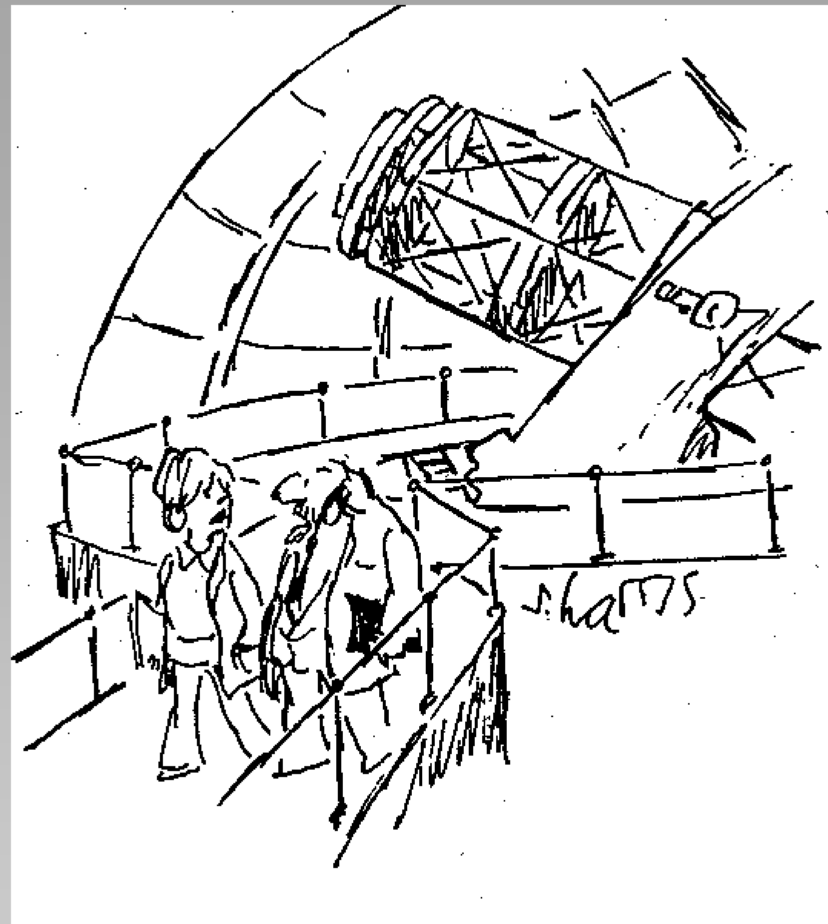
Optical/IR Observational Astronomy

Detectors I

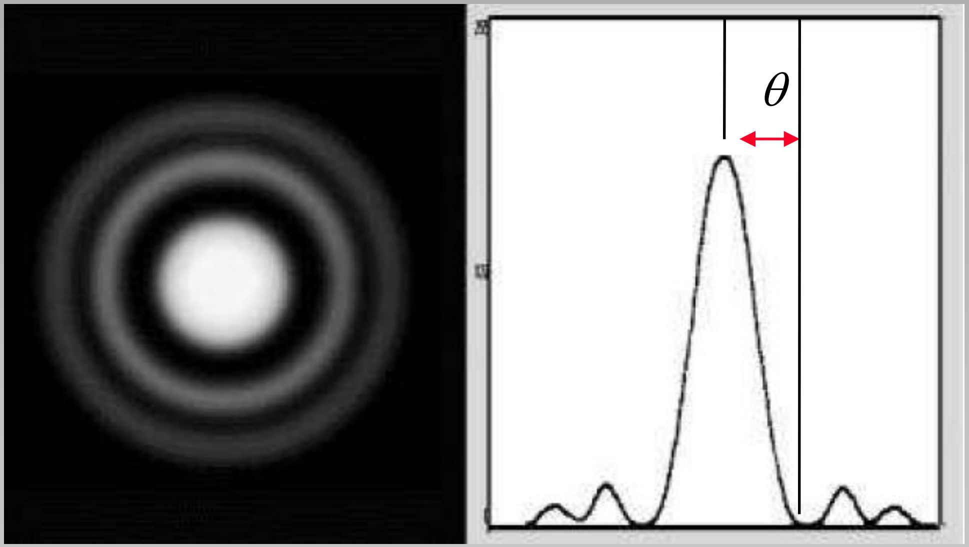


"I've seen out to the limit of the observable universe, and believe me, it's no better out there than it is here."

David Buckley, SALT

Key parameters for an astronomical telescope:

- **Resolution**

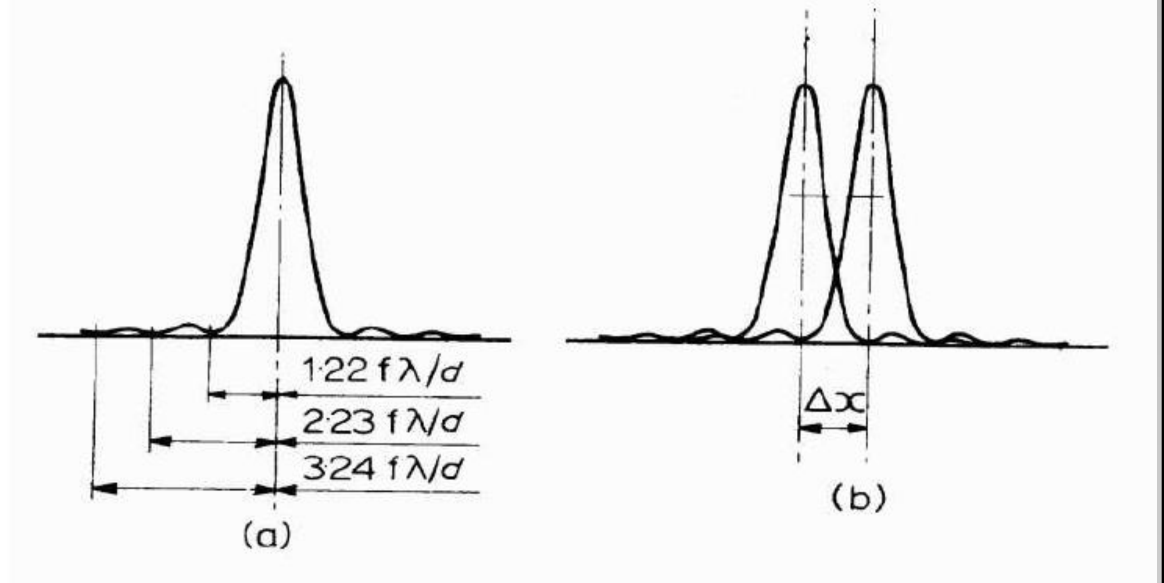


$$\theta = 1.22 \frac{\lambda}{a}$$

Detectors I

Resolvability:

- **Two point sources are said to be *resolved* if the peak of the central maximum of one diffraction pattern falls onto the first dark ring of the other**
- **This is referred to as the *Rayleigh criterion***



(a) Airy disk; (b) Diffraction limit to resolution

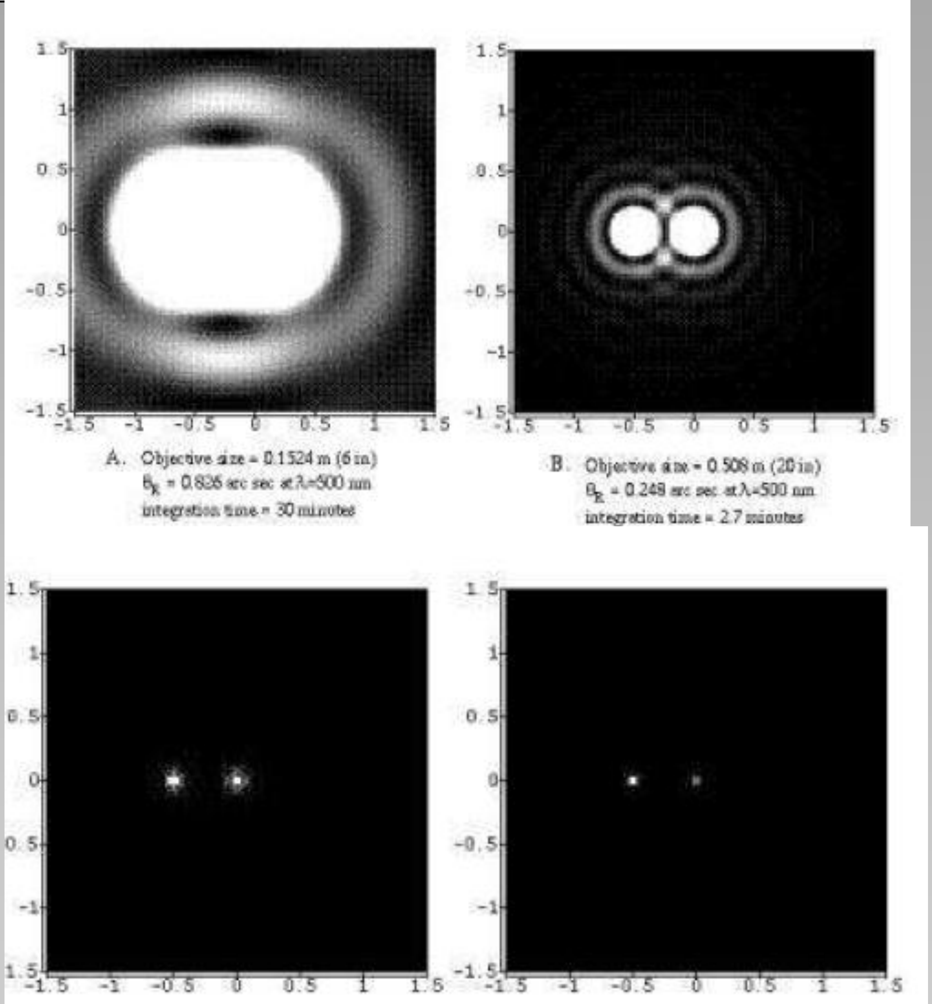
Resolvability:

- **Ignoring atmospheric effects, the resolution of an ideal telescope is just defined by its *size***

- ***Examples:***

  D = 0.13 m, 0.50 m, 2.5m

  & 5 m diameter telescopes



A. Objective size = 0.1524 m (6 in)
θ_R = 0.836 arc sec at λ=500 nm
integration time = 30 minutes

B. Objective size = 0.508 m (20 in)
θ_R = 0.248 arc sec at λ=500 nm
integration time = 2.7 minutes

C. Objective size = 2.3876 m (94 in)
θ_R = 0.0527 arc sec at λ=500 nm
integration time = 7.3 seconds

D. Objective size = 5.08 m (200 in)
θ_R = 0.0248 arc sec at λ=500 nm
integration time = 1.6 seconds

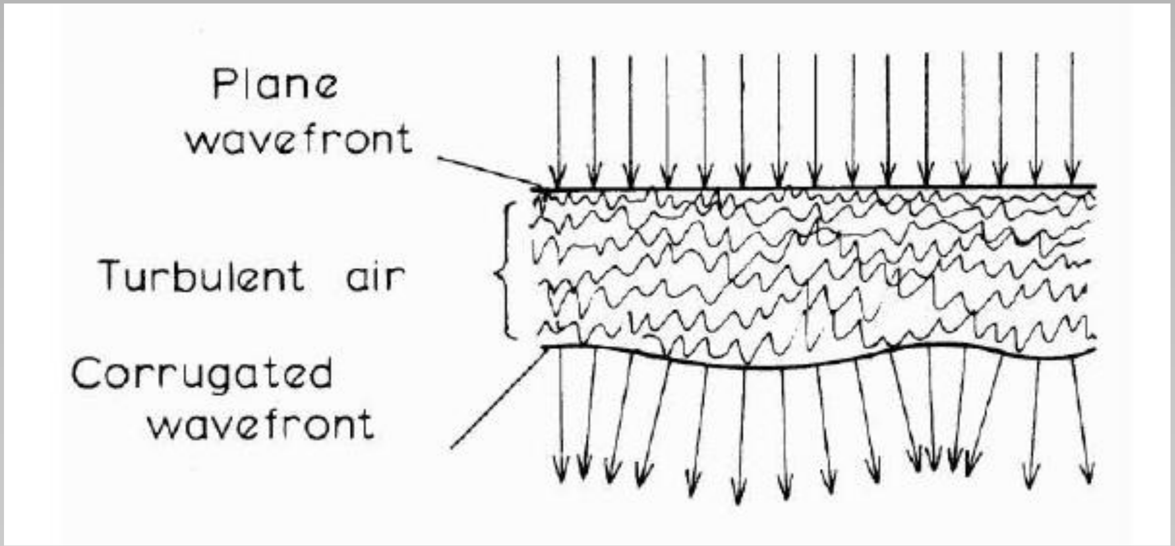
Some other Telescope Parameters

Resolvability:

- **Other effects can limit resolvabilty in *real* images**
  - **Problems associated with saturation by bright objects**
  - **Other diffraction effects**

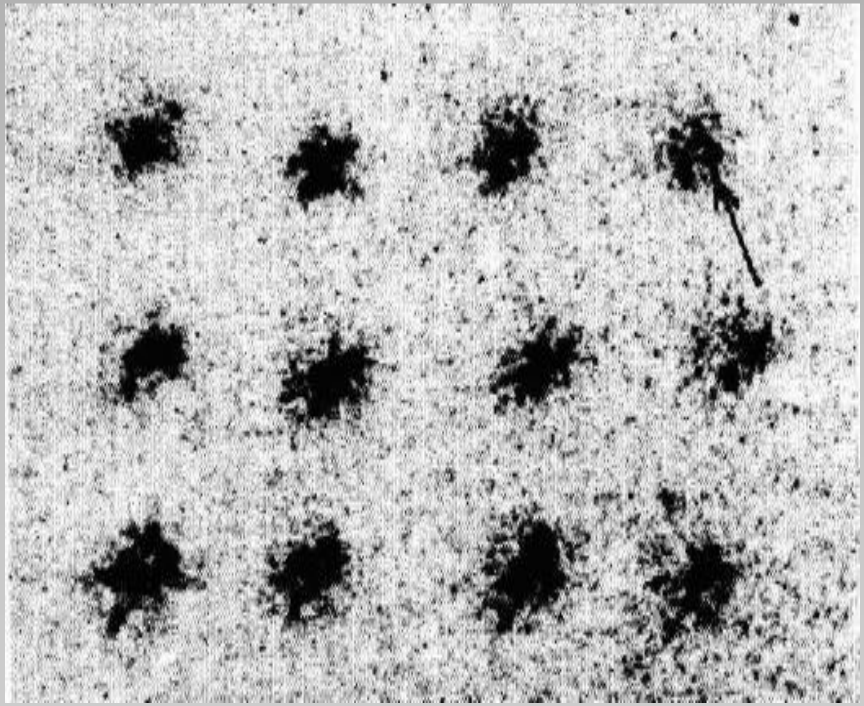
Atmospheric seeing:

- **Also, because of the atmosphere, telescope optics are often not built to be *diffraction limited***
  - **Expensive & unnecessary, unless the atmosphere (“seeing”)can be corrected**



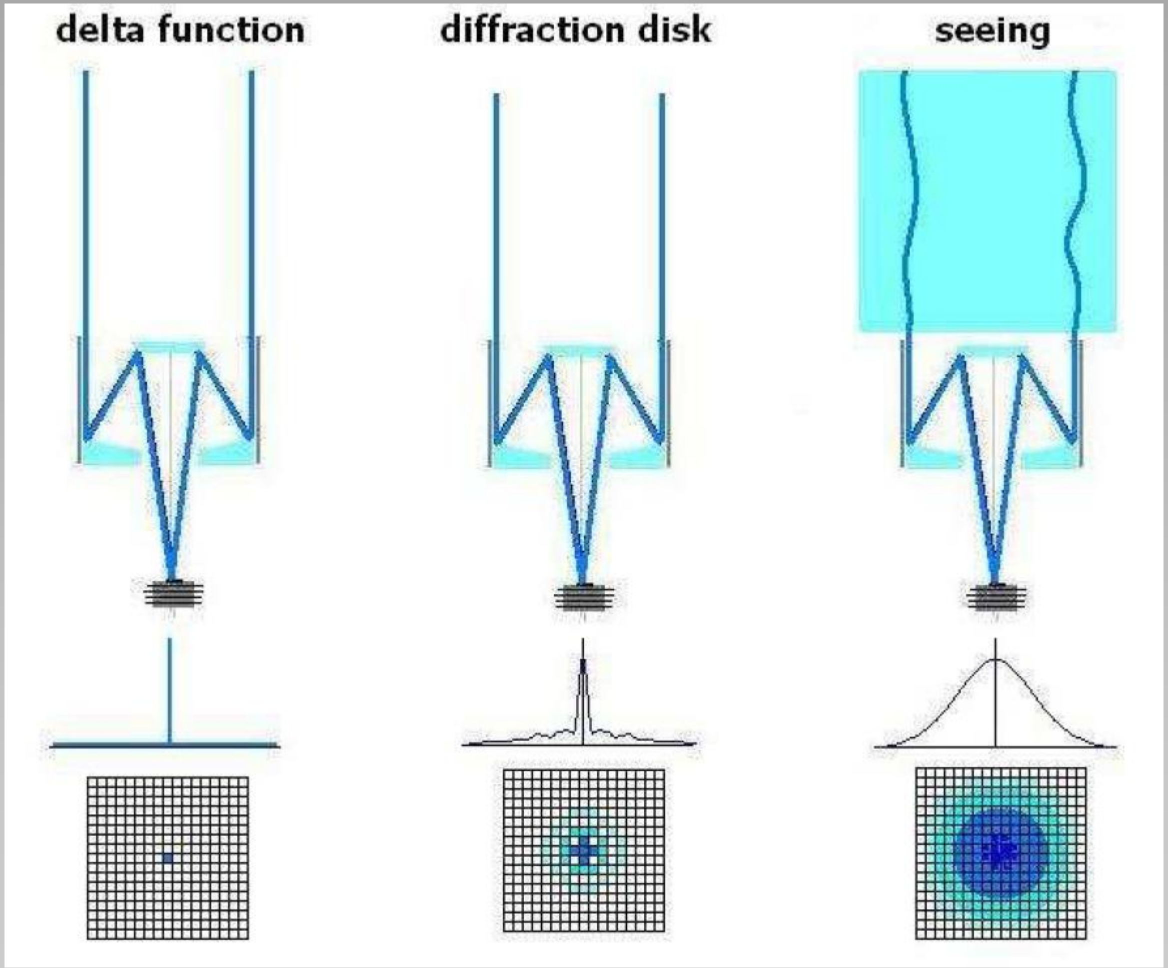
Atmospheric seeing:

- **Fast phase changes cause a *scintillation* pattern.**
- **Only seen if exposures are short (milliseconds) as images get blurred out**



Consecutive 2 ms images of a bright star

Telescope Systems for Different Assumptions



Geometric Optics *Wave Optics* *Real Atmosphere*

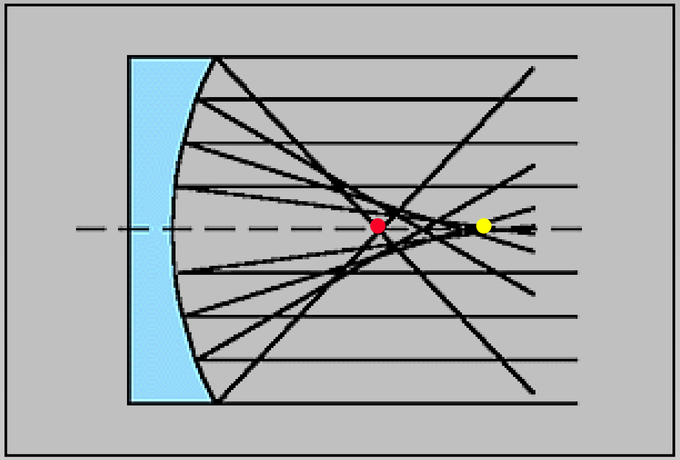
Ideal

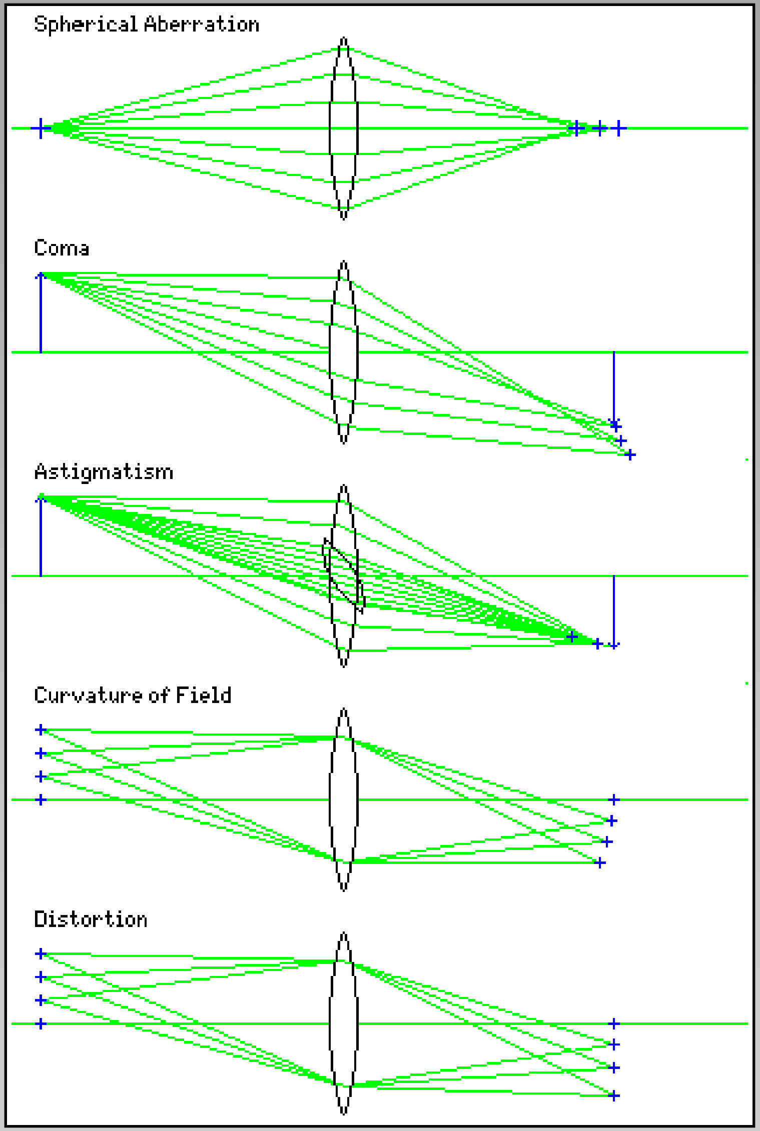
Optical Aberrations

The Seidel aberrations:

1. Spherical Aberration

Different focus points between paraxial (passing along optical axis) and marginal (furthest from optical axis) rays.

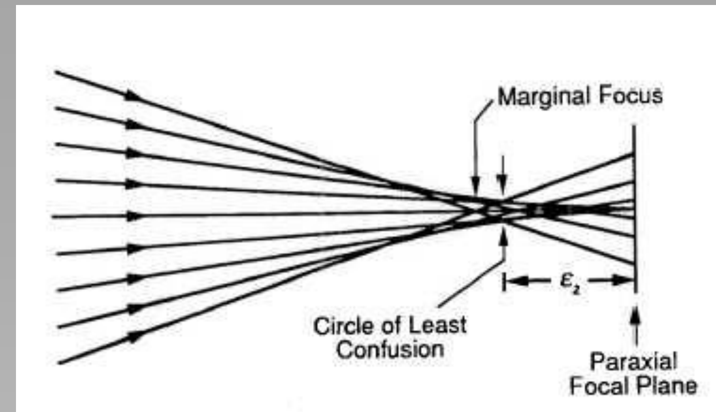


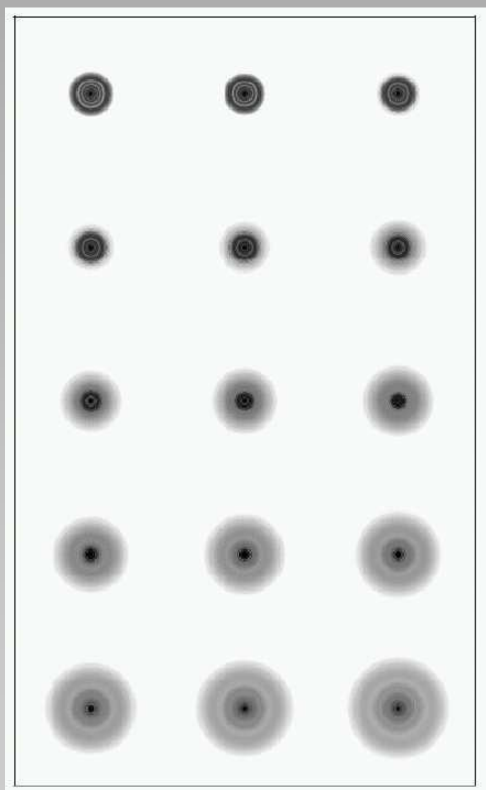


Optical Aberrations

1. Spherical Aberration

Different focus point





Spherical because a sphere images just like this.

- ***perfect image only of centre of curvature***
- ***any optic (spherical or not) can show exhibit it***
- ***ideal mirror to image on-axis object at ∞ is a paraboloid (as used in most telescope primary mirrors).***

SALT

Since SALT is deliberately designed to have a spherical primary mirror it suffers from severe spherical aberration

- ***circle of least confusion ~10 arcmin (1/3rd Lunar diameter)***

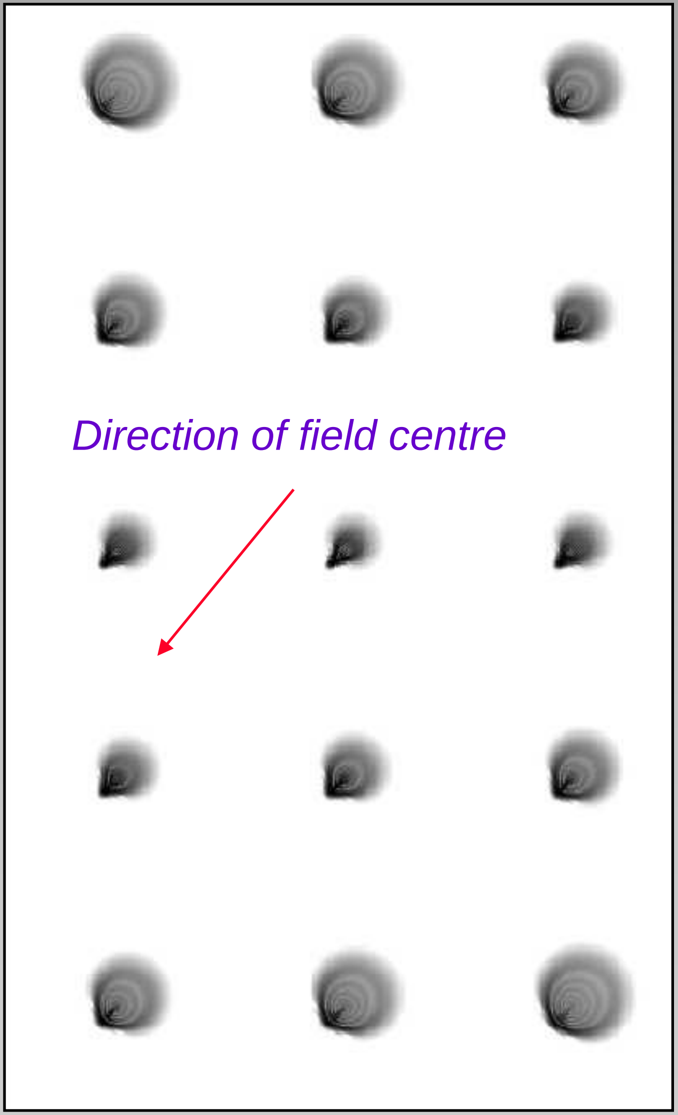
Optical Aberrations

2. Coma

Image at a particular field position is produced by overlapping images produced by annular zones centred on the optical axis.

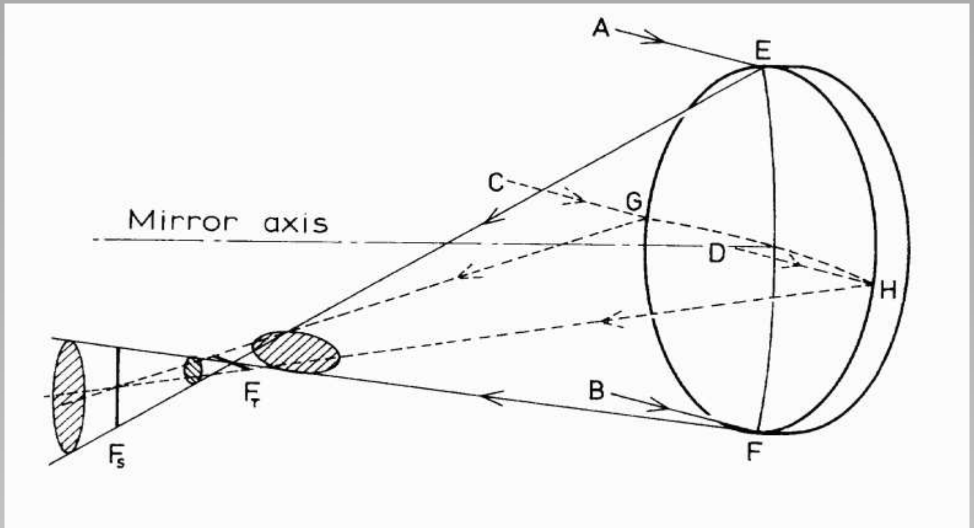
Because their angular displacement is a function of annulus size, the images are spread out along a radius vector to the field centre.

Called "coma" due to their comet-like appearance

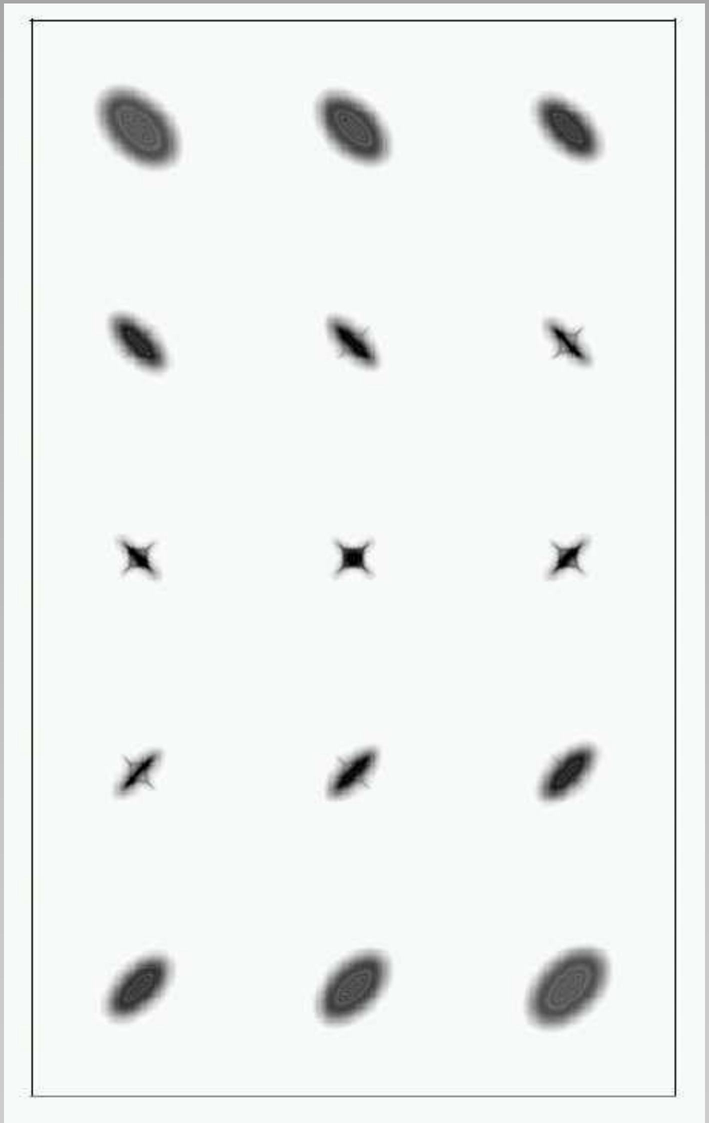


Optical Aberrations

3. Astigmatism



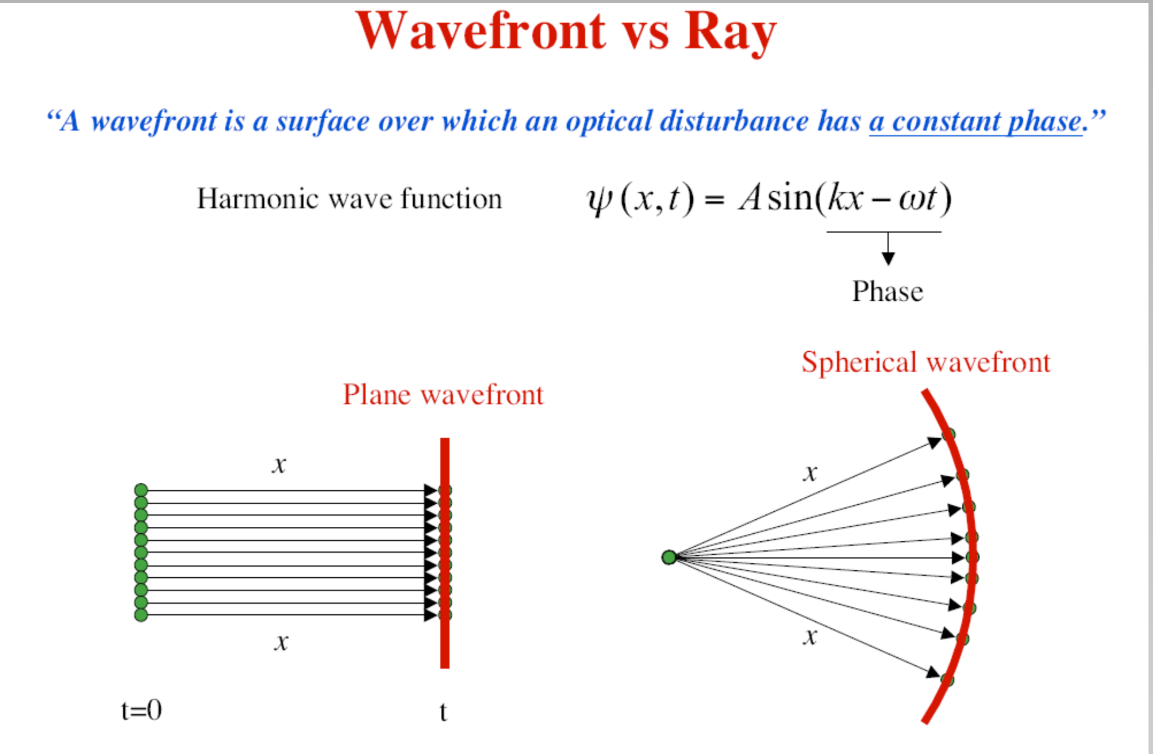
Oblique astigmatism due to a concave mirror



- **Characteristic pattern is an elongation along symmetry axis, or orthogonal to it.**
- **Furthermore, as one moves through focus, axis rotates by 90º**
- **In-focus images are symmetrical and round**

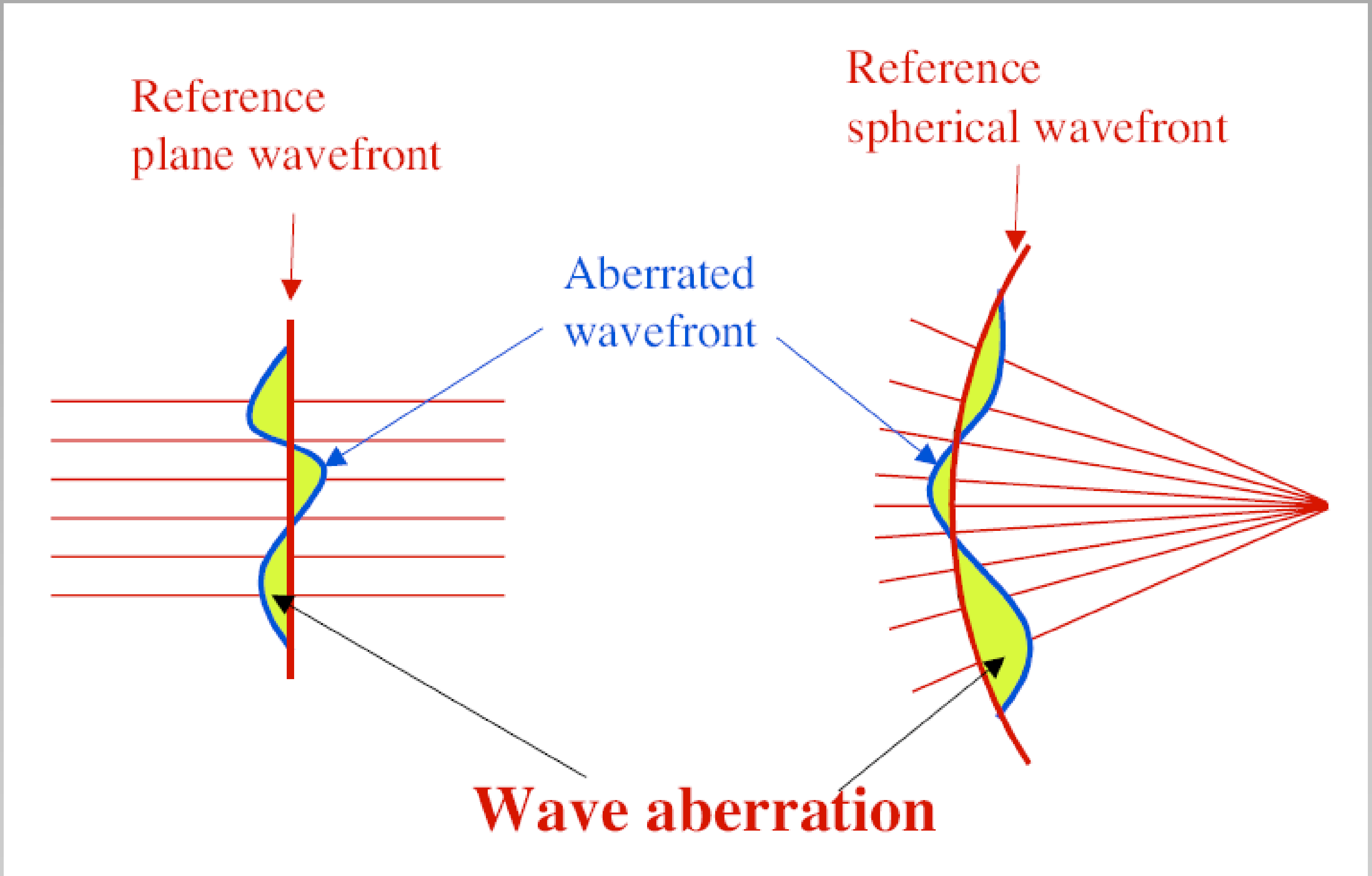
Optical Aberrations: Zernike polynomials

- **Can describe optical aberrations as a wavefront perturbation**
- **Consider the *entrance pupil* (e.g. objective lens in a refractor) and the imperfections of this surface**
- **Can describe aberrations as phase changes that change with position over such a pupil**



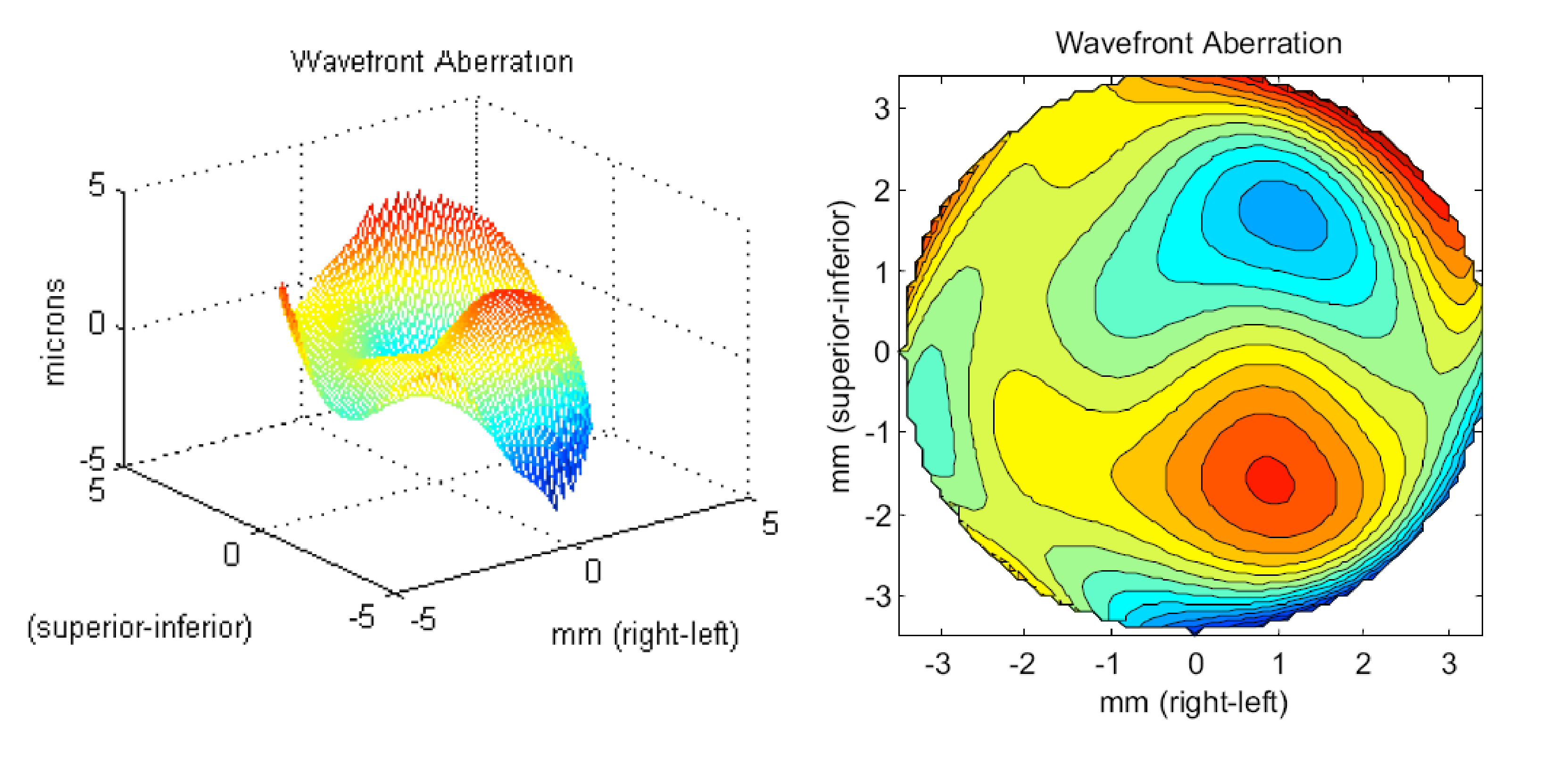
Optical Aberrations: Zernike polynomials

- **Wavefront perturbations**



Optical Aberrations: Zernike polynomials

- **Can describe the phase variations as a *surface* showing departure from the ideal wavefront**



Optical Aberrations: Zernike polynomials

- **Mathematically, describe as a surface in ρ, θ coordinates**

$$W(\rho,\theta) = \sum C_n^m Z_n^m(\rho,\theta)$$

Wavefront aberration

Zernike coefficient

Zernike polynomials (wavefront mode)

Optical Aberrations: Zernike polynomials

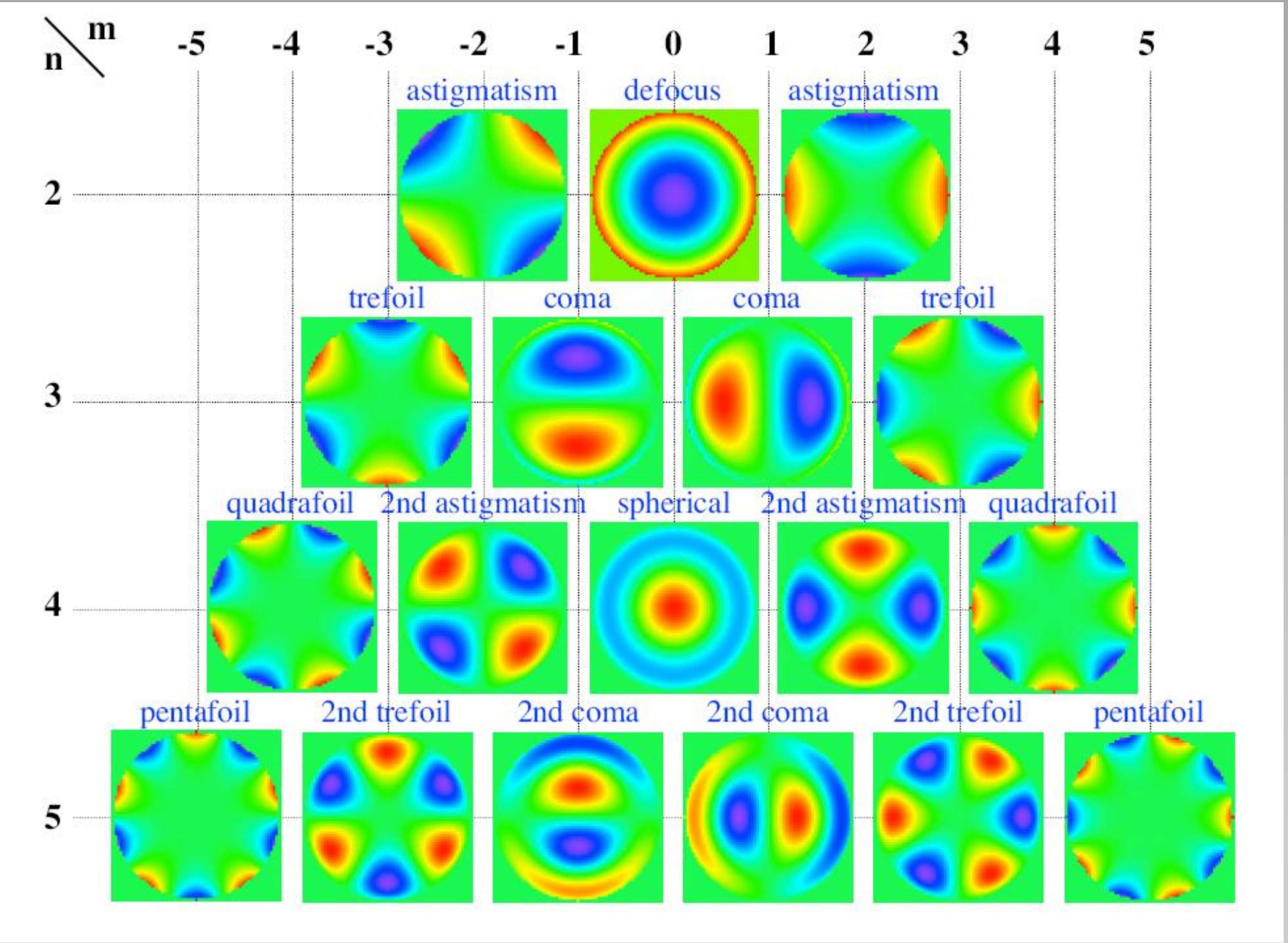
- **Zernike polynomials:**

n = order	m = frequency	$Z_n^m(\rho,\theta)$
0	0	1
1	-1	$2\ \rho \sin\theta$
1	1	$2\ \rho \cos\theta$
2	-2	$\sqrt{6}\ \rho^2 \sin 2\theta$
2	0	$\sqrt{3}\ (2\rho^2-1)$
2	2	$\sqrt{6}\ \rho^2 \cos 2\theta$
3	-3	$\sqrt{8}\ \rho^3 \sin 3\theta$
3	-1	$\sqrt{8}\ (3\rho^3-2\rho) \sin\theta$
3	1	$\sqrt{8}\ (3\rho^3-2\rho) \cos\theta$
3	3	$\sqrt{8}\ \rho^3 \cos 3\theta$
4	-4	$\sqrt{10}\ \rho^4 \sin 4\theta$
4	-2	$\sqrt{10}\ (4\rho^4-3\rho^2) \sin 2\theta$
4	0	$\sqrt{5}\ (6\rho^4-6\rho^2+1)$
4	2	$\sqrt{10}\ (4\rho^4-3\rho^2) \cos 2\theta$
4	4	$\sqrt{10}\ \rho^4 \cos 4\theta$
5	-5	$\sqrt{12}\ \rho^5 \sin 5\theta$
5	-3	$\sqrt{12}\ (5\rho^5-4\rho^3) \sin 3\theta$
5	-1	$\sqrt{12}\ (10\rho^5-12\rho^3+3\rho) \sin\theta$
5	1	$\sqrt{12}\ (10\rho^5-12\rho^3+3\rho) \cos\theta$
5	3	$\sqrt{12}\ (5\rho^5-4\rho^3) \cos 3\theta$

Second order aberrations (n = 2)

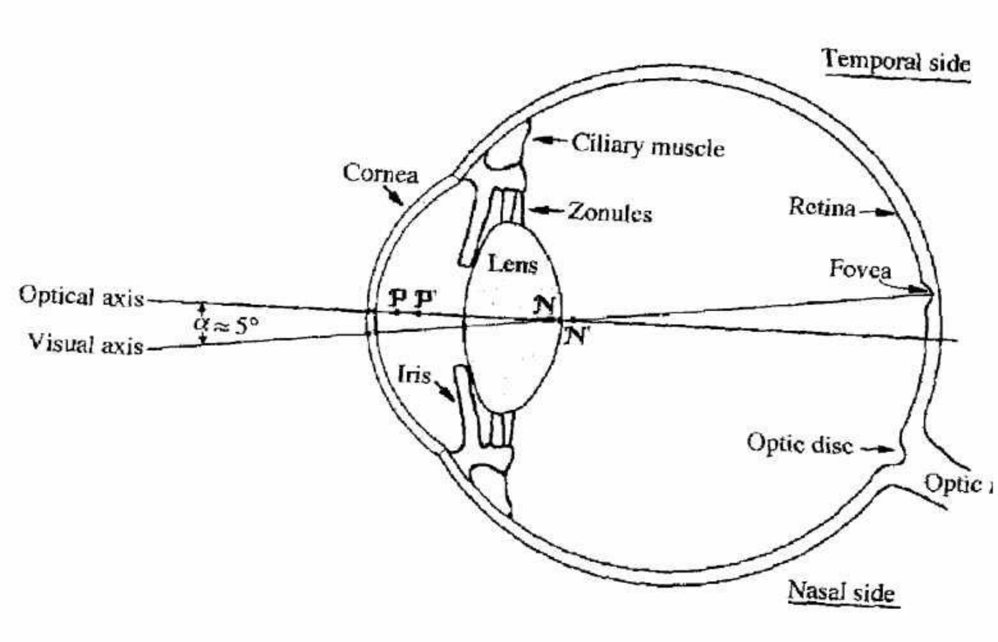
Higher order aberrations (n = 3 to 5)

Optical Aberrations: Zernike polynomials



How we (*mostly*) perceive the Universe

- First perceptions were by eye by our ancestors
  - The "visible" region of the electromagnetic spectrum
  - Human eye sensitive over a small range of wavelength: 390 - 780 nm
  - An optical imaging system
    - » Cornea & lens combine to form a curved focal surface on the retina

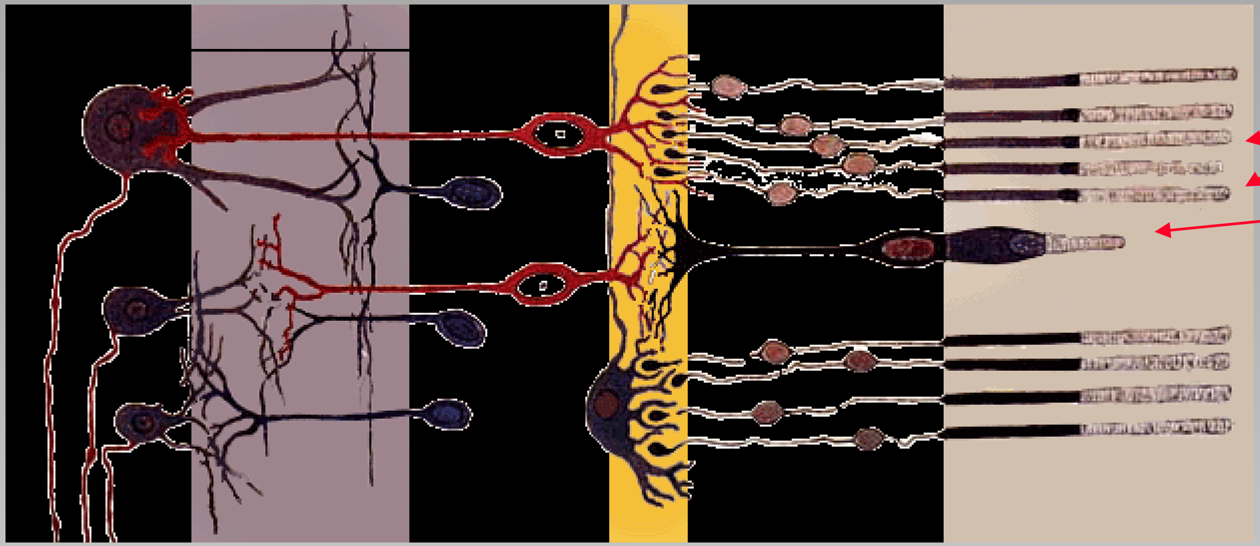


- Eye-brain is an amazing detector
  - Removes aberrations (clever image processing; stereoscopic; scanning)
  - Capable of a 10^9 dynamic range ($< 10^6$ for CCDs), ~0.6 arcmin resolution
  - Equivalent to a 576 megapixel digital video camera!
  - The first astronomical detector was the human retina
    - » Capable of resolving objects of ~1 arcmin in size (pupil diameter = 6mm for fully dilated)
    - » A two-dimensional (2-D) video detector (~30 frames / sec)
    - » Capable of photometry: measuring the brightness and colour of stars

The Eye

Cross section of the retina:

Light in



- **How it works:**
  - Retina consists of photo-receptor cells (rods & cones)
    - » In rods rhodopsin (visual purple; 40,000 amu molecule) absorbs photons
      - Fragments into retinaldehyde (286 amu; a chromophore vitamin A derivative) & opsin
      - Results in changing electrical properties of cell ⇒ signal
    - » In cones, similar mechanism with molecule odopsin
      - But 3 different variants S, M & L (in ratio 1:4:8)

The Eye

- Photoreceptors
  - Rods (~120 million x 2µm only detect B&W
    - » Mostly what's used at night
    - » Average sensitivity peaks at ~510nm
    - » 1-10 photons needed to trigger a rod
    - » Several rods have to trigger together to send a signal to the brain
  - Cones (~6 million x 1.5 – 6.0 µm) detect colour
    - » 3 types: S (437nm), M (533nm) & L (564nm)
    - » Only work at high light levels (daytime)
    - » Concentrated on-axis (around the fovea, where they're also smaller in size)
    - » Only 1% as sensitive as rods, overall sensitivity peaks at 550nm

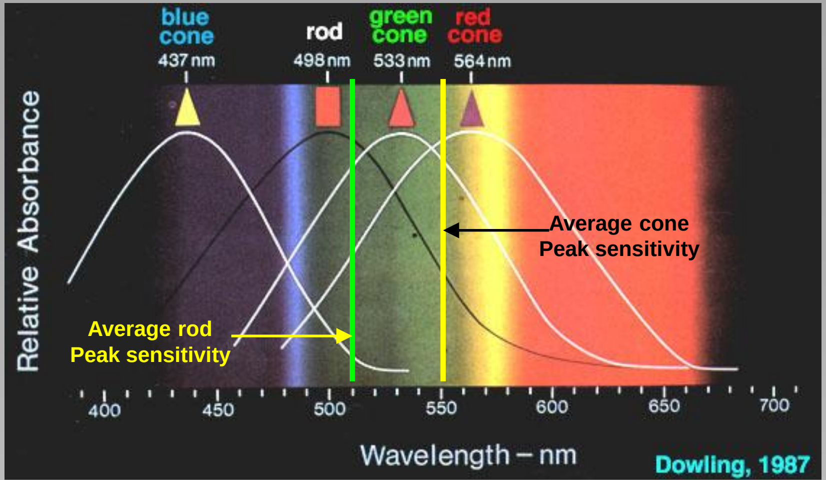
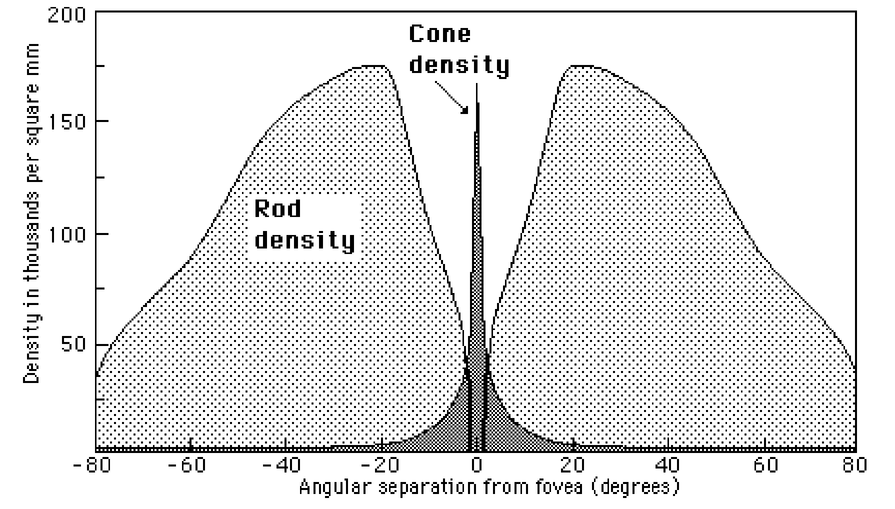


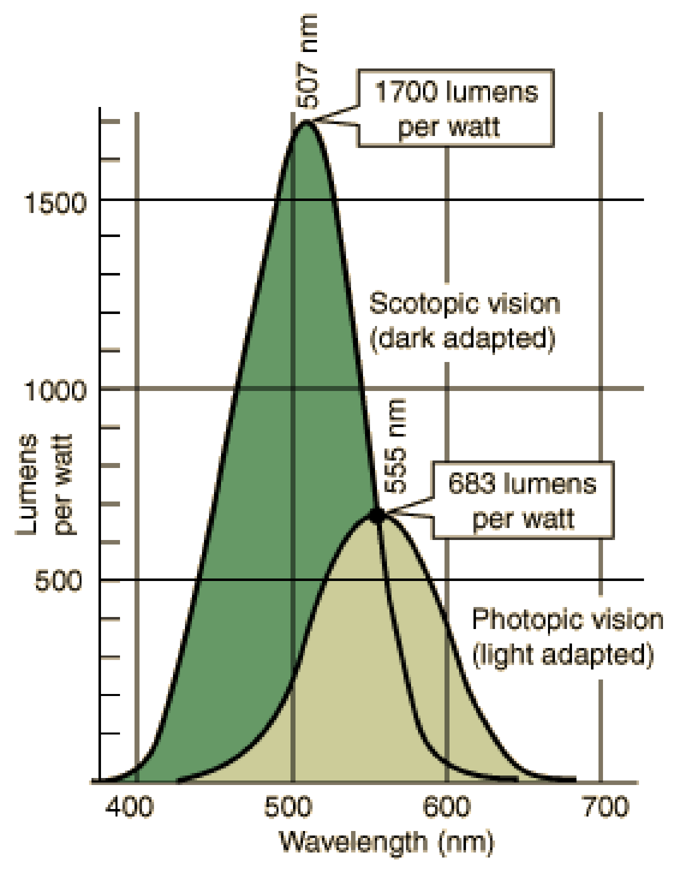
Fig. 14.The peak spectral sensitivities of the the 3 cone types and the the rods in the primate retina (Brown and Wald, 1963). From Dowling's book (1987).



The Eye

Photoreceptors

- At night fovea is a ‘blind spot’ (0.3mm) because cones are inoperative at low light levels
- “Averted vision” helps detect faint objects using peripheral vision rods
  - at field edge, ~100 rods are connected to one nerve fibre, so lower resolution than field centre where cones are individually connected)
- When eye is exposed to bright light (photopic vision), amount of rhodopsin available for photon detection is diminished
  - Cones detect light, so sensitivity moves to the red (closer to average cone sensitivity)
  - Overall sensitivity decreases
- When eye is fully dark-adapted and exposed to low light levels (scotopic vision) eye is more sensitive, but cannot sense colour
  - Dark adaption takes ~30min, about as long as twilight



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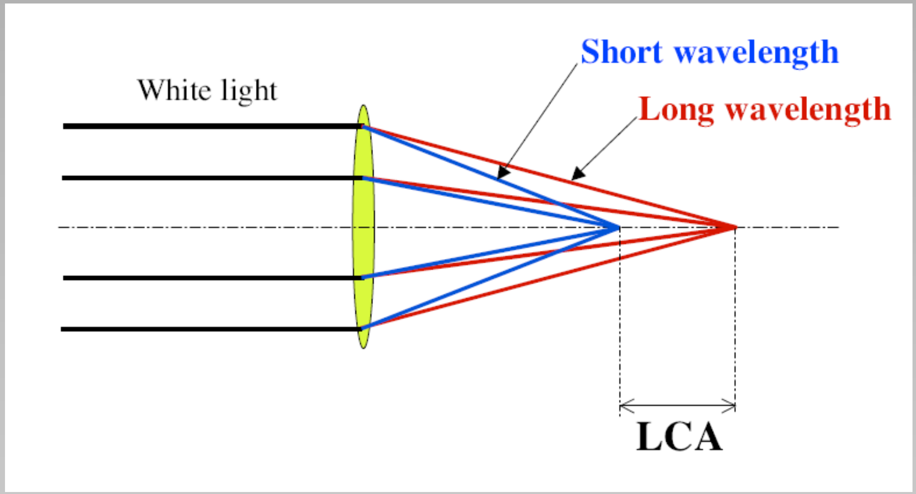
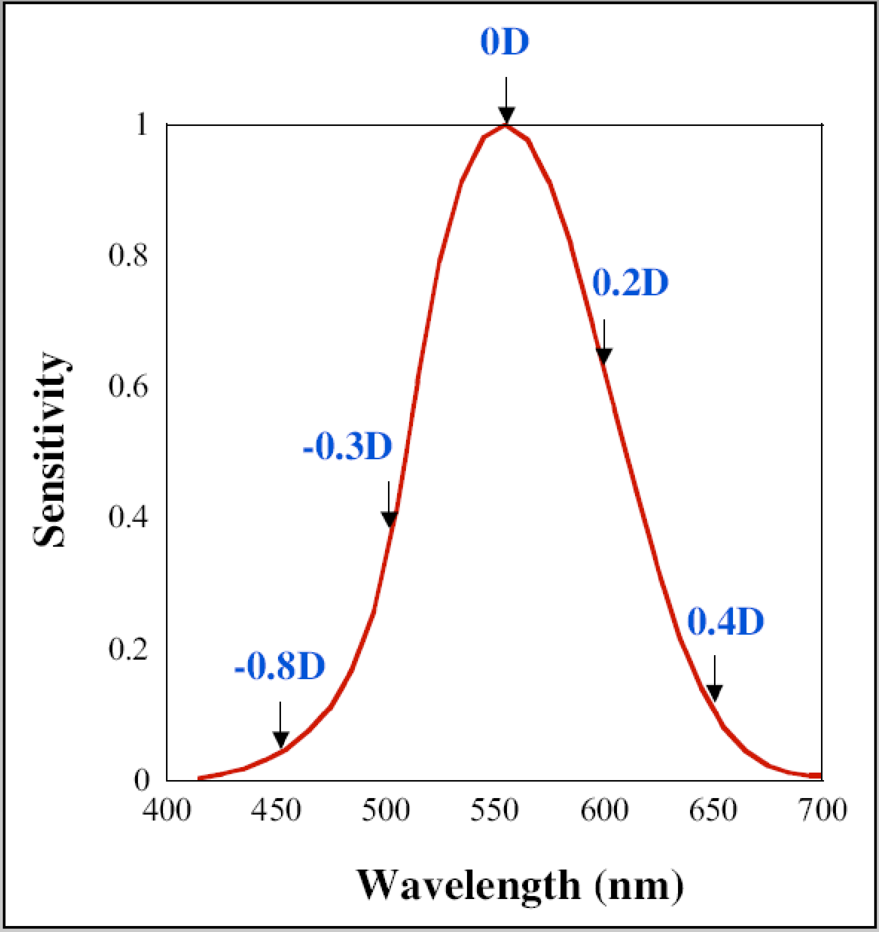
  - Equivalent to a 576 megapixel digital video camera!

Sensitivity of the Eye

- **Graph shows relative sensitivity**
- **Also relative defocus due to longitudinal chromatic aberration (LCA)**

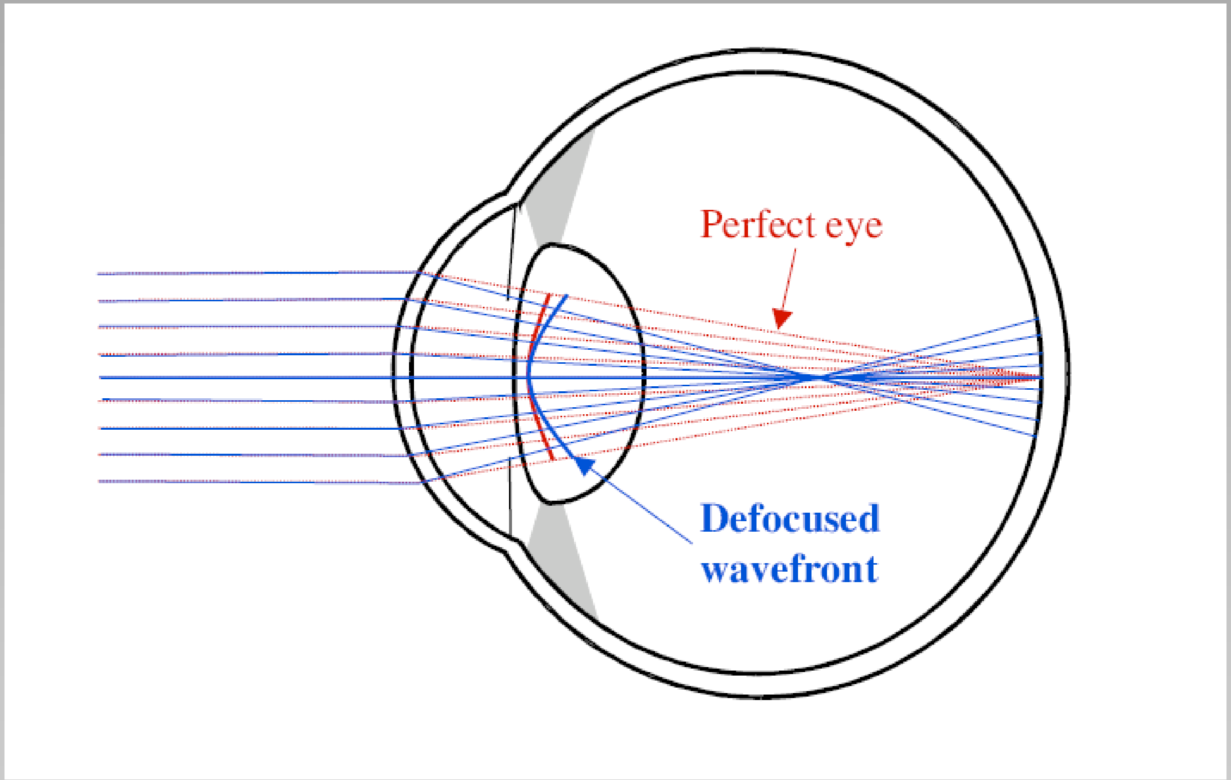




- **Effective defocus of ~2 dioptres over wavelength extremes**
  - **Δ Focal Length of ~0.5 mm (LCA)**

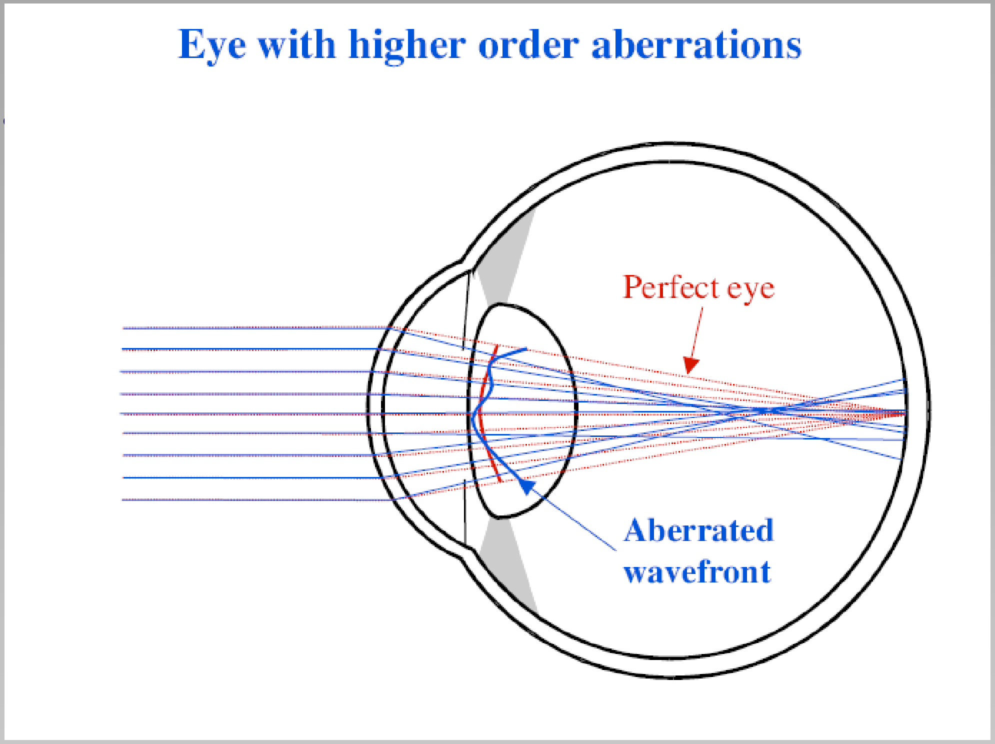
Optical Aberrations in the eye

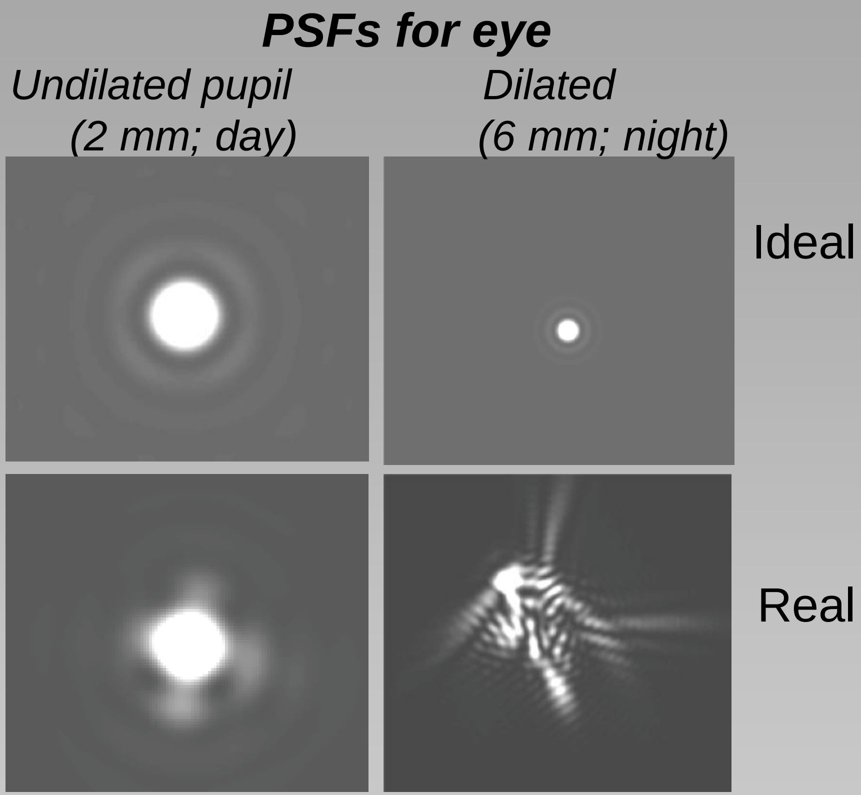
- **Example of an aberration (de-focus)**



What is this aberration commonly know as?

Aberrations in the Human Eye





- **Dioptre (as used in optometry) is a unit of *optical power***

  D = 1 / Focal Length (measured in metres)
  - **Human eye has a power of ~60 dioptres (~2/3 power from cornea, 1/3 from the lens, and typical corrections for short- or far-sightedness are -6 to +6 dioptres**
  - **Corrections for chromatic aberrations are ~2 dioptres (400 – 700 nm)**

The Magnitude Scale

- **The stellar "magnitude scale" – based on range of star brightness that the eye perceives – was invented around 120 BC by Hipparchus (*the same guy who discovered precession*)**
  - » **he devised 6 "steps" of brightness between the brightest and faintest stars seen by the eye (where *smaller* magnitudes implies *brighter* stars!)**
  - » **The eye perceives the same *ratio changes* in brightness as equal intervals of brightness**
  - » **Magnitude difference are related to the ratio of intensities:**

$$m_1 - m_2 = -2.5\ log \frac{I_1}{I_2}$$

Or:

$$\frac{I_2}{I_1} = 2.512^{m_1 - m_2}$$

  - » **So the difference in apparent magnitude difference of two stars, one of which has 100x the intensity of the other, is $\Delta m = 2.5 \log (100) = 5$ magnitudes.**
  - » **The conversion between magnitudes and intensity is given as:**

$$m = -2.5\ log\ I + constant$$

  - » **The constant is referred to as the *zero point* of the system, and is determined for a specific telescope-instrument-detector combination.**

The Magnitude Scale

Interesting magnitudes values (in the V-band filter which approximates the human eye response)

- ***Sun: m = -26.7 (1.2 x 10^{10} brighter than the brightest naked eye star; m = -10.7 / arcsec^2)***
- ***Full moon: m = -12.6 (but only m = 3.4 / arcsec^2)***
- ***Sirius (brightest star at night): m = -1.5***
- ***Naked eye limit: m = 6***
- ***Brightest stars in Andromeda galaxy: m = 19***
- ***Present day limit for biggest telescopes: m ~ 29 (6 x 10^{-9} fainter than faintest naked eye star)***
- ***Night sky brightness: m = 21.5 / arcsec^2 (best sites, dark Moon time)***
- ***Night sky: m = 18 / arcsec^2 (bright Moon time)***

How we perceive the Universe

Improvements came with the invention of new detection methods, other than just the human eye, to record light. This improved the faintness limit of telescopes, since the new techniques were more sensitive by >10 than the eye.

- **The end of the 19th Century saw the invention of *photography.***
- **Light causes chemical reactions in silver halide salts bonded into a gelatin layer, which converts them to metallic silver. "Developing" results in permanent changes: the film negative is black (due to silver metal) where light was absorbed and transparent where there was no light.**
- **Next revolution in optical astronomy was astrophotography**
  - ***Pioneered at the Royal Observatory, Cape of Good Hope (Sir David Gill)***

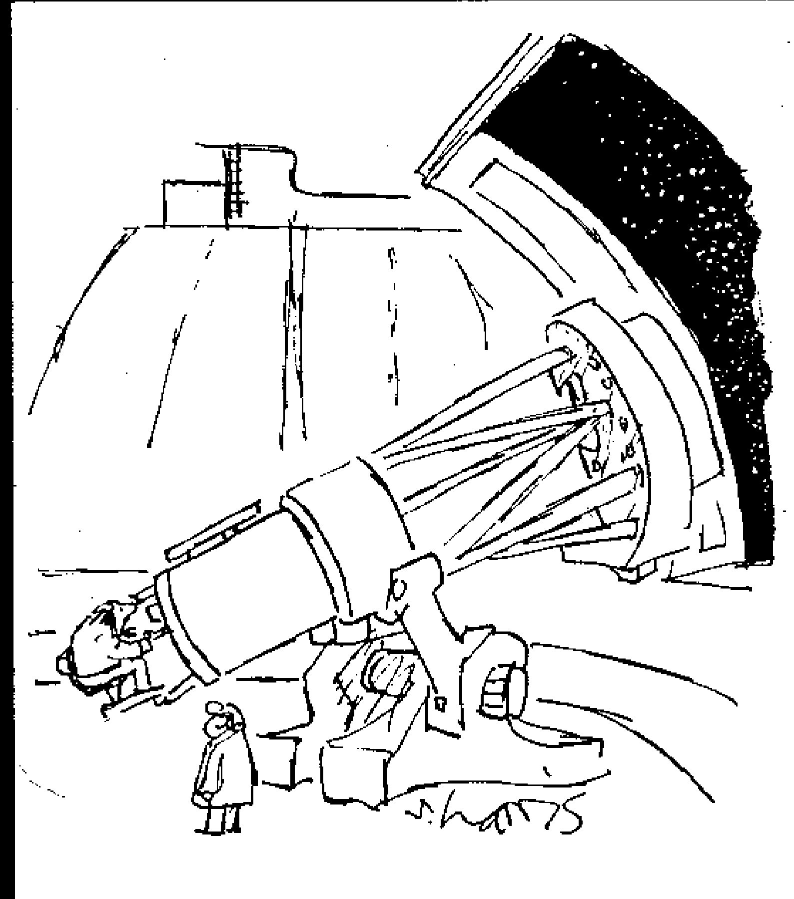
Detectors I

- **Led to mapping the skies:**

  "Astrographic Catalogue" and the *Carte du Ciel*" atlas (late 19th C), initiated at Paris Observatory in 1887

- **Catalogue and map postions of all stars down to m_V = 11-12**
  - **5,176,000 positions from 22 observatories around the world**
  - **From 22,000 glass photographic plates**
  - **Split up into different Dec zones**
  - **Cape Observatory produced the largest single number of positions from observations taken between 1897 & 1912**
    - » **540,000 in the zone -41º < Dec < -51º**

- **"Cape Durchmusterung" catalog of astrometric positions and magnitudes**



"Let's see, now ... picking up where we left off ... one billion, sixty-two million, thirty thousand, four hundred and thirteen ... one billion, sixty-two million, thirty thousand, four hundred and fourteen ... "

Astrophotography

A huge leap forward in astronomy!

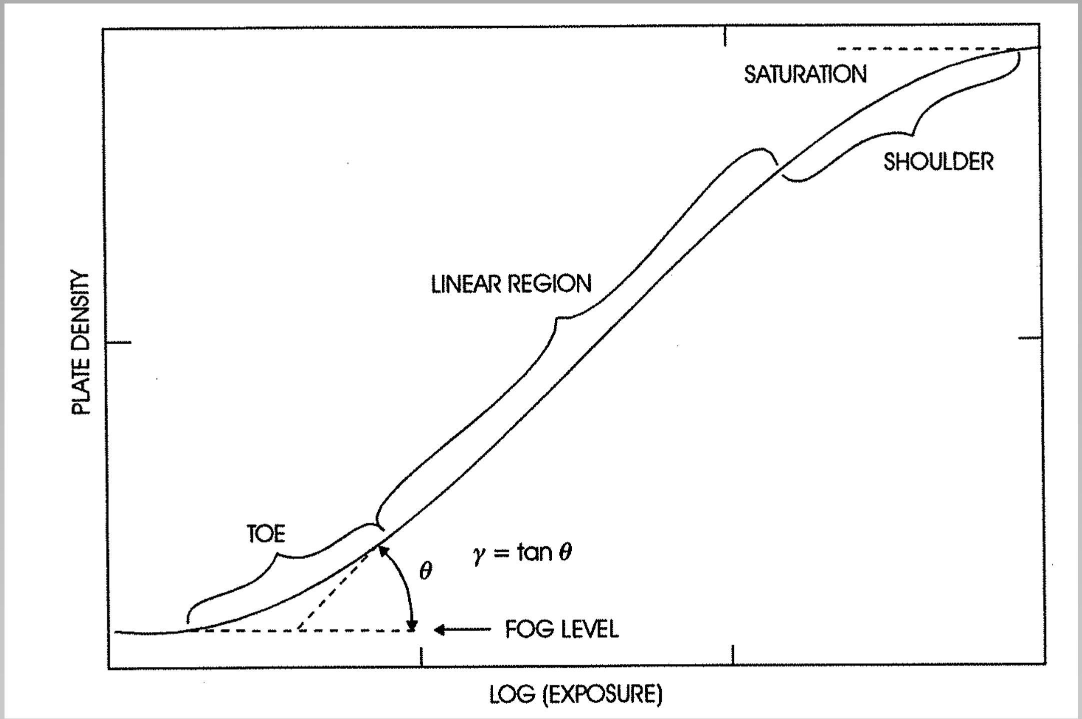
- *Able to record – permanently – positions of thousands of objects at a time*
- *More sensitive than the eye: QEs of ~5-10% compared to 2-3%*
- *Could be large*
  - *e.g. 350 x 350 mm for UK Schmidt: 6º x 6º*
- *Lots of information content*
  - *Fine photographic emulsions could have resolutions of ~10μm, implying a UK Schmidt plate is ~35,000 x 35,000 pixels, or 1.2 x 10^9 pixels (= 1.2 Gpixels)!*
  - *Digitize to 6 bits, i.e. 2^6 = 64 intensity levels*
    - $\Rightarrow$ *8 x 10^{10} bits of information per plate (= 5GB!)*

But there are disadvantages:

- They are analogue devices
  - Have to be digitized by scanning: a time consuming process
- They do deteriorate over timescales of decades
  - Chemical degradation ("gold spot disease")
- They are non-linear in their response

Astrophotography

- ***Typical non-linear response of a photographic emulsion:***



Only linear in the regime where the signal increases linearly with log of exposure time.

Slope is termed 'Gamma' (γ), and is a measure of the contrast of the emulsion.

Below the 'toe' signal lost in the 'fog' f the background

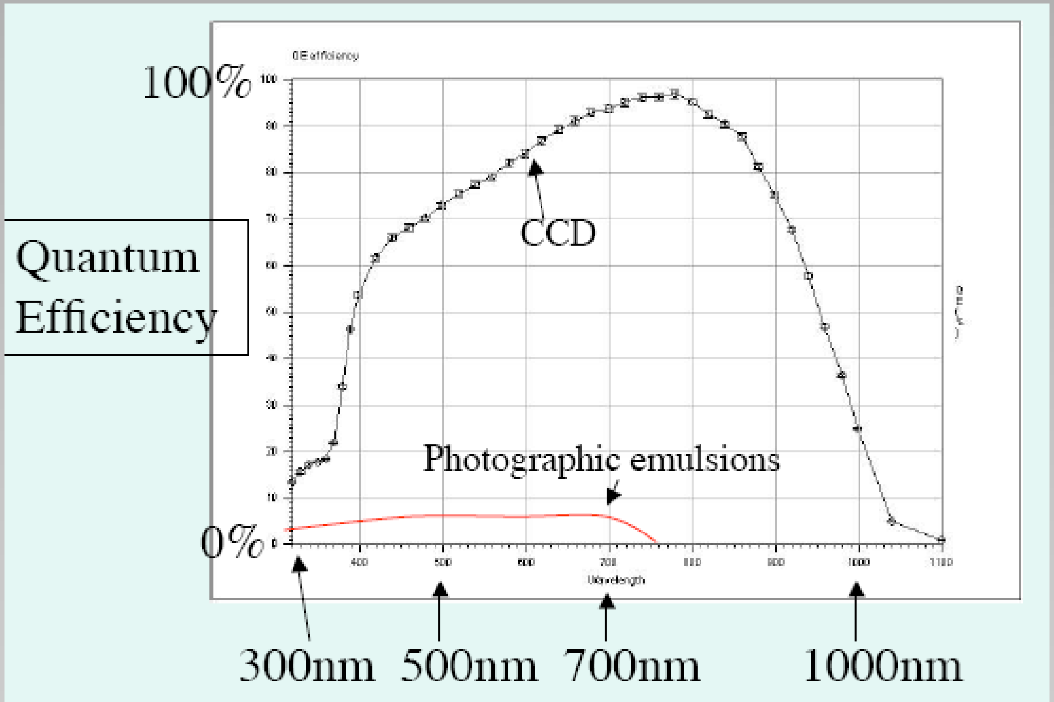
In the 'toe' faint stars dominated by fog, hence non-linear

In the 'shoulder', bright stars saturate

- ***To get best QE, need to "hypersensitize"***
  - *Fiddly & time consuming process involving "baking" plates in $N_2 - H_2$ gas*

How we perceive the Universe

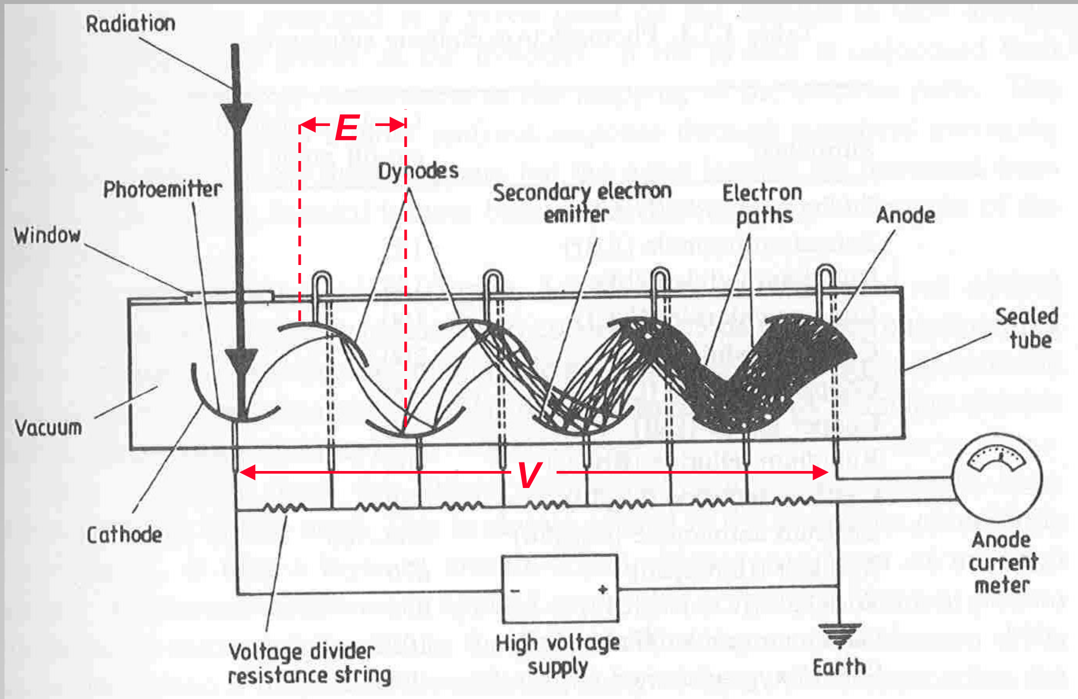
- **The 20th Century has seen the invention of devices that record photons by absorbing and recording their energy**
- **The quantum and wave theories of radiation have impacted on all areas of detection of electromagnetic waves**
  - **Harnesses the photoelectric effect**
    - » **Photomultiplier tubes**
    - » **QEs typically of 20-30% max**
  - **Development of semi-conductor devices, with much higher QE**
    - » **Charge Coupled Devices (CCDs)**
      can now reach QEs of ~90%



These devices spelled the end of photographic plates, although CCDs still don't have the area coverage of the largest photographic plates.

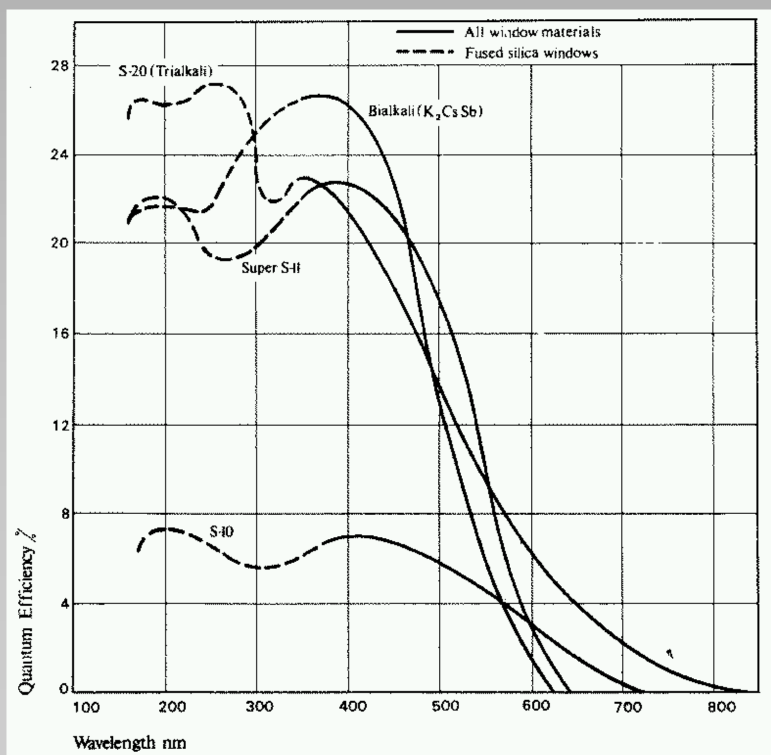
Photomultiplier Tube (PMT) Detectors

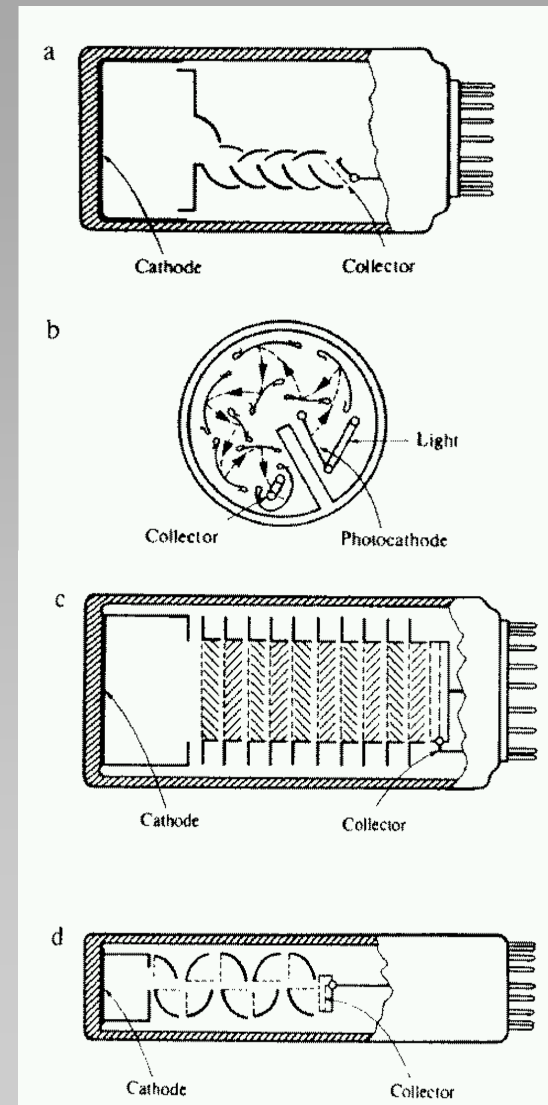
- **Based on the photoelectric effect: a *photoemissive cathode* *(at a -ve voltage)* emits a *photoelectron* on absorption of a photon**
- **Amplification from a series of n *dynodes* *at increasing +ve voltage***
- **Results in a *gain (g)* each time electrons collide with dynodes (& final anode)**
  - *g = 3 – 5; n = 10 – 12, typically*
  - *Total gain of tube $G = g^n$*
  - *$G = 10^5$ to 10^8*
  - *$g \propto E^\alpha$, where $\alpha = 0.7 – 0.8$*
    (E is the dynode Δvoltage)
  - *Total cathode-anode voltage V*
    $\Rightarrow E = V / (n+1)$
    $\Rightarrow g \propto V^\alpha$
    $\Rightarrow G \propto V^{\alpha n}$
  - *$\alpha n = 7 – 10$*
    $\Rightarrow$ *gain highly dependent on V*
    $\Rightarrow$ *need to have very stable V*
  - *V typically 10kV*



Photomultiplier Tube (PMT) Detectors

- **Different dynode architectures for different purposes**
  - Focussed tubes (a) for fast response
  - "squirrel cage" (b) for compactness
  - "Venetian blind" (c) for large photocathode area
- **Photocathode material metallic-like designed to work in the UV-Visible range (200-900nm)**





Photomultiplier Tube (PMT) Detectors

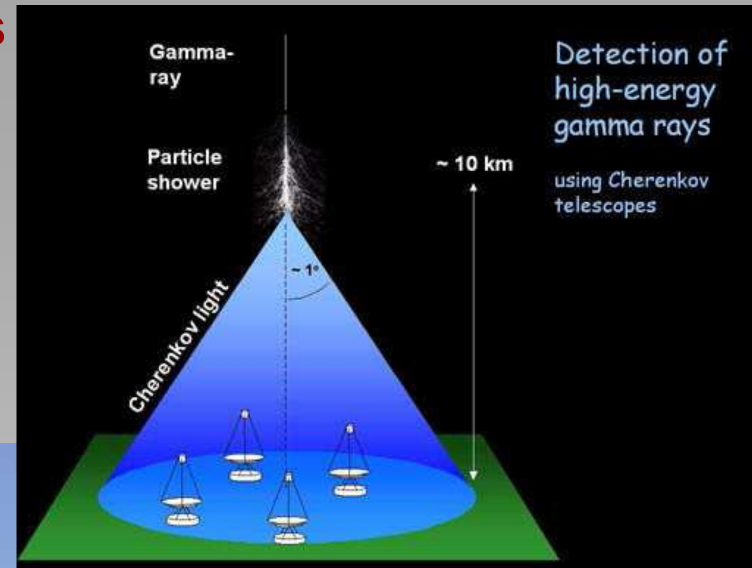
- **Low noise photon counting devices**
- **"Dark current" present from thermal excitation of electrons from photocathode & dynodes**
  - Reduce effect by cooling tubes
  - A GaAs tube cooled to -20C will reduce dark current by factor of several 1000
- **But only *single* channel**
  - Single photocathode
  - No "multiplex advantage"
  - Like a single cell in the retina

- ***Well, not quite accurate!***
  - *Arrays of PMTs can do crude imaging by combining signals*
  - *Focal plane detector for Cerenkov gamma ray telescopes*
    - » *Picking up "faster than light" particles emitting optical photons*
  - *Liquid tank detectors for neutrinos*

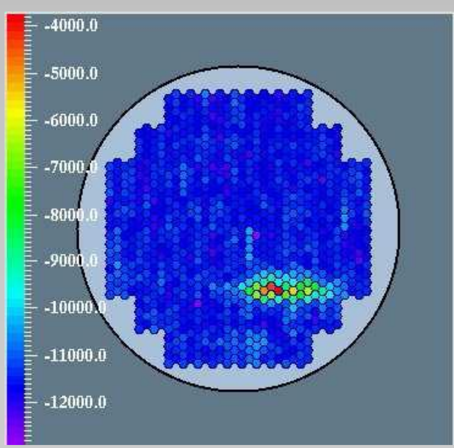
Optical/IR Observational Astronomy

Detectors I

Arrays of PMTs



- *HESS* in Namibia” TeV gamma ray Cerenkov telescope

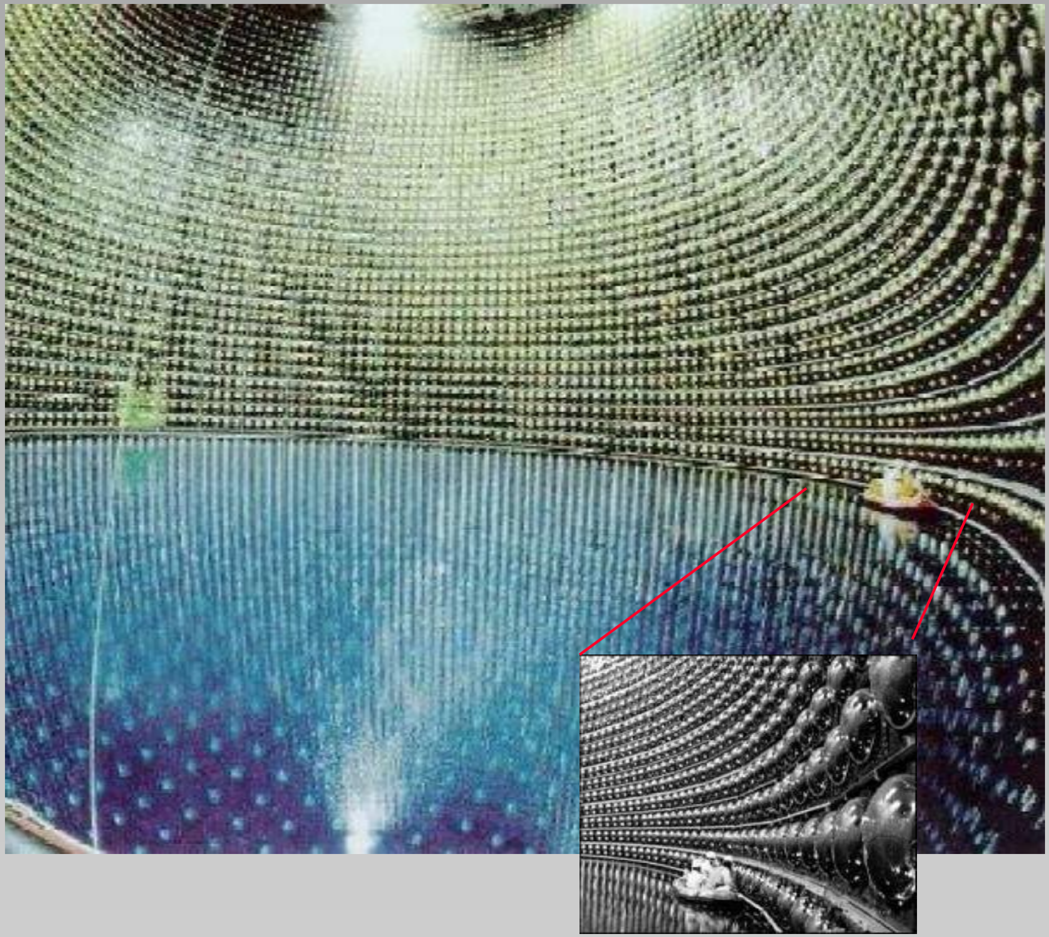


960 PMTs

Array of PMTs

Super Kamiokande neutrino "telescope" in Japan

- *– 11,200 50cm diameter PMTs*
- *– Inside a 40-m high tank*
- *– 50,000 tons of water!*
- *– 1 km underground*

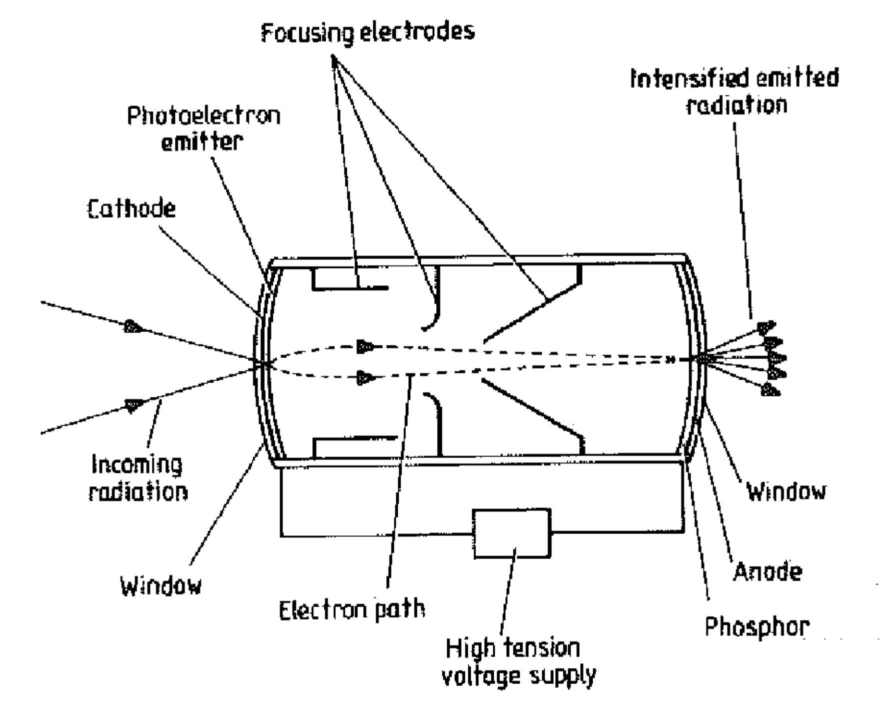


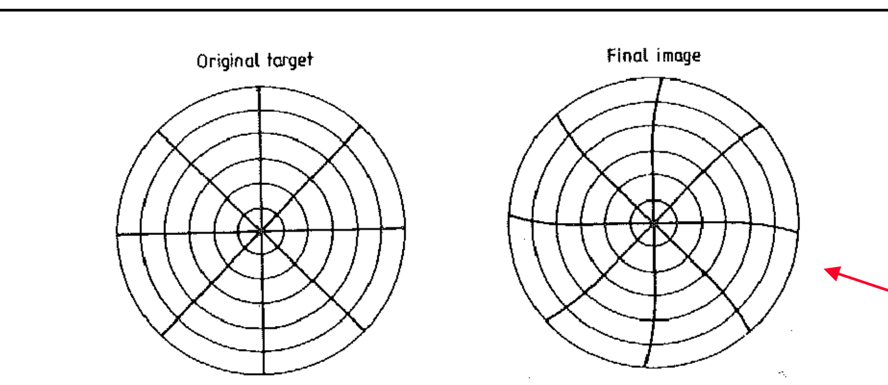
"Three men in a boat"

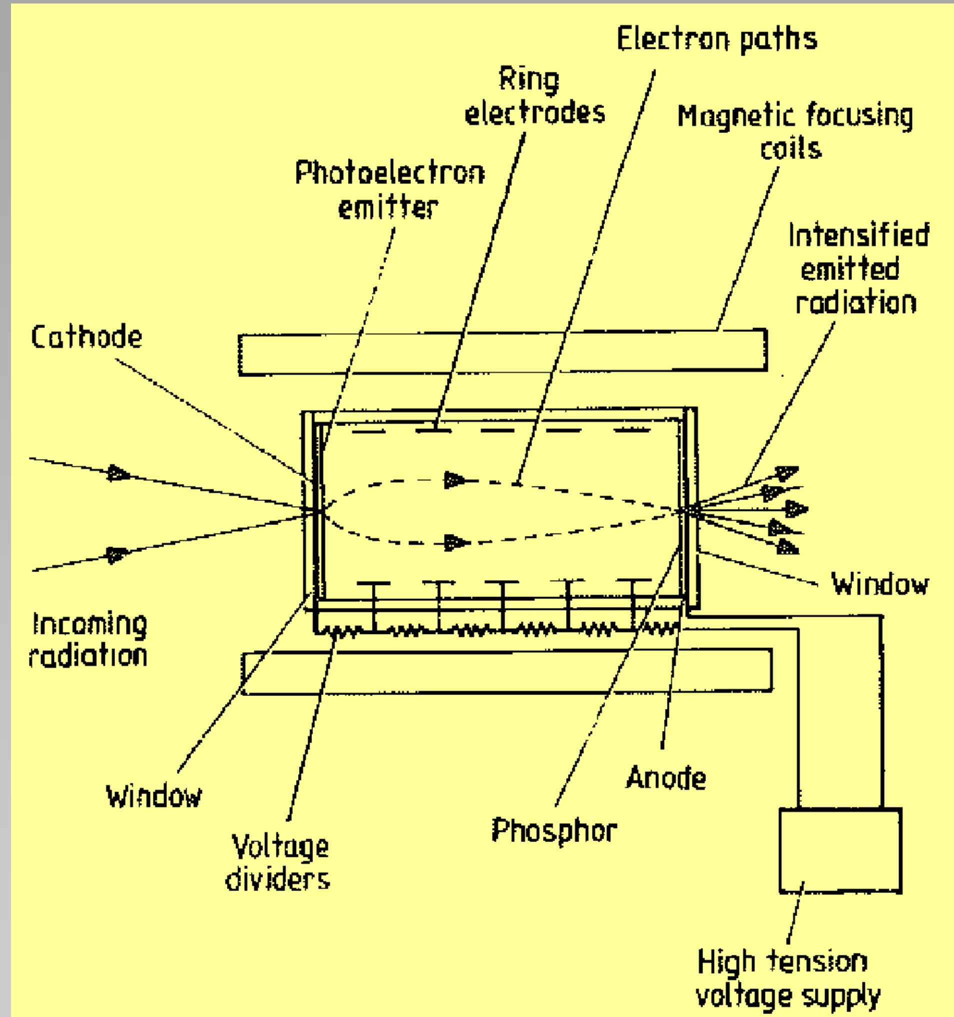
Photomultiplier Tube (PMT) 2-D Detectors

- Need for efficient, low noise “panoramic” (2-D) detector better than a photographic plate
- First attempts involved a hybrid of image tubes and photographic plates
  - Used photocathode to produce and accelerate photoelectrons
  - But no secondary collisions with dynodes
  - Rather use either electric or magnetic fields to ‘focus’ photoelectrons onto a phosphor screen
  - Phosphor then produces photons from excitation by electrons
    - » Single photon > releases photoelectron at photocathode > accelerates due to E/M field and gains E > collides with phosphor > produces many photons
    - » Photographic plate were in contact with phosphor
- Then came fully electronic devices
  - e.g. using semiconductors

Image Tubes





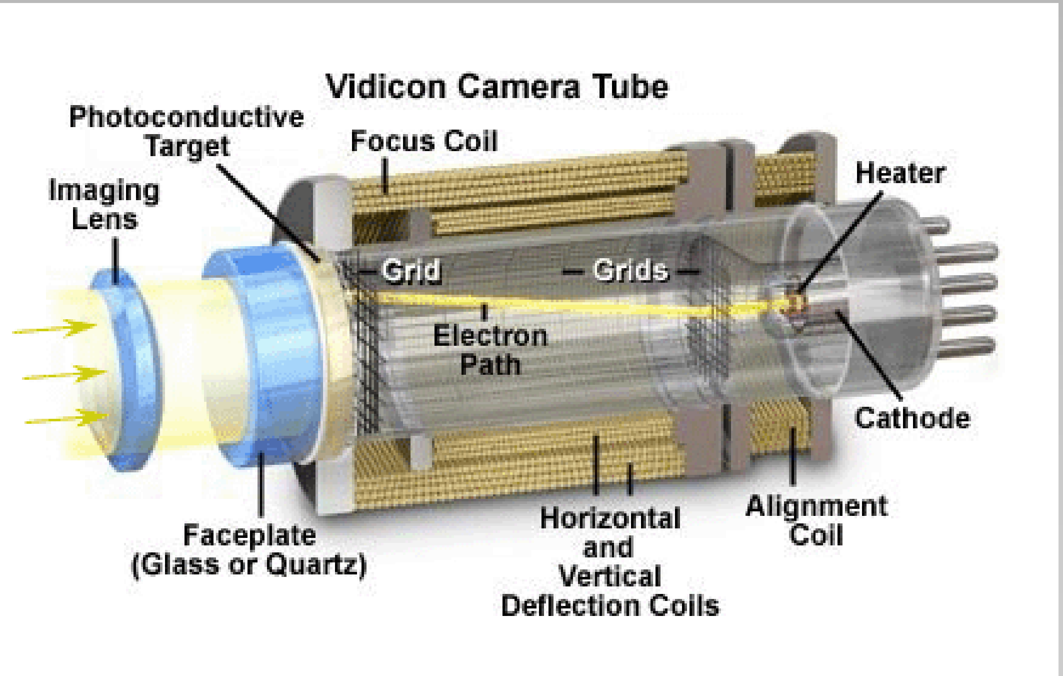


E-M focusing of electrons prone to image distortion: S- & "pin cushion"

TV Image Tubes

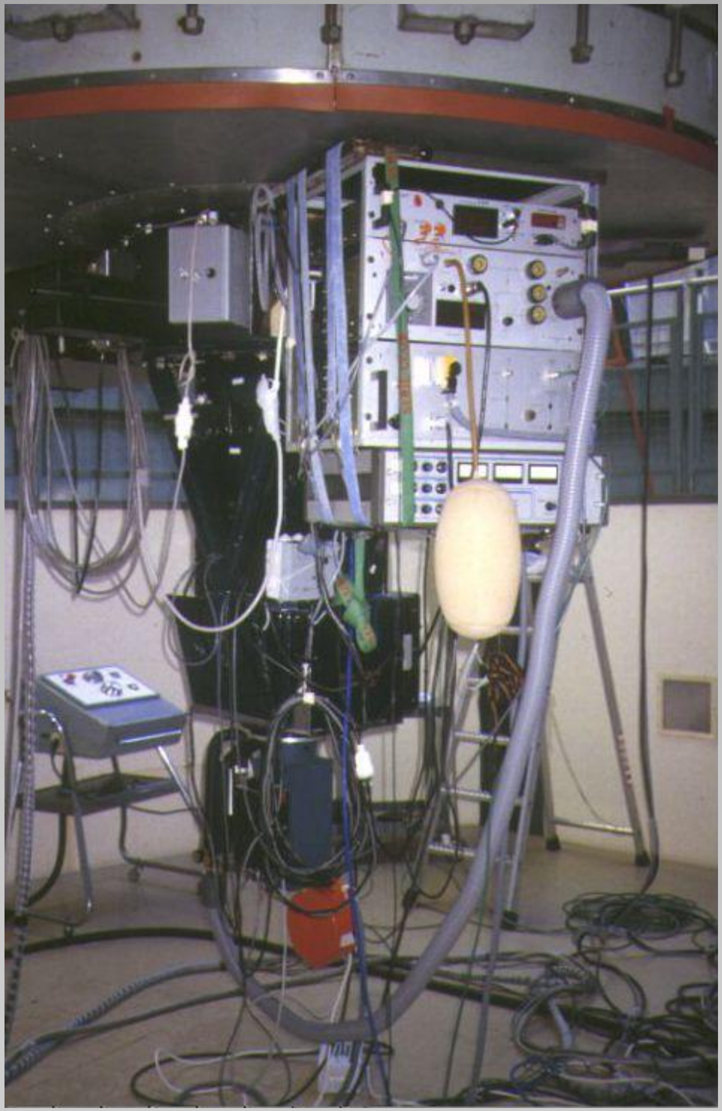
Problems

- Bulky & complex
- Lots of electronics (stable HT voltage needs)
- Subject to distortions
  - Earth's and telescope's ambient environment E-M fields a problem
- Can be fragile
  - Thin windows or faceplates under vacuum



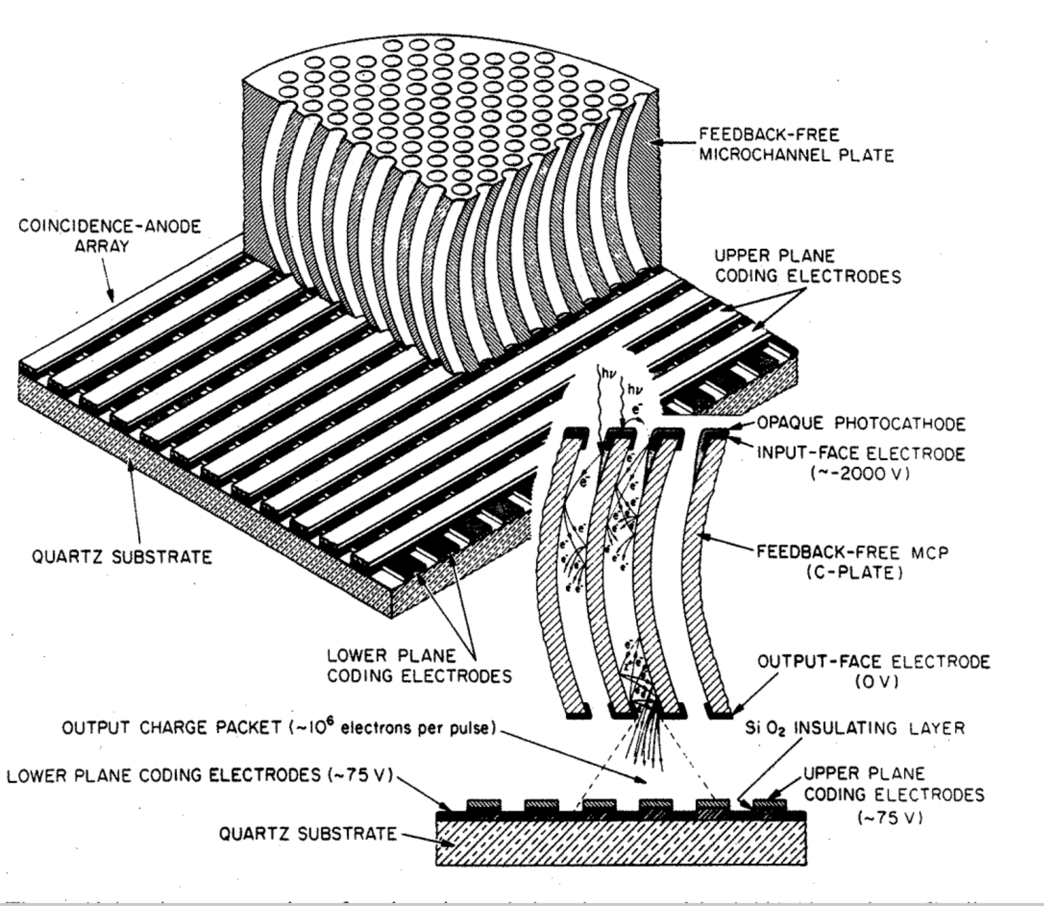
Semiconductor Image Tubes

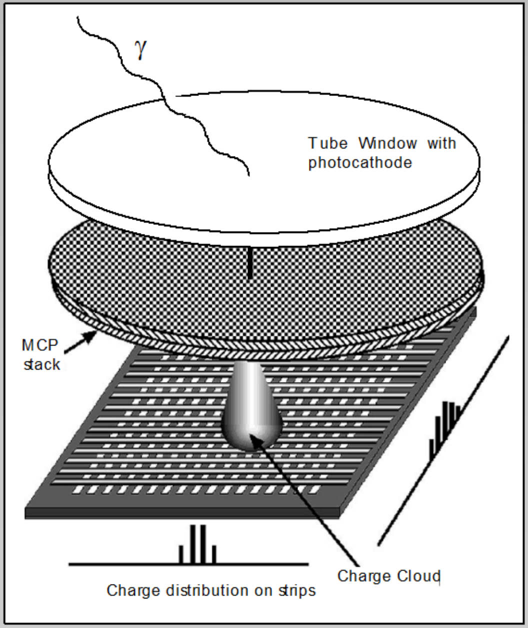
- **Further developments involved replacing TV detector with semiconductor devices**
- **RPCS (operated at SAAO until early 1990s)**
  - **Used a linear array of ~2000 photodiodes**
  - **1-D detector just for spectroscopy**
- **IPCS and PCA**
  - **Used CCD detectors**
- **New developments involves eliminating focusing E-M fields in favour of "mechanical" intensification**
  - **Micro Channel Plates (MCPs)**



Microchannel Plates (MCPs)

- Small hollow pores ‘channel’ photoelectrons
- Voltage applied from top-bottom
- Electrons gain E
- Electrons collide with walls releasing secondary electrons
- Large charge pulses can be read out with position sensing detectors
  - e.g. strip anode

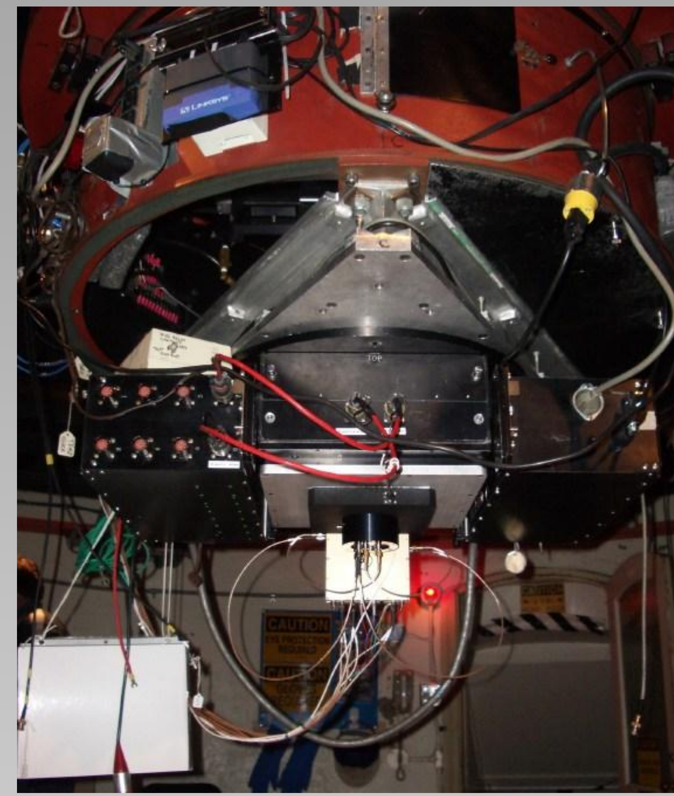




Optical/IR Observational Astronomy

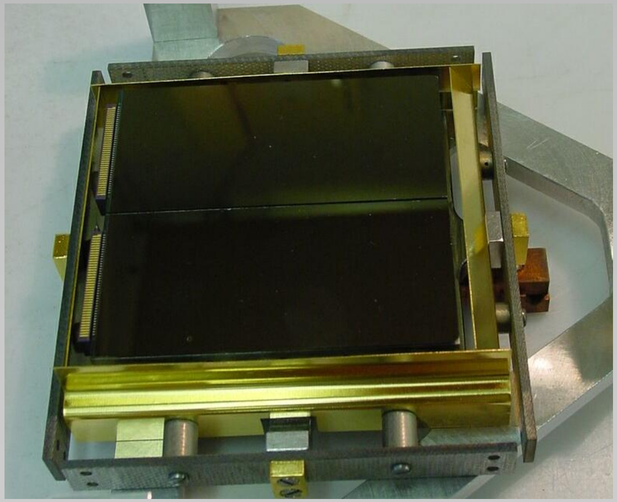
Detectors I

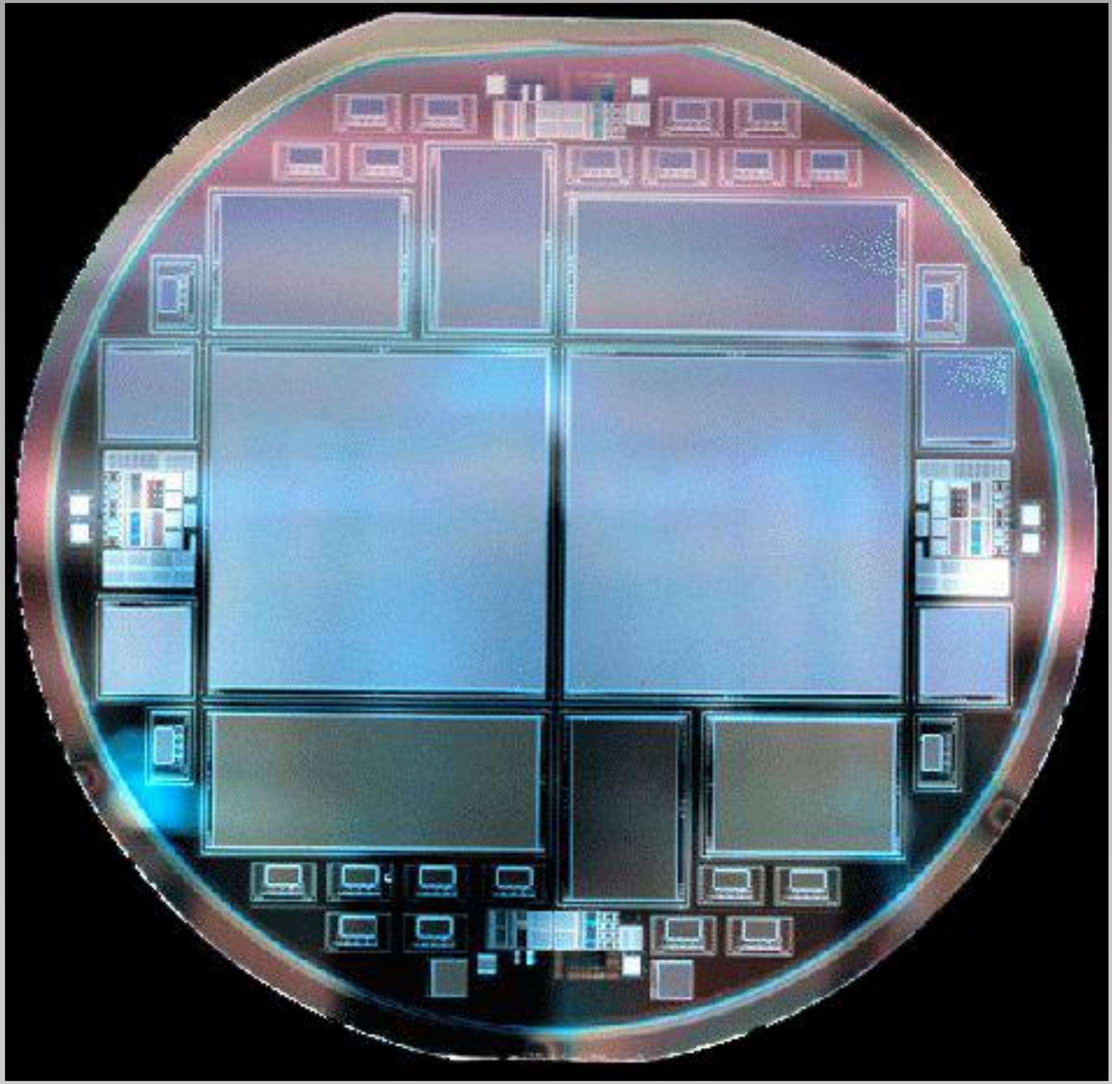
Microchannel Plate (MCP) Detectors



- **Photon Counting detector**
- **Noise is just Poisson ($\sqrt{N}$)**
- **Capable of high time resolution**
  - **Time tagging to 50 ns**
- **Good in UV**
- **Used on Hubble Space Telescope**
  - **MAMA detector**
- **Recently installed on SALT (“BVIT”)**
  - **Very compact**

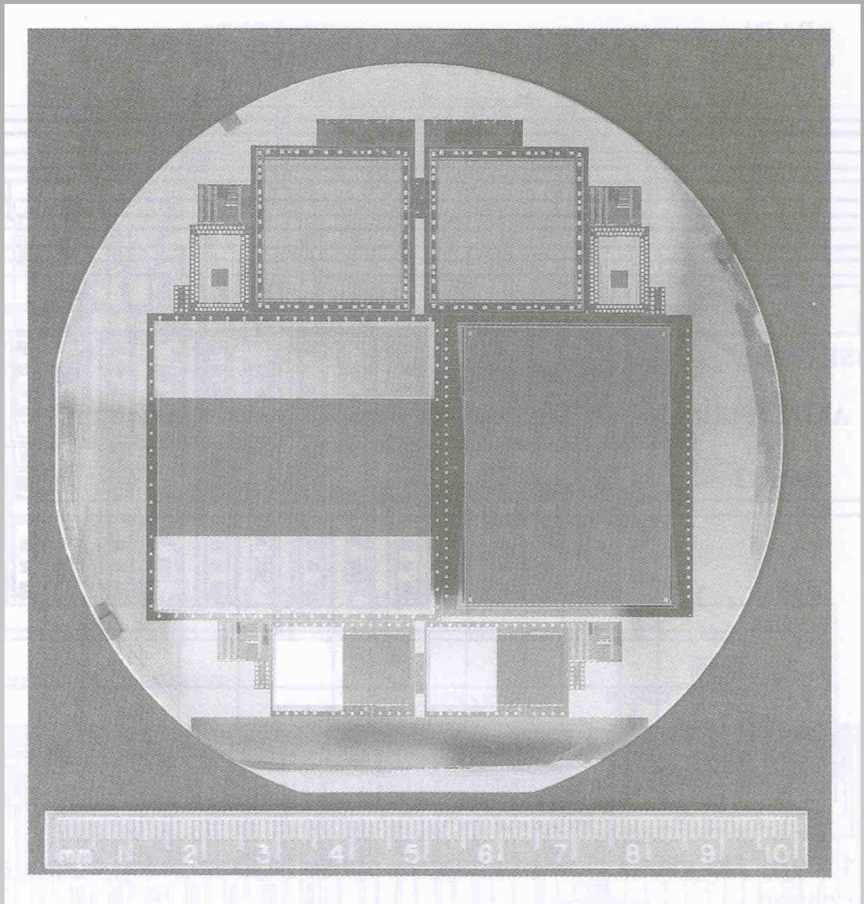
The Next Revolution: Charge Couple Device Detectors (CCDs)

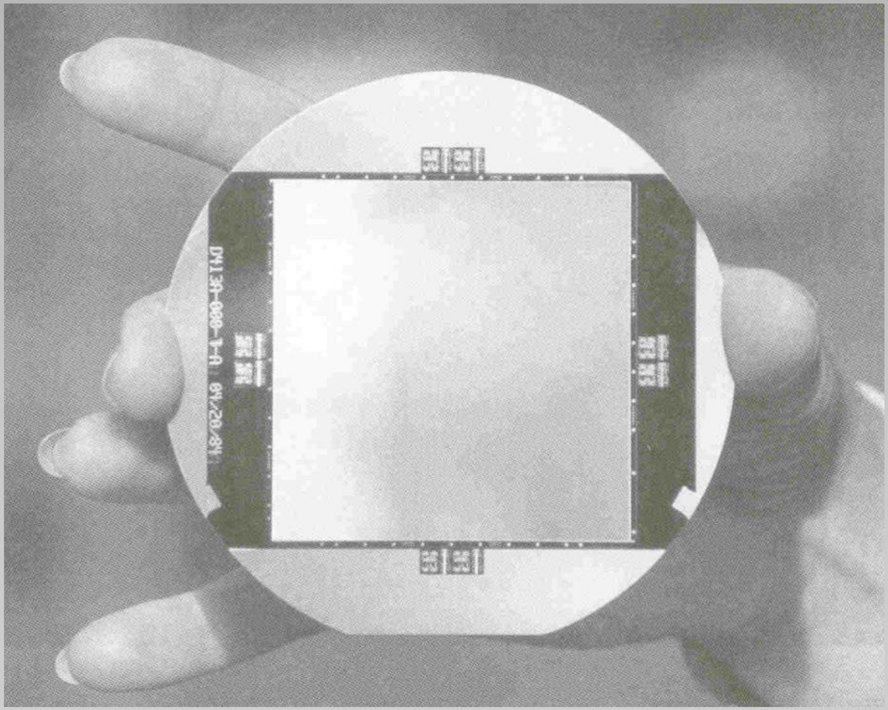




CCDs

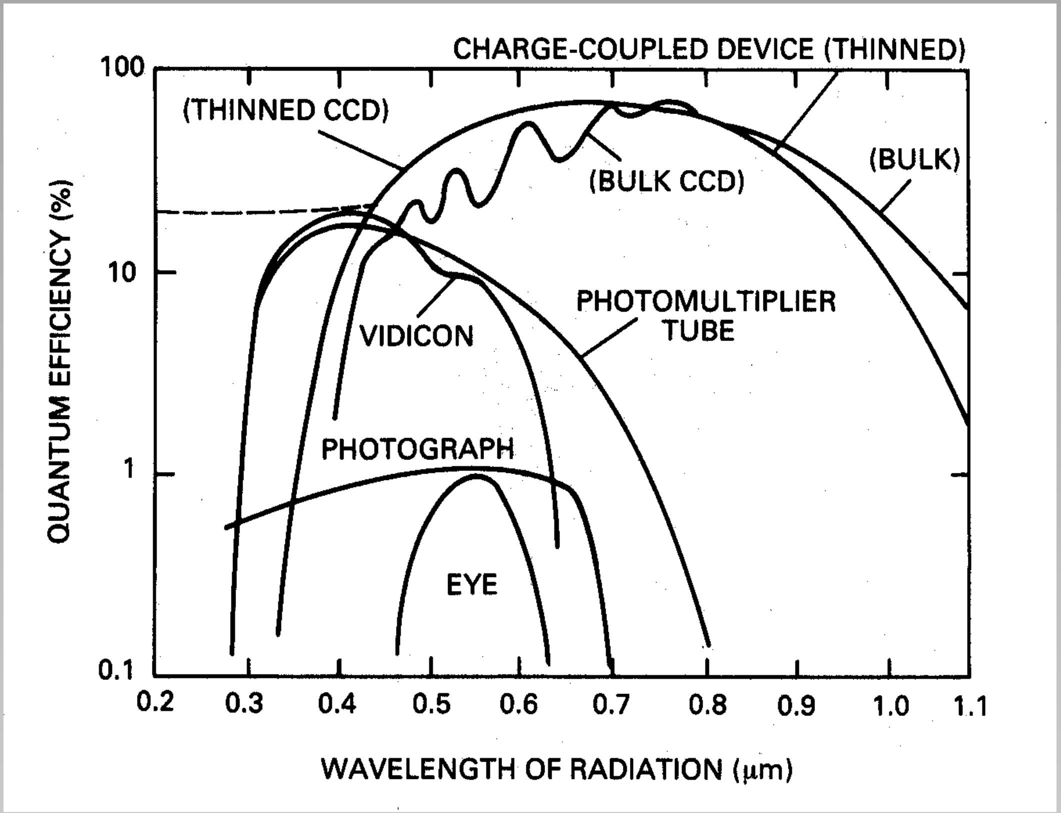
- **Integrated semi-conductor detector**
  - **From photon detection (pair production) to final digitization of signal**
- **Manufactured from a Si wafer, as in ICs**





Major advantages of CCDs

- **Some of the many advantages of CCDs over conventional electronic and photographic imaging mentioned include:**
    1. Compact, rugged, stable, durable, low-power (using 10's instead of 1000's of volts)
    2. Excellent stability and linearity
    3. No image distortion (direct image onto a Si array fixed in fabrication process
    4. Relative ease of operation, and reasonable cost due to mass production
    5. Unprecedented sensitivity (i.e. quantum efficiency) over wide λ range



History of the invention of CCDs

- **It was already known that charge could be stored by insulating a small metal plate placed on the surface of a Si crystal.**
  - **Stringing these 'storage sites' together and using voltage differences between them to pass the charge along constituted the innovative idea**
  - **It took just few weeks to produce a proto-type 8-element device, and the first paper on a 'CCD' (for *charge-coupled device*, a name coined by Boyle) was published in April 1970 (*Bell System Technical Journal*, Vol. 49, 1970)**
  - **Wording from that paper reads:**
    - » *"A new semiconductor device concept has been devised which shows promise of having wide application" Boyle & Smith*
  - **Within a few months many types of applications were listed – some actually of relevance to a phone company!**

History of the invention of CCDs

- **The CCD was invented by Willard S. Boyle and George E. Smith of Bell Labs (where the transistor was invented) in 1969**

They were jointly awarded the Nobel Prize for Physics in 2009

Invention of CCDs

***Aside*: R & D departments of many large technology corporations in the USA have employed scientists to develop ‘esoteric’ devices, with no immediately apparent applications**

- » **The ‘seeds on fertile ground’ approach – something positive will eventuate**

– **Penzias and Wilson, who were from the same labs as Boyle & Smith, first detected antenna ‘noise’ from a microwave receiver and interpreted as the *3ºK background radiation*, a relic of the Big Bang (predicted by theory)**

- » **This earned them a Nobel Prize too, well before Boyle & Smith**

– **Boyle and Smith were investigating new ways of imaging with Si solid-state devices in an effort to develop a *Picturephone™* (as in “2001: A Space Odyssey”!)**

- » **Market research failed to convince Bell that the Picturephone was worth developing at that time**

PICTUREPHONE

(So, who has seen “2001: A Space Odyssey” ?)

Detectors I


HARDIN
search ID: pha0160
"What makes the universe so hard to comprehend is that there's nothing to compare it with."