Astronomical Observing Techniques 2019

Lecture 4: Eyes to the Skies

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http://astron.nl/new-sky-map-detects-hundreds-thousands-unknown-galaxies

Chris Evans
@ChrisEvans

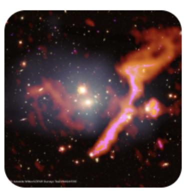
Follow

I can't even describe how much I love this.

"their radio signals have traveled billions of light years before reaching earth" (ONE light year is 5.8 trillion miles)

"black holes more than a BILLION times the mass of our sun"

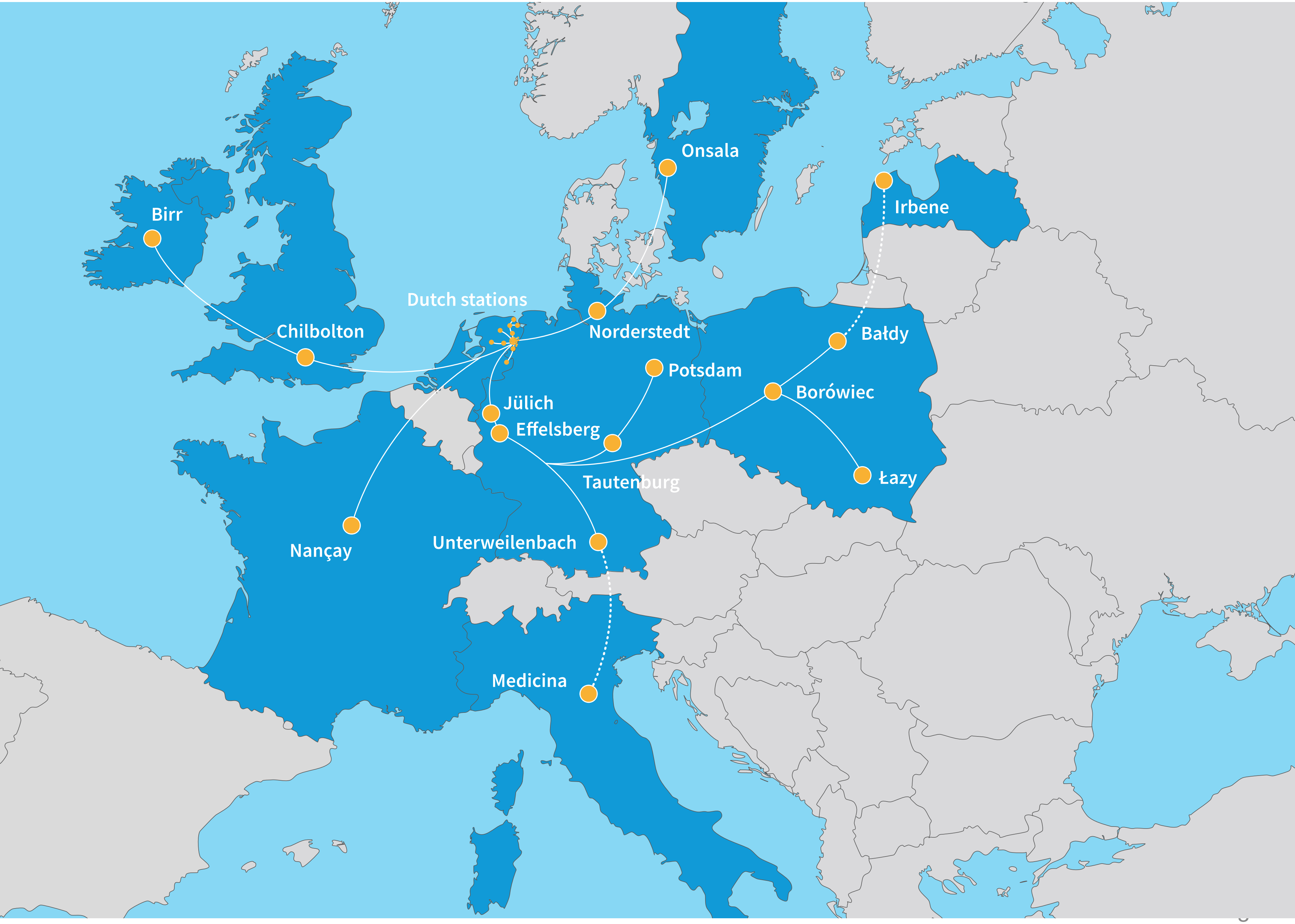
Think about these numbers. I'm overwhelmed with awe.



Low Frequency Array @LOFAR
Big sky survey by @LOFAR has detected hundreds of thousands of previously undetected galaxies, shedding new light on black holes & how clusters of galaxies evolve. The first 26 articles have just been published in @AandA_journal astron.nl/new-sky-map-de…

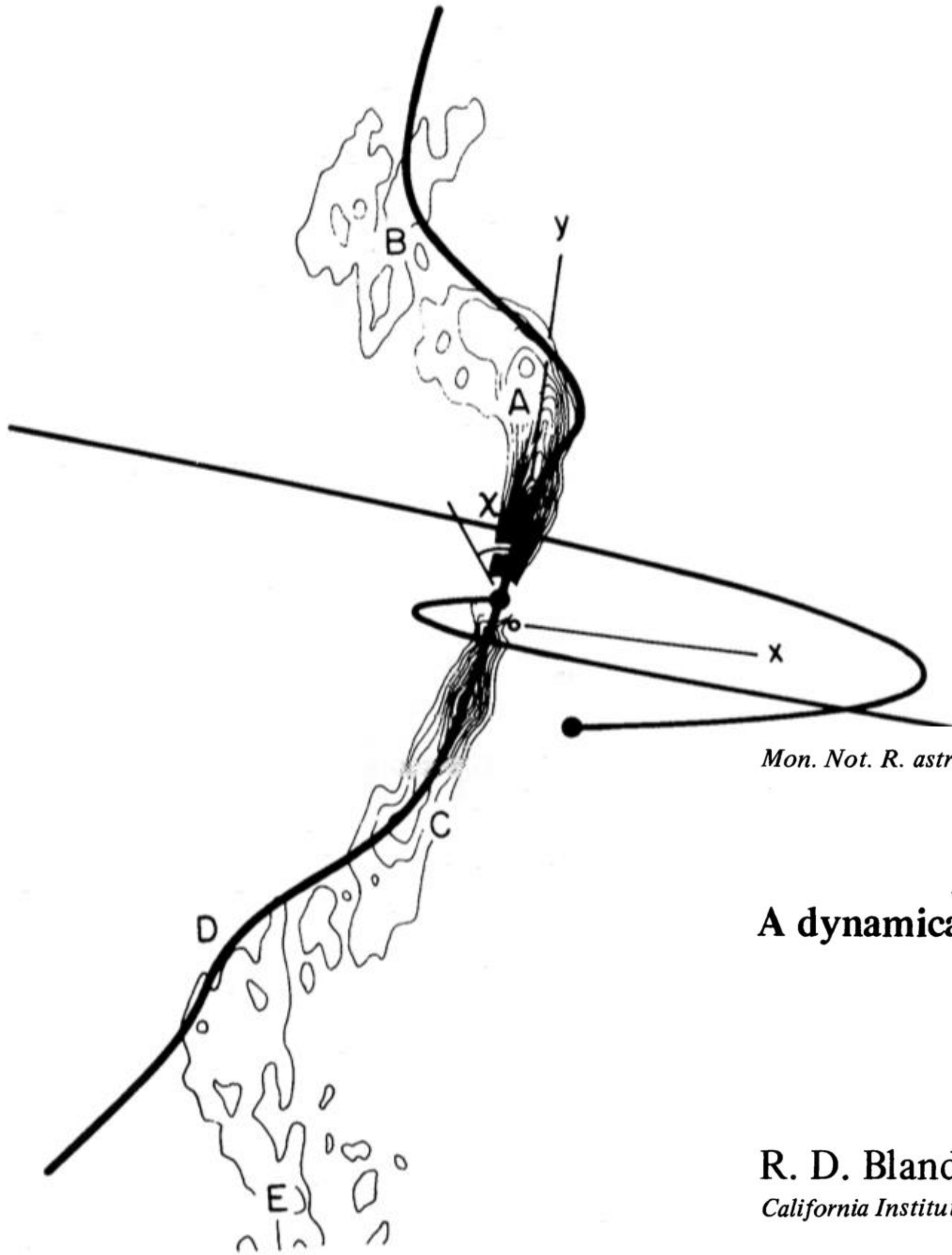
7:50 AM - 19 Feb 2019


LOFAR
(LOw-FREQUENCY ARRAY)


Onsala
Irbene
Birr
Dutch stations
Chilbolton
Norderstedt
Bałdy
Potsdam
Borówiec
Jülich
Effelsberg
Tautenburg
Łazy
Nançay
Unterweilenbach
Medicina

Zooming in on extra-galactic objects
observed by the LOFAR radio telescope


LOFAR

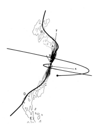


Mon. Not. R. astr. Soc. (1978) **185**, 527–538

A dynamical interpretation of the radio jet in 3C 31

R. D. Blandford and V. Icke *W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

Received 1978 May 3; in original form 1978 March 28



B
y
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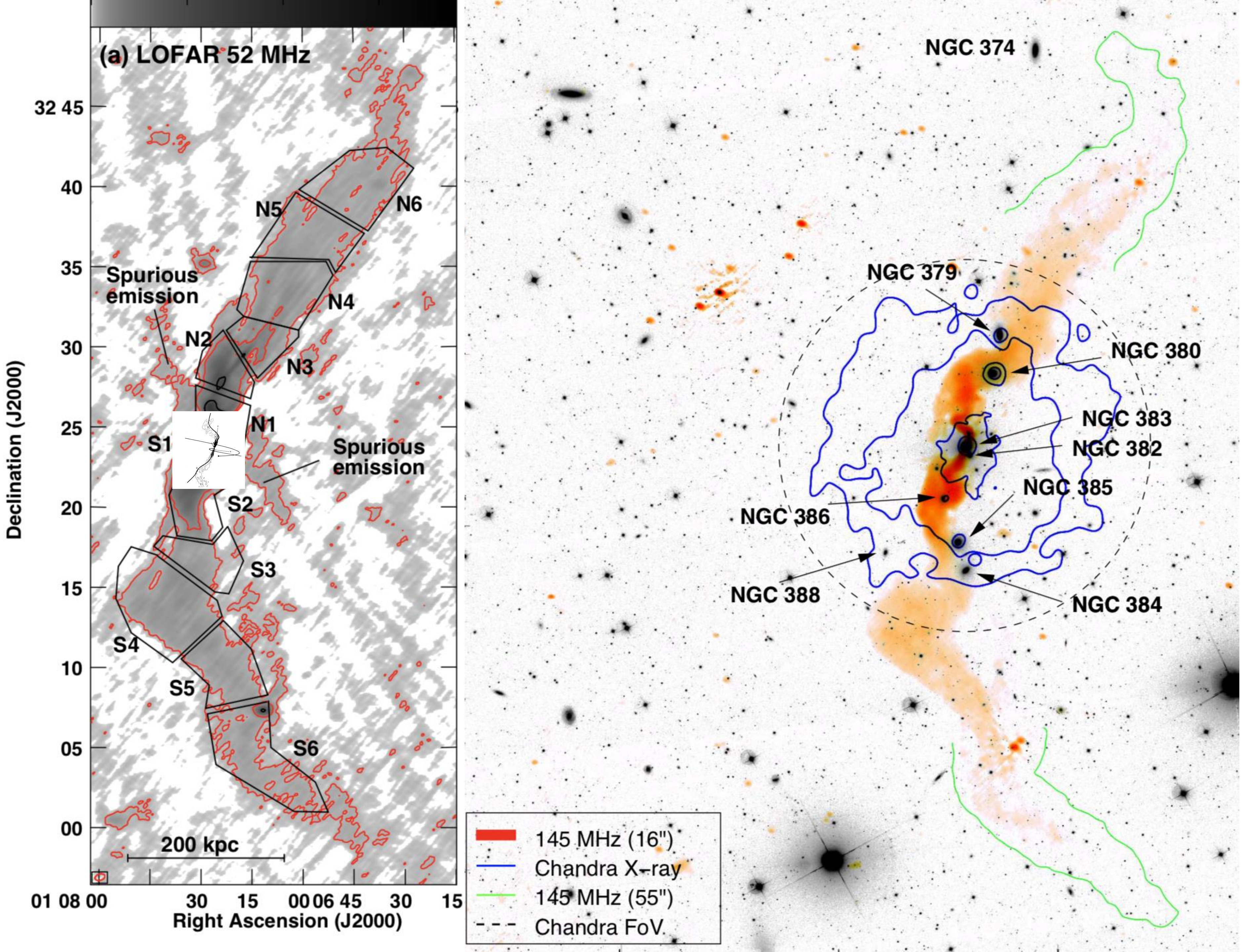

(a) LOFAR 52 MHz
Declination (J2000)
Right Ascension (J2000)
32 45
40
35
30
25
20
15
10
05
00
01 08 00
30
15
00
06 45
30
15
Spurious emission
Spurious emission
N1
N2
N3
N4
N5
N6
S1
S2
S3
S4
S5
S6
200 kpc
NGC 374
NGC 379
NGC 380
NGC 383
NGC 382
NGC 385
NGC 386
NGC 388
NGC 384
145 MHz (16")
Chandra X-ray
145 MHz (55")
Chandra FoV

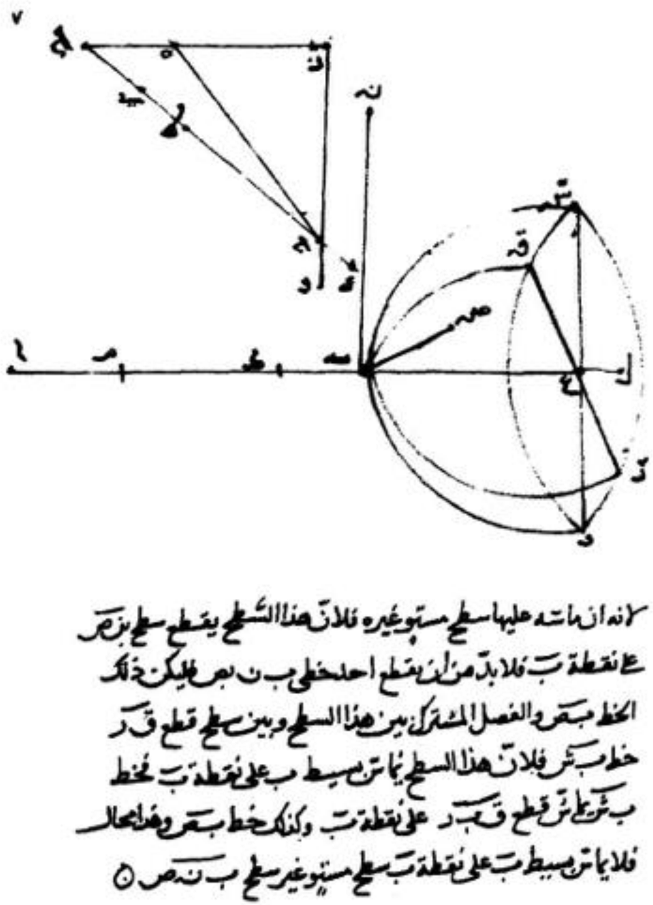
LOFAR

- LOw Frequency Array
- 2 types of low-cost antennae:
  - Low Band Antenna (LBA, 10-90 MHz)
  - High Band Antenna (HBA, 110-250 MHz)
- Antennae organized in 36 stations over 100 km
- Each station has 96 LBAs and 48 HBAs
- 13 stations with baselines: 100m – 1500km

Content

1. LOFAR
2. History
3. Optical telescopes
4. Space Telescope Orbits
5. Radio Telescopes
6. X-ray Telescopes

History of geometrical optics I



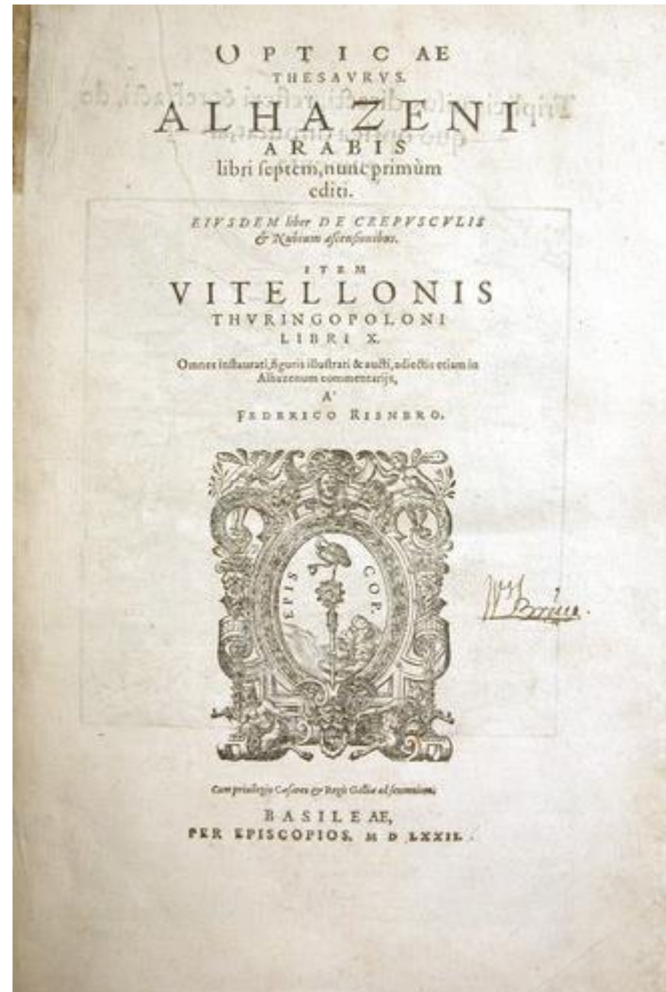
Ibn Sahl (AD 940-1000), Persian, Muslim mathematician, physicist and optical engineer of the Islamic Golden Age. He is credited with first discovering the law of refraction, usually called Snell's law.

History of geometrical optics II

Ibn al-Haytham (AD 965 – 1040), also known by the Latinization Alhazen or Alhacen,was an Arab, Muslim scientist, mathematician, astronomer, and philosopher. Ibn al-Haytham made significant contributions to the principles of optics (and his famous book of optics), astronomy, mathematics, visual perception, and the scientific method.

In his book of optics (Kitab al-Manazir), Alhazen reports experiments on lenses, mirrors, refraction, reflection, and spectroscopy.

Great influence on Leonardo Da Vinci, Galileo Galilei, Huygens, Kepler, …



The (refractive) telescope

Dutch eyeglass maker Hans Lippershey applied for a patent on the refractive telescope in 1608, and got denied:

The telescope was "common knowledge" in the early 1600s! As common as eyeglasses.

Galileo Galilei circa 1609-1610
first (reported) astronomical use of the telescope

Image by Hulton Archive/Getty Images

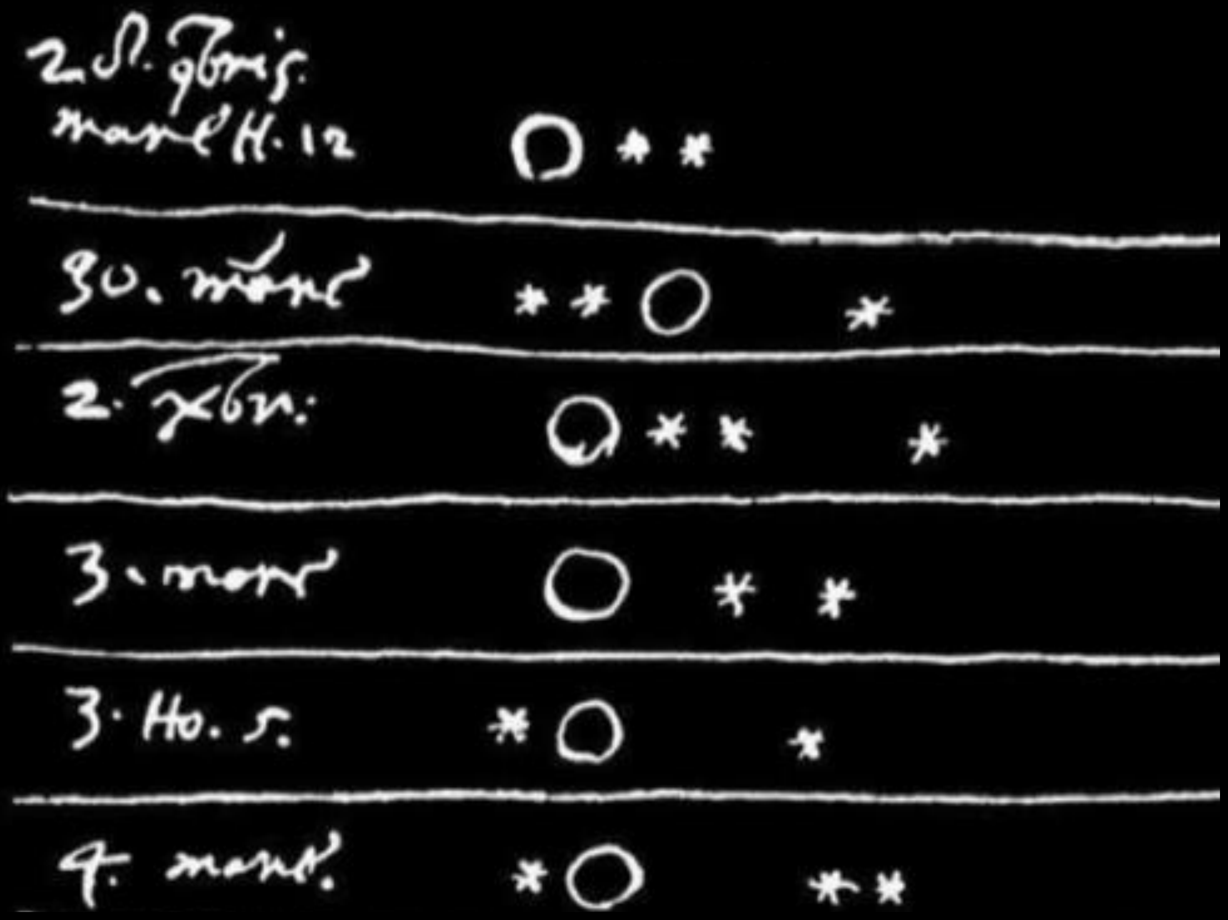
GALILEO, 1610

Mountains, craters on the Moon

GALILEO, 1610

Phases of Venus

GALILEO, 1610

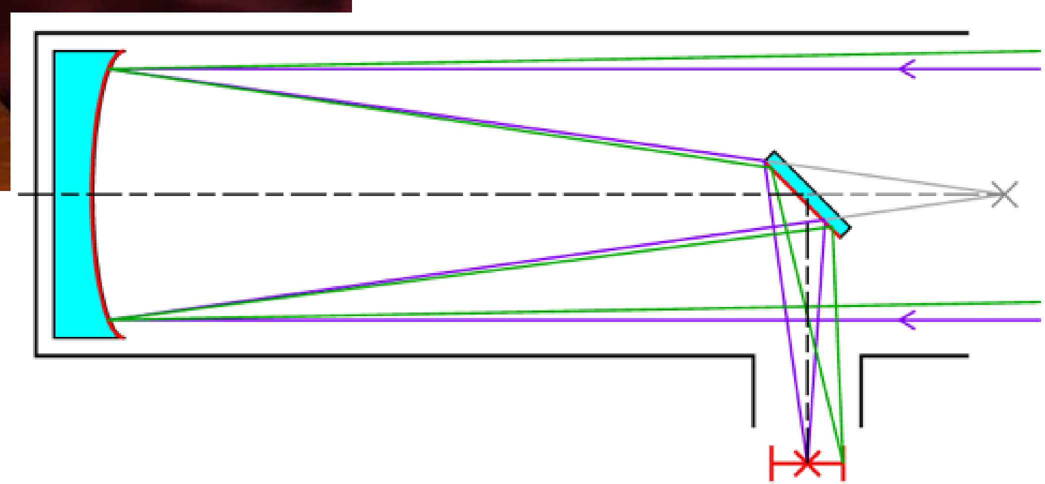


Moons orbiting around Jupiter

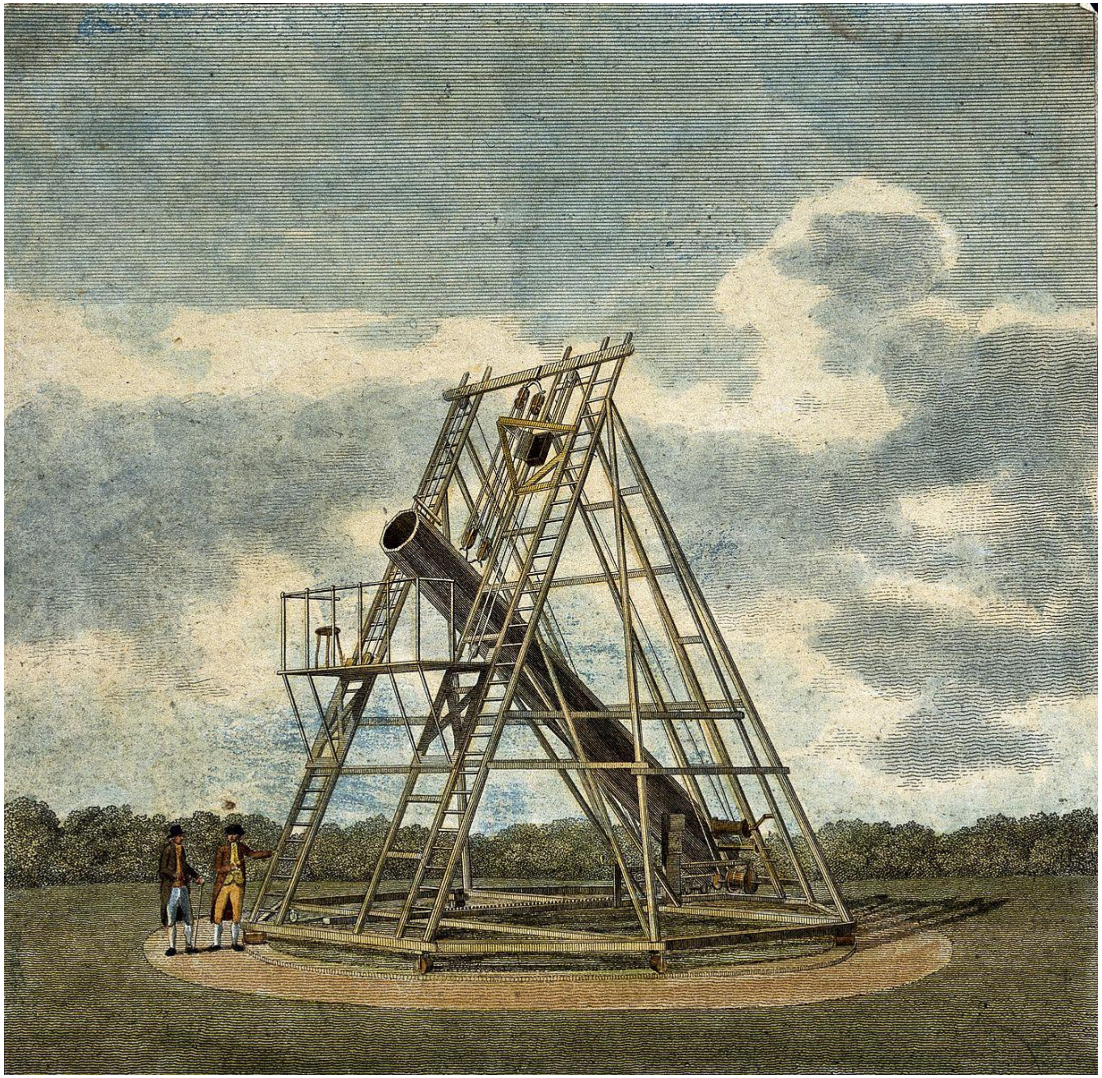
Newton: 1668 – first reflector

Uses mirror to prevent chromatic aberrations present in refractors: $n_{glass}(\lambda)$

Reflection is achromatic!



Herschel 1789 – 40 ft refractor



https://en.wikipedia.org/wiki/40-foot_telescope

The 40 ft (12 m) tube was made of iron.

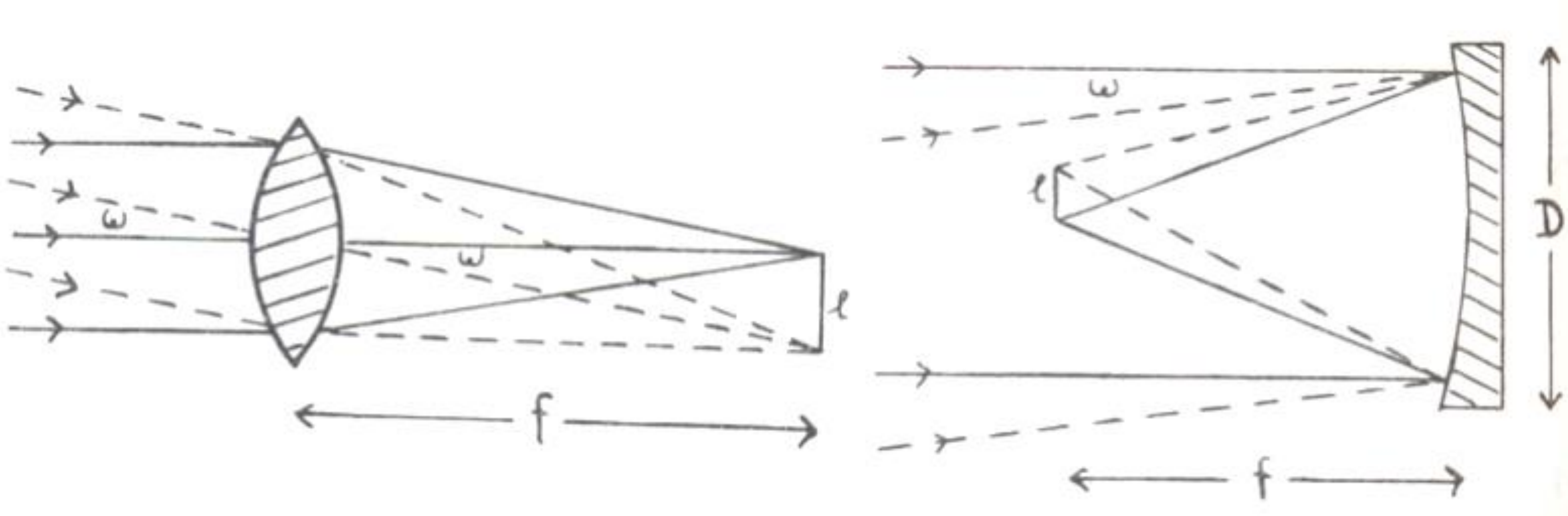
The telescope was mounted on a fully rotatable als-azimuth mount.

48-inch (120 cm) concave metal mirrors were made for the telescope, each with a focal ratio of f/10.

Telescope design considerations

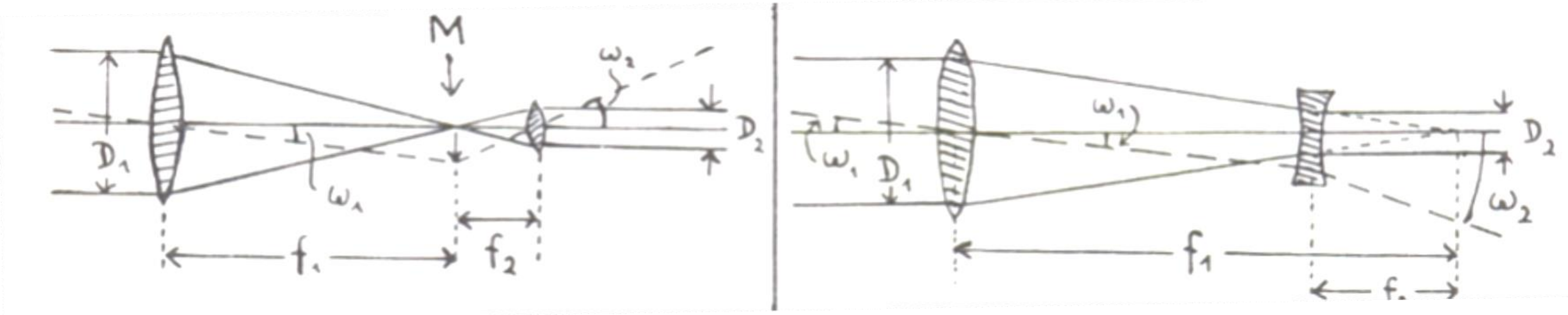
- F number/Plate scale/magnification/field of view
- Collecting area
- Focus configuration
- Mounts

Plate scale



- rays from two sources close to the optical axis preserve ω upon exit from the lens.
  $\tan \omega \sim \omega \sim l / f$.
  Hence plate or focal scale: $\omega / x = l / f$.
- Plate scale = $4.85 \times 10^{-6} f$ mm arcsec^{-1}

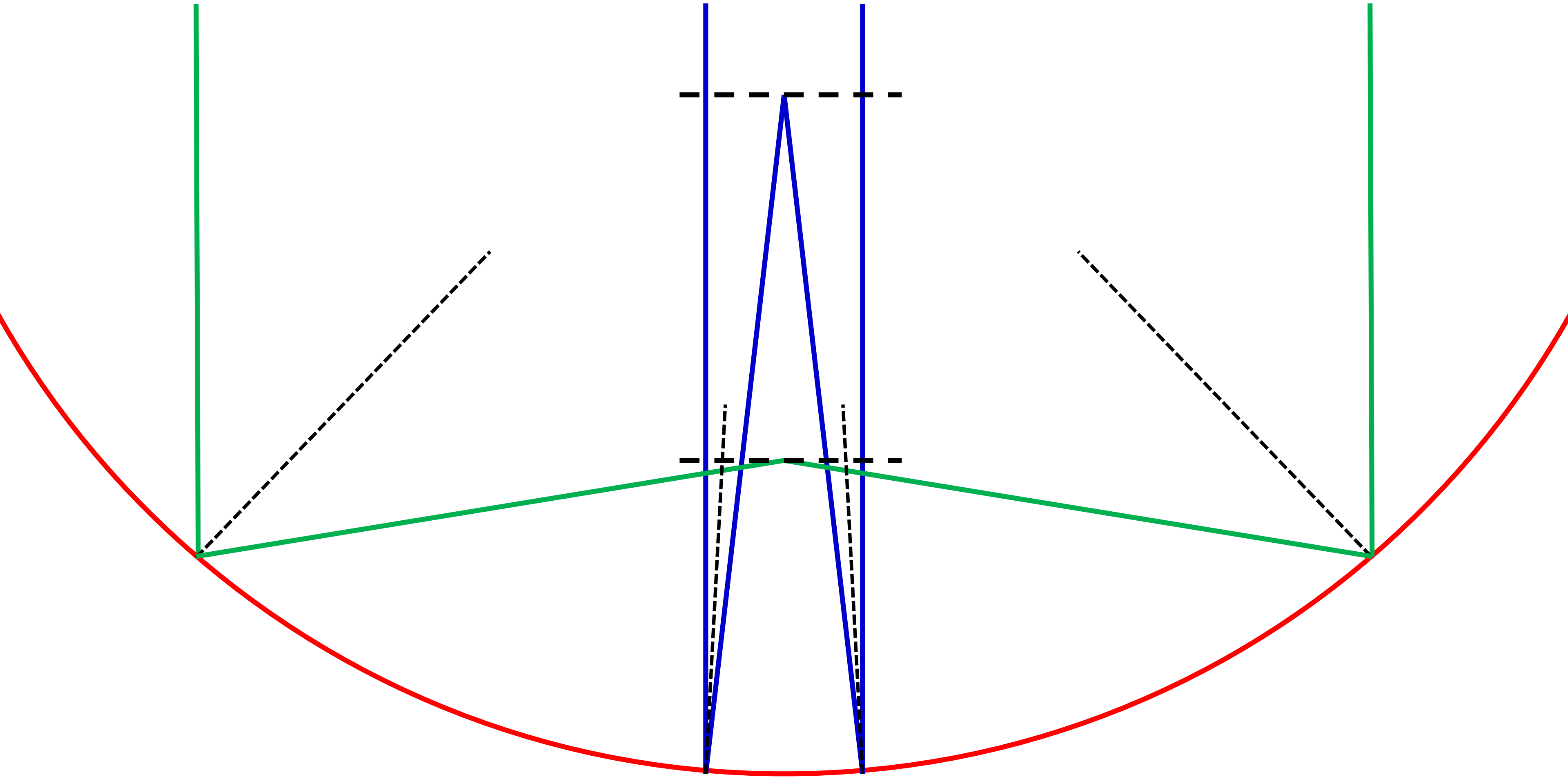
Magnification



Magnification: $$V = \frac{f_1}{f_2} = \frac{D_1}{D_2} = \frac{\omega_2}{\omega_1}$$

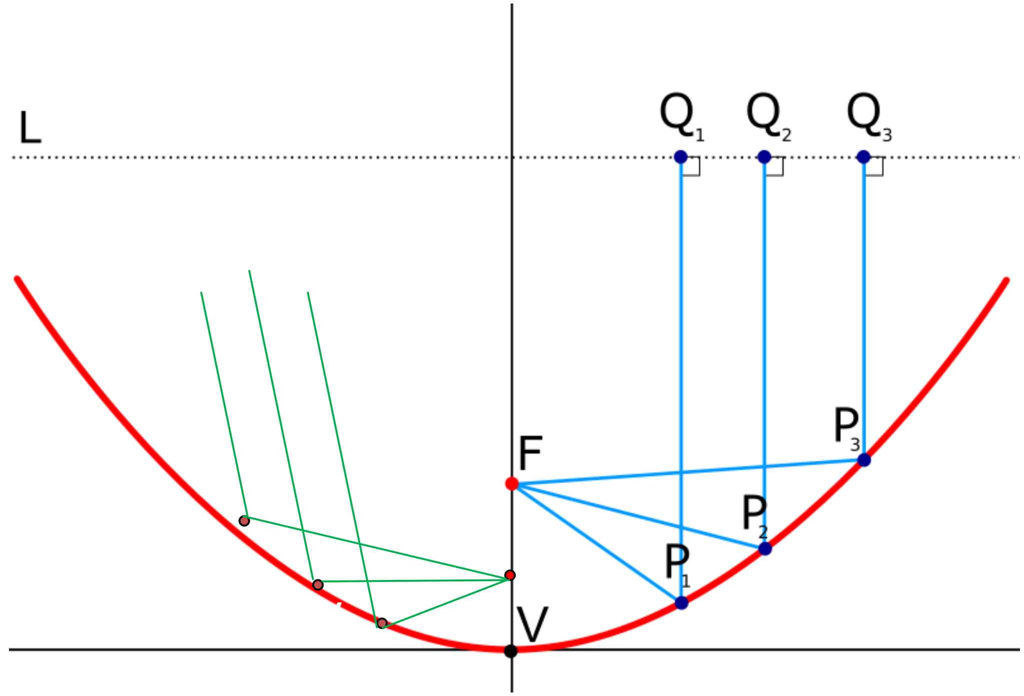
Spherical Mirrors

Spherical primary mirrors provide a large field of view (FOW) but rays more distant from the optical axis have a different focal point → aberrations → limited size, curvature!



Parabolic Mirrors

Parabolic primary mirrors focus all rays from the same direction to one point.
But: different directions have different focal points.



→ FOV is limited by aberrations: the bigger the mirror the bigger the difference [parabola – sphere] near the edge → bigger telescopes have smaller FOVs (~<1 deg).

Field of View

- Want large plate scale => faster primary (small F)
- Prime focus usually has smallest F, and thus largest FoV
- Vignetting: the size of the secondary mirror is the first limiting factor for FoV at Cass focus
- Telescope design fundamental trade-off: FoV vs image quality

Collecting area

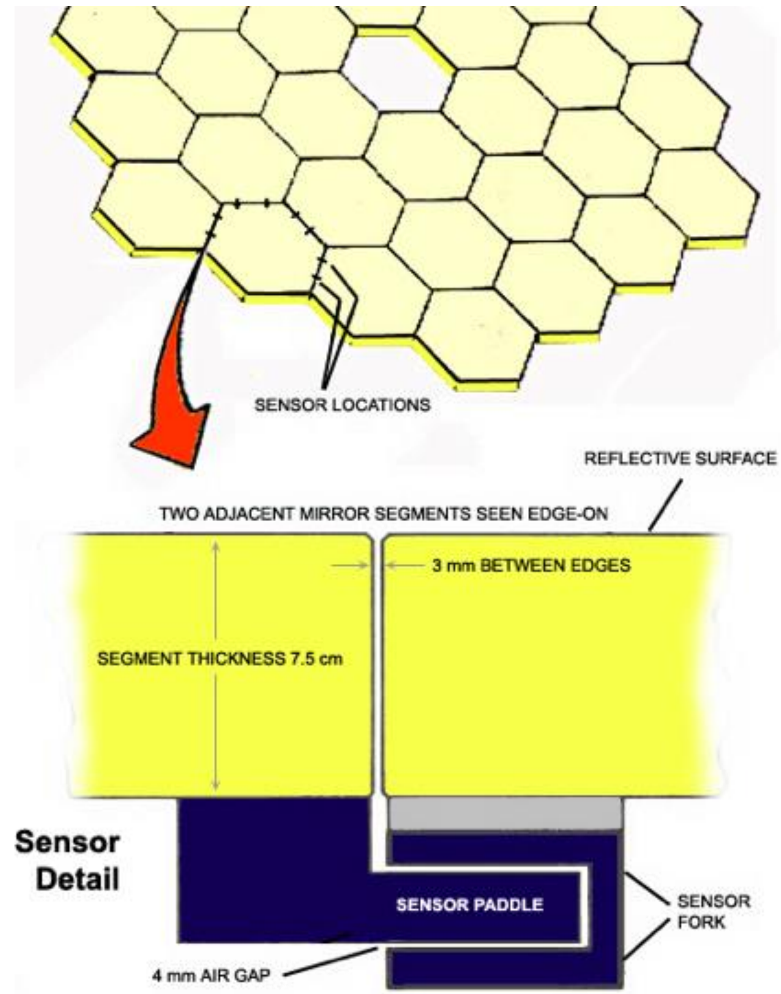
- Number of collected photons grow as D^2: size matters!
- Gap between 1949 (Palomar 200-inch Hale telescope) and 1992 (Keck telescopes)
  - Difficulty in manufacturing large pieces of glass
  - Difficulty in supporting large mirrors (gravity sag)
  - Thermal properties difficult to manage

Solution for large telescopes: Segmented mirrors (e.g. Keck, SALT, JWST, TMT)

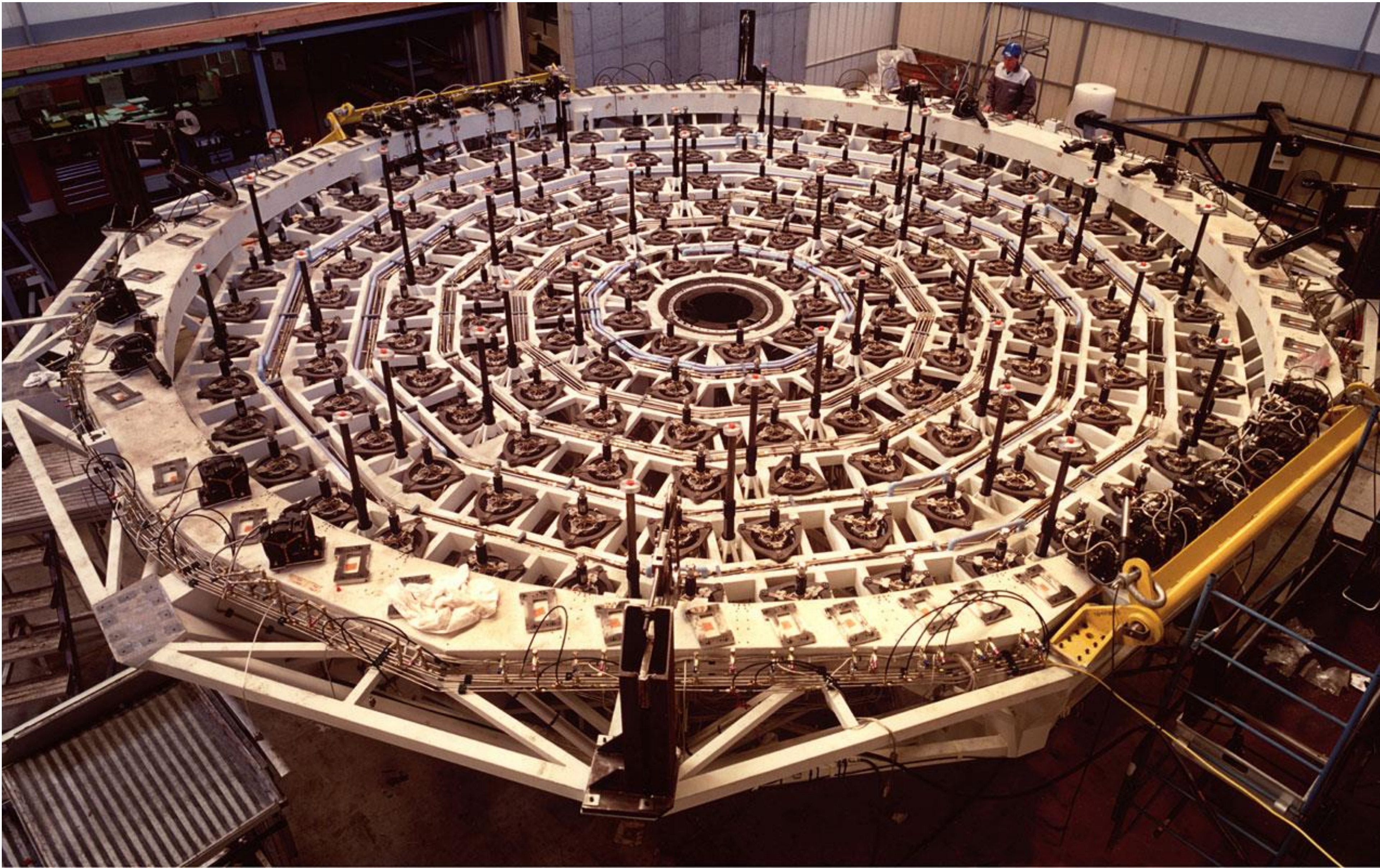
Keck primary mirror:

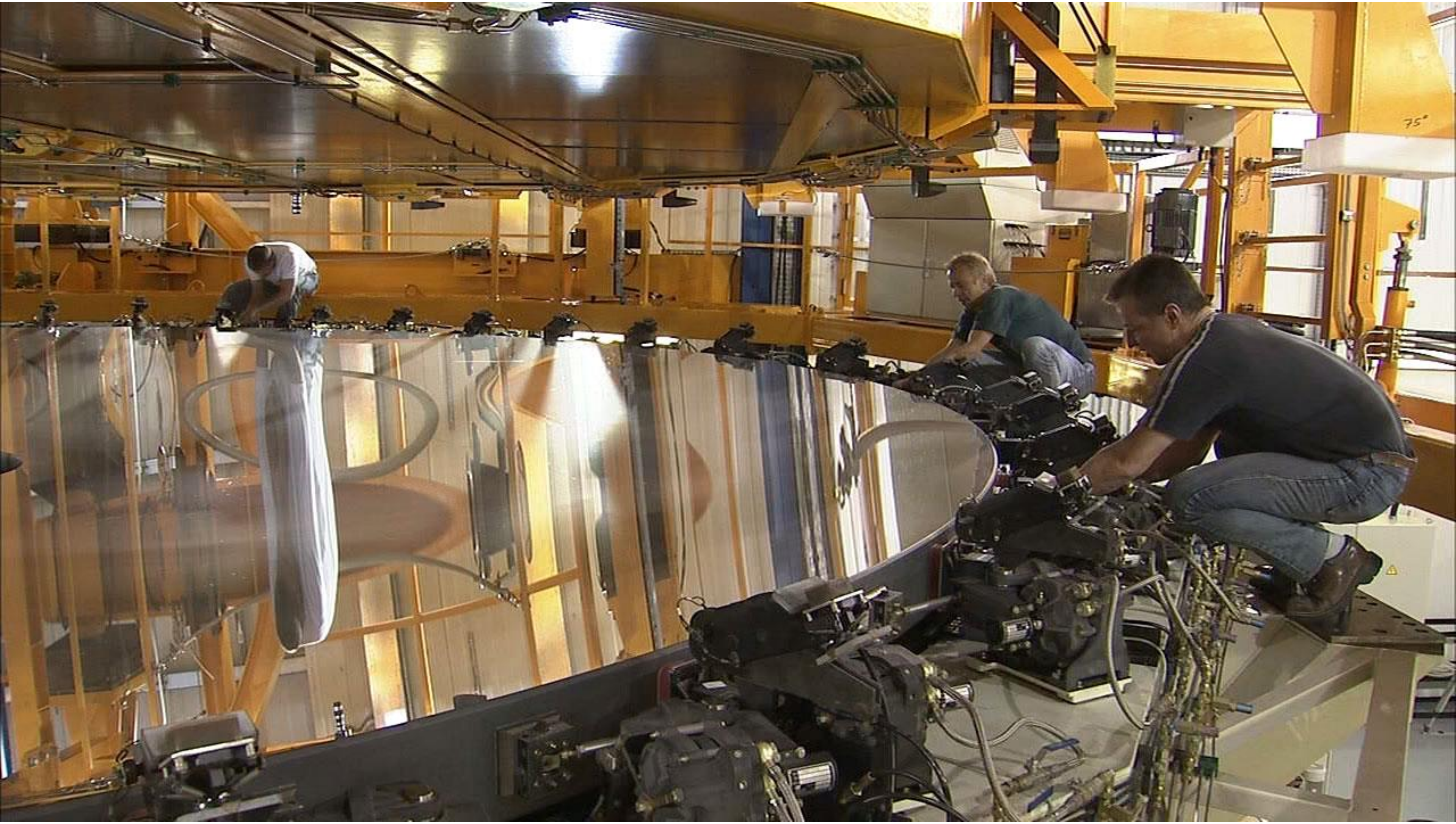
Each segment is 1.8 meter; active control system keeps segments to proper figure under gravity (edge sensors)

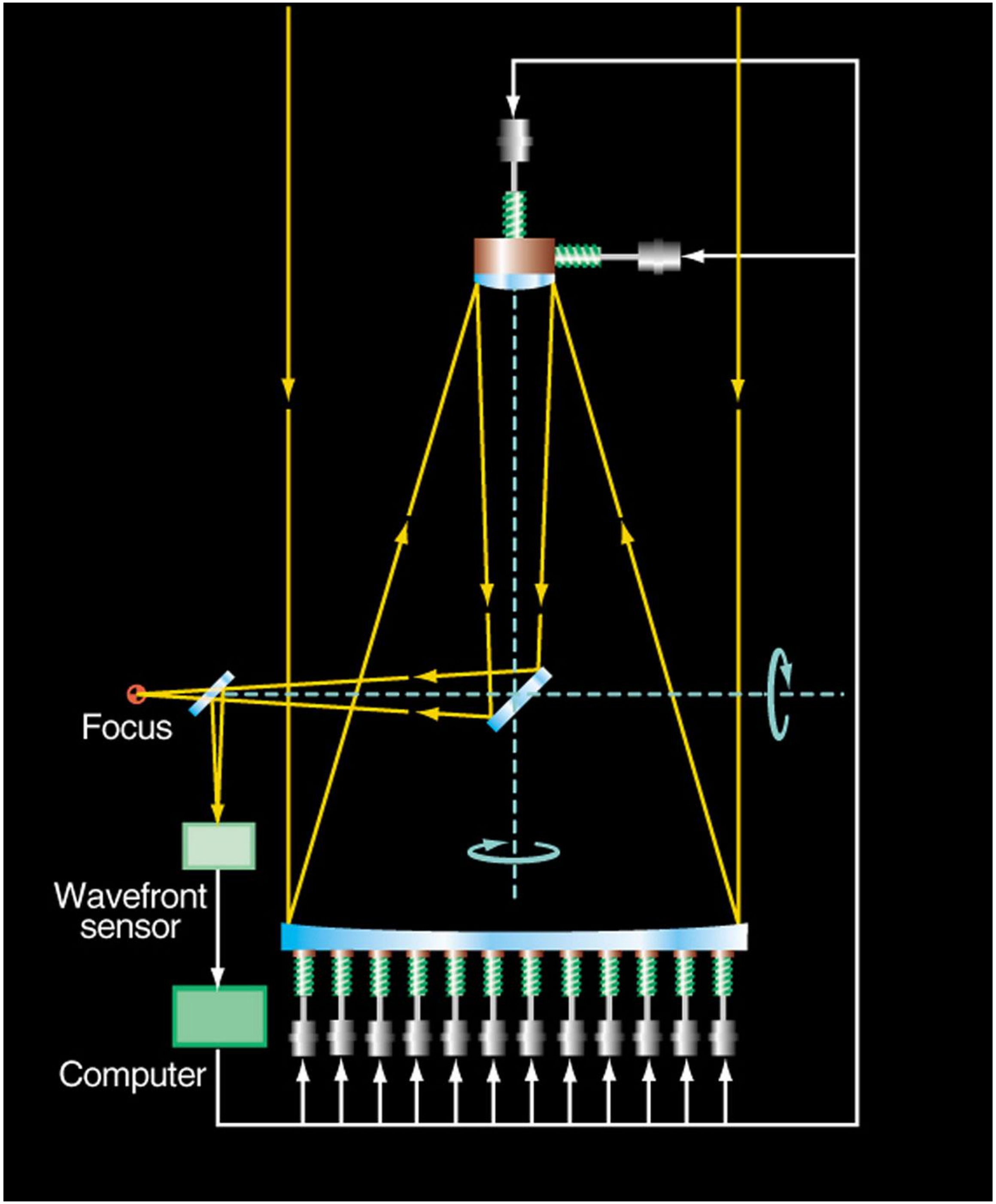
Optically aligned (co-phased) every week/ month



VLT: thin mirror plus active optics

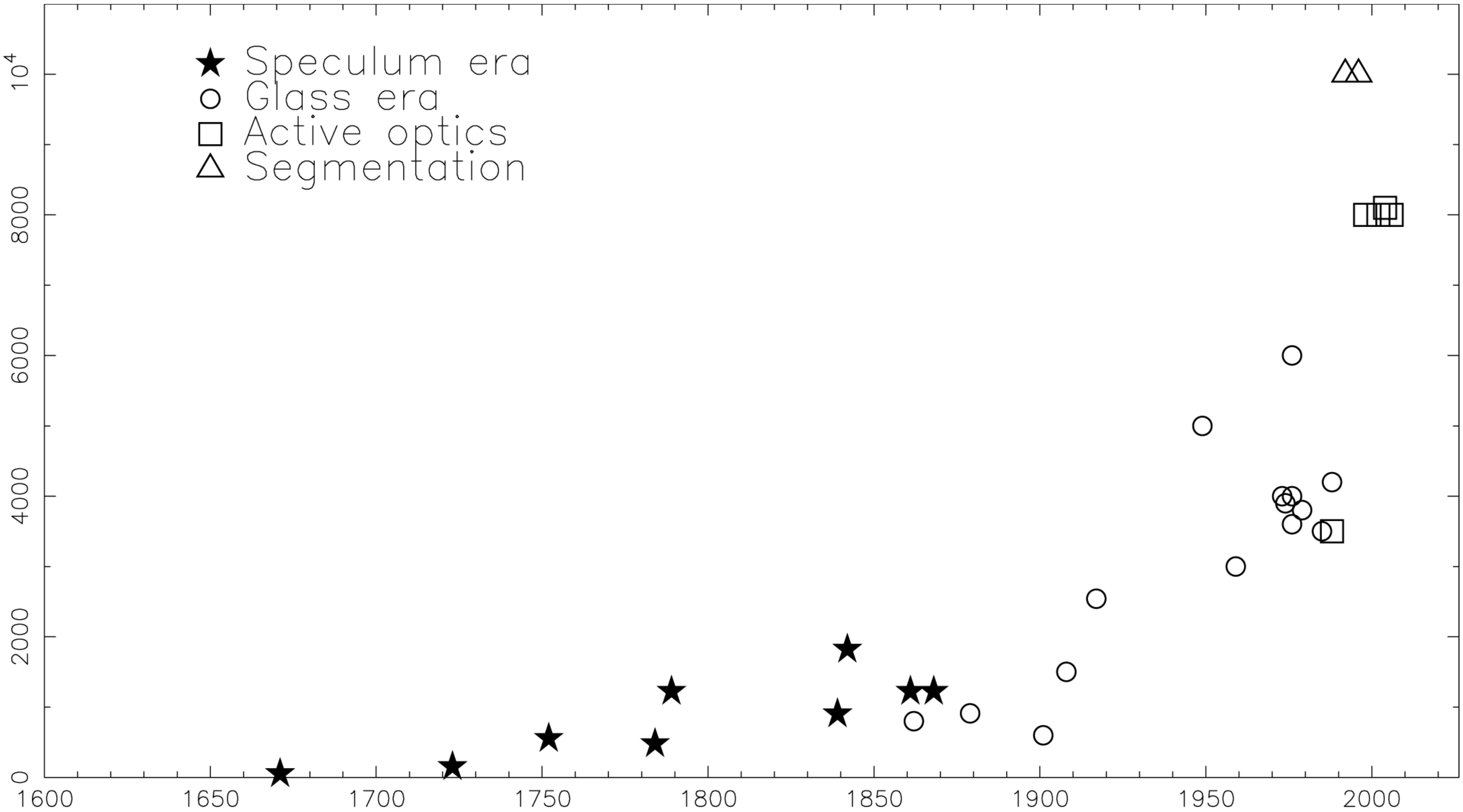




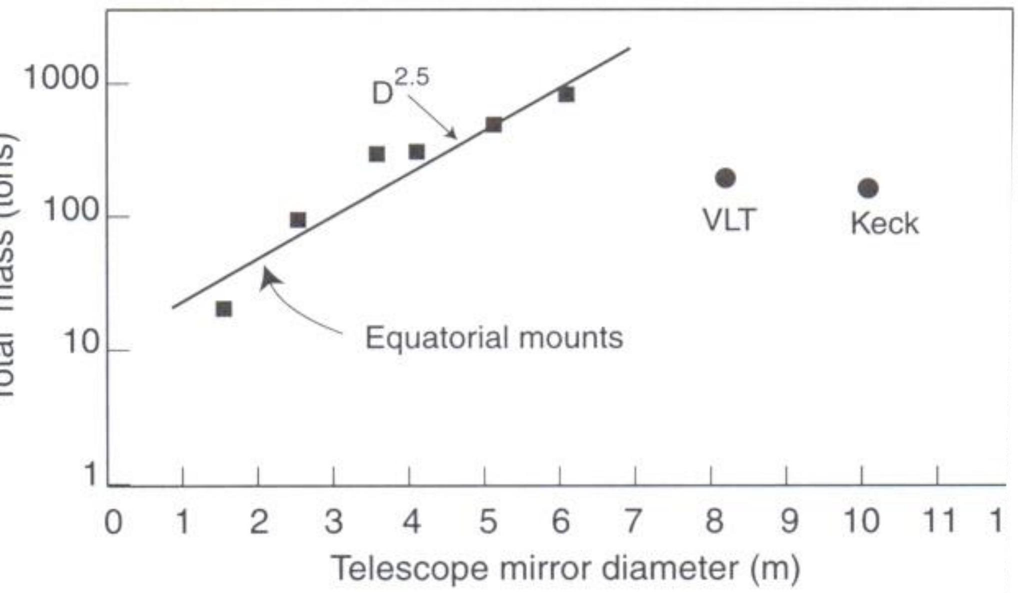

Focus
Wavefront sensor
Computer

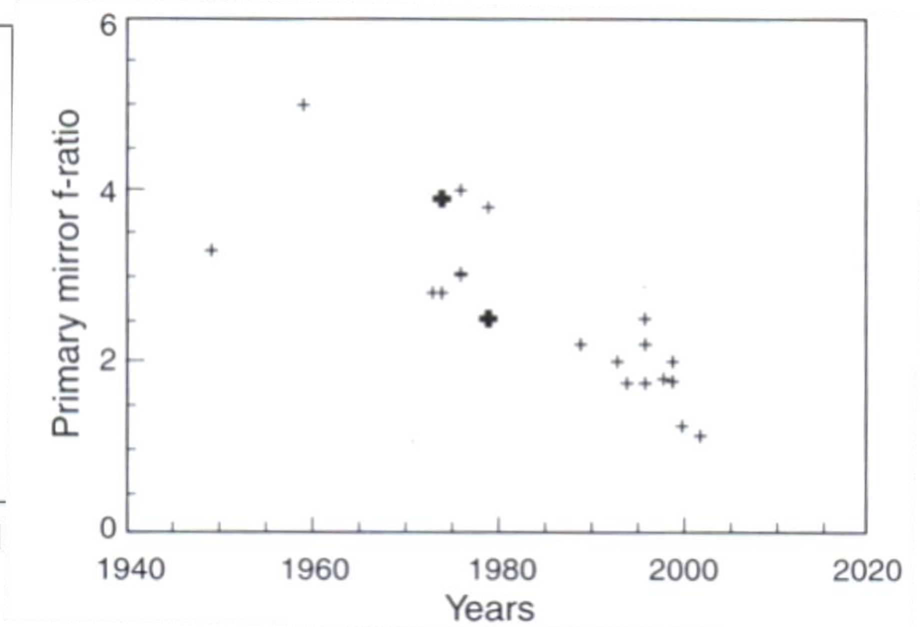
Honeycomb Mirrors

Growth of Telescope Collecting Area



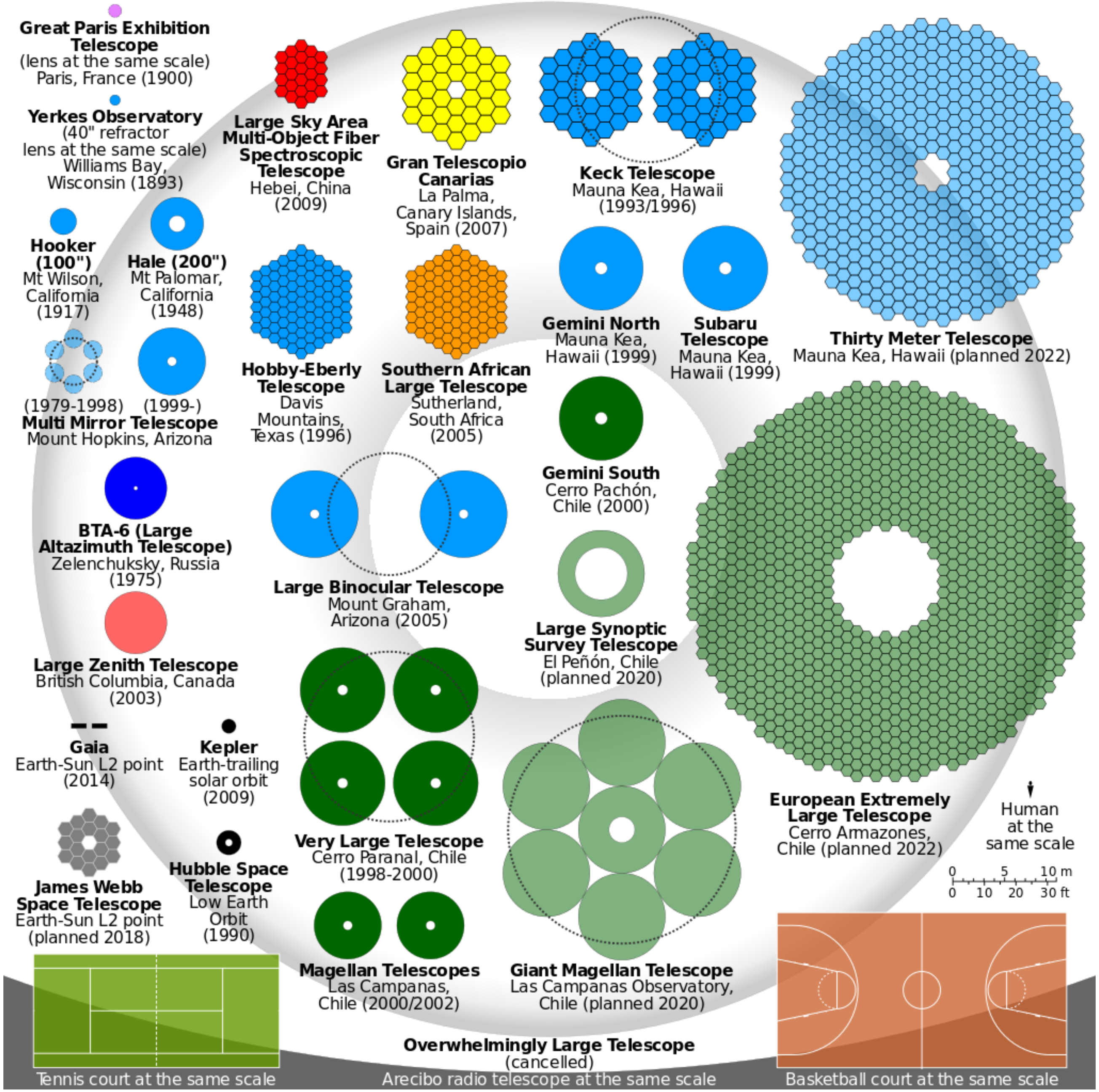
Mass Limitations





Most important innovations:

1. faster mirrors → smaller telescopes → smaller domes
2. faster mirrors ← new polishing techniques
3. bigger mirrors ← thinner / segmented mirrors ← active support



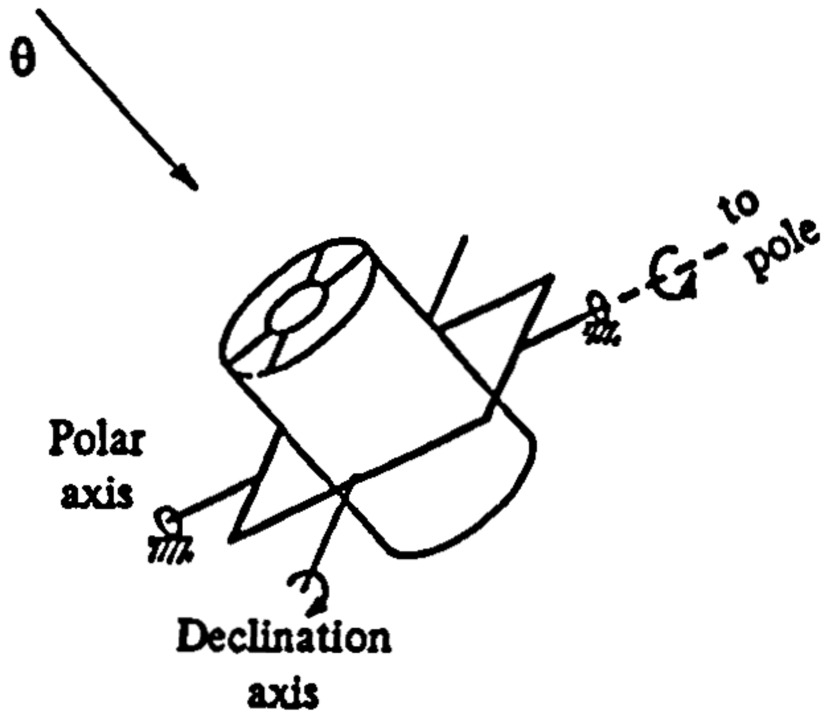
commons.wikimedia.org/wiki/File:Comparison_optical_telescope_primary_mirrors.svg

James Web Space Telescope

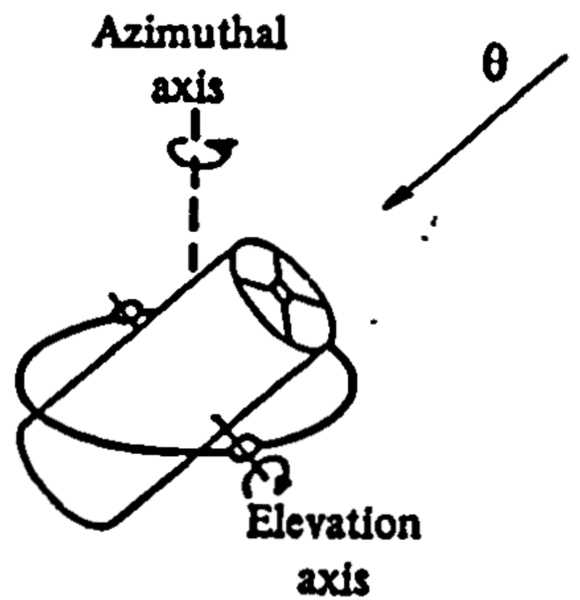
Optical Telescopes in Comparison

	Palomar	Keck	JWST
Telescope aperture	5 m	10 m	6.5 m
Telescope mass	600 t	300 t	6.5 t
# of segments	1	36	18
Segment size	5 m	1.8 m	1.3 m
Mass / segment	14’500 kg	400 kg	20 kg

Telescope mounts

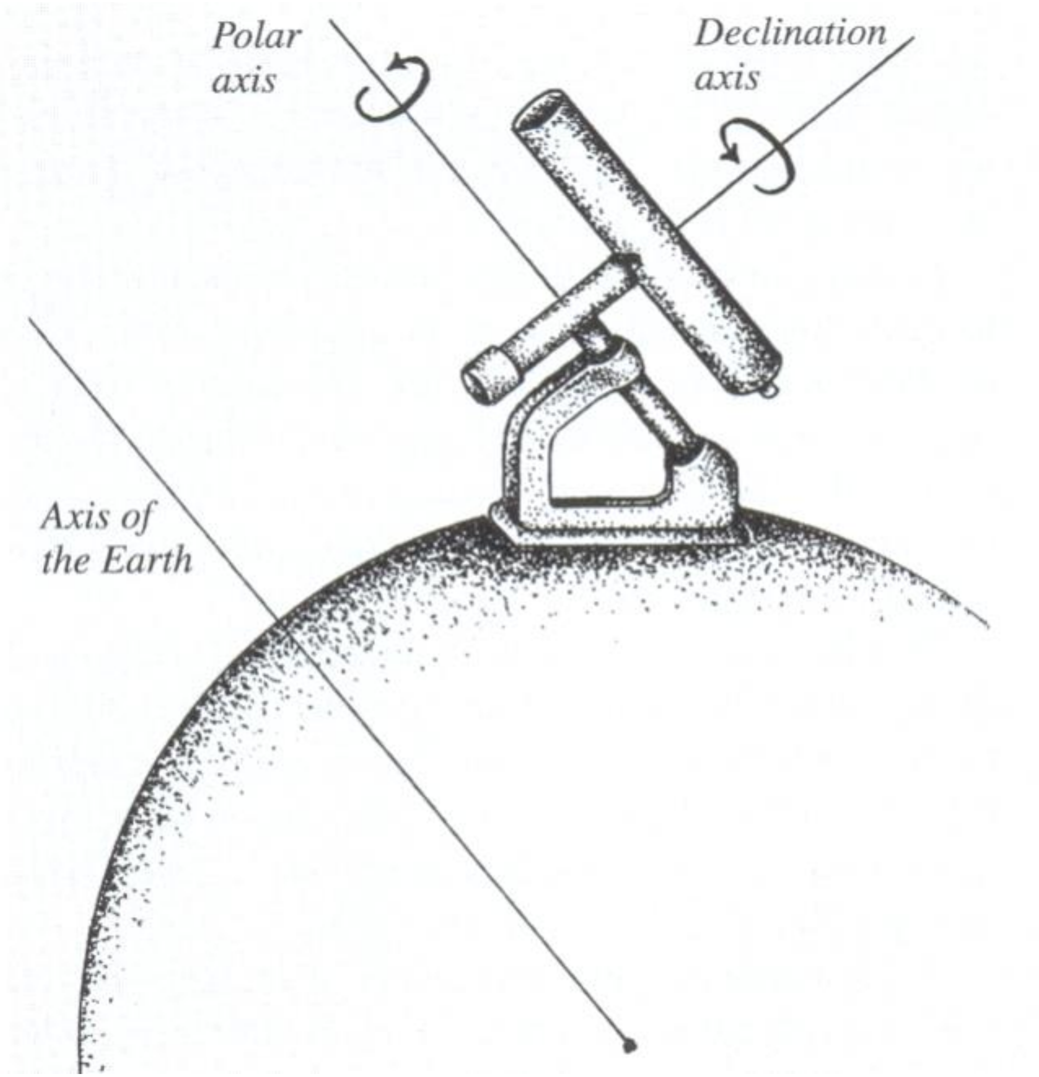


Equatorial



Altitude-Azimuth (altaz)

Equatorial Mount

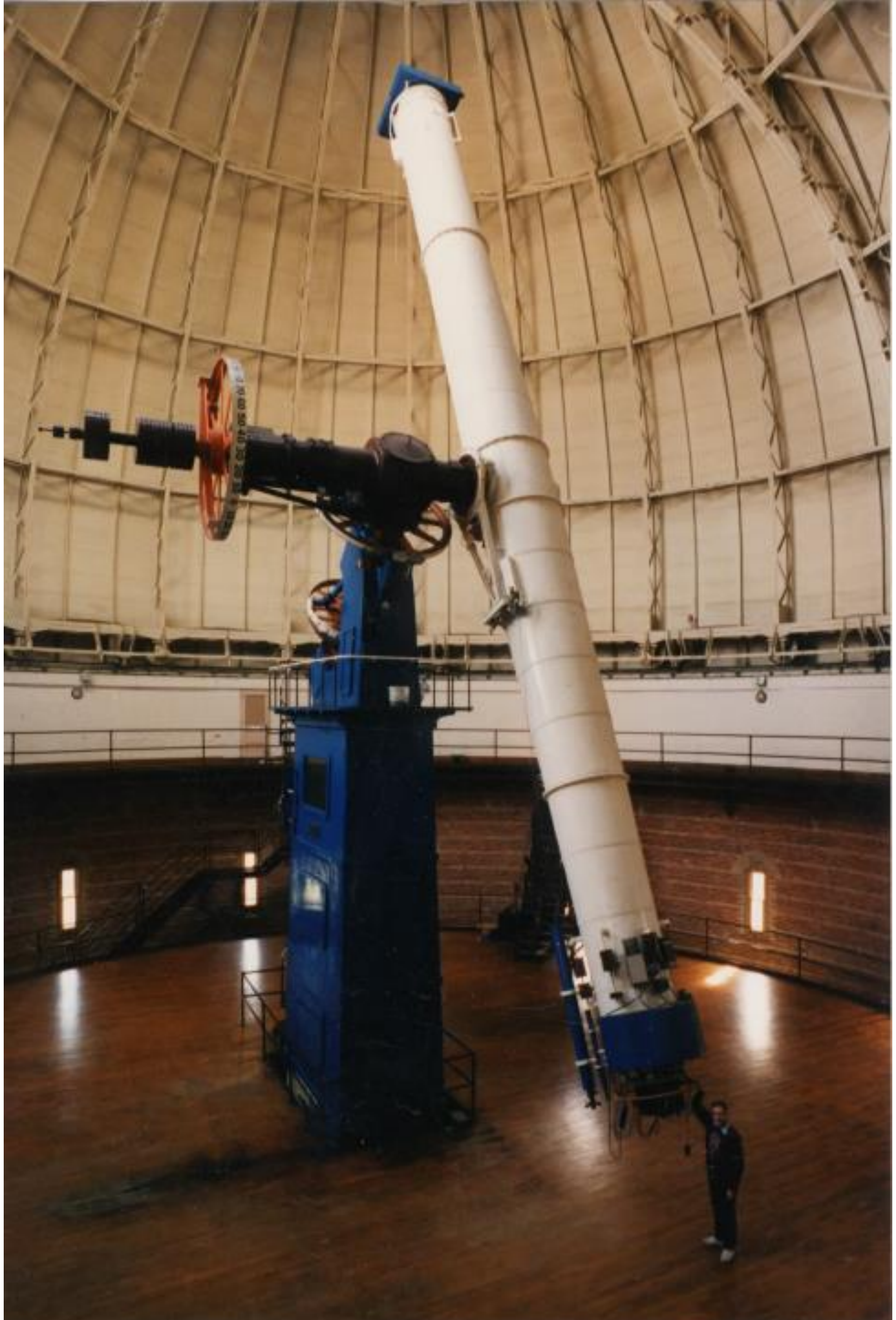


Advantages:

- single moving axis following earth rotation
- constant rotation
- no image rotation

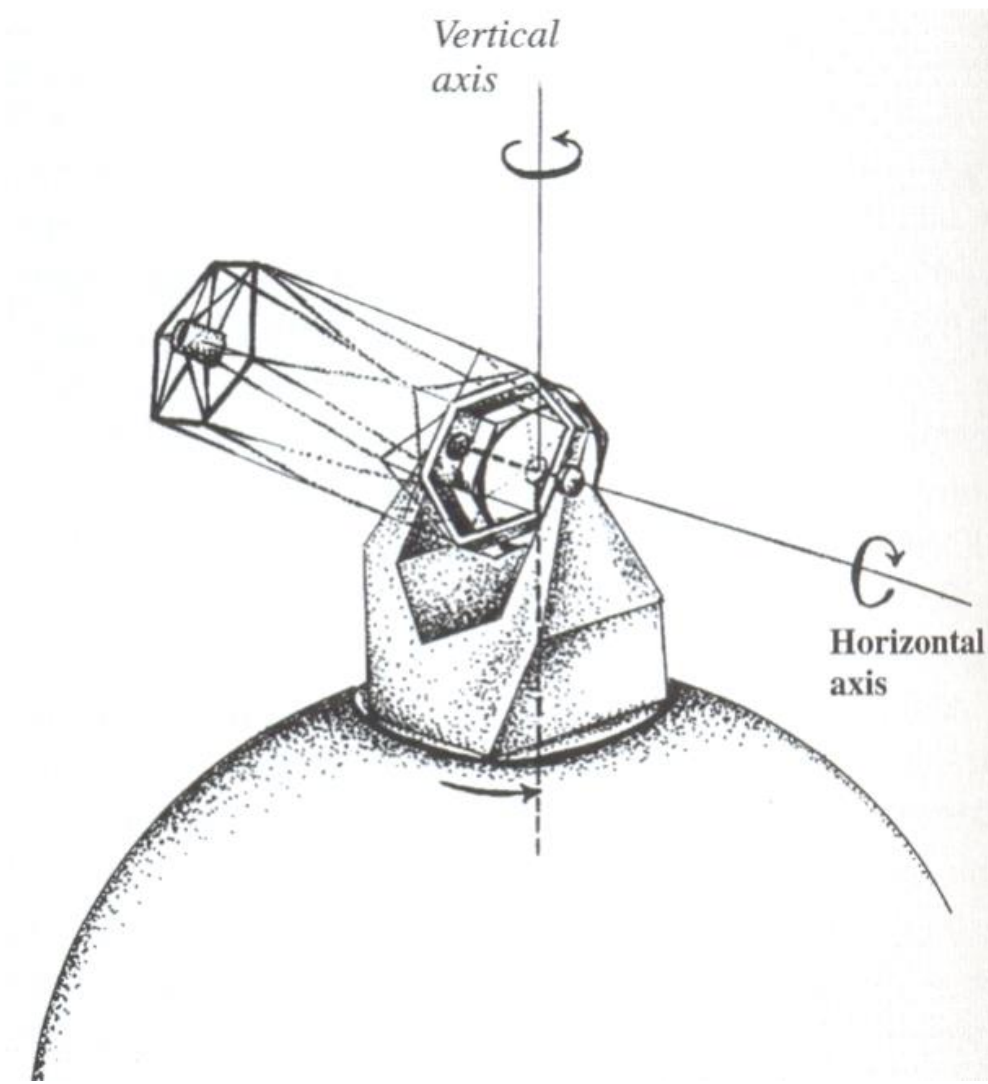
Disadvantages:

- large, heavy
- instruments: varying gravity vector
- design depends on latitude



1897:
40-inch (100 cm) refractor,
Yerkes Observatory
Williams Bay, Wisconsin

Azimuthal Mount



Advantages:

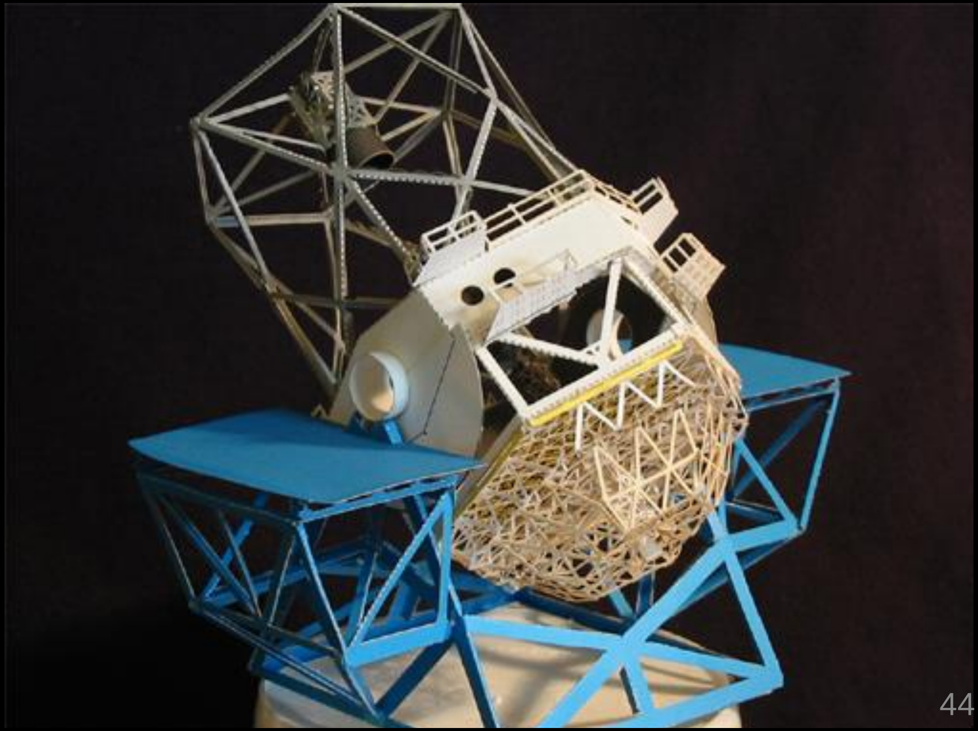
- light and symmetric
- design independent of latitude
- fixed gravity on bearings
- two fixed-gravity ports

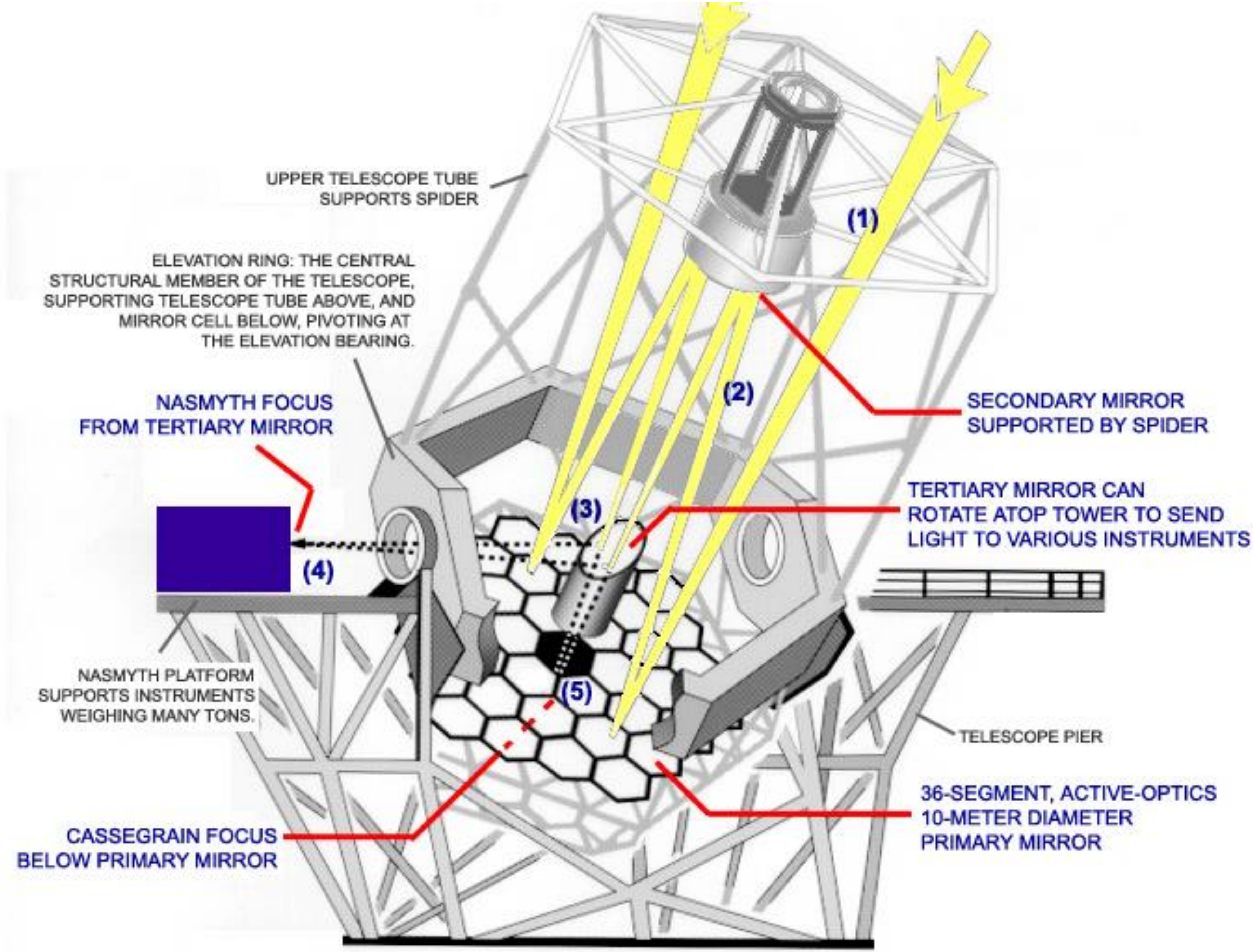
Disadvantages:

- two moving axes, requiring computer control
- variable rotation rate
- image rotation

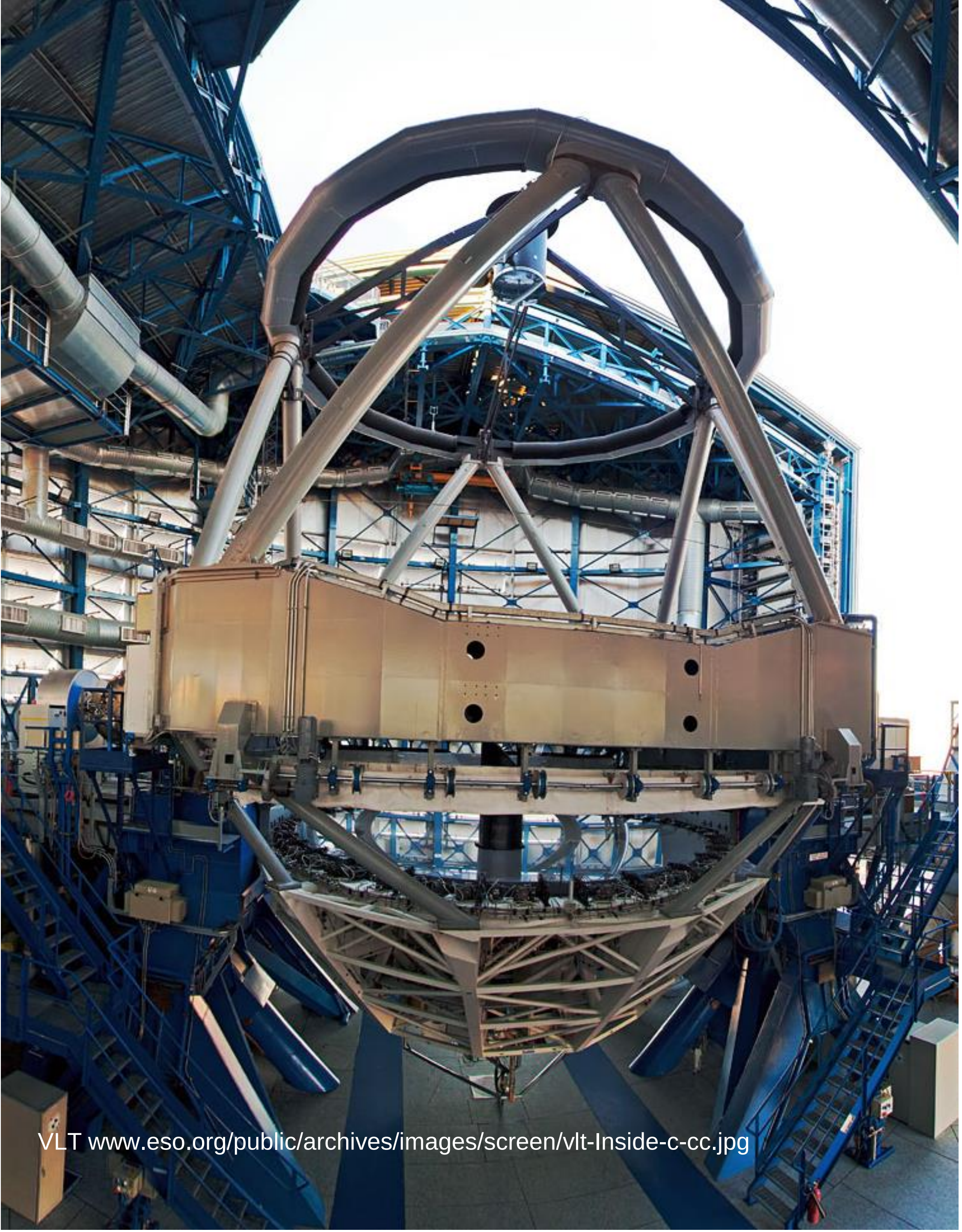
Altaz mount example: Keck telescope (1992)

- **Need to point and track in both elevation and azimuth**
- **Two axis motion**
- **Field of view rotates with Parallactic angle as the telescope tracks!**
  - **Needs image derotator!**





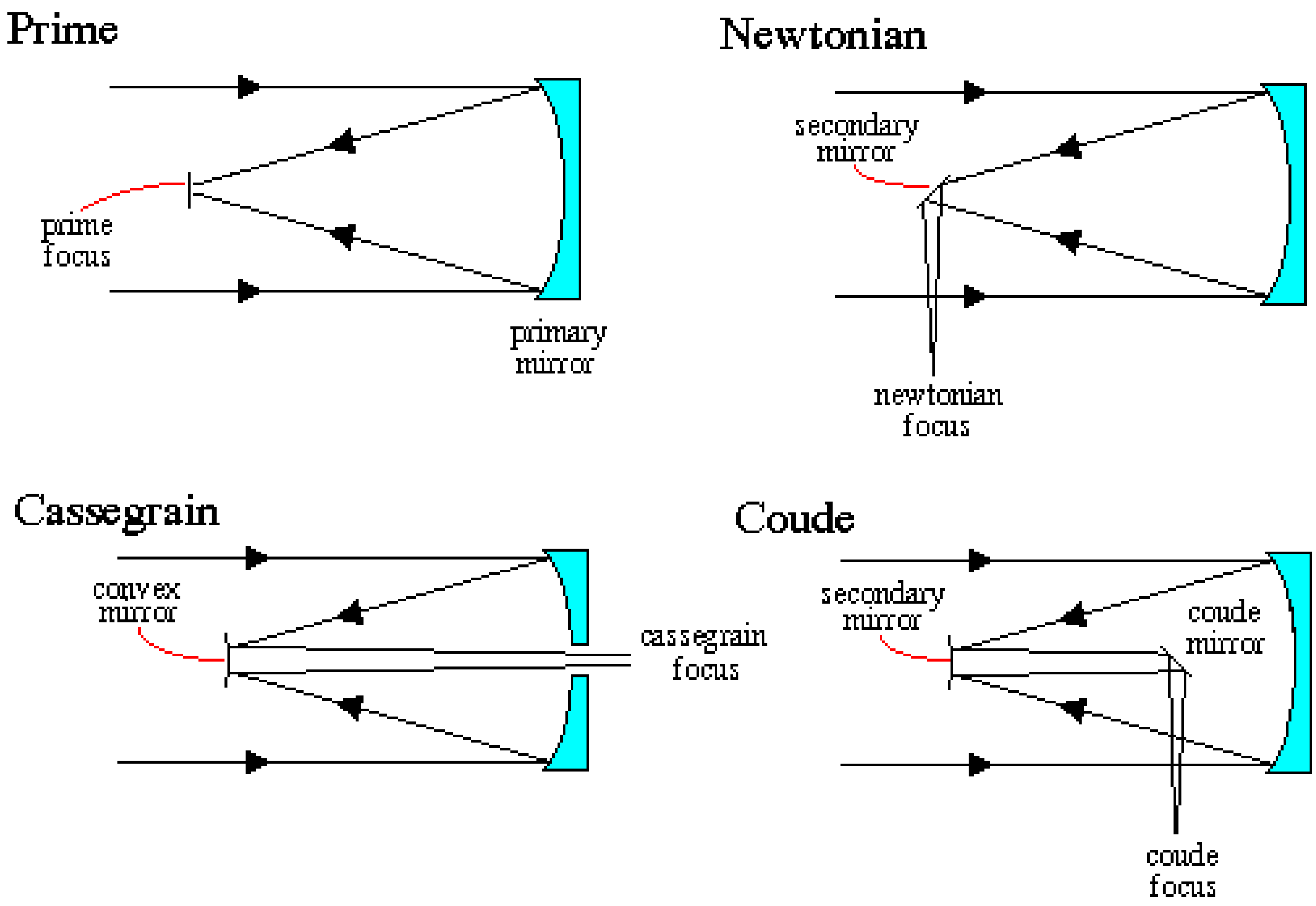
https://naturalsciencesresearch.wordpress.com/2012/08/24/adventures-in-ground-based-astronomy-an-inside-view-part-ii/



VLT

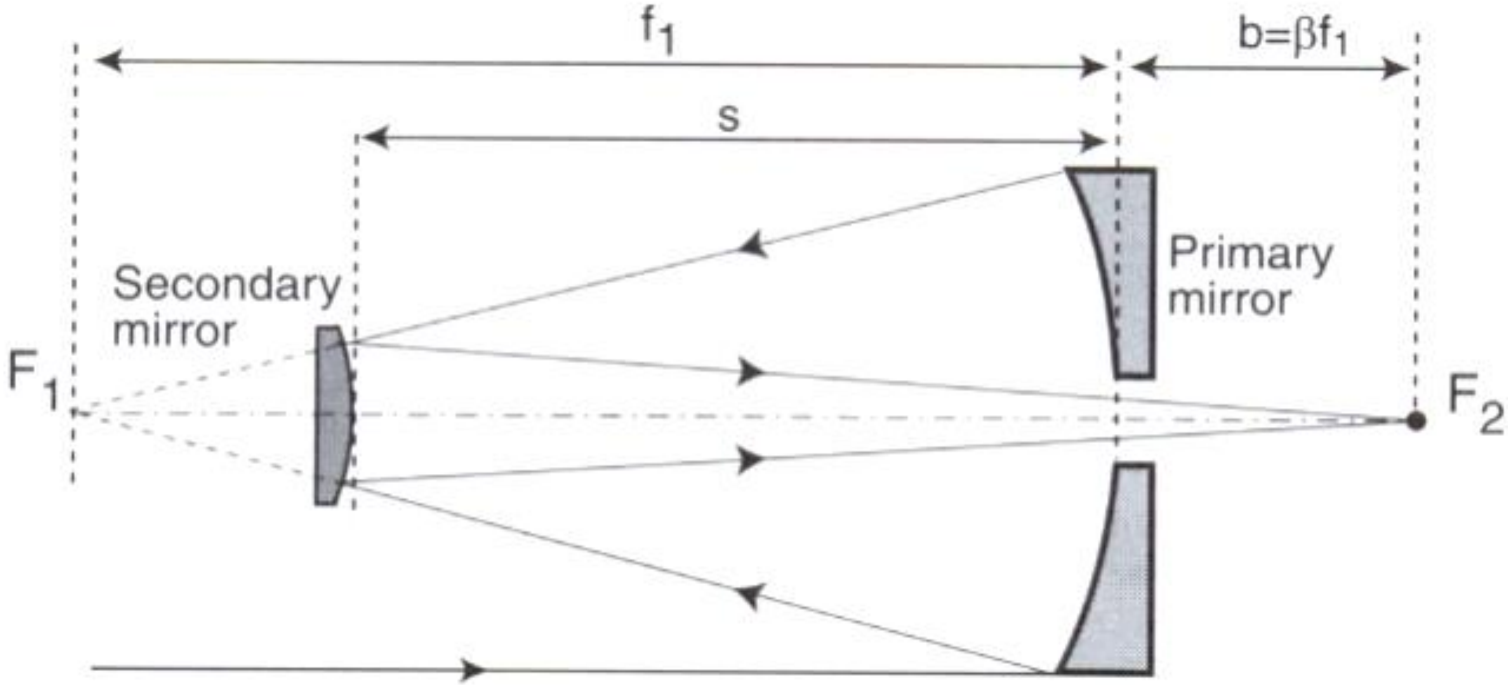
Azimuthal Telescope

Telescope focus configurations



Ritchey-Chrétien Configuration

Modified Cassegrain with hyperbolic primary mirror (≈parabola) and hyperbolic secondary mirror eliminates spherical aberration and coma



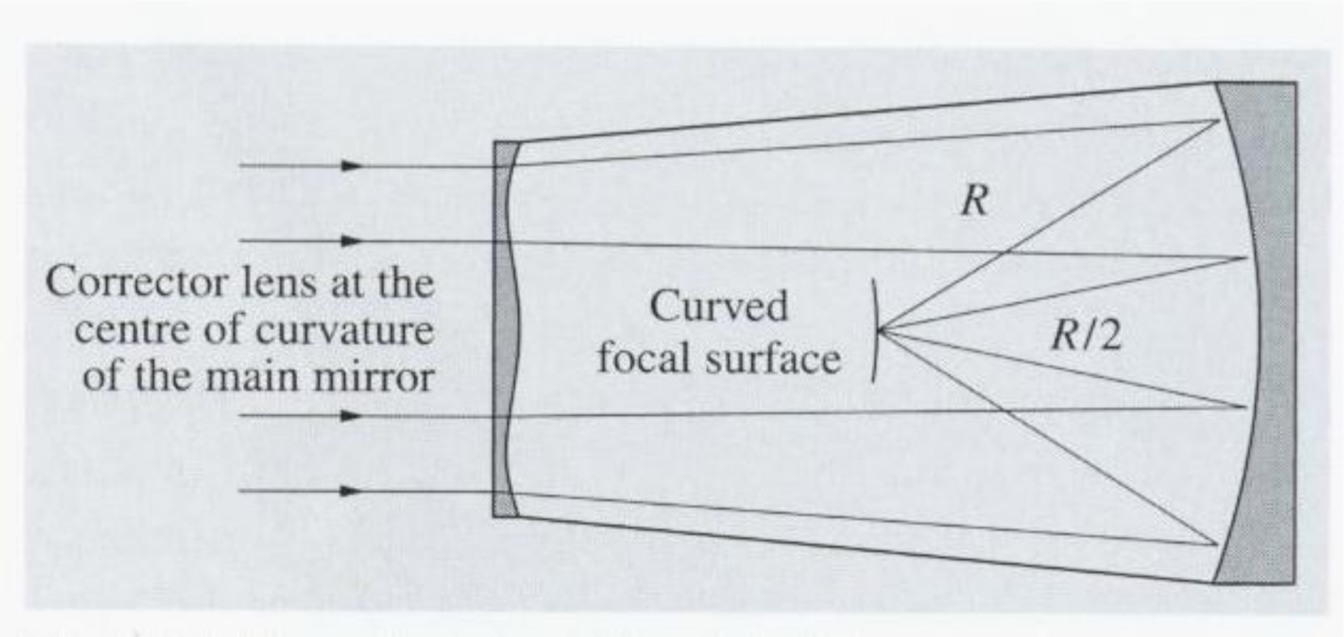
→large field of view, compact design, astigmatism

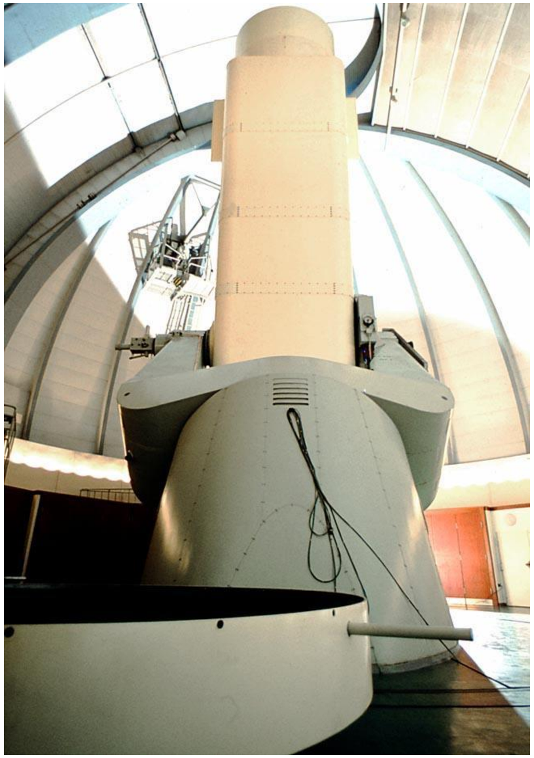
Ritchey-Chrétien Telescopes

Ritchey-Chrétien Telescope

Schmidt Telescope

- Spherical primary mirror for maximum field of view (>5 deg) → no off-axis asymmetry *but* spherical aberrations
- correct spherical aberrations with corrector lens

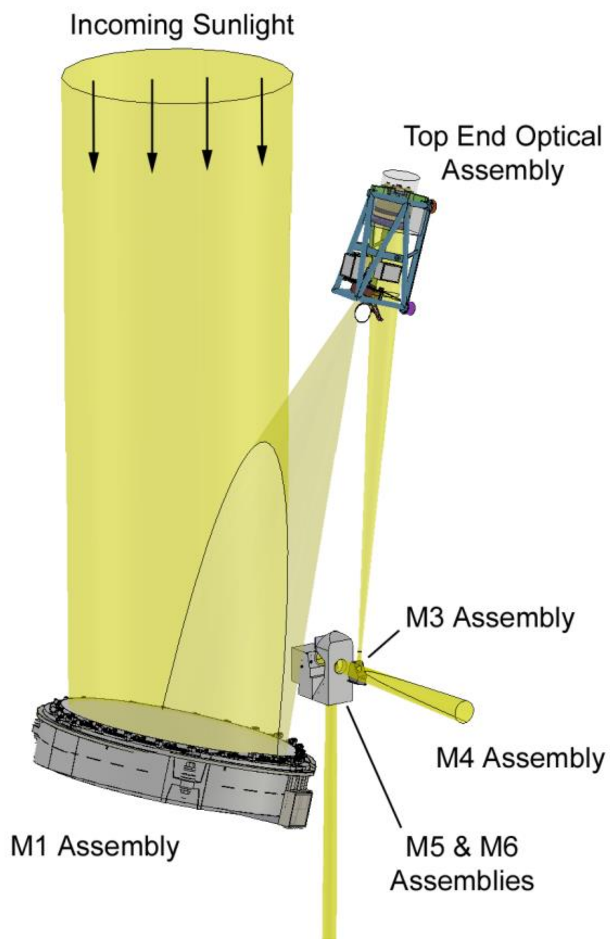




Two-meter Alfred-Jensch-Telescope in Tautenburg, the largest Schmidt camera in the world.

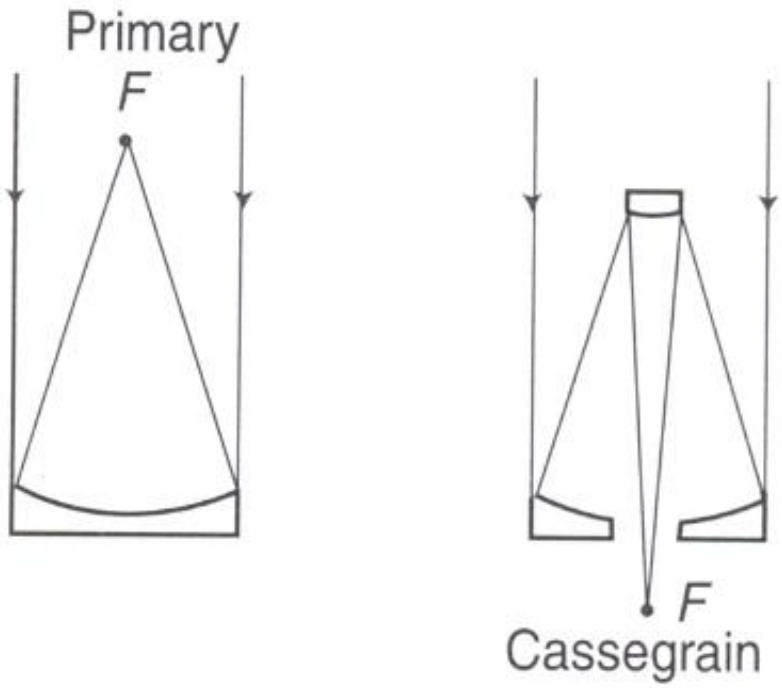
Gregorian Telescopes

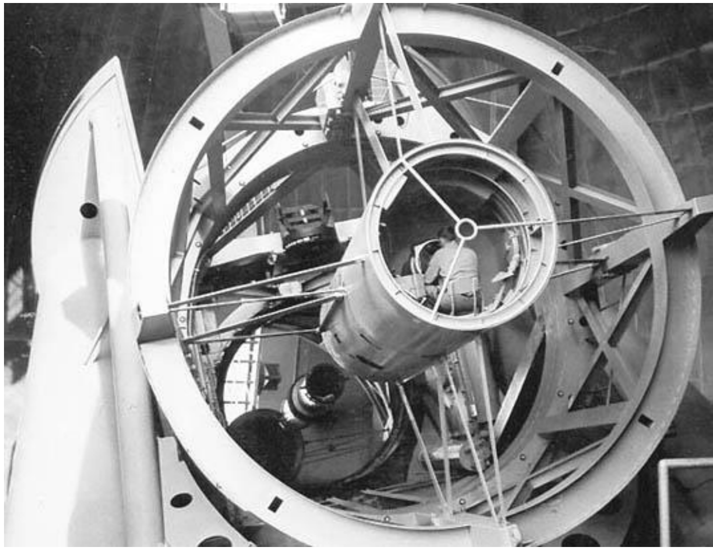
Large Binocular Telescope

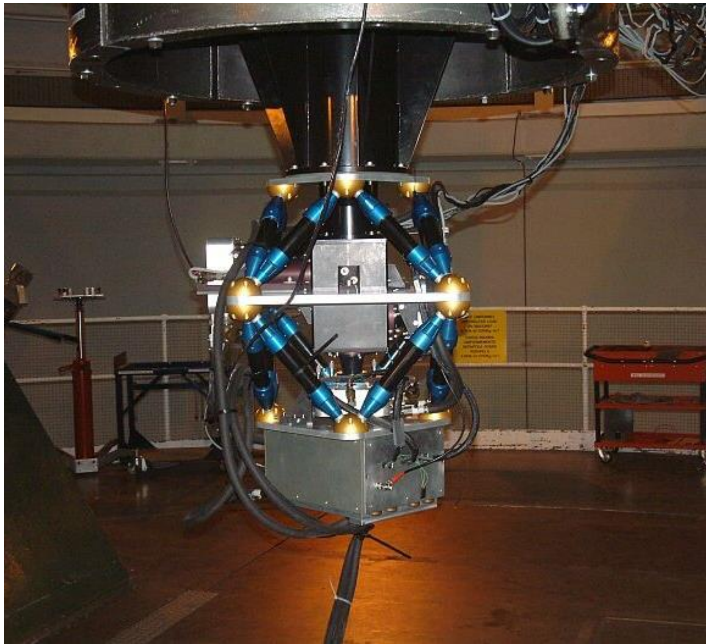


DKIST Solar Telescope

Telescope Foci – where to put the instruments



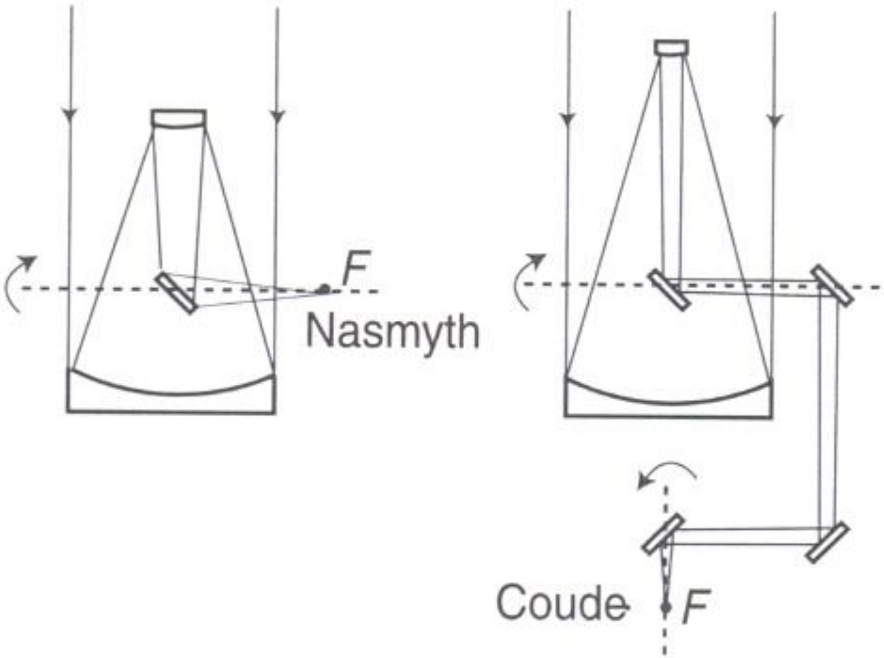




Prime focus – wide field, fast beam but difficult to access and not suitable for heavy instruments

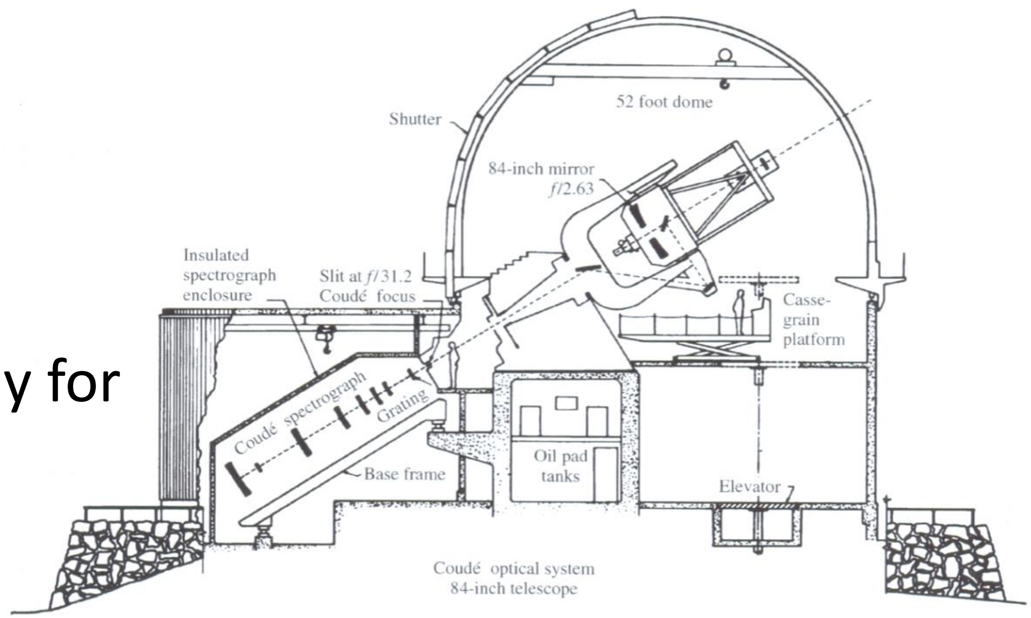
Cassegrain focus – moves with the telescope, no image rotation, but flexure may be a problem

Telescope Foci – where to put instruments (2)



Nasmyth – ideal for heavy instruments to put on a stable platform, but field rotates

Coudé – very slow beam, usually for large spectrographs in the "basement"



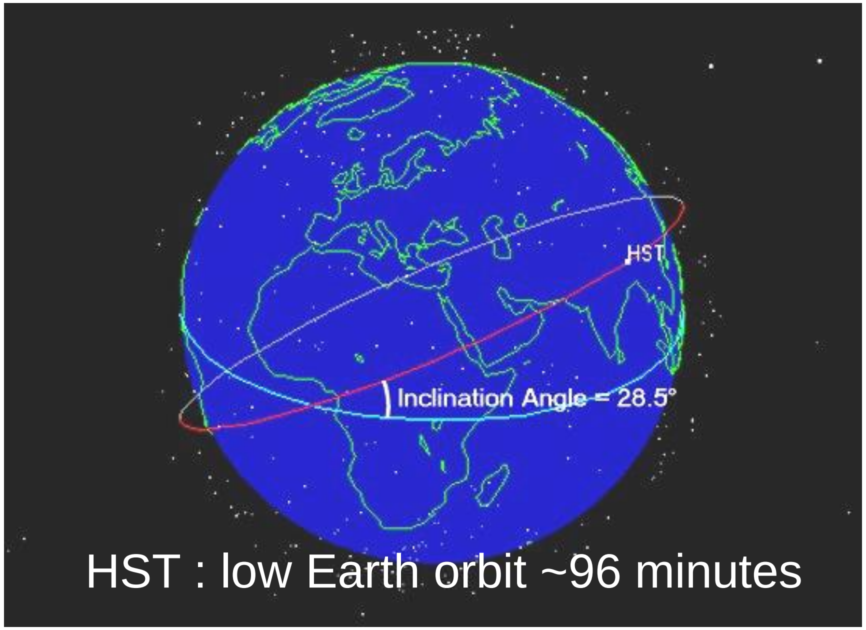
Space Telescope Orbits

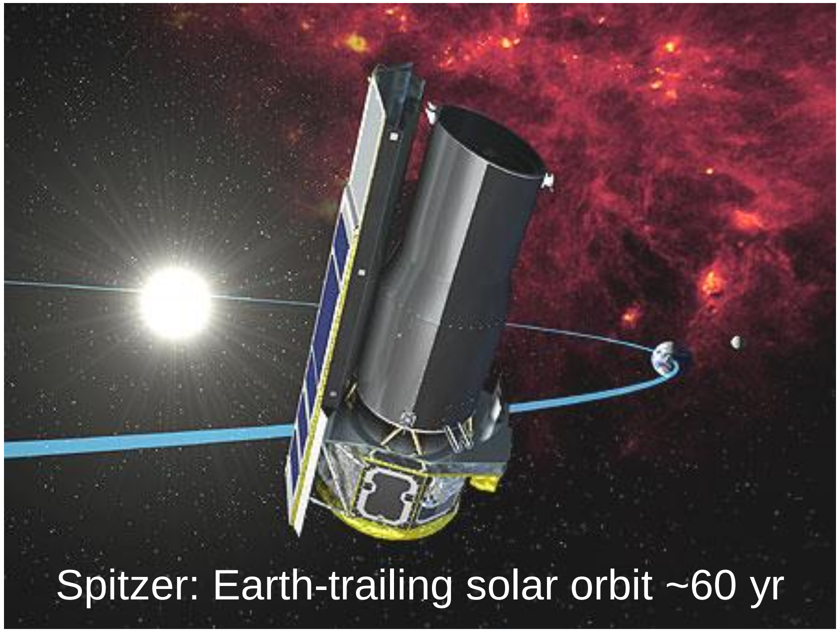
Types of Orbits

- low Earth
- sun-synchronous
- geostationary
- Earth-trailing
- L2

Influence on Orbit Choice

- communications
- thermal background radiation
- space weather
- sky coverage
- access (servicing)



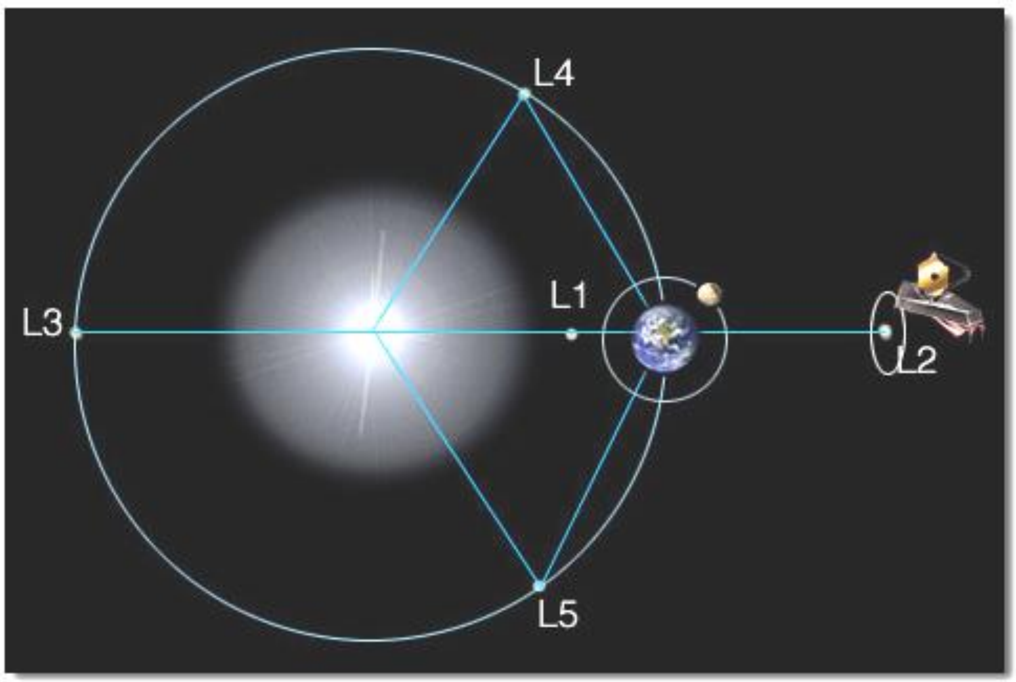


Lagrange Points

Is there a stable configuration in which three bodies* could orbit each other, yet stay in the same position relative to each other?

Joseph-Louis Lagrange: mathematician (1736 – 1813)

→ five solutions, the five Lagrange points.



*Sun-Earth-Satellite

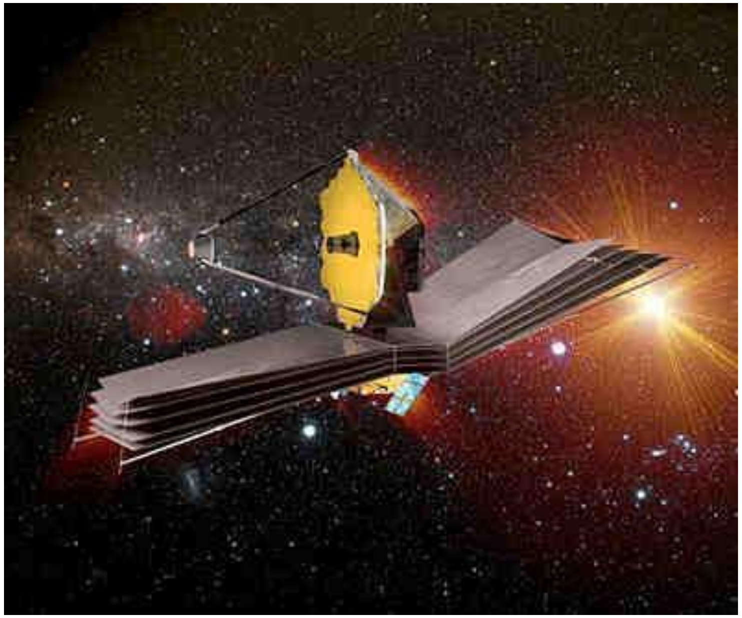
An object placed at any one of these 5 points will stay in place relative to the other two.

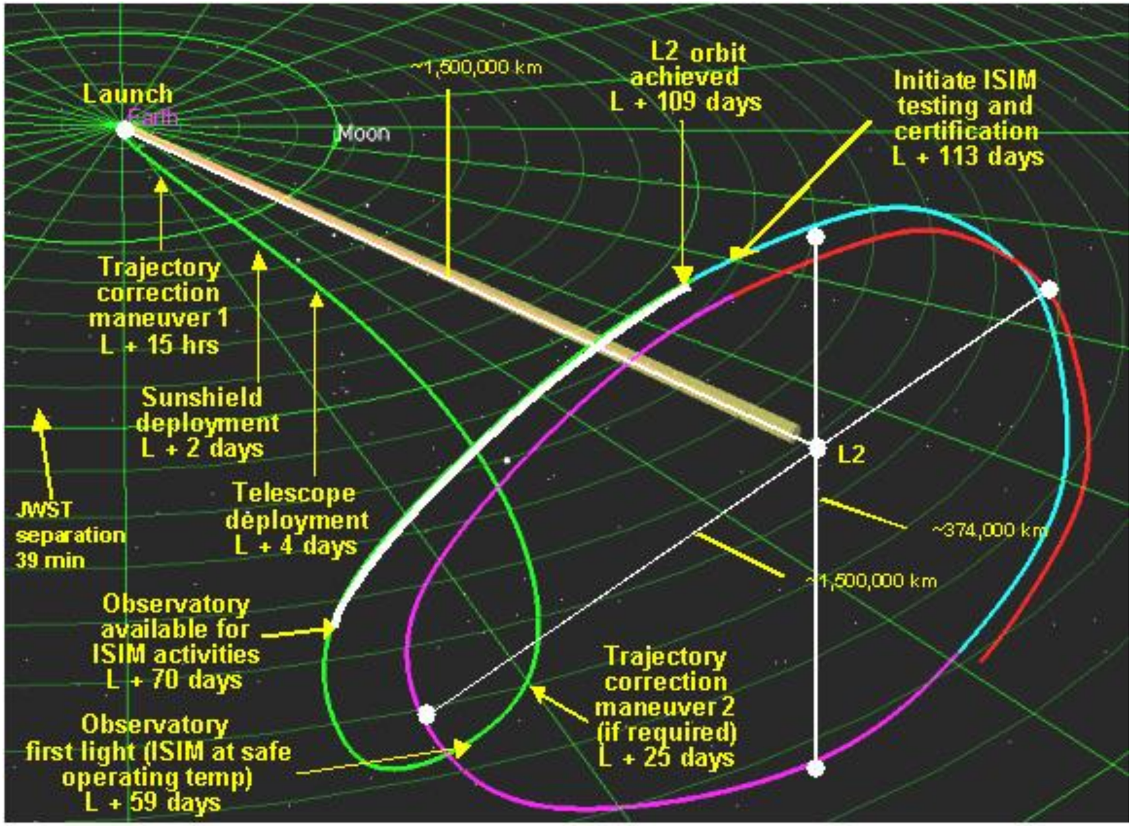
JWST, WMAP, GAIA, Herschel in orbits around L2

+ sun-shields

- orbit around L2

- radiation

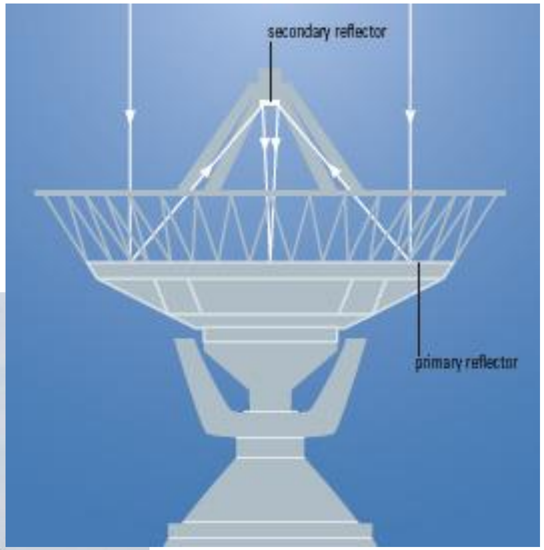




Extremely Large Telescope (ELT)

Radio Telescopes

Dishes similar to optical telescopes but with much lower surface accuracy




Arecibo, Puerto Rico – 305m single-aperture telescope

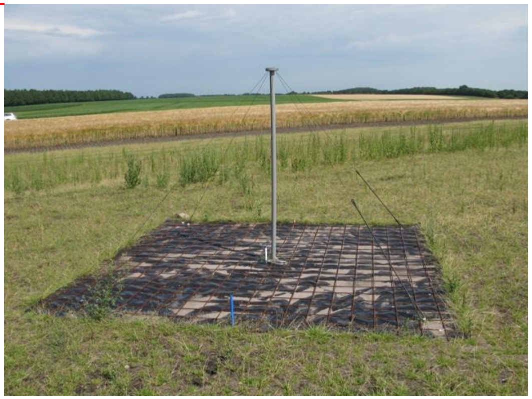

Effelsberg, Germany – 100m fully steerable telescope


Greenbank, USA – after structural collapse (now rebuilt)

Arrays and Interferometers

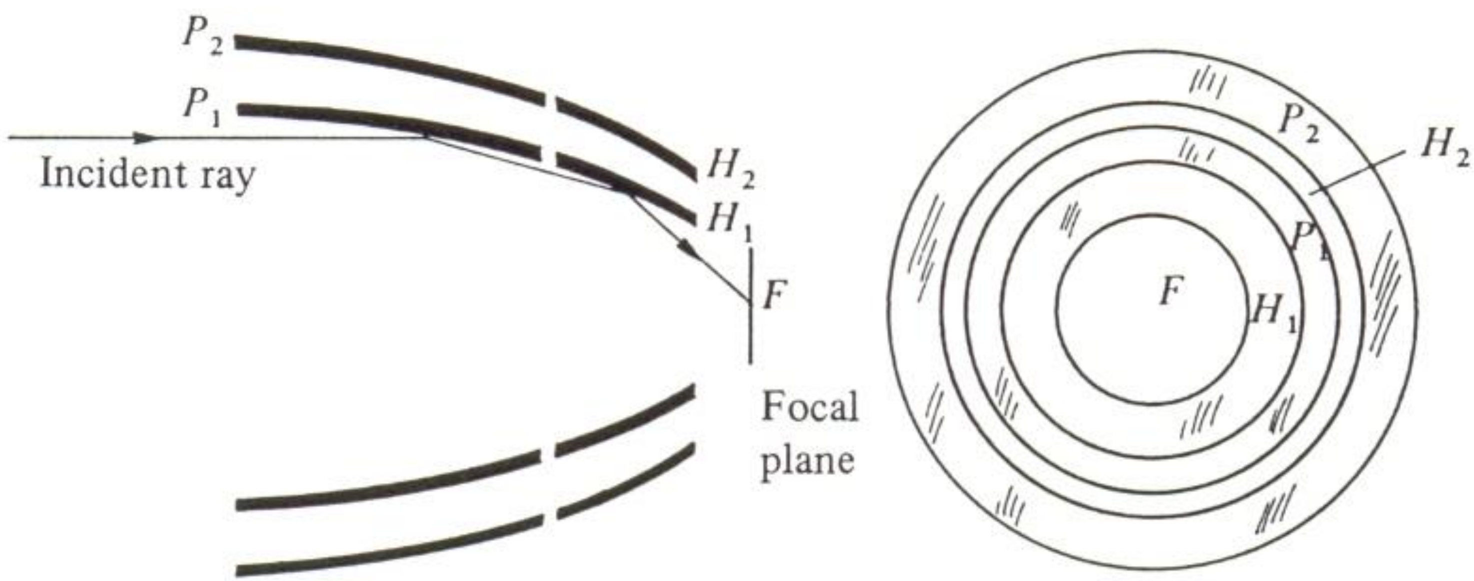
LOFAR

- LOw Frequency Array
- 2 types of low-cost antennae:
  - Low Band Antenna (LBA, 10-90 MHz)
  - High Band Antenna (HBA, 110-250 MHz)
- Antennae organized in 36 stations over 100 km
- Each station has 96 LBAs and 48 HBAs
- Baselines: 100m – 1500km

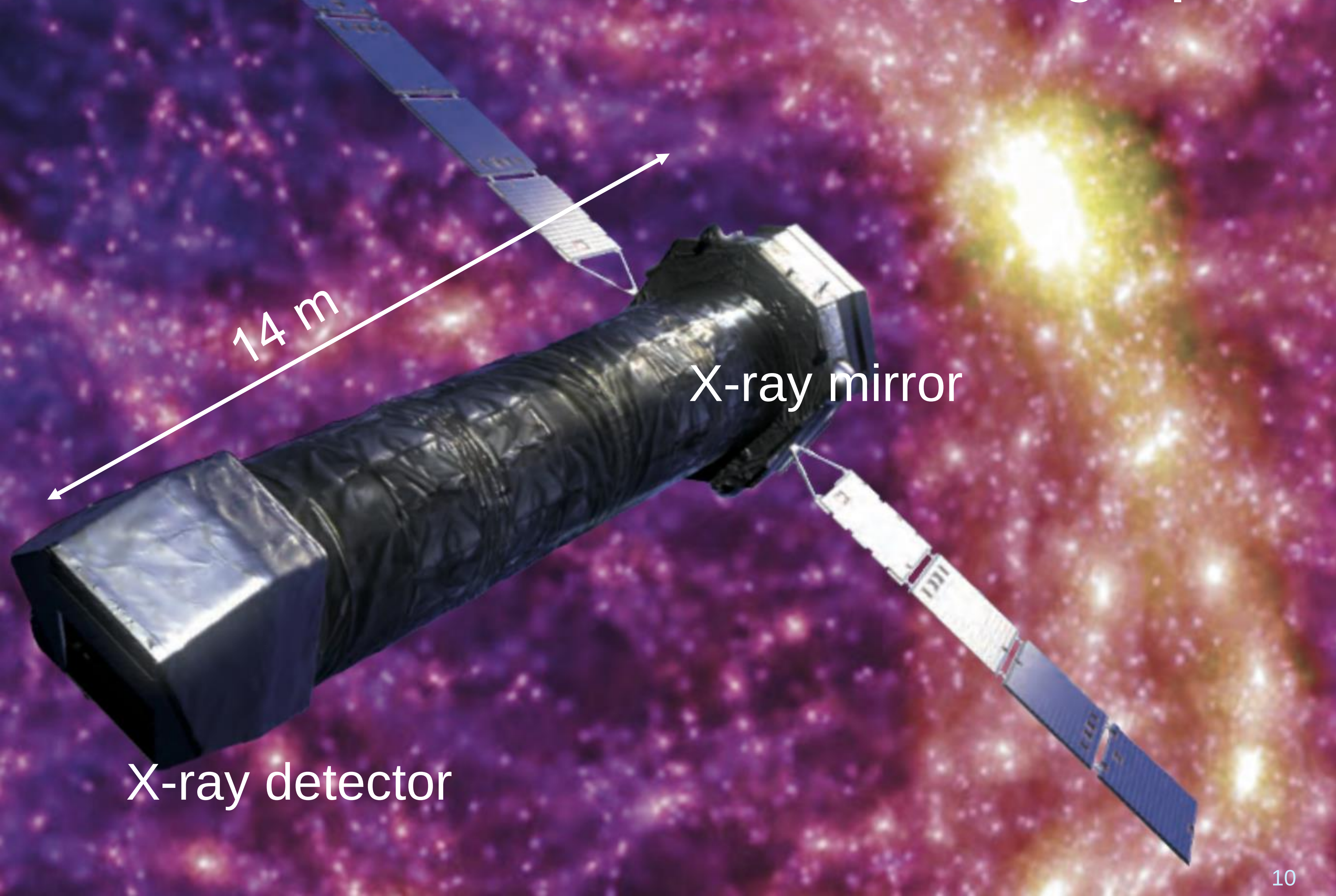


X-ray Telescopes

- X-rays close to normal incidence are largely absorbed, not reflected
- telescope optics based on glancing angle reflection
- typical reflecting materials for X-ray mirrors are gold and iridium (gold: critical reflection angle of 3.7 deg at 1 keV)



2031: The Athena mission: an ESA flagship



Dutch enabling technology II

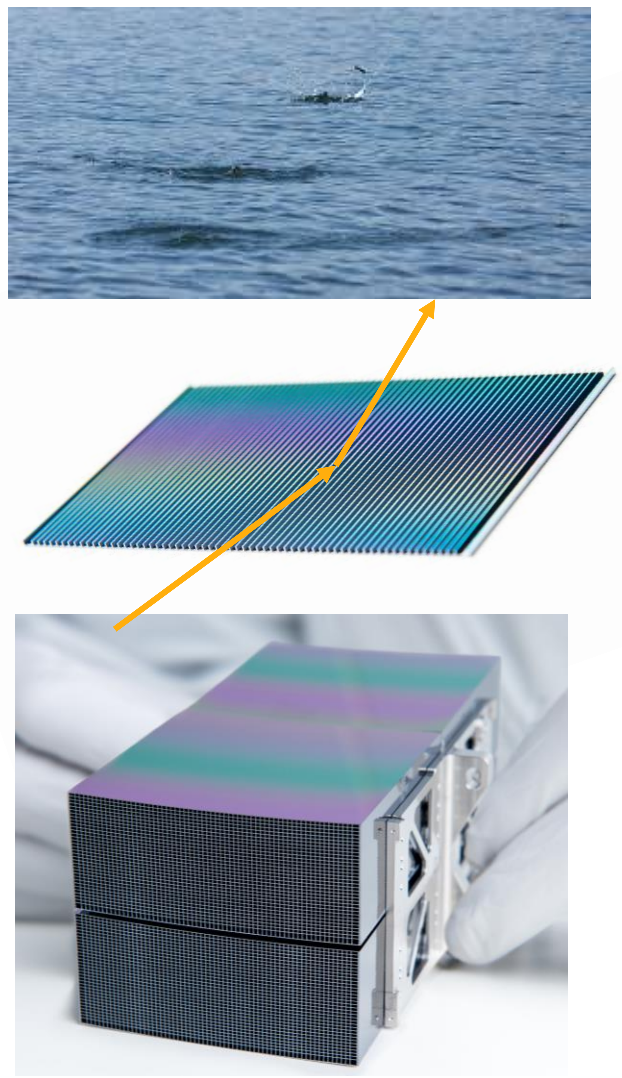
Stacked wafers as X-ray mirrors

Problem I: X-ray photons can only be **reflected at very small angles** equivalent to bouncing flat pebbles of a water surface

Solution I: **grazing incidence**

Problem II: astronomy needs **large collecting area**

Solution II: **ultra flat stacked wafers** from semi-conductor industry



Credits

http://www.astro.caltech.edu/~dmawet/teaching/2016-2017/ay122a_telescopei.pdf by Dimitri Mawet (Caltech/JPL)