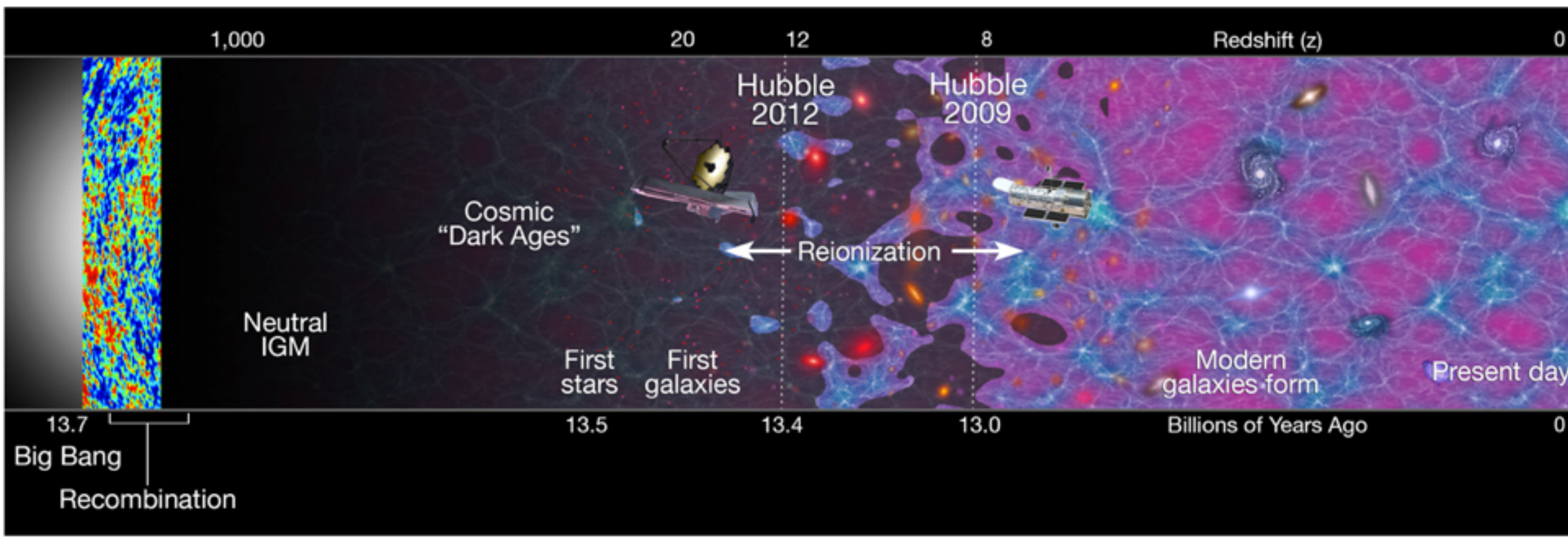
Observational Techniques for Cosmology

Søren Larsen, Department of Astrophysics/IMAPP

Cosmic history

Accessible to observations



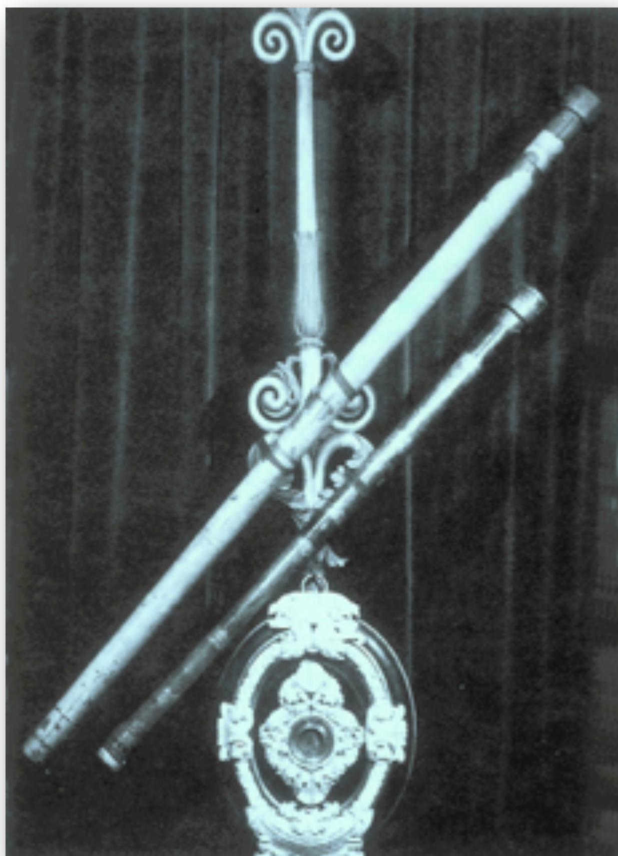
http://www.ph.ed.ac.uk/news/astronomers-shed-new-light-cosmic-dawn-11-12-12

Cosmology “bootcamp” - Astronomy

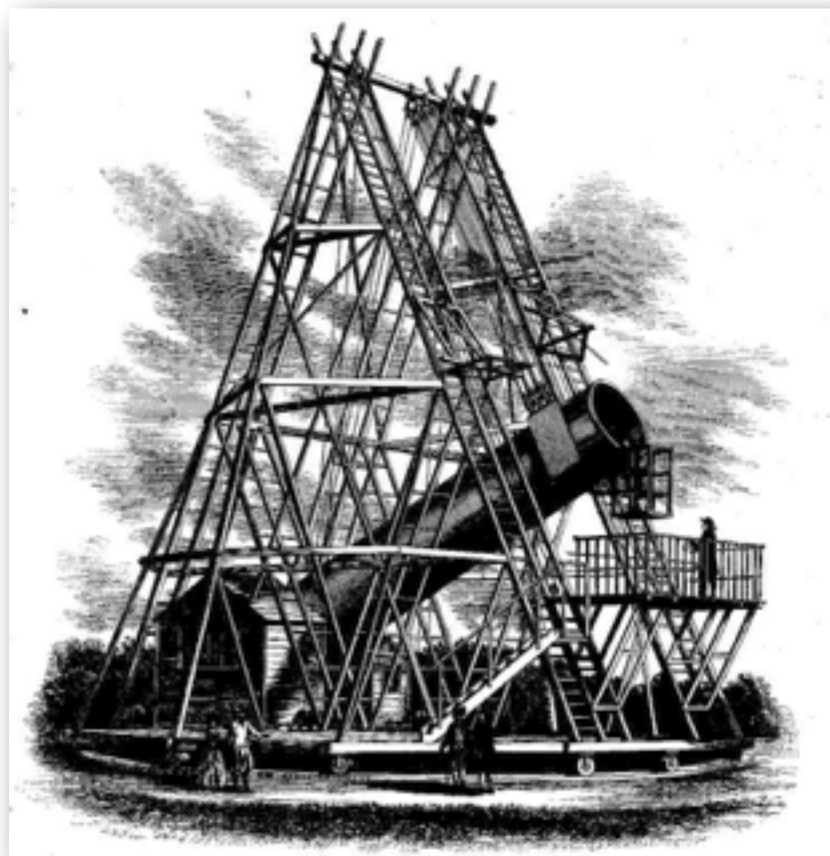
- **Observational Techniques for Cosmology**
- Distance determination
- The Hubble sequence; structure and evolution of galaxies
- The development of modern Cosmology in the 20th century

Telescopes: the past..

1610: Galileo's telescope (D~2 cm)



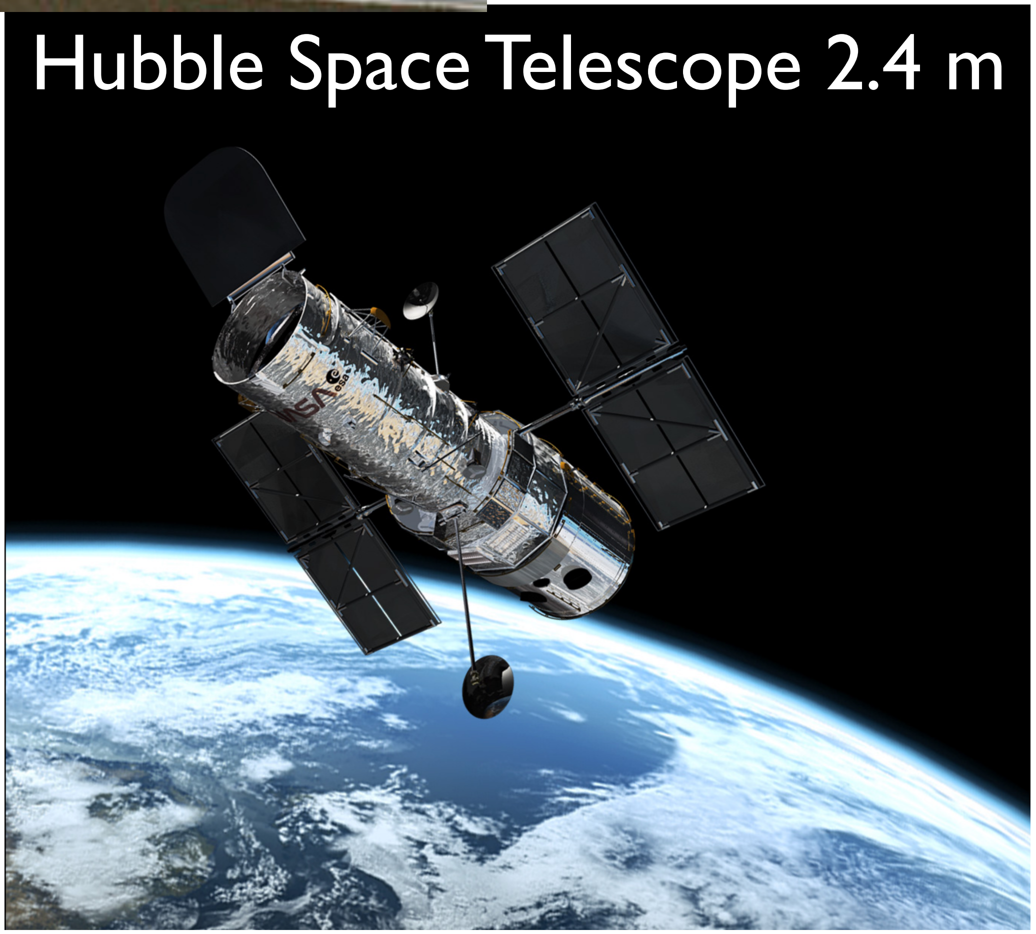
1780: Herschel's telescope (D=126 cm)



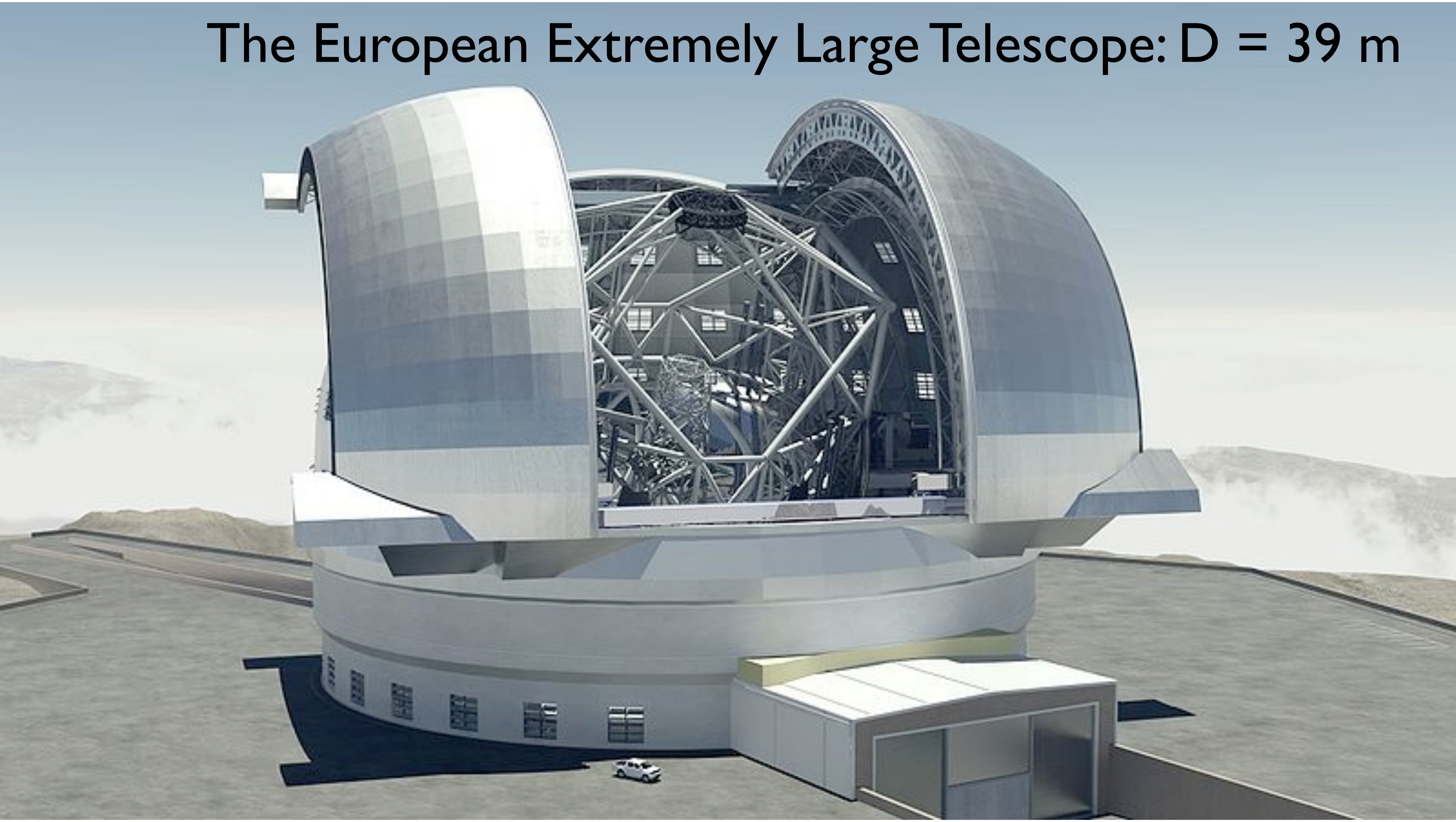
1948: Hale telescope (D=500 cm)

The most important property of a telescope is the size of the primary mirror / lens

.. the present



.. and the future:



To be built on *Cerro Armazones*, Chile. Ready around 2024. Price: 1 G€

E-ELT mirror mock-up: 800 segments of 1.4 m diameter

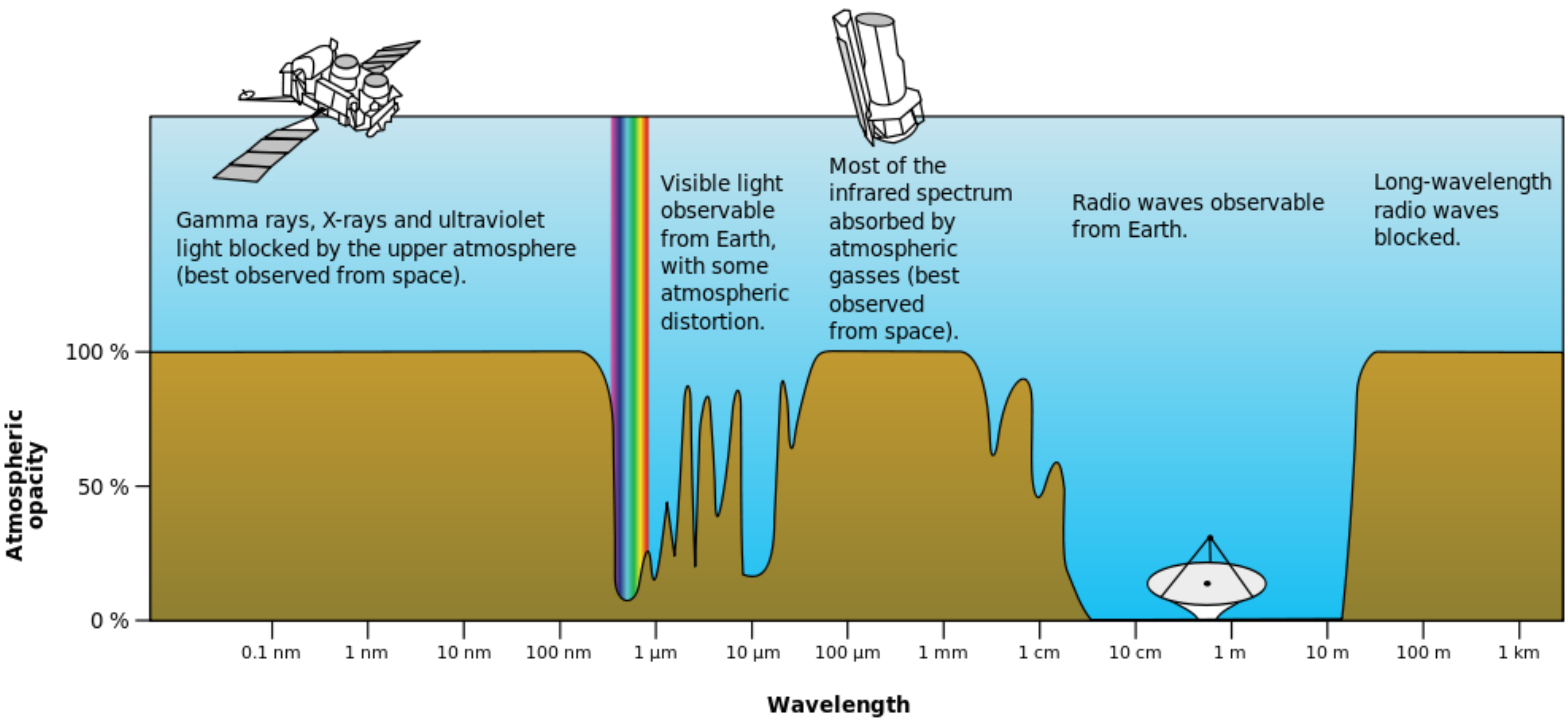
E-ELT construction, 2014

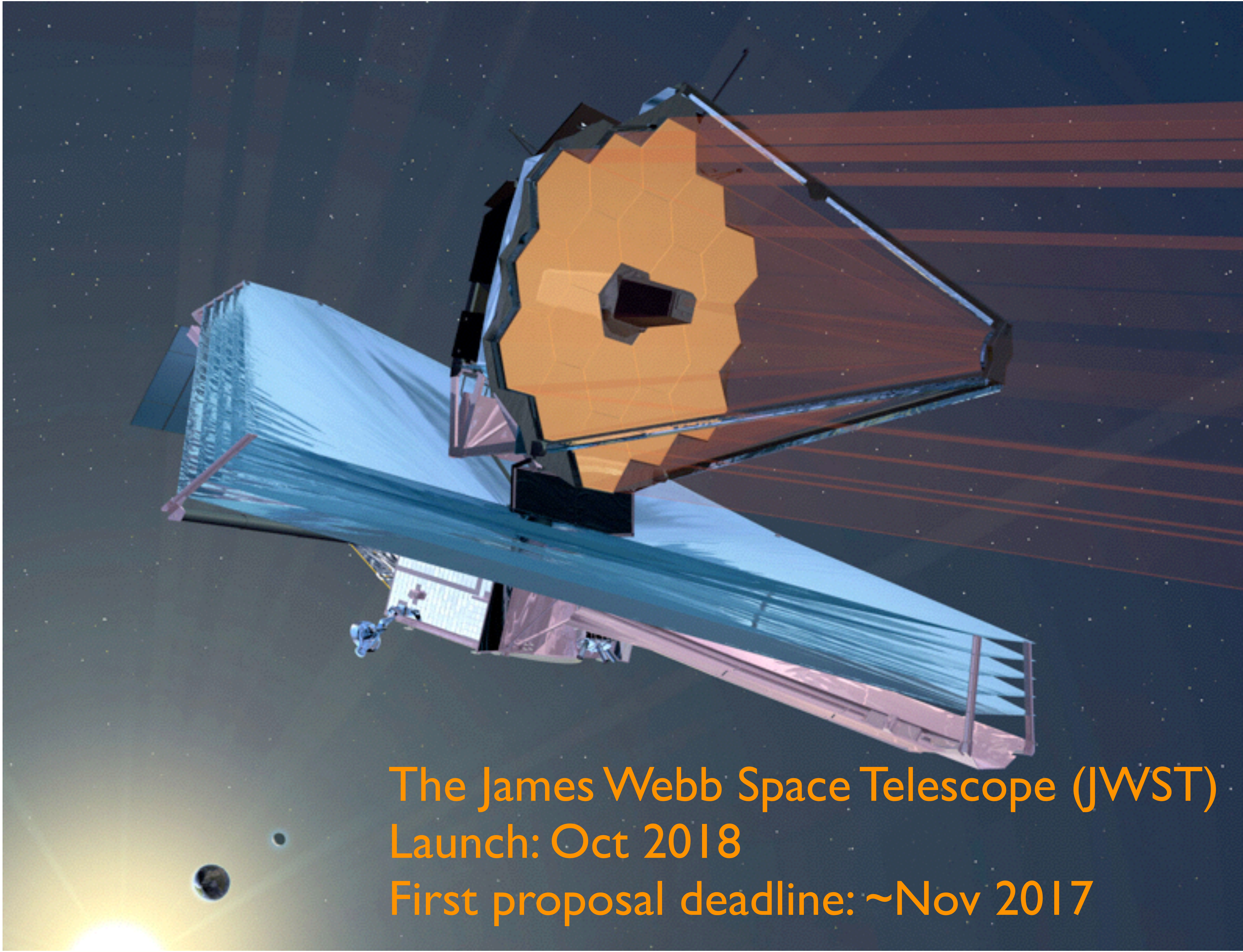
July 2015

EUROPEAN SOUTHERN OBSERVATORY
Organización Europea para la Investigación Astronómica en el Hemisferio Austral
OBRA:
Construcción del camino, plataforma y zanja de servicio para el E-ELT en Cerro Armazones, Chile, y trabajos posteriores de mantenimiento del camino.
FECHA DE INICIO : 03 de Marzo de 2014
FECHA DE TÉRMINO : 02 de Julio de 2015
PLAZO : 16 Meses
CONSTRUYE:
brotec
icafal

The Atmospheric Windows

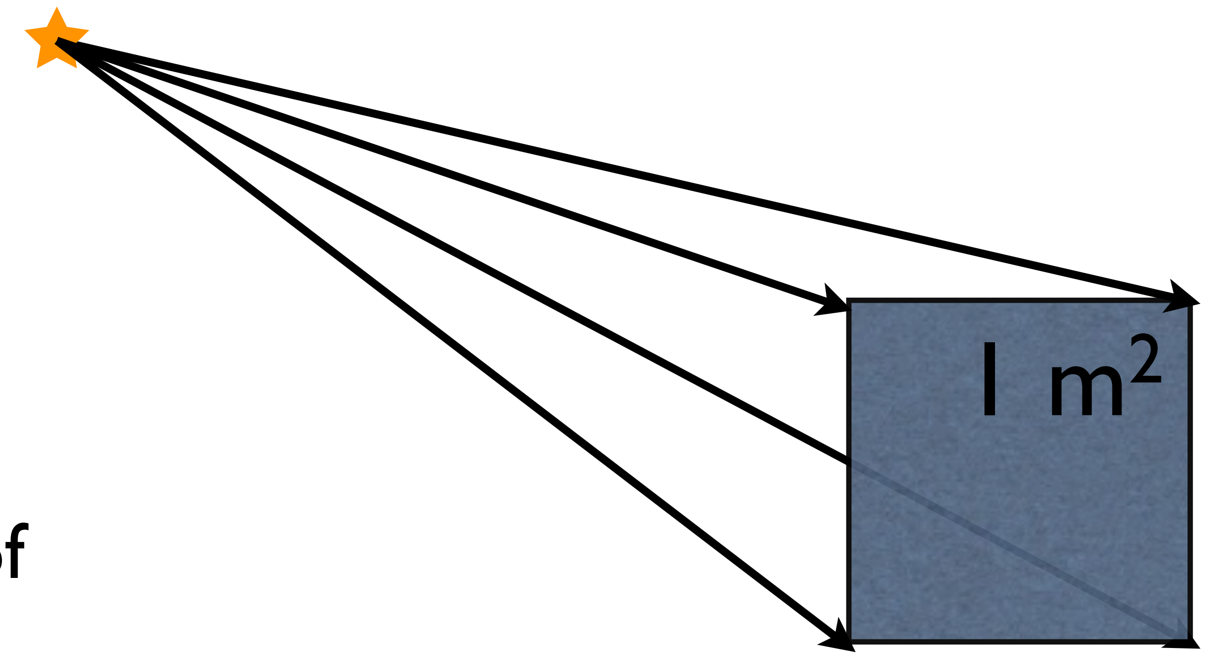
Only a small part of the electromagnetic spectrum is observable from the ground - the rest is blocked by the atmosphere.




The James Webb Space Telescope (JWST)
Launch: Oct 2018
First proposal deadline: ~Nov 2017

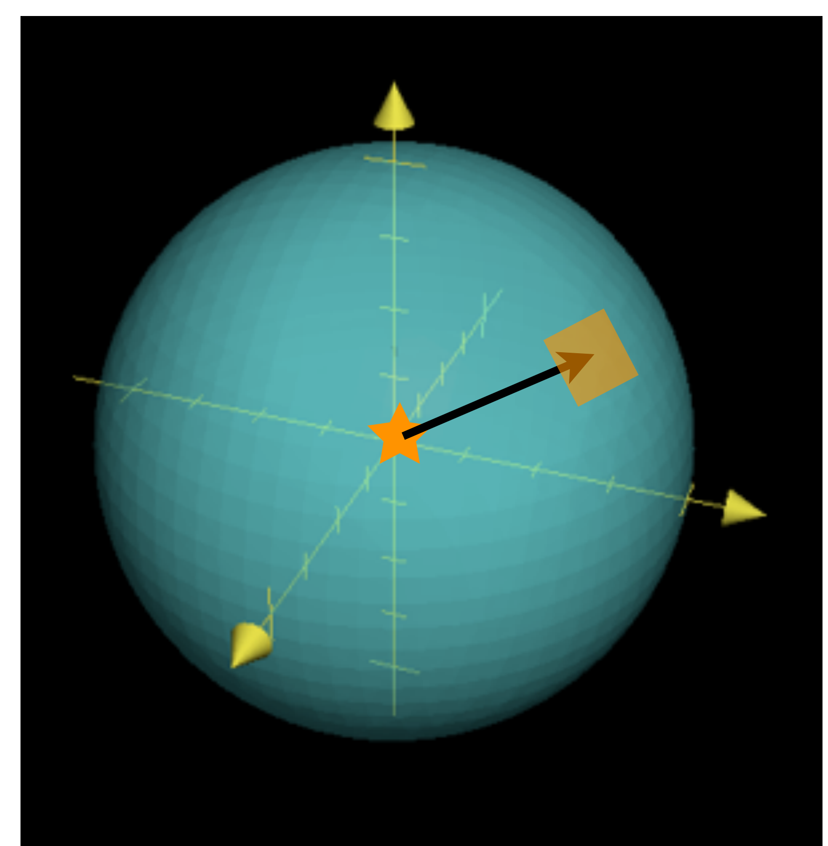
Flux:

The *energy* passing through a surface of *unit area* per *unit time* interval.



Flux *F* received from a celestial source of luminosity *L* at a distance D follows the *inverse square law*:

The luminosity *L* is distributed over a sphere with area 4 π D^2, i.e.

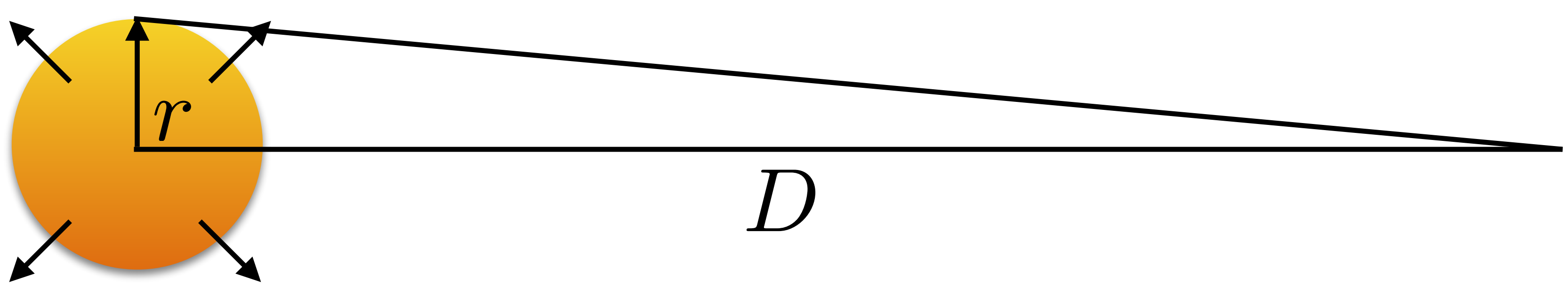


$$F = \frac{L}{4\pi D^2}$$

Intensity:

The *energy* passing through a surface of *unit area* per *unit time* interval per *unit solid angle*.

Flux : $F = L/4\pi D^2$
Power per unit surface area : $s = L/4\pi r^2$
Solid angle: $\Omega = \pi\,(r/D)^2$
Intensity: $I = F\,/\,\Omega = \dfrac{L}{4\pi D^2}\dfrac{D^2}{\pi r^2} = \dfrac{L}{4\pi^2 r^2} = \dfrac{s}{\pi}$



Under the (implicit) assumptions (- which?) in this calculation, intensity is independent of distance.

Instrumental vs. Physical units

- In general, measurements need to be *calibrated* to eliminate instrumental signature
- The "brightness" of a source (measured by some detector) may be expressed in "counts per sec"
- Conversion of "counts" to flux depends on many instrumental factors, e.g:
  - Sensitivity, telescope size, reflectivity of mirrors, absorption in atmosphere, etc..
- Whenever possible, measurements are made relative to a *standard* source with known flux.

Magnitudes

- Introduced by Greek astronomers (probably first Hipparchus); used by Ptolemy in the *Almagest* around 150 A.D.
- Scale from 1 - 6, where 6 is the faintest (visible to the naked eye)
- Extension to fainter stars required more precise definition:
- N. Pogson (1856, MNRAS 17, 12) proposed to use a "light ratio" of 2.512 between successive magnitude steps - still used today (5 mag = factor 100 in flux)
- *Absolute* magnitude (Kapteyn 1902; Publ. Gron. 11, 1): Apparent magnitude a star would have for a parallax of 0.1" (D=10 pc)

Magnitudes

- The fluxes (F_1 and F_2) and apparent magnitudes (m_1 and m_2) of two objects are related as:

$$m_1 - m_2 = -2.5 \log_{10} \left(\frac{F_1}{F_2} \right)$$

- If the zero-point (zp) of the scale is known, then

$$m = -2.5 \log_{10} F + \mathrm{zp}$$

- The star Vega is often used as a reference: $m(\mathrm{Vega}) \equiv 0$

- Sun: V = -26.7
- Full moon: V = -12.6
- Venus: V = -4.7
- Brightest star (Sirius): V = -1.47
- Faintest stars visible to naked eye: V=6
- Faintest objects detected in Hubble Ultra Deep Field: V ~ 29.5

Apparent (*m*) and absolute (*M*) magnitude:

$$m = -2.5 \log\left(\frac{L}{4\pi D^2}\right) + \text{const}$$

Assuming no absorption!

$$M = -2.5 \log\left(\frac{L}{4\pi (10\text{pc})^2}\right) + \text{const}$$

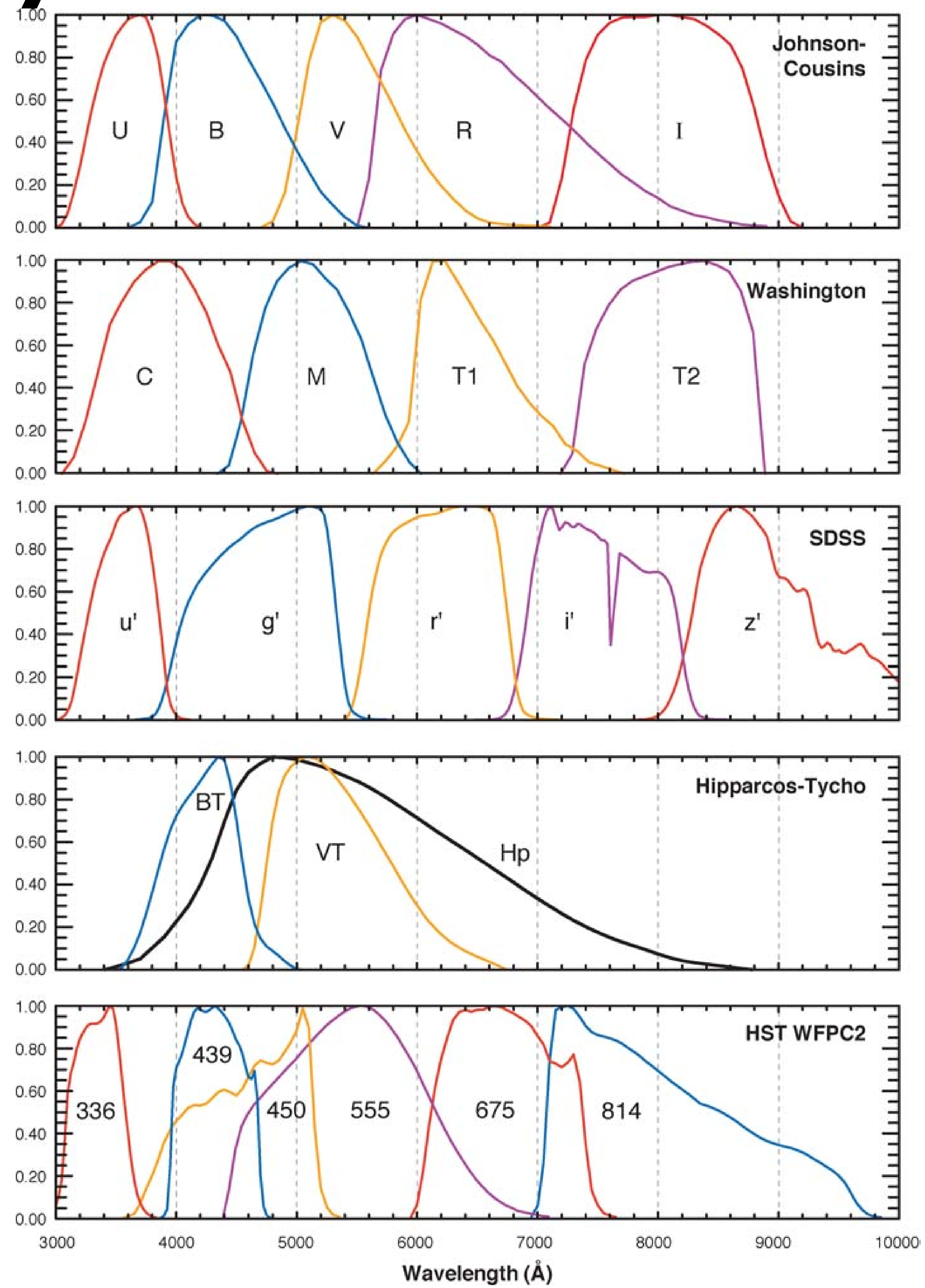
m-M = distance modulus

$$m - M = -2.5\left[\log\left(\frac{L}{4\pi D^2}\right) - \log\left(\frac{L}{4\pi (10\text{pc})^2}\right)\right]$$

$$= -2.5 \log\left(\frac{10\text{pc}}{D}\right)^2 \qquad = -5 \log\left(\frac{10\text{pc}}{D}\right)$$

Photometric Systems

- Magnitude systems: Defined by sets of *standard stars*. E.g. UBVRI, roughly normalised to Vega.
- Observations must be transformed from the *instrumental* system of the observer to the *standard* system.



Bessell 2005

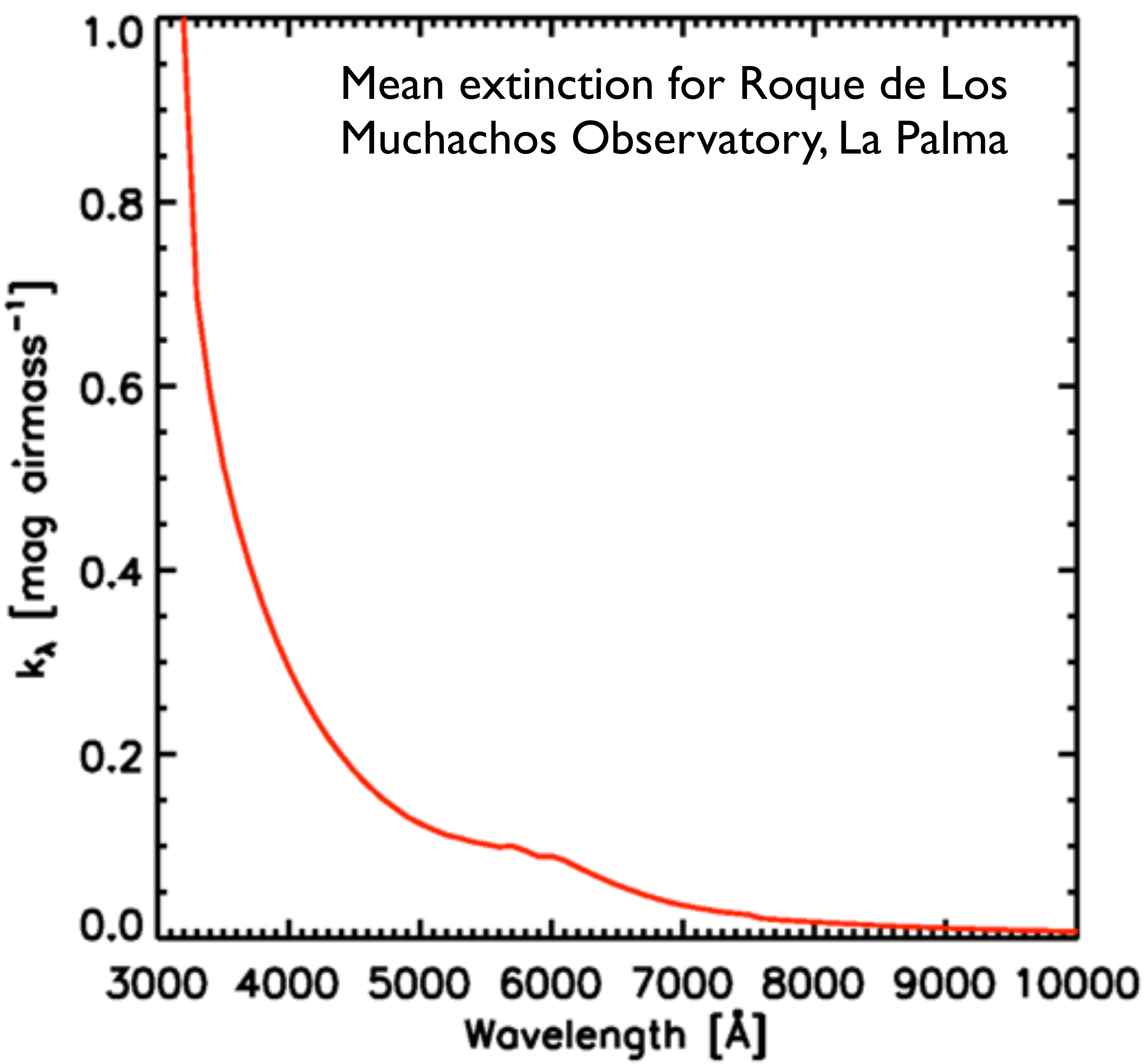
Colours

- Colours defined analogously to magnitudes, e.g.

$$B - V = -2.5\log_{10}\left(\frac{F_B}{F_V}\right) + \mathrm{zp_{B-V}}$$

$$U - B = -2.5\log_{10}\left(\frac{F_U}{F_B}\right) + \mathrm{zp_{U-B}}$$

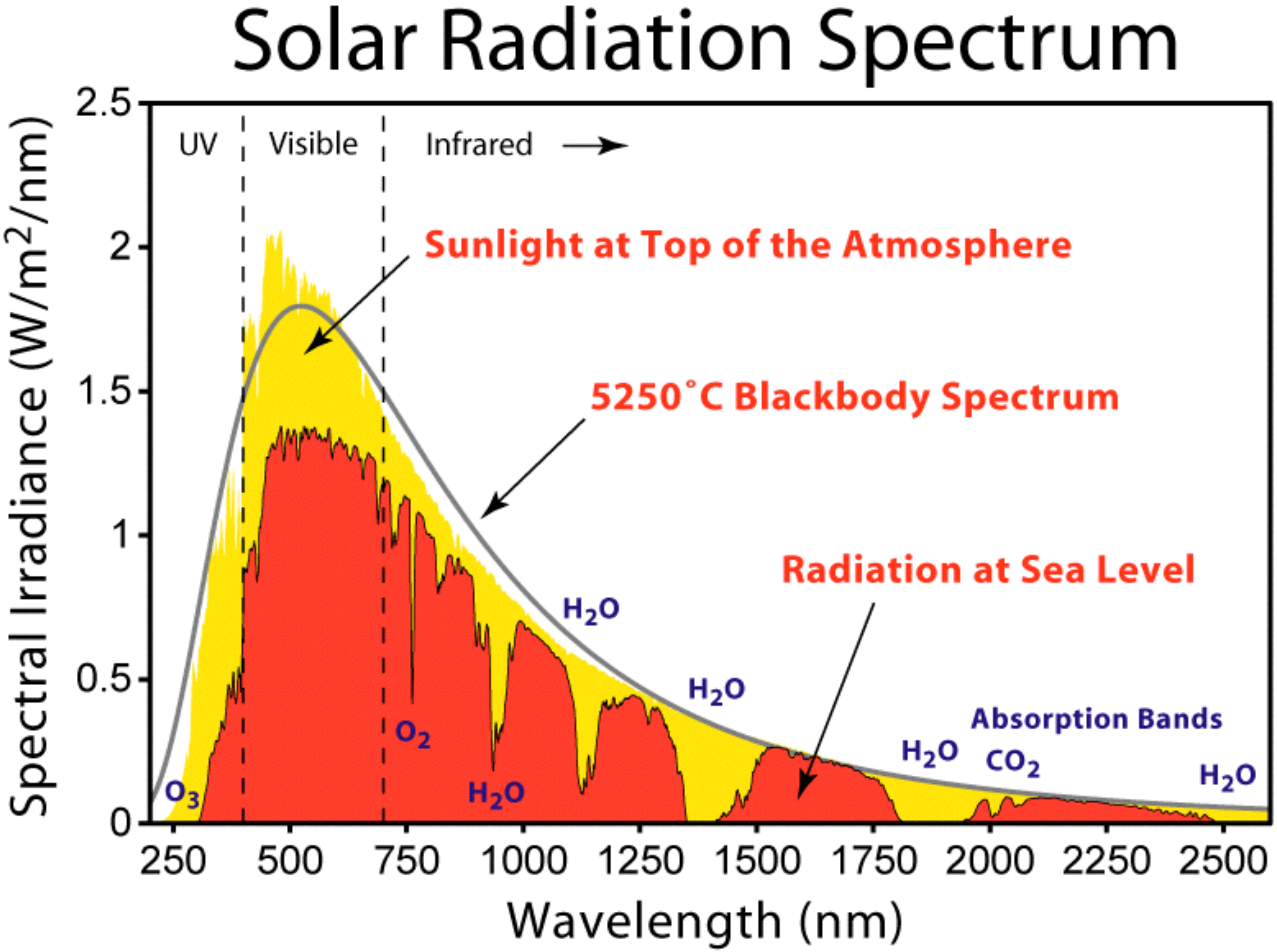
Atmospheric extinction



Extinction is wavelength-dependent.

Typical values:
k_U = 0.4 mag airmass^{-1}
k_B = 0.2 mag airmass^{-1}
k_V = 0.1 mag airmass^{-1}

k_λ increases strongly below ~3400 Å (atmospheric cut-off)

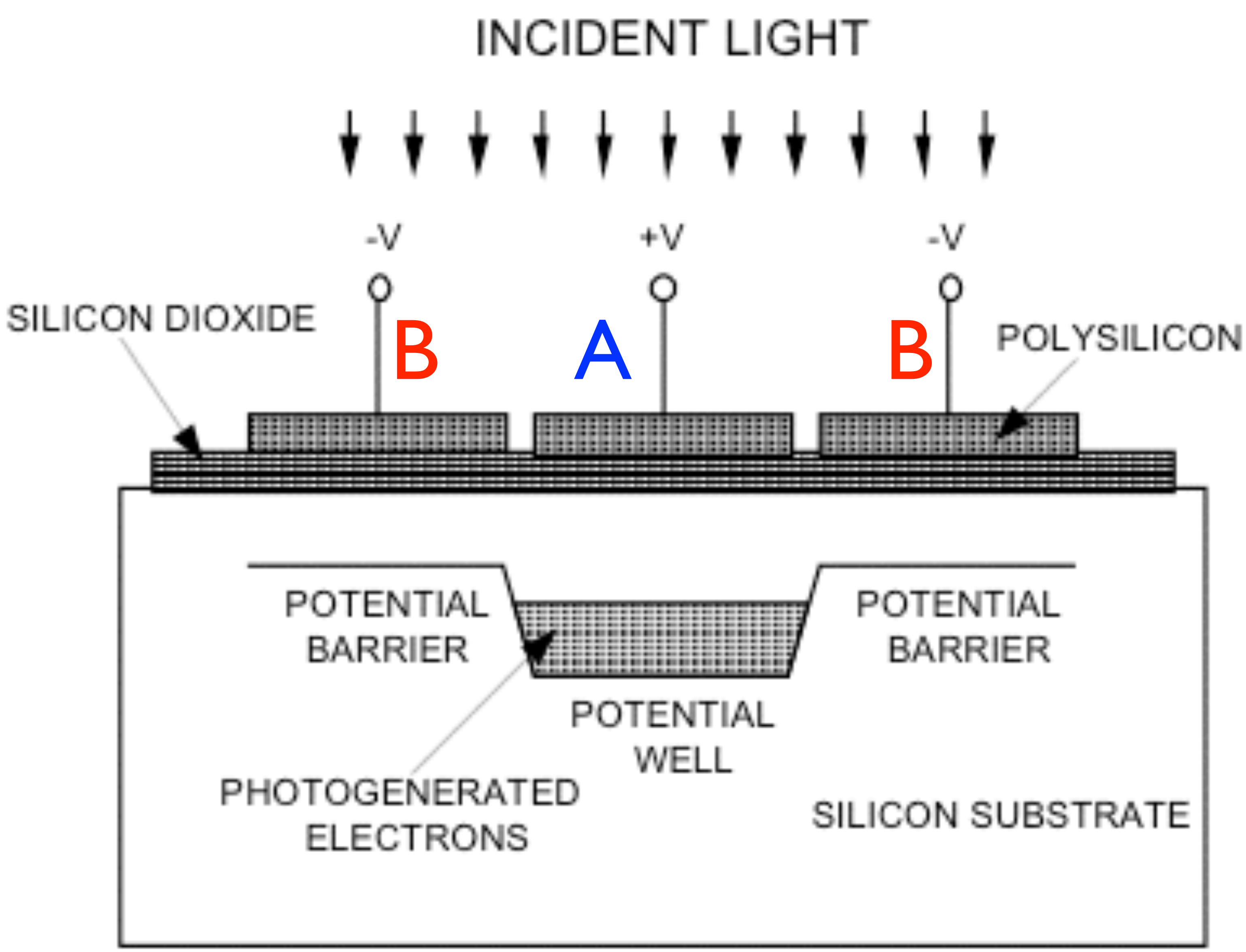


Solar Radiation Spectrum
Spectral Irradiance (W/m2/nm)
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250˚C Blackbody Spectrum
Radiation at Sea Level
H2O
H2O
O2
H2O
O3
Absorption Bands
H2O
CO2
H2O
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

Charge Coupled Devices (CCDs)

- Developed in 1969 at AT&T Bell Labs, originally as computer memory
- First used in astronomy around 1975. The first devices were small, ~100×100 pixels
- Typical sizes are now 2048^2 or 2048×4096 pixels

The CCD detector

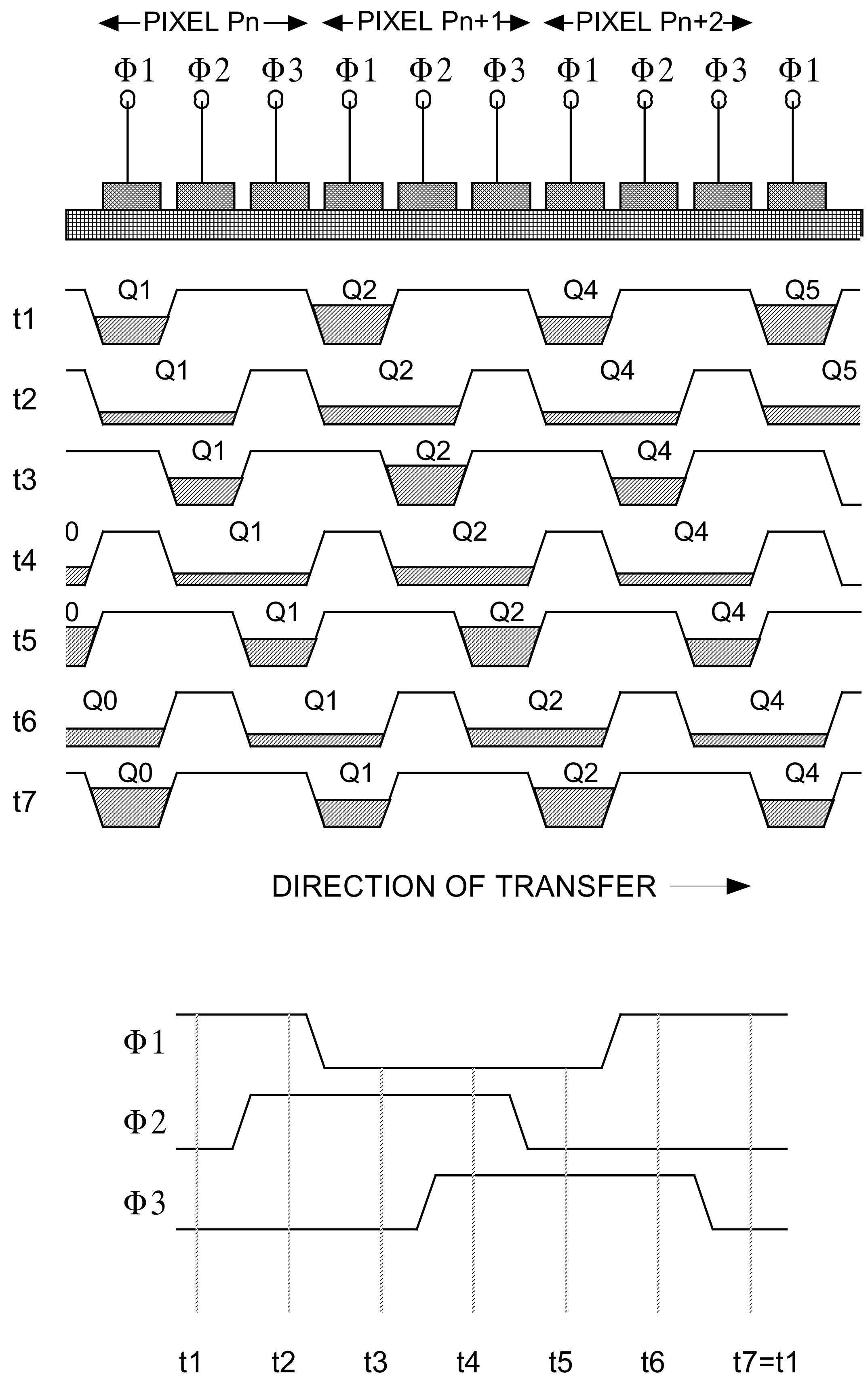


Schematic illustration of a CCD pixel

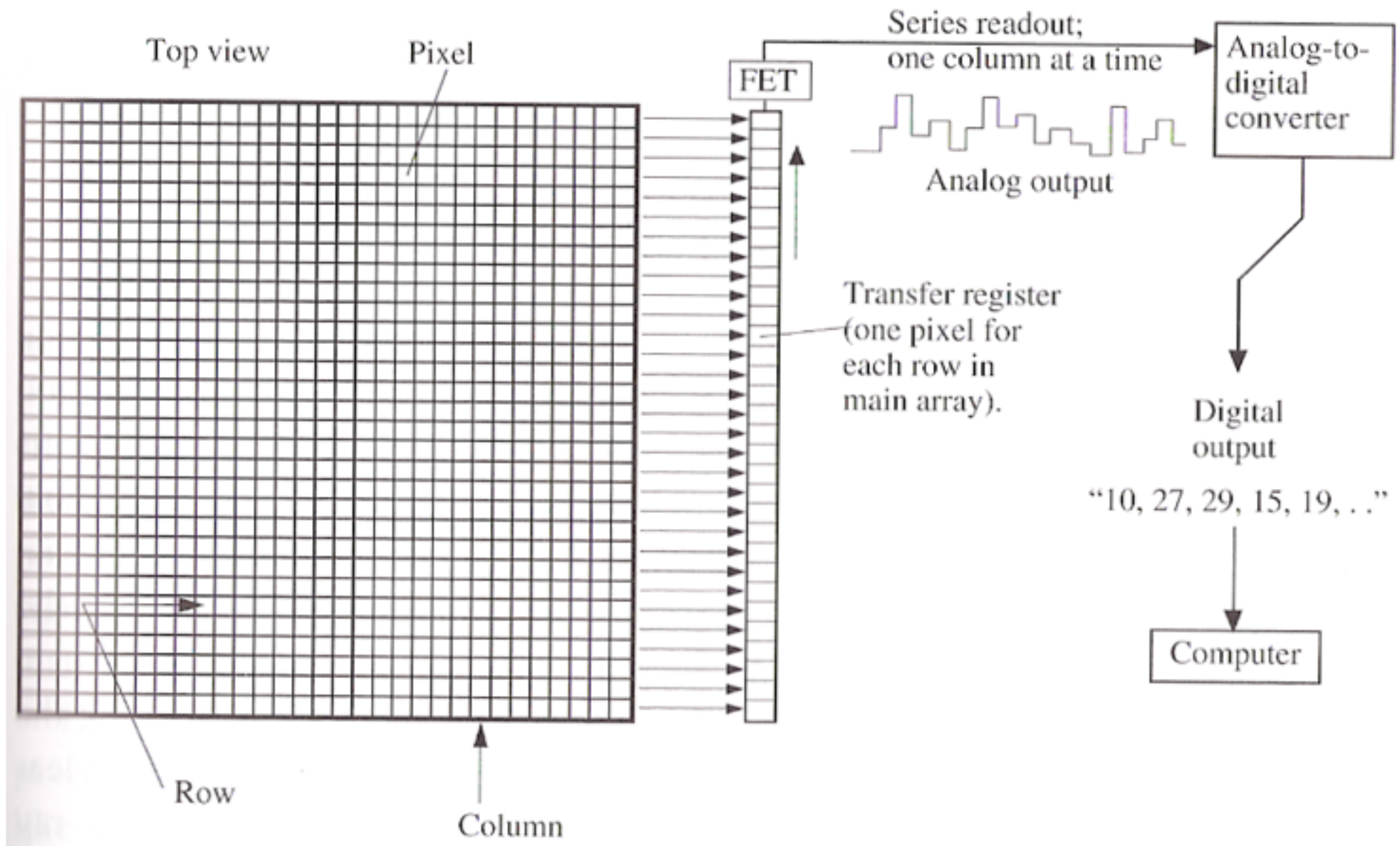
Electron-hole pairs are generated by incoming photons (photo-electric effect).

The electrons are kept in place by positive and negative electric voltages (electrodes "A" and "B")

CCD Primer, Eastman Kodak (2001)



At the end of the exposure, the electric charges are shifted across the CCD by cycling the voltages on the electrodes.

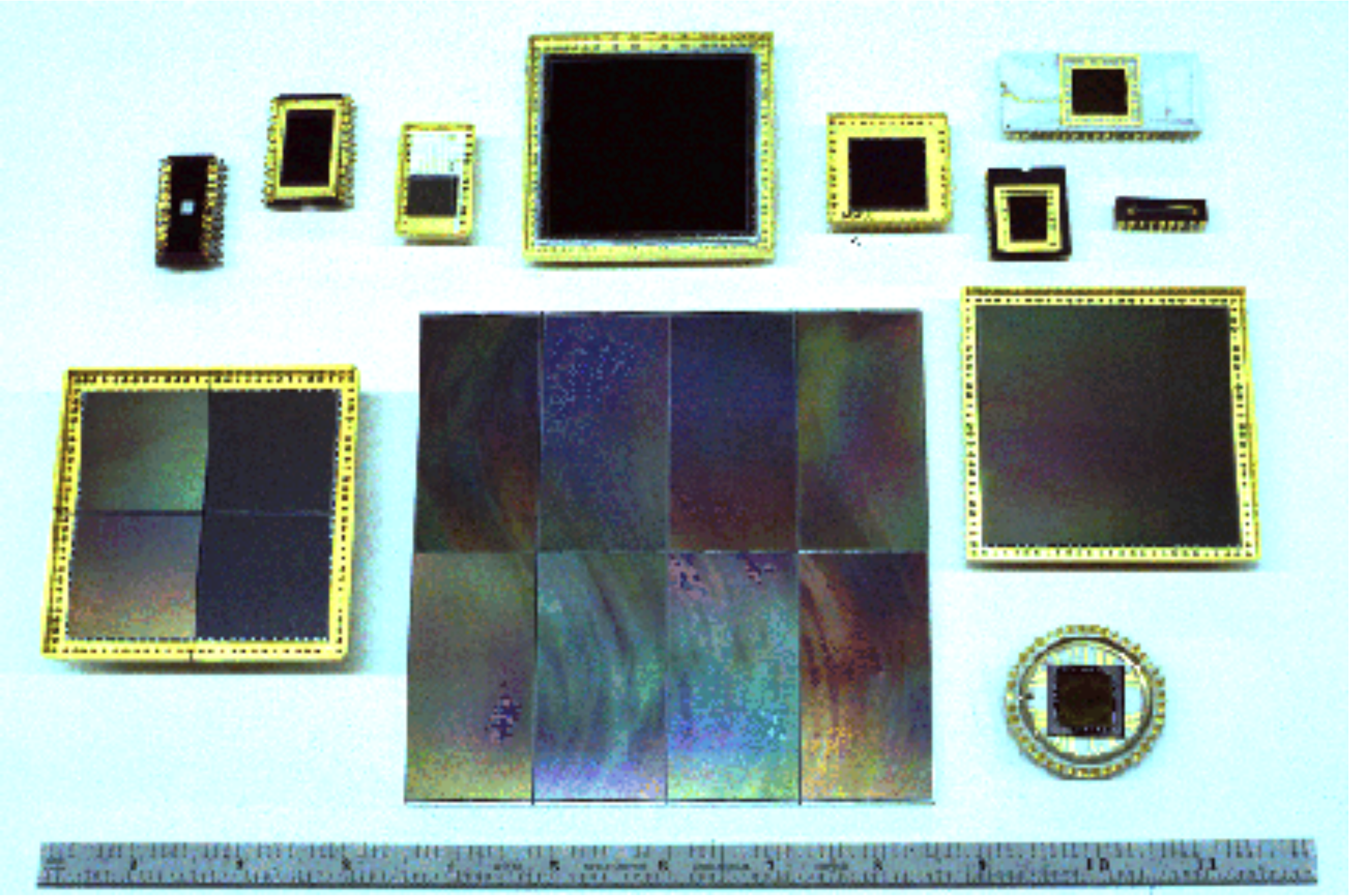


Each column is read separately, pixel by pixel. The charges are converted to an electric current, and then converted to a digital number via an A/D converter.

CCD properties

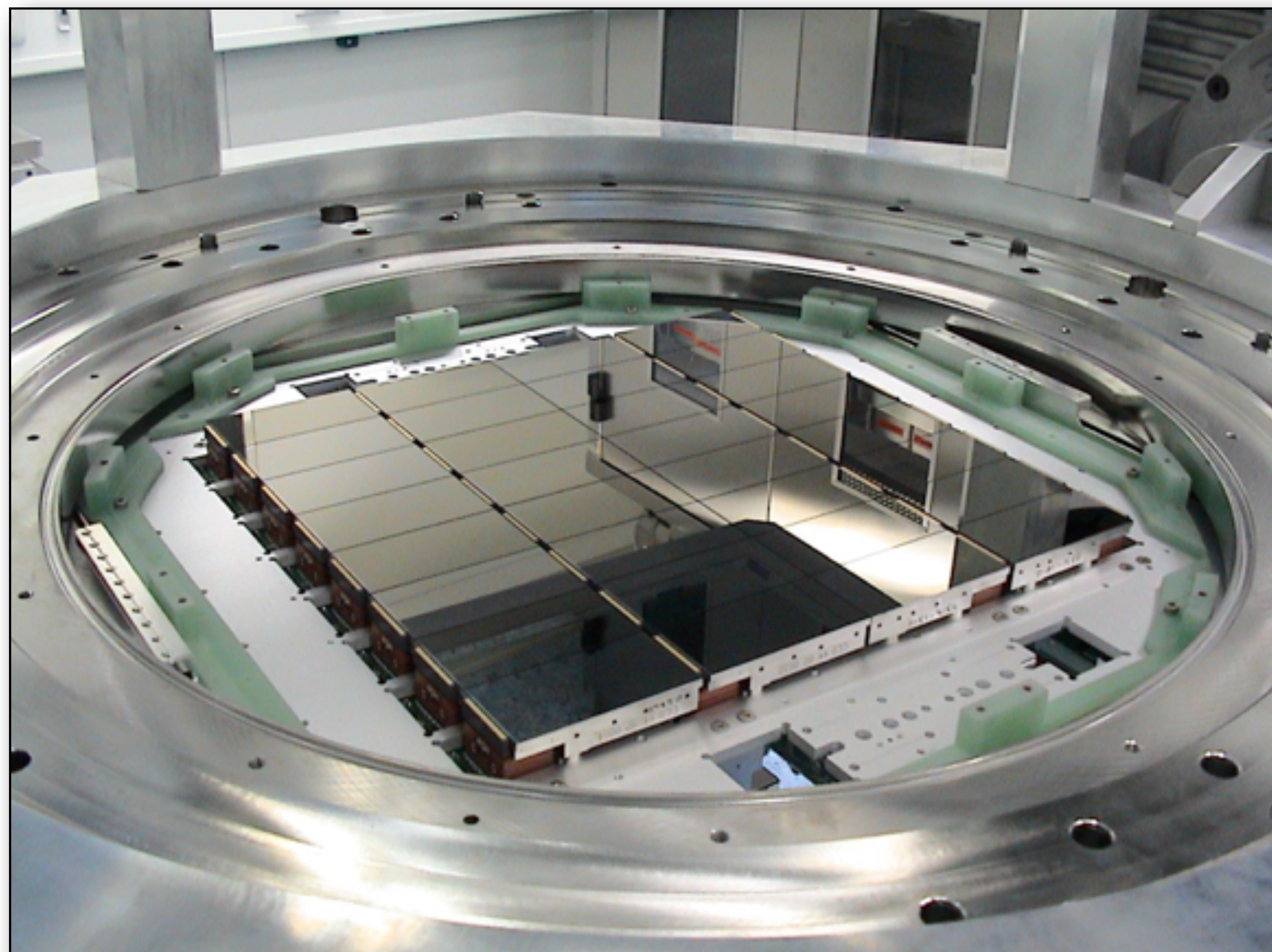
- High *quantum efficiency*: >90% of the photons create electron-hole pairs.
- Large dynamic range - "full well capacity" typically $\sim 10^5$ electrons
- Linear response - simple conversion between "counts" and flux/intensity
- Sensitive to wavelengths from ~300 nm to ~1 μm

CCDs



http://star-www.rl.ac.uk/docs/sc5.htx/node7.html

OmegaCam on the ESO 2.6 m VST (“VLT survey telescope”):
Mosaic of 32 CCDs of 2048x4096 pixels, total 16k x16 k (=256 Megapixels).
Field of view = 1x1 degree^2.



CCDs of Gaia satellite:
106 CCDs of 4500x1966 pixels.   Total: 938 Megapixels

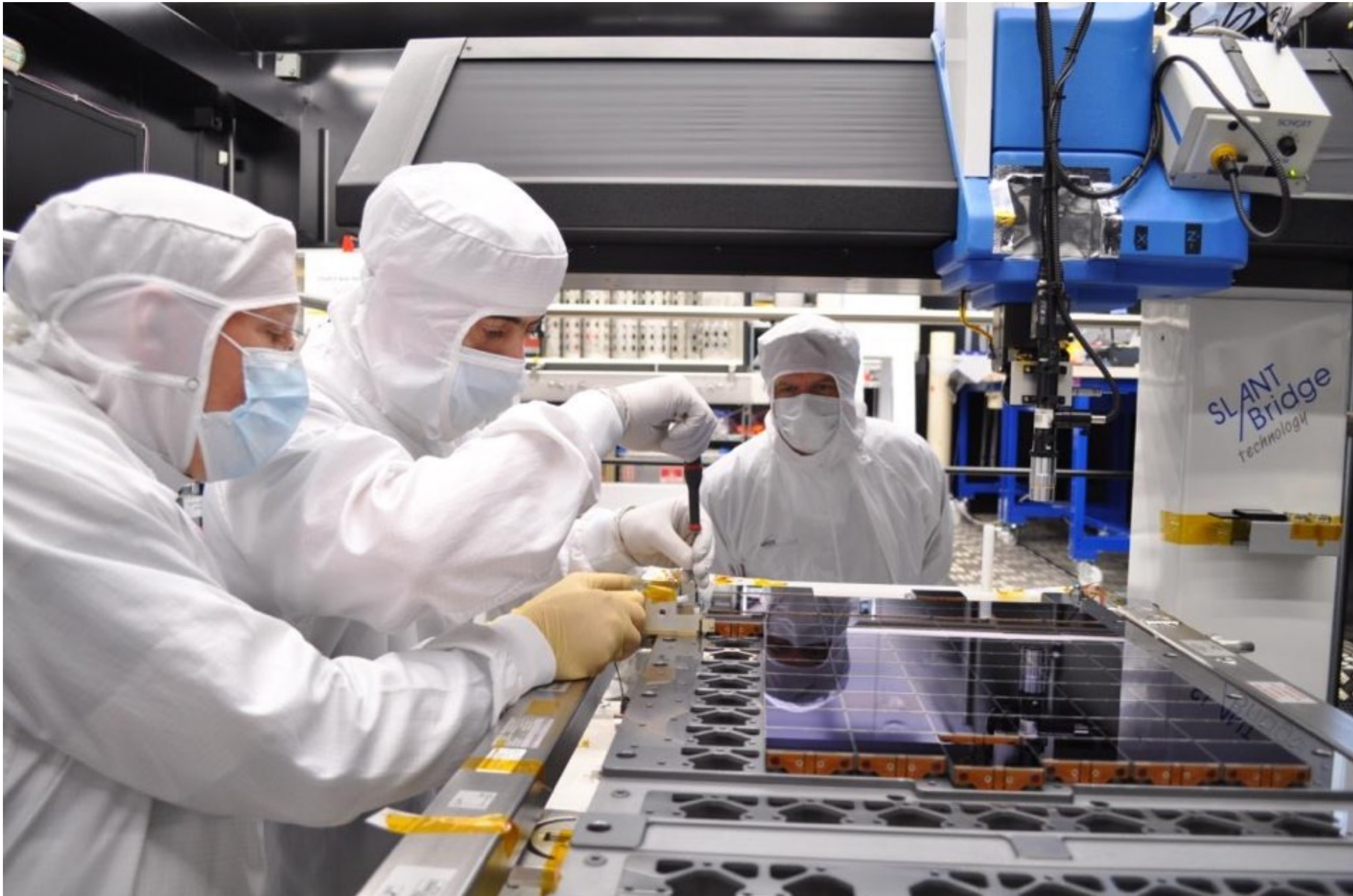
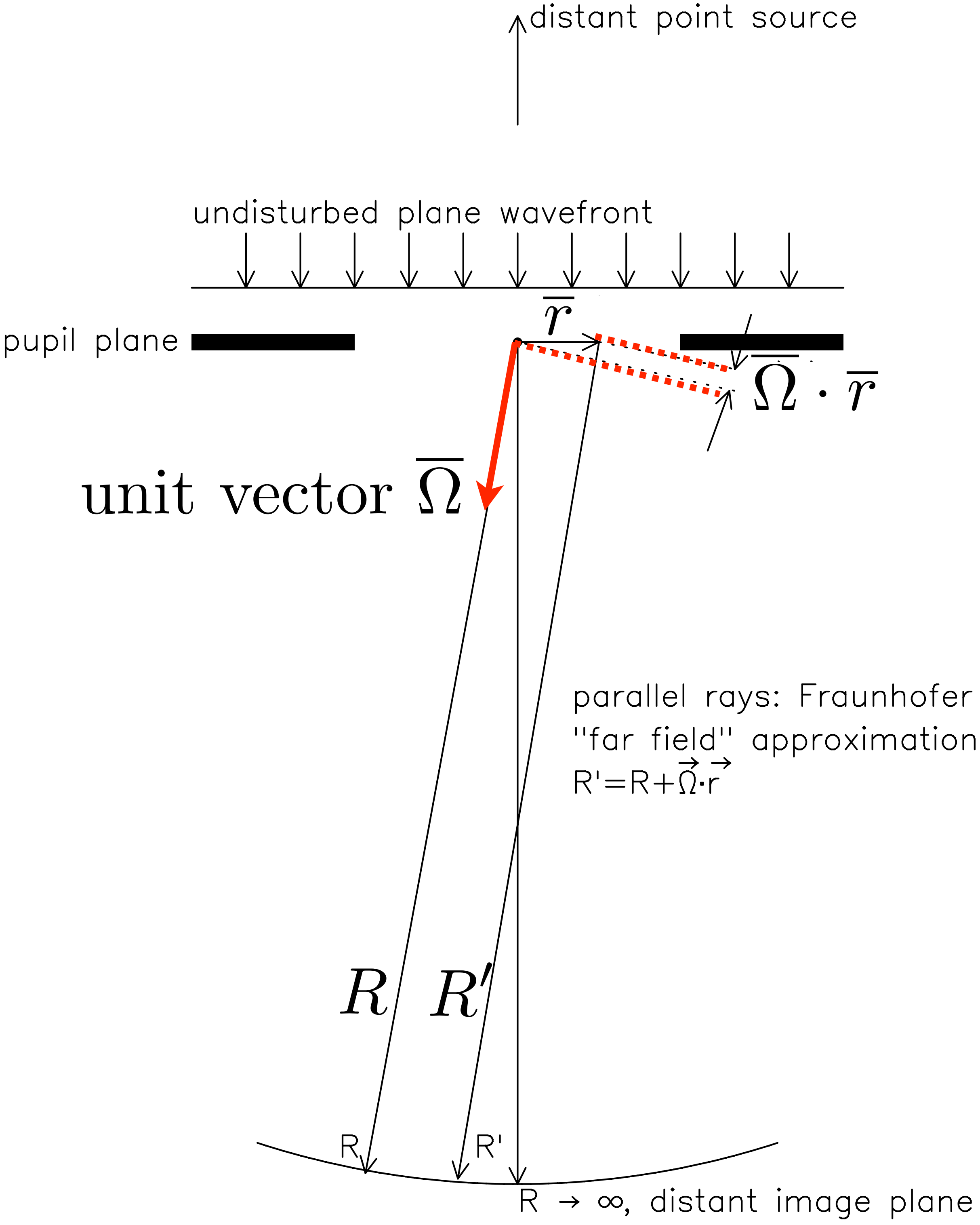


Image formation in telescope



Amplitude of electric field vector at *pupil*

$$E(t) = E_0 e^{i2\pi\nu t}$$

Intensity: $I = \langle E E^\star \rangle$

Integral over pupil, at focal plane:

$$E_{\rm sum} = \int\int_{\rm pupil} \frac{C}{R'} E_0 e^{i2\pi\nu\left(t - \frac{R+\overline{\Omega}\cdot\overline{r}}{c}\right)} d\overline{r}$$

Amplitude diffraction pattern:

$$a(\overline{\Omega}) = \frac{\lambda}{R}\mathcal{F}\{P(\overline{r}/\lambda)\}$$

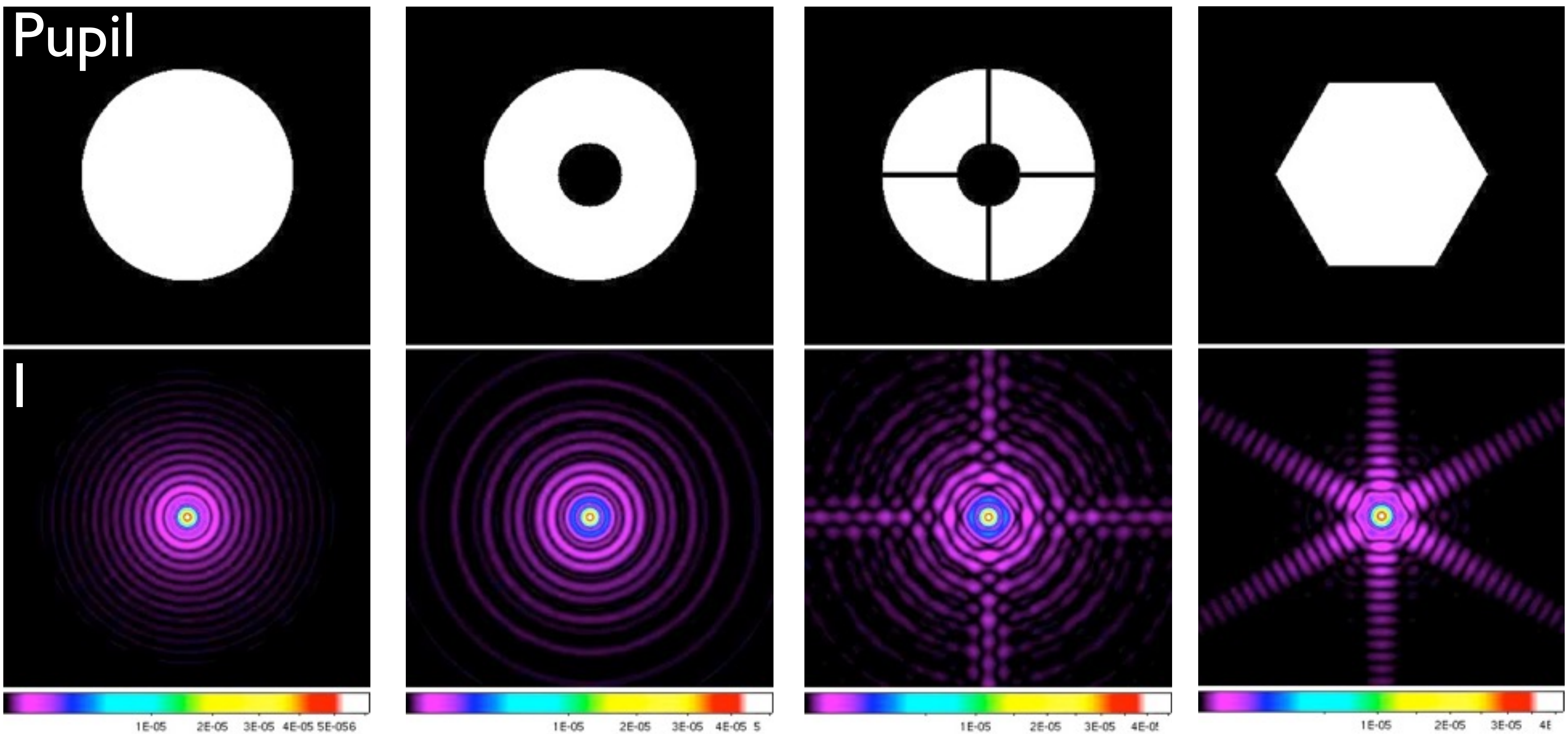
Intensity diffraction pattern:

$$I(\overline{\Omega}) = \left|a(\overline{\Omega})\right|^2$$

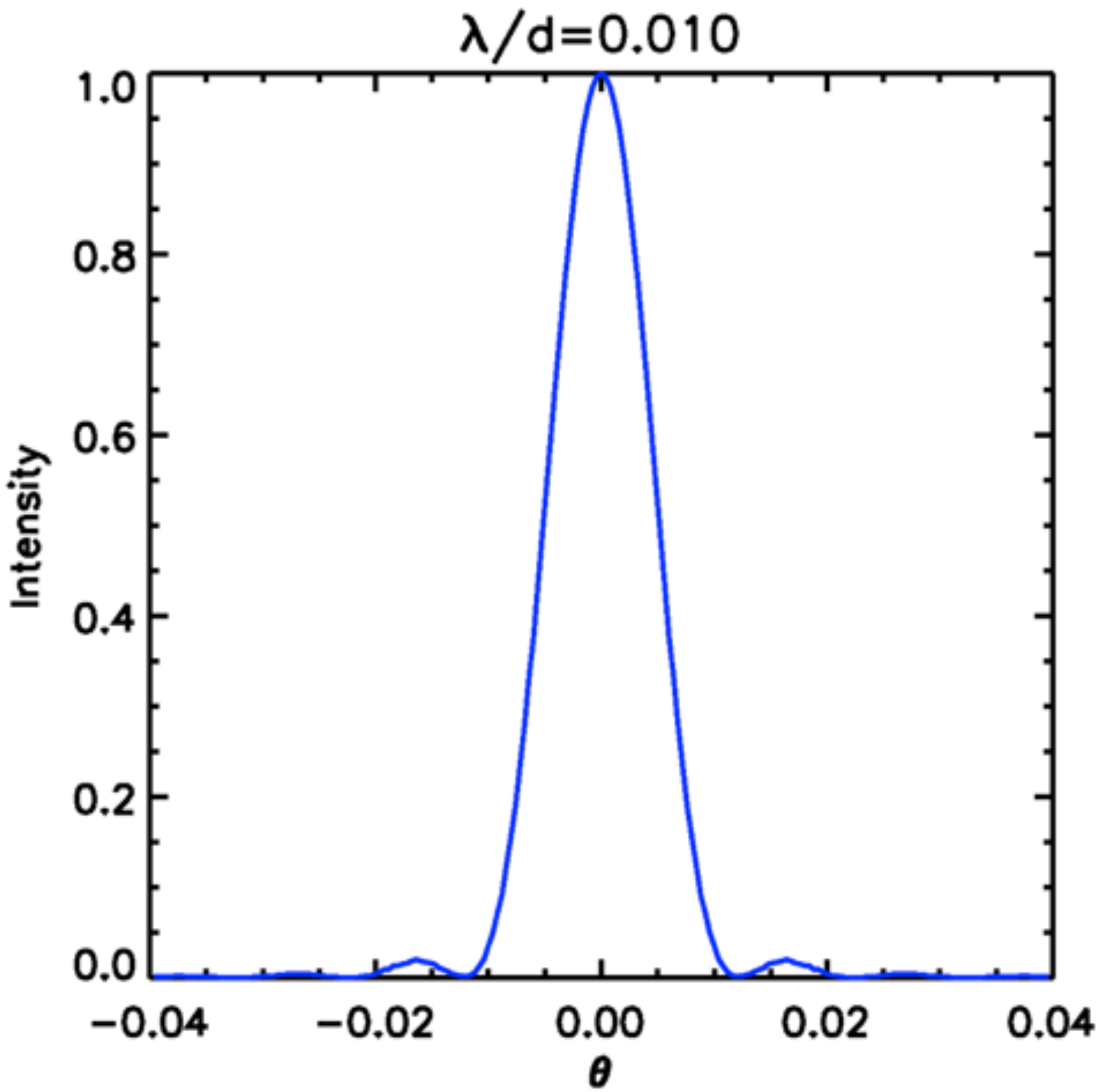
$$= a(\overline{\Omega})a^\star(\overline{\Omega})$$

Diffraction patterns of different apertures

Circular aperture	Hole in the middle	Secondary mirror support	Hexagonal mirror



The Rayleigh criterion



Diffraction pattern for circular aperture.

Minima at

$$\theta = 1.22\frac{\lambda}{d},\ 2.33\frac{\lambda}{d},\ 3.24\frac{\lambda}{d},\cdots$$

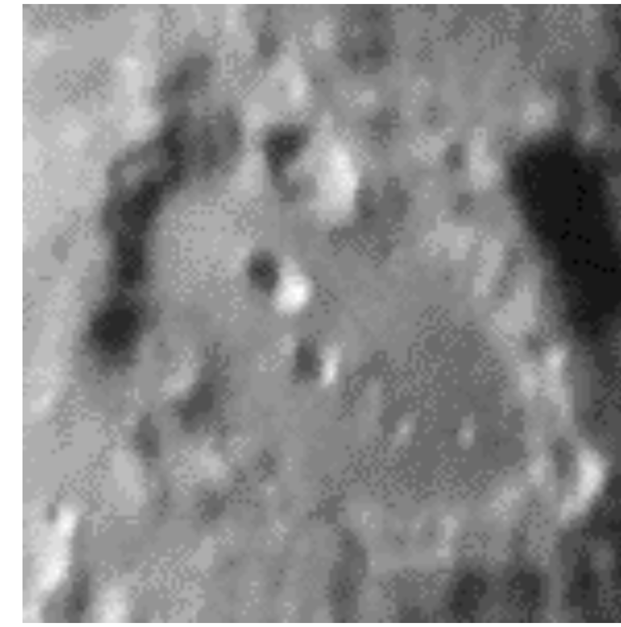
Rayleigh criterium for resolving power of a telescope with diameter *d*:

$$\theta_R = 1.22\frac{\lambda}{d}$$

Rayleigh criterion: examples

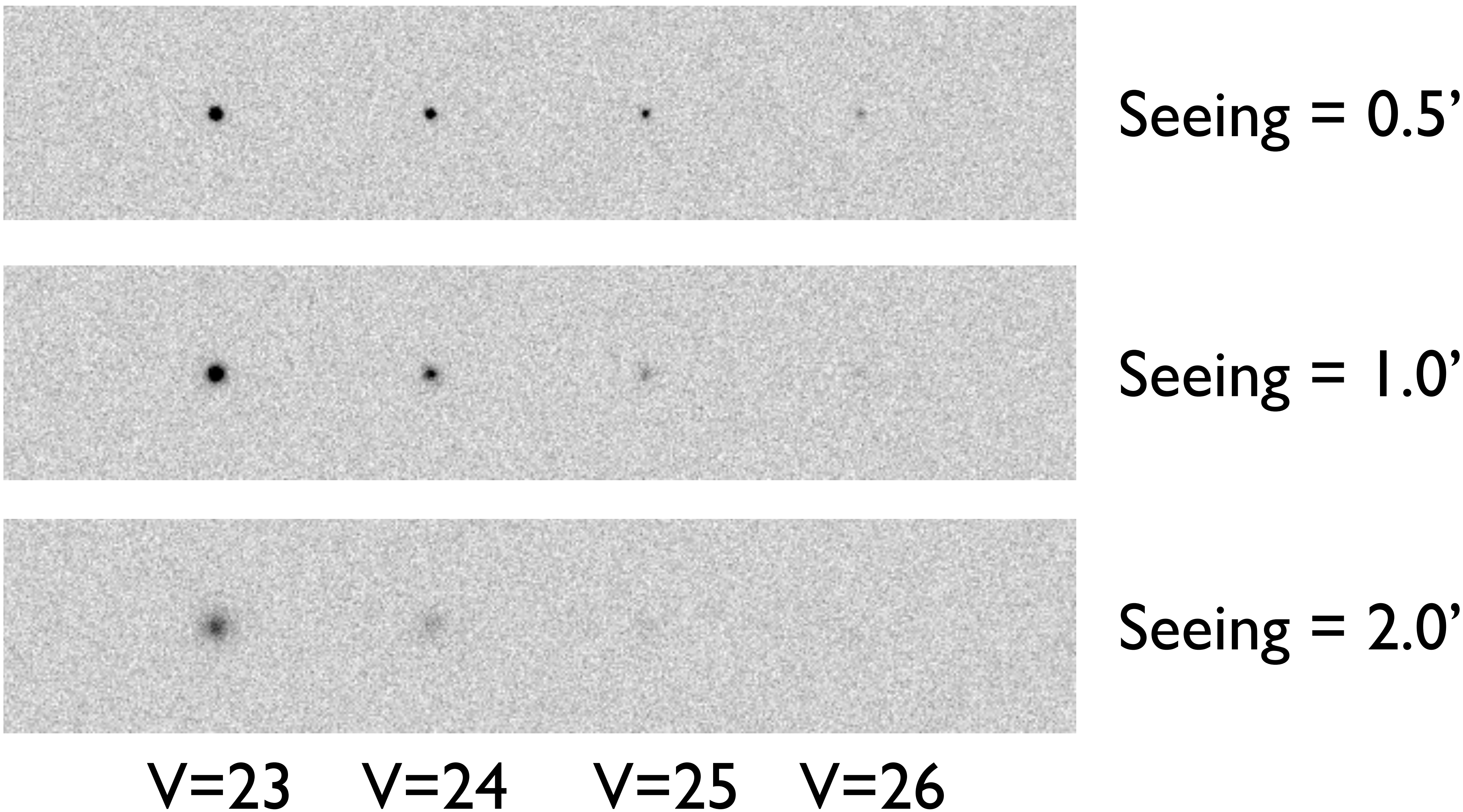
- Human eye: d~6 mm, λ~500 nm → θ_R = 17 arc seconds (in practice: 1-2 arc minutes)
- 20 cm telescope, visible light: θ_R = 0.5 arc seconds
- In practice: resolution limited to ~1 arc second because of atmospheric turbulence.
- Hubble Space Telescope, UV (d=240 cm, λ~200 nm) → θ_R = 0.02 arc seconds
- 100 m radio telescope, λ=21 cm → θ_R = 7 arc minutes

Seeing



- Turbulence in the atmosphere degrades the image quality - best achievable resolution is typically 0.5” - 1.0”
- It can be (partially) corrected with *Adaptive Optics*
- The best “seeing” conditions are found where atmospheric turbulence is minimal. For example on mountain peaks near the ocean (Chile, California, Hawaii, Canary Islands).

Simulated 1000 s V-filter exposures with an 8 m telescope



Seeing and exposure time

$$S/N = \frac{N_{\rm star}}{\sqrt{N_{\rm star} + N_{\rm sky} + \sigma^2_{\rm instr}}}$$

Poisson statistics!

If noise dominated by sky (almost always true for faint sources):

Signal: $S \propto N_{\rm star} \propto t_{\rm exp} F_{\rm star}$

Noise: $N \propto \sqrt{N_{\rm sky}} \propto \sqrt{t_{\rm exp} I_{\rm sky} {\rm FWHM}^2}$

$$S/N \propto \frac{t_{\rm exp} F_{\rm star}}{\sqrt{t_{\rm exp} I_{\rm sky} {\rm FWHM}^2}} \propto \left(\frac{F_{\rm star}}{\sqrt{I_{\rm sky}}}\right)\left(\frac{\sqrt{t_{\rm exp}}}{\rm FWHM}\right)$$

For a given source, sky background, and S/N,

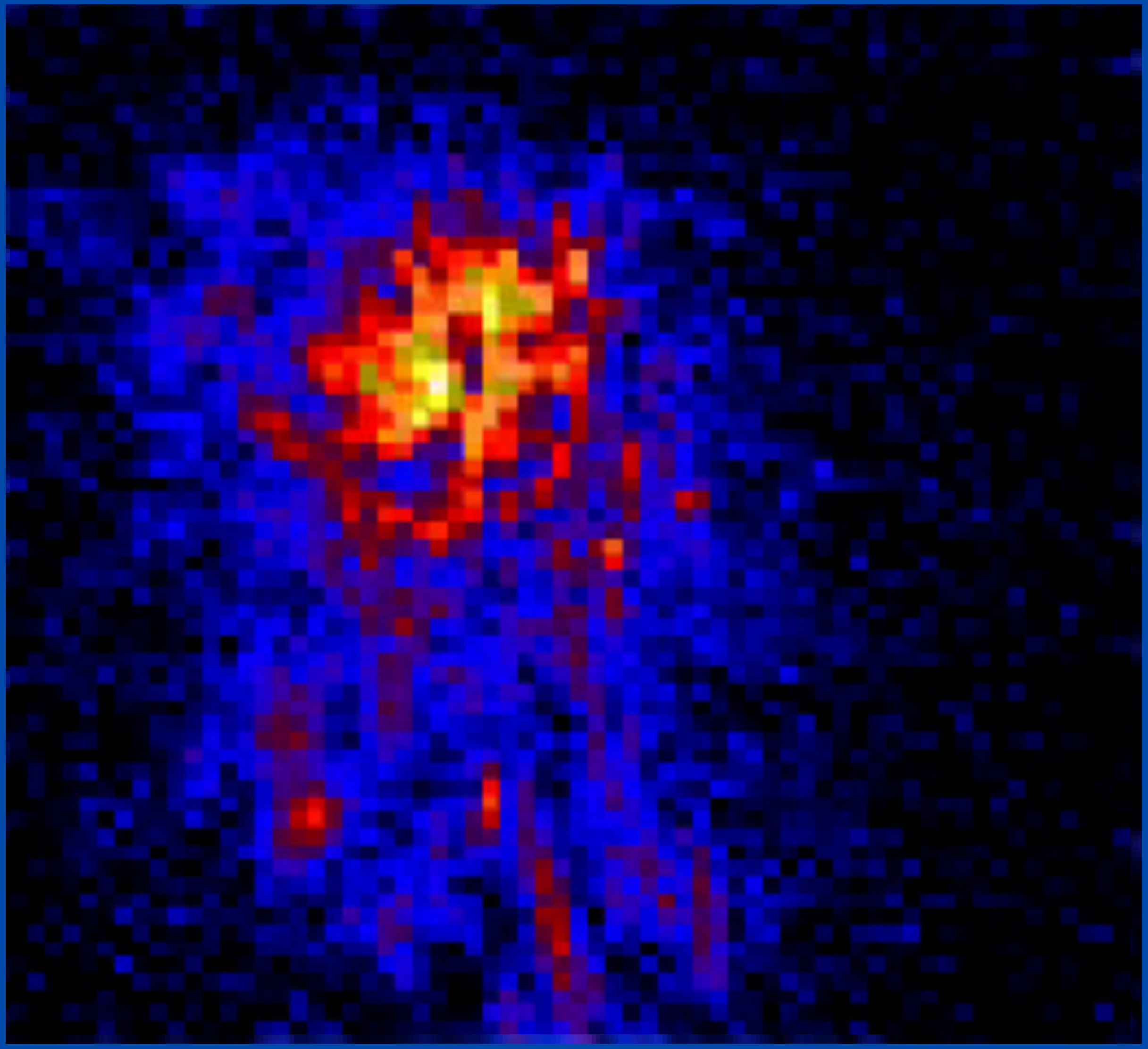
$$t_{\rm exp} \propto {\rm FWHM}^2$$

This is why it is worthwhile to select locations carefully!

Credit: Claire E. Max, UCSC

Turbulence changes rapidly with time

Image is spread out into speckles



Centroid jumps around (image motion)

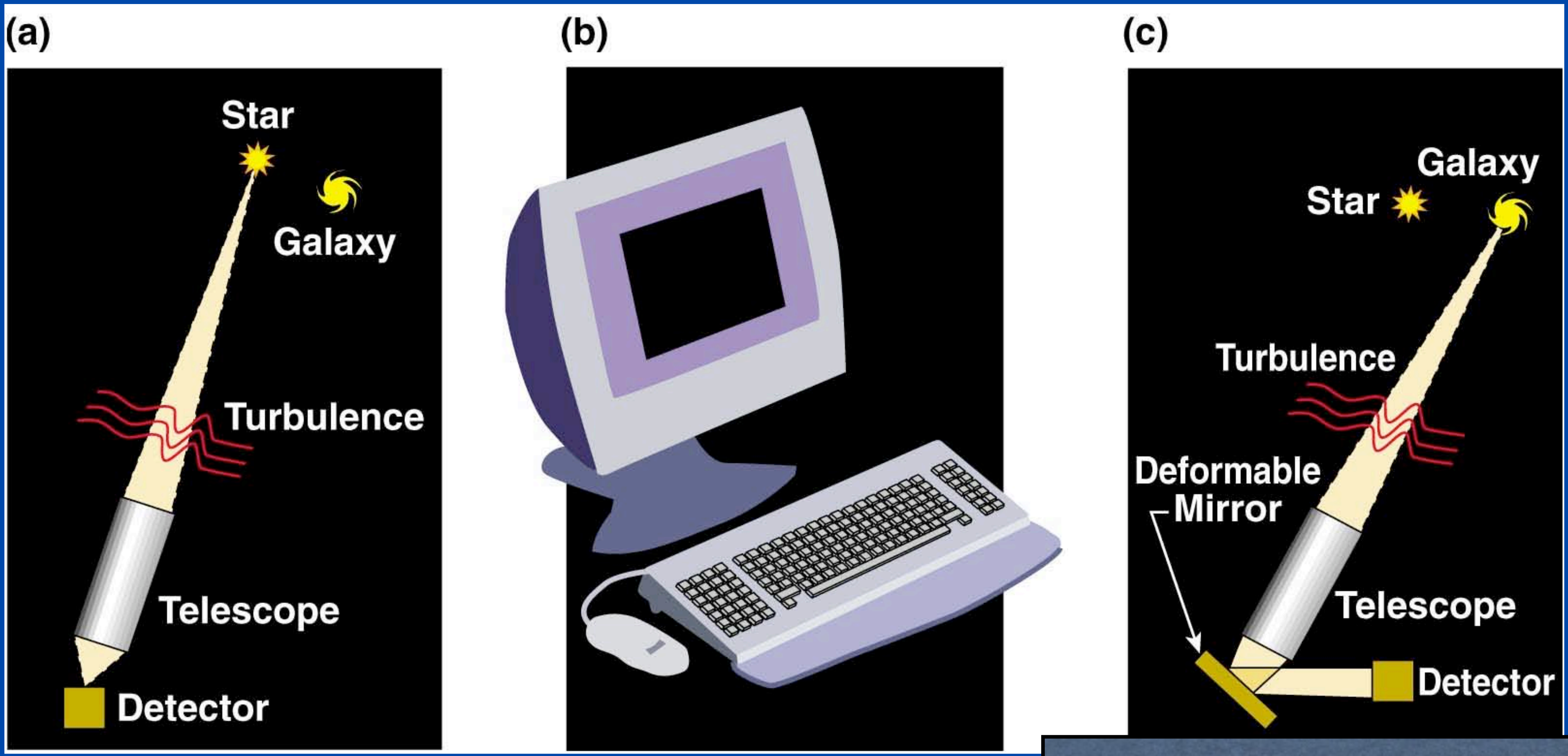
"Speckle images": sequence of short snapshots of a star, taken at Lick Observatory using the IRCAL infra-red camera

How does adaptive optics help? (cartoon approximation)

Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

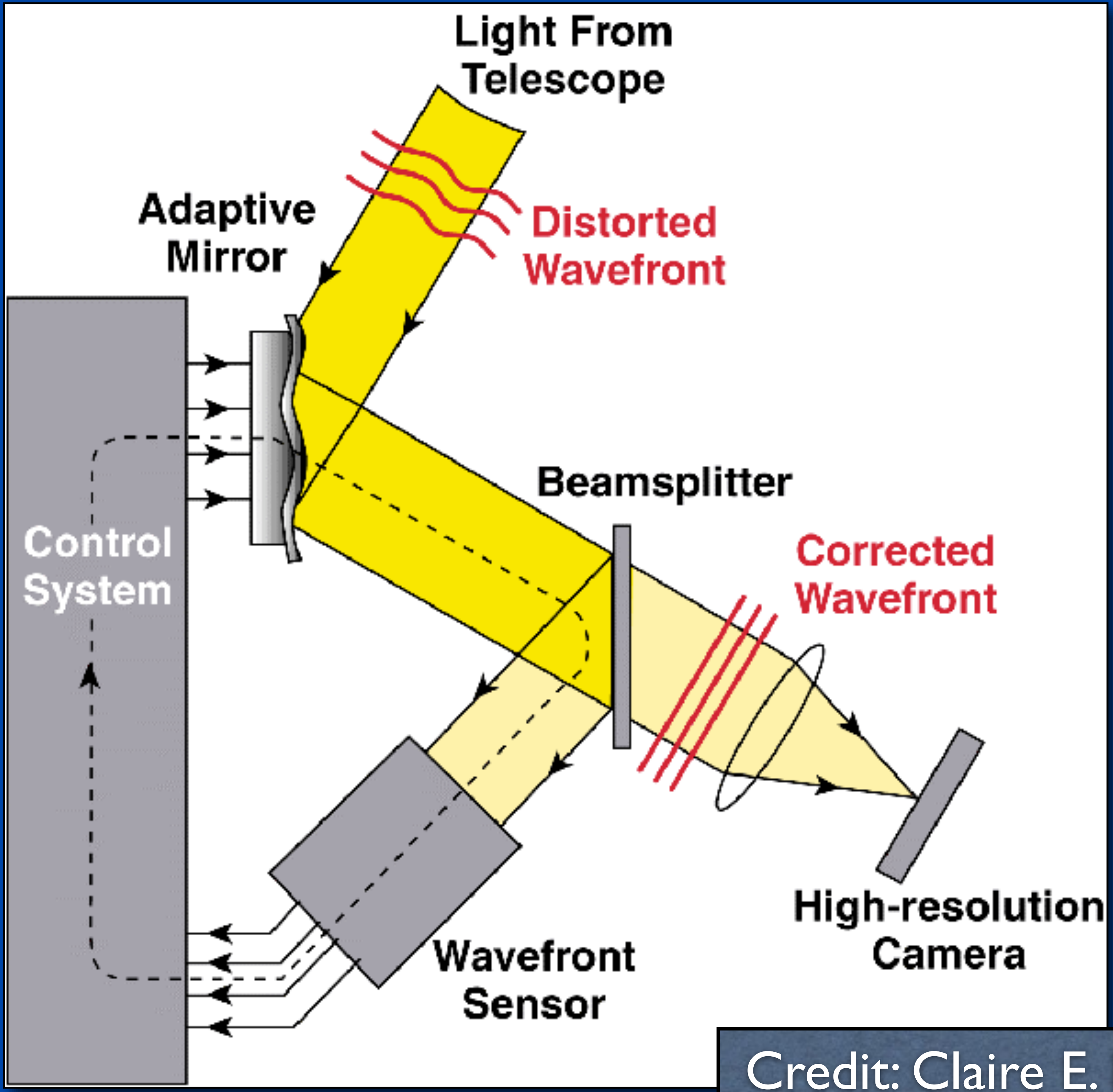
Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



Credit: Claire E. Max, UCSC

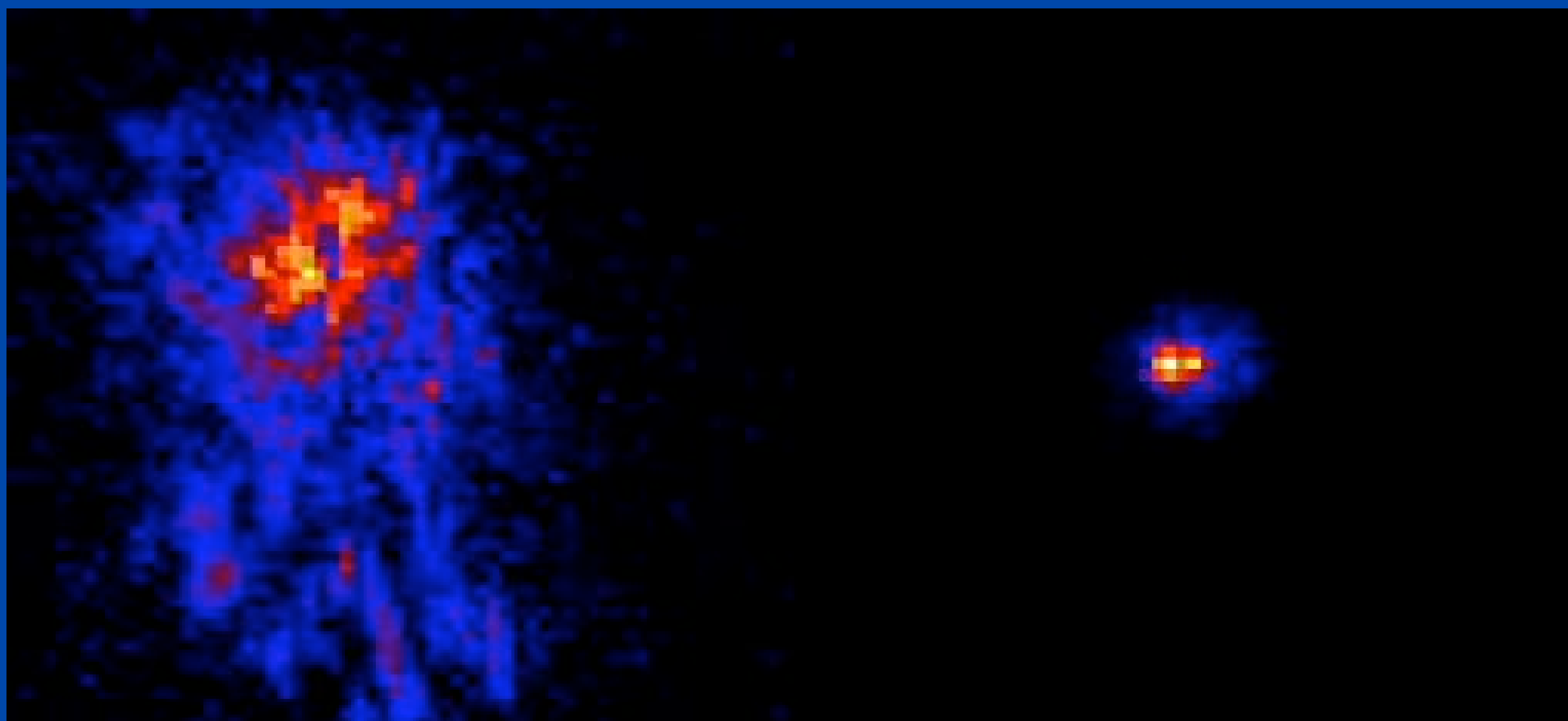
Schematic of adaptive optics system

Feedback loop: next cycle corrects the (small) errors of the last cycle



Credit: Claire E. Max, UCSC

Infra-red images of a star, from Lick Observatory adaptive optics system



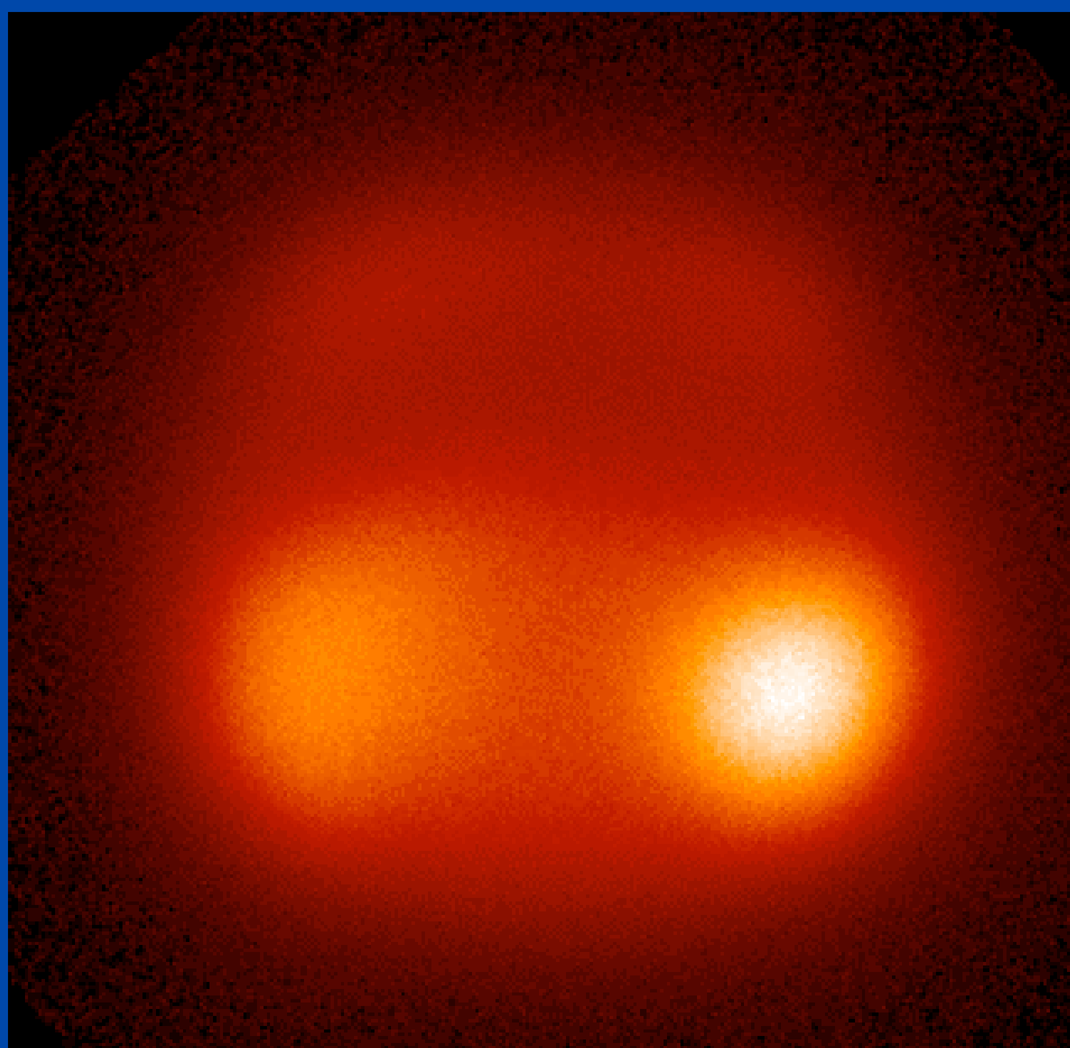
No adaptive optics With adaptive optics

Note: "colors" (blue, red, yellow, white) indicate increasing intensity

Credit: Claire E. Max, UCSC

Neptune in infra-red light (1.65 microns)

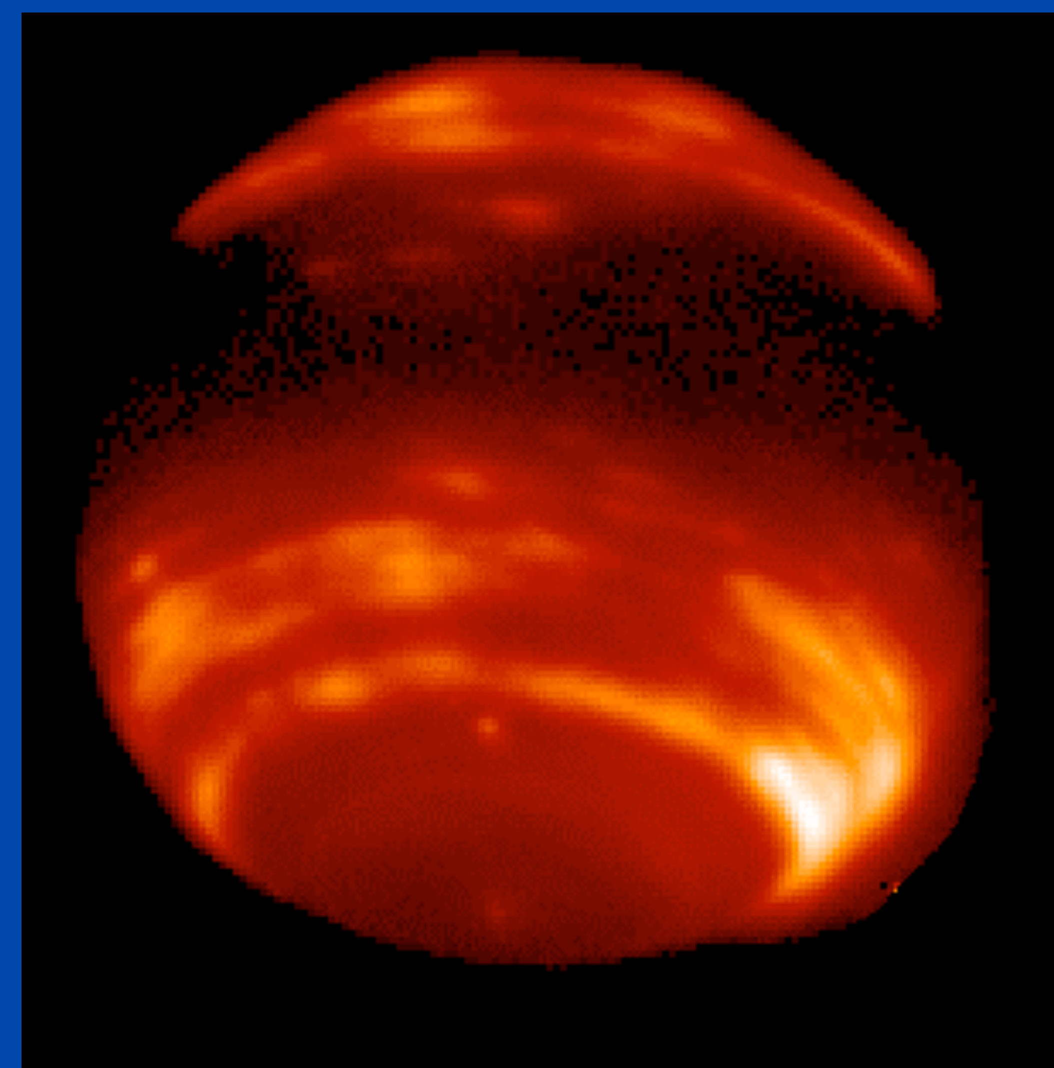
Without adaptive optics



May 24, 1999

2.3 arc sec

With Keck adaptive optics

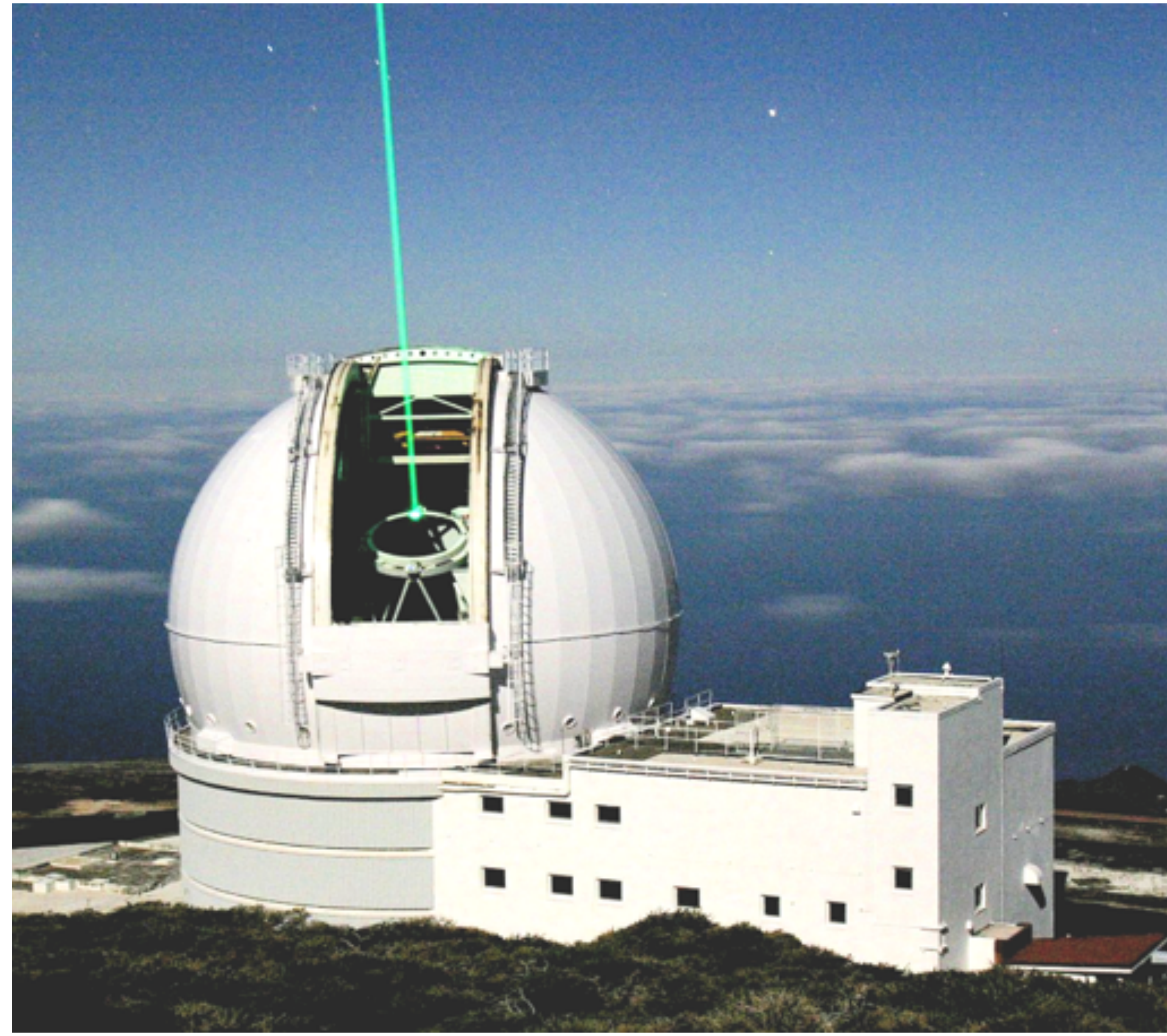


June 27, 1999

Credit: Claire E. Max, UCSC

VLT, Paranal, Chile

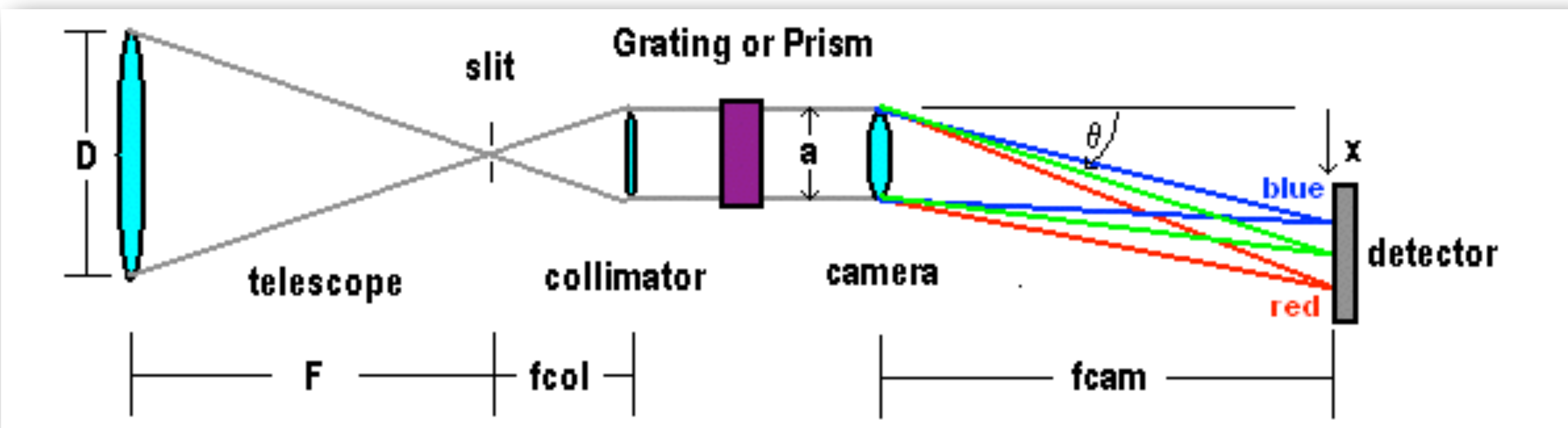
First Light of the VLT Laser Guide Star



William Herschel Telescope,
La Palma

Spectrographs

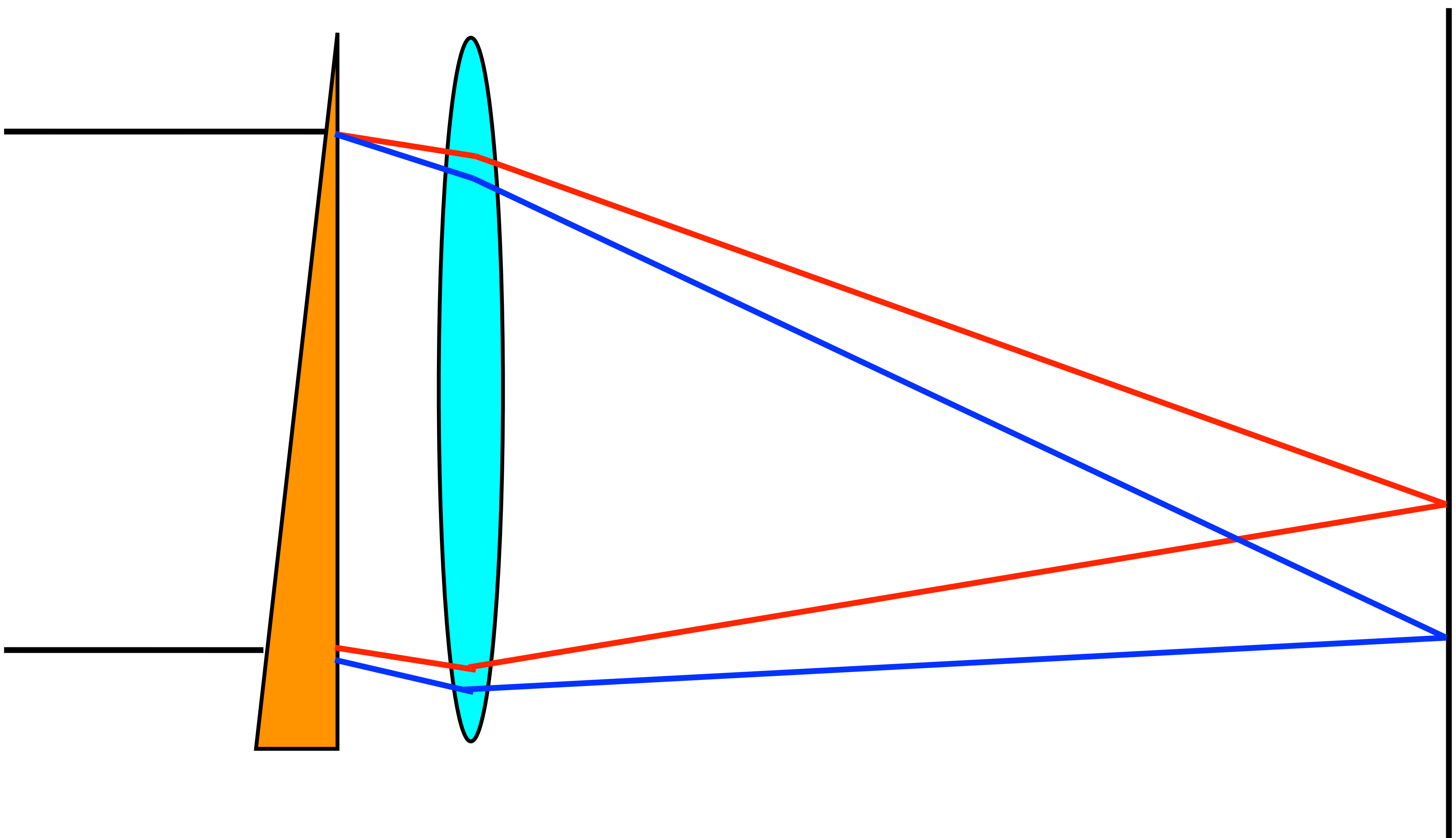
In most spectrographs:
- Light is collected and focussed by a *telescope*.
- The light from the target of interest is isolated by a *slit*
- The converging light beam from the telescope is made parallel again by a *collimator*.
- The parallel beam is dispersed (grating/prism/grism)
- Finally the spectrum is imaged onto a detector by a *camera*.



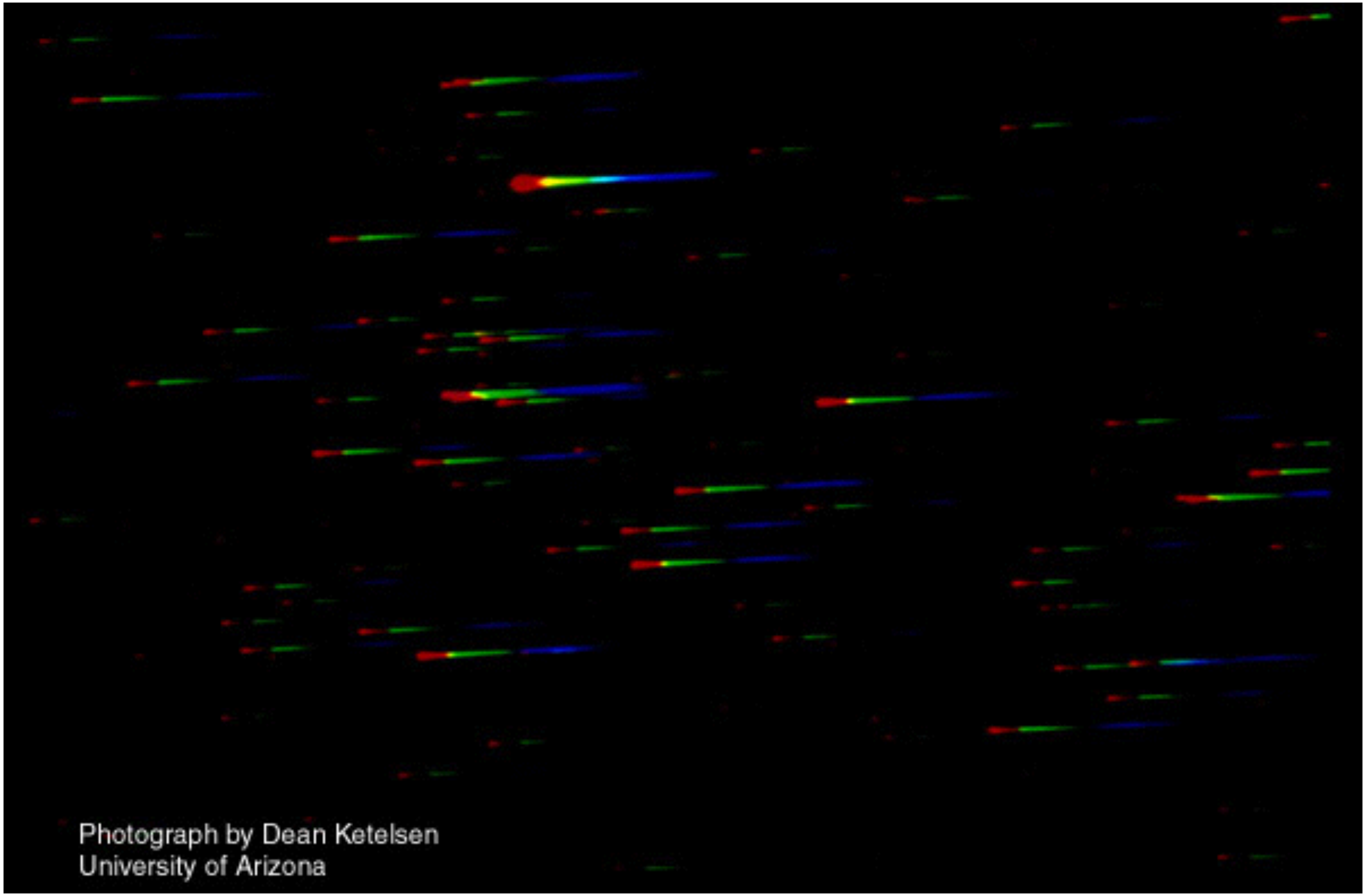
Note: The slit mainly serves to isolate light from the target and is sometimes omitted.

Objective Prisms

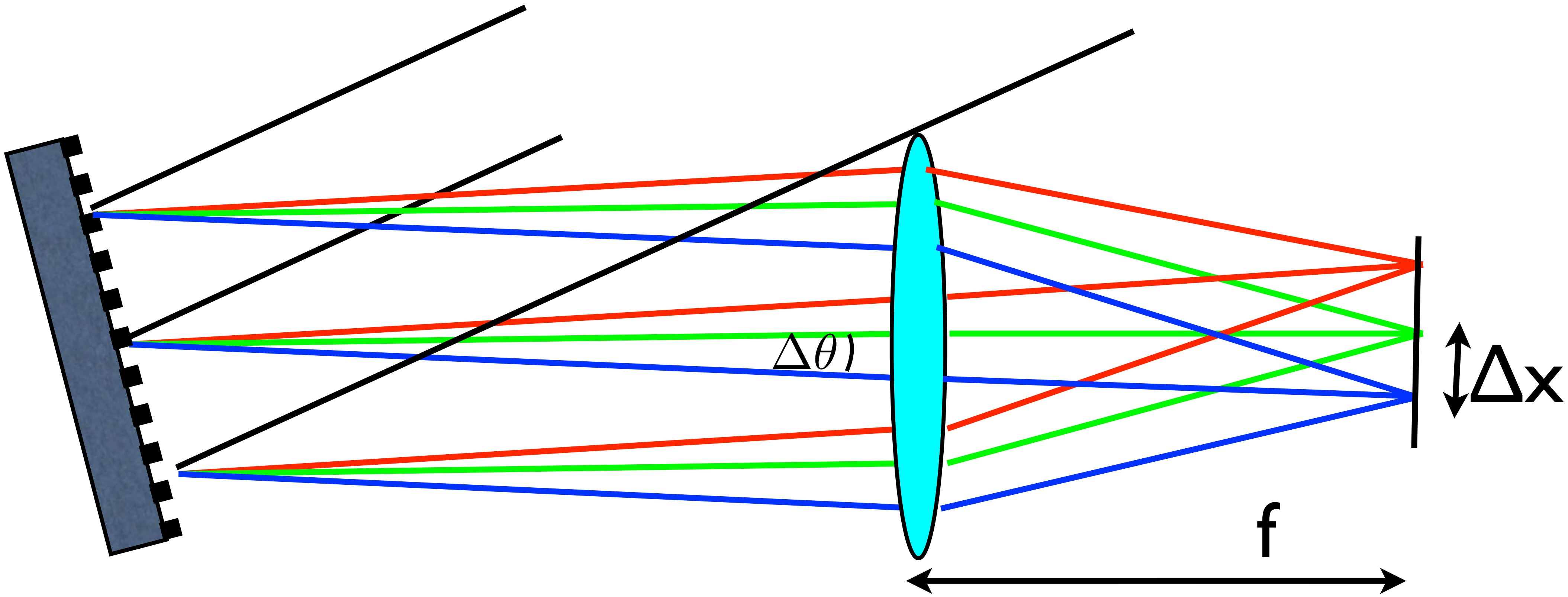
Mounted directly in front of telescope objective. Allows simultaneous recording of large number of spectra.



Objective prism image of Hyades



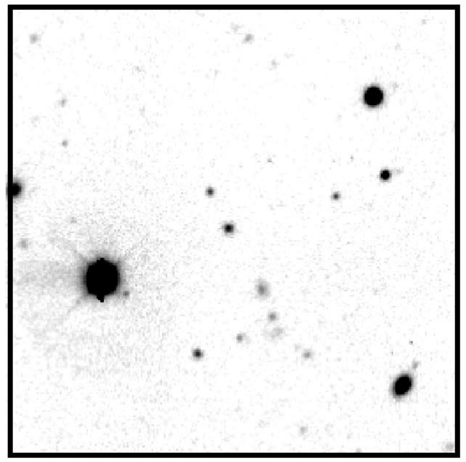
Grating dispersion



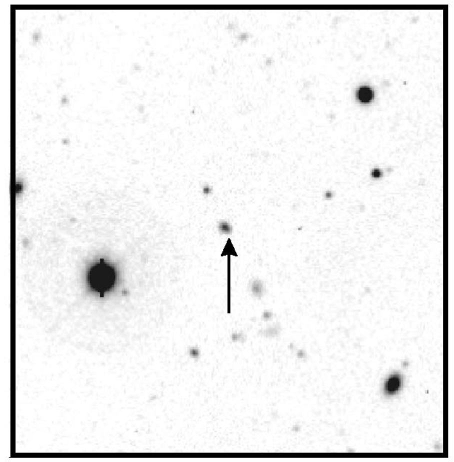
For camera of focal length *f*, grating groove separation *d*, fringe order *m*:

$$\frac{d\lambda}{dx} = \frac{d\cos\theta}{fm} \approx \text{const}$$

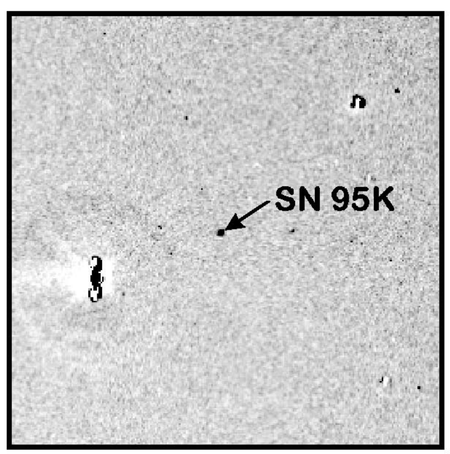
Unlike prisms, gratings provide nearly linear dispersion relations



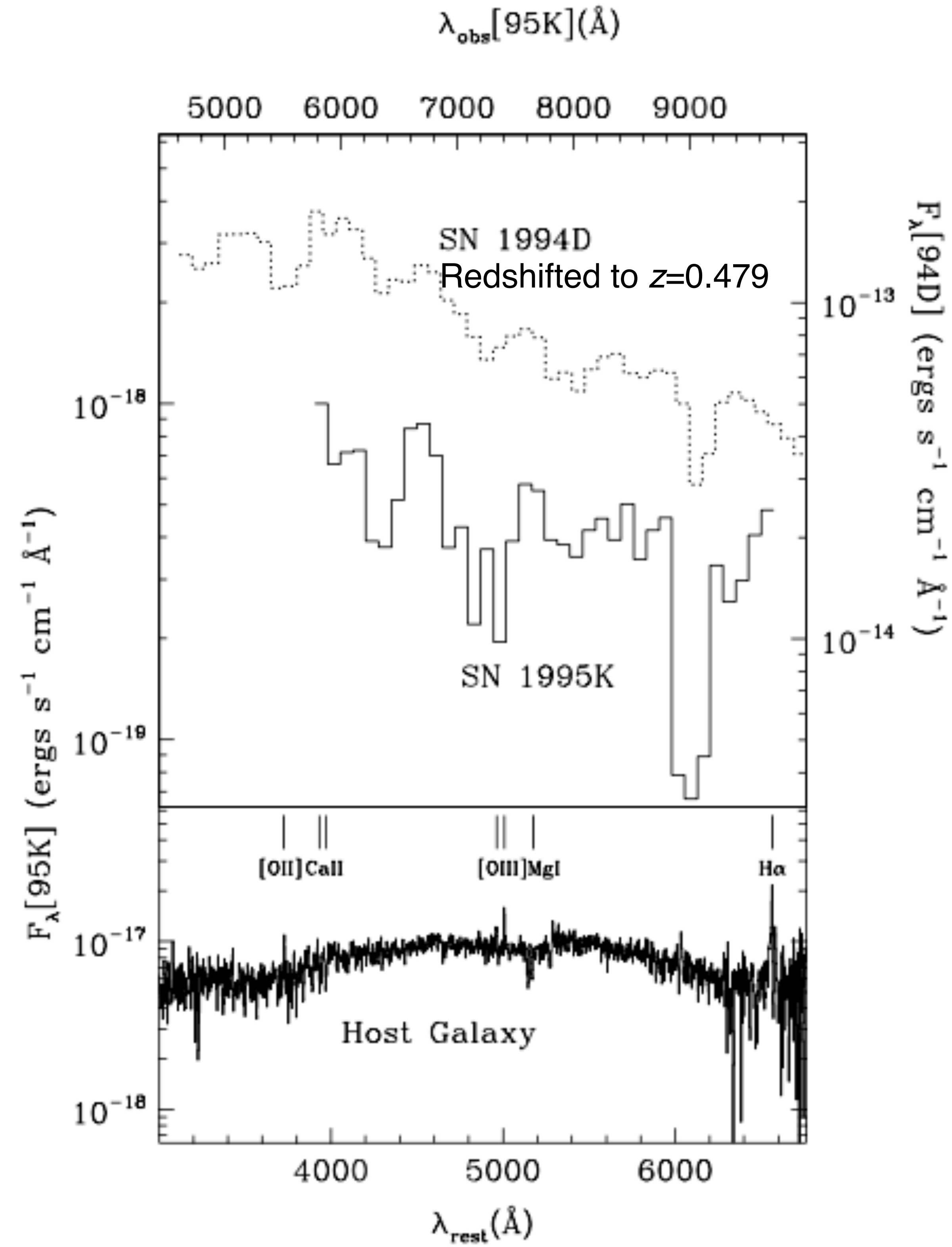
7 Mar

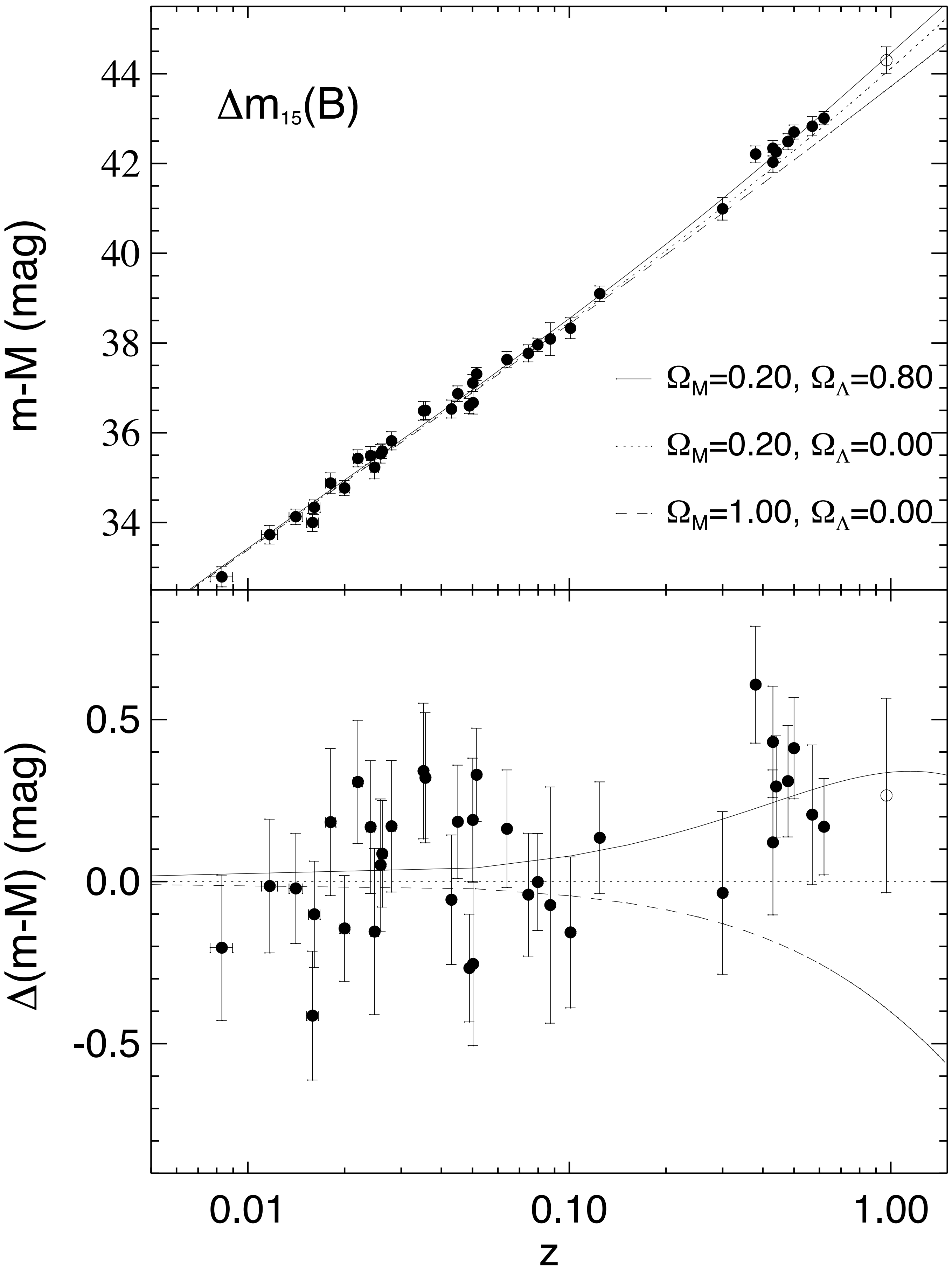


30 Mar



(30 Mar) - (7 Mar)





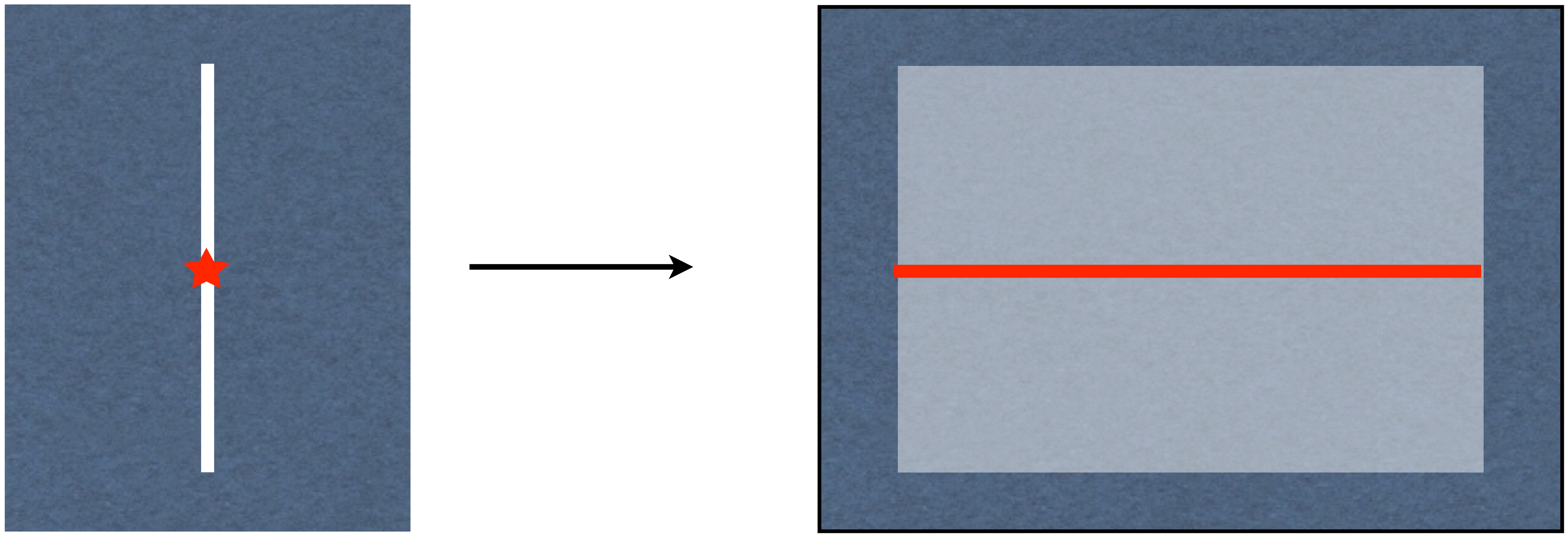
The distant SNe appear fainter than they would in a Universe with Ω_Λ=0.

(In fact, fainter even than for an empty Universe)

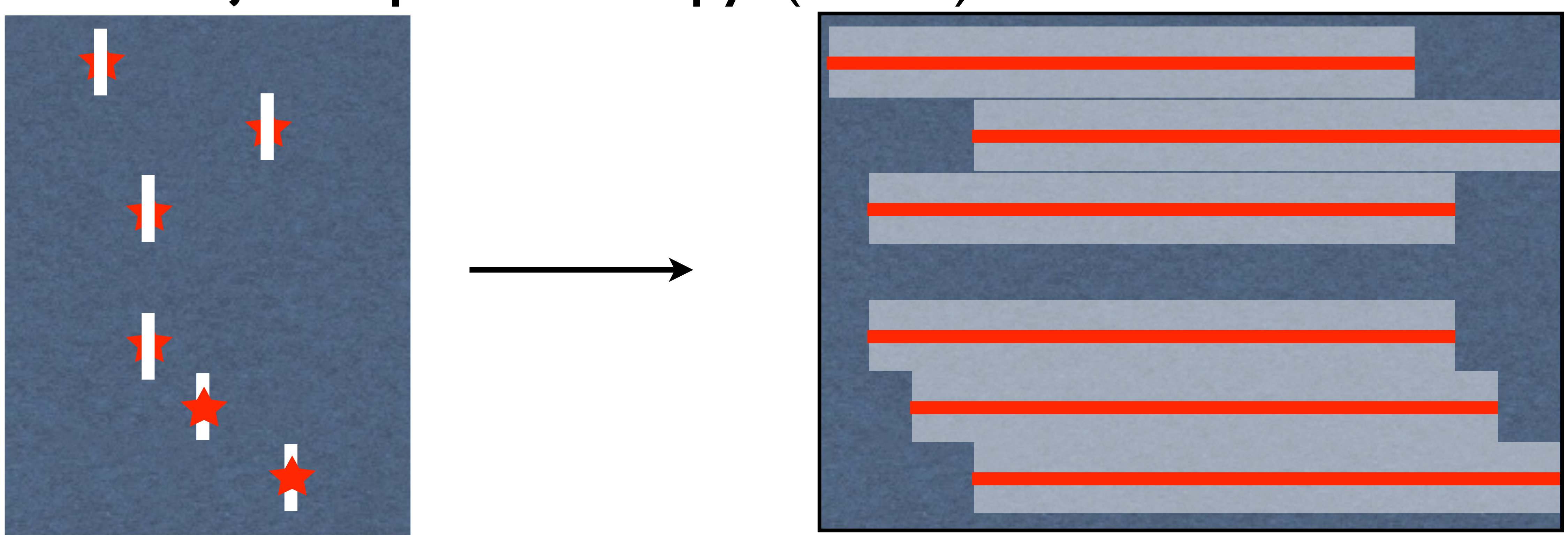
Data can be fit by model in which Universe is flat with Ω_0~0.2 and Ω_Λ~0.8

Riess et al. (1998)

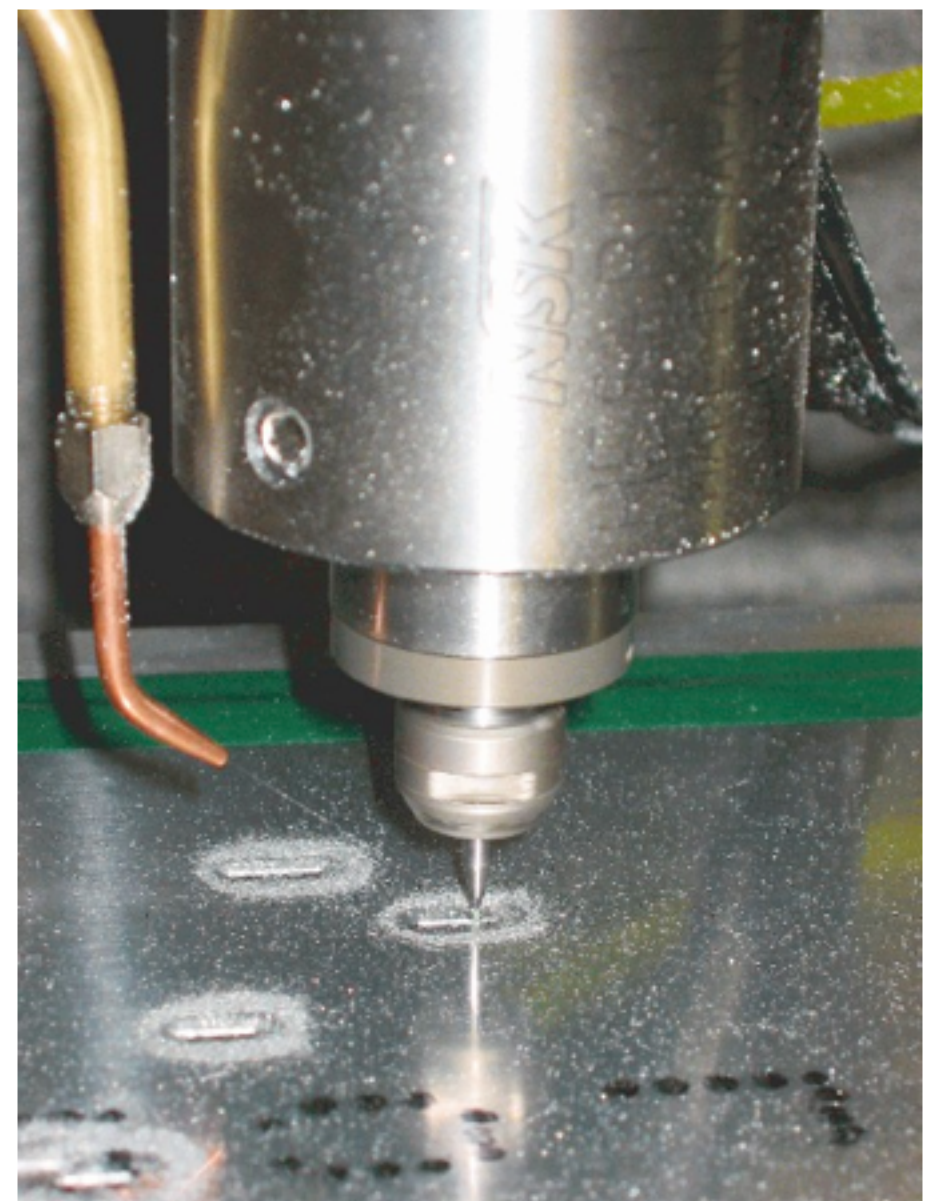
Long-slit spectrum:



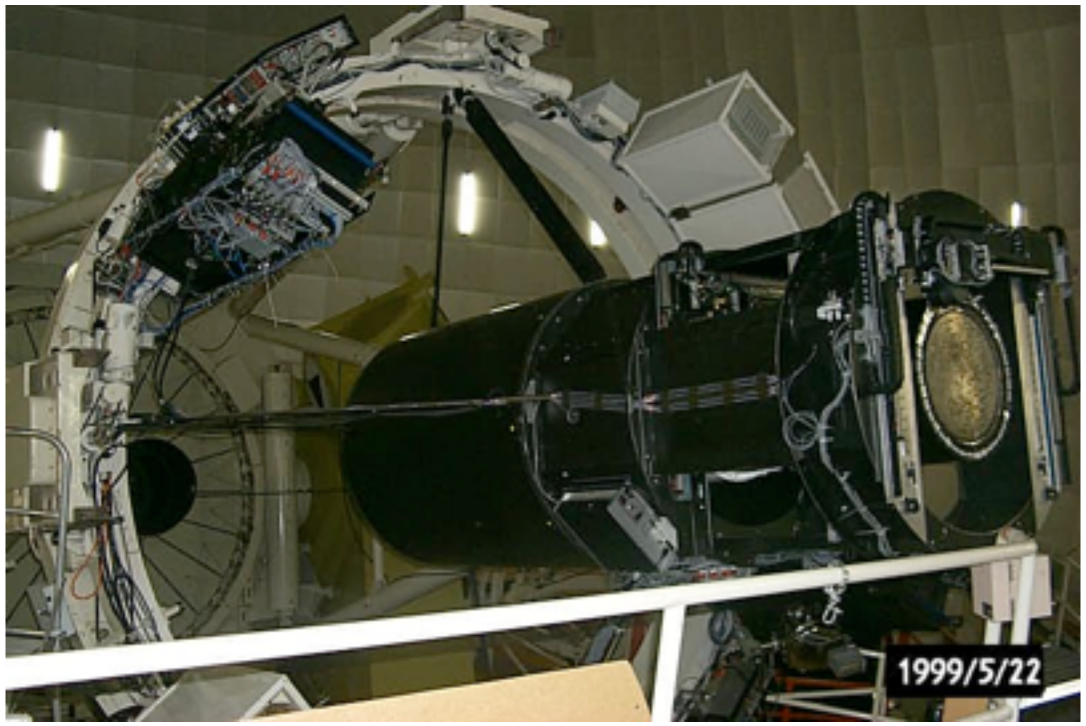
Multi-object spectroscopy (MOS)



Milling of slitmask for Keck/DEIMOS

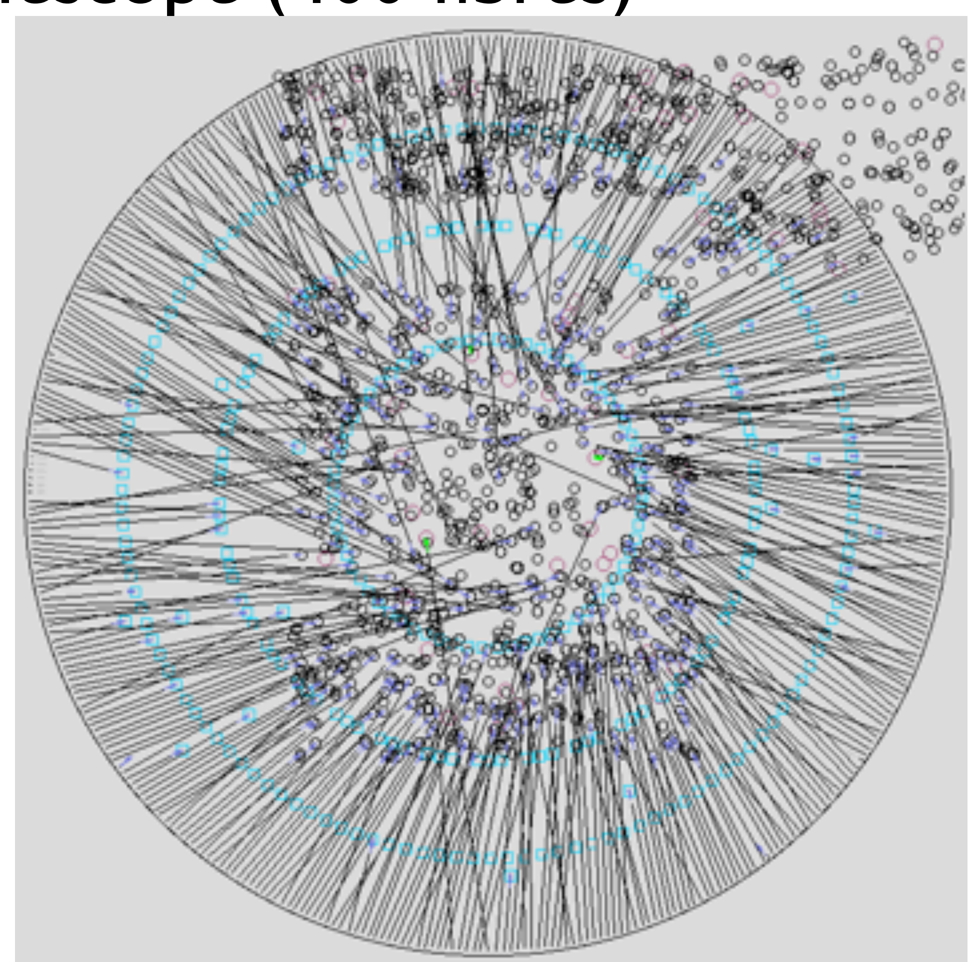


Fibre-fed spectrographs

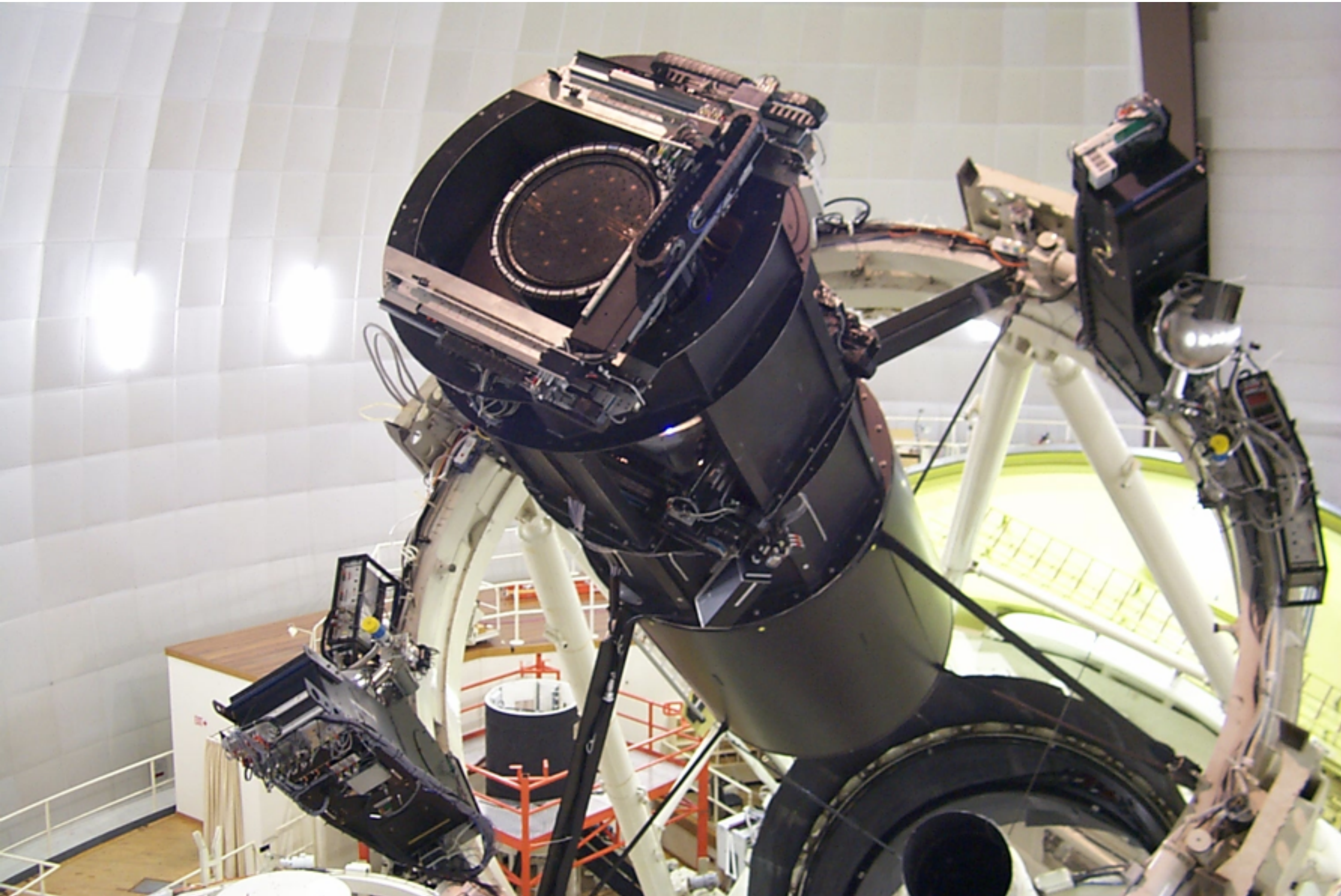


Instead of slits, a spectrograph can also be fed via optical fibres.
These are then bundled and fed into entrance slit of spectrograph

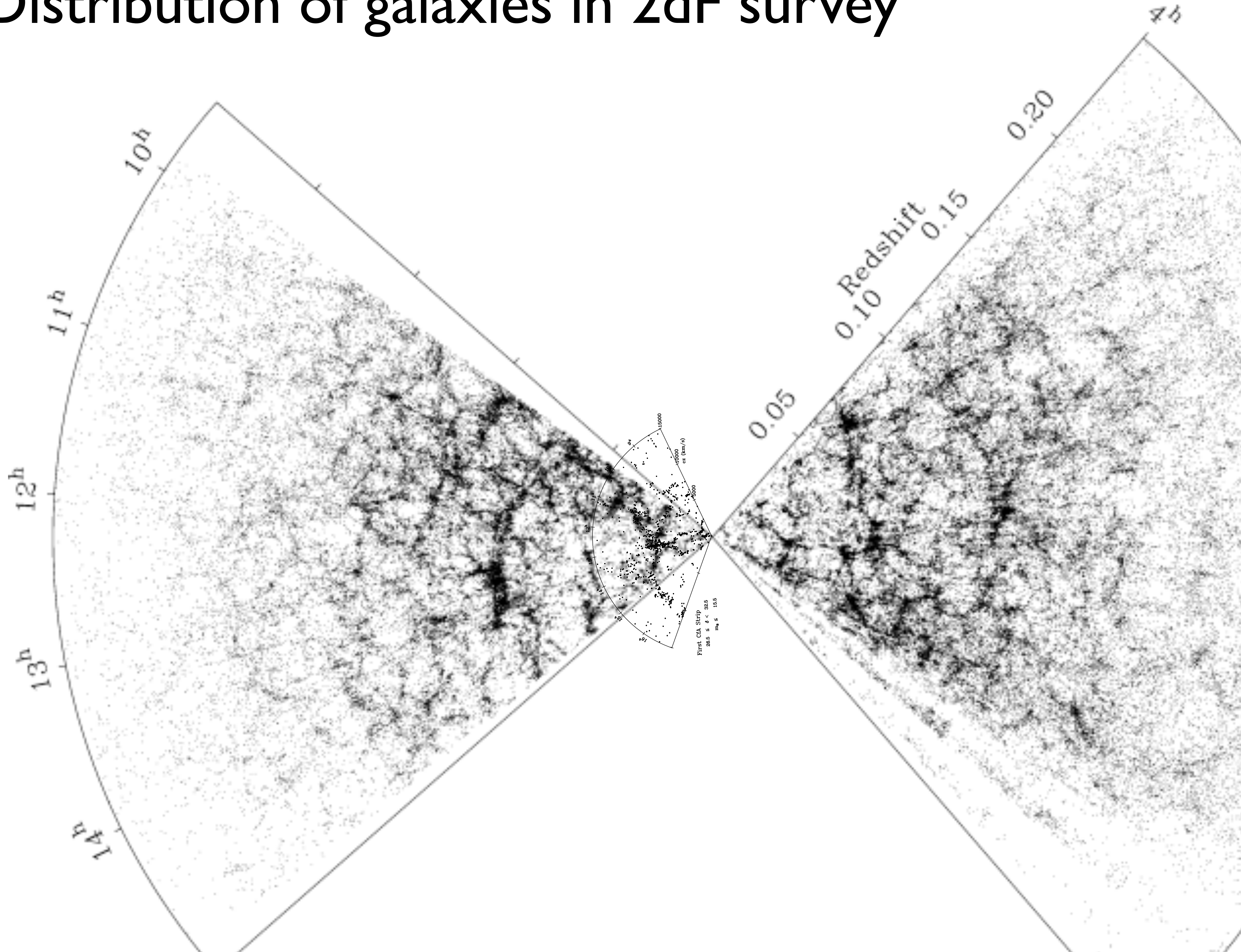
Shown here: 2dF (two-degree field) spectrograph on the Anglo-Australian Telescope (400 fibres)



Anglo-Australian Telescope
Built in 1974 at Siding Spring Observatory
4 m main mirror



Distribution of galaxies in 2dF survey



Large voids with sizes up to $\Delta z \sim 0.01\text{-}0.02$
Physical scales $\Delta r = \Delta cz/H_0 \sim$ 40-80 Mpc

Colless et al. (2001)