Radio & mm Interferometry

- Good u-v plane coverage with many antennas + Earth rotation synthesis mapping
- Antenna based calibration using PWV
- Need source to stay constant over day timescales
- Largest spatial scales sampled limited by primary beam diameter of each dish
- $\lambda/2b$ vs. λ/D
- No zero spacing data, fill in with single dish

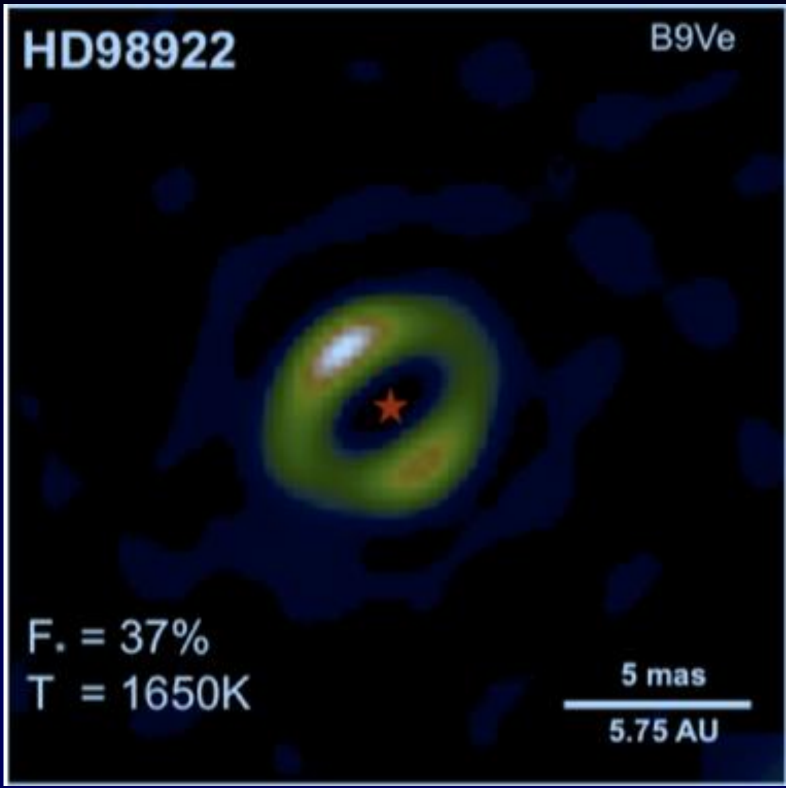
Optical/IR interferometry

Separated telescopes allow longer baselines (~100m) to give milli-arcsec resolution at near-IR wavelengths, but with a small number of telescopes.

Interferometry at short wavelengths is restricted to ~6 telescopes because of the need to split the light in the correlation process

The VLTI offers 4 x 8-m UTs or 4 x 1.8m ATs. The telescopes need AO to fully use the apertures

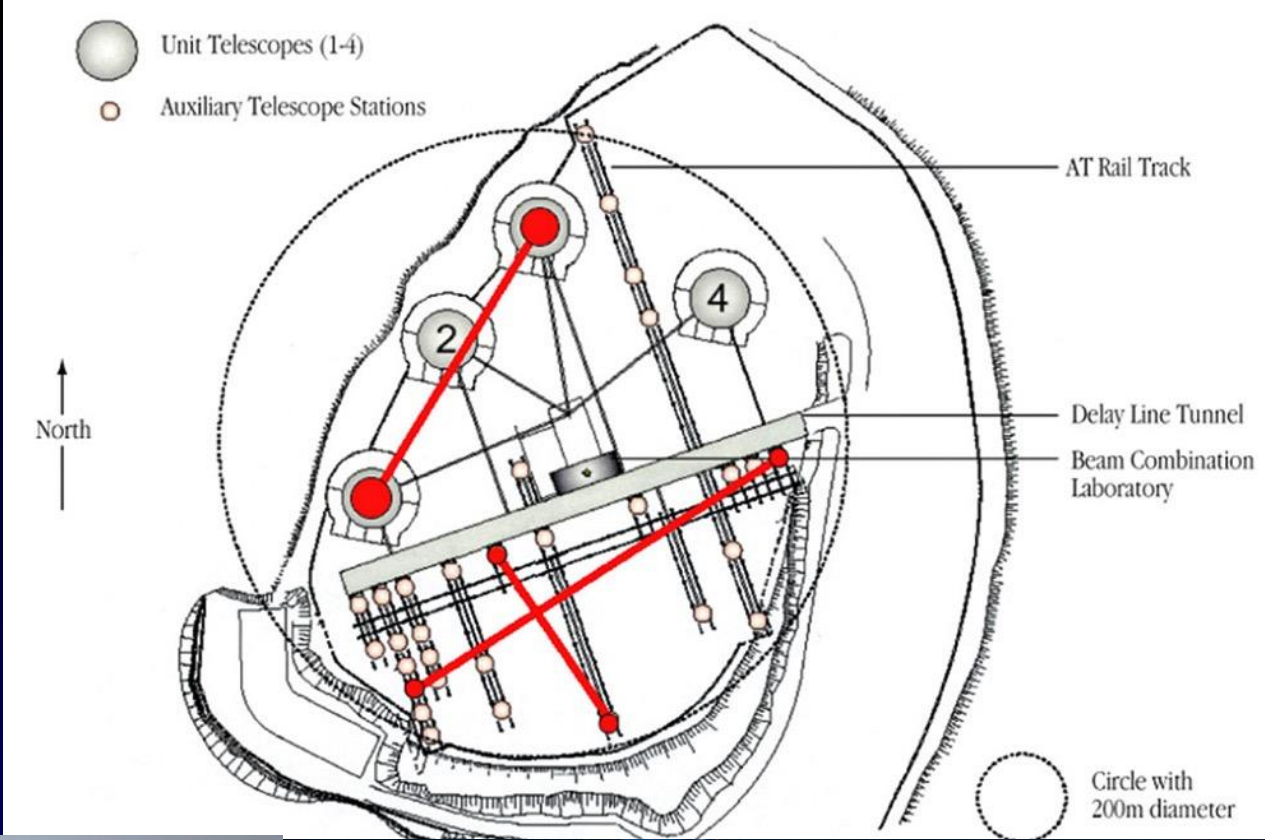
Imaging is rather crude with 6 baselines and 4 different closure phases, but rotational synthesis means that good quality imaging is possible in the near-IR with GRAVITYand in the mid-IR with MATISSE.

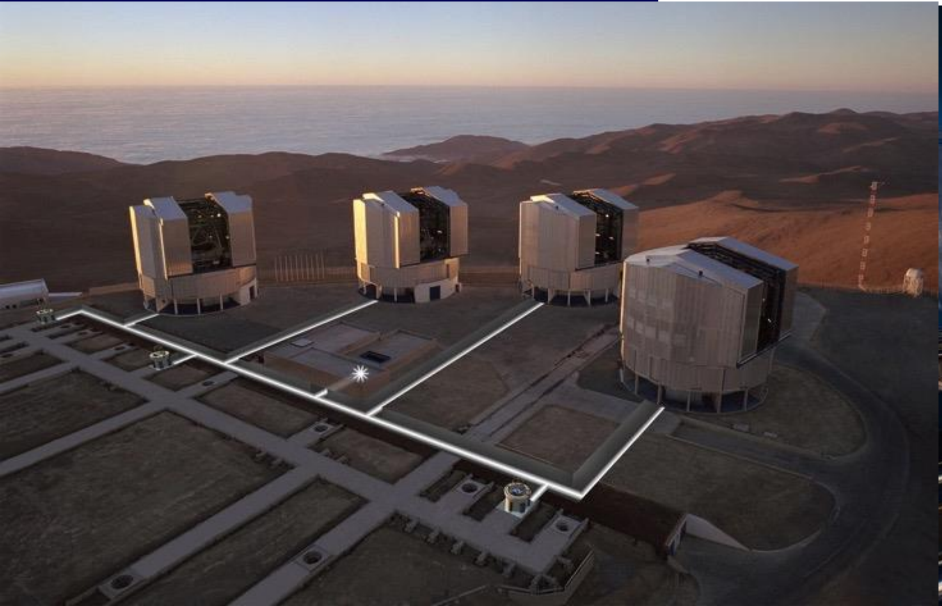


VLTI/PIONIER image reconstruction of the Be star HD98922 (Kluska et al 2013)

The VLTI

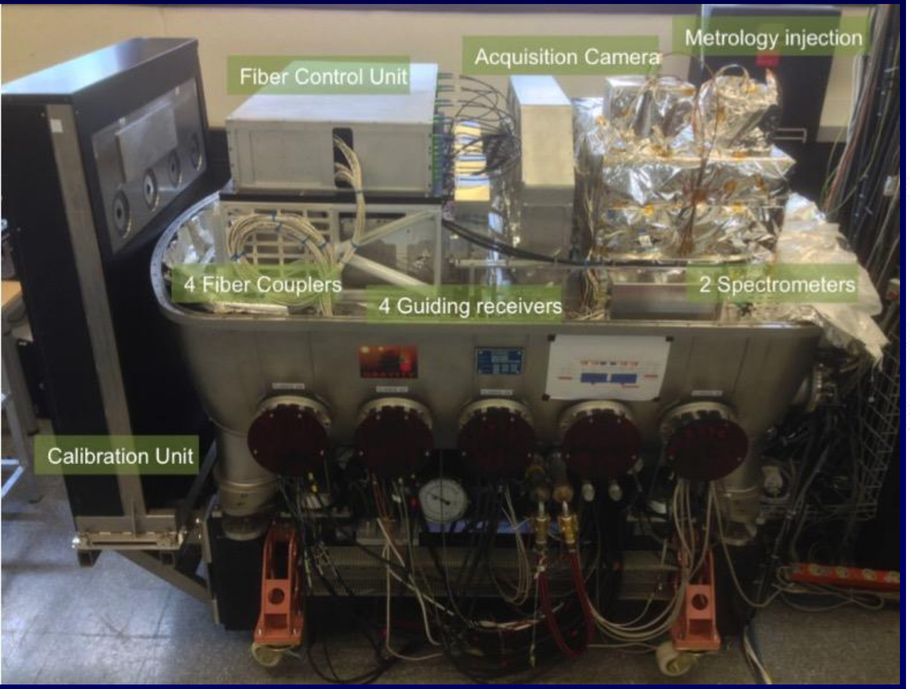
The light from the four 8-m VLT or four movable auxiliary telescopes can be combined to simulate a telescope with an aperture of 130m. This gives milliarcsec resolution

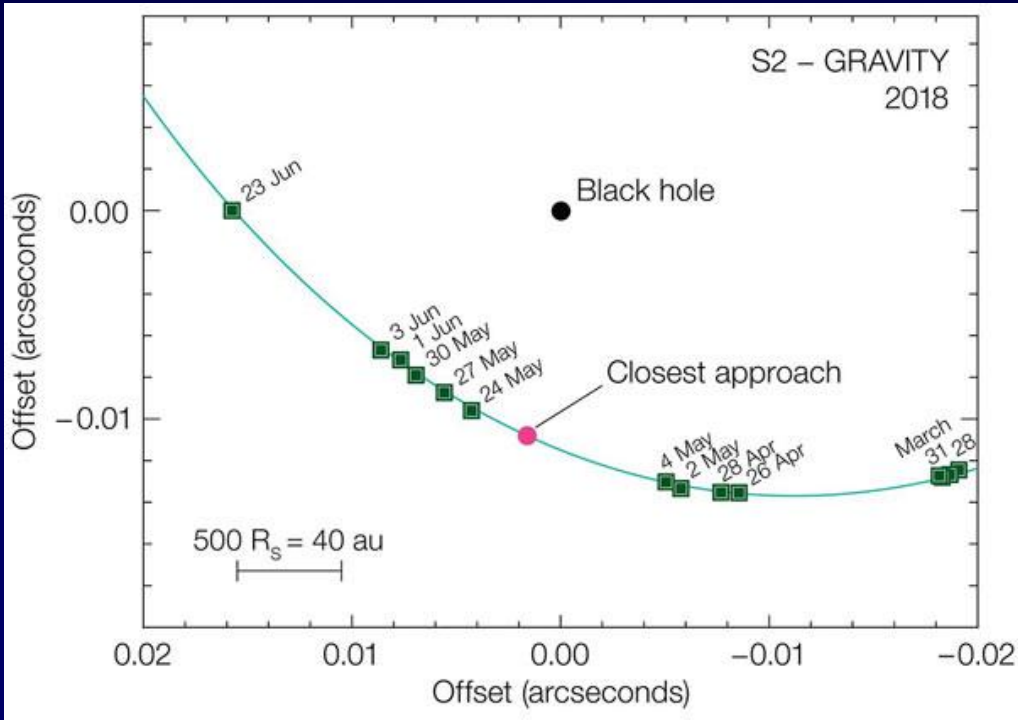




A new VLTI instrument, Gravity was commissioned in 2017. One of its prime targets is the measurement of the position of star S2 in its orbit and closest approach to the Black Hole.

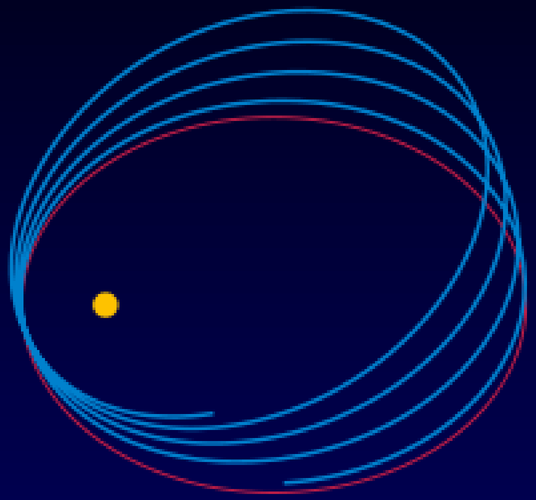
It combines the infrared light from all four 8-m telescopes (or the four 1.8m auxiliary telescopes) to make precise measurements of the stars in the Galactic Centre and to investigate the origin of IR flares in Sgr A*. It requires very high precision control of hundreds of optical elements and compensation for vibrations



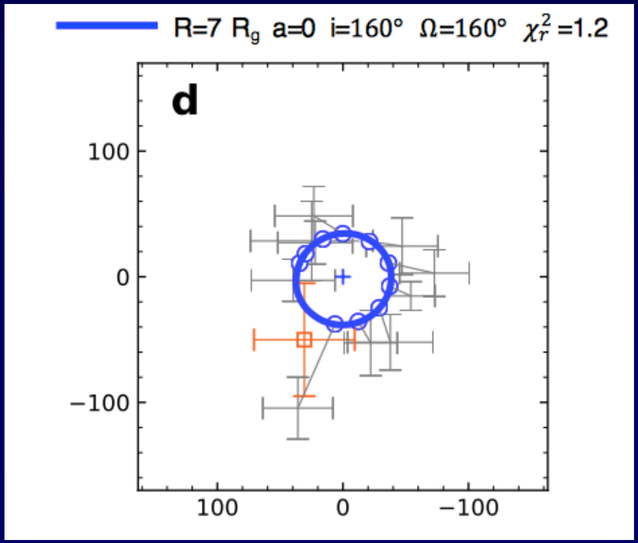


GRAVITY has precisely measured the orbital position of star S2 as it moves through the Black Hole's gravitational potential, testing gravitational redshift and orbital precession in the strong gravity regime. The opportunity will not arise again until 2034

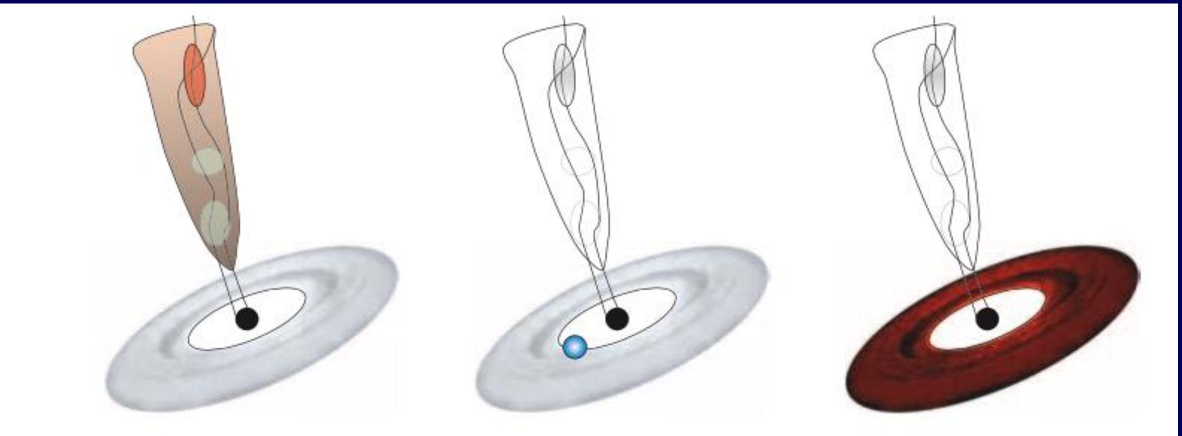
GRAVITY



It has also located the position of theIR flares – The results indicate that they arise in an accretion disk around the Black Hole rather than in a jet of material ejected from the circumnuclear disk.

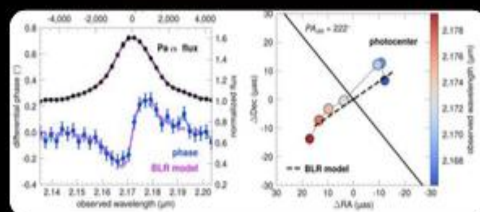


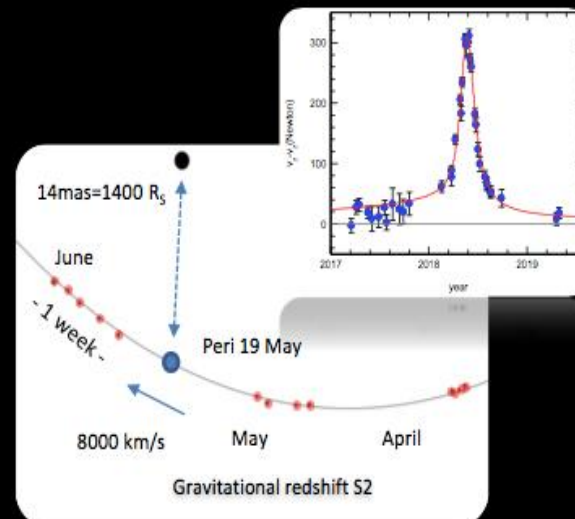
R Abuter et al 2018



Gravity team (MPE) Eisenhauer et al

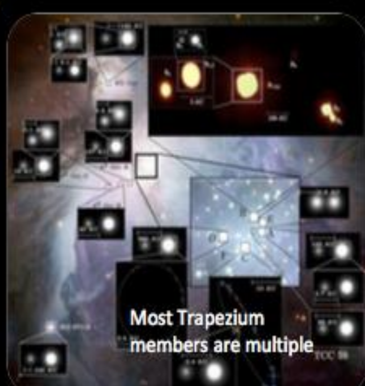
GRAVITY's Firsts



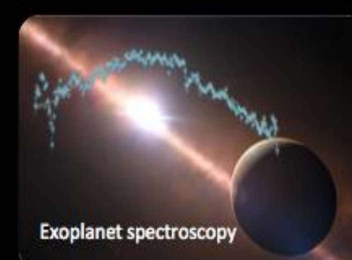


High resolution spectroscopy

19+ mag limiting magnitude & polarimetry



<50 μas imaging astrometry



Micro-arcsec spectral differential astrometry

2 x 4 milli-arcsec resolution imaging

ALMA : Atacama Large Millimetre/sub-millimetre Array

66 Antennas on the Chajnantor plane at 5000-m in the Chilean Atacama desert operating between 0.3 – 3mm.
The antennas can be arranged in a variety of configurations with baselines from 500m to 15km

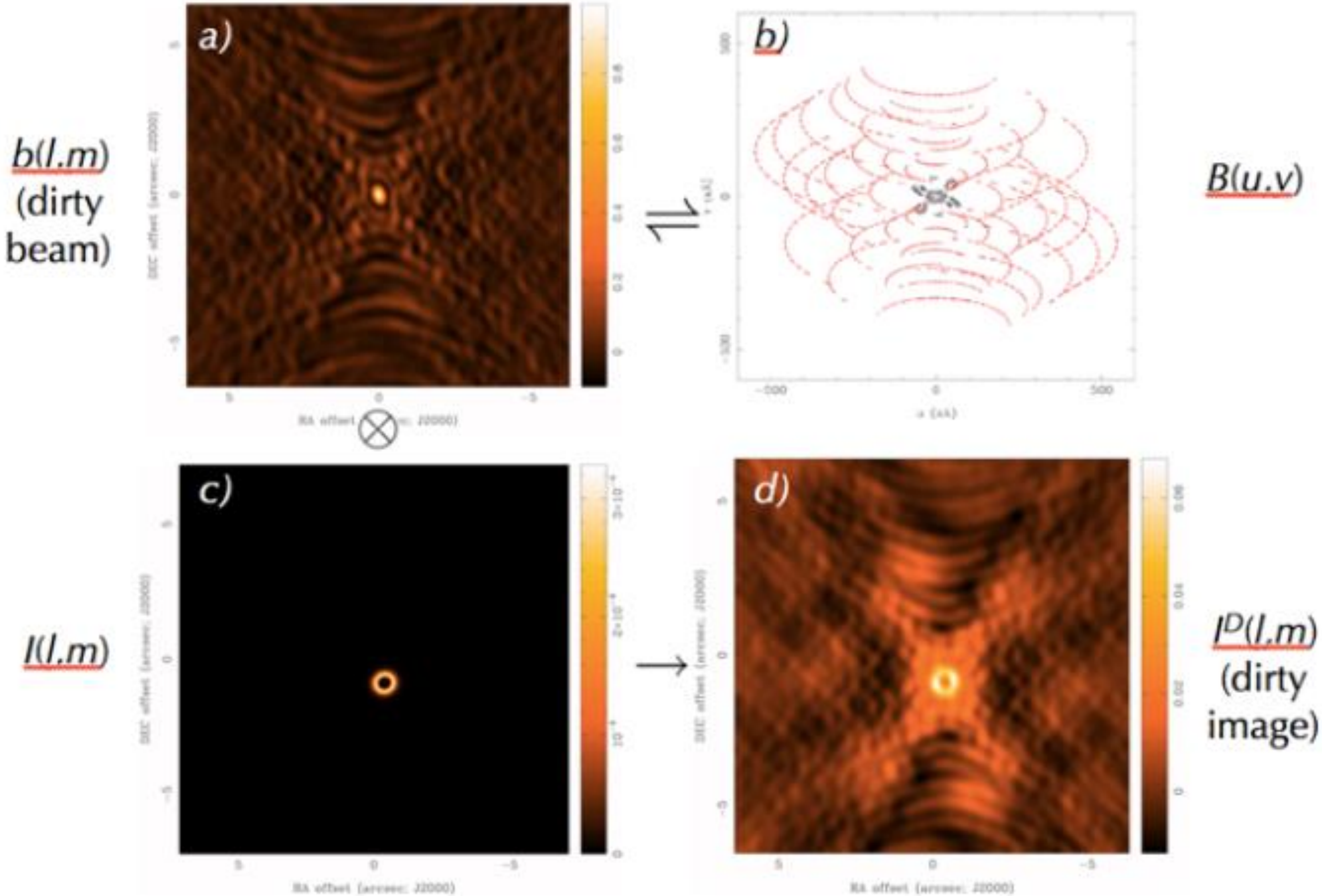


Figure 3.5: Imaging concepts. *Panel a (upper left)*: Example of a dirty beam, $b(l, m)$. *Panel b (upper right)*: The related ensemble of discrete points sampled in the uv-plane, $B(u, v)$. The black points were obtained from a compact configuration while the red ones were obtained from an extended configuration. *Panel c (lower left)*: Example of a true sky distribution, $I(l, m)$. *Panel d (lower right)*: The dirty image $I^D(l, m)$ resulting from observing $I(l, m)$ over the baselines of $B(u, v)$, or equivalently the convolution of $I(l, m)$ by $b(l, m)$. The antenna power response, $\mathcal{A}(l, m)$, has been ignored in this illustration since it is much wider than the true sky brightness distribution. (Figure courtesy of D. Wilner.)

Chapter 3 of the ALMA Technical Handbook gives a good introduction to interferometry, with lots of details of configurations, correlation etc.

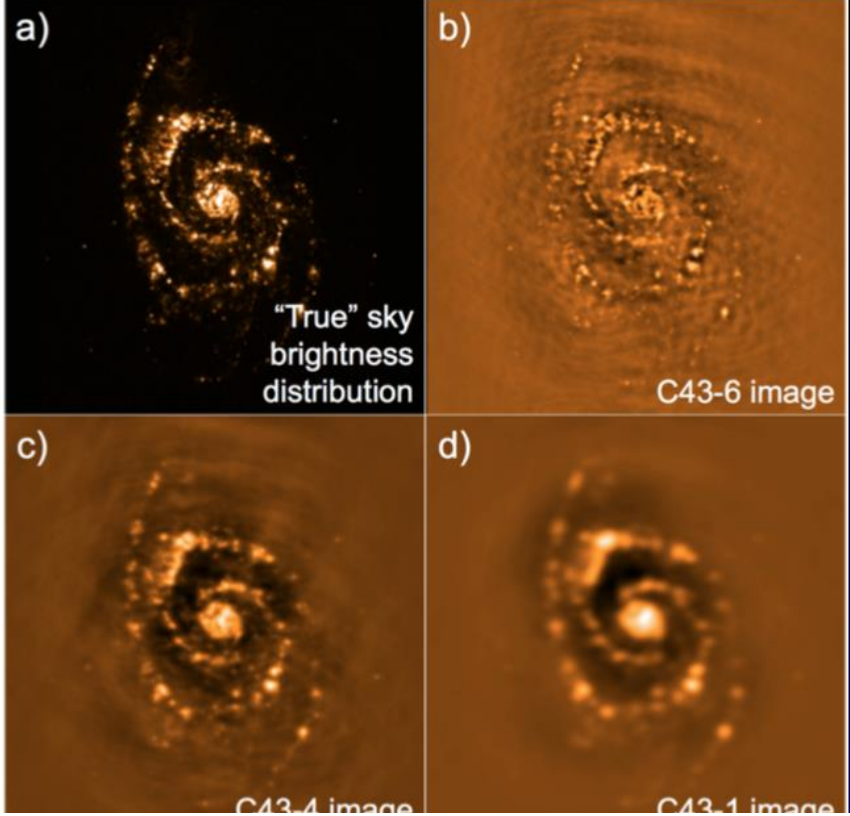


Figure 3.6: Examples of spatial filtering using the CASA task *simobserve* and actual ALMA configurations for Cycle 7. *Panel a (upper left)*: An optical image of the galaxy M51 used as a template for a true sky brightness distribution for the simulations. The frequency of the emission has been changed to 100 GHz, the image size has been scaled to $\sim 3' \times 3'$, and its declination has been changed to -40° to allow ALMA observations to be simulated. For the simulations, the galaxy was "observed" over a mosaic of 33 pointings, for ~10 hours in total. The resulting dirty images were CLEANed. *Panel b (upper right)*: The high-resolution image of the galaxy obtained when observed in the ALMA C43-6 configuration with maximum baseline of 2516.9 m, respectively. The resulting synthesized beam is $\sim 0.47''$ and the maximum recoverable scale is $\sim 4''$. *Panel c (lower left)*: Medium-resolution image of the galaxy when observed in the ALMA C43-4 configuration with maximum baseline of 783.5 m, respectively. The resulting synthesized beam is $\sim 1.3''$ and the maximum recoverable scale is $\sim 11''$. *Panel d (lower right)*: Low-resolution image of the galaxy when observed in ALMA configuration C43-1 with maximum baselines of 160.7 m, respectively. The resulting synthesized beam is $\sim 4.3''$ and the maximum recoverable scale is $\sim 28''$.

ALMA Interferometer Configurations

Configuration	7-m	C43-1	C43-2	C43-3	C43-4	C43-5
Minimum baseline (m)	8.7	14.6	14.6	14.6	14.6	14.6
5th percentile or L05 (m)	9.1	21.4	27.0	37.6	54.1	90.9
80th percentile or L80 (m)	30.7	107.1	143.8	235.4	369.2	623.8
Maximum baseline (m)	45.0	160.7	313.7	500.2	783.5	1397.9
Configuration	C43-6	C43-7	C43-8	C43-9	C43-10	
Minimum baseline (m)	14.6	64.0	110.4	367.6	244.0	
5th percentile or L05 (m)	148.6	235.2	427.3	746.9	1228.1	
80th percentile or L80 (m)	1172.5	1673.1	3527.3	6482.6	8685.9	
Maximum baseline (m)	2516.9	3637.8	8547.7	13894.2	16194.0	

Table 7.2: Basic parameters of the 7-m Array configuration and the ten 12-m Array configurations offered during Cycle 7. The baselines are projected for a transiting source (HA = ± 1h) at a declination of −23°. Note that C43-8 and C43-10 will not be available for Bands 8-10.

The ALMA 12-m dishes only occupy 50 of the available 192 antenna pads, and can be arranged with maximum baselines from 150m to 15km.

In practice a limited number of configurations is used and they are scheduled according to the seasonal constraints (high frequency, long baseline observations are not possible in the worst weather) and RA requirements of the science programme.

The highest resolution is obtained with Very Long Baseline Interferometry – transcontinental baselines, where correlation is done off-site on accurately time-stamped data from large dishes.

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.735	0.52	0.389
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C43-2	θ_{res} (arcsec)	2.3	1.53	1.24	0.999	0.666	0.499	0.353	0.264
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.9	3.47	2.59
C43-3	θ_{res} (arcsec)	1.42	0.943	0.765	0.615	0.41	0.308	0.218	0.163
	θ_{MRS} (arcsec)	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C43-4	θ_{res} (arcsec)	0.918	0.612	0.496	0.399	0.266	0.2	0.141	0.106
	θ_{MRS} (arcsec)	11.2	7.5	6.08	4.89	3.26	2.44	1.73	1.29
C43-5	θ_{res} (arcsec)	0.545	0.363	0.295	0.237	0.158	0.118	0.0838	0.0626
	θ_{MRS} (arcsec)	6.7	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C43-6	θ_{res} (arcsec)	0.306	0.204	0.165	0.133	0.0887	0.0665	0.0471	0.0352
	θ_{MRS} (arcsec)	4.11	2.74	2.22	1.78	1.19	0.892	0.632	0.472
C43-7	θ_{res} (arcsec)	0.211	0.141	0.114	0.0917	0.0612	0.0459	0.0325	0.0243
	θ_{MRS} (arcsec)	2.58	1.72	1.4	1.12	0.749	0.562	0.398	0.297
C43-8	θ_{res} (arcsec)	0.096	0.064	0.0519	0.0417	0.0278	-	-	-
	θ_{MRS} (arcsec)	1.42	0.947	0.768	0.618	0.412	-	-	-
C43-9	θ_{res} (arcsec)	0.057	0.038	0.0308	0.0248	0.0165	-	-	-
	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

Table 7.1: Resolution (θ_{res}) and maximum recoverable scale (θ_{MRS}) for the 7-m Array and 12-m Array configurations available during Cycle 7 as a function of a representative frequency in a band. The value of θ_{MRS} is computed using the 5th percentile baseline (L05) from Table 7.2 and Equation 7.7. The value of θ_{res} is the mean

ALMA Antennas

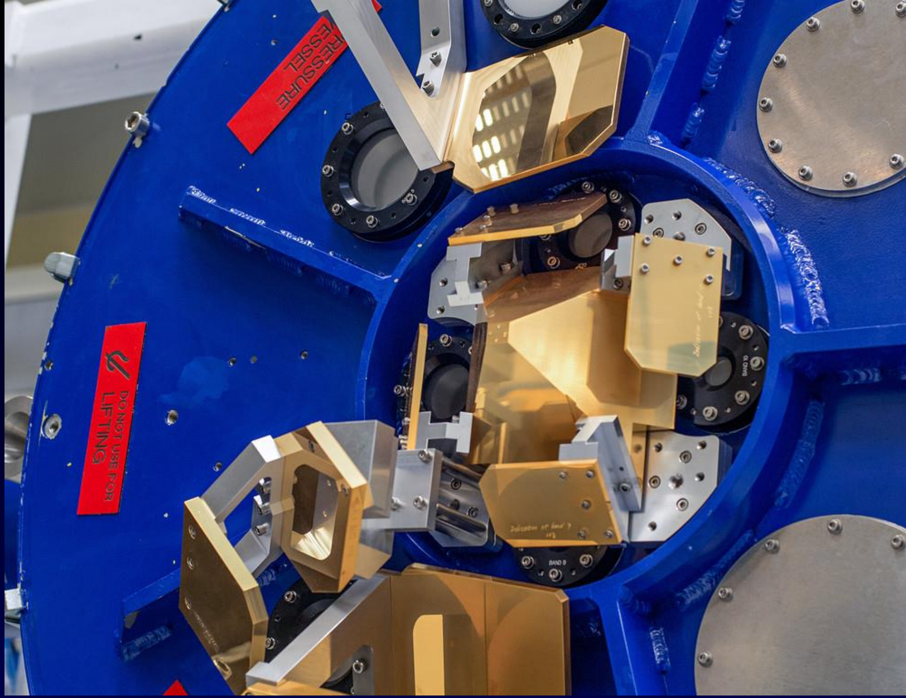
50 x 12-m dishes

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

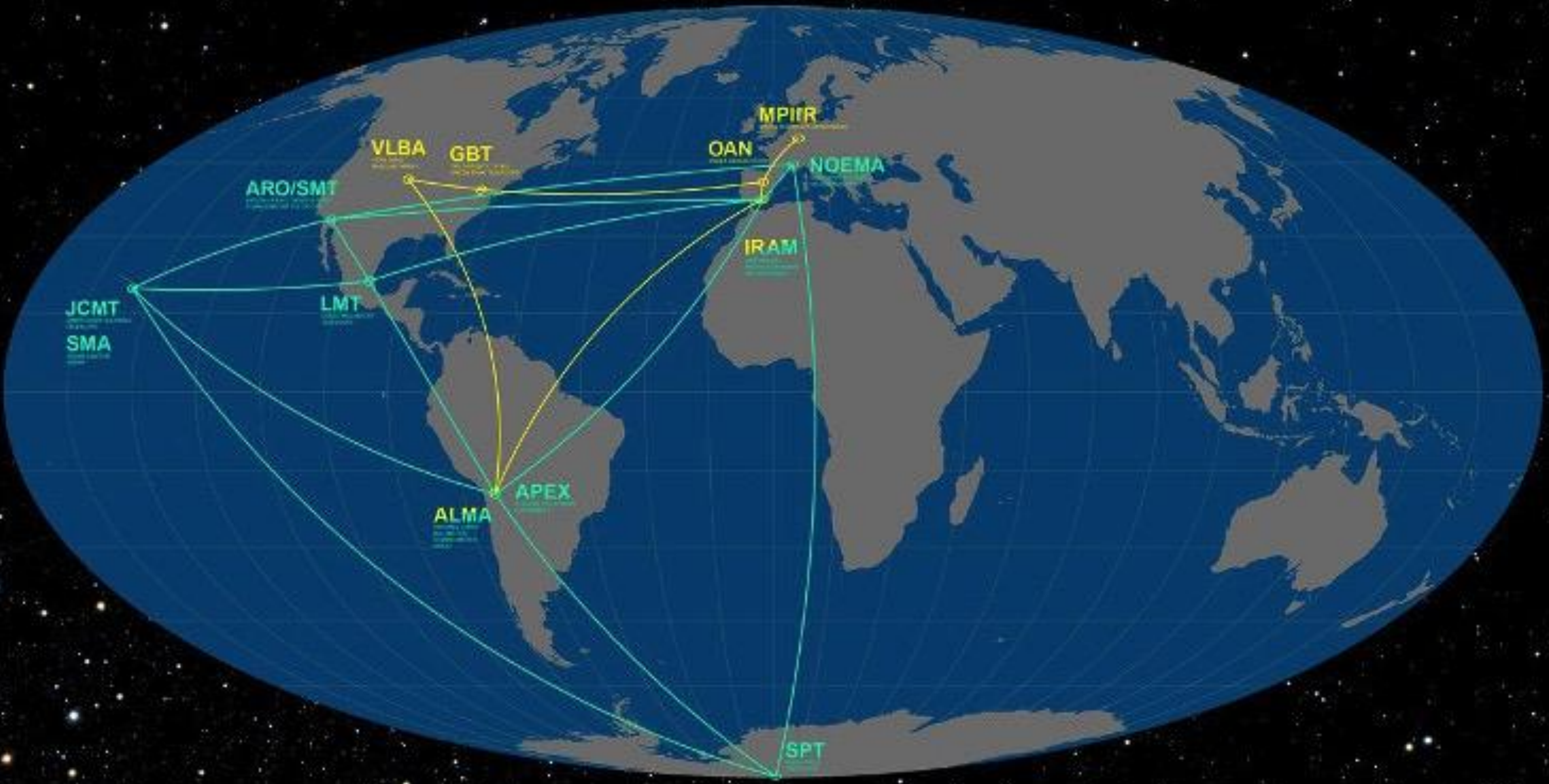
Fast switching/slewing for calibration

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.



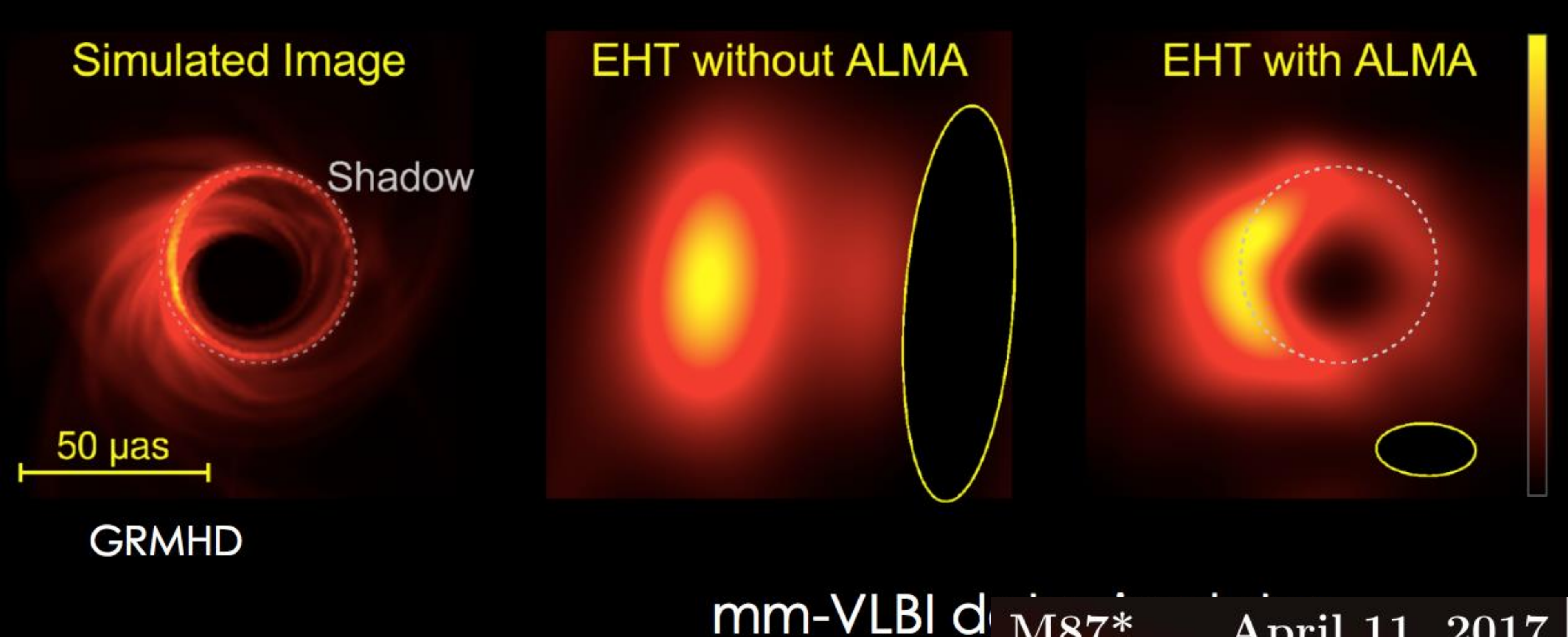
The Event Horizon Telescope Intercontinental Baselines

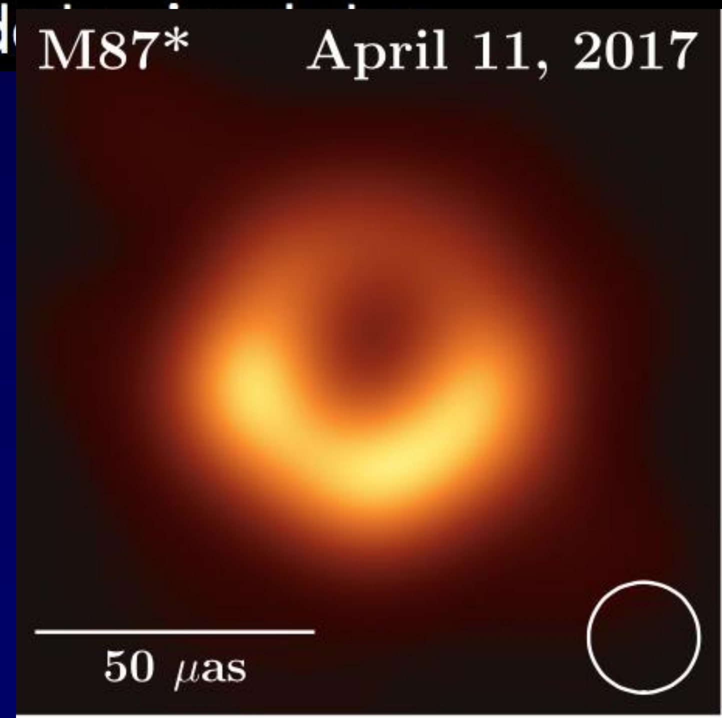


Giving resolutions of 15 micro-arcsec or about 1.5 times the Event Horizon radius
Data streams from the individual telescopes are time stamped using atomic clocks and then correlated together and analysed

ALMA and the EHT

- Very Long Baseline Interferometry requires careful co-ordination between the observatories, observing simultaneously to simulate an Earth-sized telescope.
- The first run observing the Galactic Centre and M87 was in April 2017
- ALMA used 45 co-phased 12-m diameter dishes equivalent to an 80-m diameter telescope
  - Because of the data rates, and the need to correlate raw datastreams, hard disks have to be flown from the South Pole, which only became possible in November 2017.



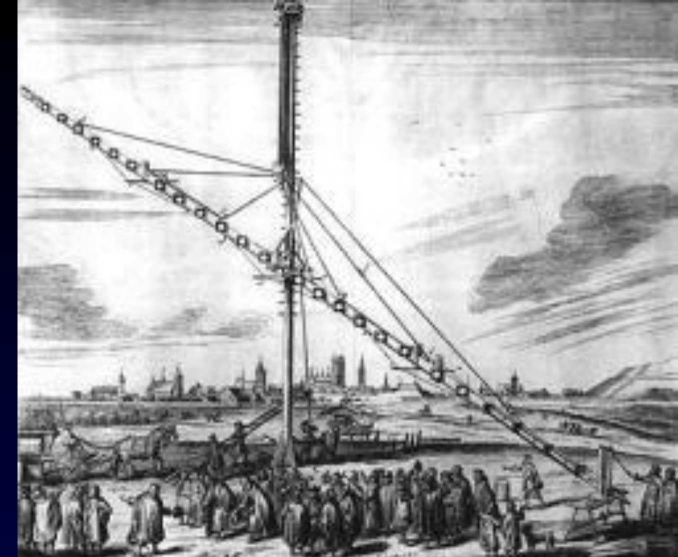


ALMA makes a big difference – largest collecting area and greatest sensitivity – essential for north-south coverage.

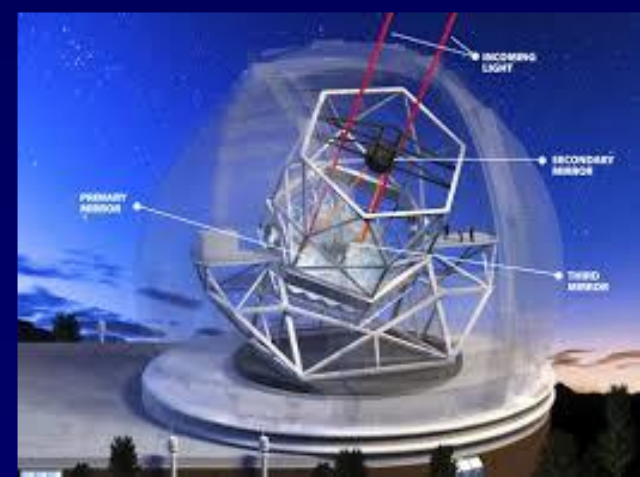
EHT

The combination of mm-wavelength observations and very long, transcontinental baseline gives the EHT the resolution needed to image the immediate vicinity of the Black Hole

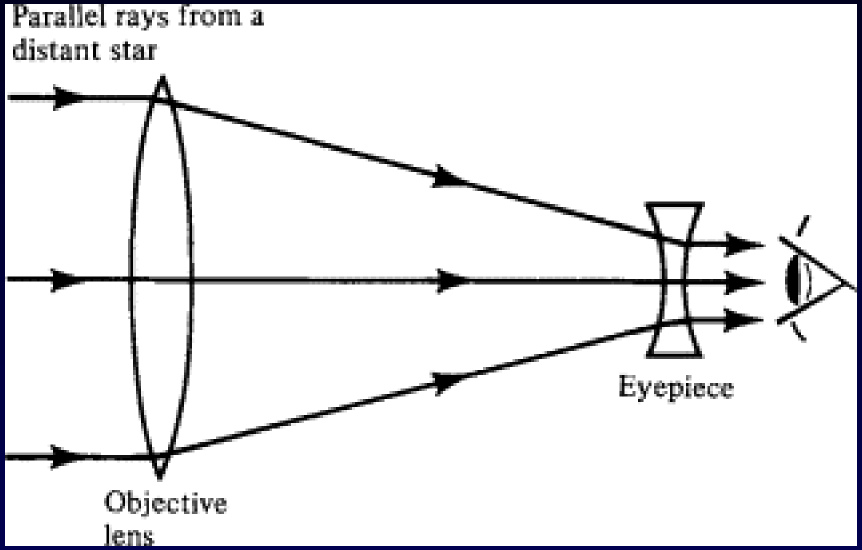
Telescopes



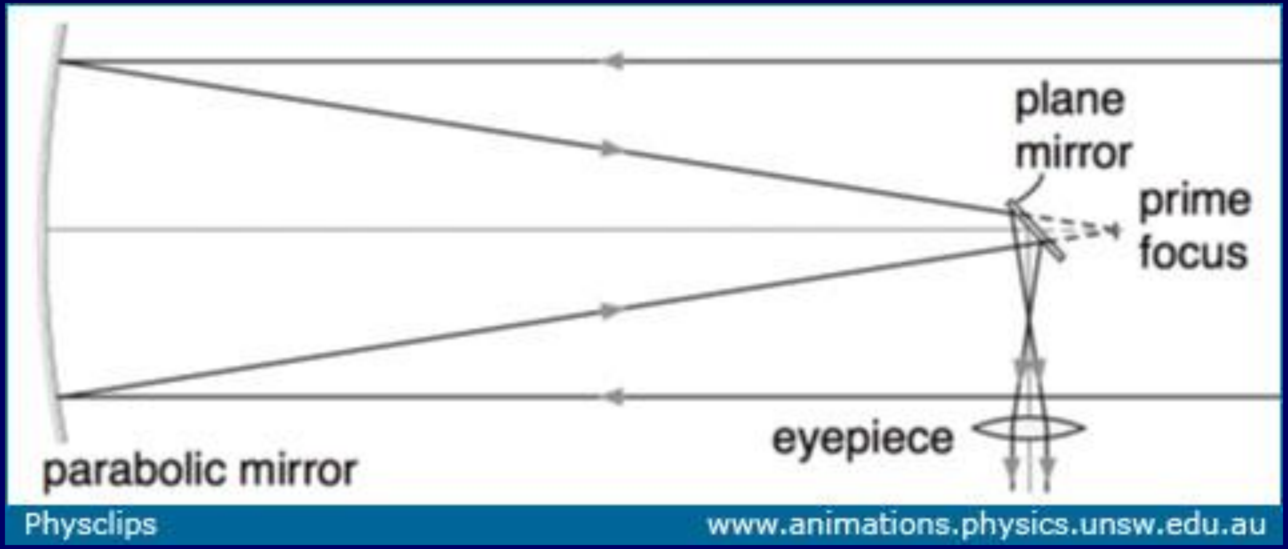
- All modern large telescopes are reflectors
- Achromatic, Efficient & Compact
- Precision engineered
  - Precision drives, encoders and control systems are needed to maintain collimation and tracking
  - active control of mirror supports & optical alignment
- Mirrors figured and polished to $< \lambda/10$
- 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



Lenses and mirrors

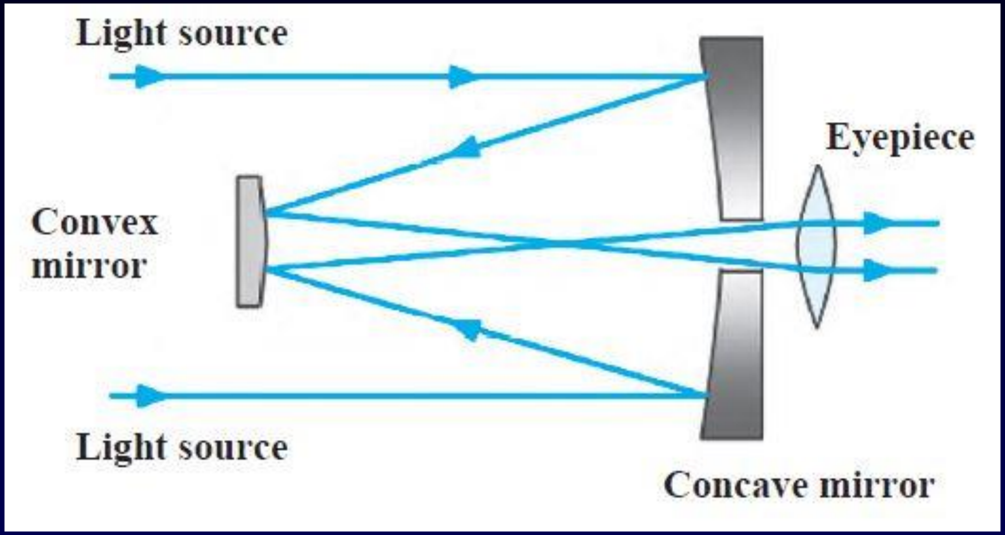


Galilean telescope

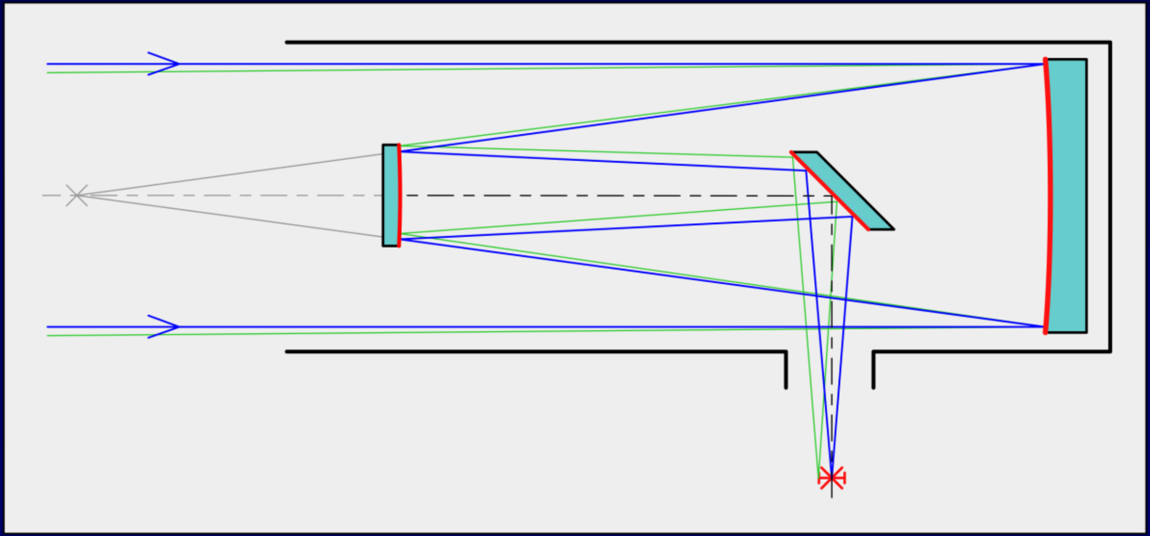


Newtonian telescope

Reflecting telescopes

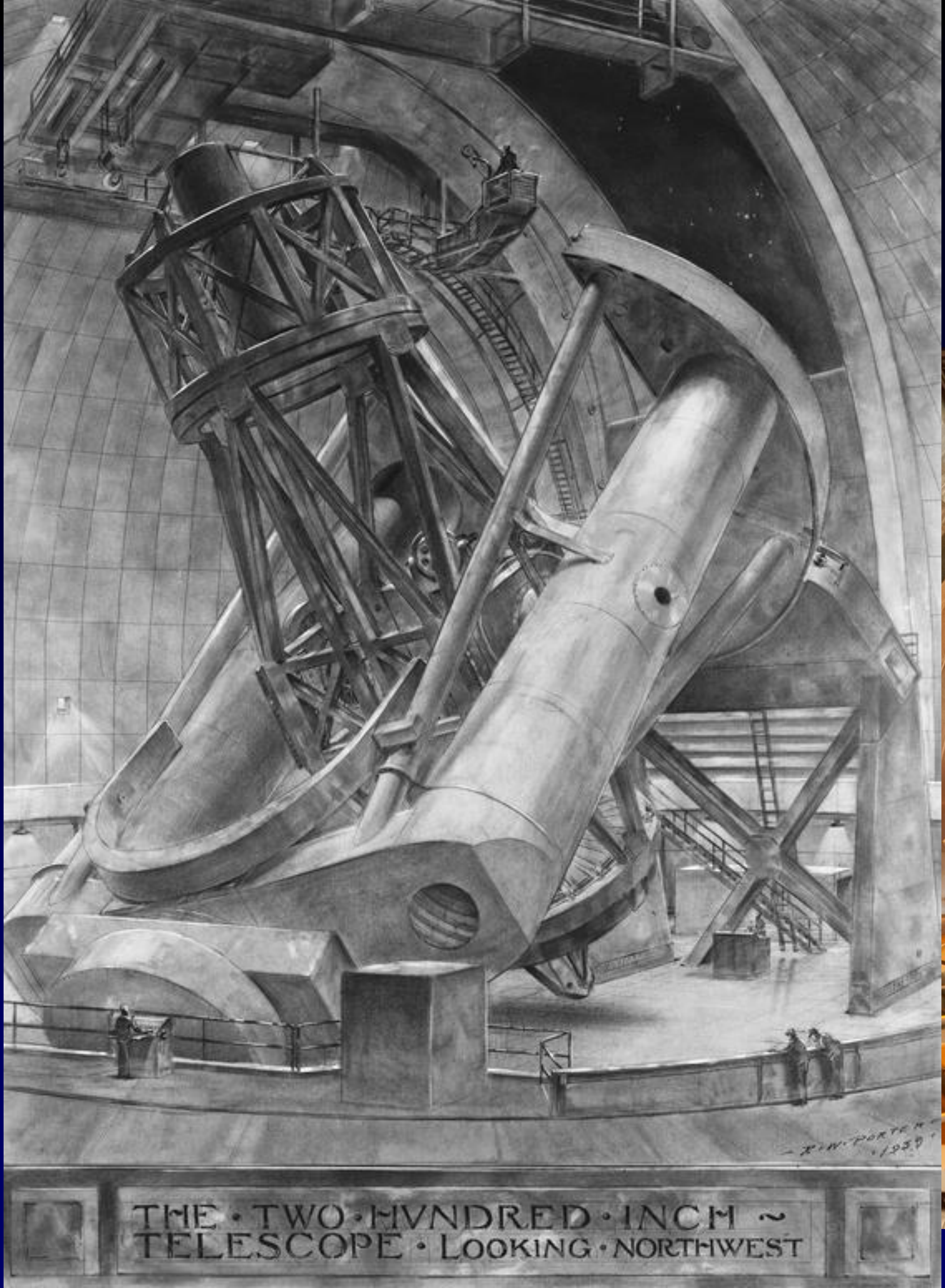


Cassegrain telescope

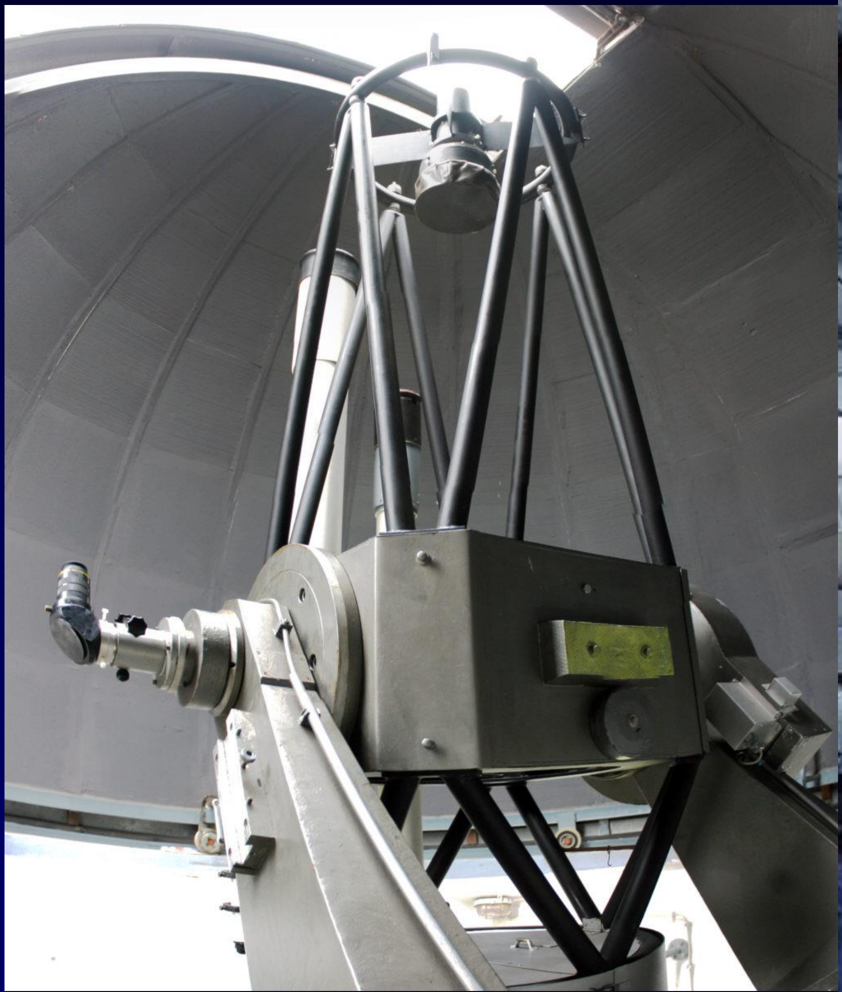


Nasmyth configuration

Telescope mounts



Alt-Az telescopes

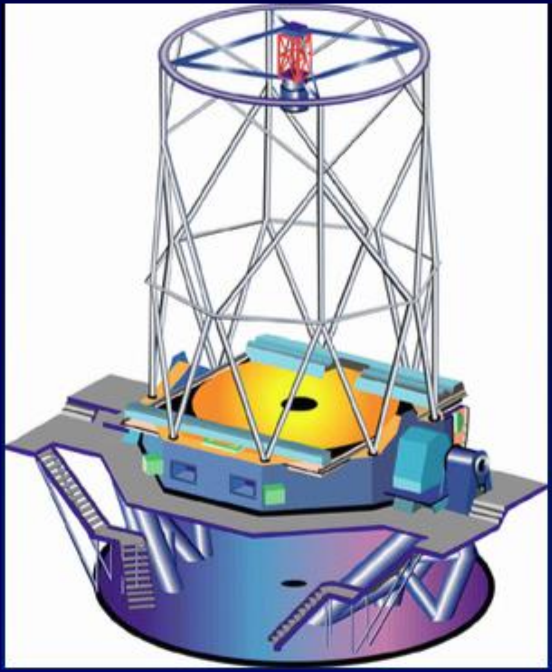


Telescope Mounts

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

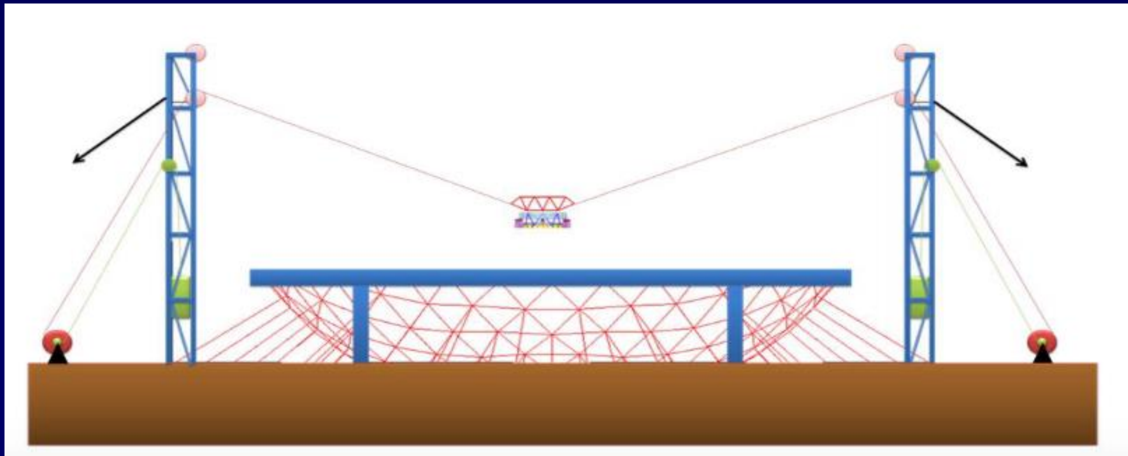
Alt-az



- 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

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



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.

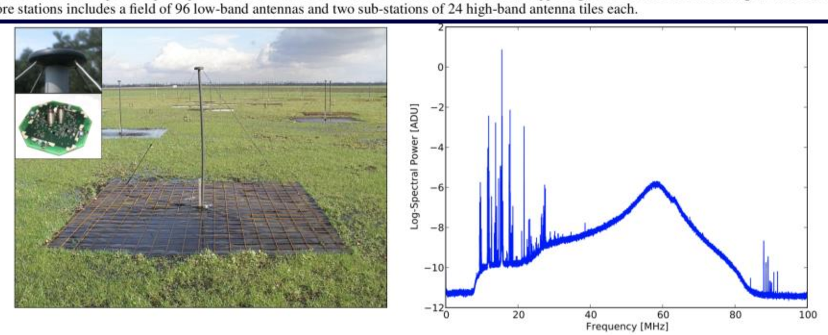
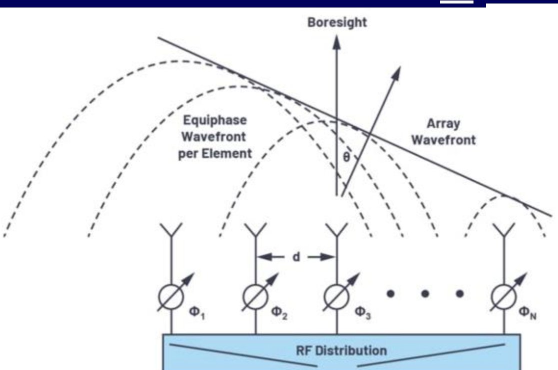


Fig. 5. *Left*: image of a single LOFAR LBA dipole including the ground plane. The inset images show the molded cap containing the LNA electronics as well as the wire attachment points. *Right*: median averaged spectrum for all LBA dipoles in station CS003. The peak of the curve near 58 MHz is clearly 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.



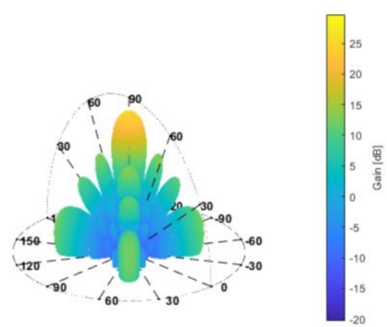


Figure 6. Unsteered beam pattern for a LOFAR tile.

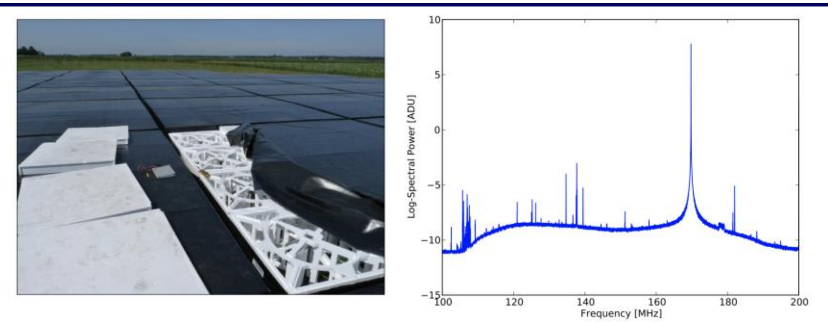


Fig. 7. *Left*: closeup image of a single LOFAR HBA tile. The protective covering has been partially removed to expose the actual dipole assembly. The circular dipole rotation mechanism is visible. *Right*: median averaged spectrum for all HBA tiles in station CS003. Various prominent RFI sources are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

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 $800 cm^2$ collecting area

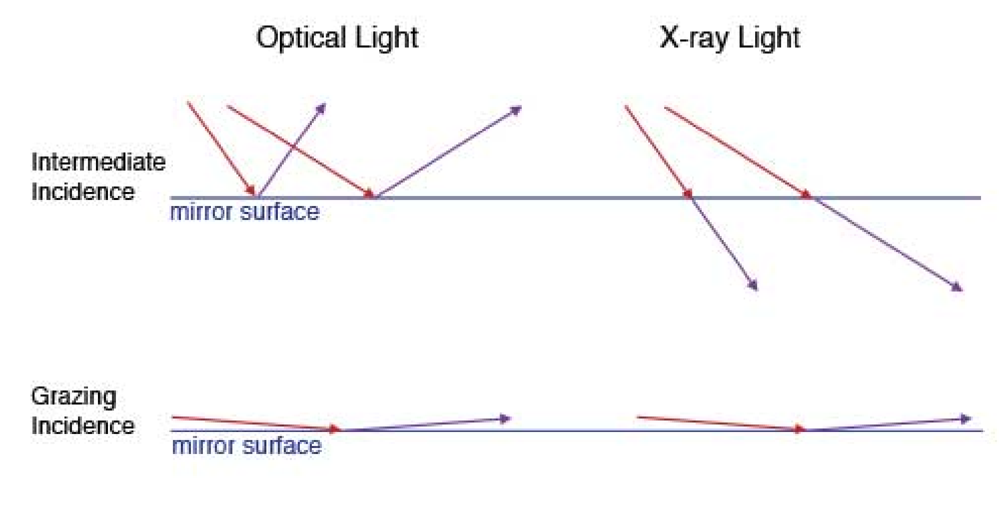
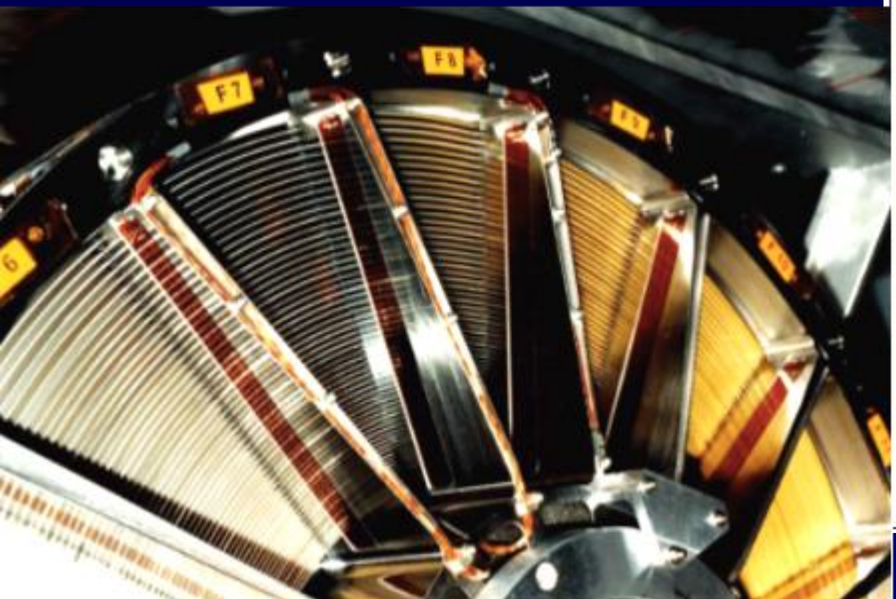


Illustration of grazing incidence. The scale in this image is exaggerated – the angle of incidence (the angle between the mirror surface and the X-ray) is actually shallower. (Credit: NASA's Imagine the Universe)



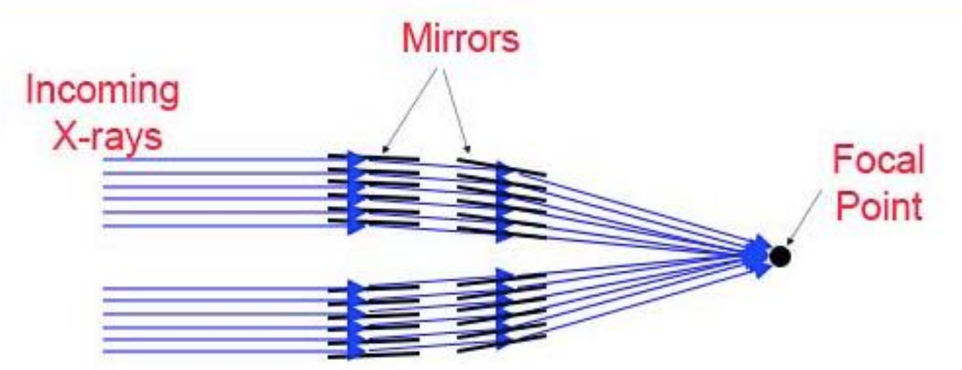


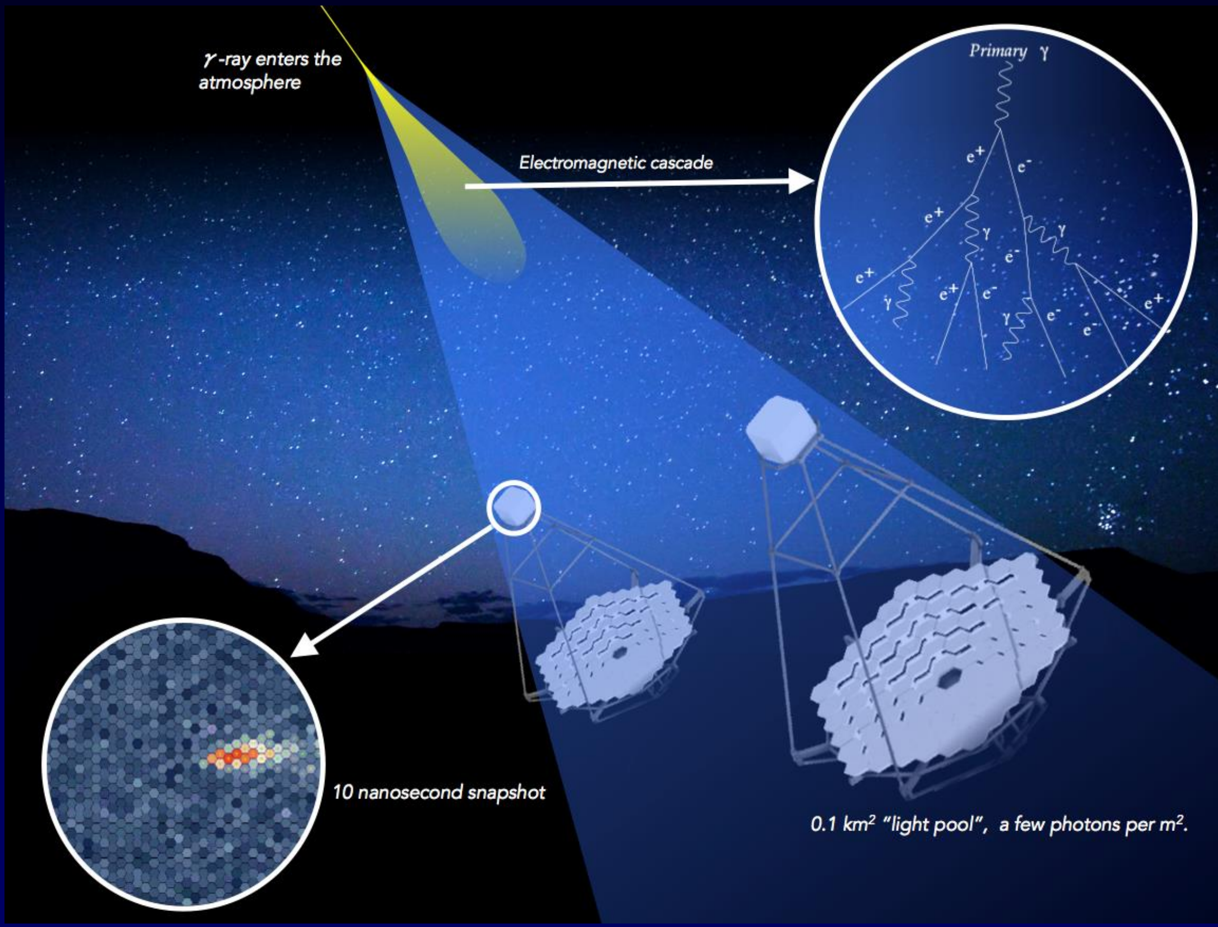
Diagram of a cut-away of an X-ray telescope with several sets of mirrors. By nesting the mirrors one within the other, more X-rays are focused, giving astronomers a brighter image. (Credit: NASA's Imagine the Universe)

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

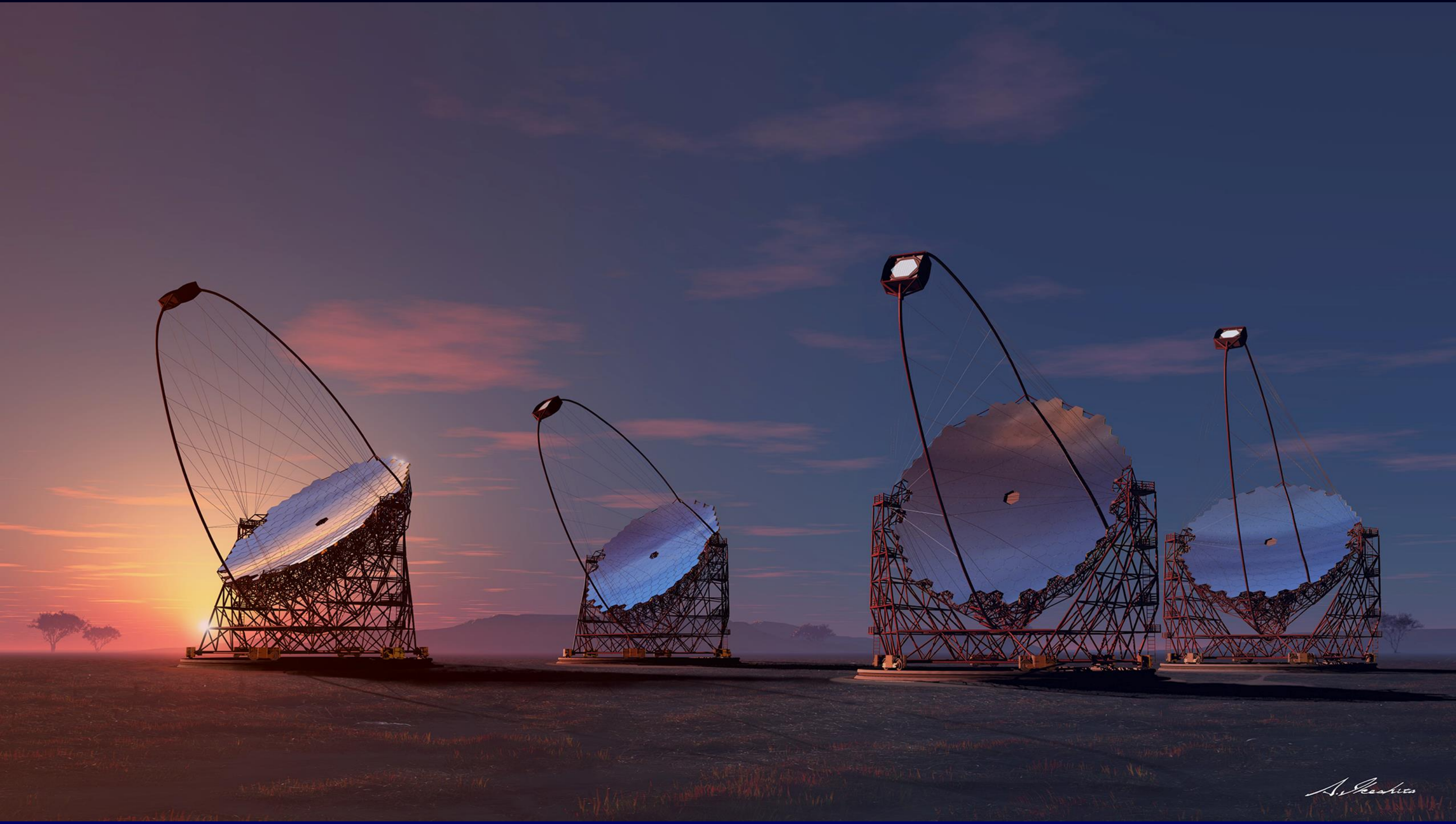
Detection of the Cerenkov light emitted by the particle cascade produced by 20 Gev to 200TeV γ-rays

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 μs	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·m^2	
Inertia azimuth	$\sim$12000 tons·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

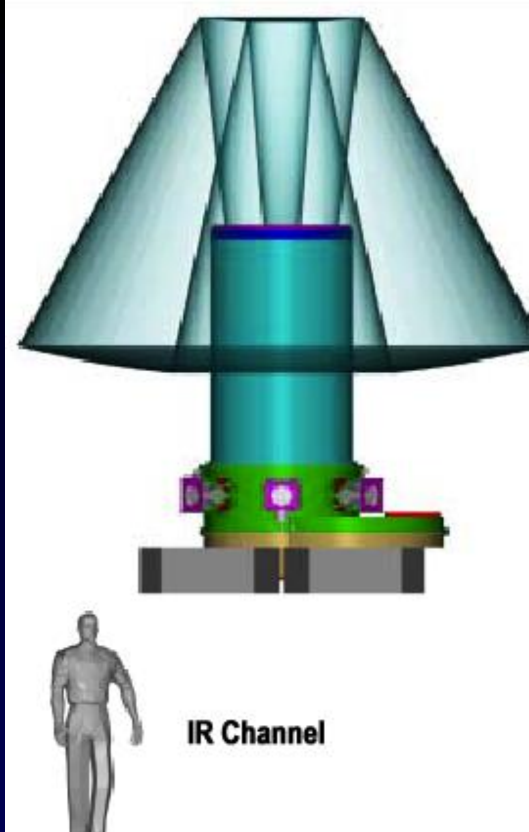
- Field of View
  - Widest field is usually available at Prime Focus, though novel cassegrain or 3-mirror designs have been developed
  - need to flatten and correct field : Prime focus corrector + ADC
  - Best Image Quality is obtained over a small central field
  - Cass field 3’ on UKIRT f/35 to 120’ 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

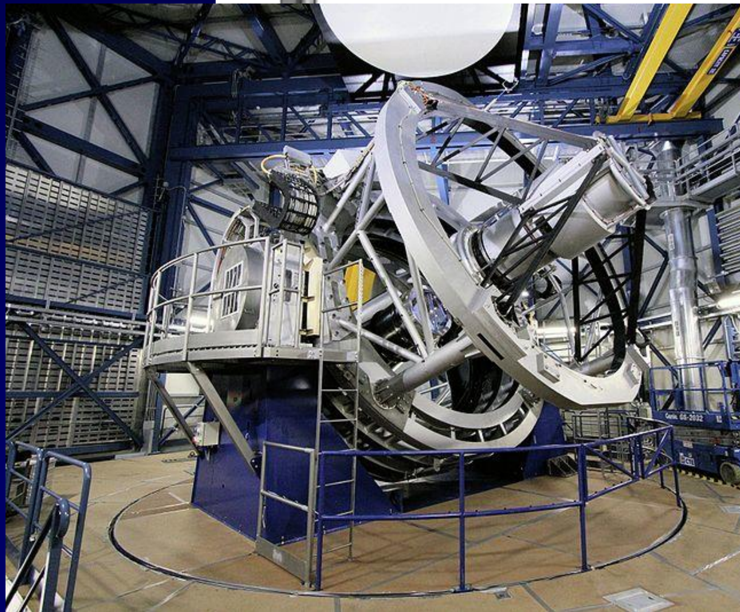
Telescope Properties

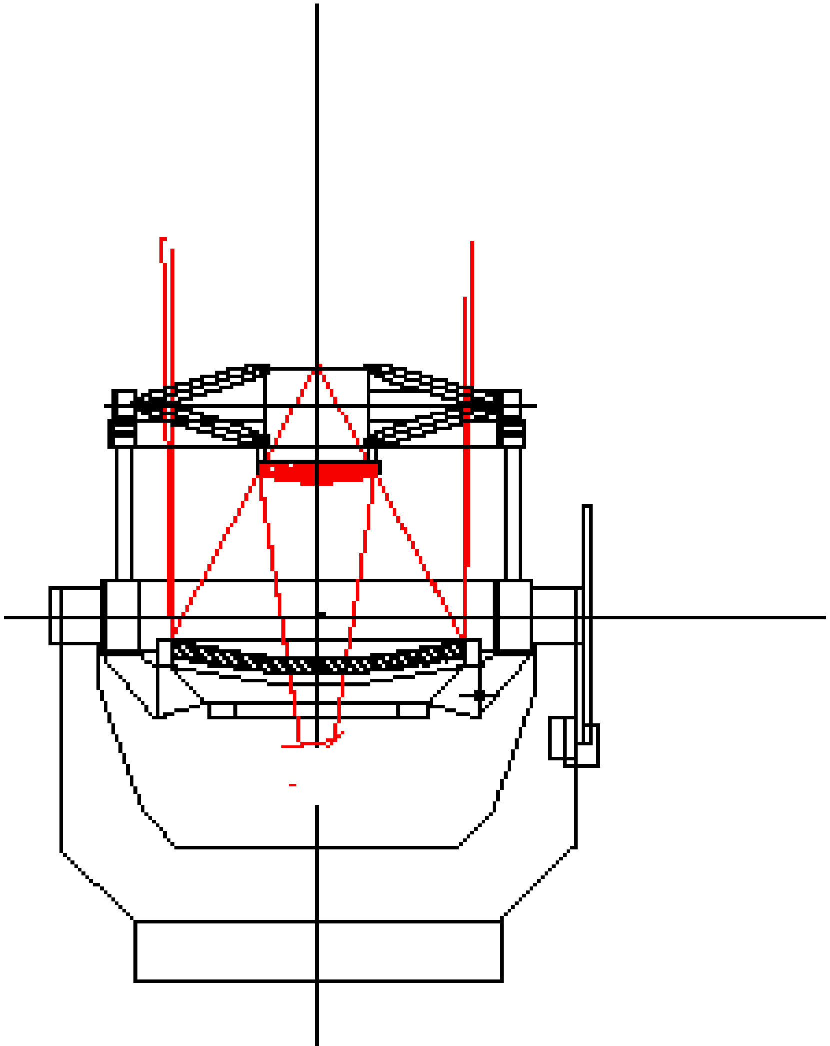
- Effective Focal Length = Df
  - 8-m telescope with a f/15 focal ratio from the secondary : EFL =120m
  - An angular displacement of 1 arcsec (4.85 x10-6 radians) gives an offset of fθ= 0.6mm in the focal plane, giving a plate scale of 1.7 arcsec/mm
- Older telescopes have several configurations, e.g. 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

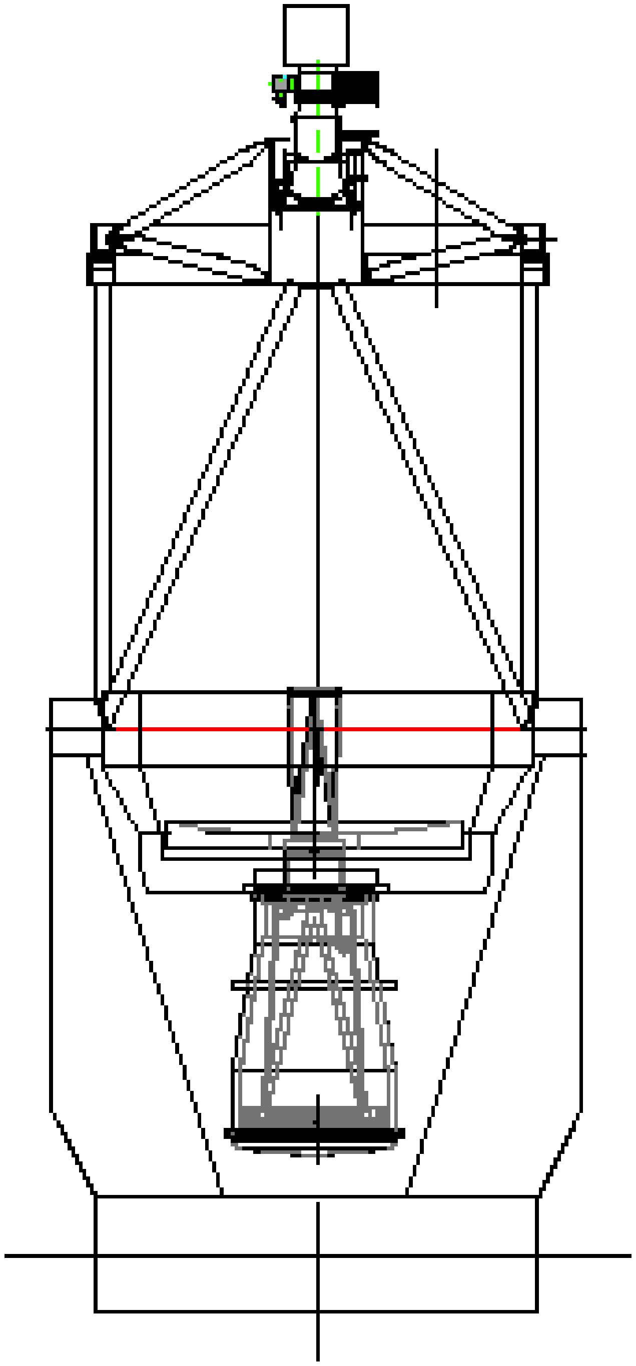
Vista: A dedicated 4.2-m IR survey telescope

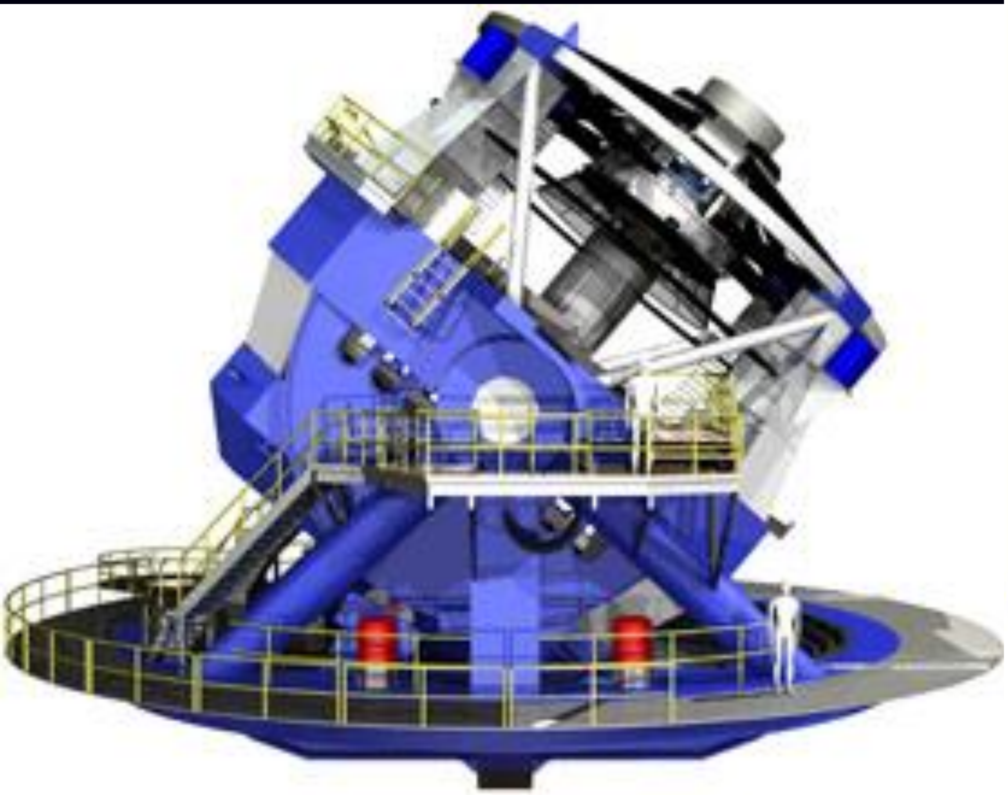
- 4.2-m diameter telescope with a 2 degree field of view Located on Mt Paranal, Chile
- Revolutionary design with f/1 primary mirror
  - very short telescope tube
  - very compact enclosure
  - but challenging optics and tolerances
- 1.25-m secondary mirror gives f/3 Cassegrain beam feeding the world's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

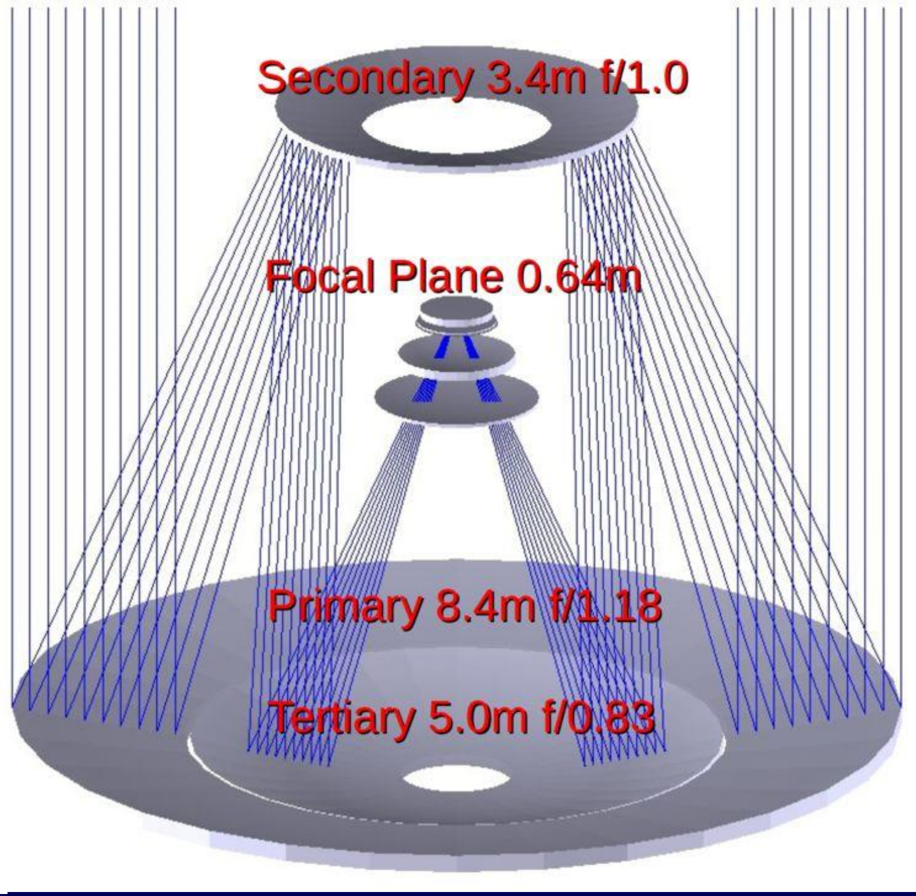






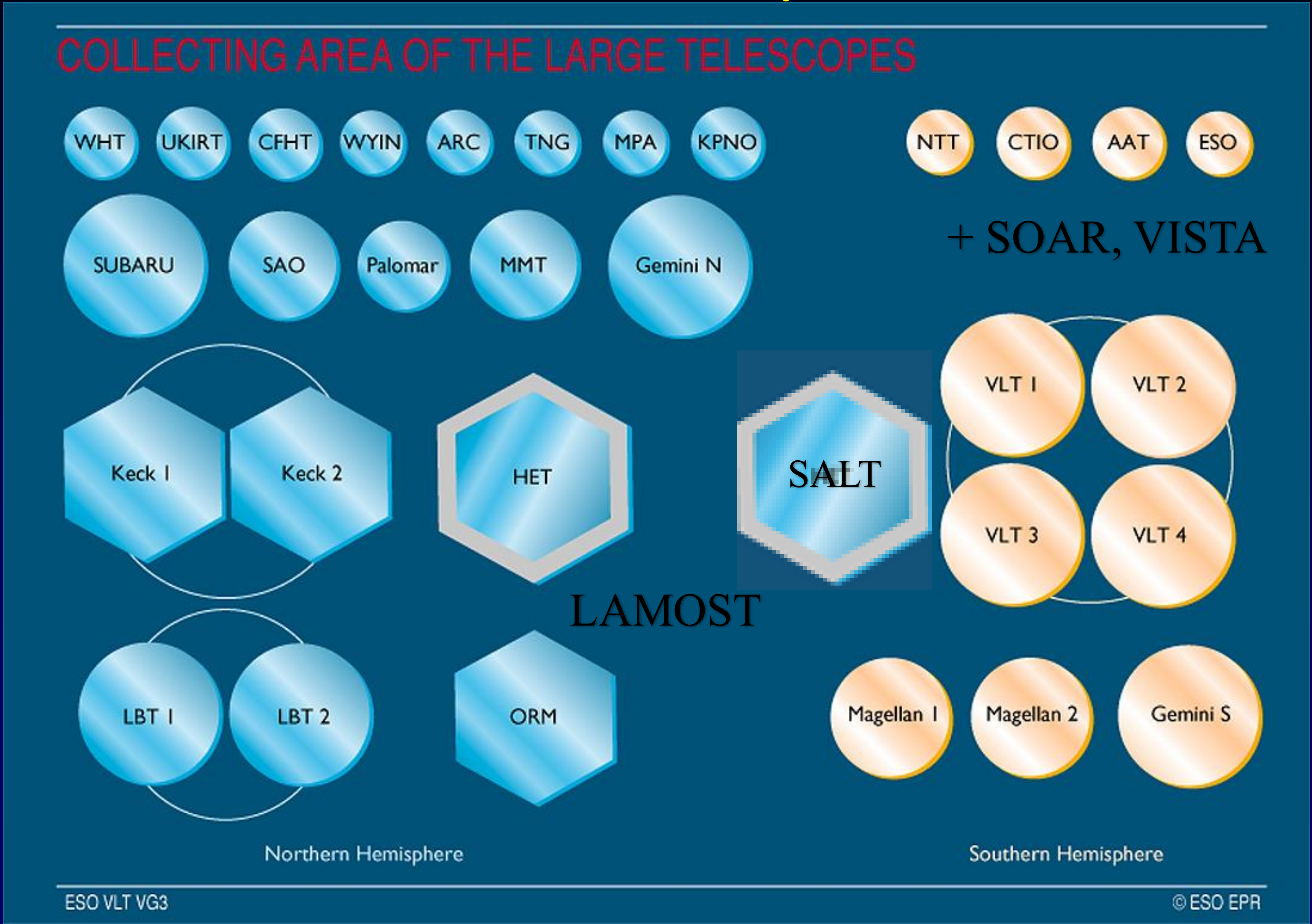




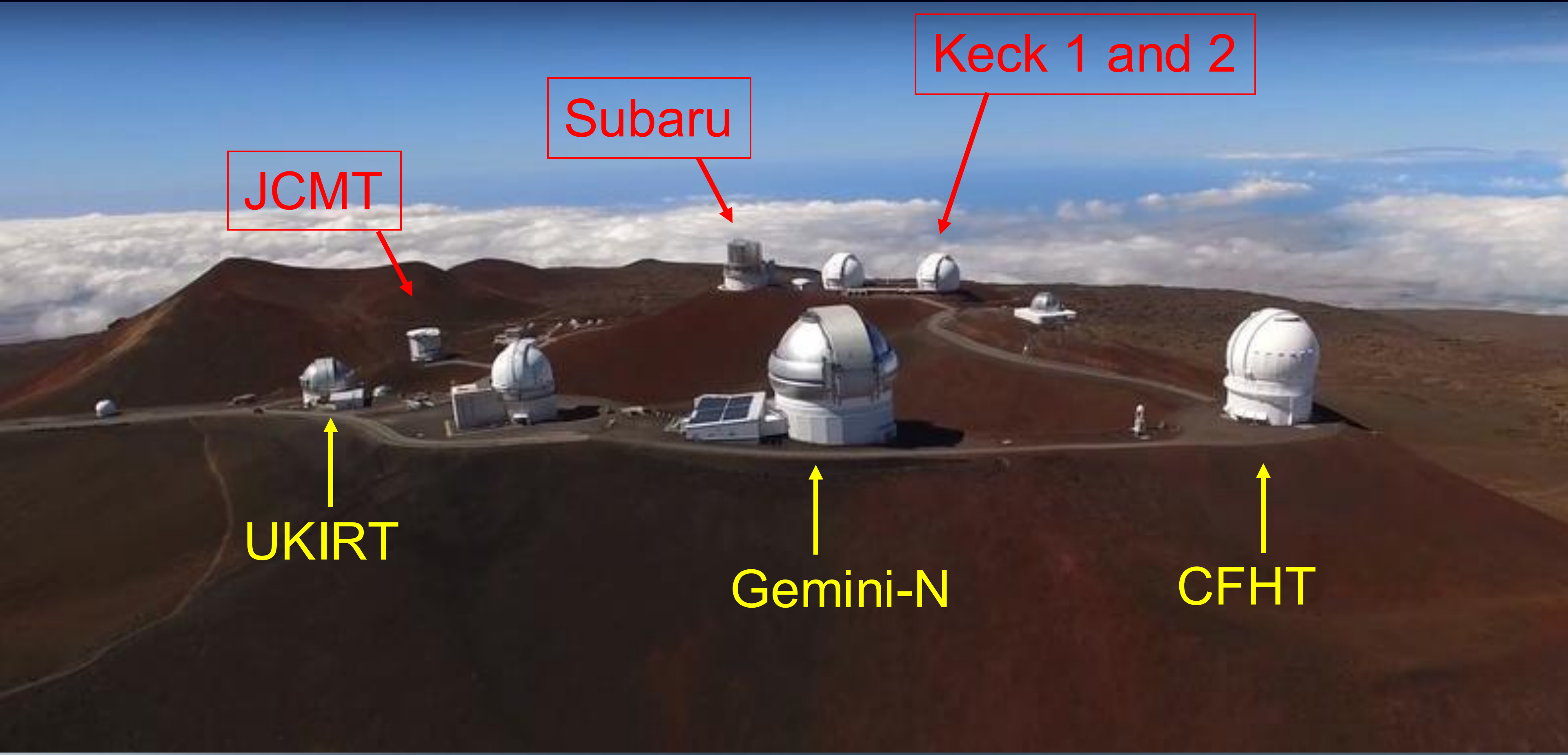


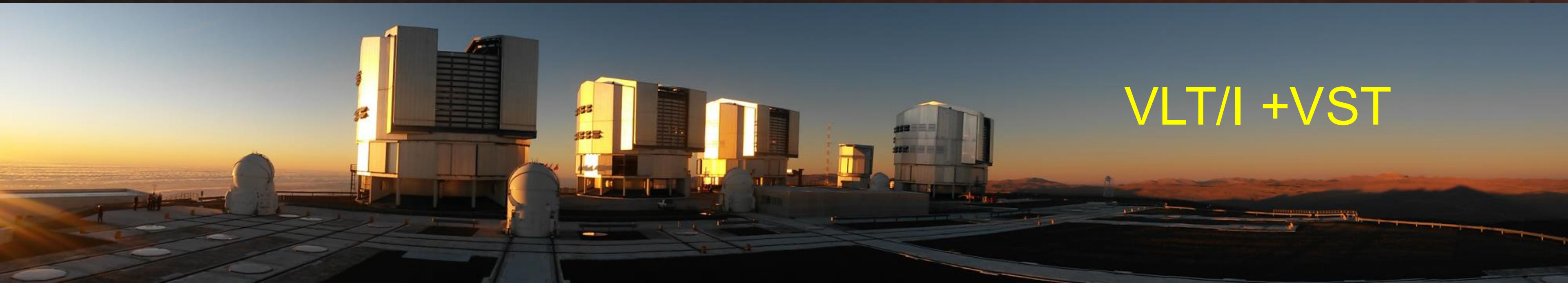
The LSST (Large Synoptic Survey Telescope) is a 3-mirror telescope designed for an extremely large (3degree) field, an 8.4-m primary mirror and a 5-m tertiary giving an effective aperture of 6.5-m. It is under construction on Cerro Pachon, Chile

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

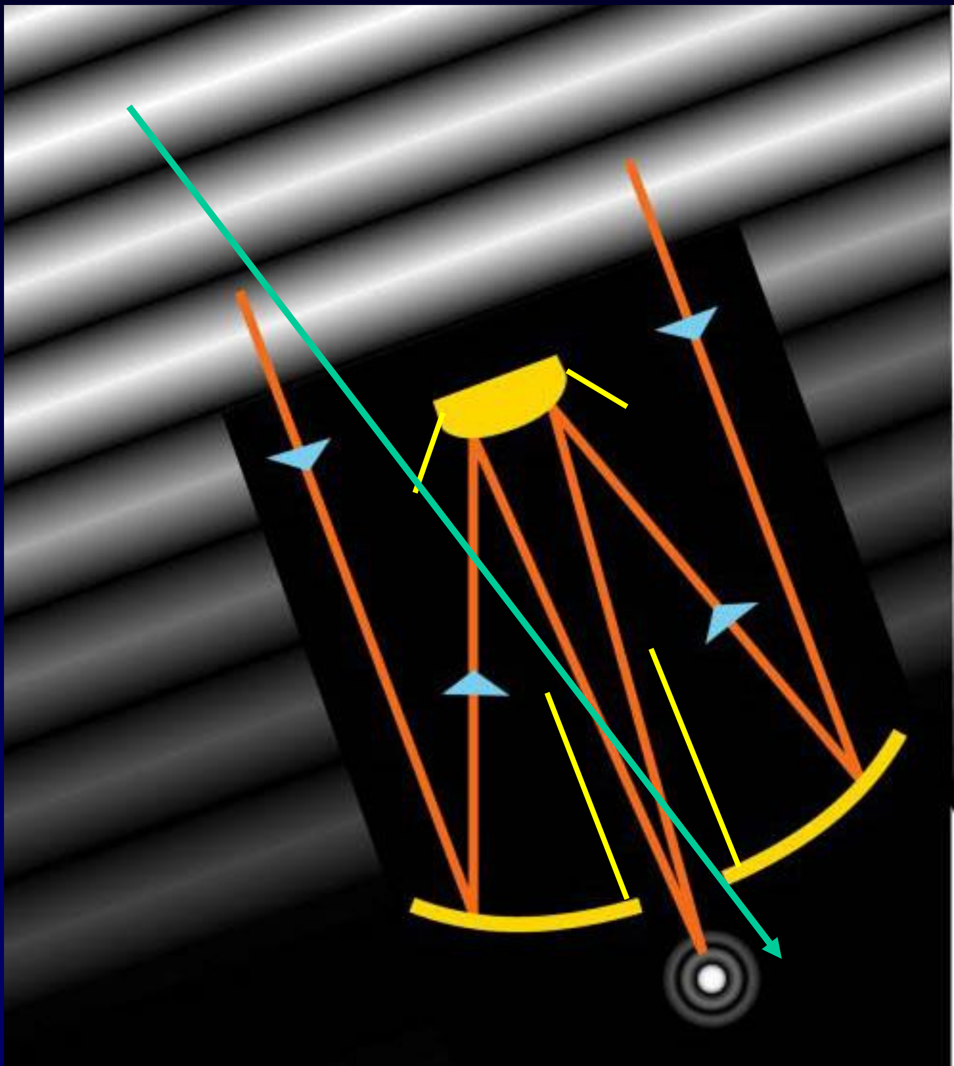
Mauna Kea, Hawaii and Paranal, Chile





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




SOTONNES


Infrared Operation

8-m Telescope Requirements

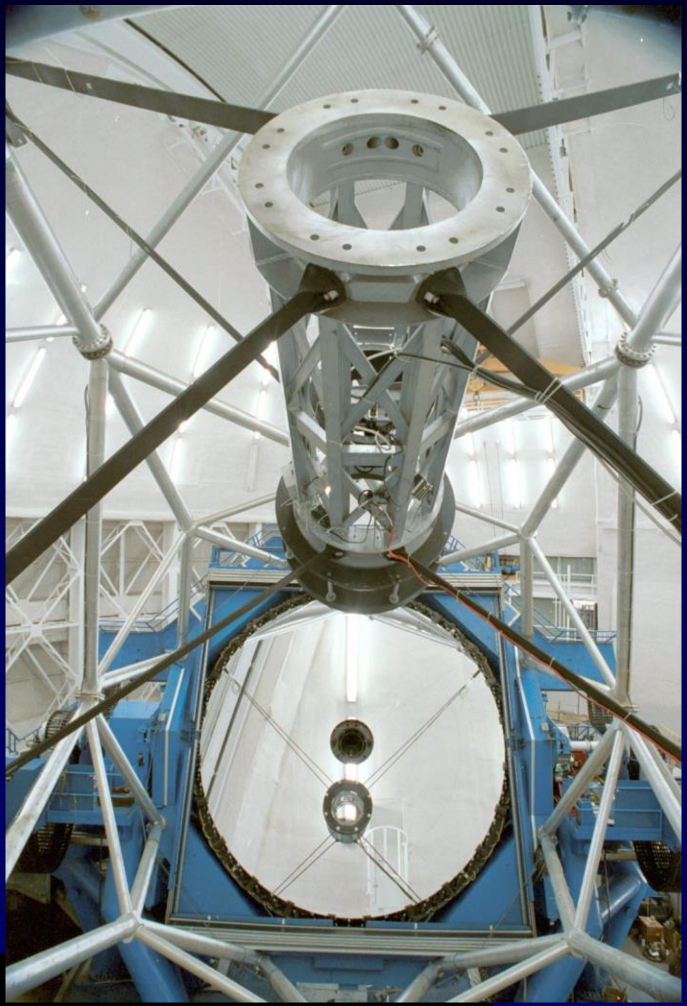
- Focus light from astronomical objects collected by 50 m^2 primary mirror to a point <0.06 mm in size and maintain position to 0.01 mm over 1hr.
- 300 ton telescope aimed blind to an accuracy better than 2 arcsec over the accessible sky.
- Maximise productivity through high reflectivity coatings, low 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


2
2
6

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

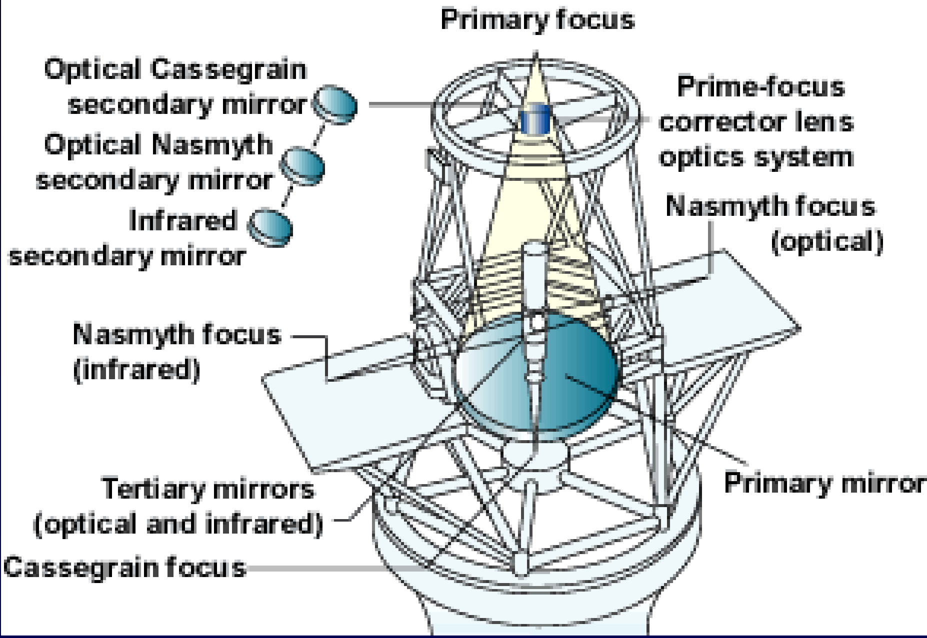
Tip/tilt corrects for windshake and the low order distortions produced by the atmosphere.

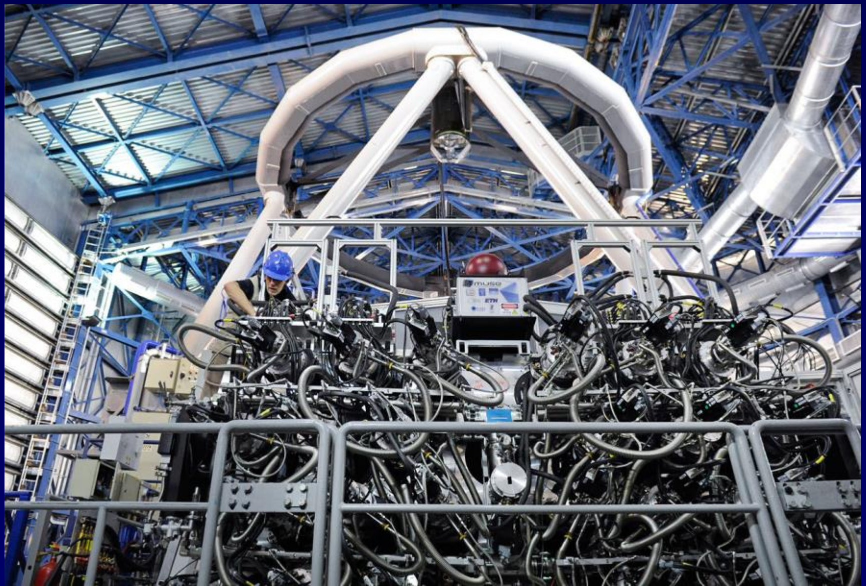
Nasmyth & Cassegrain Foci

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.

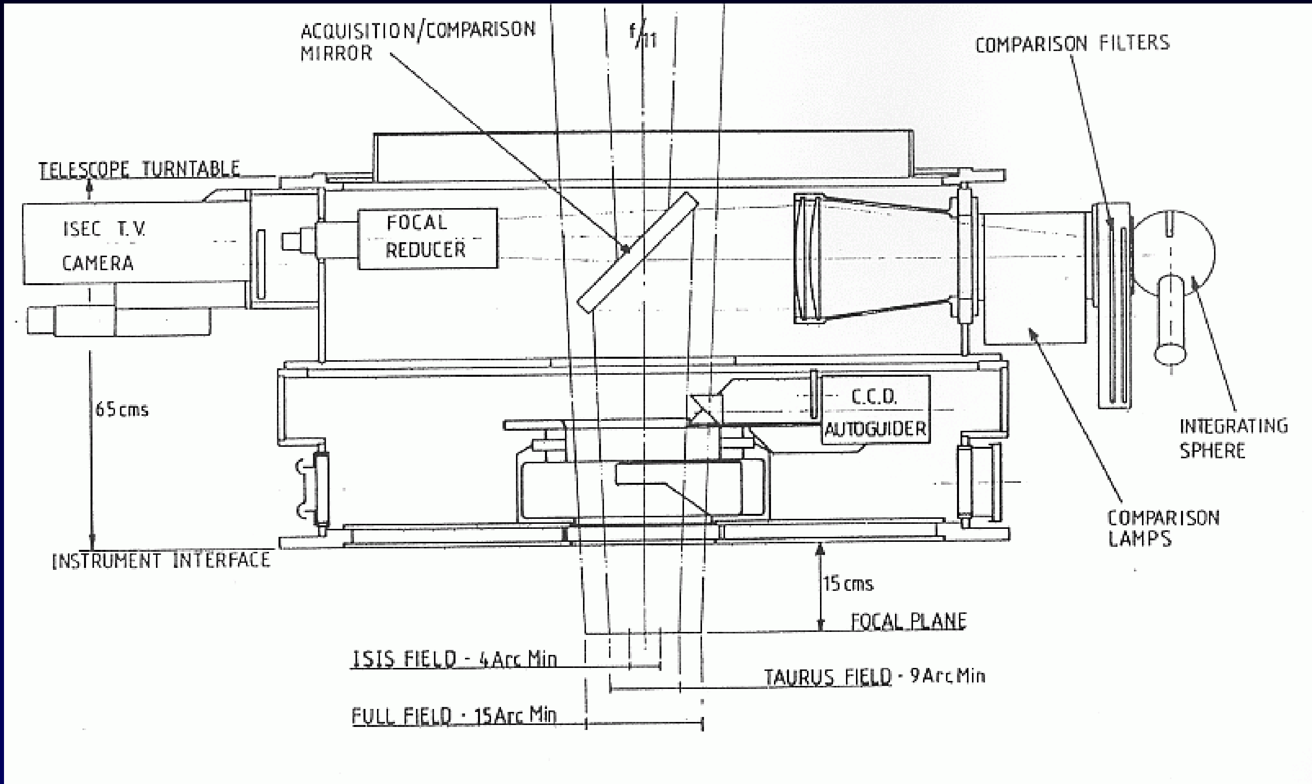




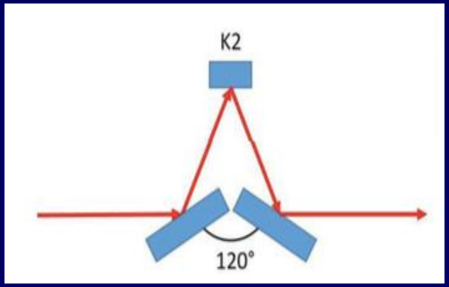
Acquisition and Guiding

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

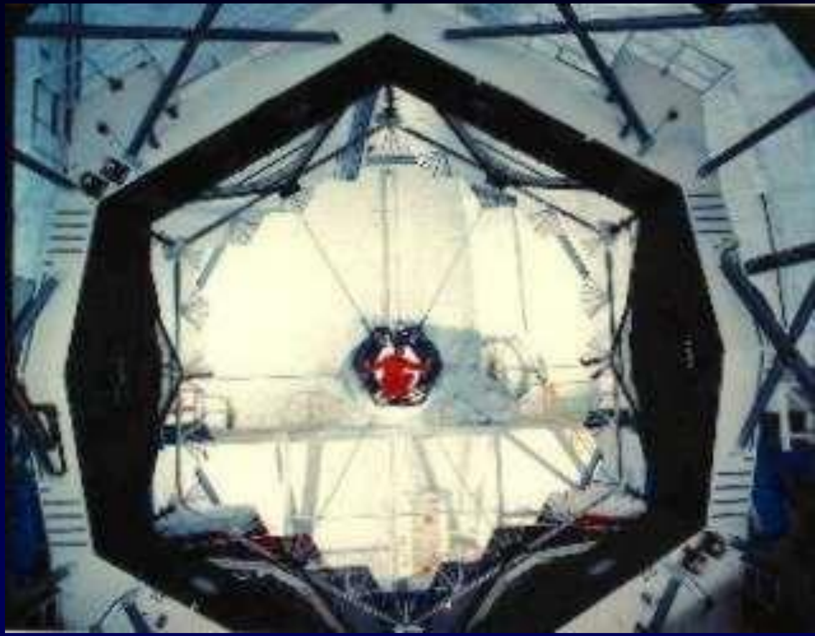


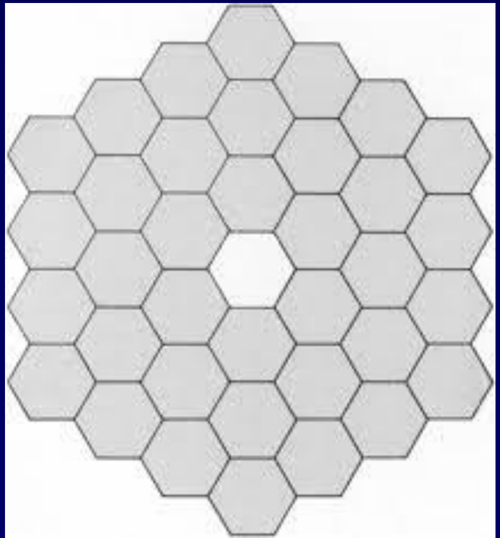
K-mirror beam rotator

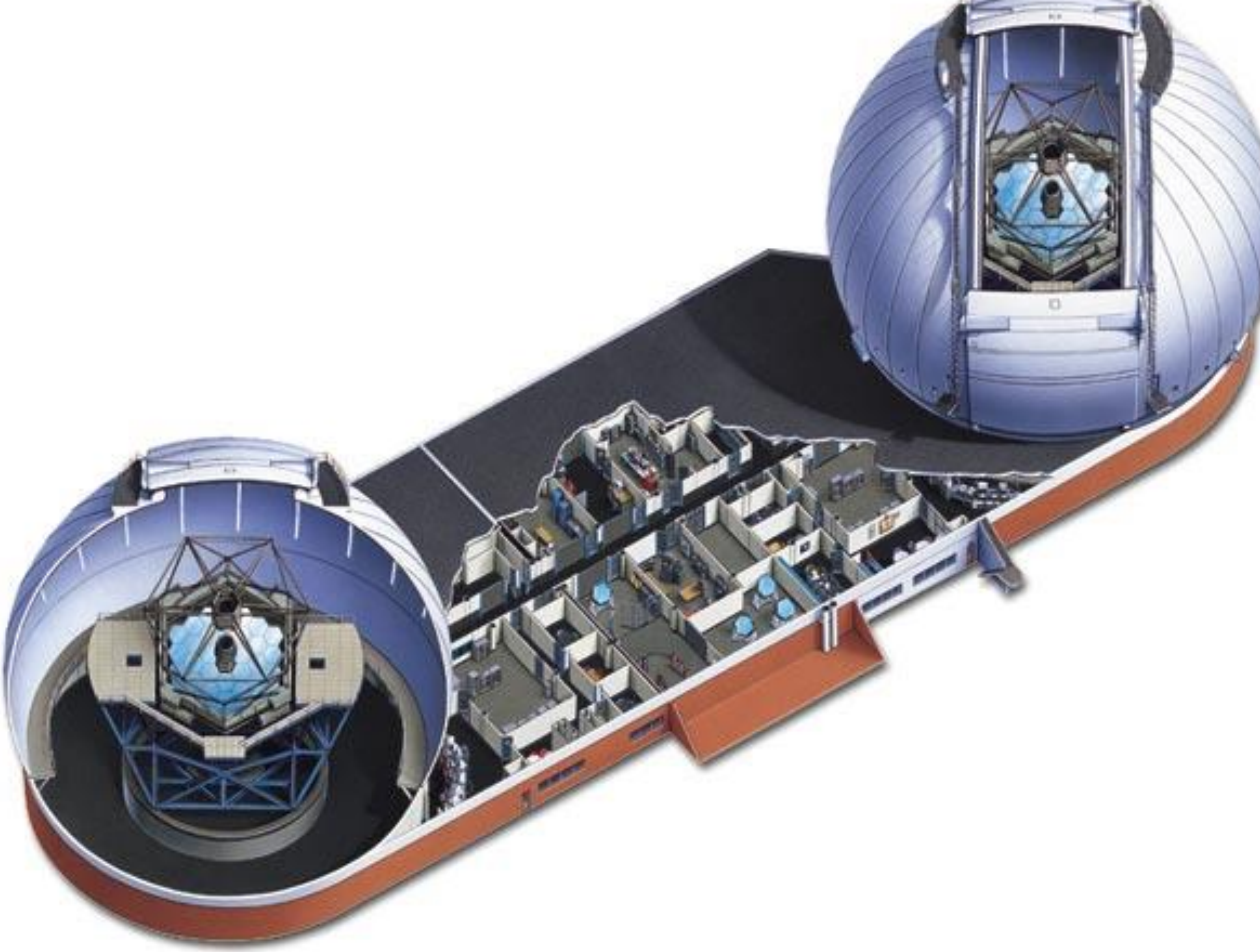


Keck 10-m telescopes

- 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

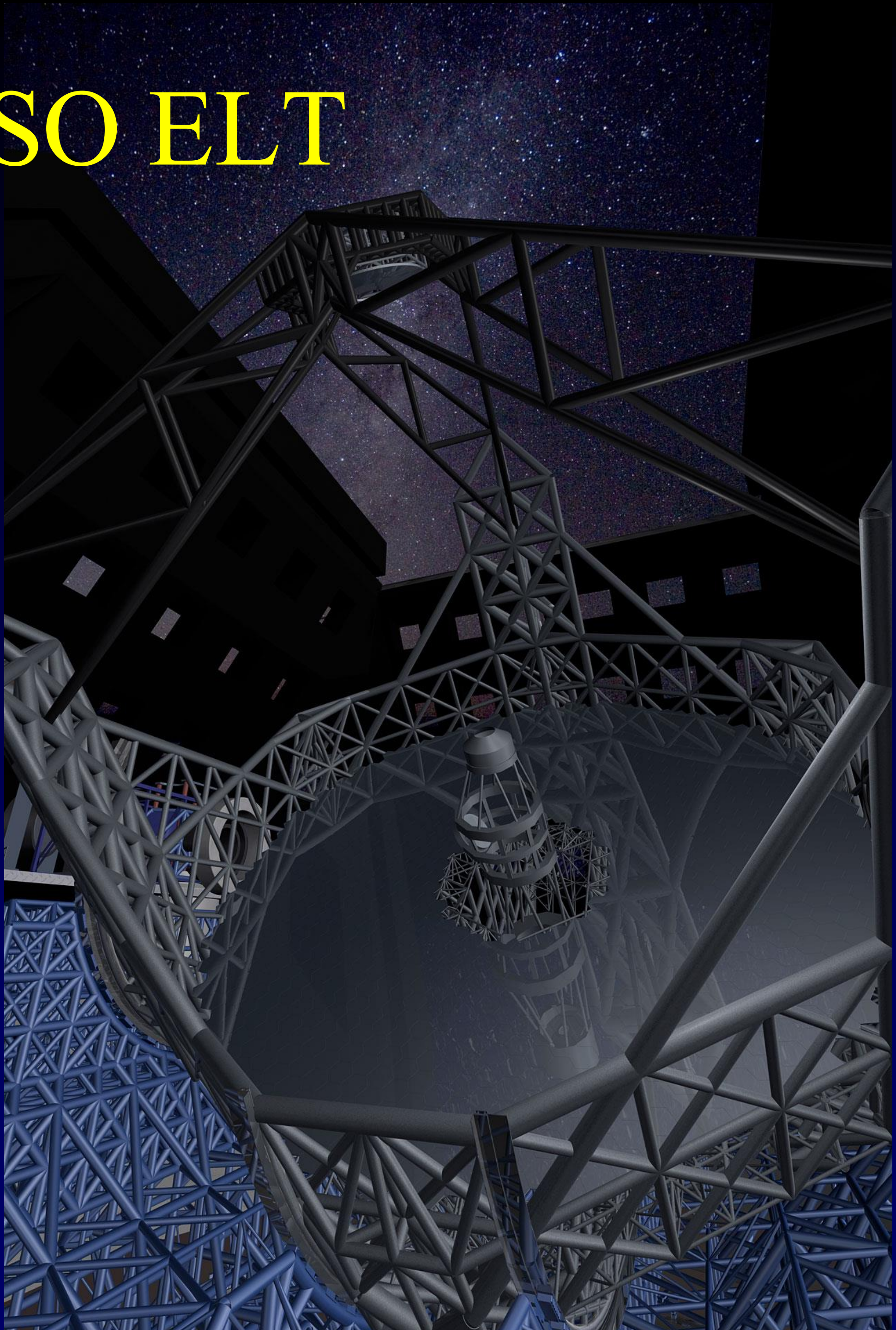
- Flexible Observing: Programmes matched to prevailing conditions.
- Exploit best conditions for highest priority science
- Aim for performance limited only by Earth's atmosphere
- Novel Instrumentation
- Maximise scientific productivity

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
- Dome nearing completion



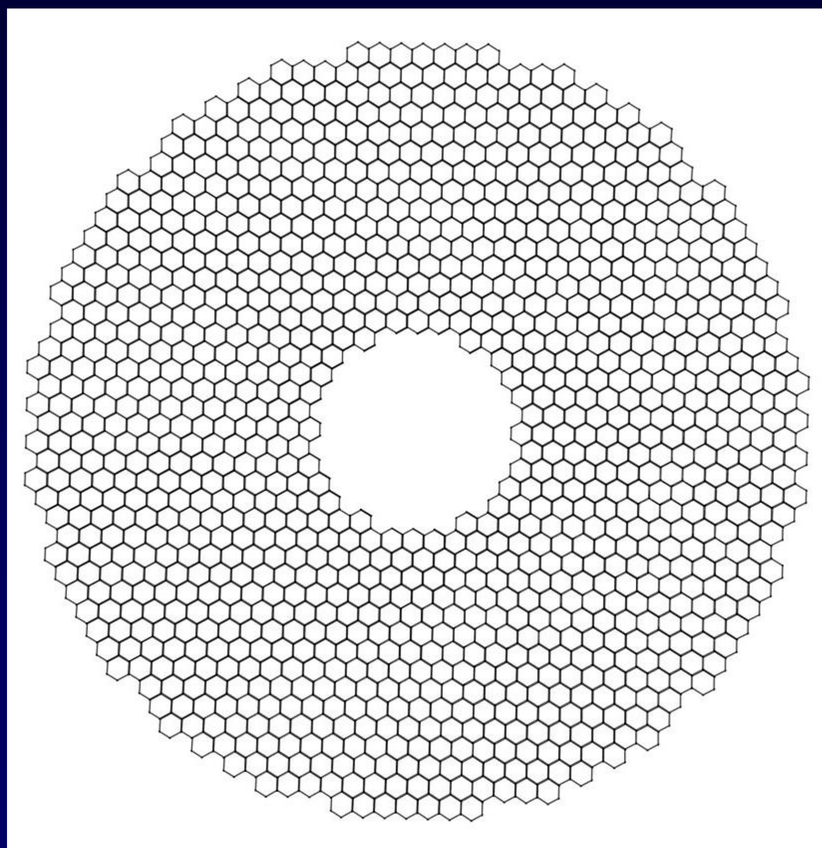
Benefits of Extremely Large Telescopes

- 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
- First Science Operations includes only 3 instruments
- ANDES, MOSAIC & PCS will be 2nd and 3rd Generation

Telescope primary mirrors

HST
2.4m

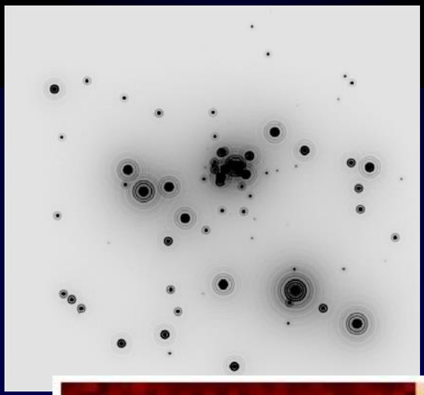
JWST
6.5m

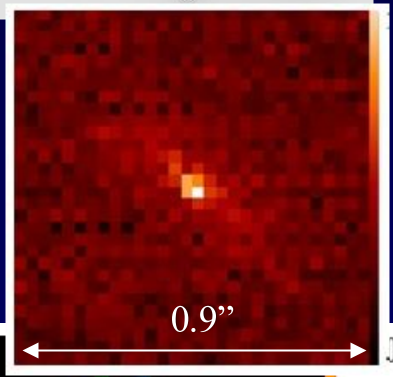


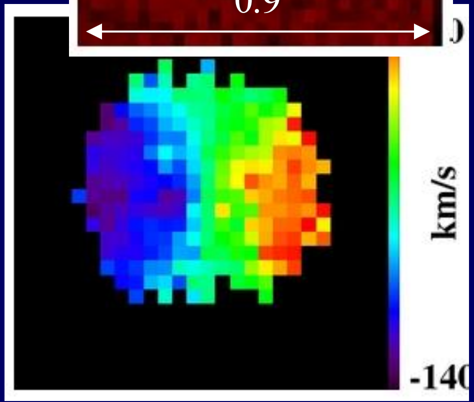
VLT
8m

Collecting area = sensitivity
Diameter = resolution (with AO)

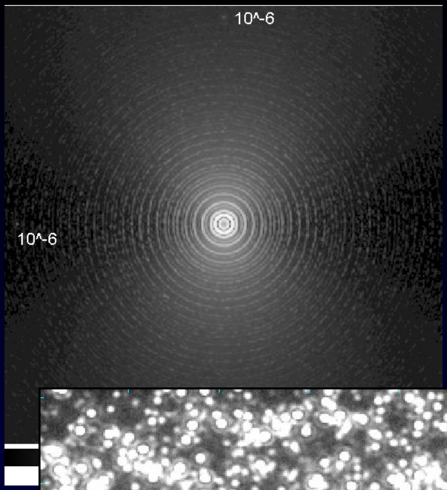
E-ELT Performance Simulations

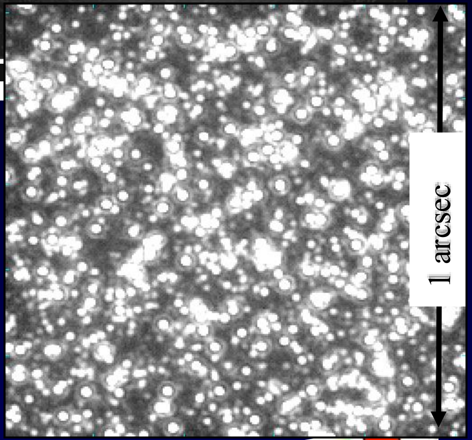


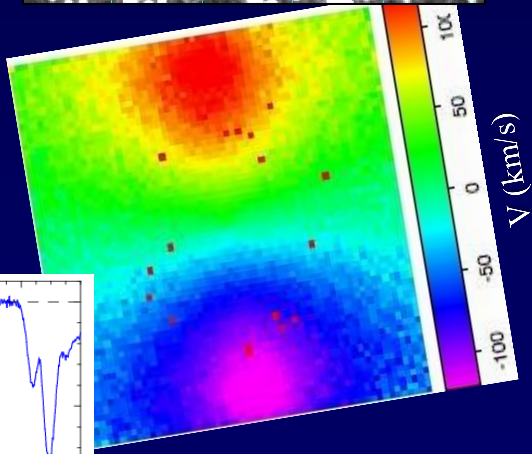


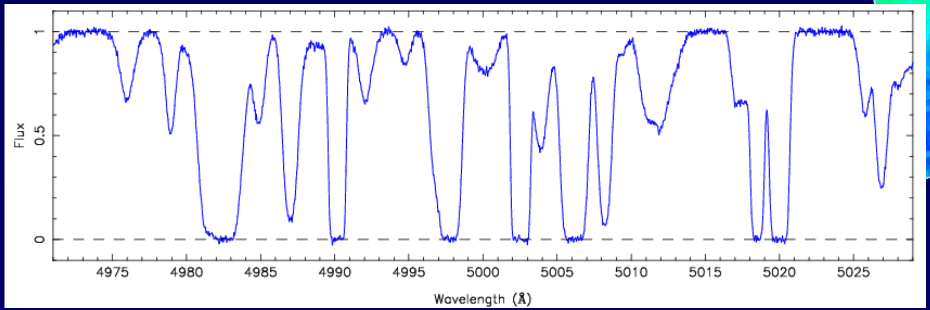


- Exo-planets
  - Direct detection
  - Radial velocity detection
- Initial Mass Function in stellar clusters
- Stellar disks
- Resolved Stellar Populations
  - Colour magnitude diagrams
  - Abundances
  - Detailed abundances and kinematics
- Black Holes
- The physics of galaxies
- Metallicity of the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









The European Extremely Large Telescope (E-ELT)

• 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

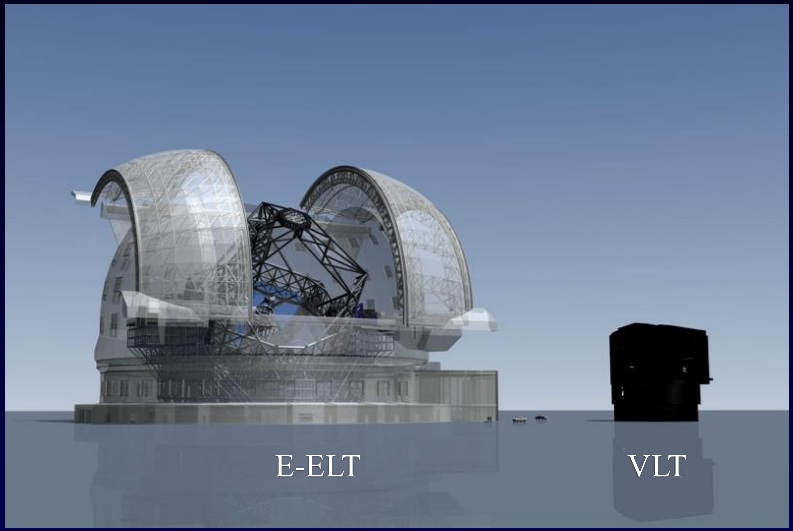
•Footprint of Dome ~100m dia, 80m high.

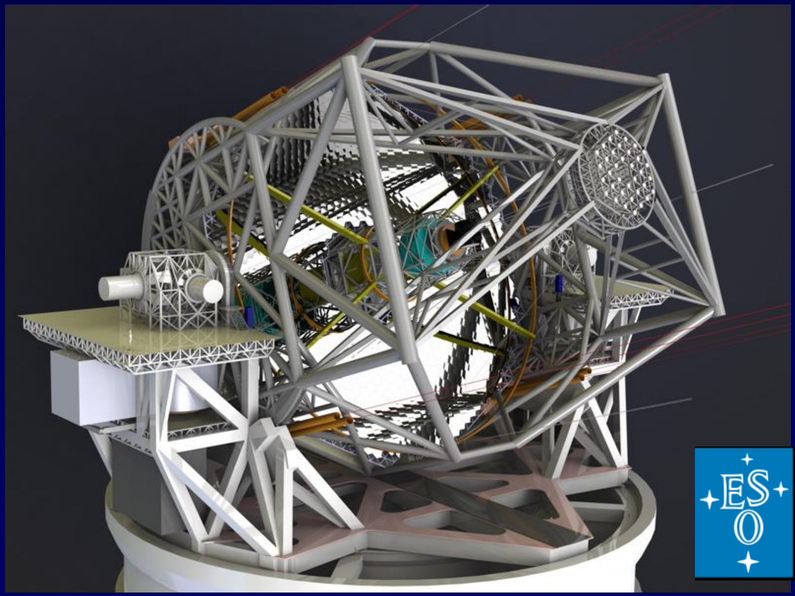
• Instrumentation: up to ten focal stations, FoV 10'

• 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 2029

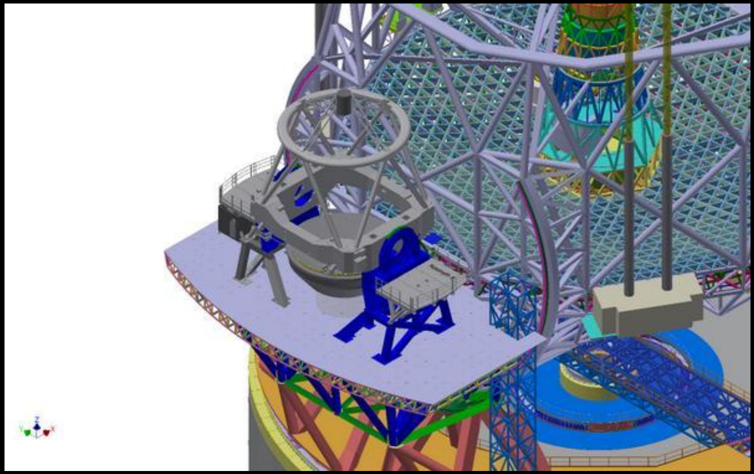
• Science goals are centred around high spatial resolution (5 mas in the J-band) and immense collecting area. Synergies with other major observatories JWST, ALMA, ...





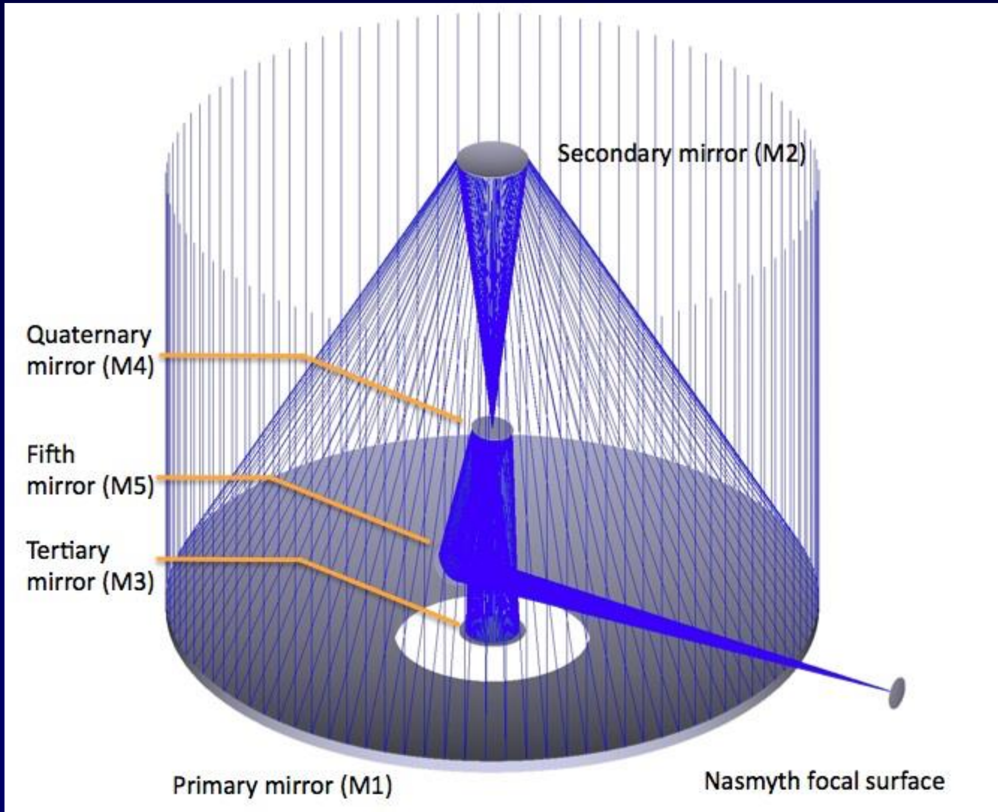
E-ELT Optical design

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



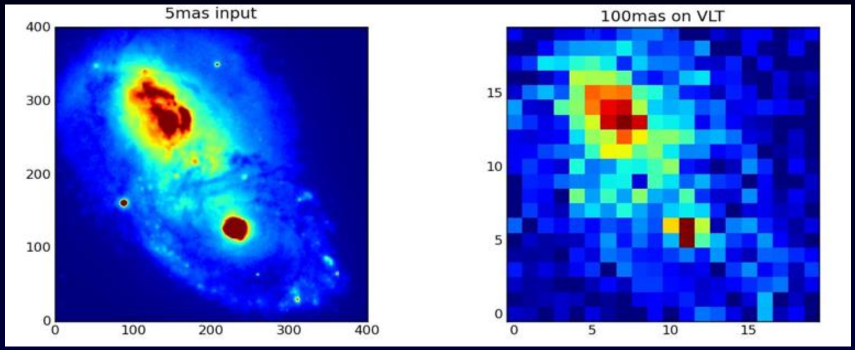
M4 is an adaptive mirror in the telescope to provide a 10 arcmin, near-diffraction-limited field of view in the IR

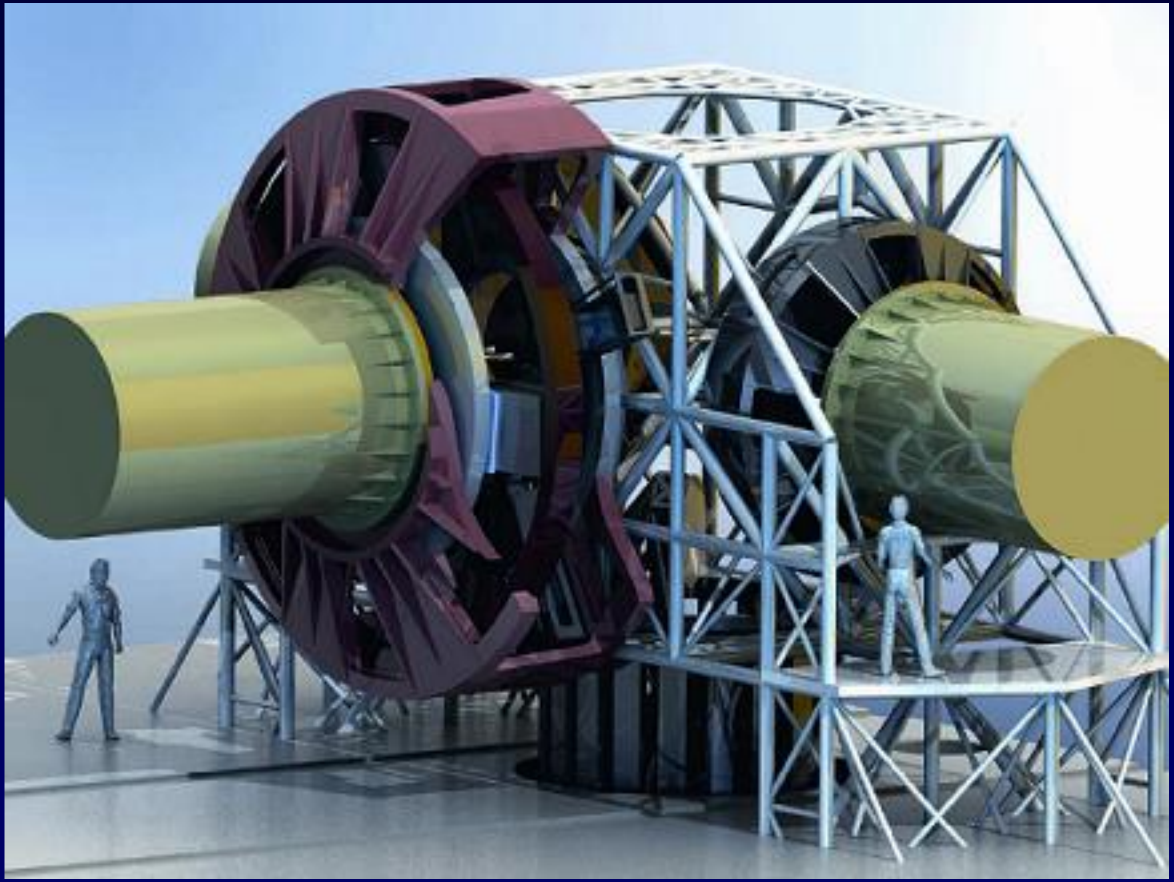
It will usually operate with a constellation of laser guide stars as references for AO



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 being built at Oxford (spectrographs)

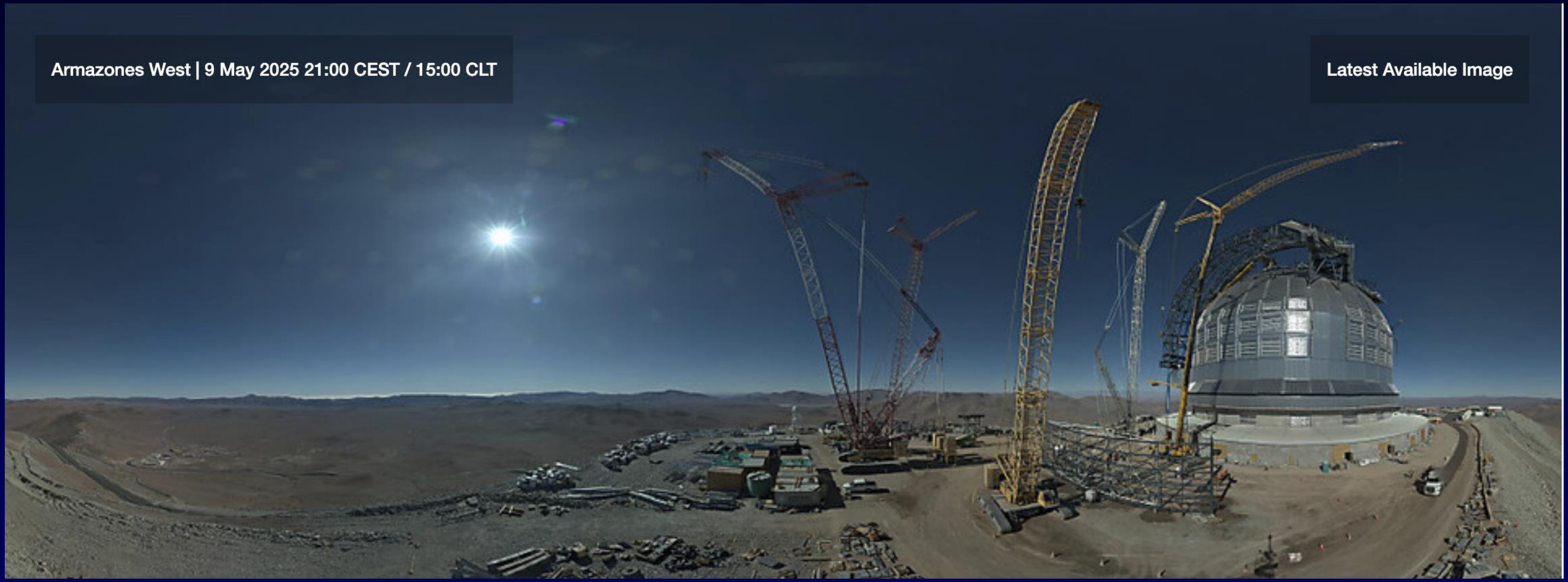




But also

- 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

Armazones Web Cam



Construction underway again after Covid interruption

First observations planned for late 2030