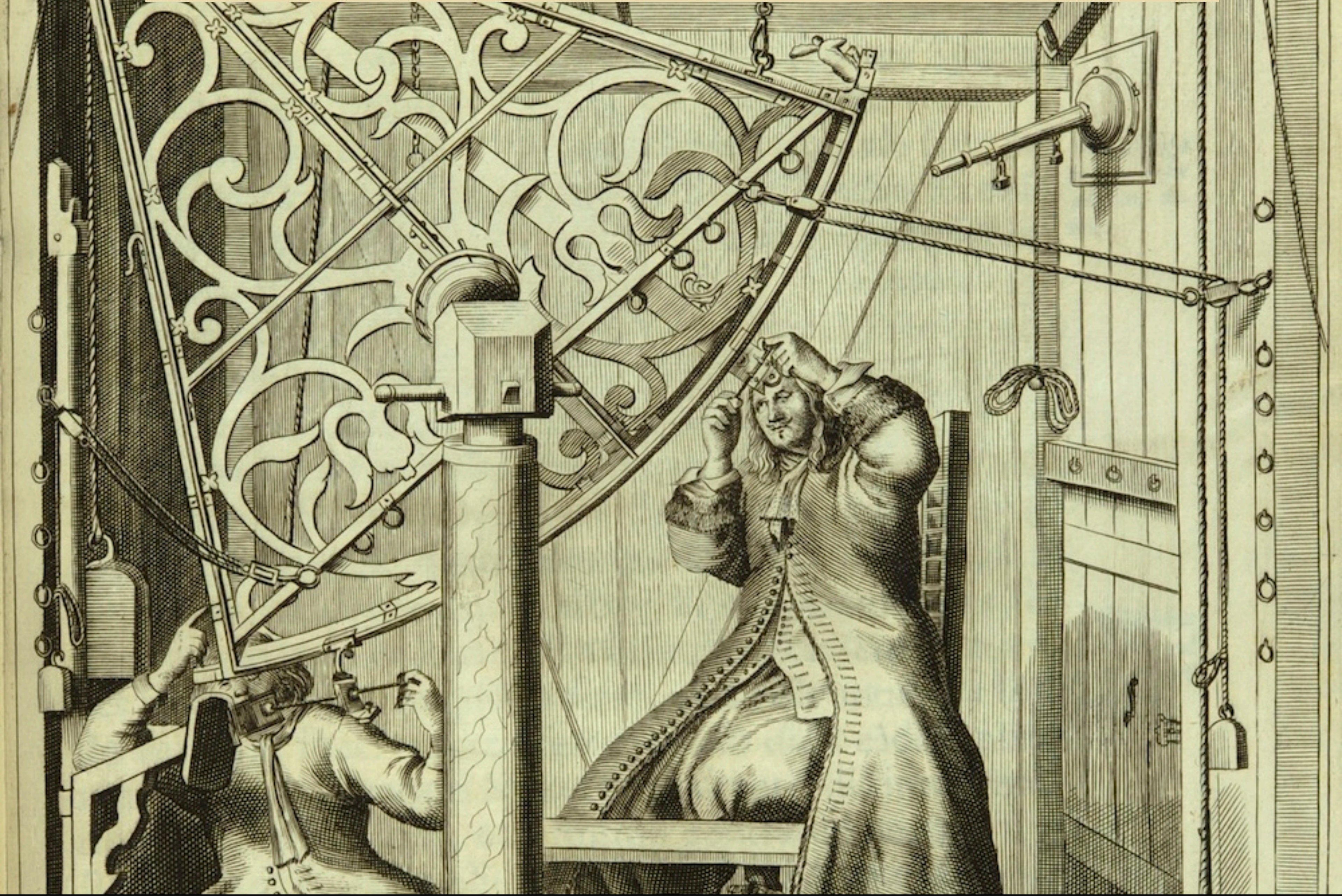
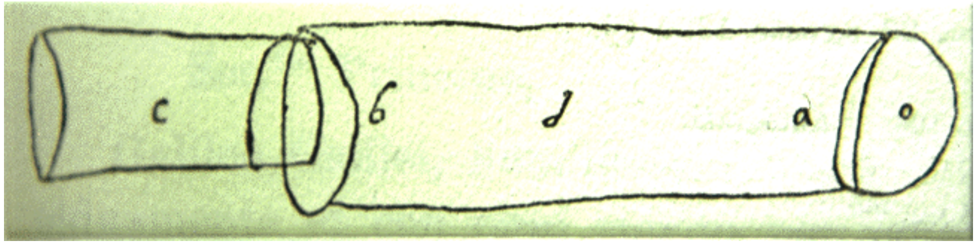
Ay1 – Lecture 3

Telescopes and Detectors

3.1 Optical Telescopes (UV, Visible, IR)

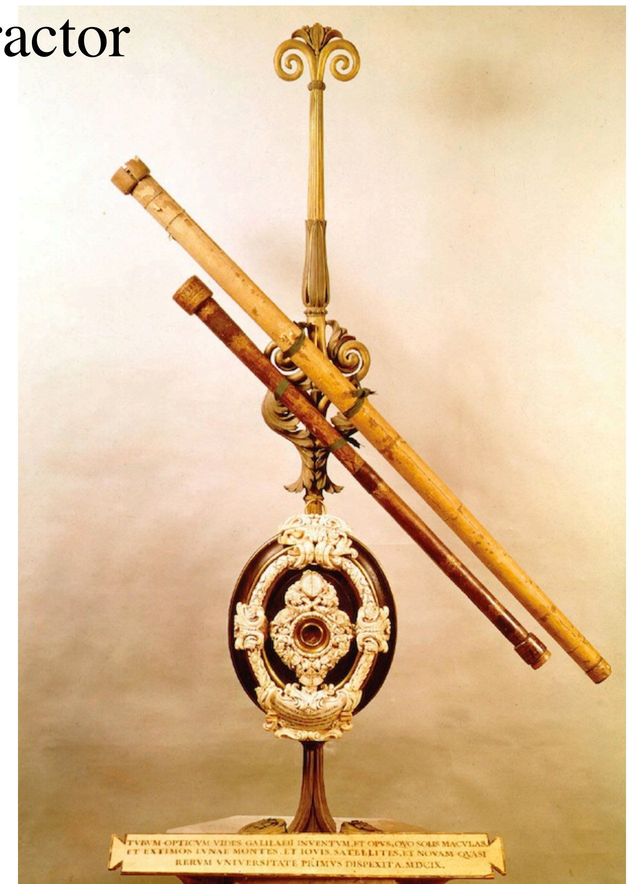


The Earliest Known Drawing of a Telescope



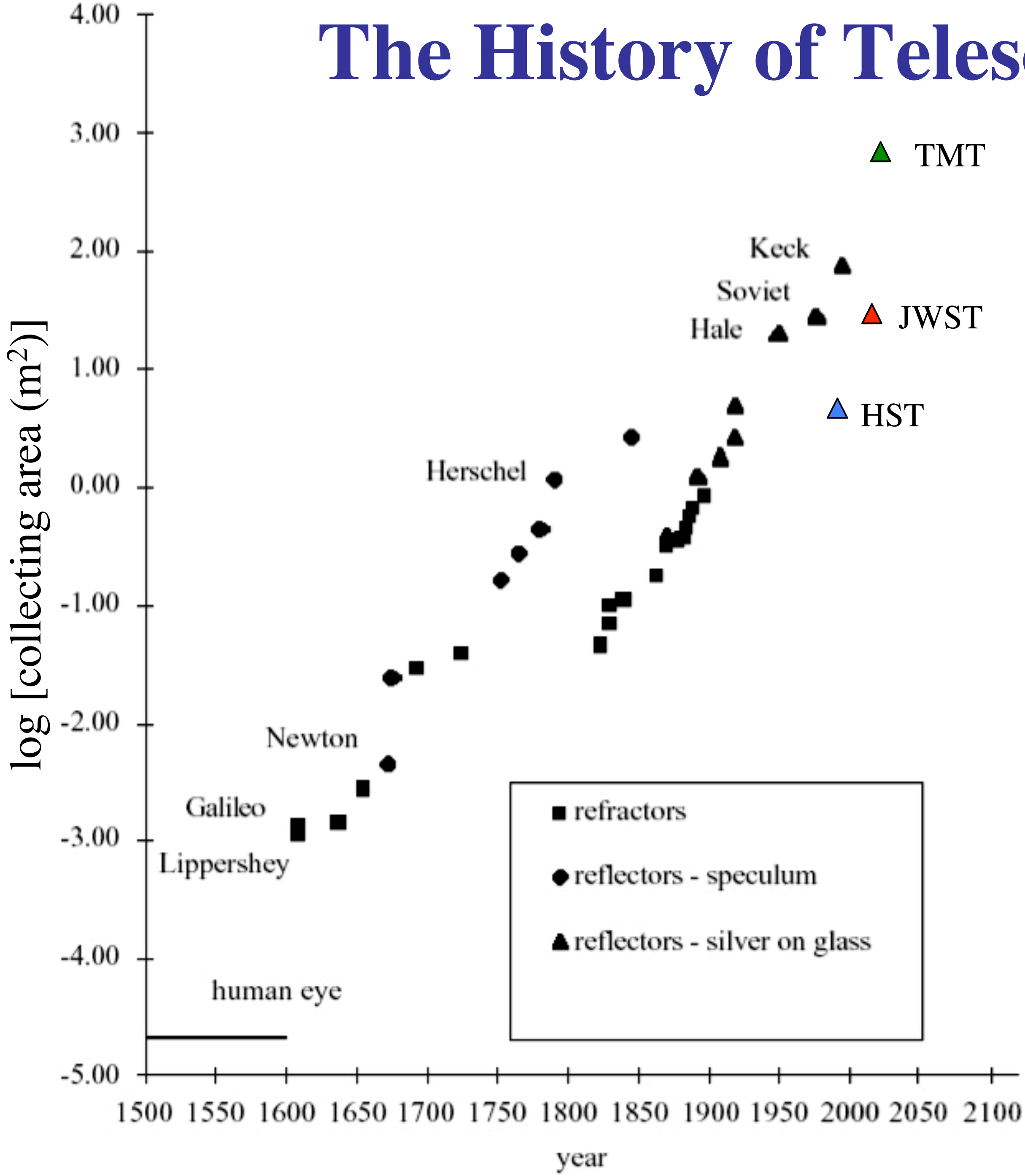
Giovanibattista della Porta included this sketch in a letter written in August 1609

Galileo's telescope (1609), refractor



Newton's telescope (1671), reflector

The History of Telescopes



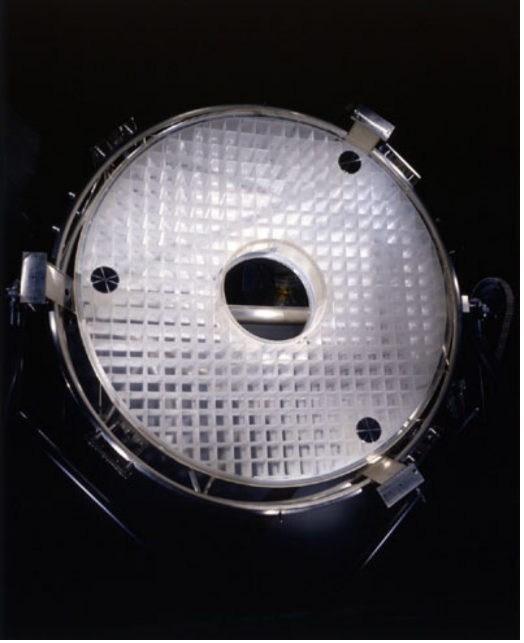
Modern Telescope Mirror Designs

- Lightweight honeycomb structures
- Thin meniscus (+ active optics)
- Segmented (all segments parts of the same conic surface); e.g., the Kecks, TMT
- Multiple (each mirror/segment a separate telescope, sharing the focus); e.g., HET, SALT
- Liquid, spinning

The critical issues:

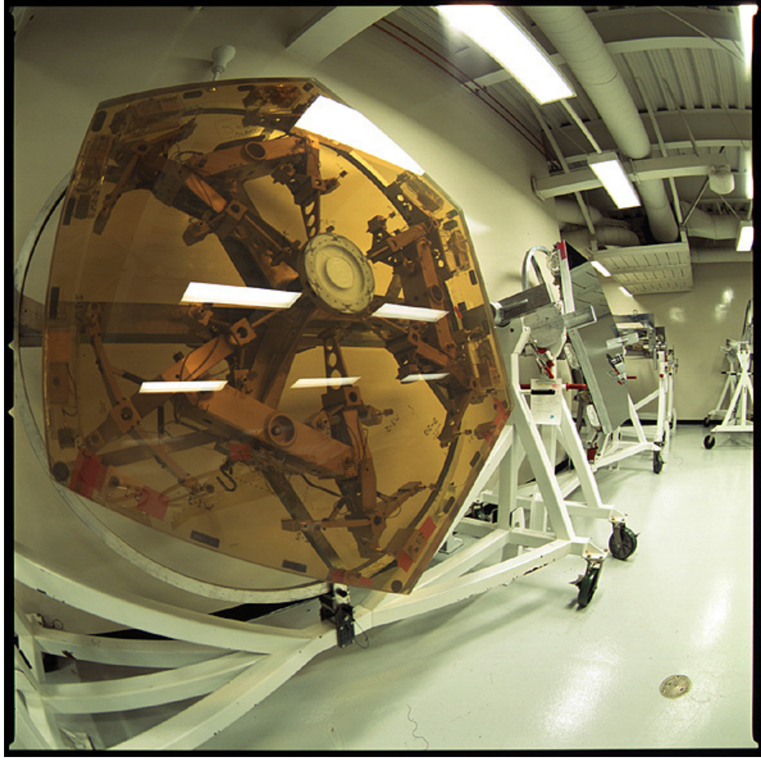
- Surface errors (should be $< \lambda/10$)
- Active figure support (weight, thermal)
- Thermal equilibrium (figure, seeing)

Polishing the 200-inch



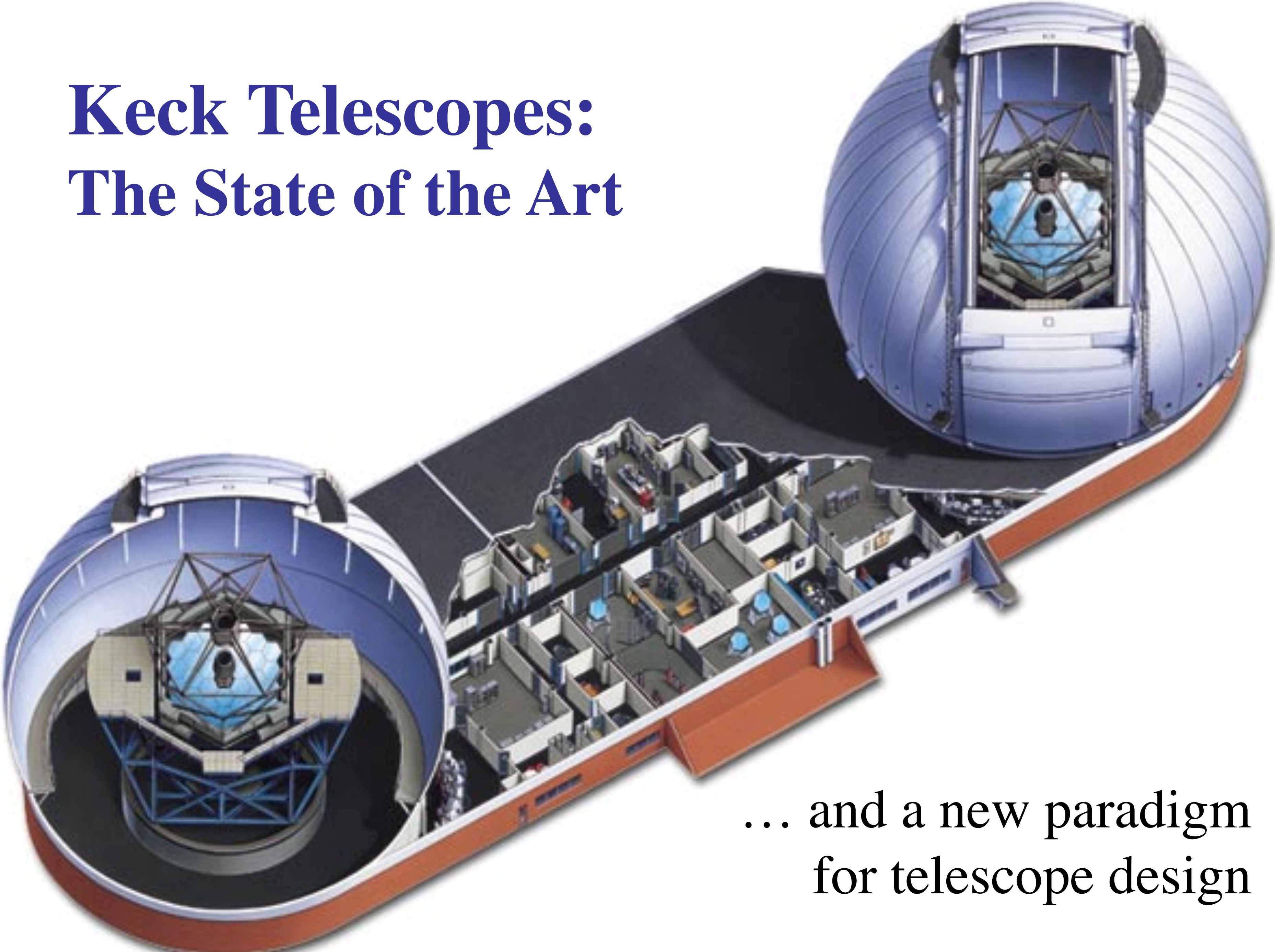
← HST mirror

Keck segment →



← VLT mirror cell

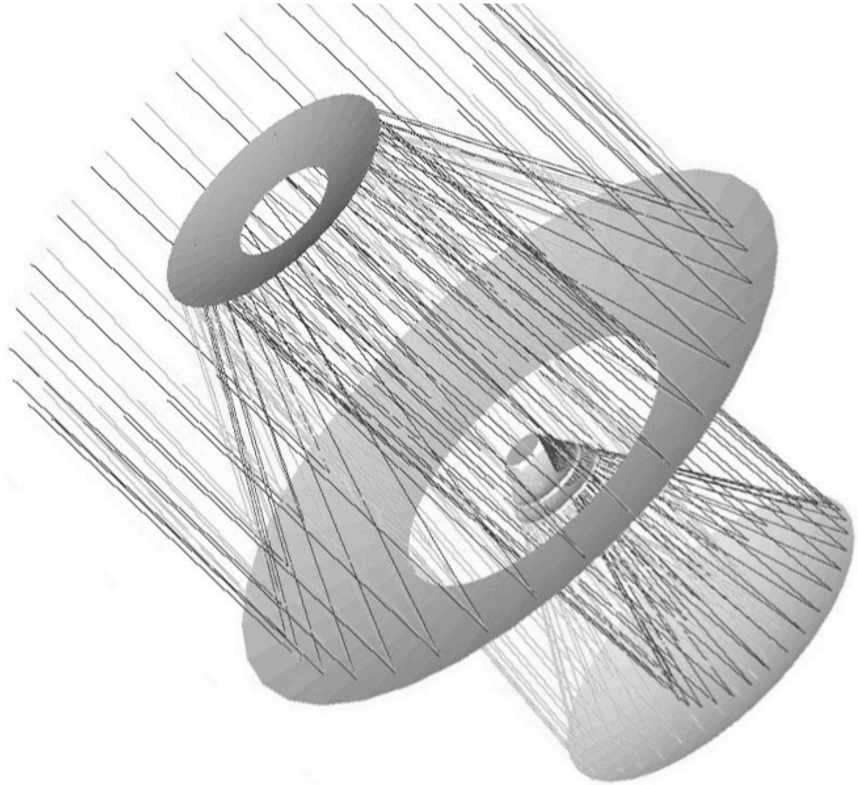
Keck Telescopes: The State of the Art

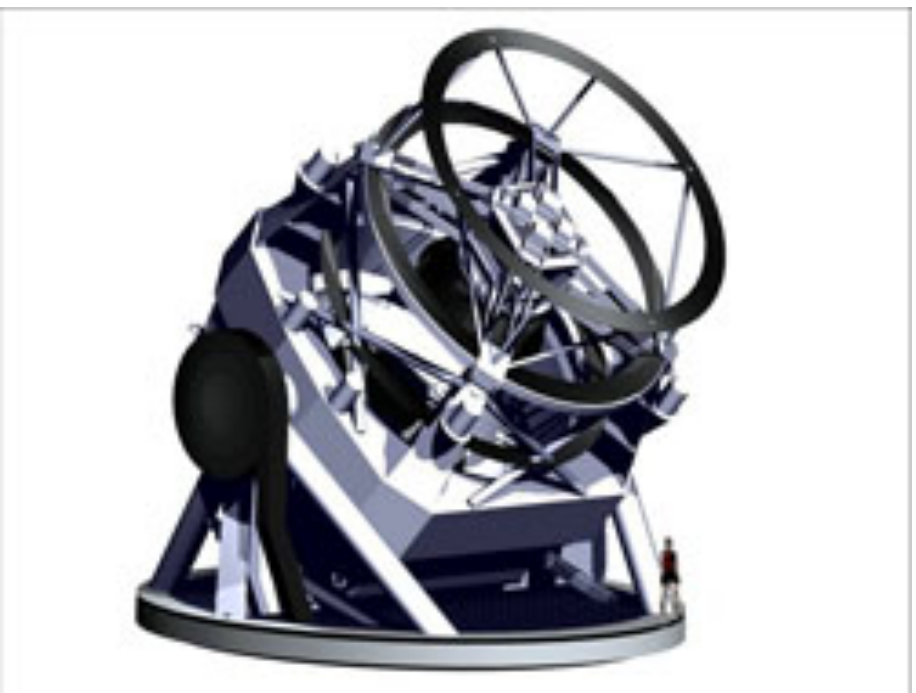


… and a new paradigm for telescope design

The Large Synoptic Survey Telescope (LSST)

- 8.4m primary, 3-mirror modified Paul-Baker design, effective aperture 6.9m, f/1.25
- FOV ~ 3.5 deg, will cover ~1/2 sky
- Time domain astronomy, large-scale weak grav. lensing survey

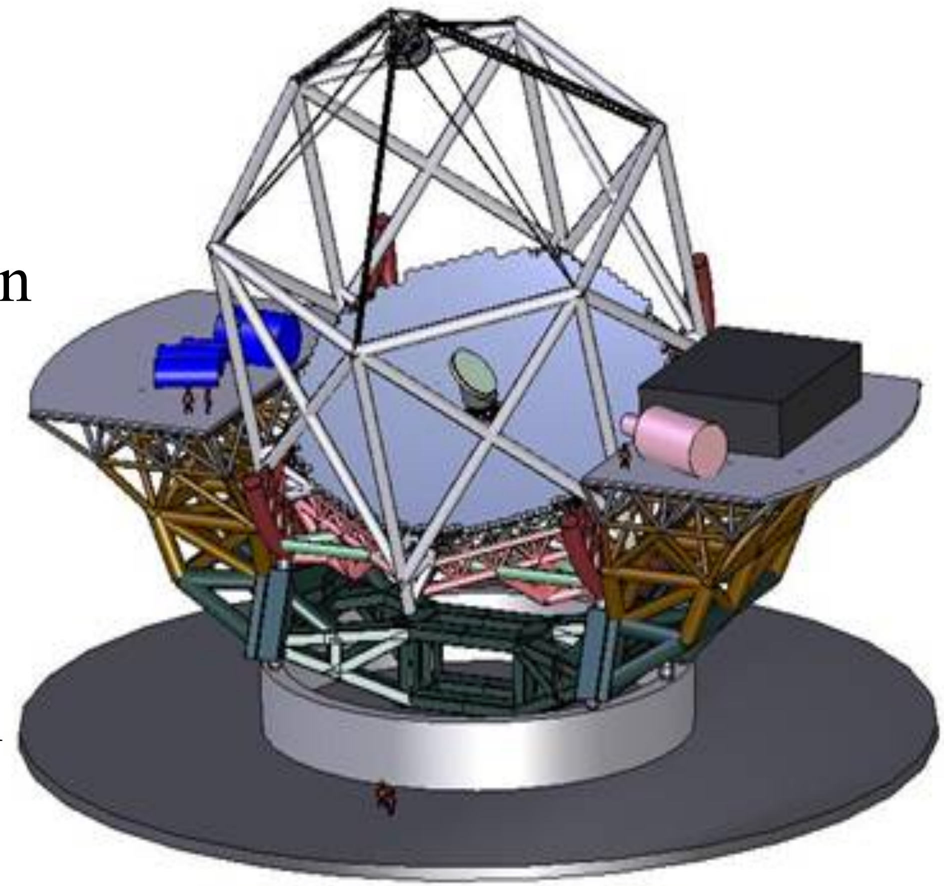




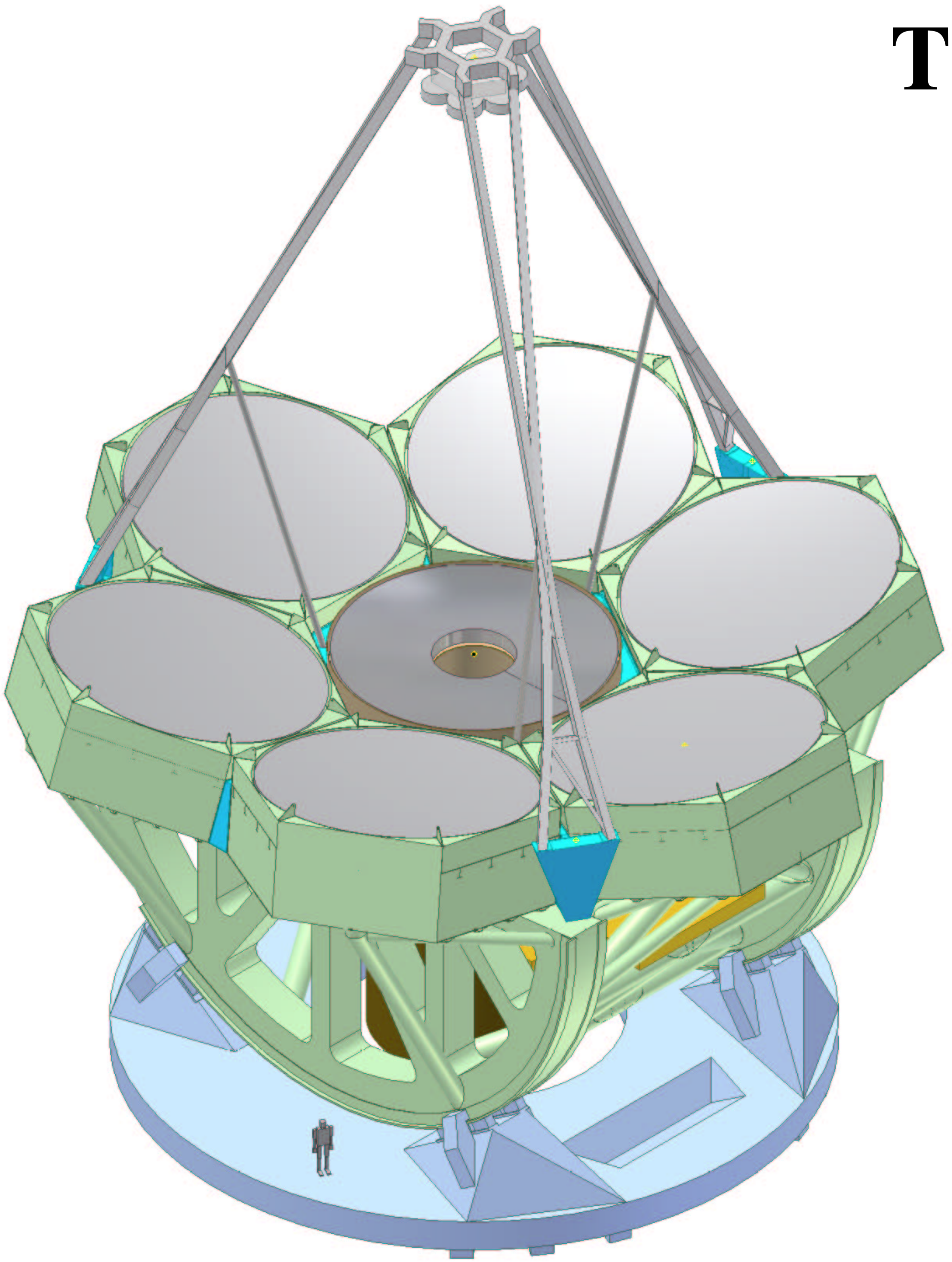
- Multiple 10s exposures, *grizy* filters, 3 Gigapixel camera
- Data rate ~ 30 TB/night, ~ 6 PB/yr
- First light ~ 2022?

The TMT Conceptual Design

- 30-meter filled aperture mirror
- 738 segments of 1.2m diameter, 4.5cm thick
- Alt-azimuth mount
- Aplanatic Gregorian-style design
- f/1 primary, f/15 final focus
- Very AO-intensive
- Field of View = 20 arcmin
- Instruments located at Nasmyth foci, multiple instruments on each Nasmyth platform addressable by agile tertiary mirror
- Location: Mauna Kea (?)



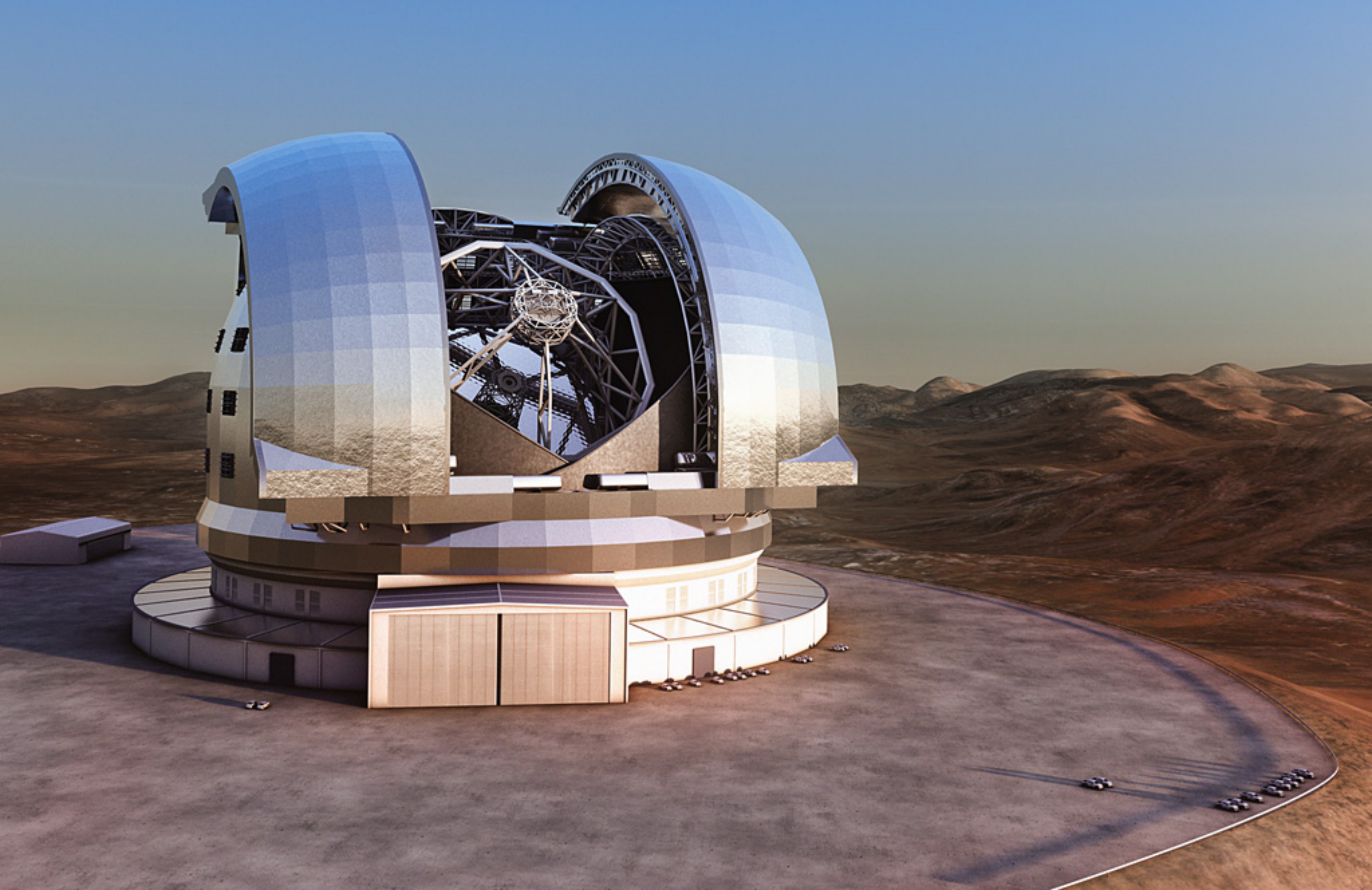
First light ~ 2025?



The Giant Magellan Telescope (GMT)

- 7 X 8.4m Segments
- 18m focal length
- f/0.7 primary
- f/8 Gregorian focus
- 21.4m equiv. collecting area
- 24.5m equiv. angular resolution
- 20-25’ FOV

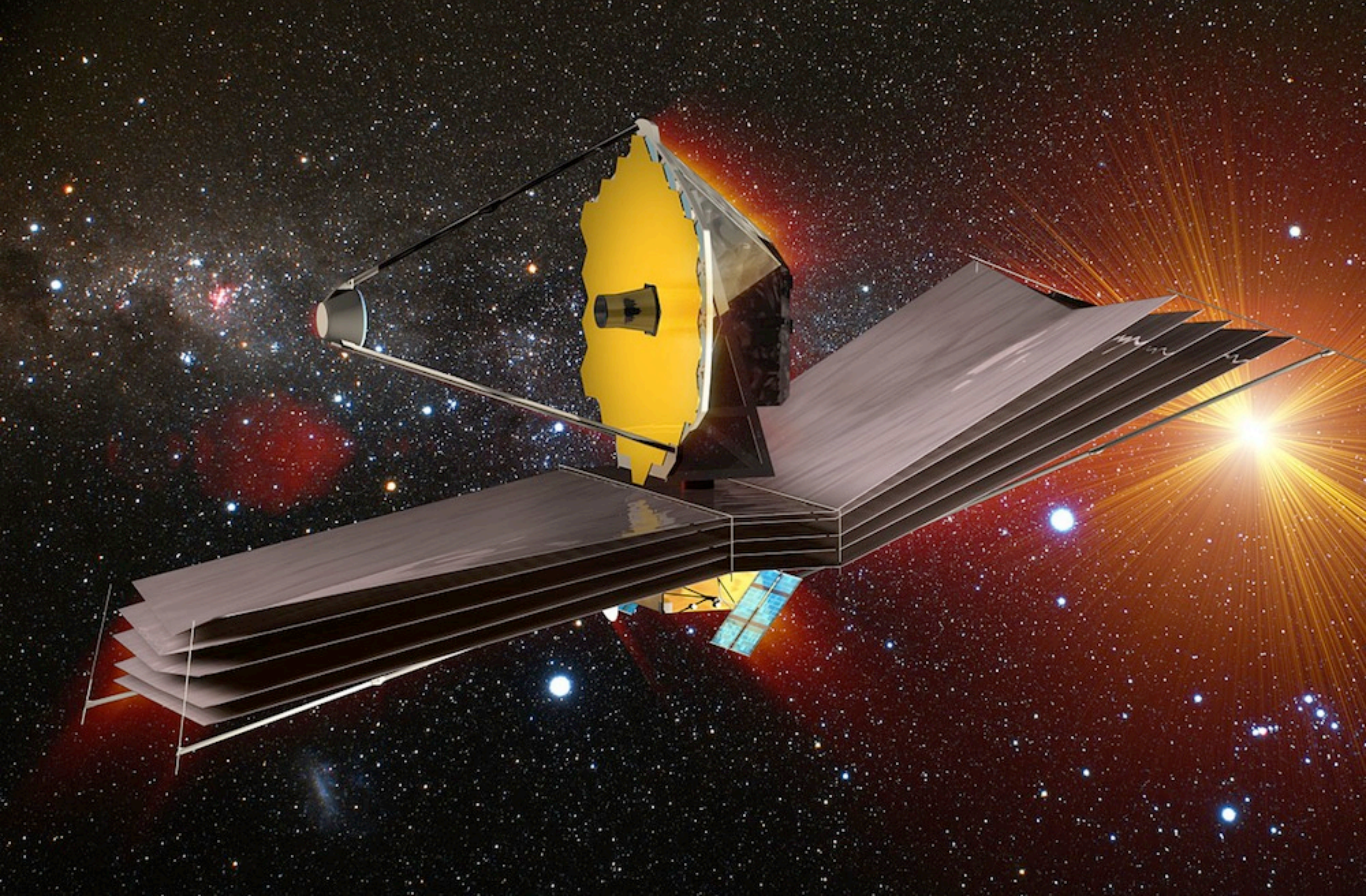
The ESO EELT (40 m)



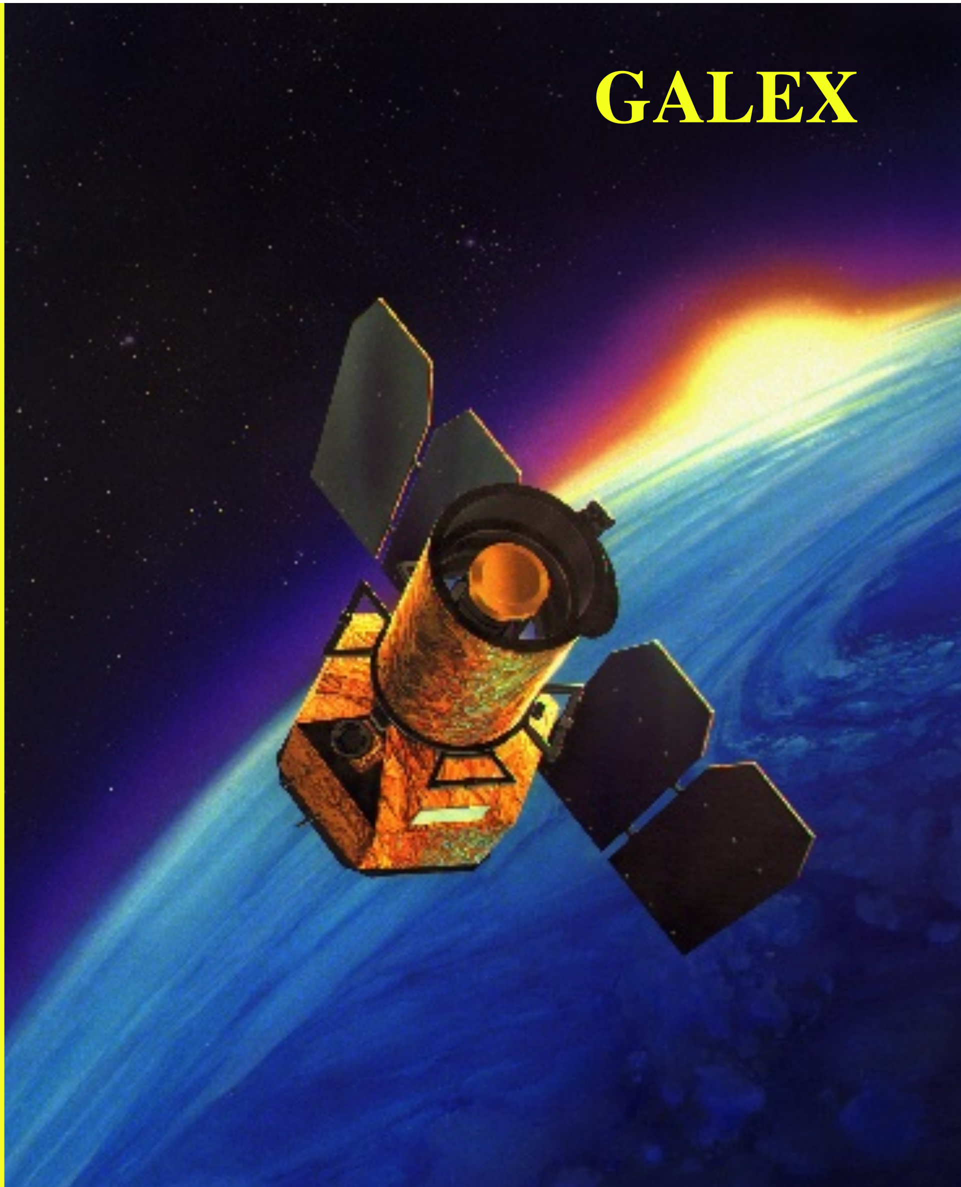
Night in America: Light Pollution

Hubble Space Telscope (HST), 2.4 m, 1990-?

James Webb Space Telscope (JWST), 6.5 m, 2021-?



Space Observatories From IR to UV



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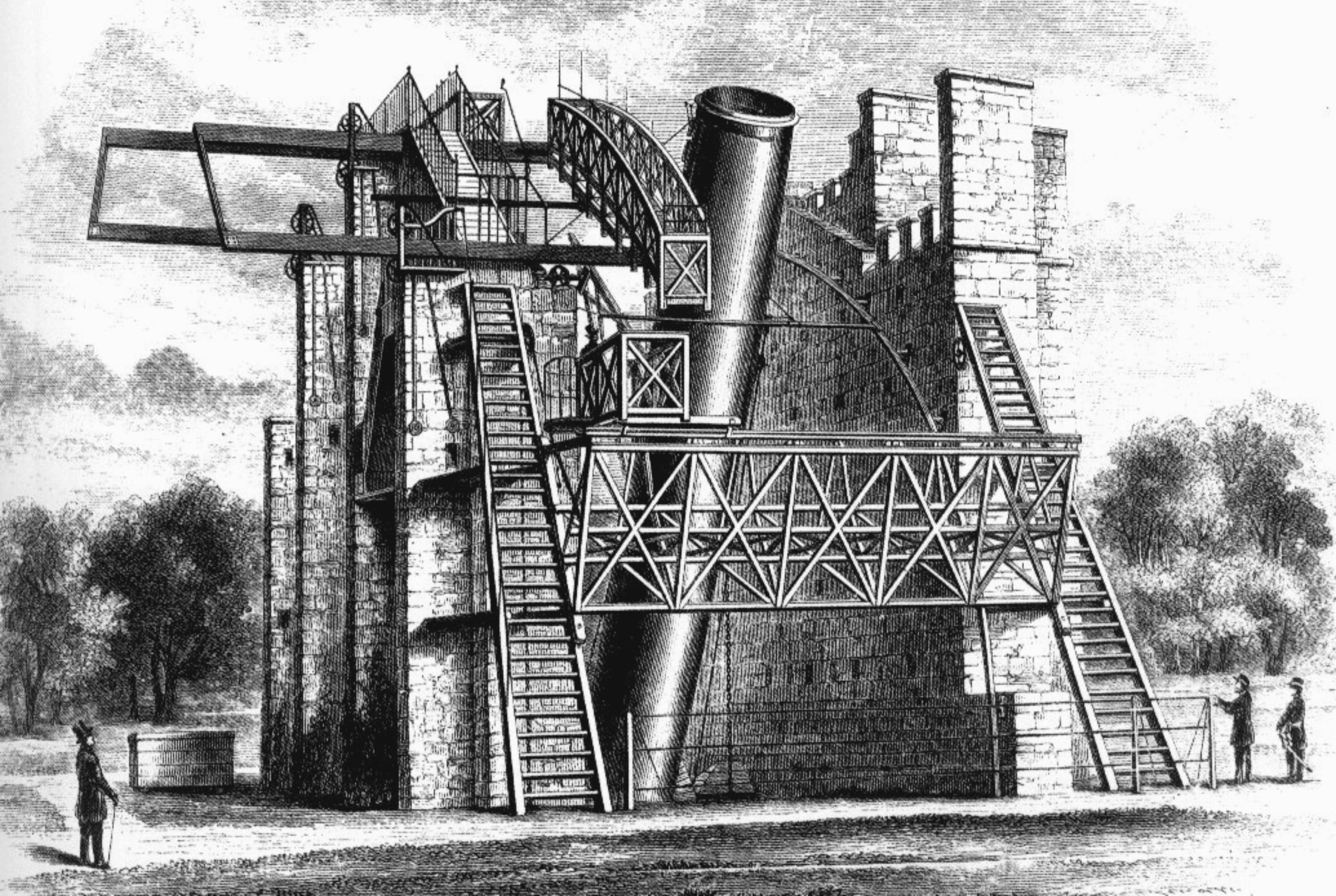
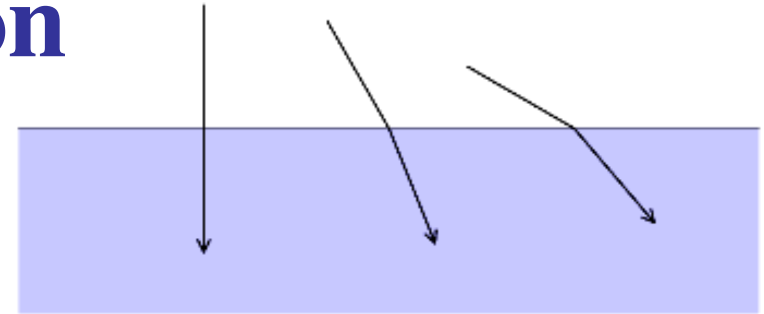
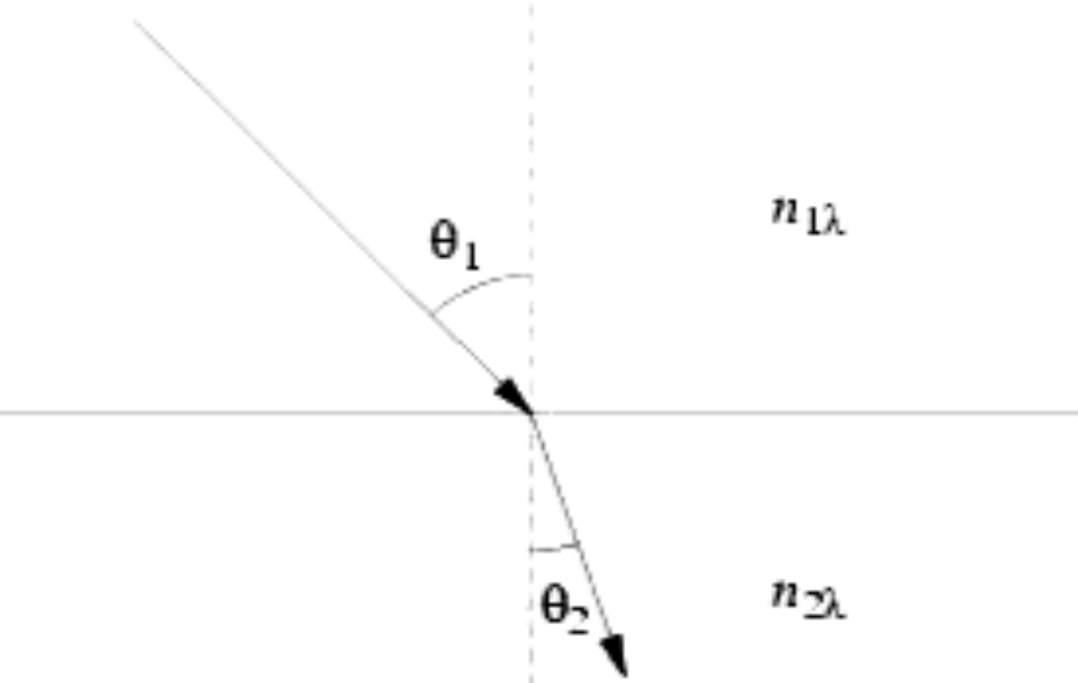
3.2 Geometric Optics, Angular Resolution



Basic Optics: Refraction





Index of refraction:
$n(\lambda) = c / v(\lambda)$

e.g., $n_{air} \approx 1.0003$,
$n_{water} \approx 1.33$,
$n_{glass} \sim 1.5$, etc.

Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

If $\sin\theta_2 = 1$, then we have a total internal reflection for $\theta_1 > \sin^{-1}(n_2/n_1)$; e.g., in optical fibers

Index of Refraction of the Air

Cauchy's approximate formula:

$n_{air} = 1.000287566 + (1.158102 \times 10^{-9}\ \mathrm{m} / \lambda)^2 + O(\lambda)^4$

➥ $\sim 5 \times 10^{-6}$ in visible light

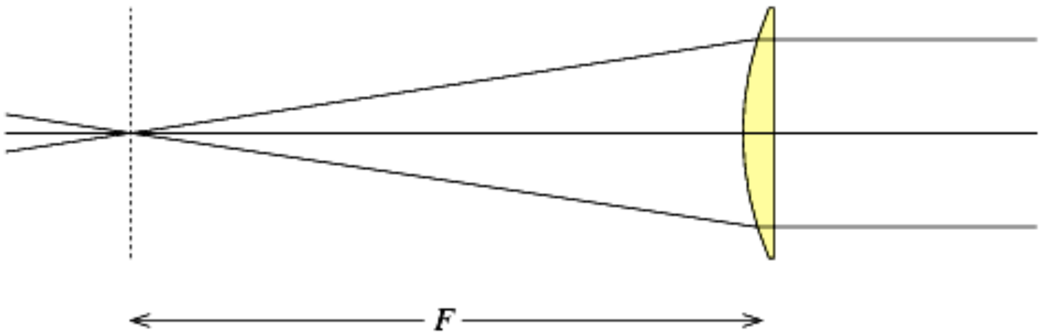
Thus, $\Delta\lambda/\lambda \sim 3 \times 10^{-4}$ in visible light ~ 1 - 3 Å

Beware of the air vs. vacuum wavelengths in spectroscopy!
Traditionally, wavelengths ≥ 3000 (2800?) Å are given as air values, and lower than that as vacuum values. Sigh.

It is a function of density and temperature. Thus,
Turbulence → Refractive Scintillation → Seeing
→ The need for AO!

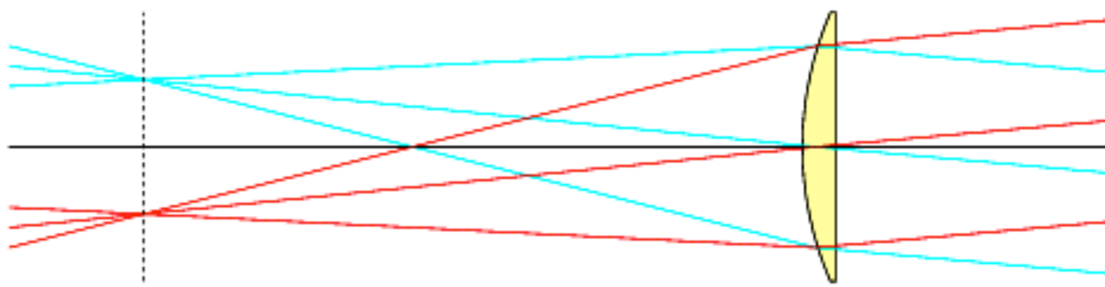
Lenses and Refractive Optics

No longer used for professional telescopes, but still widely used within instruments

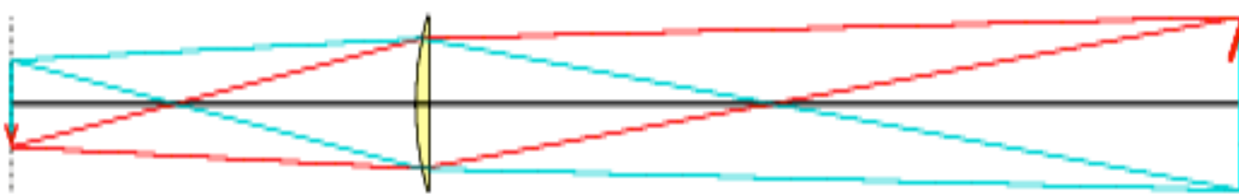


Focal length

Focal plane



Inverted images



Lensmaker's Formula

Using the Snell's law, it can be shown that

$1/f = (n-1)\,(1/R_1 + 1/R_2)$

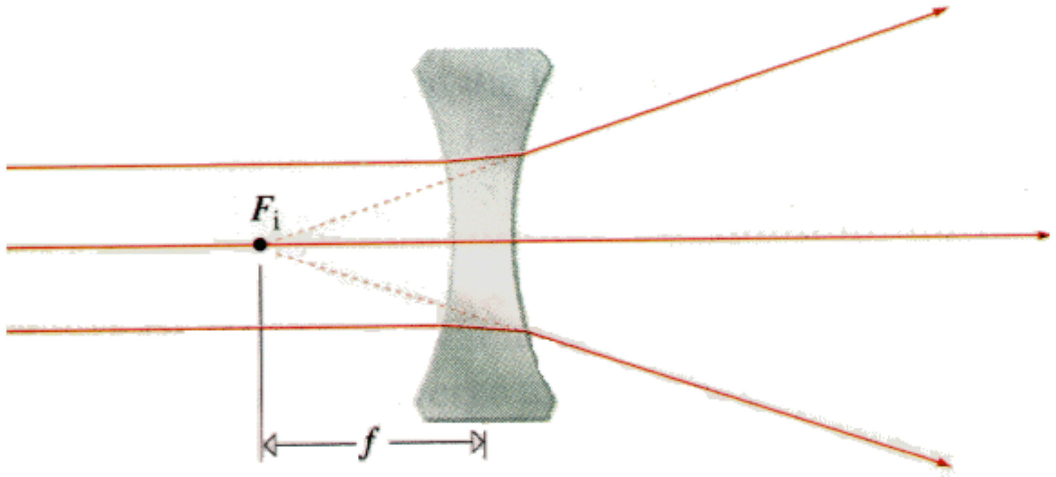
(aka the "lens power")

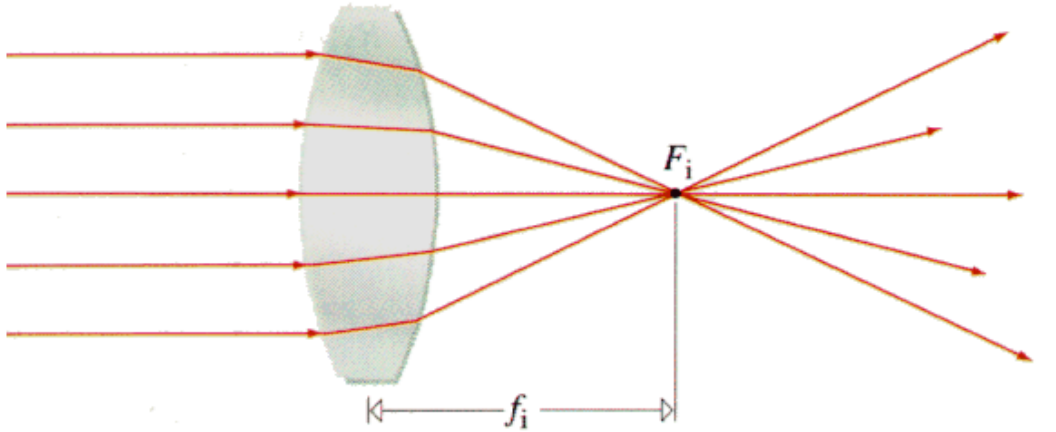
where:

f = focal length

R_1, R_2 = curvature radii of the two lens surfaces

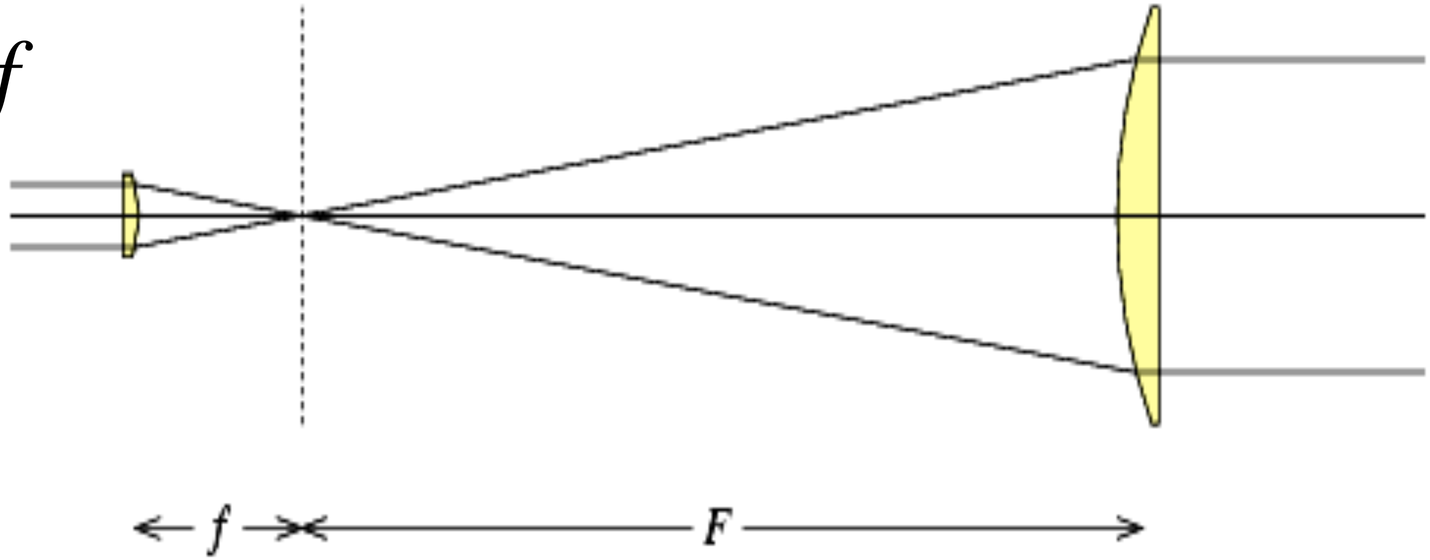
Note that for a spherical mirror, $f = R/2$

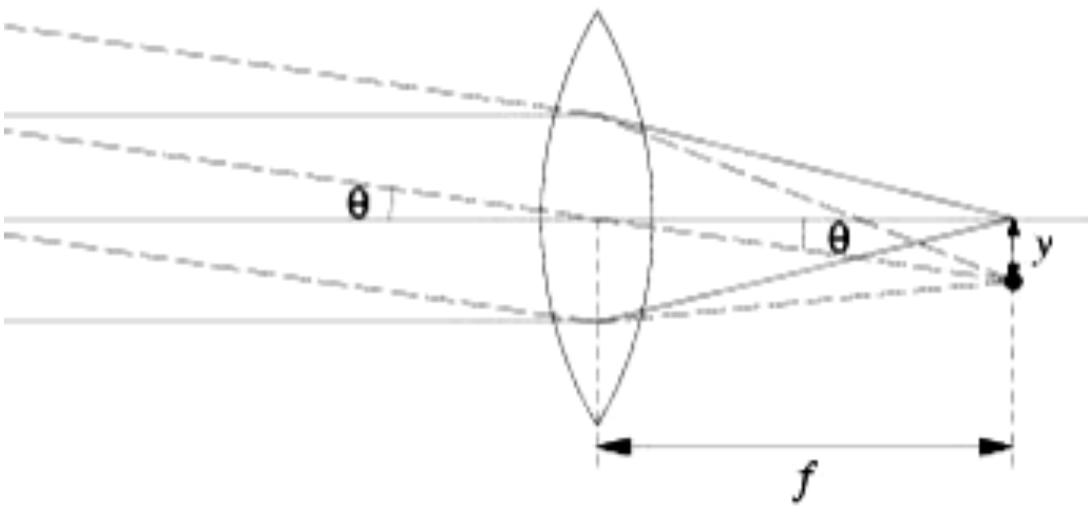




Magnification and Image Scale

$$M = F\,/\,f$$





$$y\ = f\ \tan\theta\ \approx f\,\theta$$

scale: $dy/d\theta = 1\,/\,f$

Aberrations

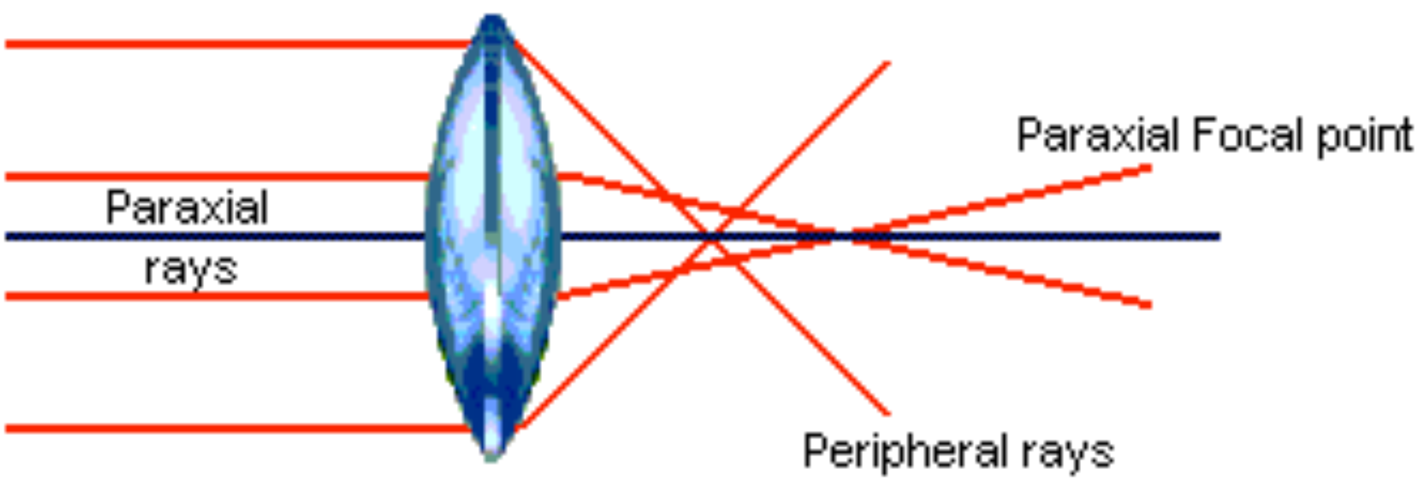
Chromatic (wavelength dependent)

Achromatic (w. independent)

Image Deterioration
(spherical aberation, coma, astigmatism)

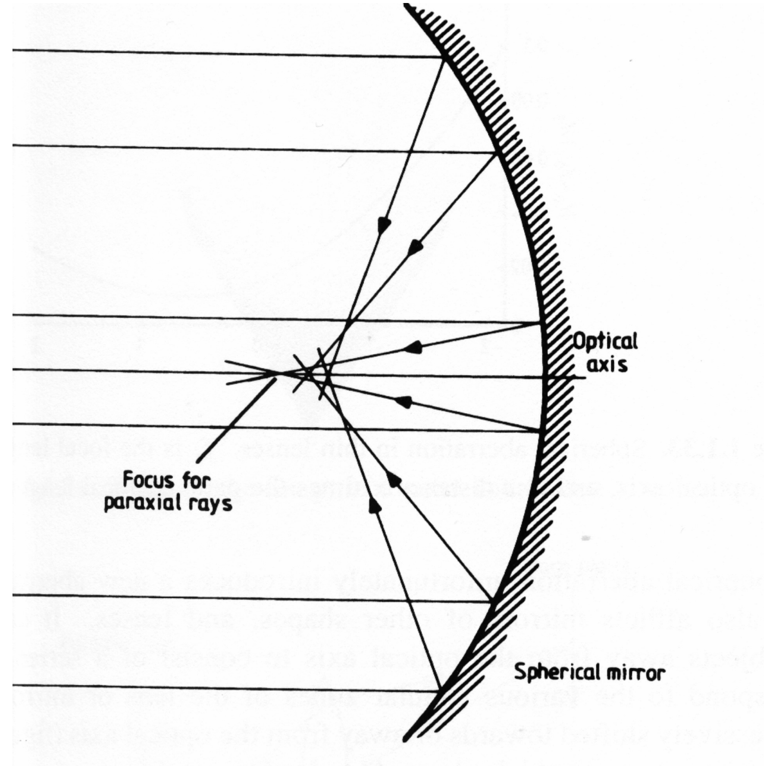
Image Distortion
(Petzval field curvature, pincushion, barrel distortion)

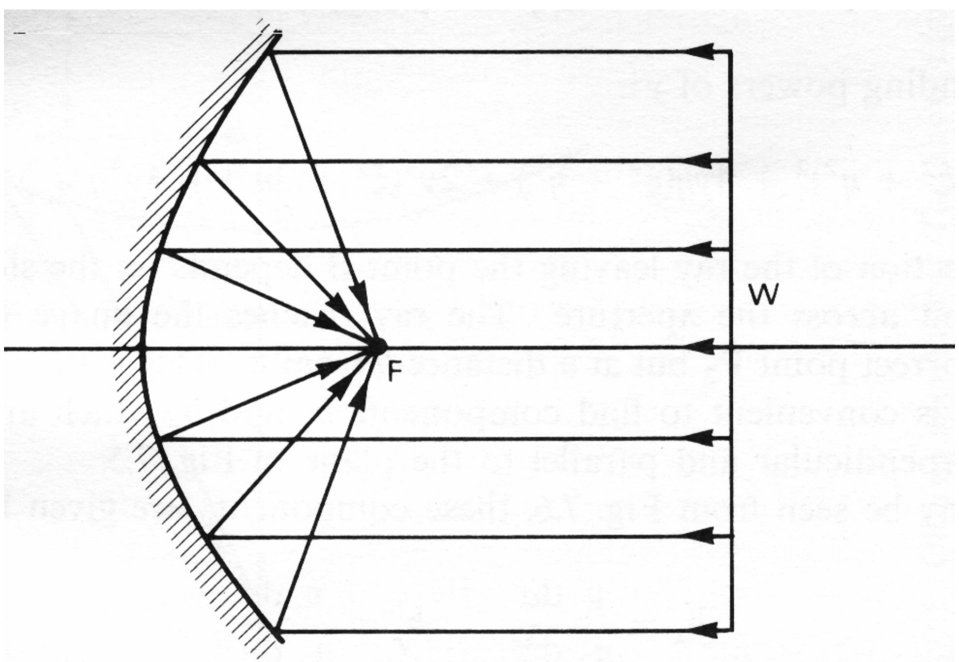
Spherical aberration:



Simple Reflecting Telescopes

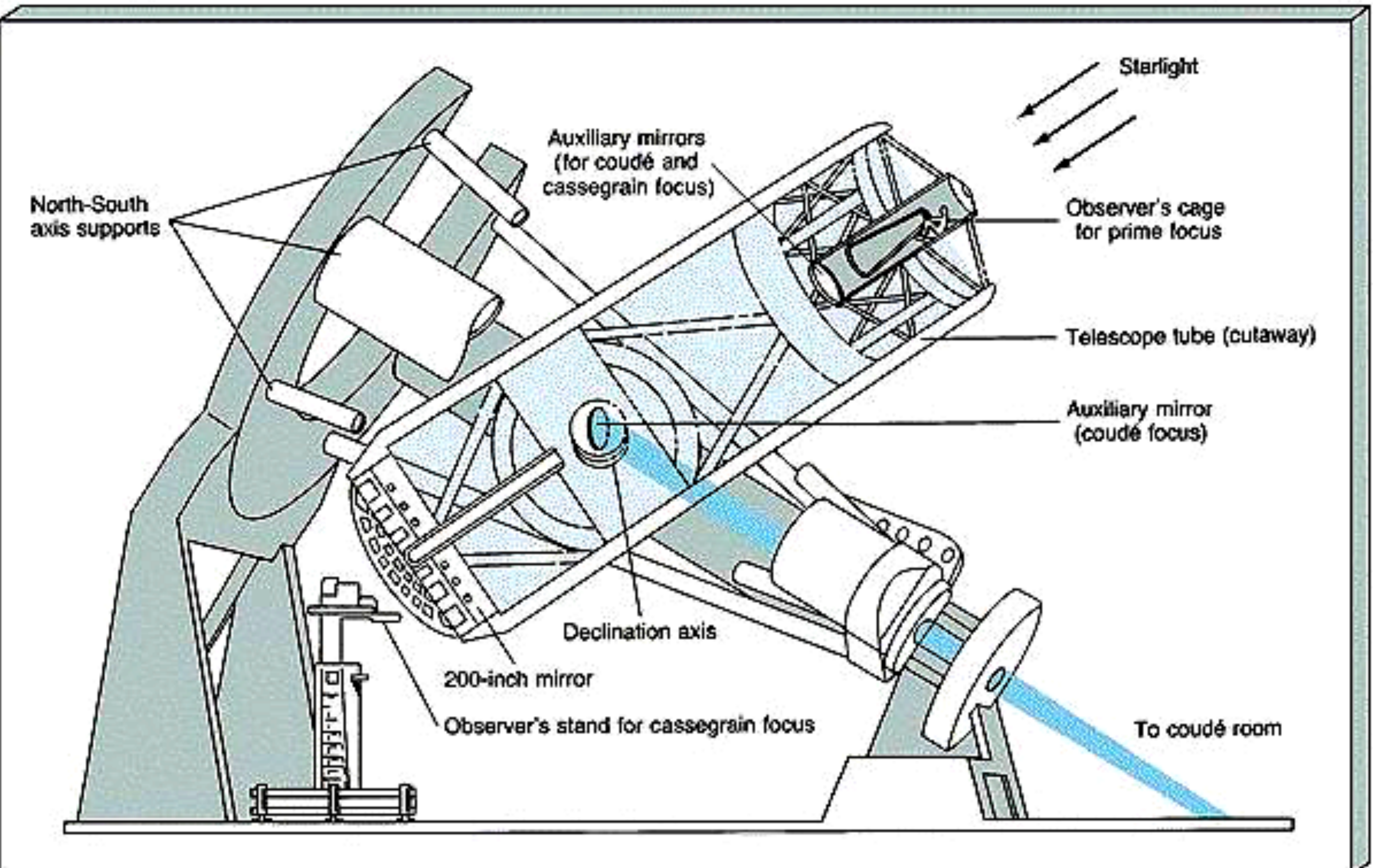
Spherical surface suffers from spherical aberration – rays hitting the outside of the dish come to focus at a different point on the optical axis from those hitting the center.



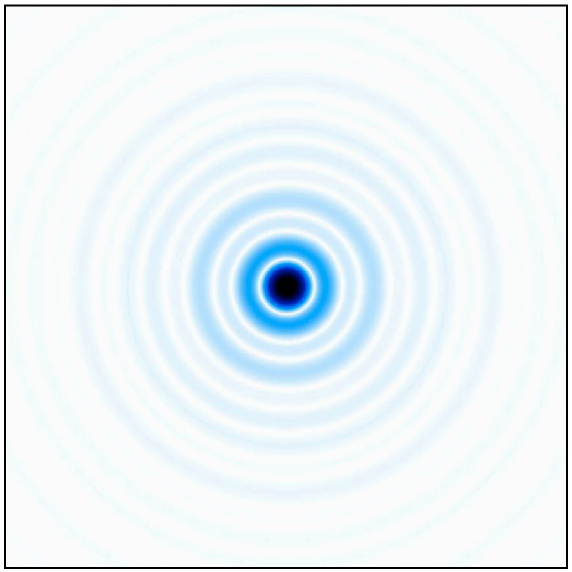


Paraboloidal reflector brings all rays to focus at the same point on the optical axis, and eliminates spherical aberration.

Palomar Hale 200-inch Telescope

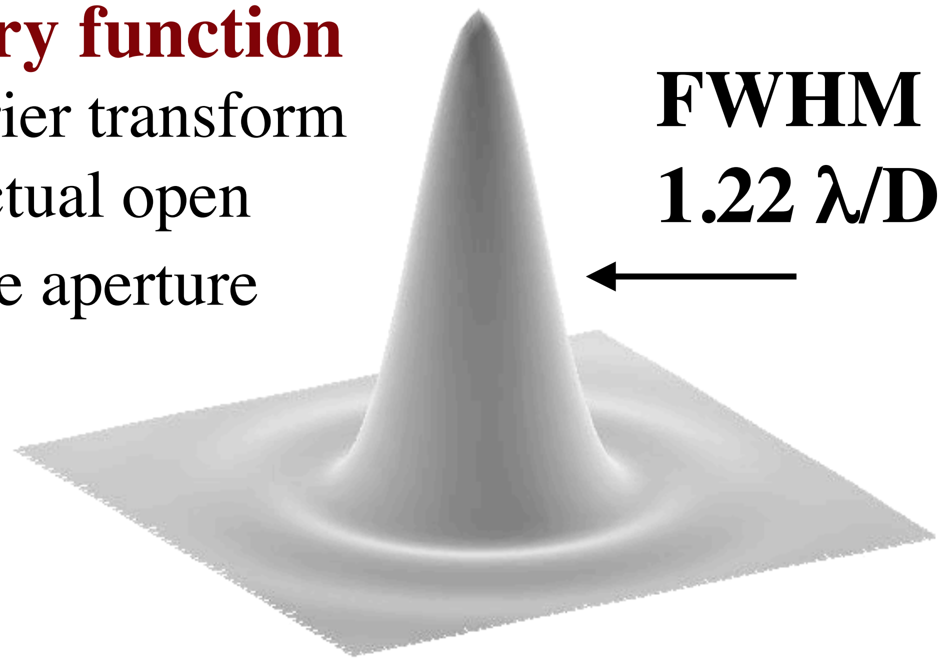


Diffraction-Limited Imaging (an ideal telescope)



The Airy function

~ a Fourier transform of the actual open telescope aperture

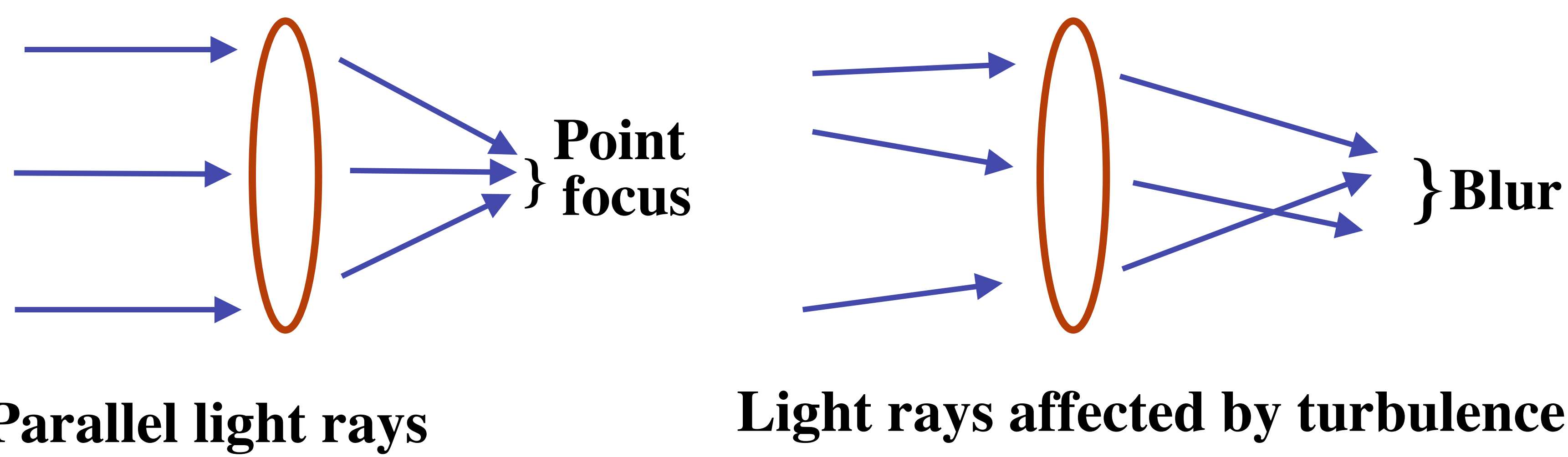


FWHM = 1.22 λ/D

In reality, it tends to be more complex, due to the mirror geometry, etc. Also, from the ground, the resolution is generally limited by the seeing, plus the instrument optics, etc.

Optical Consequences of Turbulence

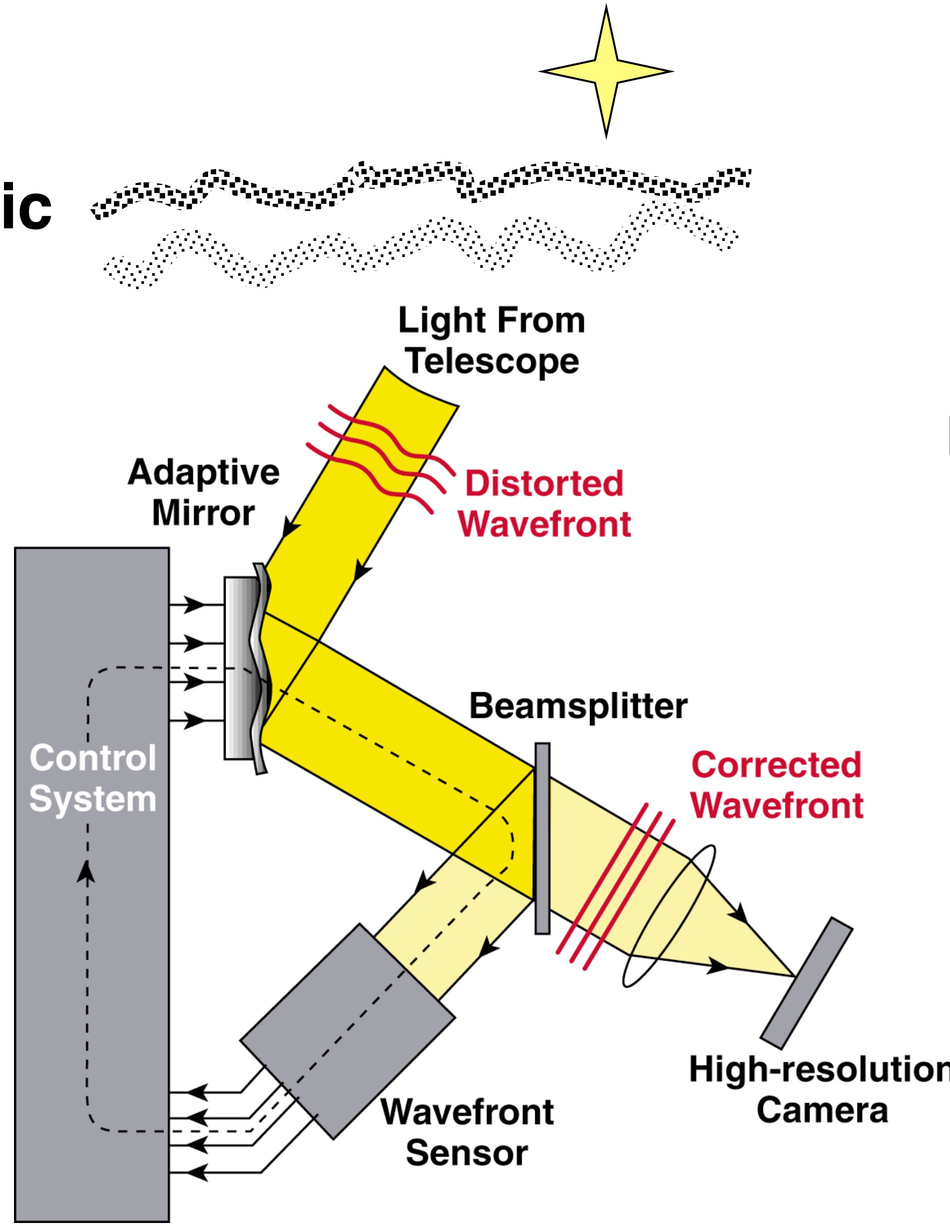
- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can't be focused to a point:

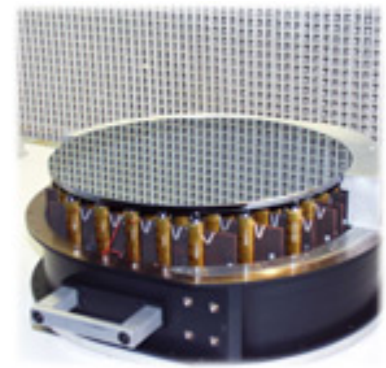


Can we compensate for this?   Yes, with **Adaptive Optics**

Schematic of Adaptive Optics System

Atmospheric turbulence



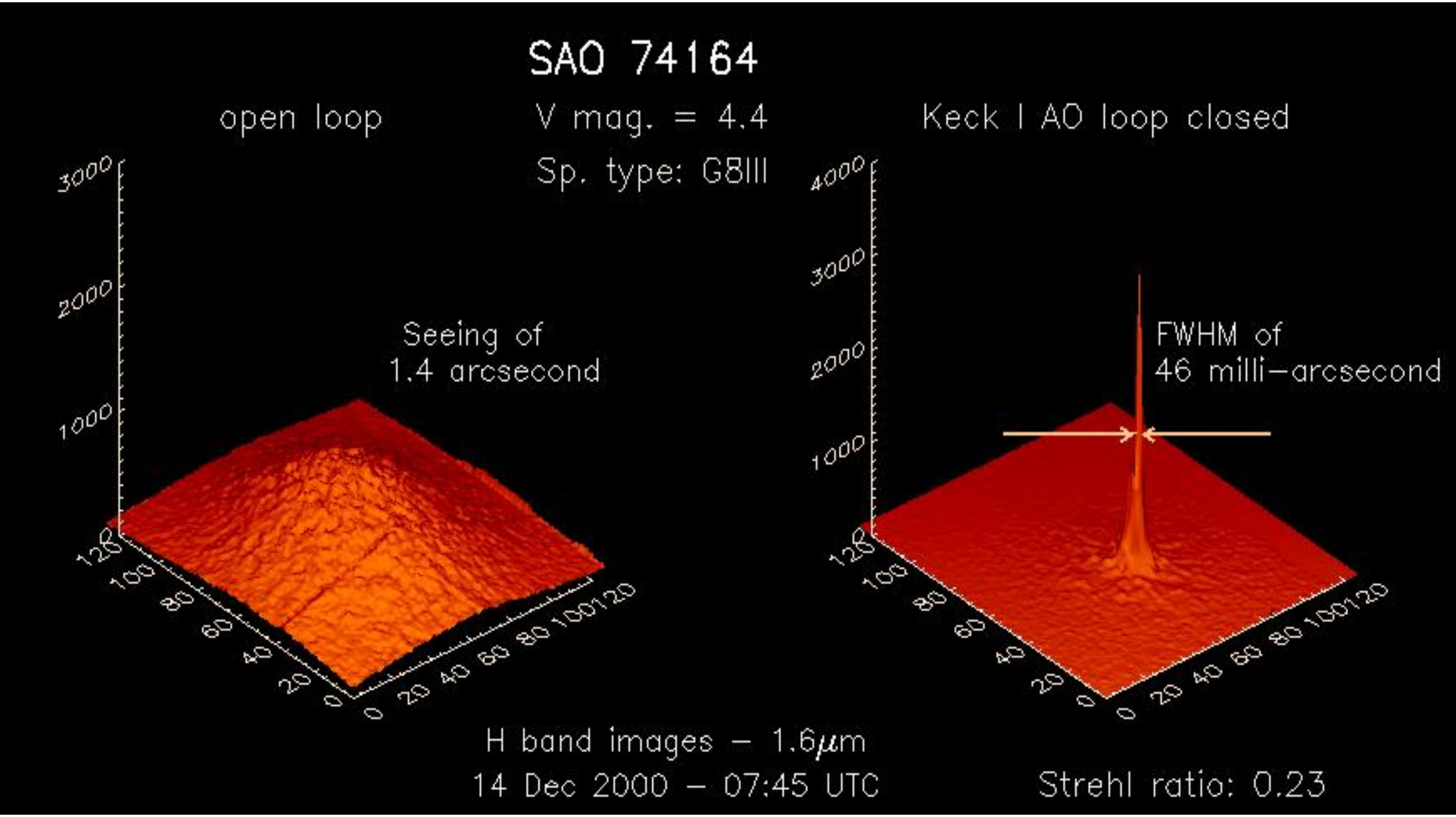


Deformable mirror

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

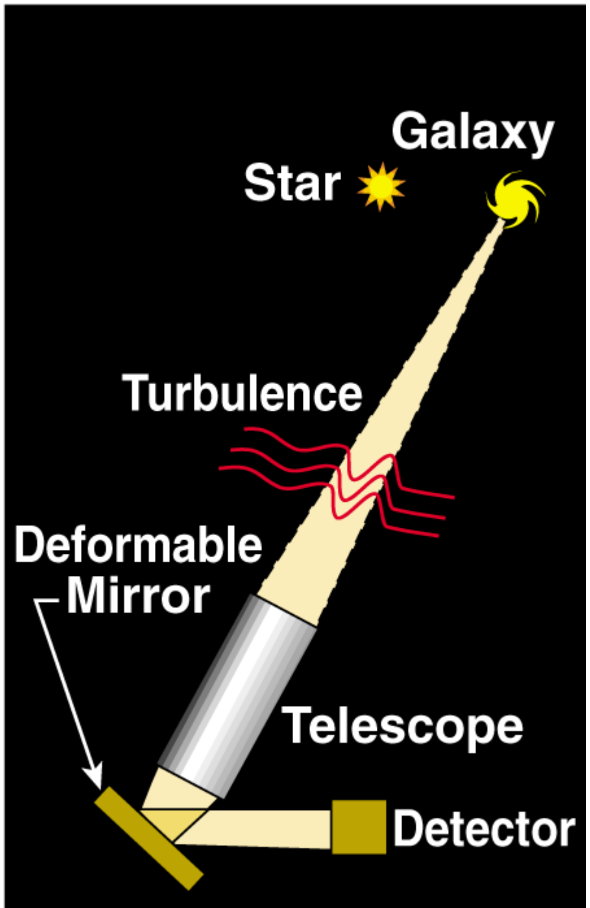
But you need a bright star very close to your target (a few arcsec) in order to compute the correction

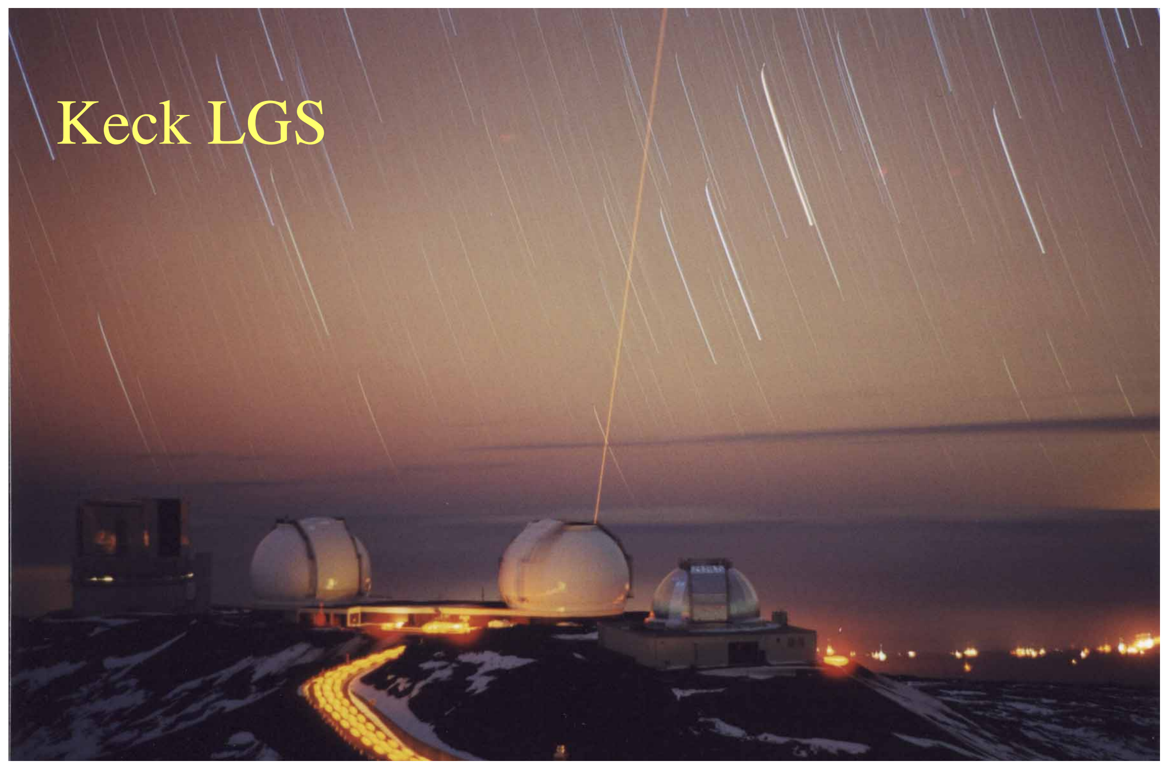
Keck AO System Performance

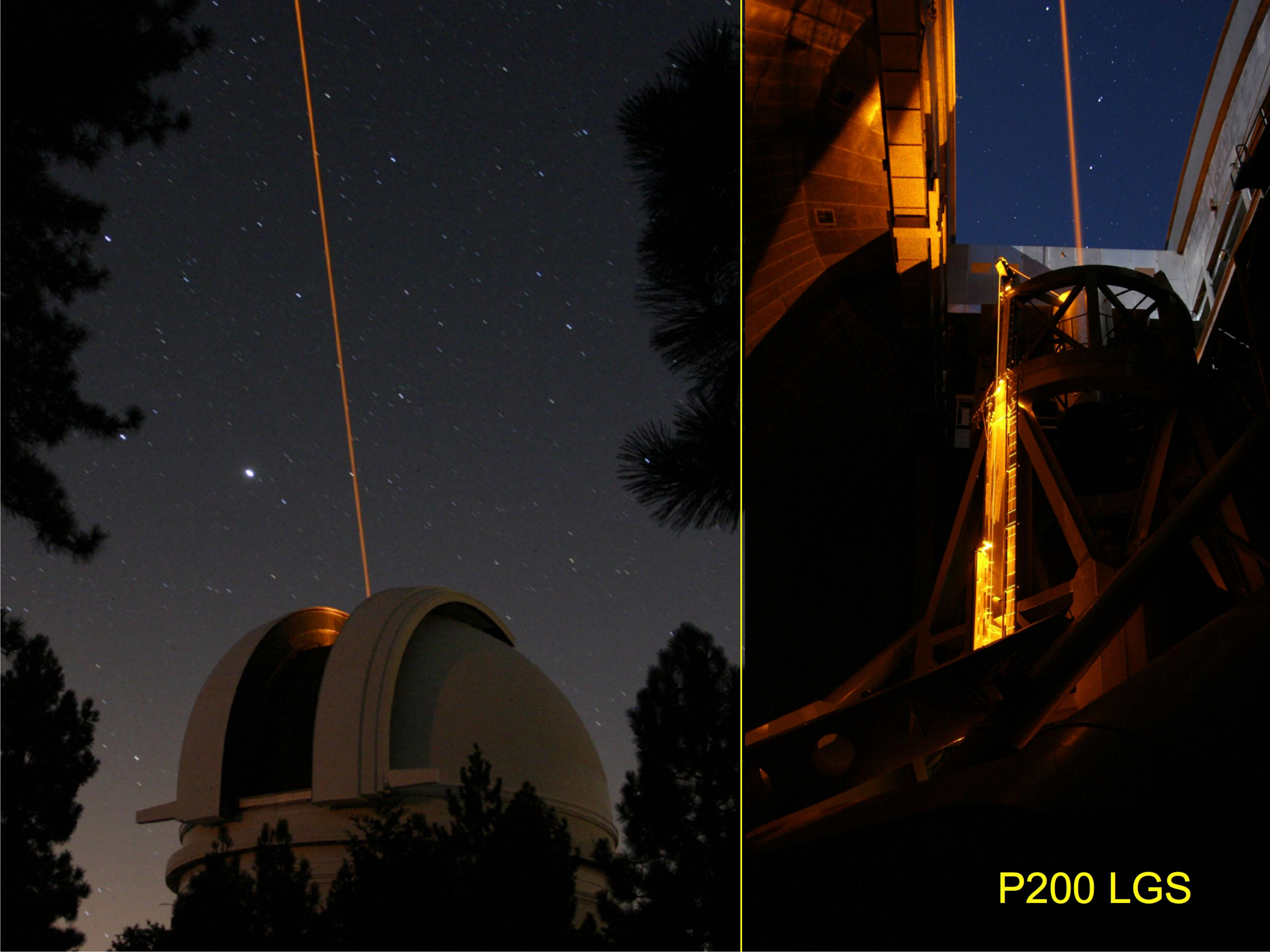


If there's no close-by bright star, create one with a laser!

Use a laser beam to create an artificial "star" at altitude of ~ 100 km (Na layer, Na D doublet)






P200 LGS

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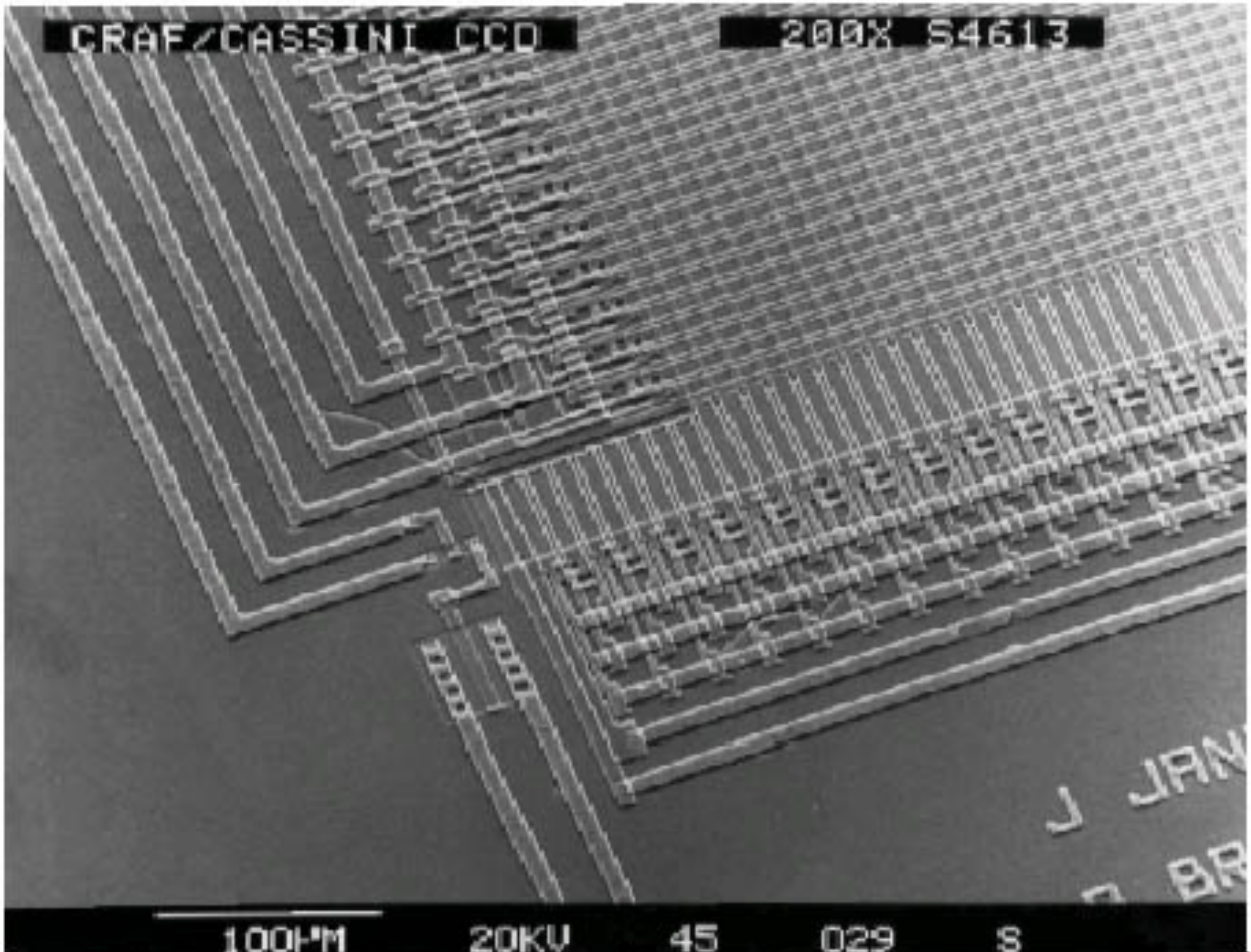
3.3 Detectors (UV, Visible and IR)



Evolution of Astronomical Detectors

- **Historical evolution:** Eye ➔ Photography ➔ Photoelectic (single-channel) devices ➔ Plate scanners ➔ TV-type imagers ➔ Semiconductor-based devices (CCDs, IR arrays, APDs, bolometers, …) ➔ Energy-resolution arrays (STJ, ETS)
- *Astronomical detectors today are applications of solid state physics*
- **Detector characteristics:** Sensitivity as a f(λ), size, number of pixels, noise characteristics, stability, cost
- **Types of noise:** Poissonian (quantum), thermal (dark current, readout), sensitivity pattern
- **Quantum efficiency:** QE = N(detected photons)/N(input photons)
- **Detective Quantum Efficiency:** $DQE = (S/N)_{out}/(S/N)_{in}$

The Classic: Photomultiplier Tubes

Typical QE ~ 5-10%
UV/B sensitive, poor in R/IR

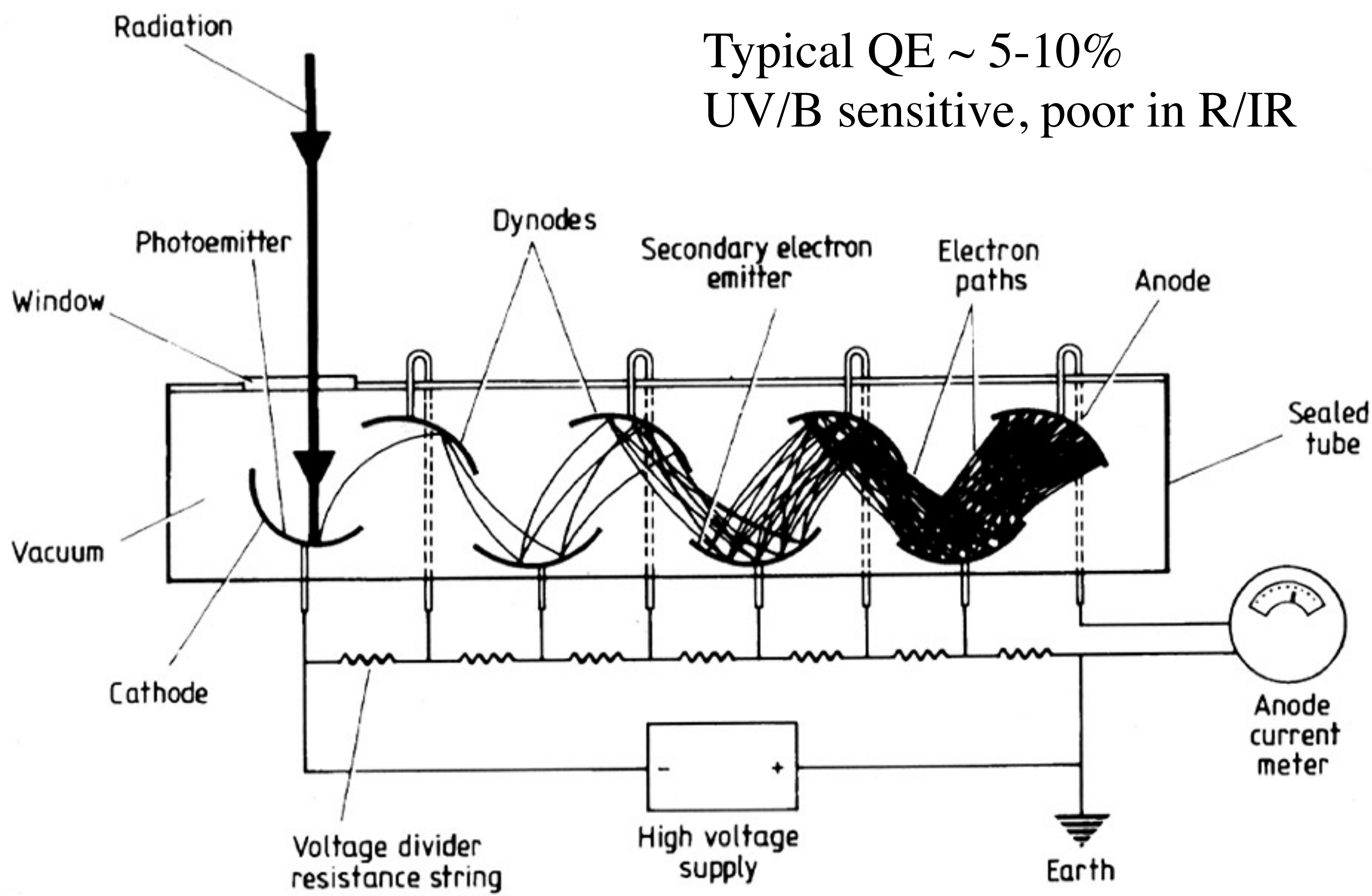
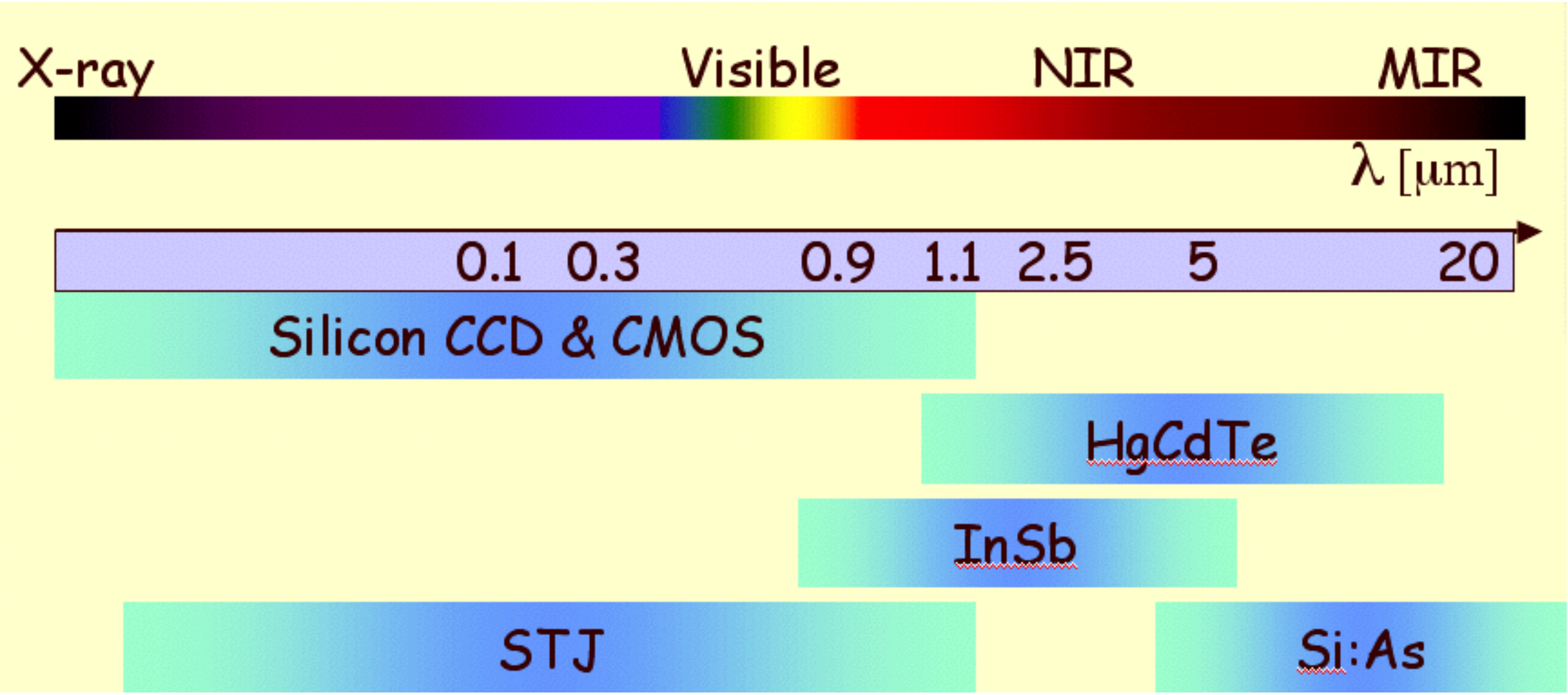


Figure 1.1.19. Schematic arrangement for a photomultiplier.

Solid-State Detector Technologies

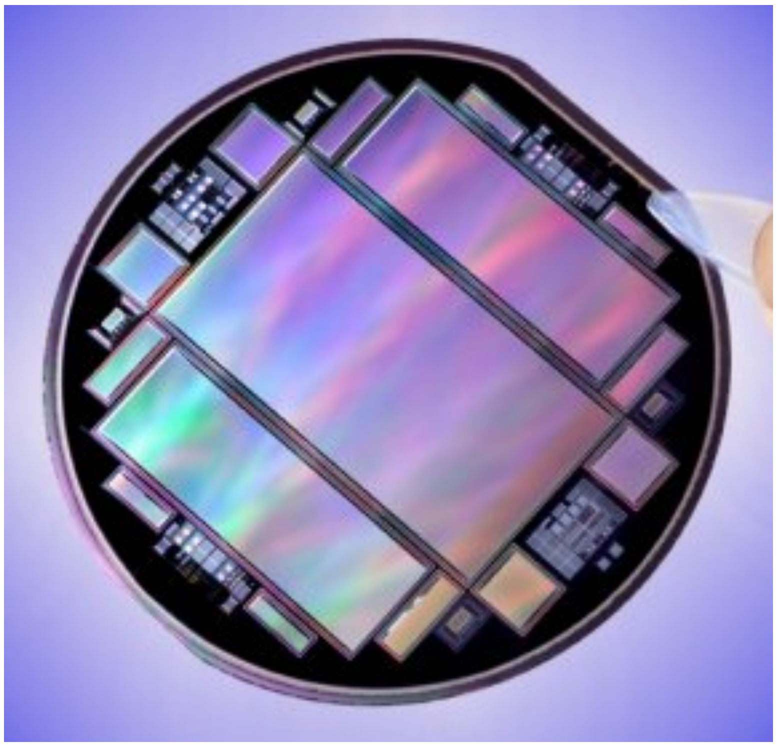


2-D focal plane arrays :

- Optical – silicon-based (CCD, CMOS)
- Infrared – IR material + silicon CMOS multiplexer

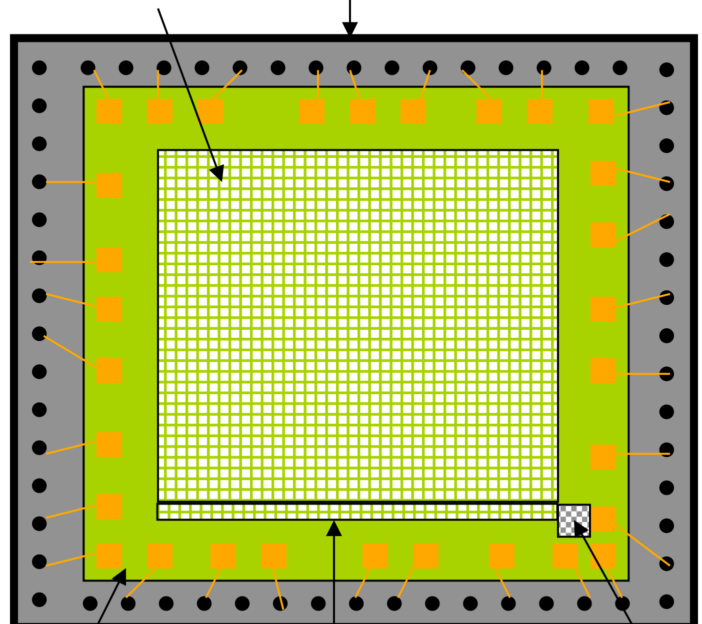
But Nowadays, Charge Coupled Devices (CCDs) Are The Detectors of Choice

(in visible, UV, and X-ray)



A whole bunch of CCDs on a wafer

Nearly ideal detectors in many ways
Counting photons in a pixel array



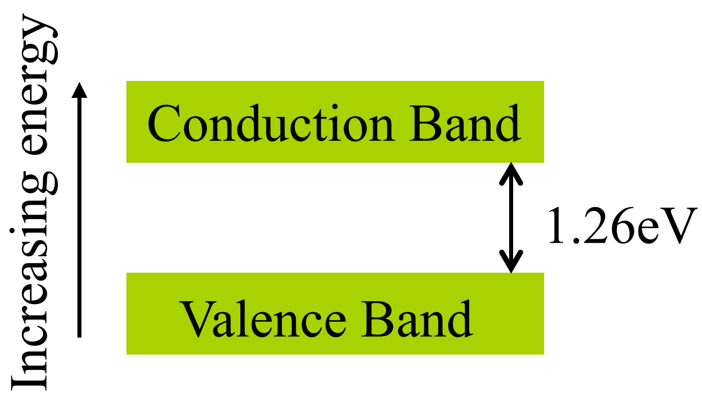
Five Basic Steps of Optical/IR Photon Detection

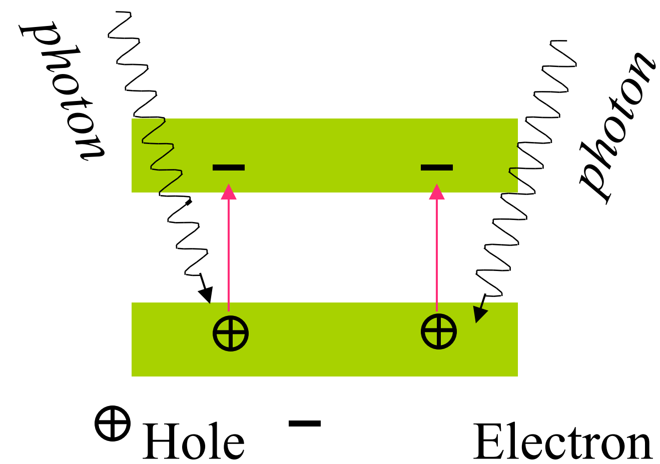
1. **Get light into the detector :** need anti-reflection coatings
2. **Charge generation :** popular materials include Si, HgCdTe, InSb
3. **Charge collection :** electrical fields within the material collect photoelectrons into pixels.
4. **Charge transfer :** in IR, no charge transfer required. For CCD, move photoelectrons to the edge where amplifiers are located.
5. **Charge amplification & digitization :** This process is noisy. In general, CCDs have lowest noise, CMOS and IR detectors have higher noise.

How Does a CCD Work?

Internal Photoelectric Effect in Doped Silicon

- Incoming photons generate electron-hole pairs
- That charge is collected in potential wells on the surface

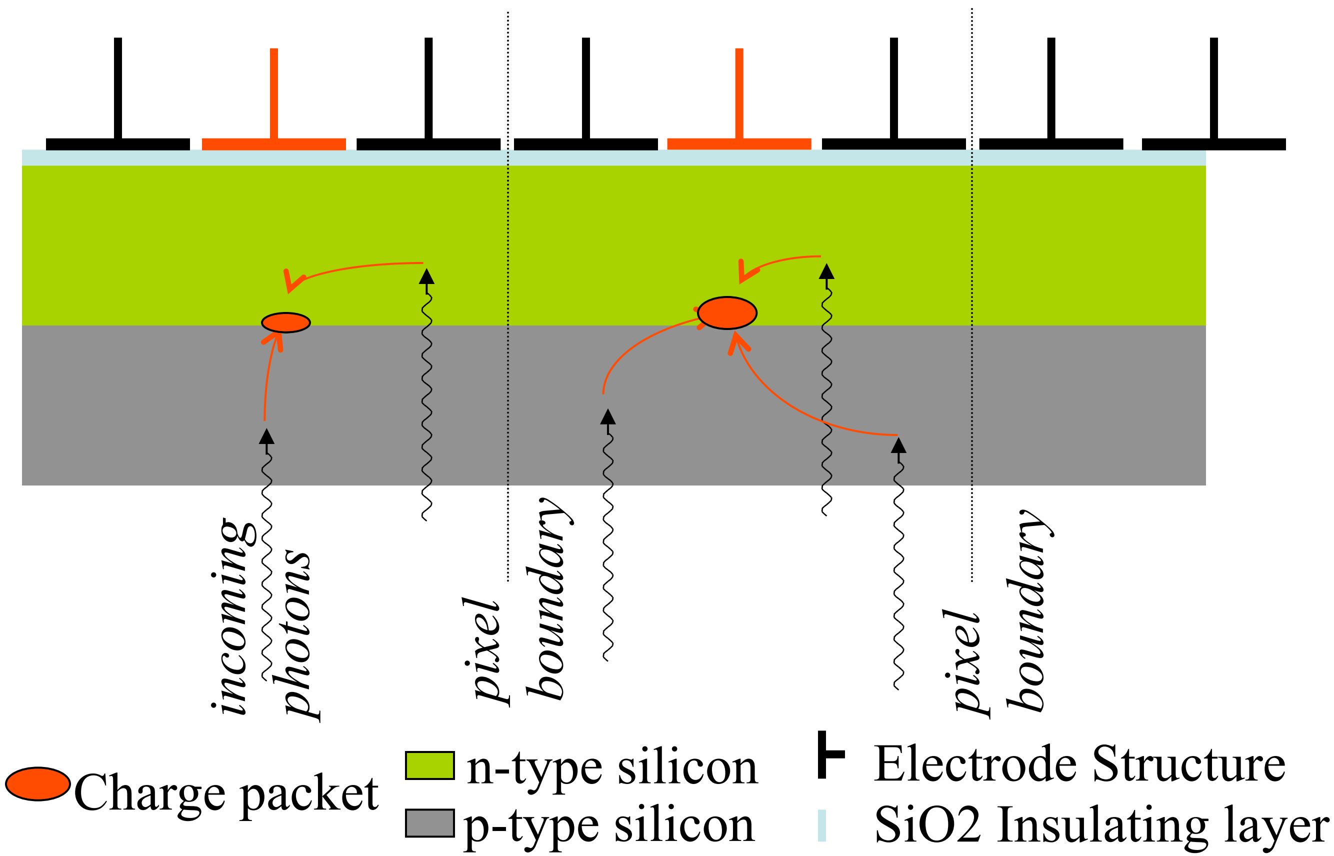




- Thermally generated electrons are indistinguishable from the photo-generated electrons ➞ Dark Current ➞ keep CCD cold!
- Silicon is transparent to photons with $E < 1.26\text{eV}$ ($\lambda \approx 1.05$ μm) ➞ Red Cutoff! Need a different type of detector for IR …

How Does a CCD Work?

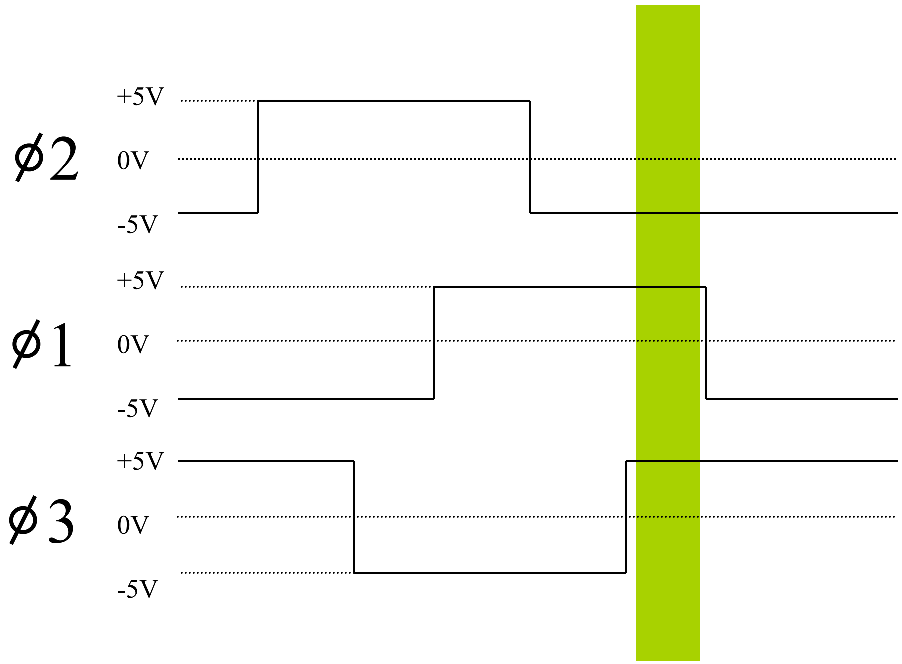
A grid of electrodes establishes a pixel grid pattern of electric potential wells, where photoelectrons are collected in "charge packets"

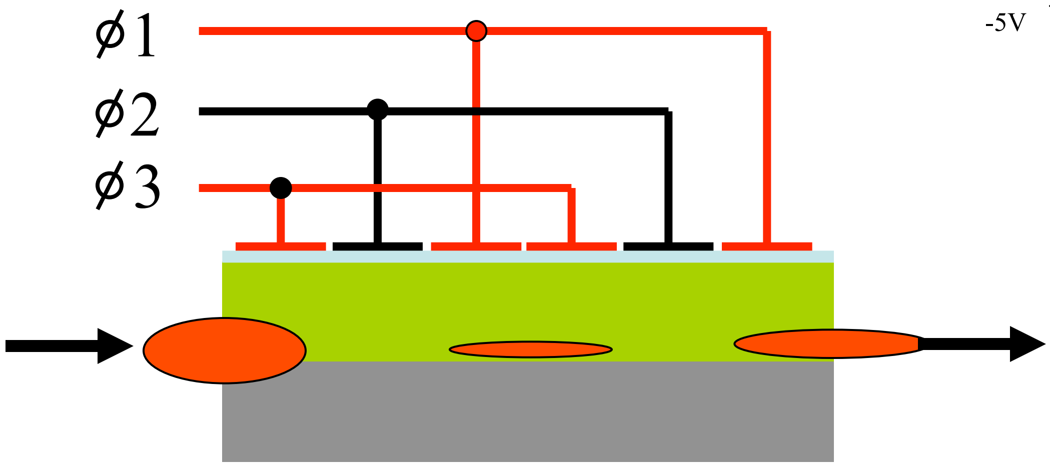


Typical well (pixel) capacity: a few $\times 10^5$ e^-. Beyond that, the charge "bleeds" along the electrodes.

Reading Out a CCD: Shift the electric potential pattern by clocking the voltages - pixel positions shift

Charge packet from subsequent pixel enters from left as first pixel exits to the right.





Pattern of collected electrons (= an image) moves with the voltage pattern, and is read out

IR (Hybrid) Arrays

Not like CCDs!

Each pixel is read out through its own transistor.

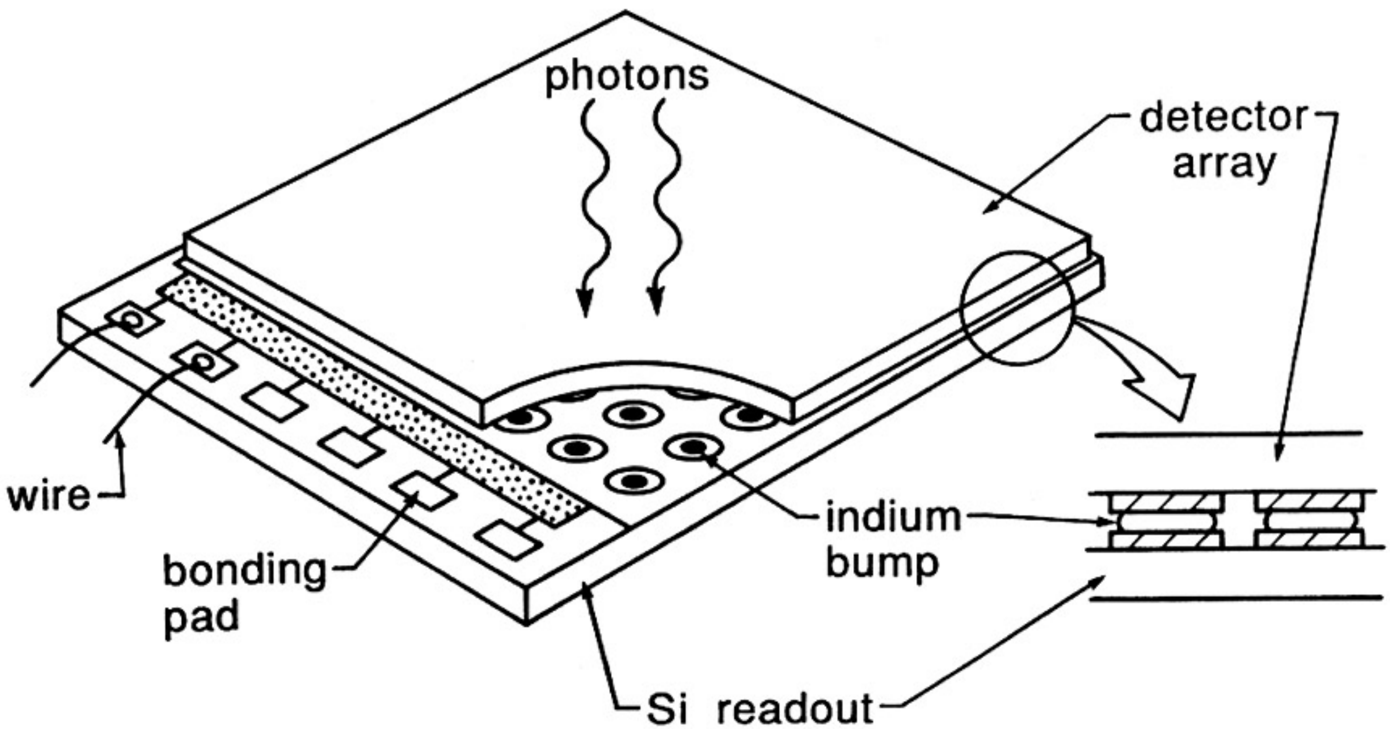
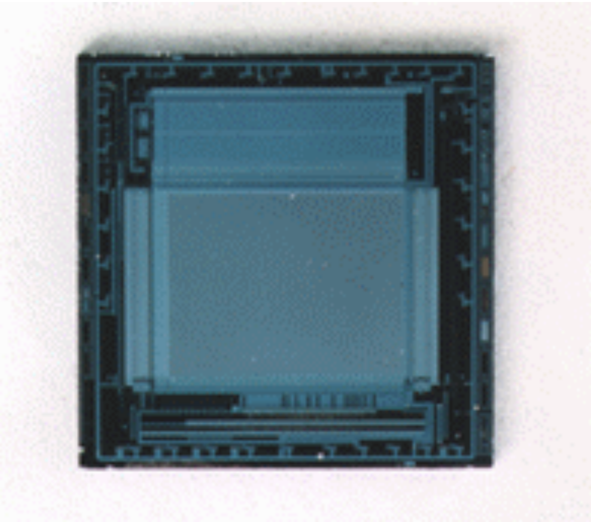


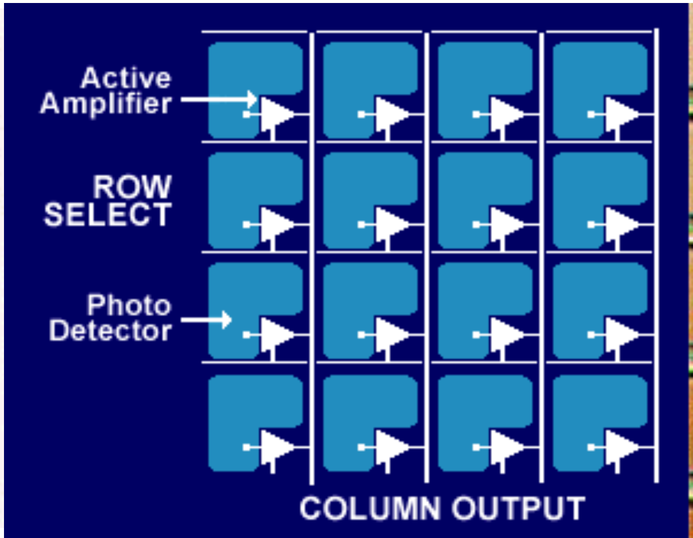
Figure 6.1. Infrared direct hybrid array.

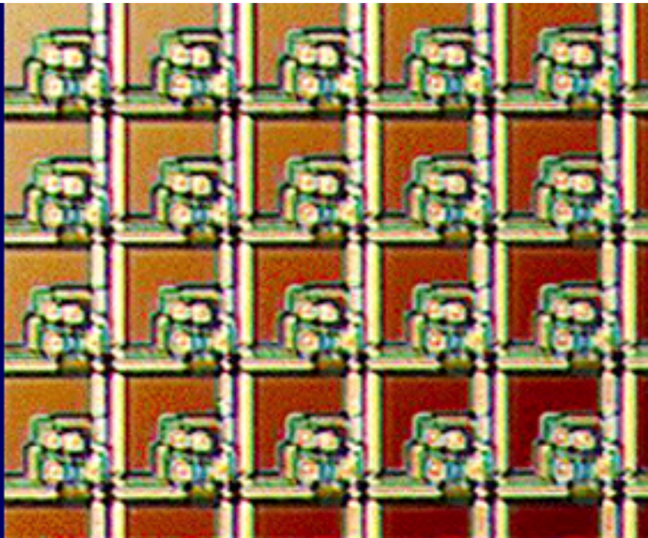
Typical materials:
HgCdTe, InSb, PtSi, InGaAs

CMOS Imagers

- CMOS = Complementary Metal Oxide Semiconductor; it is a process, not a particular device
- Each pixel has its own readout transistor. Could build special electronics on the same chip. Can be read out in a random access fashion.
- Noisier, less sensitive, and with a lower dynamical range than CCDs, but much cheaper; and have some other advantages

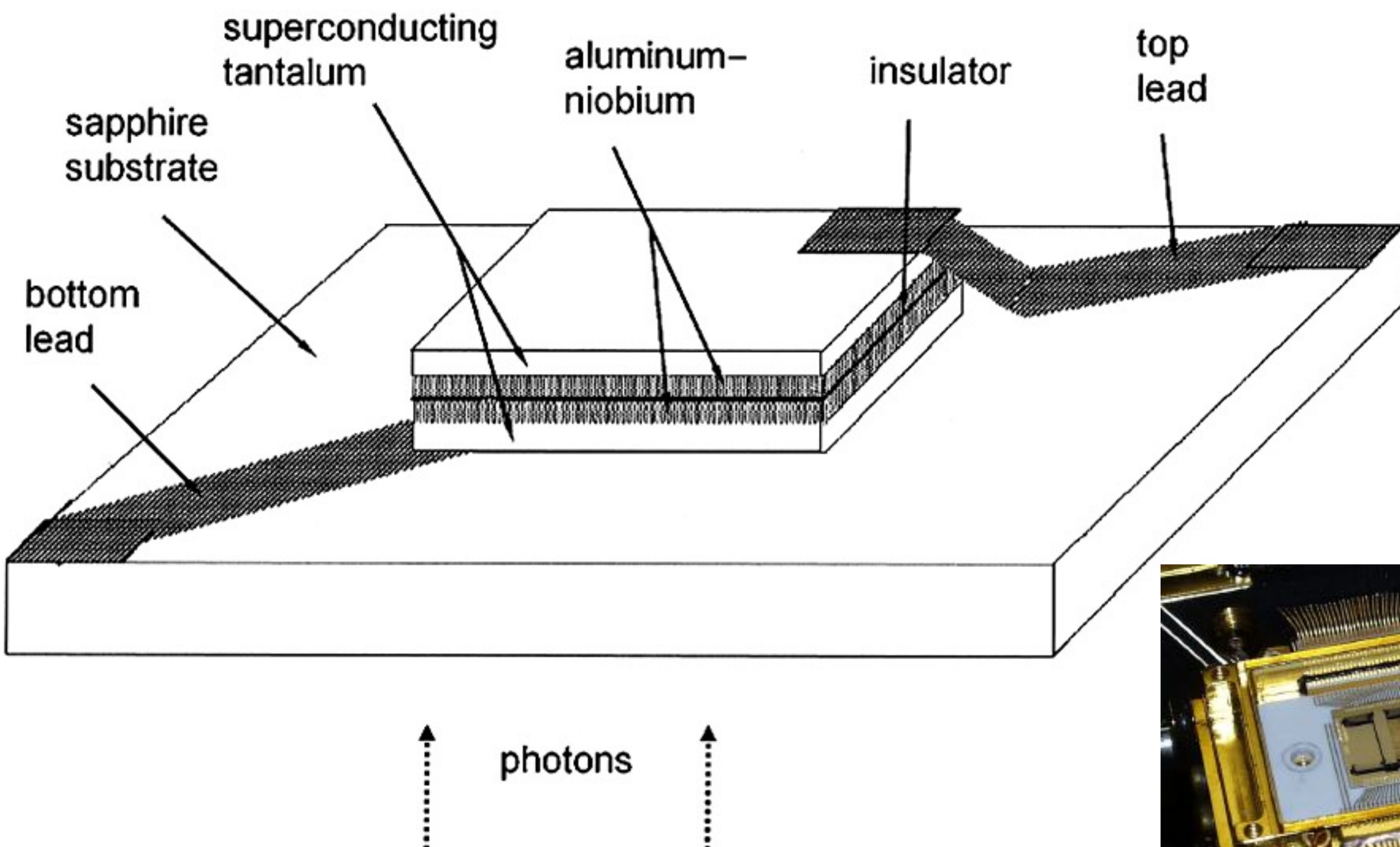


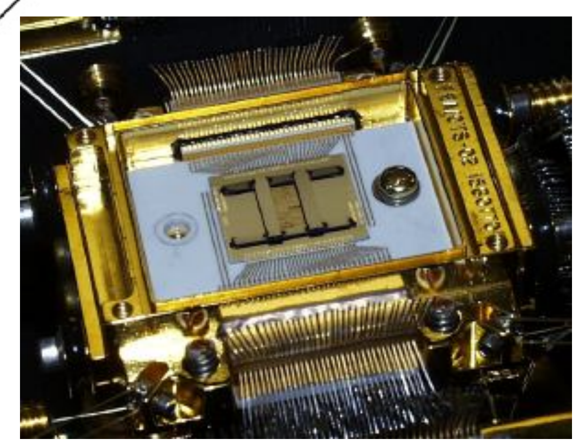




Upcoming: Energy-Resolving Arrays

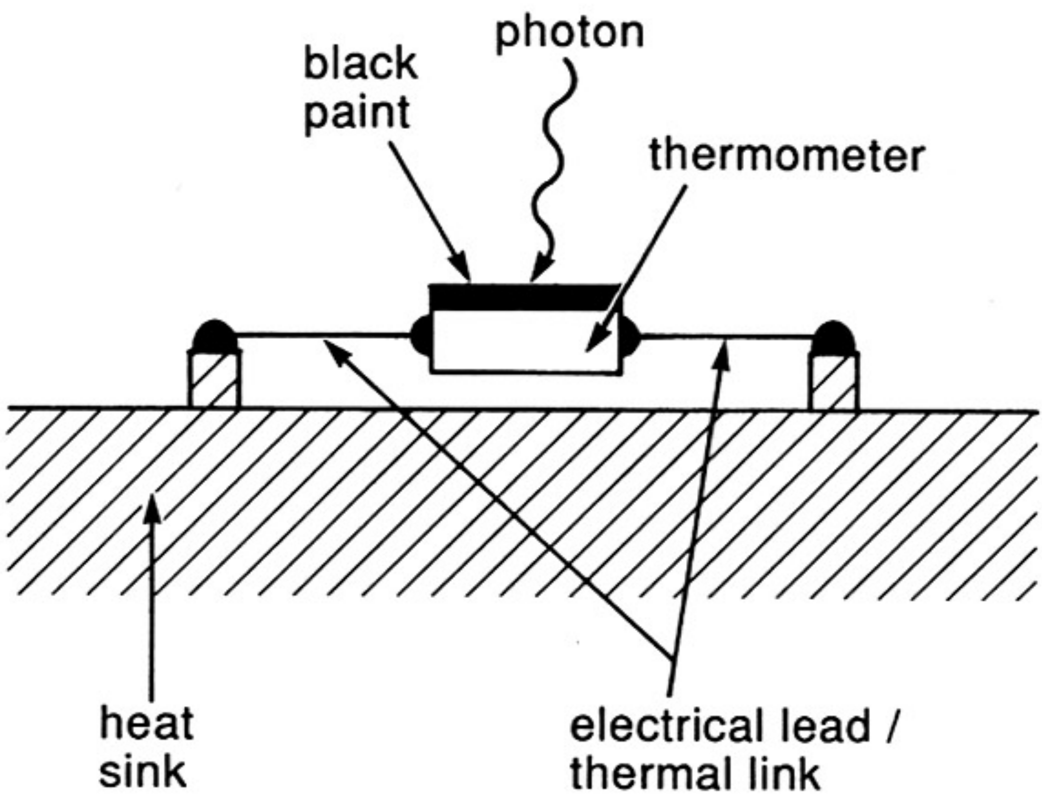
Superconducting Tunnel Junctions (STJ),
And Transition-Edge Sensors (TES)

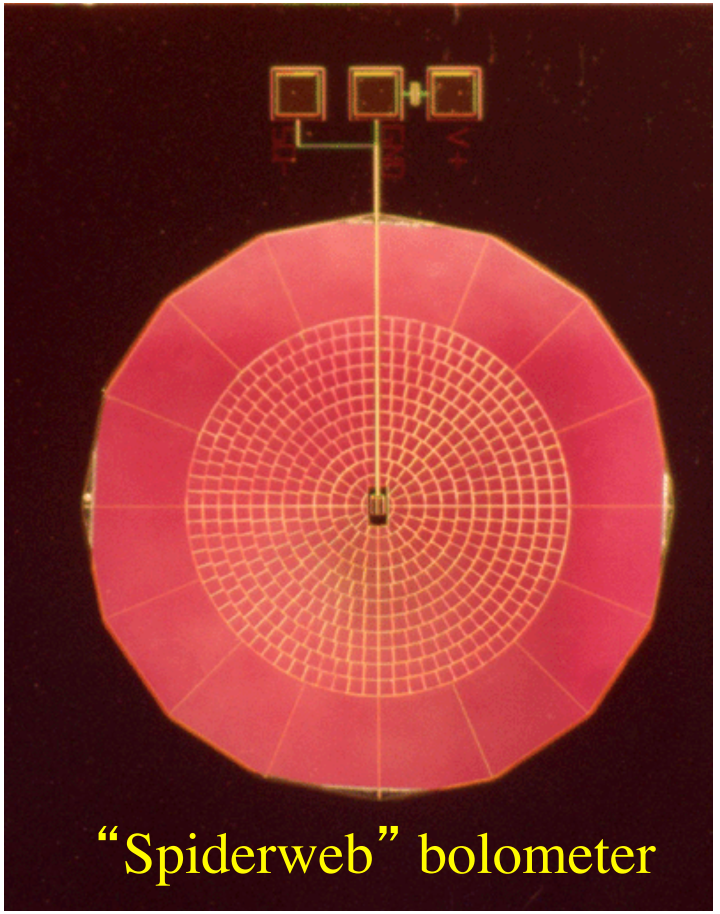




Bolometers

- Measure the energy from a radiation field, usually from a change in resistance of some device as it is heated by the radiation
- Mainly used in FIR/sub-mm/microwave regime

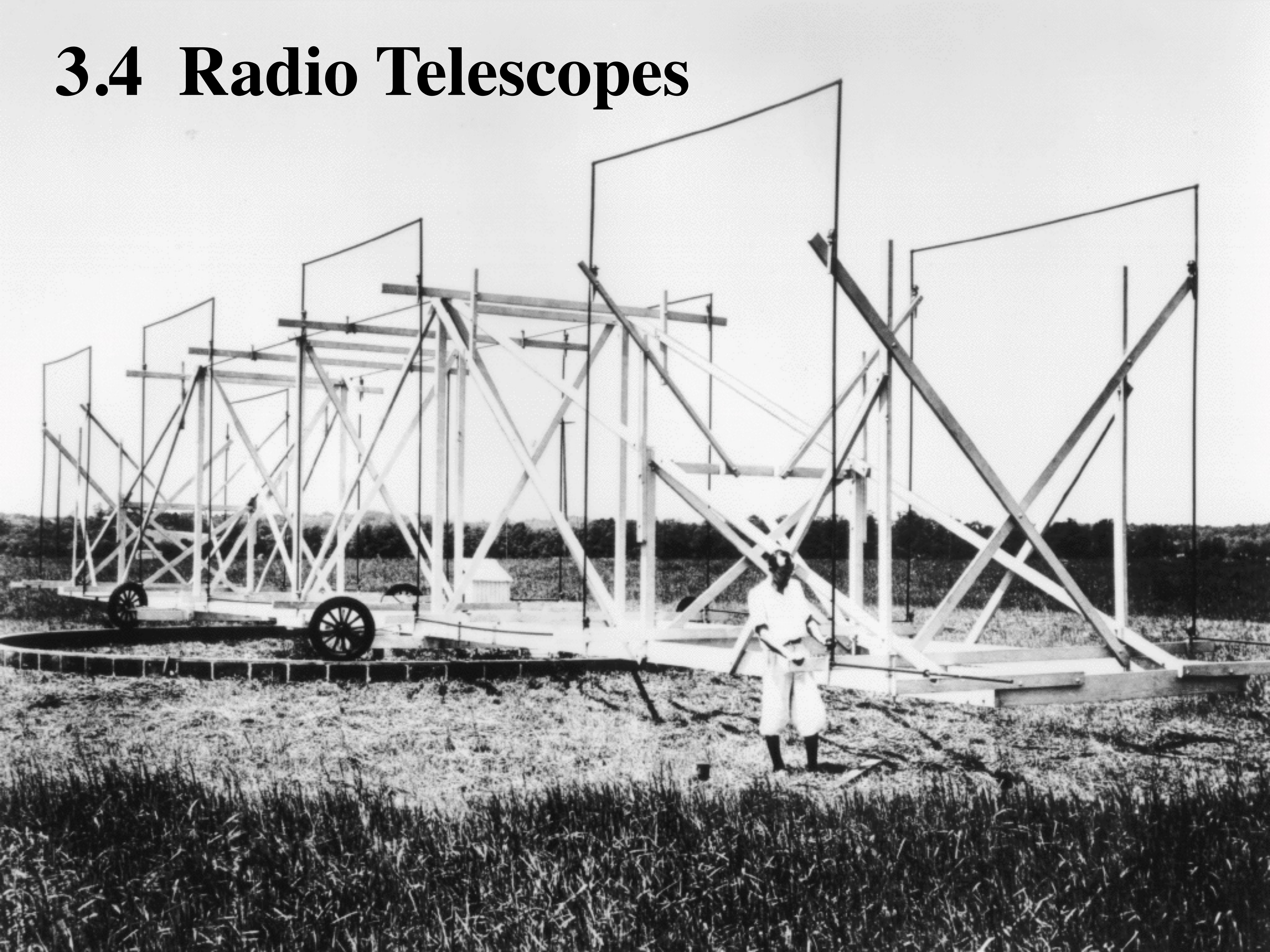




"Spiderweb" bolometer

?

3.4 Radio Telescopes



Single Dish (the bigger the better) …

The Green Bank Telescope (GBT), D = 100 m ⤵

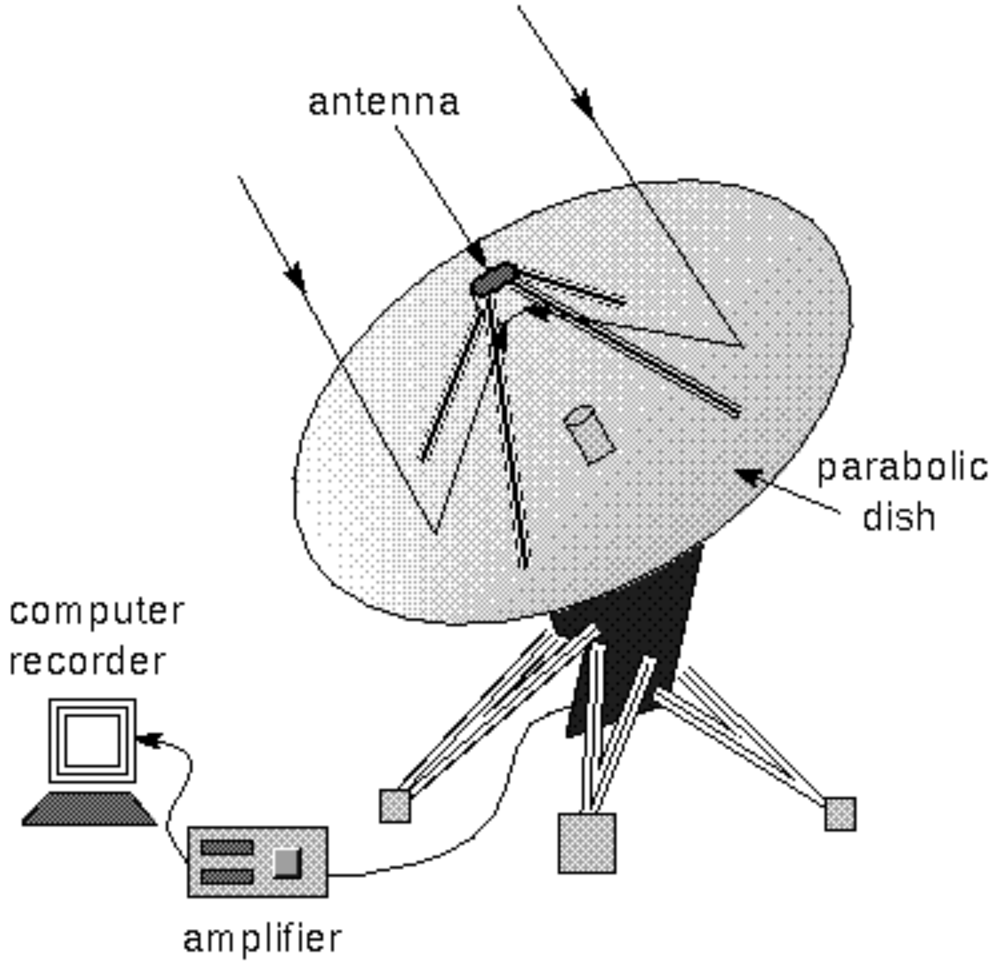
Arecibo, D = 300 m ⤵

… and Interferometers

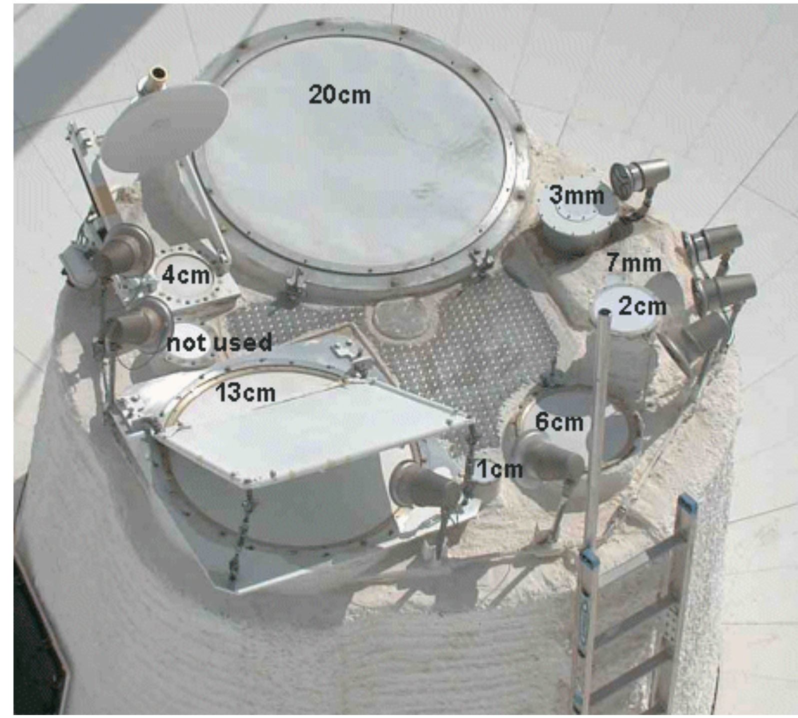
They achieve the angular resolution corresponding to the largest baseline between the elements (dishes), but the collecting area is just the sum …

ALMA Interferometer

How a Radio Telescope Works



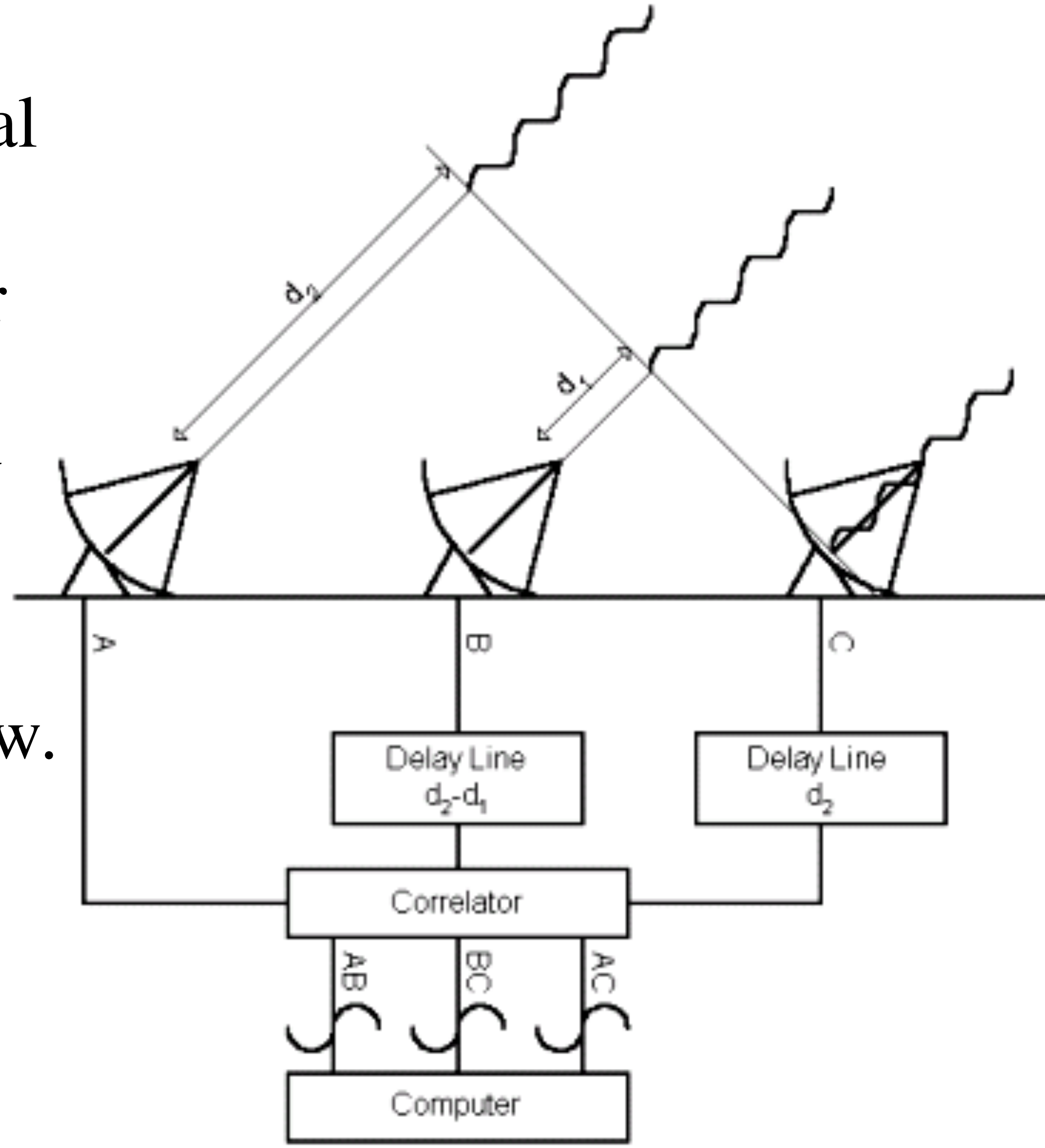
A radio telescope reflects radio waves to a focus at the antenna. Because radio wavelengths are very large, the radio dish must be very large.



VLA instrument feed pedestal

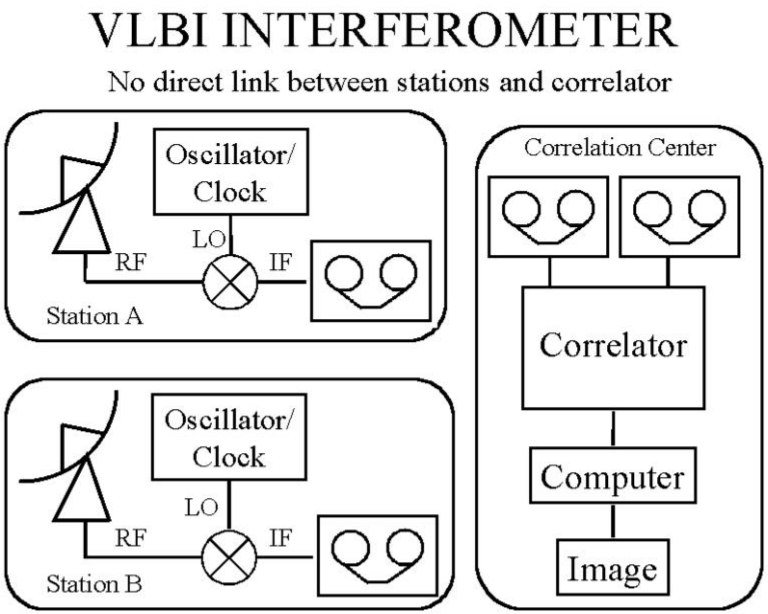
… how interferometer works …

Signals from individual elements are delayed electronically, in order to simulate a flat wavefront, for slightly different arrival directions - thus mapping a field of view.



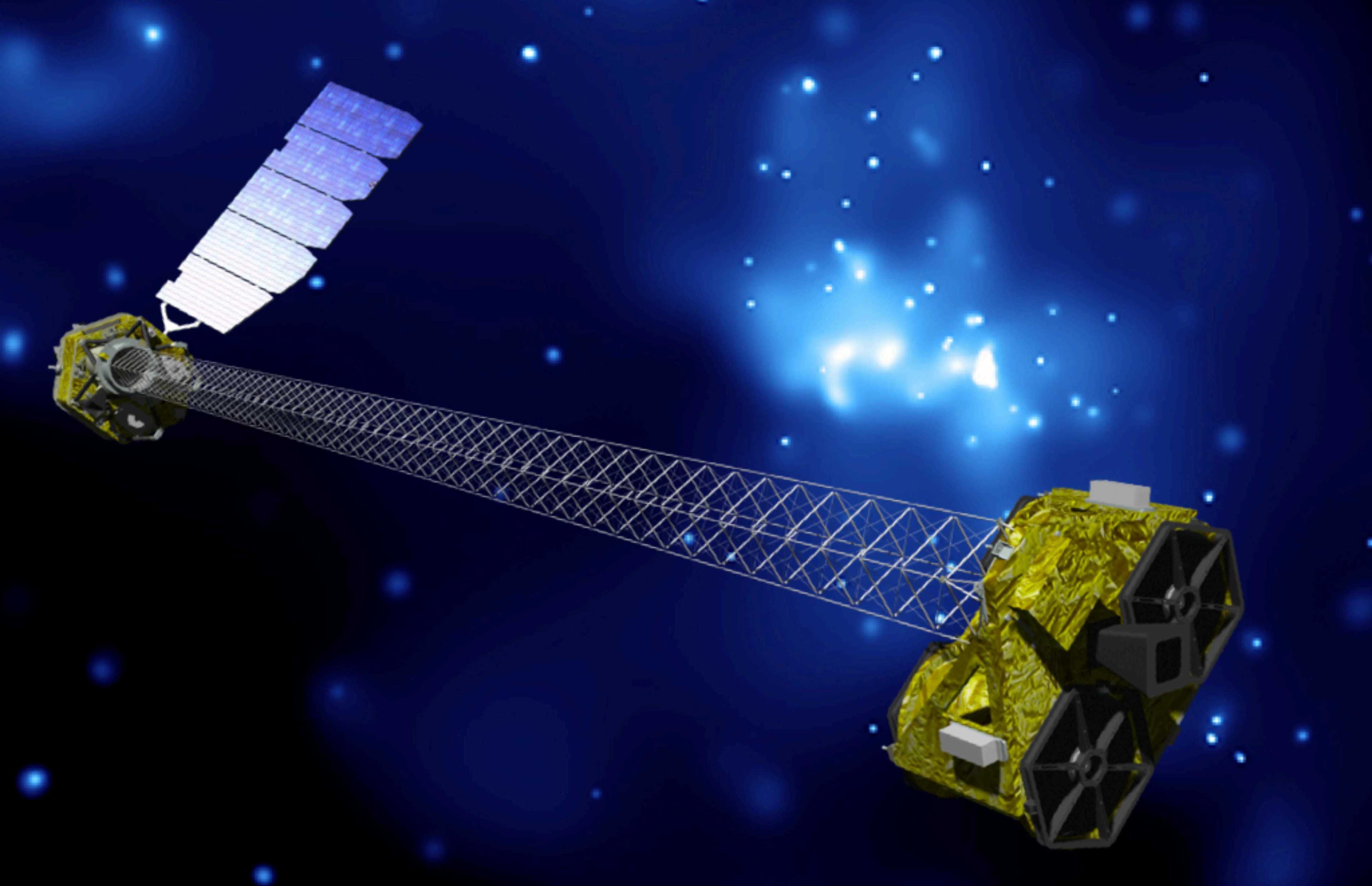
Very Long Baseline Interferometry (VLBI)

- Antennas very far apart (~ Earth size)
  - ★ Resolution very high: milli-arcsec
- Record signals on tape, correlate later
- Now VLBA(rray)



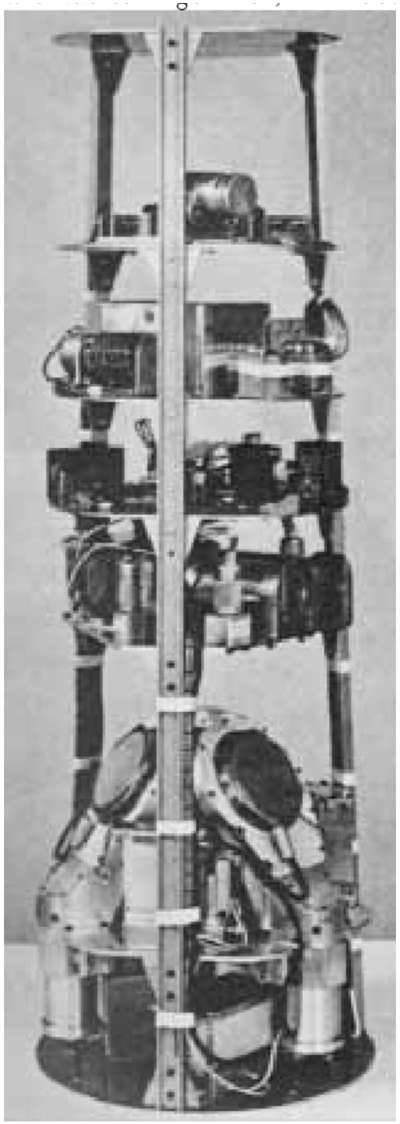
The Future: Square Kilometer Array (SKA)

?



3.5 X-Ray and Gamma-Ray Telescopes

The Birth of X-Ray Astronomy: Rocket Flight (1962)



Looked for the X-rays from the Moon; did not detect them, but discovered the first extrasolar X-ray source (Sco X-1) and the Cosmic X-Ray Background, leading to the Nobel Prize for Giacconi in 2002

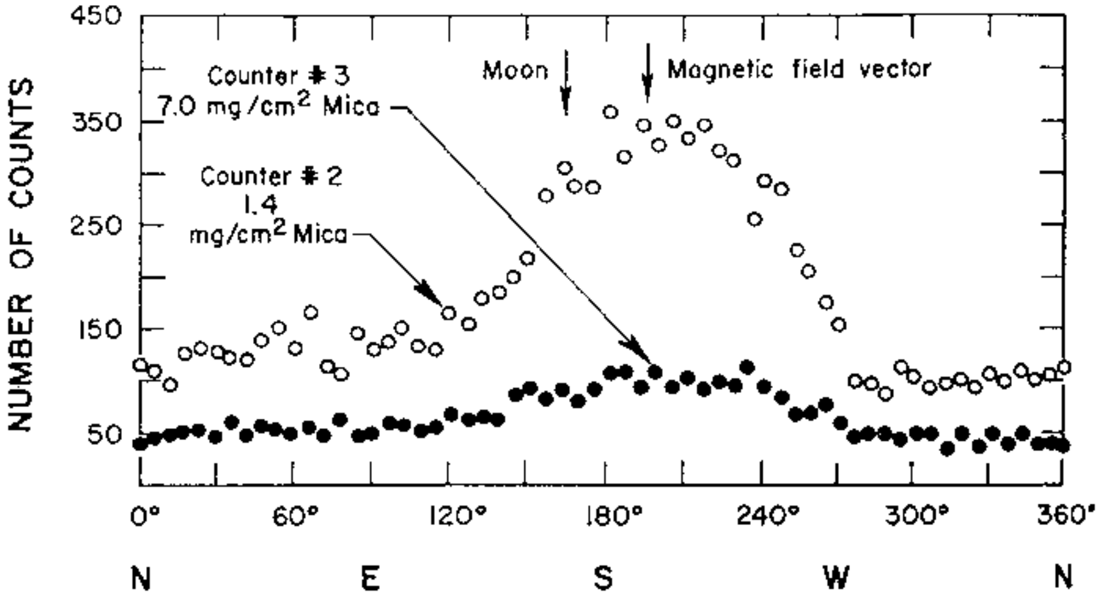
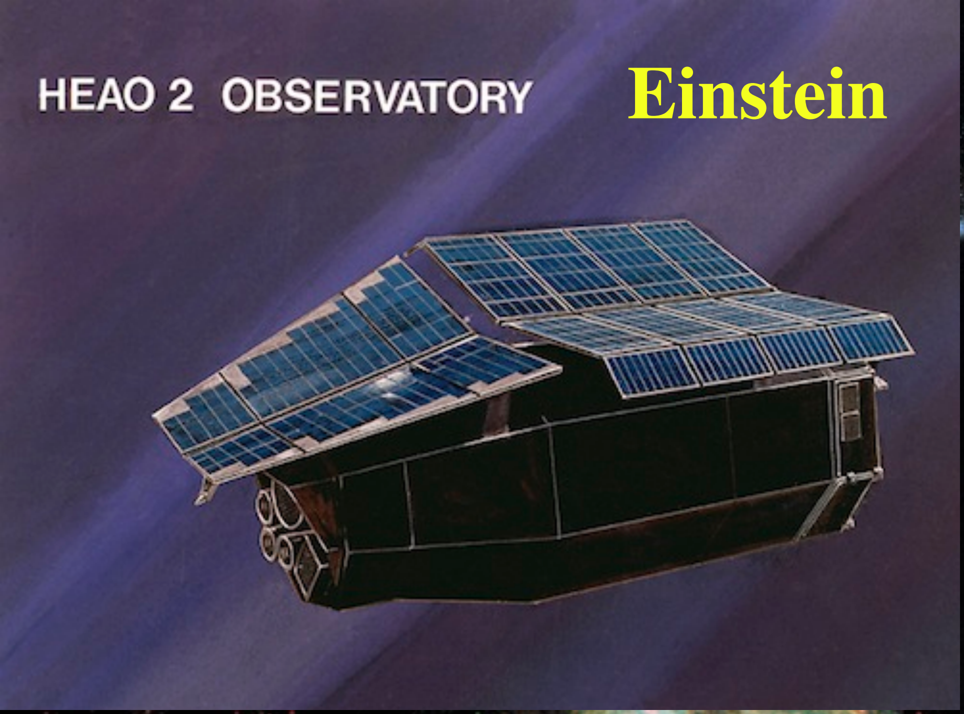
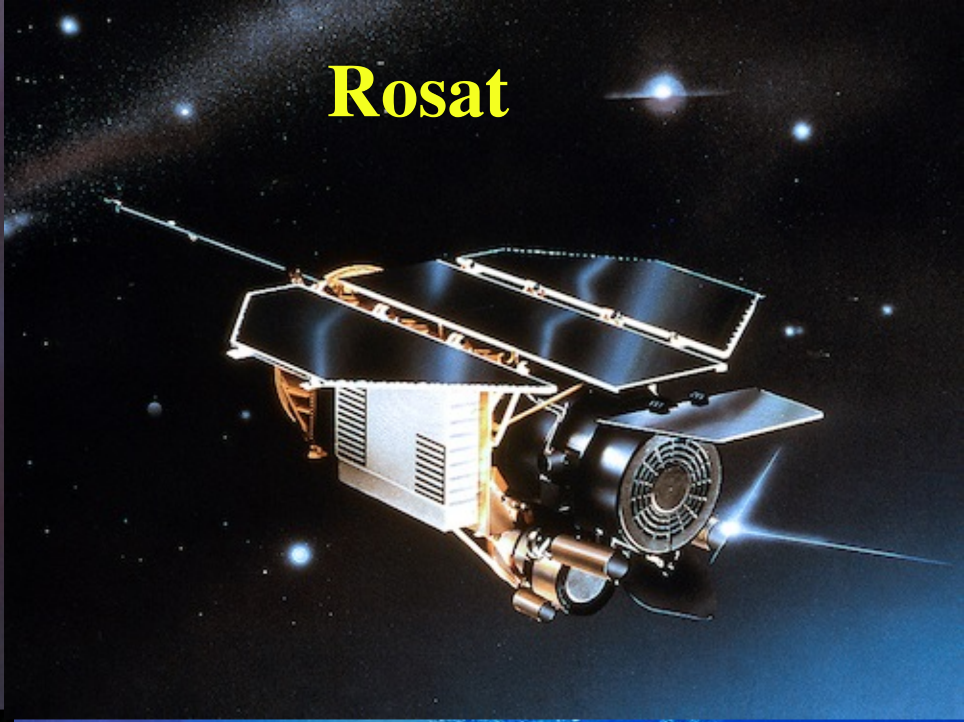
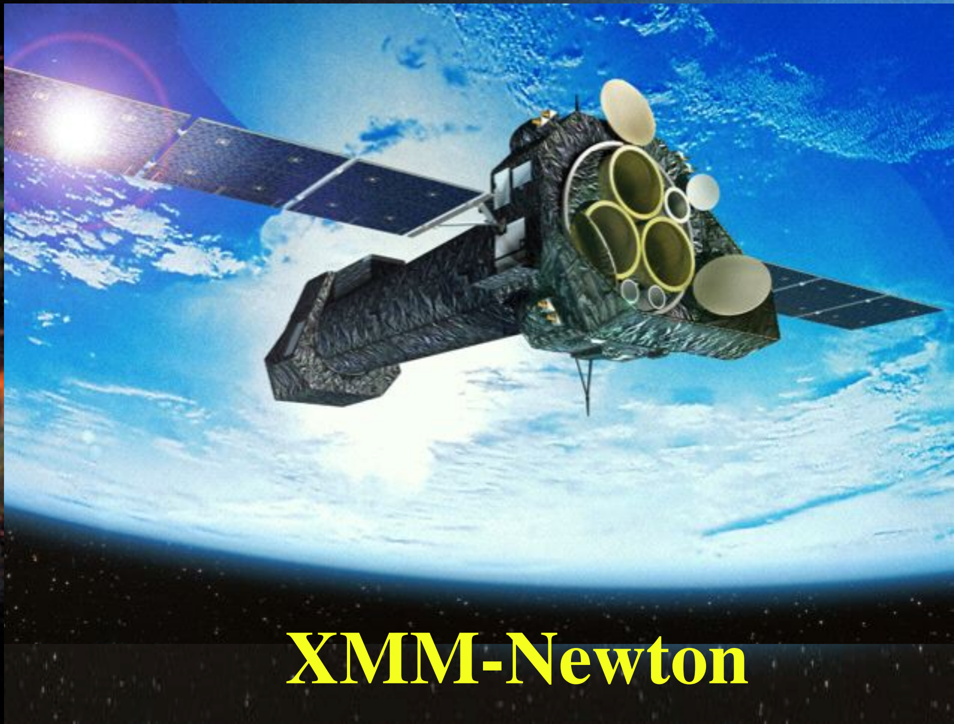
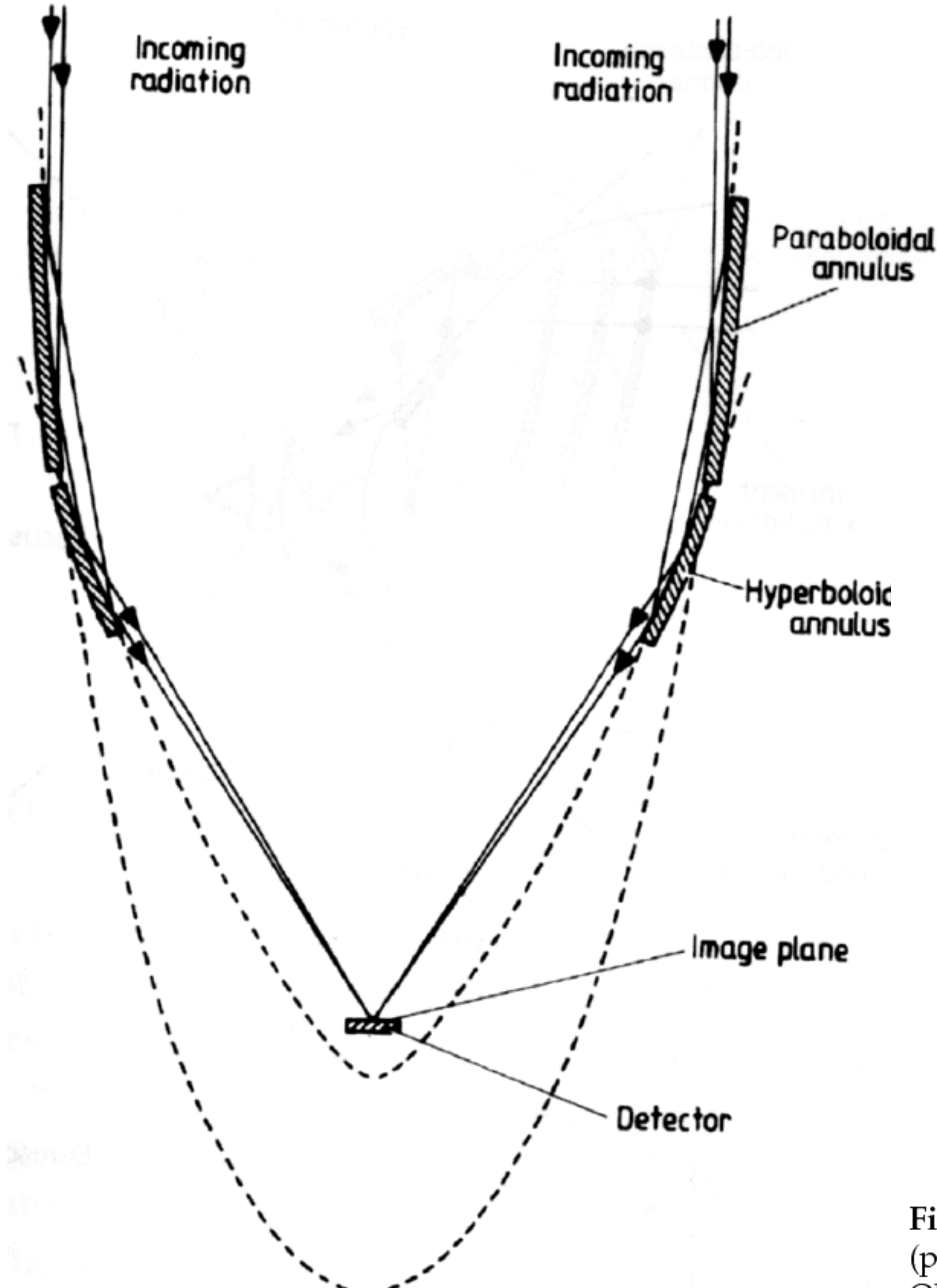


Figure 2. The first observation of Sco X–1 and of the x–ray background in the June, 12, 1962 flight. From Giacconi, *et al.*, 1962.


HEAO 2 OBSERVATORY
Einstein

Rosat

Chandra

XMM-Newton



X-Ray telescopes:

Grazing incidence mirrors

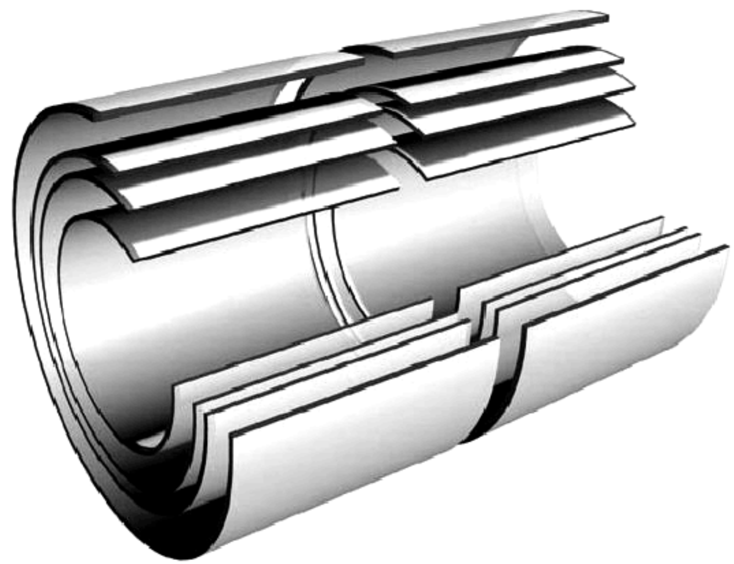
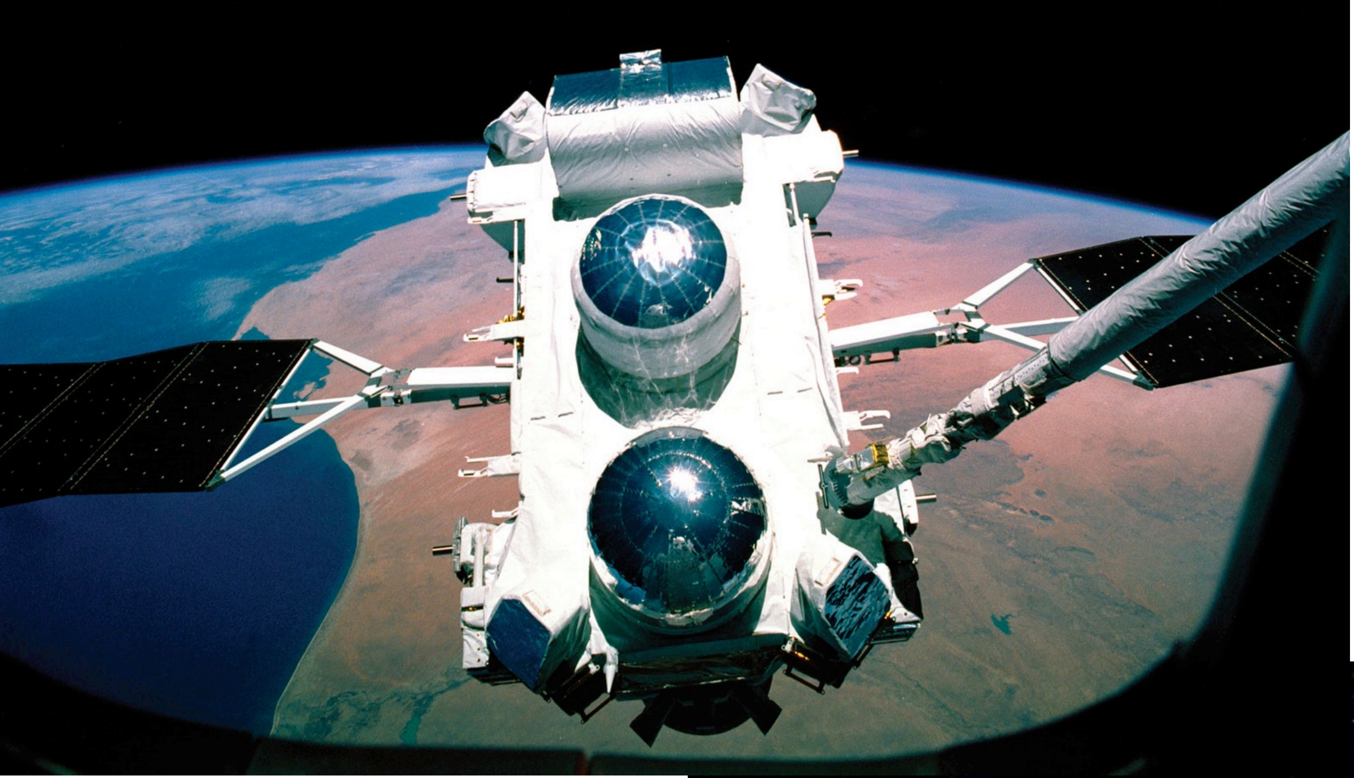


Figure 3. Cutaway schematic drawing of the nested four shells (paraboloid and hyperboloids) of the Chandra X-ray Observatory (courtesy of the Raytheon Co).

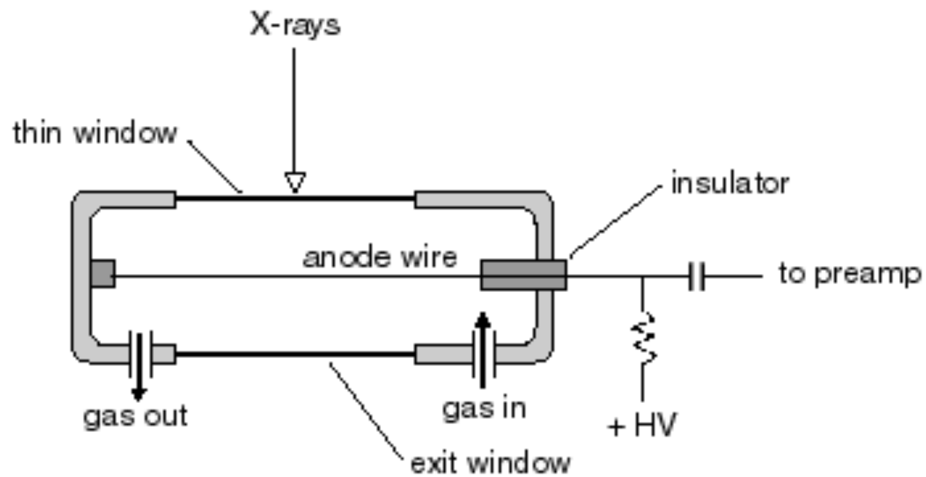


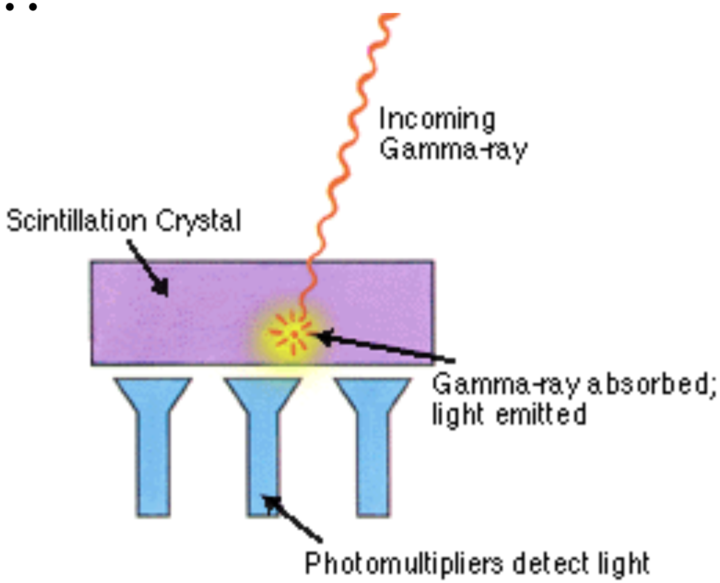
Compton Gamma-Ray Observatory

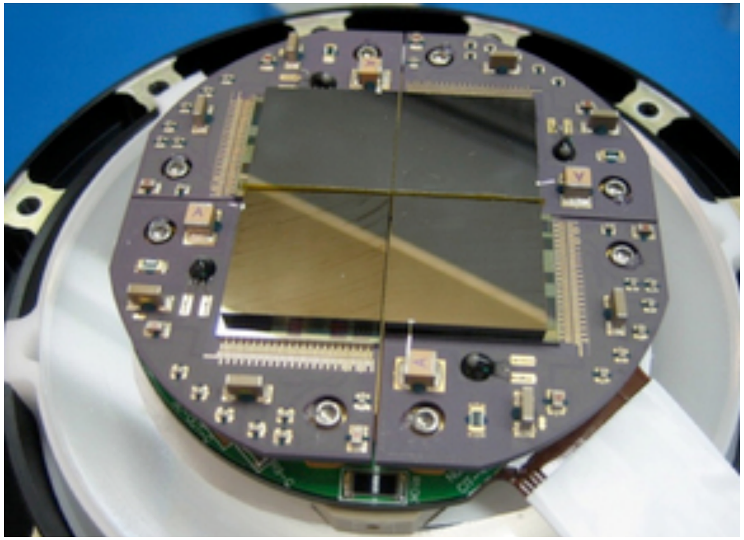
Fermi

X-Ray and Gamma Ray Detectors

- Proportional counters
- Scintillation crystals
- X-ray CCDs
- Solid state CdZnTe arrays
- …

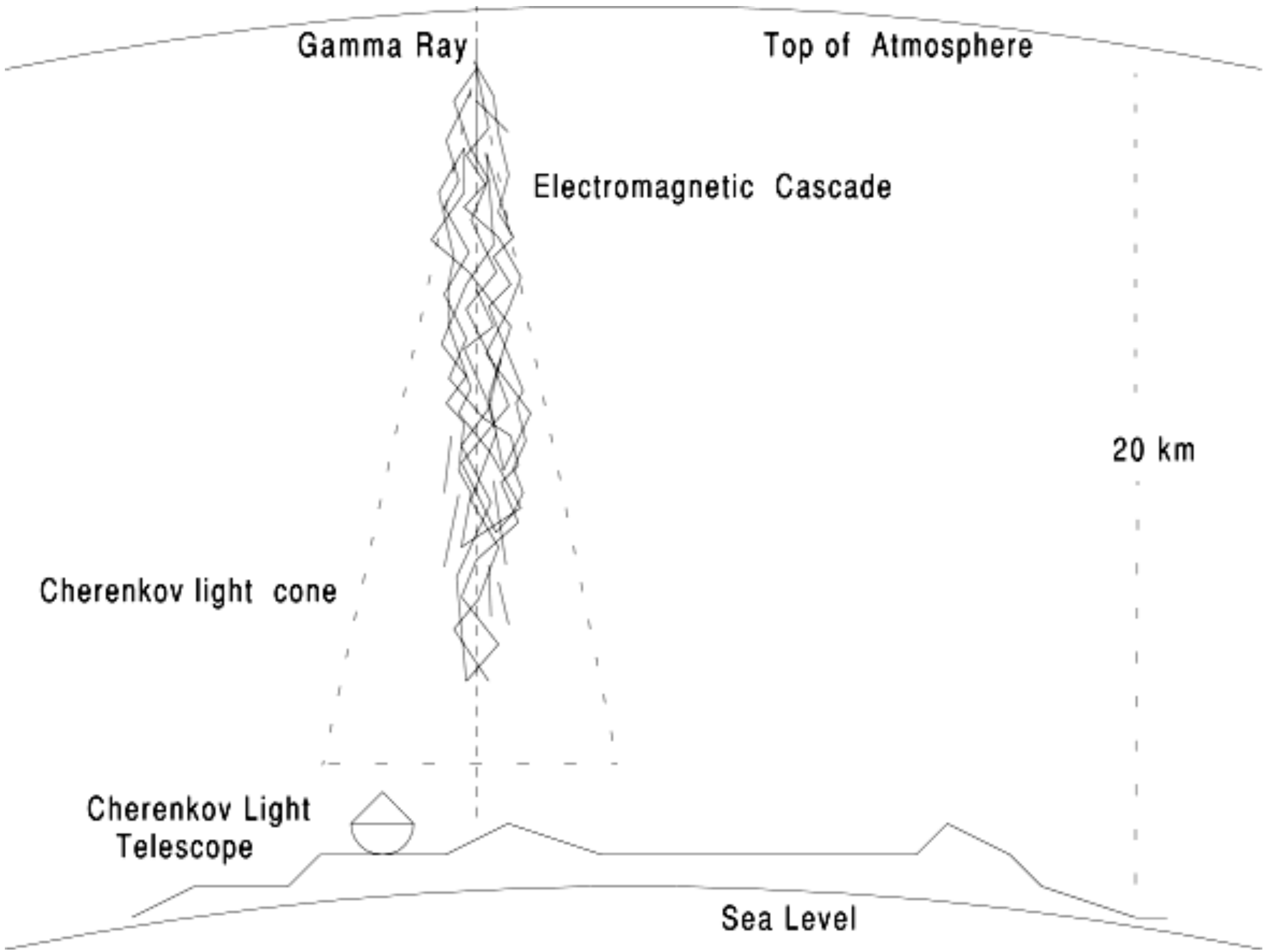




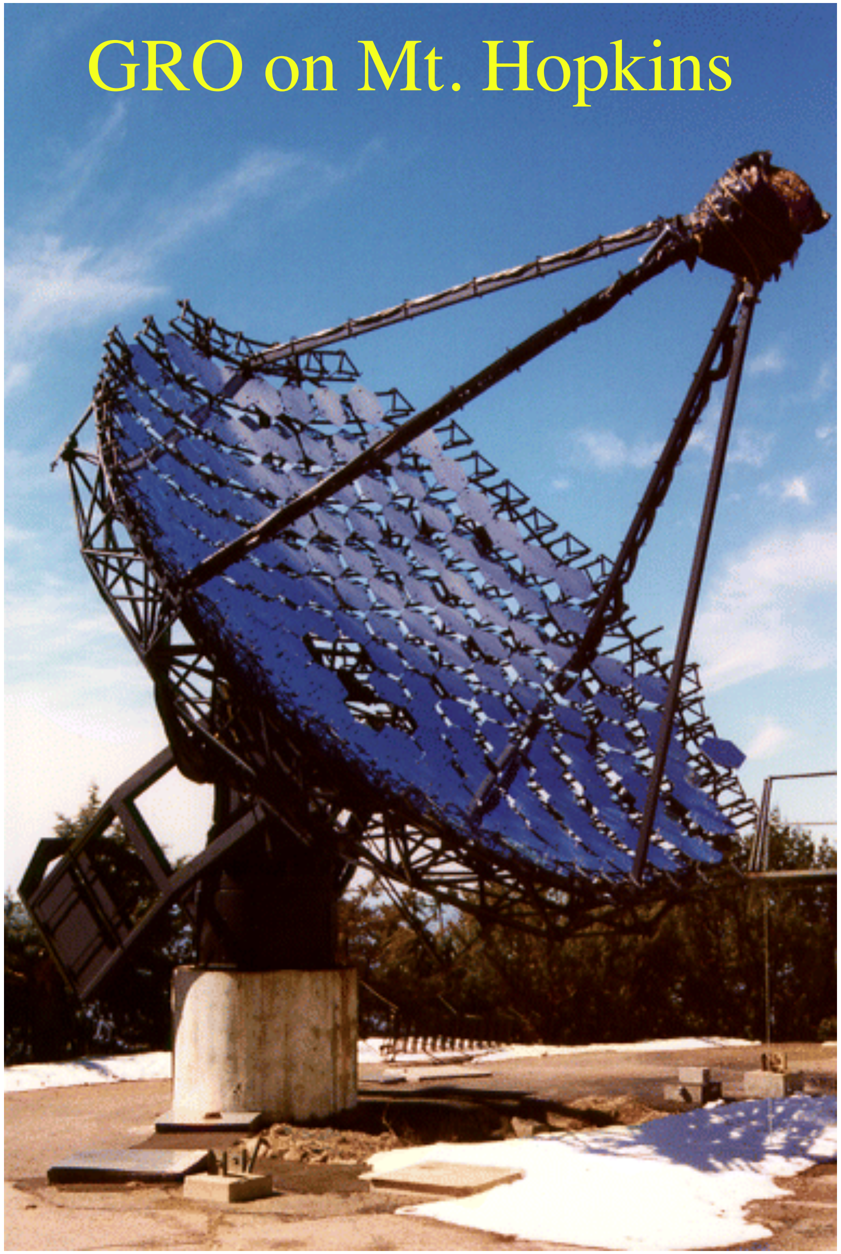


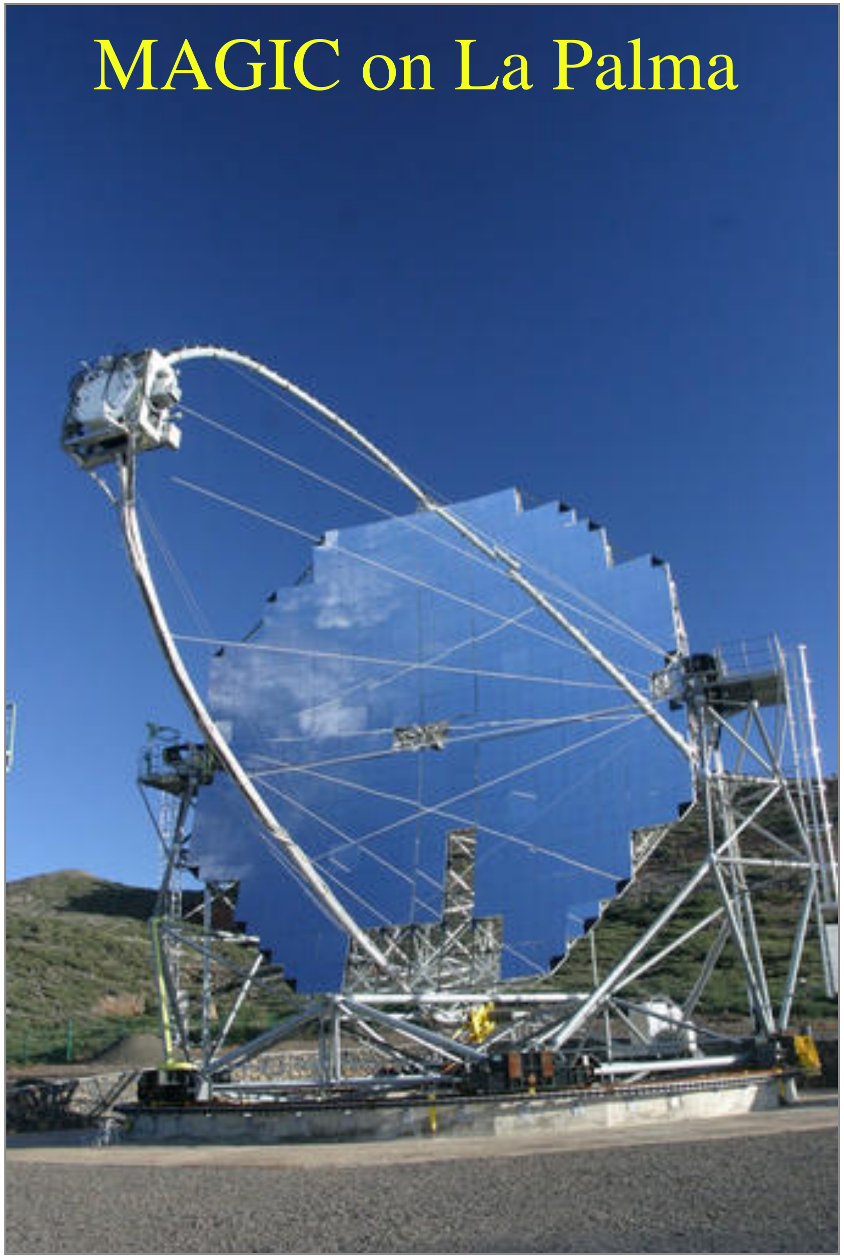
- Air Cerenkov detectors

Detecting Ultra-High Energy Gamma Rays



High-Energy Gamma-Ray (Cherenkov) Telescopes





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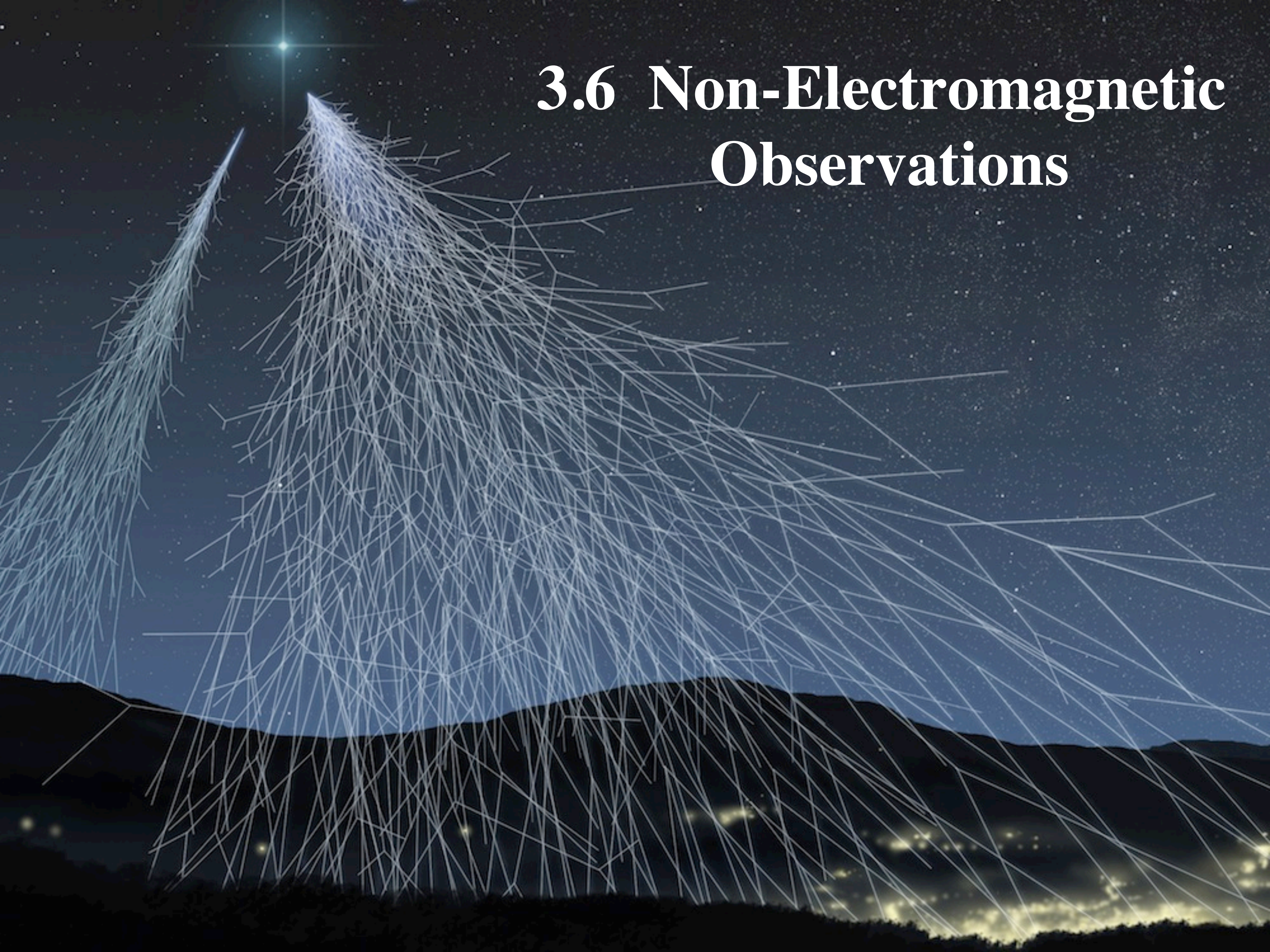
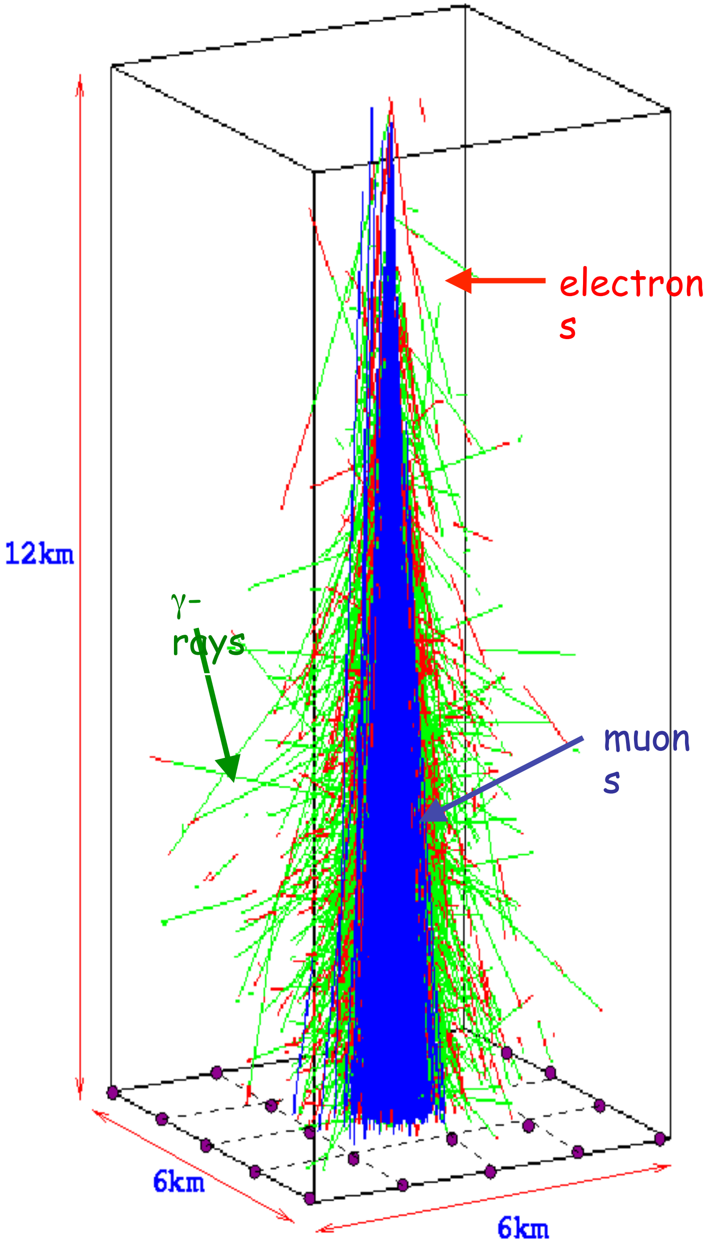
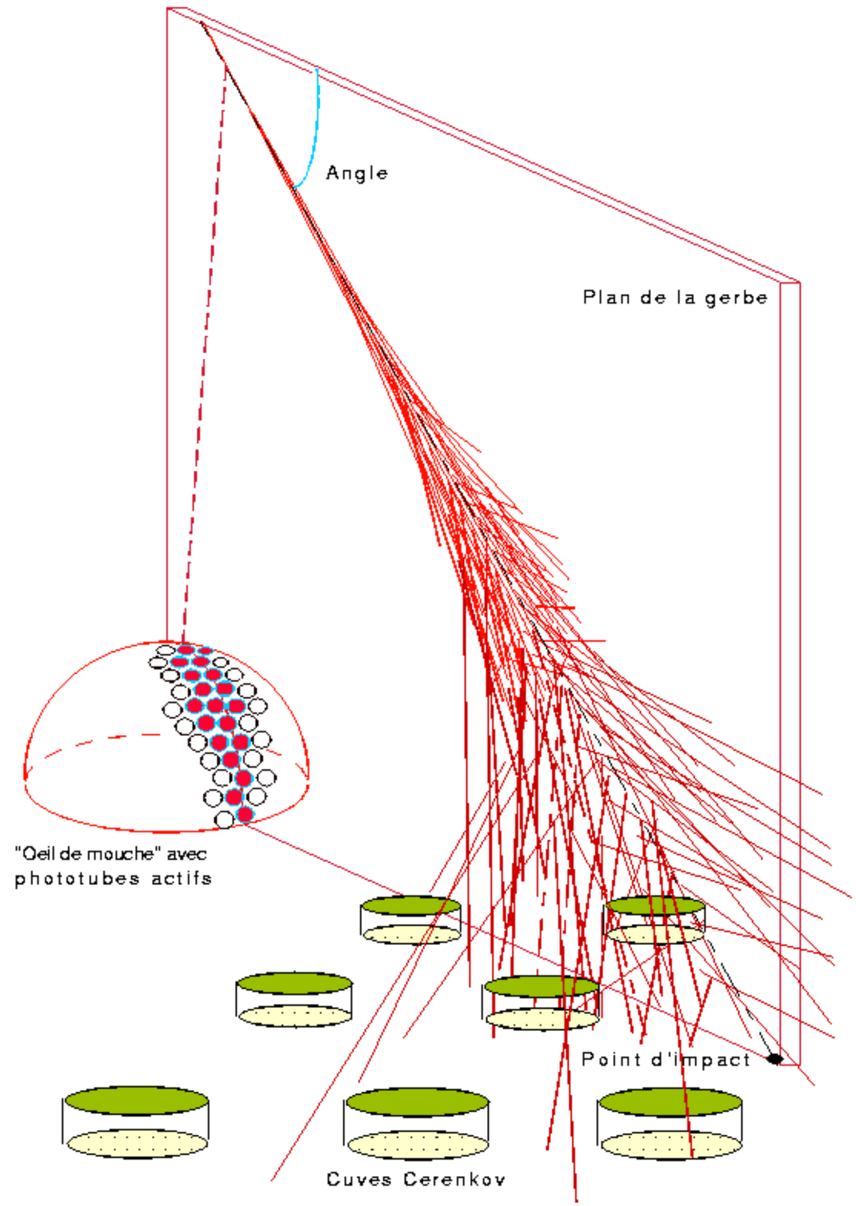
3.6 Non-Electromagnetic Observations



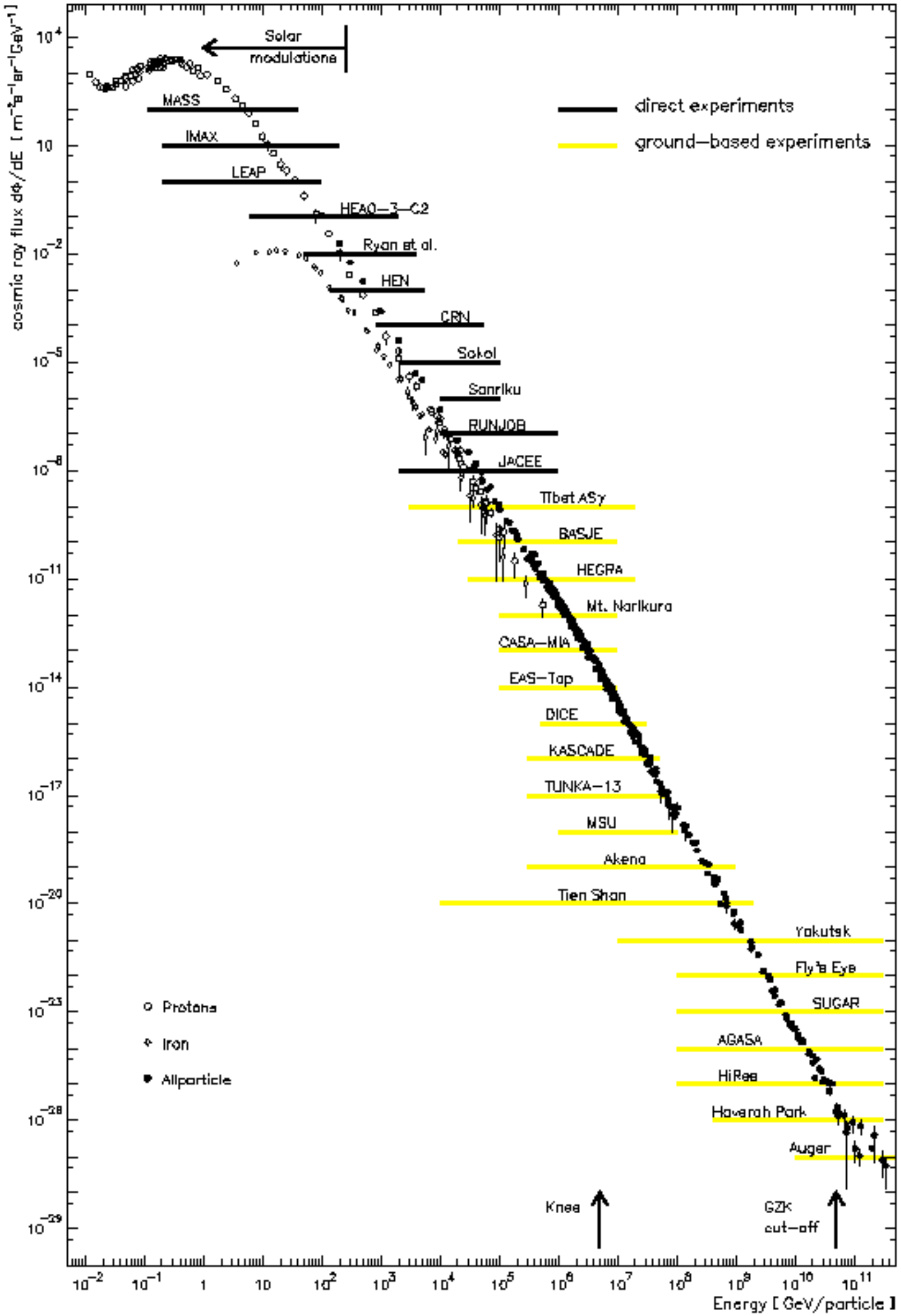
High-Energy Cosmic Rays: Atmospheric Showers





High-Energy Cosmic Rays

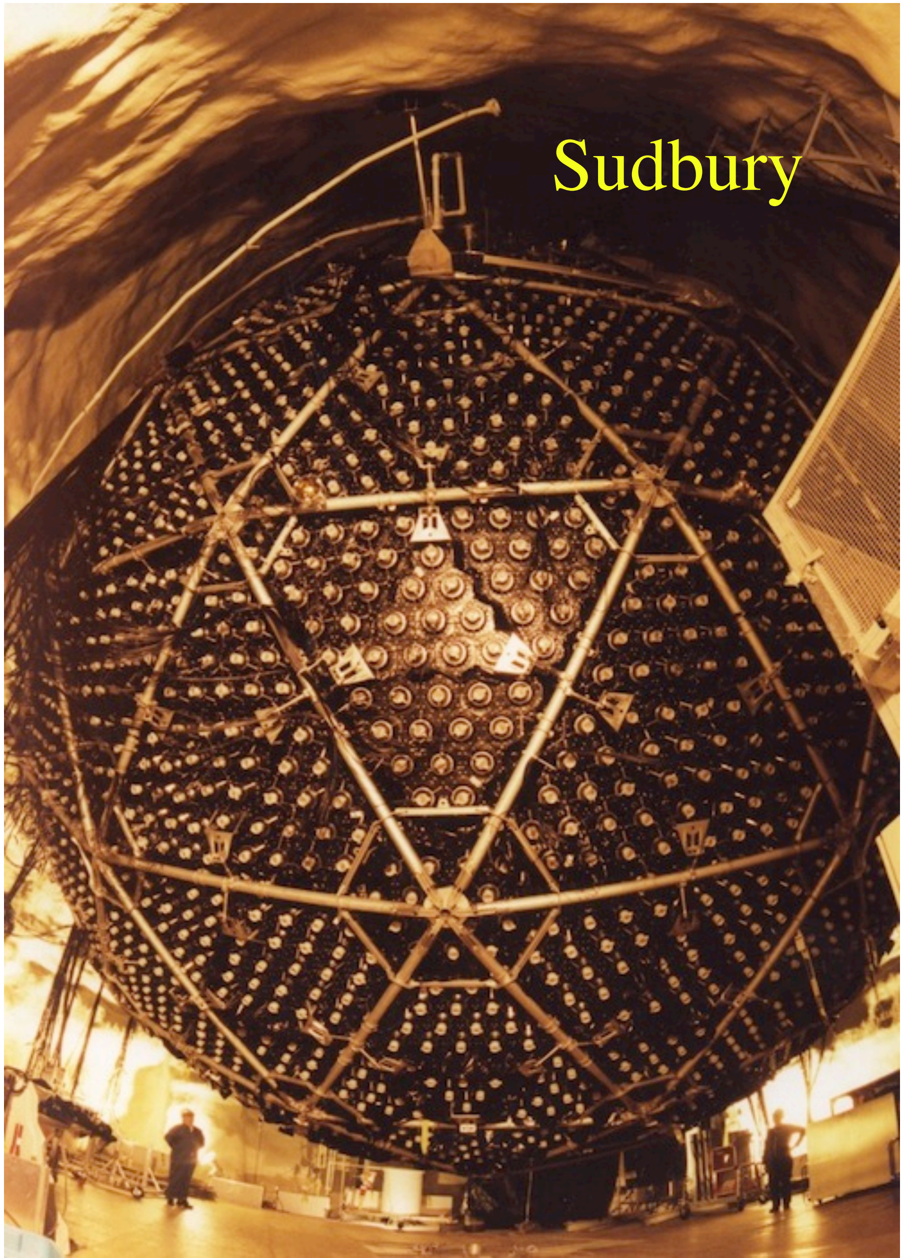
The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux!

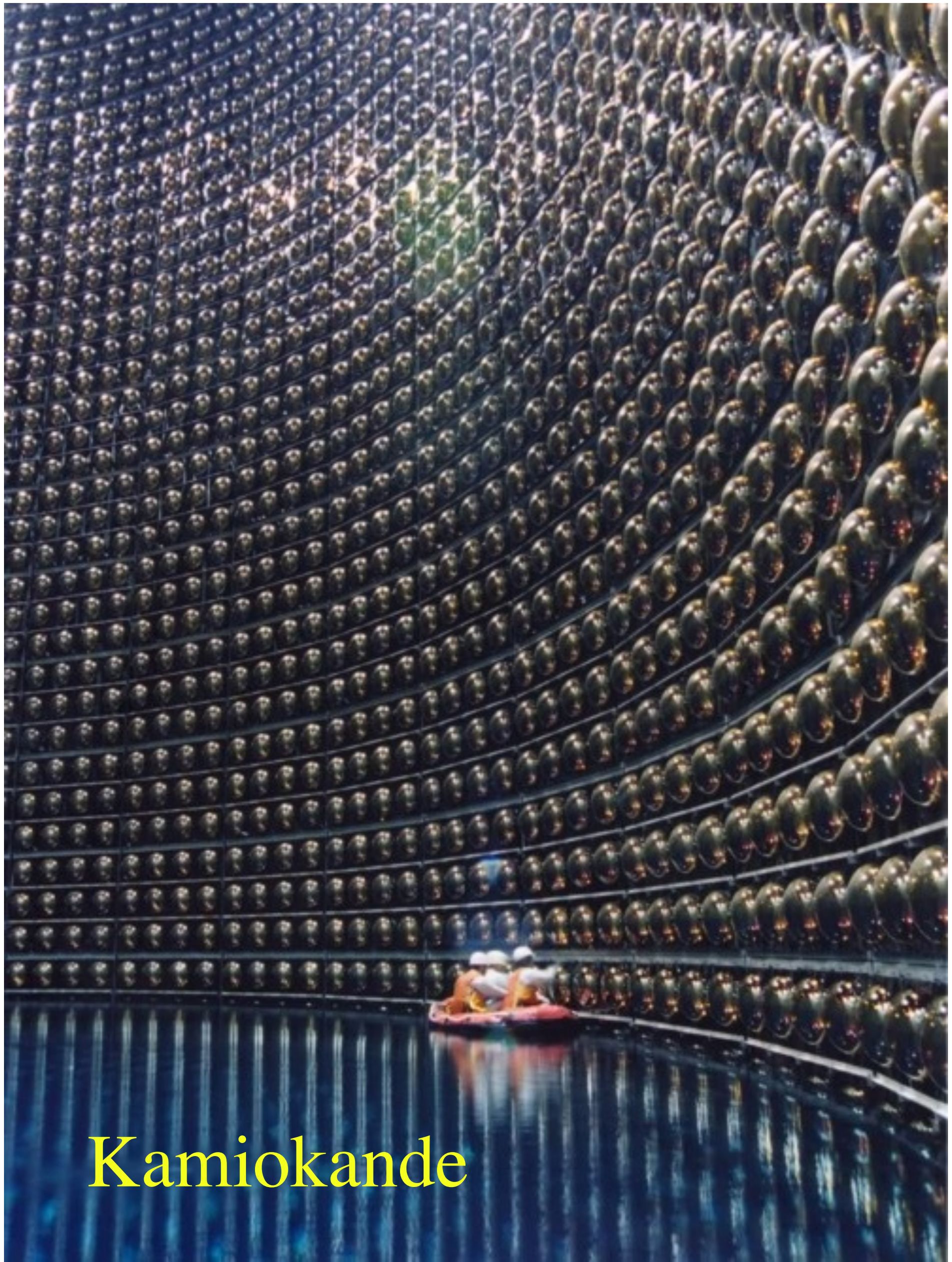


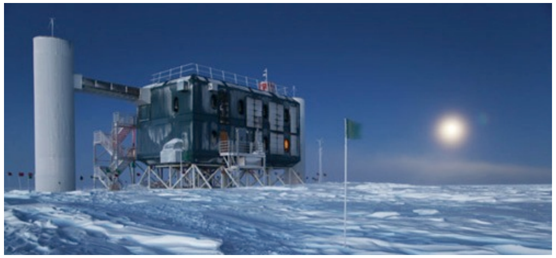
Pierre Auger
Observatory concept

Milagro:

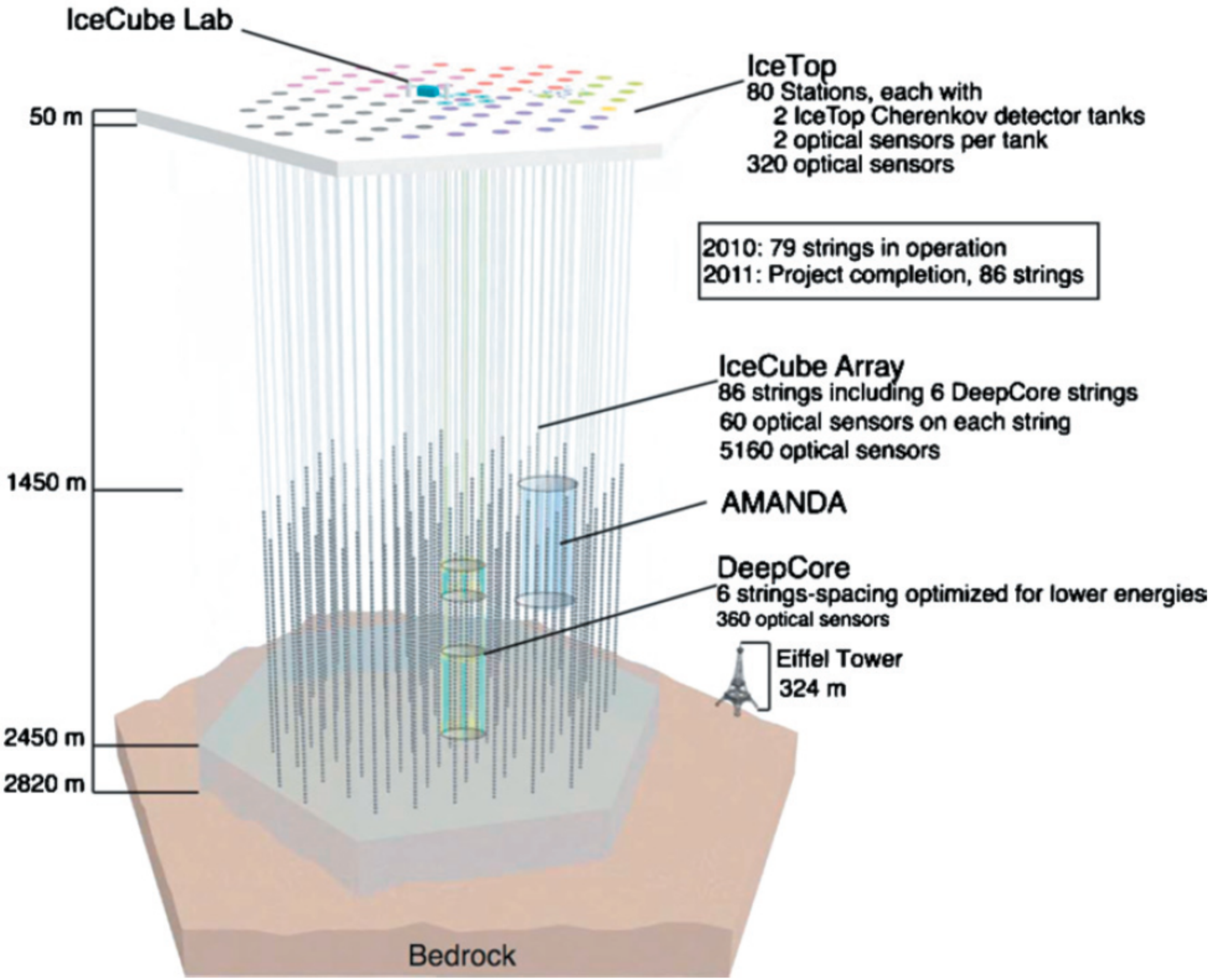
Neutrino Detectors

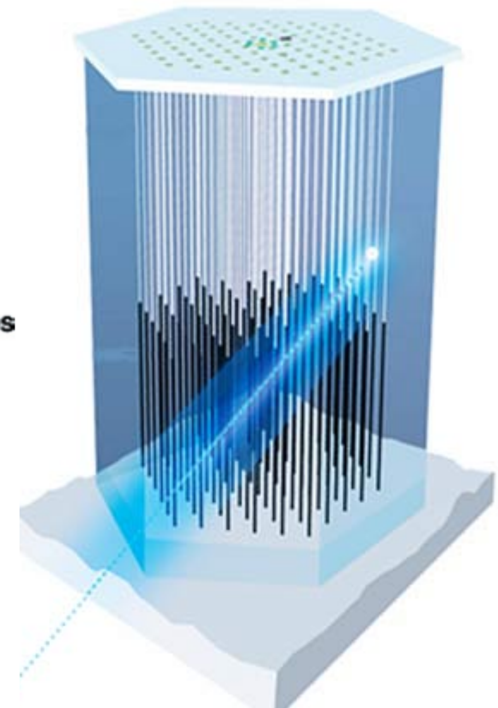


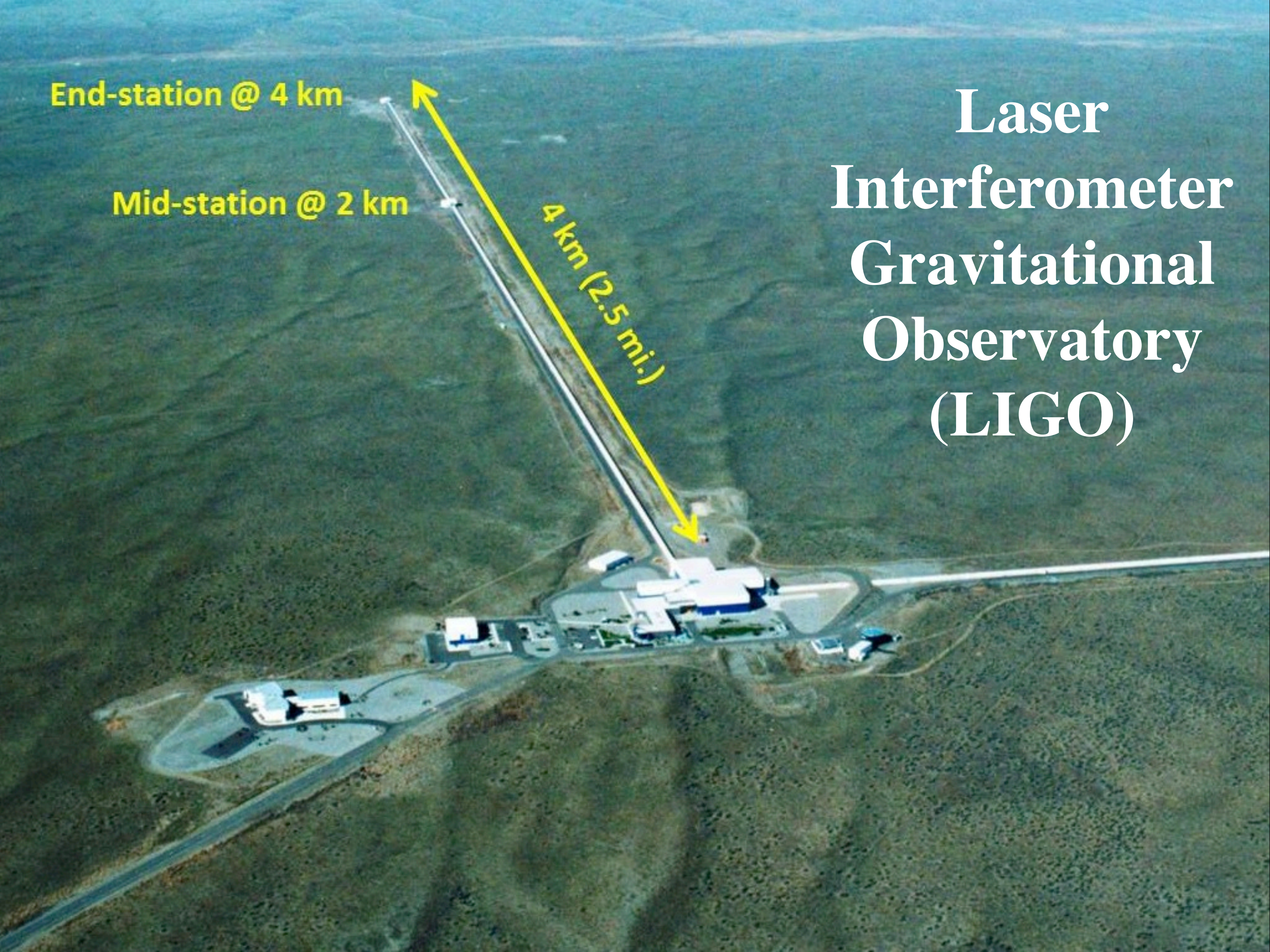




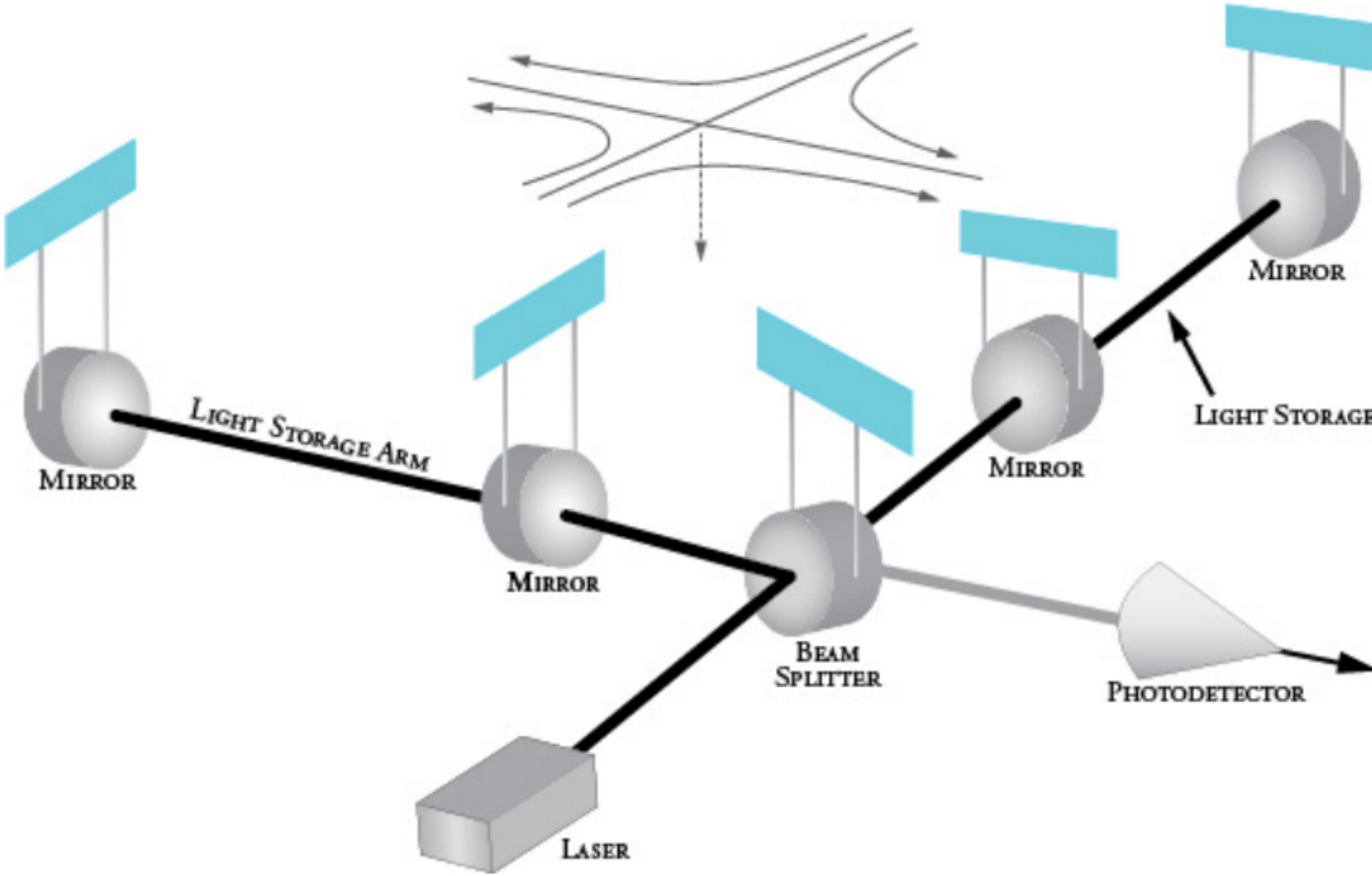
IceCube Neutrino Observatory @ South Pole






Laser
Interferometer
Gravitational
Observatory
(LIGO)
End-station @ 4 km
Mid-station @ 2 km
4 km (2.5 mi.)

How LIGO works: a laser interferometer



Measurement precision: 1 / 1,000,000,000,000,000,000,000

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