Units

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AstroTwinCoLo2018
Leiden Observatory

Slides borrowed (with consent) from (with minor edits):
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Swinburne University of Technology, Australia

As waves:

$c = \nu\lambda$ $c = 3\times 10^8$ m/s (in vacuum)

As particles:

$E = h\nu$ $h = 6.63\times 10^{-34}$ J s

Useful quantities:

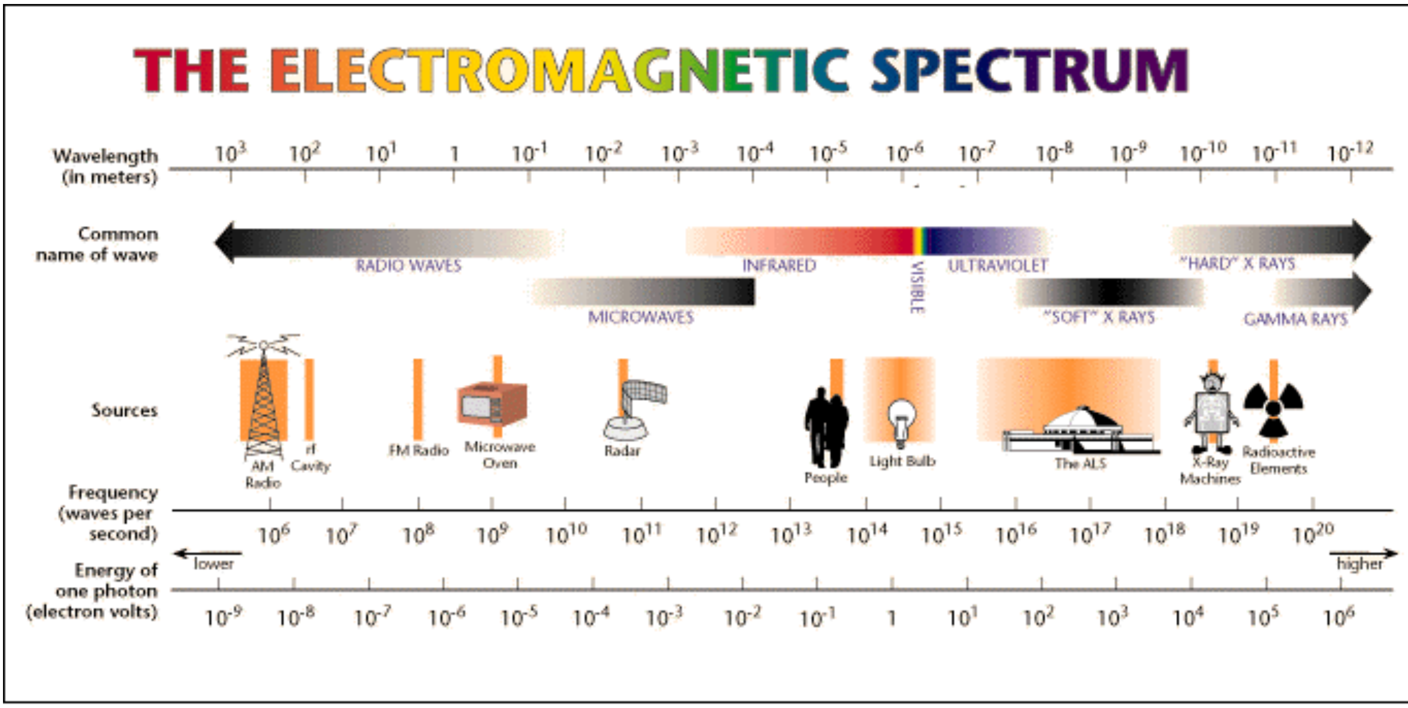
1eV = 1.6×10^{-19} J

1 Angström (Å) = 10^{-10} m

1 μm = 1000 nm = 10,000 Å

1mm → 300 Ghz

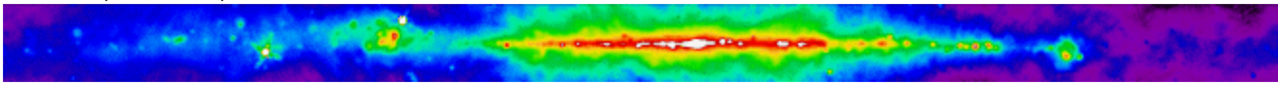
21cm → 1.4Ghz



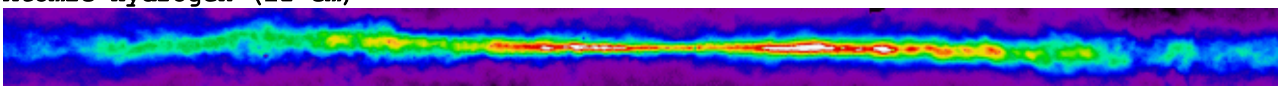
Band	**WaveLength**	**Frequency**	**Other Units**
MF medium frequency	100-1000m	300-3000 kHz	
HF high frequency	10-100m	3-30 MHz	
Radio	20 cm - 20 m	15 MHz - 1.5 GHz	
FM	2.5-3.5 m	85-120 MHz	
ShortWave	20 cm - 2.5 m	120 MHz - 1.5 GHz	
Microwave	0.01-20 cm	1.5-3000 GHz	
EHF extremely high frequency		30-300 GHz	
Far Infrared	20,000-100,000 nm	$3\text{-}15\times10^{12}$ Hz	20-100 μm
Near Infrared	700-20,000 nm	$1.5\text{-}43\times10^{13}$ Hz	0.7-20 μm
Visible	400-700 nm	$4.3\text{-}7.5\times10^{14}$ Hz	4000-7000Å
Red	620-760 nm		
Orange	570-620 nm		
Yellow	550-570 nm		
Green	470-550 nm		
Blue	440-470 nm		
Violet	380-440 nm		
Ultraviolet	4-400 nm	$0.04\text{-}7.5\times10^{16}$ Hz	3-300 eV, 40-4000 Å
Soft XRay	1-4 nm	$0.7\text{-}3\times10^{17}$ Hz	0.3-1 keV
Hard XRay	0.1-1 nm	$3\text{-}3\times10^{18}$ Hz	1-10 keV
Gamma Ray	<0.1 nm	$>10^{19}$ Hz	>10 keV

The Milky Way Galaxy at various wavelengths

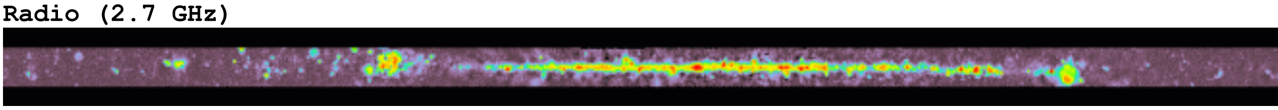
Radio (0.4 GHz)



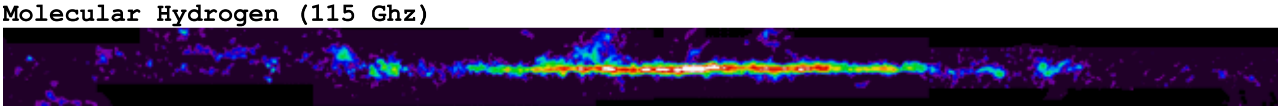
Atomic Hydrogen (21 cm)



Radio (2.7 GHz)



Molecular Hydrogen (115 Ghz)



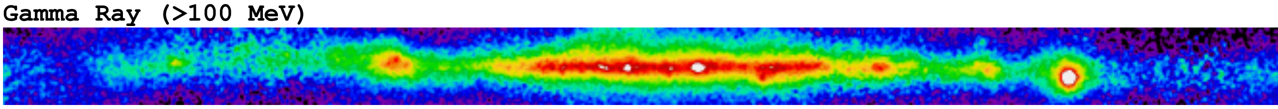
Infrared (IRAS 10-100 μm)

Near Infrared (1-3 μm)

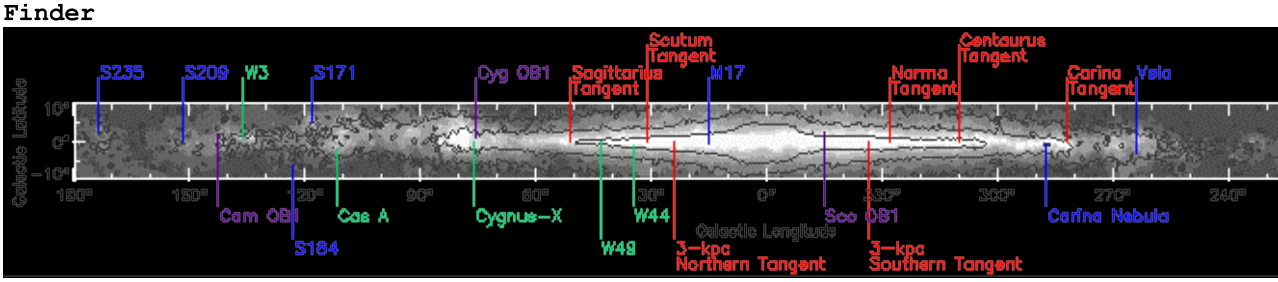
Optical (5000Å)

X-Ray (0.25-1.25 keV)

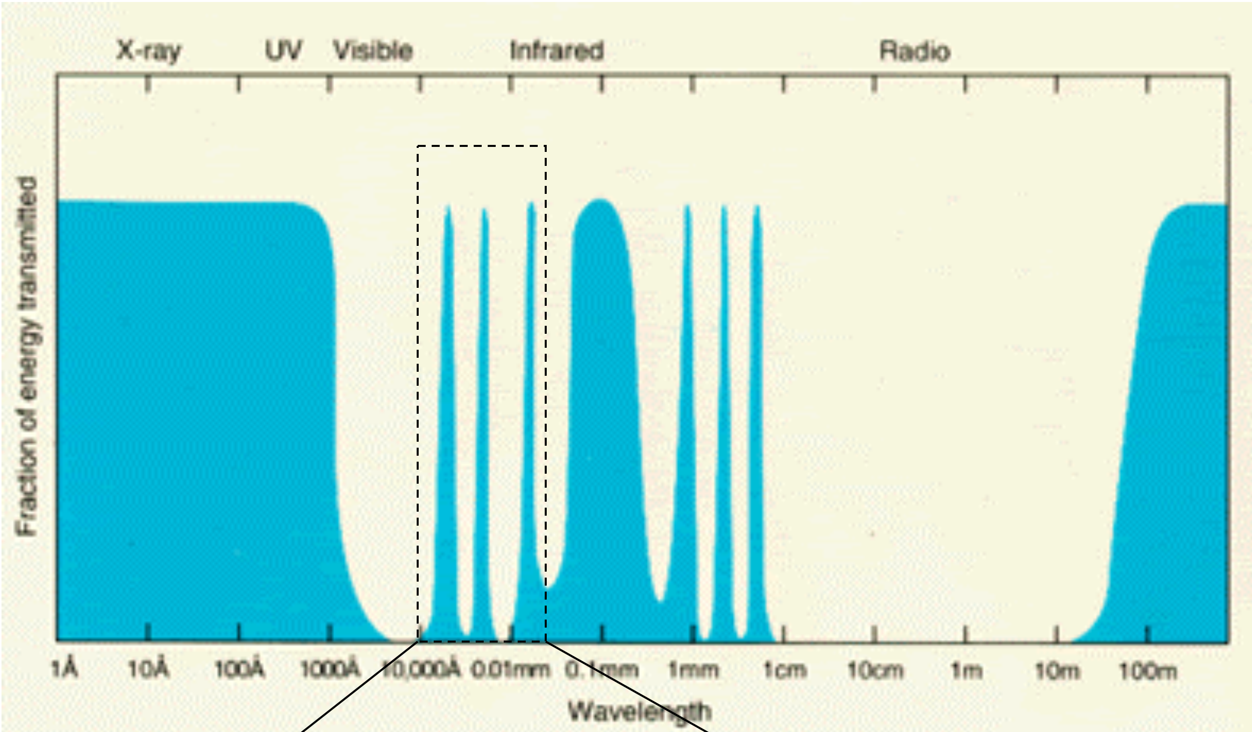
Gamma Ray (>100 MeV)



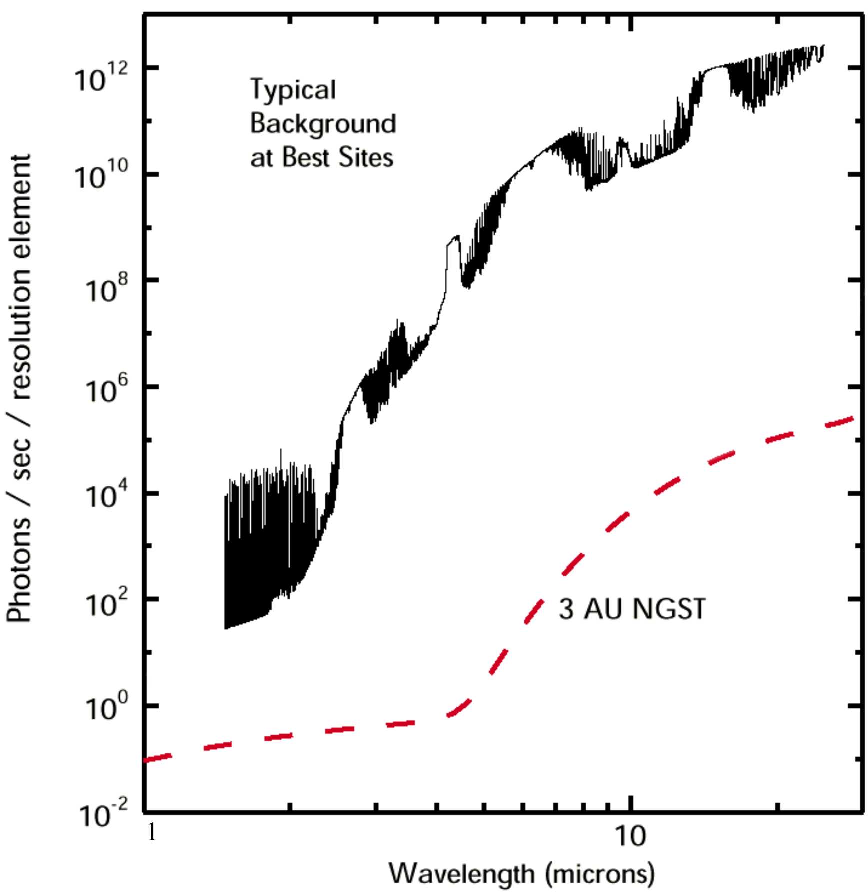
Finder



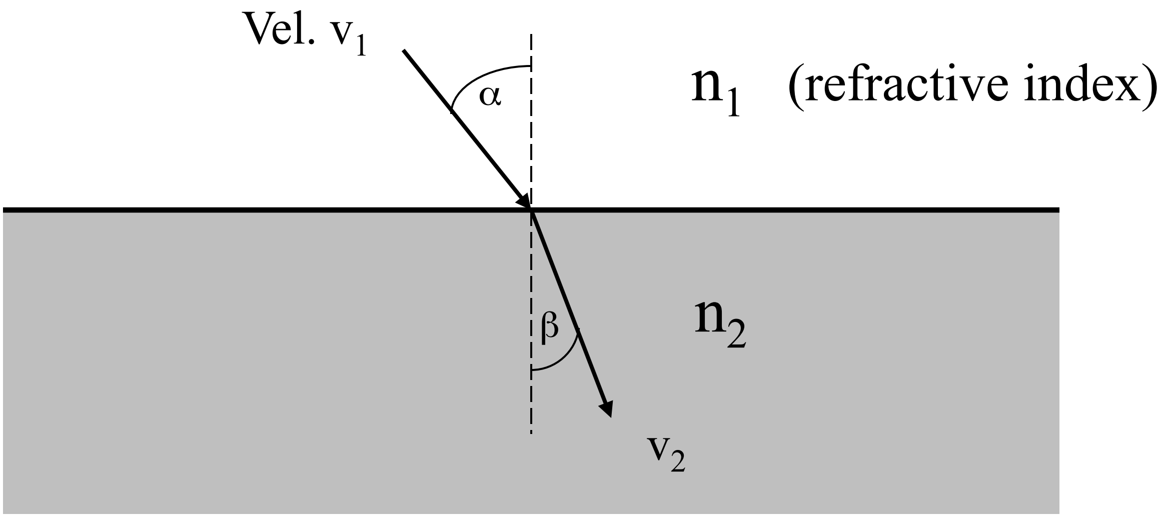
Atmospheric Transmission



Atmospheric *Emission*



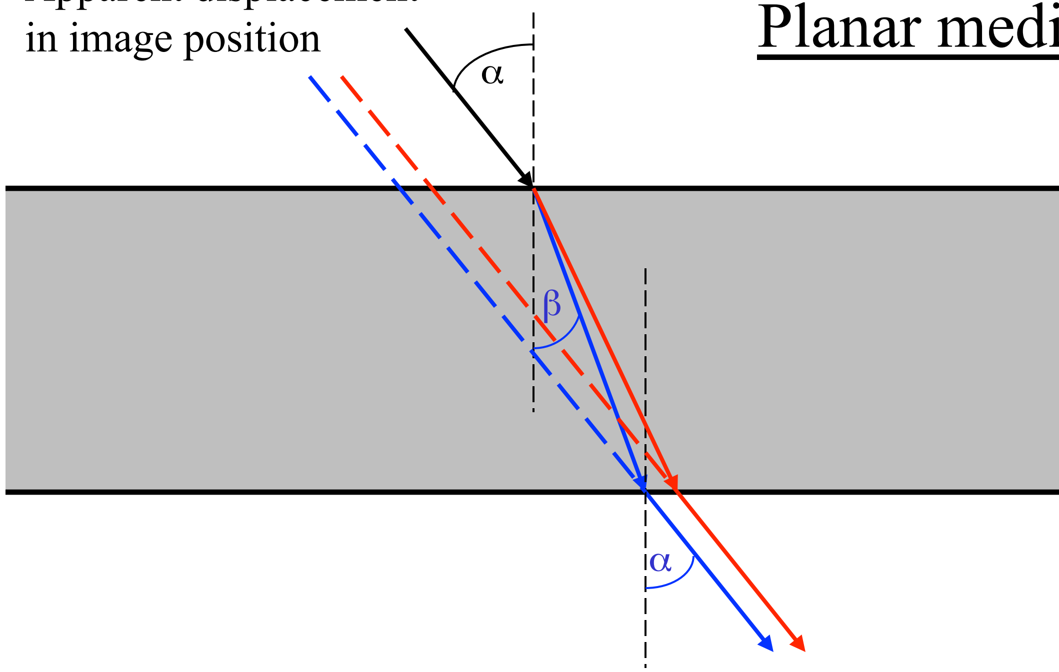
Law of Refraction



Refractive index of medium n = c / v
Vacuum, n=1 by definition
Air n=1.00029 (STP)
Water n=1.33
Common glass n=1.44
Sapphire n=1.77
Diamond n=2.42

Snell's Law: $n_1 / n_2 = \sin\beta / \sin\alpha = v_2/v_1$

Dispersion



Planar medium

Schott BK7 glass (λ, n):

4861Å	1.52237330	(Blue/green, Hβ, "F") ($\Delta n \sim 10^{-2}$)
5876Å	1.51679591	(Yellow, HeI, "D")*
6563Å	1.51431928	(Red, Ha, "C")

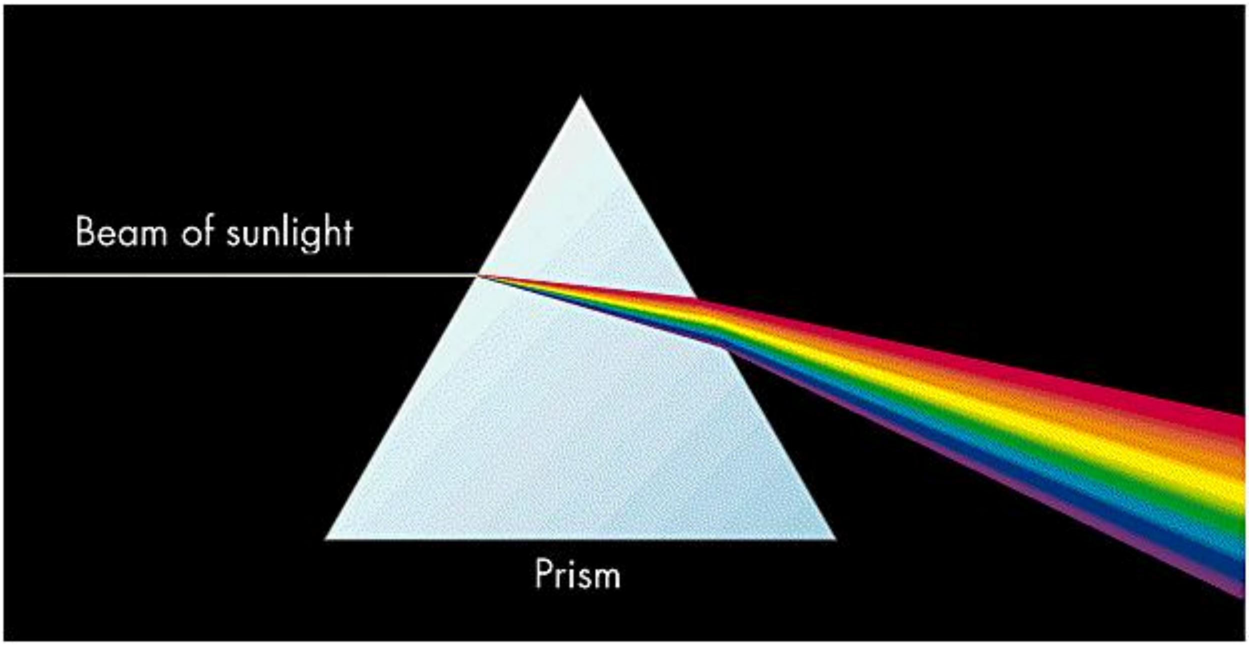
($\Rightarrow \nu_0$ = 884Å)

"Constringence"
"Abbe Number"
Range 20⇒60
64 for BK7

Disp. Power = $(n_F - n_C)/(n_D - 1) = 1/\nu$

* Also Na D 5892Å

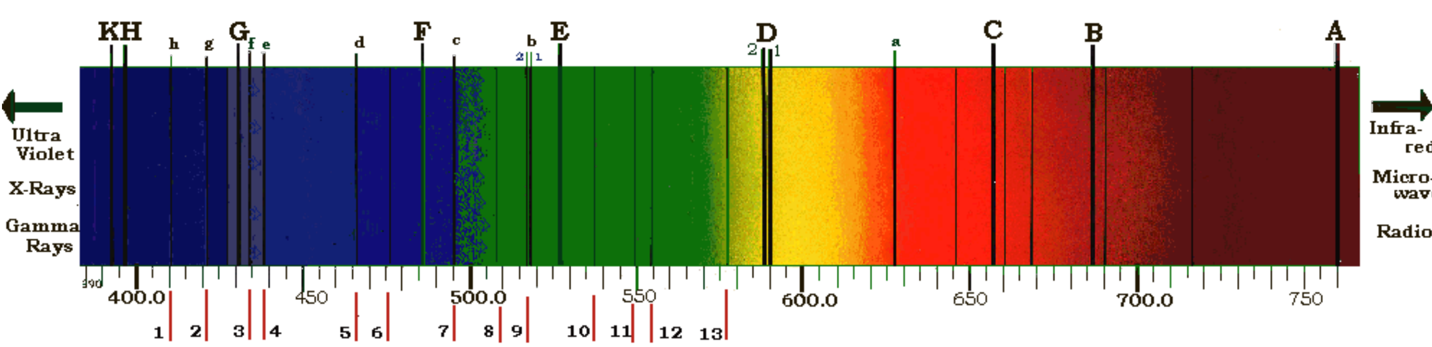
Dispersion by a prism



Discovered by Sir Isaac Newton

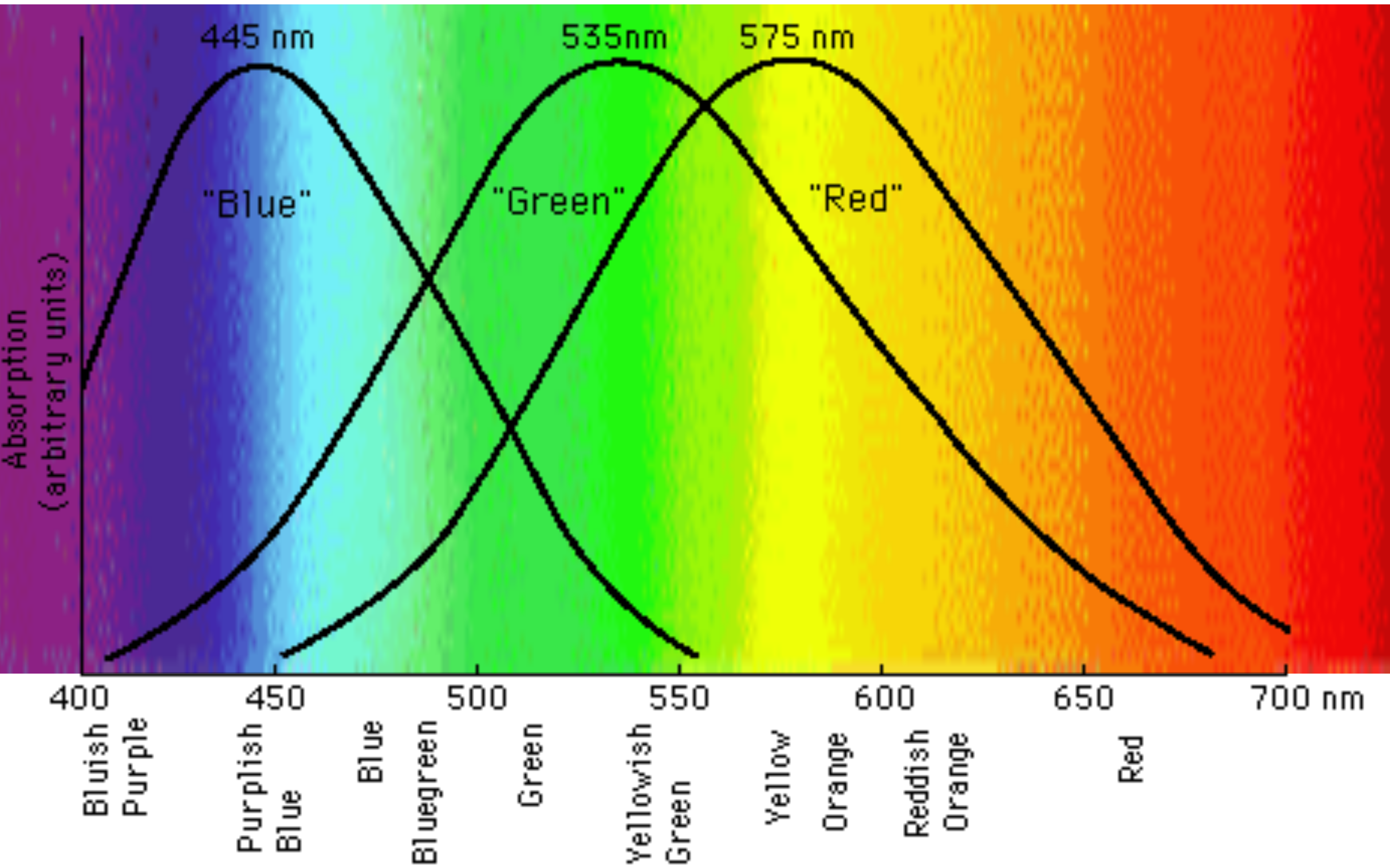
Prismatic dispersion of sunlight – first *spectrograph*.

Revealed Franhöfer lines in Solar Spectrum



Digression - *color*

Response of the human eye *cones*



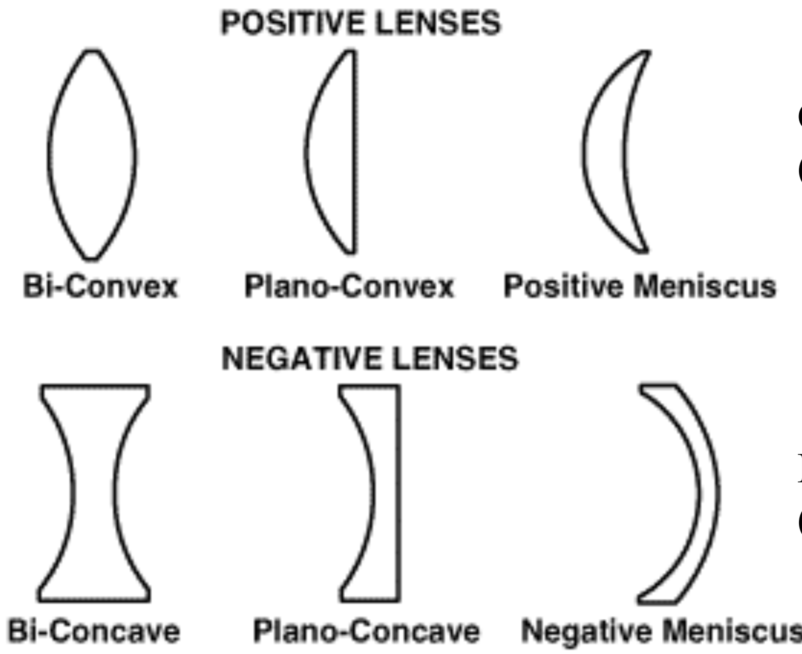
Red/Green/Blue cones all see broad range of wavelengths – very much like an astronomical filter

Color is a perception, e.g. the NaD line (5892Å) looks "yellow" to us – but what would it look like to a eagle with *five* cones?

2dF Micro Prisms

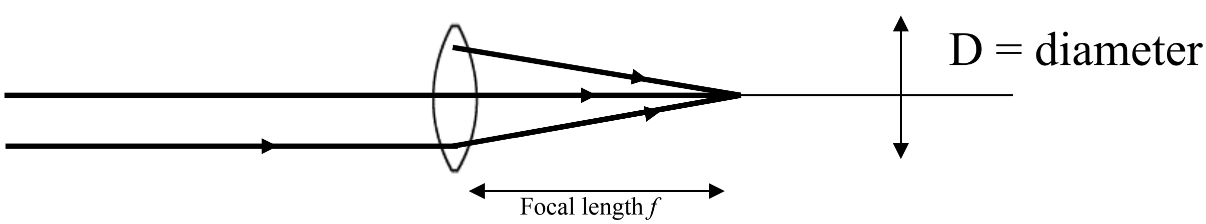
Lenses - types

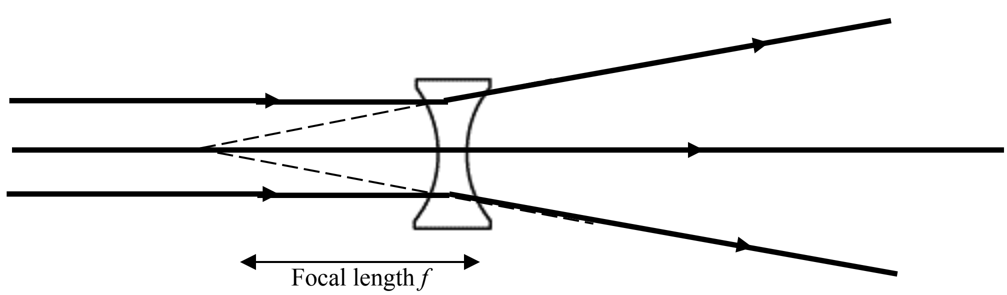
Or "Equiconvex/Equiconcave"



Converging
(thin in center)

Diverging
(thin in center)

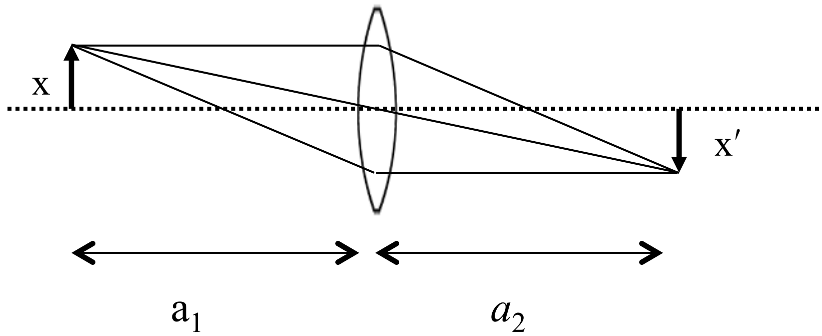




'Power'
= inverse

Focal ratio = D/f, e.g. "f/4" means D/f = 1/4

Thin Lens formulae



Focal length: $$\frac{1}{a_1} + \frac{1}{a_2} = \frac{1}{f}$$

a_2 & f –ve if lens diverging

Magnification $= -a_2 / a_1$

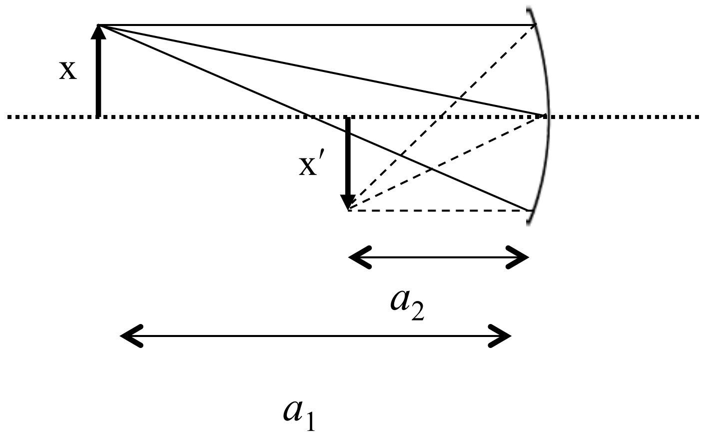
Multiple lenses: $$\frac{1}{f_{tot}} = \frac{1}{f_1} + \frac{1}{f_2}$$

Lens makers formula:

$$\frac{1}{f} = (n-1) \left[\frac{1}{r_1} + \frac{1}{r_2}\right]$$

(r_1,r_2 = radii of curvature, negative for diverging lens)

Mirror formulae

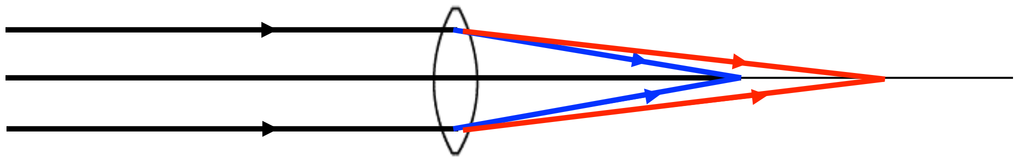


Focal length: $$\frac{1}{a_1} + \frac{1}{a_2} = \frac{1}{f} = -\frac{2}{R}$$

(Convention: R negative, f positive for converging mirror, reverse for diverging)

Magnification $= -a_2 / a_1$
(same as lens)

Chromatic Aberration of a lens



Since n = f(λ), so is *f*

Does not affect mirrors

Solution: Achromatic doublet

Cancels at ***two*** wavelengths λ_1,λ_2

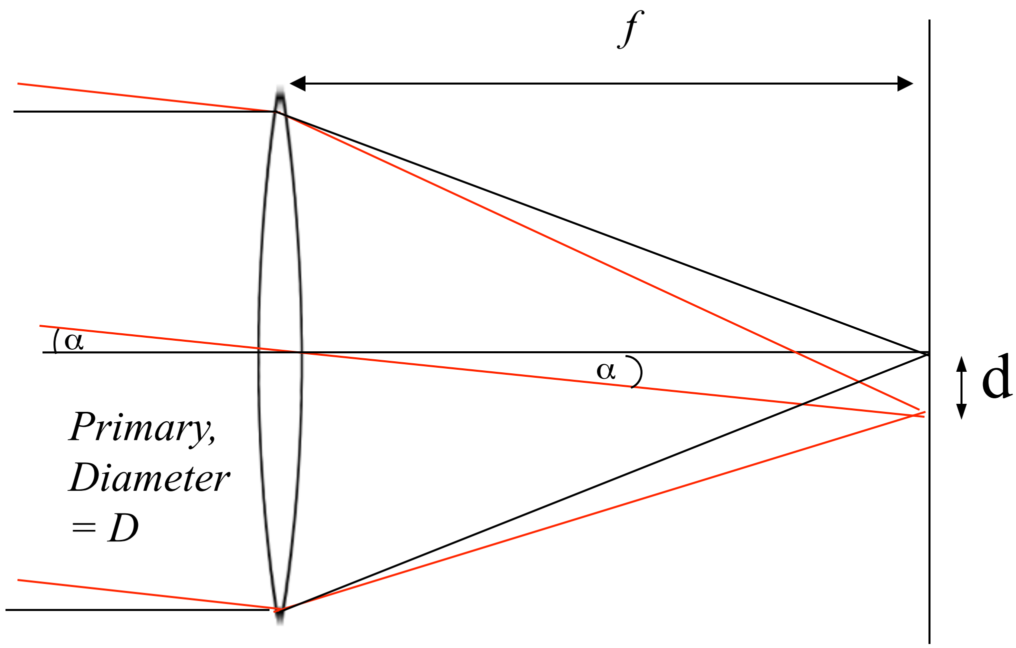
(choose blue/red)

ν= costringence

$$f_1\,\nu_1 = -f_2\,\nu_2$$

So need +ve and –ve lens with two different focal lenghts, e.g. flint and crown glass

f/ratios



"The ARC 3.5m is an f/10 telescope"

Means F = f/D = 10 in *final beam*

Scale: dist. d = f tan α = DF tan α

Small F:

"Fast beam," small image,

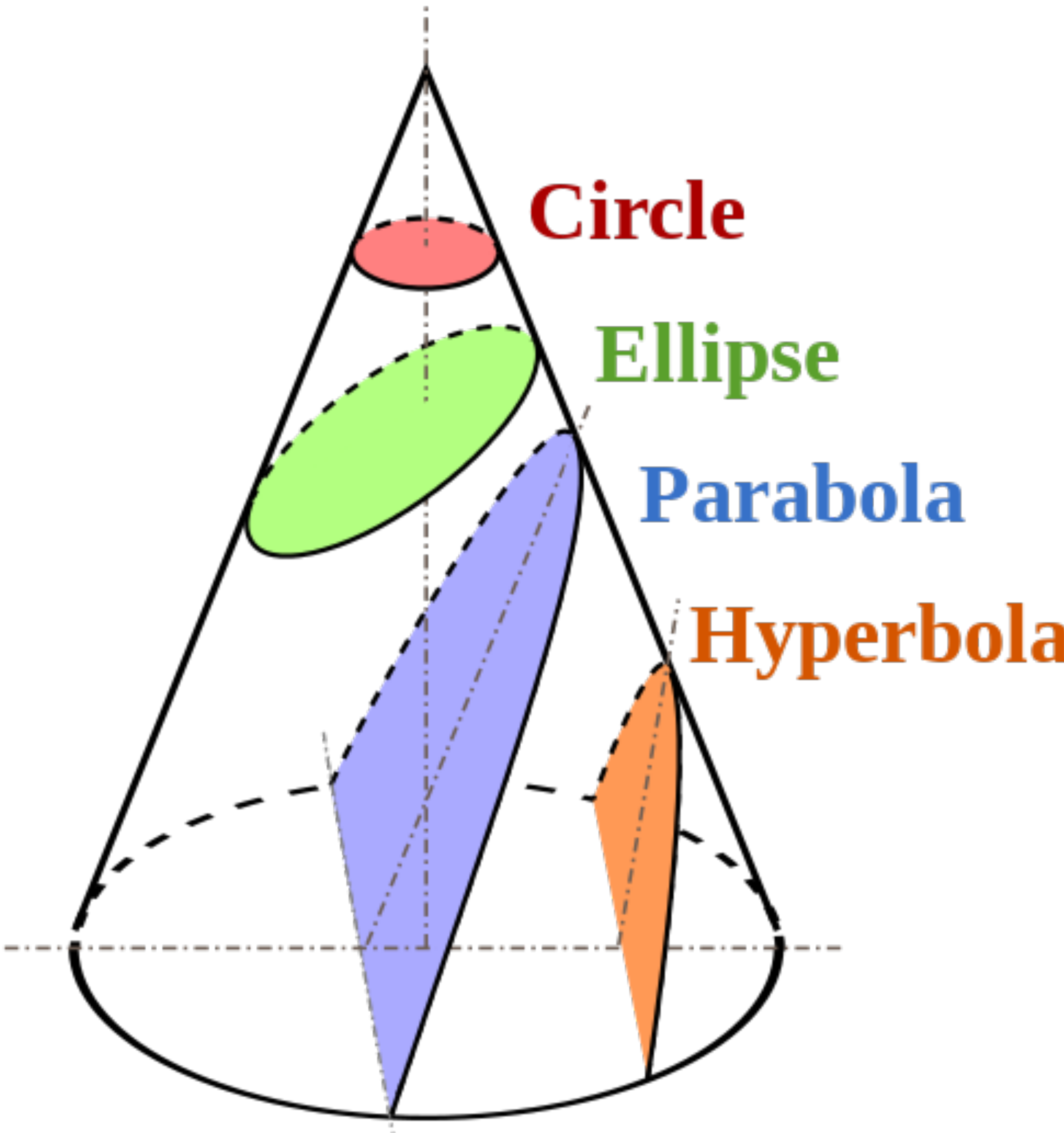
compact design

More aberrations (small angle approx. ⇒ bad)

Large F:

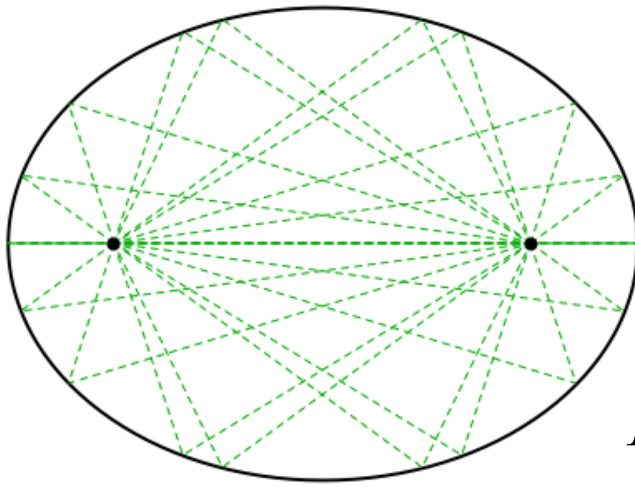
"Slow beam," large image, less aberrations

Conic sections

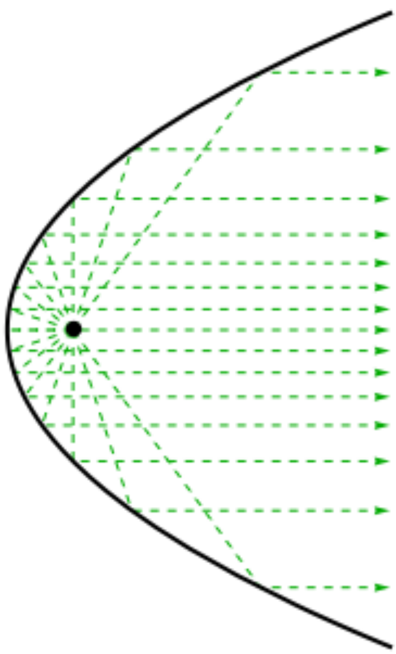


All have a *focusing* property for reflected rays

Conic sections: focus

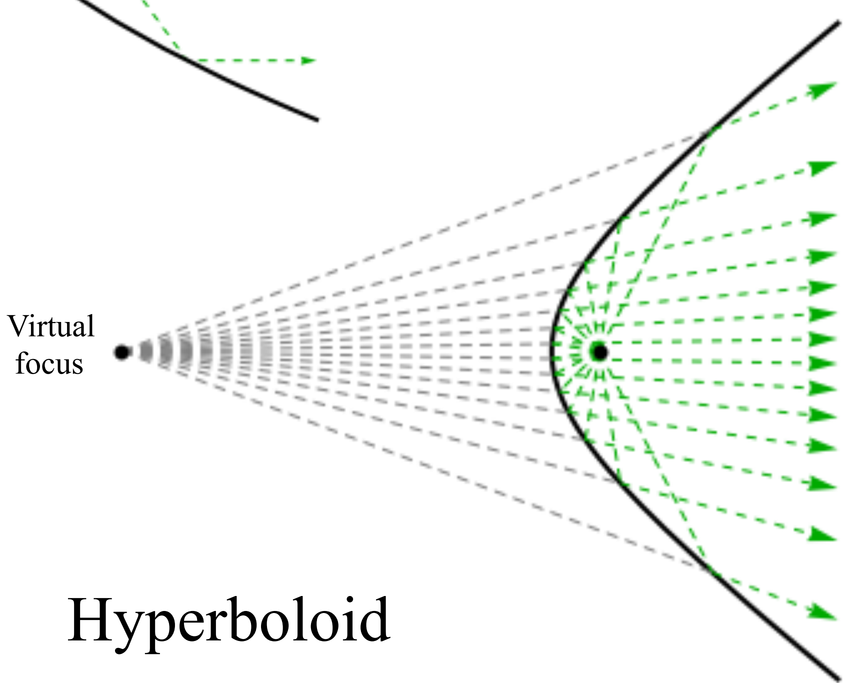


Ellipsoid



Paraboloid

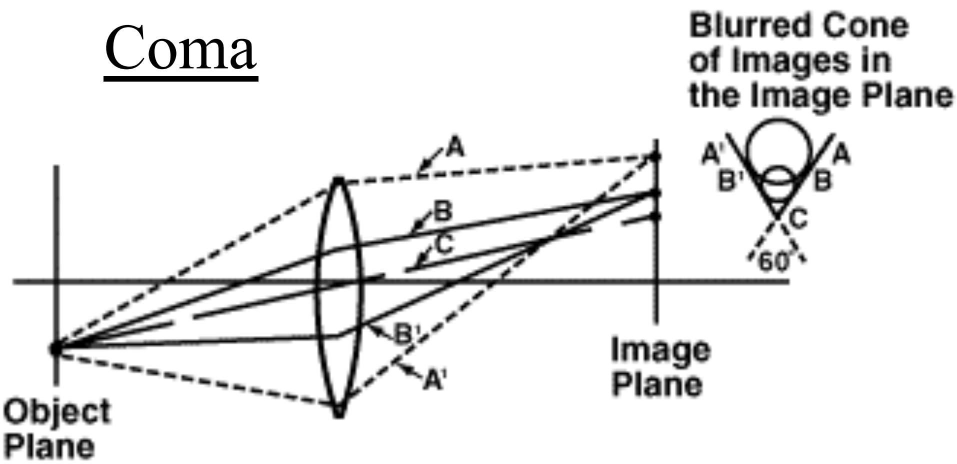
Match multiple mirrors in optical train by having shared focal point (e.g. Cass telescope parabolic focus feeds convex hyperbola).

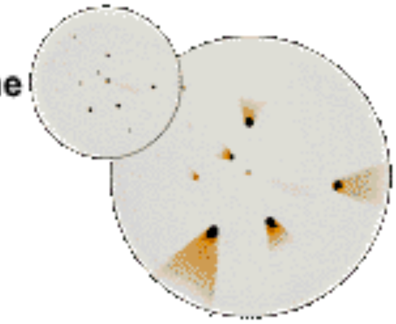


Hyperboloid

Coma & Astigmatism

Coma



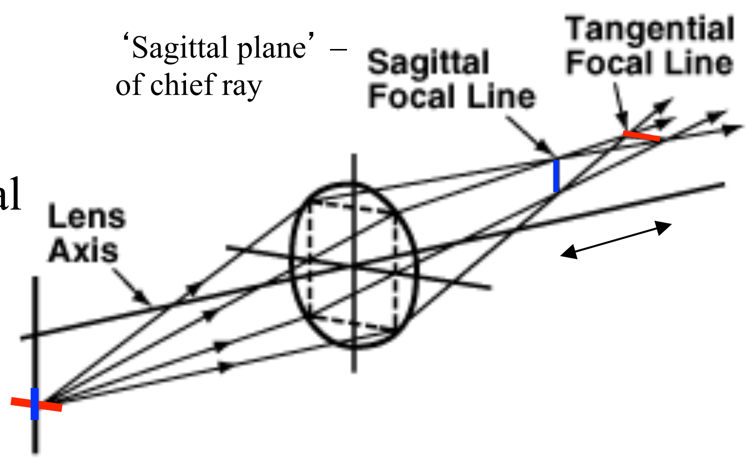


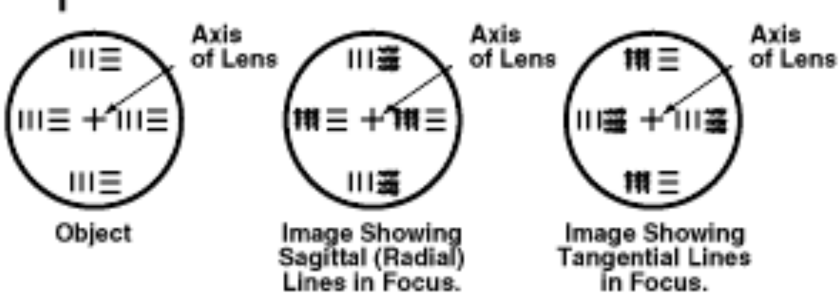
Point present a comet-shaped appearance.

Paraxial and peripheral rays (off axis) have different magnification

Astigmatism

Sagittal and Tangential rays have different focal lengths (off-axis circle projects on lens asymmetrically)



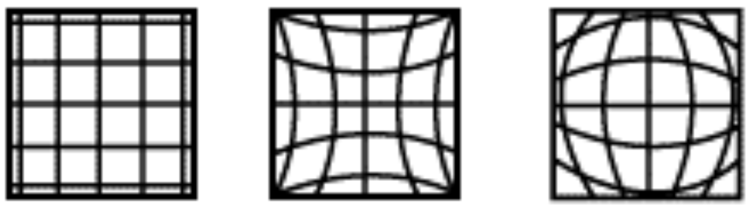


Note: ***is symmetrical*** wrt rotations (this is For perfect spherical lens)

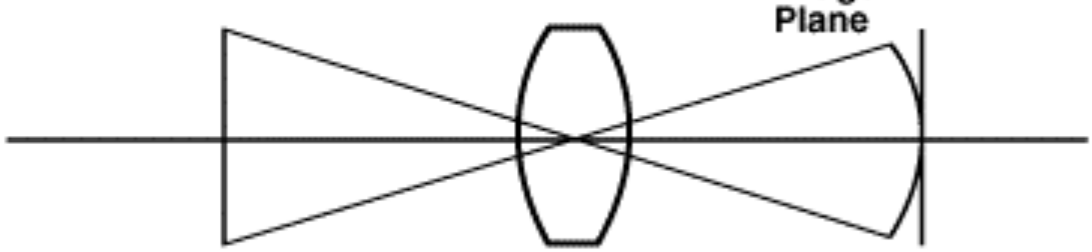
Karl's eyes (at ∞)!

Distortion

In the absence of spherical, comatic and astigmatic aberrations you still have:

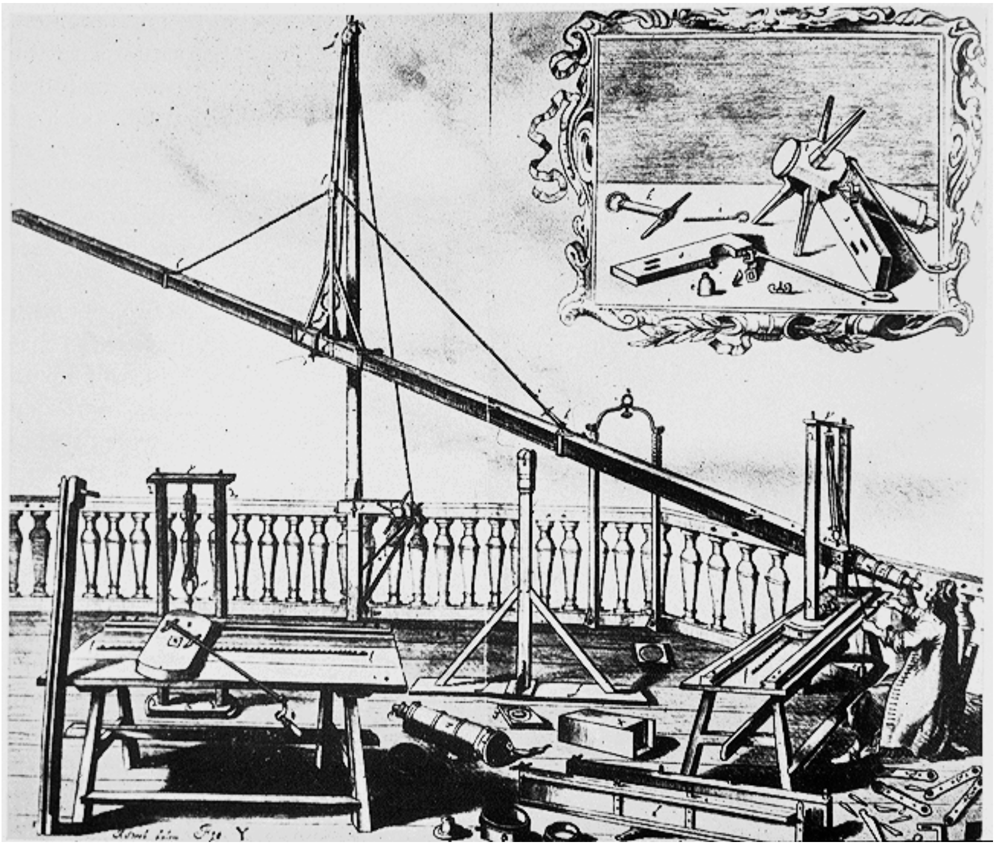


Field curvature

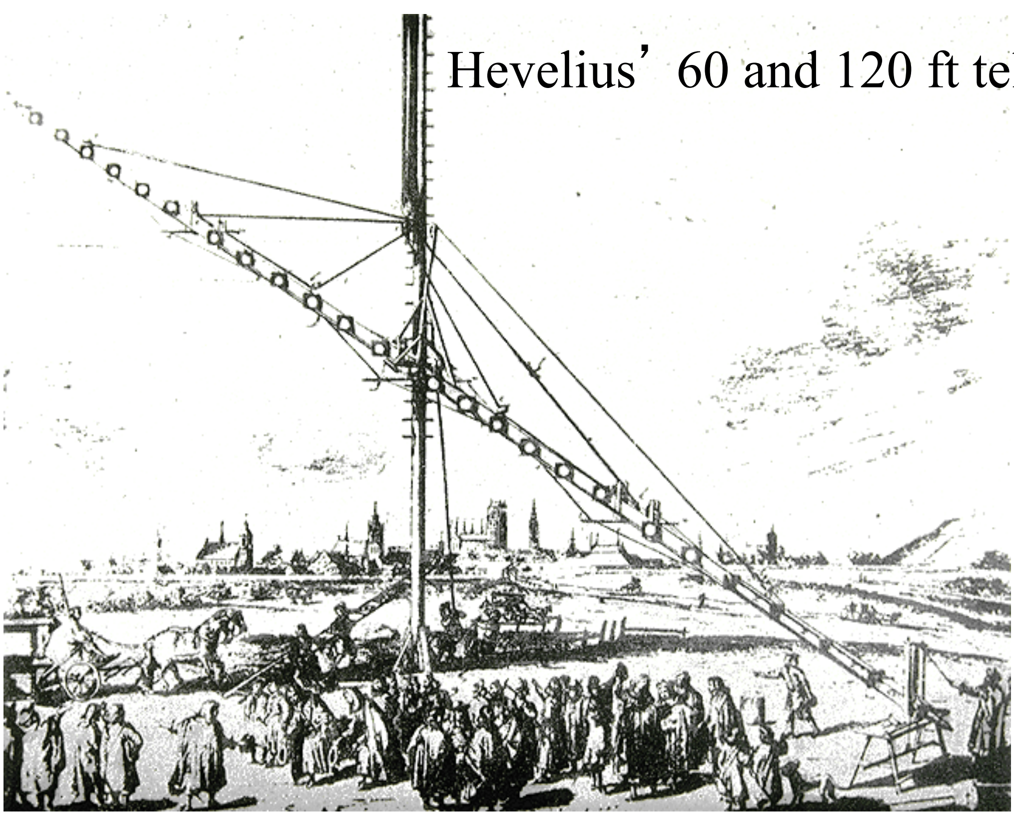


e.g. wide field Schmidt telescopes, *bend* the photographic plate to match the field curvature

Early telescopes!

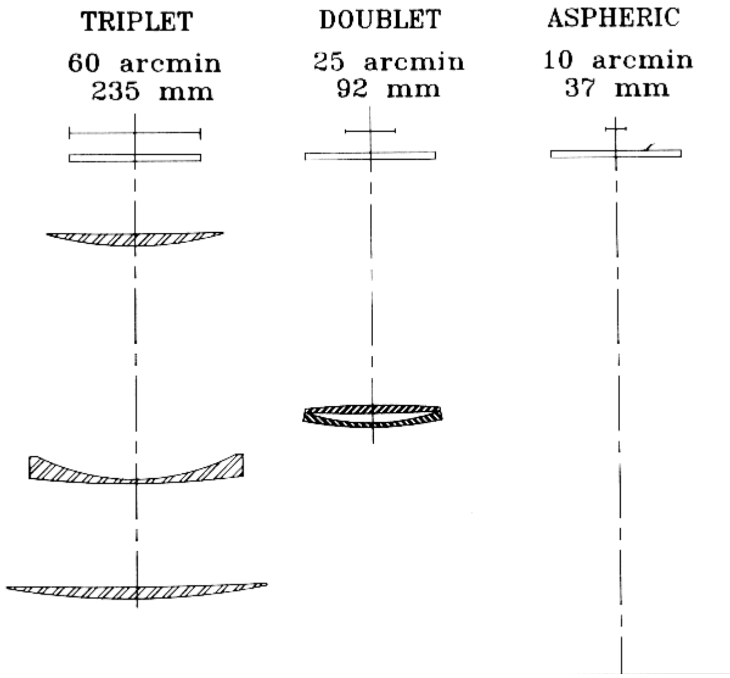


The first telescope was built by Dutch lensmaker Hans Lippershey in 1608.

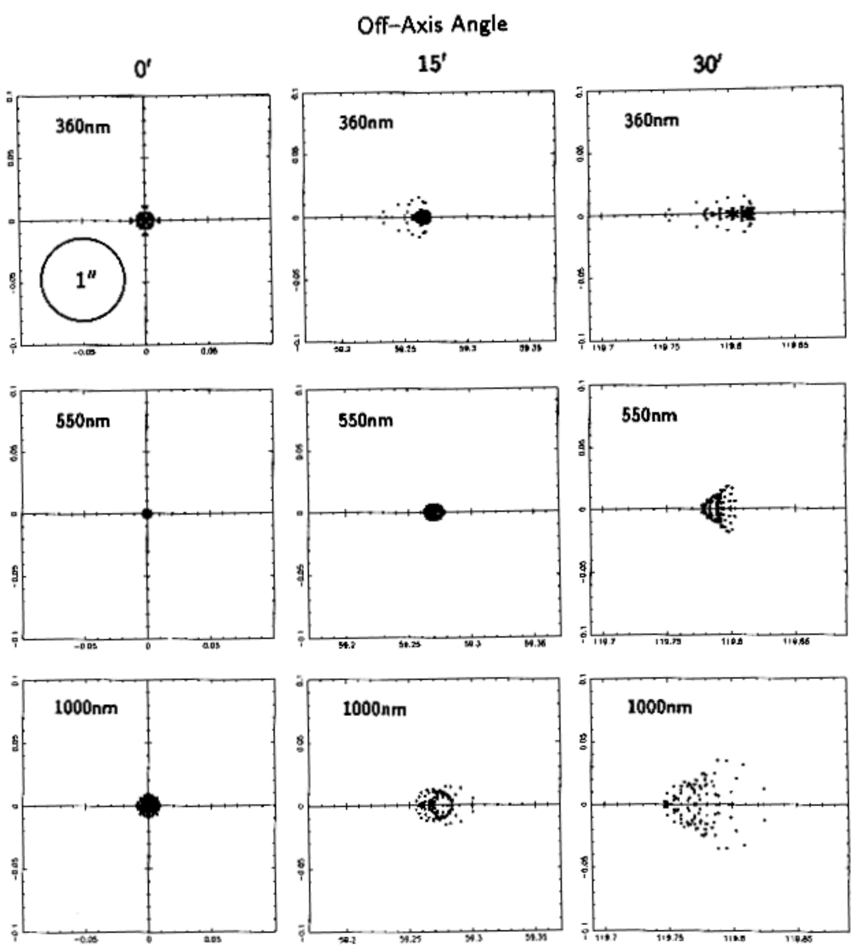


Hevelius’ 60 and 120 ft telescopes, 1673

Modern wide field imaging



At f/3.3 focus of 3.9m AAT, note ***hyperbolic*** primary – 8 arcsec images without corrector! (Designed for Cass use with hyperbolic secondary)



‘Spot’ diagrams for triplet corrector

Optical Telescopes

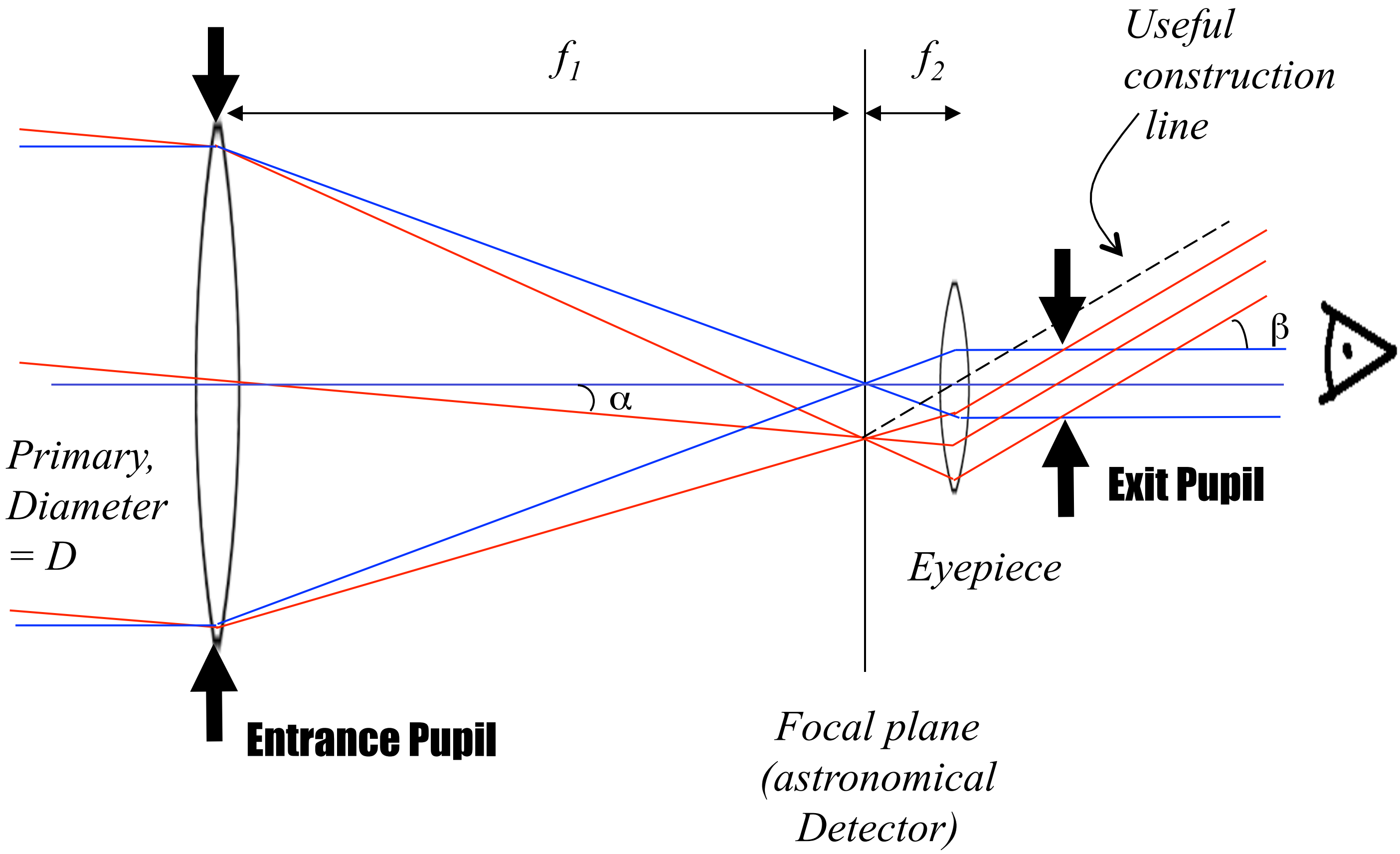
Large telescopes:

- Use mirrors
- Paraboloid gives perfect on-axis images
- No spherical abberation
- No chromatic abberation
- Mirror can be back supported
- Only *surface* needs to be good
- Actively support a mirror

Sizes:

- 4-5m common (ARC, KPNO,…)
- 6-10m: Magellan, Gemini, Keck
- >10m: plans for 20-100m's!

Basic telescope



α=angular size on sky of two points

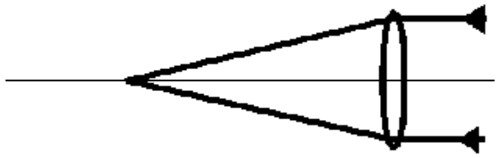
Size of image on focal plane = $f_1 \tan \alpha = f_2 \tan \beta$

Angular mag. $M = \tan \beta / \tan \alpha = f_1 / f_2 \sim \beta/\alpha$

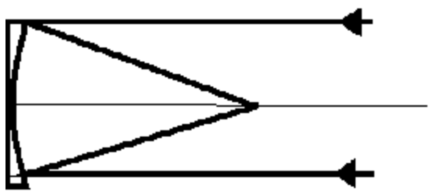
Pupil size P = D / M (human eye ~ 3 mm)

Scale at focal plane, e.g. ARC 3.5m at f/10
Focal length = 35m
Size of 1 arcsec disk = f_1 tan(1 arsec) = 170 μm

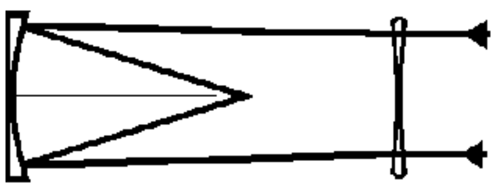
Telescope Focusing Types



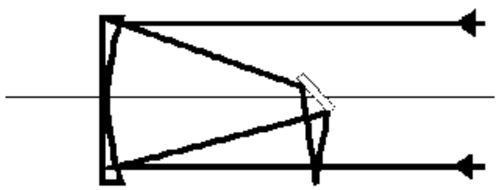
Refracting - uses refraction from lenses to focus the light. Not often used in larger telescopes due to the problem of correcting chromatic aberration.



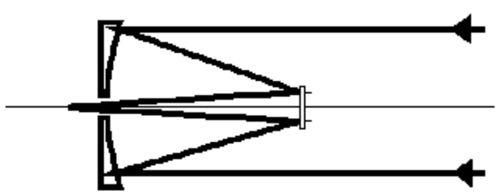
Prime focus - has shortest focal length which is good for observing faint objects. A problem is you have to sit inside the telescope.



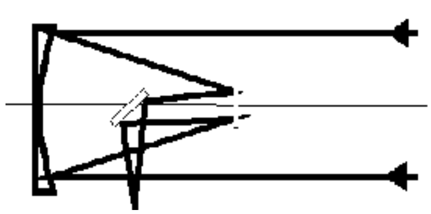
Schmidt focus - uses a lens to correct for spherical aberration of a spherical mirror. Can make a wide field of view and a short focal length hence it is good for surveys of the sky.



Newtonian focus - minimizes the amount of light blocked at the focus. Used in the least expensive amateur telescopes.

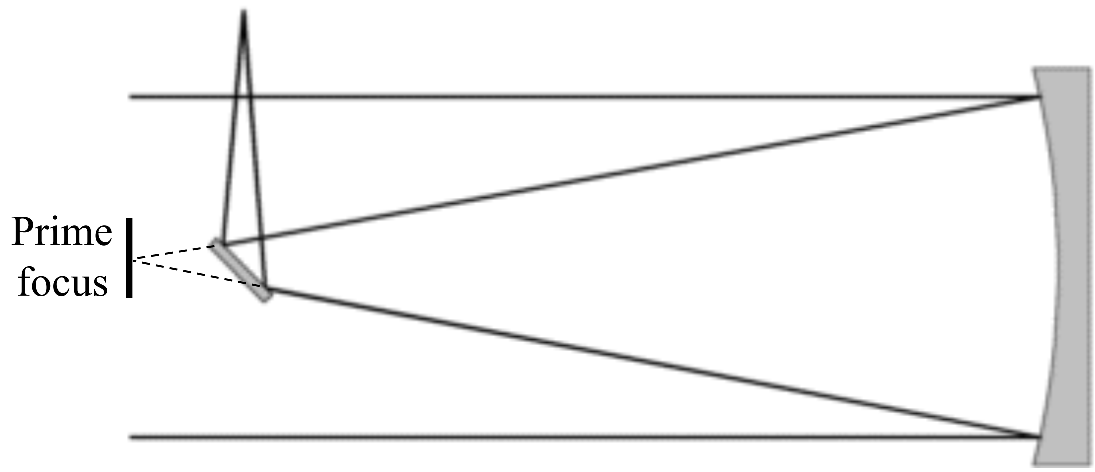


Cassegrain - intermediate in focal length between Prime and Coude for a given mirror. Instruments out of the telescope. Used in the HST.



Coude focus - longest focal length for a given objective mirror. This is good for making a high resolution image of distant objects.

Newtonian Telescope

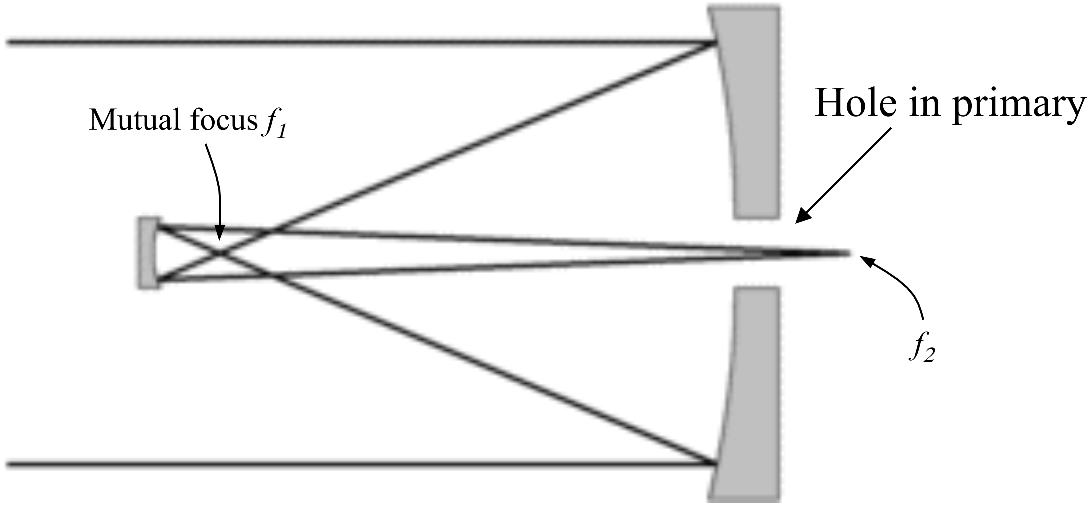


Primary: paraboloid, Secondary: flat

Easiest to make, strong coma for faster than *f/4*

Prime focus popular for wide field (short focal length gives small scale) – note modern PF telescopes are more complex than simple Newtonian

Gregorian Telescope



Primary: *paraboloid*, Secondary: *ellipsoid*

Two concave surfaces (easier to figure)

f_1 is the focus of the paraboloid

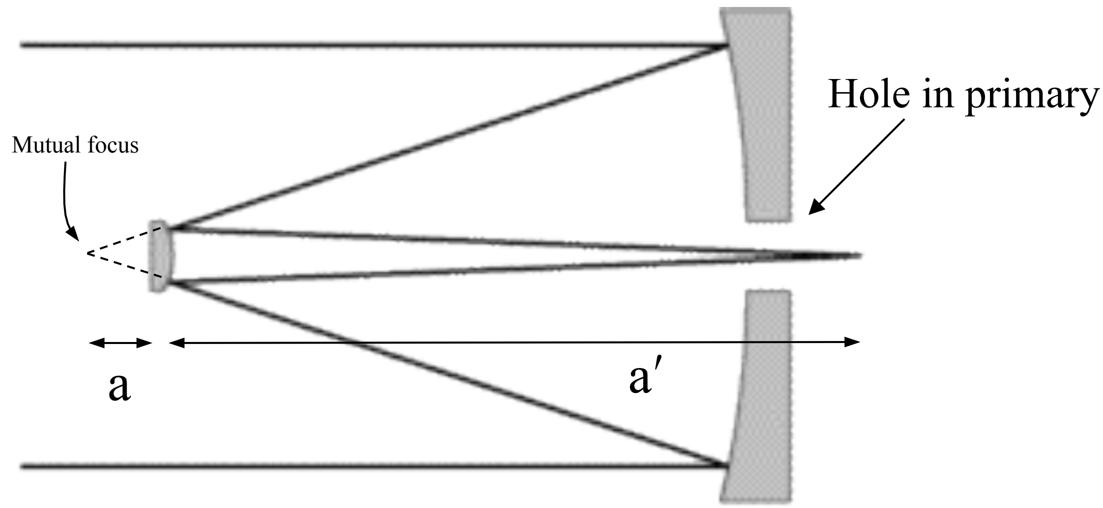
f_1 and f_2 are the two foci of the ellipsoid secondary

$\Rightarrow f_2$ is an exact focus for the light of the combined system (coming from ∞)

Two concave surfaces (easy to figure)

Cassegrain Telescope

e.g. Wilson 2.5m, Palomar 5m



Primary: *paraboloid*, Secondary: *hyperboloid*

Secondary is convex – difficult to figure

Telescope is more compact than Gregorian

Strong coma

Focal length of system increased

$$f_{sys} = (a'/a)\, f_{tel}$$

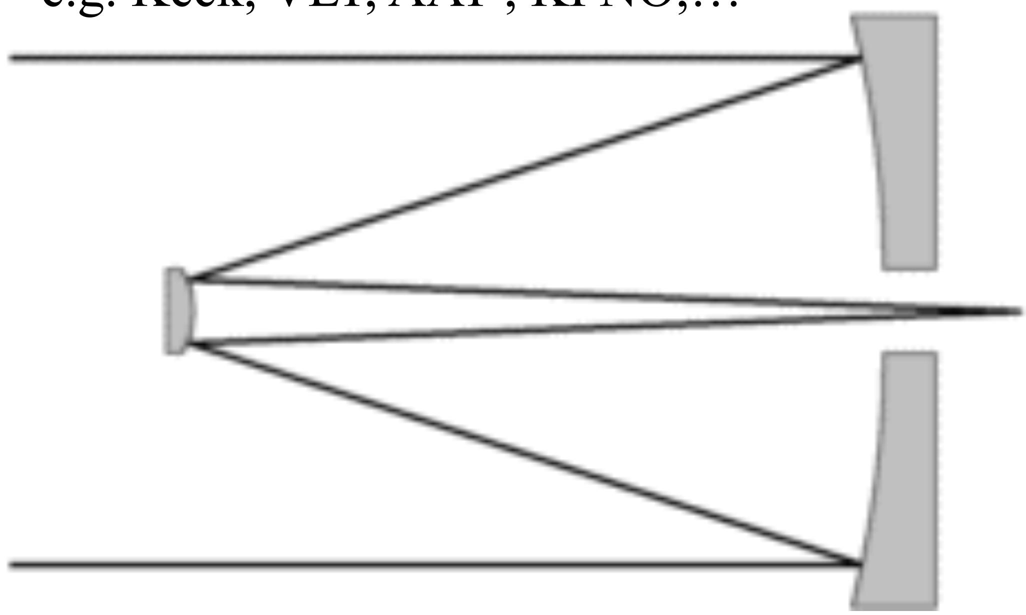
Use final focal ratio f_{sys} for things like computing image scales etc.

"We produce an image at f/8"

Almost always refers to the primary optic

Ritchey-Chrétien

e.g. Keck, VLT, AAT , KPNO,…



<u>Primary</u>: *concave hyperboloid*

<u>Secondary</u>: *convex hyperboloid*

Complex surfaces, but gives zero coma!

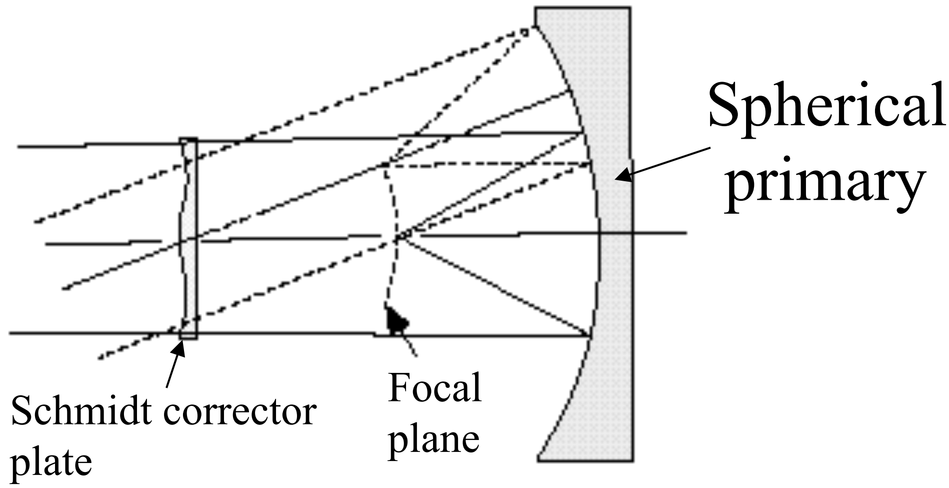
Used for wide-field imaging

Extra-corrector lens can remove astigmatism + field curvature

$\Rightarrow$ No aberrations, e.g. HST

Wide PF field (with corrector), e.g. 2dF/AAT

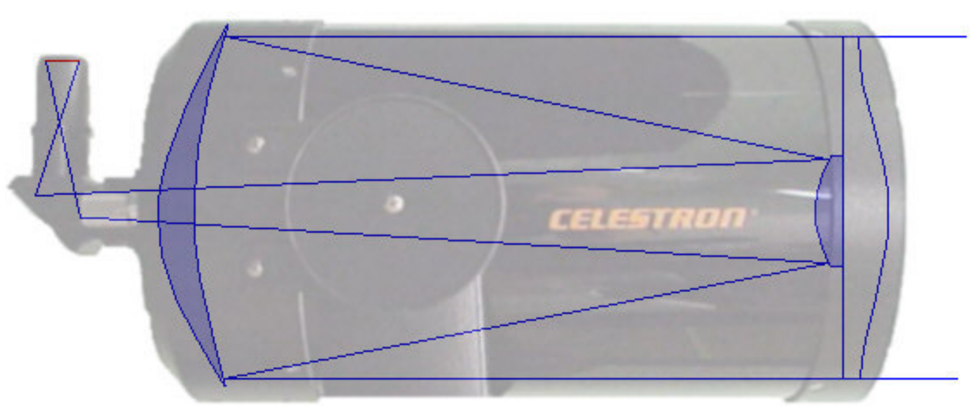
Schmidt Camera



Aspheric refracting element removes spherical aberration, catadioptric design (i.e. lens+mirror)

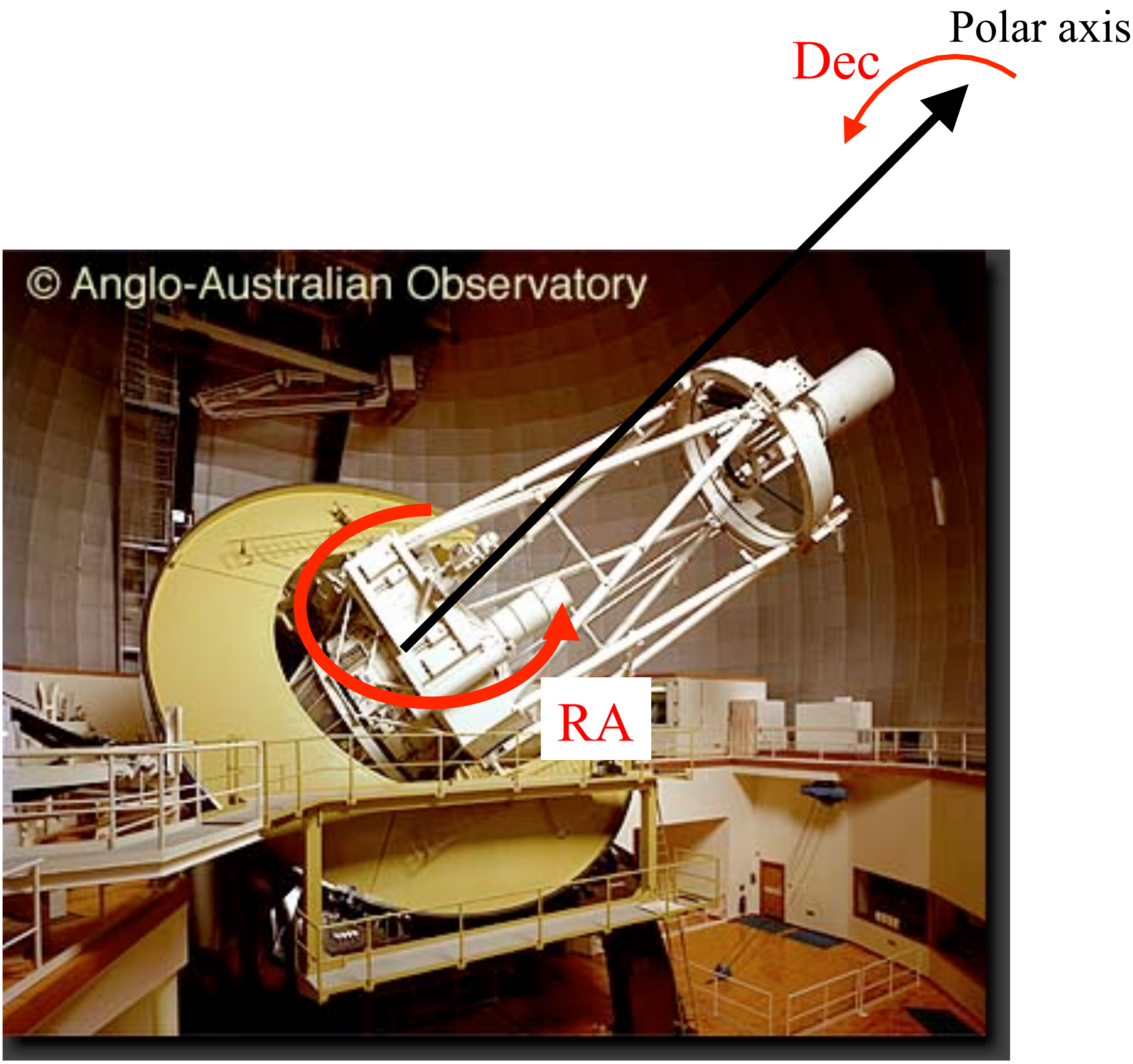
Wide-field (e.g. 6° Schmidt photographic plate) and short focal length

Schmidt-Cassegrain



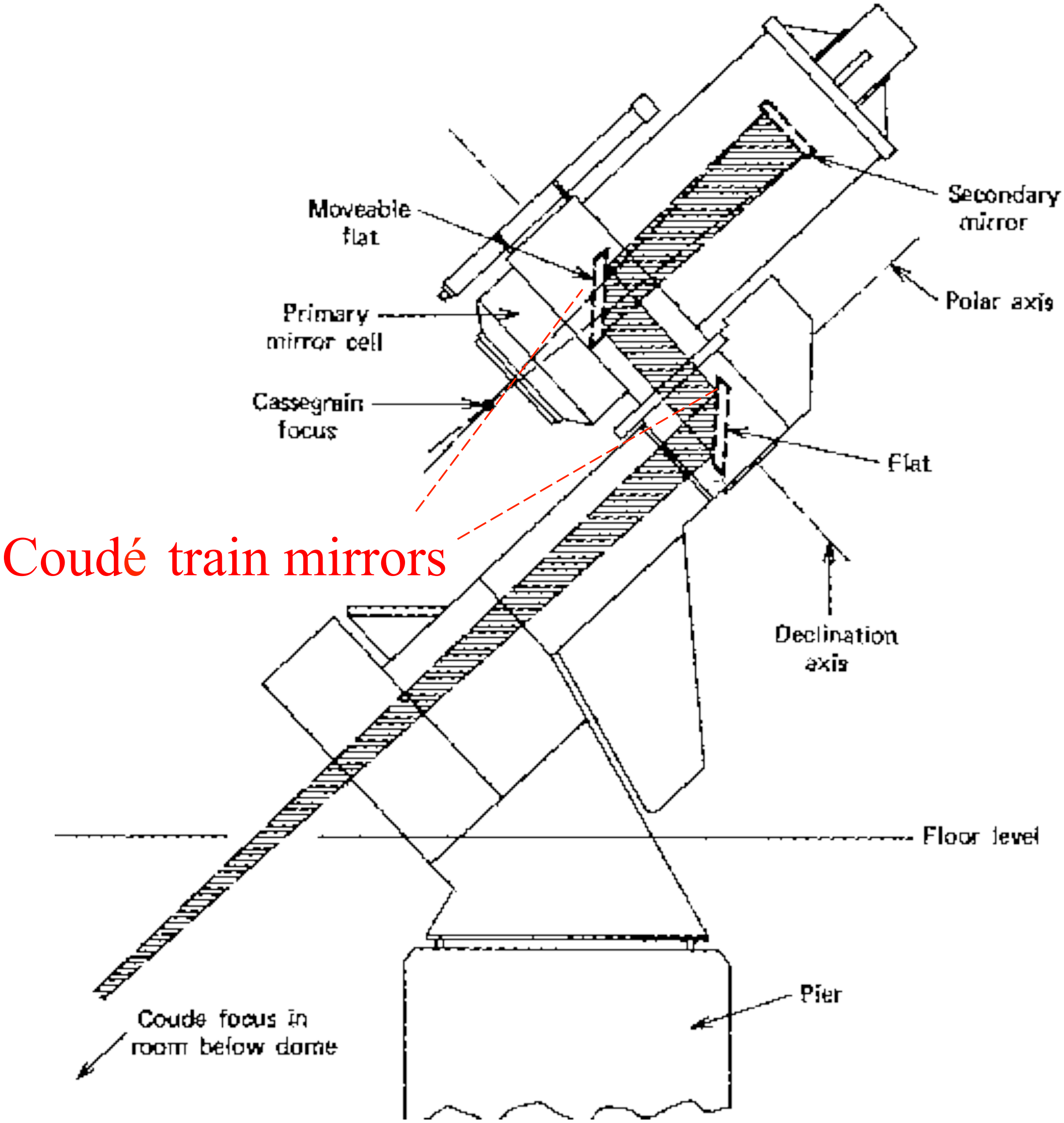
e.g. Celestron amateur telescopes

Equatorial Mount



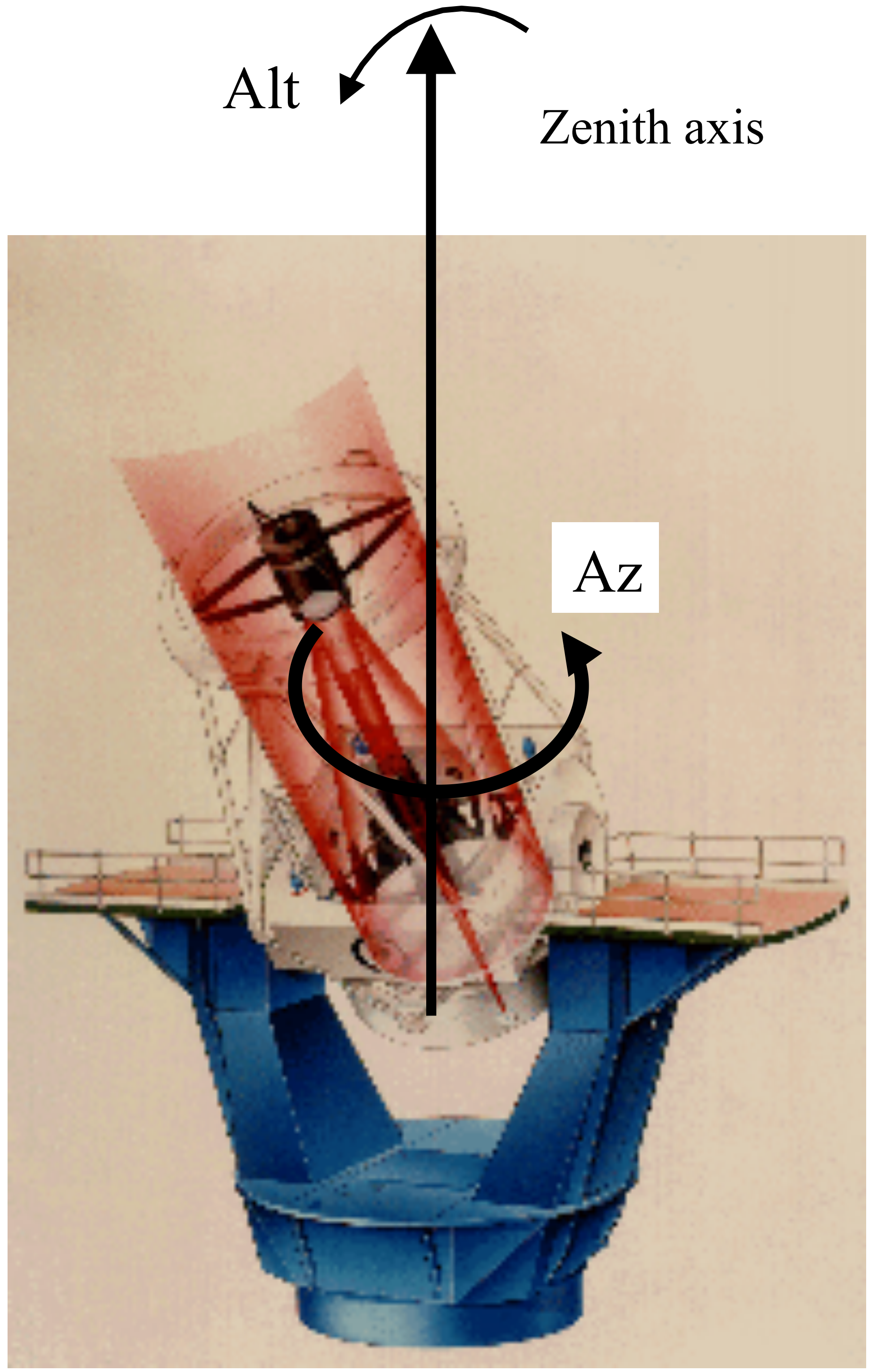
Only move one axis (RA) to track object
Can have pure mechanical control (no computers)
No image rotation
Titled support: heavy and expensive

Coudé Focus



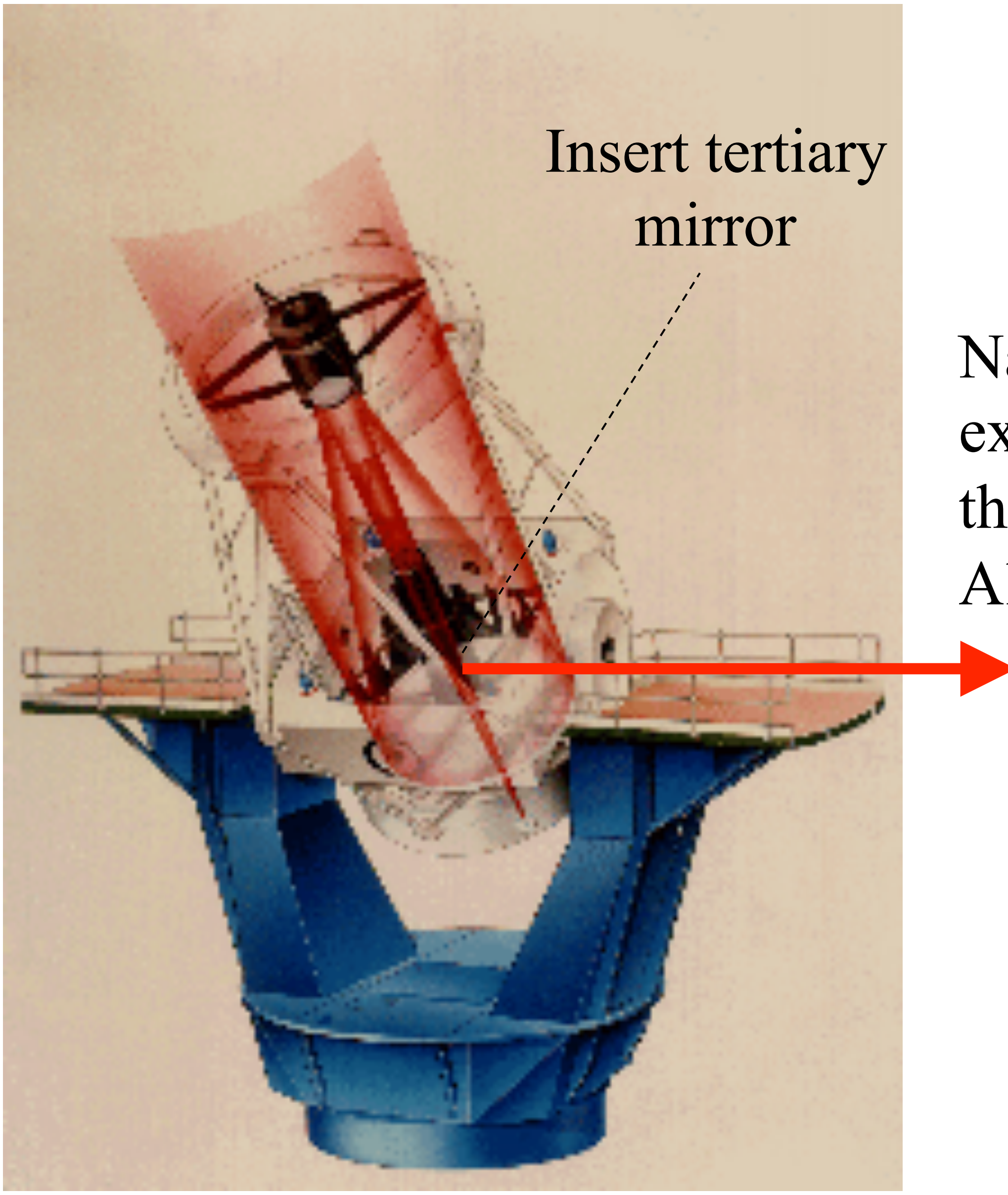
Coudé light exits through DEC axis
If instrument fixed (to floor), need field de-rotating optics

Alt-azimuth telescope



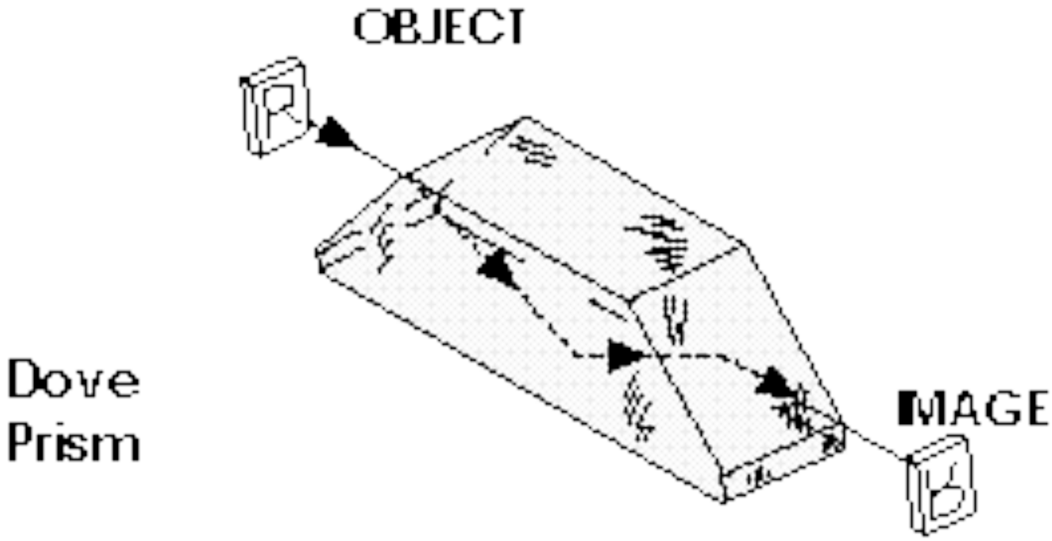
Computer control of 2-axis motion required
Vertical support mechanically simpler/cheaper

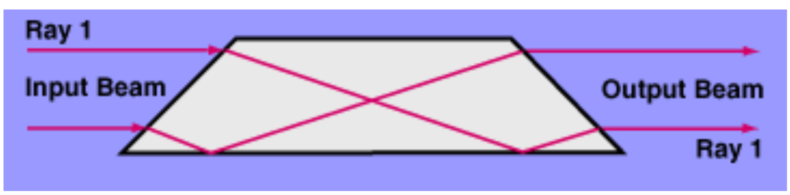
Nasmyth focus



Again need field de-rotation
Even at Cass (mechanical rotator)

Optical Field de-rotation (e.g. Nasmyth)





Dove prism

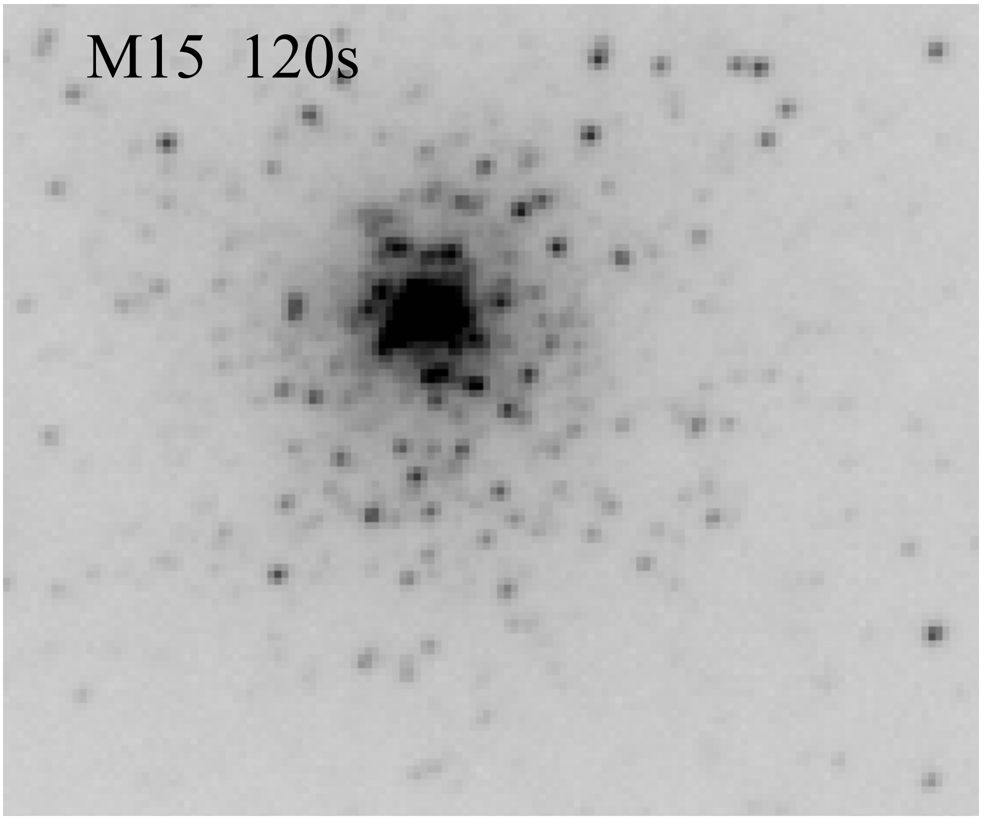
Works by total internal reflection

Rotate by θ, image rotates by 2θ

No deviation of light path

Can also use multiple mirrors

Image formation



Basic image properties

Total flux

Counts (on detector) W m^{-2} ergs s^{-1} cm^{-2}

Size

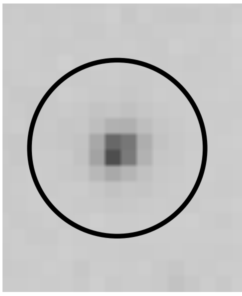
arcsecs (on sky) pixels/μm (on detector)

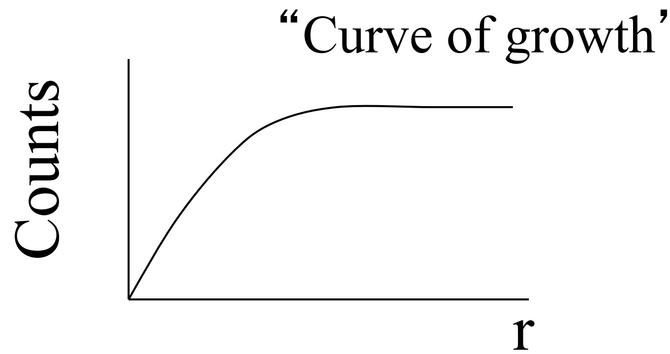
Brightness

Counts/pixel W m^{-2} $arcsec^{-2}$

W m^{-2} μm^{-2}

Total flux





Convert total counts ⇒ flux

using reference (standard star)

Curve of growth and "total" reasonably
well defined for isolated point source
(known Point Spread Function)

Not so well defined for crowded field,

extended objects (galaxies)

Physical Units:

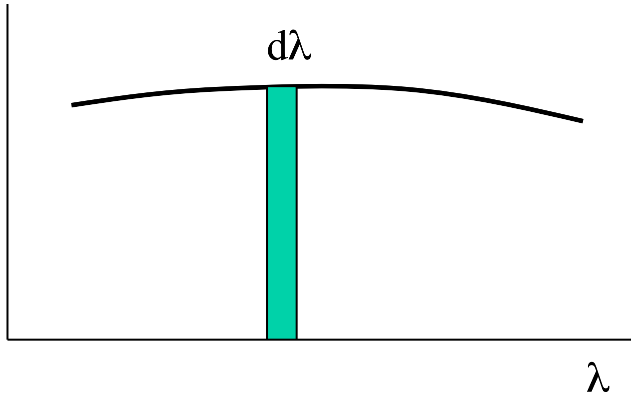
SI⇒CGS, × 10^3

W m^{-2} (SI)   ergs s^{-1} cm^{-2} (CGS)

Flux density: W m^{-2} $Å^{-1}$ (F_λ)

per unit wavelength or frequency   W m^{-2} Hz^{-1} (F_ν)

Useful relations



Energy content of chunk of spectrum:

$$dE = f_\lambda \, d\lambda = f_\nu \, d\nu$$
$$= \lambda f_\lambda \, d\log\lambda = \nu f_\nu \, d\log\nu$$

Also from $c = \nu\lambda$:

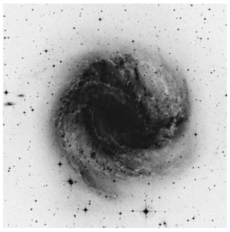
$$\frac{d\lambda}{\lambda} = \frac{d\nu}{\nu}$$

Useful astronomical unit:

1 Jansky (Jy)

$= 10^{-26}$ W m^{-2} Hz^{-1}

Image Size



d μm (on detector) α arcsec on sky

Physical size on detector = focal length × tan (α)

e.g. UKST telescope (f/2.5)

focal length = 3.07m

1 deg = 0.05m

⇒M83, diameter 12 arcmin ⇒ 0.01m on UKST plate

e.g. Keck (10m f/15)

M83 would be 0.5m!

Image brightness

Image ‘brightness’ is defined as

Flux / unit area on detector

c.f. Keck & UKST

0.5m vs 0.01m, but 70× more mirror area

flux/unit area ~ UKST/Keck = 36!

A detector on the UKST will record the image *faster* than Keck

[Of course Keck has heaps more Signal/ Noise for *total* image]

In general a *faster* focal ratio (e.g. f/2) reaches a given brightness limit faster than a slow focal ratio (*f*/15), as images are physically smaller

$$\boxed{\begin{aligned}\text{Counts / unit area} &= (\text{primary diameter / focal length})^2 \\ &= (\text{F/ratio})^{-2}\end{aligned}}$$

Counts @ detector

$$= E \qquad (\mathrm{Wm}^{-2}\mathrm{Hz}^{-1})$$

$$\times (h\nu)^{-1} \qquad (\text{to } Photons \ \mathrm{m}^{-2}\mathrm{Hz}^{-1})$$

$$\times T_{atm} \qquad (\text{transmission of atmosphere})$$

$$\times A \qquad (\text{Area of mirror m}^2)$$

“system efficiency”

$$\left\{ \begin{array}{ll} \times R_{mirror} & (\text{reflectivity of telescope mirror(s)}) \\ \times T_{optics} & (\text{transmission of instrument optics}) \\ \times QE & (\text{Quantum efficiency of detector}) \end{array} \right.$$

$$\times \Delta\nu \qquad (\text{bandwidth of optics \& detector})$$

$\boxed{\text{Range } 0 \rightarrow 1}$

e.g. 4m telescope, system eff=60%

Star α Lyrae @ 5000 Å, 3530 Jy

$T_{atm} = 0.97 \quad \Delta\lambda = 1000$Å

$\Rightarrow 10^{11}$ photons/sec

c.f. naked eye, 3mm pupil eff ~ 1%

$\Rightarrow 10^{3}$ photons/sec

Astronomical photometry: Magnitudes

History:

Human eye's perceived response to light ~ log(incident flux)

Dynamic range: Sun ⇒ faintest visible star: $\times 10^{13}$ in light intensity!

⇒ faintest galaxy large telescope $\times 10^{23}$!

Hipparchus (120 B.C.): classed star brightness "1" [bright] to "6" [faint]

Pogson (1856): 5 mags ~ 100 × in flux

Define exactly: 1 mag diff: flux × $100^{1/5} = 2.512\times$

Scale *backwards*

Modern:

$$\boxed{\begin{aligned} m &= -2.5\log_{10} flux \quad + \text{const.} \\ &= -2.5\log_{10}\left[flux \big/ flux_0 \right] \\ \text{or} \quad & flux \propto 10^{-0.4m} \\ & flux_1 \big/ flux_2 = 10^{-0.4(m_1 - m_2)} \end{aligned}}$$

Magnitude errors

$$m = -2.5 \log_{10} f \; + \; \text{const.}$$
$$= -1.086 \ln f \; + \; \text{const.}$$

2.5/ln(10)

$$\boxed{dm = -1.086 \, \frac{df}{f}}$$

Almost (but not quite a natural log scale), purely by coincidence

So a flux error of 5% $\Rightarrow \Delta m \approx 0.05$

10% $\Rightarrow \Delta m \approx 0.1$

Very convenient!

Apparent & Absolute Magnitude

Apparent magnitude is the kind we have seen, i.e. –2.5 log flux

Absolute magnitude is a magnitude scale analog of luminosity

Definition: apparent mag of object if it were 10 parsecs away

Usually: *m* for apparent

M for absolute

e.g. Sun is –27 apparent visual mag

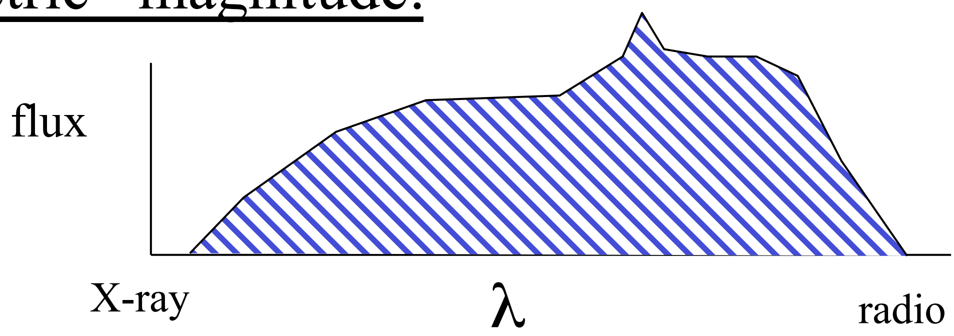
but +5

Milky Way Galaxy is M~ −19

Euclidean formula : $m - M = 5\log\left[\frac{D}{10\,pc}\right]$

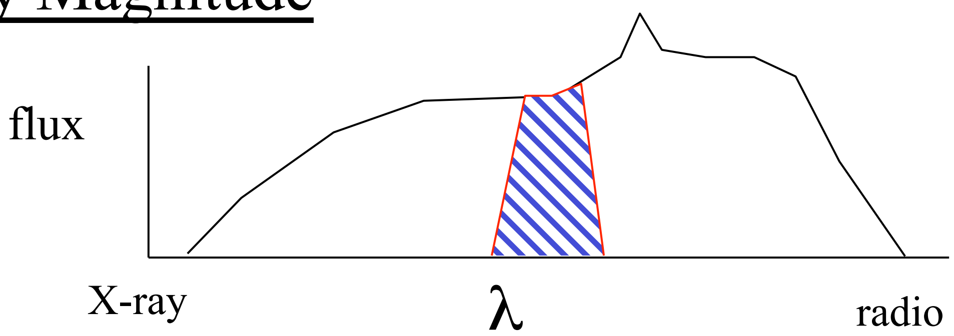
More Types of Magnitudes

'Bolometric' magnitude:



'Bolometric', i.e. total flux, hard to measure!

Everyday Magnitude



Defined by some *bandpass* limited by spectral range of system (atmosphere, telescope, instrument transmission, filter, detector sensitivity). Note: combination is *unique*.

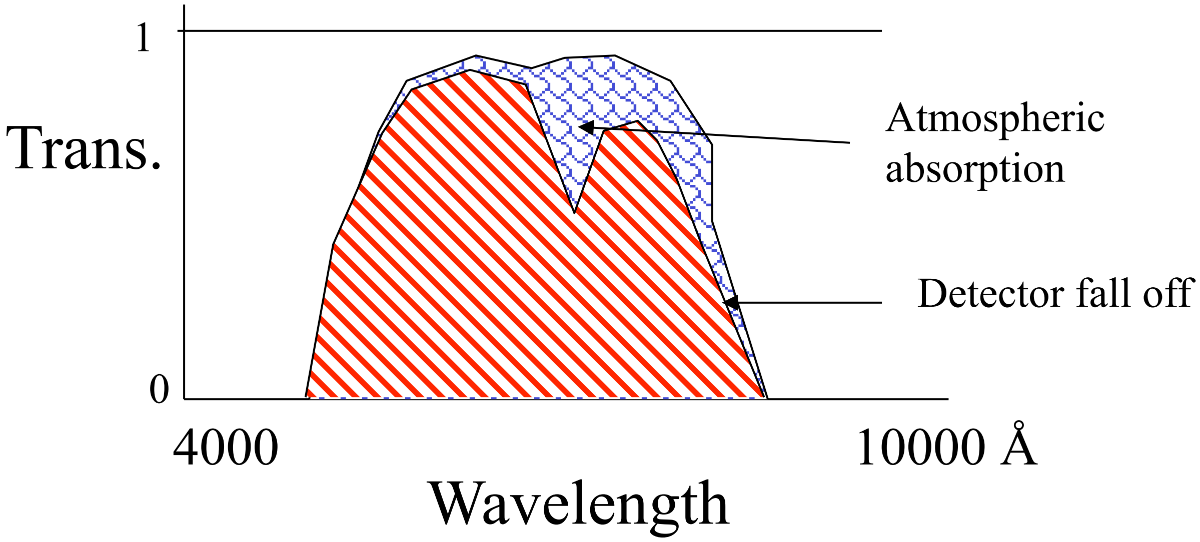
Can talk about 'bolometric absolute mag', etc.

Astronomical Photometry

Basic concept: some atmosphere/telescope/ instrument/filter/detector combination defines a band.

Usually the *filter* is dominant, the other terms are small corrections to the shape ⇒ *effective filter*

Example Filter profile T_λ



'Effective wavelength'

$$\lambda_{eff} = \frac{\int_{-\infty}^{+\infty} \lambda T(\lambda)\, d\lambda}{\int_{-\infty}^{+\infty} T(\lambda)\, d\lambda}$$

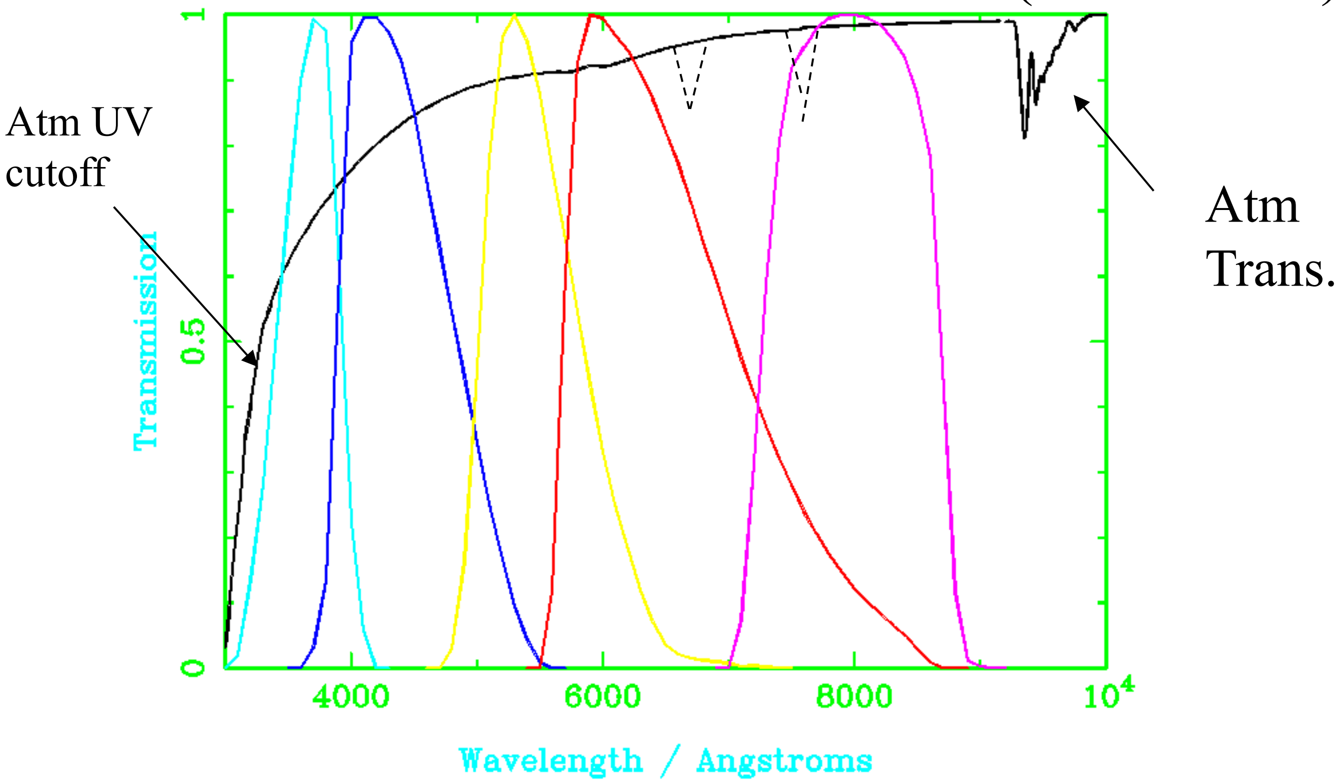
'bandwidth' $\Delta\lambda$ either FWHM or 'effective bandwidth'

$$\Delta\lambda_{eff} = \int_{-\infty}^{+\infty} T(\lambda)\, d\lambda$$

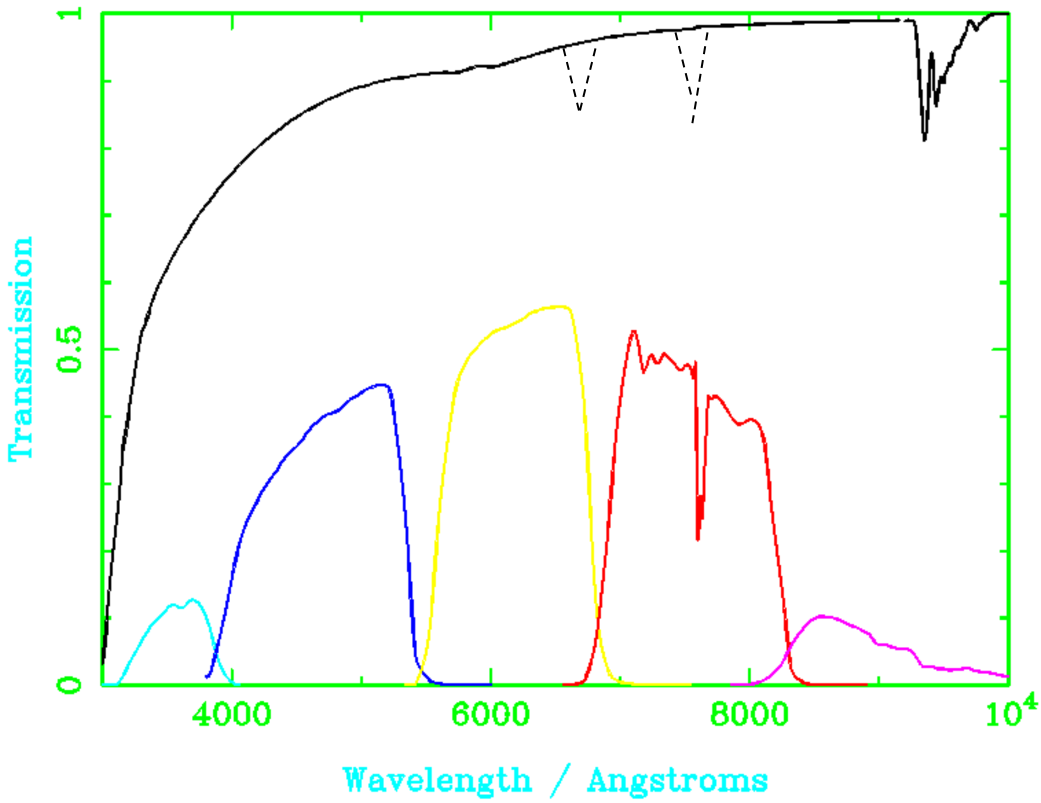
= Area under curve

Common Filters

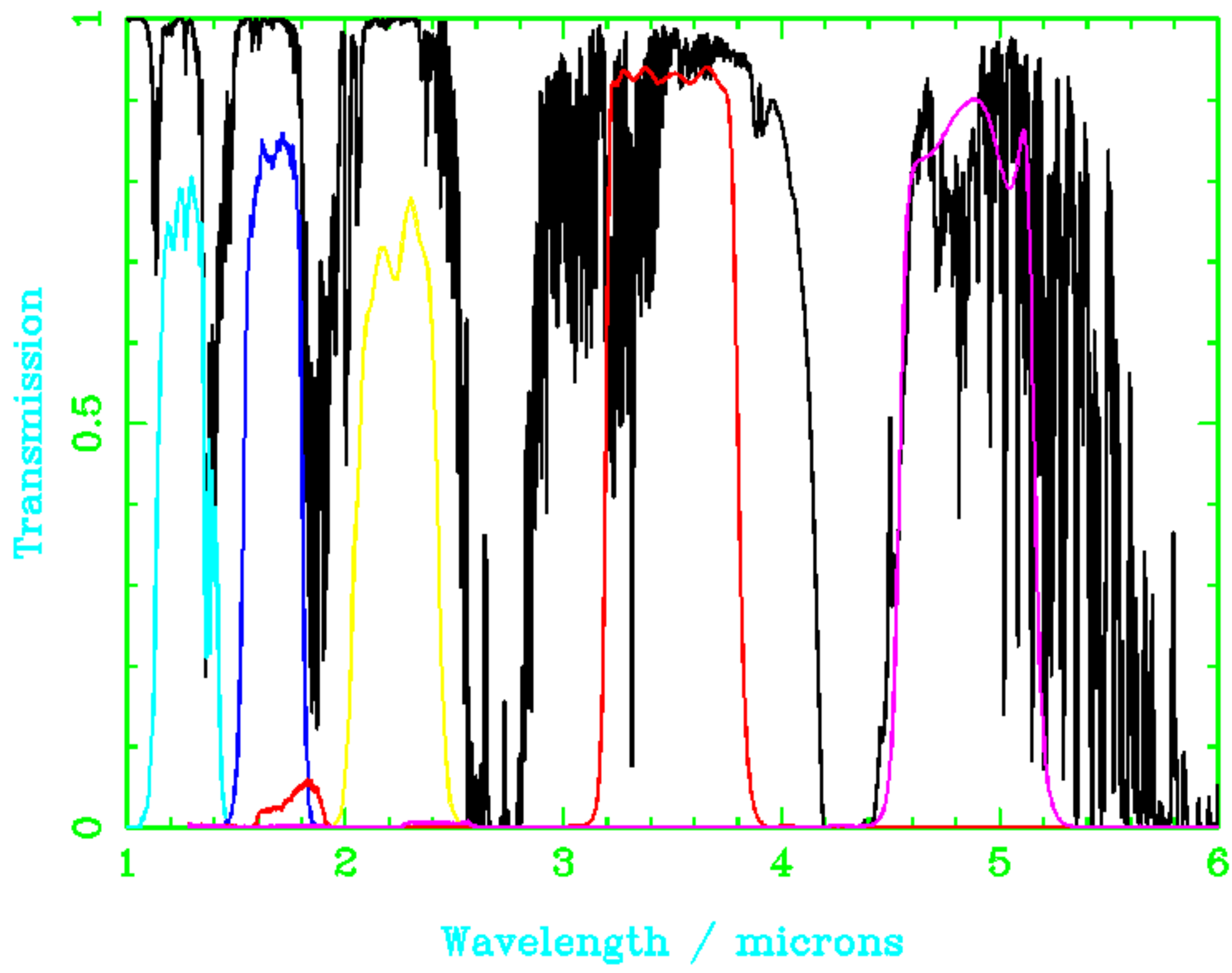
UBV Johnson and RI Cousin filters (normalized)



u′g′r′i′z′ SDSS (Gunn) filters filters (incl. Atm+CCD)



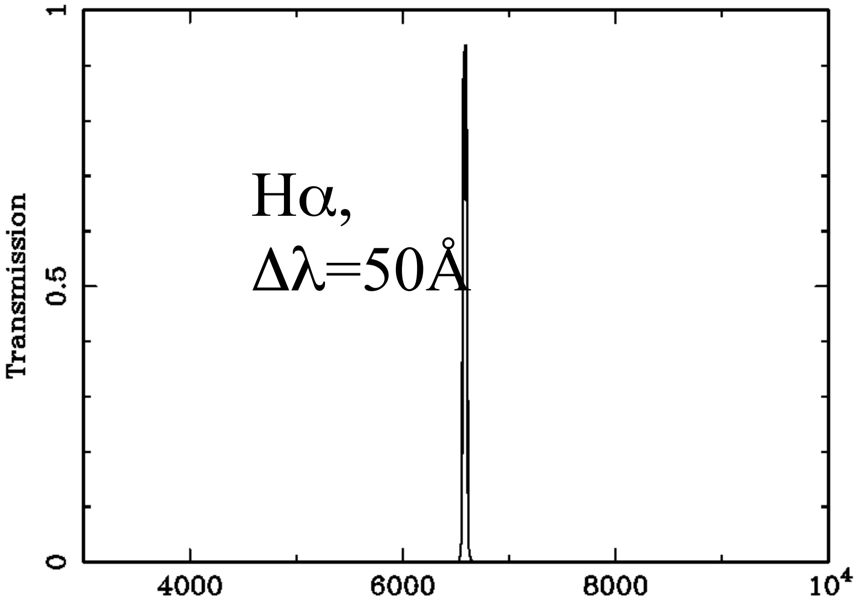
JHKLM Infrared filters



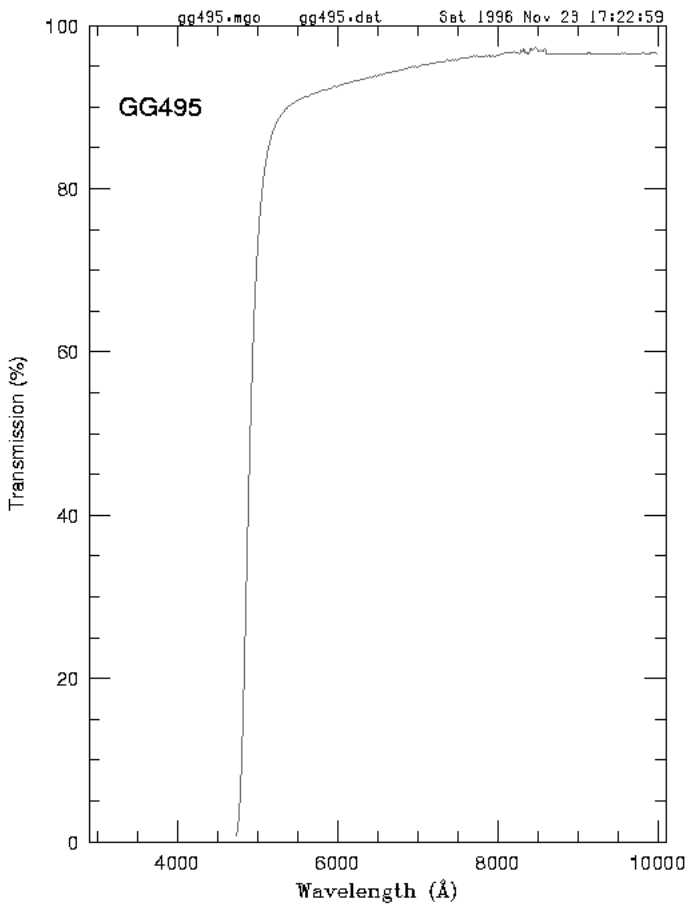
Filters locations constrained by atmospheric transmission holes

Other kinds of filters

Narrow band filter



Inverse is called a 'notch' filter



'Cutoff' or 'order-sorting' or 'blocking'

Filter, edge $\Delta\lambda \sim 200$Å

Making filters

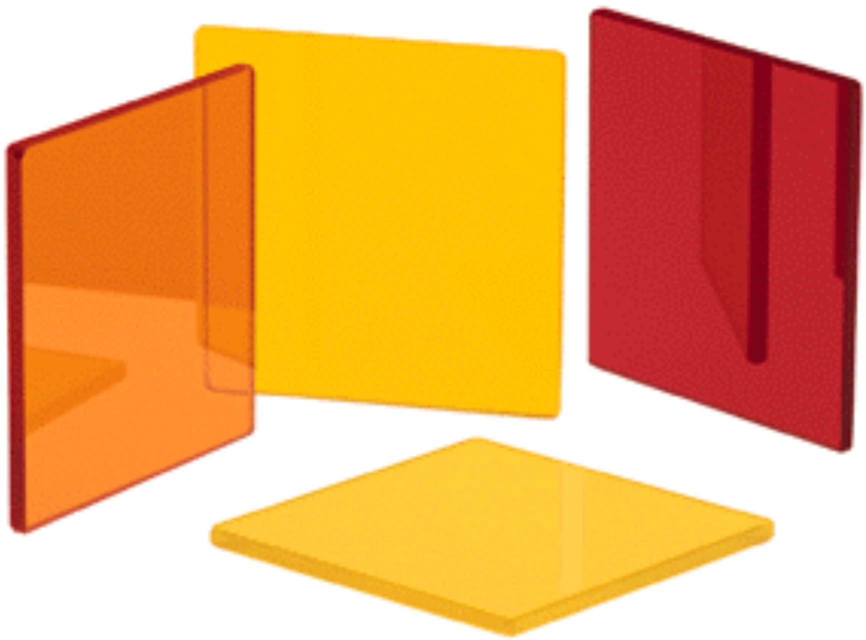
Absorption:

Colored glasses which absorb across a range of wavelengths

e.g. GG495 'green glass'

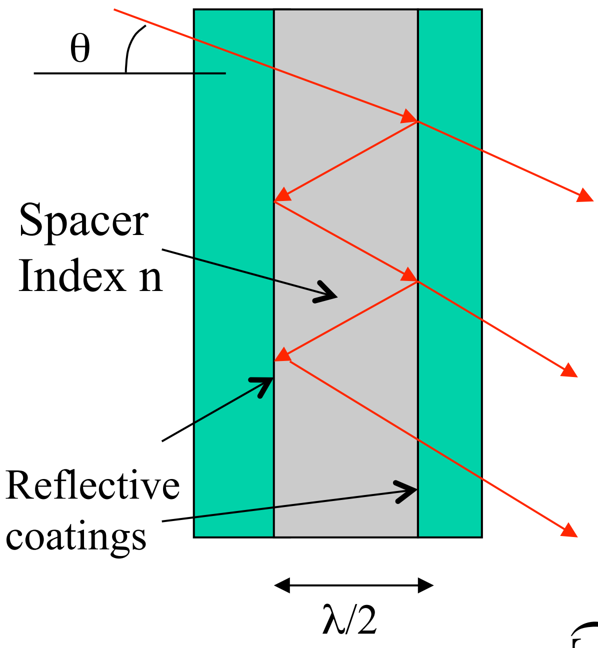
OG550 'orange glass'

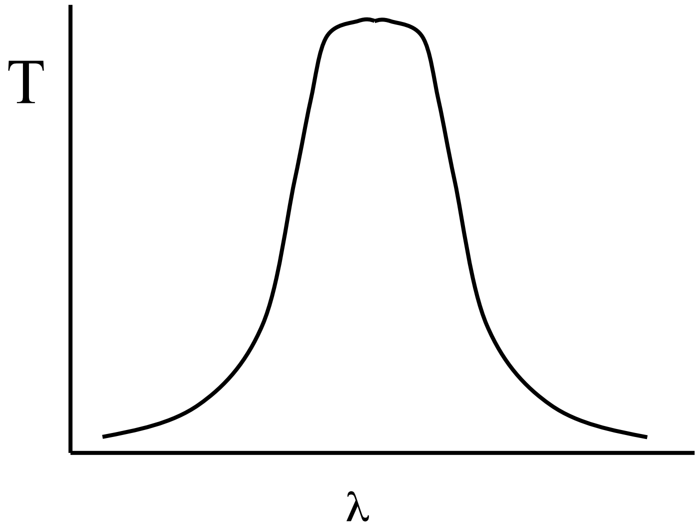
Combine multiple glasses ⇒ cut-on + cut-off ⇒ broad-band filter



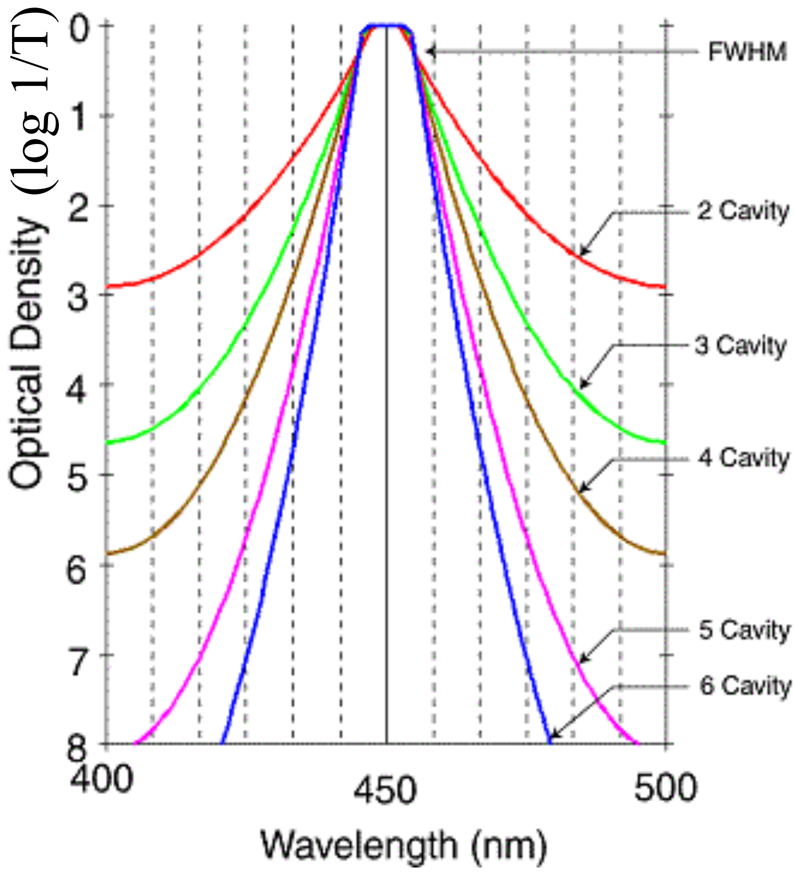
Interference filters

Operation: same principle as Fabry-Perot étalon, broad & narrow band





Multiple cavities square up profile



$$\lambda_{eff} = \lambda_0 \sqrt{1 - \frac{\sin^2\theta}{n^2}}$$

$$= \lambda_0 \cos\theta \quad (n = 1)$$

Photometry

Bad news: Defined for atmosphere, telescope, instrument transmission, filter, detector combination ⇒ *unique*

specified exactly for precision photometry

Good news: For approximate work (0.2-0.5mag photometry) difference between different species of B filter are not important (most astronomical objects have smooth spectra)

For any observation one can define:

Instr. Mag. = -2.5 log (Response)

Response is linear (CCDs) or can be linearized (photographic plates) with incident light

Real Mag – Instr. Mag = const. (modulo differences between effective filters)

“Response”

For photon counting device (e.g. CCD):

$$\text{Response} = \int \underset{\Rightarrow \text{ photons}}{\uparrow}\!\!\lambda\, \underbrace{T_\lambda f_\lambda \; d\lambda}_{\text{Energy}}$$

For Bolometer:

$$\text{Response} = \int T_\lambda f_\lambda \; d\lambda$$

In general may not be photons or energy even after effective transmission T_λ is known

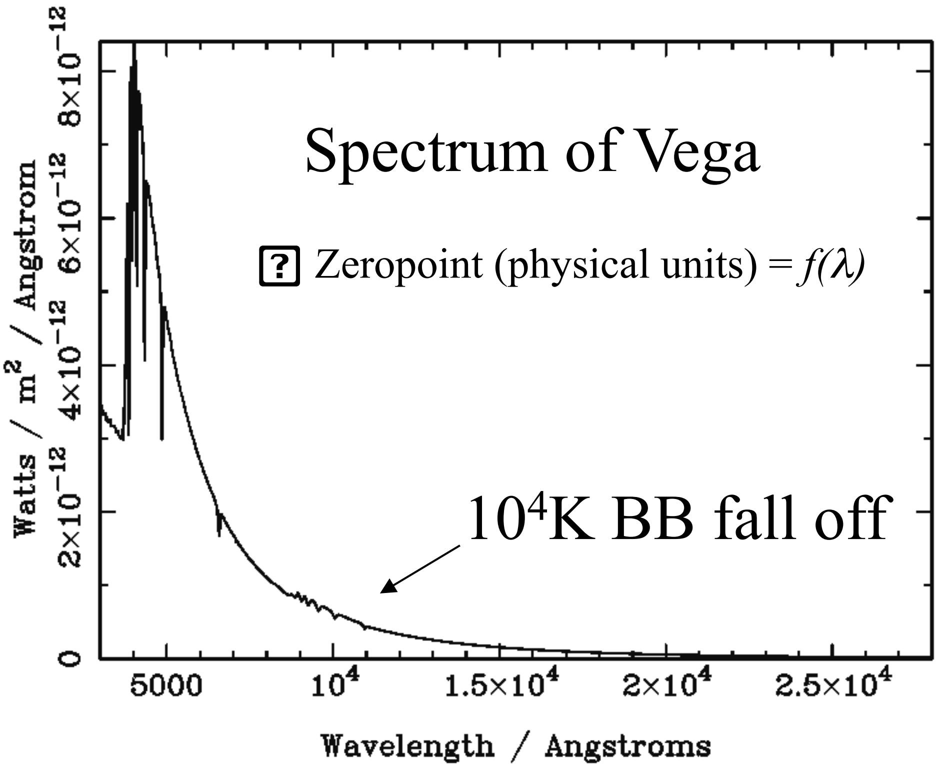
Worry about this when computing a magnitude from a spectrum f_λ

“Zeropointing” mags

Standard, “Johnson”, “Vega” magnitudes, empirical zeropoint:

Define the A0 star Vega to have mag=0 in all filters (BVRI…)

[In reality use an average of ~10 A0 stars and Vega is now V=+0.03]



CCD mags:

$$m = -2.5\log\frac{\int \lambda\, T_\lambda f_\lambda\, d\lambda}{\int \lambda\, T_\lambda V_\lambda\, d\lambda} = -2.5\log\frac{\int \nu^{-1} T_\nu f_\nu\, d\nu}{\int \nu^{-1} T_\nu V_\nu\, d\nu}$$

photons

Vega

$T_\nu = T_\lambda$ = Transmission of filter

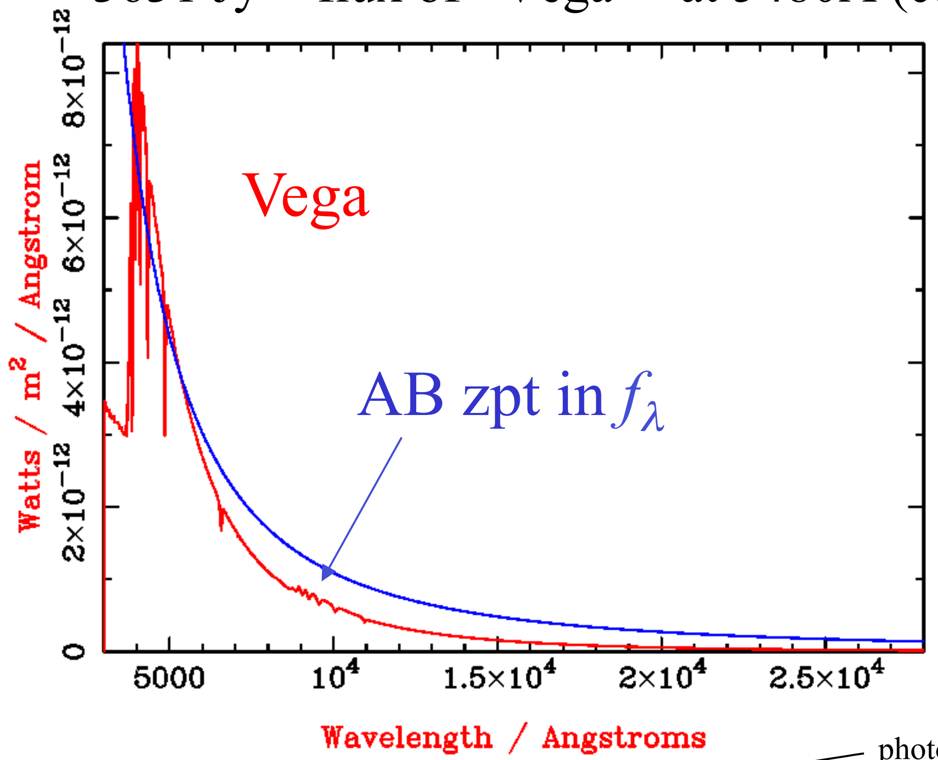
AB magnitudes

Introduced by Oke & Gunn 1983

More physical basis:

$$AB_\nu = -2.5 \log f_\nu - 48.60$$

where f_ν is in ergs s^{-1} cm^{-2} i.e. physical units (zeropoint = 3631 Jy = flux of "Vega"* at 5480Å (ctr of V filter))



photons

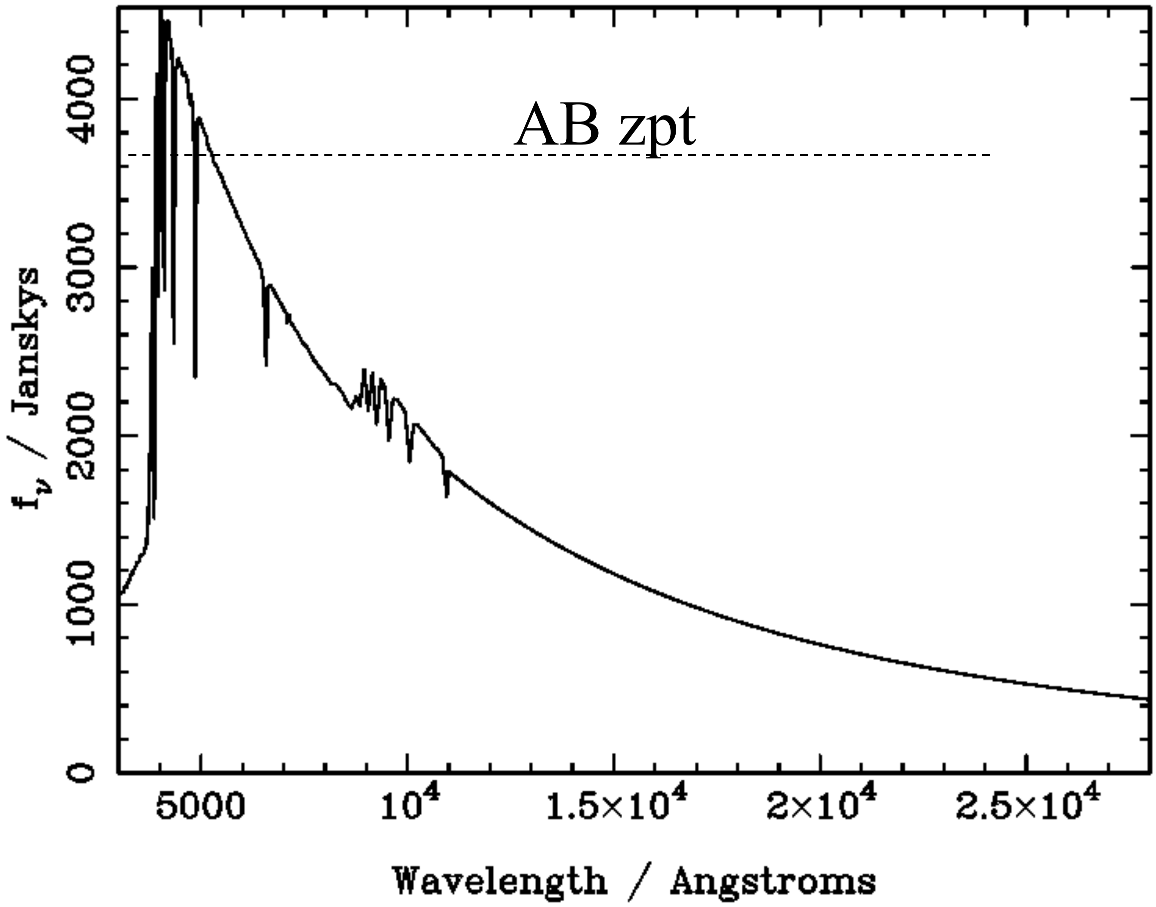
CCD mags: $$m = -2.5 \log \frac{\int \nu^{-1} T_\nu f_\nu \, d\nu}{\int \nu^{-1} T_\nu \, d\nu} + 48.60$$

$$\approx \left\langle \frac{f_\nu}{3631\,\mathrm{Jy}} \right\rangle_{band}$$

$T_\nu = T_\lambda =$ Transmission of filter

*True Vega is +0.03 like ST system

Vega in f_ν



Spectrum much less steep –f_ν vs λ us useful for plotting
Note area under curve is not physically meaningful

Useful relations

Filter	$\lambda/\mu m$	$\Delta\lambda/\mu m$	S_0/Jy	P_{20}
U	0.365	0.068	1380	38.778
B	0.44	0.098	4390	147.477
V	0.55	0.089	3530	86.157
R	0.7	0.22	2770	131.308
I	0.9	0.24	2290	92.107
J	1.25	0.38	1600	73.363
H	1.65	0.29	1020	27.04
K	2.2	0.48	657	21.621
L	3.45	0.7	290	8.875
M	4.8	-----	163	5.122*
N	10.1	-----	40	0.597*
Q	20	-----	10	0.075*

* = per unit micron

S_0 = flux of 0th magnitude star. 1 Jy = 10^{-26} W/m^2/Hz
P_{20} = Photons/sec/m^2 from 20th magnitude object

F_λ = ? 3?10^{-16} / λ^2 (F_λ: W/m^2/Å F_ν: Jy λ: microns)

U->I from Hayes & Latham, 1975, ApJ 197, 593 with M(Vega)=0.
J->Q from NASA IRTF photometry manual with M(Vega)=0.

[Absolute accuracy is probably 5-10%]

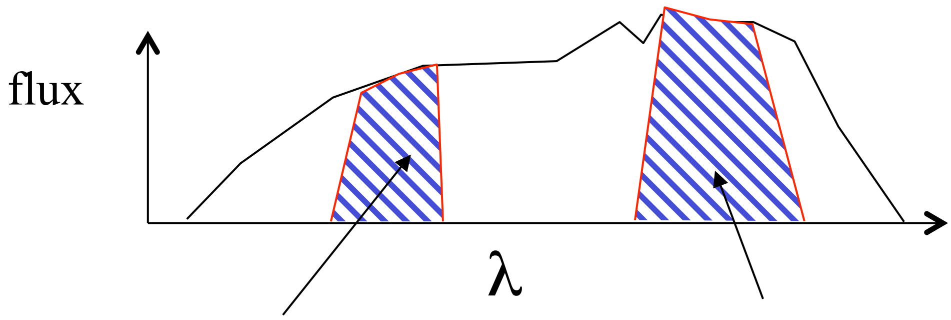
m(AB) = 8.90 - 2.5 log (S/Jy)   0 mag (AB) = 3631 Jy

AB(B) = B - 0.21   AB(J) = J + 0.89   For flat spectrum in S: B-R = 0.50
AB(R) = R + 0.29   AB(H) = H + 1.38   R-I = 0.21
AB(I) = I + 0.50   AB(K) = K + 1.86   R-K = 1.57

$$\text{Continuum}: L_B = 8.14108 \times 10^{24} \times 10^{-0.4 M_B} \quad \text{Watts/Angstrom}$$

'Color'

Consider two mags in different bands:



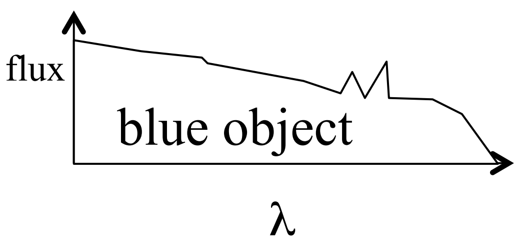
$m_1 = -2.5 \log f_1 / Z_1 \qquad m_2 = -2.5 \log f_2 / Z_2$

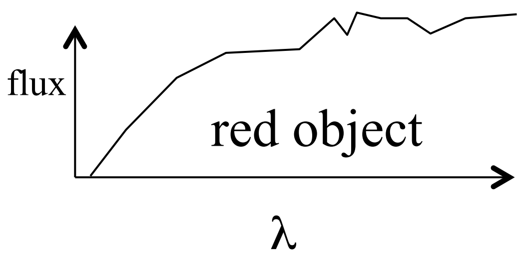
where f_1/f_2 are the fluxes integrated through the two filters

Color = $m_1 - m_2 = -2.5 \log f_1 / f_2 \quad + \text{const}$

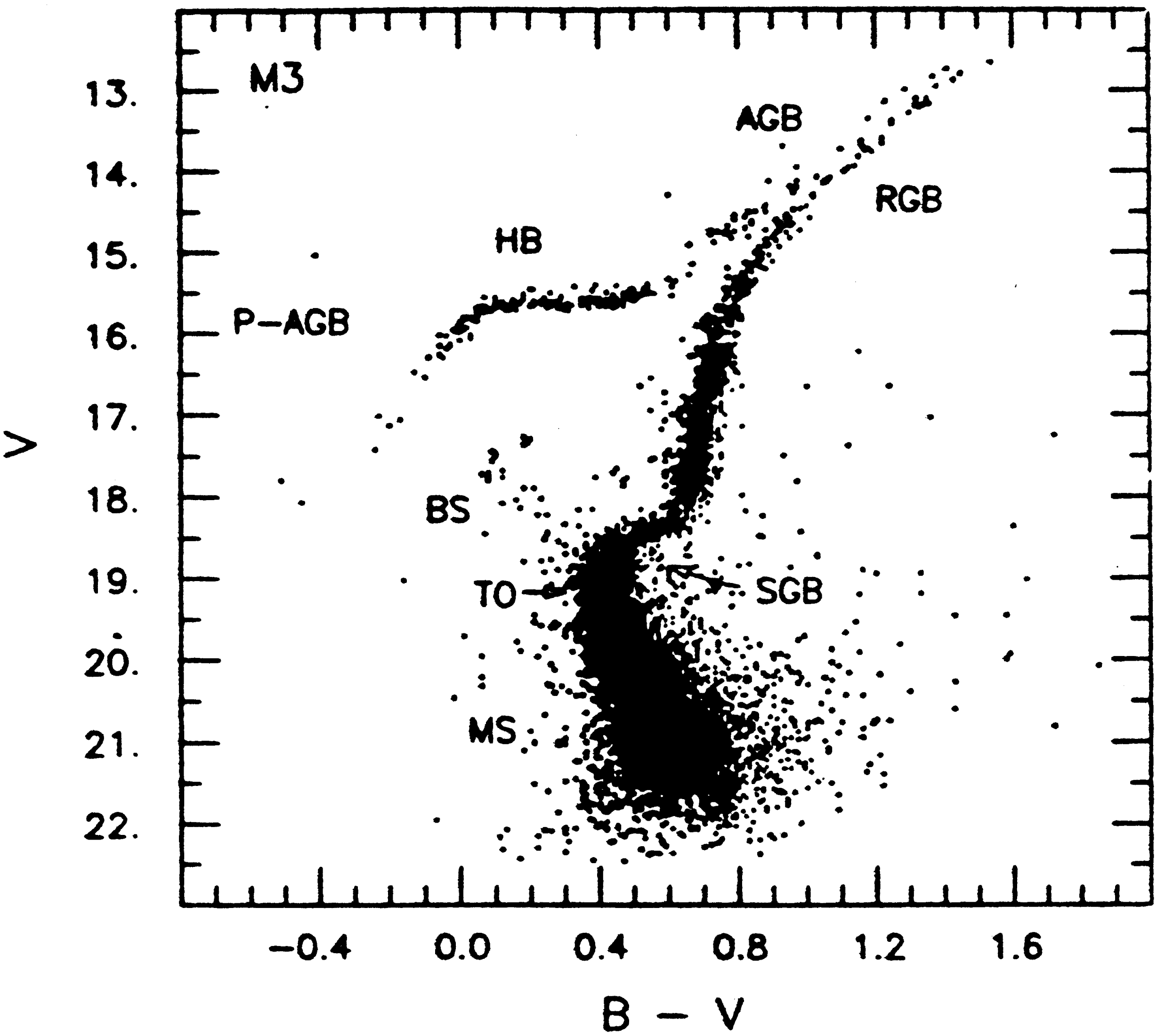
A flux ratio translates to a *difference* in color

As red flux/blue flux ↑ *color* increases





Color-Mag diagram



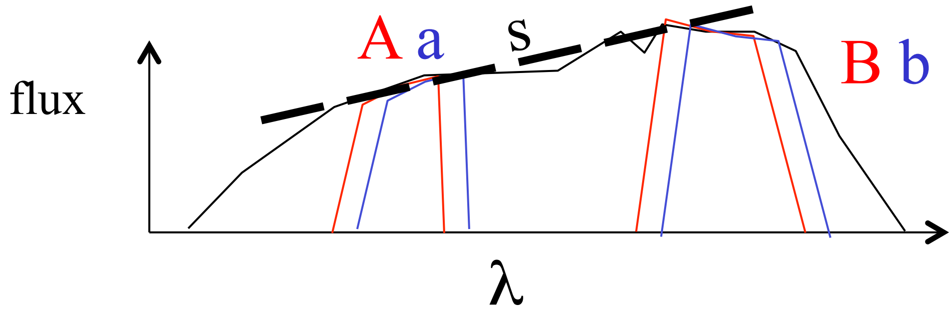
M92 globular cluster, all stars at ~ same distance

So $V \propto \log$ Luminosity

$B\text{-}V \propto \log$ Temperature

Hertzsprung-Russell, "HR" diagram

‘Color equations’



Consider two similar sets of filters AB and ab (e.g. Johnson filters but with slightly different detectors)

Then from extrapolation (in log space):

$$a - A \propto s\,(\lambda_a - \lambda_b)$$
$$\propto A - B \approx a - b$$

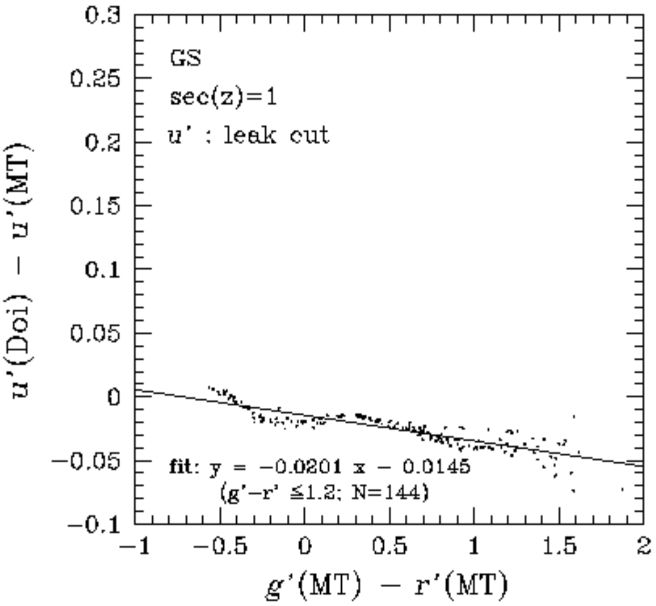
i.e. the error you make will depend to 1st order on the color of the object

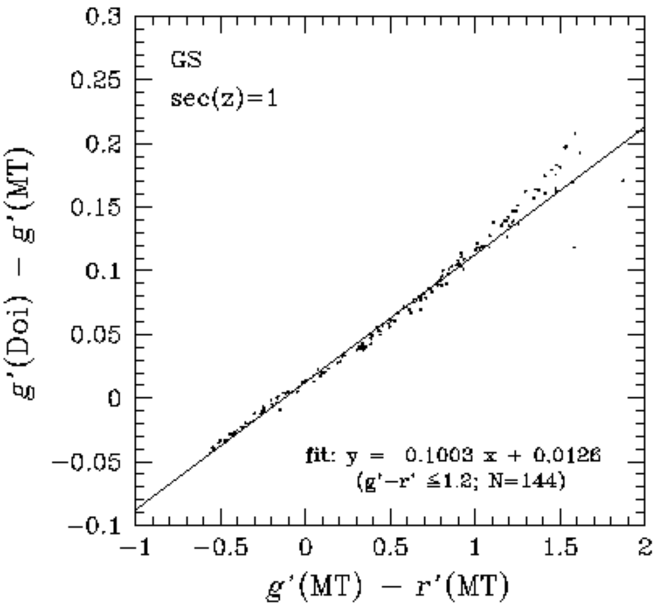
Make system of *color* equations:

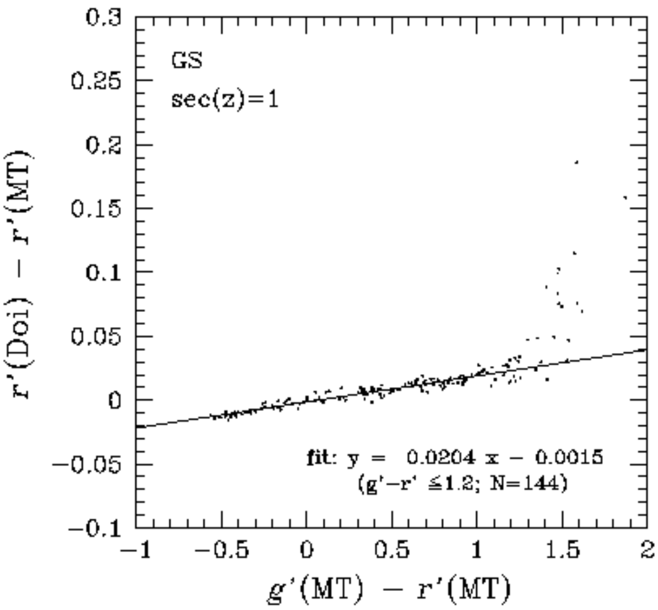
empirical set
of transforms

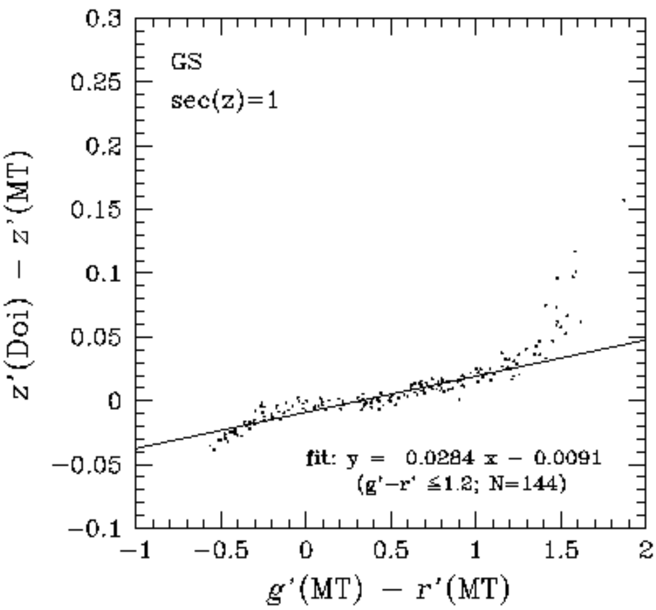
A,B,C,D,… ⇒ a,b,c,d,…

Practical photometry





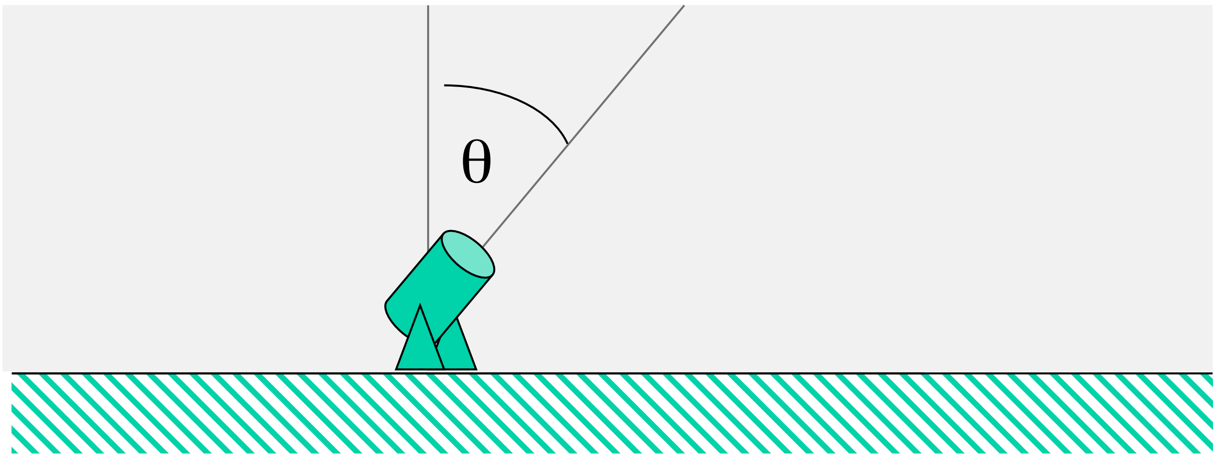




SDSS MT $\Rightarrow$ SDSS 2.5m camera

Extinction corrections

Atmospheric extinction:



Uniform atmosphere: thickness d ∝ 1/cos θ = sec θ
Atmospheric absorption:

$$I = I_0 e^{-k_1 d}$$

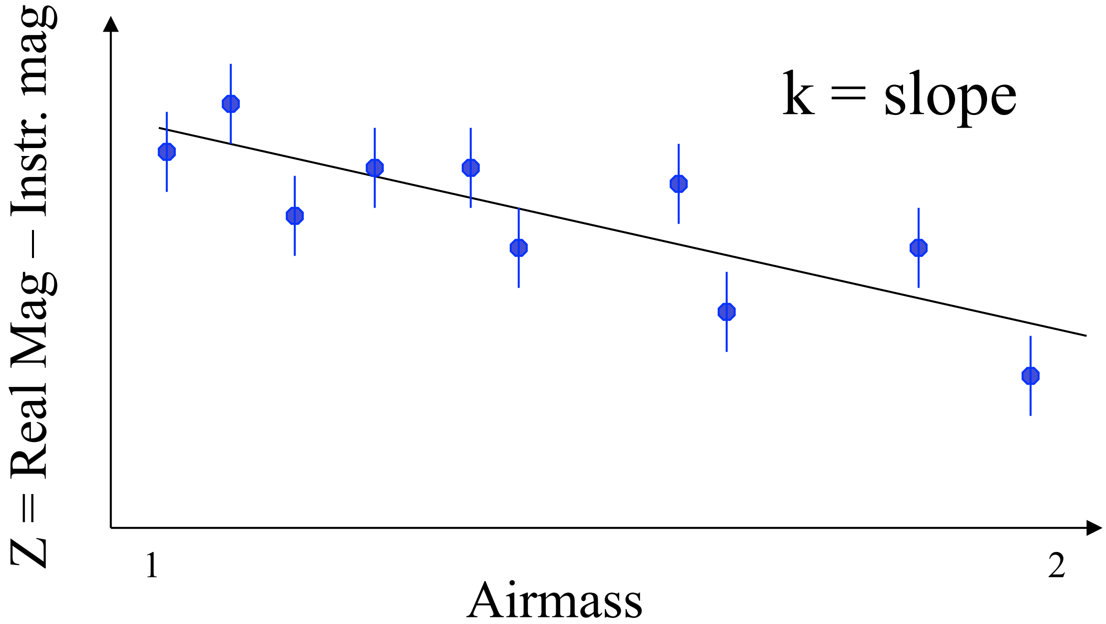
$$\Delta m = k_2 d = k \sec\theta$$

sec θ is often referred to as the 'airmass'

Zenith distance	Airmass
0°	1.0
45°	1.4
60°	2.0
80°	5.8

'Extinction coefficient' : k ~ 0.1-0.3 mags/airmass
(in optical red⇒blue)

Extinction plot



Fit Z_0,k in linear relation:

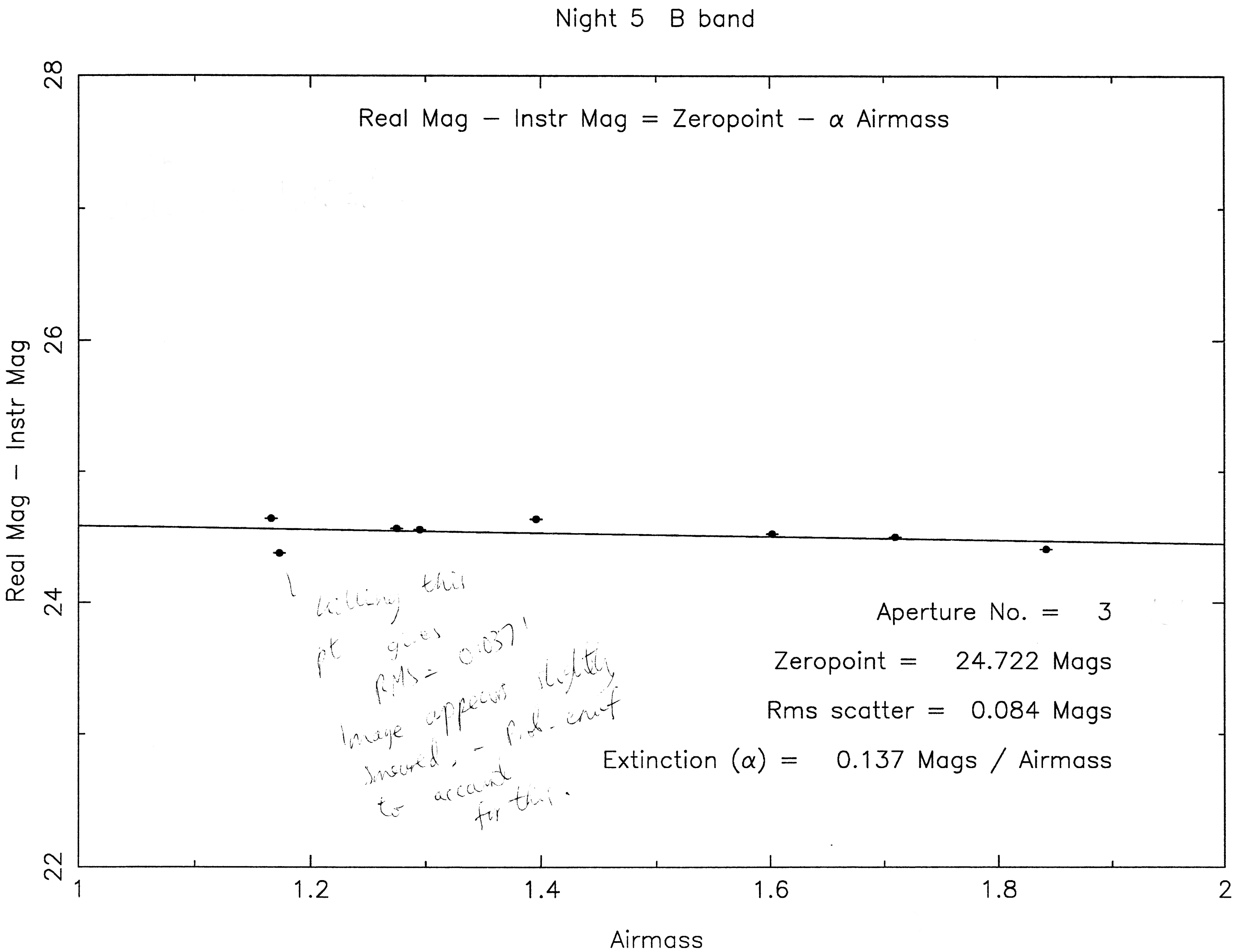
$$Z = \text{Real mag} - \text{Instr mag}$$
$$= \text{Real mag} + 2.5\log\left[\text{counts/sec}\right] = Z_0 - k\sec\theta$$

k is extinction coefficient 'mags/airmass'
Z_0 is the zeropoint 'at the top of the atmosphere', i.e. corrected to airmass = 0
<u>'Real mag'</u> (e.g. 'V=8.6') would ideally be in the same filter system, but if not can incorporate a color equation term, *e.g.*:

$$\underset{\uparrow\ \text{Landolt system}}{V_L} - \underbrace{\text{Instr mag}}_{V_{instr}} = Z_0 - k\sec\theta + \underset{\uparrow\ \text{Color coefficient}}{C}\,(\overbrace{V_L - R_L}^{\text{some color}})$$

Fit for k and C simultaneously

<u>Real example: WHT 1991. Taurus imaging</u>



Digression: night sky brightness

So far have only considered incident photons from object. What about *foreground* diffuse emission from the atmosphere + telescope?

Optical: atmosphere dominant, airglow + scattered light

NIR: as ⇒ 2μm thermal emission↑ (atmosphere + telescope BB)

Brightness:

Night sky at La Silla

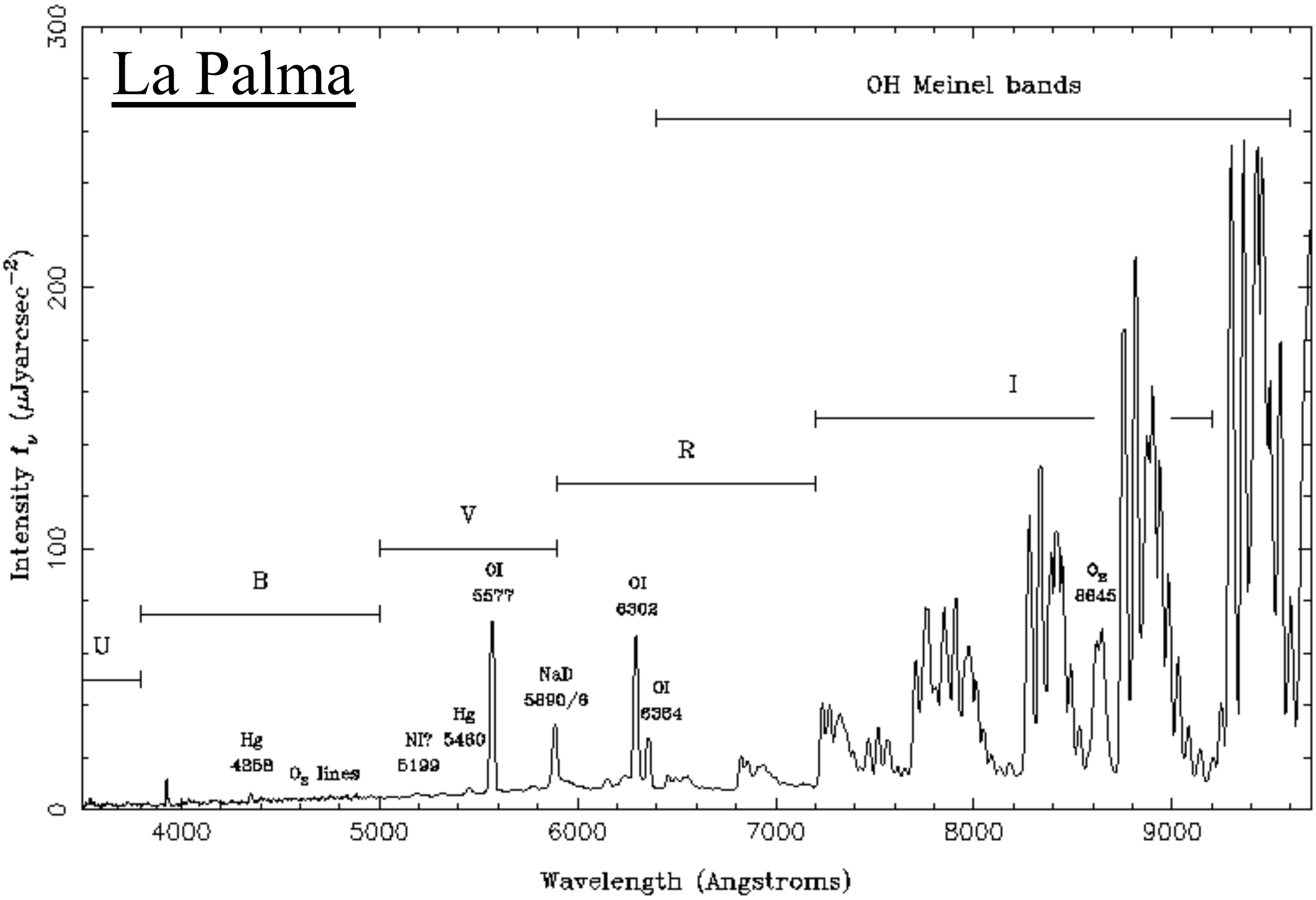
Days from New Moon	*U*	*B*	*V*	*R*	*I*
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Blue end sensitive to moon, e.g. ***B*** increases ×20!

Units: mag / square arcsecond !!

Mag is **not** linear with area!!!!!!

Night sky spectrum

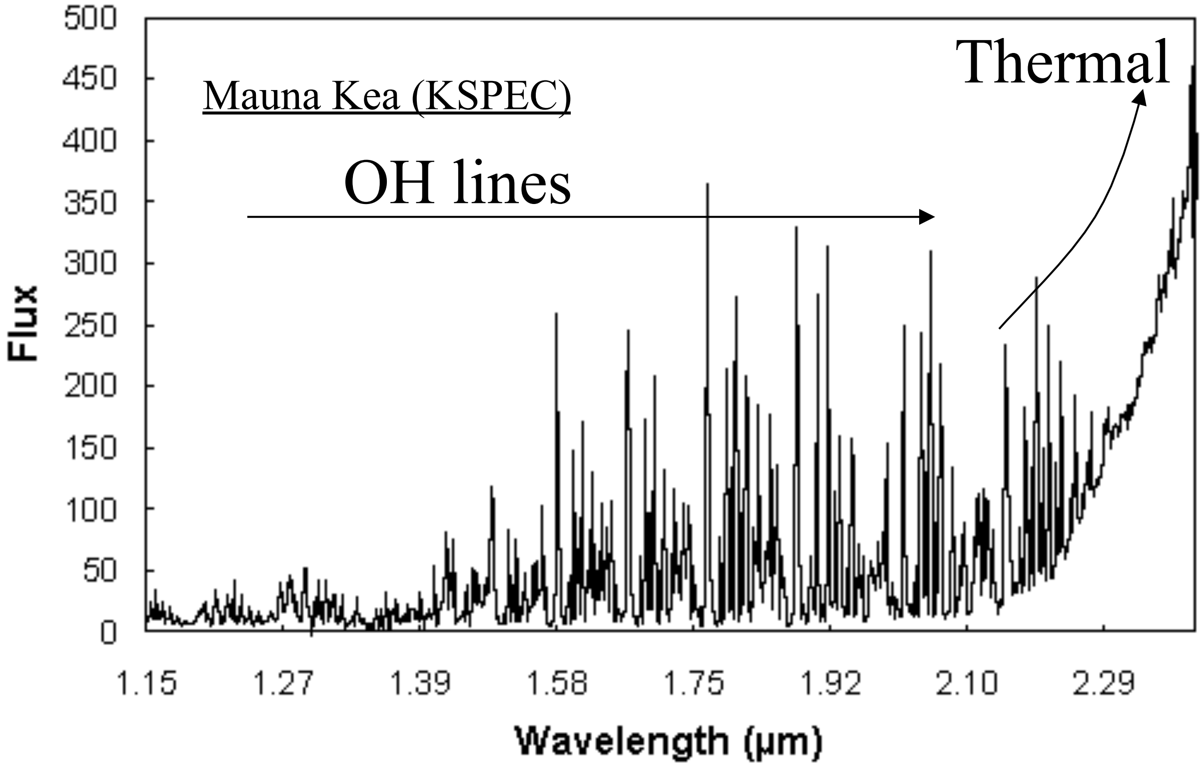


Narrow lines: airglow/auroral lines.

Time dependence

λ>7000Å, airglow from OH radicals at 80-90km attitude dominate, and continue 1-2μm.

IR night sky



These nasties make IR spectroscopy a problem

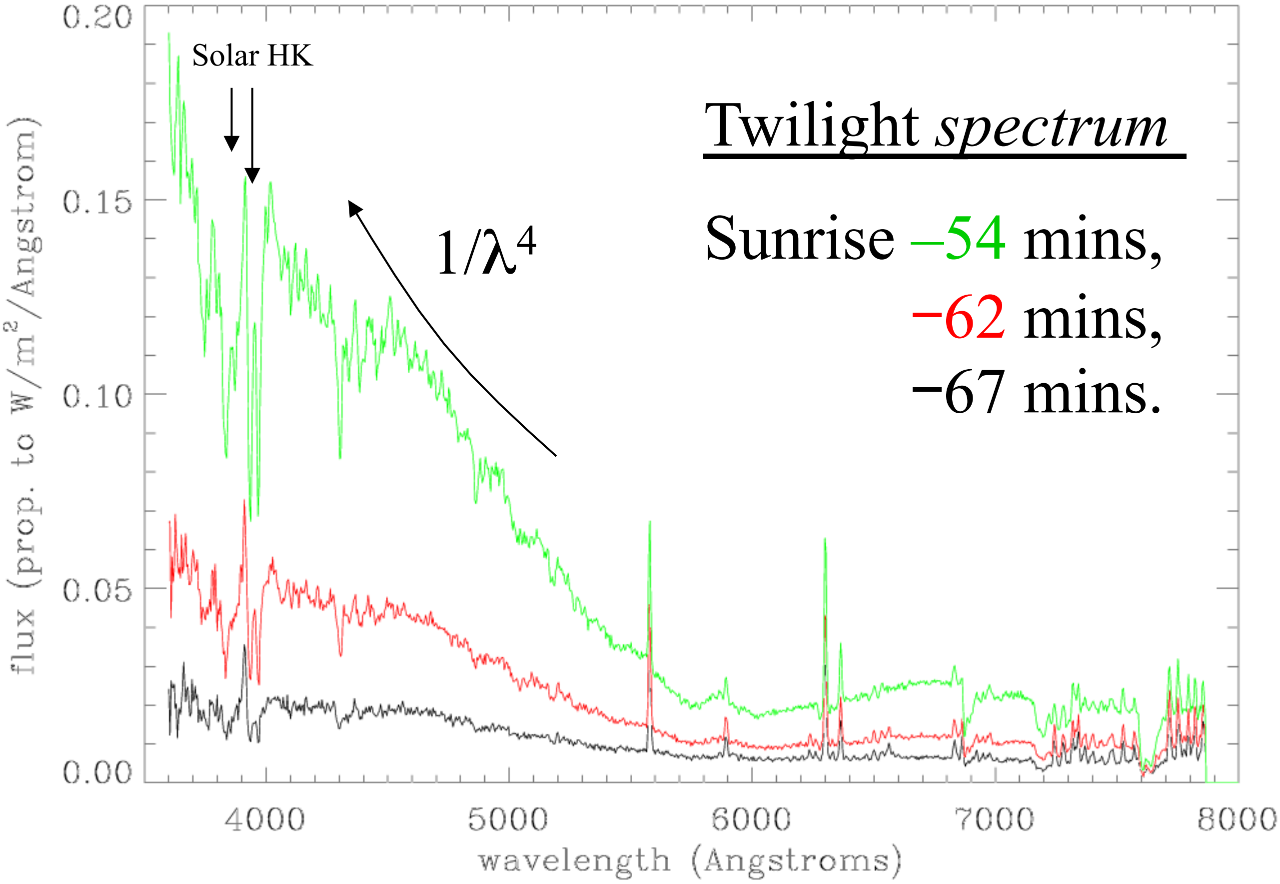
Make IR imaging very noisy:

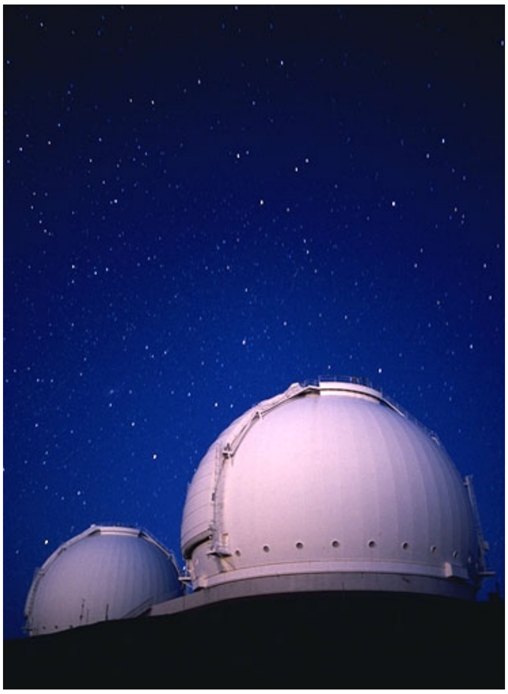
<u>Backgrounds</u>:

J	15.0 mags/arcsec^2
H	13.7 mags/arcsec^2
K	12.5 mags/arcsec^2
(K′	13.7 mags/arcsec^2)

c.f. optical values 19-22

Twilight Sky





Blue component: rises dramatically as Sun comes up, steep slope of $1/\lambda^4$ Rayleigh scattering.

Scattering also explains why the full moon produces a bright sky.

Much less important in IR, both $1/\lambda^4$ & intrinsic airglow

Sunrise…

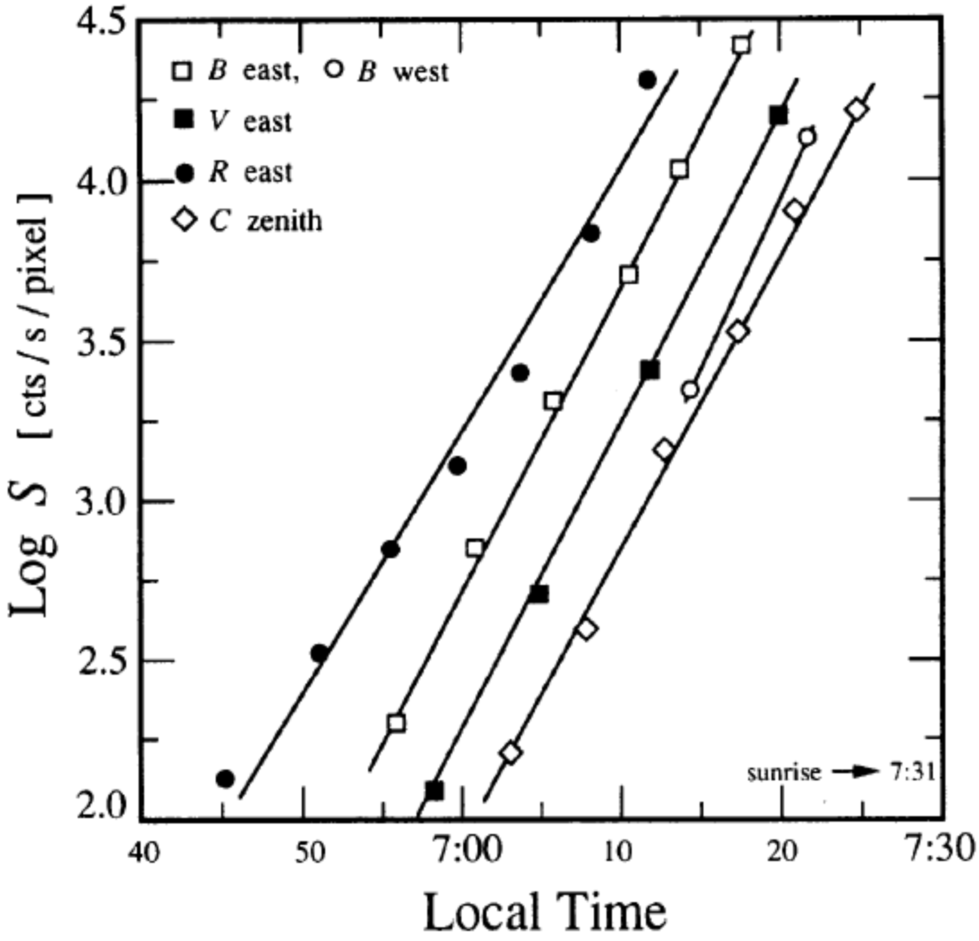


FIG. 1. Log of the twilight sky surface brightness vs local time for four broadband filters: Washington C ($\lambda_{\text{eff}} = 3900$ Å), and Harris B, V, R. All filters display a similar rate of change of surface brightness. This effect appears to be independent of direction (within 2 airmasses of the zenith) as evidenced by the similarity of slopes for data obtained while pointing east, west, and toward the zenith before sunrise.

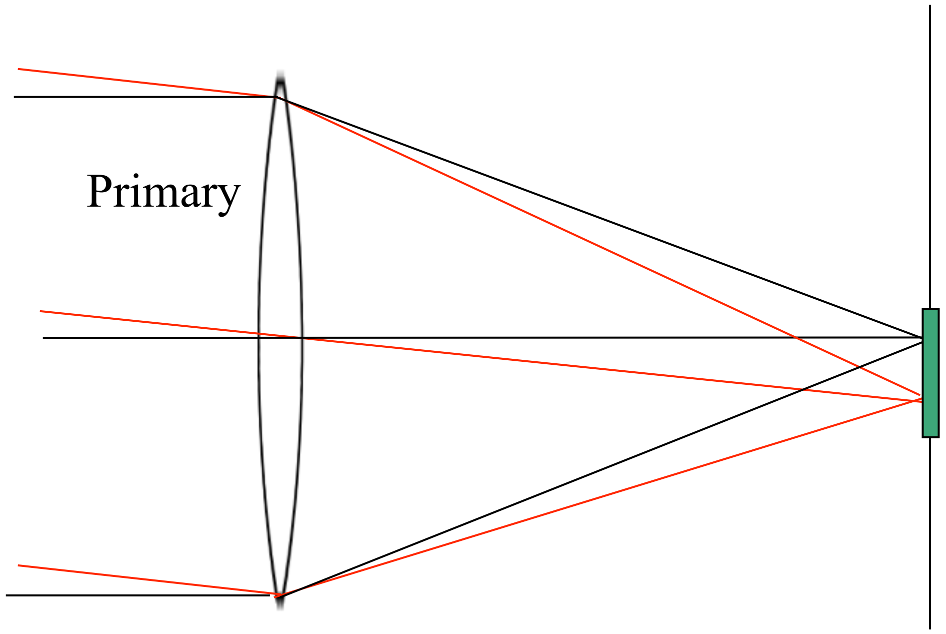
1993AJ,105.1206

Daytime: Visual ~ 7 mags / arcsec^2 ~ −2 mags/arcmin^2

~ eye resolution 30

Imaging camera

Basic camera:



Telescope primary [+secondary] images directly onto detector

'native focus' $\Rightarrow$ no instrument!

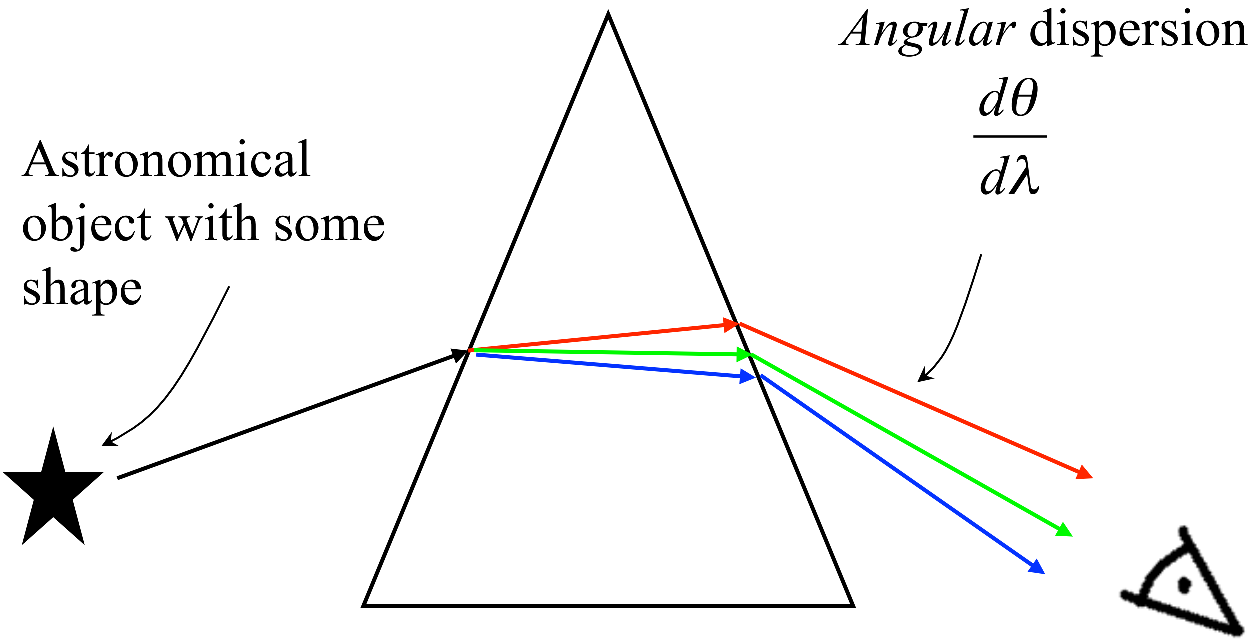
Detector scale governed by focal length of telescope

24 μm pixel $\Rightarrow$ 0.3 arcsec image 4m

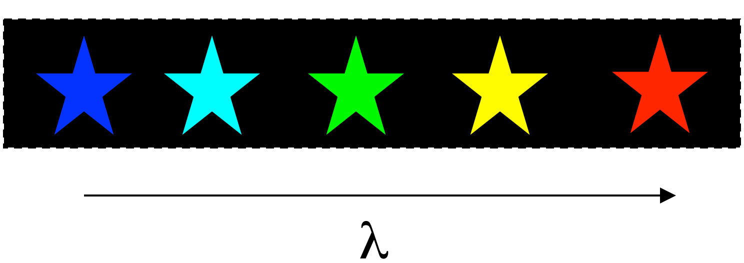
$\Rightarrow \sim f/4 \Rightarrow$ *prime focus* location

Spectroscopy

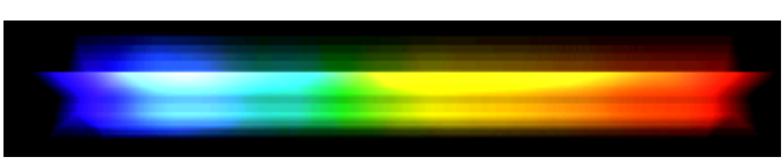
Reconsider dispersion by a prism:



Observed image is a *spectrum*:



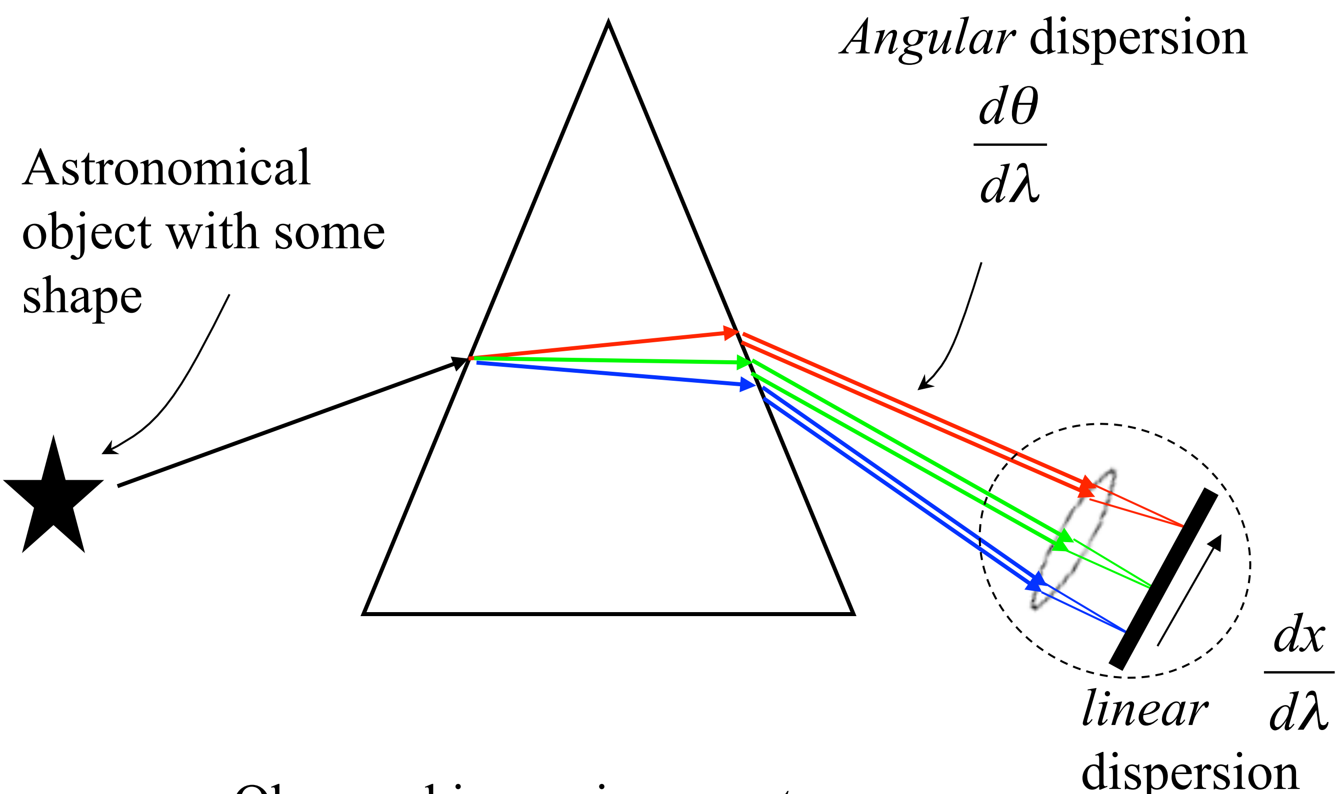
Source with discrete emission at single wavelengths (e.g. HII region)



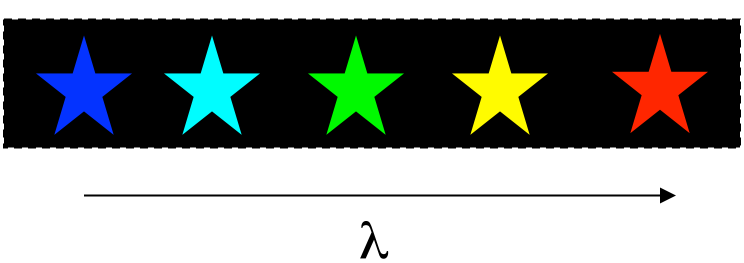
Source with continuous λ continuum emission e.g. star

Spectroscopy

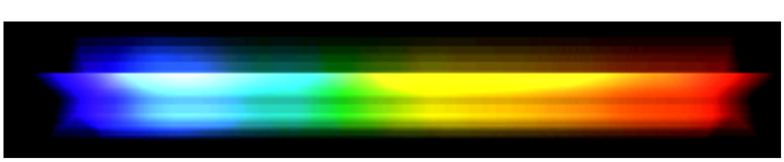
Replace eye with lens + detector:



Observed image is a *spectrum*:

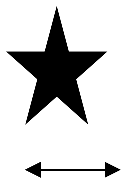


Source with discrete emission at single wavelengths



Source with continuous λ continuum emission

Spectroscopic image formation



source,
size D

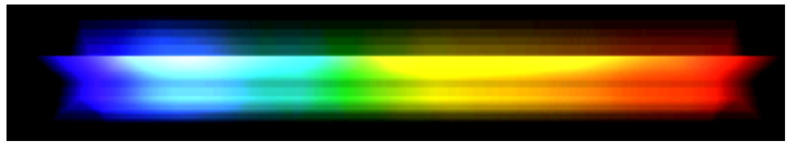
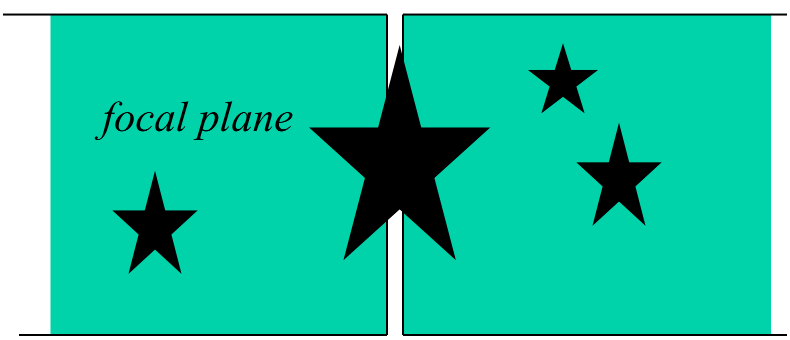


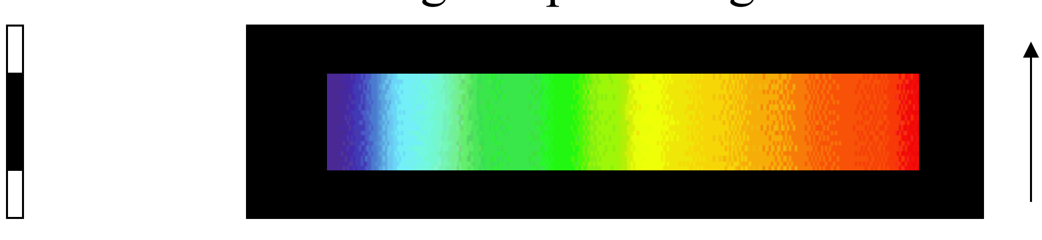
image = source with image position
dispersed according to wavelength

Clearly spectroscopic resolution limited by source image size D

Define aperture cleanly by means of a slit:



Spectrograph: image plane (onto slit)
collimator (remake angular plane)
dispersing element
re-image dispersed light



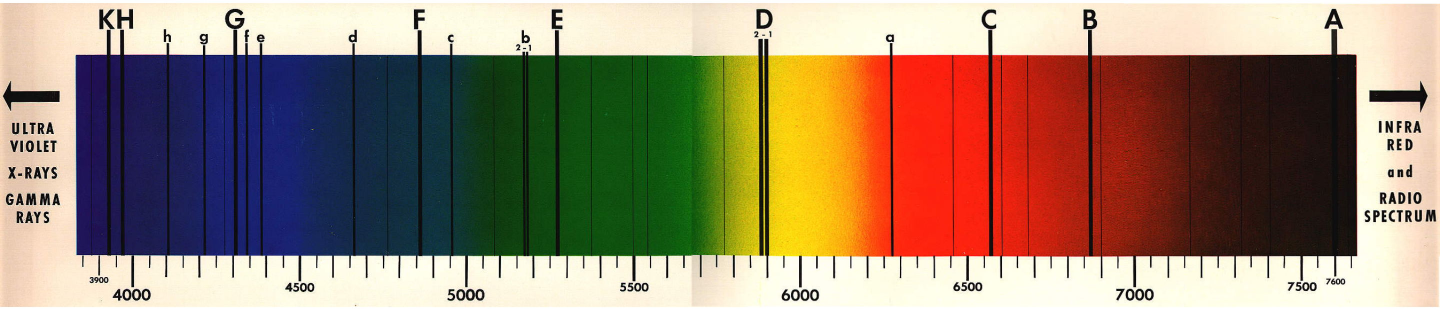
spatial slit
coordinate
x

source

spectral image

λ

Example – the solar spectrum

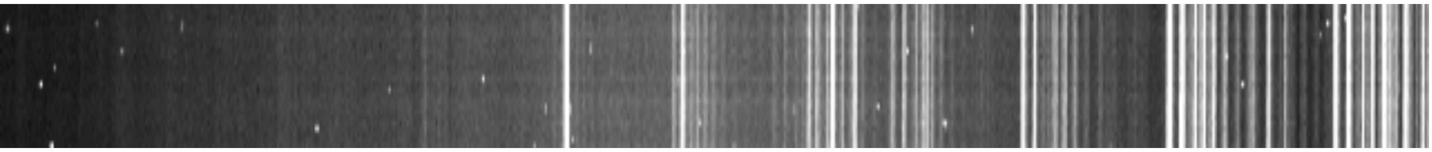


'Fraunhöffer lines,' not explained until advent of QM

In reality of course, only the eye *sees* color, if you built a spectrograph and recorded the slit image on a CCD or photograph you would see something like this:

Observe some wavelength calibration source to work out λ(position)

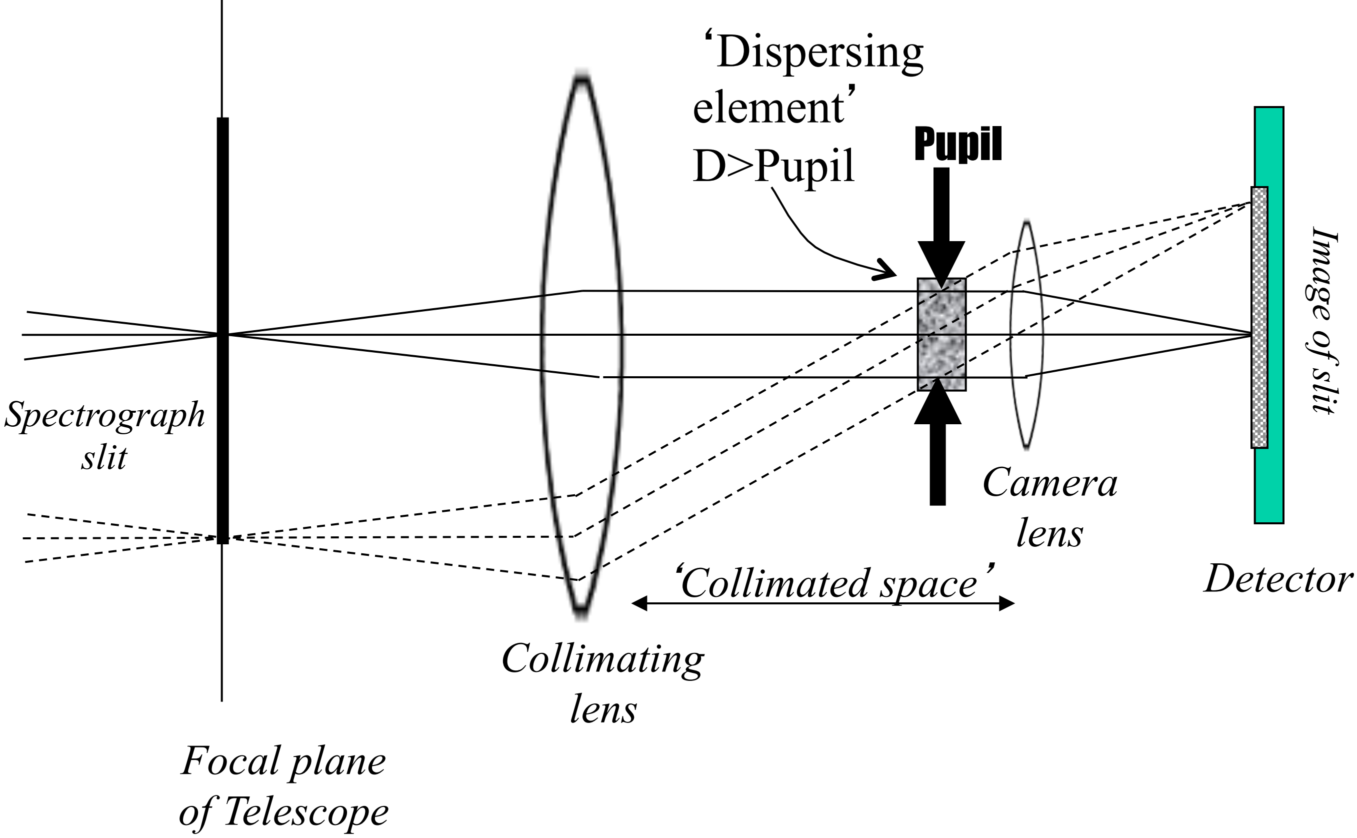
or this:



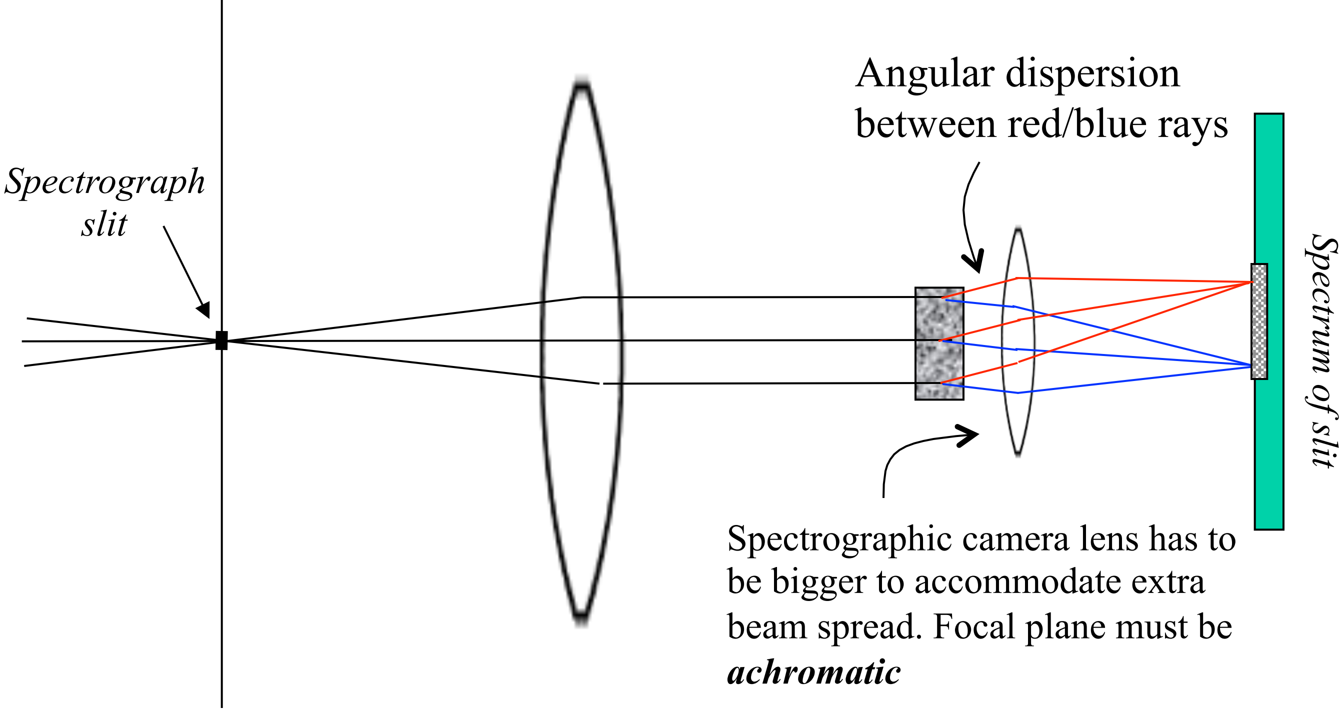
any guesses as to what this source is?

Schematic spectrograph

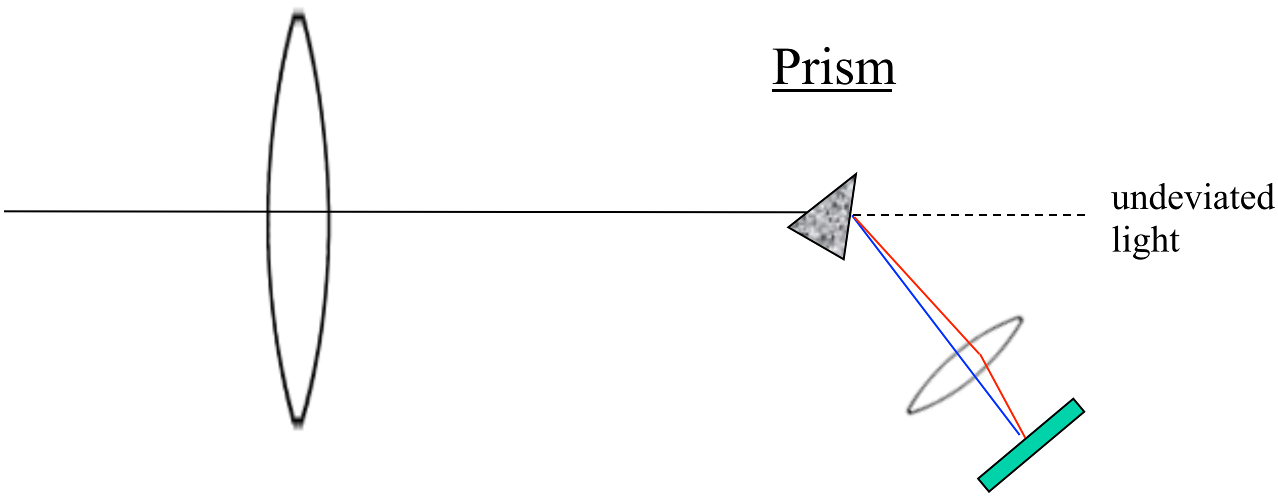
Side view (slit vertical)

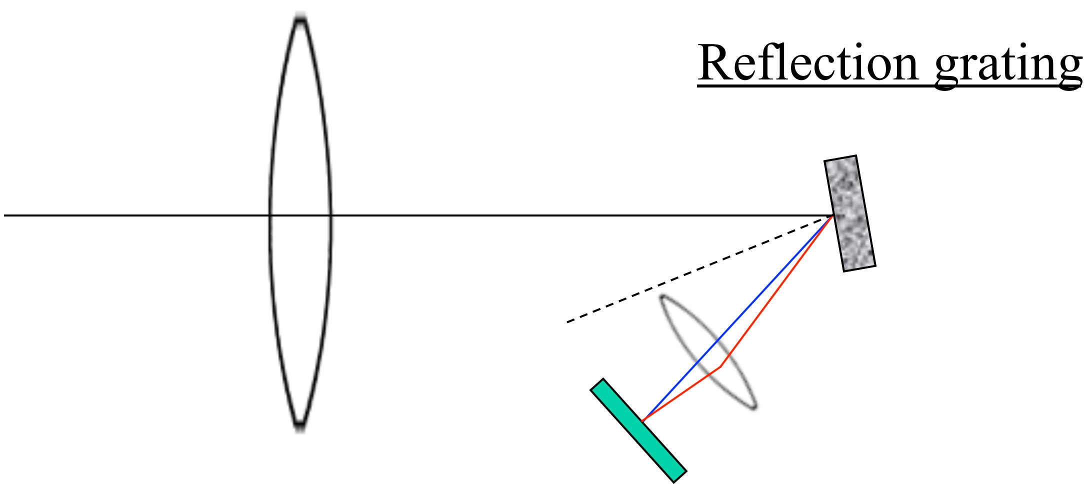


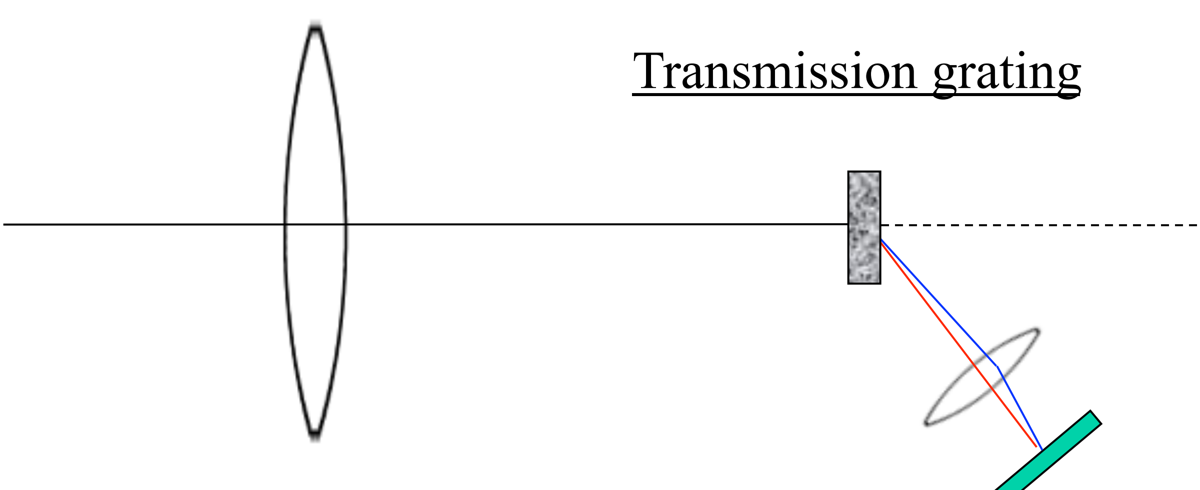
Top view (slit into paper)



In reality:

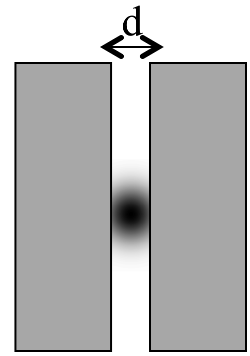






⇒ 'anamorphic magnification'

What determines spectral resolution?

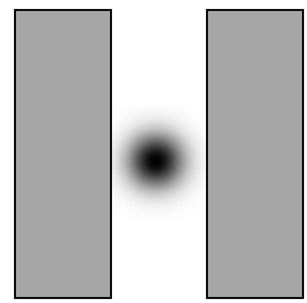


Slit width: spectral PSF is the image of the object through the slit at one λ.

Point sources: d ~ seeing ($d\theta$ ~1 arcsec)

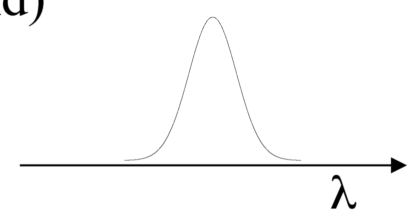
Can make narrower ⇒ higher resolution

BUT LOSE LIGHT



If make slit very wide: PSF is determined by seeing and not slit (but let in lots of sky background)

Spectral PSF is the image of an emission line



Intrinsic dispersive power of the element:

$$\frac{d\lambda}{d\theta}$$

Δarcsecs ⇒ ΔÅ

Angular magnification of your imaging system:

$$M = \frac{D}{P}$$ (no anamorphism)

1 arcsec on the sky ⇒ several degrees at pupil

⇒ lower spectral resolution

LARGE PUPIL: HIGHER SPECTRAL RESOLUTION
(but bigger & more expensive instrument & dispersing element)

Dispersing elements: prisms

Define spectral resolution at wavelength λ *dimensionously*: $R=\lambda/\Delta\lambda$

Recall dispersive power of refracting medium:

Schott BK7 glass (λ, n): (Δn ~ 10^{-2})

4861Å	1.52237330	(Blue/green, Hβ, "F")
5876Å	1.51679591	(Yellow, HeI, "D")*
6563Å	1.51431928	(Red, Ha, "C")

* Also Na D 5892Å

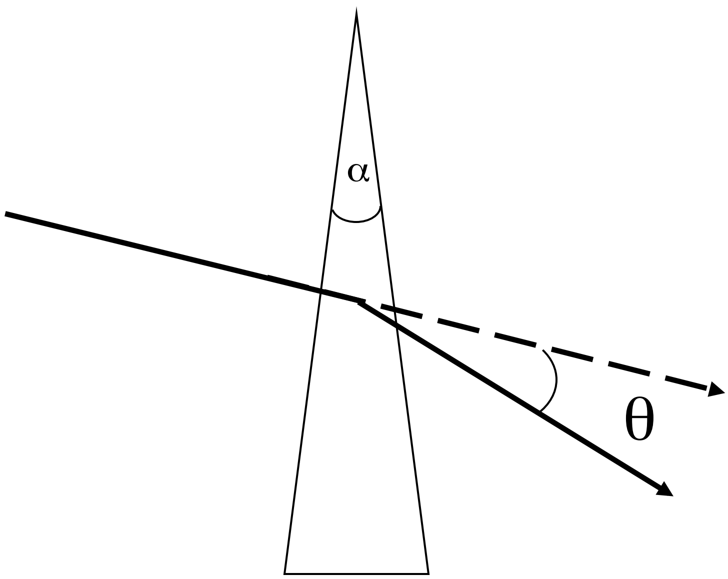
Disp. Power $= \dfrac{n_F - n_C}{n_D - 1} = \dfrac{1}{\nu}$

"Constringence"
"Abbe Number"
higher for less dispersive glasses

$$i.e. \quad \nu = \frac{n-1}{\Delta n_0} = 64 \ \ (BK7)$$

$$\frac{dn}{d\lambda} \approx \frac{\Delta n_0}{\Delta \lambda_0} = \frac{1}{\nu}\frac{n-1}{\Delta\lambda_0} = \frac{1}{\nu}\frac{n-1}{1700\text{Å}}$$

Thin Prism



Small angles (in radians):

factors ~ O(1) even for thick prisms

$$\theta = (n-1)\alpha$$

$$Angular\ Dispersion: \frac{d\theta}{d\lambda} = \frac{d\theta}{dn}\frac{dn}{d\lambda} = \alpha \frac{n-1}{\nu\, \Delta\lambda_0}$$

<u>Example</u>:
4m optical telescope, 100mm pupil: M=40, 1 arcsec (sky) ⇒ 40 arcsec (pupil). 10° prism

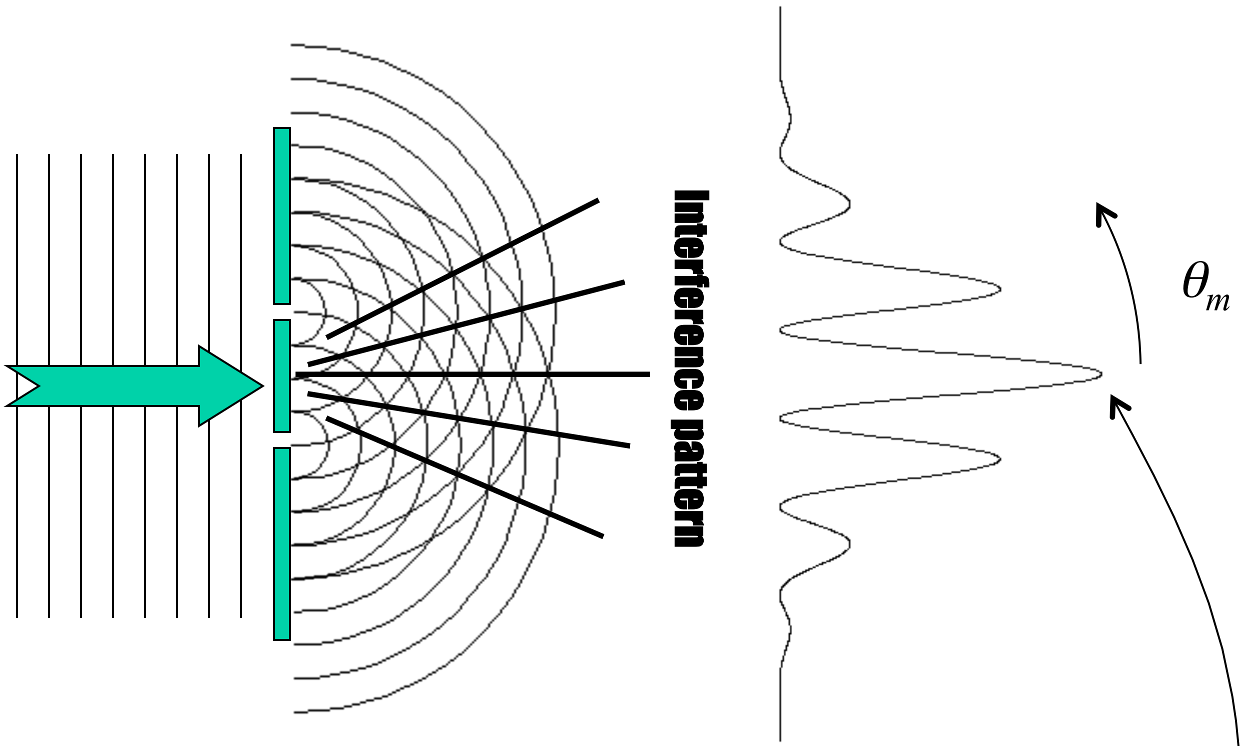
BK7 glass: 1 arcsec (sky) ⇒ 242 Å

Spectral resolution $R=\lambda/\Delta\lambda$ = 5500Å/242 Å = 21

VERY LOW!!

Dispersing elements: Diffraction Gratings

Two Slit Diffraction revisited:



Peaks occur at $\sin\theta_m = \dfrac{m\lambda}{d}$

Alternatively, consider broad-band wide light

Each peak will be an angular spread of colour:

1st order: $\sin\theta(\lambda) = \dfrac{\lambda}{d}$

2nd order: $\sin\theta(\lambda) = \dfrac{2\lambda}{d}$

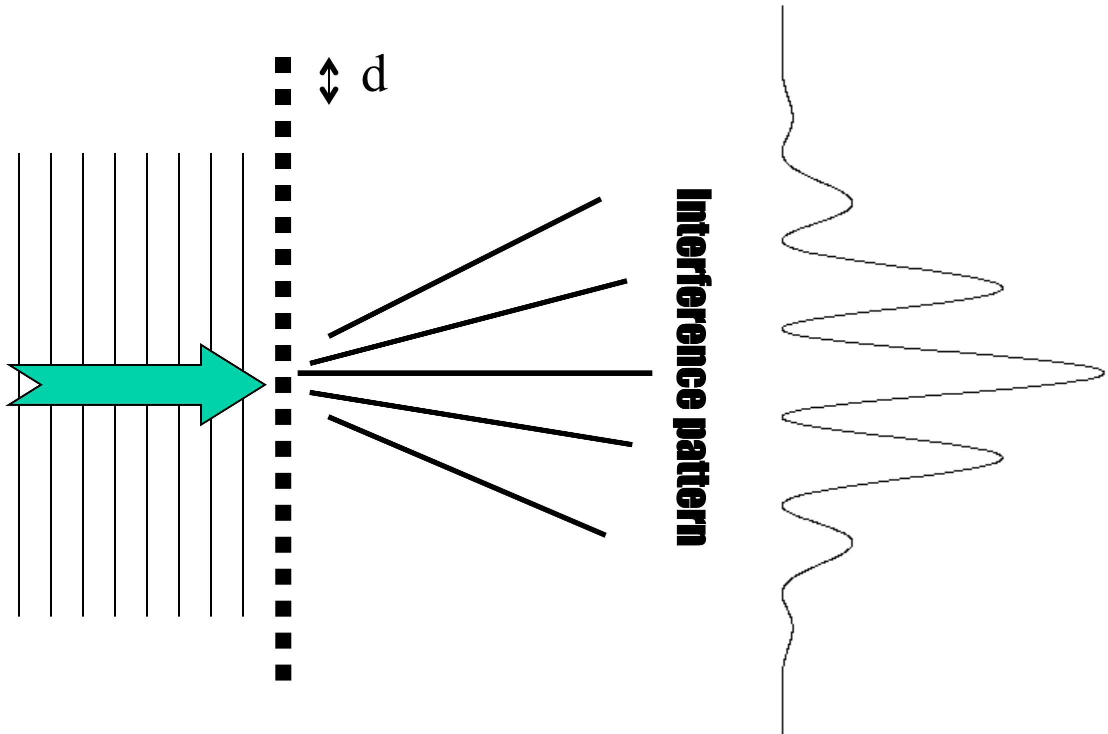
3rd order: $\sin\theta(\lambda) = \dfrac{3\lambda}{d}$

…

m=0
'zeroeth order'
⇒ white light'

max order: d/λ

Diffraction grating:



$$\boxed{\text{Grating Equation}: m\lambda = d\sin\theta_m}$$

Efficiencies as high as 90% are possible, ~50% are normal

Note: red light is dispersed more than blue (opposite to prism)

Dispersive power:

$$\frac{d\theta}{d\lambda} = \frac{m}{d\cos\theta} = \frac{L\,m}{\cos\theta}$$

Ruling density: lines/mm
(L=100-2400 common)

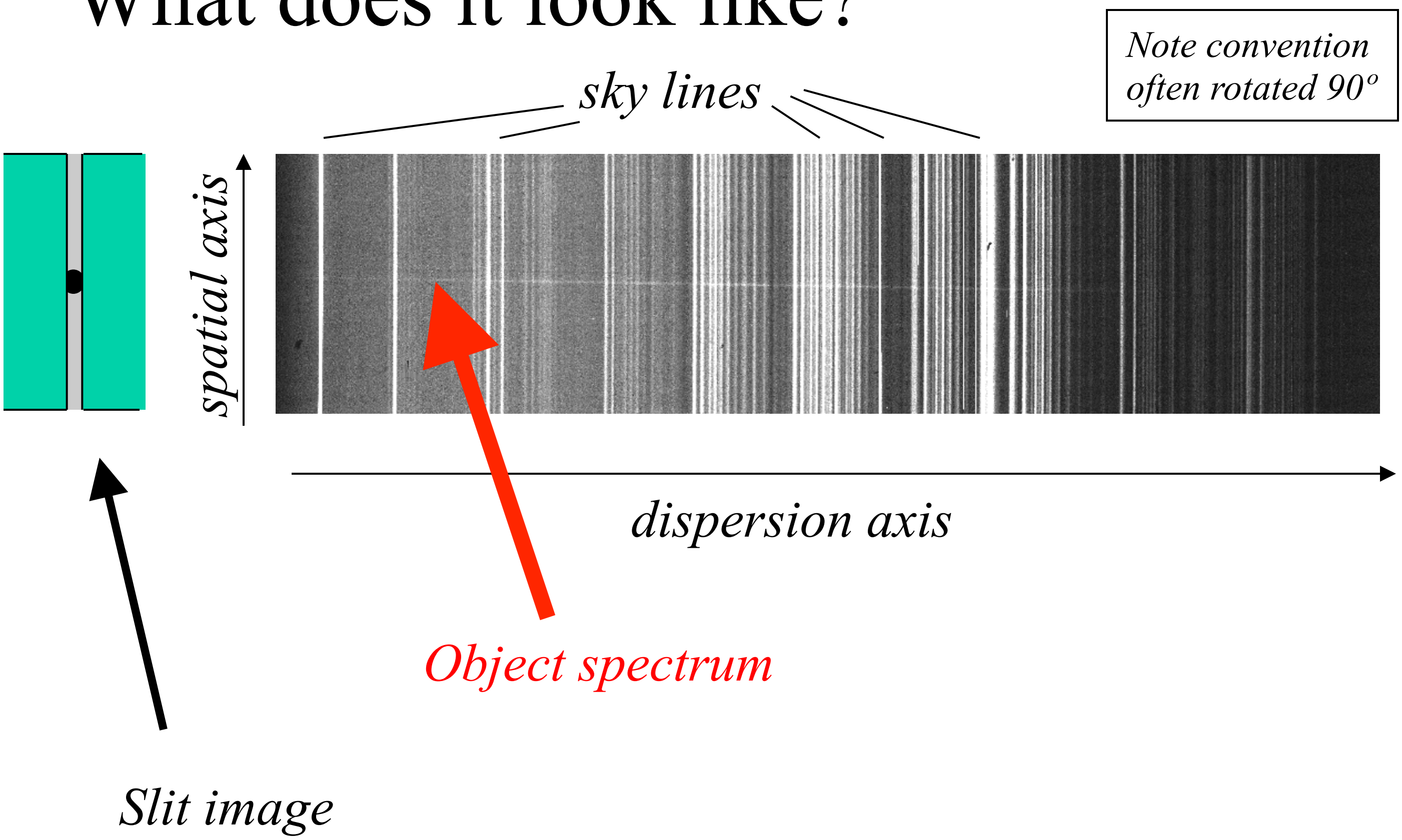
$$\therefore \Delta\theta \sim 0.3m \quad (L = 300\text{mm}^{-1} \ \Delta\lambda = 0.3\mu\text{m})$$

HIGHER ORDERS HAVE HIGHER DISPERSION

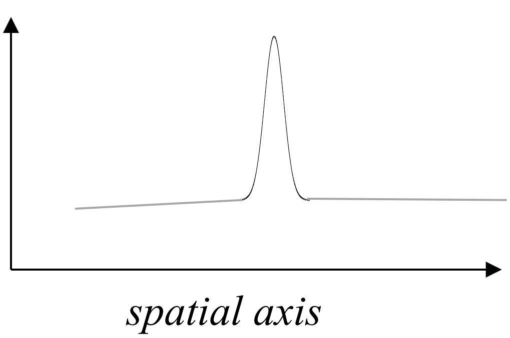
$$c.f.\ prism: \frac{d\theta}{d\lambda} = \alpha \frac{n-1}{\nu\,\Delta\lambda_0} \Rightarrow \Delta\theta \sim 10^{-2}$$

Simple longslit data

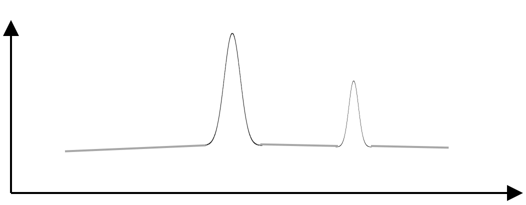
What does it look like?



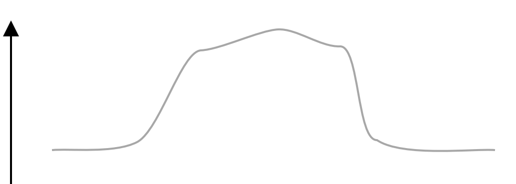
Slit profile:



Two stars on the slit:



Galaxy on the slit:



Multi-object spectroscopy

Goal: a modern telescope has a FOV of arcmins – degrees at focus

A slit spectrograph only uses a few arcsecs of this field

➔ Massive multiplex is possible

Two common solutions:

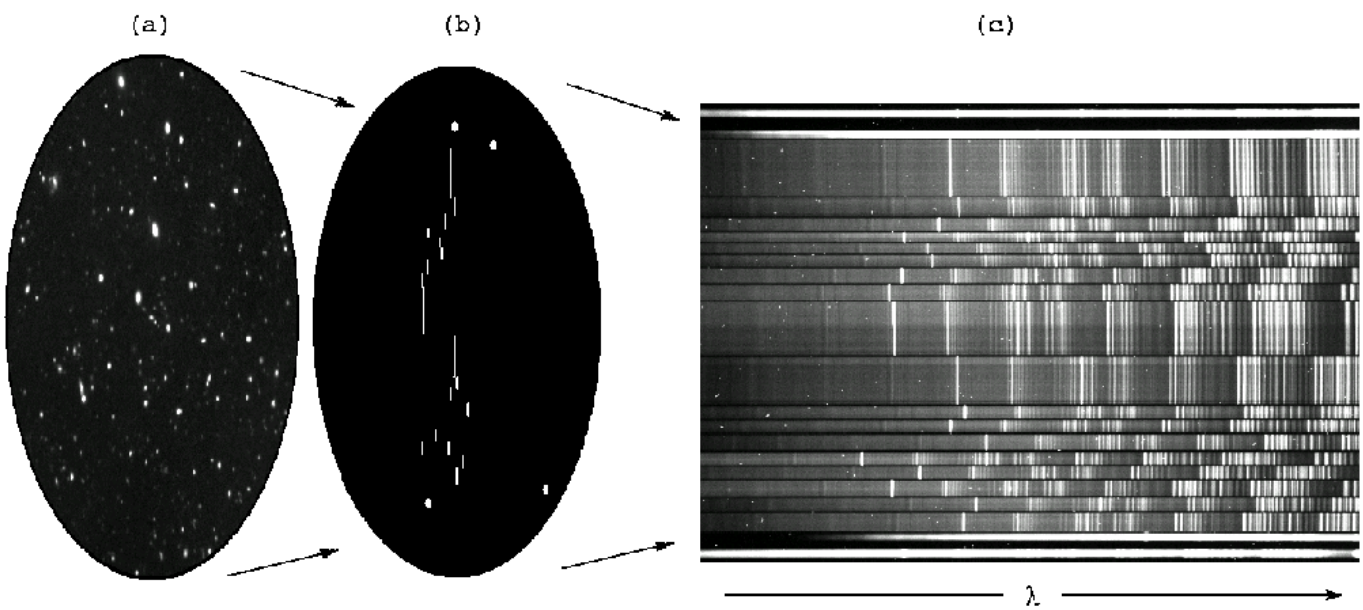
Multi-slit spectrographs

Multi-fiber spectrographs

Multi-slit spectrographs

Concept: replace the single longslit with a multiple slit mask:

Remember a spectrograph is an *imaging* system, just smeared out in the dispersion direction

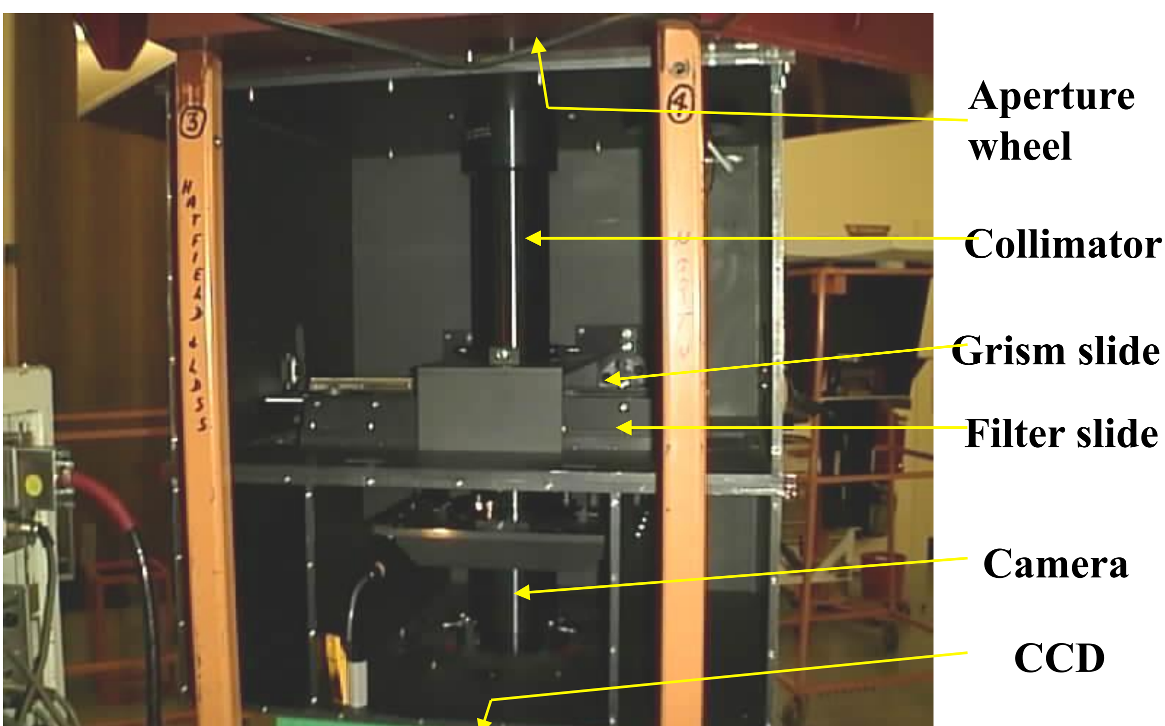


Each slit forms it's own image, if the slits are displaced on the sky in the dispersion direction then the spectra will be similarly displaced on the detector

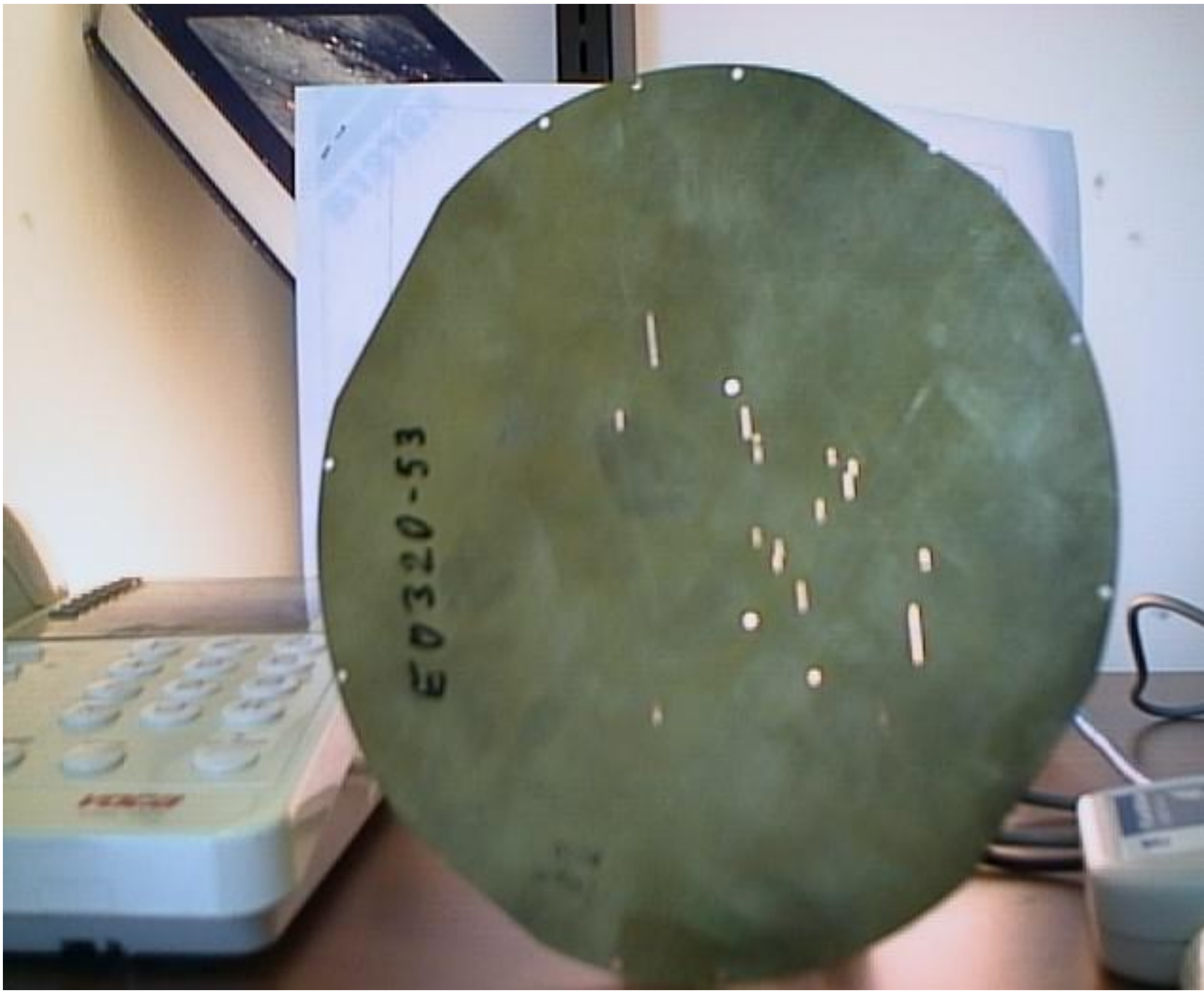
Data reduction: treat each as a independent longslit spectrum

Example: LDSS

AAT's Low Dispersion Survey Spectrograph for faint multi-slit spectroscopy (12 arcmin FOV)



Slit masks



Apertures cut in an opaque material

Manufacture:

- cut with milling machine or laser
- materials: metal (brass/invar/…), carbon fiber

Multislit pros and cons

Pros:

- Good sky subtraction via slits
  - (Limited by slit roughness from manufacture)
- Ability to image field
- Simple high-efficiency optics

Cons:

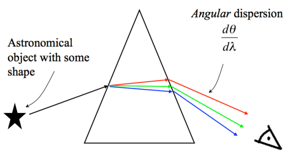
- Entire Field of View has to be imaged $\Rightarrow$ enormous collimator (e.g. LRIS is 363mm for 8 arcmin)
- Efficiency of packing objects is limited by their location on the sky
- Parallactic Angle

‘Slitless spectroscopy’

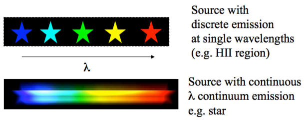
Hubble Space Telescope ACS Grism

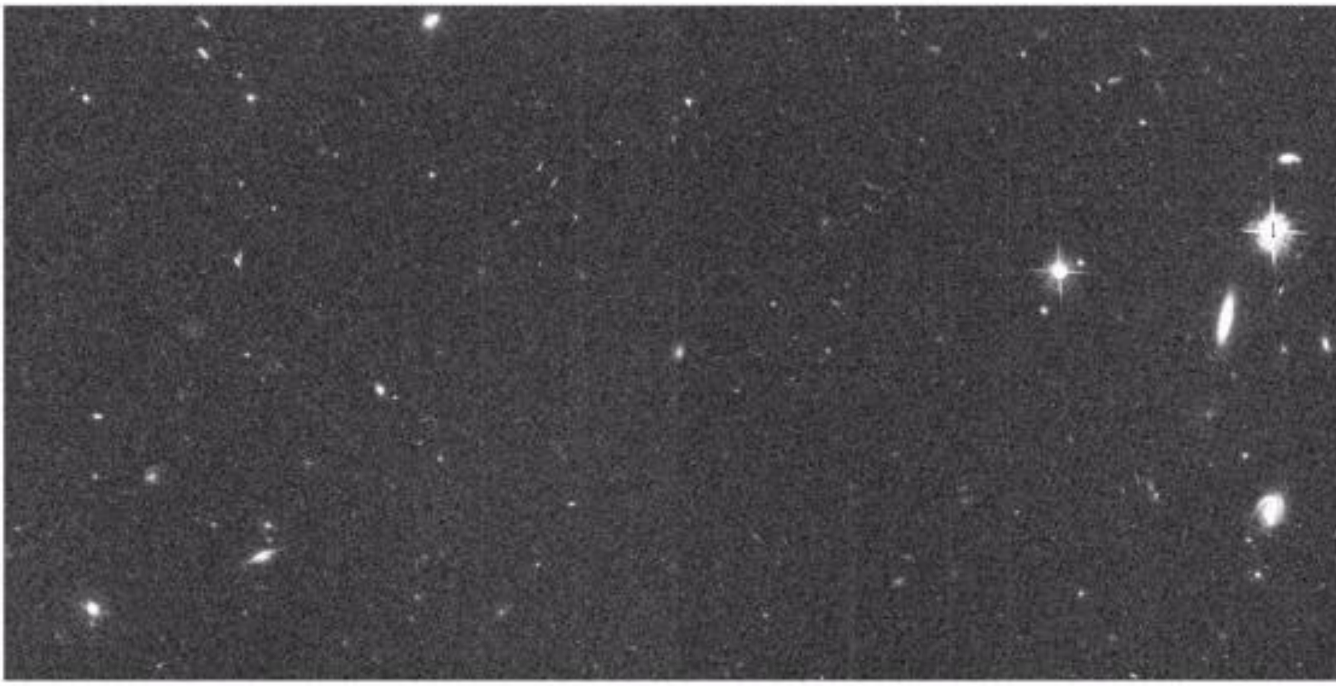
Spectroscopy

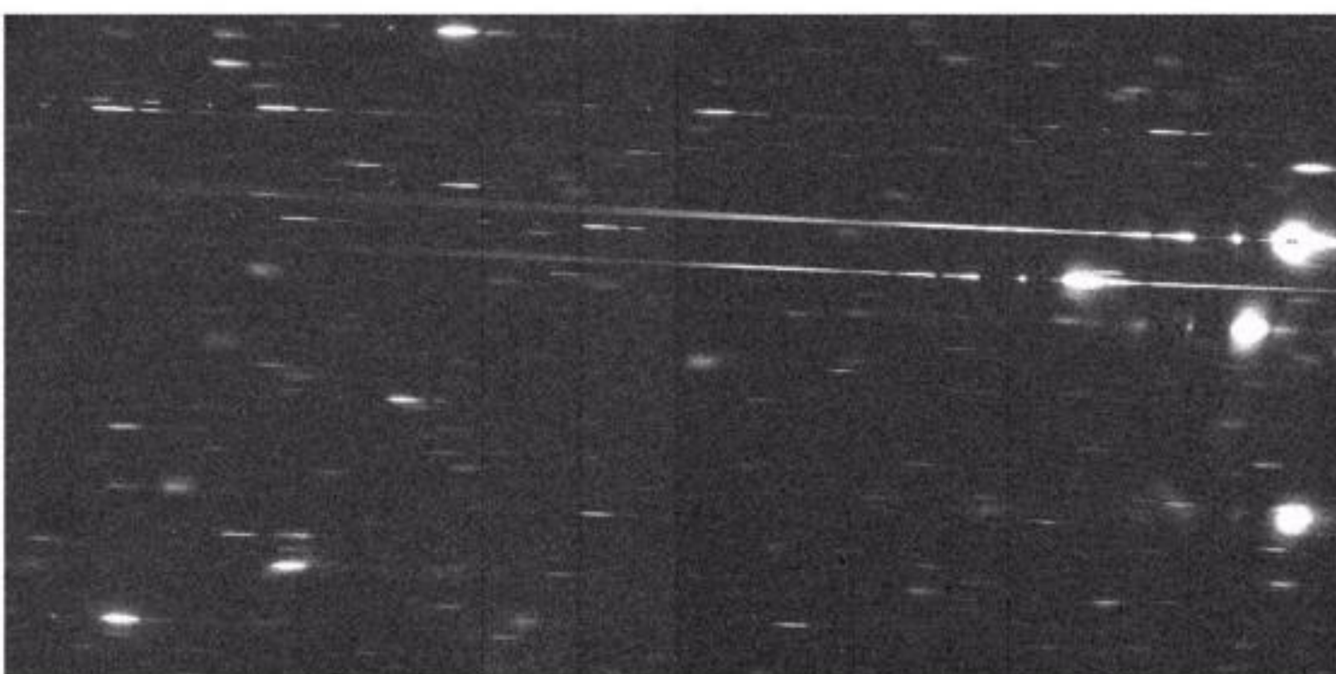
Reconsider dispersion by a prism:

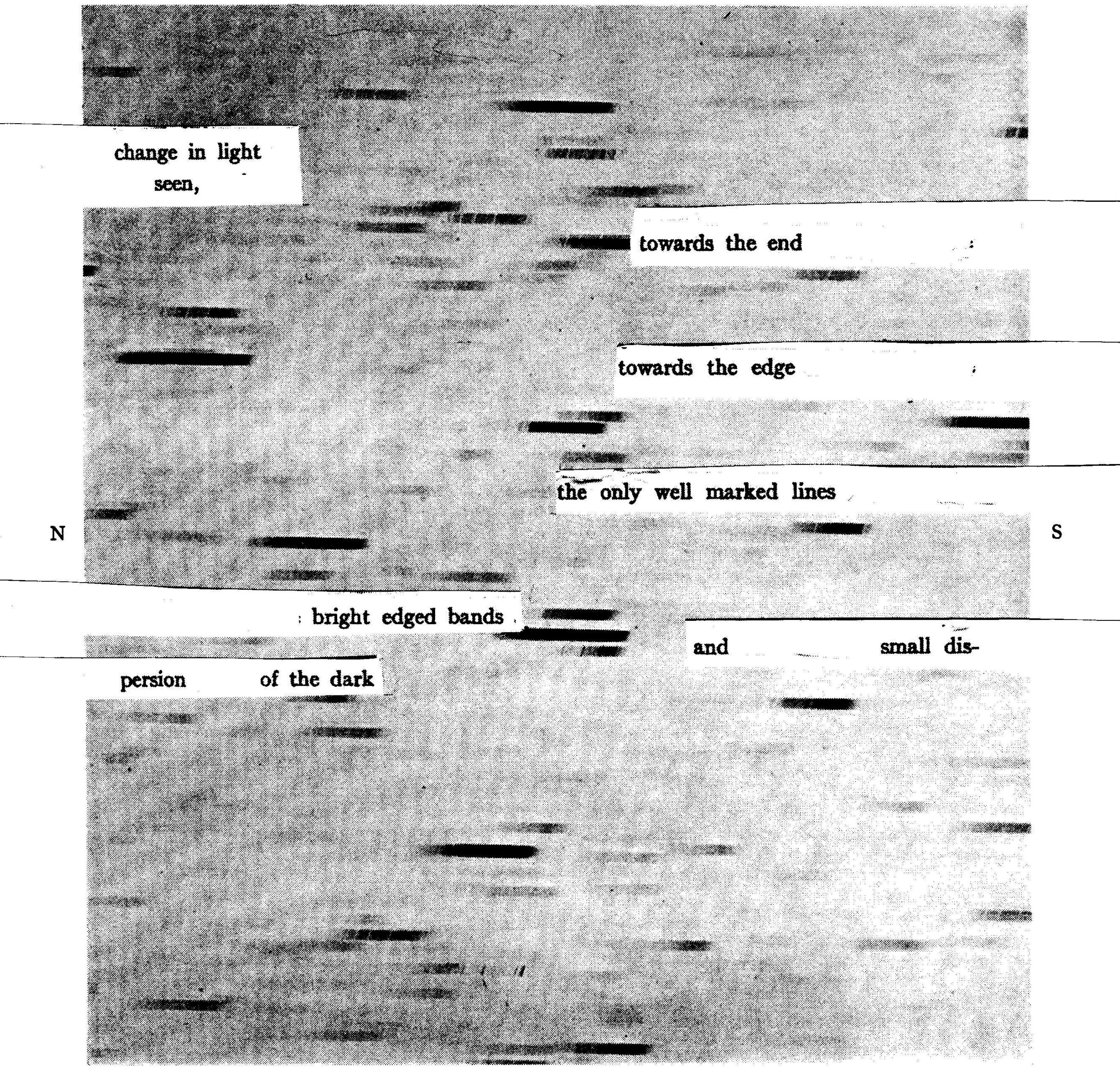


Observed image is a *spectrum*:







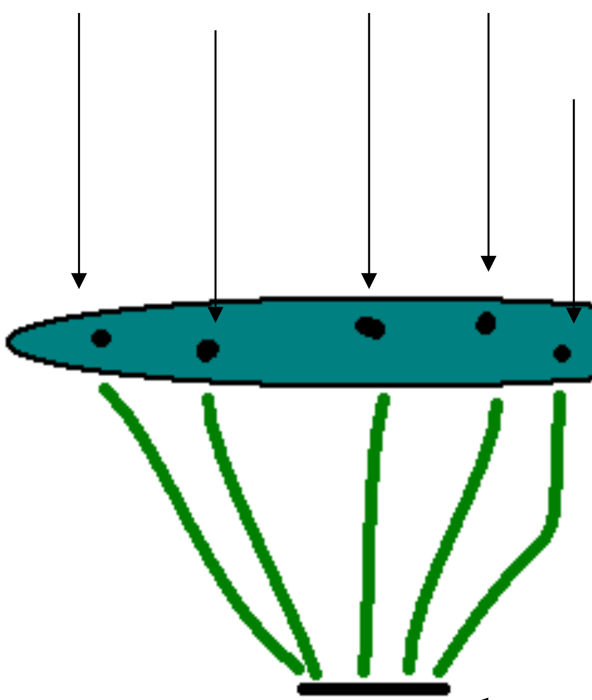


PHOTOGRAPH WITH OBJECTIVE PRISM.

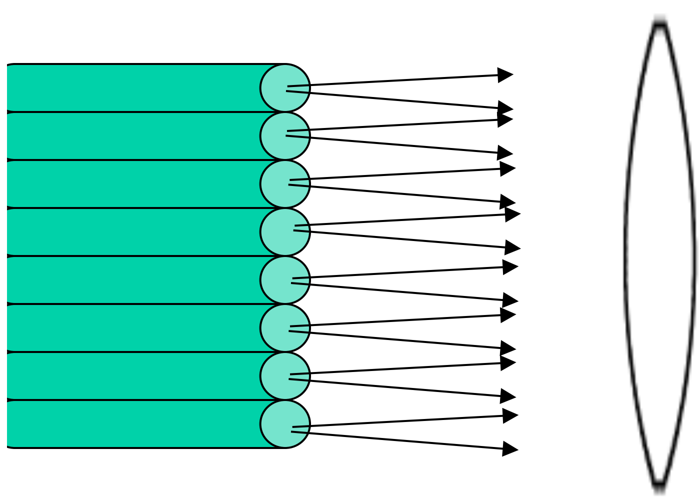
Problem: OBJECTS dispersed, SKY background ~ undispersed

Fiber MOS

Idea: reformat focal plane by optical fibers



Fiber ends lined up to form slit of a spectrograph:



To 3D spectroscopy

None of the solutions we have seen are 'ideal'

We want 3D spectroscopy, but we don't want to scan.

A longslit makes optimum use of the detection in the way we want

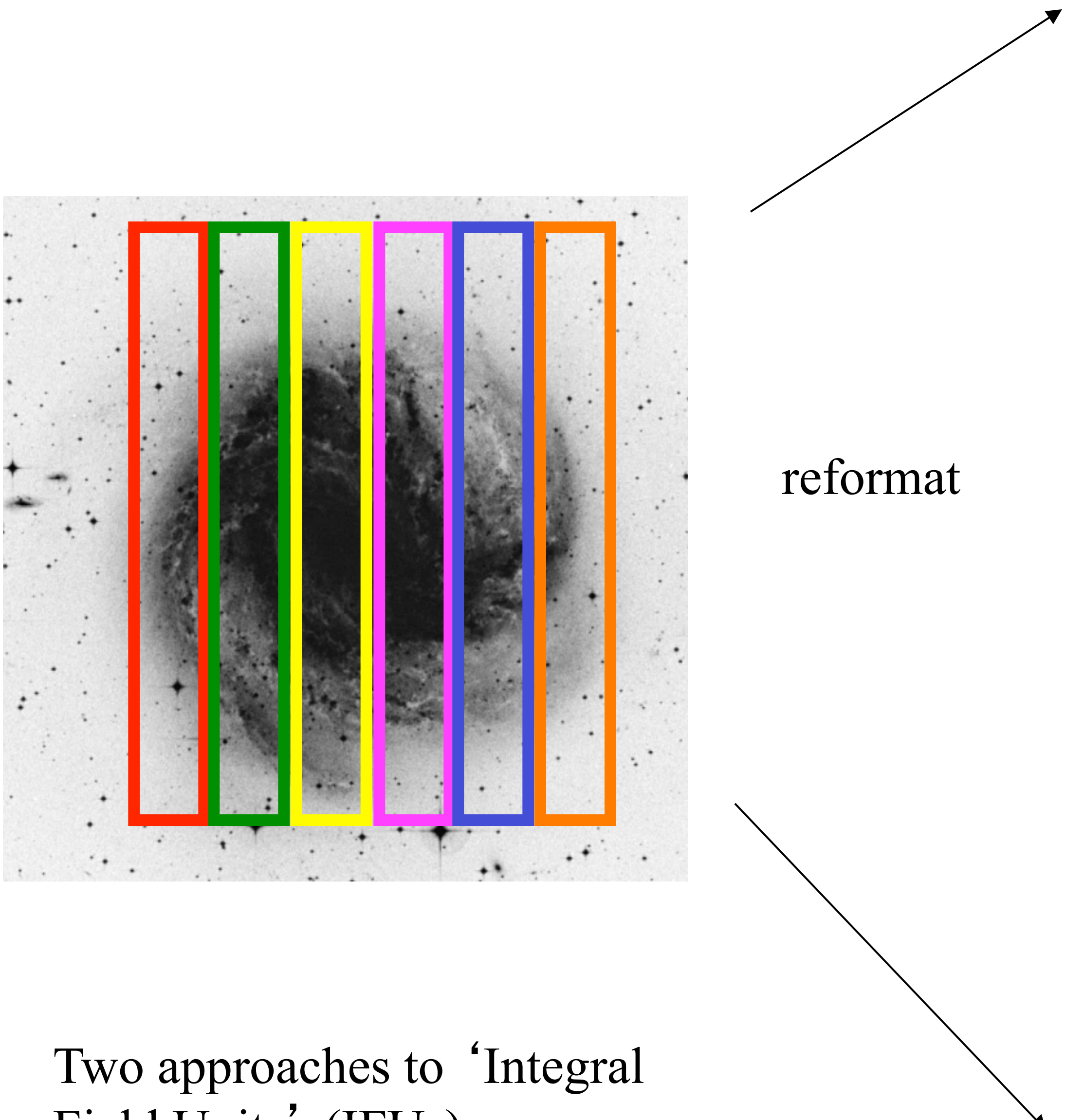
x = spatial y = spectral

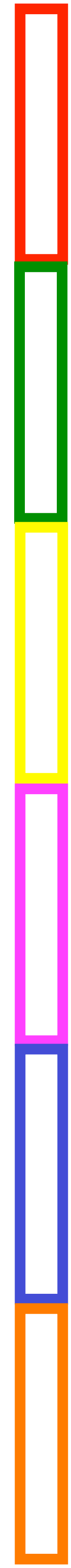
Except we want the spatial information to be 2D (over a smaller FOV) rather than 1D

e.g. replace a 6 arcmin × 1 arcsec longslit with a 19 × (19 arcsec × 1 arcsec slits)

Reformatting

The idea 3D spectrograph:

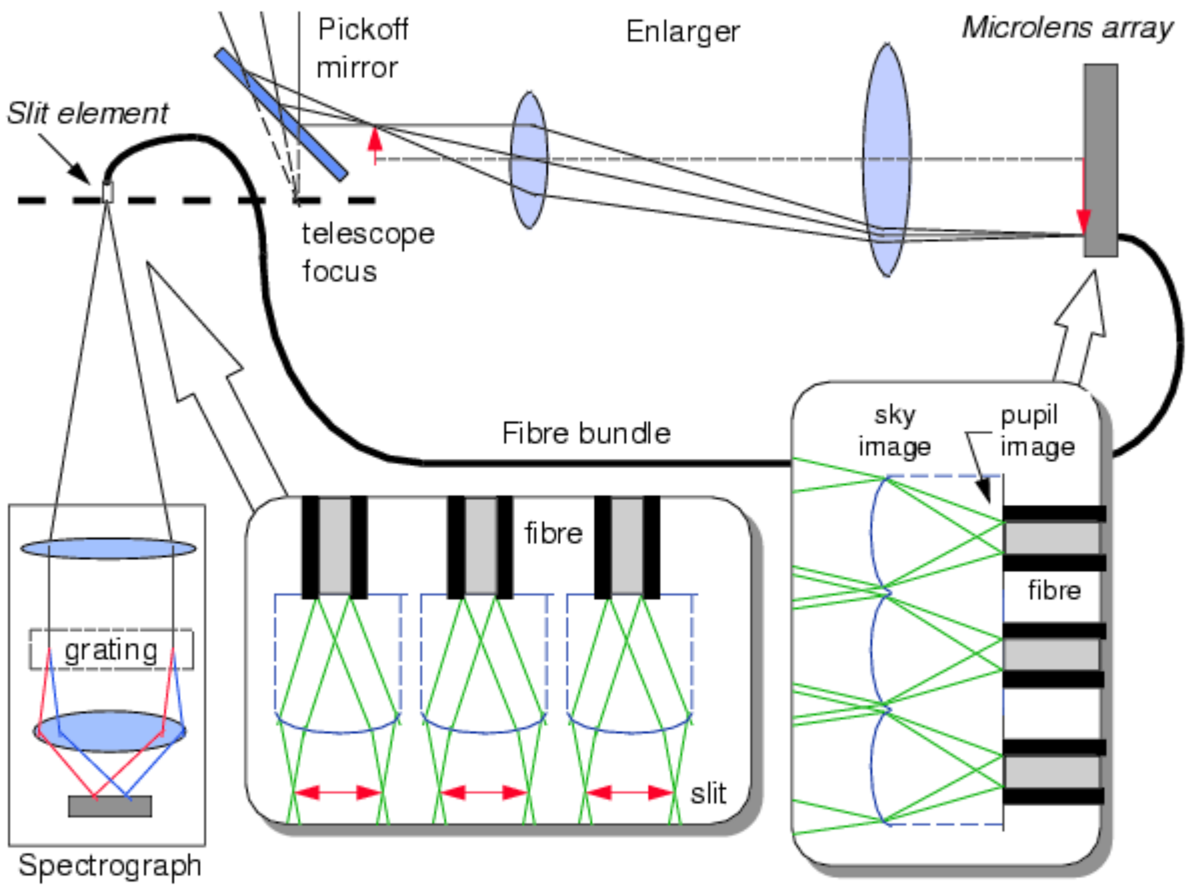




Two approaches to 'Integral Field Units' (IFUs):

Microlens/fiber array
Image slicer
(Pupil imagery)

Fiber IFU



A schematic diagram showing the layout and principles of the GMOS integral field unit.

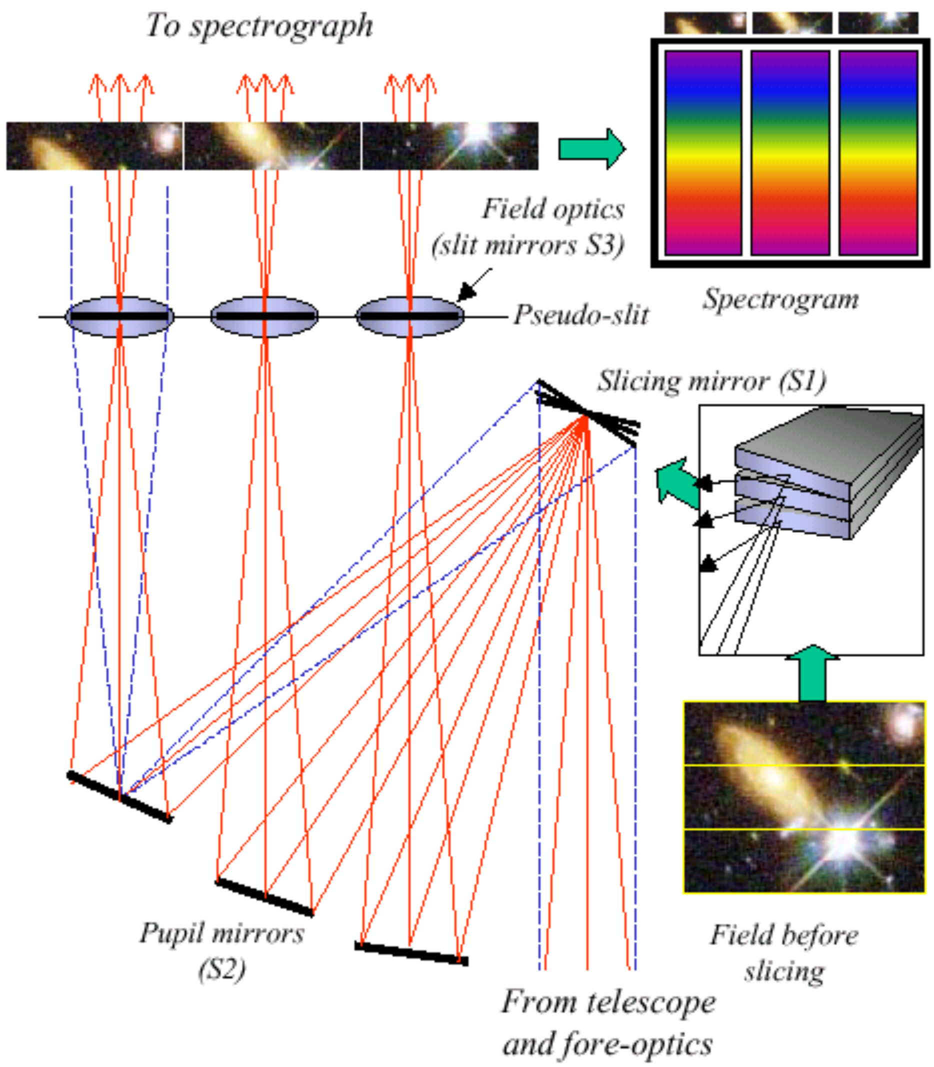
Use light guide properties of fibers to reformat

Microlens array maintains correct f/ratio and image contiguity

<u>Advantages</u>: flexibility, ability to arbitrarily reformat.

<u>Disadvantages</u>: fiber issues. General 2D image discontiguity

Image slicer



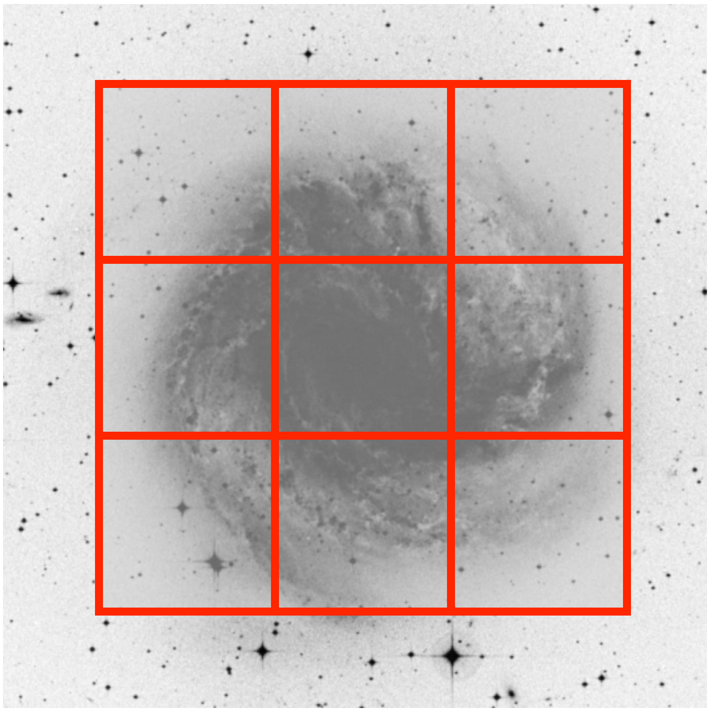
Proposed NGST image slicer (Durham)

A 'staircase' mirror redirects the light beam and 'stacks' the slits optically

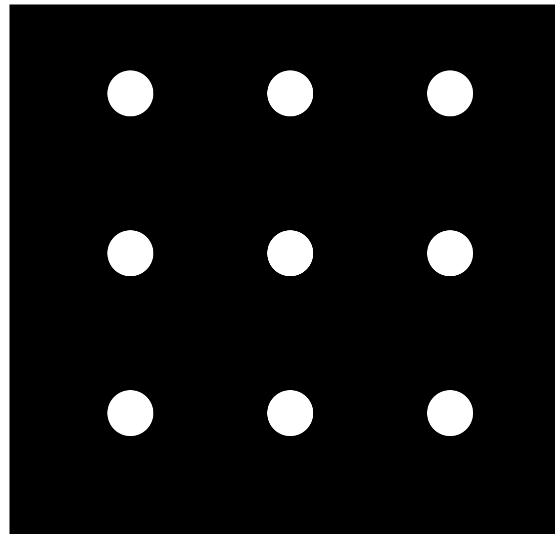
Maintaining this complex optical alignment is difficult

Advantage: each slice is a true contiguous slit

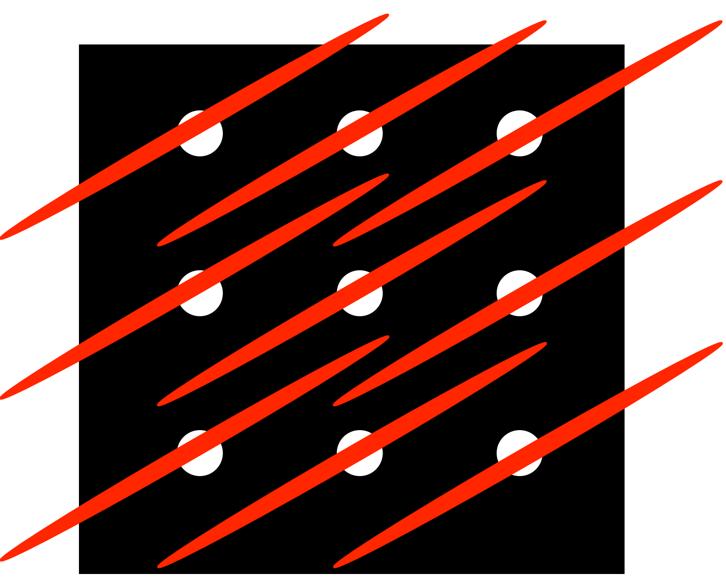
Simple lenslet array



Segment focal plane with lens array



Multiple Pupil image



Spectra. Direction of dispersion cleverly tilted so spectra do not overlap on detector.

Spectral range is limited though

Remarks on IFUs

Most efficient way of doing areal spectroscopy on small objects (galaxies)

Sky subtraction difficult

$\Rightarrow$ beamswitch IFU array from object to sky

$\Rightarrow$ image slicer allows slit subtraction

Very new instrumentation technology – this is the cutting edge in both instrumentation construction and data reduction!

In principle is ideal instrument for single-galaxy astrophysical studies, a longslit is just a slice through an object

Velocity field (mass)

Stellar populations

Metallicity

Ionization