Observational Techniques & Instrumentation for Astronomy

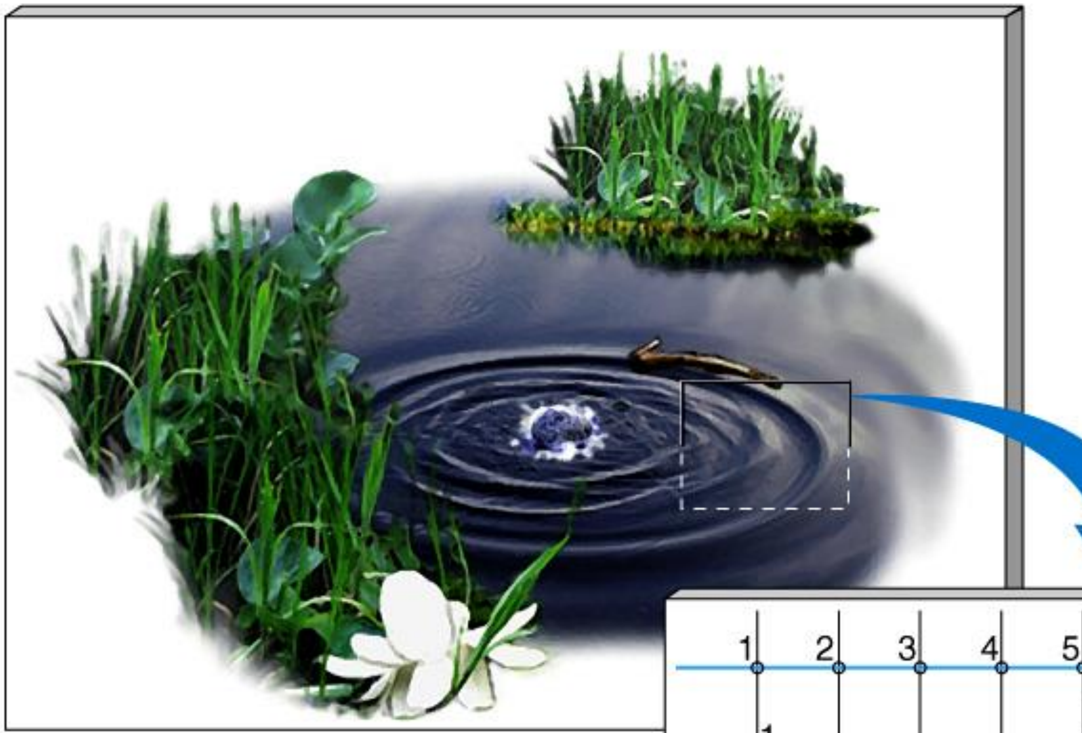
Stephen Eikenberry

30 Jan 2017

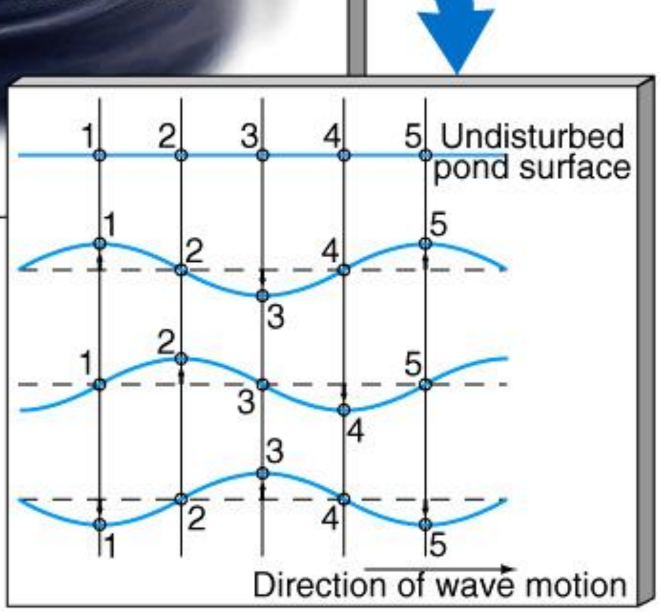
Observational Astronomy – What?

- Astronomy gathers the vast majority of its information from the LIGHT emitted by astrophysical sources
- The fundamental question asked/answered is "How Bright?". Common modifiers to the question include:
  - Versus angular direction (α, β)
  - Versus light wavelength λ
  - Versus time t
  - Versus polarization state (Q,U,V)
- Telescopes/instruments are used to collect, manipulate, and sort the light
- That's pretty much all there is to it ! ☺

Properties of Light - I

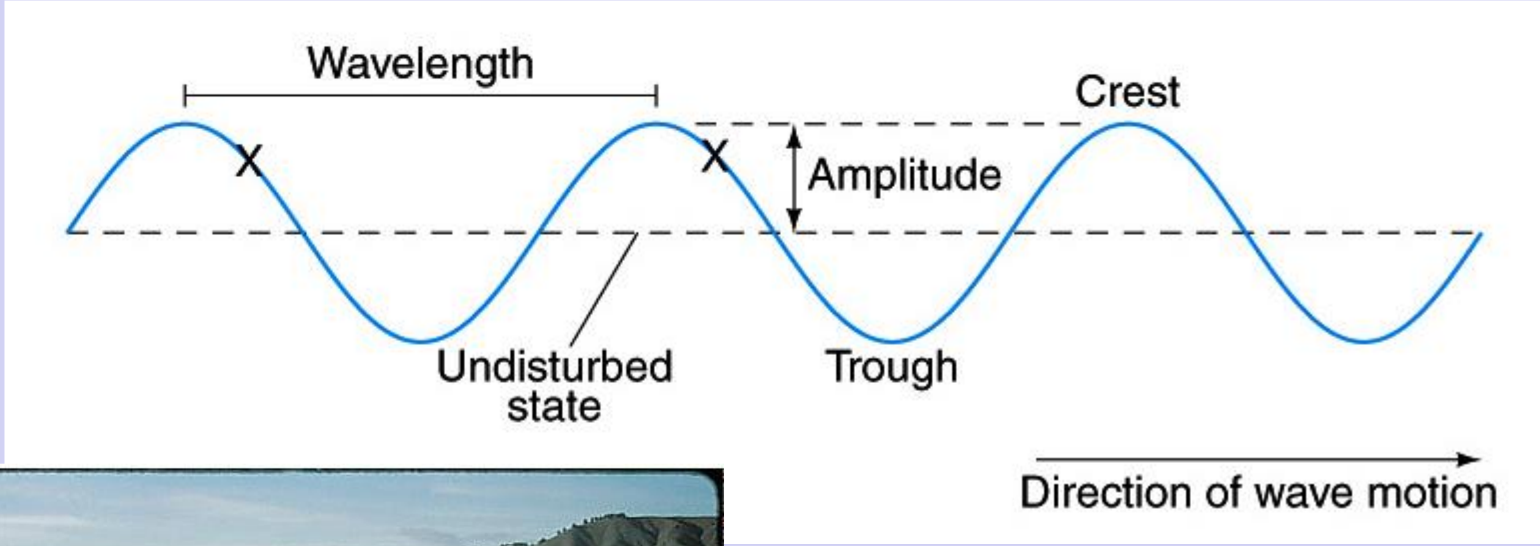


- “Information” is carried from place to place without physical movement of material from/to those places



Particles move up/down, but the wave pattern propagates left/right

Properties of Light - II



Wave Characteristics

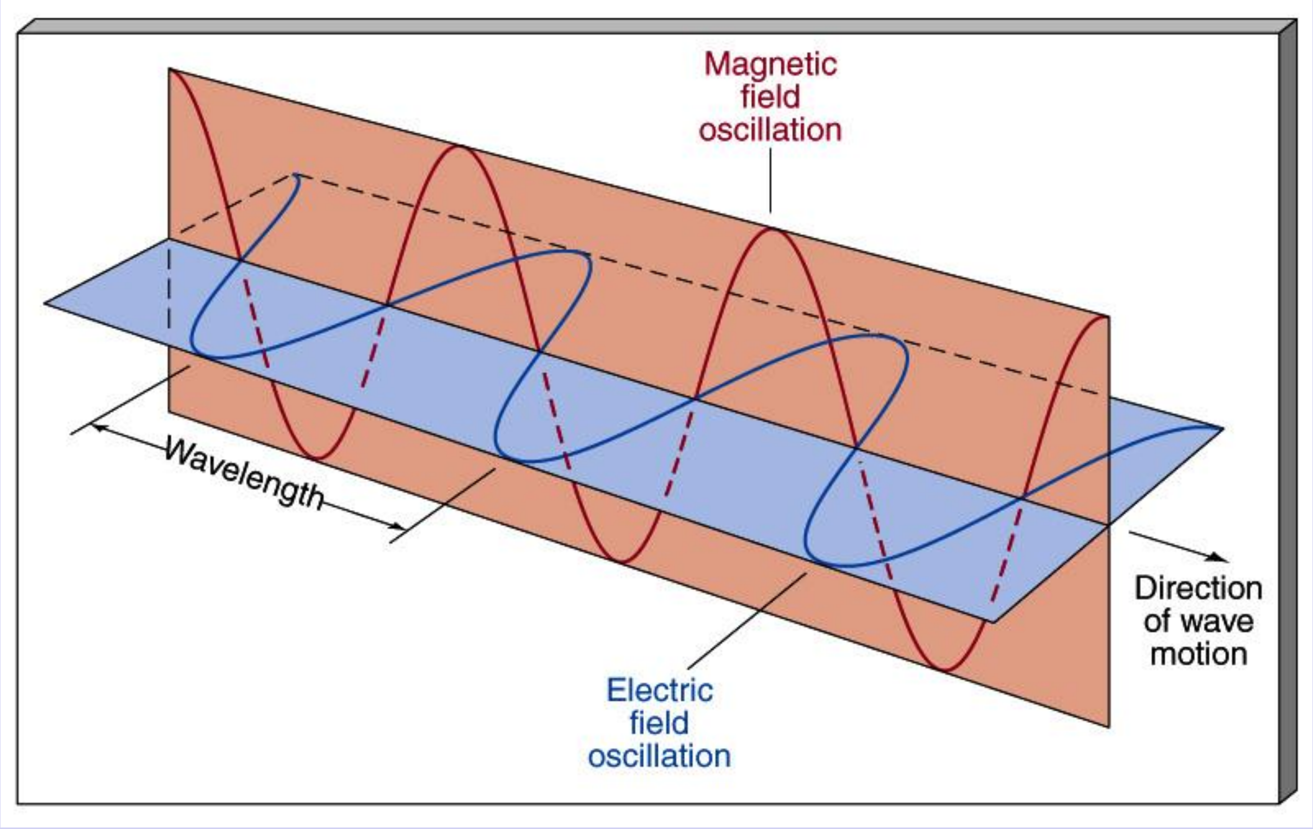
Light Speed is $3x10^8$ m/s

4

Properties of Light - III

Magnetic and *Electric* fields are coupled – a change in one creates the other!

Ripples in the Electro-Magnetic field are LIGHT



Spherical Waves

- Stars (and pretty much any other light source) emits light as a spherical wave
- We can also envision light as moving in straight lines (rays) which are the perpendicular vectors to the wavefront
- Seen from a large distance, the spherical waves appear "flat" or planar

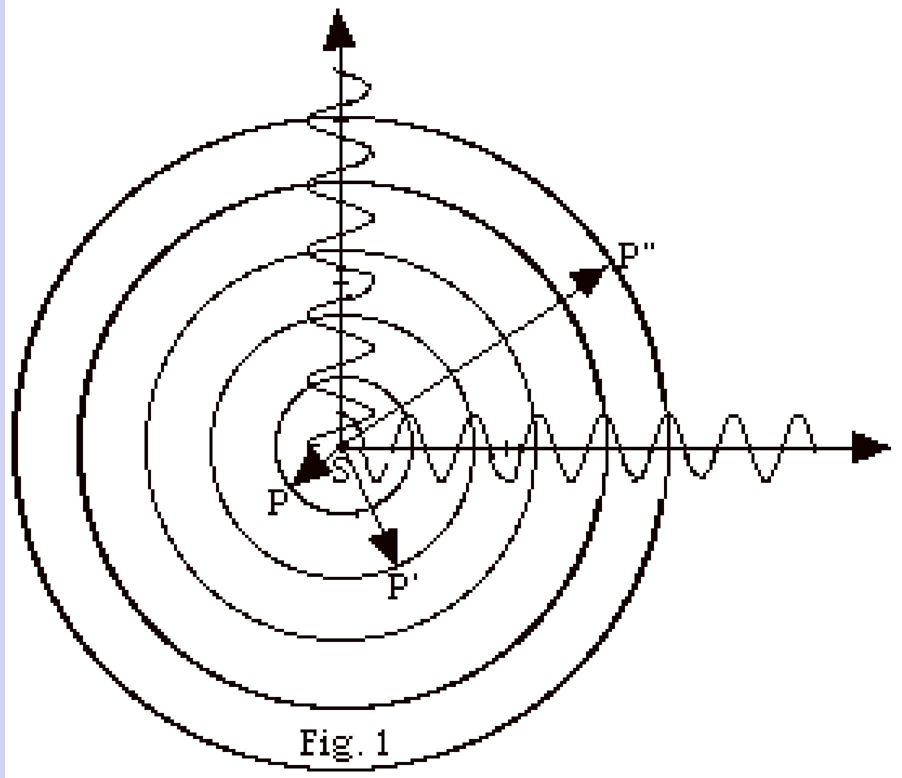


Fig. 1

Wave properties

- Light, as a wave, has “phase” as well as amplitude
- That means it also can have interference (destructive and constructive)

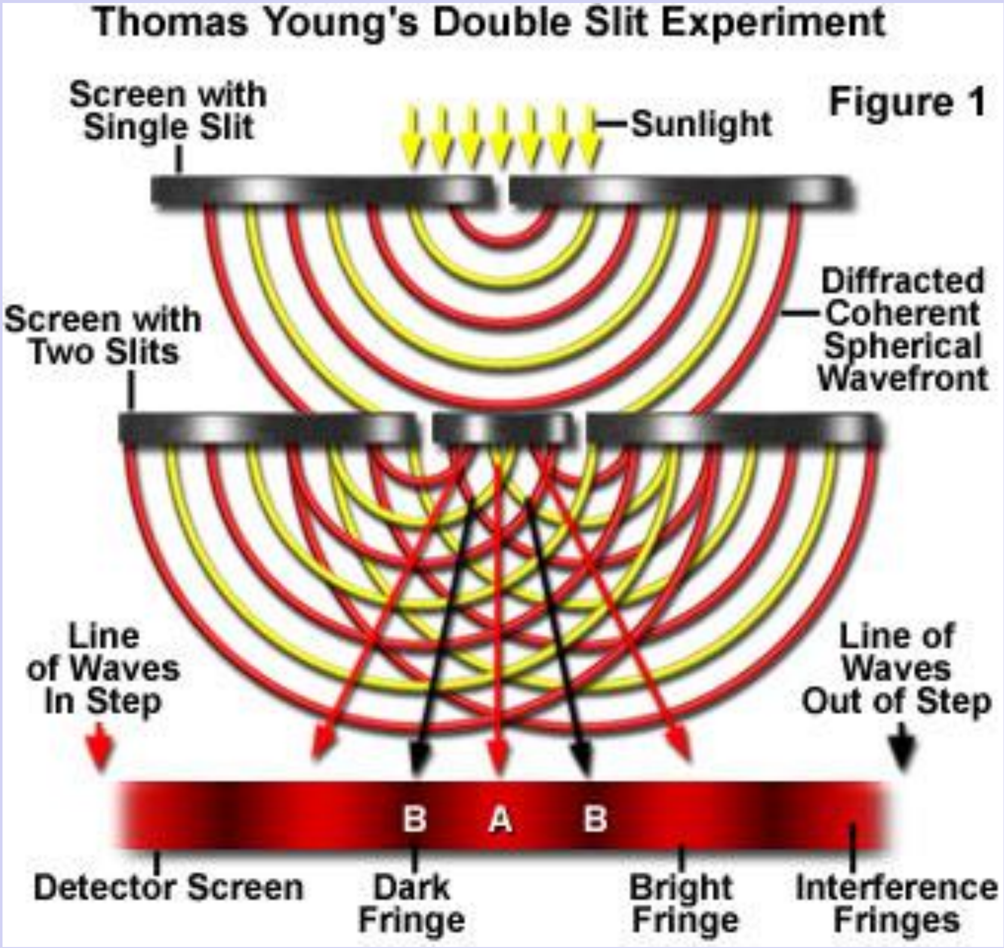
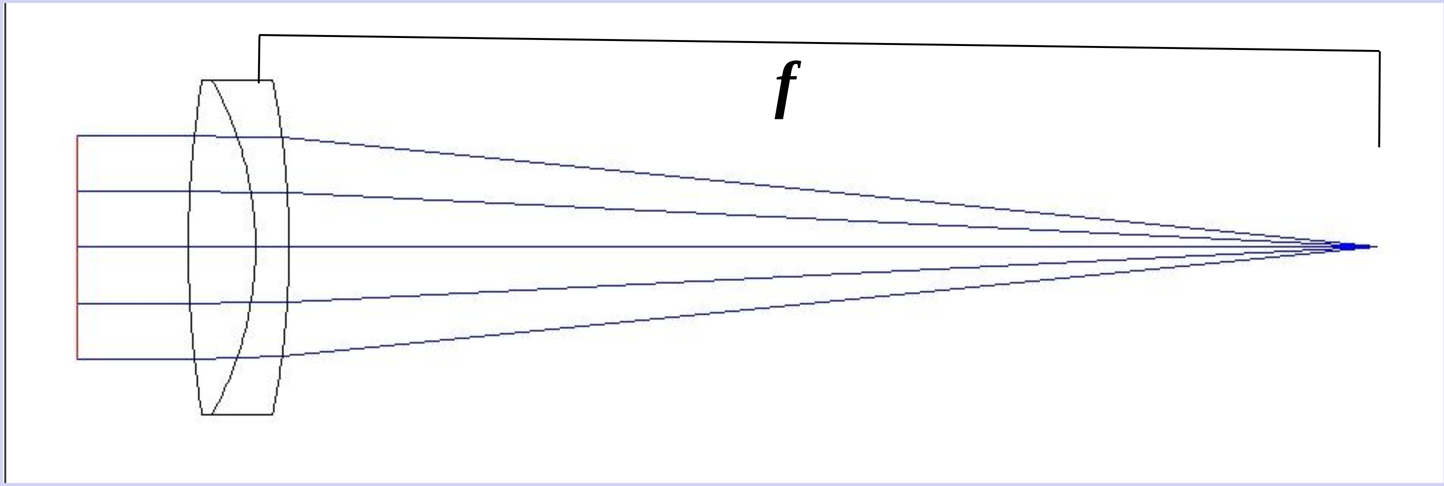


Image: National Magnet Lab

Optics & Focus

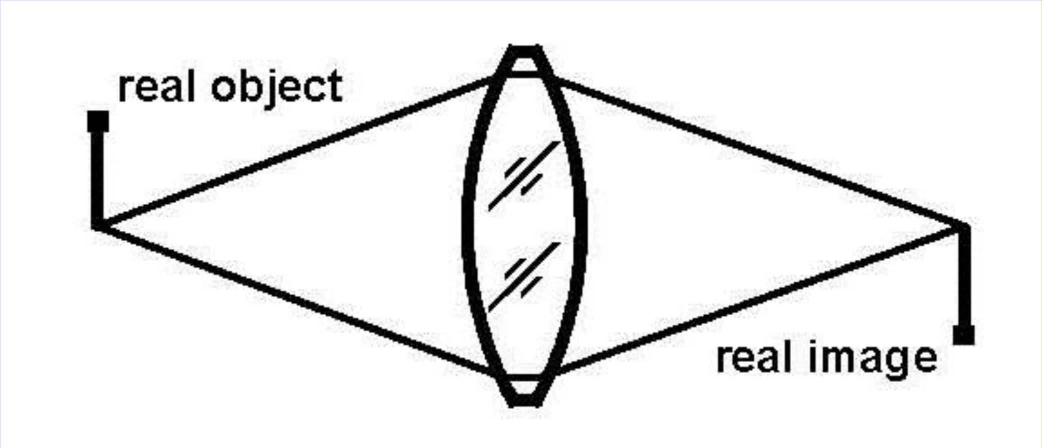
- **Optics shown below is a doublet lens**
- **Parallel rays coming from left are made to converge**



- **Location where the rays cross the optical axis is the "focal point"**
- **Distance from a fiducial point in the lens to the focal point is the "focal length" (*f*)**

Images

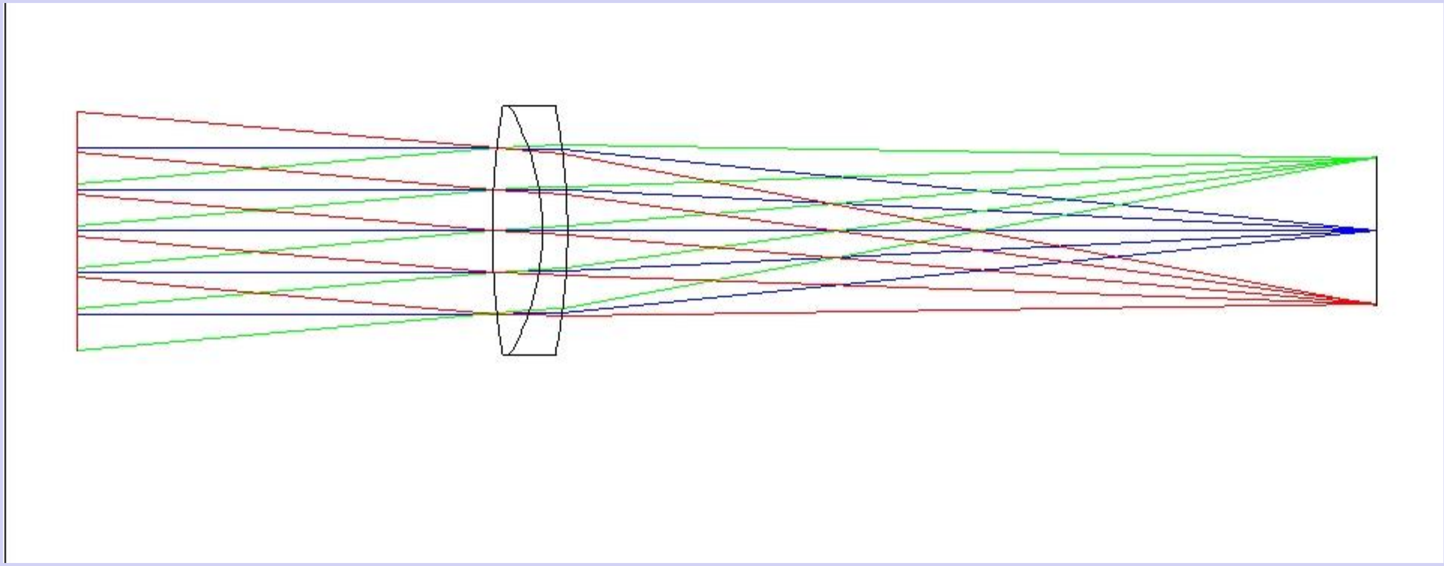
- **Object plane ("source" for astronomers)**
- **Image plane**
- **These are "conjugates" of each other**
- **Conjugate distances are:**
  - s_1 , s_2
- $1/s_1 + 1/s_2 = 1/f$



- **Magnification of the system is given by m =** s_1/s_2

Images

- Object plane ("source" for astronomers)
- Image plane



- For astronomy, usually the object plane distance can be approximated as infinity
  - Then, object angle ⇔ image position
  - And, object position ⇔ image angle

Focal length and f/#

- **Effective focal length** (EFL) is the distance from the optic to the focal point
- f/# is the ratio of the focal length to the optic diameter (f/# = *f*/D)
- f/1 (e.g.) is "fast" (typically difficult to make optics this fast to faster)
- f/30 (e.g.) is "slow" (typically easy to make optics this slow)

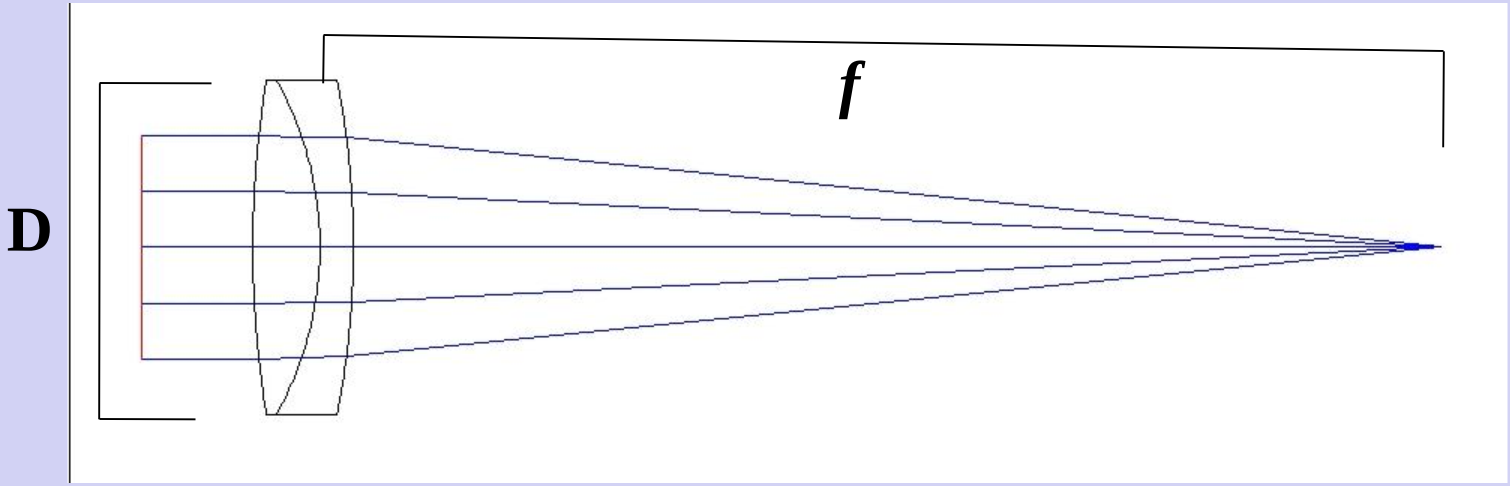


Plate Scale Calculation

- For a given optic with EFL = f, the image-plane scale is given by:
  - PS = 1 radian/f   (radians/m)
  - PS = 206265 / f (arcsec/mm)
- For instance, a telescope with EFL = 10-m (1.2-m at f/8), plate scale is:
  - 206265/10000 ≅ 20.6 arcsec/mm
- A telescope with EFL = 170m (GTC 10-m at f/17) has plate scale of:
  - 206265/170000 ≅ 1.2 arcsec/mm
- That's why it is MUCH easier to have a small wide-field telescope than a big wide-field telescope

Etendue

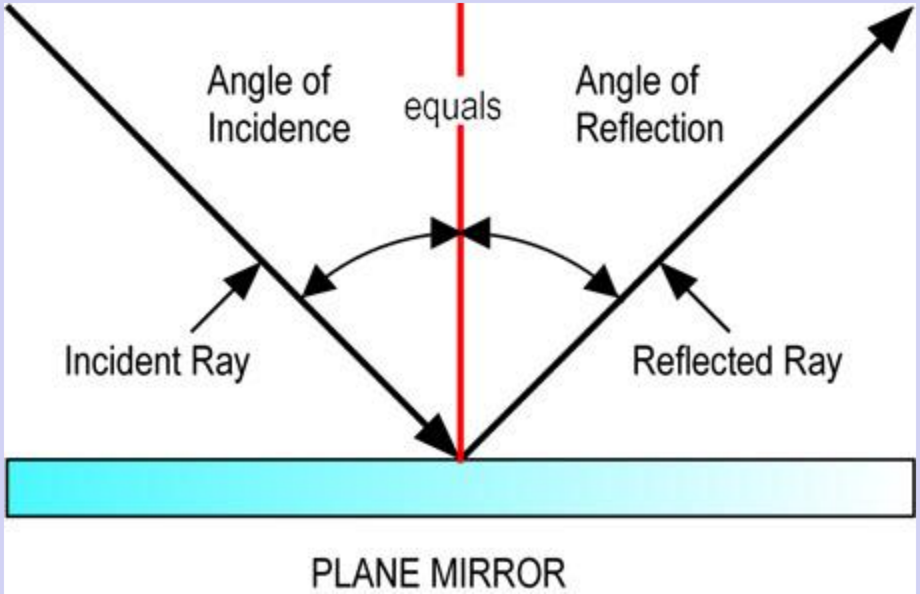
- **Etendue = AΩx (area times solid angle)**
- **Etendue is conserved for any optical system**
- **This is the same as conservation of energy. So ... Believe it!**
- **High etendue is good. Why? Higher etendue means more energy passes through the system (and thus, more photons hit the detector!)**

Mirrors

- **Things that reflect light**
- **This is not as simple as it seems – read Feynman's book QED**
- **For optical/IR astronomy, they are typically glass, ceramic, or metal (aluminum) substrates with a reflective coating (gold, silver, aluminum, etc.)**
- **Light rays hit the mirror surface and "bounce" off (albeit with less than 100% efficiency; why? See QED)**

Law of Reflection

- Incidence angle *i*
- Reflected angle *r*
- *i = r*
- That is (almost) all you need to know
- Now … go design a 3-mirror anastigmat!



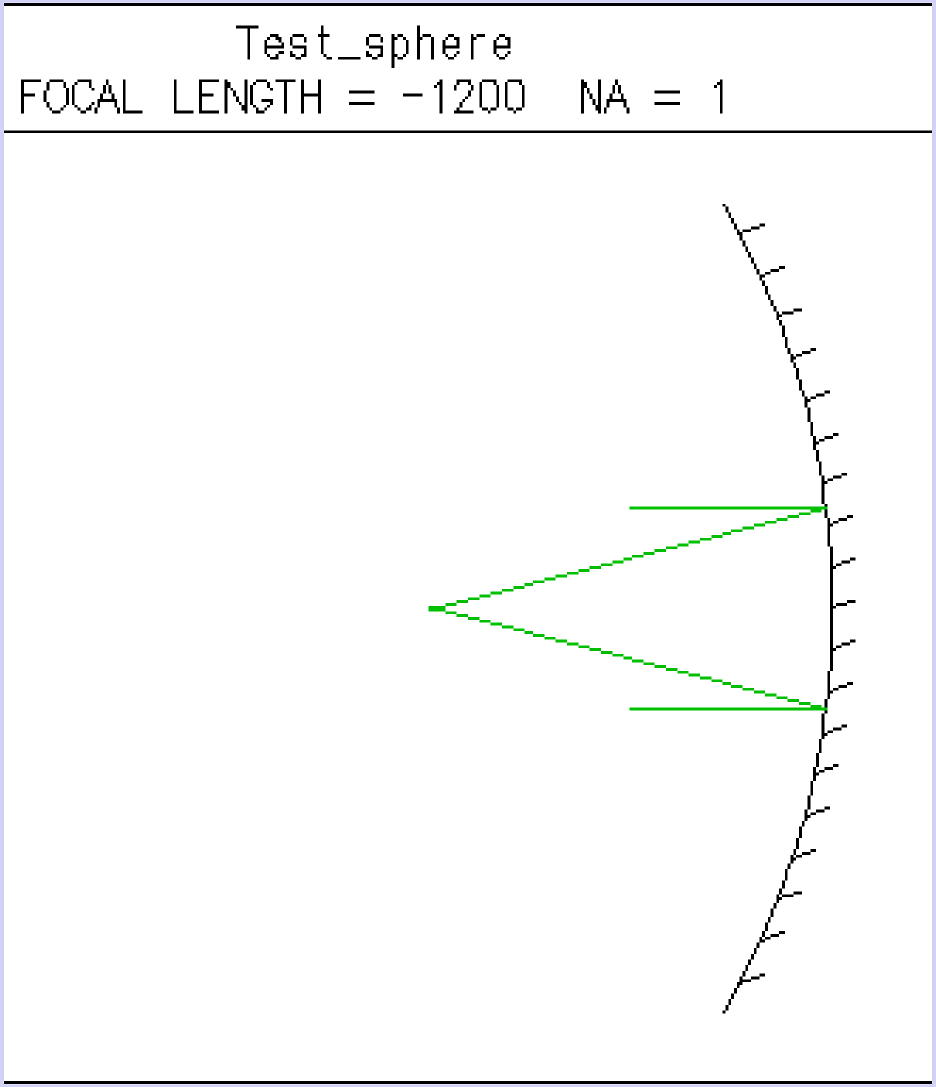
http://laser.physics.sunysb.edu/~amy/wise2000/websites/Mirror348.jpg

Flat mirrors

- Change direction; not much else
- Useful for “folding” in optical systems, but not collecting, sorting light (by themselves)
- (Draw on board)

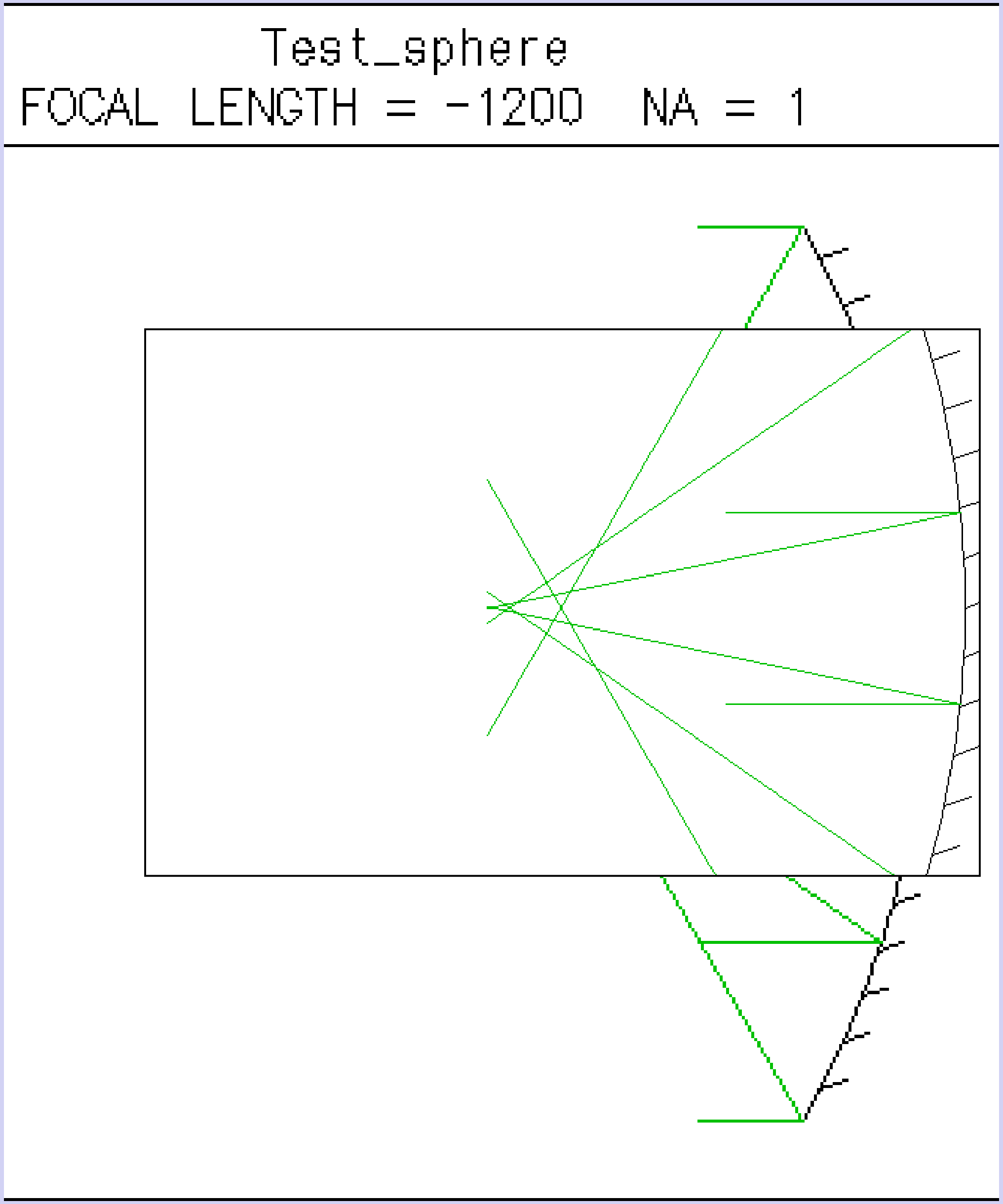
Spherical mirrors

- Simplest "focusing" mirror
- Easy to make (planetary polishing)
- Focal length f = R/2 (derive this)



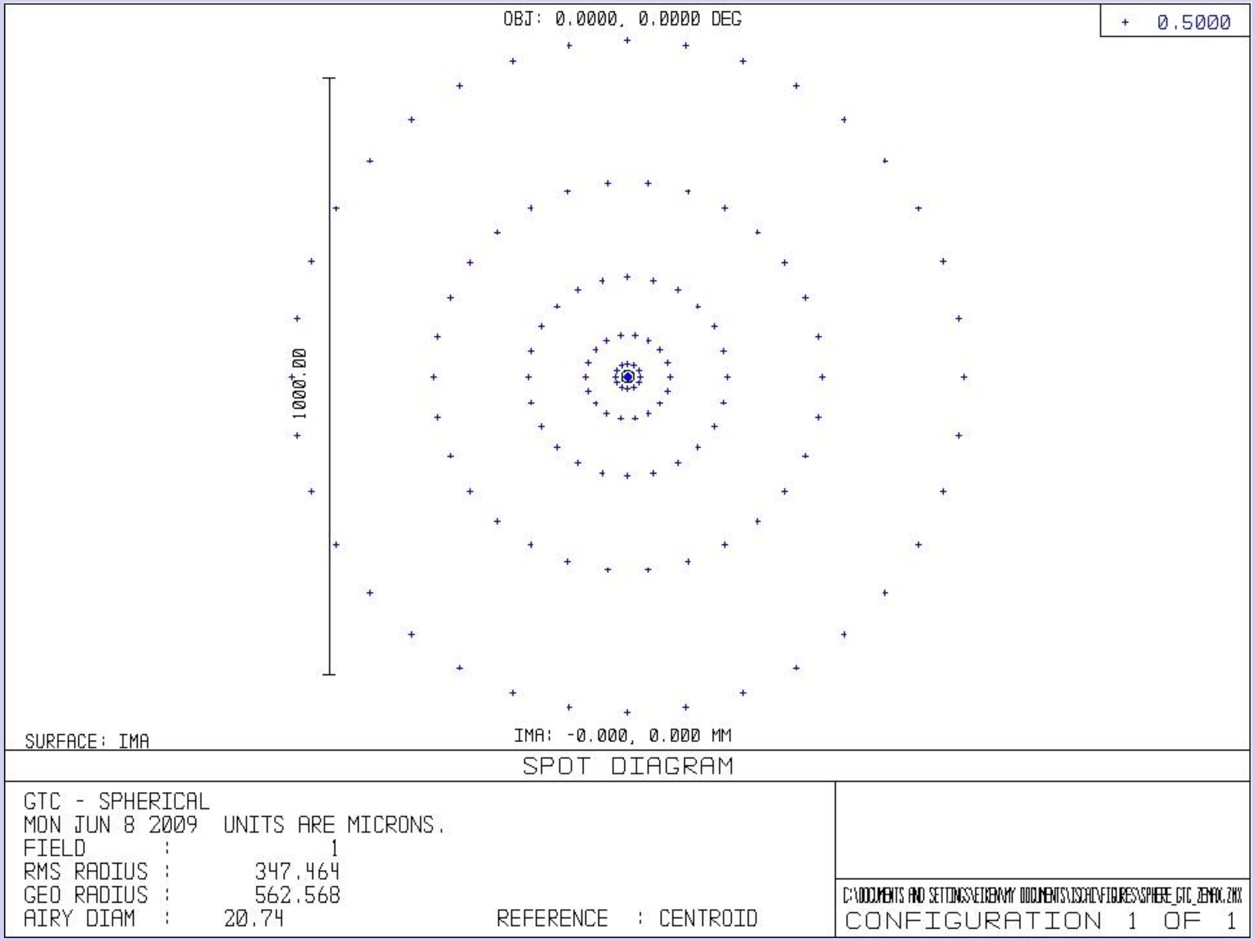
Spherical mirrors

- **But … I cheated on the math!**
- **Same mirror – more rays**
- **Spherical Aberration**
- **Math to describe it**
- **How bad is it?? Try “Spherical GTC”**



Spherical GTC - I

- 10.4-meter diameter mirror
- f/17 ⇒ Focal length = 17*10.4m = 176.8m
- So … ROC = 2f = 353.6m

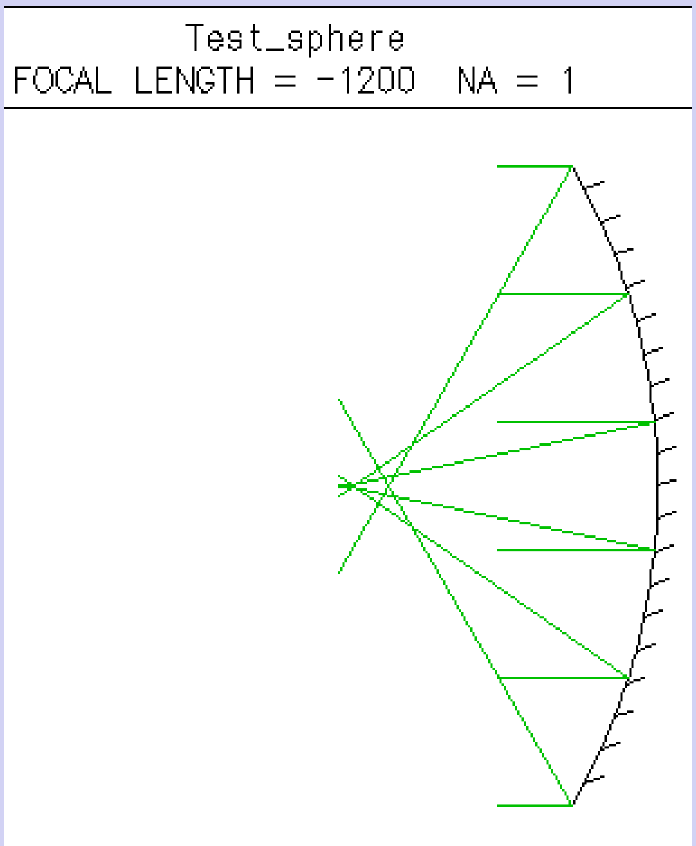


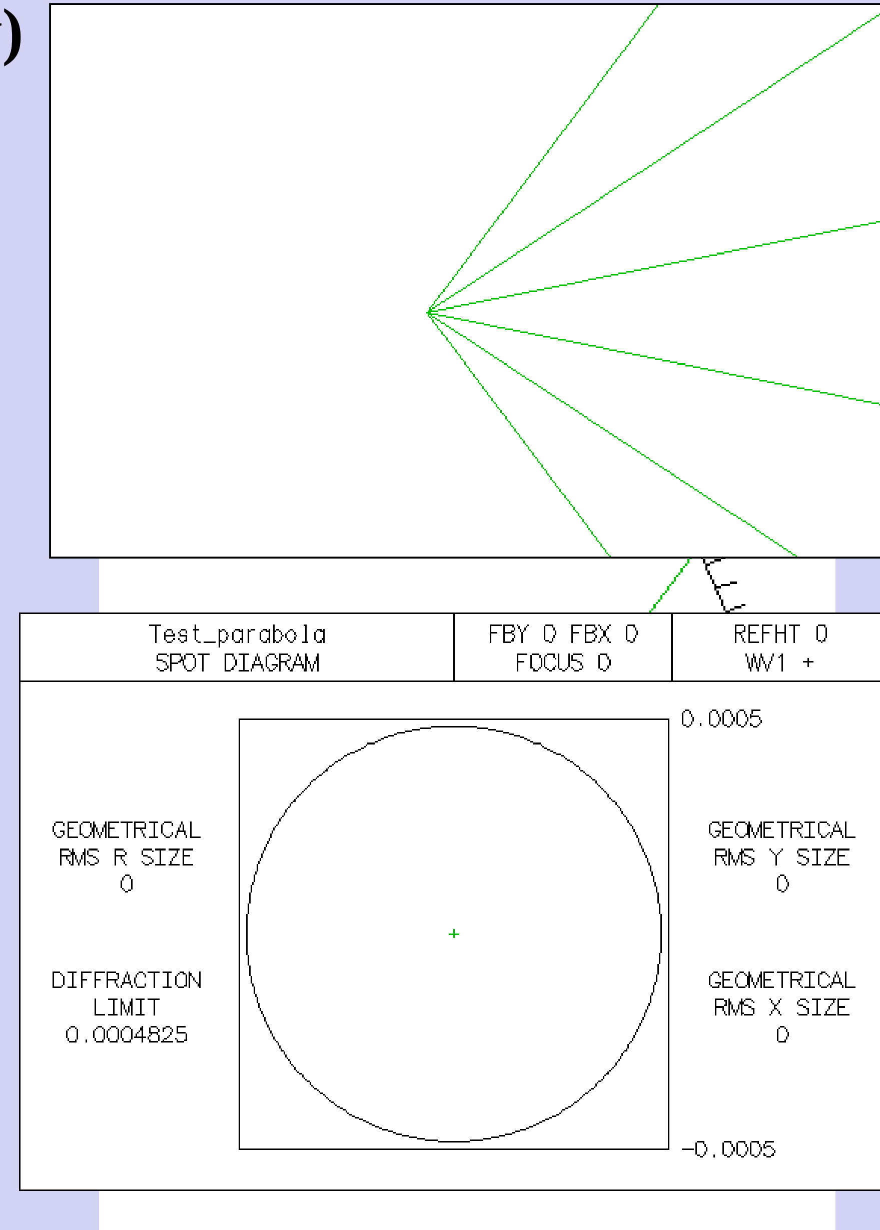
Parabolic mirrors

- $h^2 = 2rz - (1+\delta)z^2$
- Above is the equation for a "surface of revolution" for a conic section (i.e. take a curve by slicing a cone, then rotate about its vertex to create a solid surface)
- Surfaces of revolution are mathematically very important for optics
- δ is the "conic constant"
  - Spheroid: $\delta=0$
  - Oblate Ellipsoid: $\delta > 0$
  - Prolate Ellipsoid: $-1 < \delta < 0$
  - Paraboloid: $\delta = -1$
  - Hyperboloid: $\delta < -1$
- Math of parabolas & conic sections (derive focal length of parabola)

Parabolic mirrors

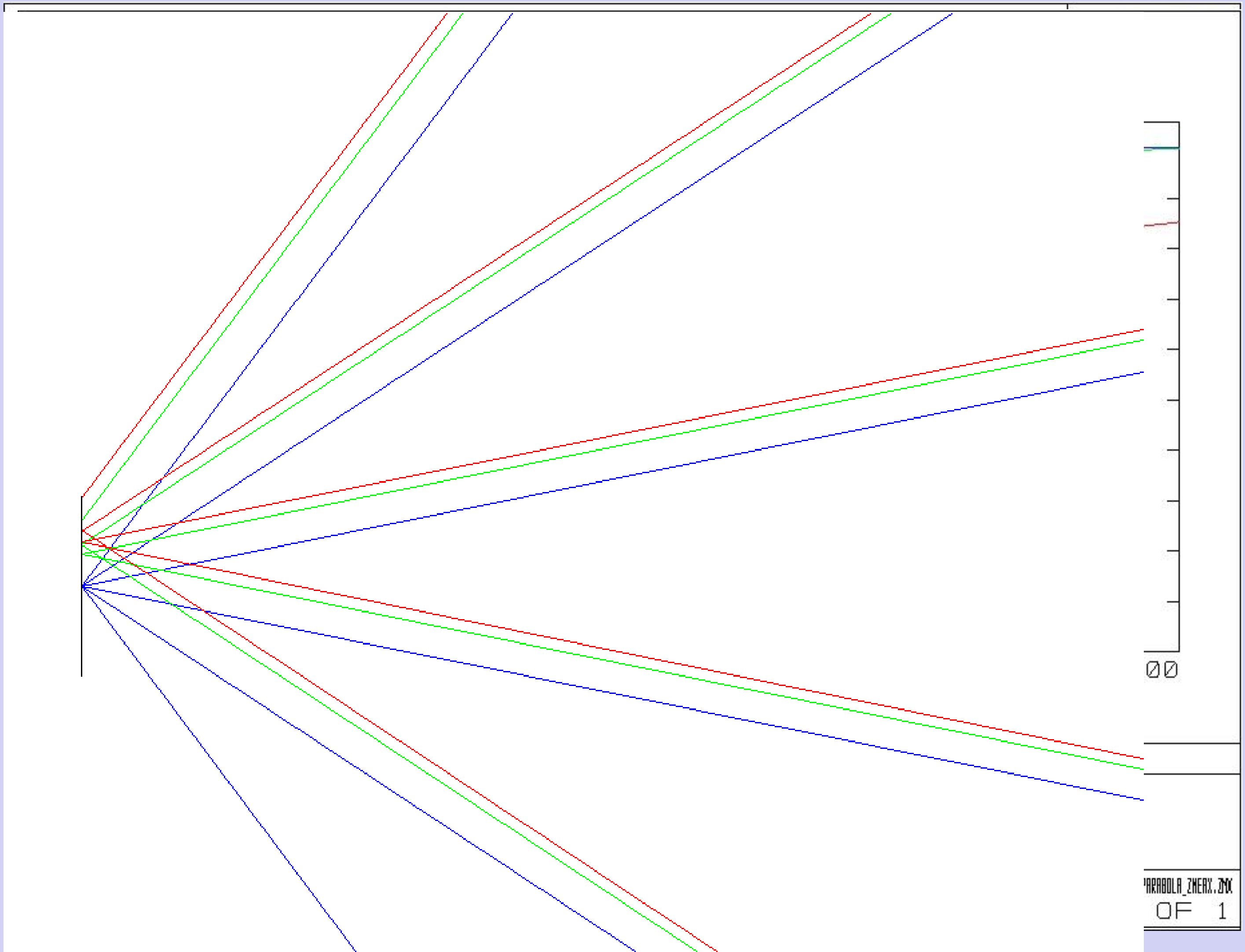
- More complex (mathematically) than spheres
  - $y = a\,x^2$
- Free from spherical aberration
  - (In fact, perfect!)





Parabolic mirrors

- Parabolas -> perfect “on-axis”
- Off-axis aberrations (coma!)

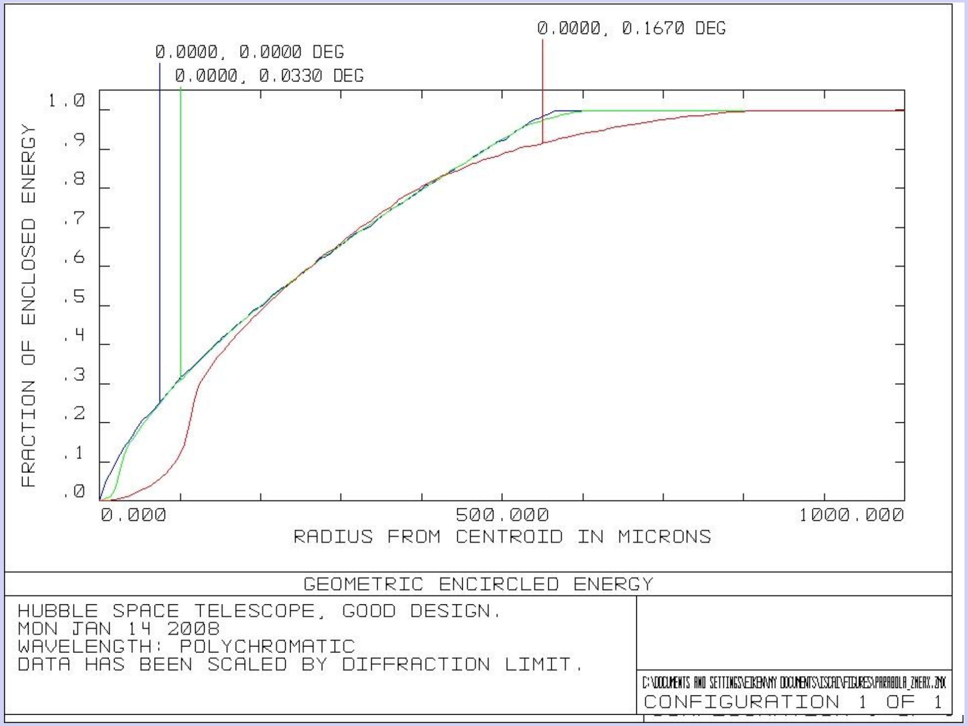


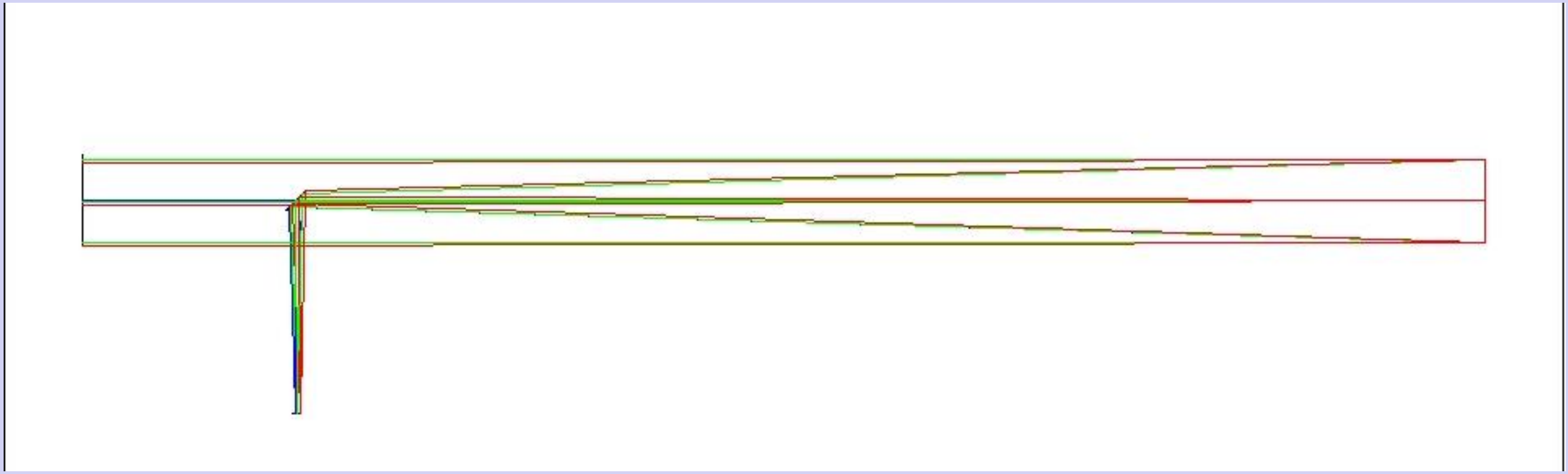
Telescopes

- **Collect light (improves S/N for information extraction)**
- **Also sets limiting resolution ($\theta_{lim} = \lambda/D$)**
  - **For 5m telescope at 500nm, θ_{lim} = 0.021-arcsec, for instance**
  - **So … "seeing-limited" requires performance <0.2-arcsec or so**
  - **"Diffraction-limited" typically will be ~0.005-arcsec $\Rightarrow$ ~40 times harder (and this gets worse for bigger telescopes!!)**

Telescopes: Newtonian

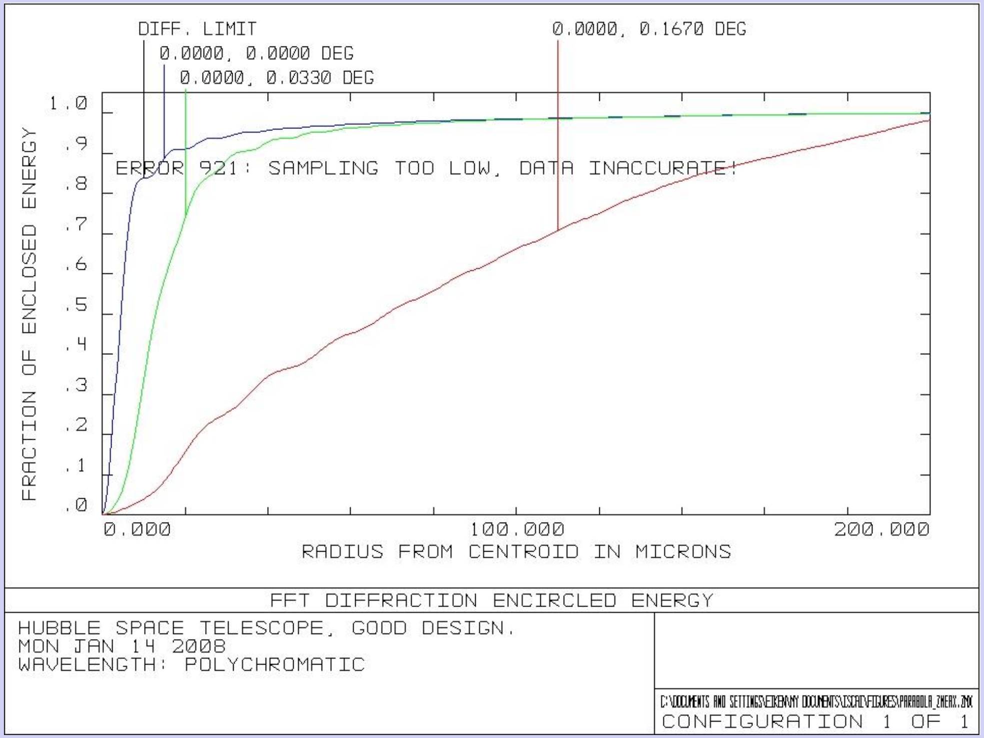
- **Spherical primary (f/17 “GTC”)**
- **Flat fold mirror (why? To get focal plane out of obscuring path)**
- **ZEMAX example**
- **Aberrations (GTC-scale example?)**

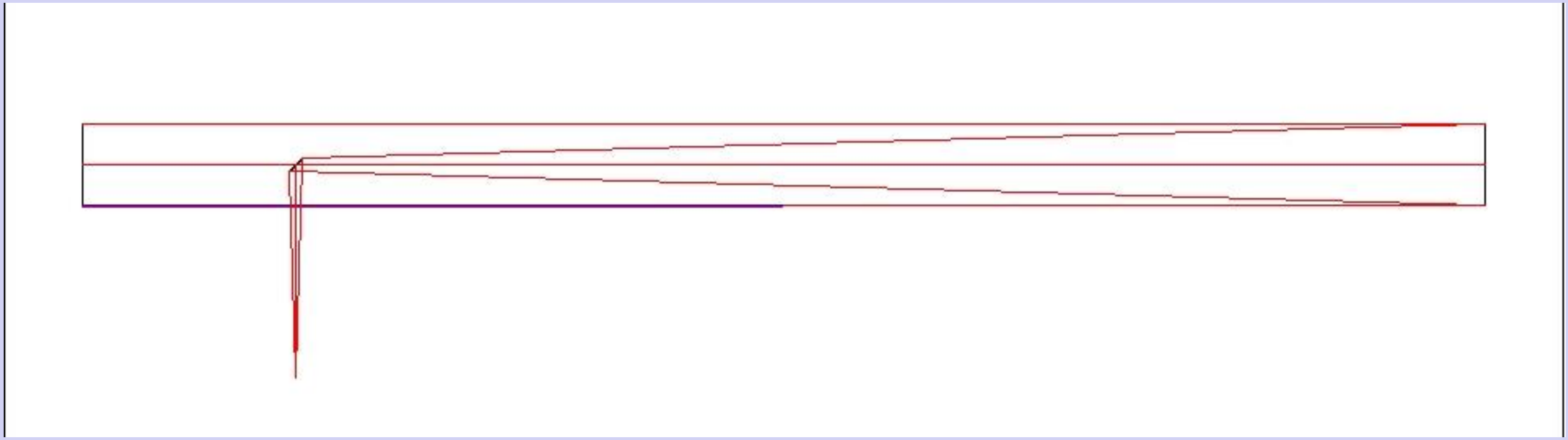




Telescopes: Parabolic

- Parabolic primary (f/17 "GTC")
- Flat fold mirror (why? To get focal plane out of obscuring path)
- ZEMAX example
- Performance



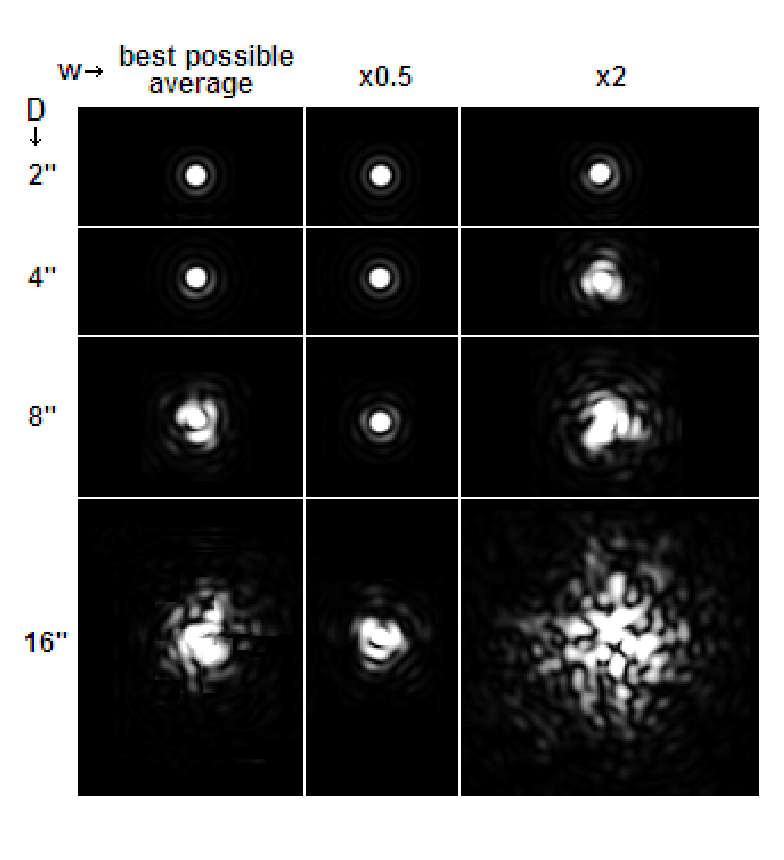


Imaging

- **What good is it?**
- **The fundamental question asked/answered is "How Bright?". Common modifiers to the question include:**
  - **Versus angular direction (α, β)**
  - **Versus light wavelength λ**
- **This is "basic imaging"**
- **But, in the real world you get neither infinite coverage nor infinite resolution (in angular-space nor in wavelength-space)**
- **How are these typically handled?**

Angular Resolution

- “Natural” limitations: Seeing
- “Seeing” = atmospheric turbulence
- Typically <1-arcsec for good astronomical sites (sometimes as sharp as ~0.3-arcsec)
- Results in “Gaussian”-like profile



www.telescope-optics.net/images/aturb.PNG

Angular Resolution

- Natural limitations: Diffraction
  - Atmosphere is not the limit with space instruments, nor with good adaptive-optics correction
  - $\theta_{lim} \cong \lambda/D_{tel}$
  - Airy disk profile (inner portion not TOO far from Gaussian either!)

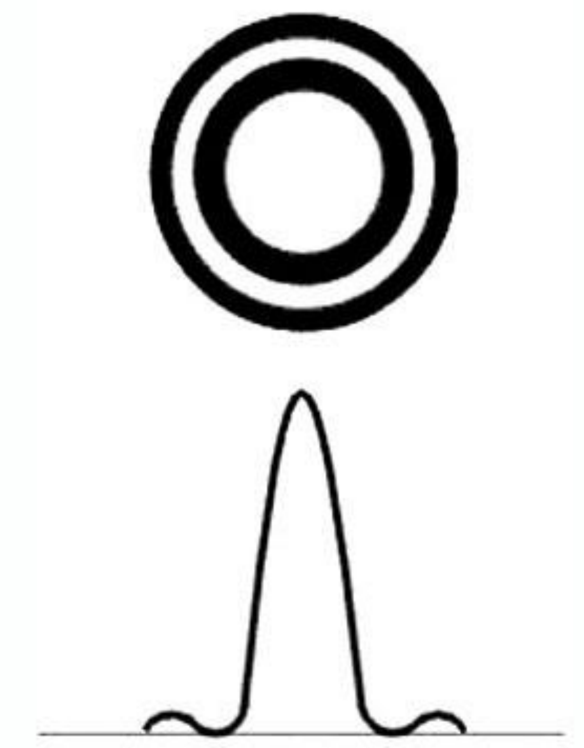
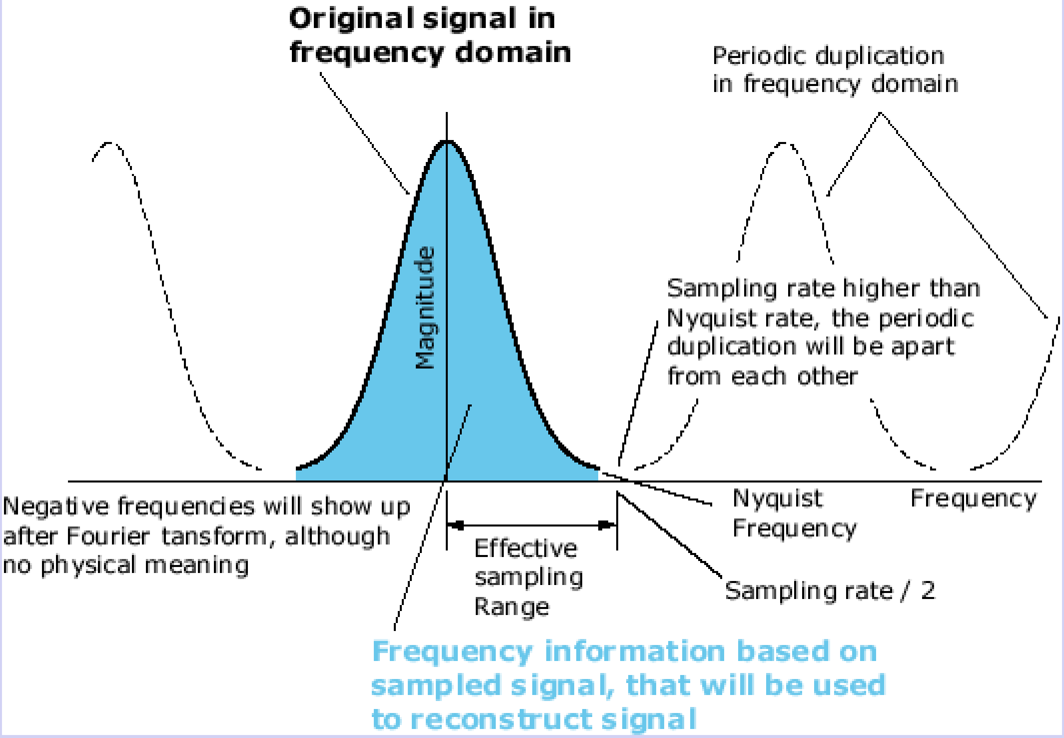


Figure 9. Point spread function (Airy disk pattern) of a point source. The upper component represents the perception of the light distribution when viewing an Airy disc (shown below).

http://webvision.med.utah.edu/imageswv/KallSpat9.jpg

Angular Resolution: Nyquist

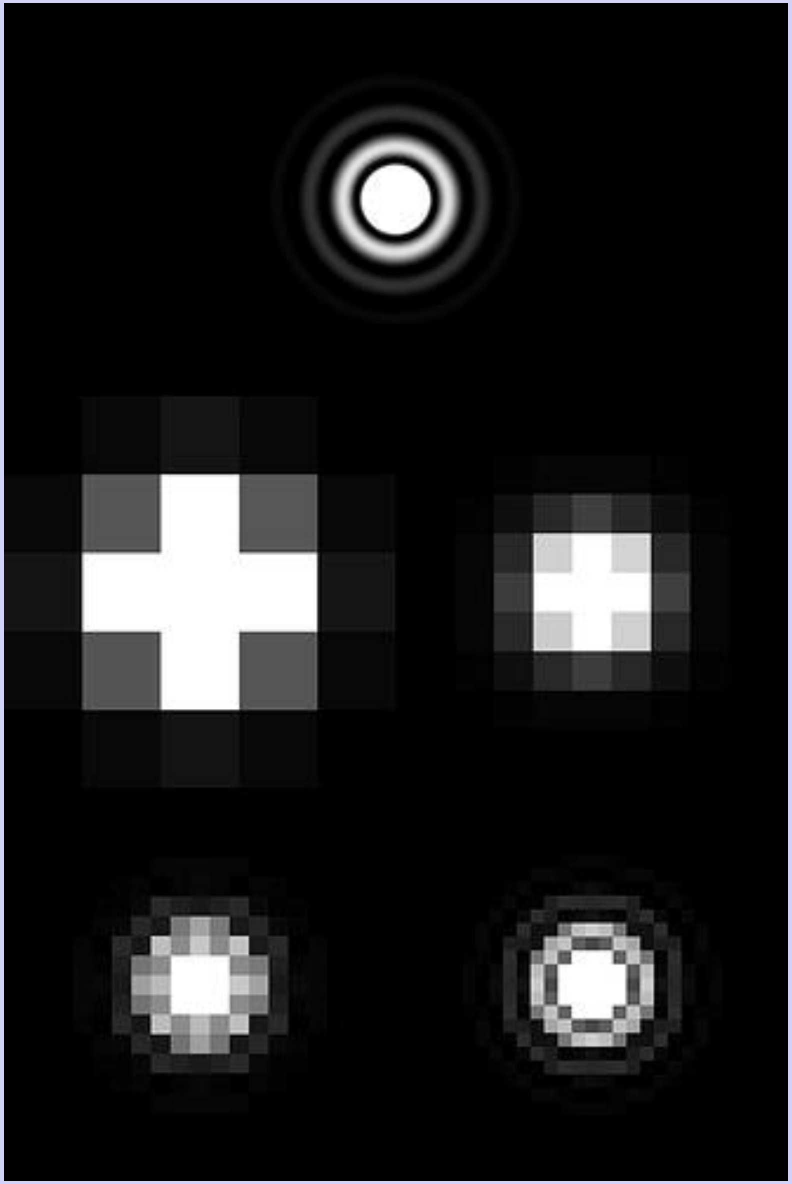
- **Sampling for an image:**
  - **Nyquist sampling requires 2 pixels per resolution element (N_{samp} = 2)**
- **This is 2 samples per Full-Width at Half-Maximum (FWHM)**



http://www.efunda.com/designstandards/sensors/methods/images/Aliasing_B.gif

Angular Resolution: Nyquist (cont)

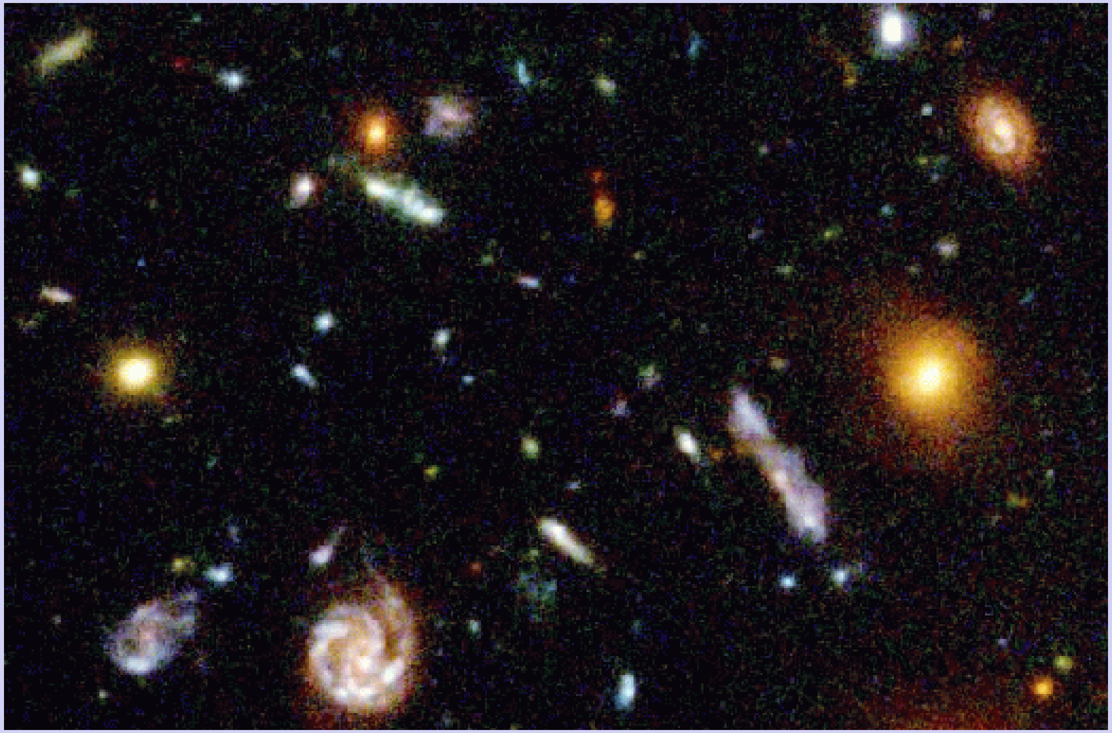
- **Note that Nyquist sampling is the hard MINIMUM required**
- **Often want finer sampling (i.e. 3-5 pixels per FWHM) to obtain better information**



http://farm3.static.flickr.com/2248/2163371597_fef5562c4e.jpg?v=0

Field of View

- Often want to look at more than one target at a time (!!)
- Minimum number of pixels needed $\propto$ (FOV/seeing)^2 * N^2_{samp}
- Detector cost proportional to N_{pix}
- Optics diameter roughly proportional to N_{pix} (for given detector scale); Optics cost typically $\propto D^2$ or D^3 (!)

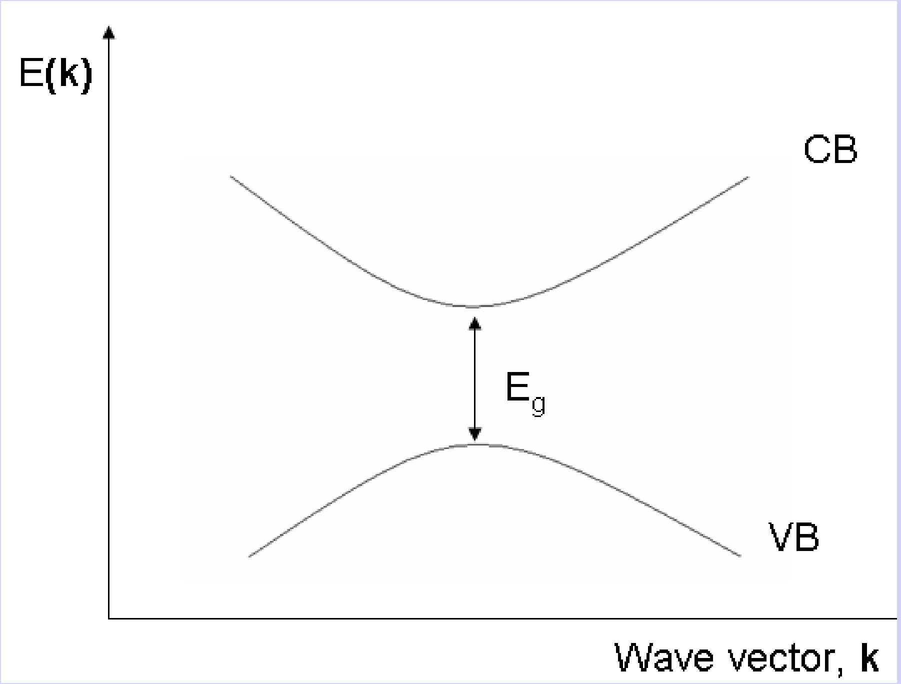


http://www.stsci.edu/ftp/science/hdf/DetailWF4.gif

Detector Noise: Dark Current

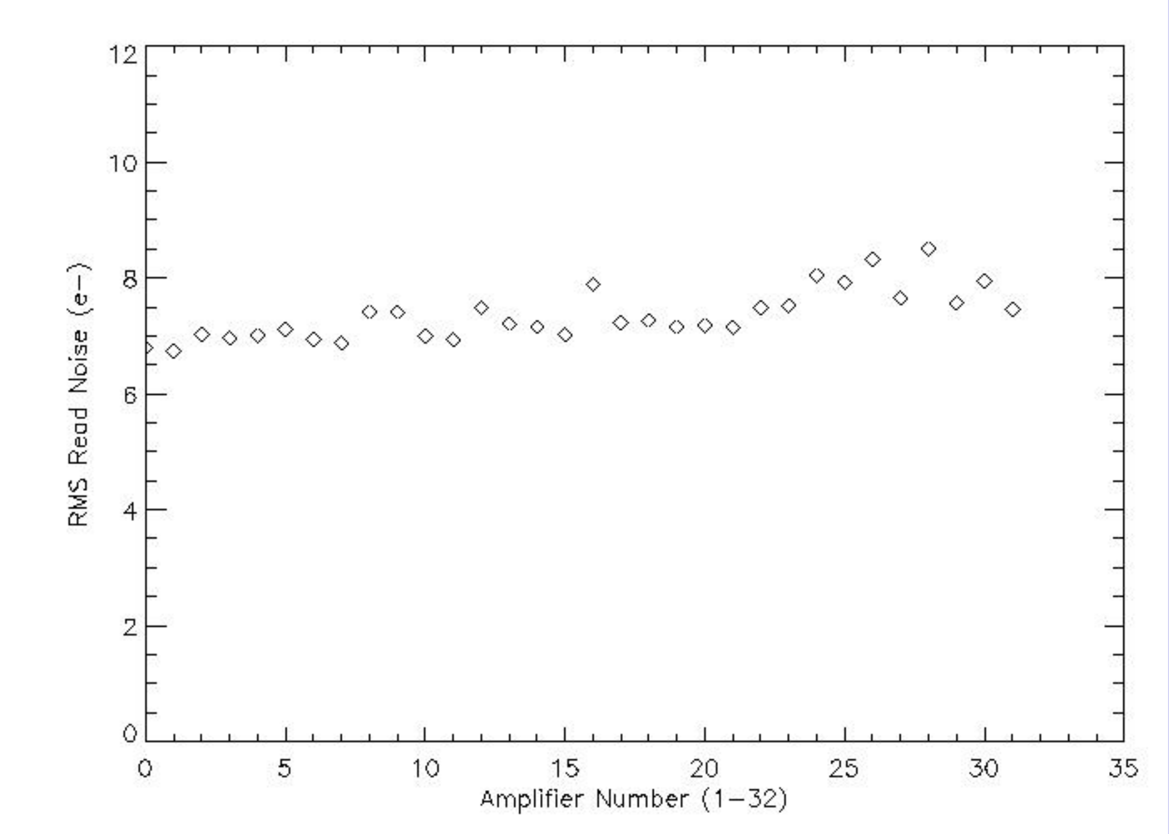
- Real-world detectors typically have some signal produced even in the ABSENCE of light
- This is generically referred to as "dark current"
- Often, related to thermal noise exciting electrons into the conduction band in semiconductor detectors (i.e. CCDs, IR arrays, etc.)
- This add shot noise

http://org.ntnu.no/solarcells/pics/chap3/Bandgap%20wave vector.png



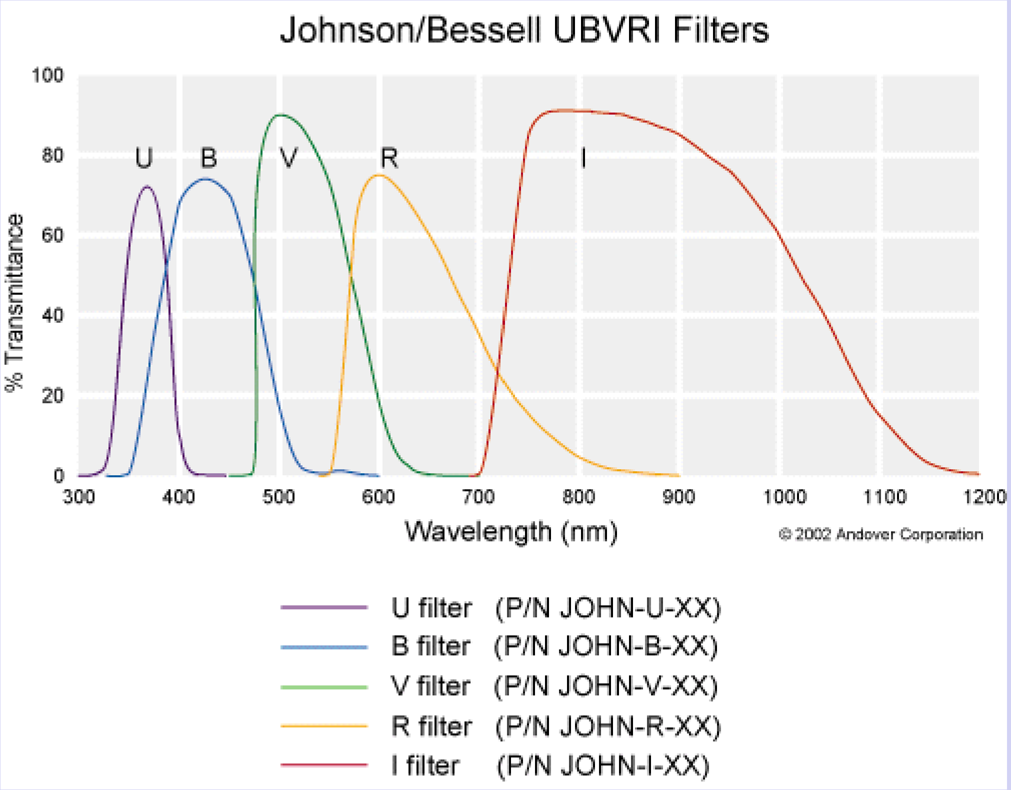
Detector Noise: Read Noise

- Readout amplifiers of real-world detectors also have some typical noise called “read noise”
- Typically expressed in electrons (RMS)
- “noise-equivalent signal” is RN^2



At what wavelength range?

- **Broader bandpass means more photons (means more signal!)**
- **But, broader bandpass means less spectral resolution (means more confusion about physical meaning of brightness)**
- **And, broader bandpass means more sky background (means more noise)**



http://www.andovercorp.com/web_store/Images/Graphs/UBVRI_Johnson.gif

Signal –to-Noise for Imaging

- **Combine all of this to determine equation for maximum signal-to-noise**

- **Instrument design requires careful balancing of spatial/spectral resolution, field of view, image quality, noise, cost – ALL compared with ultimate scientific information extraction**

“Real” Telescopes

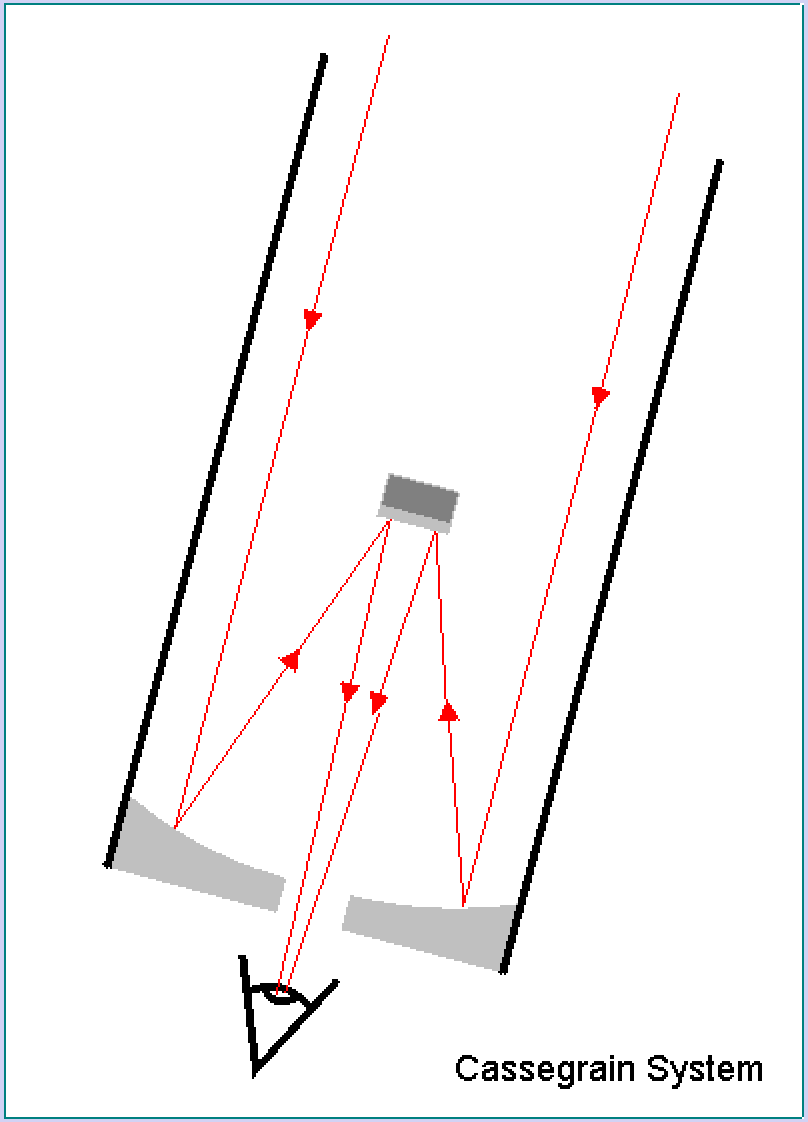
- Research observatories no longer build Newtonian or Parabolic telescopes for optical/IR astronomy
  - Aberrations from their single powered optical surface are too large
- More advanced telescopes available
- Typically, for us, these are “2-mirror” (meaning 2 powered mirrors) telescopes
- The secondary mirror is curved, as well as the primary
- Two powered surfaces means that we can use the combination to “correct” aberrations from a single-mirror approach

Common 2-Mirror Scopes

Telescope	Primary	Secondary
Cassegrain	Parabola	Hyperbola
Gregorian	Parabola	Prolate Ellipse
Ritchey-Chretien (Aplanatic Cass)	Hyperbola	Hyperbola
Aplanatic Gregorian	Ellipse	Prolate Ellipse

Cassegrain

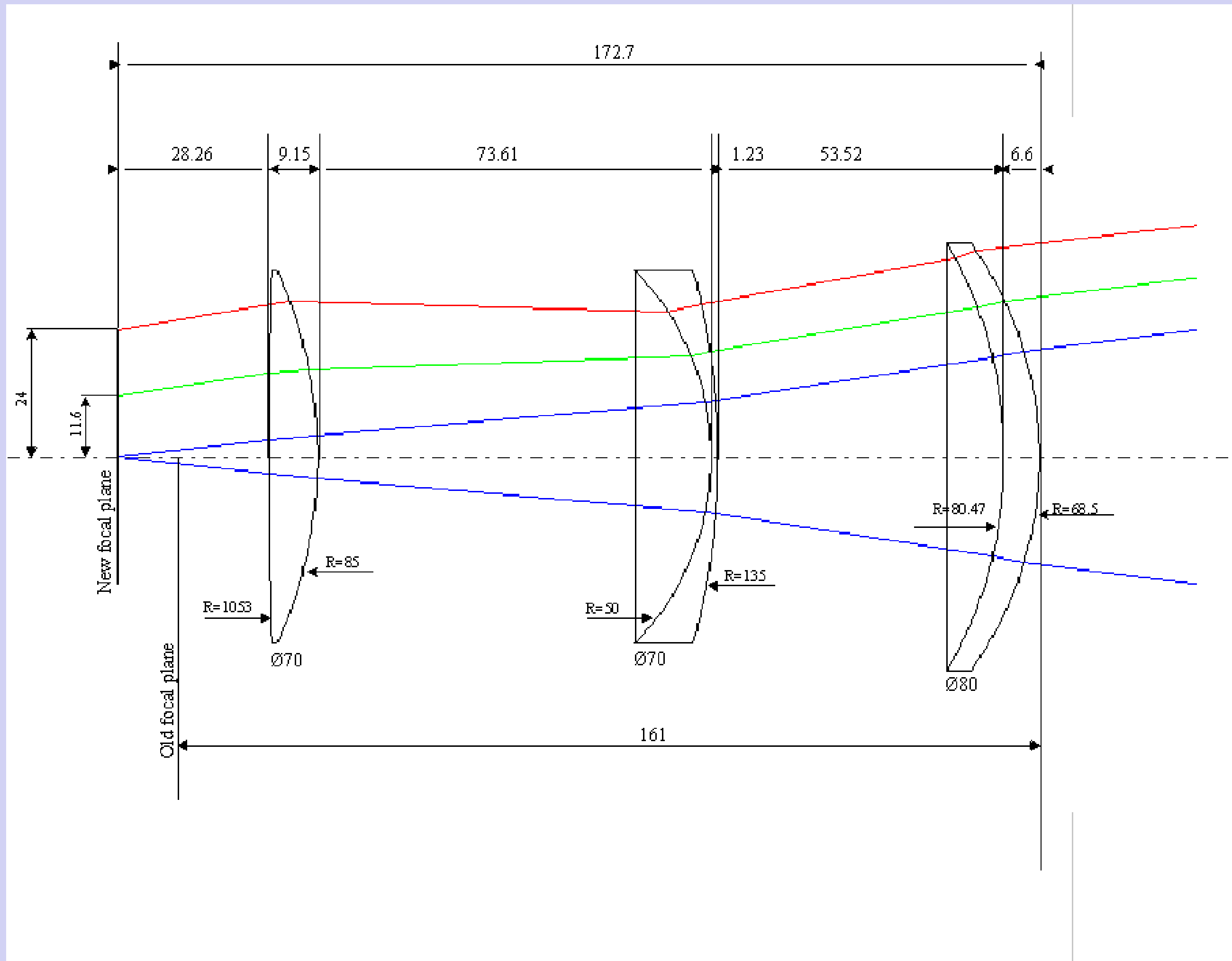
- All well-designed 2-mirror scopes of this sort have good performance on/near-axis
- Cass field-of-view is typically limited by coma
- Field curvature also an issue



http://www.daviddarling.info/images/Cassegrain.gif

Cameras: Prime Focus

- **Prime Focus Corrector**
- **Wynne solution**



Focal length increase : 10%, here F4 beam

http://www.astrosurf.com/cavadore/optique/Wynne/index.html

Sampling, etc.

- **Sampling for an image:**
  - **Nyquist sampling requires 2 pixels per resolution element (N_{samp} = 2)**
  - **Typical experience is that for high-accuracy photometry, often want 3-5 pixels per resolution element (N_{samp} = 3-5)**
- **Field-of-View:**
  - **Number of pixels needed $\propto$ (FOV/seeing)^2 * N^2_{samp}**
  - **Detector cost proportional to N_{pix}**
- **Detector noise:**
  - **Read noise and detector noise add in quadrature for independent pixels**
  - **So … noise $\propto$ N_{samp}**

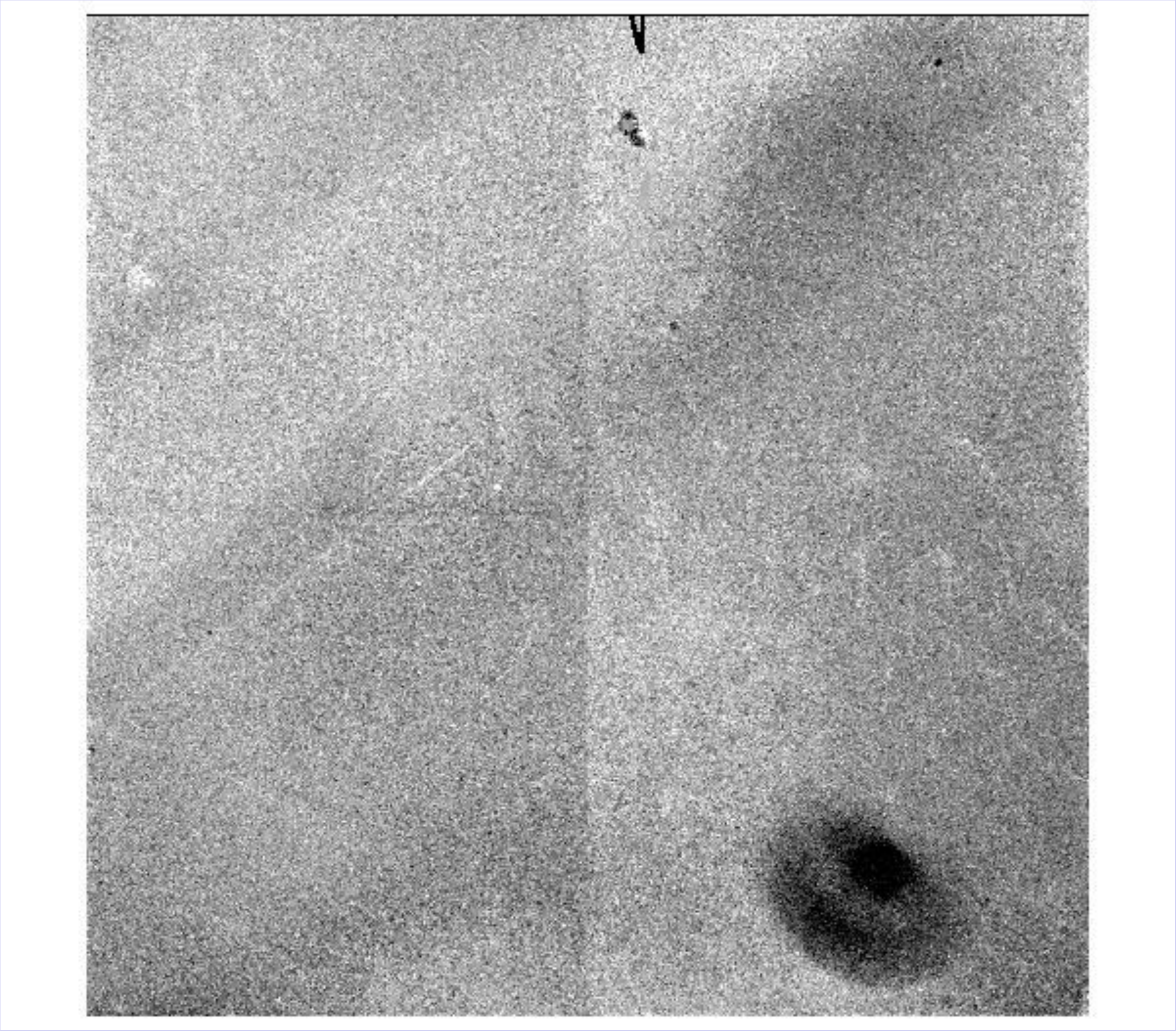
Focal Reducers

- Also known as “beam accelerator”
- Variation on direct imaging
- If we KNOW we want a certain pixel scale, then we know the resulting EFL we need for the system
- Insert a lens of appropriate focal length to modify the EFL of the telescope to match this

What's Wrong with Reduction?

- Perfectly fine for many applications
- Where do the filters go? Right in front of the detector
- Why? Cost often proportional to diameter$^{2-3}$
- What does that mean for filter defects or dust spots? They are projected onto the detector (!!)
- This means that the system throughput can change dramatically from point to point
- Why is that bad? We can use a "flatfield" image to correct this
- But … flatfield accuracy seldom much better than ~0.1-1%
- So … if we introduce large spatial variations into the camera response function, we introduce photometric noise (even for differential photometry)

Dust Example

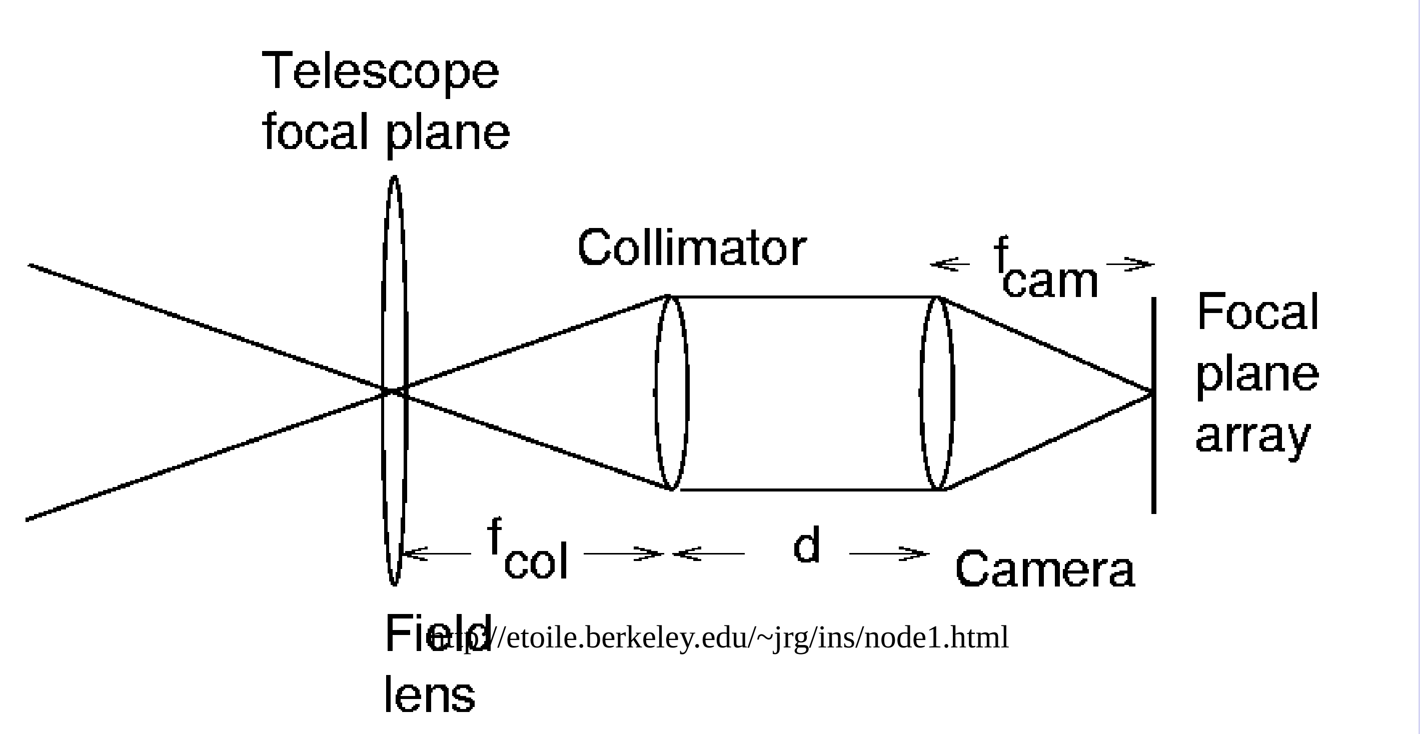


- http://www.not.iac.es/instruments/notcam/guide/dust.jpg

Camera/Collimator Approach

- These systems use a "collimator" to create an image of the telescope exit pupil
- Light rays from a given field point are parallel ("collimated" after the collimator optics
- Another optical system (the "camera") accepts light from the collimator and re-focuses the image plane onto a detector

http://etoile.berkeley.edu/~jrg/ins/node1.html

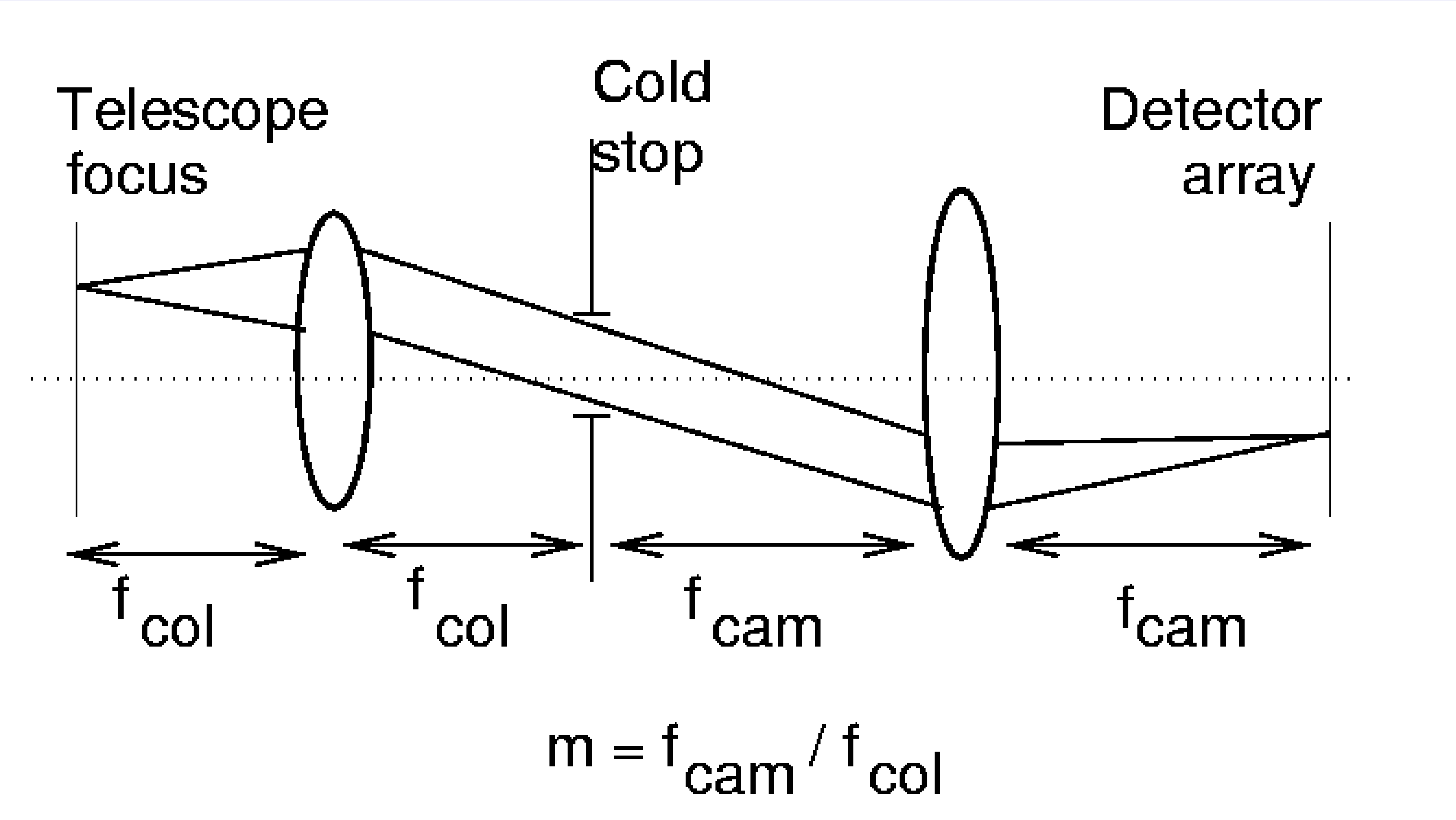


Camera/Collimator & Filters

- **Pupil image is where the parallel rays from different field points cross**
- **A filter can now be placed at the pupil image**
- **Any dust spots on the filter reduce the total system throughput**
- **However, they are now projected onto the pupil, NOT the image plane**
- **Thus, this light loss is now IDENTICAL for all field points**
- **This eliminates the contribution to flatfield “noise”!!**

Infrared Cameras

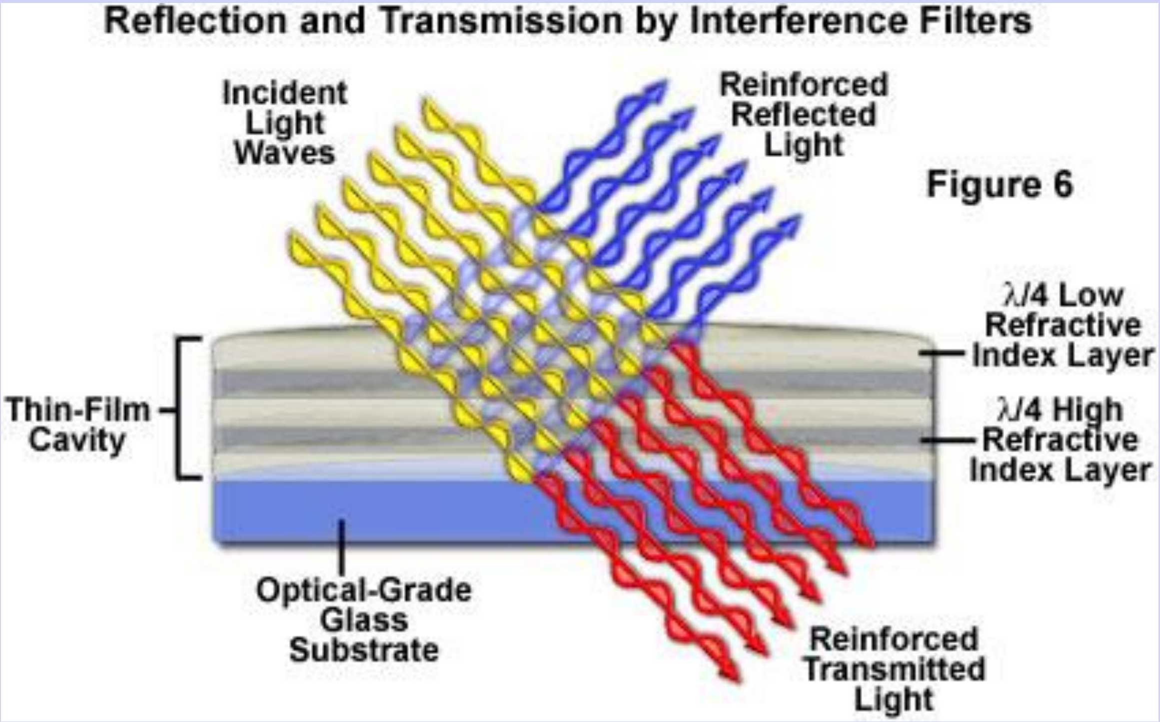
- **Need for cold stop**



http://etoile.berkeley.edu/~jrg/ins/node1.html

Interference Filters

- How they work (roughly)
- Angular dependence
- Field dependence versus wavelength spread
- Example



http://www.olympusmicro.com/primer/lightandcolor/filtersintro.html

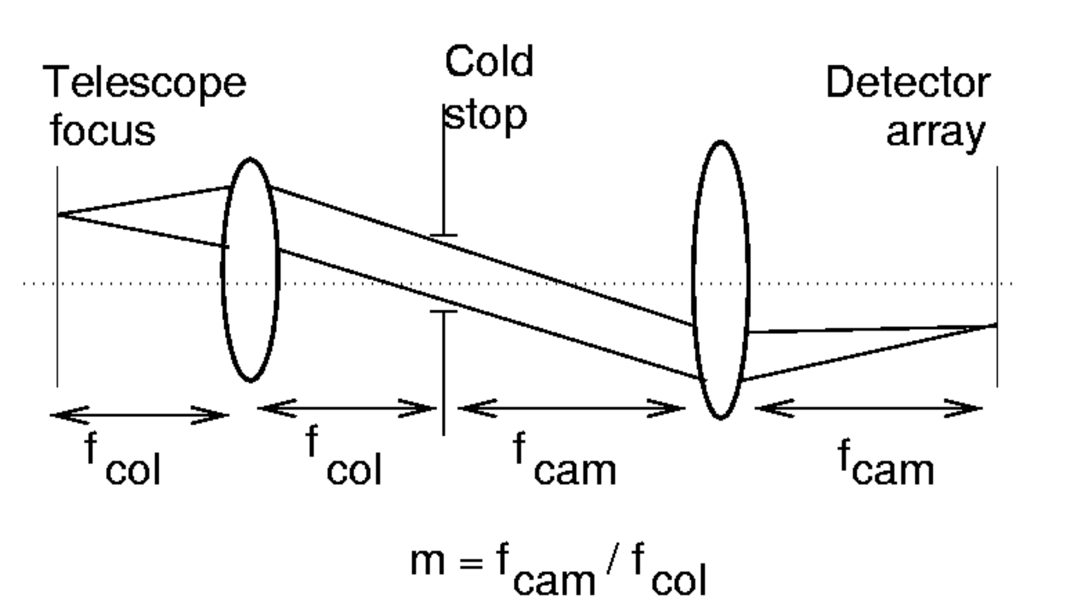
Spectroscopy: What is it?

- How Bright? (our favorite question):
  - Versus position on the sky
  - Versus wavelength/energy of light
  - Typically "spectroscopy" means $R = \lambda/\Delta\lambda > 10$ or so …
- One approach: energy-sensitive detectors
  - Works for X-rays! CCDs get energy for every photon that hits them!
  - Also STJs for optical; but poor QE & R, plus limited arrays
- Another approach:
  - Spread ("disperse") the light out across the detector, so that particular positions correspond to particular λ
  - "Standard" approach to optical/IR spectroscopy

Conjugate, conjugate, conjugate

- **Conjugates table for collimator/camera**

Plane	X	θ	Conjugate To
Telescope pupil	Position on pupil	Angle on Sky	-
Telescope focus	Angle on sky	Position on primary	-
Collimator focus (Pupil Image)	Position on pupil	Angle on sky	Telescope pupil
Camera focus (detector)	Angle on Sky	Position on pupil	Telescope focus



Dispersion Conundrum

- **Hard to find dispersers that map wavelength to position**
- **Easy to find dispersers that map wavelength to angle (prisms, gratings, etc.)**
- **Hard to find detectors that are angle-sensitive**
- **Easy to find detectors that are position-sensitive (CCDs, etc.)**

- **We want an easy life! $\Rightarrow$ find a way to use angular dispersion to map into position at detector**
- **Solution: place an angular disperser at a place where angle eventually gets mapped into position on detector $\Rightarrow$ at/near the image of the pupil in a collimator/camera design!**

Slits and Spectroscopy

- **Problem:**
  - **Detector position [x1,y1] corresponds to sky position [α1,β1] at wavelength λ1**
  - **Detector position [x1,y1] ALSO corresponds to sky position [α2,β2] at wavelength λ2 !!**
  - **Need to find some way to eliminate this confusing "Crosstalk"**
- **Common Solution:**
  - **Introduce a small-aperture field stop at the focal plane, and only allow light from one source through**
  - **This is called a spectrograph "slit"**

Angular dispersion

- Define $d\beta/d\lambda$ for generic disperser (draw on board)
- Derive linear dispersion on detector
  - Shift $x = \theta * f_{cam}$
  - $dx/d\lambda = d\beta/d\lambda * f_{cam} = A * f_{cam}$

Limiting resolution

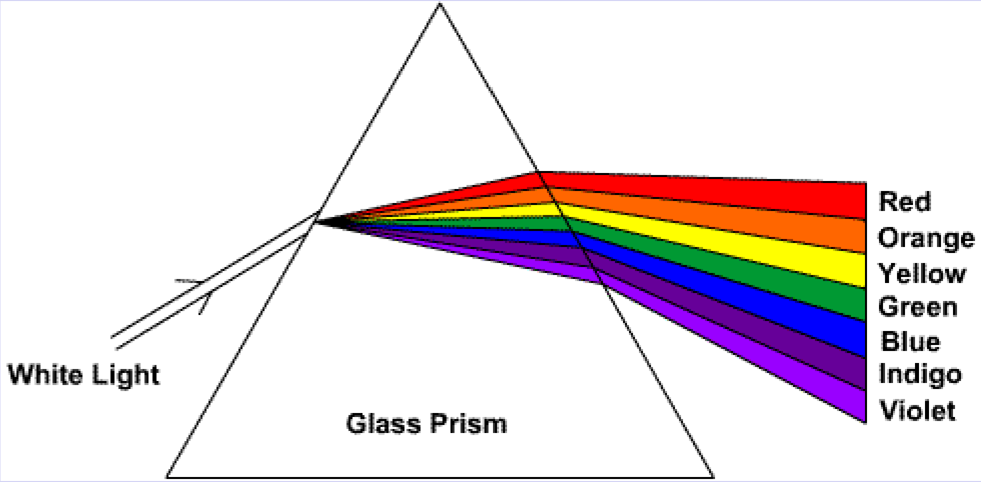
- **Derive relation for limiting resolution**
  - **$R \equiv \lambda / (\Delta\lambda)$**
  - **$R = \lambda A D_{pupil} / (\theta_{slit} D_{tel})$**
- **Note that this is NOT a "magic formula"**

Slit width: I

- **Note impact of slit width on resolution:**
  - **Wide slit $\Rightarrow$ low resolution**
  - **Skinny slit $\Rightarrow$ high resolution**
- **How wide of a slit? Critical issue for spectrograph design (draw on board)**
- **Higher width $\Rightarrow$**
  - **Higher throughput (and thus higher S/N)**
  - **But lower resolution**
  - **And higher background/contamination (and thus lower S/N)**

Dispersers: Prisms

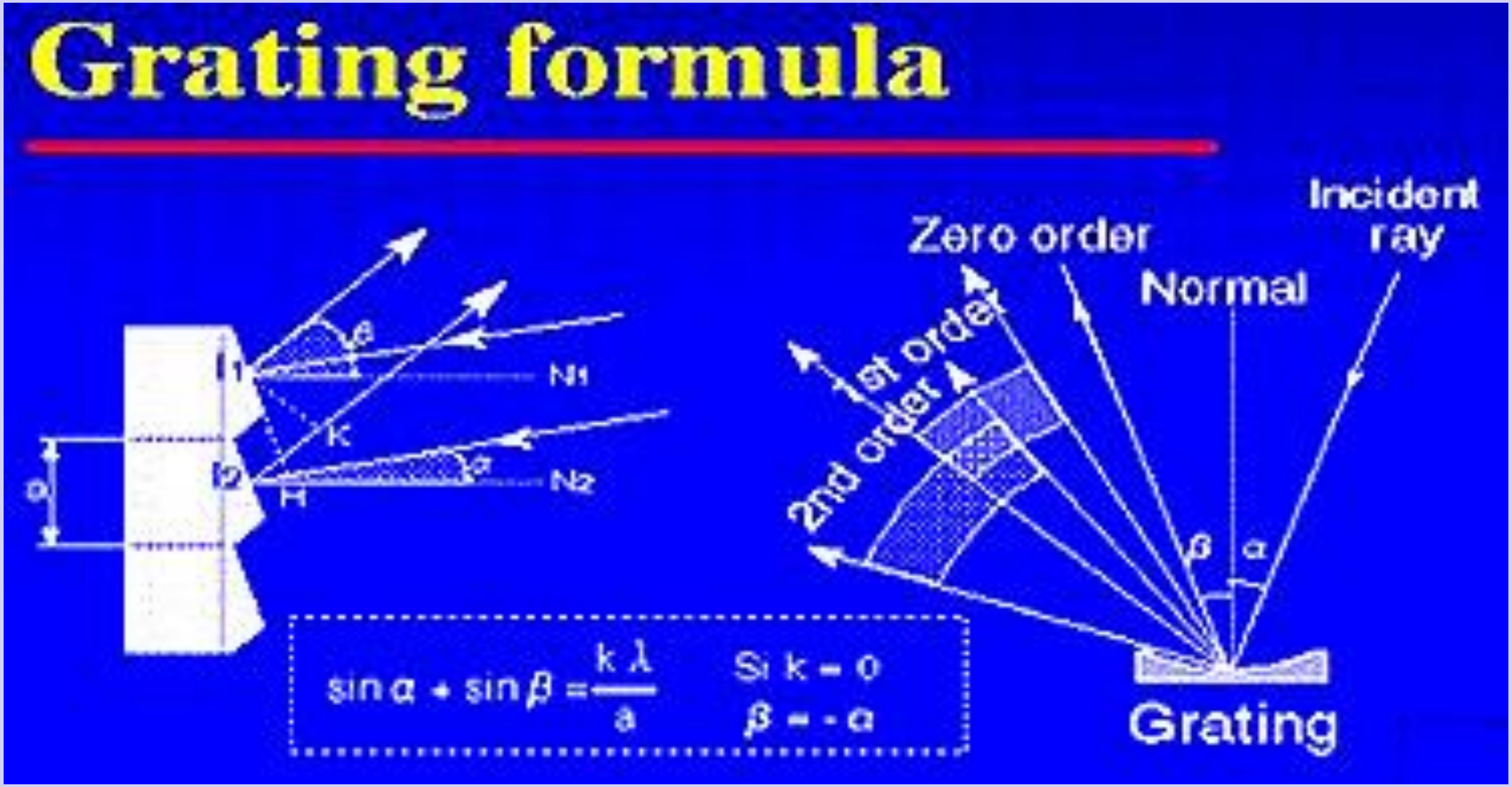
- Derive dispersion relation
  - $A = \alpha \, dn/d\lambda$
  - $A = t/a \, dn/d\lambda$
- Limiting resolution of prisms



http://www.school-for-champions.com/science/images/light_dispersion1.gif

Dispersers: Diffraction Gratings

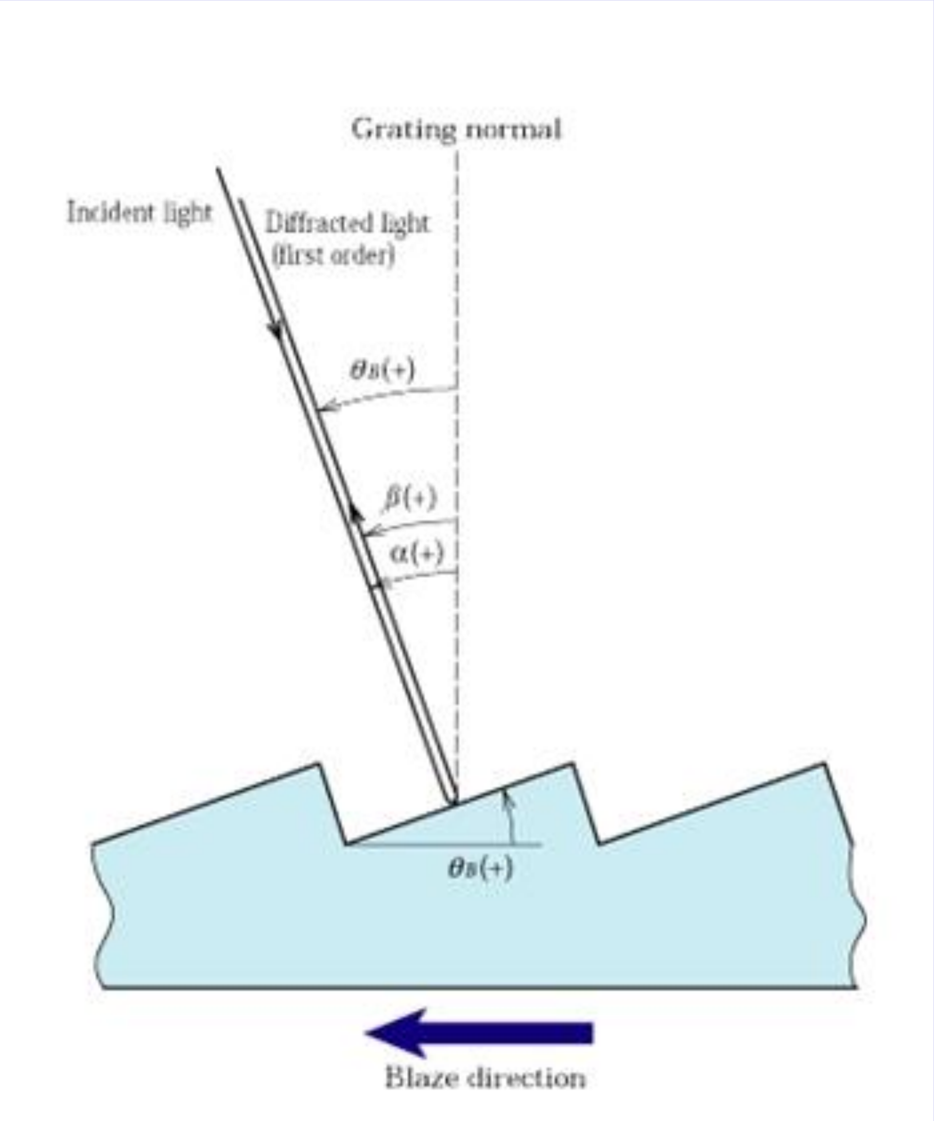
- Grating equation: $m\lambda = \sigma\,(\sin\alpha + \sin\beta)$
- Angular dispersion: $A = (\sin\alpha + \sin\beta) / (\lambda \cos\beta) = m/(\sigma \cos\beta)$
- Note independence of relation between A, λ and m/σ



http://rst.gsfc.nasa.gov/Sect13/grating12.jpg

Dispersers: Diffraction Gratings

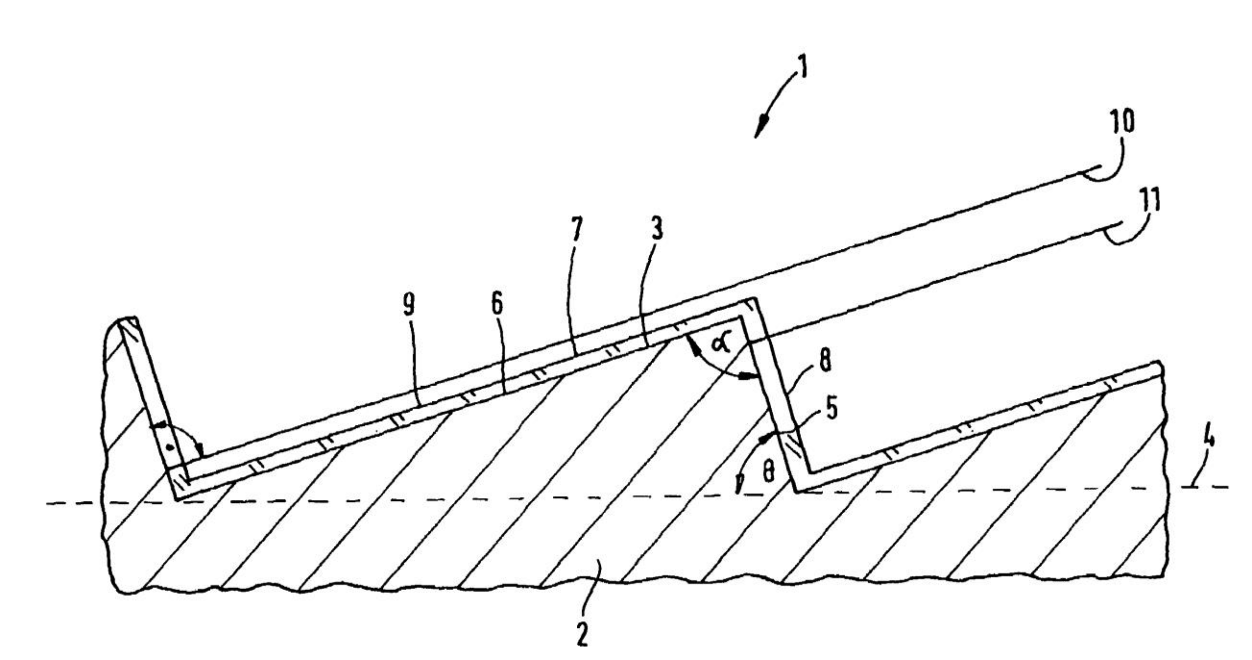
- Note order overlap/limits, need for order-sorters
- Littrow configuration ($\alpha=\beta=\delta$)
- Results:
  - $A = 2 \tan\delta / \lambda$
  - $R = m\, W\, \lambda / (\sigma\phi D)$
  - $R = m\, N\, \lambda / (\phi D)$
- Quasi-Littrow used (why?)
- Do some examples



http://www.shimadzu.com/products/opt/oh80jt0000001uz0-img/oh80jt00000020ol.gif

Blaze Function

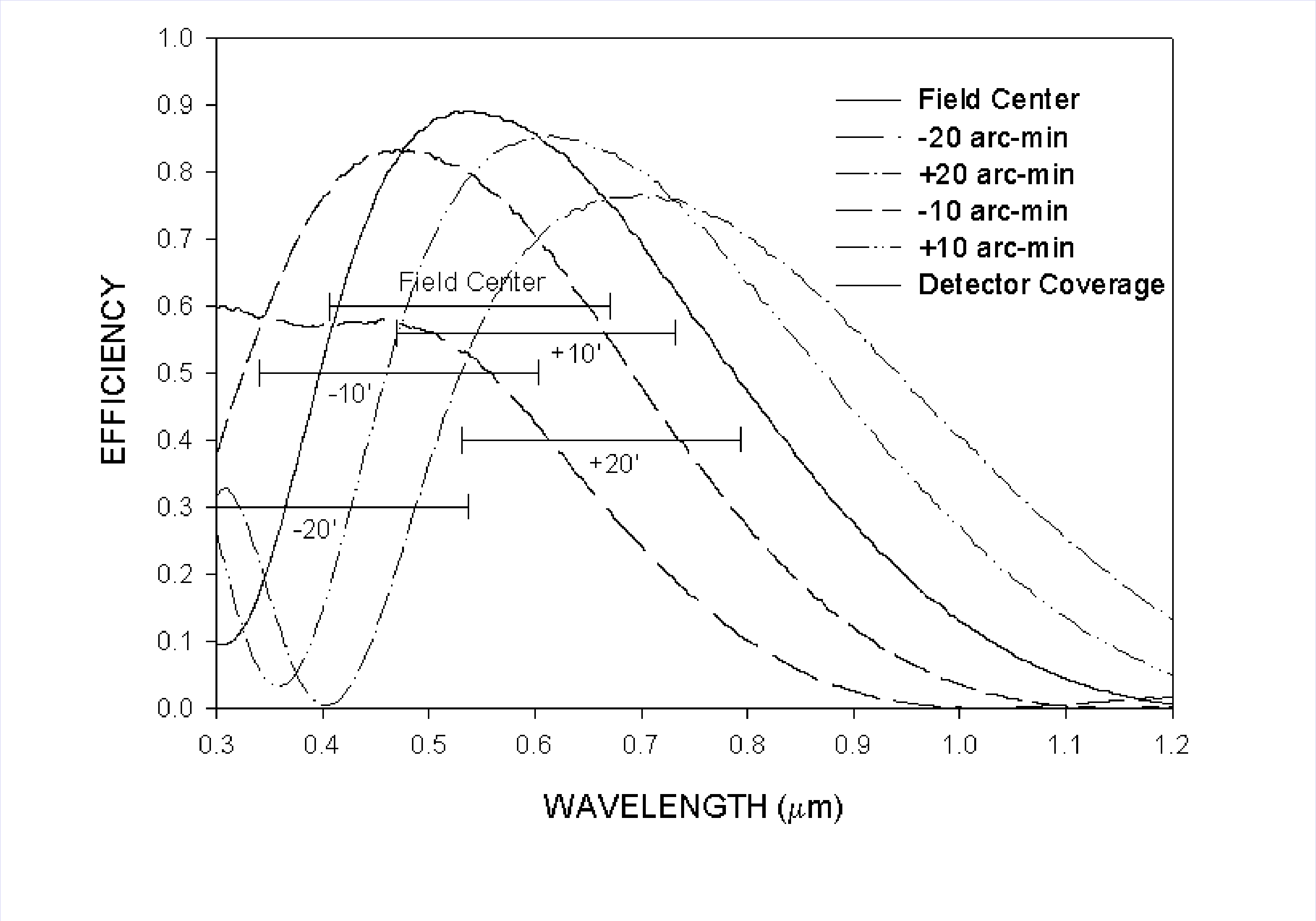
- **Define and show basic geometry**



http://www.freepatentsonline.com/7187499-0-large.jpg

Blaze Function

- Impact
- How we can "tune" this

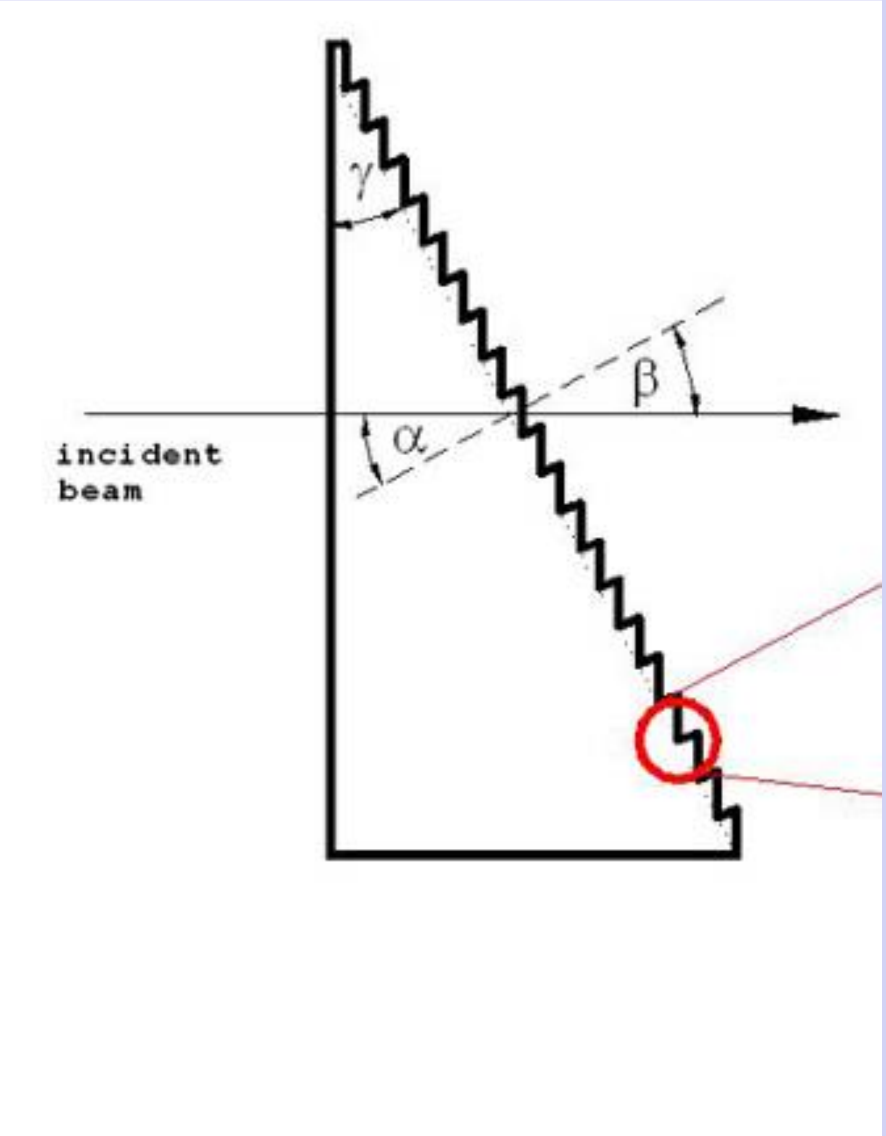


Free Spectral Range

- **Blaze function and order number**
- **Define & give rule of thumb:**
    - **FSR = “high-efficiency” wavelength range of grating**
    - **FSR ~= λ/m (VERY crude approximation)**

Dispersers: Grisms

- Transmission grating + prism = "grism"
- Dispersion is done by the grating, typically quasi-Littrow
- Treat grating as always
- Prism angle is chosen so that the "blaze wavelength" is deviated EXACTLY opposite to the angular deviation of the grating



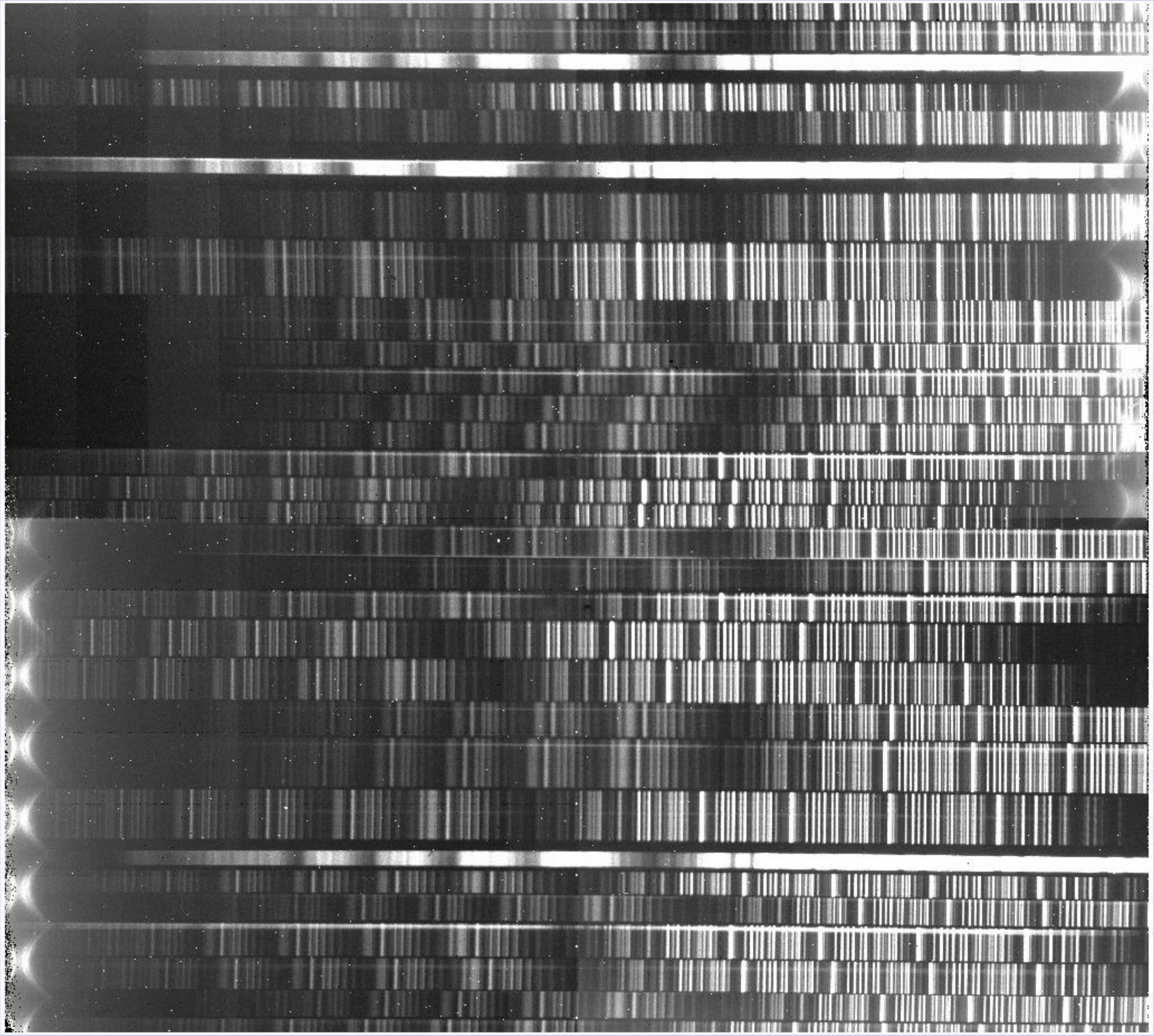
http://www.as.utexas.edu/astronomy/research/people/jaffe/imgs/grism_basic_lg.jpg

Dispersers: Grisms

- **Combination means you get the dispersion of the grating, but without having to "tilt" the post-grating optics $\Rightarrow$ "straight-through" collimator/camera (just like imaging)**
- **Allows combination of a collimator/camera to be used for imaging as well as spectroscopy (nice advantage)**
- **Can't tilt grism to adjust central wavelength (drawback)**
- **Typically limited to low resolutions (R ~1000 up to ~3000)**

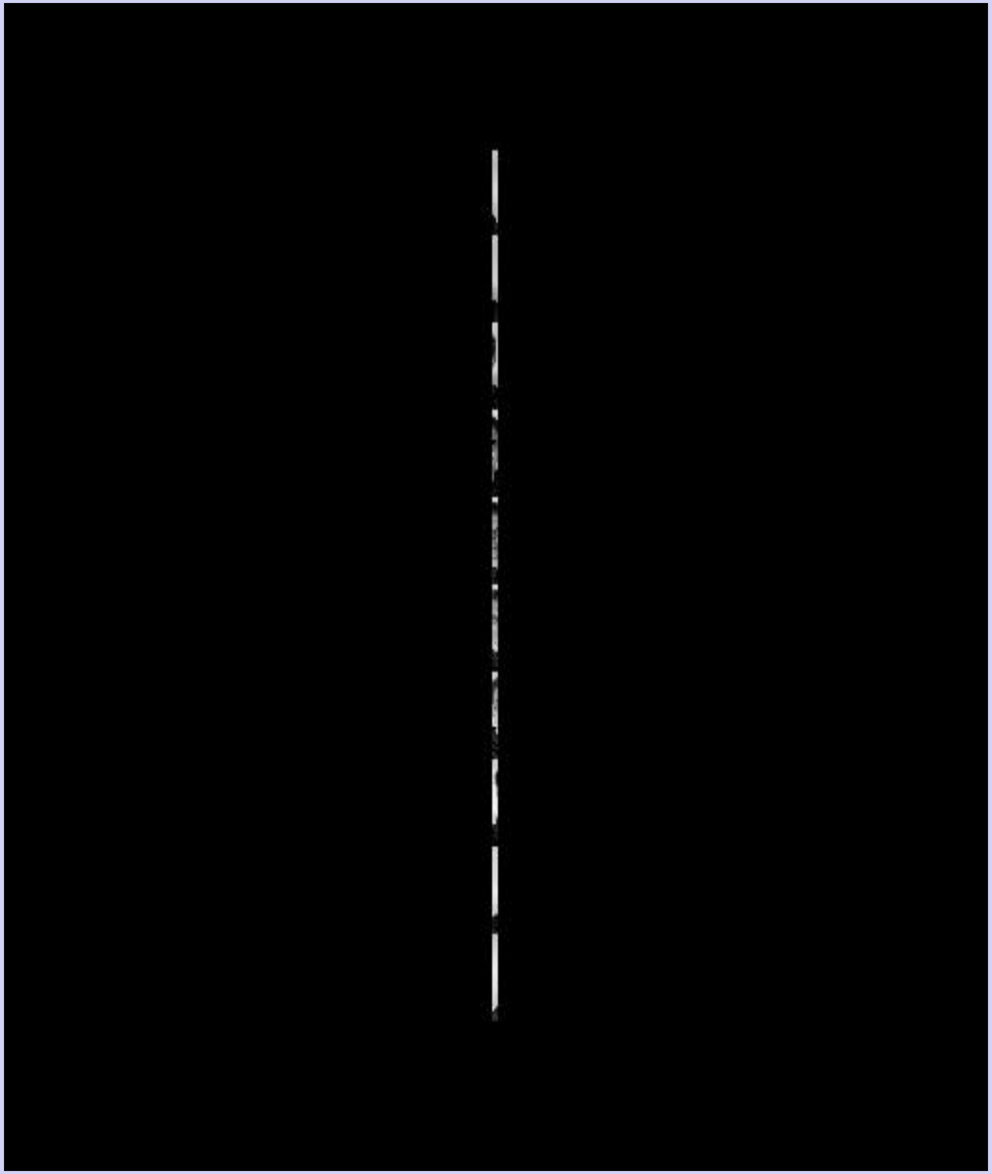
Multi-Object Spectroscopy

- Imaging MOS
- Fiber-fed MOS (pseudo-longslit)



Integral field Spectroscopy

- **Image slicer**



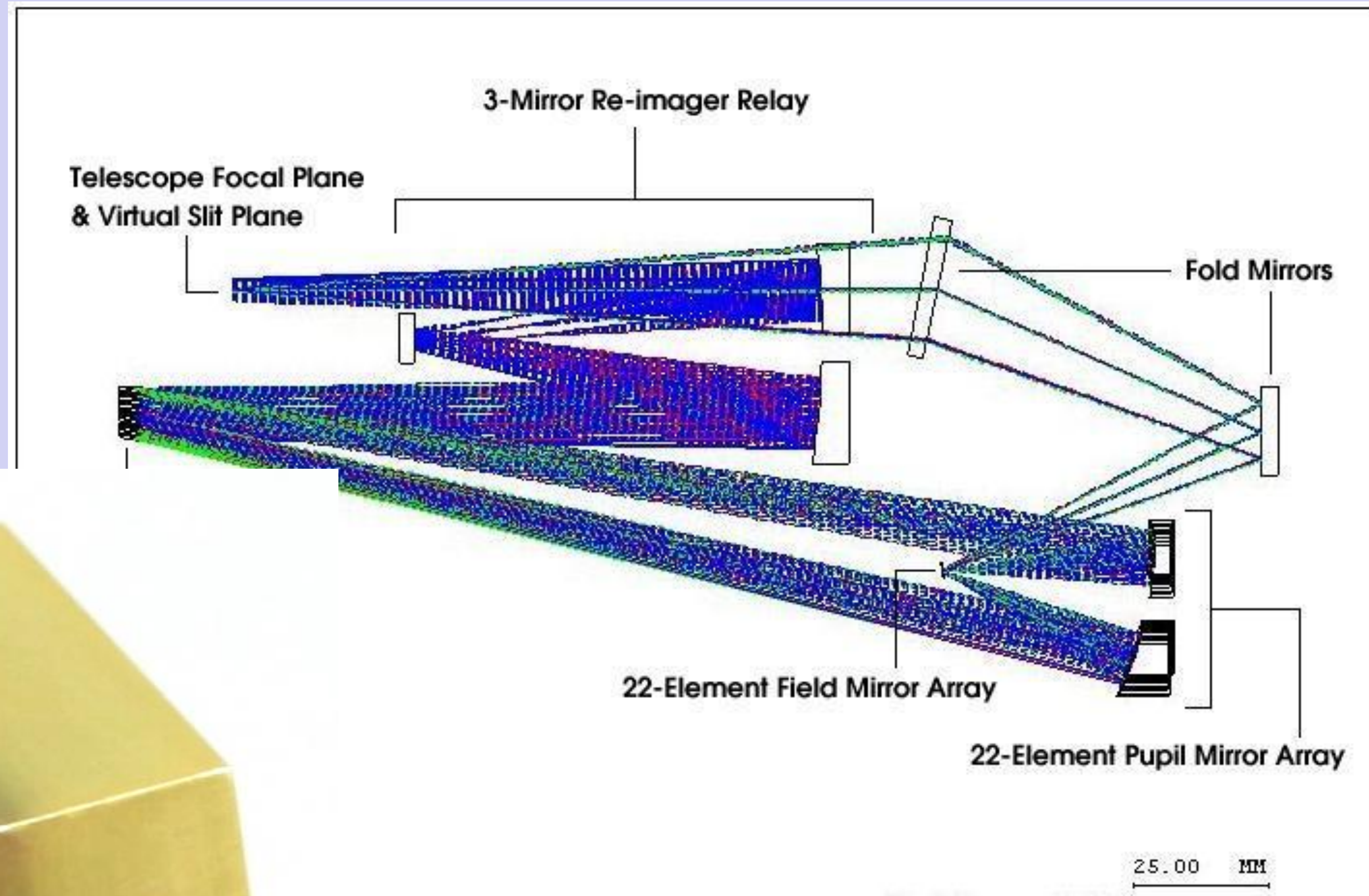
Optical Fiber Feeds

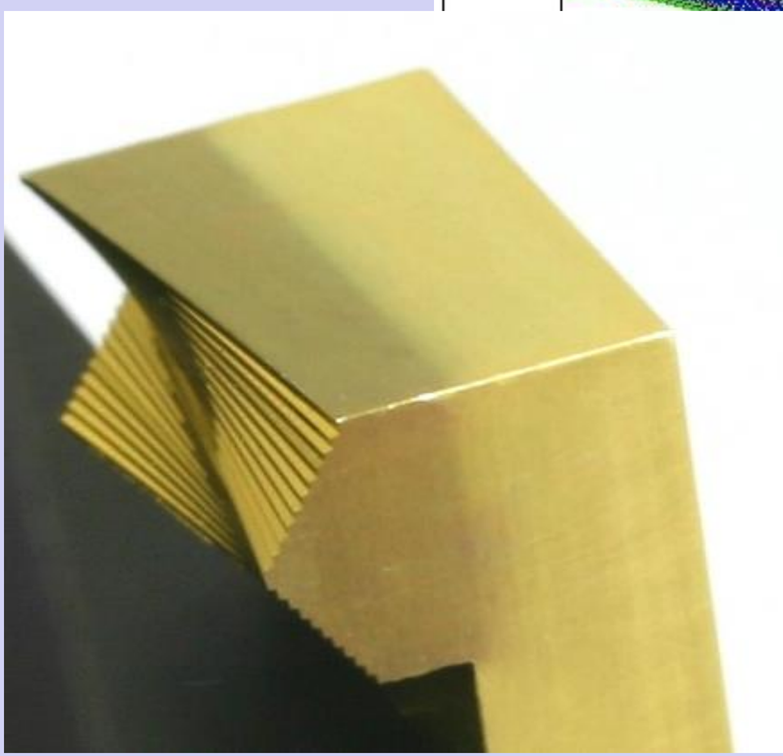
- **Optical fibers can be used as flexible "light pipes" to intercept light at the telescope focal plane and feed to the input focal plane of the spectrograph**
- **Why?**
  - **Move the fibers to have adjustable target positions, but maintain fixed input to the spectrograph**
  - **Fibers can be used to cover a HUGE (degrees) field even on large telescopes, while keeping a simple/small input to the spectrograph**
  - **Can move the spectrograph far from the telescope focal plane (allows for relatively large/massive floor-mounted spectrograph)**

Optical Fiber Feeds - Issues

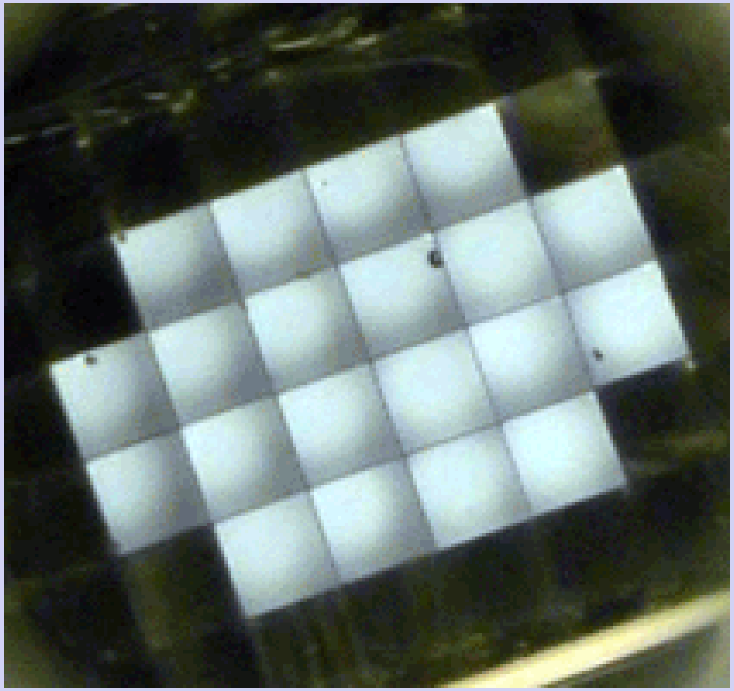
- Fiber transmission is generally good in the optical, but not perfect; transmission not always high for large bandpasses, nor in the IR bandpass
- Focal Ratio Degradation (FRD) – effective f/# at fiber output is larger than input beam from telescope (drives up the collimator and grating size compared to a "standard slit" of the same width)
- Coupling at the telescope – fiber sizes are limited in range (i.e. no 800 μm fibers to cover 1-arcsec at GTC), and in minimum f/# (about f/4 –ish or slower)
  - Microlenses can be placed on the fiber tip to couple larger focal plane area onto small fiber (miniature focal reducer!)
  - Fabrication/alignment are not easy (often result in reduced throughput)
  - Sometimes limited by f/#

Image Slicer

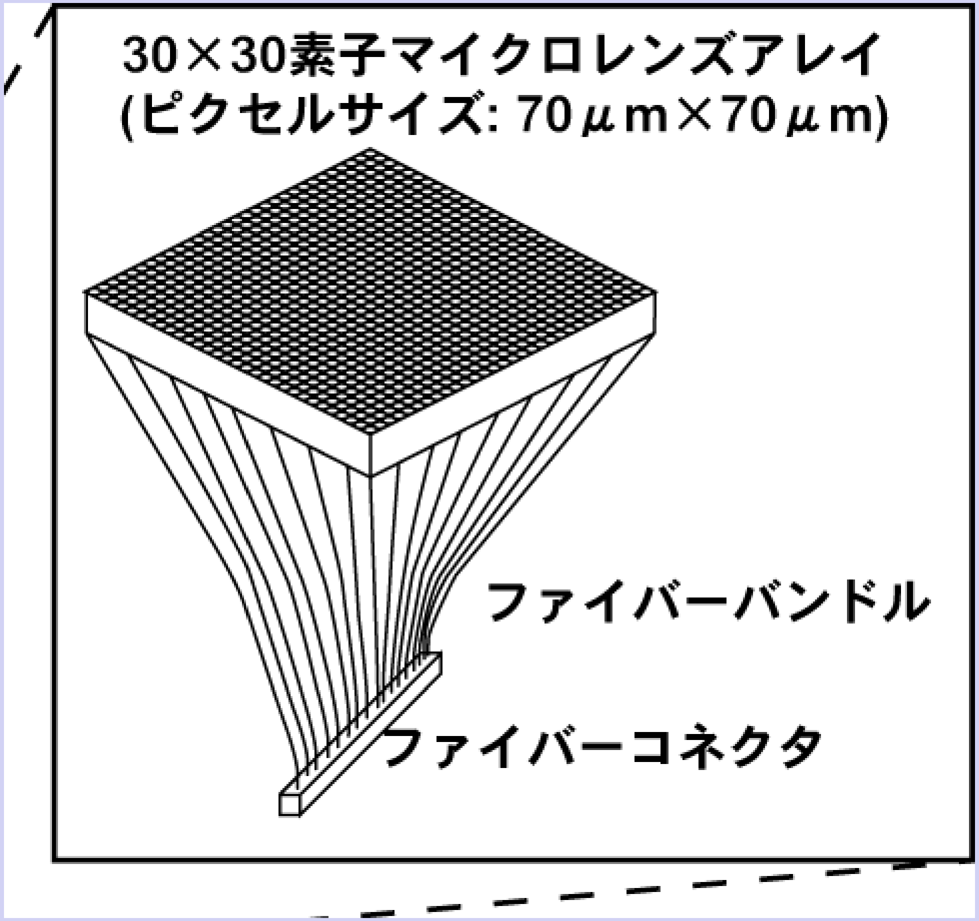




Fiber IFU



http://www.eso.org/instruments/flames/img/IFU_zoom.gif



http://www.kusastro.kyoto-u.ac.jp/~maihara/Faculty/Maihara_70tel_ifu_v1.gif