Telescope sensitivity to faint sources: Importance of collecting area

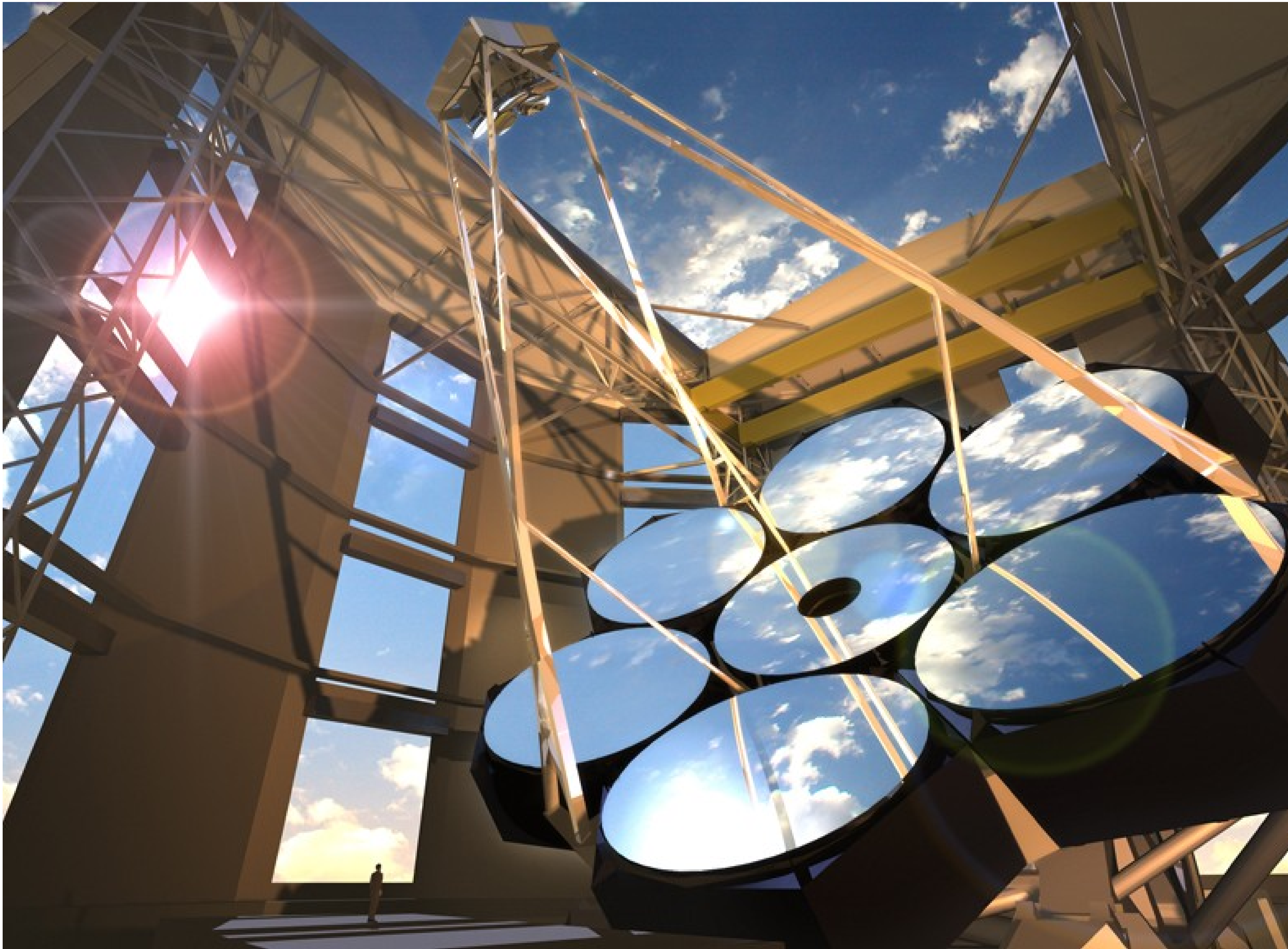
Astronomical measurements are very often flux-limited: limited number of photon available from the source.
Example:
Typical nearby (by cosmological standards) galaxy : $m_V \sim 15$
In V band, with 0.1 μm bandpass, a 1 m^2 telescope with 50% efficiency: 5000 $ph.s^{-1}$
Imaging structure in the galaxy (details in spiral arms, bright clusters), will require >> 5000 ph

Detailed study of astrophysical objects requires spectroscopy and/or angular resolution → total number of photon required grows larger to take advantage of spectral and angular resolution

Study of faint objects is essential for astronomy, pushing for larger telescopes.
With larger telescopes:
- a given type of object can be imaged further away
  For example, imaging stars in nearby galaxy for stellar population studies allows better understanding of the galaxy architecture and history
- statistical studies require large samples. Sample size for a given type of object increases as sensitivity improves
- Cosmology requires the study of the distant (=young) universe. Finite speed of light used to look back in time

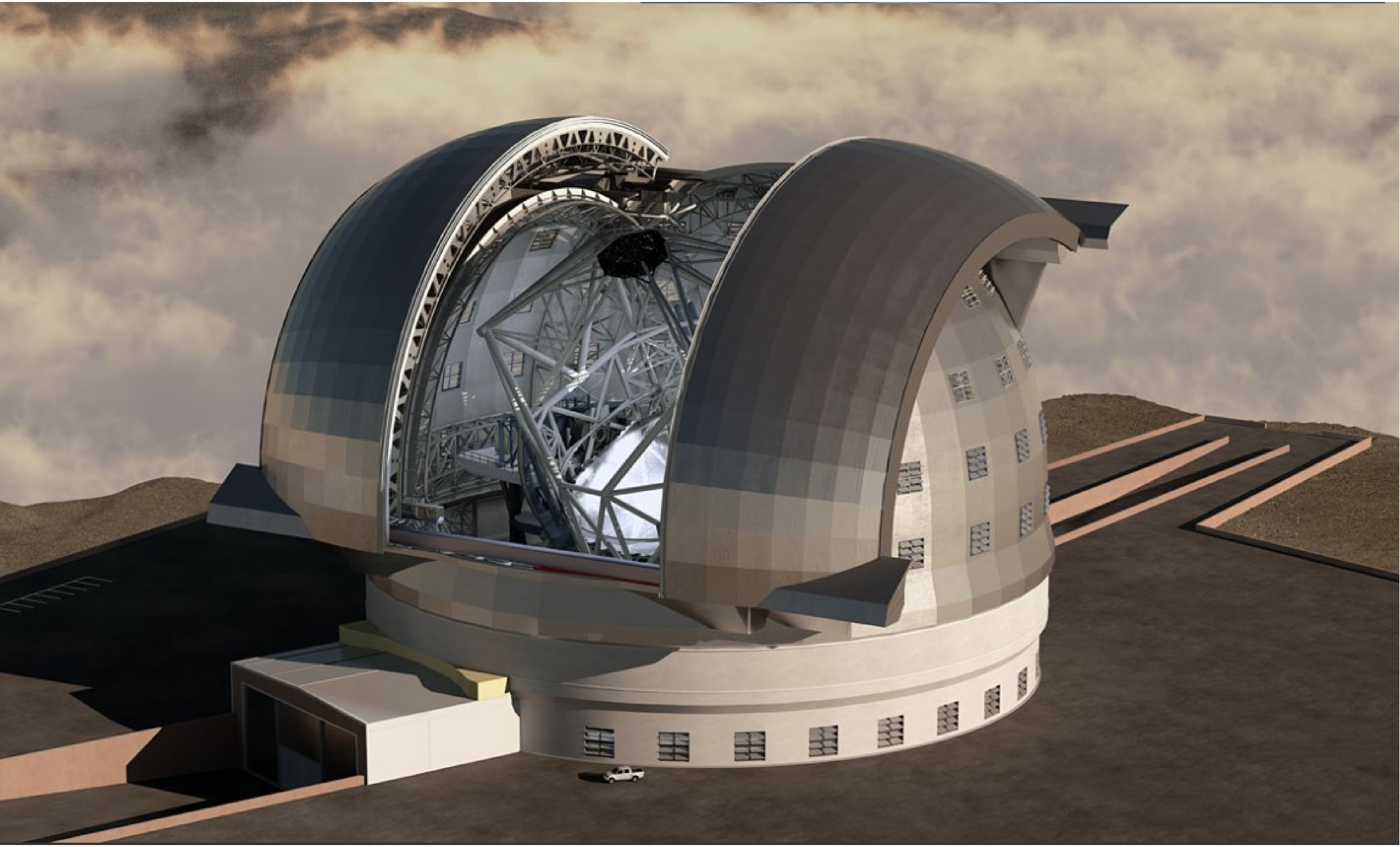
Current large telescope at 8m to 10m diameter, next generation will be 25m to 42m diameter

Giant Magellan Telescope (GMT) project: 24.5 m



Thirty Meter Telescope (TMT) project

European Extremely Large Telescope (EELT) project



Angular resolution

Without adaptive optics, angular resolution is limited to ~0.5” in good sites in optical.
Hubble space telescope diffraction limit = 0.05” (10x better)

With Adaptive Optics (AO), diffraction limit is reached in near-IR (> 1 um) → 0.05” on the current generation of large telescopes (up to 10m diameter).
Next generation of large telescopes (GMT, TMT, EELT) all include adaptive optics.

The two drivers for high angular resolution are:

(1) Ability to resolve small structures:
- Mitigate confusion limit problem (too many sources too close together)
- Astrometry (measure position of stars accurately)
- Image and study complex structures (map star forming clouds in galaxy)

(2) Sensitivity
At the faint end of the detection limit, the detection is a background limited problem: more light comes from the background (airglow, zodiacal light, thermal emission of telescope and sky) than from the source itself. Background is constant spatially, so it can be removed, but it photon noise (Poisson noise) is left.
This is especially important in the IR (higher background)
No background: sensitivity goes as D^2
Background-limited: sensitivity goes as D^4 if diffraction limited

Problem #2:

Repeat problem #1 with zodi + airglow background, assuming no AO (1” image) and AO (diffraction limited image), assuming a dark sky at m_V = 21 mag.arcsec^{-2}

Solution to problem #2

We have already computed in problem #1:
Zero point: zp = 1.79E13 ph./hr/m^2
Apparent magnitude of a Sun-like star in Andromeda: m_V = 28.98
Number of photon collected per hour from the star: N = zp x $2.512^{-28.98}$ = 45.9 $ph.m^{-2}$
With D the telescope diameter in [m], N = 45.9 ($\pi D^2/4$) [ph] = 36 D^2 [ph]

Number of photon collected per hour from the background
Without AO, the image is 1" wide (we assume that the photons are collected over a 1 $arcsec^2$ area, corresponding to a 1" by 1" square)
N_b = zp x 2.512^{-21} = 7.12E5 [$ph.m^{-2}$] = 7.12E4 ($\pi D^2/4$) [ph] = 5.59E4 D^2 [ph]
With AO, the image is λ/D wide (we assume that the photons are collected over a λ/D x λ/D square region). In $arcsec^2$, the area is:
$A_{AO} = ((\lambda/D)/\pi*180*3600)^2$ [$arcsec^2$] = 0.0129 D^{-2} [$arcsec^2$]
and the total number of background photons collected in the area in 1h is:
N_{bAO} = 0.0129 zp (π/4) 2.512^{-21} = 700 [ph] (note: this is independent of telescope diameter)

Telescope diameter required for SNR = 5
Signal = photons collected from the star = 36 D^2 [ph]
Noise = square root of number of photons
= sqrt(36 D^2 + 5.59E4 D^2) without AO
= sqrt(36 D^2 + 700) with AO
Solving for SNR = 5 gives:
D = 33 m (without AO)
D = 2.0 m (with AO) → Huge gain in sensitivity offered by improved resolution !!!

Imaging Field of View (FOV)

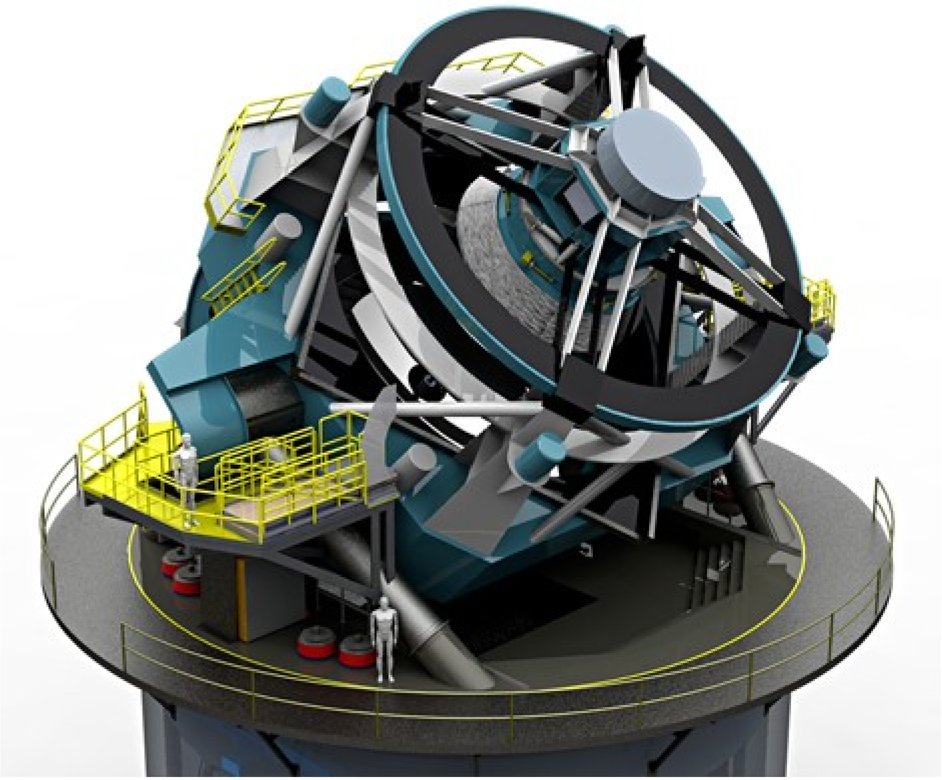
Field of view is important for survey astronomy.

Large sample of object needed.
Discovering new objects, compiling large catalogs of objects for statistical studies.
Examples:
- map 3-D large scale structure of the universe
- identify potentially dangerous asteroids
- galactic archeology through statistical study of our galaxy's stars

Most important is the survey efficiency, also called étendue, or AΩ product:

étendue = collecting area [m^2] x field of view [deg^2]

Time required to carry out a given survey = 1/étendue

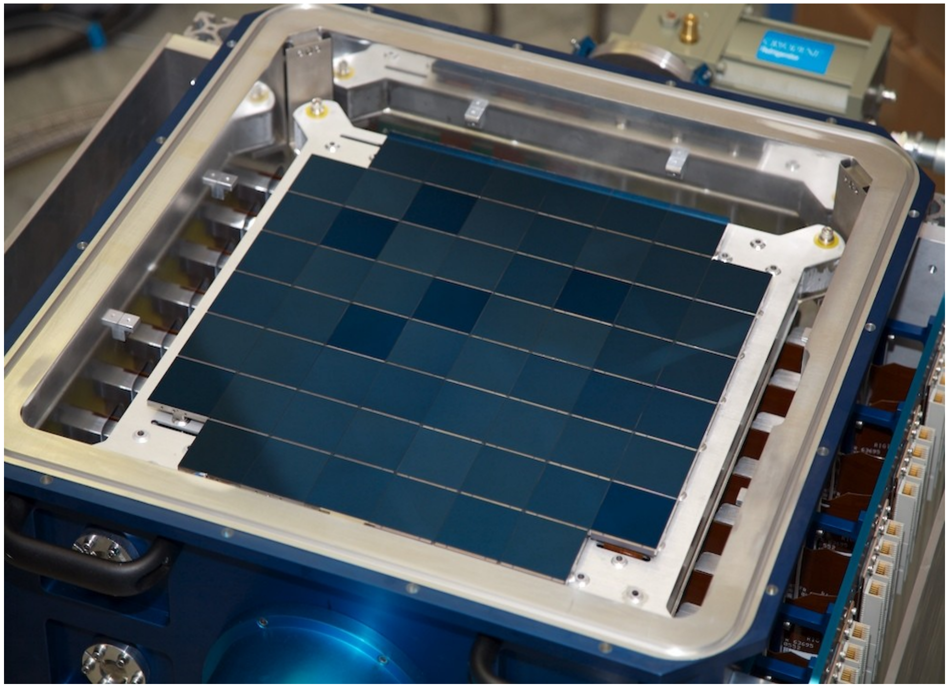


LSST telescope design (8.4m wide field telescope 9.6 deg^2 FOV)

Large étendue requires special telescope designs, with large corrector optics (see Lagrange invariant), and large focal plane arrays. Modern large étendue systems are becoming optically very different from conventional telescopes.

Imaging Field of View (FOV)

Large FOV + high angular resolution
= lots of pixels !



Pan-STARRS 1 focal plane array:
1.4 billion pixel

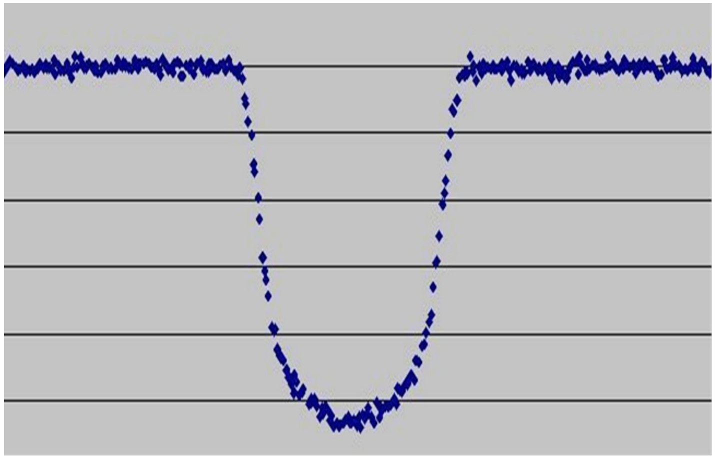
Time domain astronomy – measuring flux as a function of time

Why time domain astronomy ?
Examples :

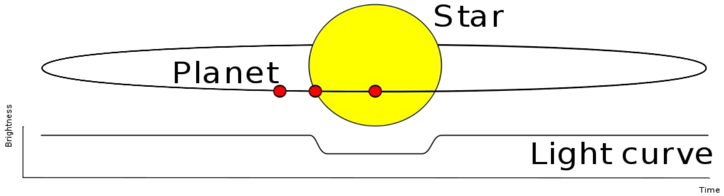
- Asteroids, comets discovery and orbit determination
- Variable stars → understanding stellar physics
- Cepheids, Type Ia supernovae → measuring distances over large scales
- Transits of exoplanets → discovery and characterization (radius, orbit)
- Understanding Gamma Ray Bursts
- Variable accretion on young stars

Some time-domain astronomy applications require very high accuracy:
exoplanet transit for Earth like planet is 1e-5 drop in apparent flux
→ very stable telescope system required, with stable pointing (space preferred)

Other applications require high cadence over multiple points in the sky: fast repointing, robotic telescopes



Kepler 6b transit light curve



Astrometry – measuring stars positions as a function of time

Why is astrometry important ?

Astrometry can directly measure distances (parallax)

Earth's orbit around the Sun gives us a 300 million km baseline: our viewing point changes by 300 million km in 6 months → closeby objects appear to move against the background of more distant objects

For nearby stars, the parallax ~ 1”, easily measured with seeing-limited ground based telescopes. Measurement gets more difficult with distance

distance to object [pc] = 1 / parallax angle [arcsec]

Astrometry of asteroids can measure their orbits

This is especially valuable for potentially dangerous Near Earth Orbit asteroids (NEOs)

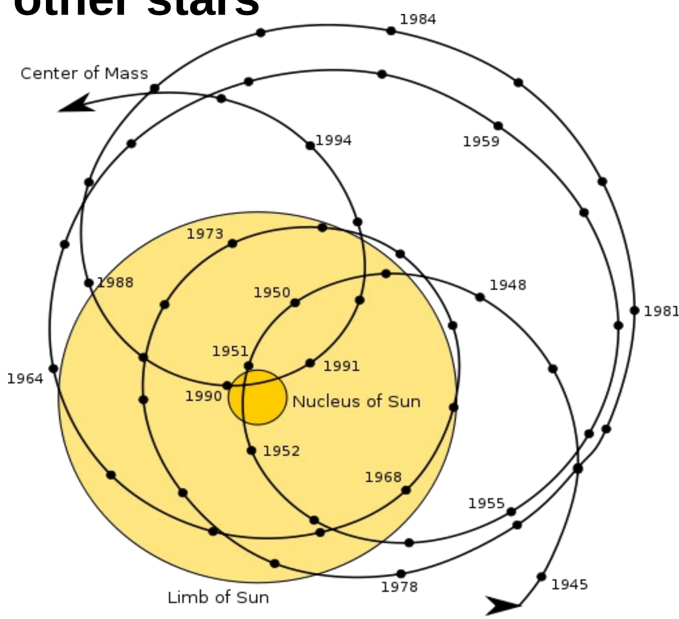
Astrometry can measure masses, and detect planets around other stars

Orbital motion directly links positions to masses

Astrometry has been used to confirm the presence of a black hole at the center of our galaxy and measure its mass

Masses of companions around stars measured by orbital period

High precision astrometry of nearby stars can reveal exoplanets: for a nearby star, Earth-like planet = ~1 micro arcsecond astrometric motion of the star

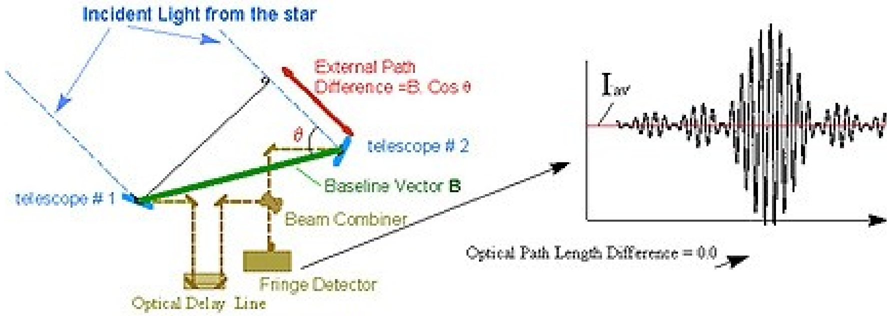


Astrometry – measuring stars positions as a function of time

Two approaches to astrometry:

Interferometry

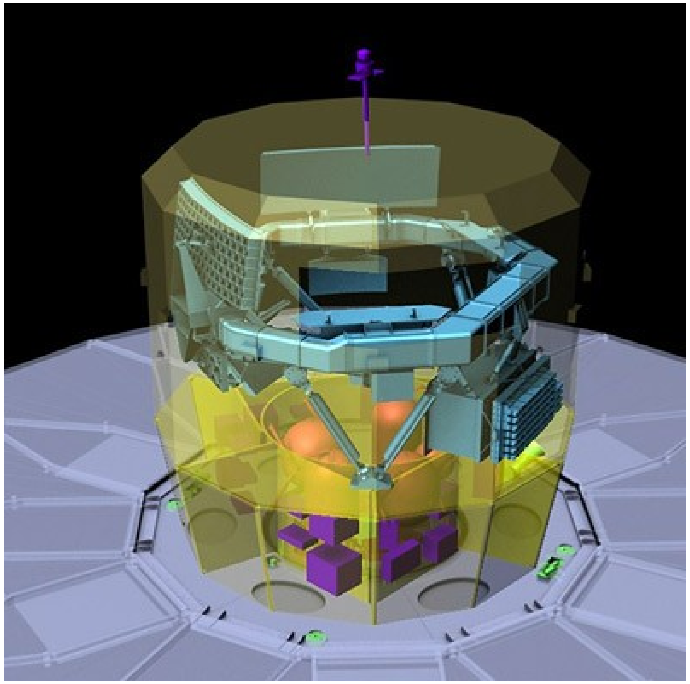
Astrometric signal mesured as an optical pathlength difference between two telescopes (= phase of interference fringes). Interferometers have an angular resolution advantage, and are the prefered solution for high precision astrometry, both on the ground and in space. Precise metrology within the interferometer is required for high precision.



Courtesy NASA/JPL-Caltech

Imaging

Astrometry is mesured from the position of the star images on the focal plane detector.
In theory, photon noise limited single axis measurement error (1-σ) = $1/(\pi \sqrt{N_{ph}})$
(but also: pixel sampling, calibration errors etc...)
This is the prefered solution when astrometric measurement of a large number of sources is required over a moderate field of view (for example, measuring the orbits of several stars around the black hole at the center of our galaxy).
Good understanding of distortions in the optical train are required.



GAIA mission (ESA)
The two primary mirrors are visible at the top of the image

Spectroscopy – measuring Intensity vs. Wavelength

Why is spectroscopy important ?

Spectroscopy is used to measure physical properties of objects.

Colors give temperature estimates

Absorption or Emission Lines can identify composition and physical conditions

Spectroscopy measures accurate velocities

Velocity measurements from shifts of lines can tell us about movement.

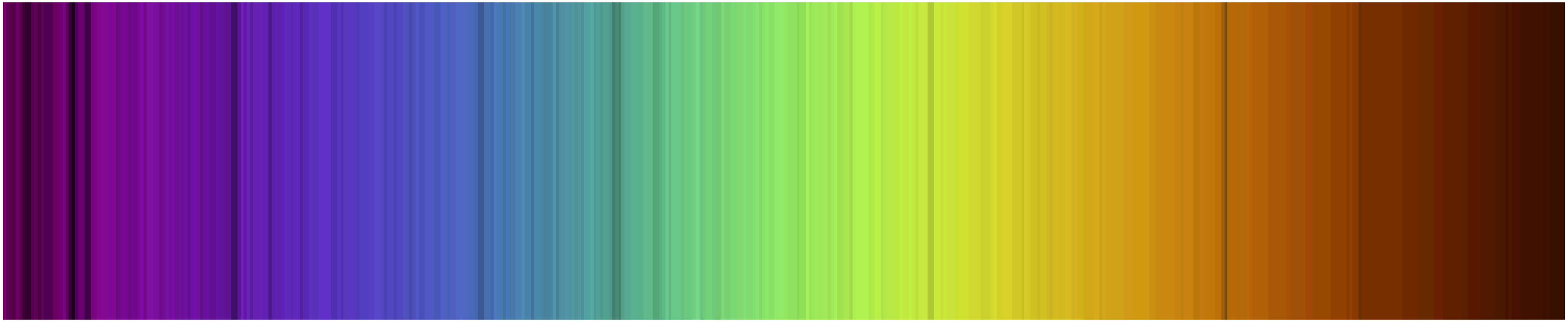
$$dl/l = v/c$$

Measure only radial component of velocity (astrometry only in plane of sky).

Example: Radial velocities of Exosolar Planets are measured by their influence on their star.

Jupiter creates a radial velocity variation of ~1 ms/ of the sun.

"Typical" intrinsic width of a stellar absorption line is ~0.005 nm



Spectroscopy – measuring Intensity vs. Wavelength

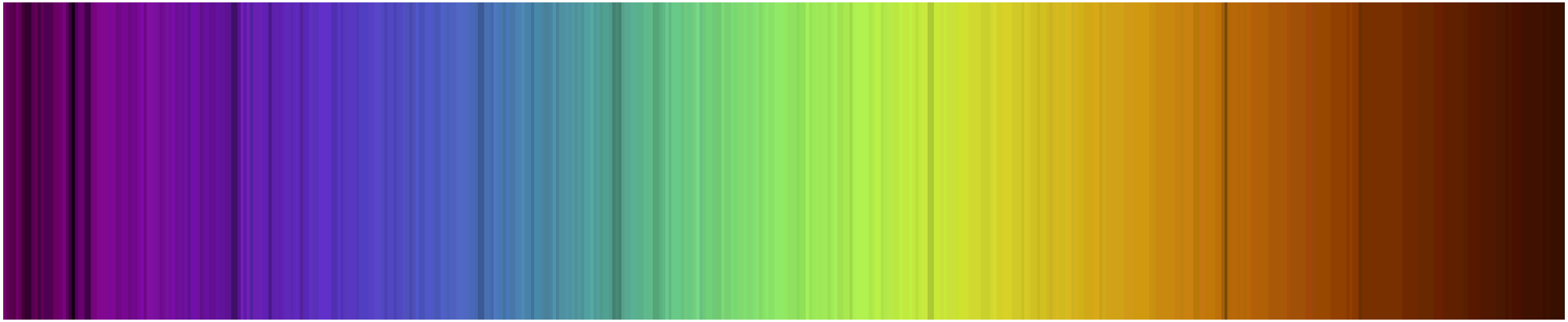
Techniques for Spectroscopy

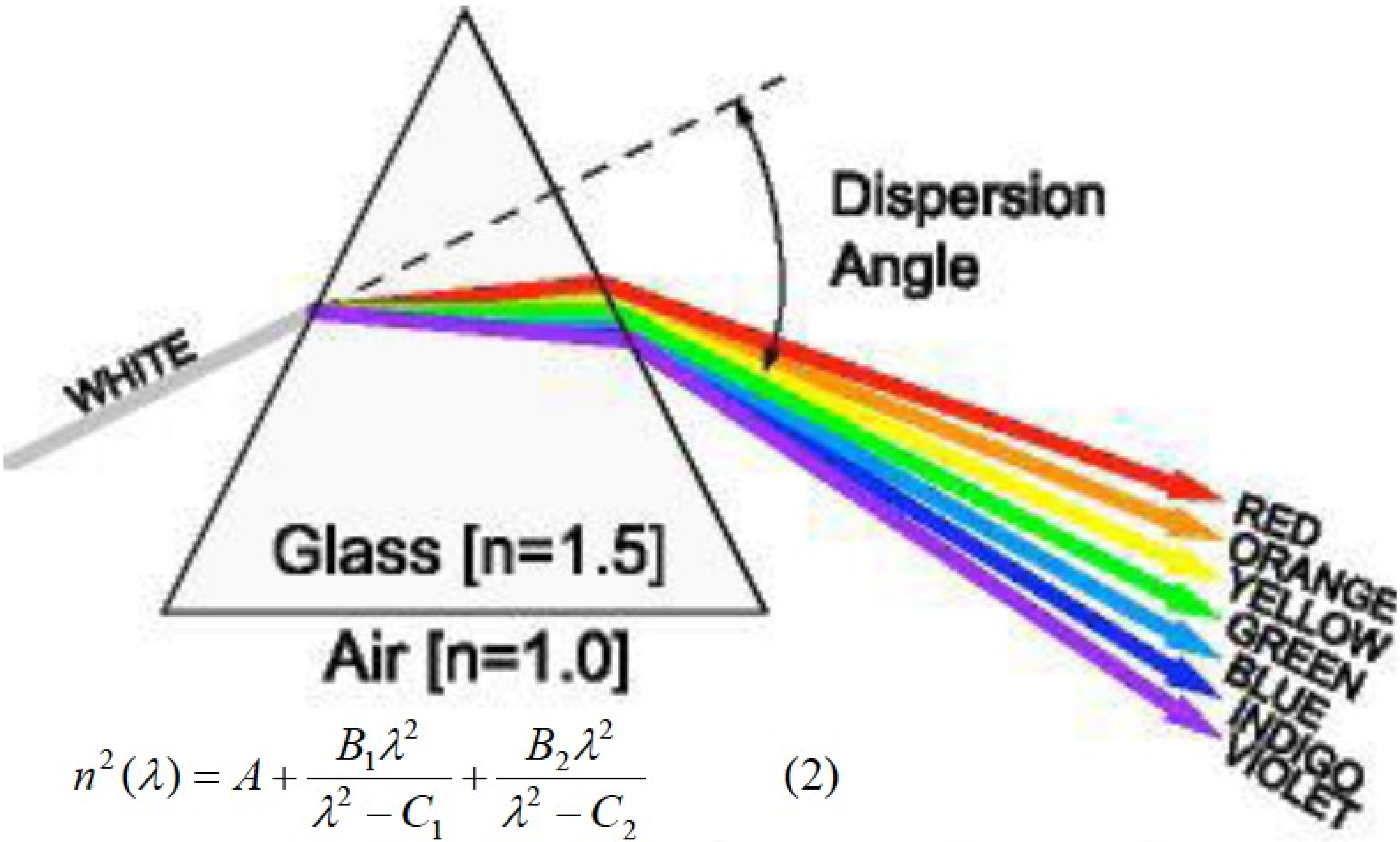
Use Differential Refraction vs. wavelength of materials(prisms)

High throughput. Efficient.
Compact.
Limited in spectral resolution achievable.
Dispersion is nonlinear.

Use Multiple Interference Effects (Diffraction Gratings)

Can obtain much higher spectral resolution
Dispersion is linear

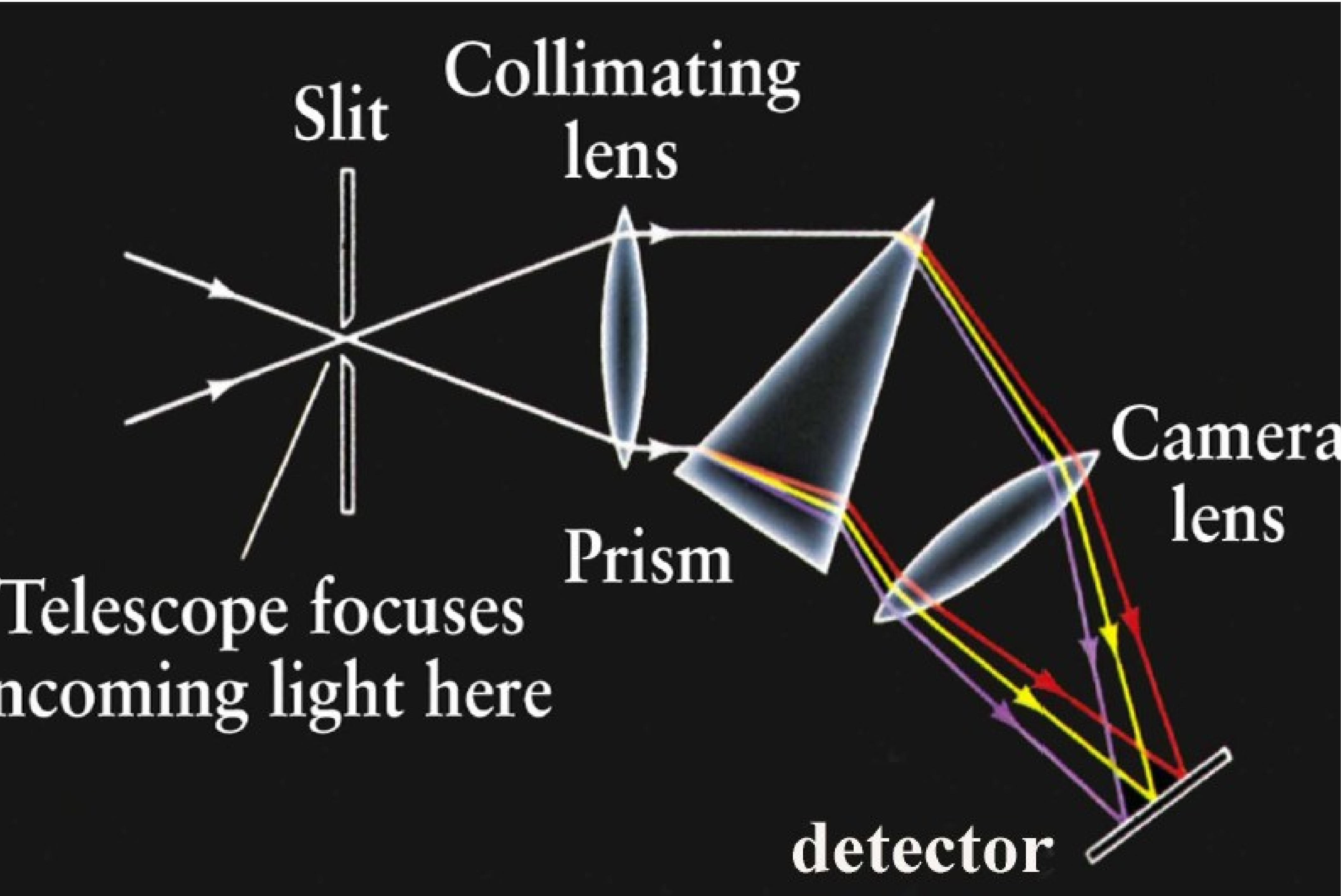




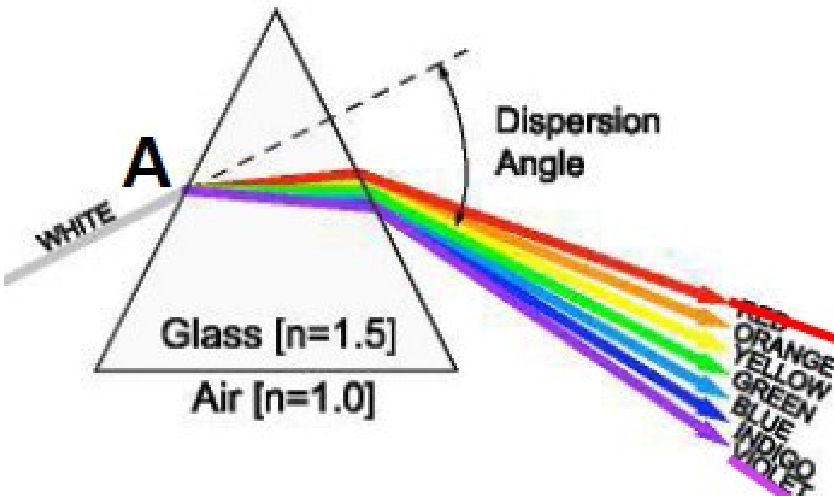
$$n^2(\lambda) = A + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} \qquad (2)$$

Slides from Rieke
Lecture on Spectroscopy at
http://ircamera.as.arizona.edu/Astr_518/syllabus_2010.htm

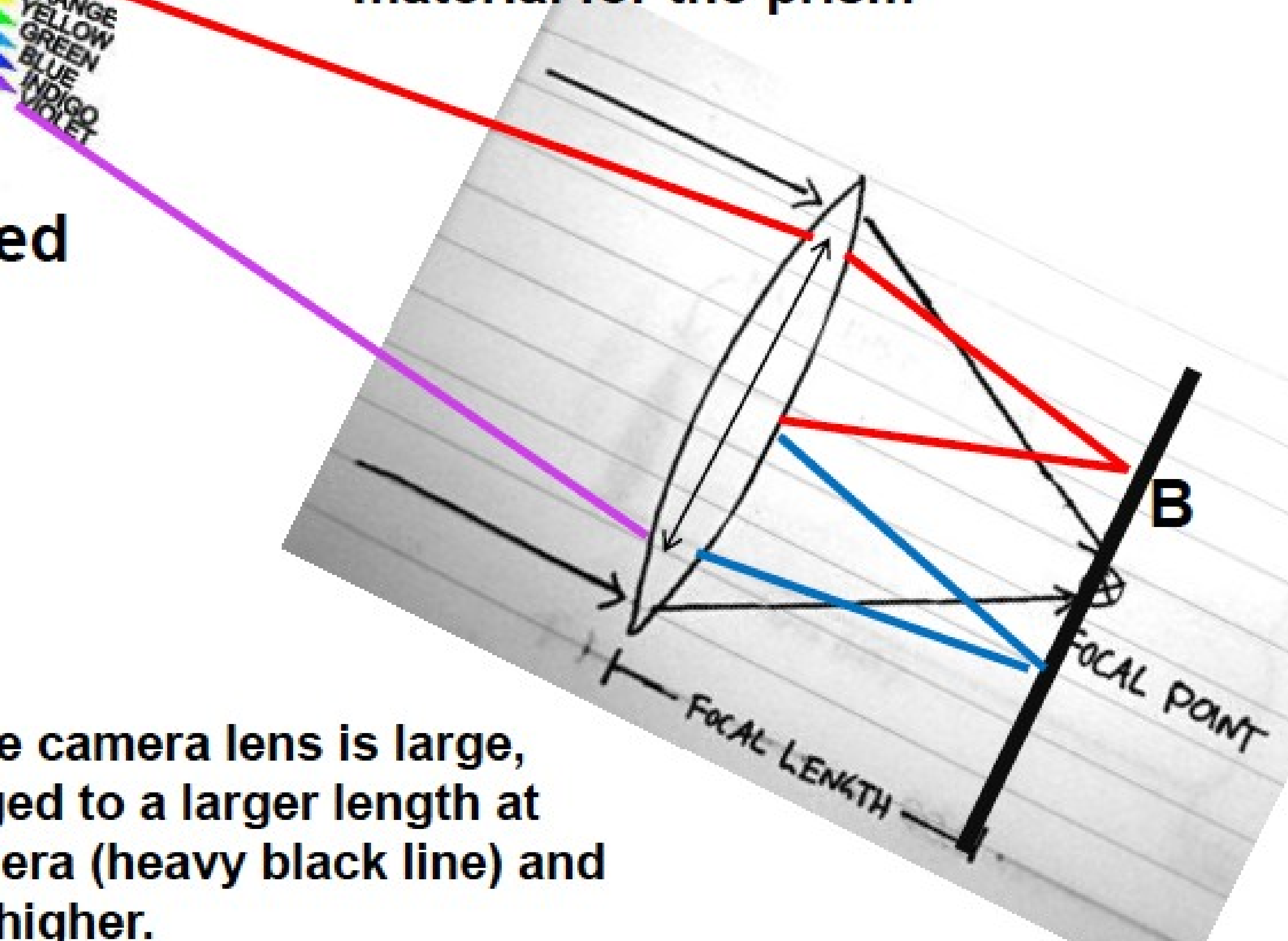
Here is how a prism spectrometer might look. Why all the optics?



What determines the spectral resolution?



We can increase the used diameter by adjusting the optical design or by selecting a more dispersive material for the prism

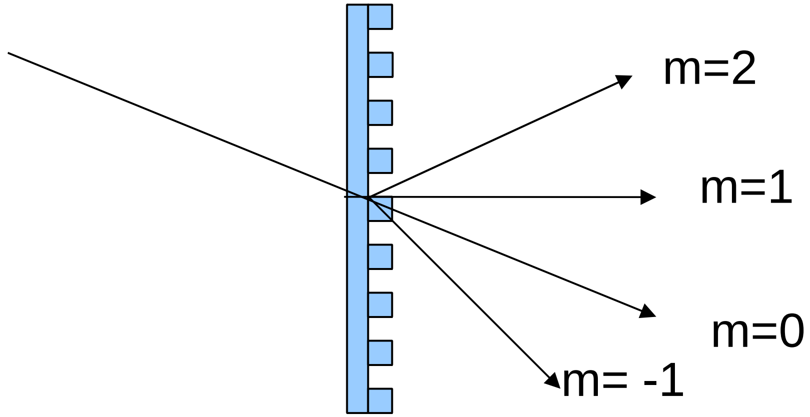


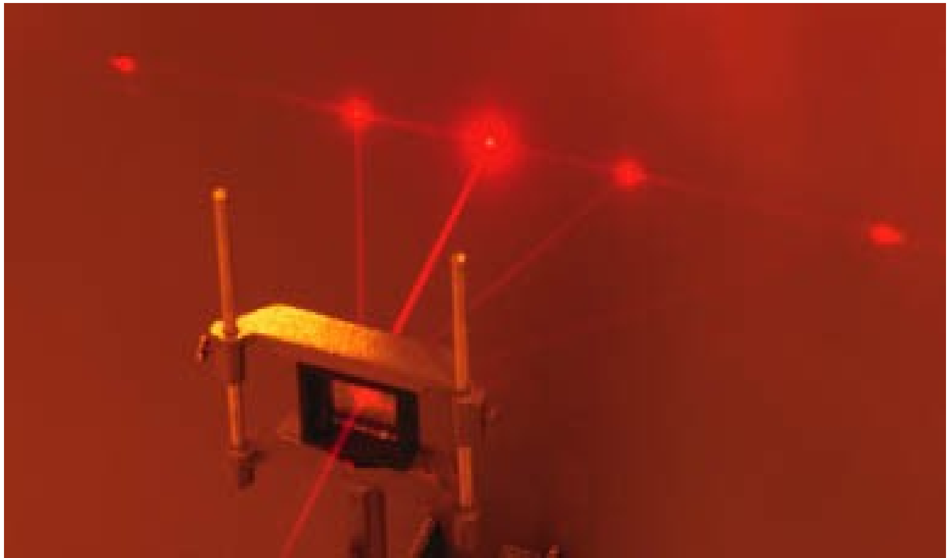
So the larger the used diameter of the camera lens, the higher the spectral resolution

If the used diameter on the camera lens is large, then the spectrum is imaged to a larger length at the focal plane of the camera (heavy black line) and the spectral resolution is higher.

Diffraction Gratings

Phenomenon: Closely spaced patterns of any sort will produce diffraction. If the pattern is regular (either in size or spacing), so is the resulting intensity pattern.

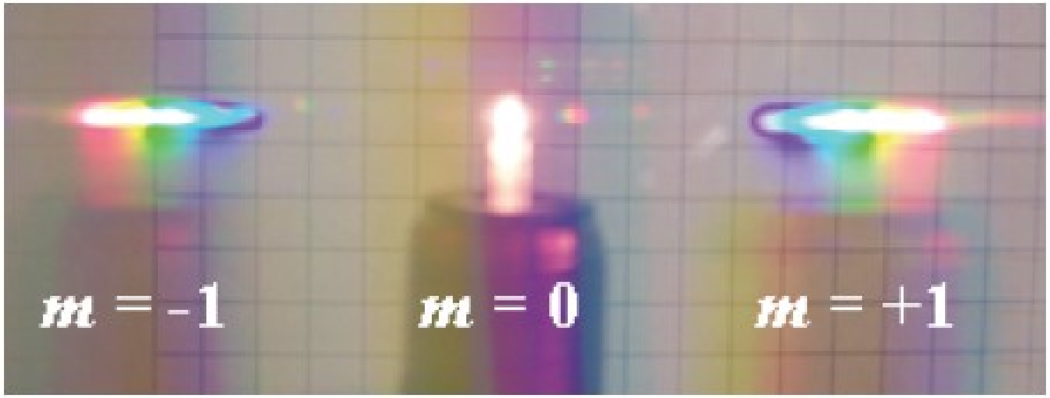




Grating Orders

For light perpendicular on a grating, the light obeys the grating equation:

$$a \sin \theta_m = m \lambda$$

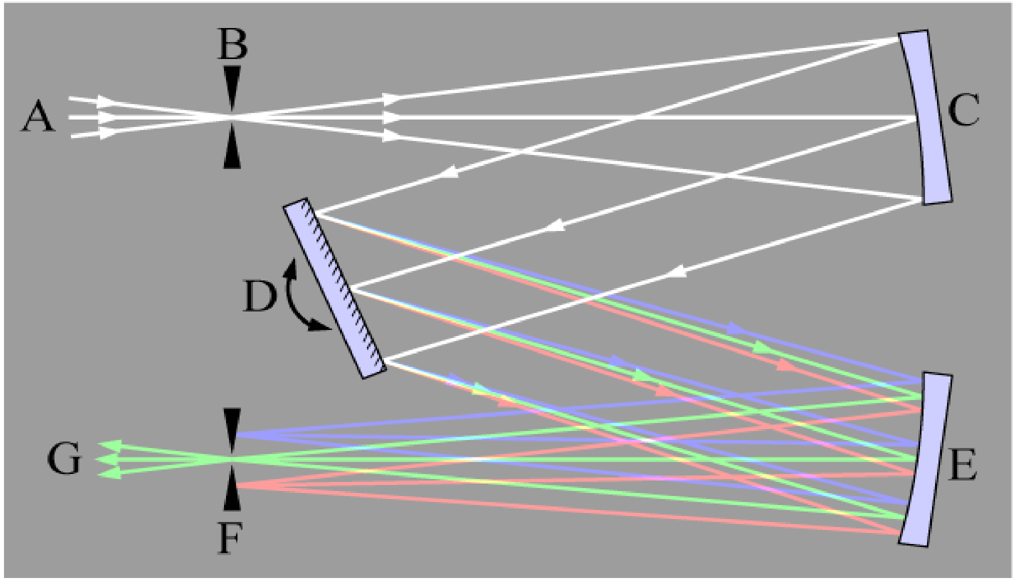


Light incident at an oblique angle satisfies the equation:

$$a(\sin \theta_m - \sin \theta_i) = m \lambda$$

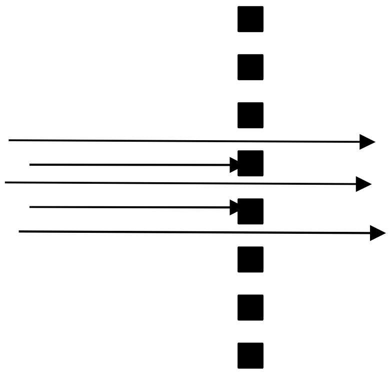
Typical Setup

- Gratings are almost always use in collimated light to avoid aberrations caused by the combination of converging light and diffraction.

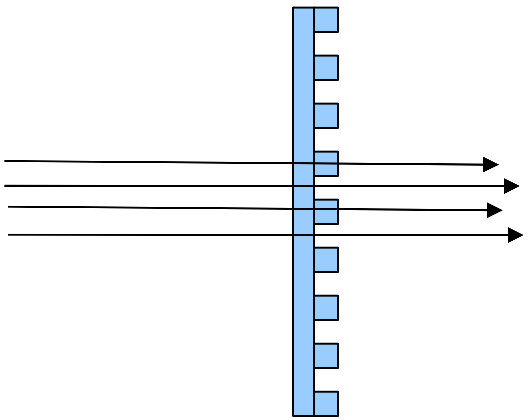


Different types of gratings

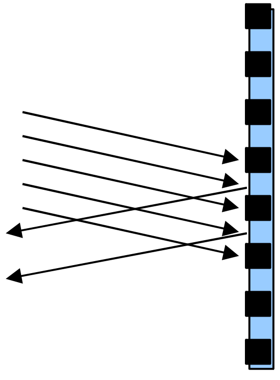
Amplitude Transmission gratings



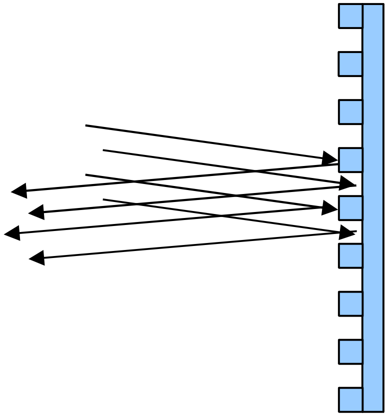
Phase Transmission Gratings



Amplitude Reflection gratings



Phase Reflection Gratings



Resolving power of a grating

- The angular extent of a monochromatic source encountering a grating is: $\Delta\theta = \dfrac{\lambda}{N a \cos(\theta_m)}$

The change in wavelength versus angle can be obtained by differentiating the grating equation:

$$D = \frac{d\theta}{d\lambda} = \frac{m}{a\cos(\theta_m)}$$

$$\Delta\lambda = \frac{a\cos(\theta_m)\Delta\theta}{m} = \frac{\lambda}{mN}$$

$$R = \frac{\lambda}{\Delta\lambda} = mN$$

Implications for optical setup

- To increase the resolving power you need to either use a higher order of the grating or increase the number of lines.
- For a fixed grating a higher resolving power requires a larger beam.

Spectral Range of a Grating

What about successive orders?

Wavelengths of successive orders overlap when they satisfy the equation:

$$a(\sin\theta_m - \sin\theta_i) = (m+1)\lambda = (m)(\lambda + \Delta\lambda)$$

So regions of the spectrum do not overlap if they are less than the free spectral range of the order:

$$\Delta\lambda_{FSR} = \frac{\lambda}{m}$$