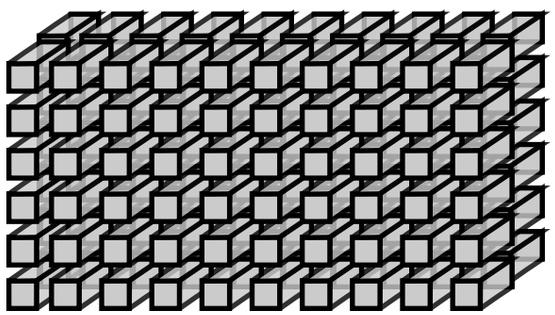
+ Readout Electronics

= Detector Array

Two types of arrays in the Optical/IR

IR Arrays

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

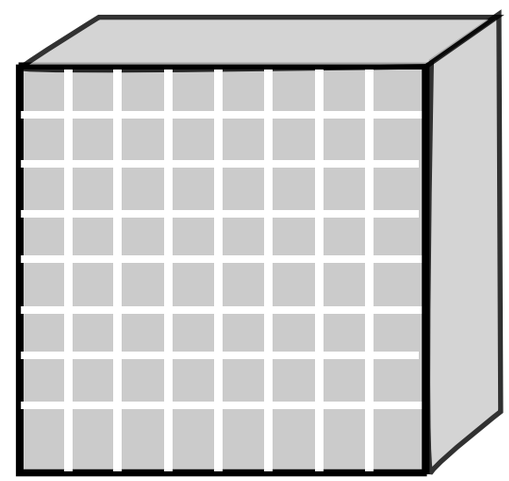


+ directly access individual pixels

- complex and expensive

Charge Coupled Devices (CCDs)

$(0.1nm - 1\mu m)$



+ monolithic structure built in Si wafer

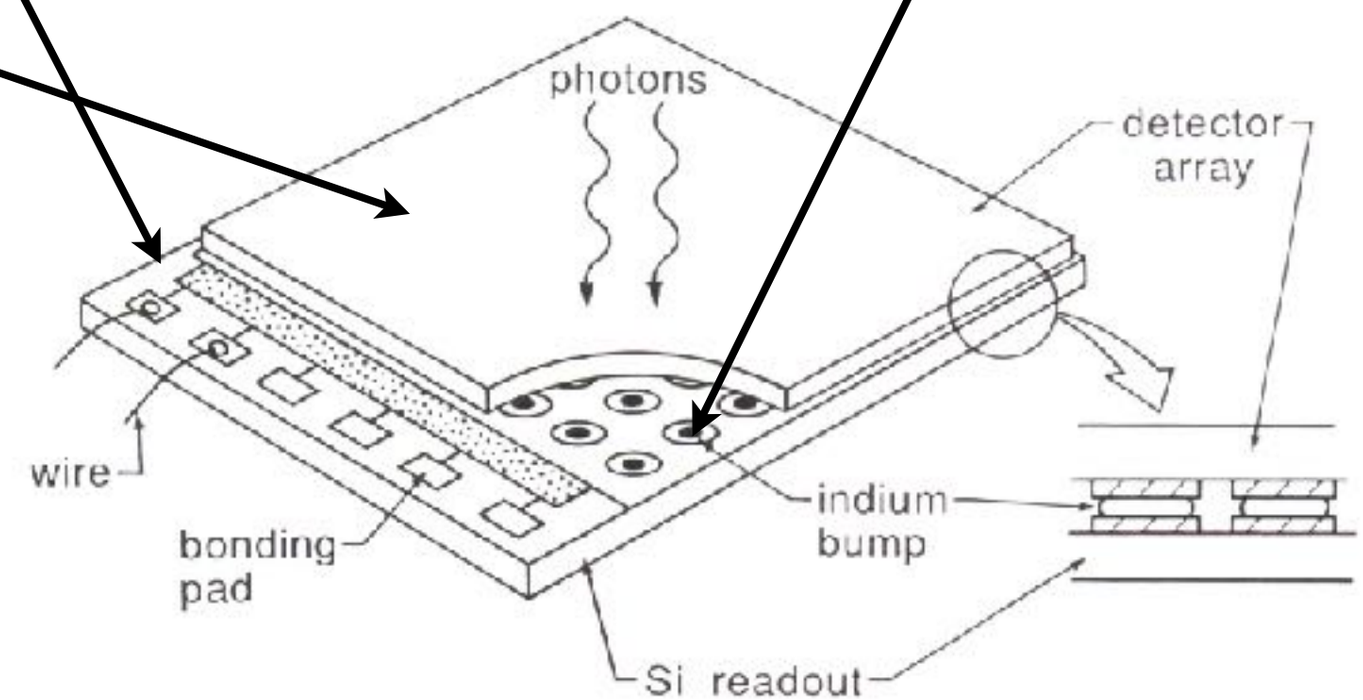
- charge transfer inefficiencies

Production of IR Arrays

Make a grid of readout amplifiers in Silicon

Deposit Indium bumps on both sides

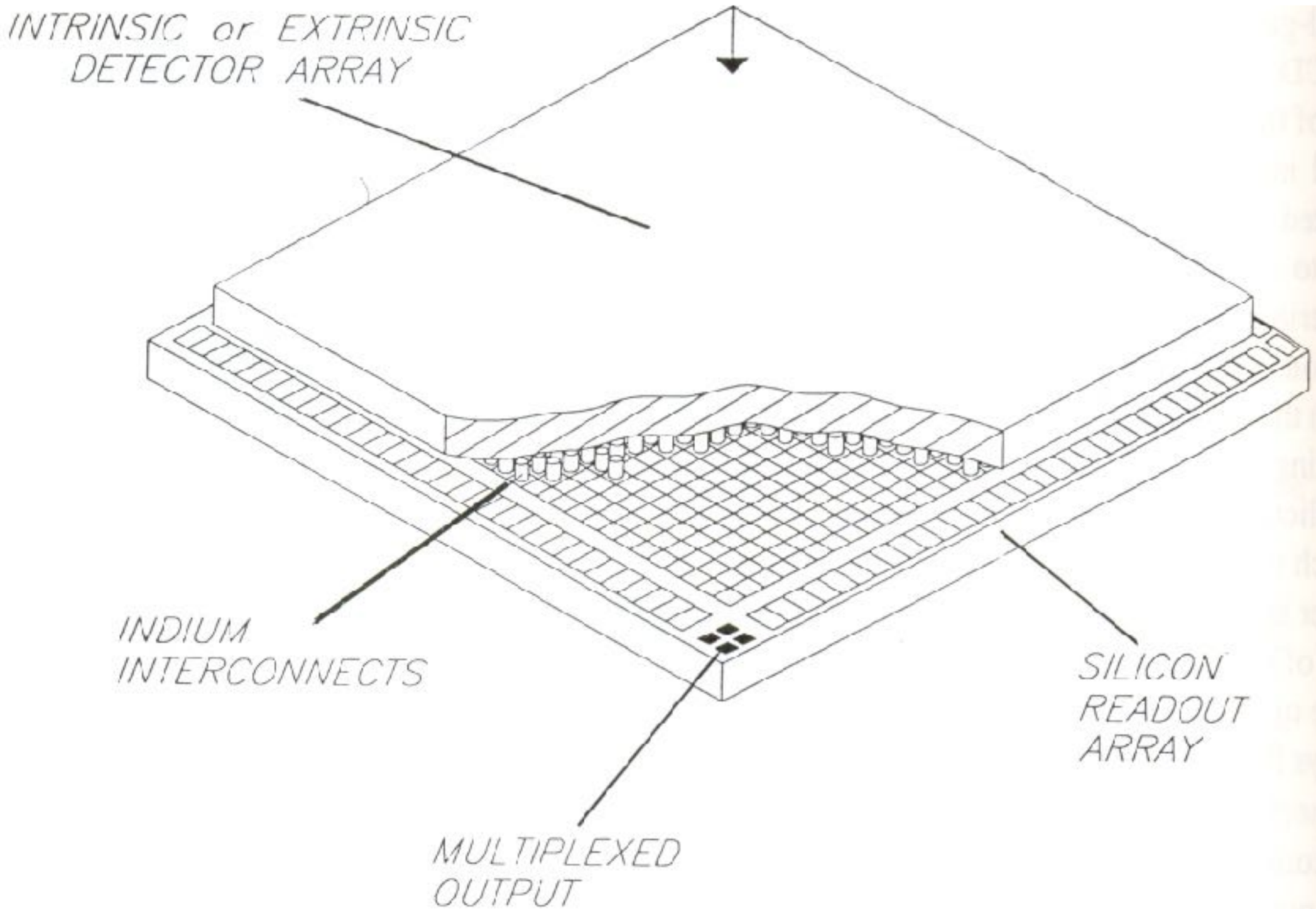
Make a matching image of detector pixels



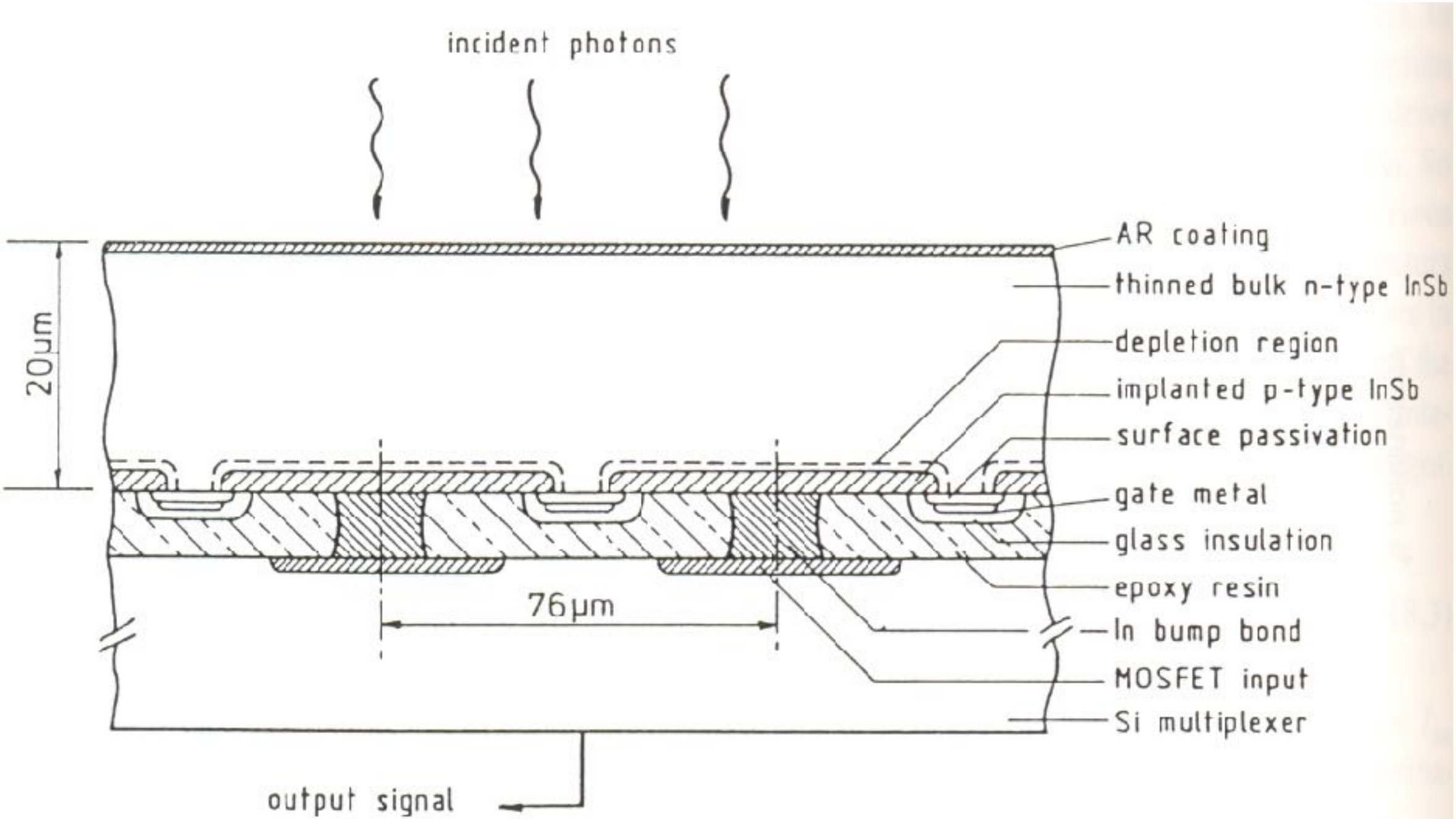
Squeeze them together to make a hybrid array

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

Production of IR Arrays

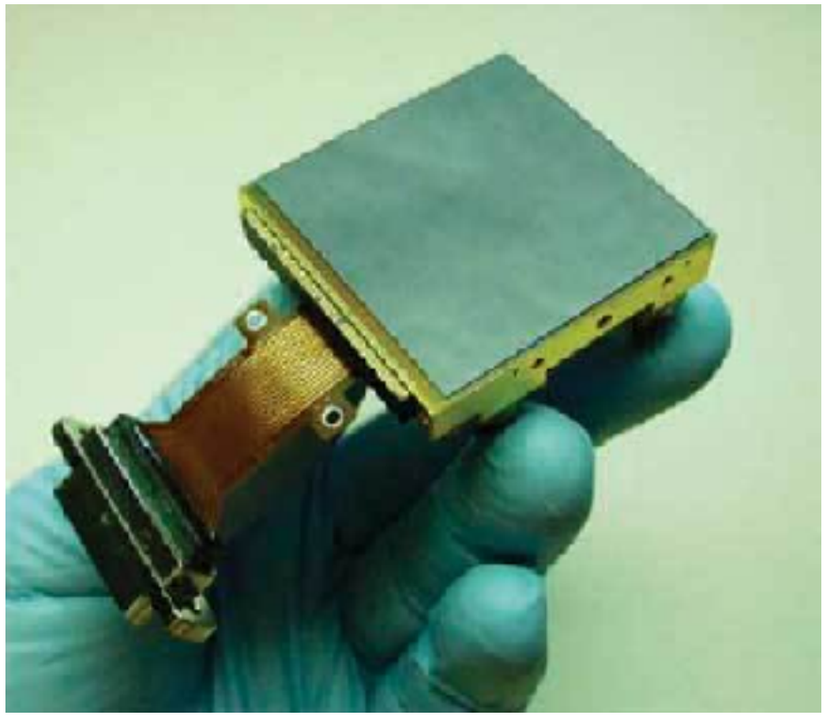


Detailed Bonding Structure of IR Array

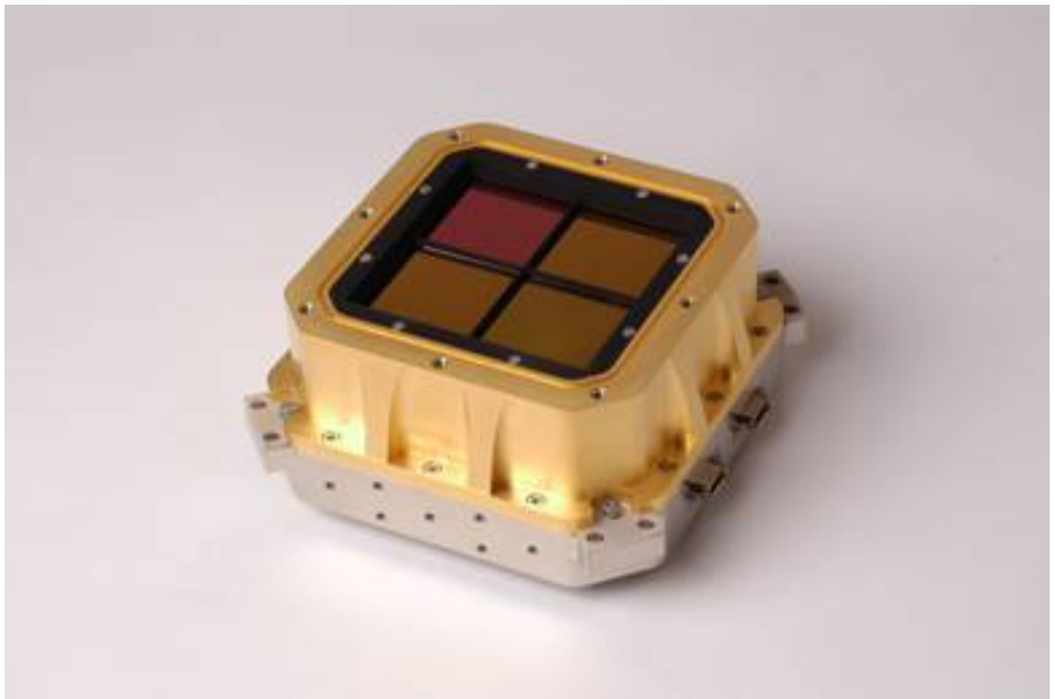


The Teledyne 2k x 2k Hawaii-2RG detector

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	$\geq$ 98%
Output ports	Signal: 1, 4, 32 selectable guide window and reference
Spectral range	0.3 - 5.3µm
Operating temperature	$\geq$ 30K
Quantum efficiency (array mean)	$\geq$ 65%
Charge storage capacity	$\geq$ 100,000e^-
Pixel operability	$\geq$ 95%
Dark current (array mean)	$\leq$ 0.1 e^-/sec (77K, 2.5 µm)
Read noise (array mean)	$\leq$ 15 e^- CDS @ 100 kHz
Power dissipation	$\leq$ 4 mW @ 100 kHz



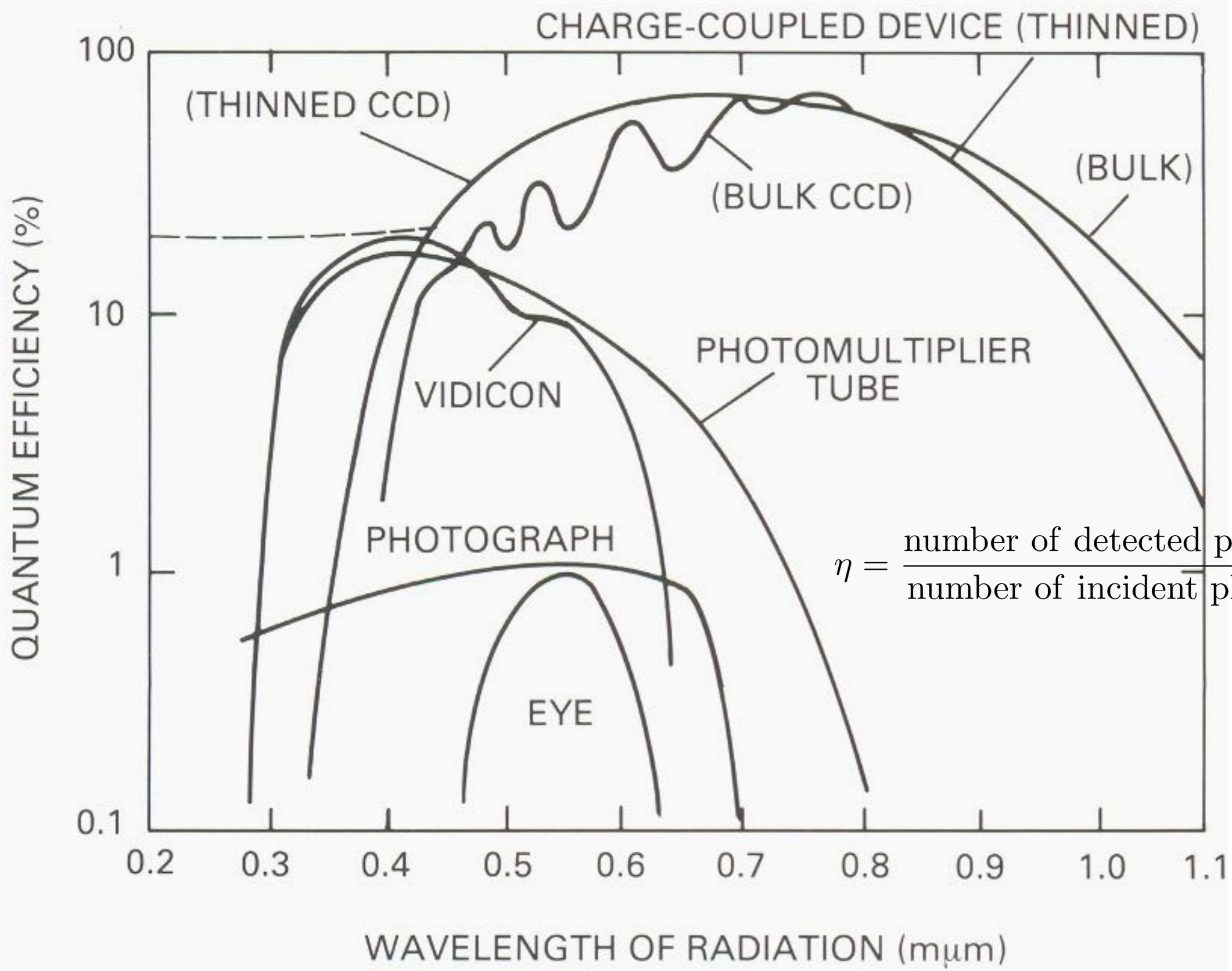
Can also be combined to a 2x2 mosaic



Some Performance Aspects of Detectors

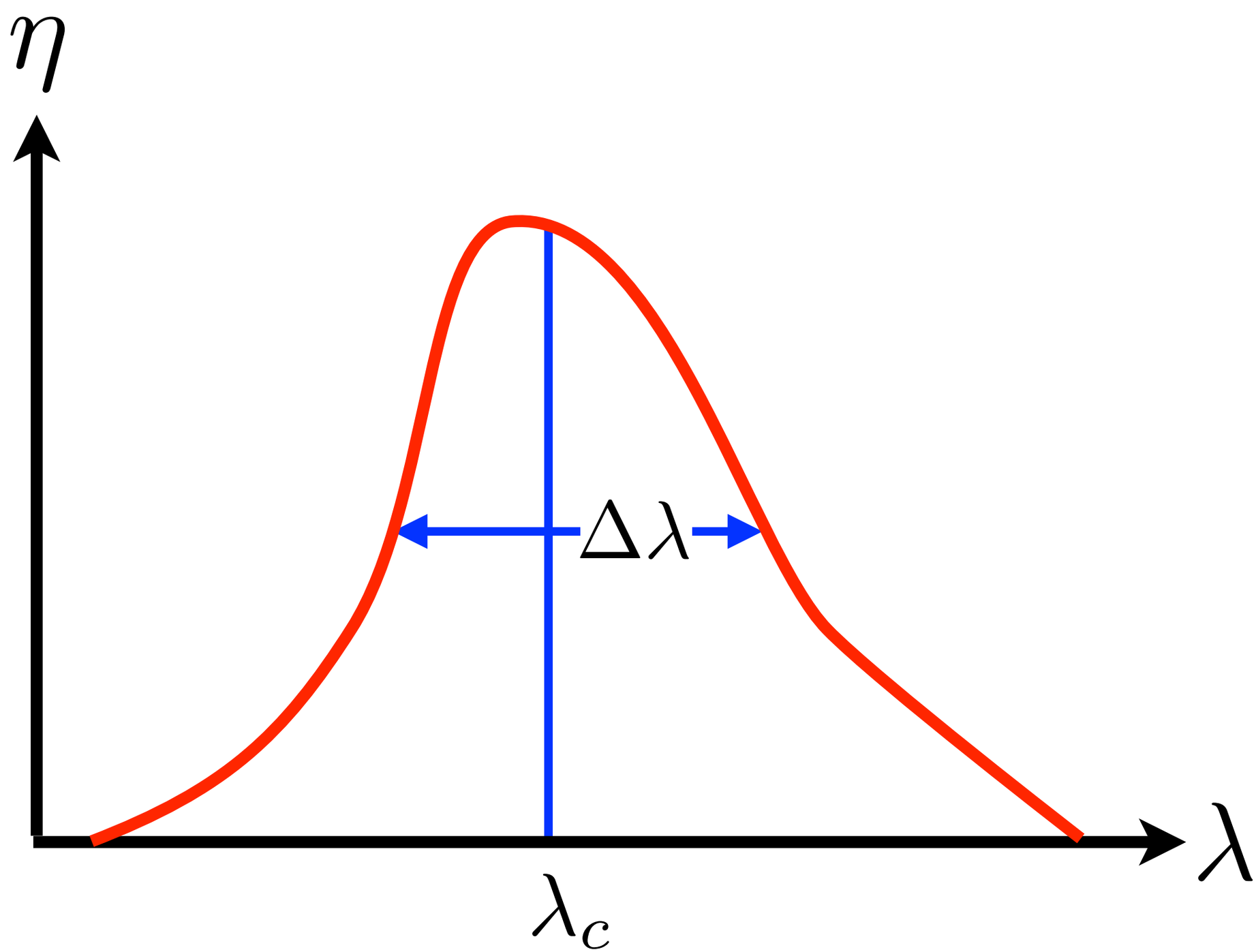
- Spectral response and bandwidth
- Linearity / saturation
- Dynamic range
- Quantum efficiency
- Noise
- Geometric properties
- Time response
- Polarization
- Operational aspects

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**

<u>Most relevant noise sources:</u>

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 $\sqrt{\sum (N_i)^2}$

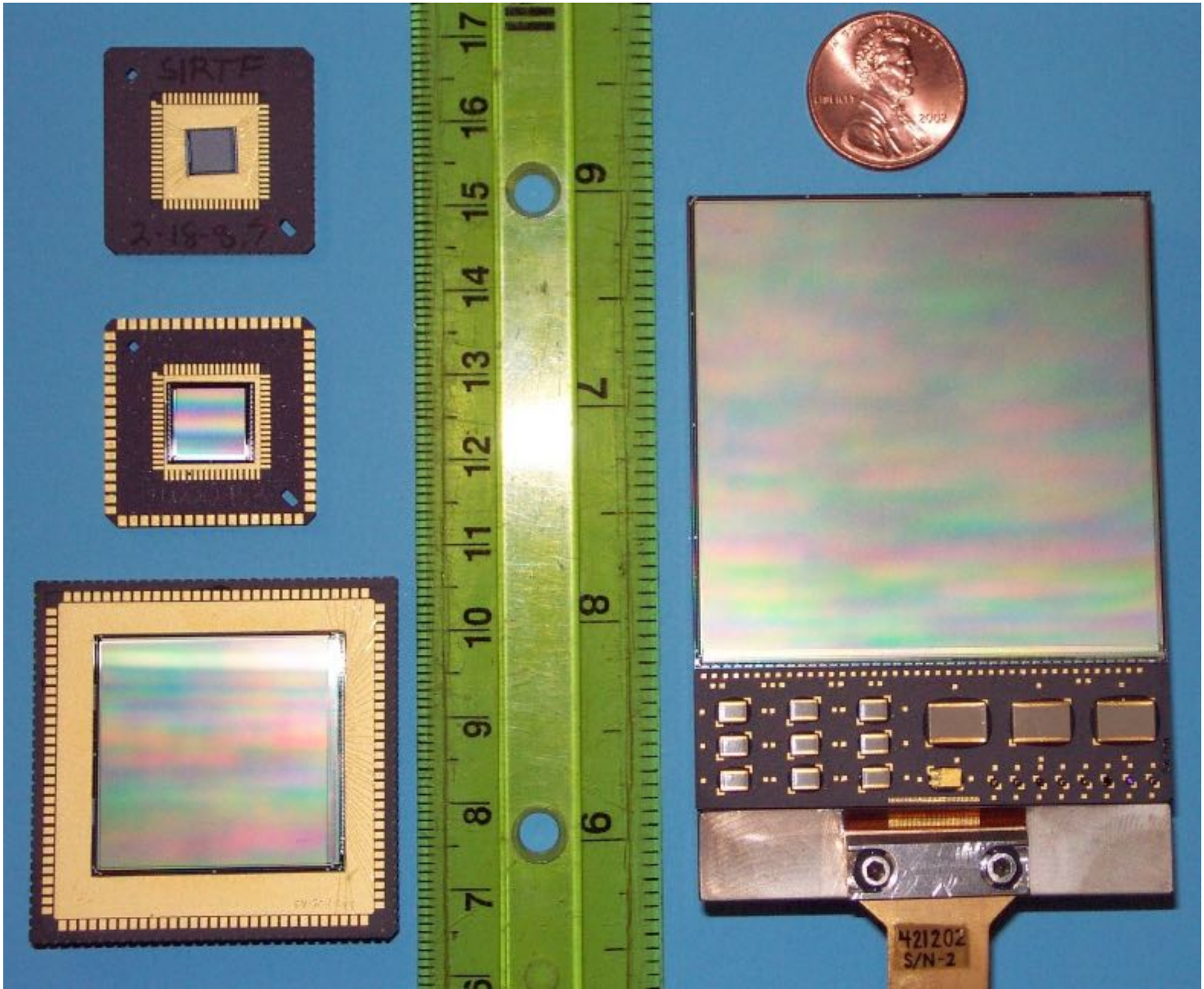
Photon noise follows Poisson statistics:

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

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)

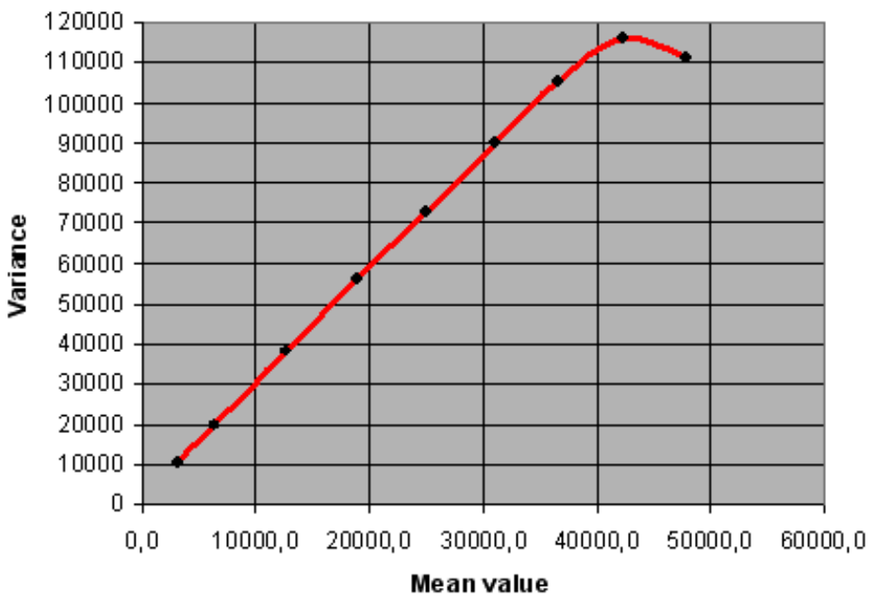
Subtract off a DARK image D to remove dark current offset (exposure time t_d)

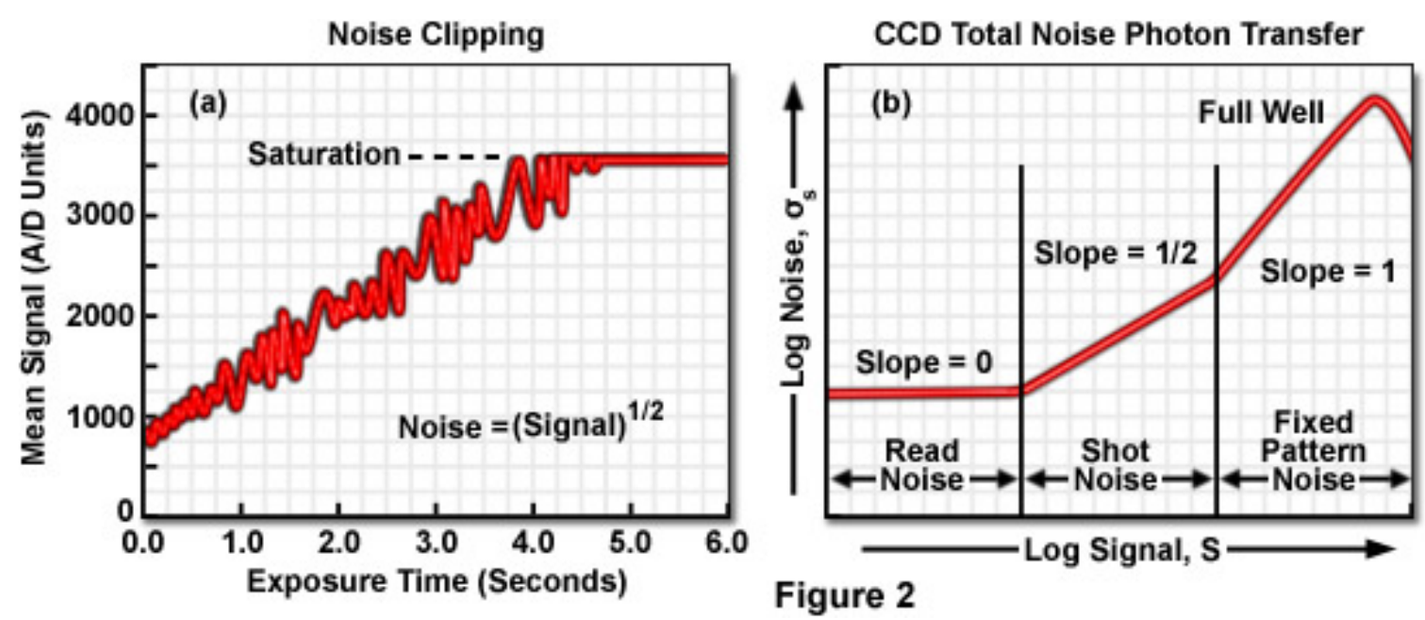
Divide by a FLAT FIELD image F to remove gain variations (exposure time t_f)

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

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

Gain, Read Noise, Saturation limit

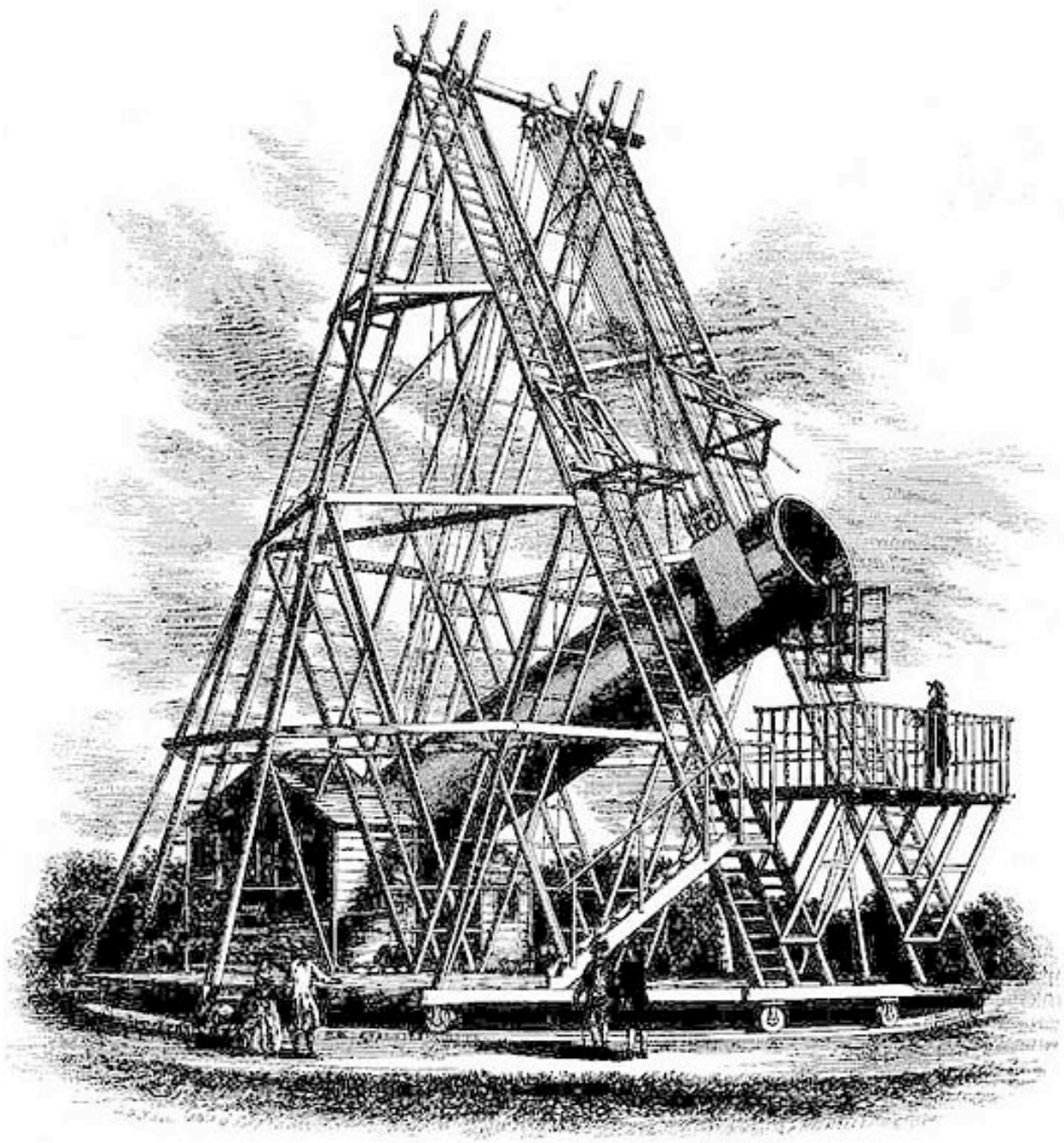




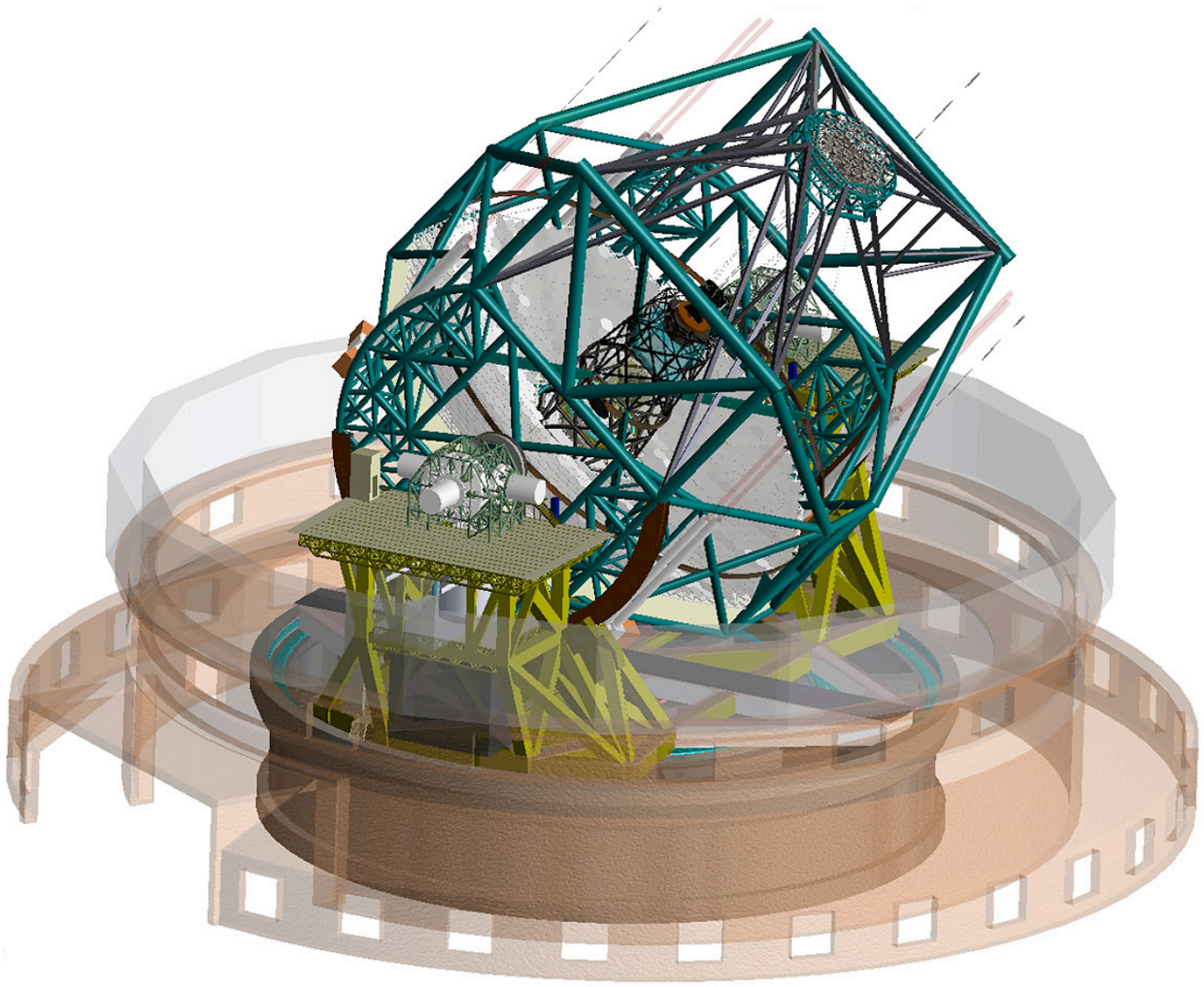
- gain (G) between arbitrary digital units (ADU, A) and number of photo-electrons (e): $A = G \cdot e$
- noise in e is given by $\sigma_e^2 = e$
- and therefore $\sigma_A^2 = G^2 \sigma_e^2 = G^2 e$
- gain G determined from $G = \frac{\sigma_A^2}{A}$

Accurately recording what you see

Looking at the sky without recording it is just tourism



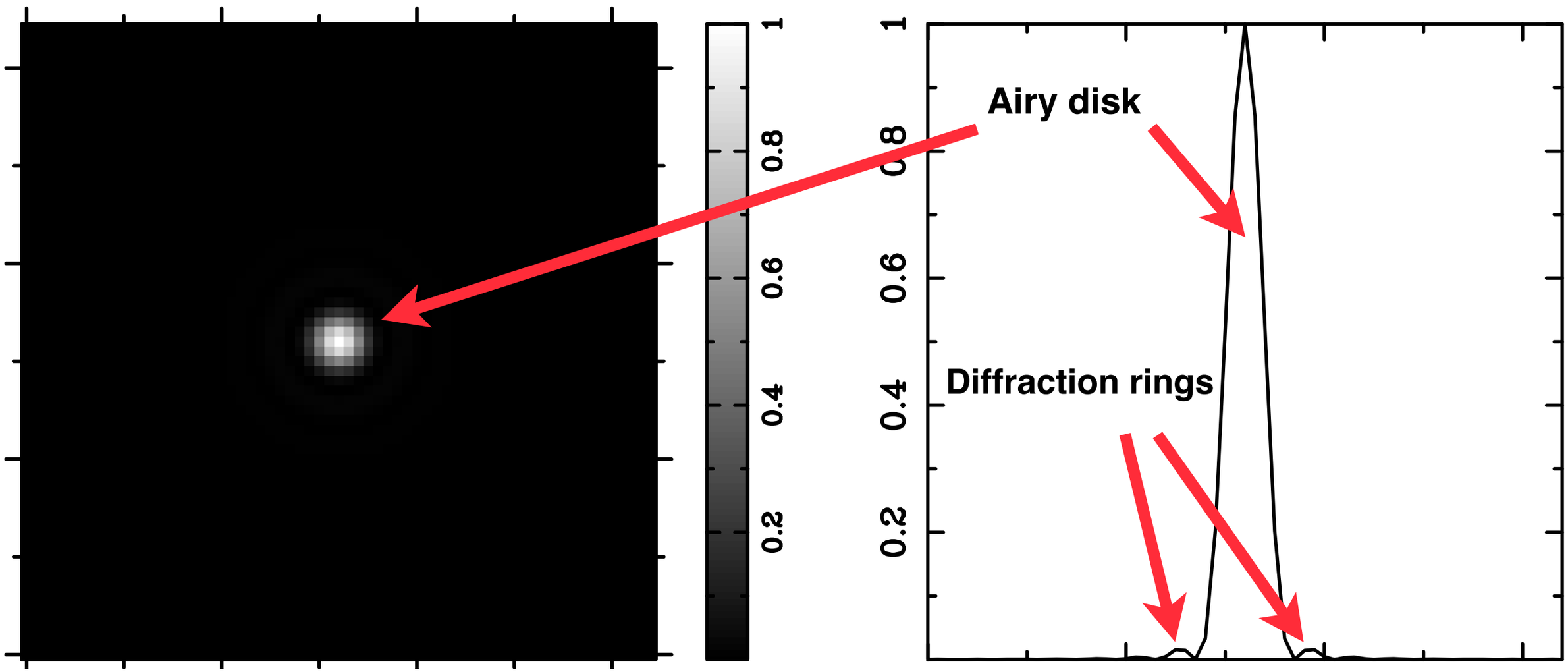
Herschel 1789



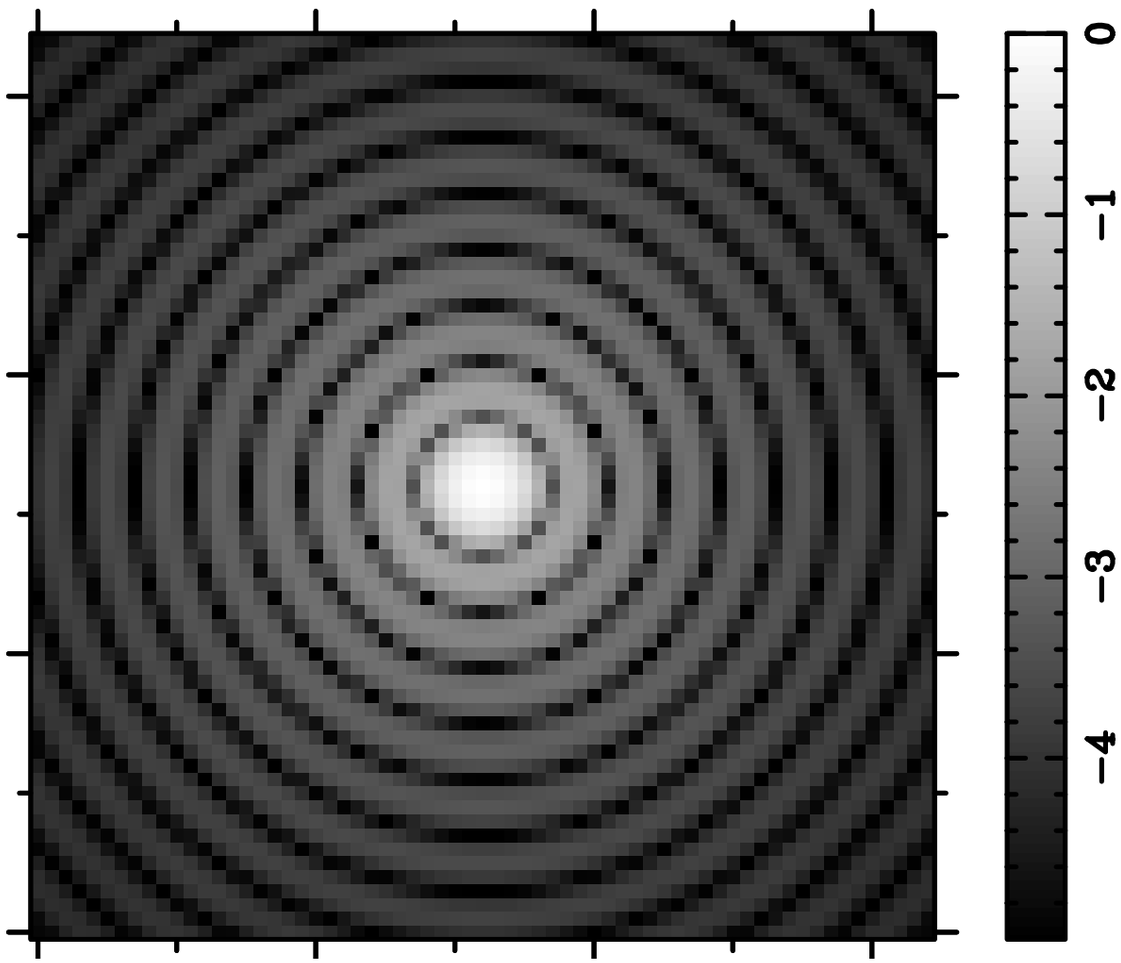
E-ELT (2026)

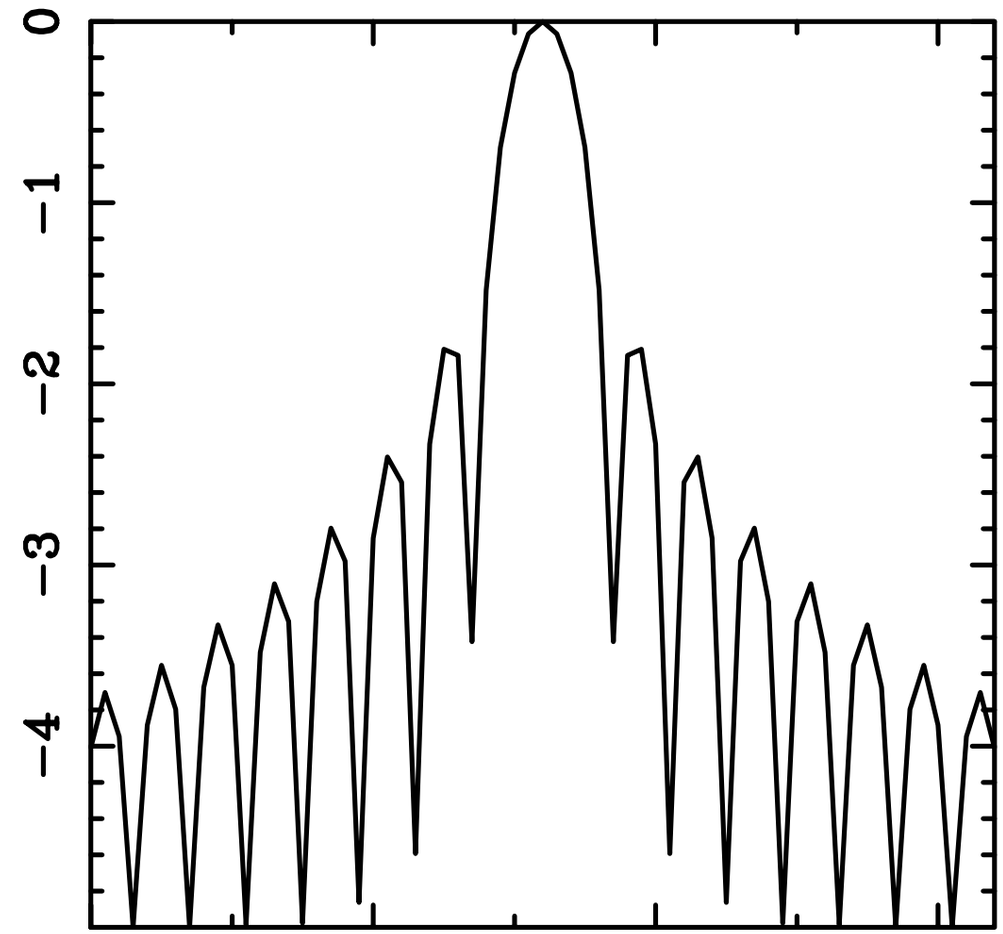
Full Width at Half Maximum (FWHM) and Airy Disk

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

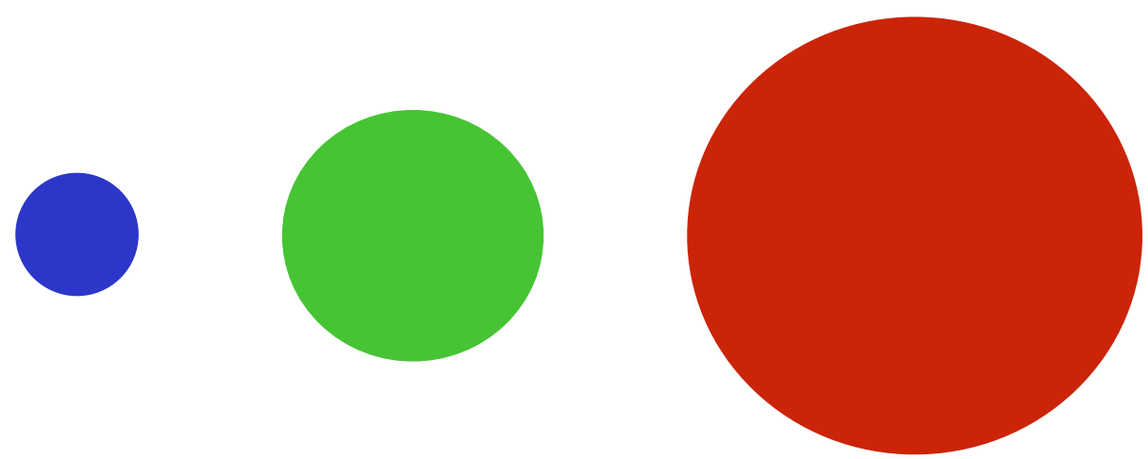


FWHM and Airy Disk (logarithmic)





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



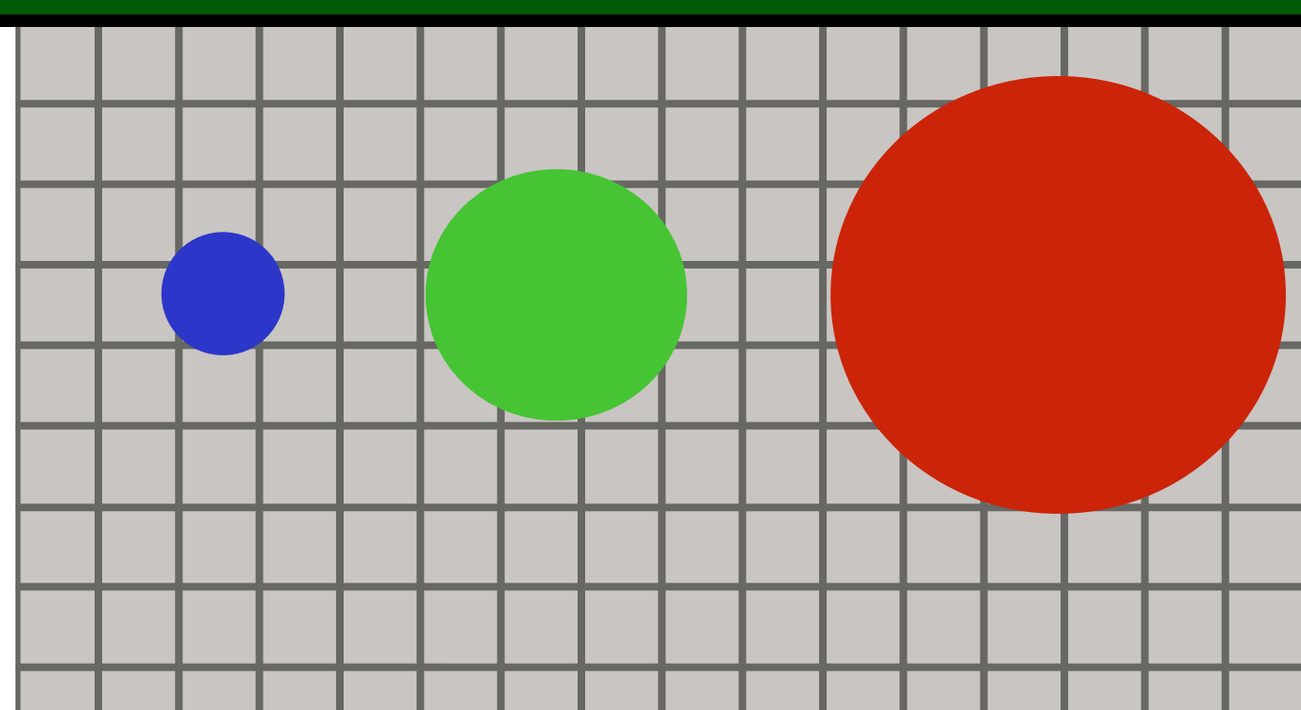
The Goldilocks Detector

There is an OPTIMUM pixel scale for a given wavelength

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

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

< 2 : undersampled

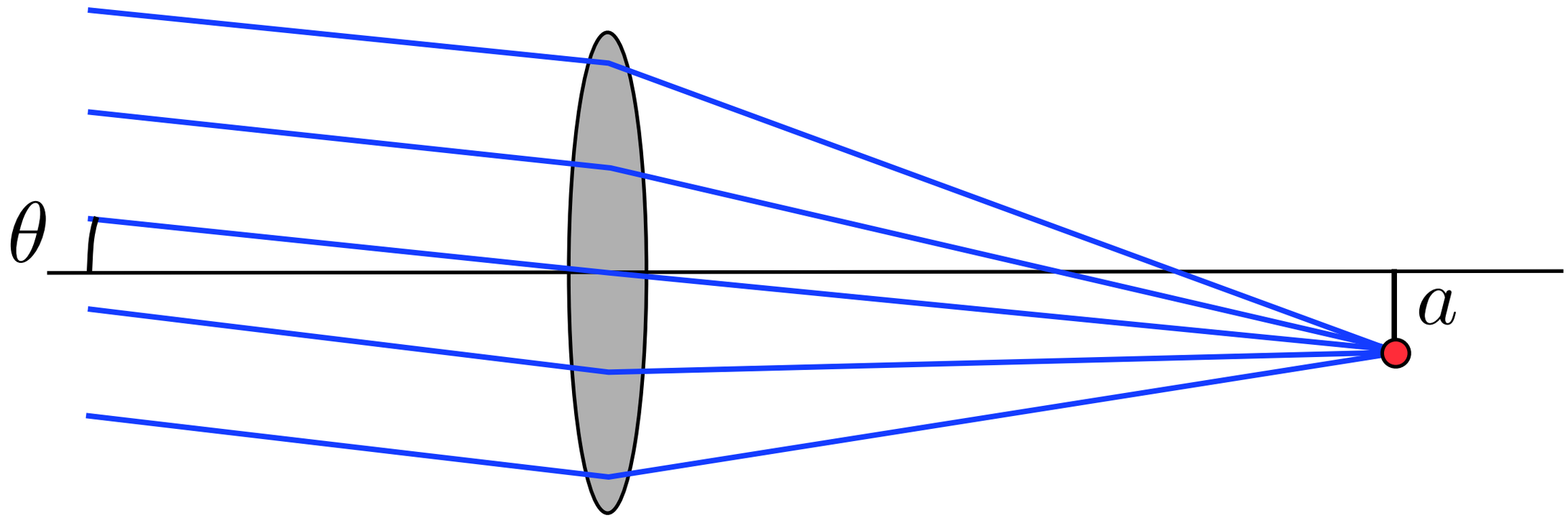


> 4 : oversampled

Imagers

The plate scale

SImple lens with diameter D and focal length f



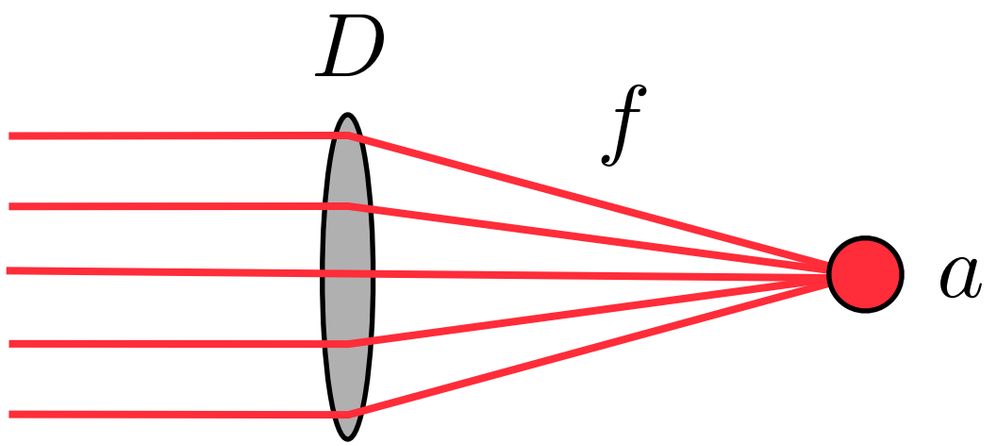
Arcseconds / mm

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

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

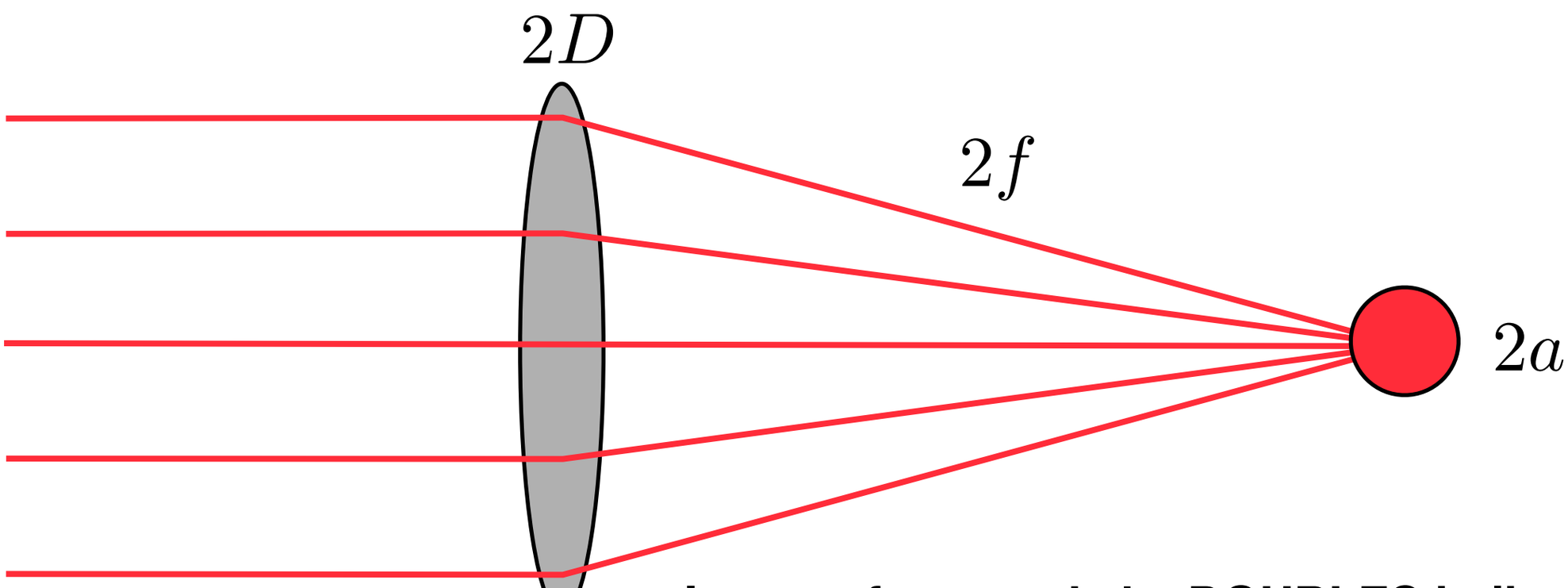
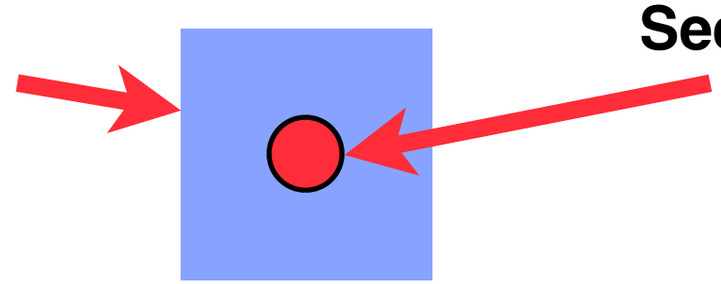


Image of star and sky DOUBLES in linear size

Seeing limited telescope sensitivity

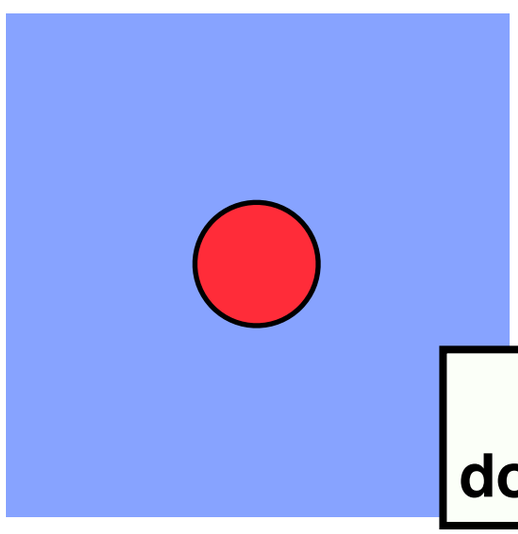
$$\text{Signal to noise} = \frac{S}{N} \propto D^2$$

Sky background
magnitudes/square arcsec



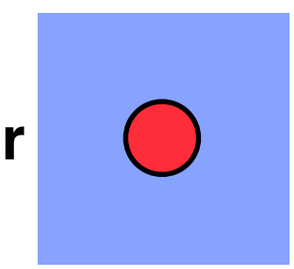
Seeing limited image of star

Double all sizes



Focal length constant

4x brighter

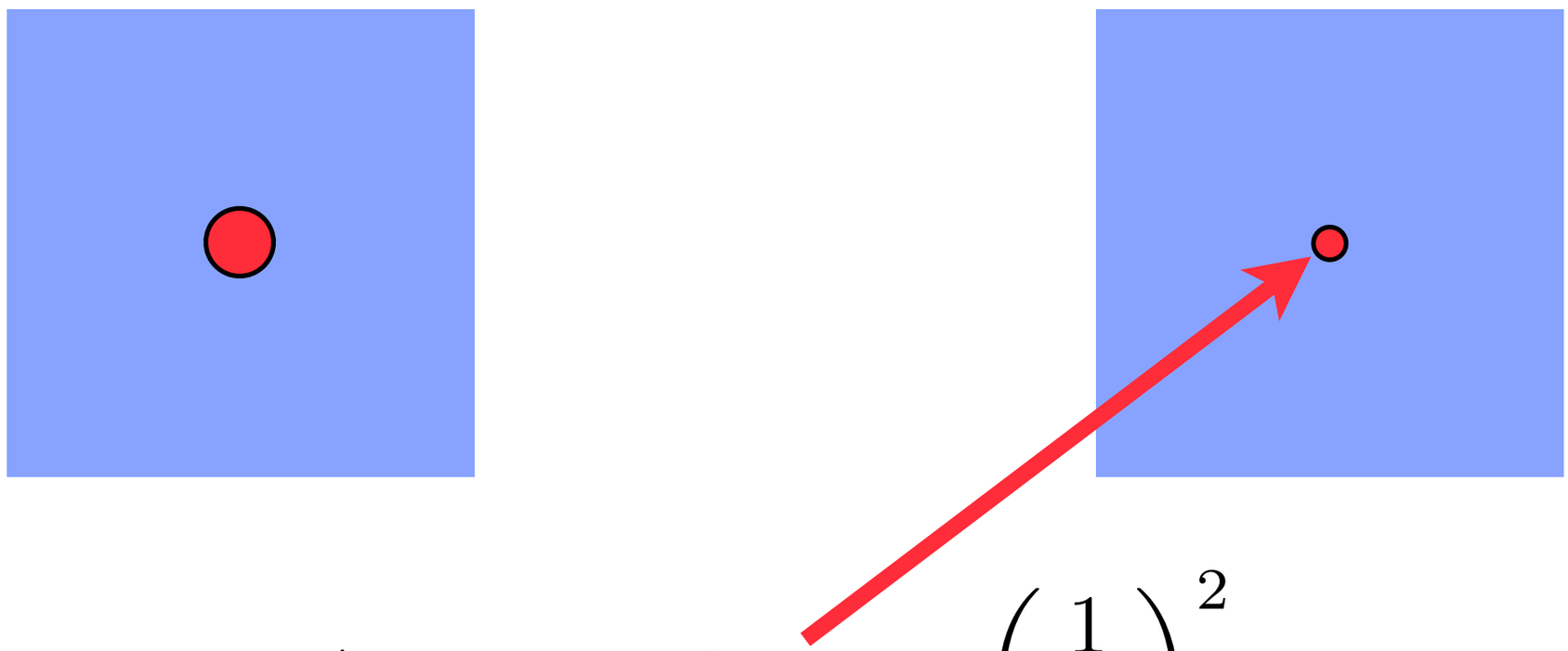


Flux/square arcsecond
does not change in either case

Diffraction limited telescope sensitivity

Diffraction limited star image is SMALLER than seeing star image

Doubling the diameter



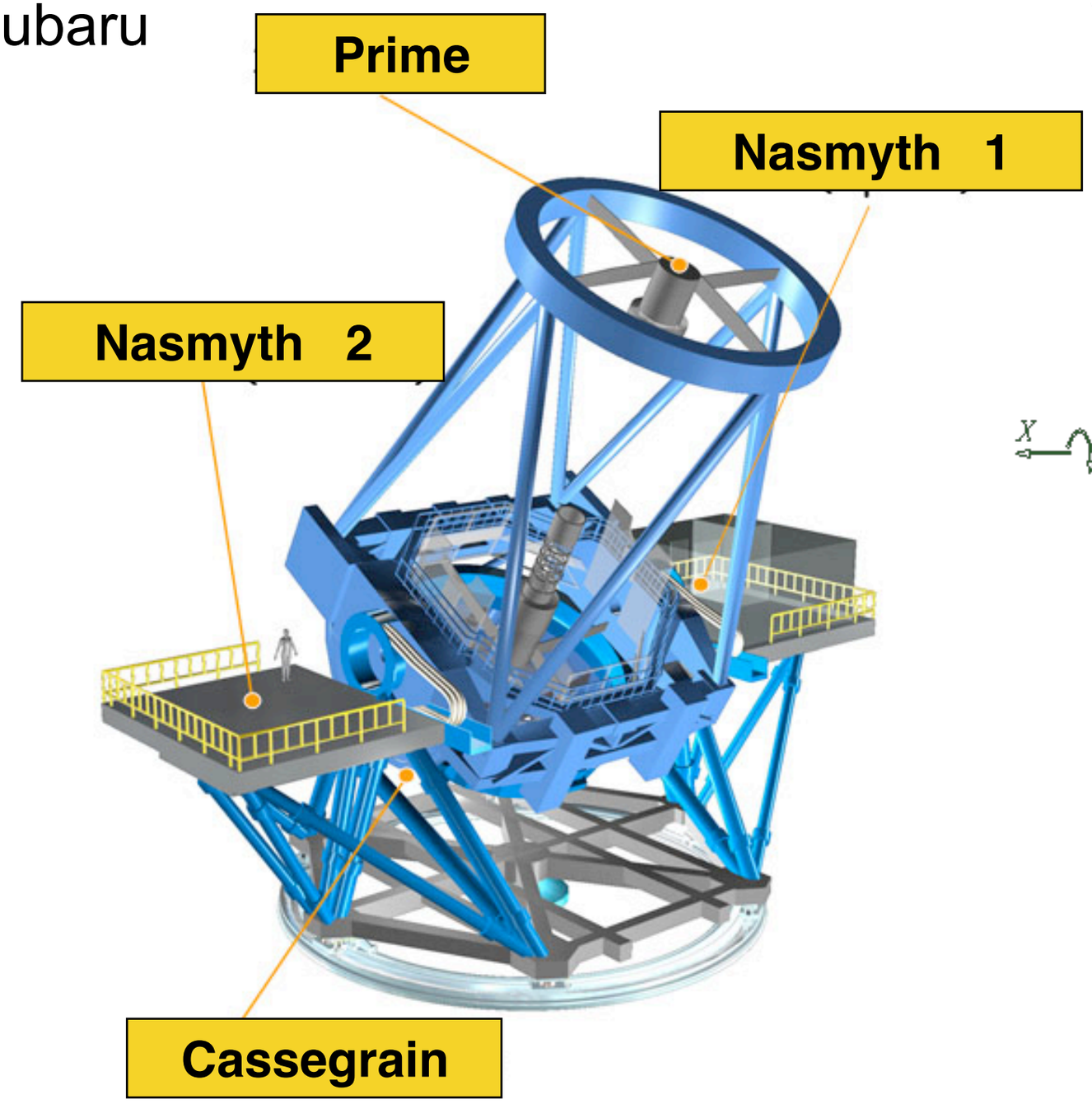
$$A_{PSF} = \pi d_{PSF} \propto \left(\frac{1}{D}\right)^2$$

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

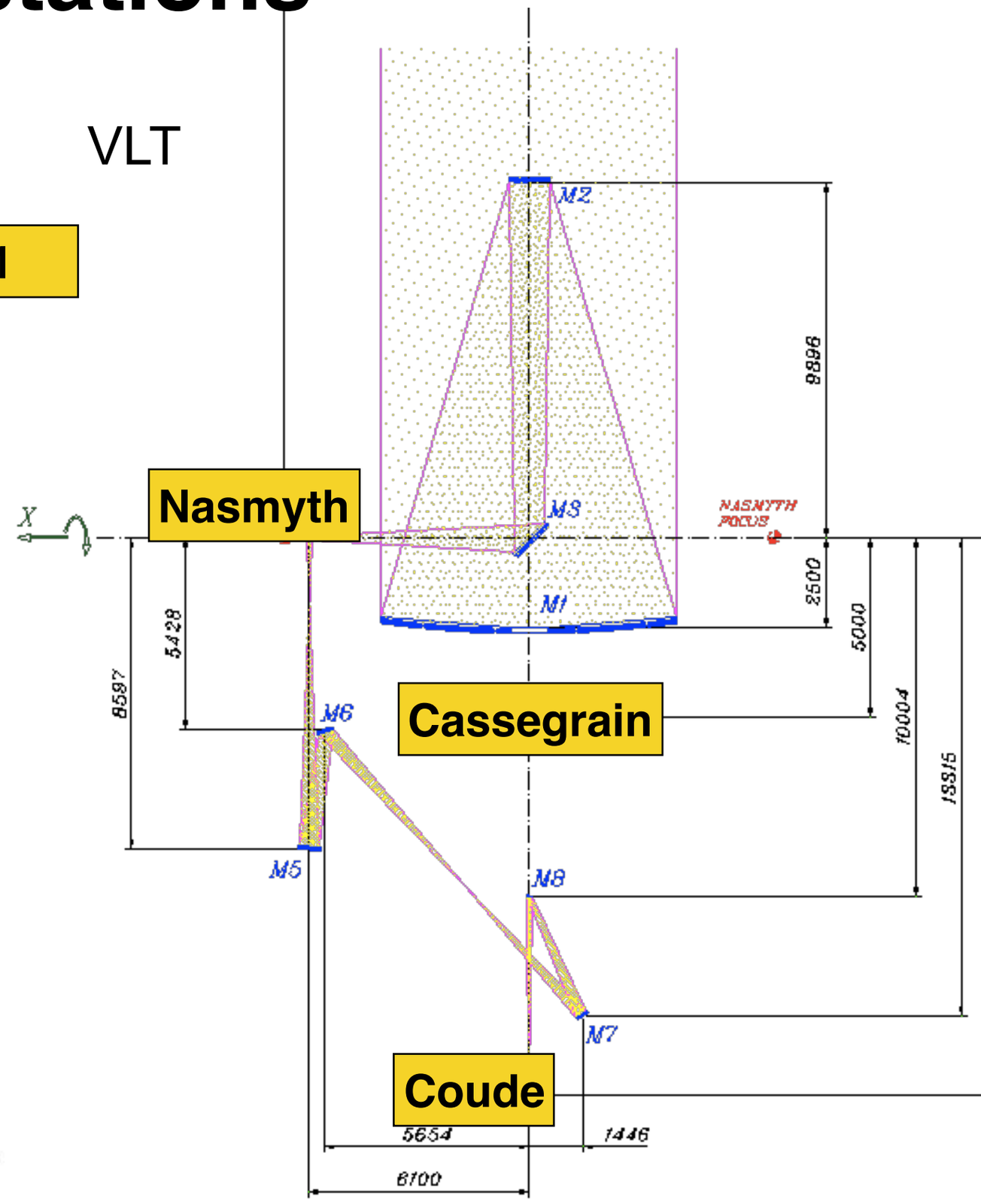
$$\text{Signal to noise} = \frac{S}{N} \propto D^4$$

Focal stations

Subaru

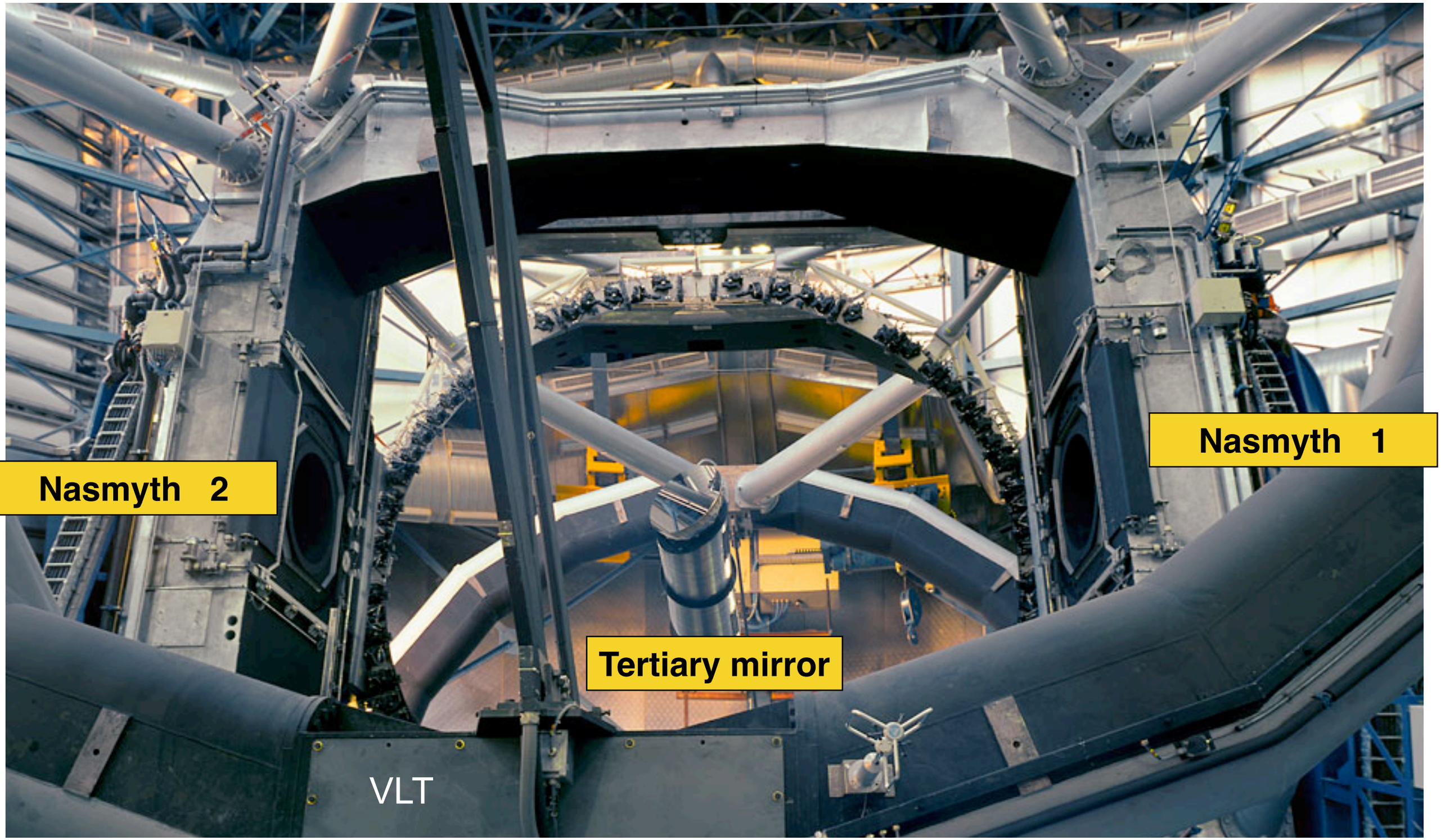


VLT

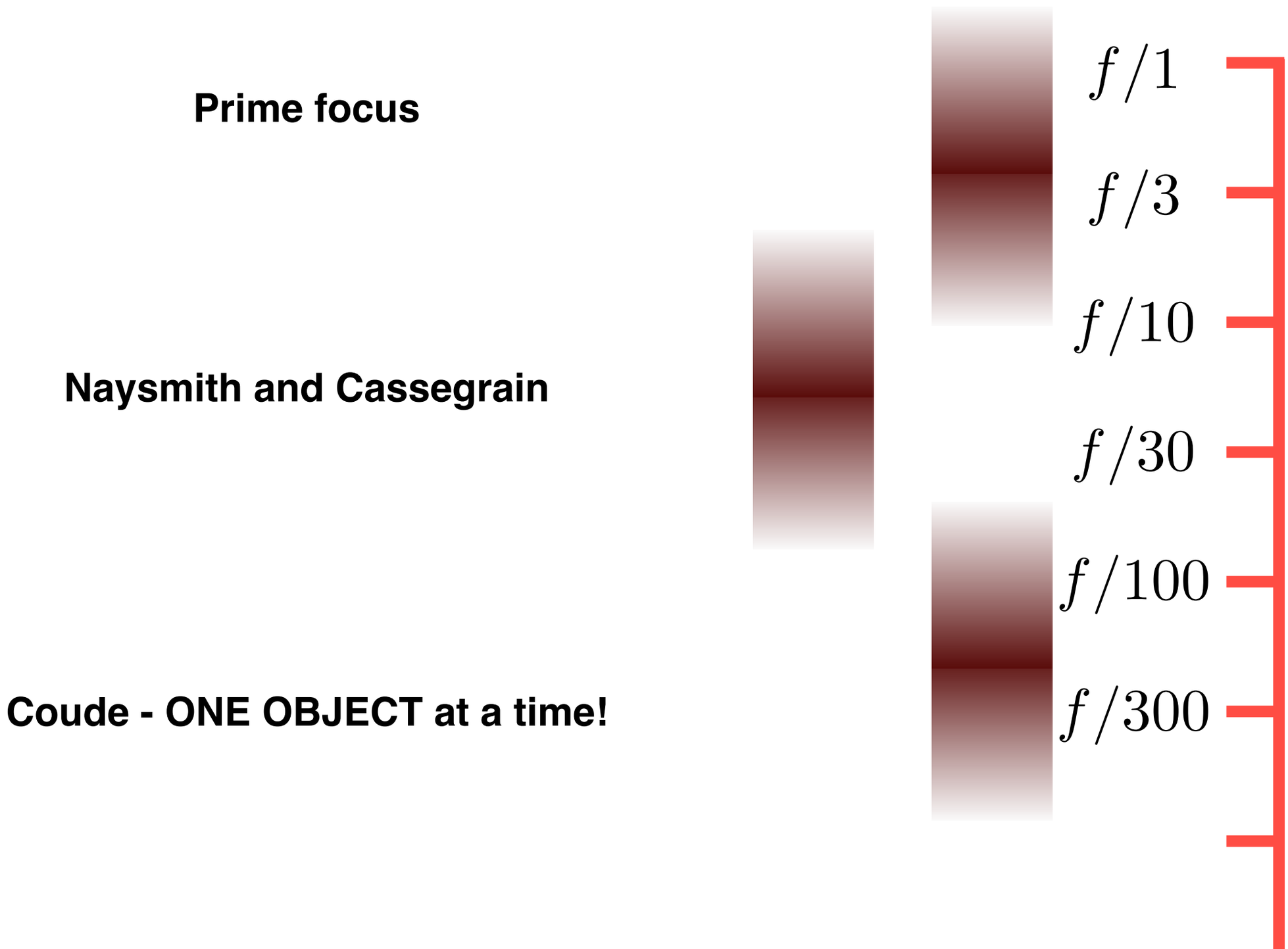


Focal stations

Sky rotates with hour angle



Focal ratios for the various foci



Prime Focus Correctors

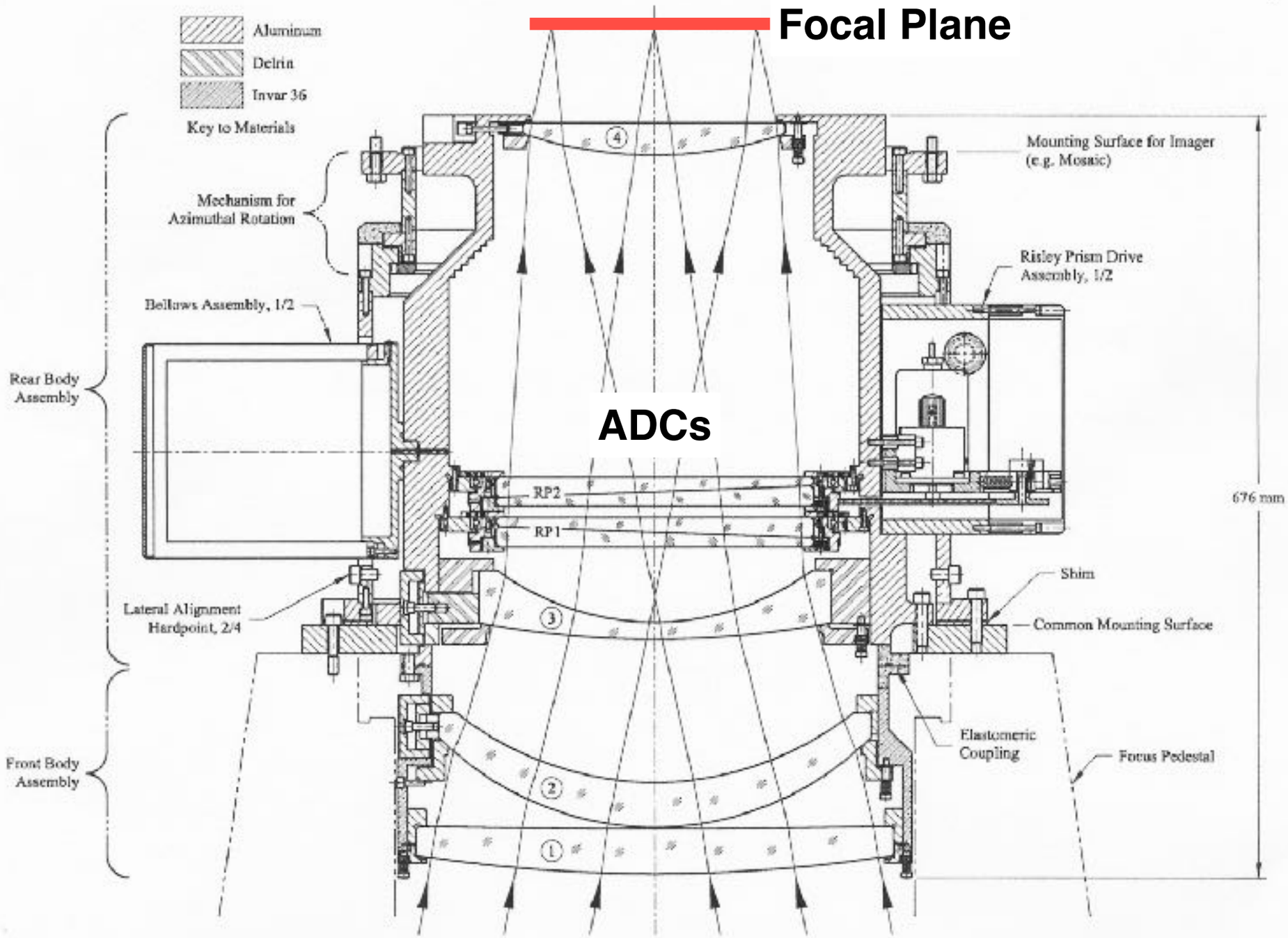


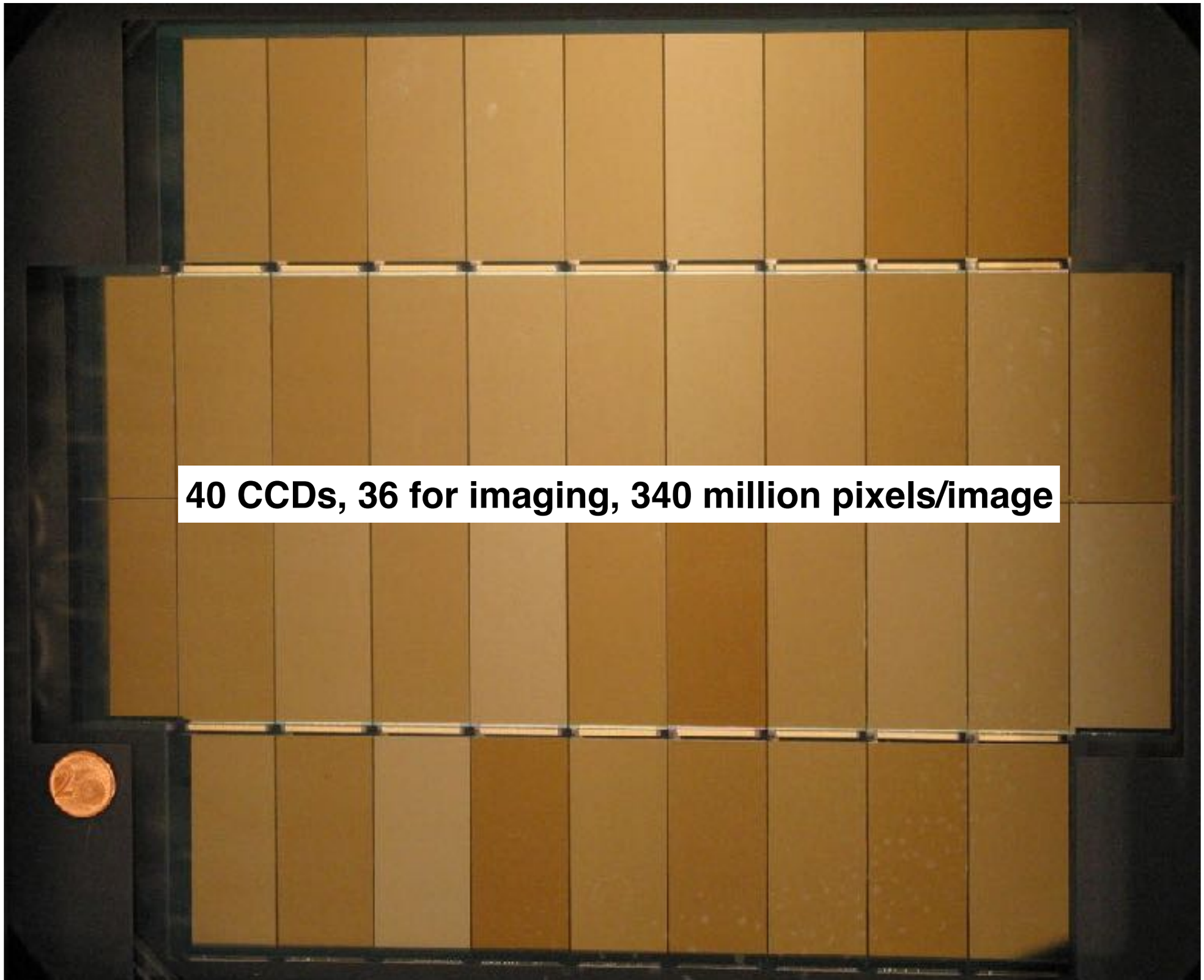
Figure 2. The opto-mechanical assembly for the new 4-m prime focus corrector. Elements #1, #2, #3, and #4 are SiO_2. The ADC materials comprising RP1 and RP2 are UBK7 (rear) and LLF6 (front), where "rear" is closer to the detector.

4m Mayall telescope on Kitt Peak

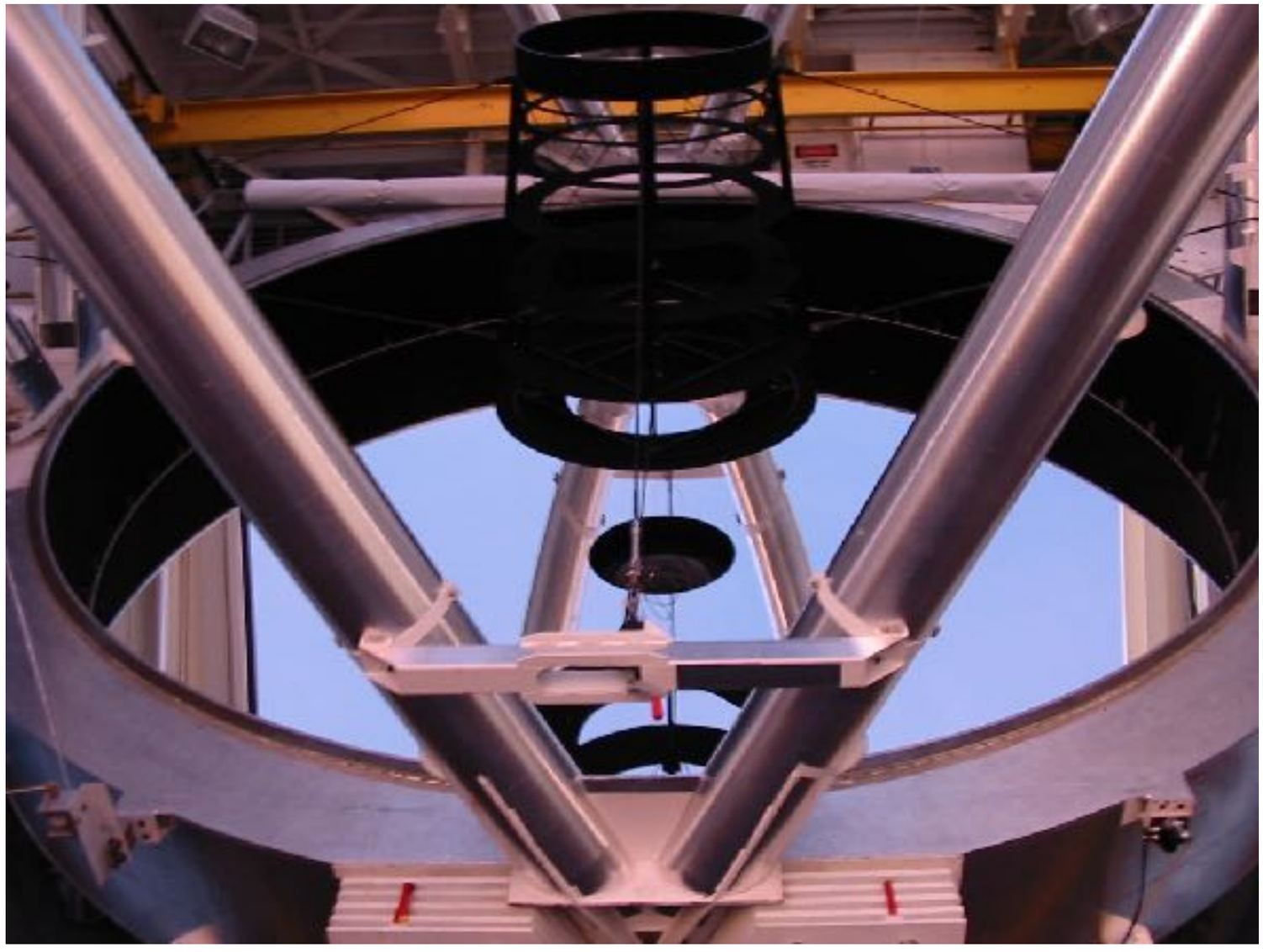
http://www-kpno.kpno.noao.edu/glaspey/mayall_params.html

Prime Focus Imagers

Ground based imaging - MEGACAM at CFHT



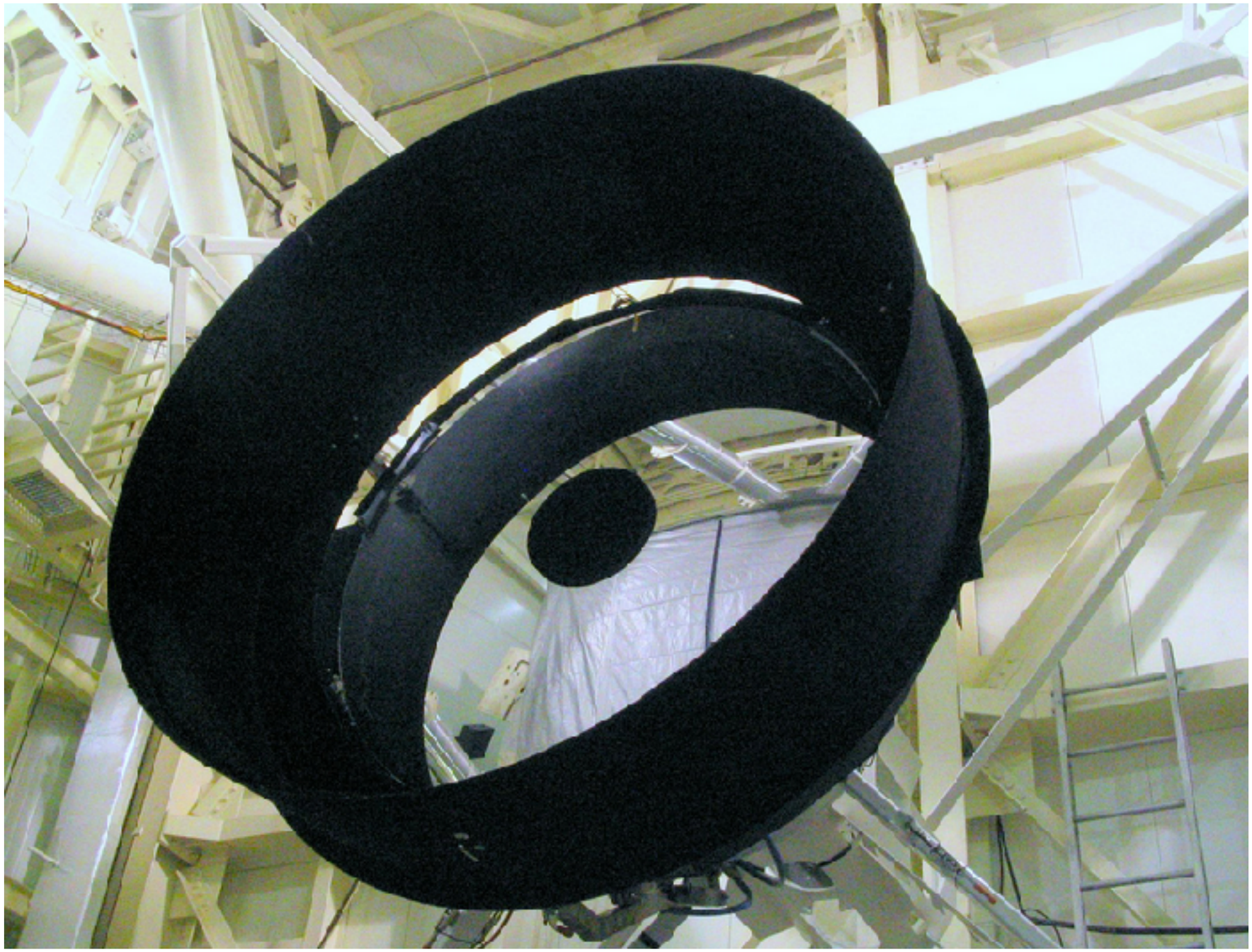
Wide Field Imagers



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

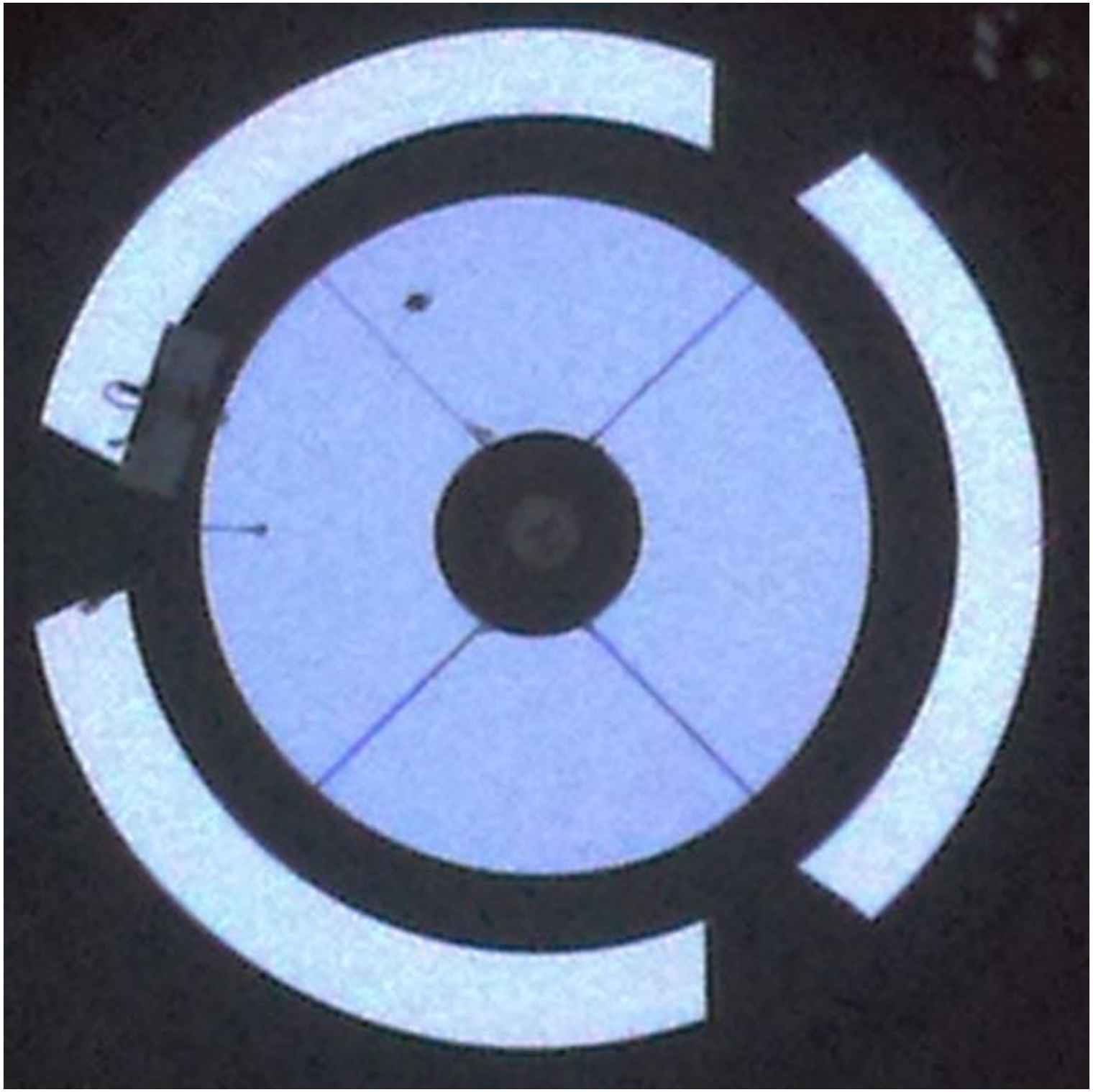
https://www.cfa.harvard.edu/~mlacasse/

Wide Field Imagers

Internal reflections from a Schmidt camera

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

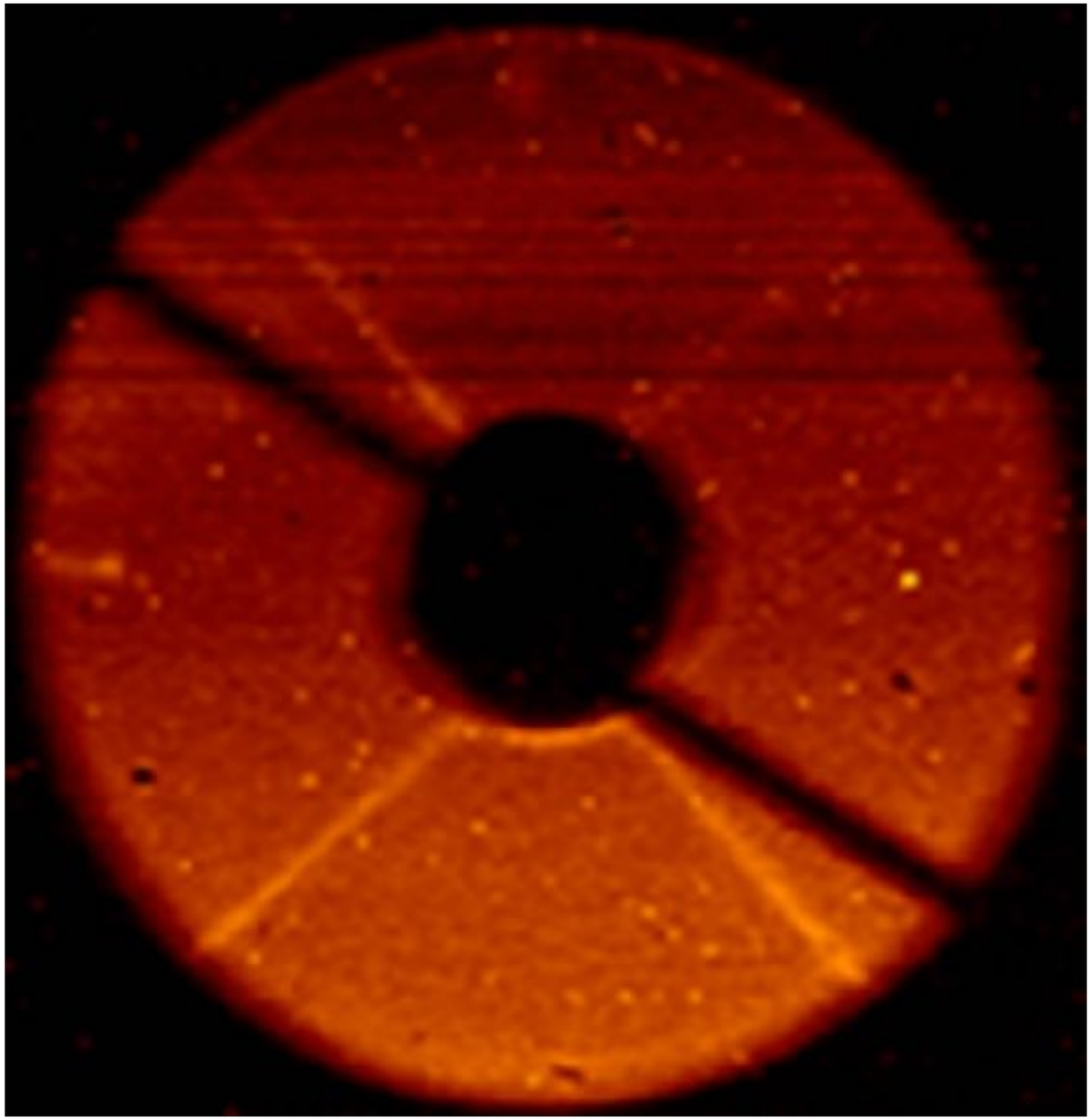
Visible Pupil image



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

Kate Morzinski

Infrared 3.4 micron Pupil image

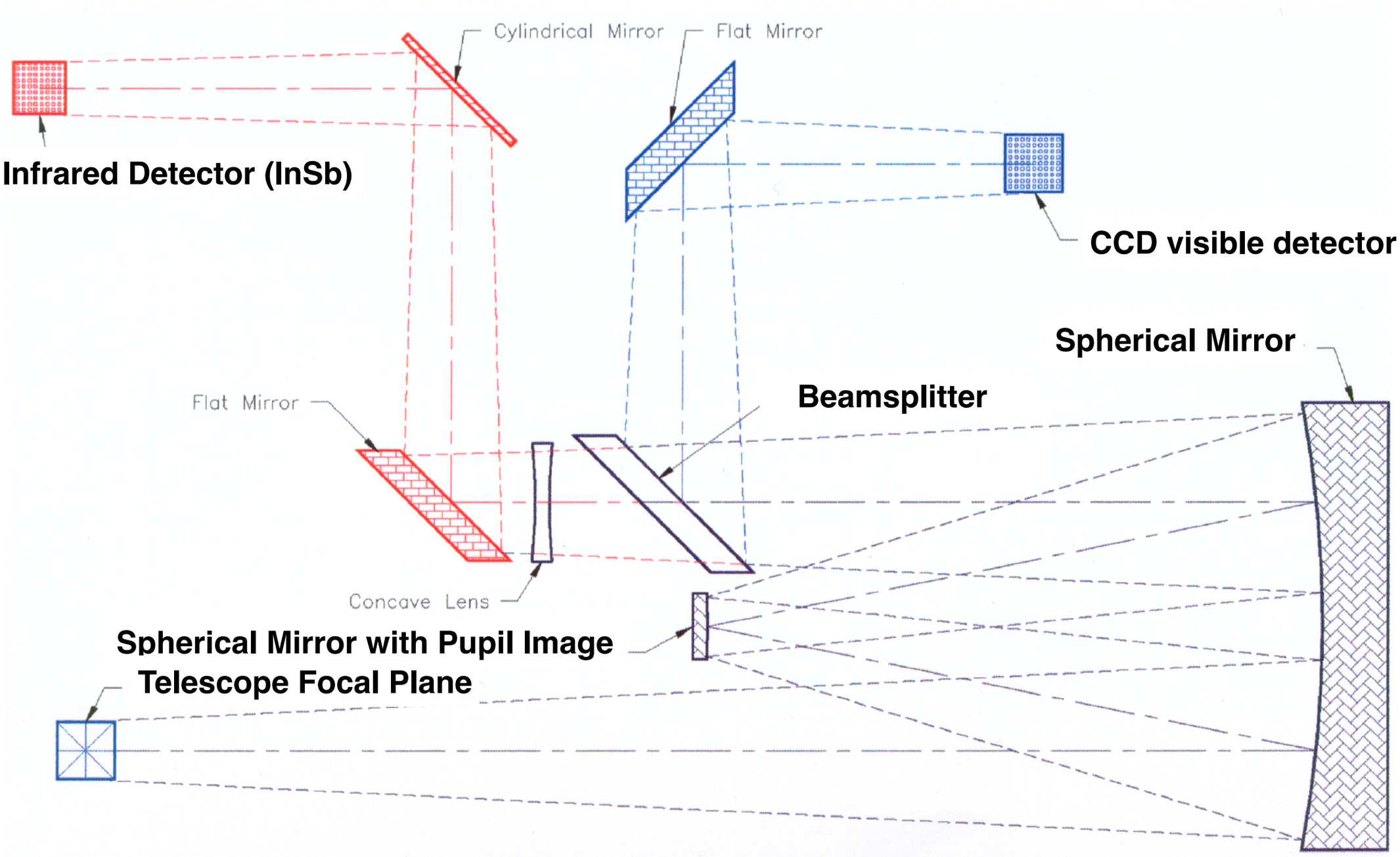


https://visao.as.arizona.edu/simulations/magao-pupils-and-fourier-optics/

Kate Morzinski

Offner Relay

Used to make cold stops in IR cameras



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