OBSERVATIONAL ASTRONOMY

FALL 2025

Lecture 3

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Maintaining figure and alignment

- In order to maintain the image quality at the limit set by diffraction (or the atmosphere) it is important to:
  - maintain the paraboloidal figure of the primary reflector
  - maintain the alignment of the optical axes of the primary, secondary and any tertiary reflector with power (i.e. non-flat)
  - maintain the relative orientation of the reflectors, i.e they must not tilt with respect to each other.

If you do not do this you get aberrations (coma and astigmatism)

Homologous deformation

- Any telescope designed to operate at a wavelength λ should have its surface manufactured to a tolerance of λ/20 to maintain diffraction limited performance.
- It should maintain this accuracy as its orientation changes, i.e. as it tracks a source across the sky.
- Mechanically this is possible for small steerable dishes (10 metres diameter or less) but difficult for larger structures.

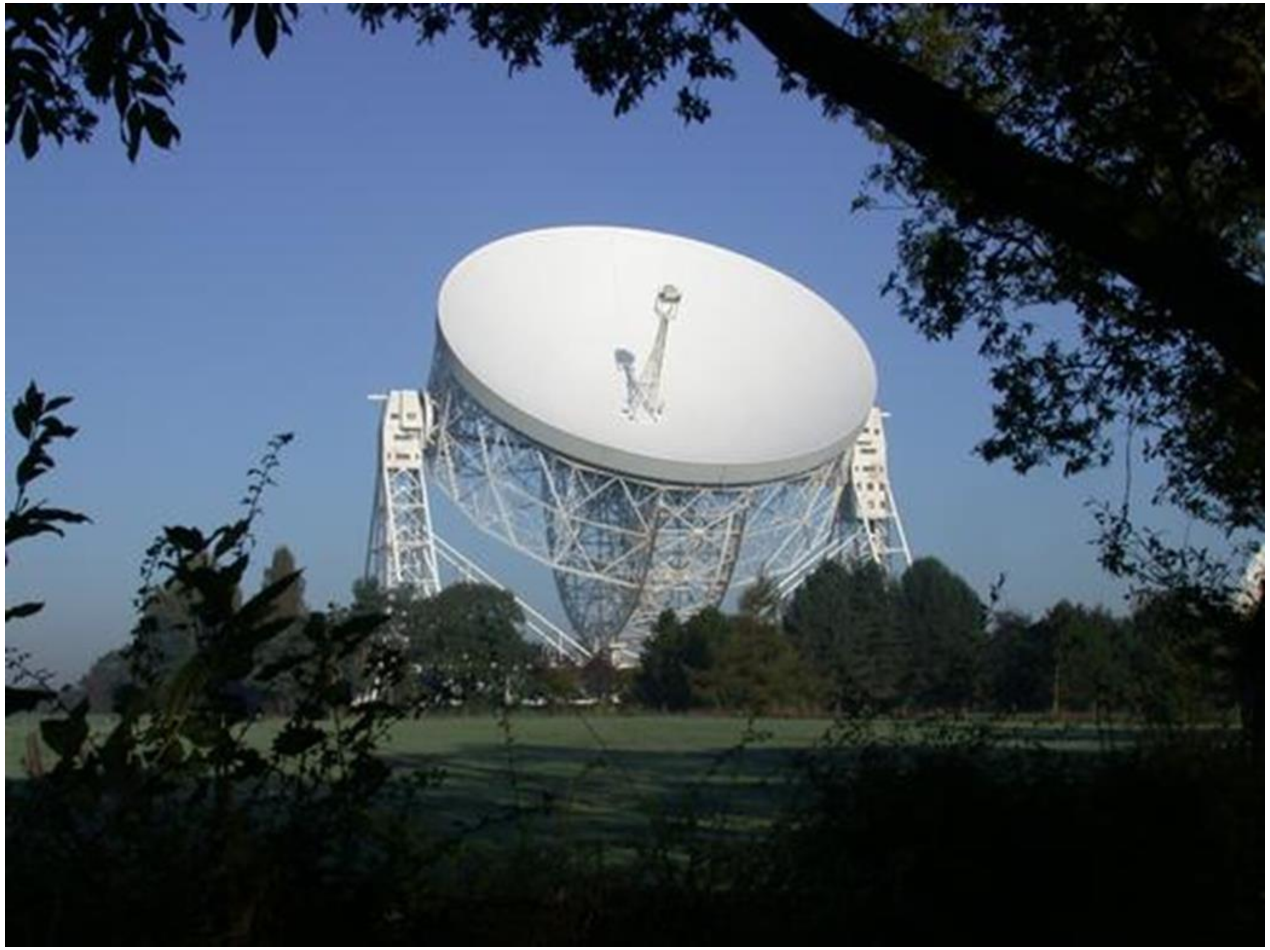
Homologous deformation (radio telescopes)

- Strictly what is required is not that its figure should not change with orientation, but that its figure should remain a paraboloid of rotation.
- Large radio telescopes are designed to deform but to remain paraboloids.
- The Effelsberg 100 metre diameter steerable dish deforms by up to 6cm, but remains a paraboloid to < 0.4 mm, so it performs to specification at wavelengths as short as 1cm.

Radio telescope performance

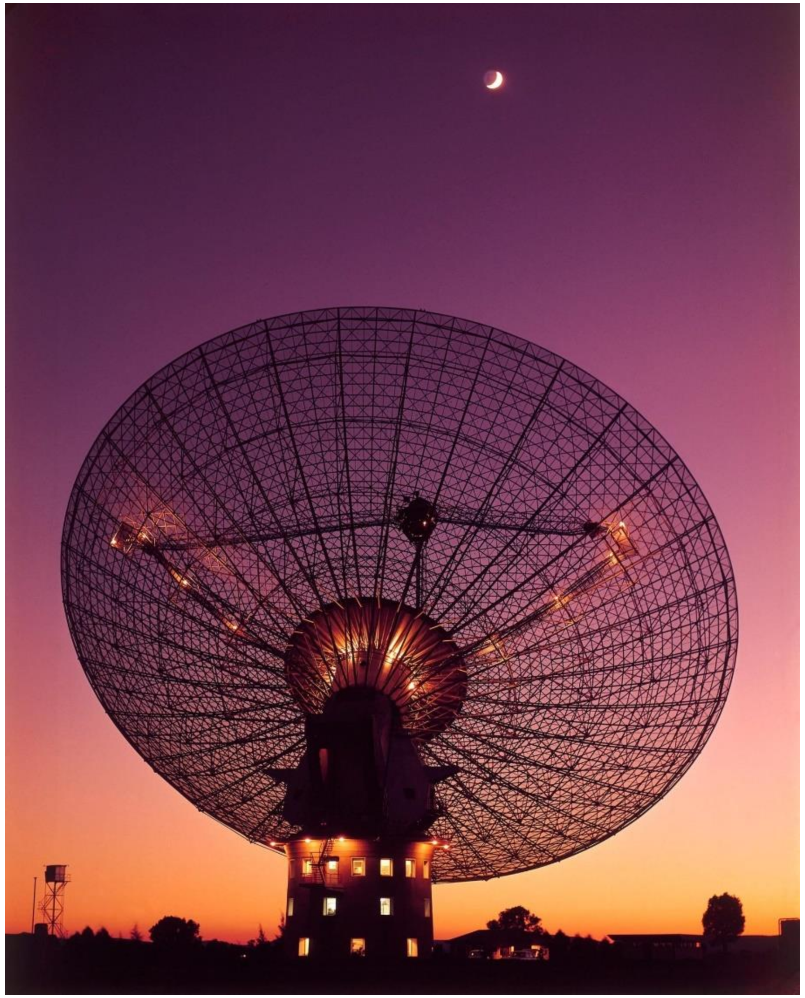
- Radio telescope performance in terms of maintaining the figure is usually limited by thermal expansion effects and by wind. For this reason, many modern high-frequency radio telescopes are not made from steel or aluminium, but from more exotic materials such as Carbon Fibre or other composite materials.

Lovell telescope at Jodrell bank



Parkes Radio telescope, Australia

64-m diameter parabolic dish

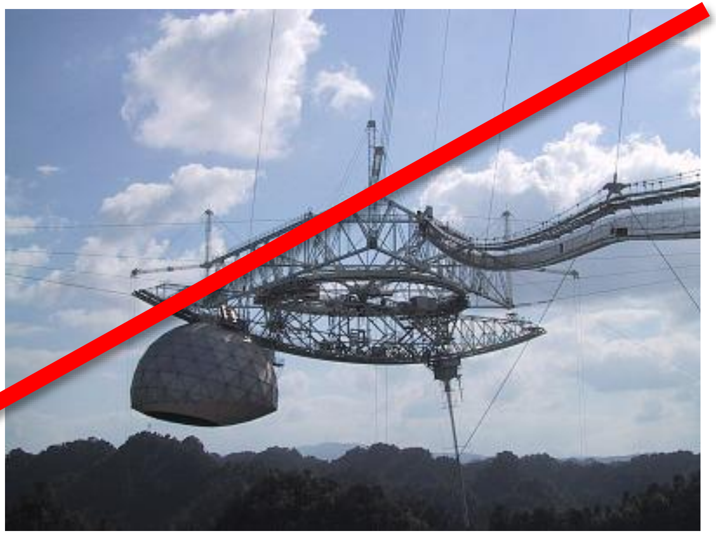


Above a modern photo, to the left in 1969.
What is the difference? Why?

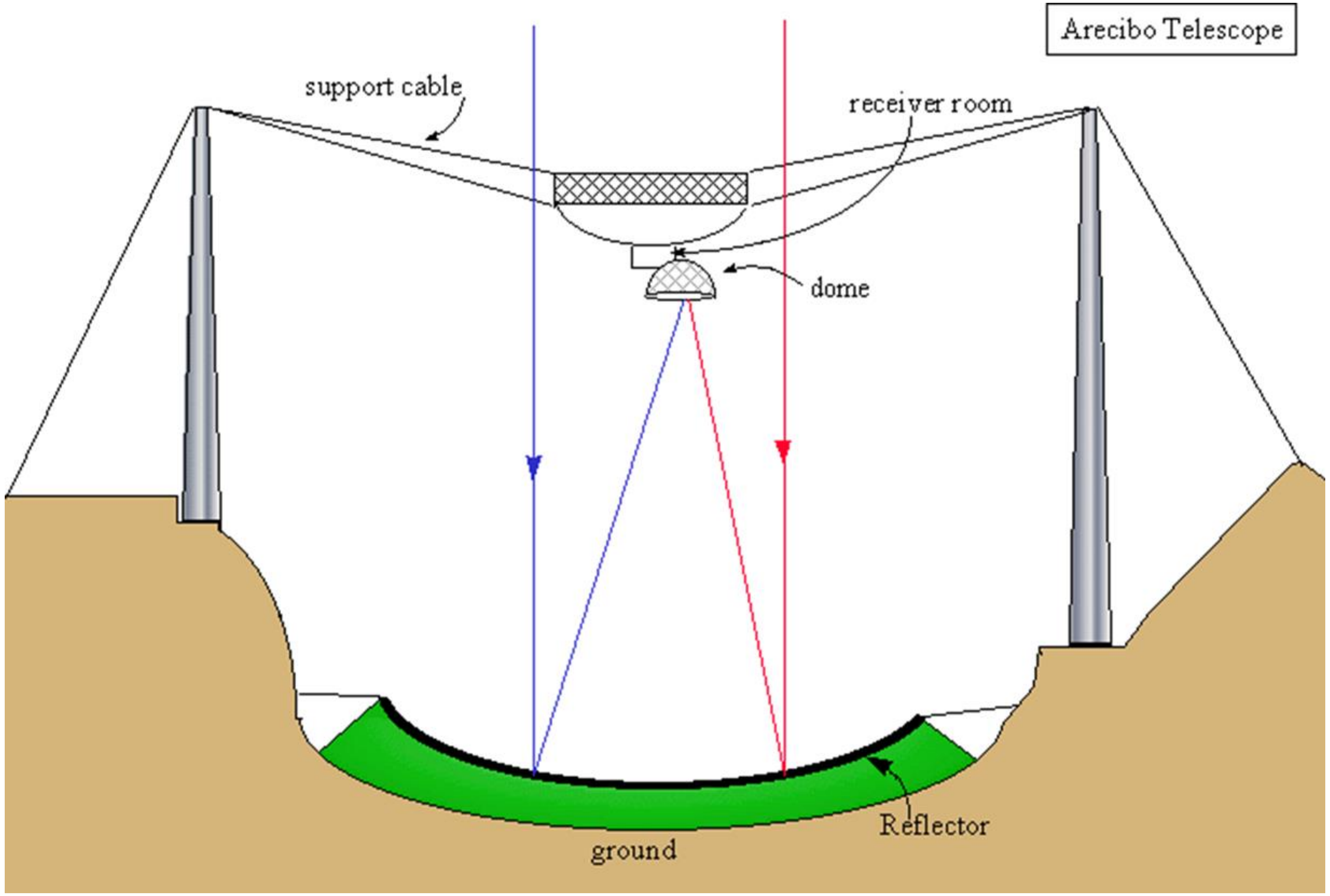
RATAN-600, Russia

A 576 m diameter circle of rectangular radio reflectors and a set of secondary reflectors and receivers

Arecibo radio telescope, Puerto Rico



Arecibo radio telescope, Puerto Rico



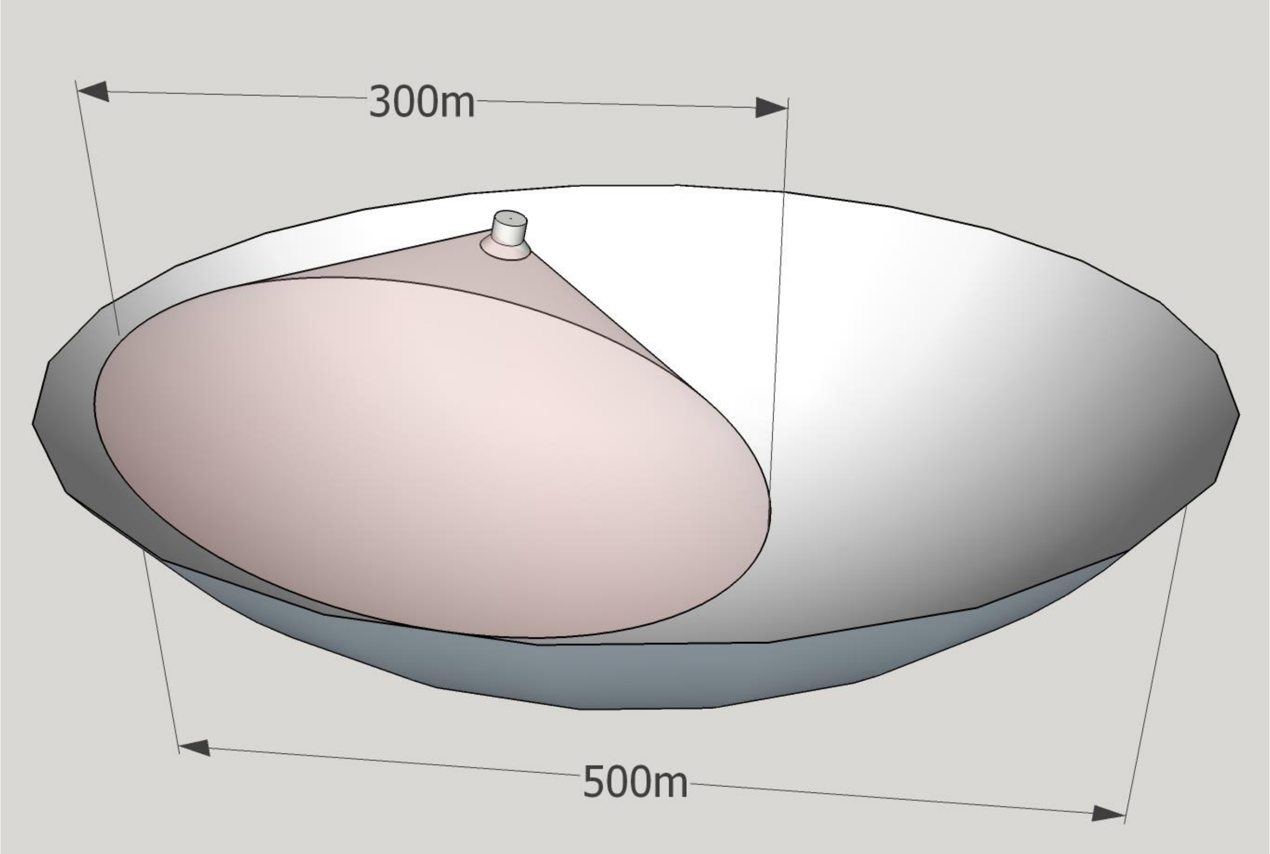
A 305 m spherical reflector

A new king of radio-astronomy – FAST (China)

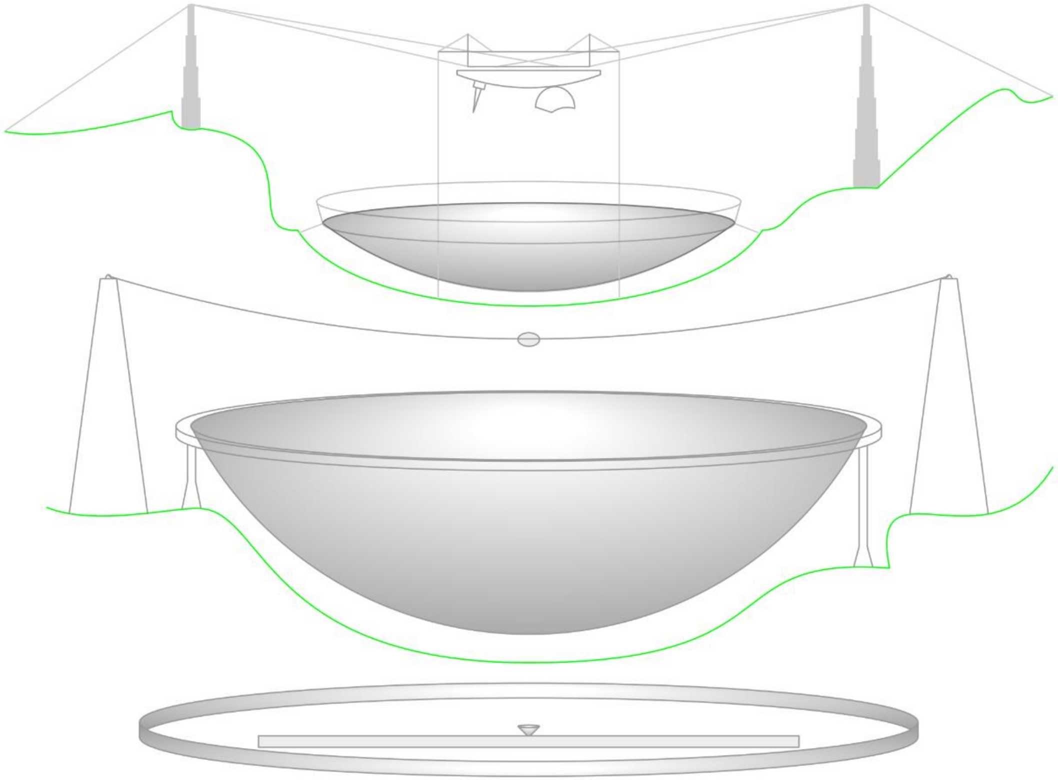
Five-hundred-meter Aperture Spherical Telescope (FAST)

FAST (China)

- Diameter: 500 m
- Illuminated diameter: 300 m



Comparison of the Arecibo (top), FAST (middle) and RATAN-600 (bottom) at the same scale.

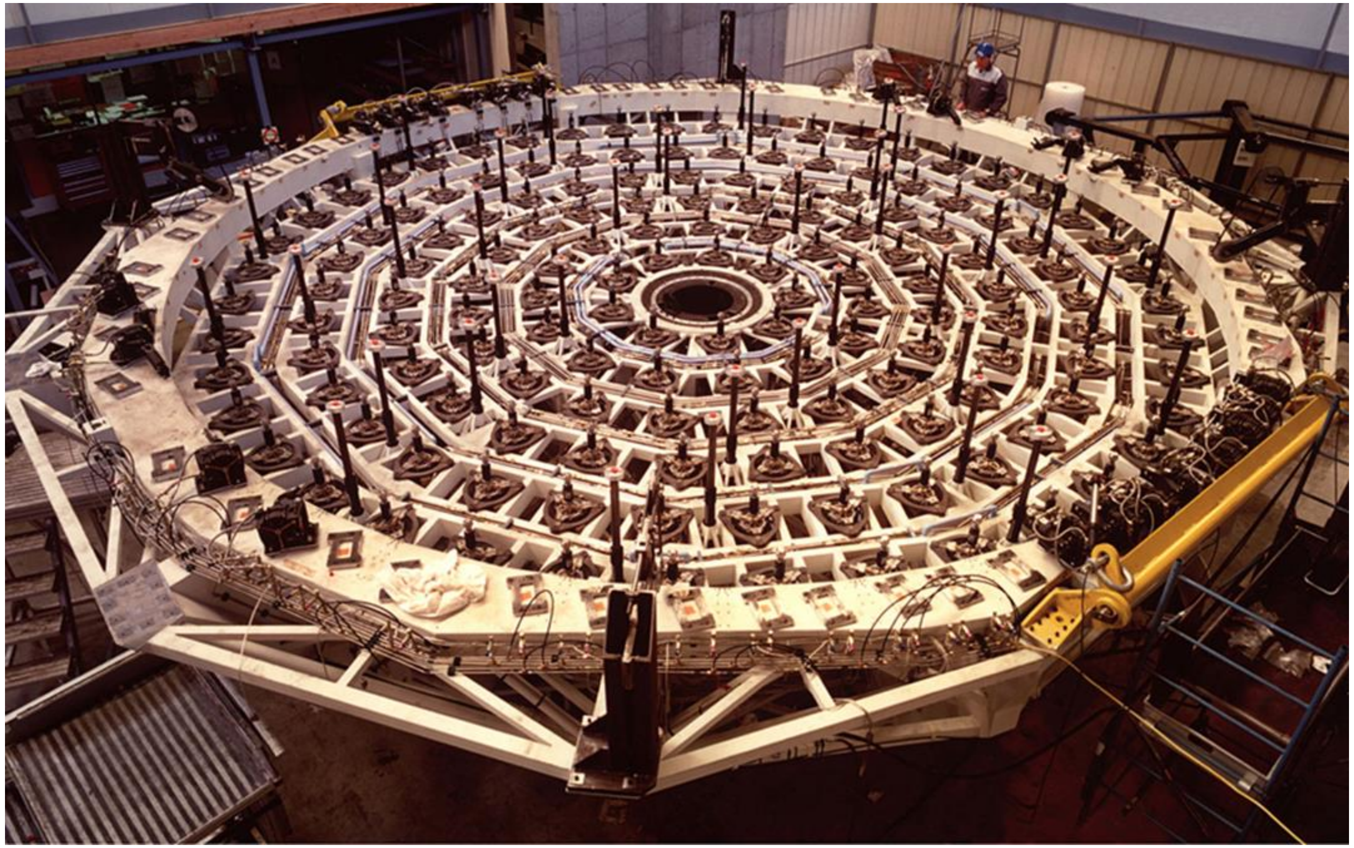


Optical telescopes - active mirror support

- In an optical telescope the primary reflector is usually a zero expansion glass surface coated with a reflecting metal. In small telescopes this can be rigid and maintain its structure.
- In larger telescopes the deformations are modelled as a function of telescope attitude, and a series of pneumatic or hydraulic actuators are used to apply the correct force at each point on the mirror to make sure the shape is maintained.

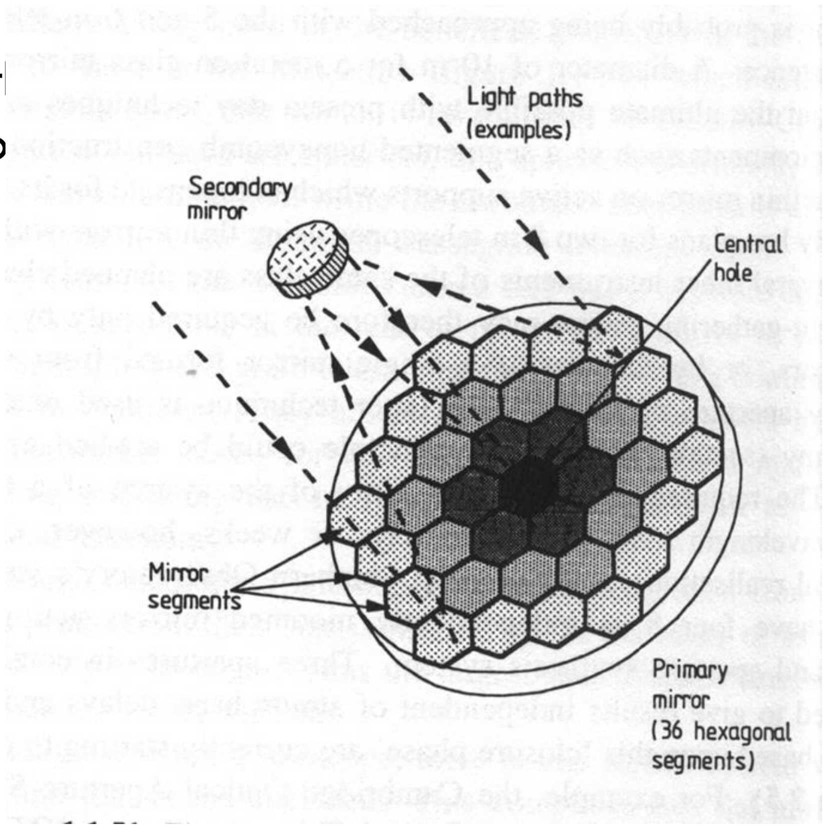
The VLT primary mirror support

The VLT primary mirror support, showing 150 actuators arranged in six concentric rings.



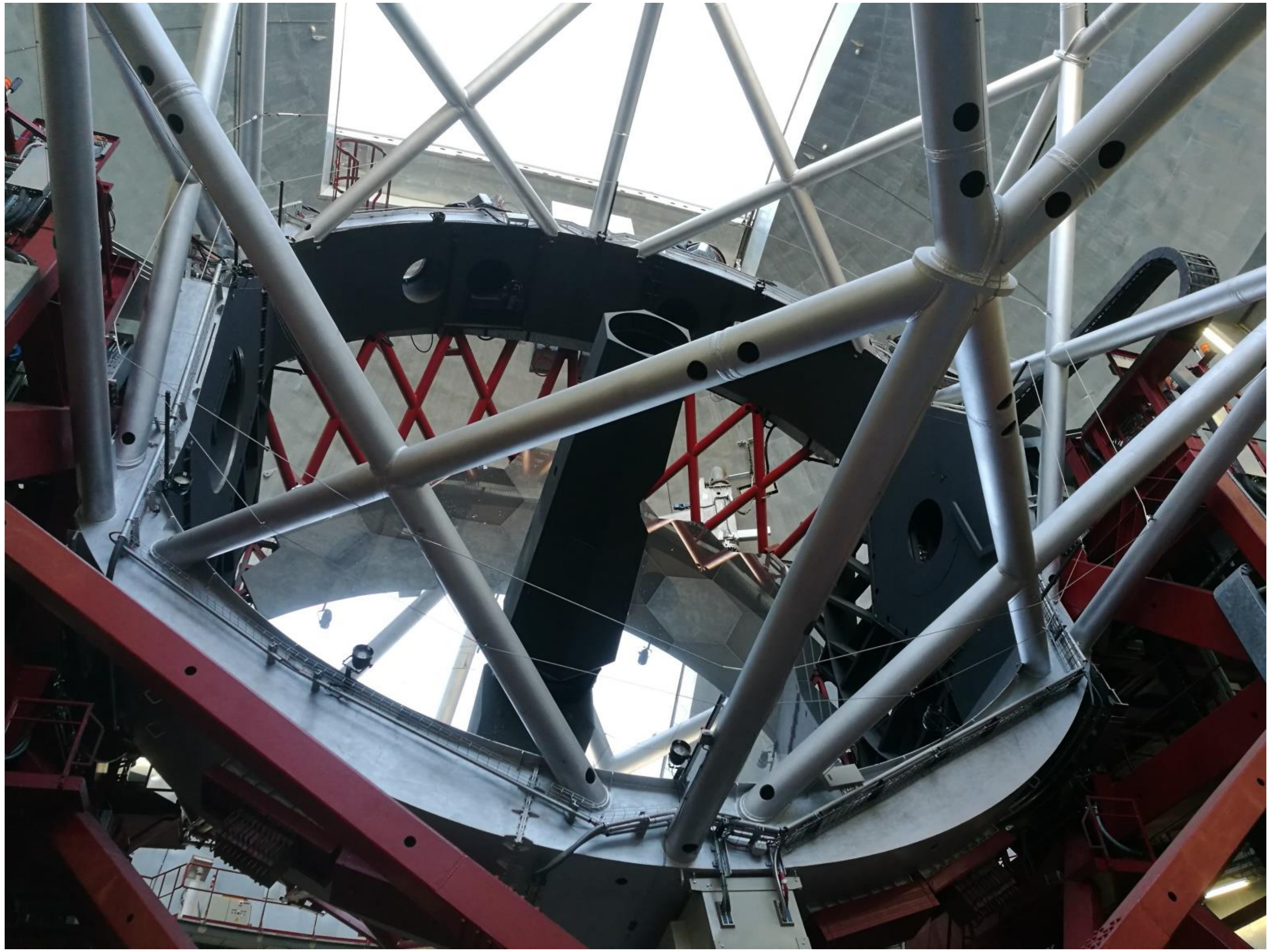
Segmented mirror telescopes

- In the Keck and GranTeCan (GTC) telescopes, instead of a single monolit mirror, the mirror is built up of hexago segments, which can be controlled accurately to bring their light to the same focus *at the same phase*. These telescopes are Cassegrain altitude-azimuth designs.



GTC telescope

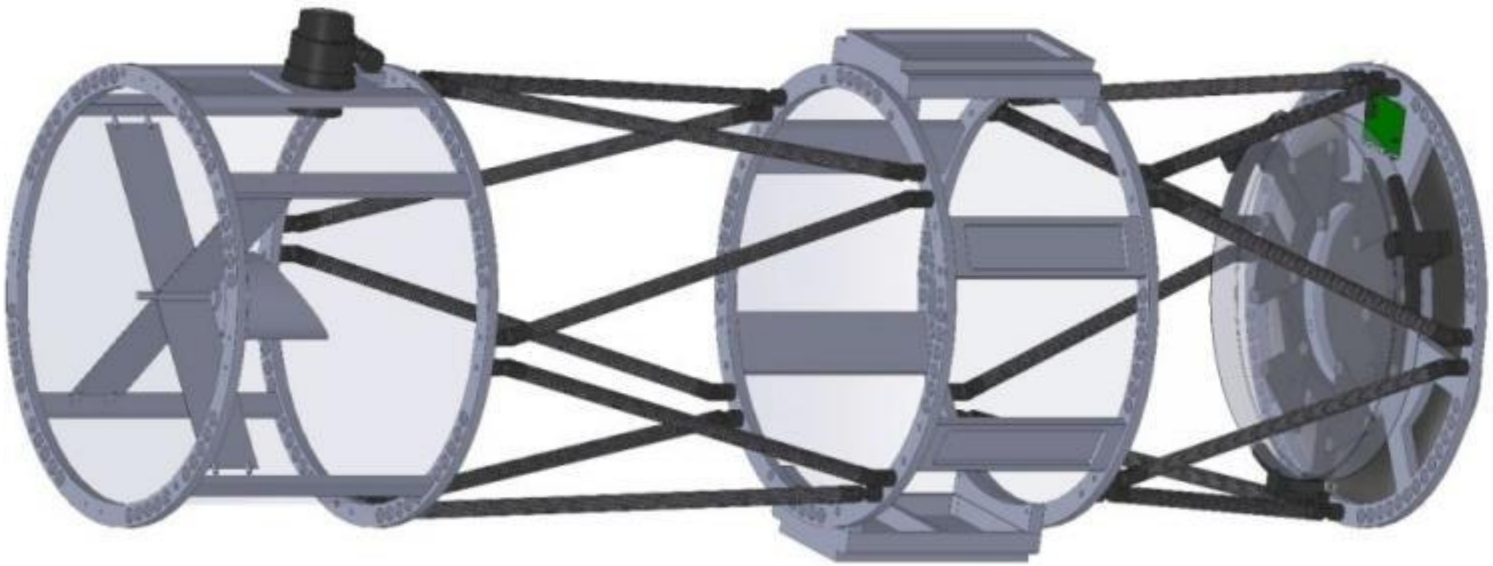
Segments are kept aligned and in phase by electromechanical support and feedback system



The Serrurier Truss

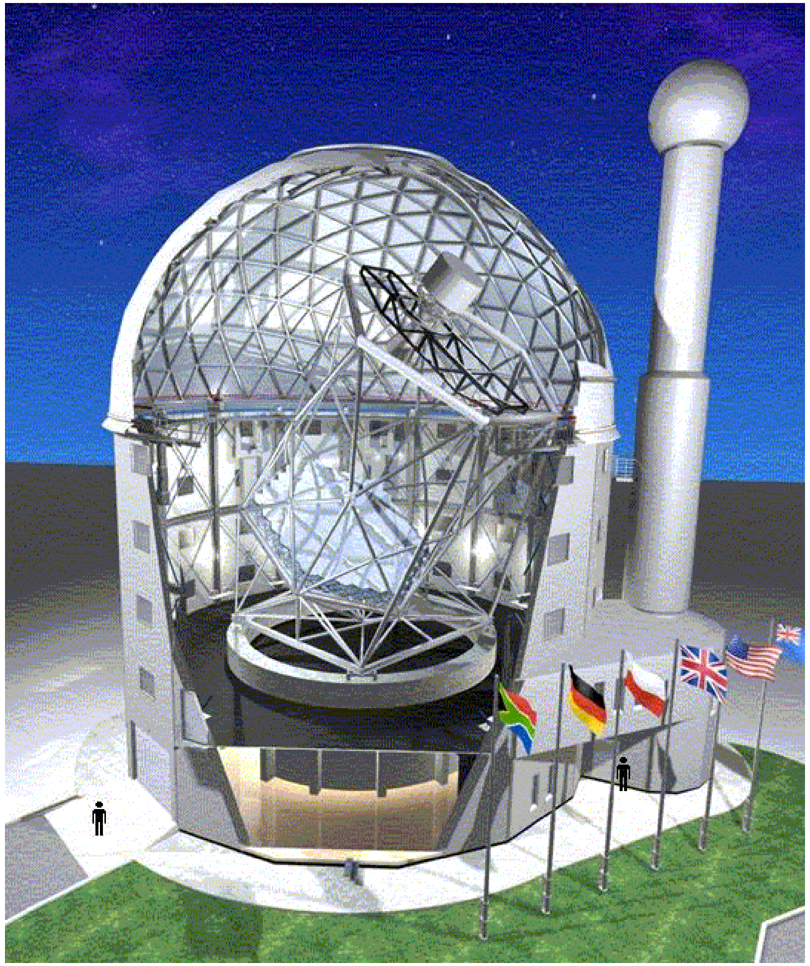
- It is very important to keep the optical axes of the paraboloidal and/or hyperboloidal primary and secondary mirrors precisely aligned, otherwise you get coma even on-axis.
- The Serrurier truss is an open "tube" structure designed so that at any orientation the flexure of primary and secondary mirrors is identical, maintaining the alignment.
- This design allows a relative rotation of primary and secondary mirrors, which can in turn be corrected by pneumatic and/or electromechanical actuators.

The Serrurier Truss



Southern African Large Telescope

- The segmented 11 by 9.8 meters mirror is spherical.
- SALT has a fixed zenith angle of 37 degrees, optimised for the Magellanic clouds.
- Azimuth only tracking.
- Prime focus top end moves Arecibo style.
- Limited sky area and tracking time.
- Much cheaper than telescopes of similar size but of classical design.



New Large Telescopes

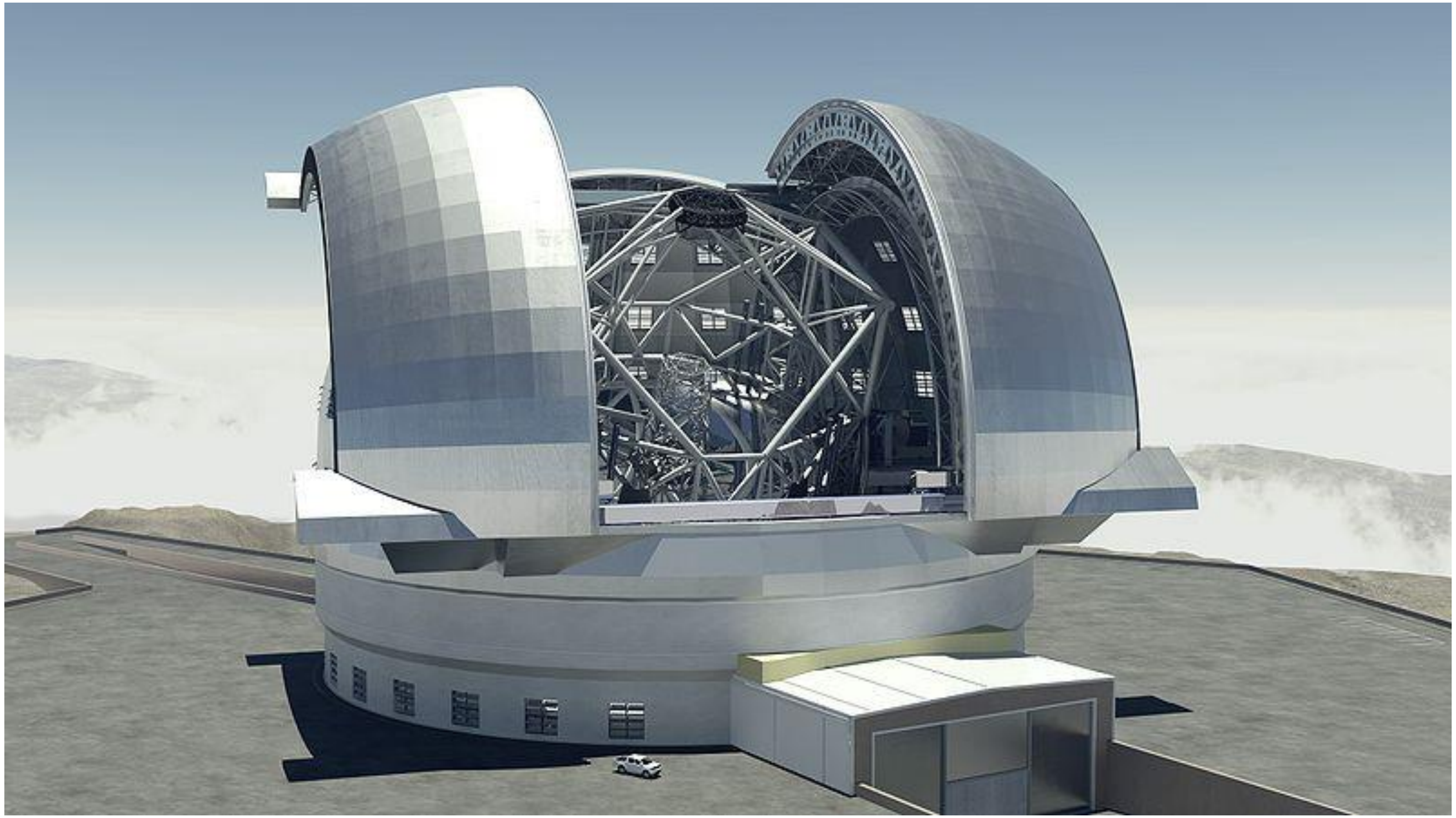
- Current state of the art in optical/near infra-red telescopes is:
  - 8.2 metre monilithic meniscus mirror (VLT)
  - 10 metre equivalent mirror with hexagonal segments (GTC).
- Various proposals for larger 20-100 metre aperture telescopes.
- The European Extremely Large Telescope (ELT) is already under construction.
- International 30 metre telescope (TMT) ~~is preparing to start construction.~~
  - In June 2025 the United States' National Science Foundation dropped support for the TMT in favor of the the Giant Magellan Telescope (GMT).

Problems of Extremely large telescopes

- Need light stiff structures, composite materials, e.g. Silicon Carbide for mirror segments.
- Large downward looking secondary is a huge problem, carbon fibre structures.
- Control loop to keep segments aligned is heavily nested hierarchical control at hundreds of Hz, beyond the scope of current hardware.
- Wind distortion a severe problem.
- Adaptive mirrors up to a metre across may be required.
- Need Multi-Conjugate Adaptive optics with laser guide stars (see next lectures).
- Huge data rates.

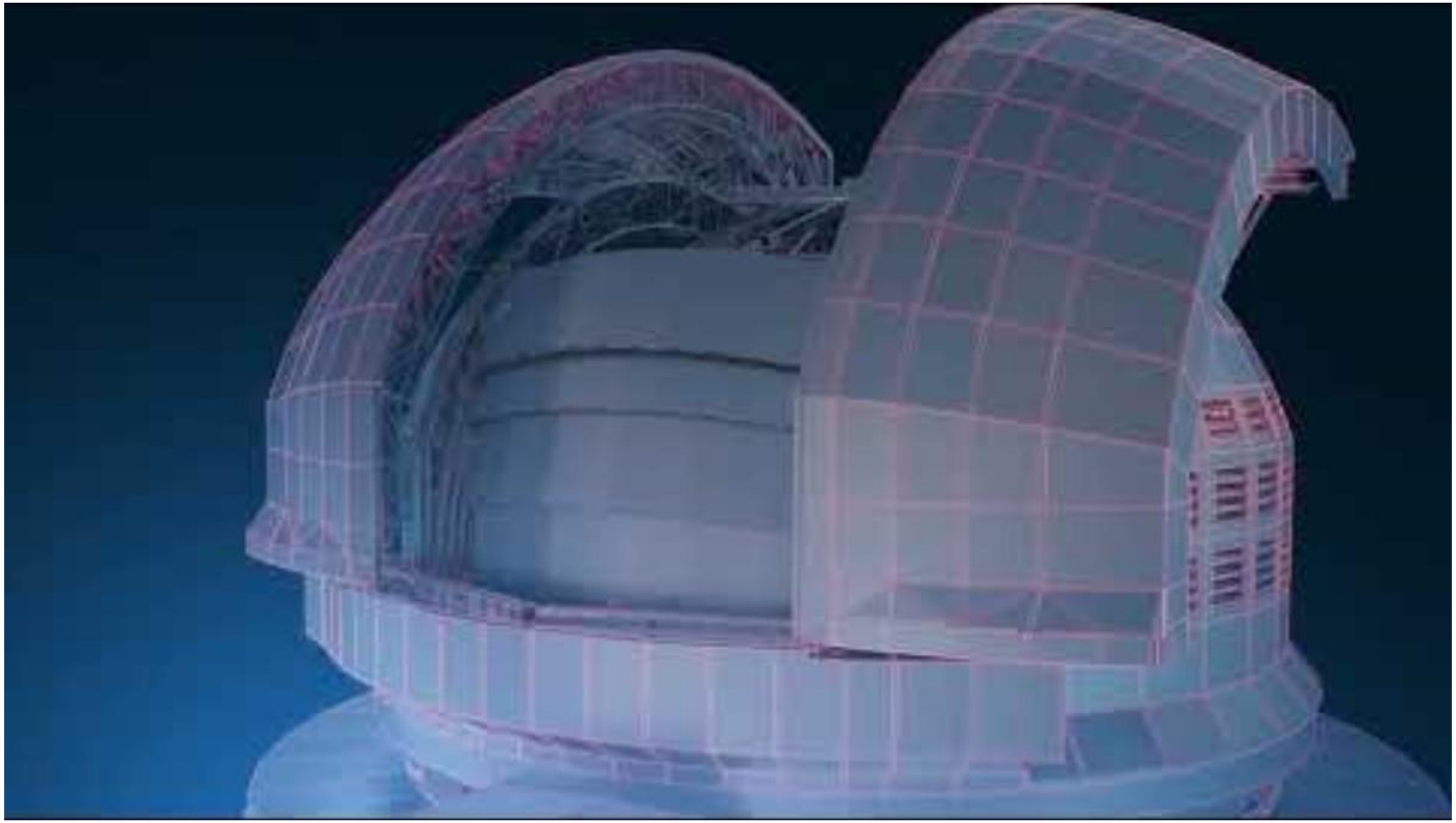
The European Extremely Large Telescope

- Diameter: 39 m (798 hexagonal 1.4 m mirror segments).



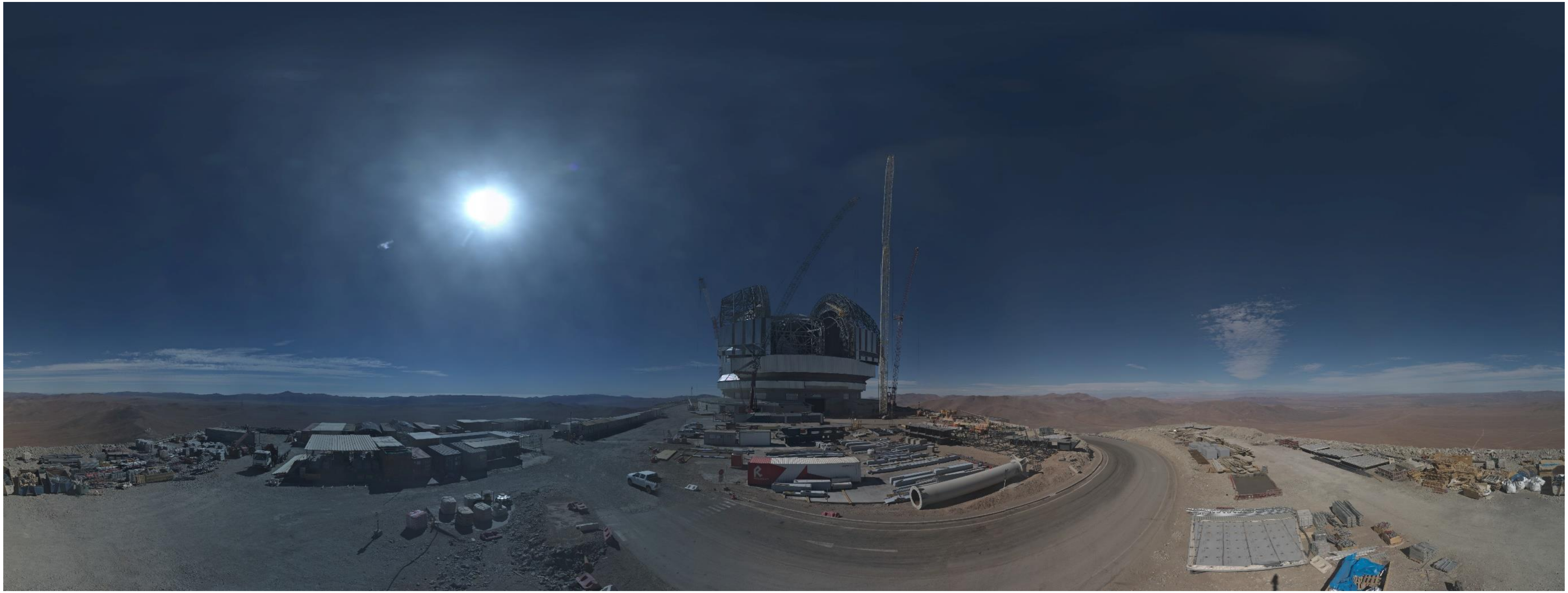
The European Extremely Large Telescope

- Diameter: 39 m (798 hexagonal 1.4 m mirror segments).

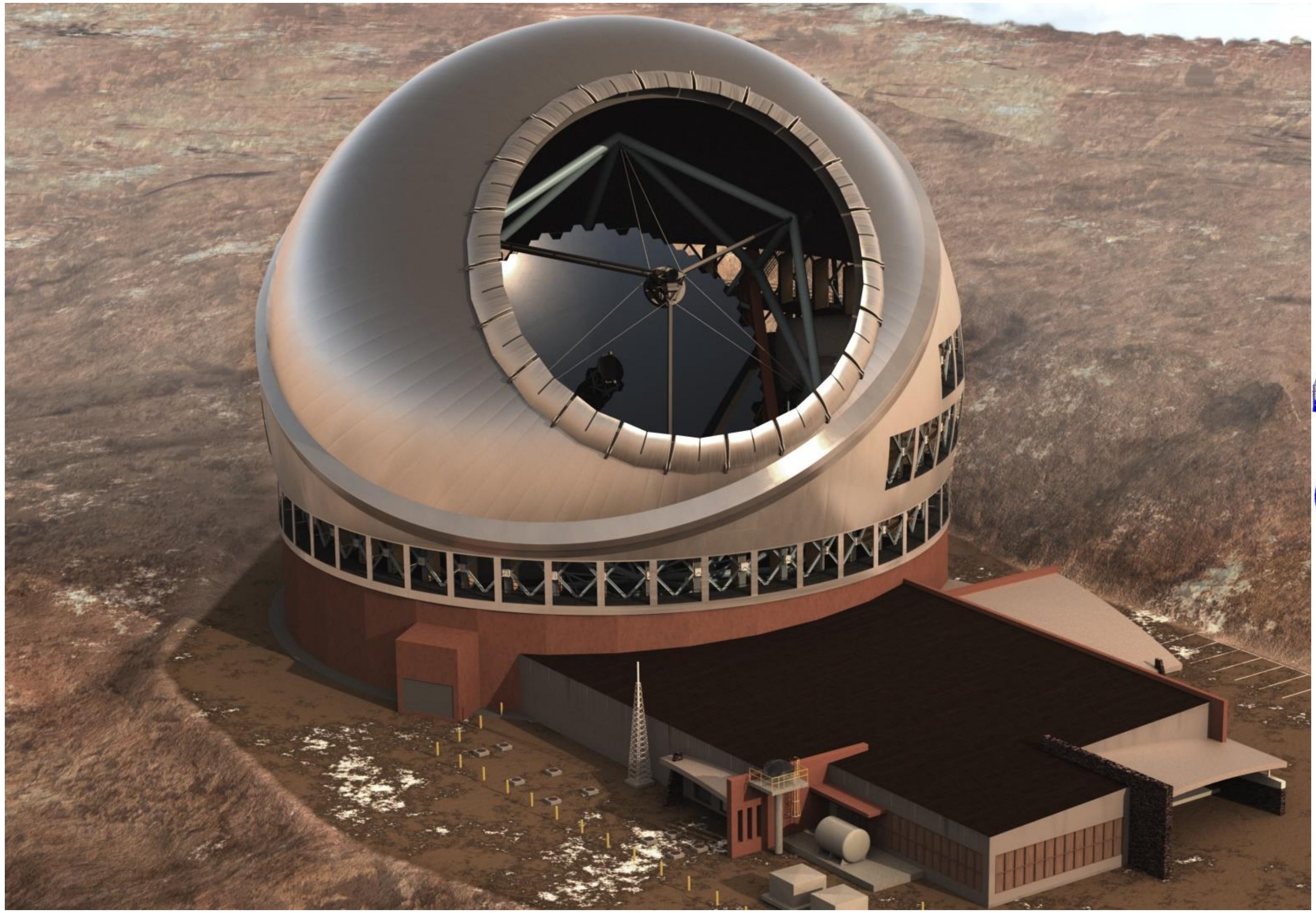


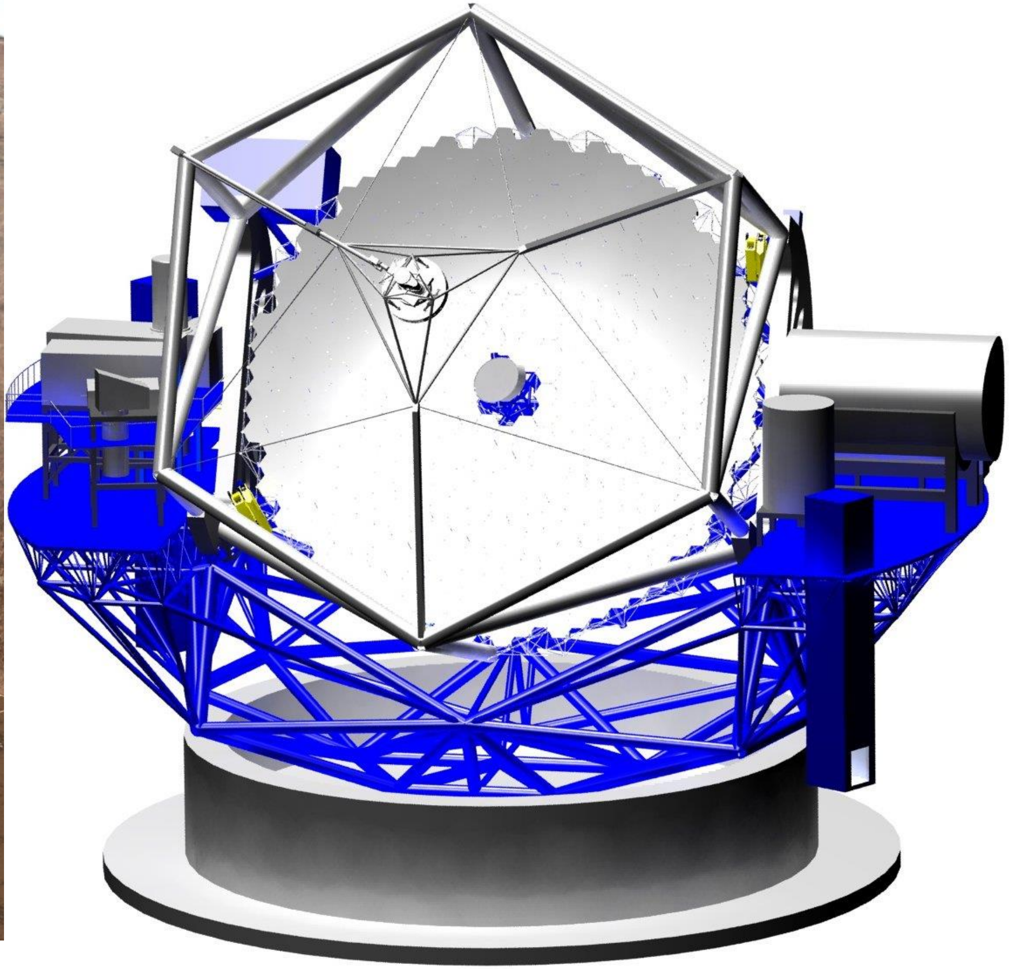
The European Extremely Large Telescope

- Current state (6 September 2025, 21:00 CEST)
- 2028 (planned): Technical first light of the ELT



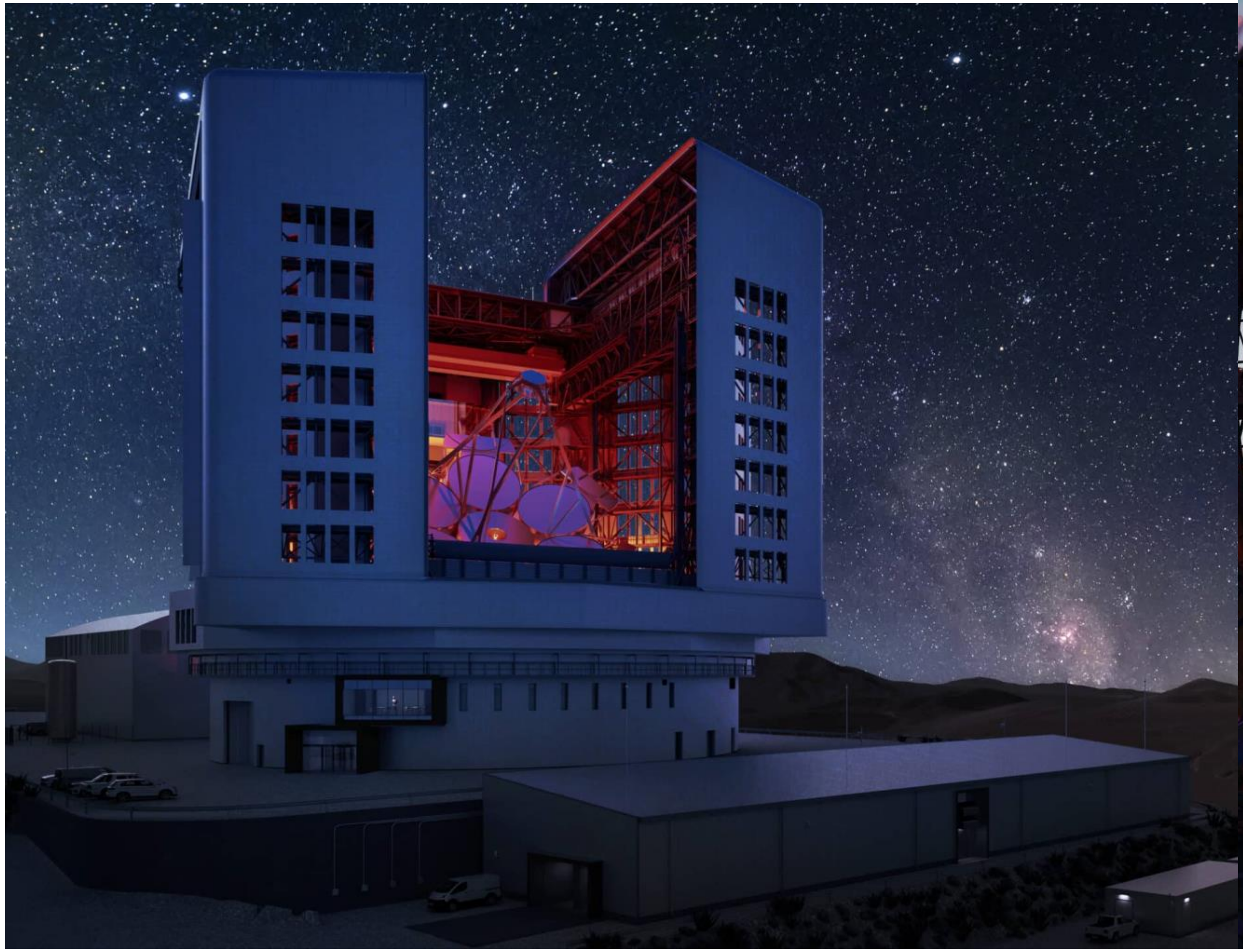
International 30 metre telescope (TMT)

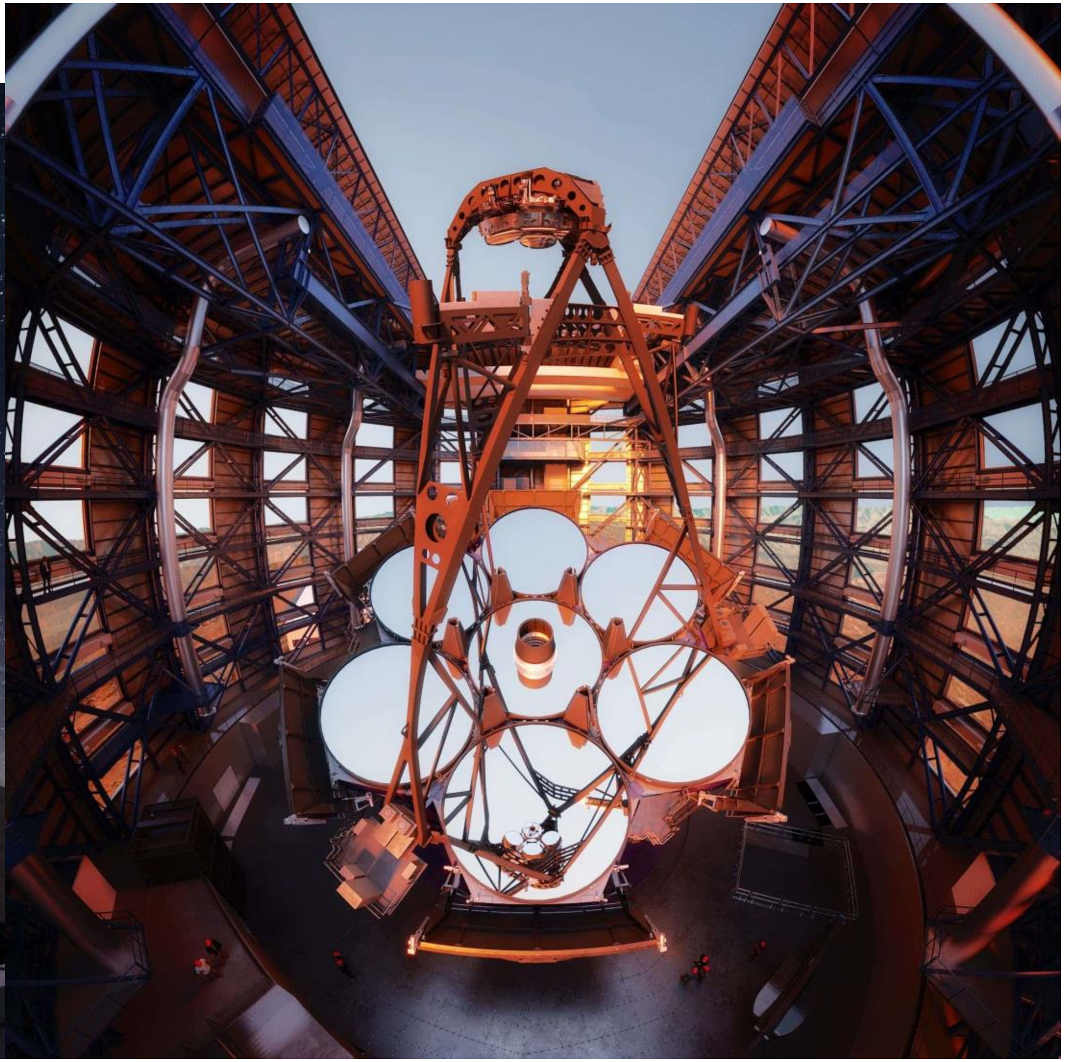




Giant Magellan Telescope (GMT)

7 x 8.4-m mirrors → a 25.4-m surface





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Telescopes for high-energy astrophysics

The high-energy spectrum

- Extreme ultraviolet (EUV): 100 – 1000 Å (12-120 eV)
- Soft X-rays: 10 – 100 Å (120 – 1200 eV)
- X-rays: 0.1 – 10 Å (1.2 – 120 keV)
- Soft γ-rays: 0.01 – 0.1 Å (120 – 1200 keV)
- γ-rays: <0.01 Å (>1.2 MeV)

$$\lambda\ [\text{Å}] = 12.40/E\ [\text{keV}]$$

The high-energy spectrum

The main production mechanisms:

- Synchrotron radiation
- The inverse Compton effect
- Free-Free (Bremsstrahlung) radiation

The flux of the radiation varies enormously with wavelength:

- The solar optical flux – 10^{21} photons m^{-2} s^{-1}
- The solar flux at 10 Å – 5×10^{9} photons m^{-2} s^{-1}
- The total flux from all sources for energies >1GeV – few photons m^{-2} **day**$^{-1}$

UV, X-ray, and γ-ray Telescopes

- All radiation at $\lambda < 3100$ Å is absorbed by the atmosphere.
- UV (2000 – 3000 Å) and hard X-rays can penetrate to an altitude of 30 – 40 km while soft X-rays only reach higher altitude:
  - therefore, all UV and X-ray observations have to be carried out from rockets or from space.
- Ultraviolet telescopes are similar to optical in design, but must be in space. The Hubble Space Telescope is the premier ultra-violet telescope.

X-ray telescopes

- Imaging of high-energy photons is a much more difficult task because of their extremely penetrating nature.
- Normal designs of telescope are impossible:
  - in a refractor the photon would be absorbed, scattered or unaffected rather than refracted by the lens;
  - in a reflector the photons would just pass through any material they impinge on at normal incidence.

X-ray telescopes

- X-rays at normal incidence are not reflected by anything, however, at energies <~100 keV, photons may be reflected with up to 50% efficiency off metal surfaces, when their angle of incidence approaches 90^o – grazing incidence.
- Approximate empirical formula for the critical angle is $\theta_C = 69 \times \sqrt{\rho}/E$ arcminutes
  where ρ is density of material in g/cm^3 and E is energy of X-rays in keV.

X-ray telescopes

- For e.g. nickel or gold, critical angle is of order few degrees for 1 keV X-rays, $<0.6^{o}$ for 10 keV X-rays, and $<0.1^{o}$ for 100 keV X-rays.

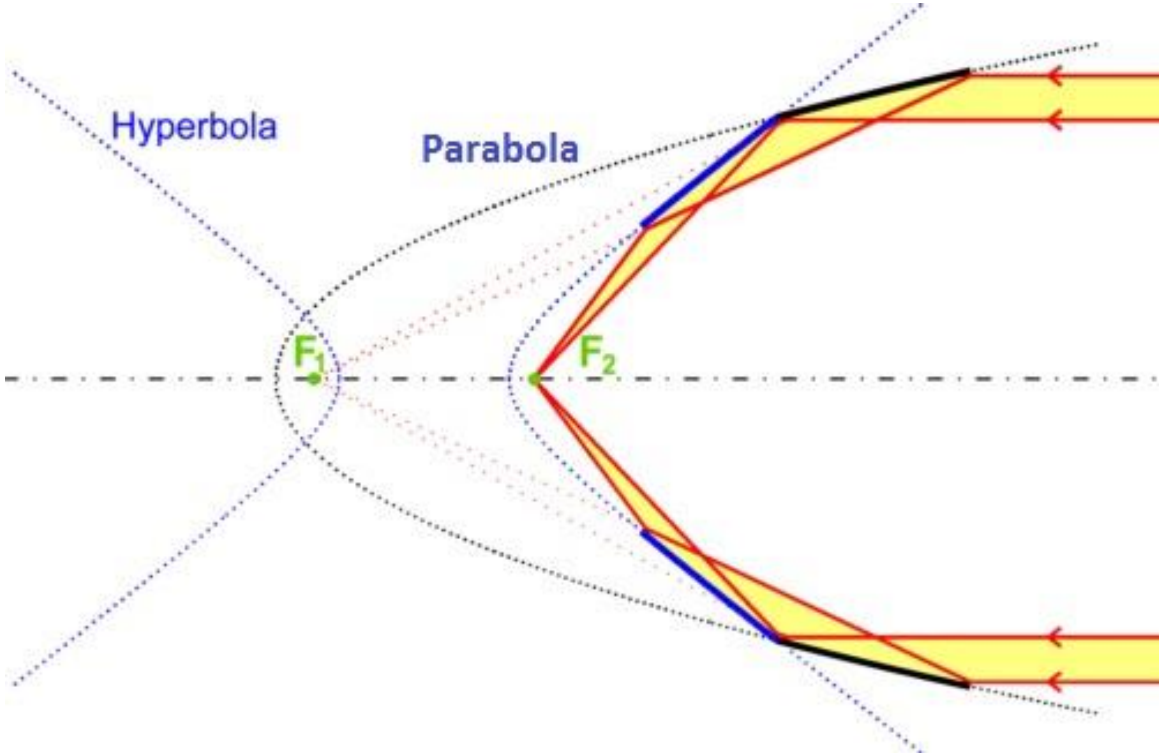
- However, at energies under a few keV, forms of reflecting telescope can be made. Imaging X-ray optical systems were introduced by **Hans Wolter**.
- Its not an easy technology though, there are some difficult problems.

Problems with grazing incidence telescopes

- A telescope with a single grazing incidence paraboloid suffers from severe astigmatism away from the optical axis.
- The aberrations can be corrected by using a pair of confocal surfaces of rotation (i.e. surfaces with a common focus), one a paraboloid and the other a hyperboloid or ellipsoid.
- Surfaces must be extremely accurate for grazing incidence mirrors to work efficiently (remember $\lambda/20$).

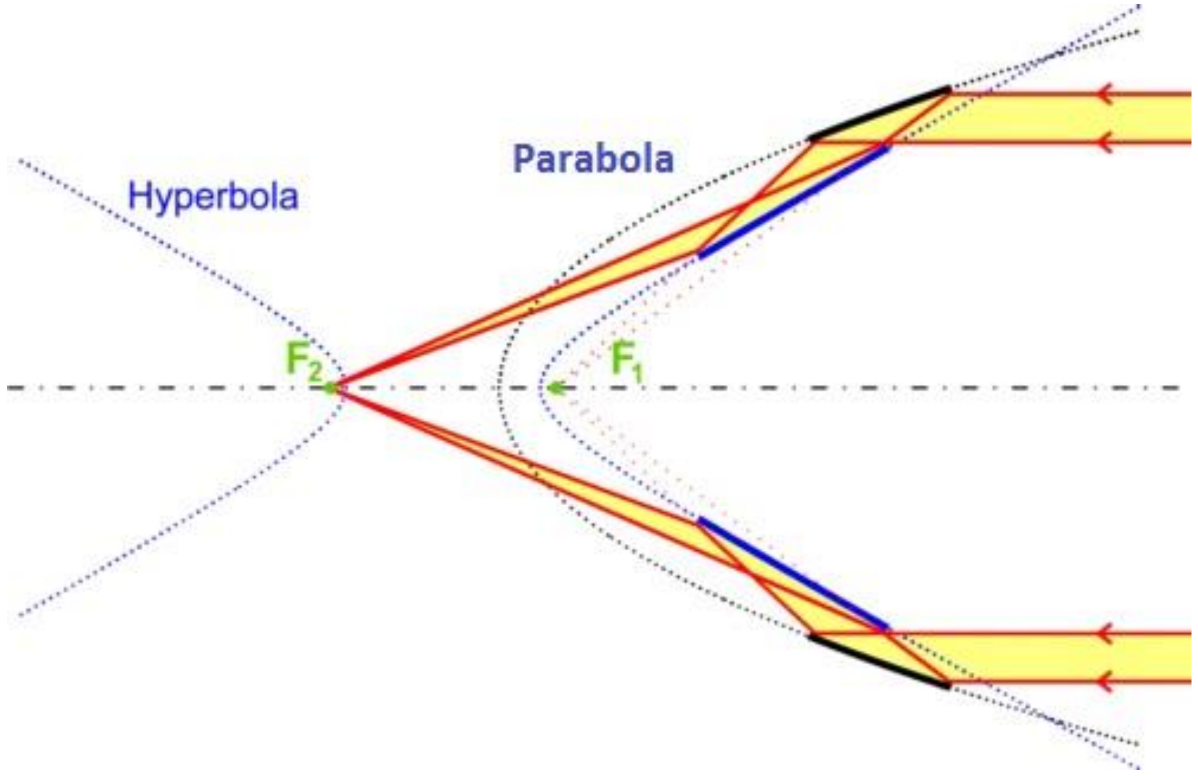
Wolter type I telescope

- Wolter Type I telescope – has a grazing incidence paraboloid followed by a grazing incidence concave hyperboloid.



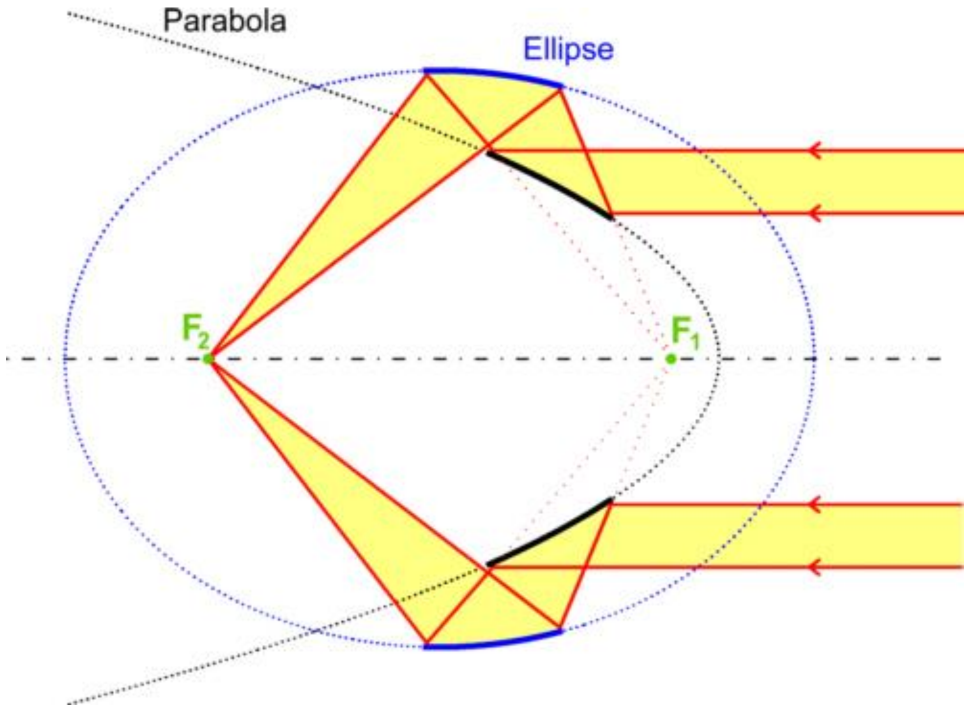
Wolter type II telescope

- Wolter Type II telescope - uses a convex secondary hyperboloid and has a longer focal length (allowing the detectors to be physically larger and easier to make).



Wolter type III telescope

- Wolter Type III - telescope uses a convex paraboloid and a concave ellipsoid, gives an even longer focal length.



Wolter telescopes (summary)

- Wolter Type I telescope – has a grazing incidence paraboloid followed by a grazing incidence concave hyperbolid.
- Wolter Type II telescope - uses a convex secondary hyperboloid instead of a concave one and has a longer focal length (allowing the detectors to be physically larger and easier to make).
- Wolter Type III - telescope uses a convex paraboloid and a concave ellipsoid, gives an even longer focal length.

Wolter telescopes

- Wolter telescopes are **two mirror** telescopes, somewhat analogous to the Cassegrain and Ritchey-Chrétien optical systems in use at longer wavelengths.

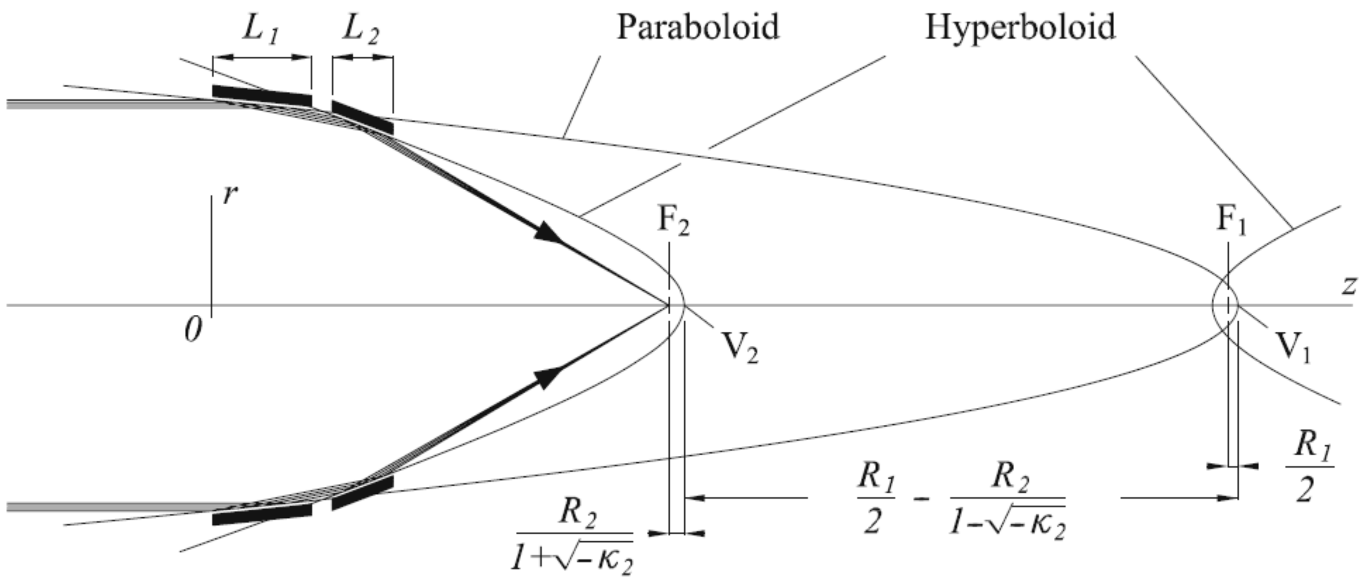
- The **Wolter Type I** is the shortest of these long systems and therefore has been extensively utilized as a *telescope* in X-ray astronomy.

General Imaging Properties

Small grazing angles result in larger focal length:

$d/f = 2 \times \sin 4\alpha$, where d is aperture size, f – focal length, α – the slope angle of the 1st mirror element (approximately the grazing angle for paraxial rays).

$\boldsymbol{d/f}$ **is typically around 1/10** for the energy band up to 10 keV



General Imaging Properties

The field-of-view: Wolter optics with a lower ratio d/f have smaller fields-of-view than those with larger ratios.

For example:

ROSAT – soft X-ray telescope ($d/f \sim 1/3$) – had field of view diameter of 2°.

XMM-Newton has the CCD cameras which cover about 30′.

General Imaging Properties

Angular Resolution: The limit of the resolution is due to surface irregularities in the mirrors, rather the diffraction limit of the system.

The lower limit of the irregularities is about 3-4 Å in size for the very best of the current production techniques – comparable with the wavelength of photons of about 1 keV.

Chandra has the resolution of <1”, XMM-Newton – 16”, Swift – 18”.

For the resolution of around 1’ the mirror shapes can be simple cones – fabrication costs are much reduced.

General Imaging Properties

Collecting Area: For small slope angles α the geometrical collecting area of a mirror shell is a thin circle with a projected area S of

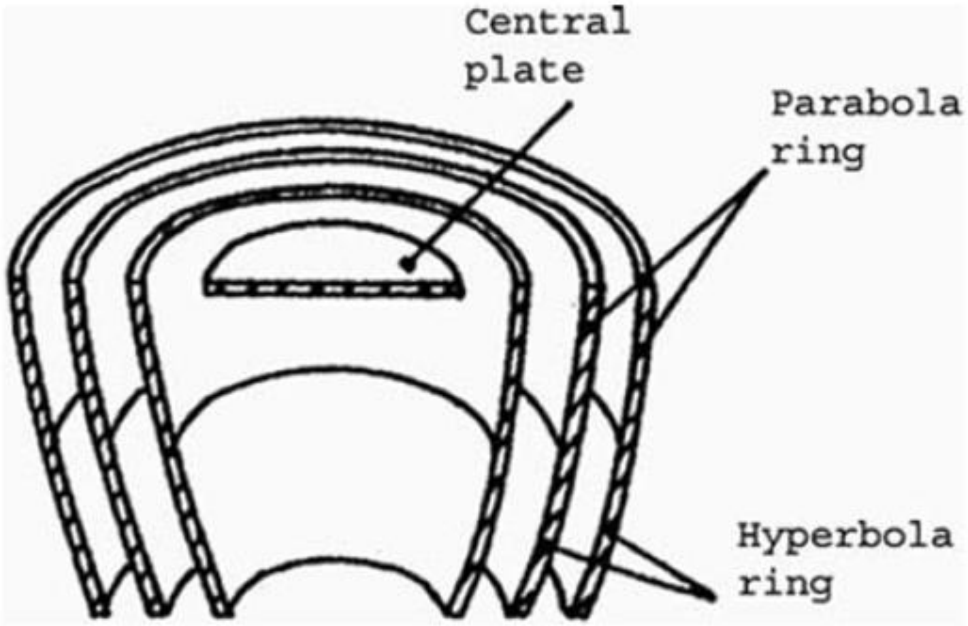
$$S \approx 2\pi r \times l \sin \alpha$$

where r is the mirror radius and l the length of a mirror element.

This is much less than the polished mirror surface.

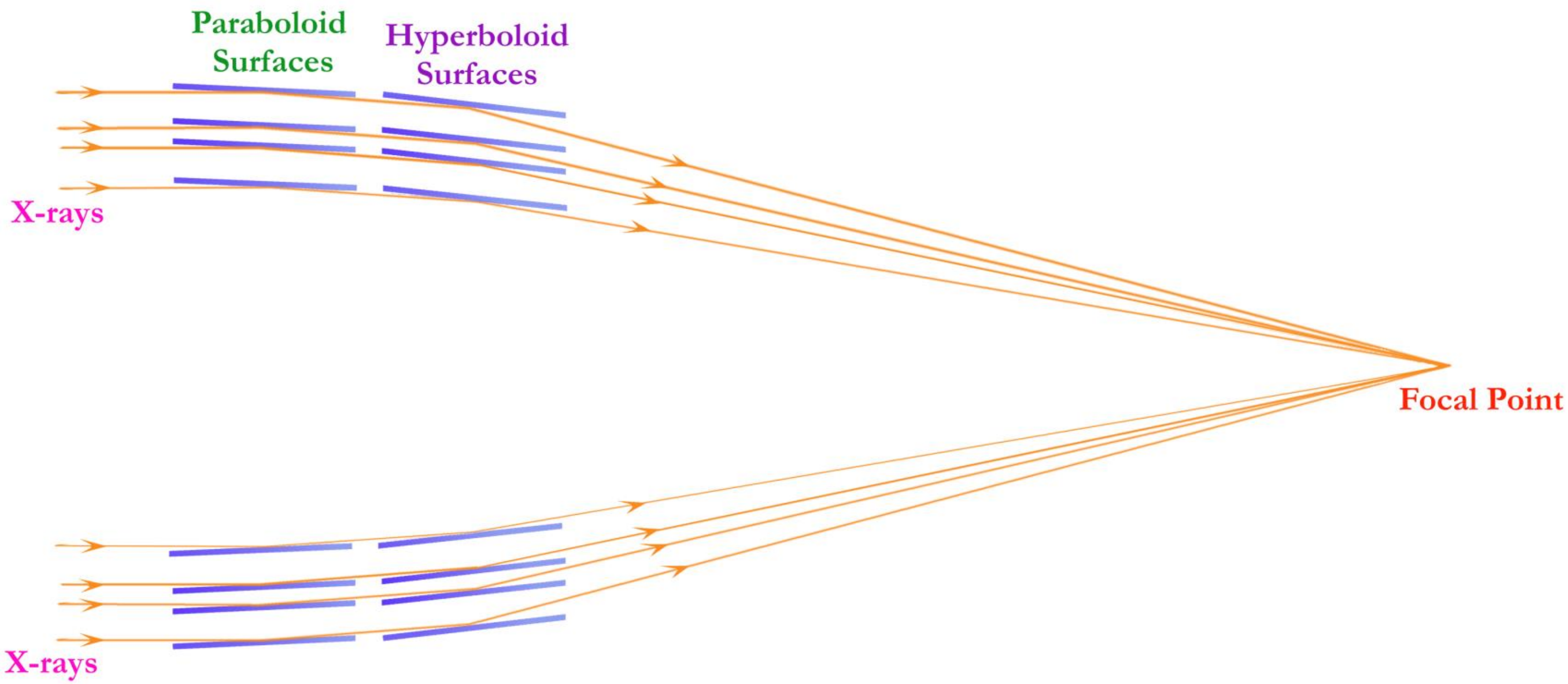
Nested grazing incidence telescopes

- Effective area can be increased by nesting grazing incidence telescopes one inside the other.

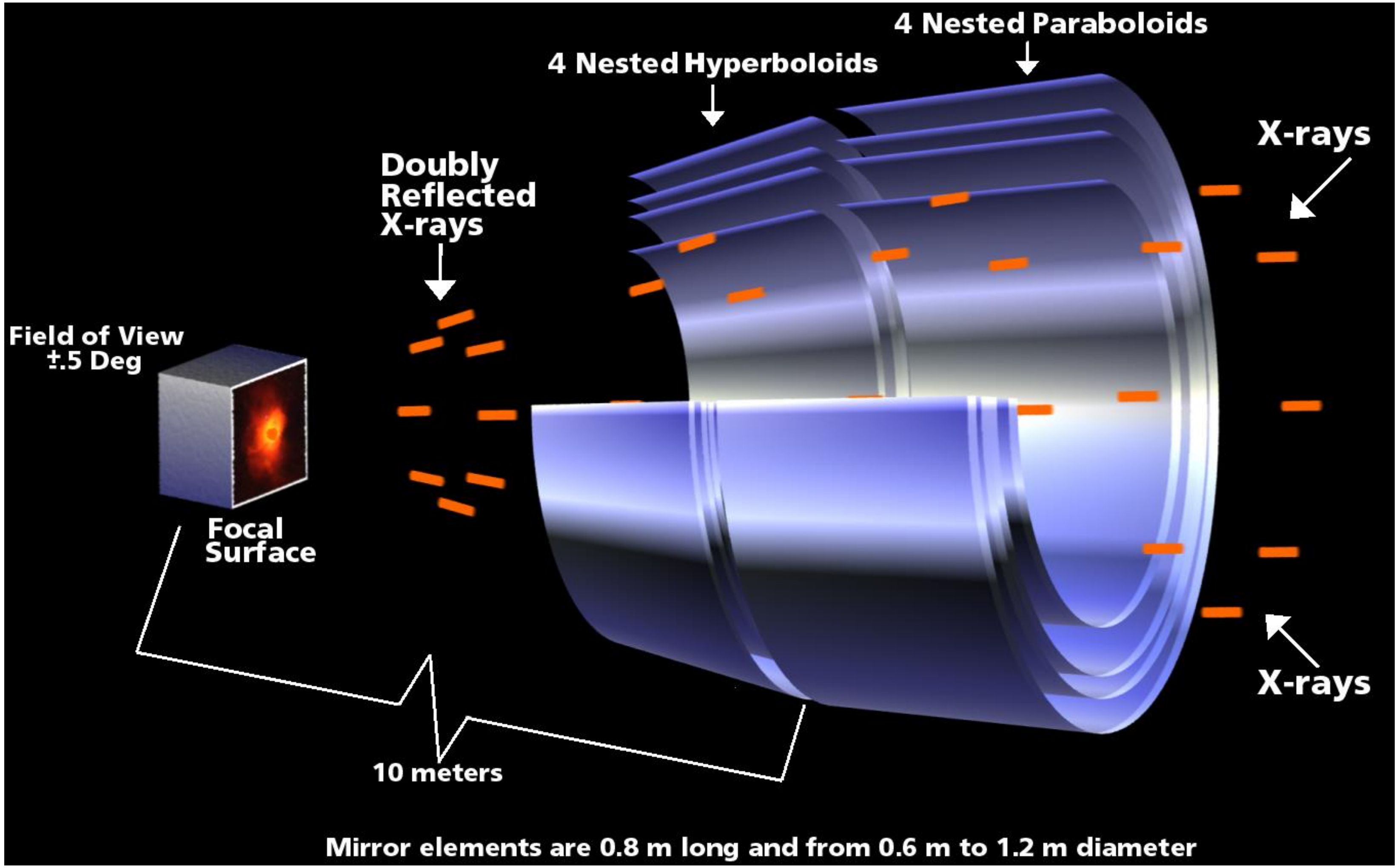


Chandra X-ray telescope

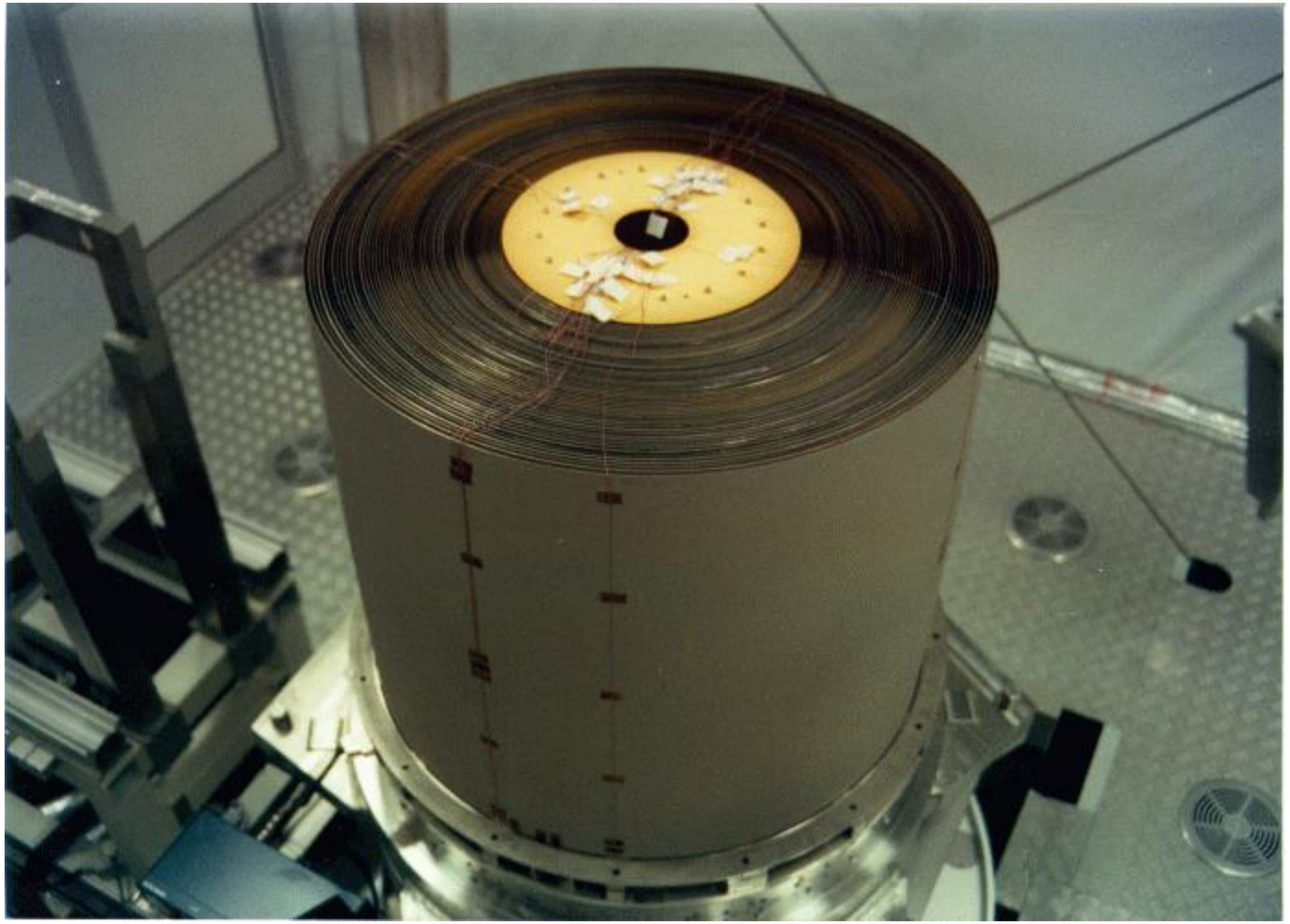
- The basic optical design of Chandra



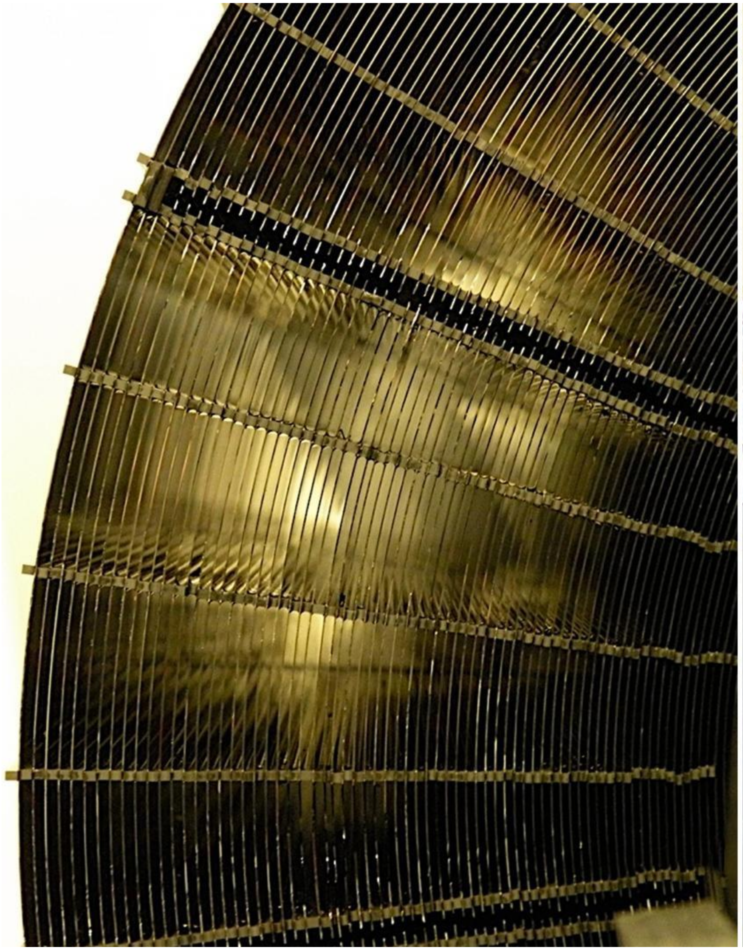
Chandra X-ray telescope

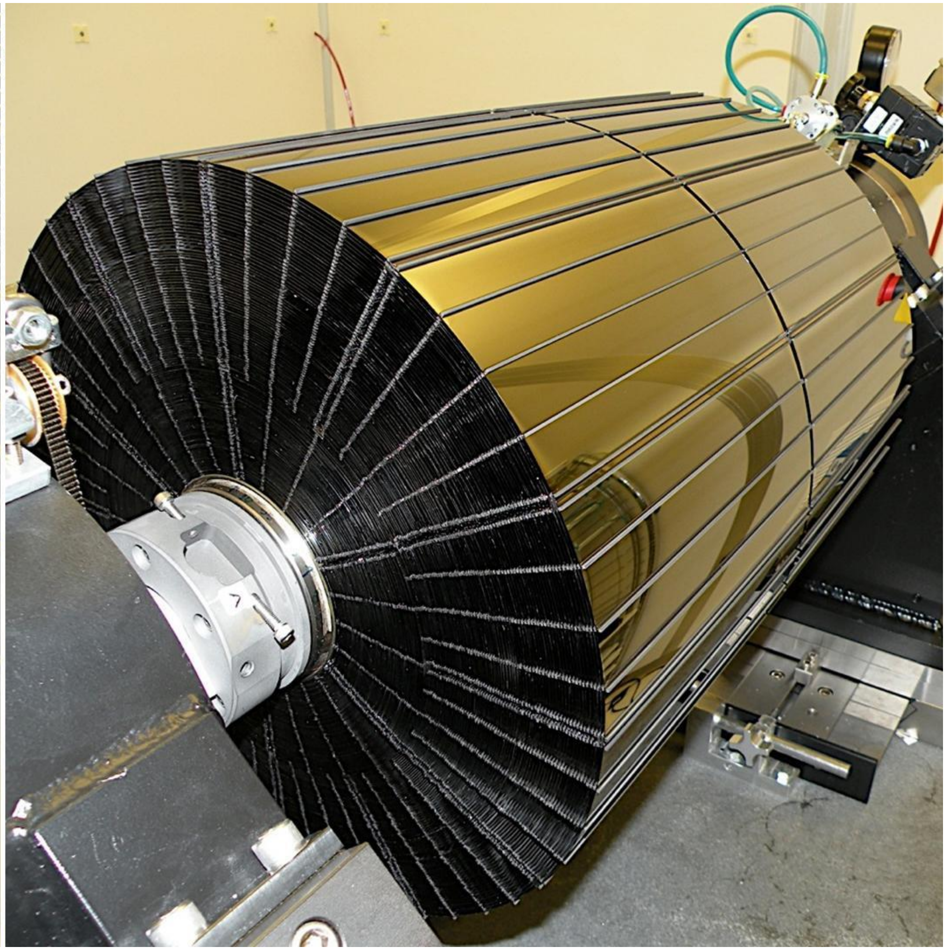


XMM-Newton 58 nested mirrors



The Nuclear Spectroscopic Telescope Array (NuSTAR)





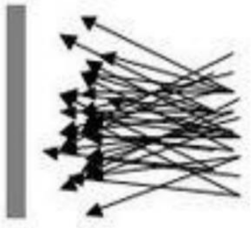
133 nested mirrors (a conical approximation)

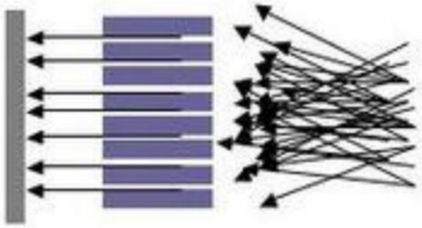
Satellite missions with Wolter telescopes

Mission	Year of launch	Upper Energy limit (keV)	Focal length (m)	Mirror modules	Degree of nesting	Effective area @ 1 keV (cm^2)	On-axis resolution
~~ROSAT~~	~~1990~~	~~0.3-2.5~~	~~2.4~~	~~1~~	~~4~~	~~420~~	~~3”~~
Chandra	1999	10	10.0	1	4	780	<1”
XMM-Newton	1999	15	7.5	3	58	4260	16”
Swift	2004	10	3.5	1	12	130	18”
~~Suzaku~~	~~2005~~	~~12~~	~~4.75~~	~~4~~	~~175~~	~~2250~~	~~120”~~
NuSTAR	2012	3-79	10.15	2	133	847 (9 keV)	45”
AstroSat	2015	8	2	1	41	200 (1.5 keV)	120”
Spektr-RG / eROSITA ART-XC	2019	 10 5-30	 1.6 2.7	 7 7	 54 28	 2400 450 (8 keV)	 16” 45”

High energy imaging by collimation

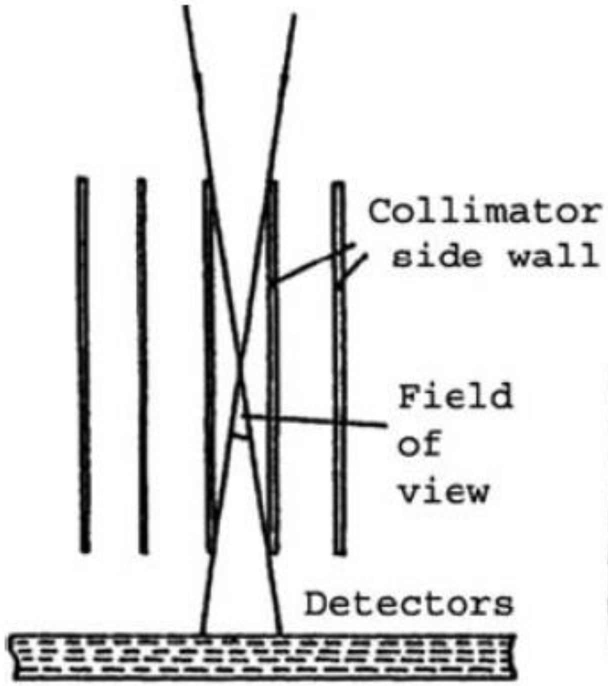
- High energy x-rays and gamma rays cannot be focussed, but some degree of directionality is possible by using a collimator, which restricts the angle of acceptance.

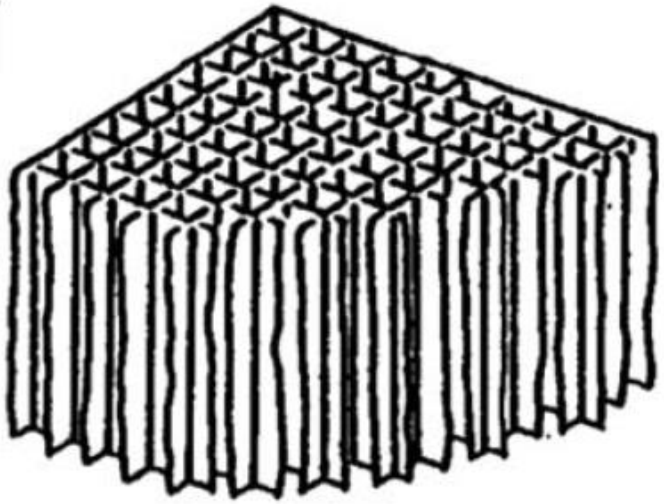




High energy imaging by collimation

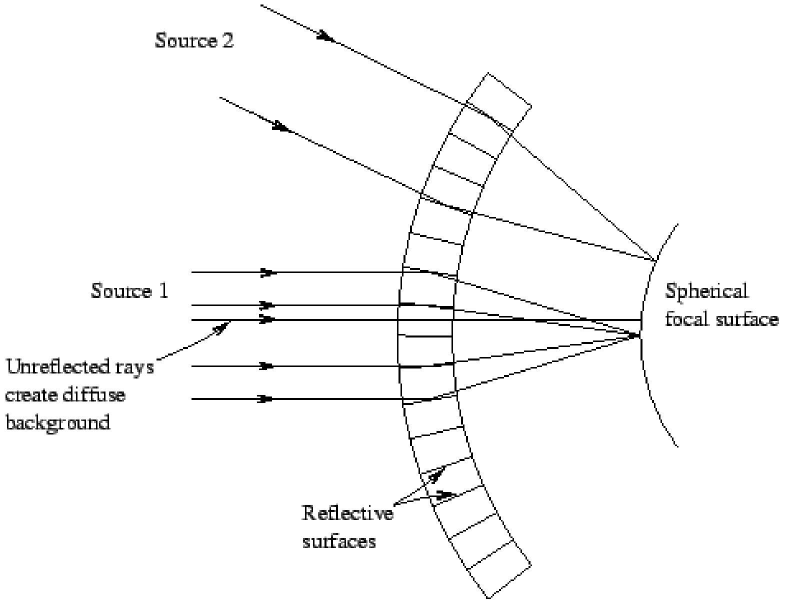
- Simplest collimator design is a honeycomb collimator which is a closely packed array of tubes.



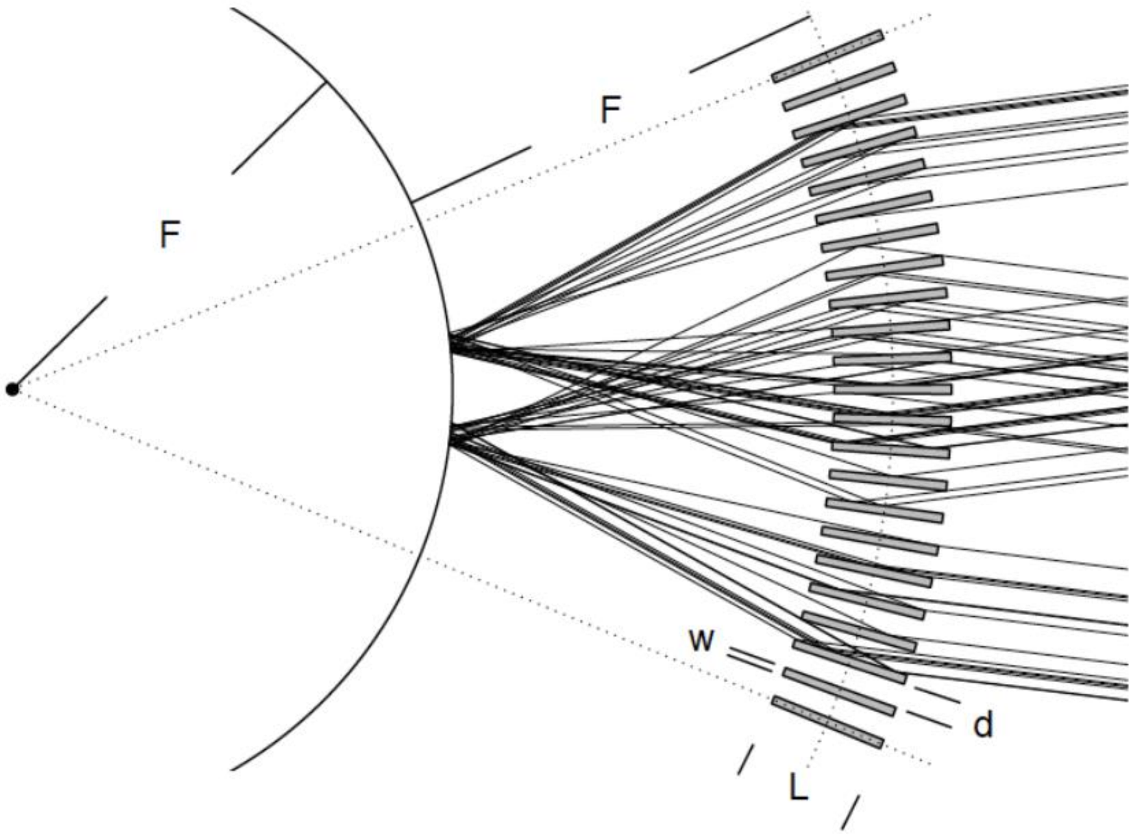


Lobster Eye imaging collimator

- Lobster Eye imaging collimator is essentially a honeycomb collimator curved into a portion of a sphere and with a position sensitive detector also curved onto a spherical surface.
- Lobster eye collimator uses grazing incidence reflection, rays which pass straight through form a background.
- Gives moderate quality imaging over a wide field.



Lobster Eye imaging collimator



The Lobster-eye X-ray Telescope (LXT) is an approved NASA mission for the study of diffuse sources.
LXT combines very large field of view with good angular and energy resolution.

Laue Diffraction

- X- and gamma-rays are diffracted by certain crystals, and give rise to a pattern of spots for a normal incidence beam.
- For some crystals (e.g. germanium) the number of spots is quite small.

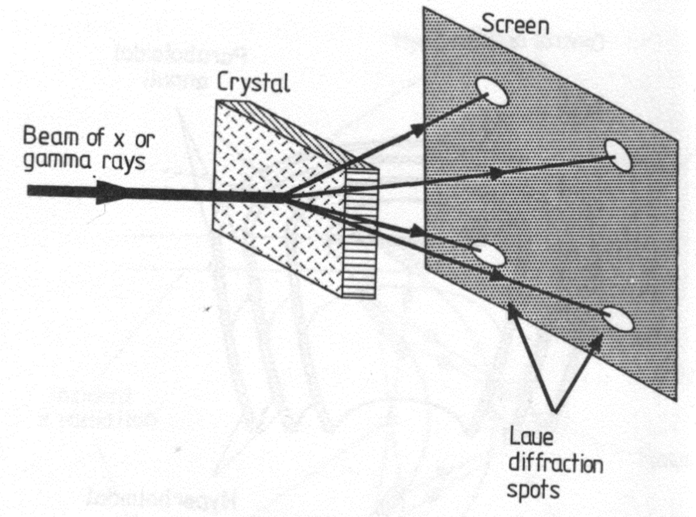
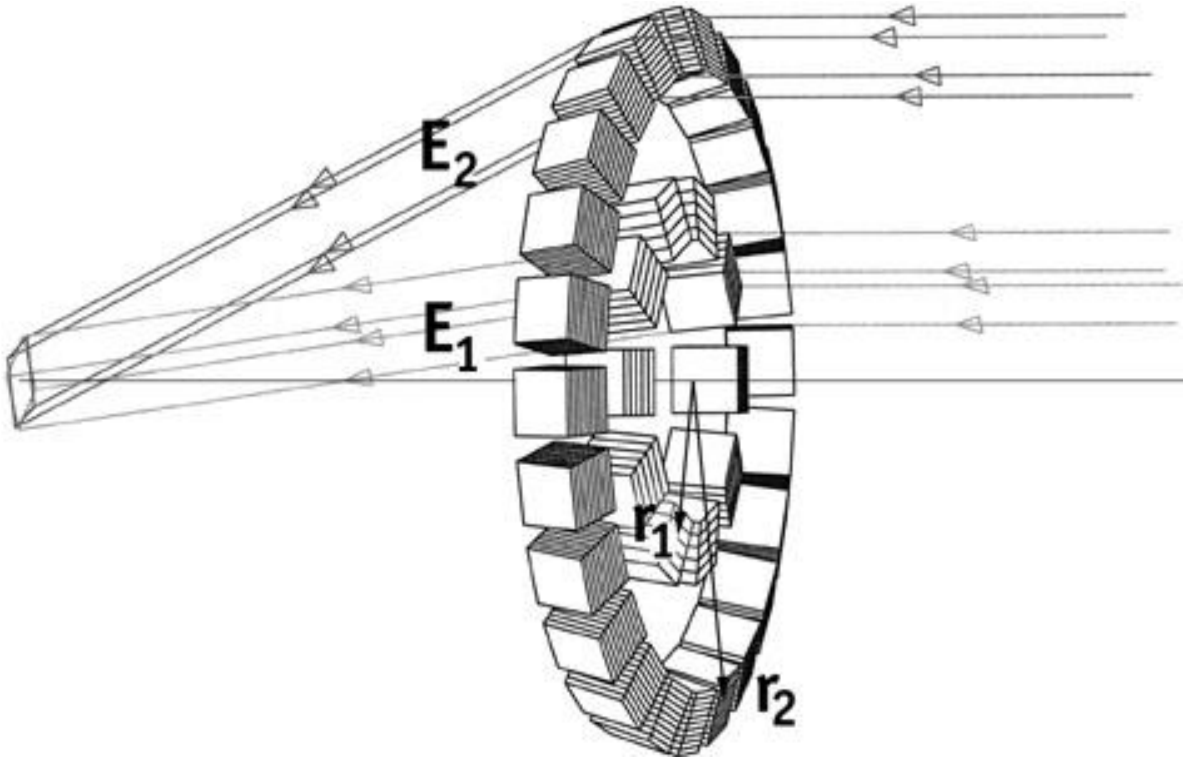


Figure 1.3.12. Laue diffraction of x- and gamma rays.

Laue Diffraction telescope



Crystals are oriented such that the spots from crystals in a ring fall on the same part of the detector.

(Still not in use, only experiments!)