

Advisor-Seminar
2008 November 5

Concepts and Characteristics of an Astronomical Telescope

Stefan Taubenberger
MPA



Tasks of telescopes: gathering light

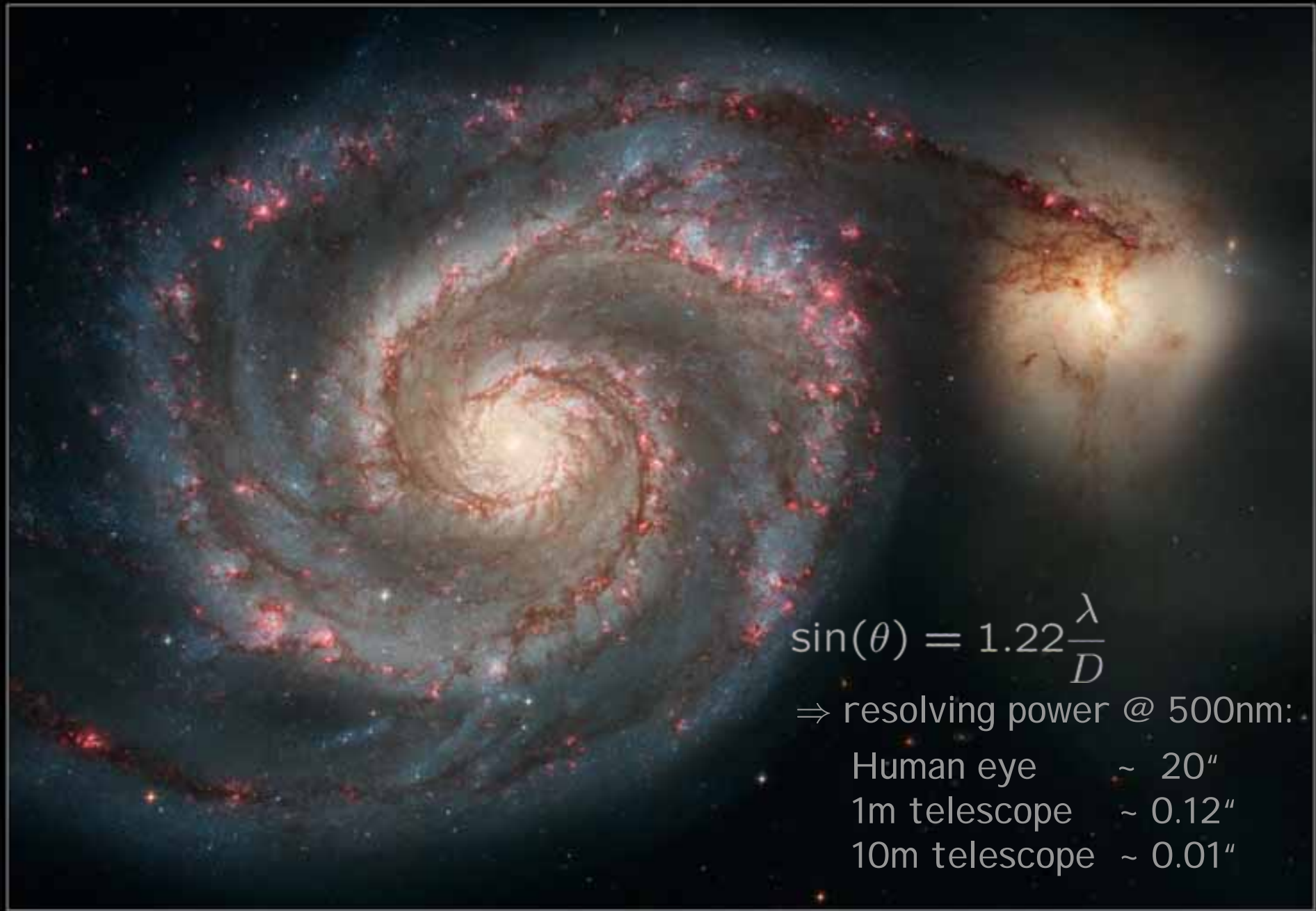
⇒ aperture:

Human eye pupil: < 8mm

1m telescope: factor 1.5×10^4 in sensitive area

10m telescope: factor 1.5×10^6 in sensitive area

Tasks of telescopes: increase angular resolution



$$\sin(\theta) = 1.22 \frac{\lambda}{D}$$

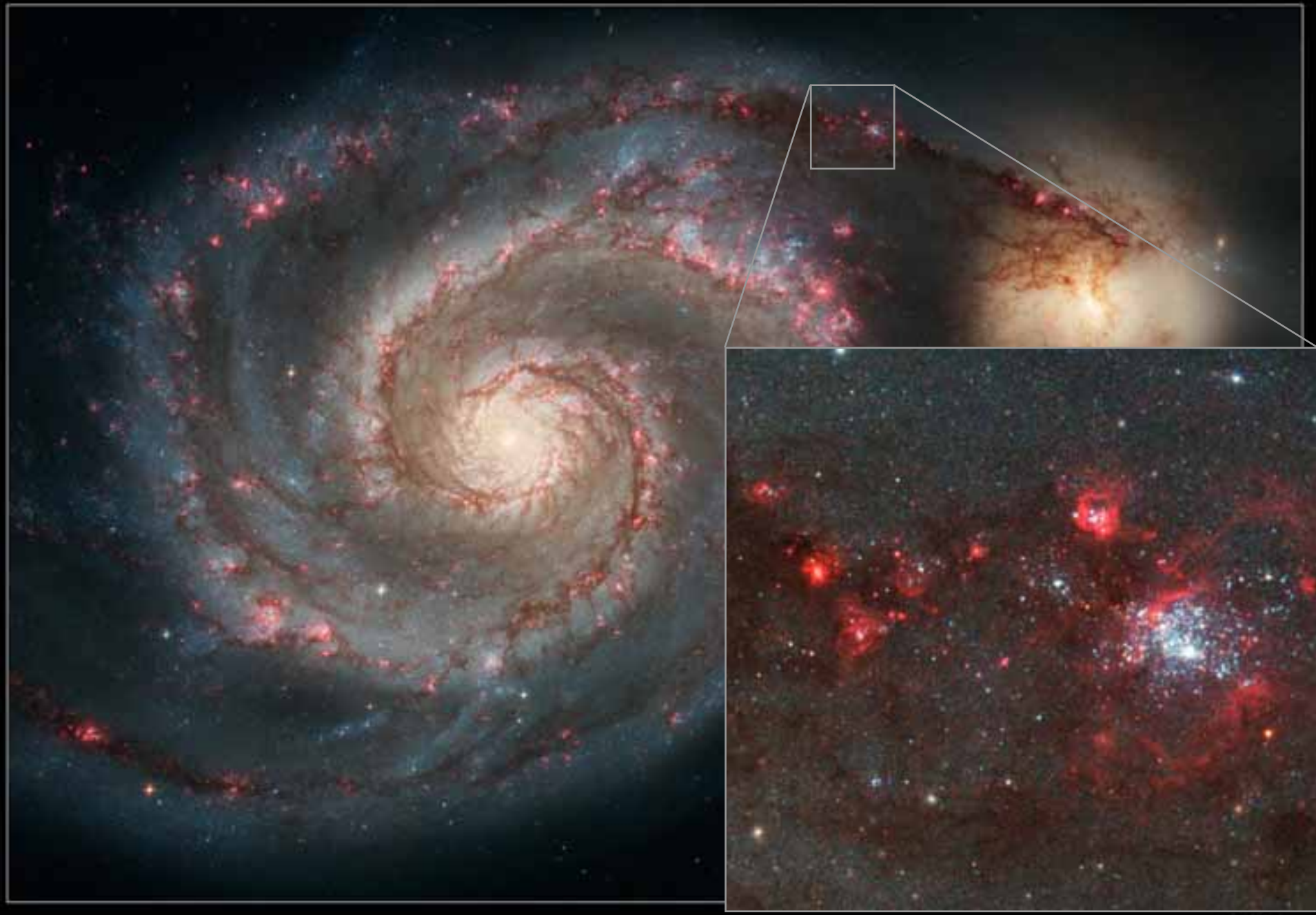
⇒ resolving power @ 500nm:

Human eye ~ 20"

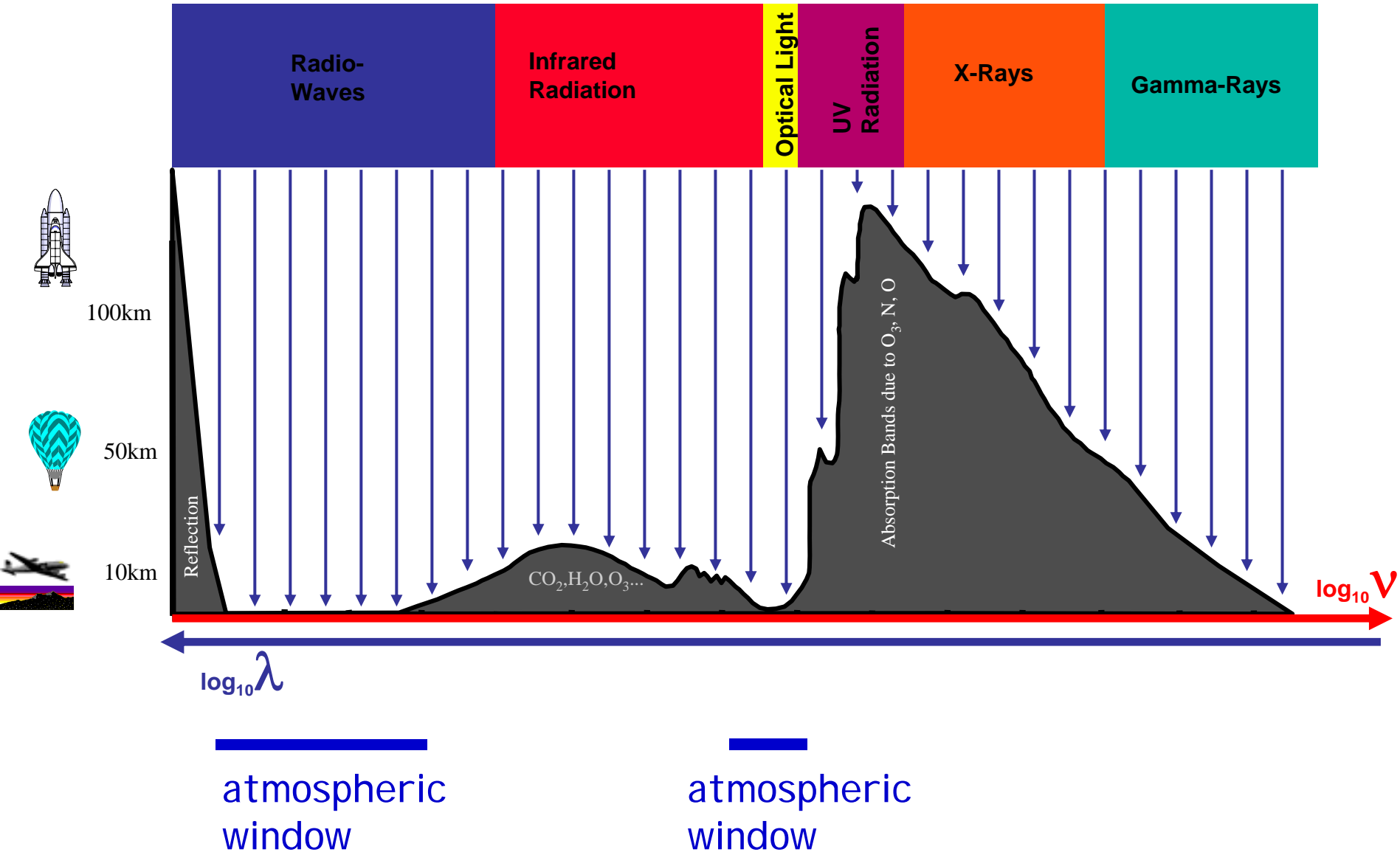
1m telescope ~ 0.12"

10m telescope ~ 0.01"

Tasks of telescopes: increase angular resolution



Transmission of the Earth's atmosphere



Basic components of an optical / near-IR telescope

- mount
 - hold the telescope
 - move it to different positions on the sky
 - tracking: compensation of the earth's rotation
 - equatorial and alt-az mounts

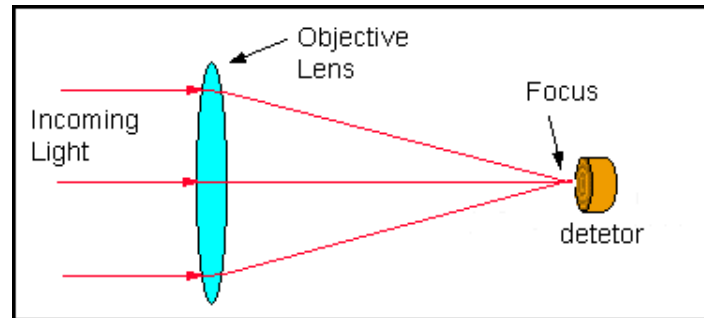


- telescope optics
 - collect and focus the light
- instruments and detectors
 - imagers / spectrographs
 - record incident photons



Refracting Telescopes

Lenses are used to bend light

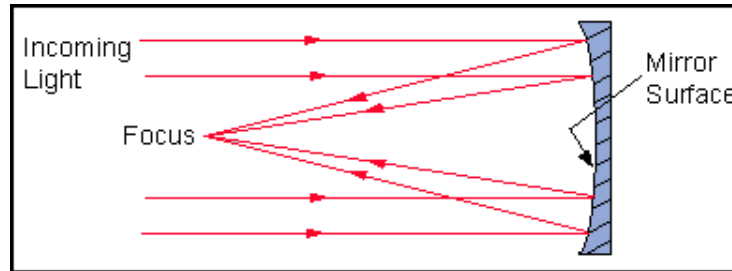


Disadvantages:

- chromatic aberration
 - compensation by using multiple lenses
 - long objective focal length
- huge mass:
 - lenses deform under own weight, 40in is maximum size
- support for large lenses is not easy

Reflecting Telescopes

Mirrors with metal coated surfaces focus parallel light rays

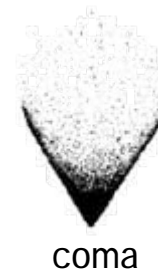


Advantages:

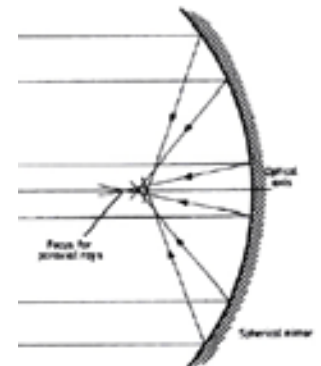
- no chromatic aberration
- telescope tubes are shorter
- mirrors can be better supported
- glasses with low thermal expansion

Disadvantages:

- spherical aberration in case of non-parabolic mirrors, coma

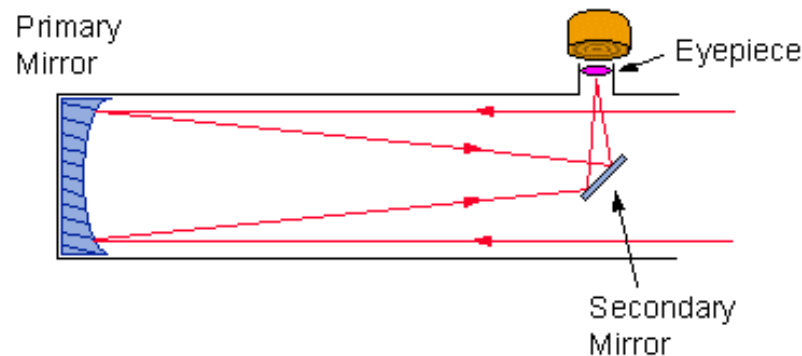


coma



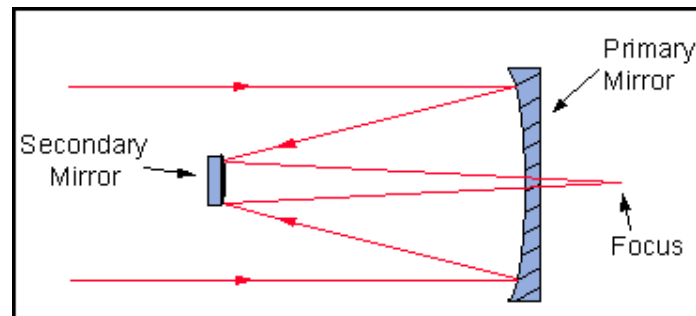
Newton Reflector

- common in small telescopes
- a plane mirror reflects the light off to the side of the tube
- the loss of light by secondary mirror is small compared to total light-gathering
- tube length \approx focal length



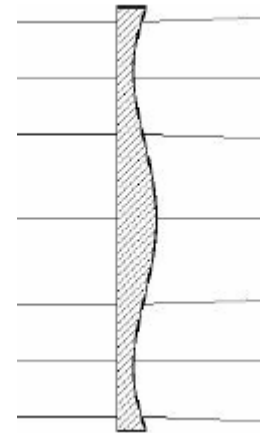
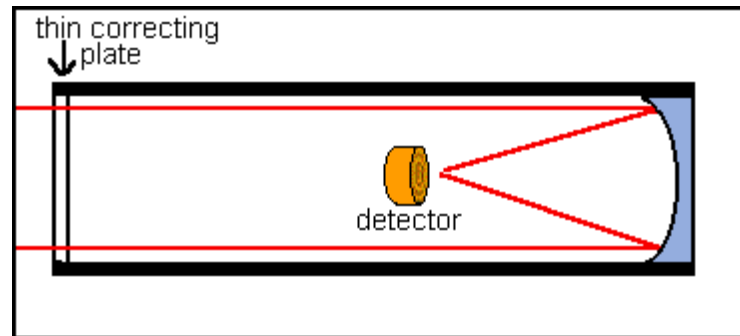
Cassegrain Reflector

- convex secondary mirror to reflect the light back through a small hole in the primary mirror
- folded light path \Rightarrow compact construction
- detectors can be placed directly behind the telescope



Schmidt Reflector

- both a mirror and a correction plate are used to avoid aberrations
- large corrected field of view
- detector inside the tube, curved focal plane



- Schmidt plate and Cassegrain Reflector can be combined
⇒ Schmidt-Cassegrain

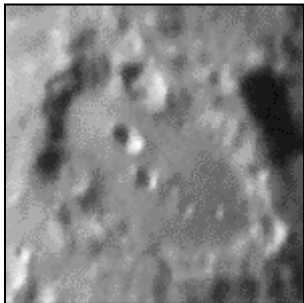
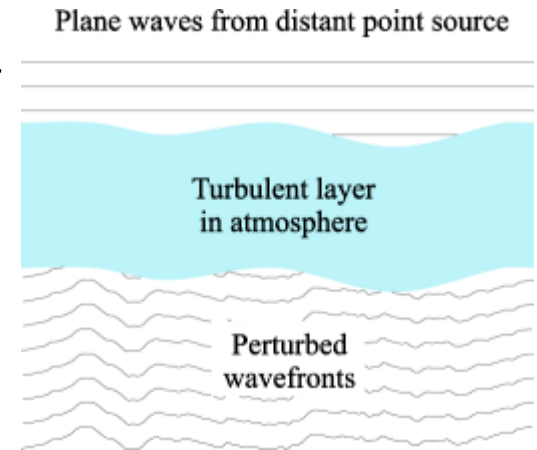
Mirrors

- LBT: largest monolithic mirrors (8.4m)
- Keck, GTC, ...: segmented mirrors ($\geq 10\text{m}$)
- active optics: mirror deformation permanently corrected by actuators

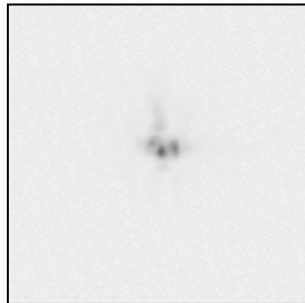


Seeing

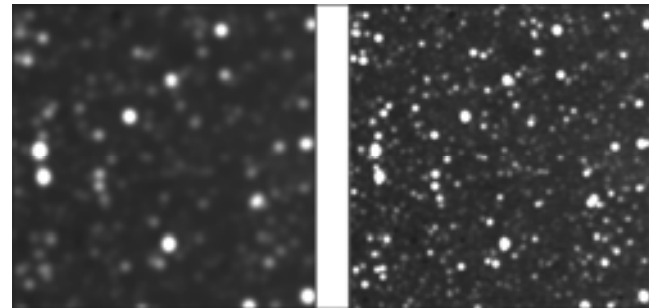
- Atmospheric turbulence ("seeing"): refraction index of the air not constant
- leads to "random walk" of point sources
- long exposures: Gaussian smearing (typ. fwhm of point sources $> 0.5''$)
- Resolution of large ground-based telescopes not diffraction-limited



extended object



point source,
slow motion



poor seeing

good seeing

Seeing

Ways to reduce negative effects of seeing:

- space telescope (very expensive)



Seeing

Ways to reduce negative effects of seeing:

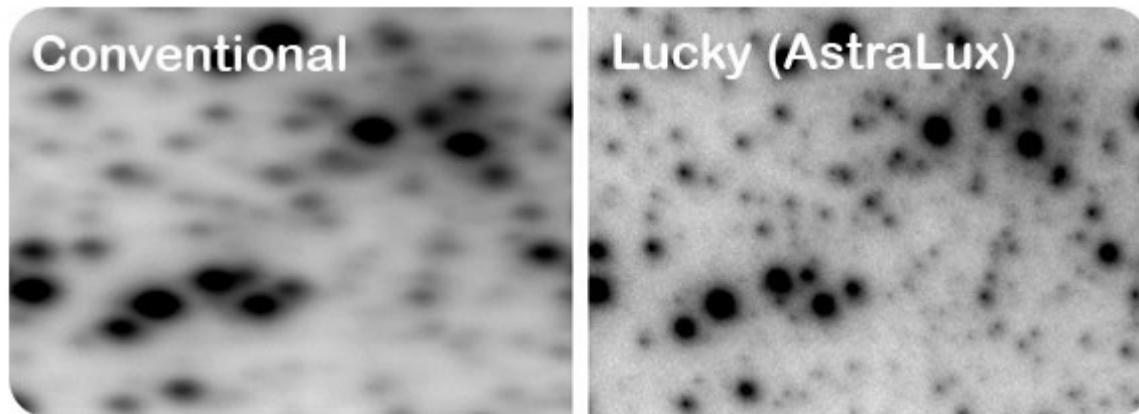
- space telescope (very expensive)
- identify sites with good seeing:
 - on top of high, isolated mountains (avoid low-altitude turbulent layers)
 - laminar flows, no obstacles in front



Seeing

Ways to reduce negative effects of seeing:

- space telescope (very expensive)
- identify sites with good seeing
- Lucky imaging / speckle imaging
 - register and stack large number of short exposures
 - advantages: cheap & efficient, large field of view possible
 - disadvantages: longer exposures, increased read noise



Seeing

HST



amateur



HST

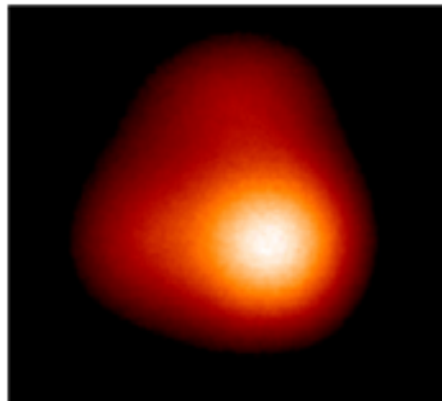


- Lucky imaging / speckle imaging
 - register and stack large number of short exposures
 - advantages: cheap & efficient, large field of view possible
 - disadvantages: longer exposures, increased read noise
 - also successfully applied by amateurs

Seeing

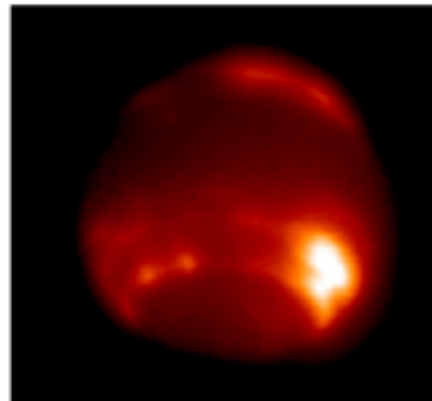
Ways to reduce negative effects of seeing:

- space telescope (very expensive)
- identify sites with good seeing
- Lucky imaging
- Adaptive optics



Neptune

without AO

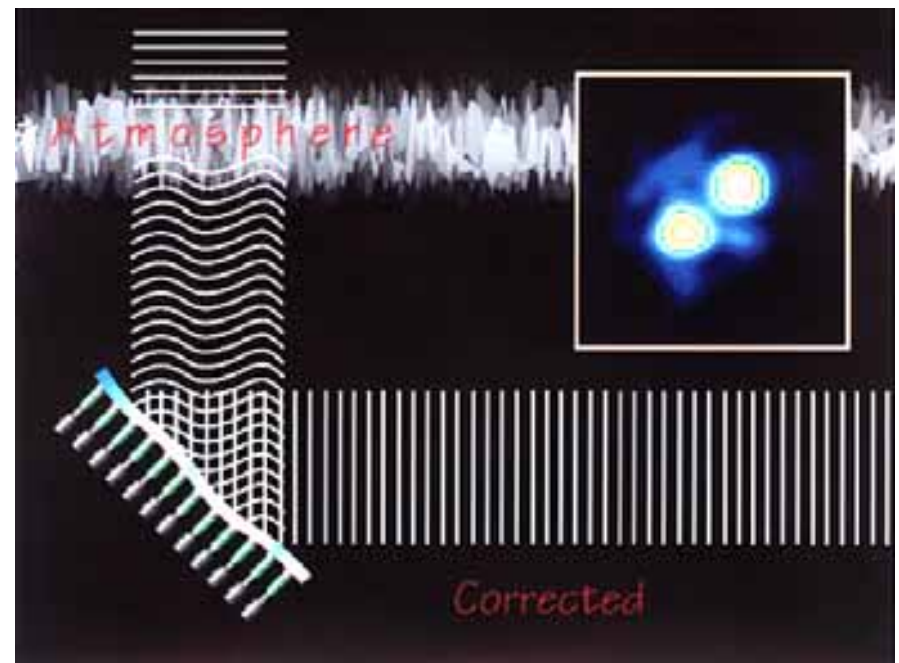
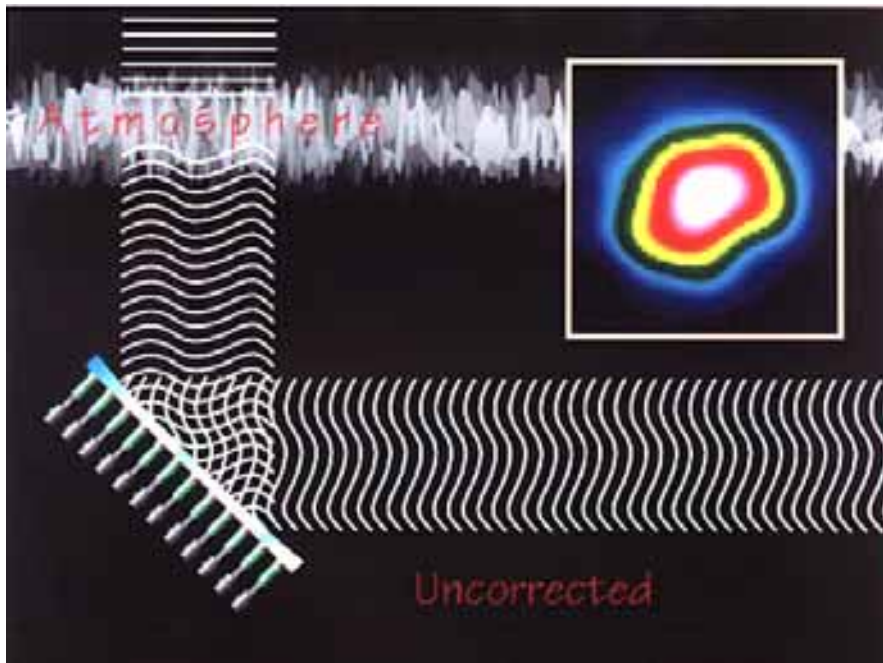


with AO

Adaptive optics

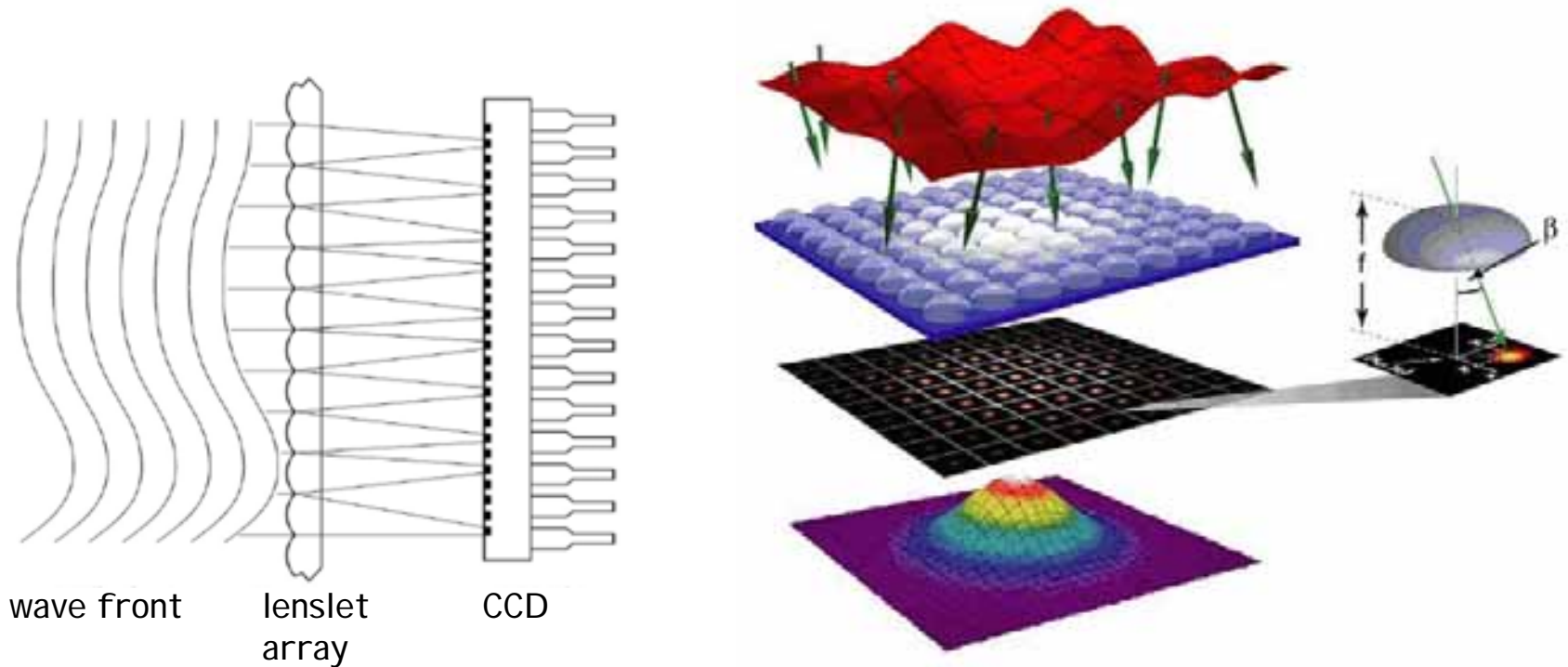
Idea: correct distorted wave fronts with a deformable mirror

- wave front sensor used to determine deformation
- corrections on ms-timescales necessary



Adaptive optics

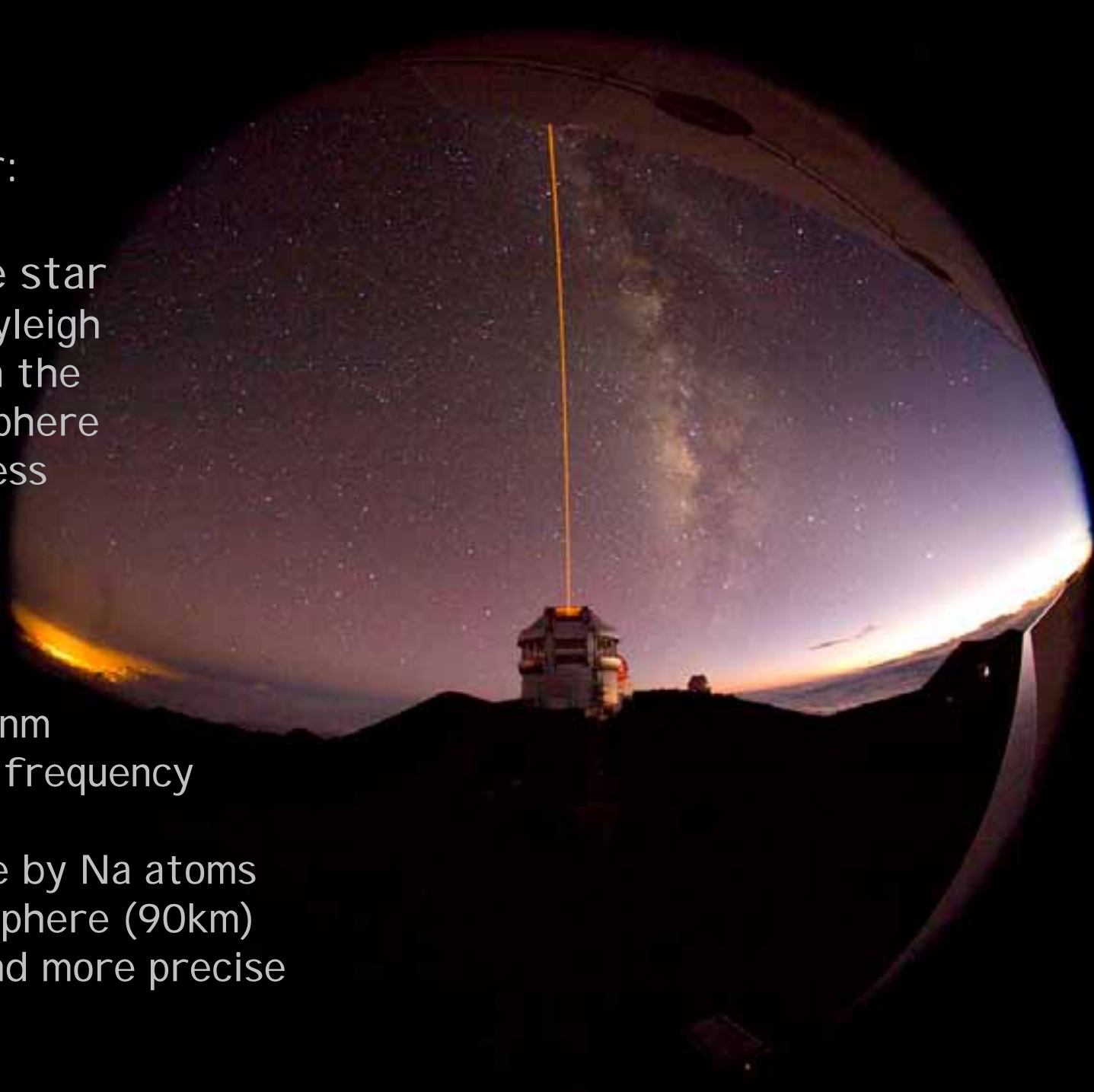
- Principle of a Hartmann-Shack wave-front sensor:



- Requires bright natural guide star near the science target or an artificial laser guide star.

Laser guide star:

- **Rayleigh** guide star
 - based on Rayleigh scattering in the lower atmosphere
 - cheap, but less precise
- **Sodium** guide star
 - laser at 589nm by nonlinear frequency mixing
 - fluorescence by Na atoms in the mesosphere (90km)
 - expensive and more precise



Adaptive optics

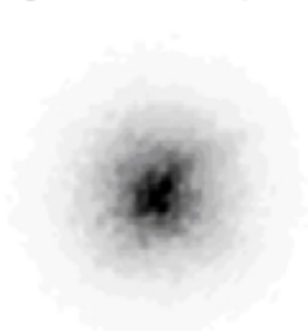
AO best way to improve seeing significantly

- better S/N, exposure time can be reduced
- differential correction over full aperture possible

Uncorrected psf (sqrt)



Integrated uncorrected psf (sqrt)



Corrected psf (sqrt)



Integrated corrected psf (sqrt)



Disadvantages:

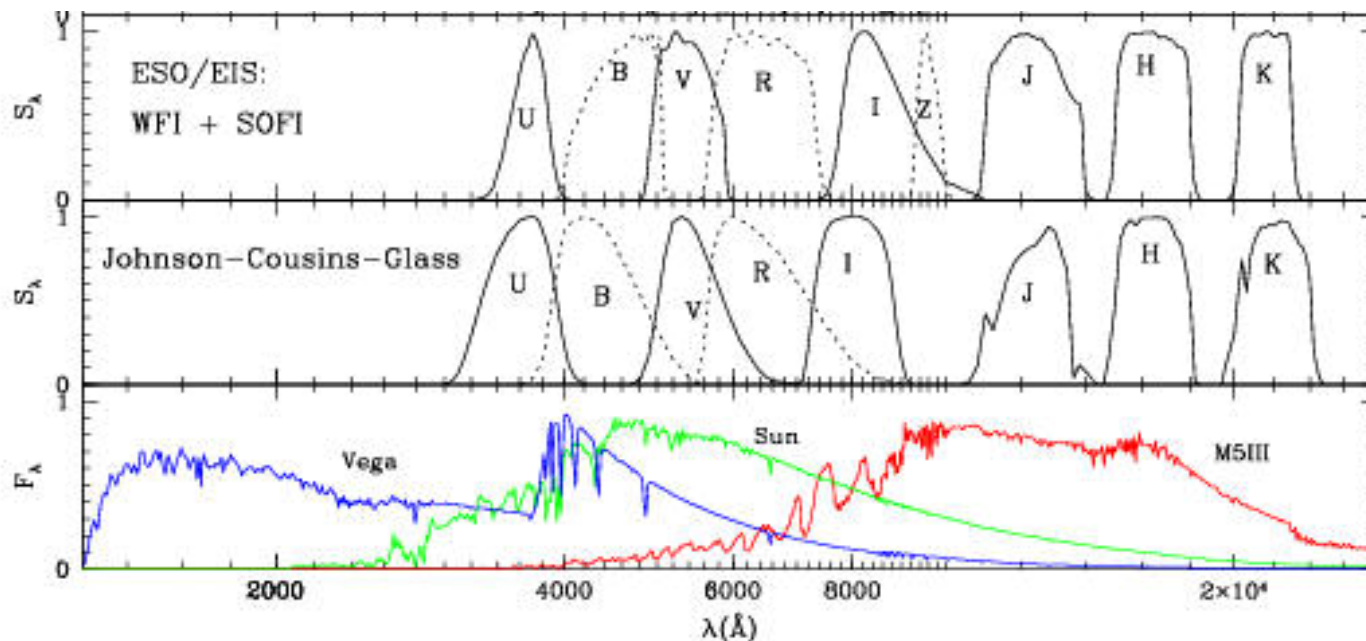
- expensive, complex
- small corrected field of view
- requires good initial seeing \Rightarrow almost solely used in near-I R

Instrumentation

- imaging / photometry
- spectroscopy
- (spectro-) polarimetry
- interferometry

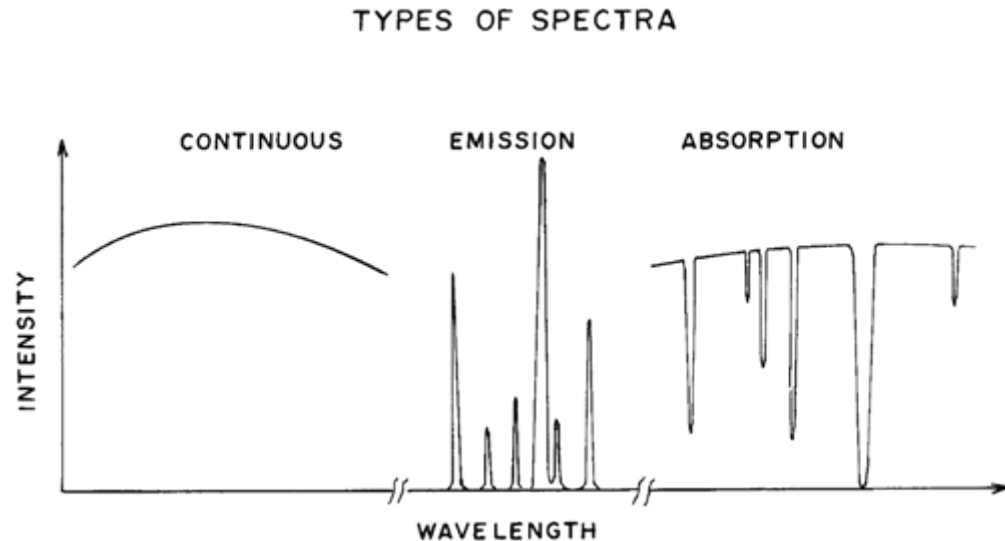
I magers

- either directly at the prime focus or with additional optics to magnify / refocus the image
- imaging through band-pass filters: well-defined photometric systems
- determine brightness by summing the counts within an aperture and comparison with calibrated standards



Spectrographs

- Spectroscopy is used to determine
 - chemical composition
 - temperature
 - radial velocity



- grating, prism or "grism" (combination of grating and prism) in the light path
- variety of resolutions $R = \lambda/\Delta\lambda$: ~100 ... ~100000

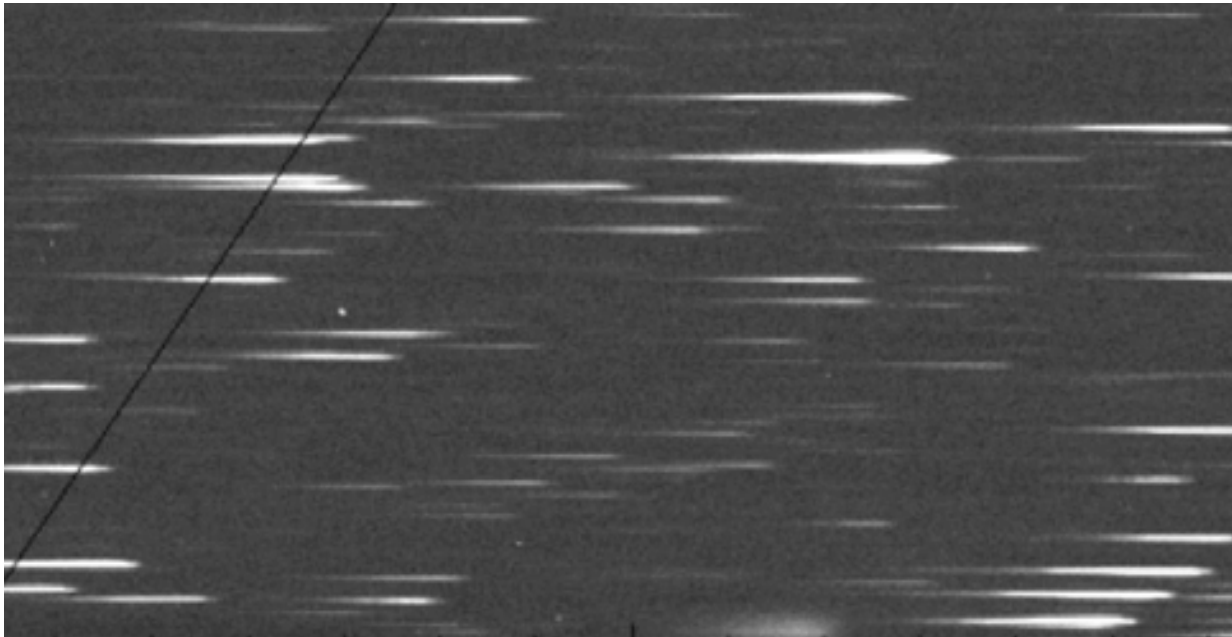
Spectrographs

➤ optical designs:

- slitless spectrograph (e.g. ACS on HST)

pro: spectra of every light source in the field, no slit losses

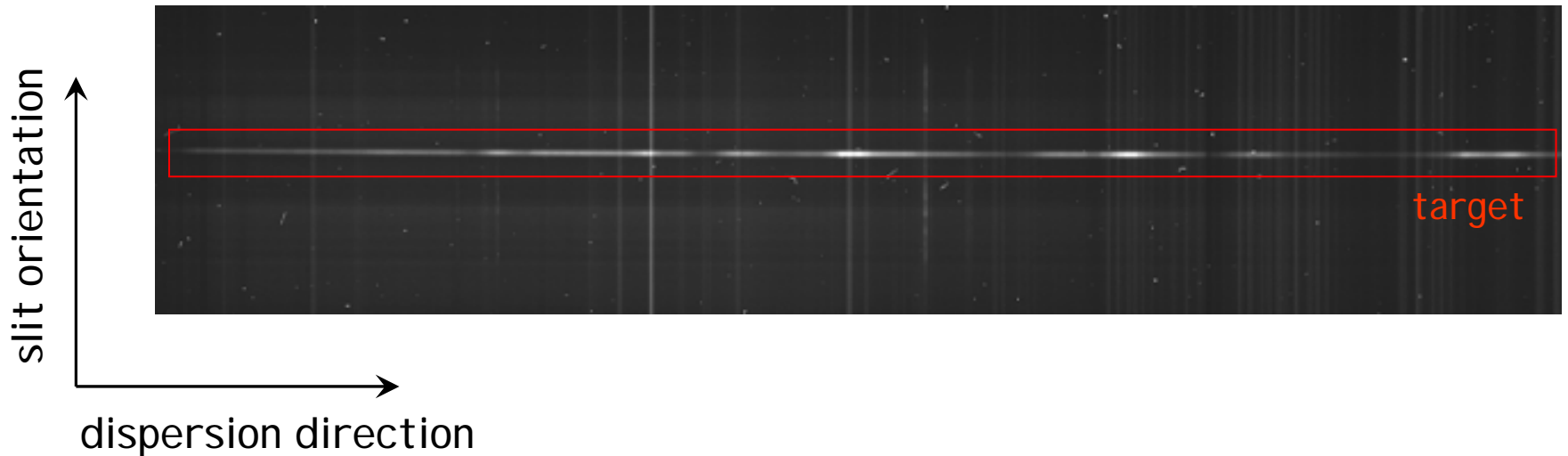
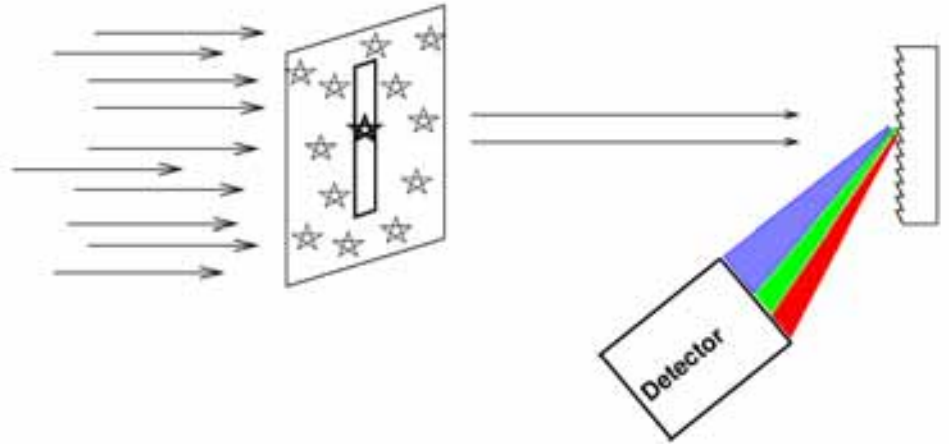
contra: sources may overlap, not useful for extended objects,
tricky wavelength calibration



Spectrographs

➤ optical designs:

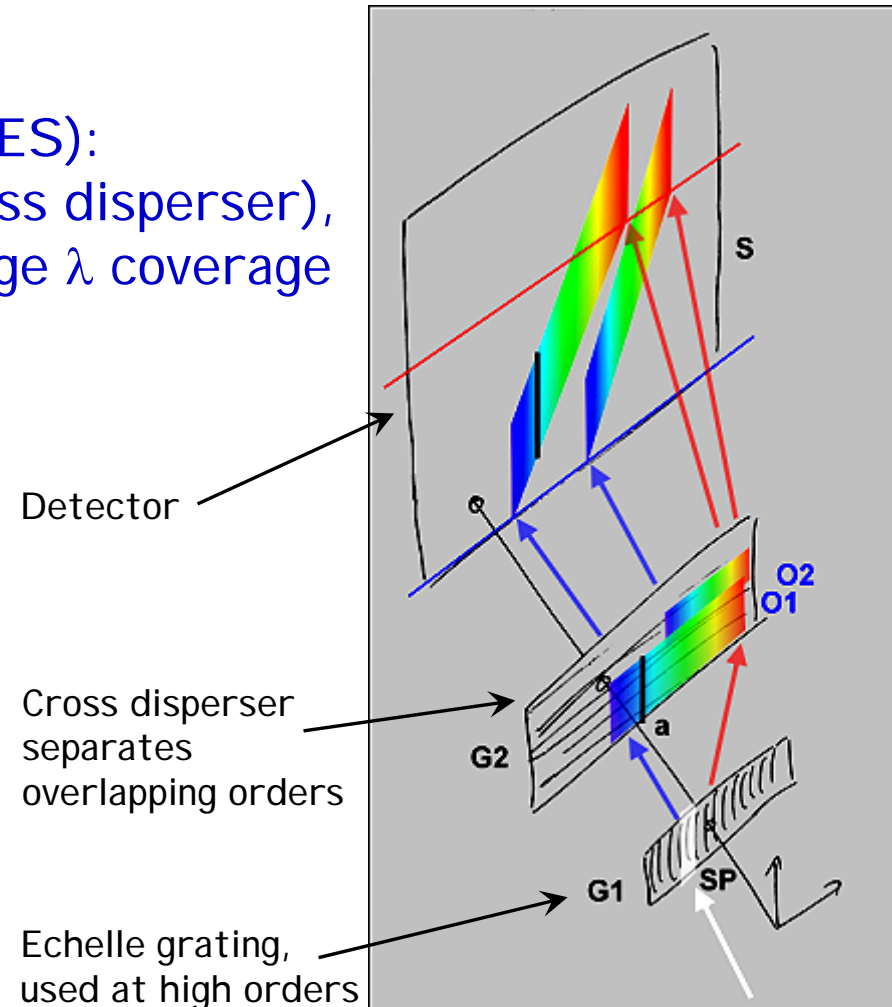
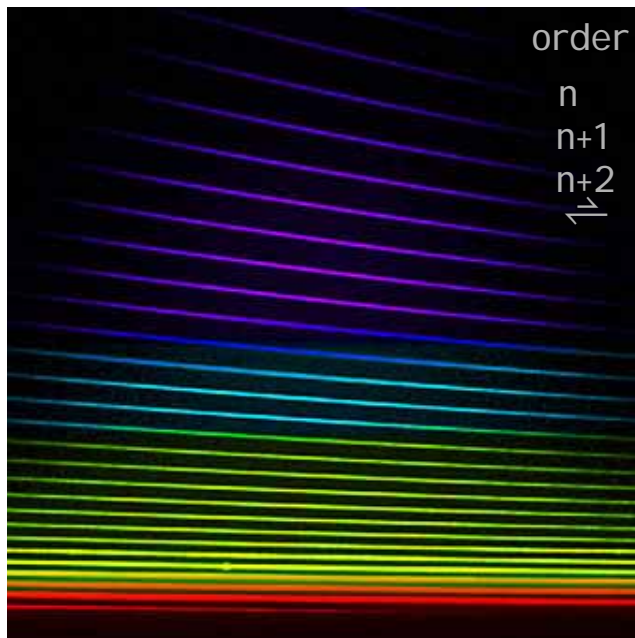
- slitless spectrograph
- longslit spectrographs (e.g. FORS):
very common,
slit used to isolate the target



Spectrographs

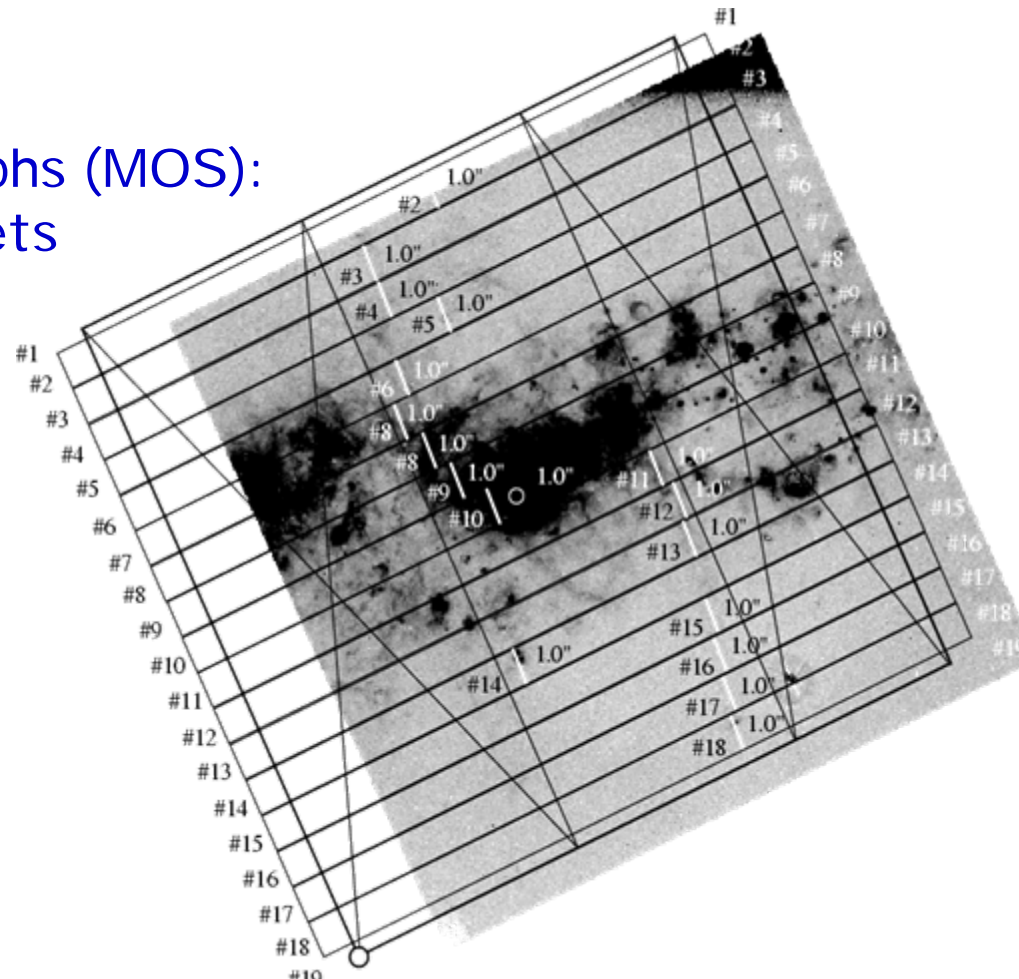
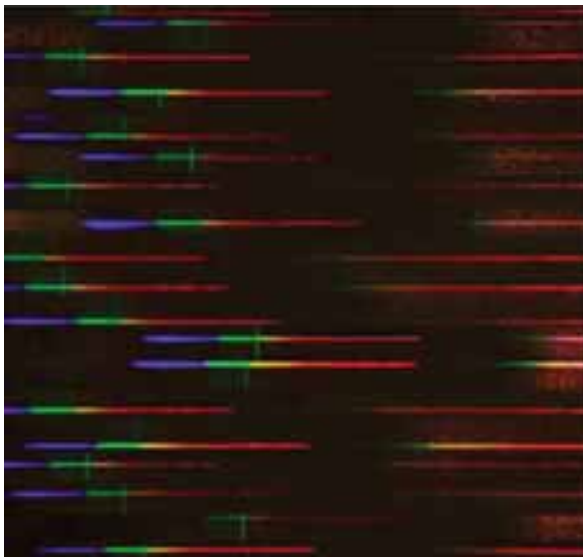
➤ optical designs:

- slitless spectrograph
- longslit spectrographs
- Echelle spectrograph (e.g. UVES):
2 gratings (echelle grat. + cross disperser),
offers high resolution and large λ coverage



Spectrographs

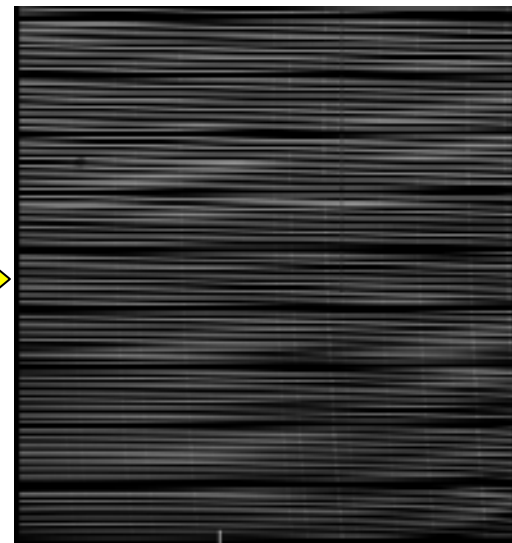
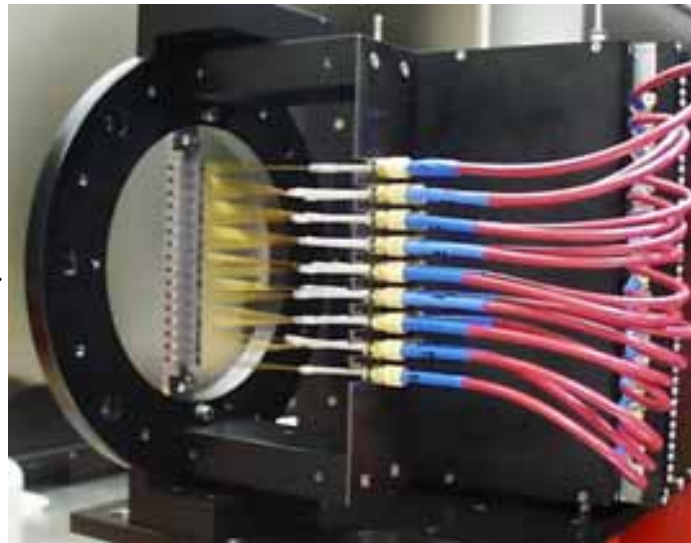
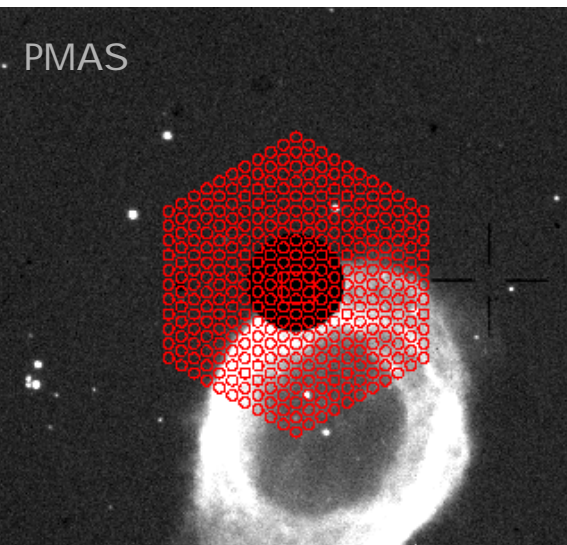
- optical designs:
 - slitless spectrograph
 - longslit spectrographs
 - Echelle spectrograph
 - Multi-object spectrographs (MOS):
mask with laser-cut slitlets
instead of single slit



Spectrographs

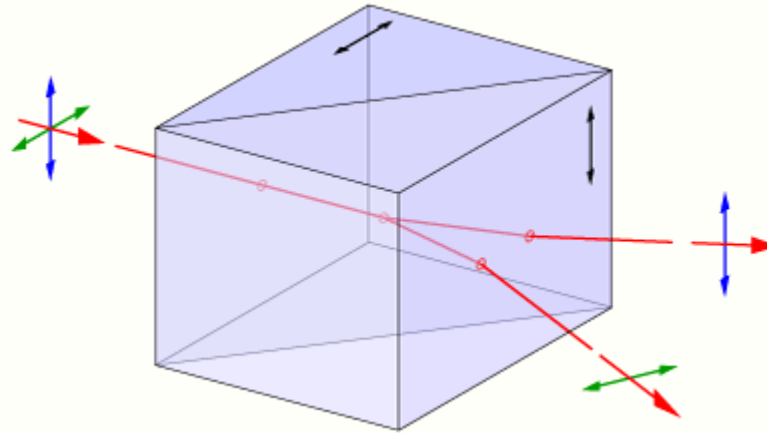
➤ optical designs:

- slitless spectrograph
- longslit spectrographs
- Echelle spectrograph
- Multi-object spectrographs
- Integral-field spectrographs (IFS):
microlens array (spaxels), light fed into glass fiber bundle,
spectrum of each spaxel → data cube



Polarimetry

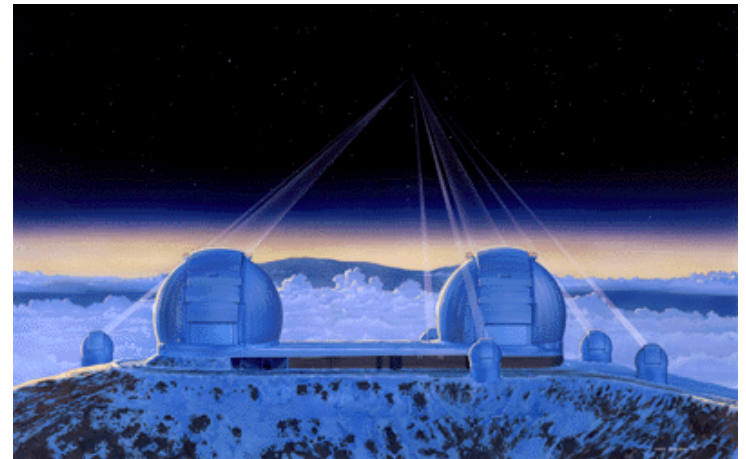
- introduce Wollaston prism (calcite bi-prism) in light path



- afterwards normal imaging or spectroscopy
- repeat with different orientations of the prism
→ degree and orientation of polarisation can be determined
- very high S/N needed if polarisation is small

Interferometry

- Idea: increase resolution by phase-true combination of the signal from two or more telescopes
- Example: Keck I & II telescopes
 - 10m mirror diameter
 - 85m away from each other
 - as interferometer:
light gathering like two 10m tel.,
angular resolution like 85m tel.
- Scientific goals:
 - direct detection of giant planets near bright stars in the IR
 - astrometric detection of planets by their gravitational action
 - high-resolution imaging of protoplanetary disks



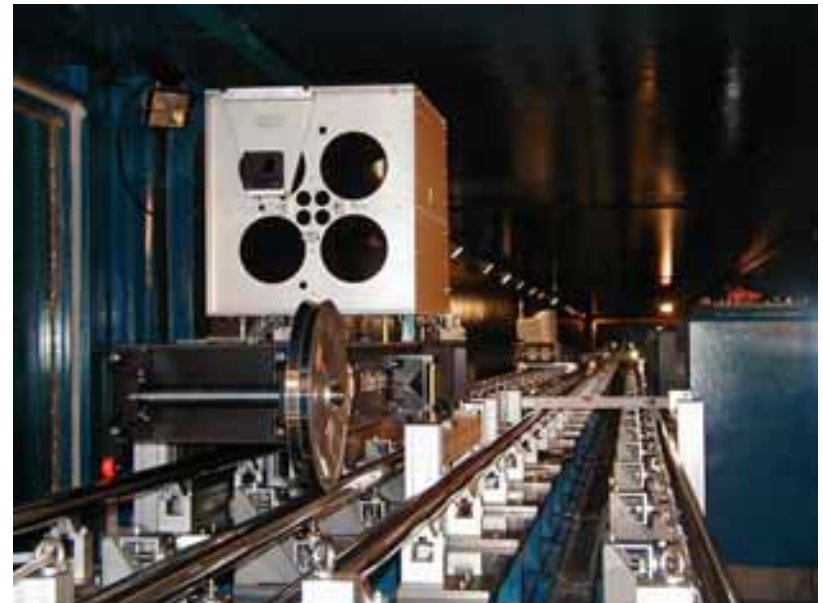
Interferometry

Technical components:

- Adaptive optics
- Interferometric tunnel
- Retroreflector Carriage:
equalises the retardation of the light collected by each telescope
(except for stars directly overhead)



VLTI Delay Lines in the Interferometric Tunnel



VLTI Delay Line Retroreflector Carriage



Detectors in optical / near-IR astronomy

Requirements for astronomical detectors:

- high efficiency
- high sensitivity
- linear response
- broad spectral response
- high spatial resolution
- ...

Types of detectors:

- photographic plates
- photomultiplier tubes (PMTs)
- CCDs / other semiconductor devices

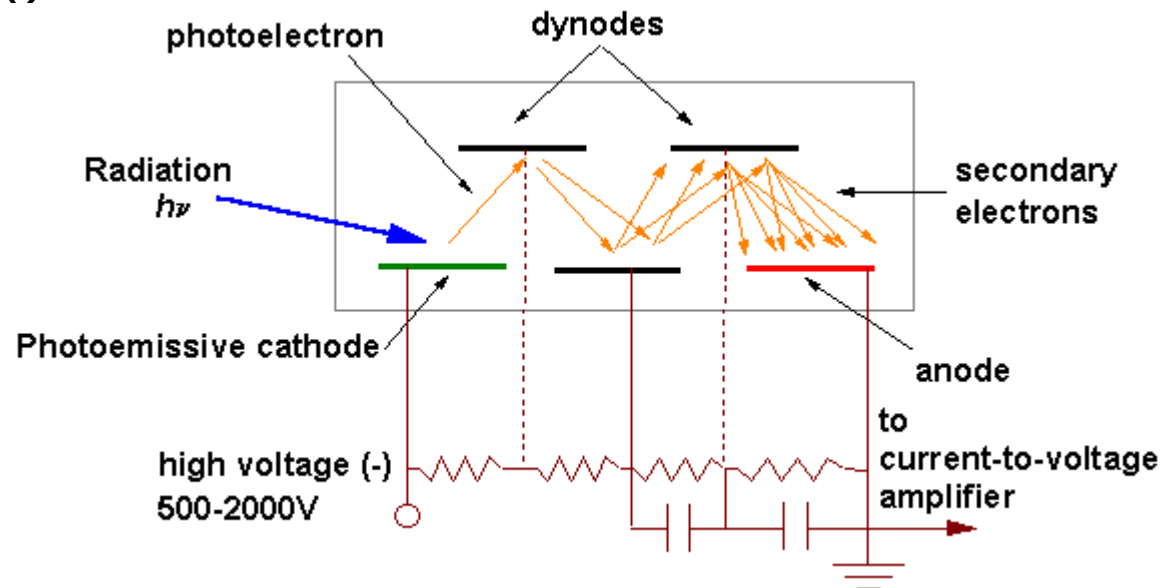
Photographic plates

- glass plates with silver bromide emulsion
- special spectroscopic emulsions available
- in use until ~1990
- advantages:
 - large sizes possible, good for surveys
- disadvantages:
 - low efficiency (~10%)
 - non-linear response to light
 - Schwarzschild-effect



Photomultiplier tubes

- consisting of a photocathode and a series of dynodes in an evacuated glass tube
- photons with sufficient energy eject photo electrons (photo effect)
- photo electrons are accelerated by a series of dynodes
- 10^5 to 10^7 e^- for each photo e^-
- mainly sensitive in the blue and UV photons

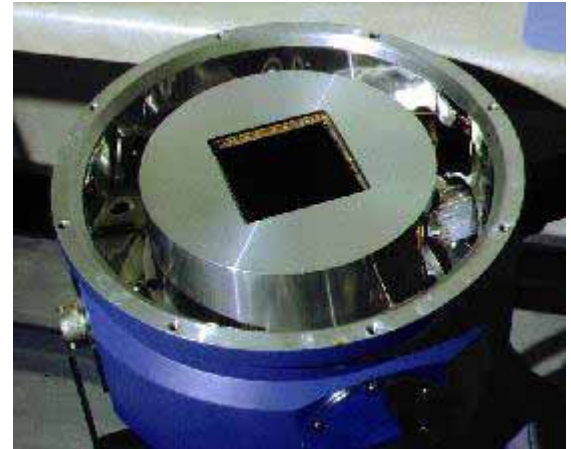


Photomultiplier tubes

- advantages:
 - extremely sensitive (single photons detectable)
 - high temporal resolution
- disadvantages:
 - less sensitive in the red
 - no real imaging or spectroscopy possible

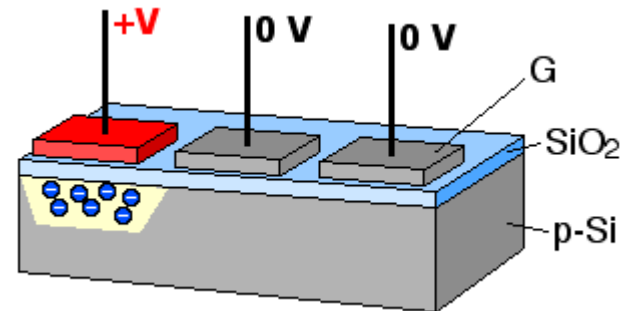
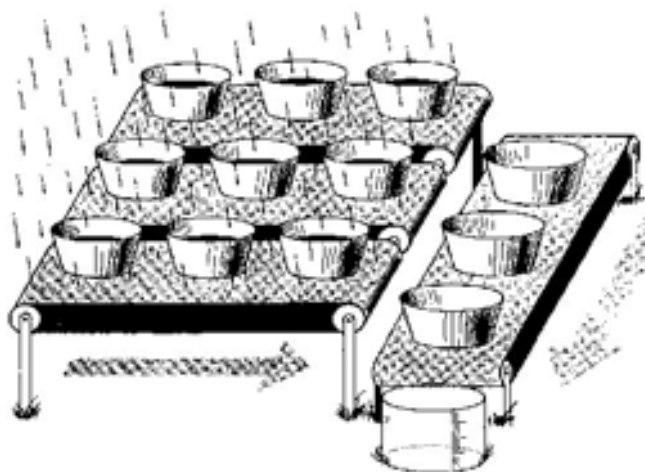
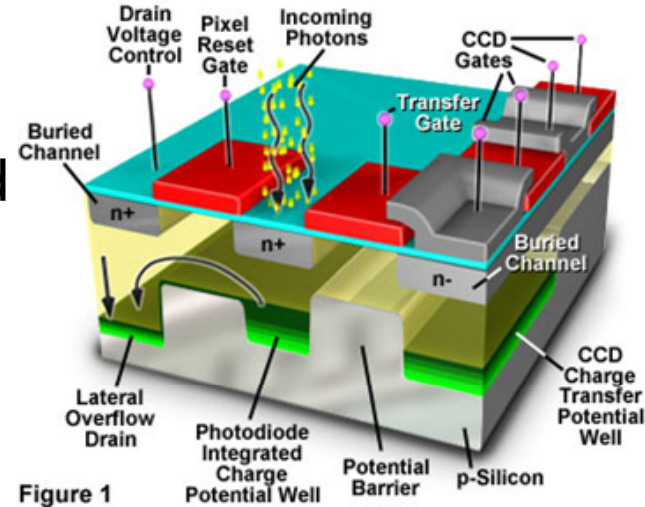
Charge Coupled Devices

- based on silicon semiconductors
- first used at Kitt Peak National Observatory in 1979
- advantages:
 - high quantum efficiency (up to 90%)
 - linear response until saturation
 - 300-1000nm, good red sensitivity
 - very flexible
- disadvantages:
 - need to be cooled to reduce dark current
 - "blooming": charge can float to neighbouring pixels in case of saturation
 - no internal amplification



Charge Coupled Devices

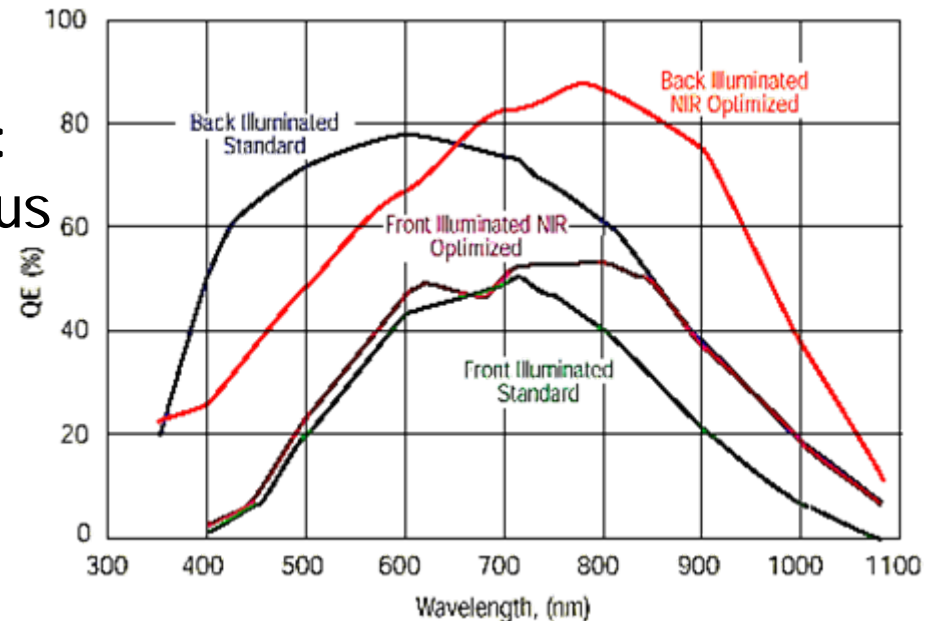
- array of photodiodes
- photons striking the chip are absorbed and produce an electron-hole pair
- electrons are stored in a potential well
- readout at the end of the exposure: periodic voltage alterations move the charge (serial readout, strictly speaking the "CCD")



Charge Coupled Devices

important parameters:

- dark current, number of “hot pixels” should be low, but LN_2 cooling helps
- full well capacity (should be large)
- charge transfer efficiency (should be 99.99..%)
- readout noise
- spectral quantum efficiency: should be high & homogeneous
Often backside-illuminated CCDs used in astronomy



Next-generation telescopes

- 
- E-ELT: European Extremely Large Telescope
 - 30-60m in diameter
 - start of construction in 2010
 - first light in 2017 (?)
 - cost: 850 million Euro (?)

Next-generation telescopes

➤ JWST: James Webb Space Telescope

➤ 6.5m mirror, lightweight

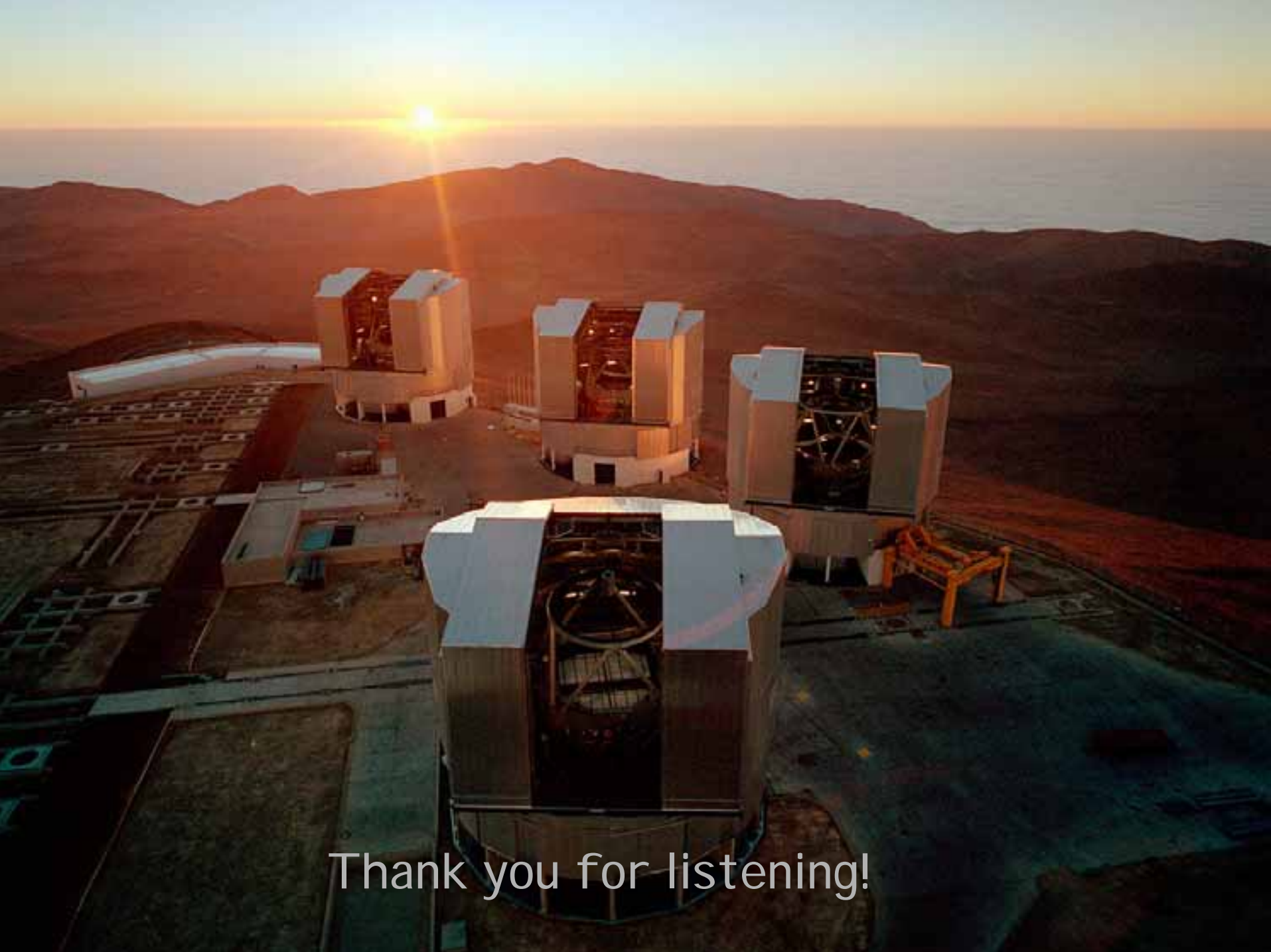
➤ passively cooled by large sunshade

➤ I R imaging and spectroscopy

➤ planned launch in 2013

➤ cost: 4.5 billion Dollars





Thank you for listening!