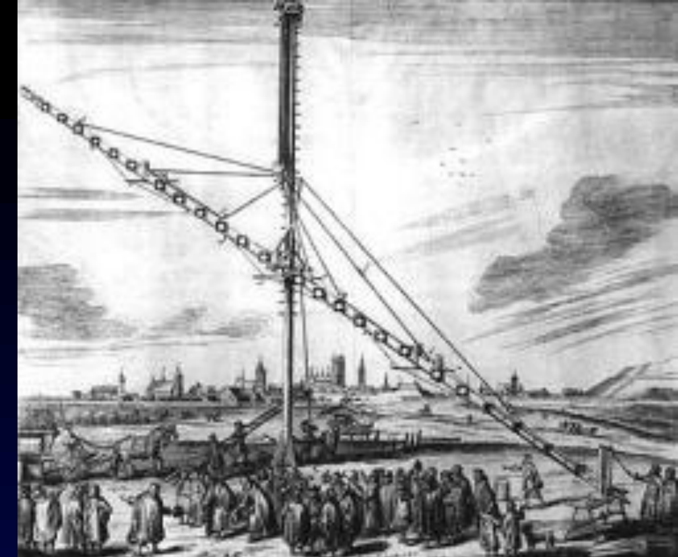
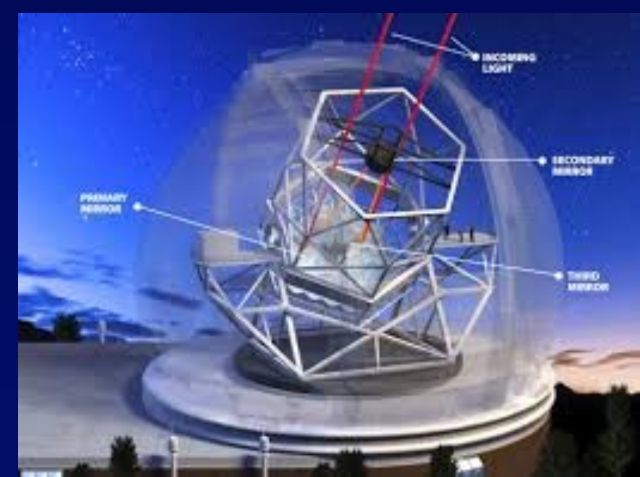
Telescopes



- All modern large telescopes are reflectors
- Achromatic, Efficient & Compact
- Precision engineered
  - Precision drives, encoders and control systems are needed to maintain collimation and tracking
  - active control of mirror supports & optical alignment
- Mirrors figured and polished to $< \lambda/10$
- Space telescopes operating at short (UV) wavelengths require smoother mirrors
  - e.g. HST is polished to 10nm
- Steel structures support the reflective mirror surfaces ~80nm thick metallic layer with mass ~20g

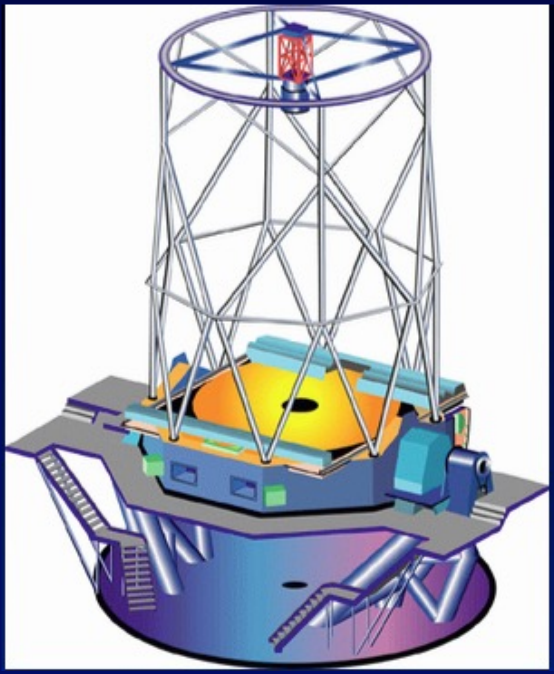


Telescope Mounts

Equatorial

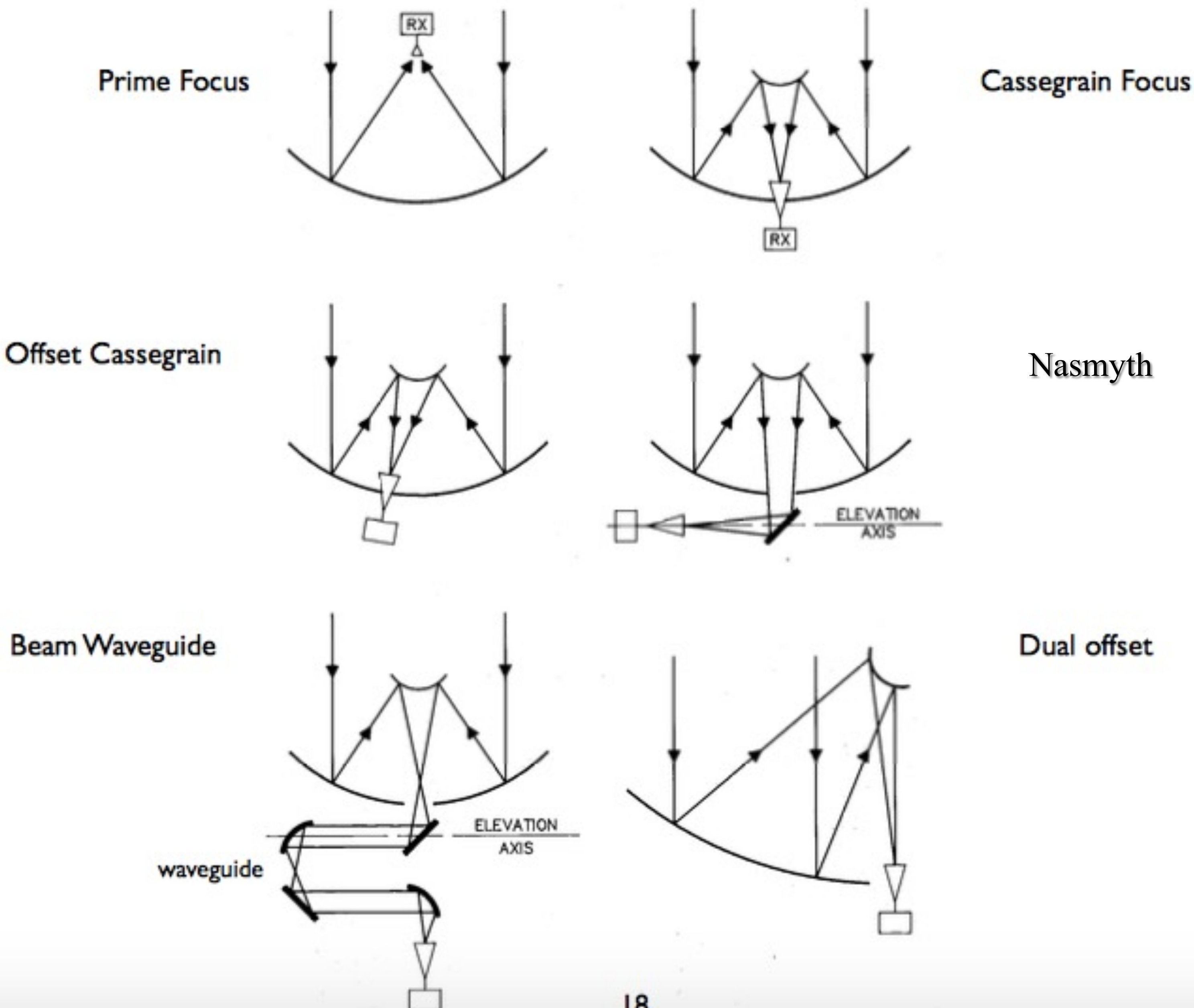
- only 1 motion required to track stars
- no field rotation
- fixed instrument only at Coudé focus (small FoV)
- most telescopes built before the 1980s

Alt-az



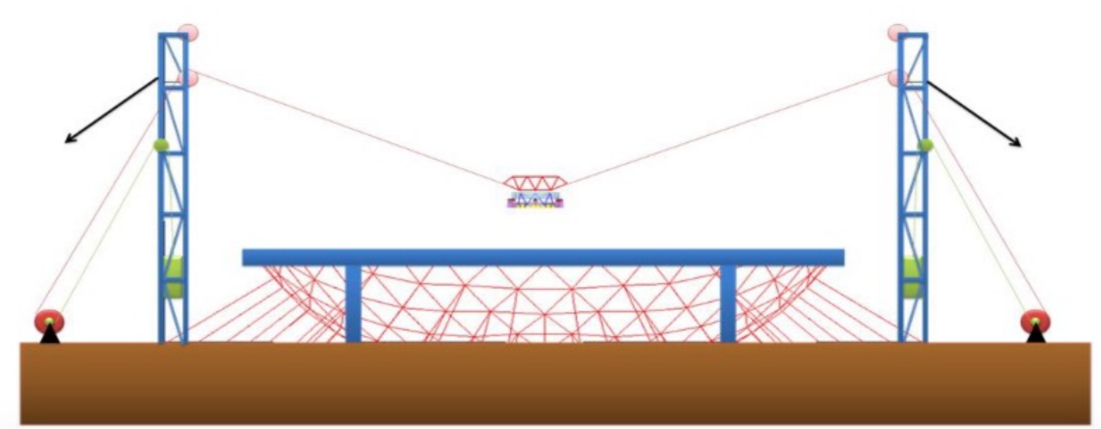
- Gravity only acts in 1 axis – engineering advantage
- field rotation and exclusion zone around zenith
- Nasymth platforms (derotation required)
- All major telescopes built since the 1980s

Reflector types



Fast Telescope

- 500-m diameter reflector in Guizhou, China
- Operating at MHz frequencies
- Fixed dish with movable aerial cabin
- Permits tracking for ~5hrs
- Limited declination accessibility



ALMA Antennas

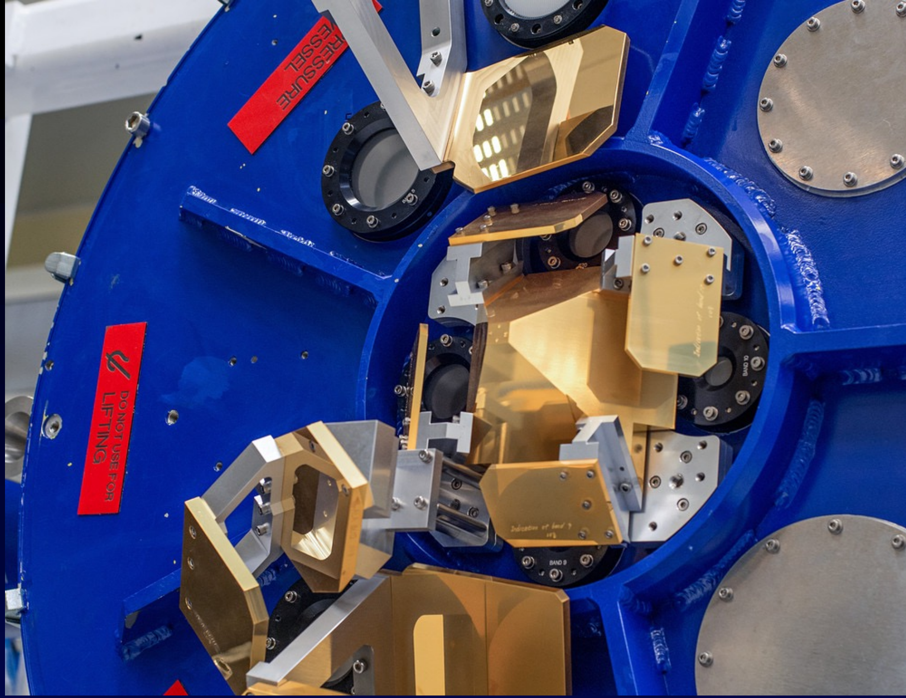
50 x 12-m dishes

+ compact array operating at 5000-m at -20 <T < 20K

Fast switching/slewing for calibration

Cassegrain configuration, with pointing error <0.6 arcsec.

Cryostats in receiver cabins hold up to 10 receivers operating from 0.35 to (eventually) 6mm cooled to 4K.



Phased Array Telescopes

Arrays of omnidirectional dipoles are ‘pointed’ by introducing relative phase delays in software during post-processing.

Simple and cheap construction – mass production with no moving parts.

Demanding data and processing rates and Moore’s law cost benefits : Lofar and SKA_Low

Fig. 1. Aerial photograph of the Superterp, the heart of the LOFAR core, from August 2011. The large circular island encompasses the six core stations that make up the Superterp. Three additional LOFAR core stations are visible in the upper right and lower left of the image. Each of these core stations includes a field of 96 low-band antennas and two sub-stations of 24 high-band antenna tiles each.

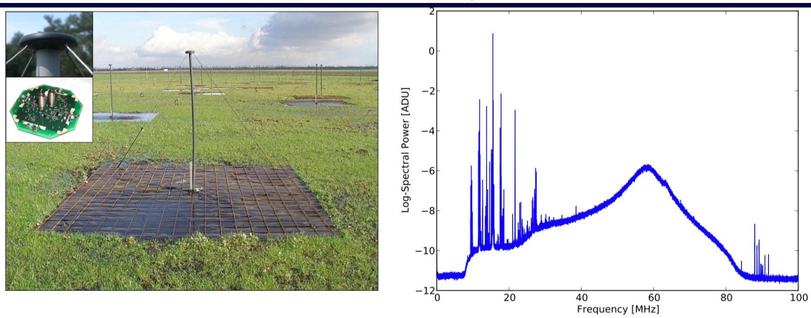


Fig. 5. *Left*: image of a single LOFAR LBA dipole including the ground plane. The inset images show the molded cap containing the LNA electronics as well as the wire attachment points. *Right*: median averaged spectrum for all LBA dipoles in station CS003. The peak of the curve near 58 MHz is clearly visible as well as strong RFI below 30 MHz, partly because of ionospheric reflection of sub-horizon RFI back toward the ground, and above 80 MHz, due to the FM band.

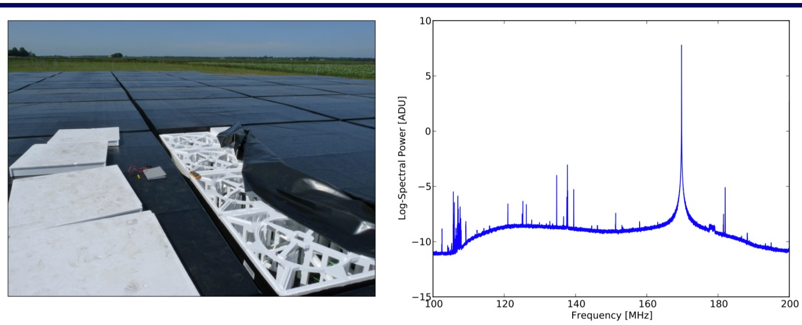
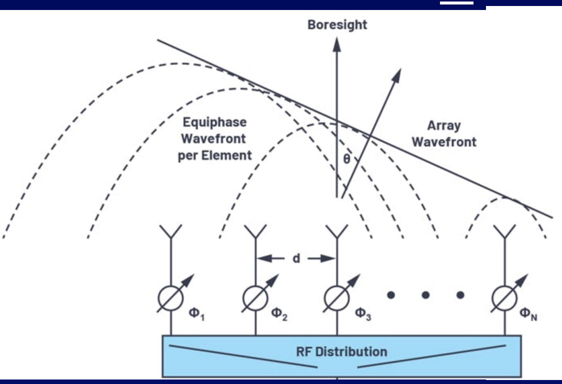


Fig. 7. *Left*: closeup image of a single LOFAR HBA tile. The protective covering has been partially removed to expose the actual dipole assembly. The circular dipole rotation mechanism is visible. *Right*: median averaged spectrum for all HBA tiles in station CS003. Various prominent RFI sources are clearly visible distributed across the band including the strong peak near 170 MHz corresponding to an emergency pager signal.



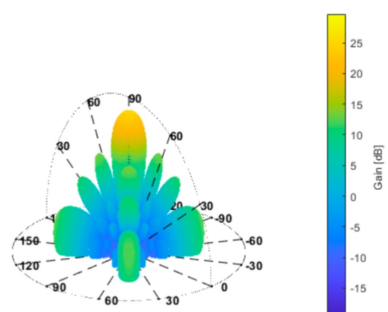


Figure 6. Unsteered beam pattern for a LOFAR tile.

High energy photons

Penetrate material rather than being reflected. But at grazing incidence, reflection is effective and can be used to focus x- and y-rays. e.g. Chandra, XMM-Newton. Chandra's telescope had a resolution of ~1" with a 800cm^2 collecting area

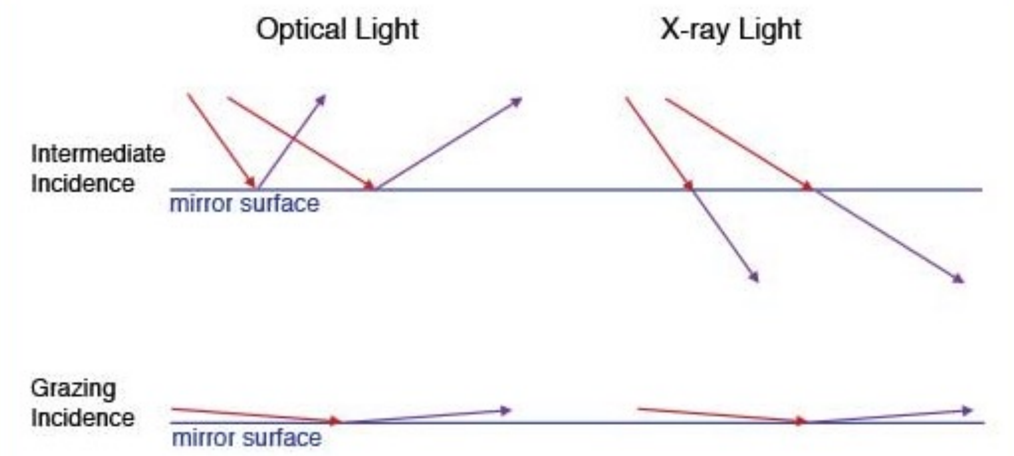


Illustration of grazing incidence. The scale in this image is exaggerated – the angle of incidence (the angle between the mirror surface and the X-ray) is actually shallower. (Credit: NASA's Imagine the Universe)

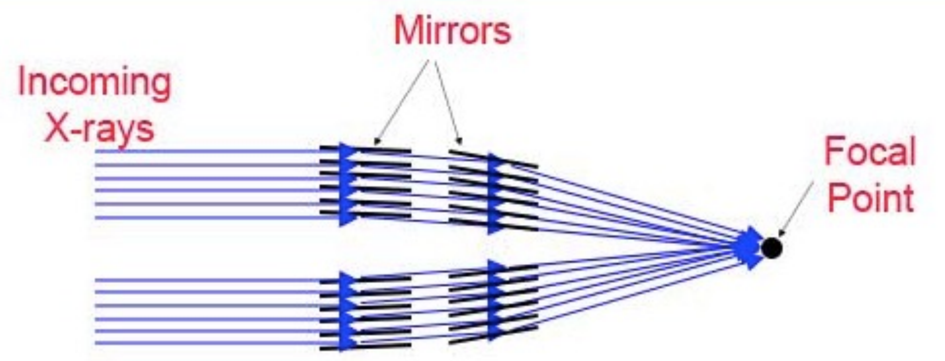
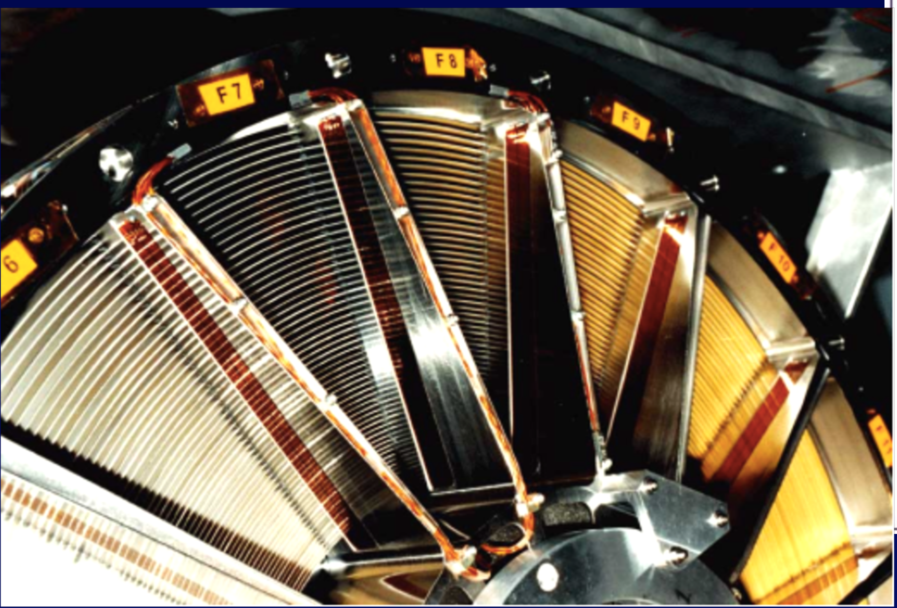


Diagram of a cut-away of an X-ray telescope with several sets of mirrors. By nesting the mirrors one within the other, more X-rays are focused, giving astronomers a brighter image. (Credit: NASA's Imagine the Universe)

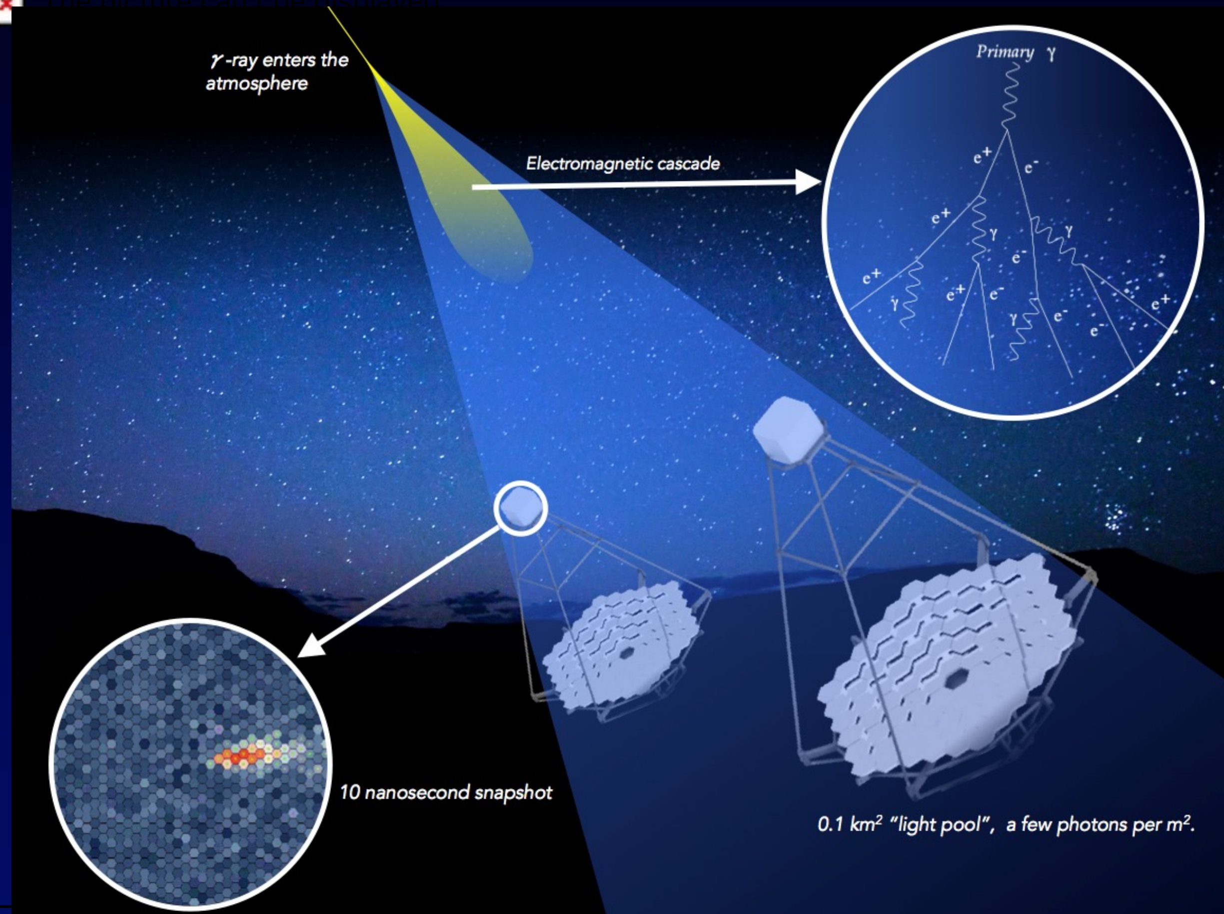


CTA : Ultra high energy γ-rays

Cherenkov Telescope Array under development in La Palma and Chile

Detecting the Cherenkov flash emitted as a result of γ-rays that enter the Earth's atmosphere

Triangulation with a number of telescopes permits position of the source to be determined



CTA Telescopes

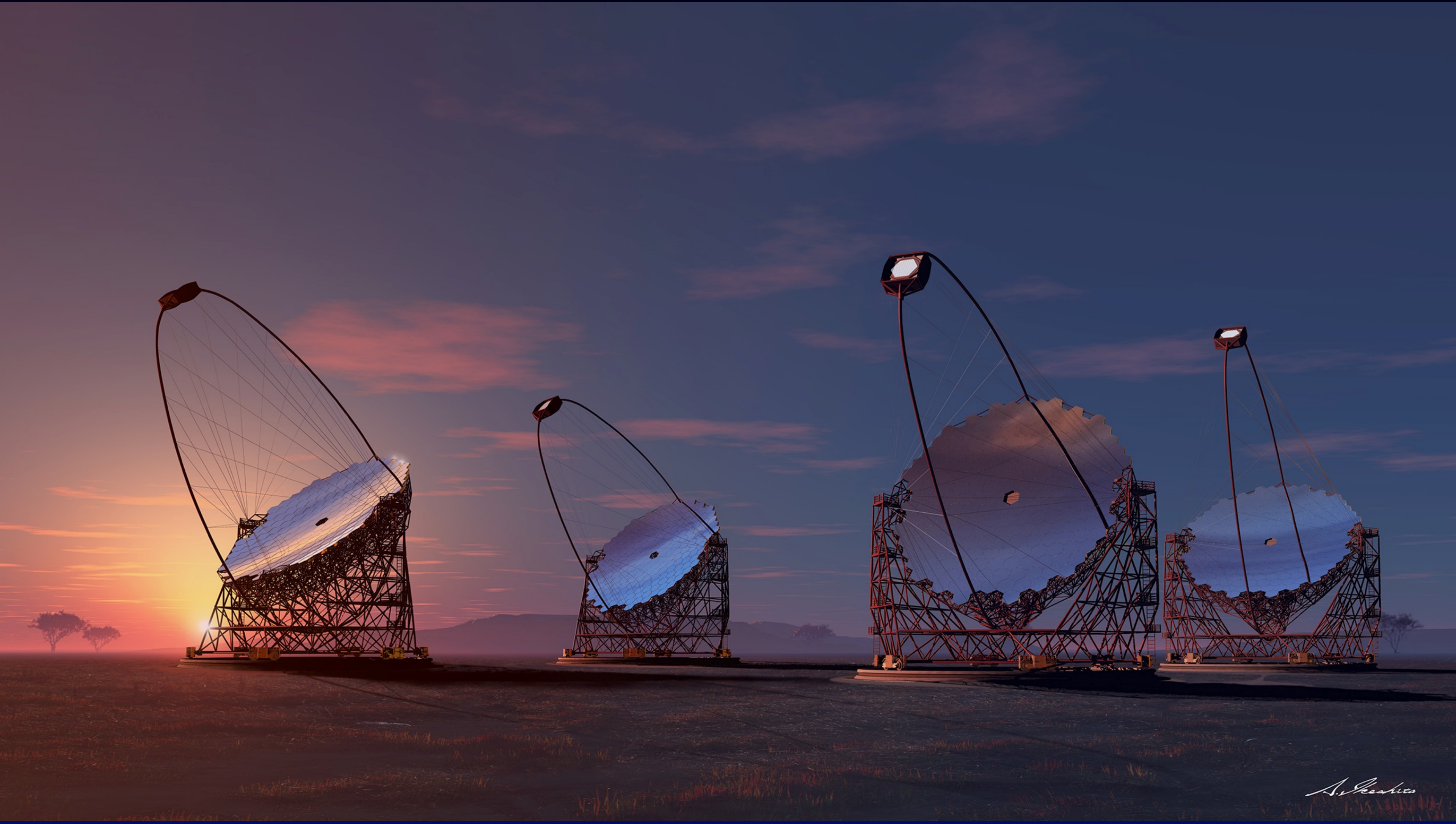
Detection of the Cerenkov light emitted by the particle cascade produced by 20 Gev to 200TeV γ-rays

Large (23m), Medium (12m) and Small (4m) sized telescopes for detection of low, medium and high energy photons within this range.

Flash durations are a few nanosec so need sensitive, fast detectors

LST Main Parameters		
Optical Parameters		
Reflector type	1-mirror, parabolic	
Focal length	28 m	
Dish diameter	23 m	
f/D	1.2	
Mirror area	$396\,m^2$	w/o shadowing
Mirror effective area	$368\,m^2$	Including shadowing
Preliminary on-axis PSF	0.05°	
Preliminary off-axis PSF	0.11°	at 1° off-axis
Preliminary tracking accuracy	20 arcsec	RMS, online precision
Pointing accuracy	14 arcsec	RMS, post-calibration precision
Camera Parameters		
Camera dimensions (LxHxW)	2.8 m x 2.9 m x 1.15 m	
Weight	$<$ 2000 kg	
Number of pixels	1855	
Pixel linear size	1.5 inch	2 inch including light concentrator
Pixel field of view	0.1°	
Camera field of view	4.5°	
Trigger region field of view	4.5°	
Sampling speed	1 GS/s	
Analogue buffer length	$4\,\mu s$	for hardware stereo trigger
Readout rate	7.5 kHz (target), 15 kHz (goal)	
Dead time	5% at 7.5 kHz	
Mechanical parameters		
Total weight	103 tons	all moving parts
Repositioning speed	20 s	for 180° in azimuth
Elevation drive range	-70° to 100°	
Azimuth drive range	408°	
Inertia elevation	$\sim$6000 $tons{\cdot}m^2$	
Inertia azimuth	$\sim$12000 $tons{\cdot}m^2$	
Park position	zenith angle 95°	locked at the camera tower
Height at Camera Access	13 m above ground	In the parking position

Rendering of CTA LSTs



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Optical Telescope Properties

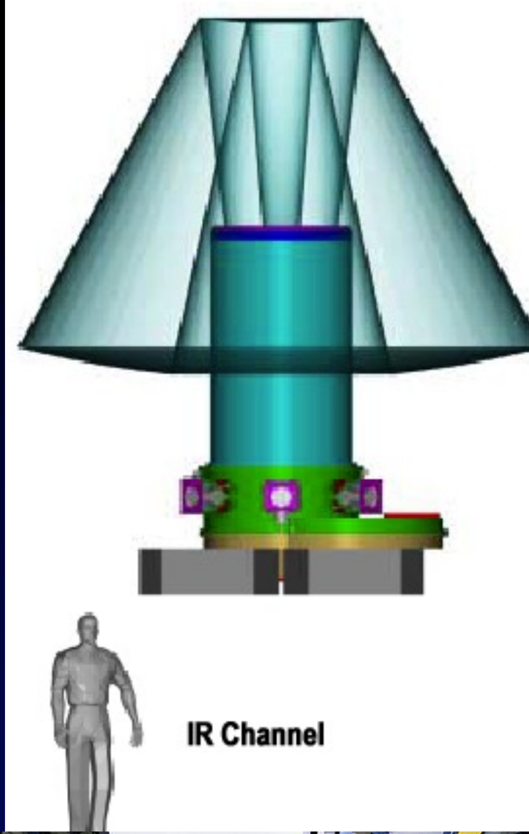
- Field of View
  - Widest field is usually available at Prime Focus, though novel cassegrain or 3-mirror designs have been developed
  - need to flatten and correct field : Prime focus corrector + ADC
  - Best Image Quality is obtained over a small central field
  - Cass field 3' on UKIRT f/35 to 120' on Vista f/3
  - Large field produces a large central obstruction in the Primary mirror pupil
  - increased light loss, push more power into diffraction halo
  - Thermal IR background considerations
- Instrument Mounting and window requirements

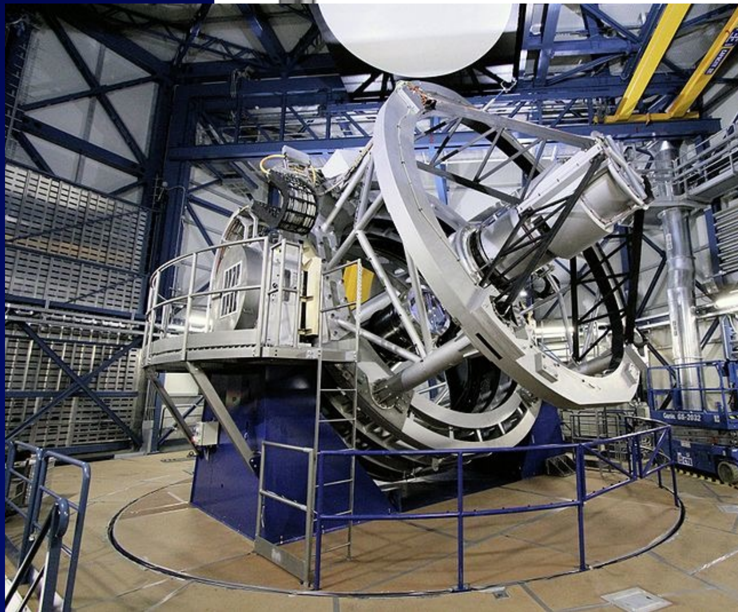
Telescope Properties

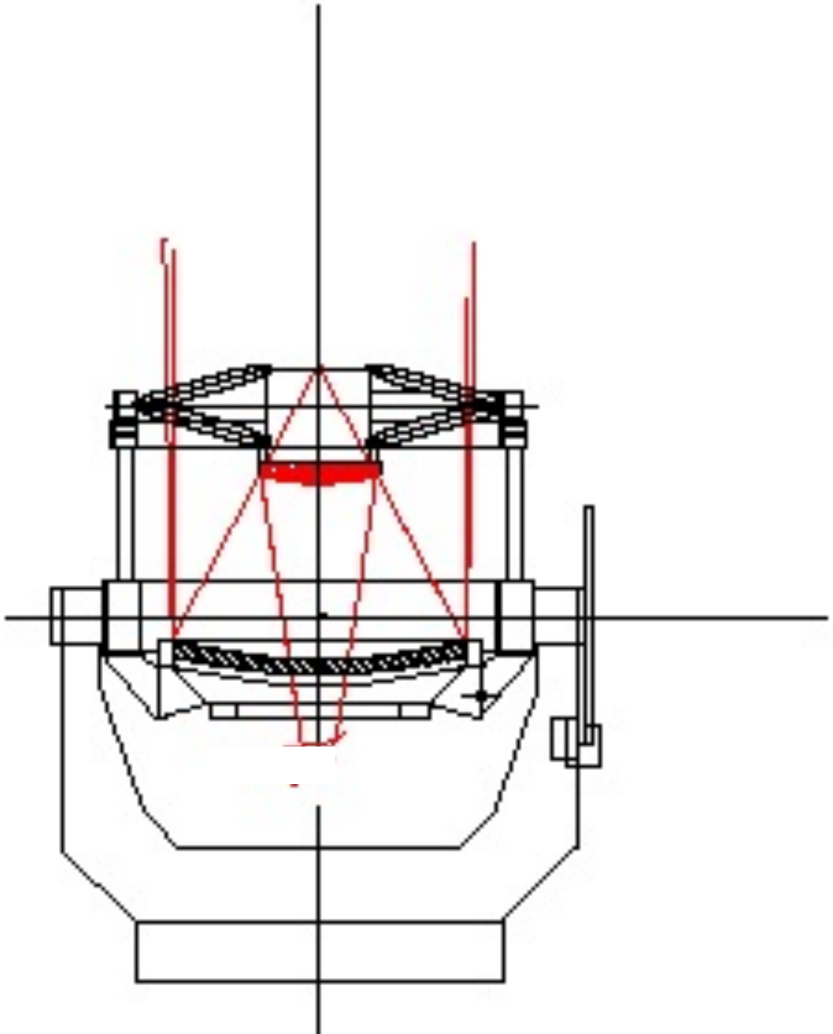
- Effective Focal Length = Df
  - 8-m telescope with a f/15 focal ratio from the secondary : EFL =120m
  - An angular displacement of 1 arcsec (4.85 x10-6 radians) gives an offset of fθ= 0.6mm in the focal plane, giving a plate scale of 1.7 arcsec/mm
- Older telescopes have several configurations, e.g. the 3.9-m AAT
  - Prime f/3.5 = 15 "/mm — 0.15" per 10µm pixel
  - Cass f/8 = 6.8"/mm — 0.07" per 10µm pixel
  - Cass f/15 = 3.6"/mm — 0.04" per 10µm pixel
  - Coude and f/36 IR 1.5 "/mm — 0.015" per 10µm pixel
- Note that typical detector pixel sizes are 10-20µm and the match between image sampling requirements and plate scale may not be optimum
- Wide Field of view implies fast f-ratios

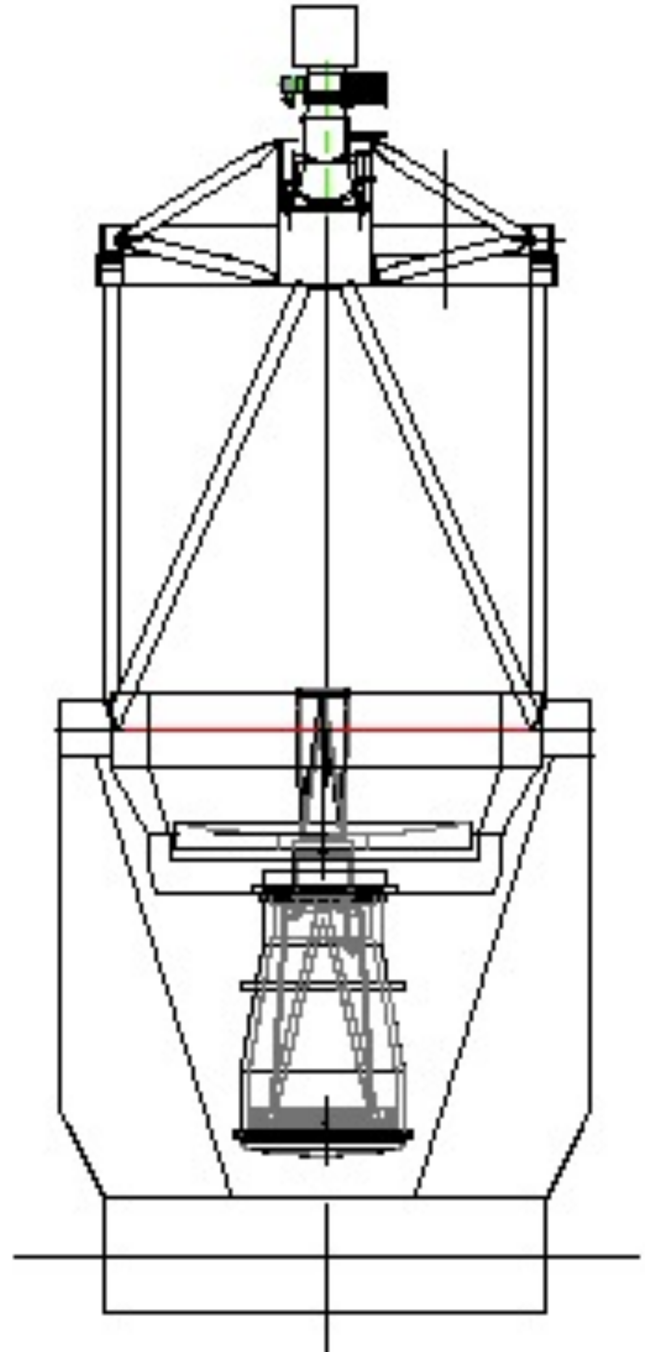
Vista: A dedicated 4.2-m IR survey telescope

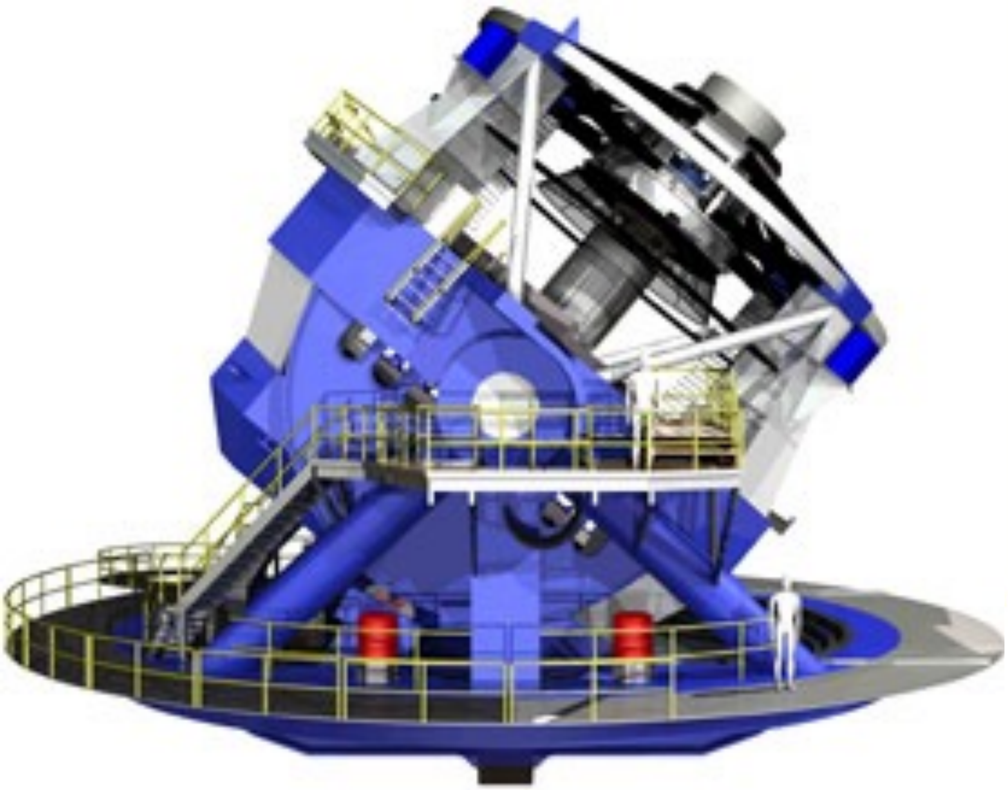
- 4.2-m diameter telescope with a 2 degree field of view Located on Mt Paranal, Chile
- Revolutionary design with f/1 primary mirror
  - very short telescope tube
  - very compact enclosure
  - but challenging optics and tolerances
- 1.25-m secondary mirror gives f/3 Cassegrain beam feeding the world's biggest infrared camera
- Special purpose facility with the instrument integrated with the telescope

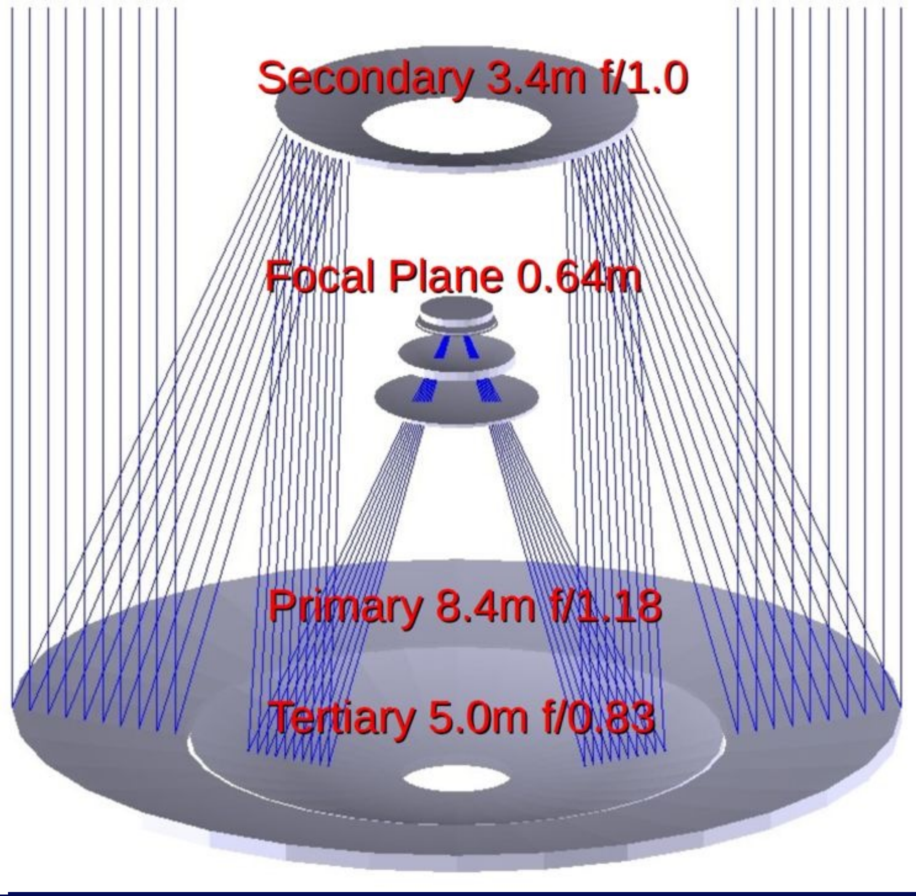






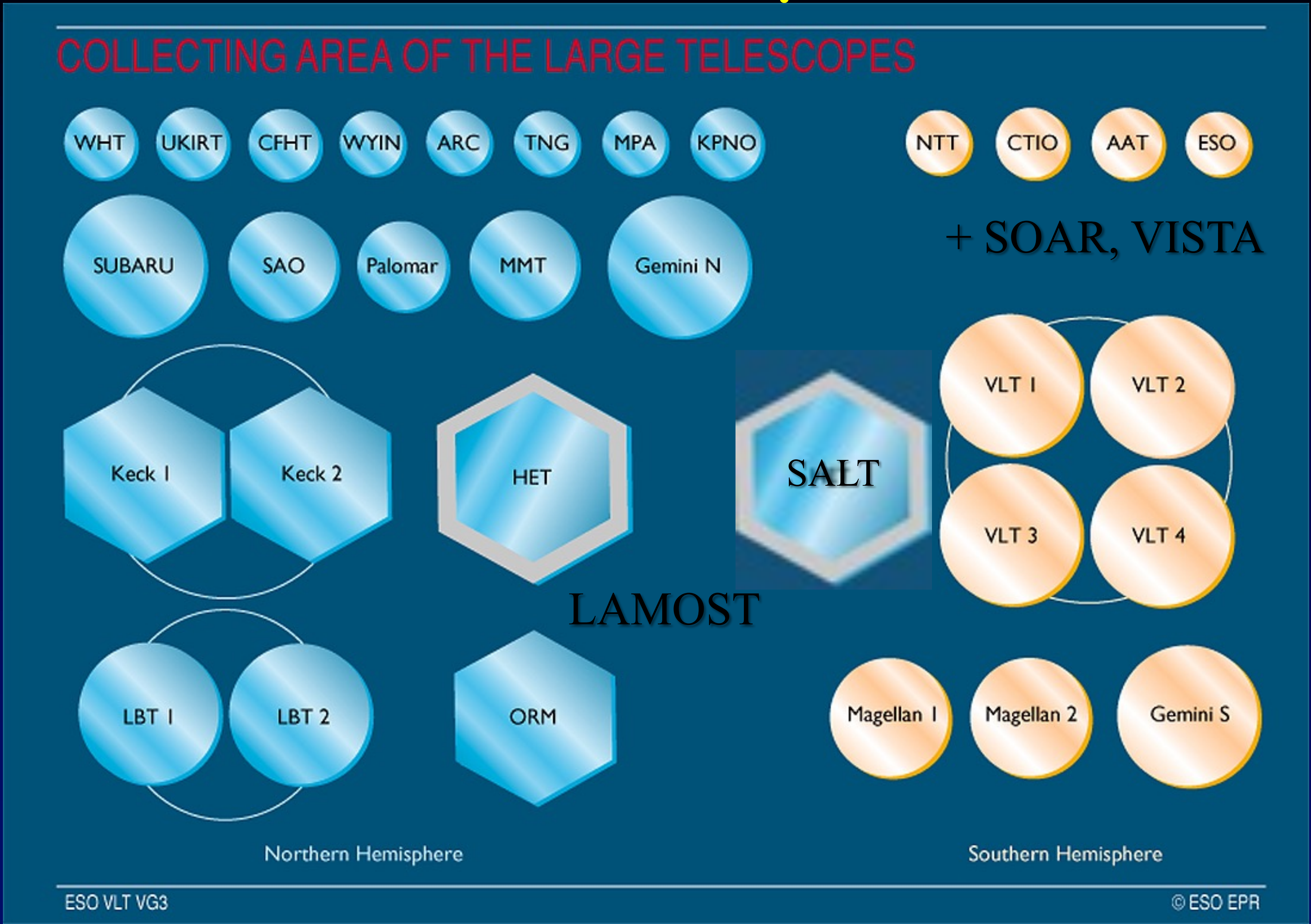




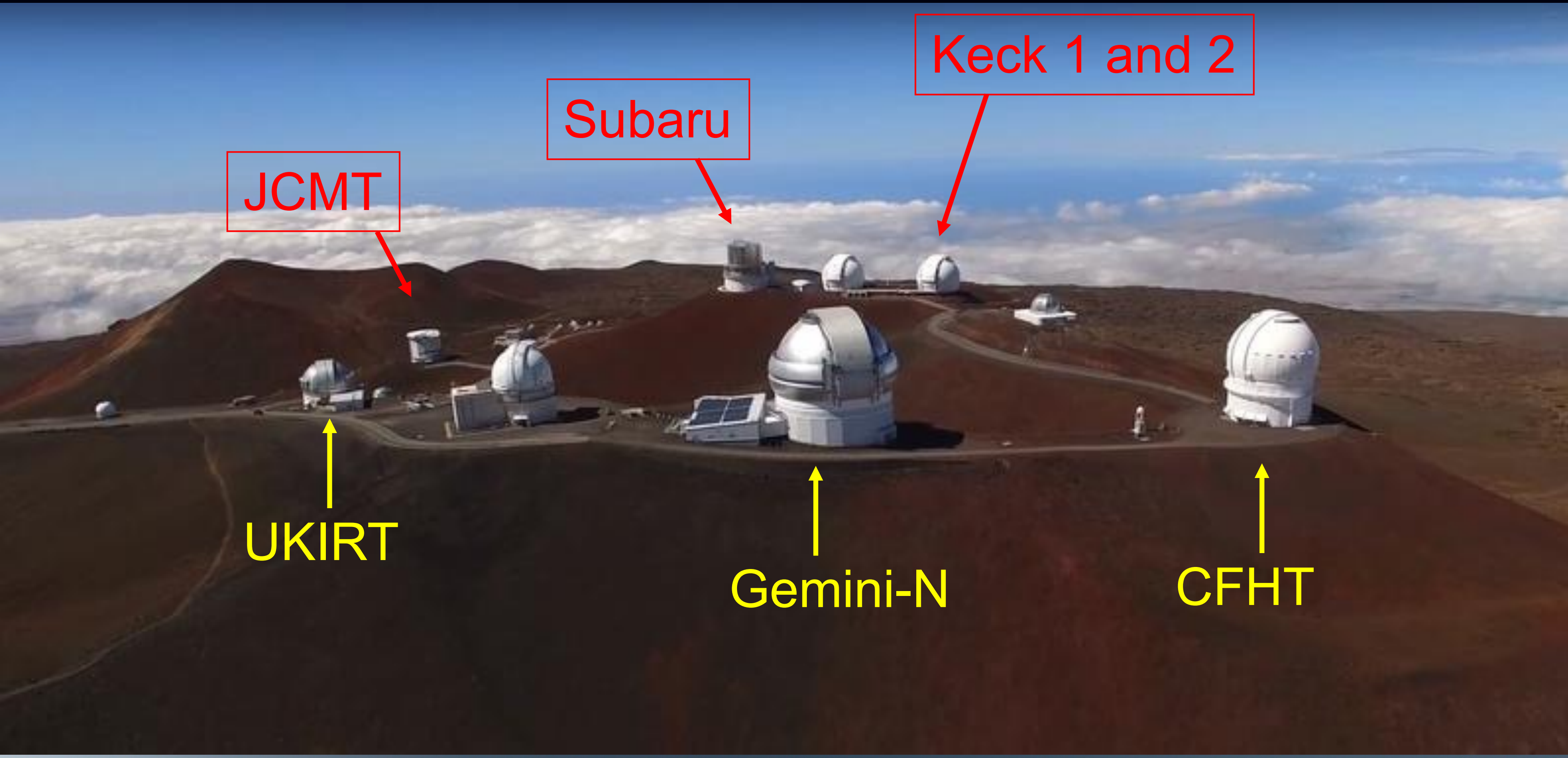


The LSST (Large Synoptic Survey Telescope) is a 3-mirror telescope designed for an extremely large (3degree) field, an 8.4-m primary mirror and a 5-m tertiary giving an effective aperture of 6.5-m. It is under construction on Cerro Pachon, Chile

Telescopes

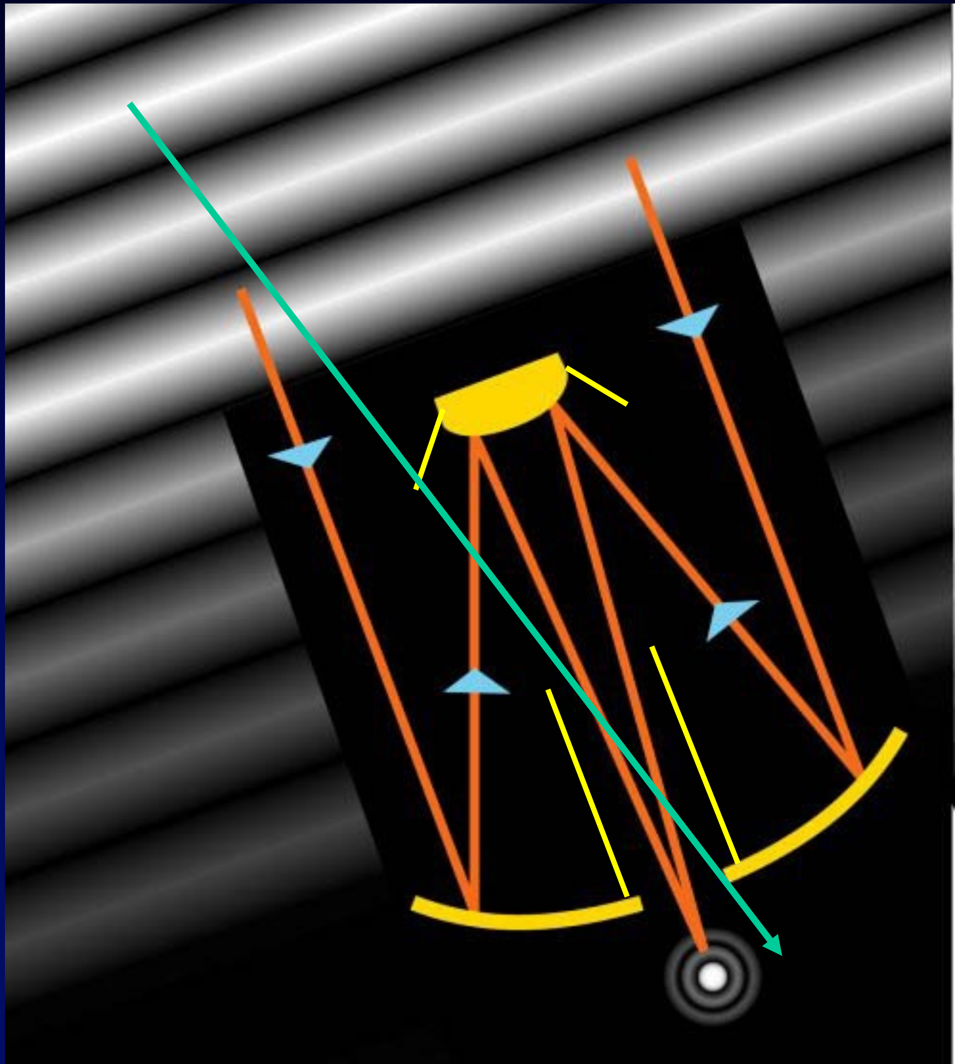

COLLECTING AREA OF THE LARGE TELESCOPES
WHT
UKIRT
CFHT
WYIN
ARC
TNG
MPA
KPNO
NTT
CTIO
AAT
ESO
+ SOAR, VISTA
SUBARU
SAO
Palomar
MMT
Gemini N
Keck 1
Keck 2
HET
SALT
VLT 1
VLT 2
VLT 3
VLT 4
LAMOST
LBT 1
LBT 2
ORM
Magellan 1
Magellan 2
Gemini S
Northern Hemisphere
Southern Hemisphere
ESO VLT VG3
© ESO EPR

Mauna Kea, Hawaii and Paranal, Chile



Visible Wavelength Operation

- Telescopes have open tubes to permit airflow and minimise turbulence
- Use black baffles to exclude out-of-field stars etc
- Ensure that detectors only see natural sky background




50TONNES

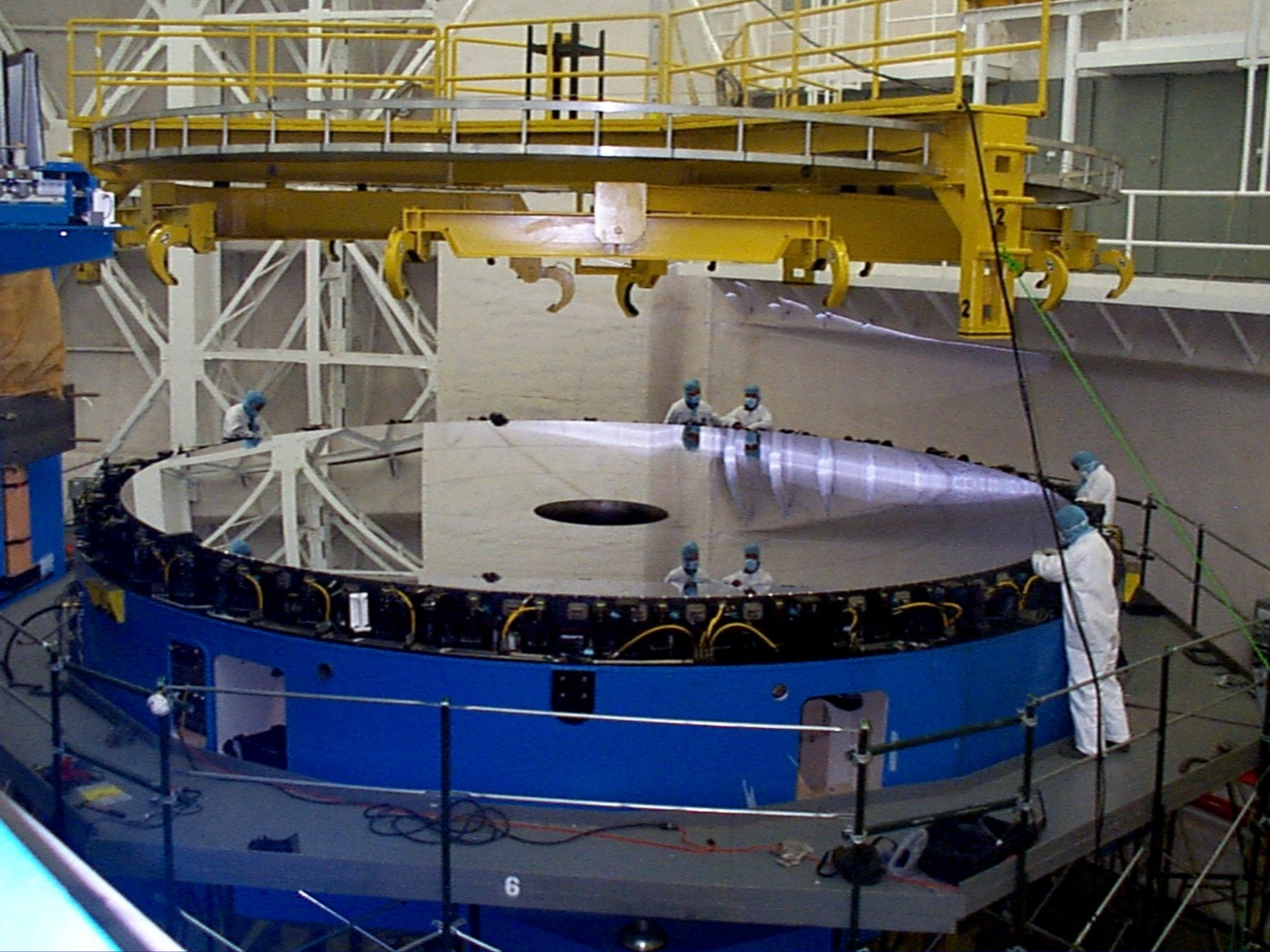

Infrared Operation

8-m Telescope Requirements

- Focus light from astronomical objects collected by 50 m^2 primary mirror to a point <0.06 mm in size and maintain position to 0.01 mm over 1hr.
- 300 ton telescope aimed blind to an accuracy better than 2 arcsec over the accessible sky.
- Maximise productivity through high reflectivity coatings, low emissivity configurations, innovative and efficient instruments and effective exploitation of prevailing weather conditions.
- Permit detection of objects up to 10^9 times fainter than the limit of the unaided human eye

Modern thin-mirror Telescopes

- Mirror blanks in low-expansion glass ceramics such as Zerodur.
- The mirror aspect ratio is ~40:1, with active control systems to maintain the correct figure.
- The mirrors are polished whilst supported on mounts comparable to those used in the telescope mirror cell to ensure the correct surface profile
- Polishing requirements for the VLT and VISTA telescopes are <40nm RMS
- M1 is supported on pneumatically controlled mirror support actuators which apply forces to control the large scale shape of the mirror in the face of varying gravity vectors and wind load
- More exotic materials e.g. SiC or Beryllium have been used for secondary mirrors – low mass and Moment of Inertia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2
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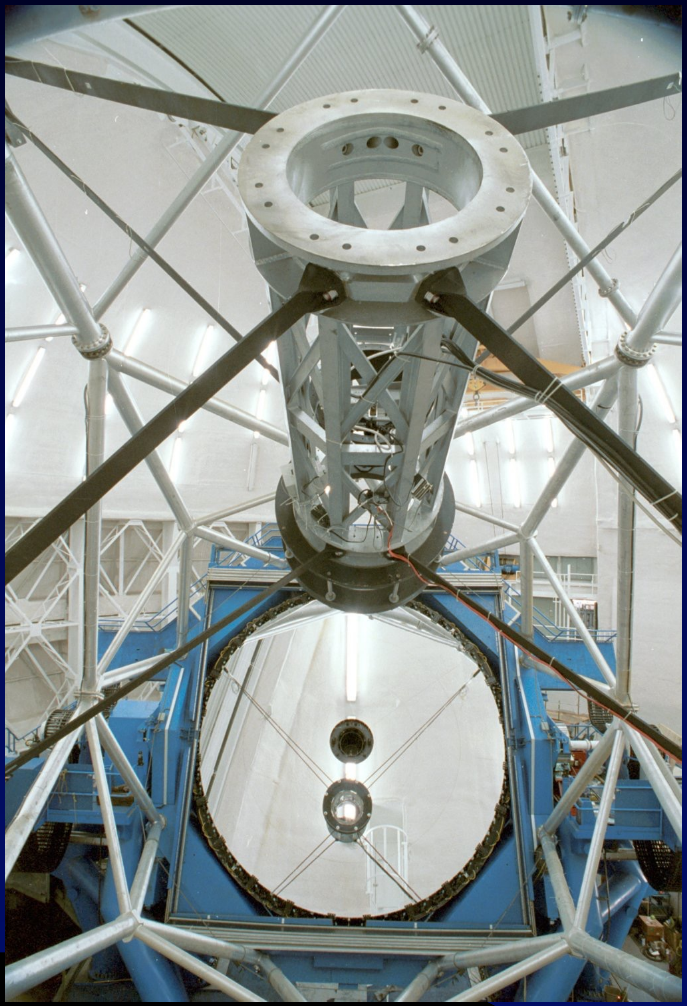
Active Optics



Active mirror control systems use wavefront sensors to analyse and maintain the mirror shape and position(s). The primary mirror support system ensures the mirror surface shape is maintained as the telescope tracks

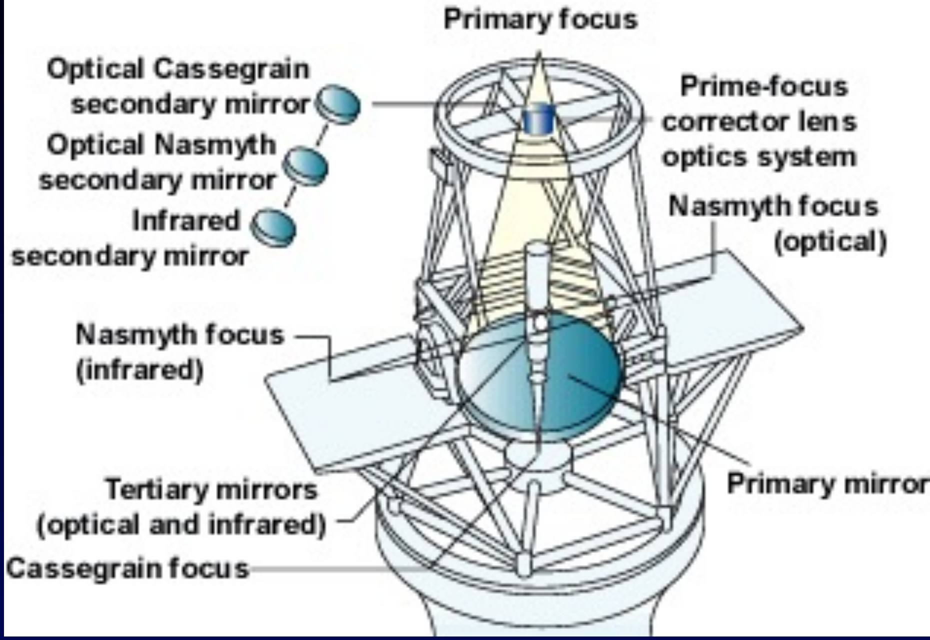
The secondary mirror moves in 5 axes:
x,y movements maintain alignment with the optical axis of the telescope and minimise aberrations

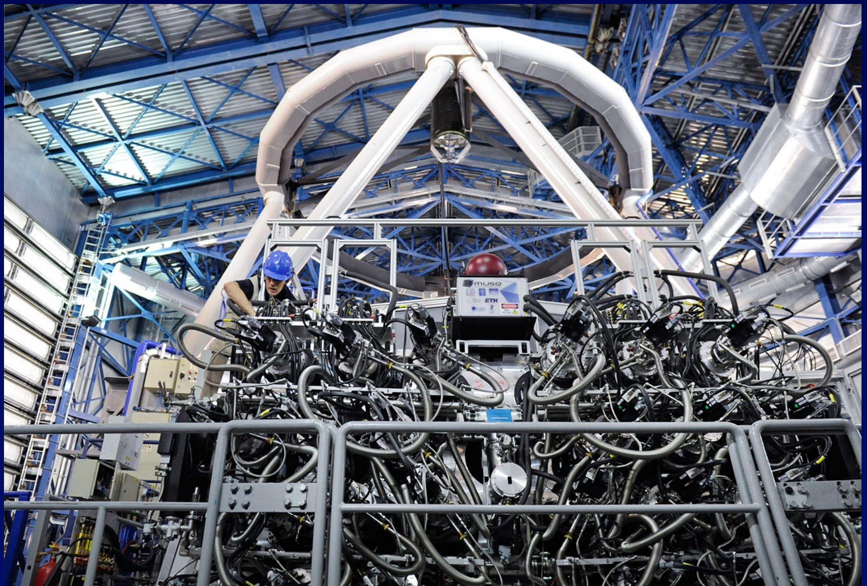
Focus corrections compensate for temperature variations in mirror separation

Tip/tilt corrects for windshake and the low order distortions produced by the atmosphere.

Nasmyth & Cassegrain Foci

- Alt-Az telescopes need field de-rotation at Cassegrain or Nasmyth foci
- Smaller instruments may be mounted at the Cassegrain or Nasmyth focus and physically rotated to track the sky.
- Large or complex instruments are usually mounted at the gravitationally stable Nasmyth platform and fed by an image rotator, Pick-off mirrors divert light from stars in the field to ensure accurate tracking.

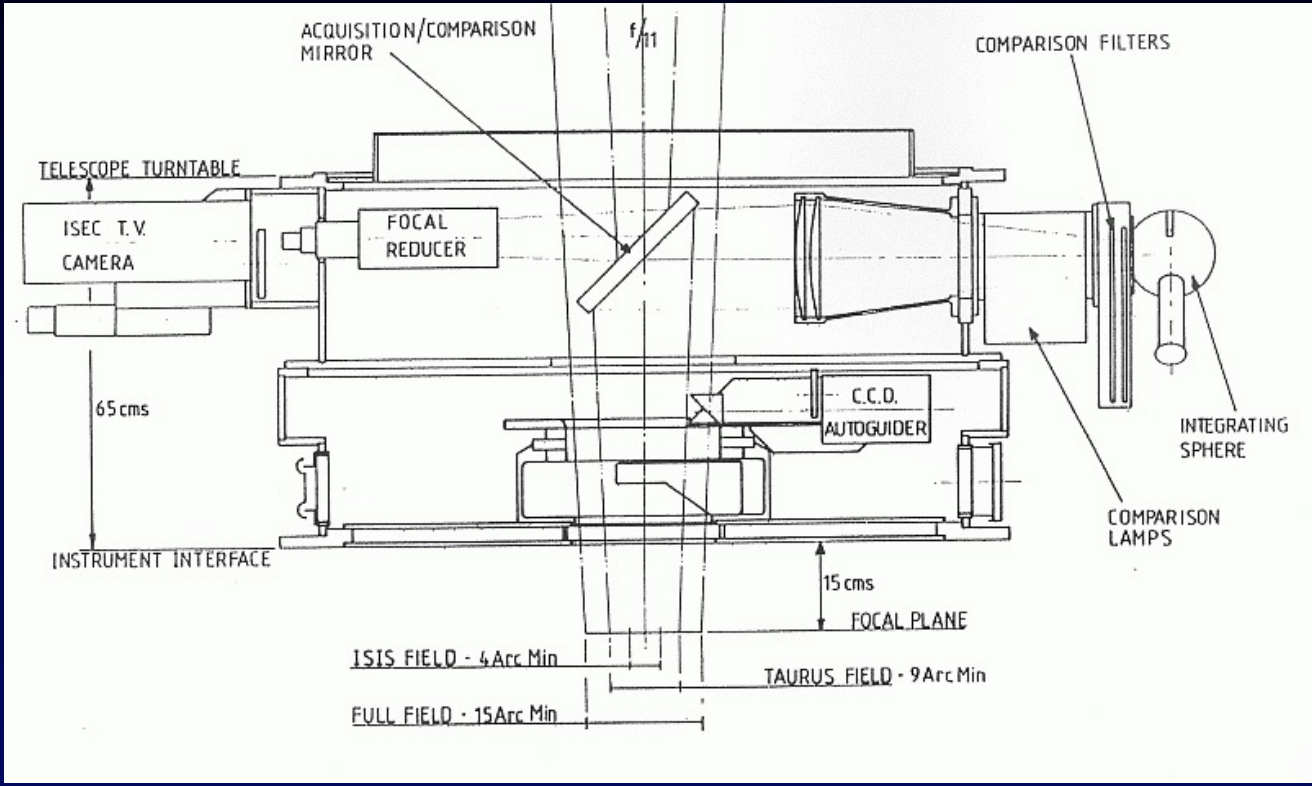




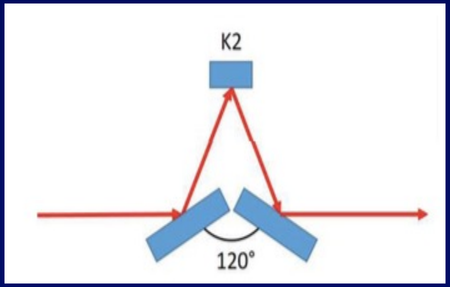
Acquisition and Guiding

Telescopes usually incorporate A&G, calibration and beam de-rotator (where necessary) facilities.

They are introduced into the beam by beam-splitters or pick-off mirrors

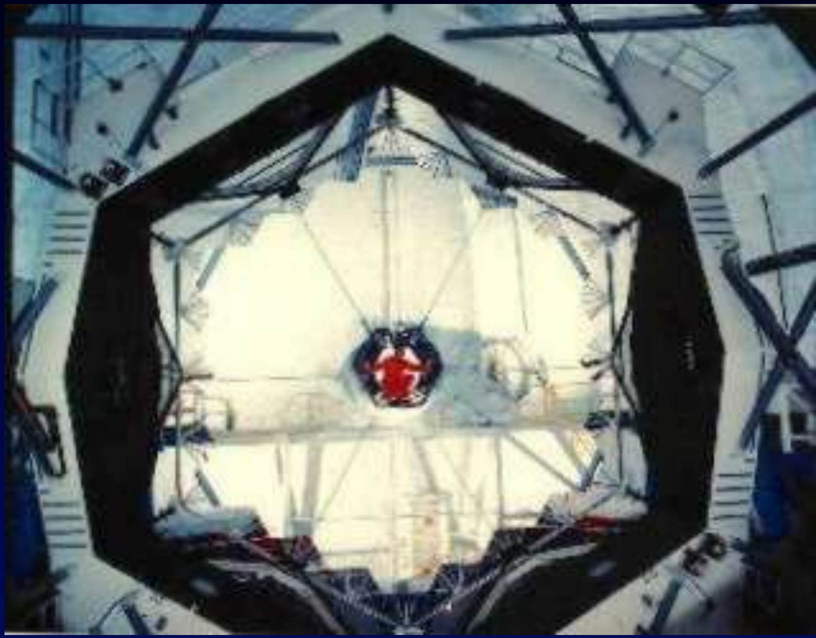


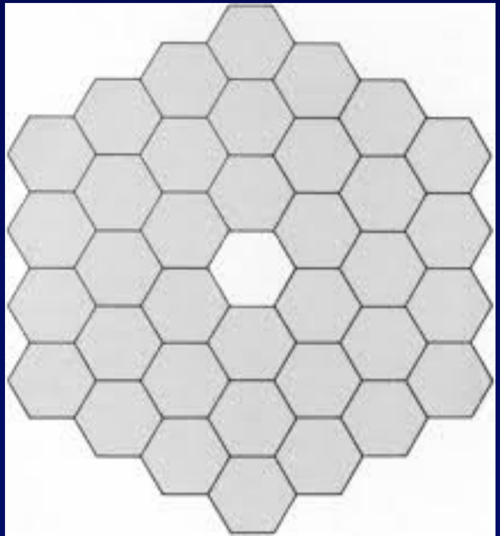
K-mirror beam rotator

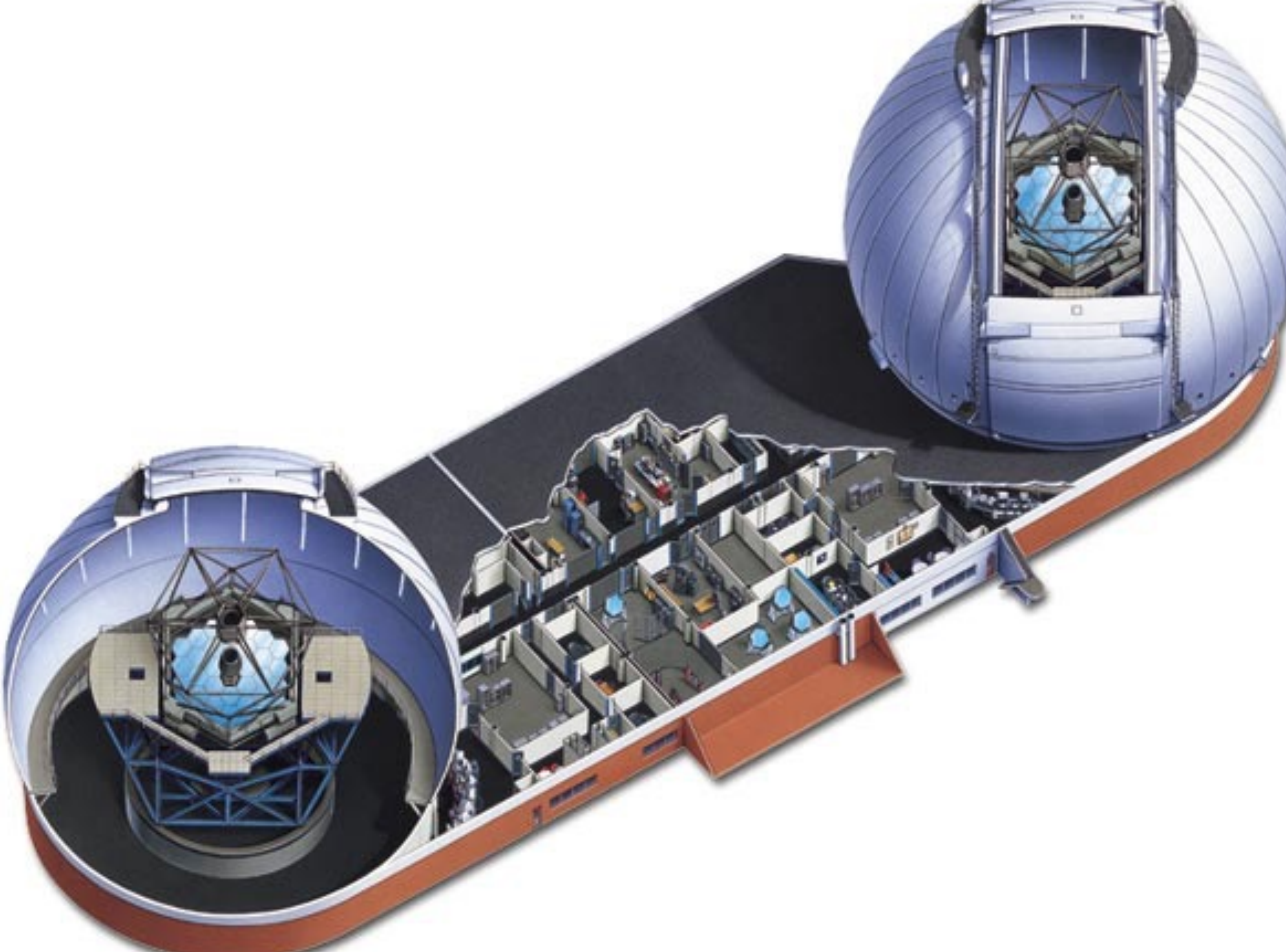


Keck 10-m telescopes

- 10-m diameter mirror made of 36 hexagonal segments, each 1.8m across and 75mm thick with a mass of 500kg
- f/1.75 primary mirror with a final focal ratio f/15 and f/25 or f/40 for IR operation
- Active alignment and co- phasing using edge sensors and 108 position actuators
- Lightweight structure ~300 tonnes
- Scalable to much larger apertures



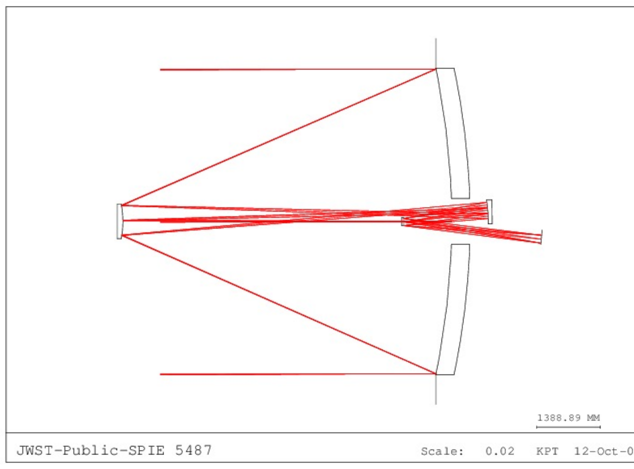




Observing Priorities

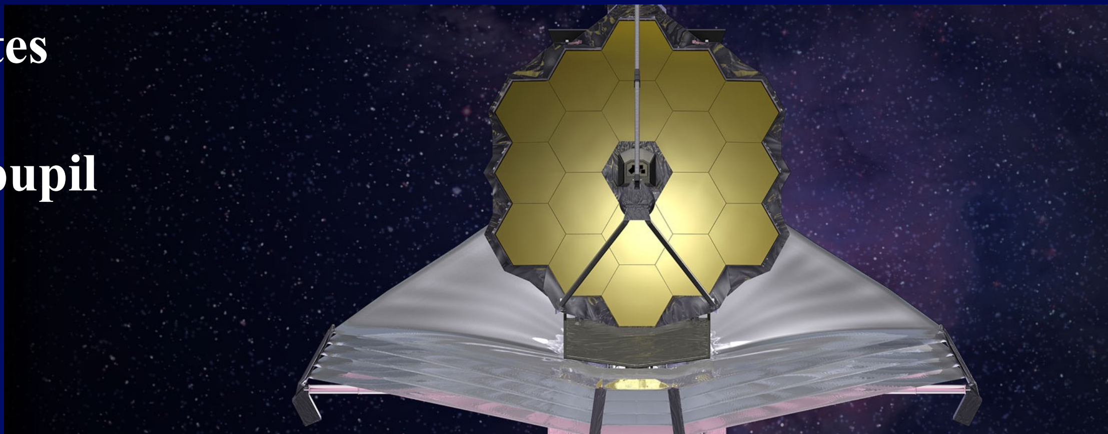
- Flexible Observing: Programmes matched to prevailing conditions.
- Exploit best conditions for highest priority science
- Aim for performance limited only by Earth's atmosphere
- Novel Instrumentation
- Maximise scientific productivity

James Webb Space Telescope



- 6.5m telescope: M1 has 18 hexagonal beryllium segments folded into rocket nosecone
- Optical surface polish 14nm RMS
- L2 orbit where telescope cools to 40K, protected by a large sunshield
- Secondary mirror supported by a tripod on struts
- Three mirror anastigmat (TMA) design, f/16.7, 29.4 m^2 collecting area

Elliptical **f/1.2 Primary Mirror**
Hyperbolic **Secondary Mirror creates f/9 intermediate image**
Elliptical **Tertiary Mirror images pupil at** ***Flat*** **Fine Steering Mirror**



JWST Constraints

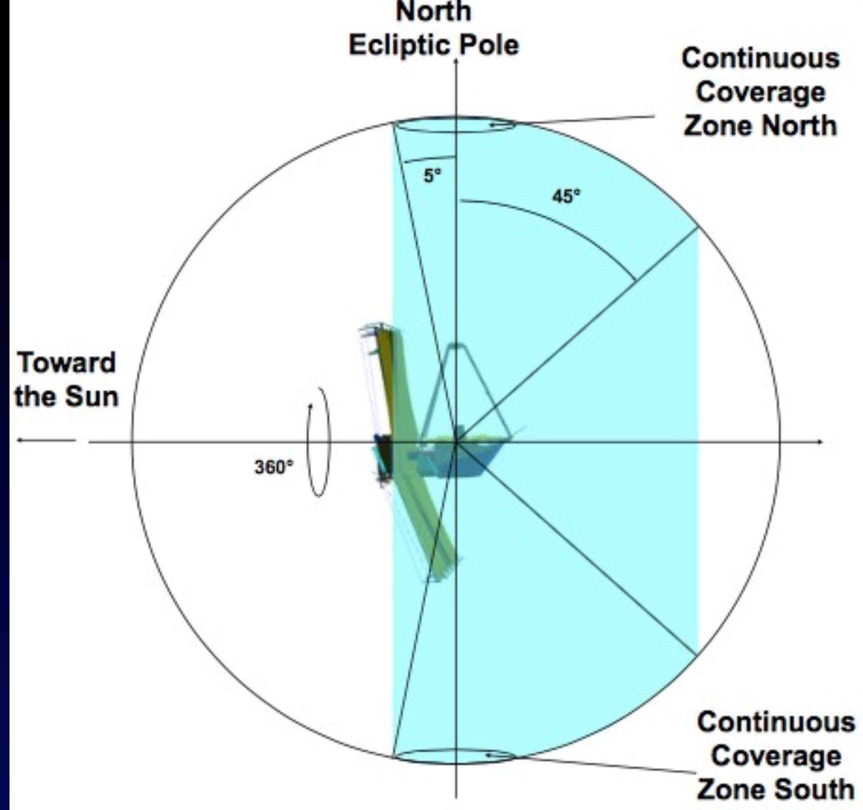
Orbit at L2, provides thermal stability

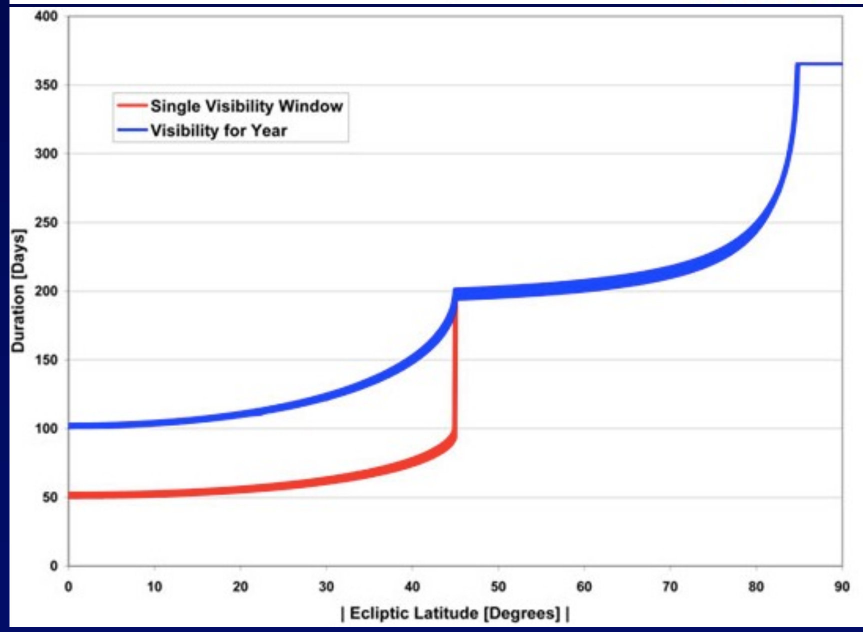
The sunshield provides at least 39% sky coverage

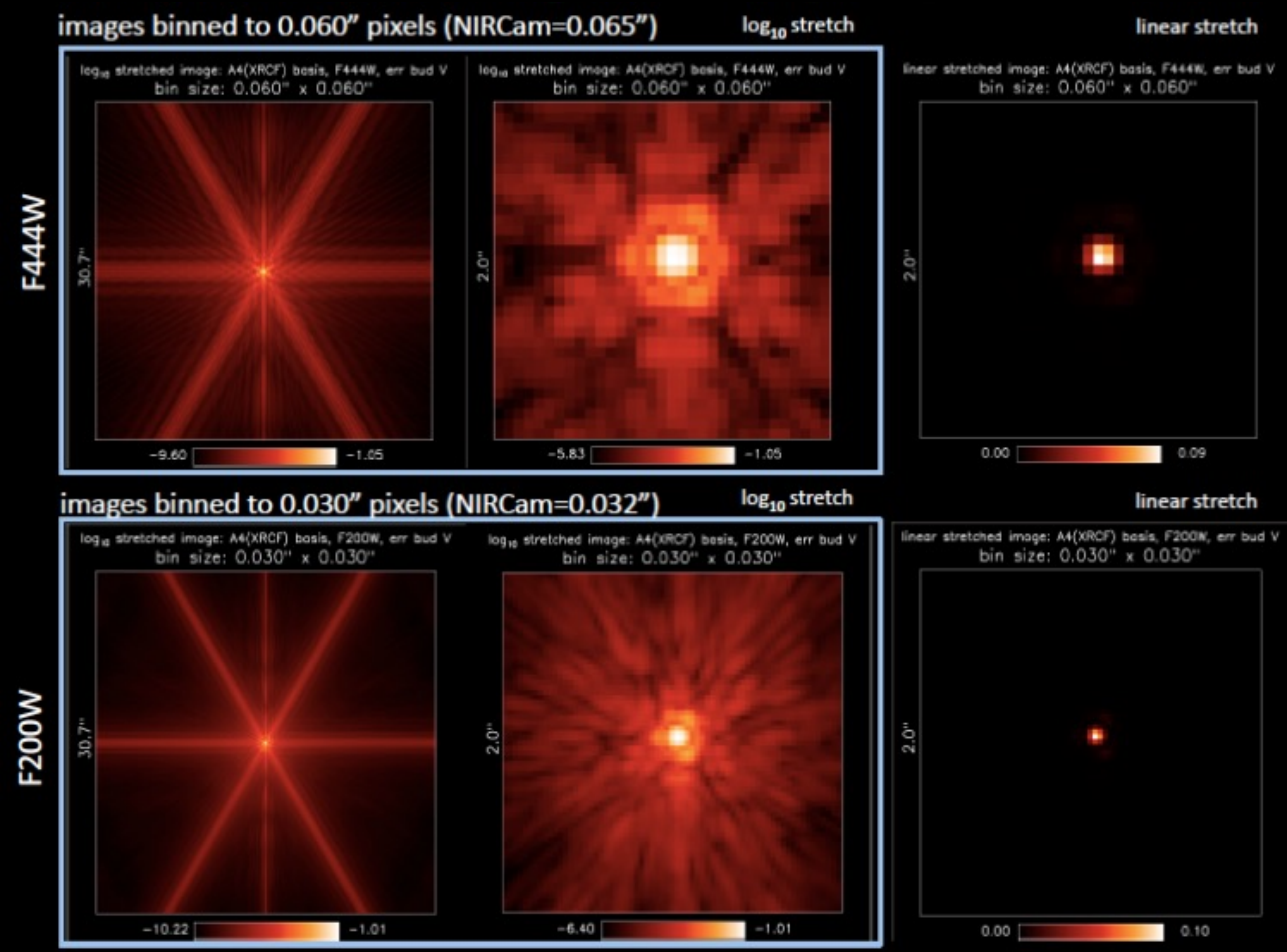
'Field of Regard' is the observable cone allowed by the requirement to keep the telescope in shade. It is an annulus with rotational symmetry about the L2-Sun axis, 50° wide

The telescope has full sky coverage over a sidereal year

Maximum object observability is near the ecliptic poles







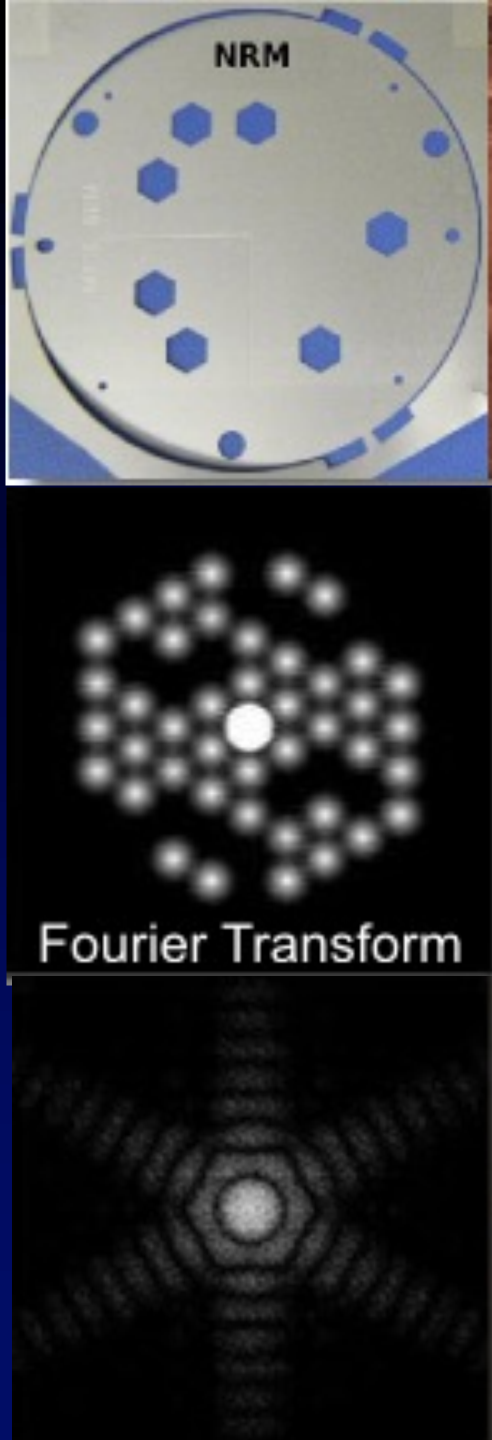
images binned to 0.060" pixels (NIRCam=0.065")
log10 stretch
linear stretch
F444W
log10 stretched image: A4(XRCF) basis, F444W, err bud V
bin size: 0.060" x 0.060"
30.7"
-9.60
-1.05
2.0"
-5.83
-1.05
linear stretched image: A4(XRCF) basis, F444W, err bud V
0.00
0.09
images binned to 0.030" pixels (NIRCam=0.032")
log10 stretch
linear stretch
F200W
log10 stretched image: A4(XRCF) basis, F200W, err bud V
bin size: 0.030" x 0.030"
30.7"
-10.22
-1.01
2.0"
-6.40
-1.01
linear stretched image: A4(XRCF) basis, F200W, err bud V
0.00
0.10

Imaging Instruments

The telescope operates from 0.6 to 25um, and will be diffraction limited beyond 1.6um.

Imaging and spectroscopic instruments, include coronagraphs, sparse aperture masks and polarimetry capability

Due for launch in October 2021, with initial proposals due in November 2020

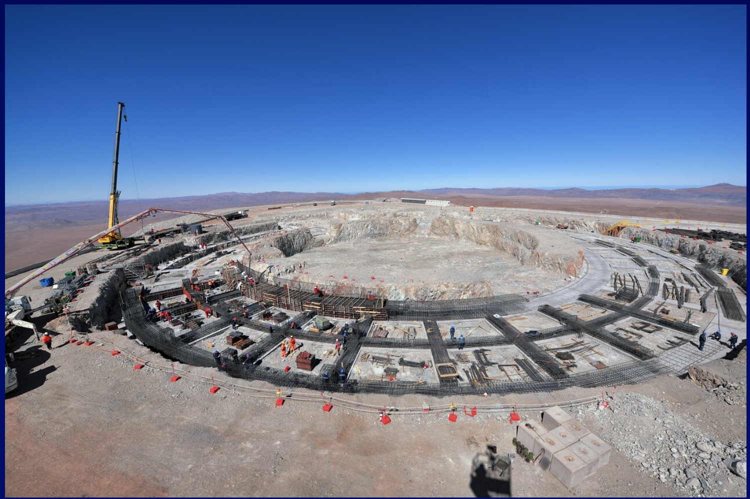


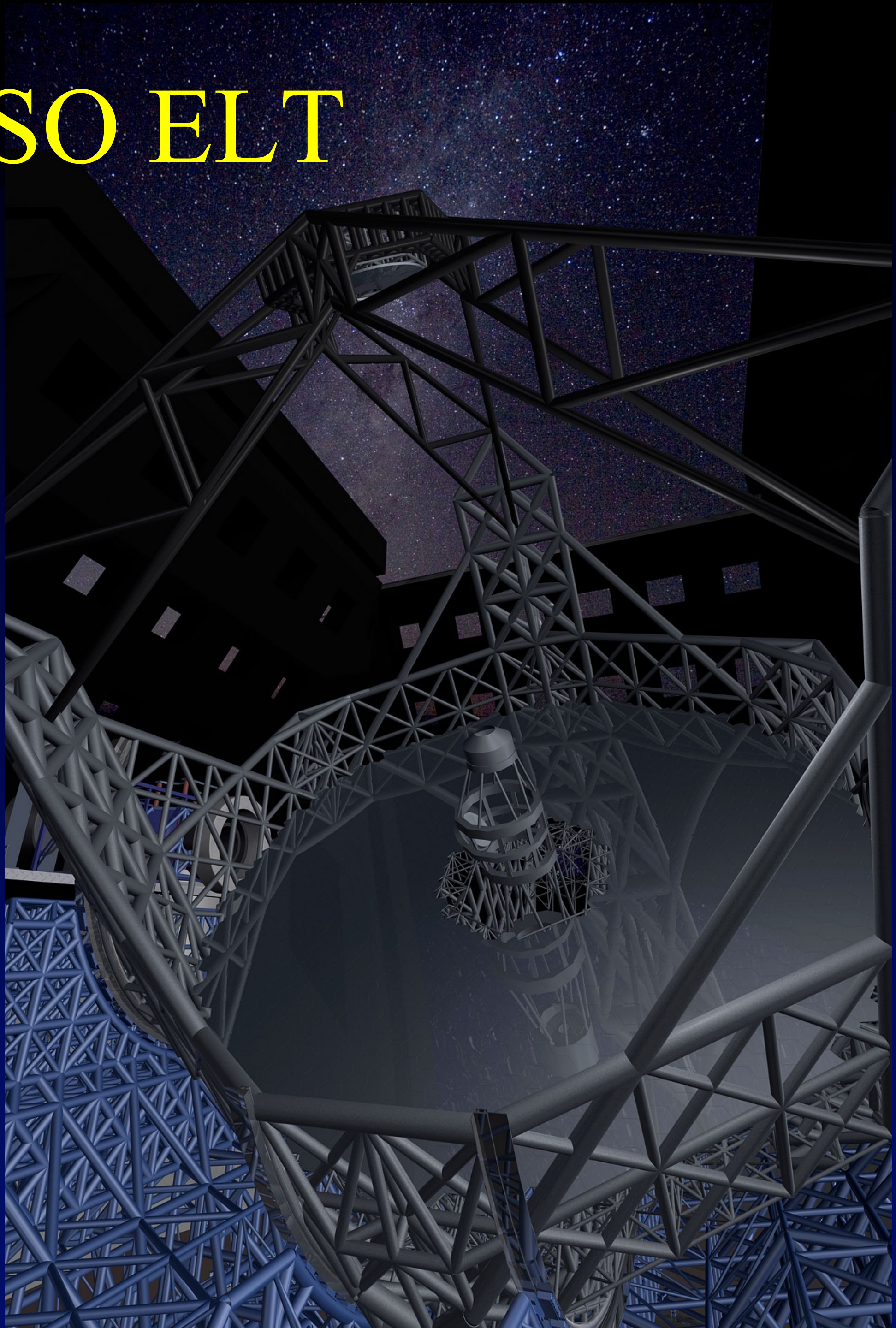
The ESO E-ELT

- ESO 16 member states cooperating in astronomy
- Budget from Member States ~180M€ pa of which UK contributes ~15%
- Operates Optical/IR telescopes in Chile on la Silla and Paranal, including the VLT and VISTA, and micro-wave telescopes at Chajnantor, APEX and ALMA
- Construction on Cerro Armazones ~30km from Paranal

The ESO ELT

- A 39m diameter, adaptive telescope - the largest optical/IR telescope in the World
- 5 mirror optical configuration feeding Nasmyth platforms
- Phase-I cost: ~ €1.2 billion
- Foundations nearing completion





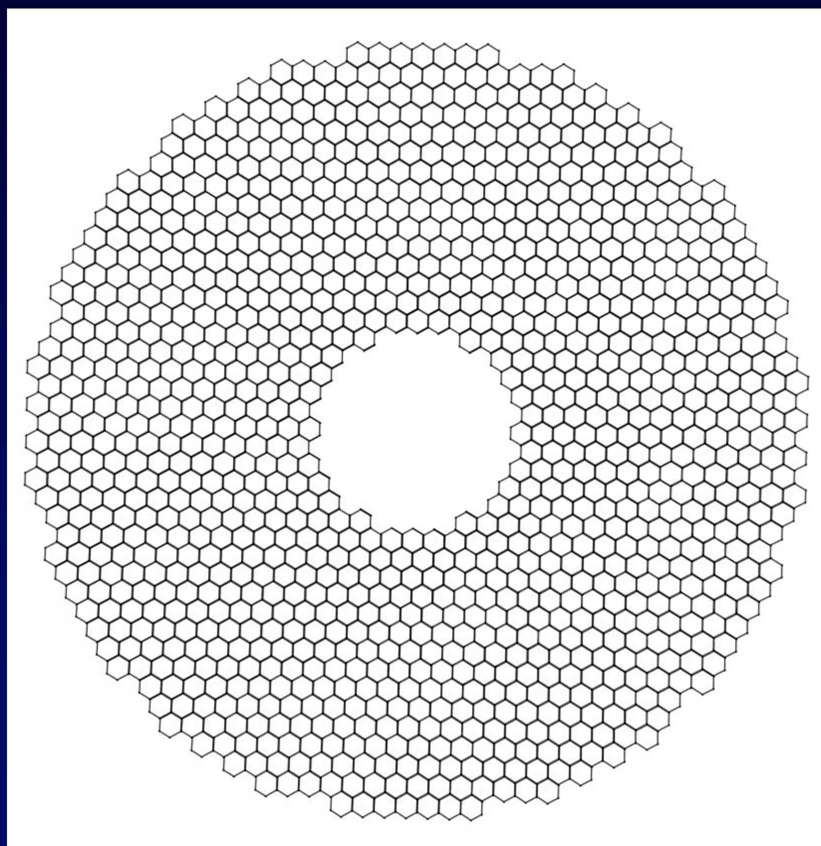
Benefits of Extremely Large Telescopes

- E-ELT collects more than 20 times as much light as an 8m telescope
- This means that the exposure time needed for a measurement is 20-500 times less.
  - So can observe the same targets in much less time
  - Or observe fainter and more distant objects than we can measure now.
  - Or get more detailed information
  - Or all of the above!!
  - But generally no advantage for surface brightness
- Currently only Phase 1 is funded : includes only 3 instruments

Telescope primary mirrors

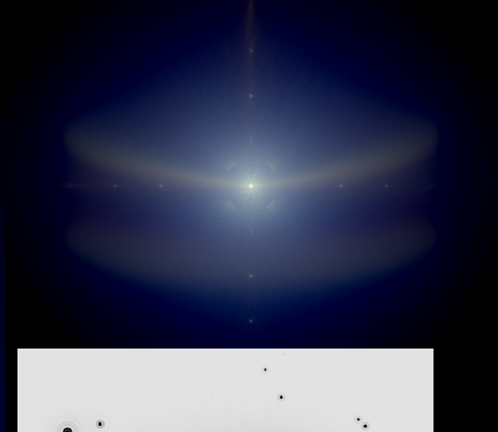
HST
2.4m

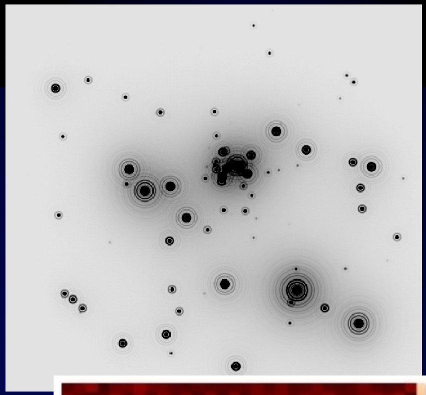
JWST
6.5m

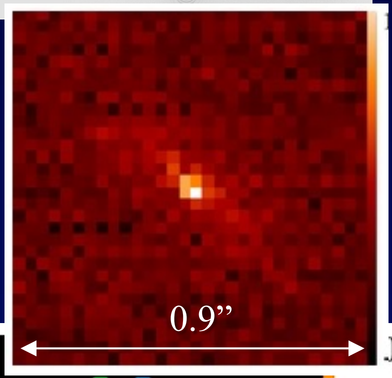


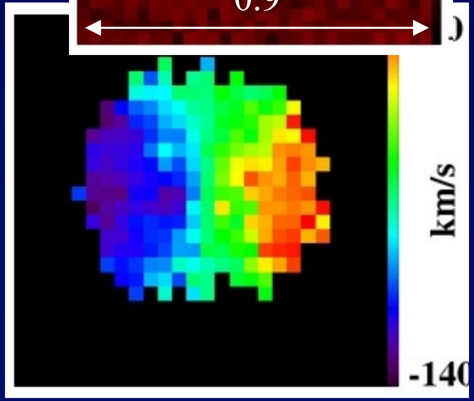
VLT
8m

Collecting area = sensitivity
Diameter = resolution (with AO)



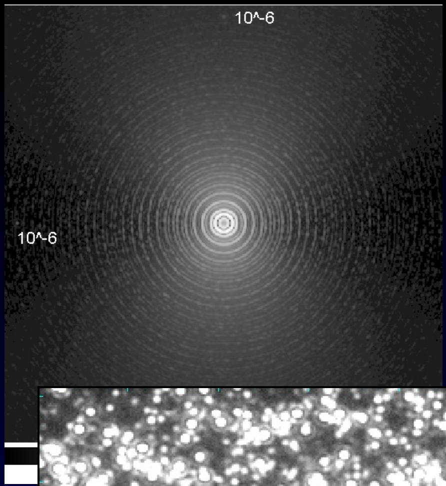


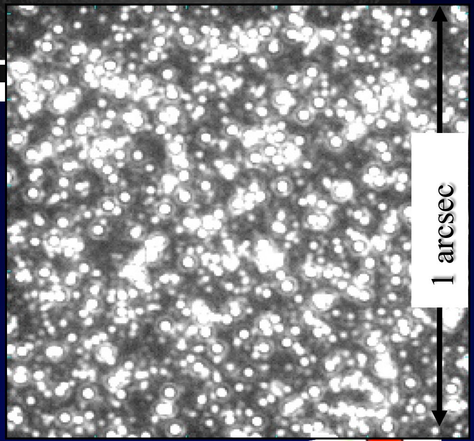


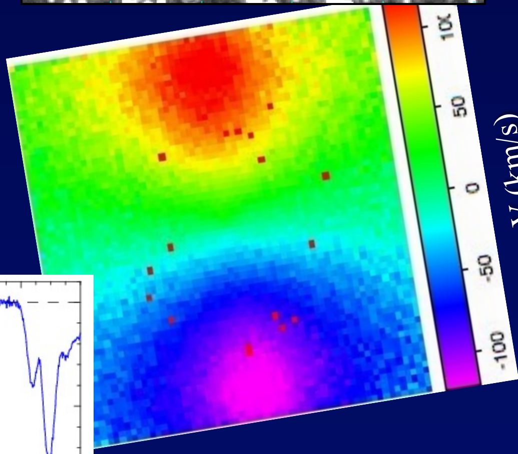


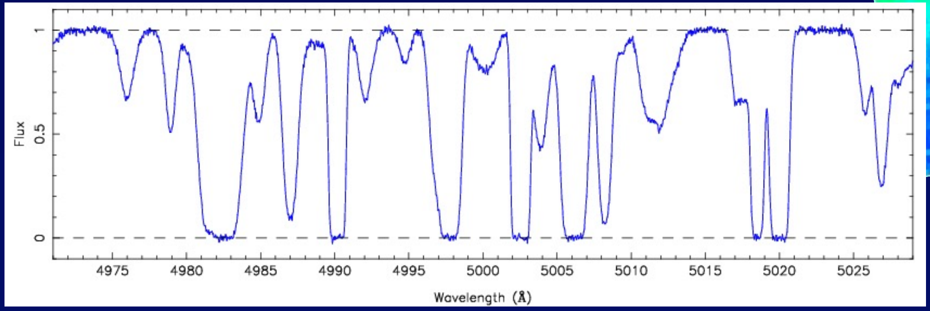
E-ELT Performance Simulations

- Exo-planets
  - Direct detection
  - Radial velocity detection
- Initial Mass Function in stellar clusters
- Stellar disks
- Resolved Stellar Populations
  - Colour magnitude diagrams
  - Abundances
  - Detailed abundances and kinematics
- Black Holes
- The physics of galaxies
- Metallicity of the low-density IGM
- The highest redshift galaxies
- Dynamical measurement of the Universal expansion









• The E-ELT will be the largest optical telescope in the world, with its 39m primary mirror, made up of ~798 precision polished 1.4-m hexagonal segments giving 39m diameter primary which is only 50mm thick

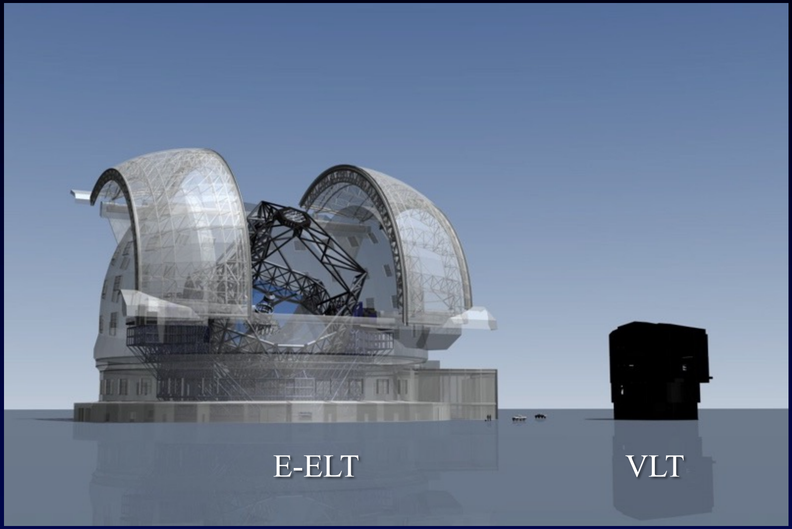
•Footprint of Dome ~100m dia, 80m high.

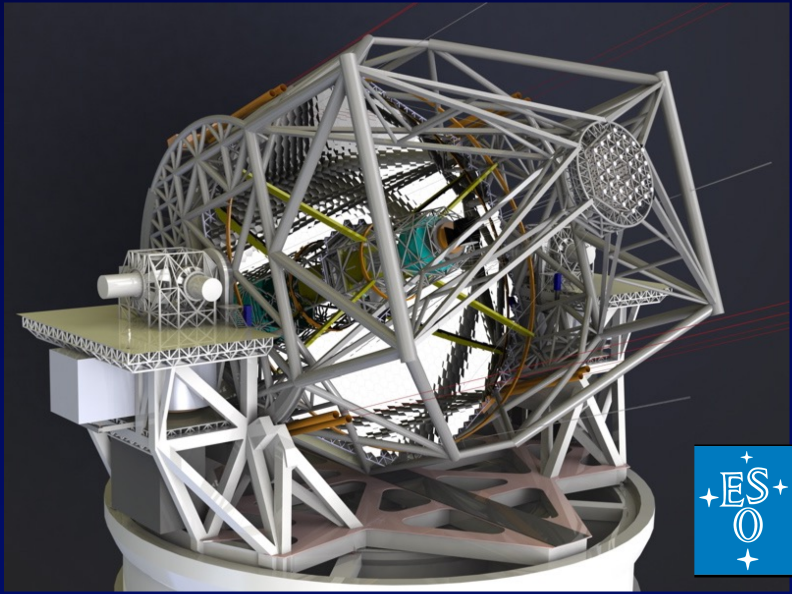
• Instrumentation: up to ten focal stations, FoV 10’

• Being built on Cerro Aramazones, Chile and operated jointly with the Paranal telescopes

• Cost: construction ~1.2 billion Euros (incl. instrumentation), operations ~€35 million/year completion of Phase 1 in 2025

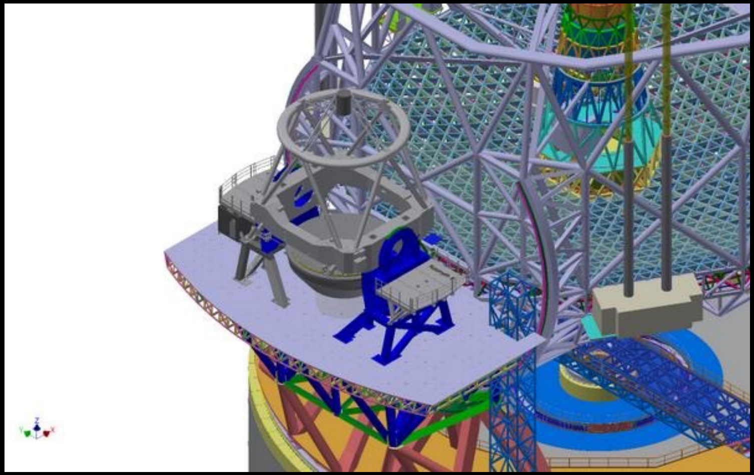
• Science goals are centred around high spatial resolution (5 mas in the J-band) and immense collecting area. Synergies with other major observatories JWST, ALMA, ...





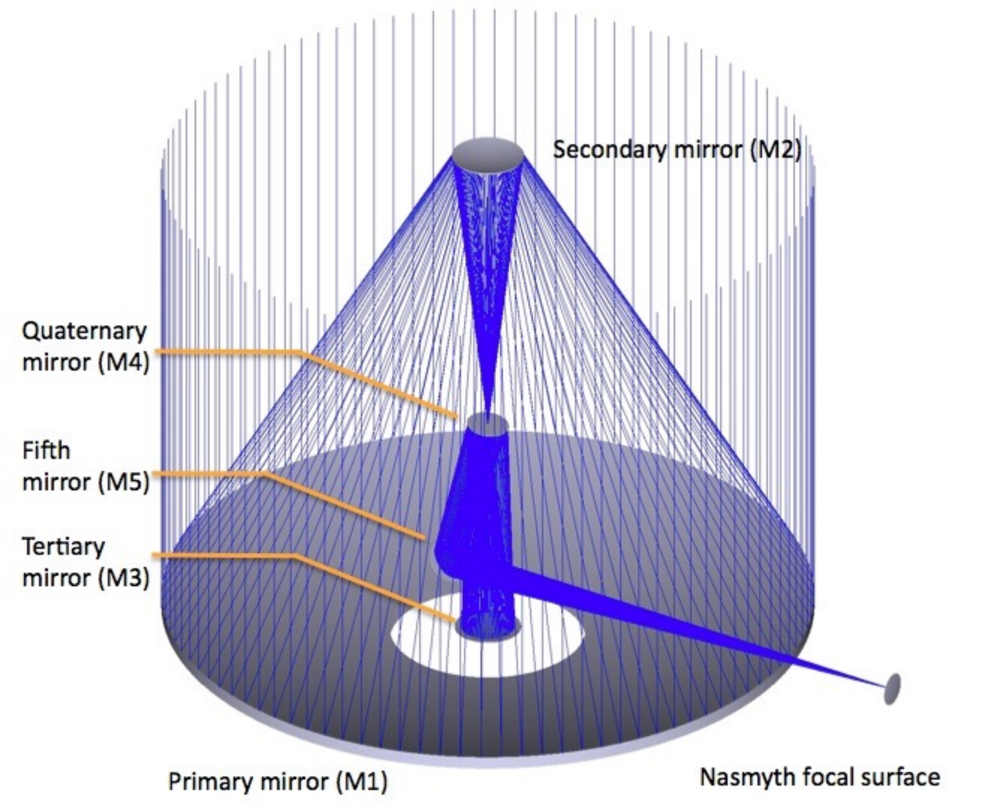
E-ELT Optical design

5-mirror anastigmat feeding instruments on the Nasmyth platforms. The first large telescope with embedded AO



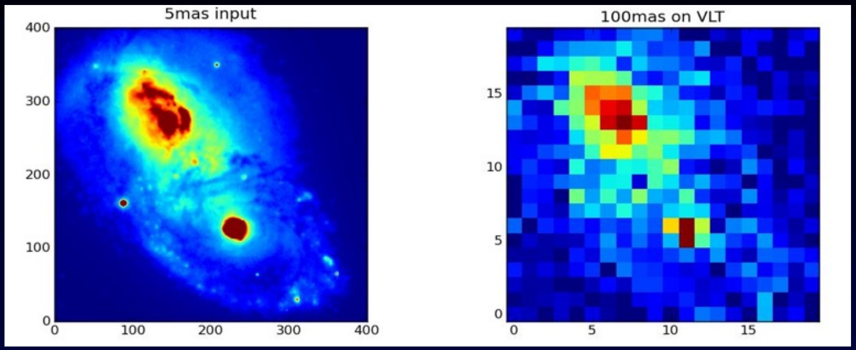
M4 is an adaptive mirror in the telescope to provide a 10 arcmin, near-diffraction-limited field of view in the IR

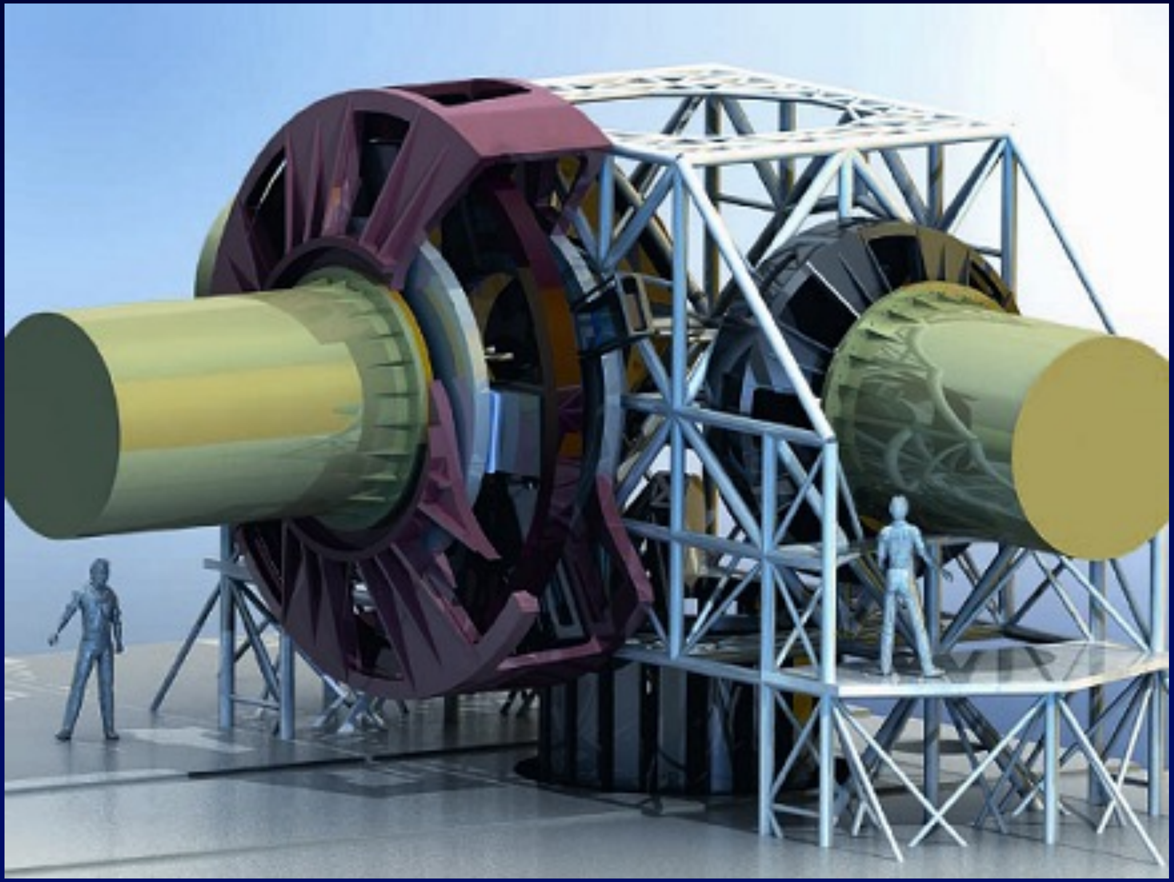
It will usually operate with a constellation of laser guide stars as references for AO



E-ELT instrumentation

- First 3 instrument concepts were selected in 2012
  - a near-IR spectrometer, Harmoni
  - a near-infrared imager, Micado
  - Both instruments operate with Adaptive optics correction
  - A thermal infrared imager/spectrometer, Metis
- Harmoni is led by Niranjan

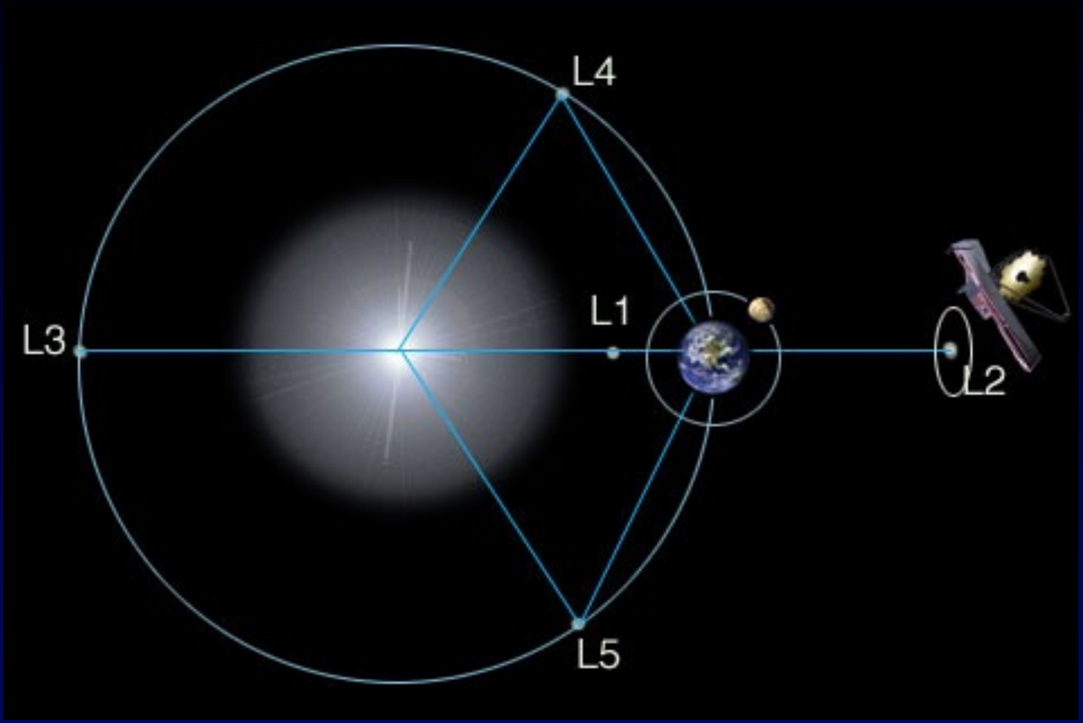




But also

- Small telescopes, or arrays of small telescopes operating remotely are being used for many important programmes
- Amateur telescopes adapted for wide field imaging
  - Exoplanets – Transits, Radial Velocities of bright stars
  - Gamma Ray burst follow-up
  - Variable and Transient objects
  - Gravitational wave sources etc
- e,g NGTS on Paranal
  - Next Generation Transit Survey
  - Array of eight 8 inch telescopes
  - Each with 8 degree f.ov.
  - and 2kx2k e2V CCD

JWST L2 orbit



JWST will circle around the 2nd Lagrangian point, 1.5 million km away, keeping out of the Earth and moonshadow for thermal stability and allowing continuous observing and communication with Earth

JWST Deployment