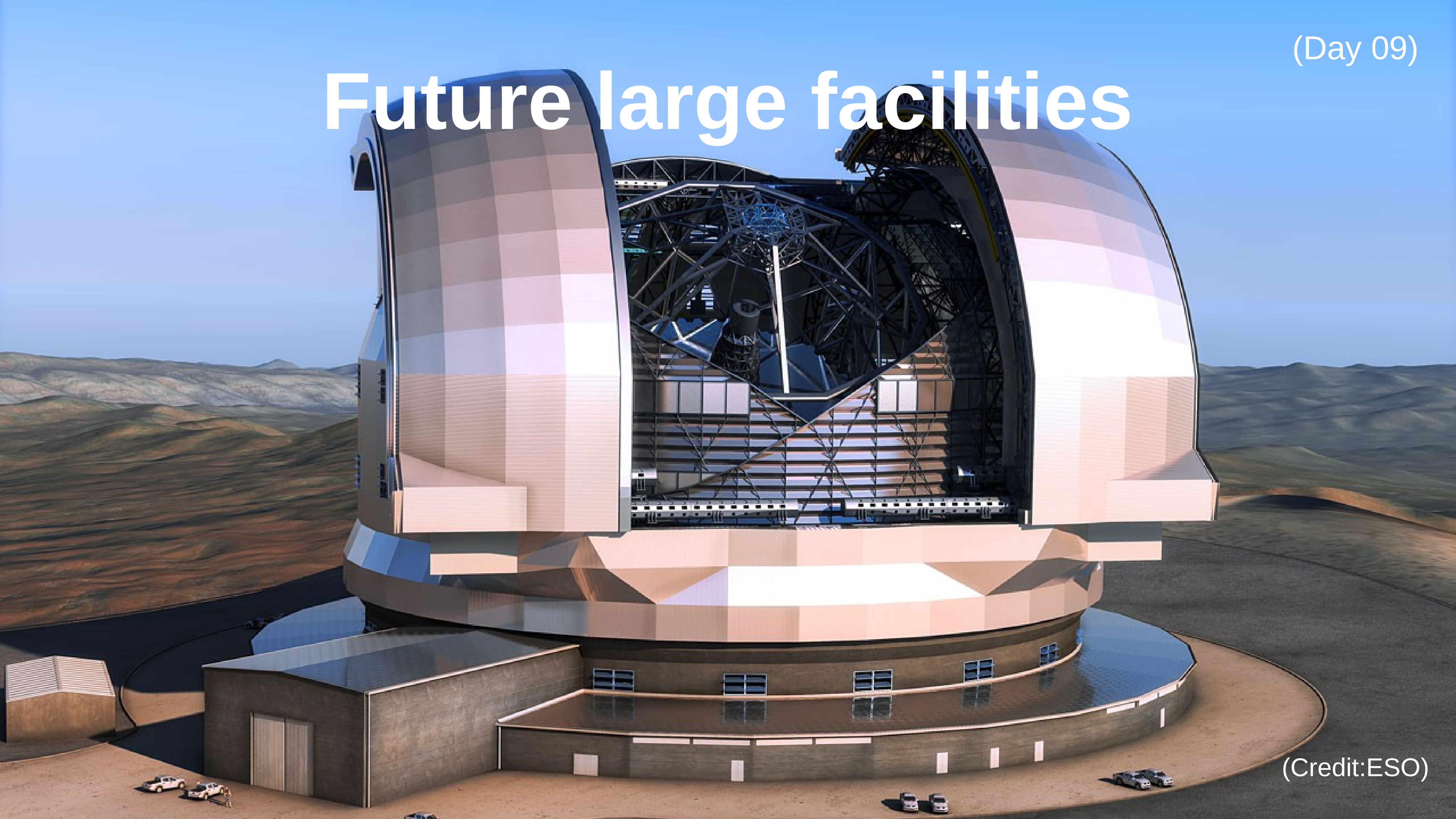
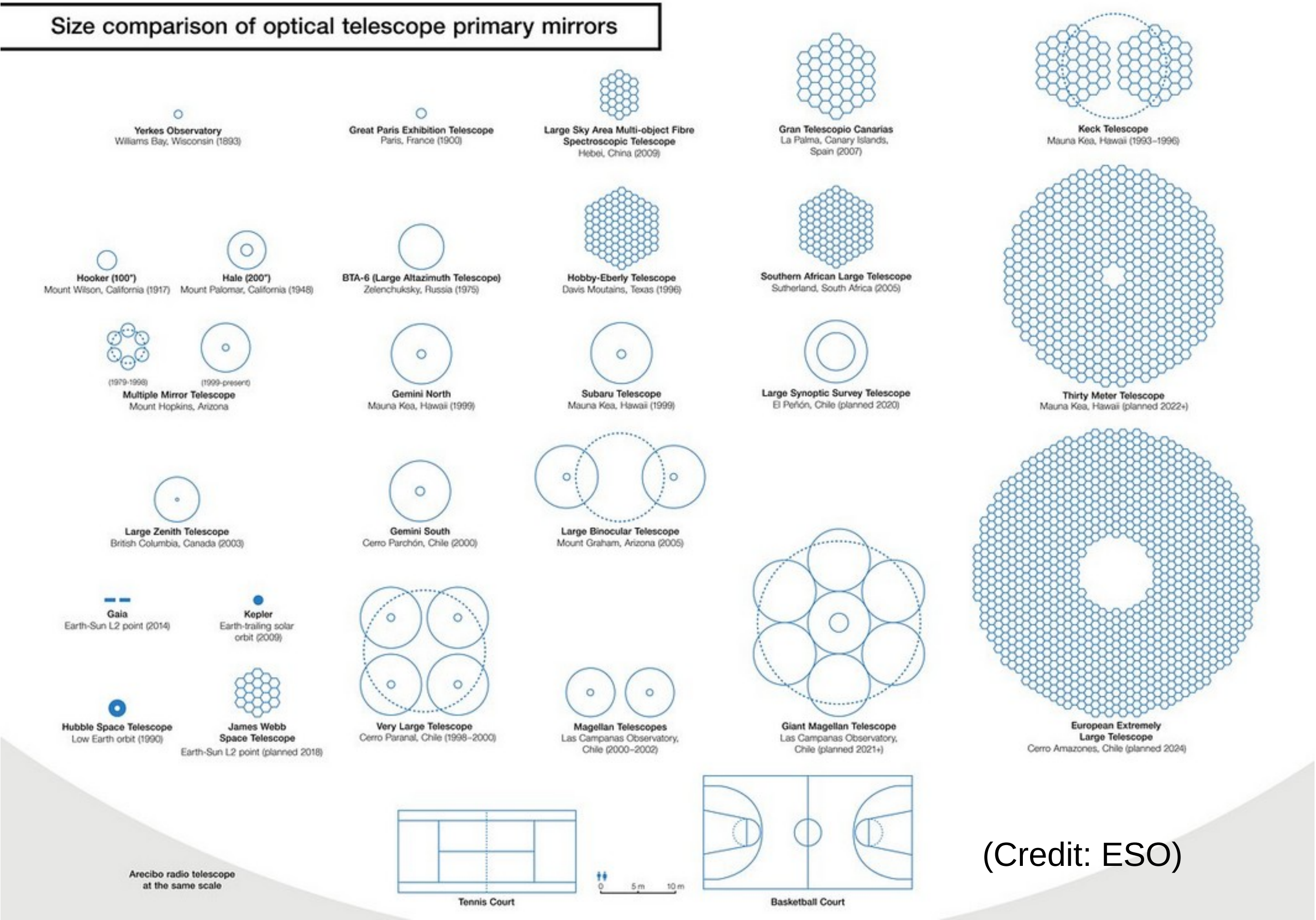
(Day 09)

Future large facilities



(Credit:ESO)

Today

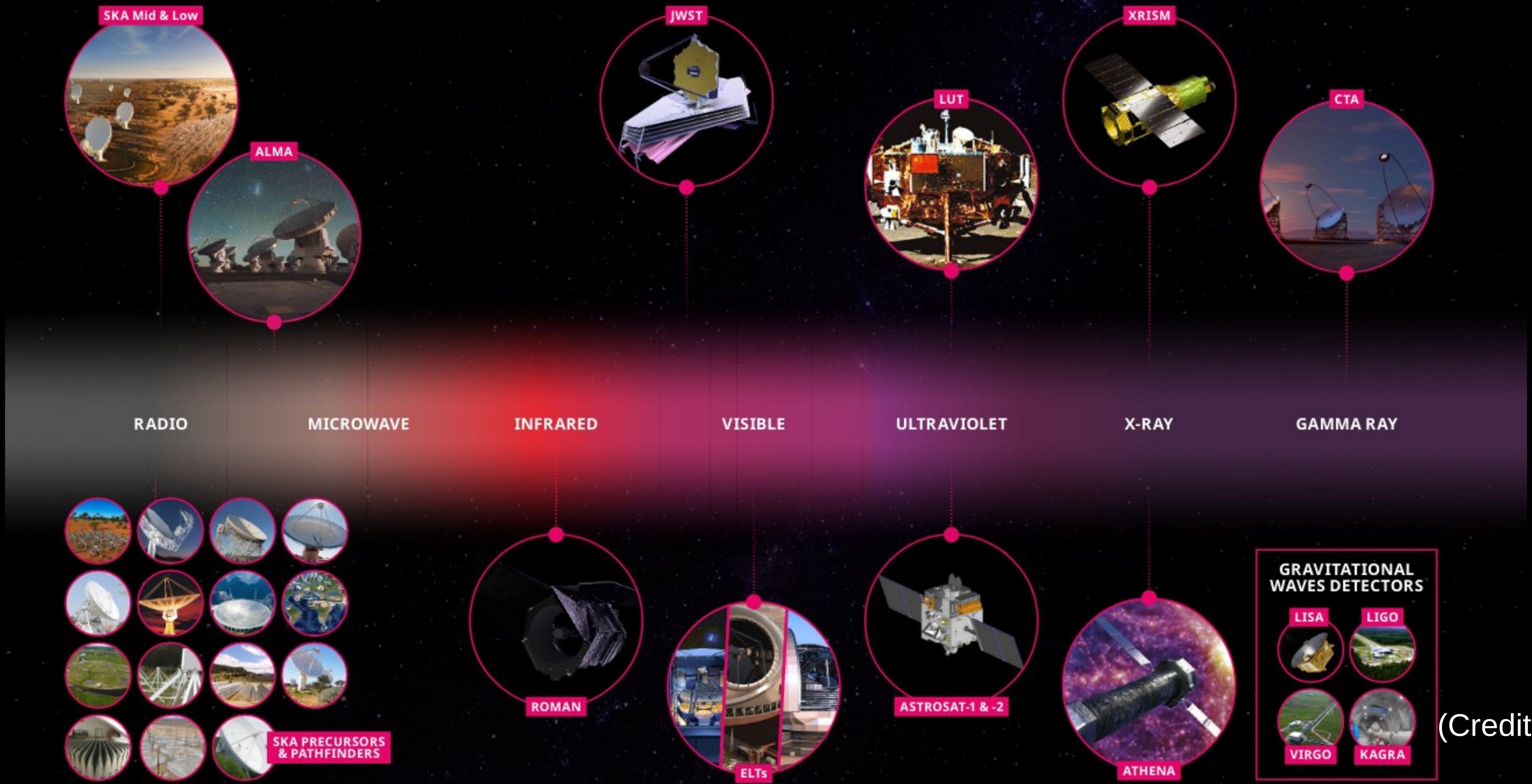


(Credit: ESO)

1. Vera Rubin Observatory
2. ESO ELT
3. TMT and GMT

21st century astronomy

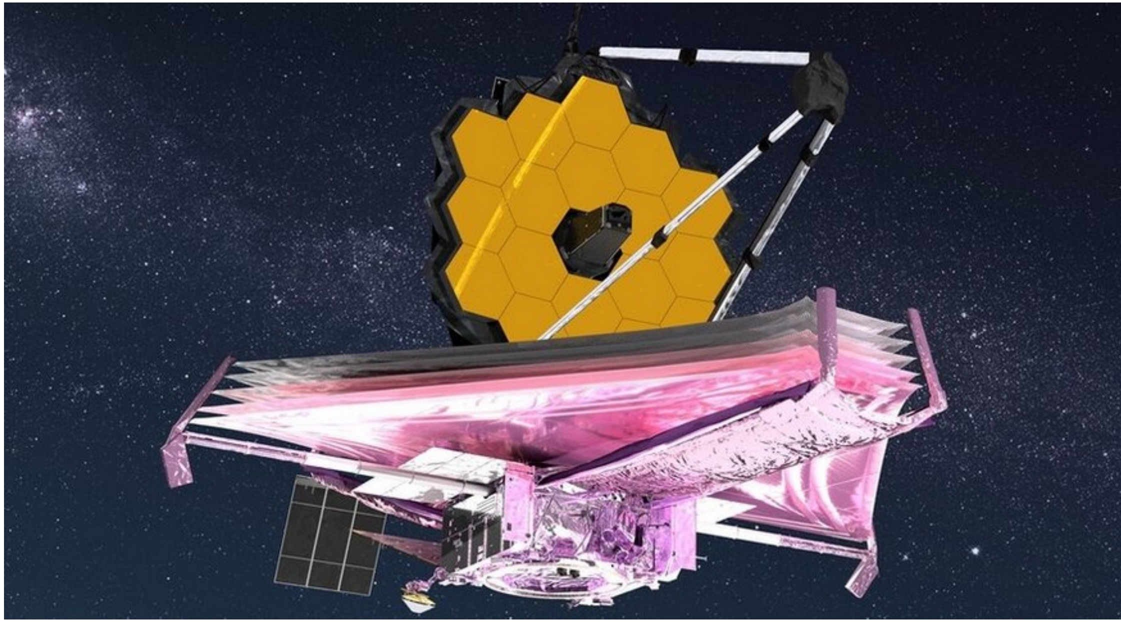
As the world's largest radio-frequency interferometer, SKA will establish itself as the radio astronomy component of a suite of major facilities spanning the electromagnetic spectrum, on the ground and in space.



(Credit:SKAO)

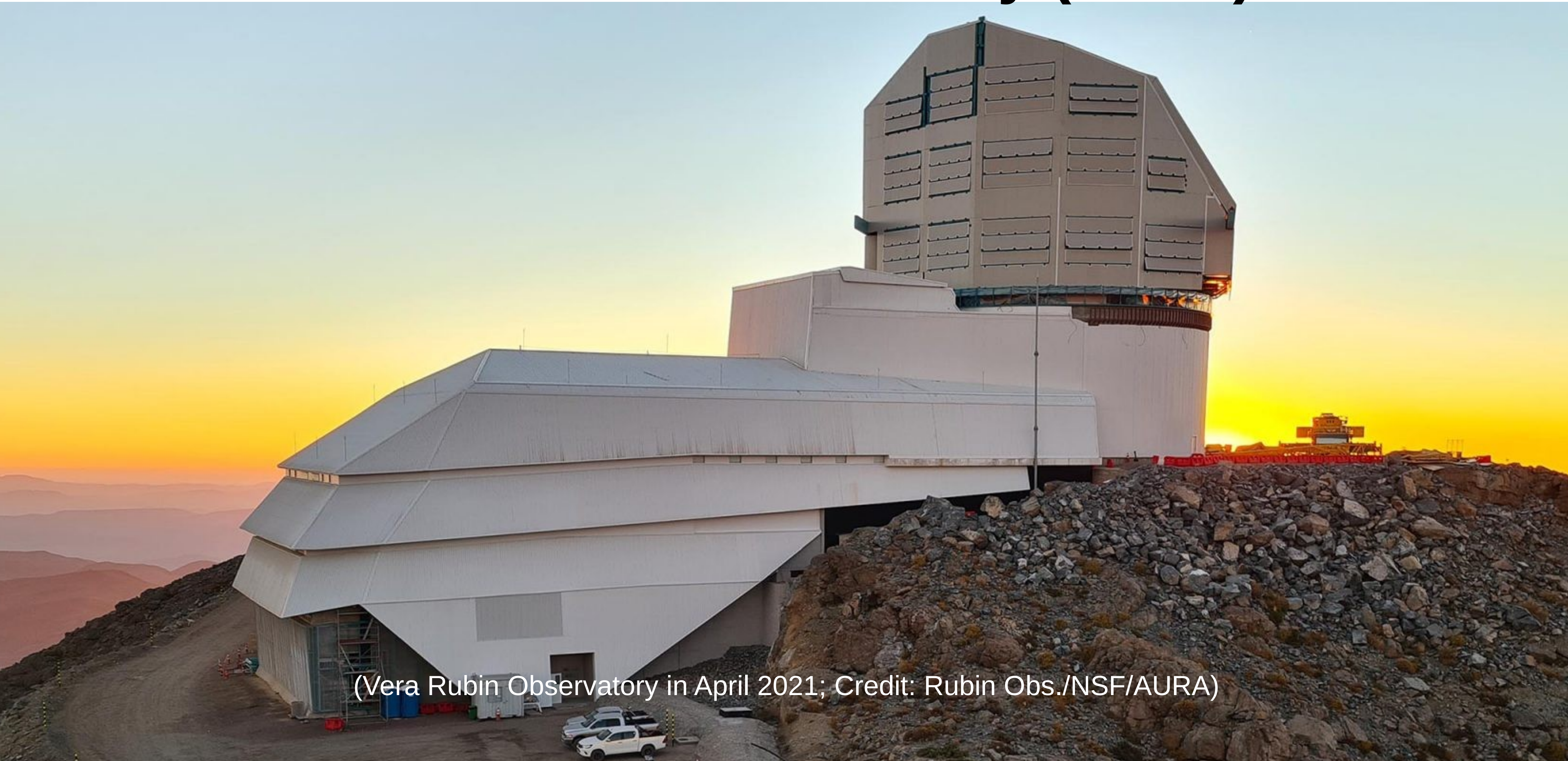
What is coming next?

- **JWST**: launched; operations by mid-2022 (0.6 to 28μm)
- **Roman Telescope**: 2.4m space telescope by 2027 (0.5-2.3μm)
- **LUVOIR**: 8 or 15m space telescope by 2039 (UV to IR)
- **SKA**: 197 x 15m dishes + 131000 antennas, 2024-2029 (50MHz-15.4GHz)
- **CTA**: 8 x 23m + 40 x 11m + 70 x 4m, 2027-beyond (20 GeV - 300 TeV)
- **ESO ELT**: under construction, 39m, by 2027 (0.5-2.4μm; 3-13μm)
- **Vera Rubin Observatory**: under construction, 8.4m, by 2023 (0.3-1.1μm)



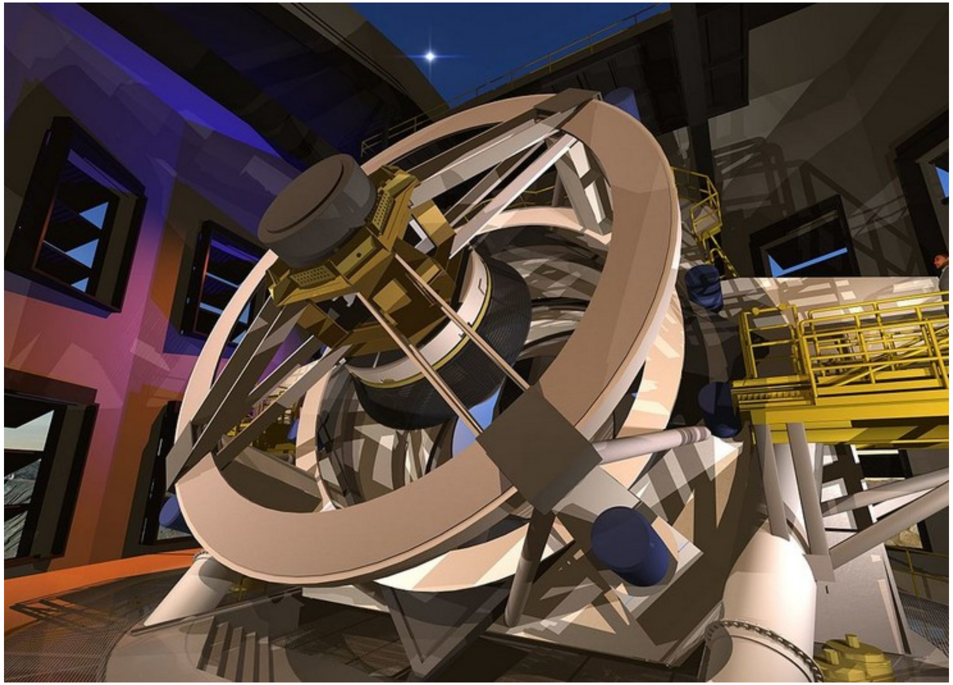
(Credit: NASA/ESA)

Vera Rubin Observatory (LSST)


(Vera Rubin Observatory in April 2021; Credit: Rubin Obs./NSF/AURA)

Optical Survey System

- 10 years – Legacy Survey of Space and Time (LSST)
- Four science areas:
  - Probing dark energy and dark matter;
  - Taking an inventory of the solar system;
  - Exploring the transient optical sky;
  - Mapping the Milky Way.
- 8.4m (6.5m effective) primary mirror
- *ugrizy* filters (320-1050nm)
- 90% of time to observe 18000deg^2 800 times (r ~ 27.5 mag)
- ~20 10^9 galaxies + ~20 10^9 stars
- 10% of time for a very deep and a very fast survey



(Credit: Todd Mason, Mason Productions Inc. / LSST Corporation)

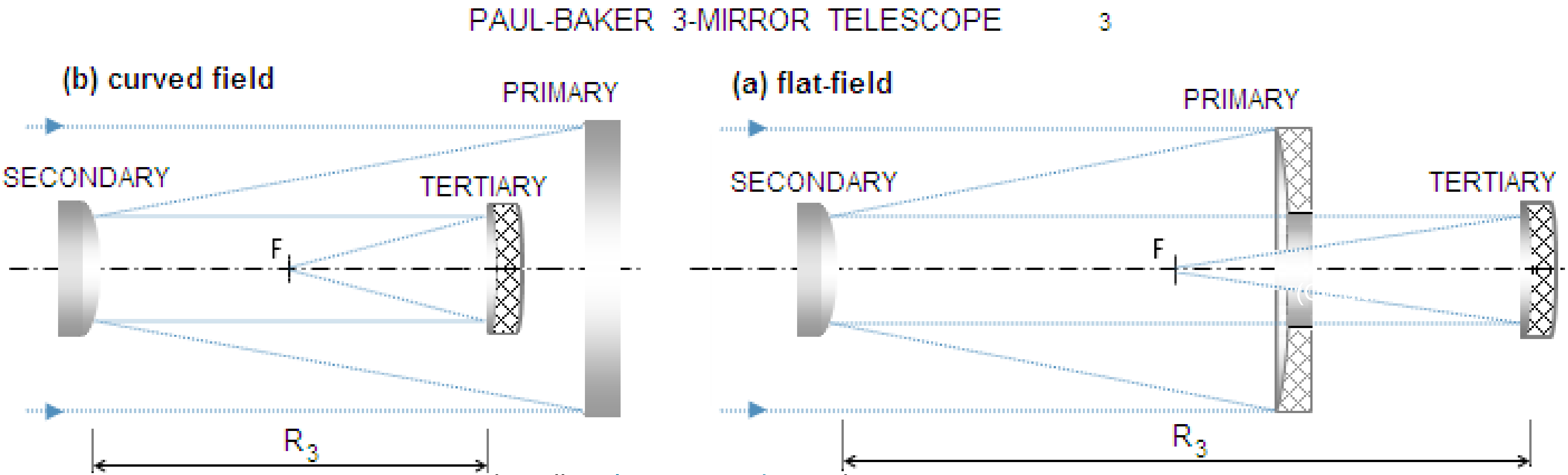
The Simonyi Survey Telescope

- Design with 3 mirrors + 3 lenses
- The world largest camera
- Wide field of view to survey the sky in 3 nights
- Large “étendue” (or throughput or grasp):
  - product between primary mirror area and field of view
  - speed to survey a given area (FoV) to a given flux limit (depth - mirror area)
  - 300 m^2 deg^2 (SDSS 2.5m has 5.9 m^2 deg^2)
- Field of view: 9.6 deg^2 (3.5 deg^2 covered by camera)
- Alt-azimuth mount
- Active optics (all 3 mirrors + hexapods for the camera)

(Credit: Rubin Observatory/NSF/AURA)

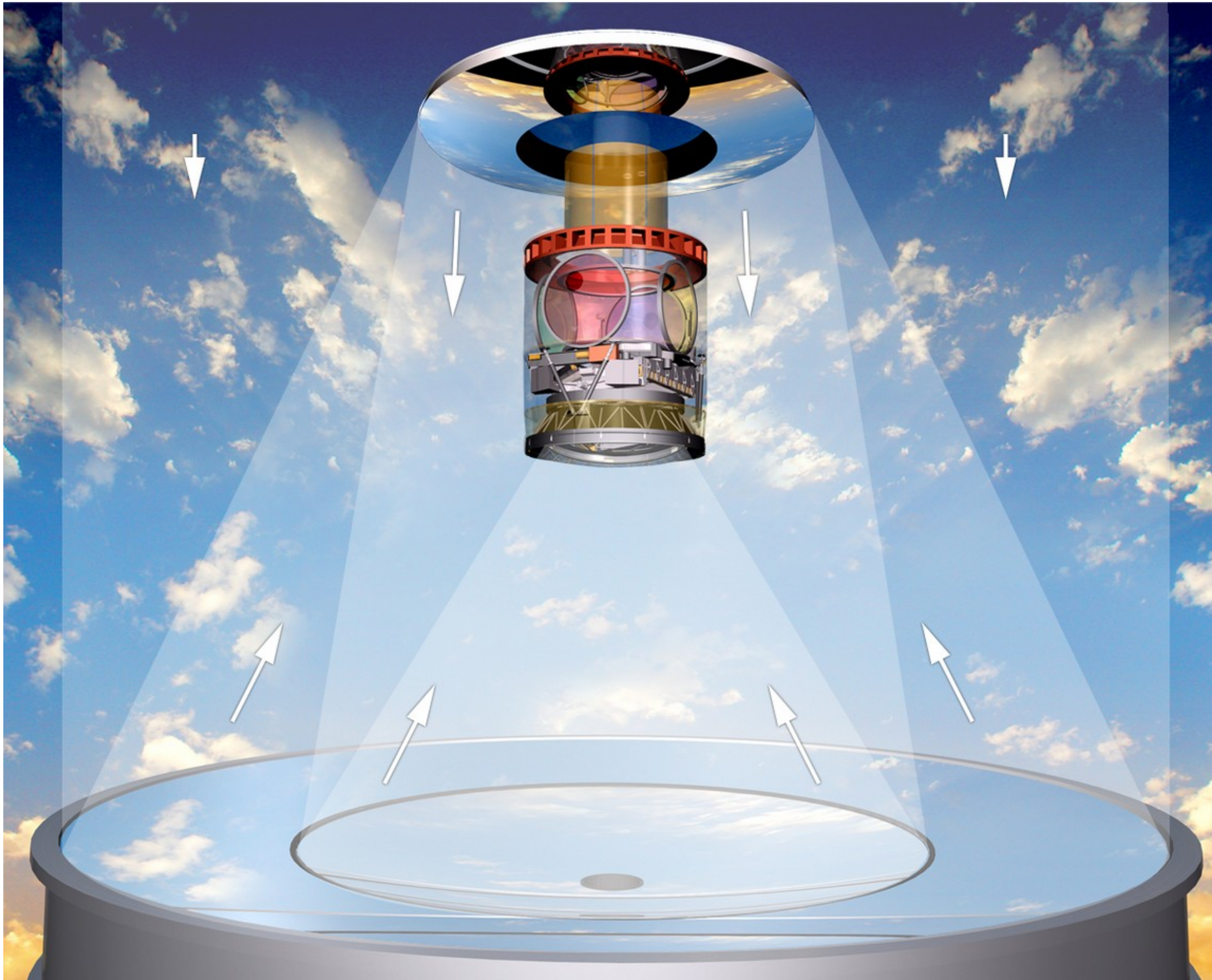
Telescope design

- Modified, 3-mirror anastigmat Paul-Baker design
- **What is a Paul-Baker design?** (Baker 1969)
- Concave paraboloidal primary, convex spherical secondary and concave spherical tertiary: Minimize spherical aberration, coma, and astigmatism



(Credit: telescope-optics.net)

- M1 and M3 are one structure
- M1: outer 8.4m, inner 5m diameter (area of ~ 6.4m mirror)
- M2: 3.4m convex
- M3: 5m concave
- Lenses correct chromatic aberration and flatten the focal plane



M1M3

- M1 and M3 share a single monolithic substrate
- Borosilicate glass, hexagonal honeycomb

  (lighter and lower cost than, e.g., zerodur, but higher coefficient of thermal expansion)
- Needs air circulation inside cells to keep temperature gradients under control
- Each honeycomb cell is a hole with 89mm diameter
- 156 actuators (active support during observations: gravity, wind, manufacturing errors)
- 6 stiff “hardpoint” actuators to position the mirror
- + static support

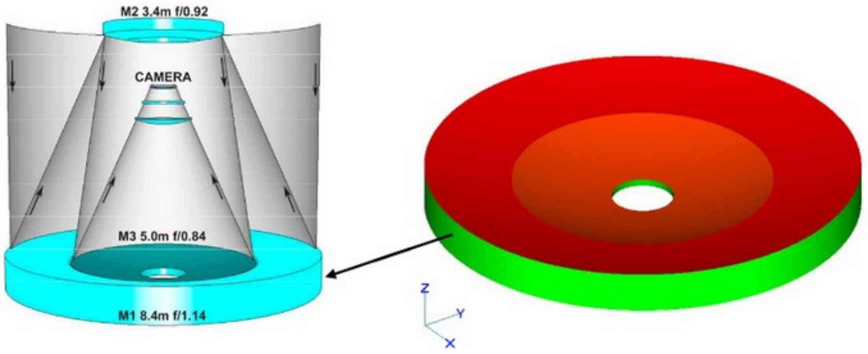


Figure 2. Optical Layout (left) and Isometric View of M1M3 Mirror Model (right).

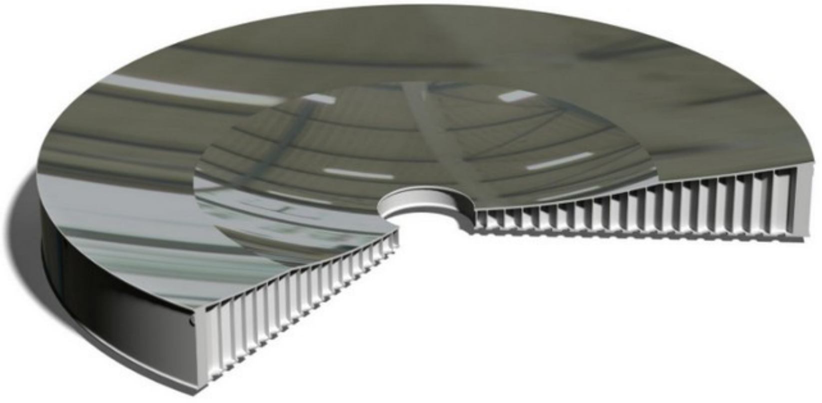
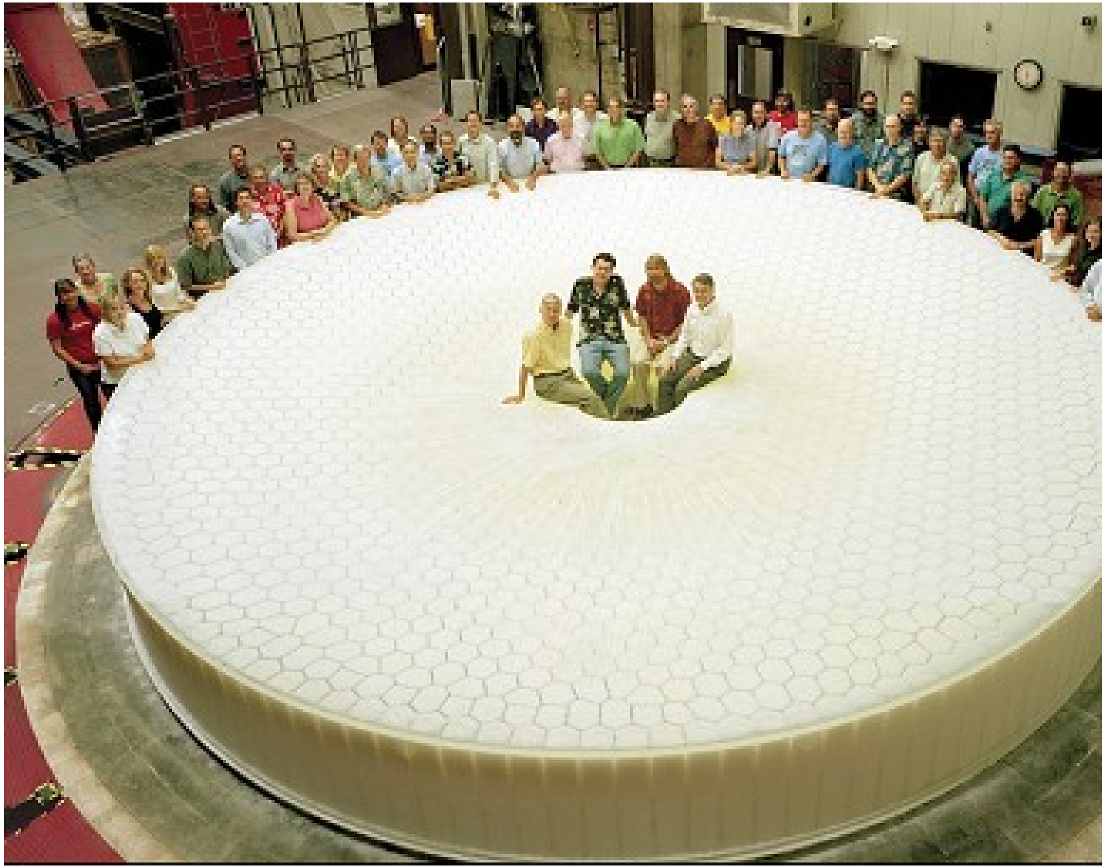
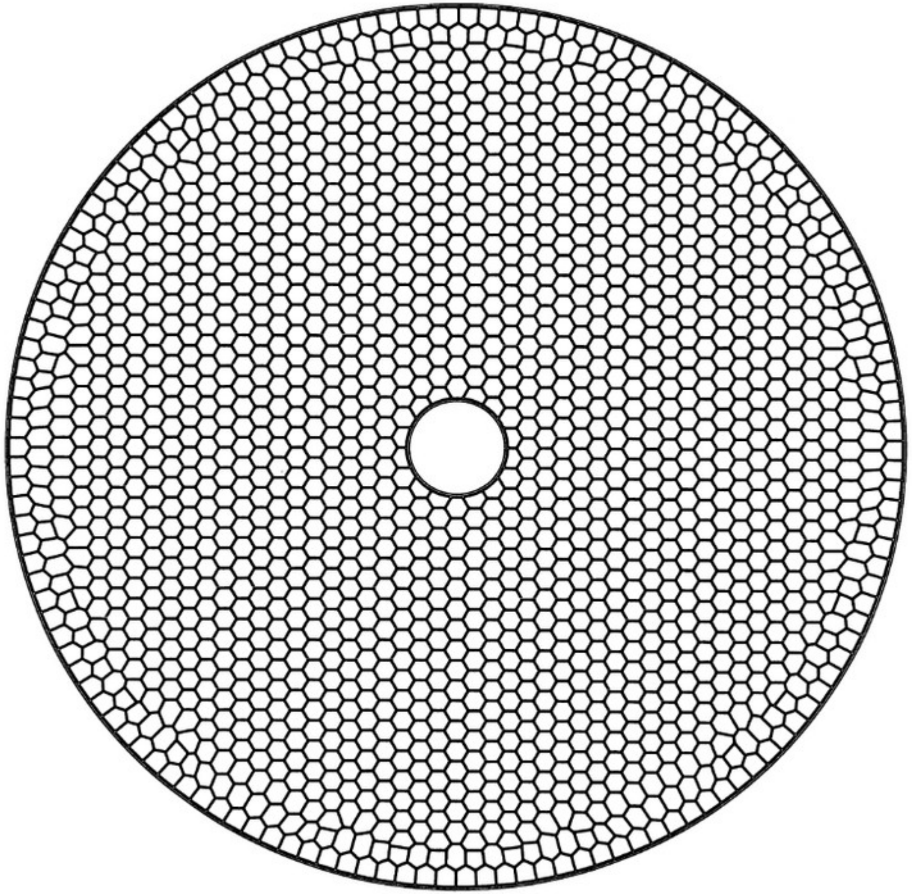


Figure 3. Primary Tertiary Monolith Mirror Design - Section View.

(Neill et al. 2016a)



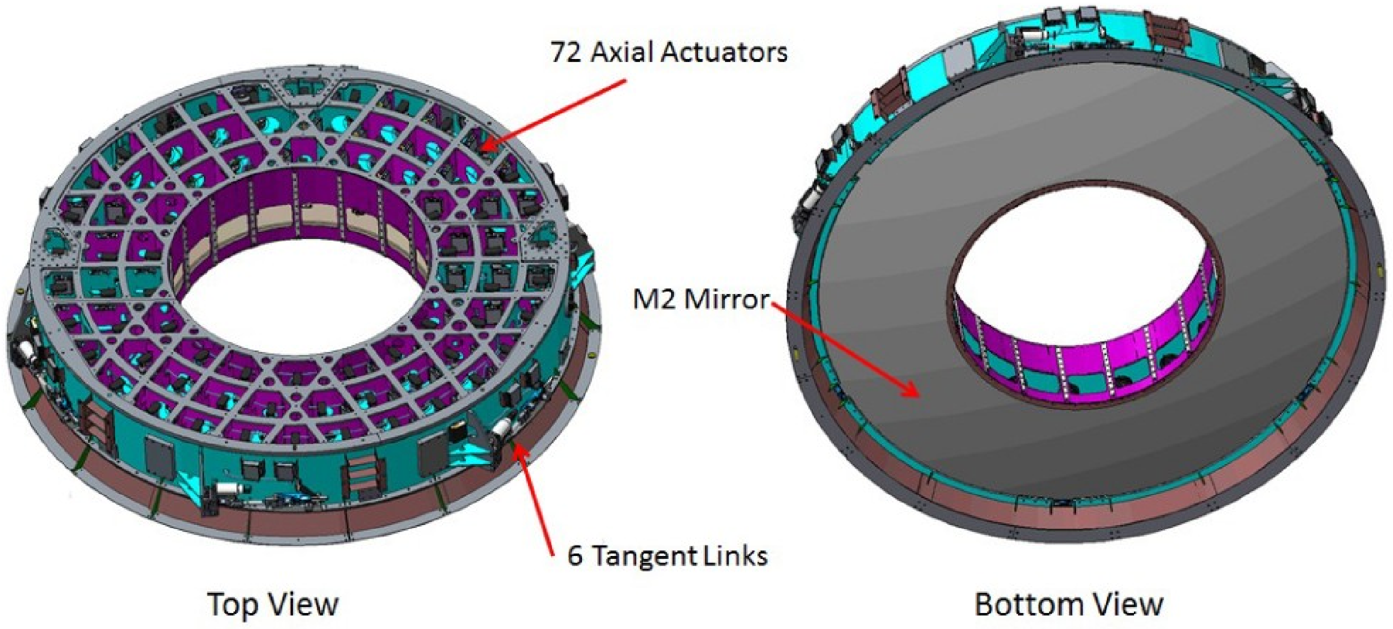
(Credit: Rubin Observatory/NSF/AURA)



(Hill et al. 1998)

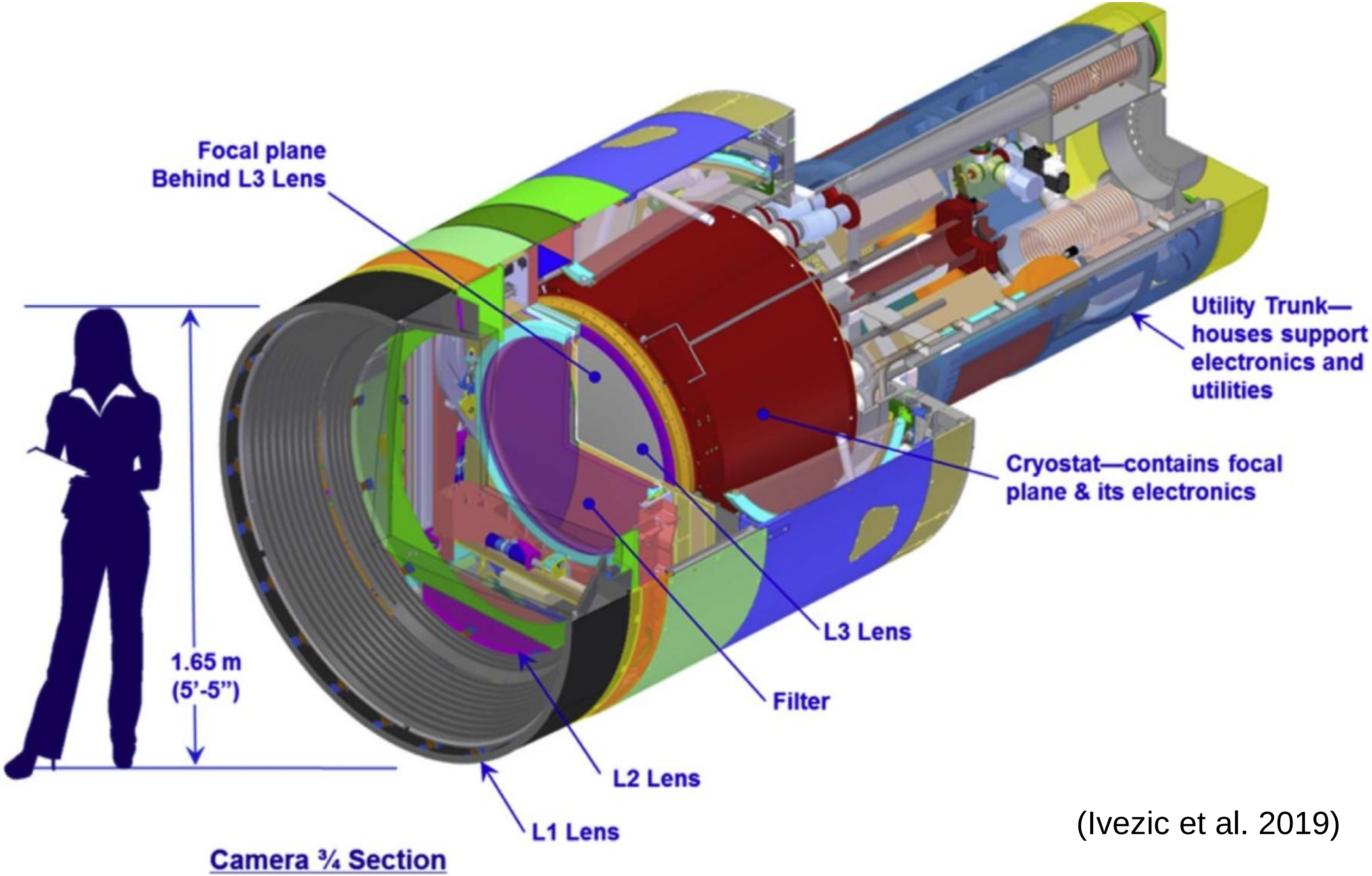
M2

- Convex ellipsoid of Corning ULE™ (Ultra Low Expansion glass)
- Mirror ~ 680 Kg (~ 2714 Kg with the whole assembly)
- 72 axial actuators (active support) + 6 tangential actuators (mirror position and support)
- Large conical baffle to avoid reflection to the camera



(Neill et al. 2016b)

The camera

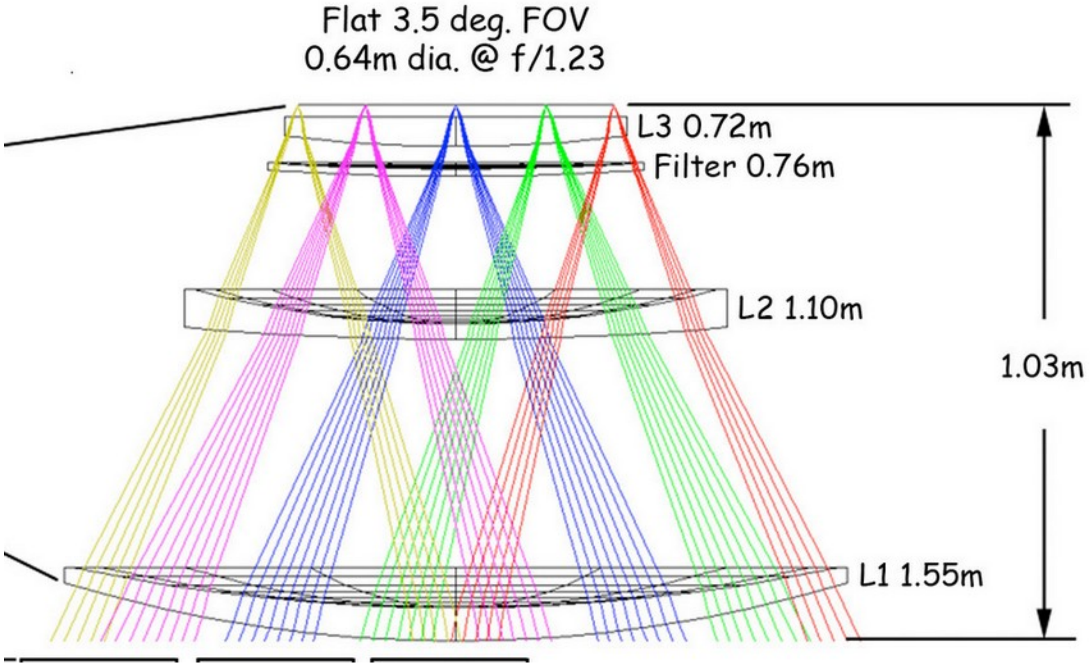


(Ivezic et al. 2019)

The camera

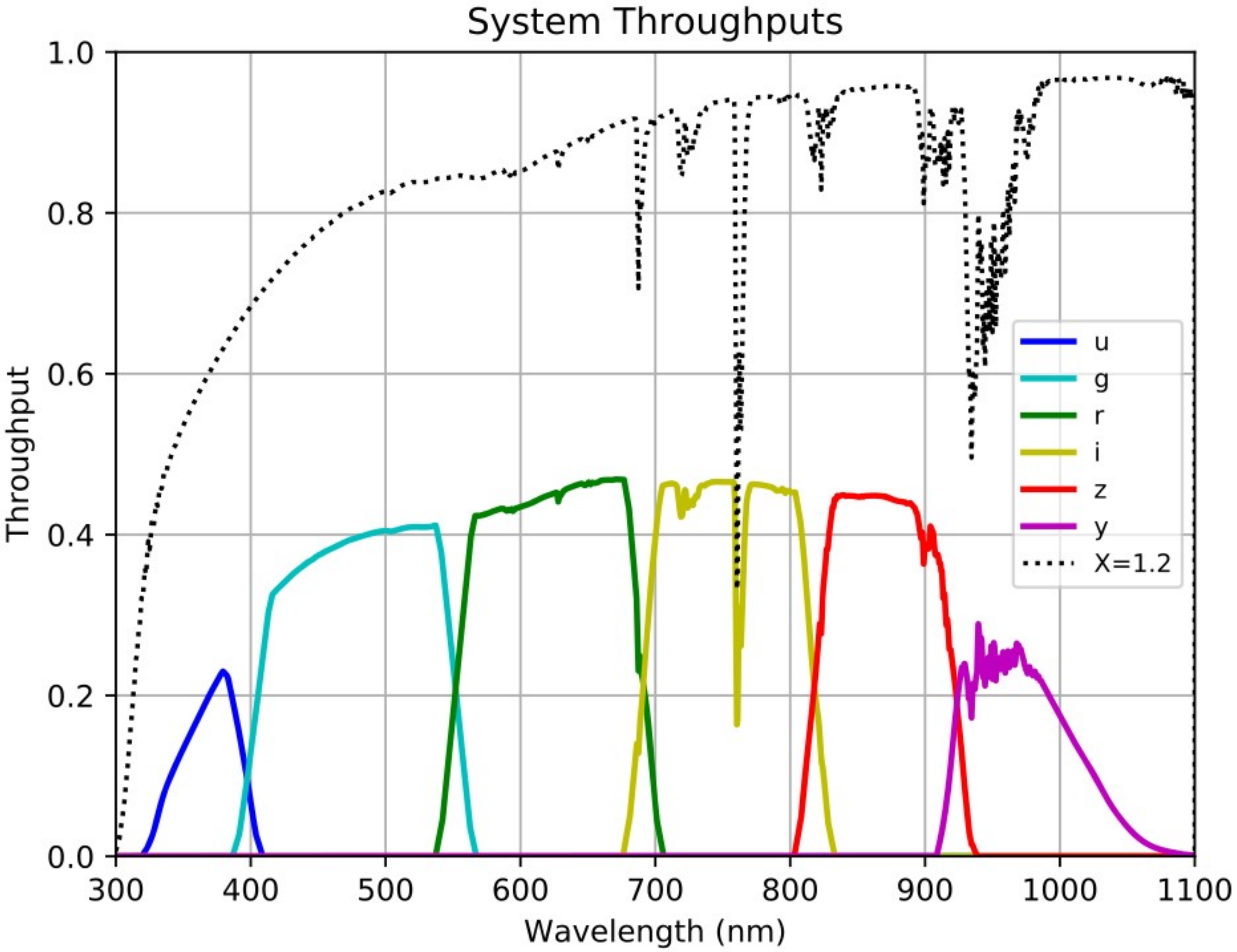
- Largest digital camera ever built
- Optics: three large fused-silica (SiO_2) lenses

  (same chemical material as fused quartz, but fused quartz has impurities that cause UV absorption; fused silica has hydroxyl ions, OH, that cause IR absorption)
- Correct chromatic aberration and provide flat focal plane
- L3 is also the vacuum barrier to the cryostat
- 2.85cm between L3 and the focal plane
- Automatic filter changing mechanism



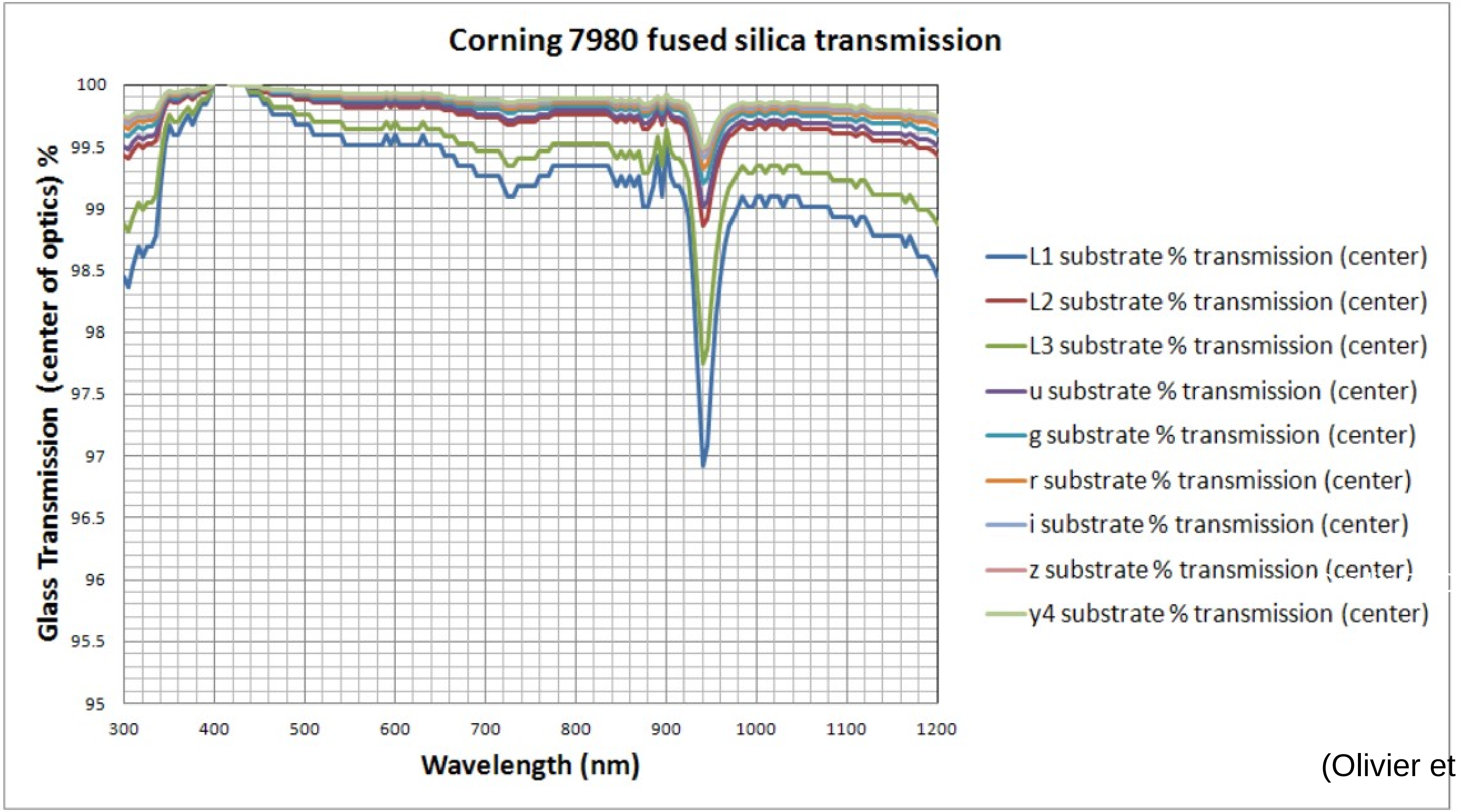
(Credit: Rubin Observatory/NSF/AURA)

The filters



(Ivezic et al. 2019)

Transmission

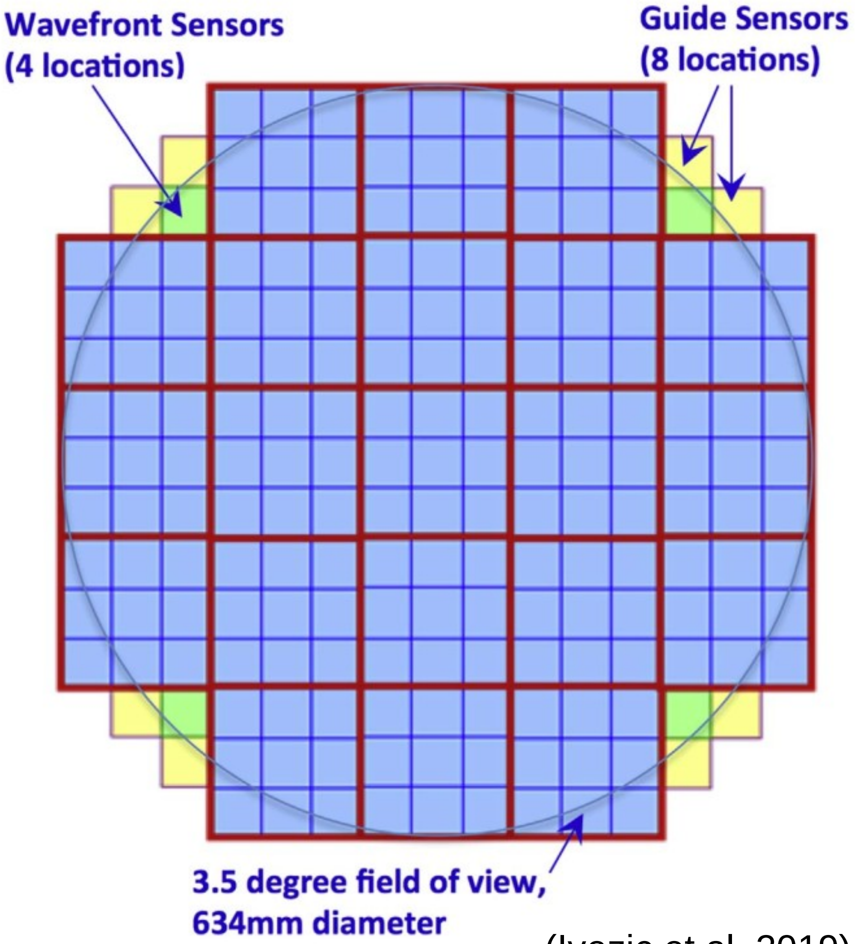


(Olivier et al. 2012)

The detectors

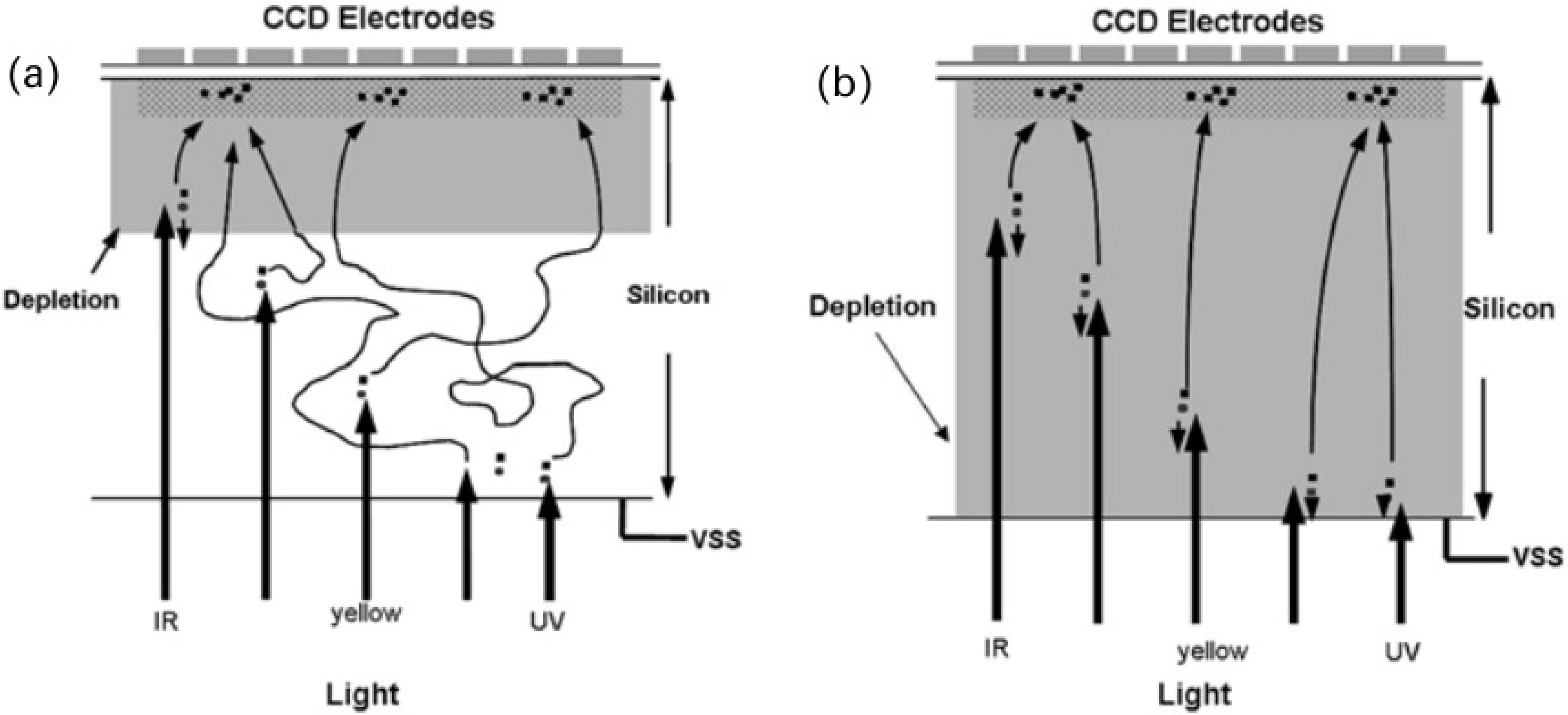
- 189 4kx4k CCDs with 10μm pixels (3.2 gigapixels)

  (at the best seeing, 0.4”, there is still 2px sampling)
- Deep depleted high-resistivity silicon back-illuminated devices (usually increases dark current)
- Liquid nitrogen to operate at 173 K
- 21 platforms (rafts) of 3x3 detectors
- Each raft with its own electronics
- Each CCD has 16 outputs
- Readout ~2s of the entire focal plane



(Ivezic et al. 2019)

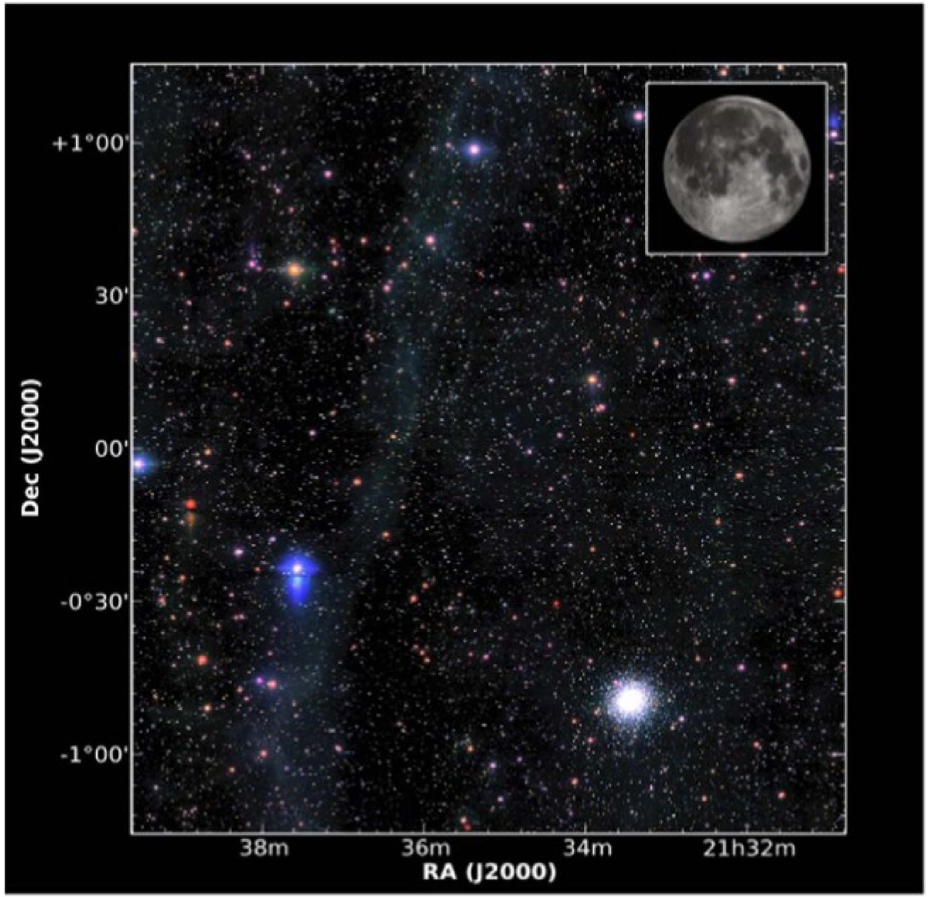
Deep depletion CCD



(McLean 2008)

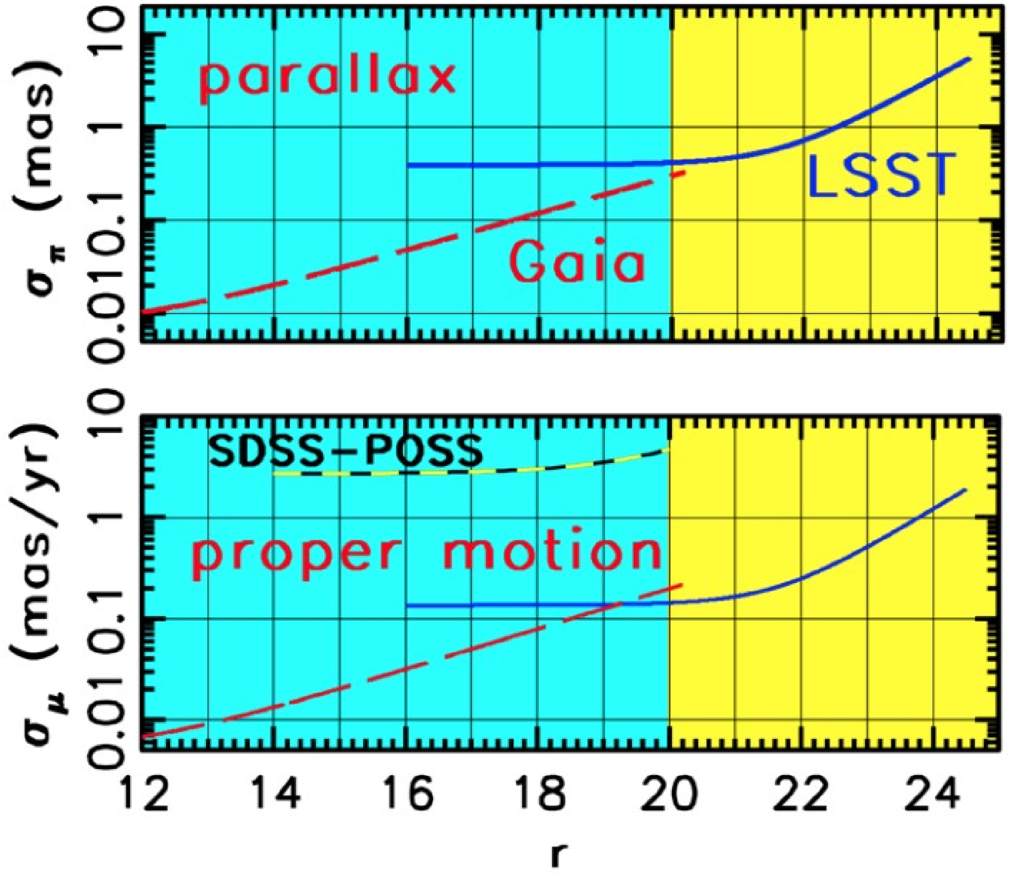
Data Management

- 15TB of raw science data per night (20 TB with calibrations)
- Data Management system to reduce the raw data, produce catalogues and images with minimum human intervention (Juric et al. 2017)
- Prompt products (transients): within 60s of the observations
- Annual DR products: (reduced and raw) single-epoch images, deep co-adds of the observed sky, catalogues of objects, and measurements
- 10 years of survey, 11 DRs, processed data ~ 500 PB, final catalogue ~ 15 PB
- Data fully public after 2 years

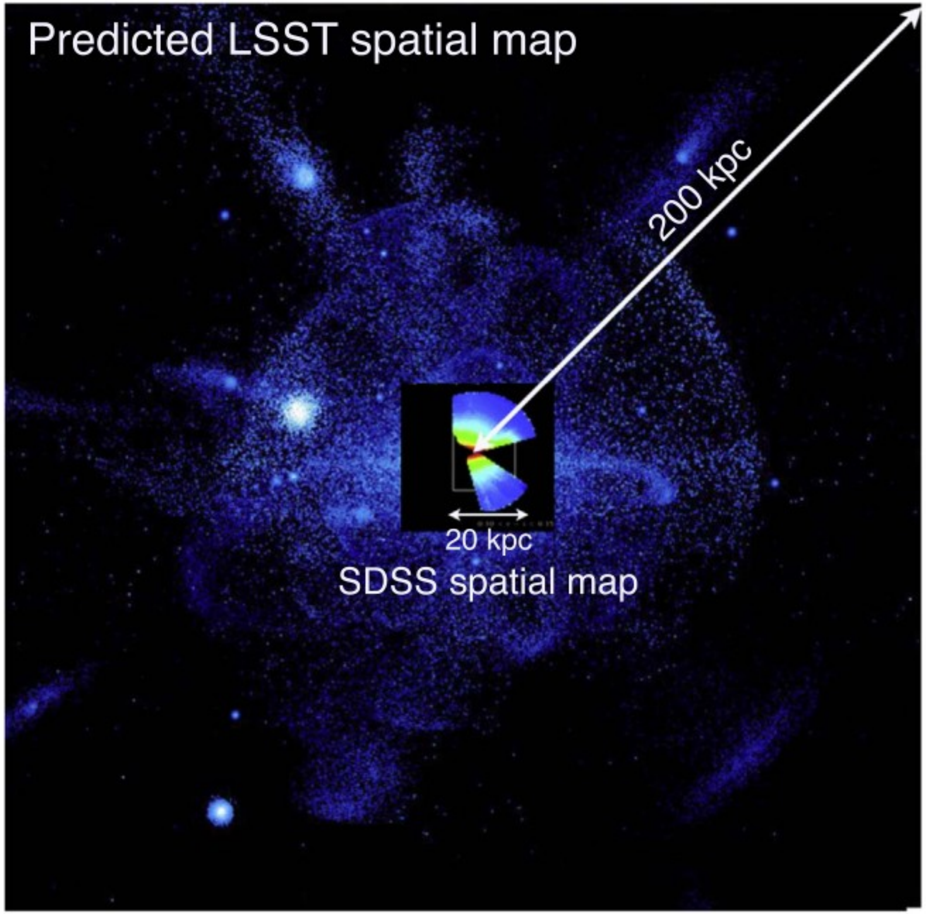


(Ivezic et al. 2019)

Milky Way Science Example



(Eyer et al. 2012)



(Ivezic et al. 2019)

Questions?

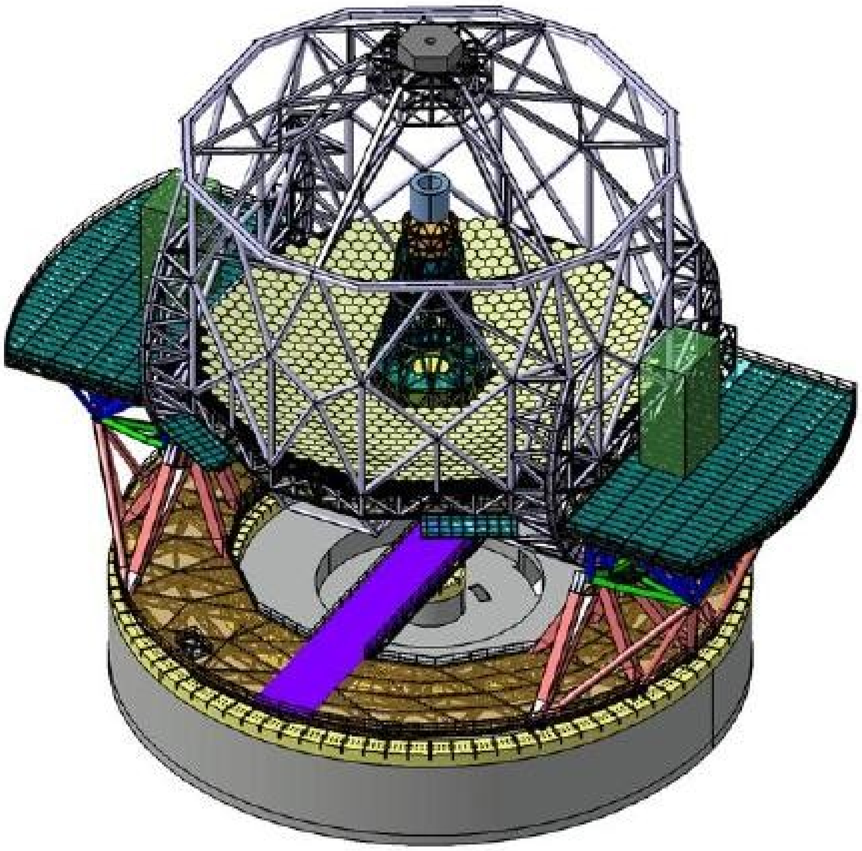
(Credit: Shutterstock)

The Extremely Large Telescope (ELT)

(Credit: ESO/P. Lapeyre)

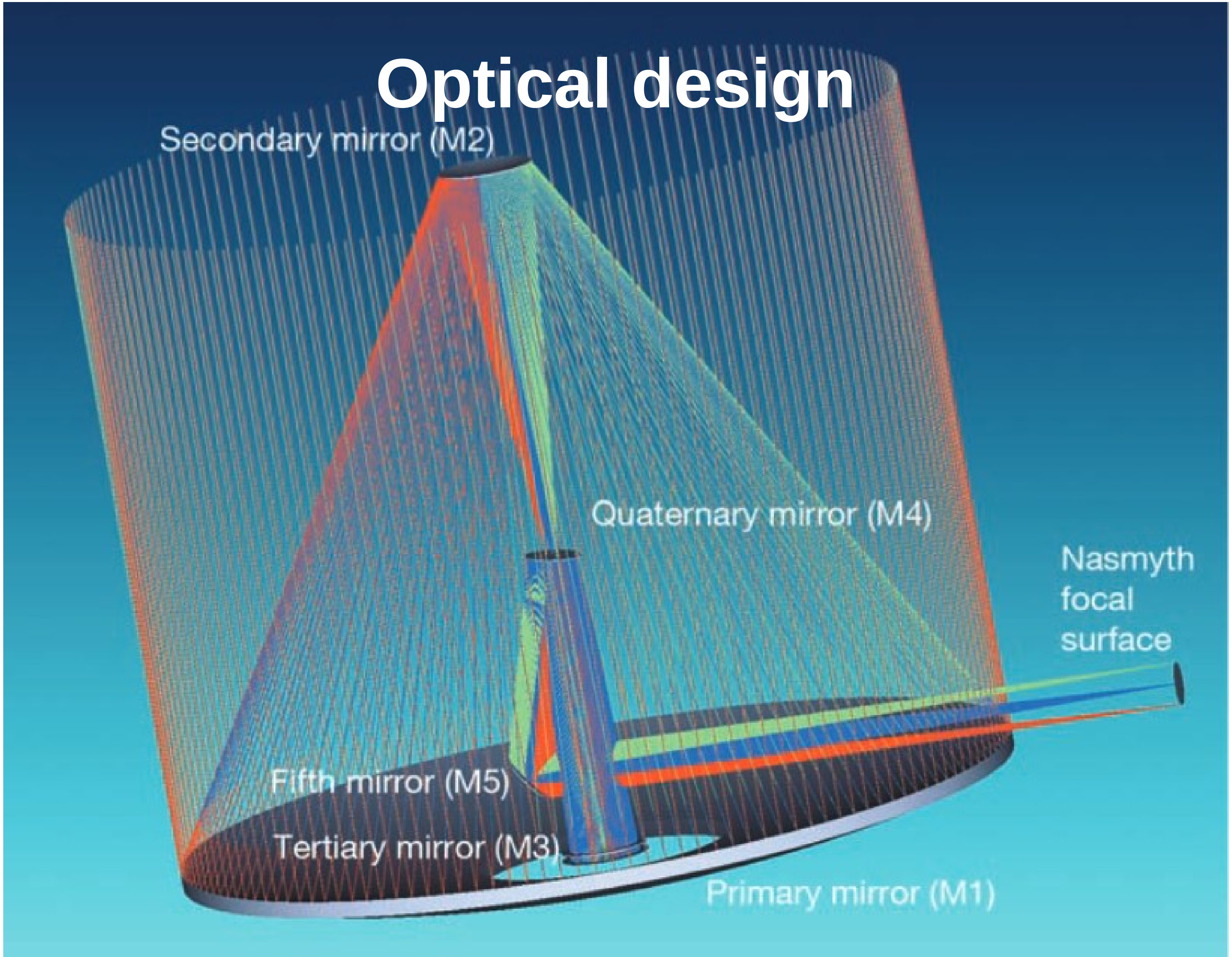
The Biggest Eye on the Sky

- 5 mirrors design: folded three-mirror anastigmat with two flat mirrors
- Two Nasmyth platforms (30m by 15 m) for hosting 3 instruments
- Alt-azimuth mount
- The structure weights ~2800 tons
- Pointing and tracking accurate to 1 and 0.3 arcseconds
- 39.3m segmented primary (initially planned to be 42m)
- FoV of 10 arcmin
- Central tower supports M3, M4 and M5, and also the ADC
- With active and adaptive optics



(Credit: ESO)

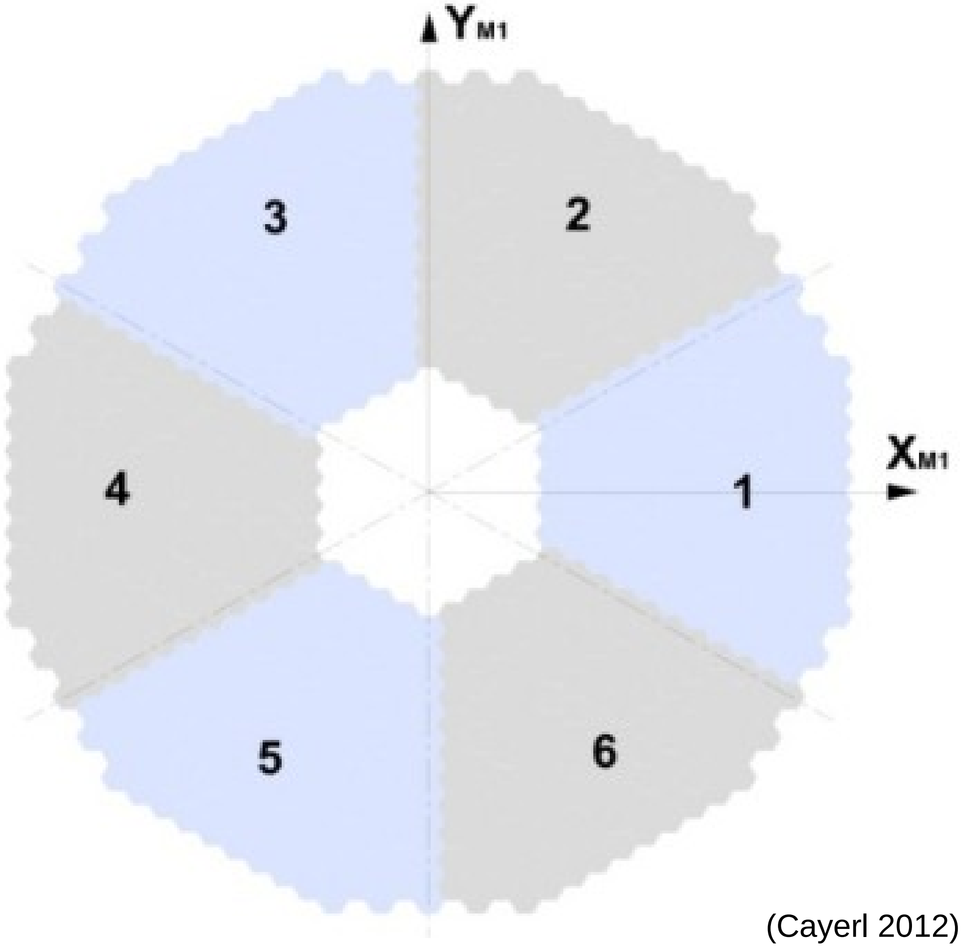
Optical design



(Credit: ESO)

Giant M1

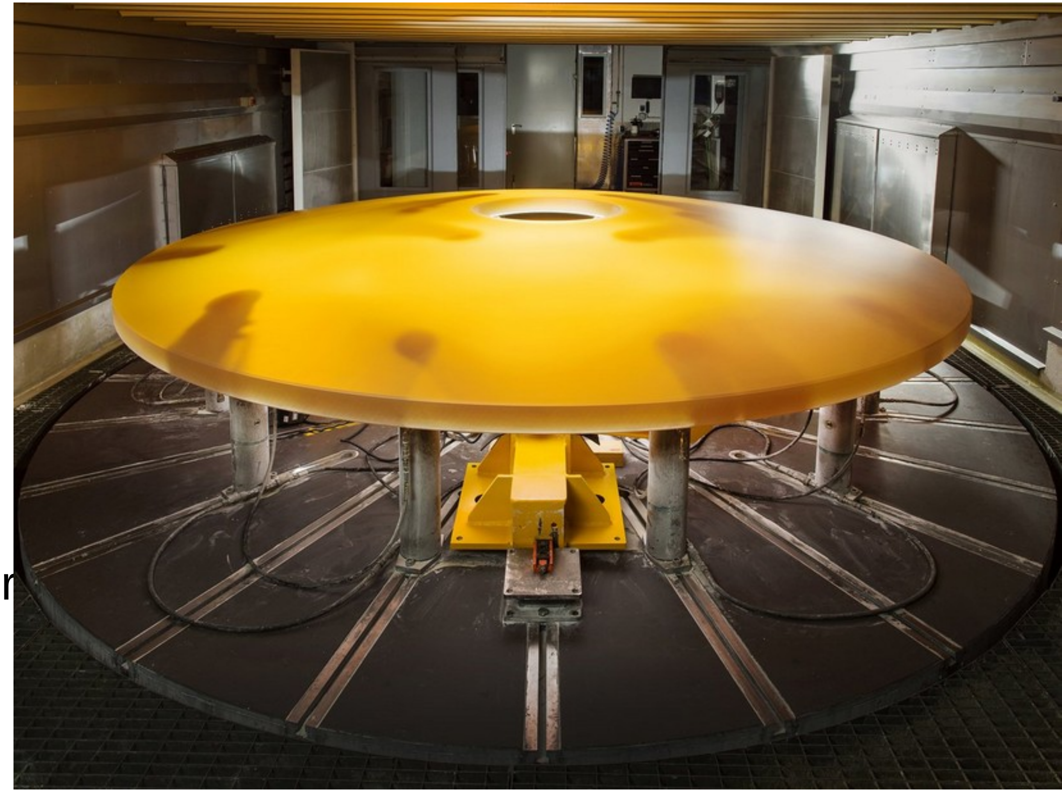
- 39.3m diameter with 11.1m central obstruction
- 798 segments (5cm thick, 1.45m, 250kg with support) made of Zerodur
- Parabolic concave, each segment aspheric
- 6 identical sectors of 133 segments (different from each other in shape and optical prescription)
- 7th sector kept for exchange during recoating
- Recoating every 18 months (1-2 segments every day)
- Each segment has 27, 6 and 3 pads for axial, lateral and azimuthal support
- 9 shape actuators for the active correction



(Cayerl 2012)

M2 and M3

- M2:
  - Convex, 4.25m thin (100mm) meniscus mirror made of Zerodur
  - 80cm central hole; aspheric surface
  - Held about 60m above ground over the M1
  - ~3.5 tons (the whole system ~12 tons)
  - 84 actuators for shape active control
- M3:
  - Concave, 4m thin (100mm) meniscus mirror made of Zerodur
  - 30-mm central hole
  - ~3.2 tons



(Credit: ESO)

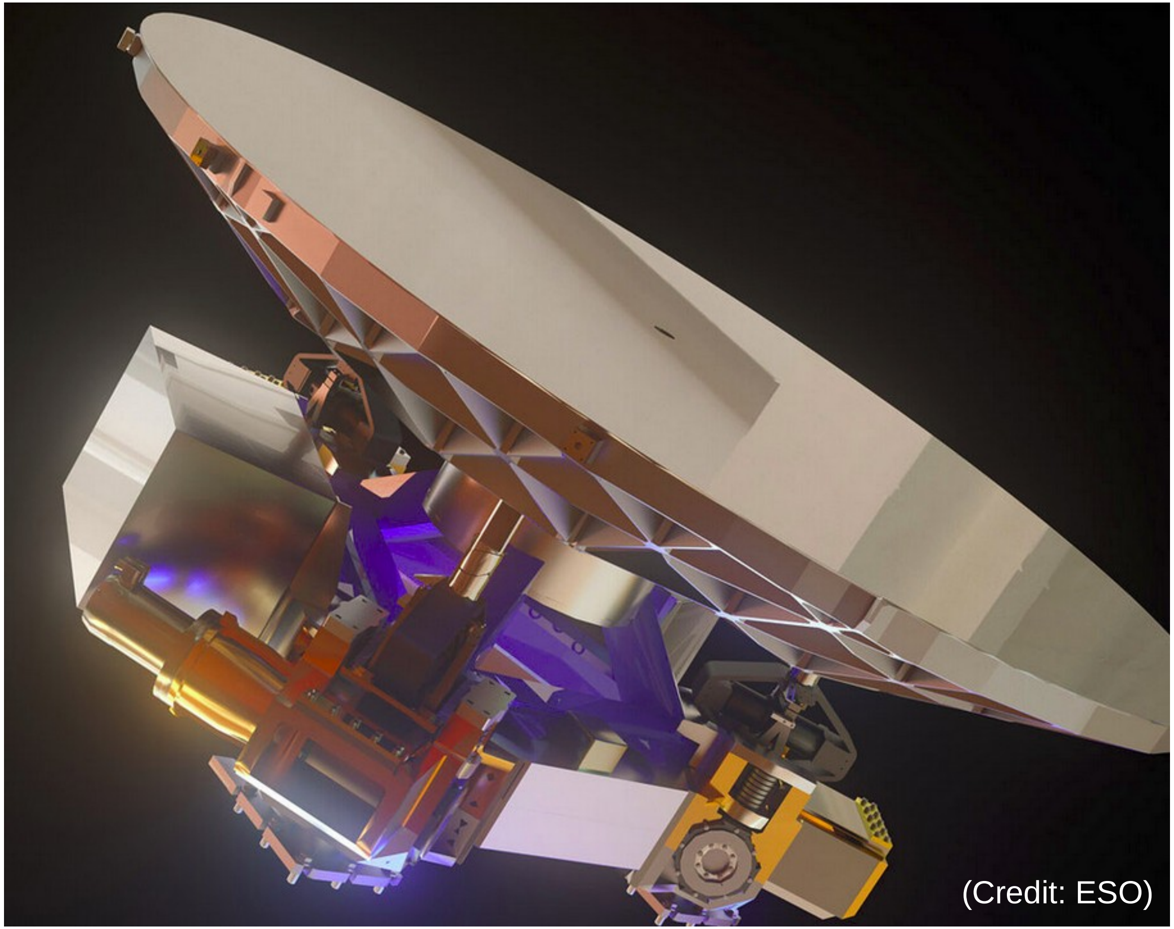
M4 (the adaptive mirror)

- 2.4m diameter, 6-petals, 1.95mm thick, flat mirror made of Zerodur
- 5000 actuators to change the shape of the mirror up to 1000 times per second
- Correct for atmospheric turbulence and vibration (its motion and wind)
- Tip, tilt, and lateral displacement control
- Sits on a reinforced structure of silicon carbide

(Credit: ESO)

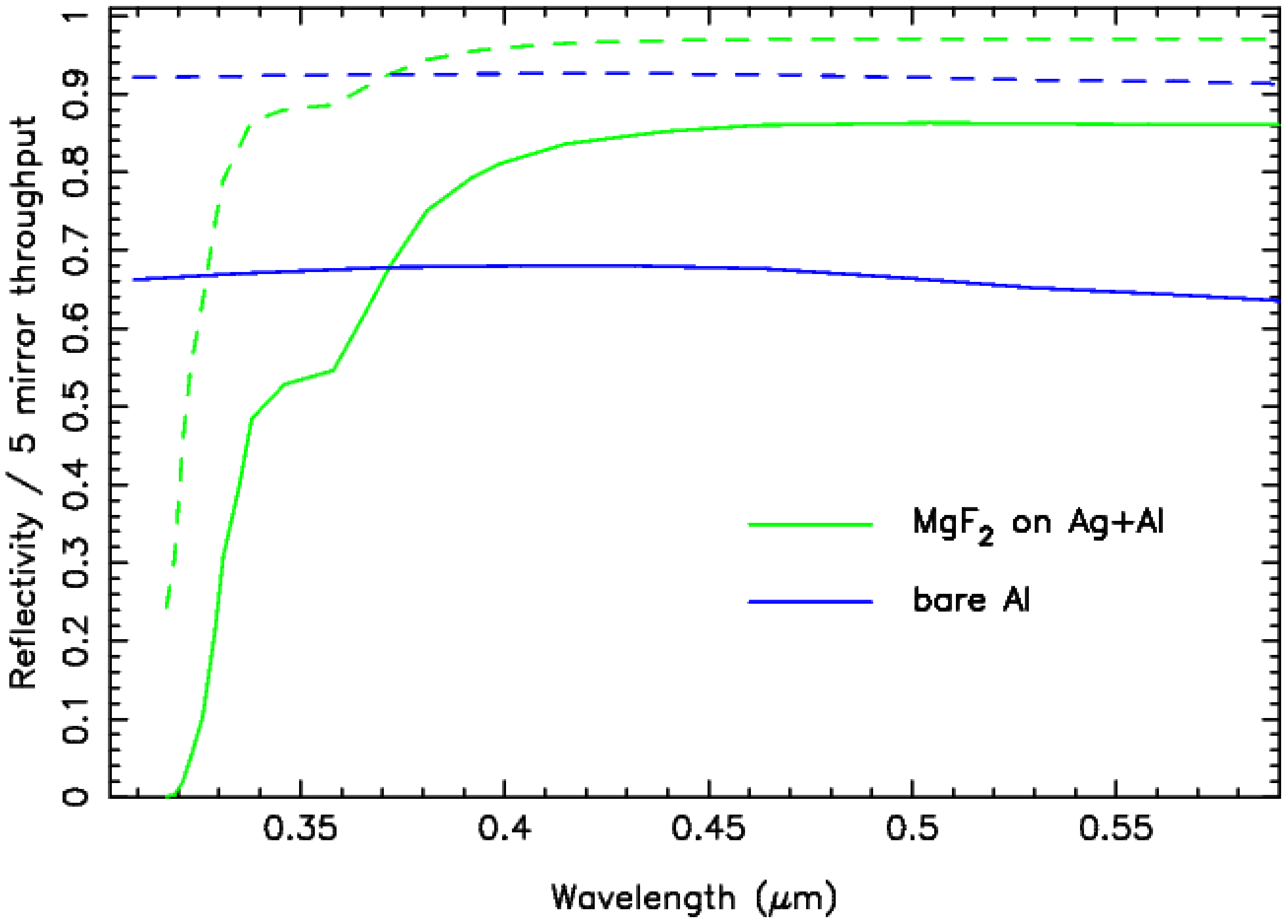
M5 (tip-tilt mirror)

- Flat mirror, elliptical shape, 2.7m x 2.2m, made of SiC (silicon carbide)
- 6 segments brazed together
- Fast (10Hz) tip-tilt system for image stabilisation
- Three tip-tilt actuators drive the mirror



(Credit: ESO)

Coating



(Credit: ESO)

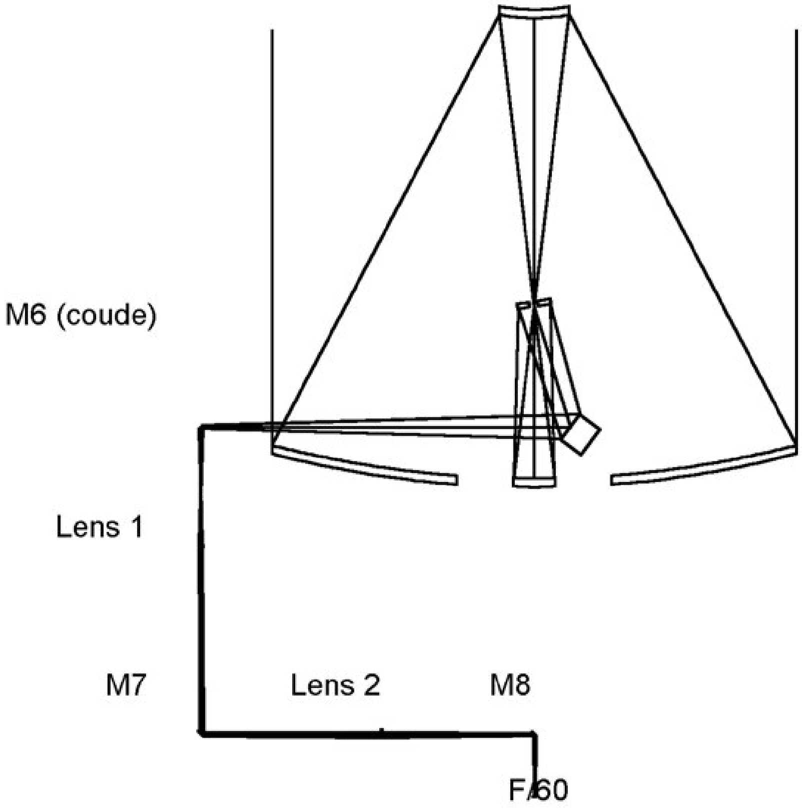
Adaptive optics

- Laser guide facility with 6-8 artificial stars
- 589nm Na laser (~80 km); same as for the VLT
- M4: deliver near infrared diffraction limited images with over 70% Strehl ratio (seeing ~ 0.85”)
- MAORY (Multi-conjugate Adaptive Optics RelaY): 3NGS + 6LGS
  - Works with near-infrared camera MICADO
  - Two deformable mirrors for extra layer of correction
- Instruments with different flavours of adaptive optics technology


(Credit: ESO)

Coude focus

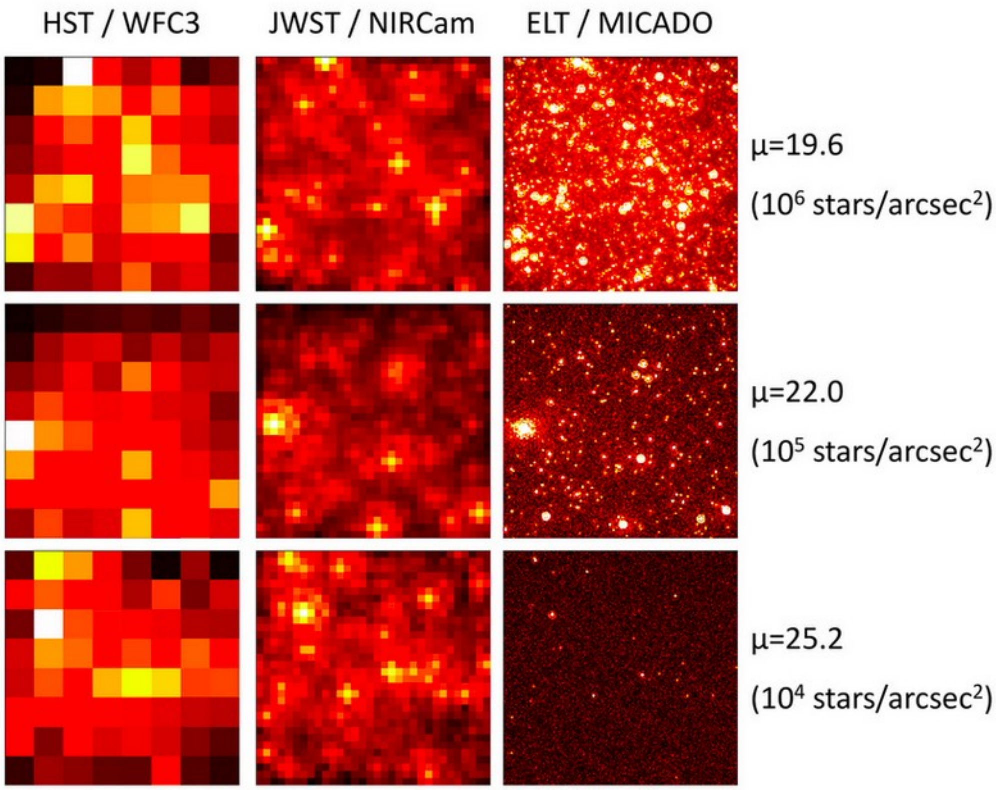
- The design allows for the beam to be redirected to a Coude focus
- Construction will have space for it at the ground level
- An instrument at this focus is not planned at this point
- But it could host a narrow field high-resolution ultra stable spectrograph
- Just in case something like this is planned in the future, all that is needed for this is being built



(Credit: ESO)

Instruments

- First generation:
  - **HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph)**
  - **MICADO (Multi-AO Imaging Camera for Deep Observations)**
  - **METIS (Mid-infrared ELT Imager and Spectrograph)**



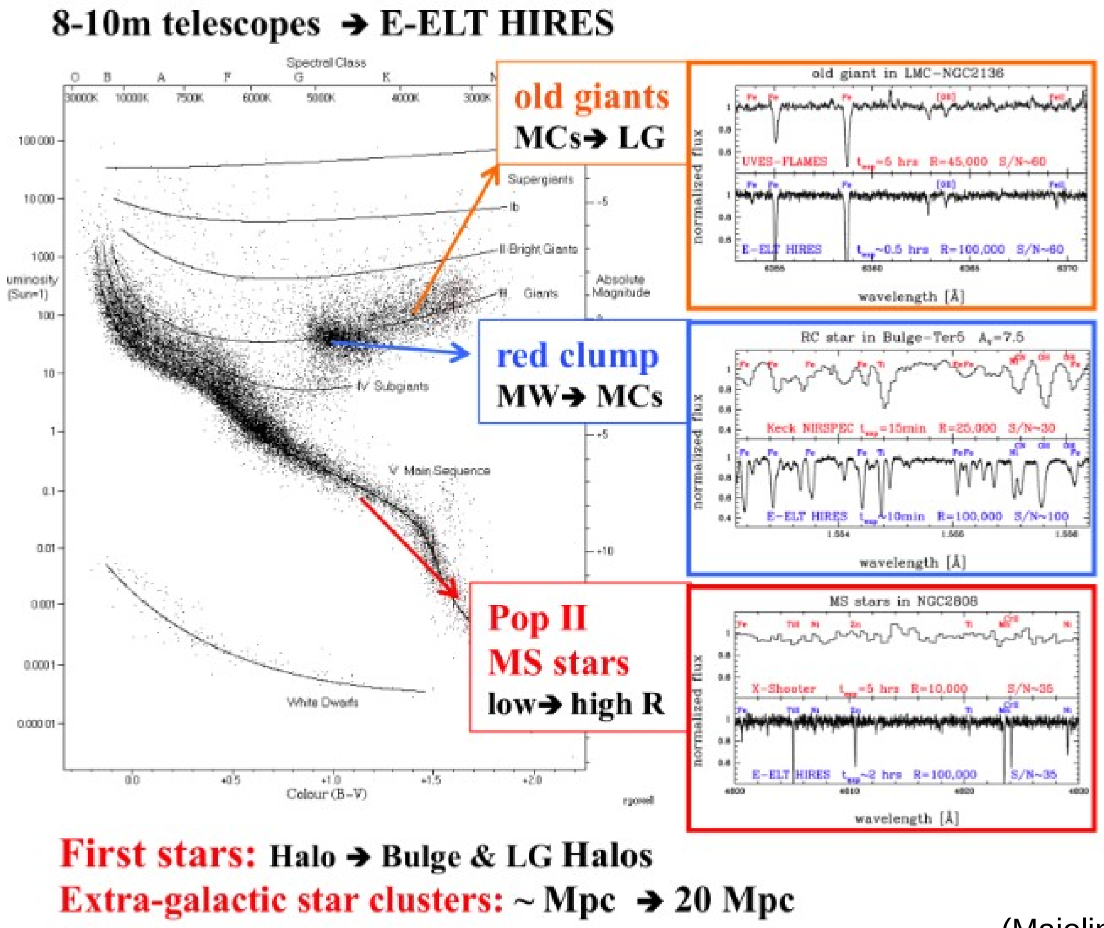
(Credit: ESO)

Instrument	Main specifications		
	Field of view/slit length/ pixel scale	Spectral resolution	Wavelength coverage (μm)
MICADO	Imager (with coronagraph) 50.5″ × 50.5″ at 4 mas/pix 19″ × 19″ at 1.5 mas/pix	*I, Z, Y, J, H, K* + narrowbands	0.8–2.45
	Single slit	*R* ~ 20 000	
MAORY	AO Module SCAO – MCAO		0.8–2.45
HARMONI + LTAO	IFU 4 spaxel scales from: 0.8″ × 0.6″ at 4 mas/pix to 6.1″ × 9.1″ at 30 × 60 mas/pix (with coronagraph)	*R* ~ 3 200 *R* ~ 7 100 *R* ~ 17 000	0.47–2.45
METIS	Imager (with coronagraph) 10.5″ × 10.5″ at 5 mas/pix in *L*, *M* 13.5″ × 13.5″ at 7 mas/pix in *N*	*L*, *M*, *N* + narrowbands	3–13
	Single slit	*R* ~ 1400 in *L* *R* ~ 1900 in *M* *R* ~ 400 in *N*	
	IFU 0.6″ × 0.9″ at 8 mas/pix (with coronagraph)	*L*, *M* bands *R* ~ 100 000	

(Credit: ESO)

Instruments

- Second generation:
  - ➔ **HIRES (HIgh REsolution Spectrograph)**
  - ➔ **MOSAIC (Multi-Object Spectrograph)**



(Maiolino et al. 2013)

Instrument	Main specifications		
	Field of view/slit length/ pixel scale	Spectral resolution	Wavelength coverage (μm)
HIRES	Single object	$R \sim 100\,000$	0.4–1.8 simultaneously
	IFU (SCAO)		
	Multi object (TBC)	$R \sim 10\,000$	
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	$R \sim 5\,000–20\,000$	0.45–1.8 (TBC)
	~ 8 IFUs (TBC)	$R \sim 5\,000–20\,000$	0.8–1.8 (TBC)

(Credit: ESO)

Instrument sizes

- The physical size of an image:

$$y = f \tan\theta = f\theta$$

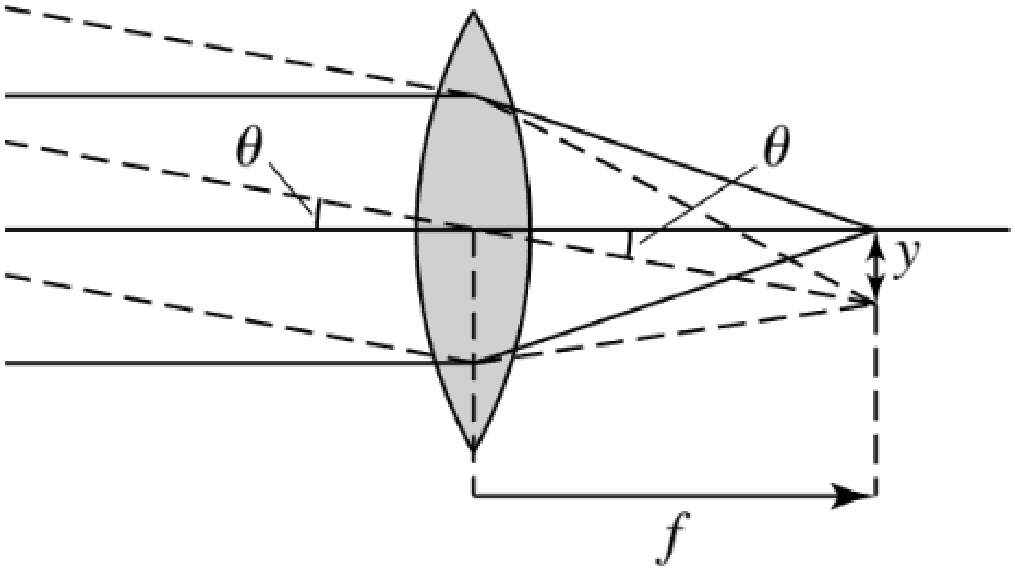
- And the f-ratio:

$$N = f/D$$

- In terms of the angle in arcsec:

$$y = 4.85 \times 10^{-6}\, N\, D\, \theta$$

- VLT Nasmyth: f/15 focal ratio
- ELT Nasmyth: f/17 focal ratio
- Image size ~5 times bigger for the ELT
- 1 arcsec is ~3.3mm
- 10 arcmin is ~ 1.98m

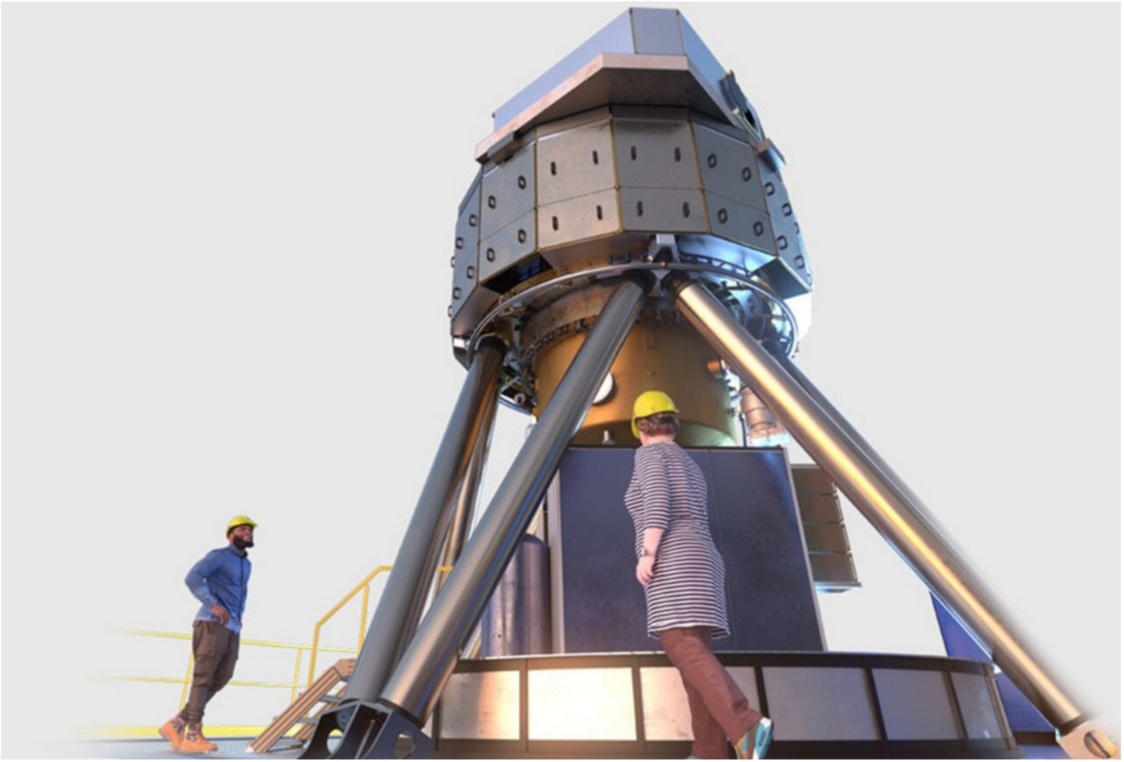


(Carroll & Ostlie 2017)

Instrument sizes

- How do you cover 2mx2m with CCDs? (4kx4k with 10μm pixels has ~4mm)

- For the instruments, you do not want to work in seeing limited case, but diffraction limited (easier in the IR)
- Tricks can be used to, e.g., slice the pupil for spectroscopy (Spano et al. 2006)
- Or you don't use the whole field:
  - MICADO has a focal plane 264x268mm (~53"x53") see Davies et al. (2010)



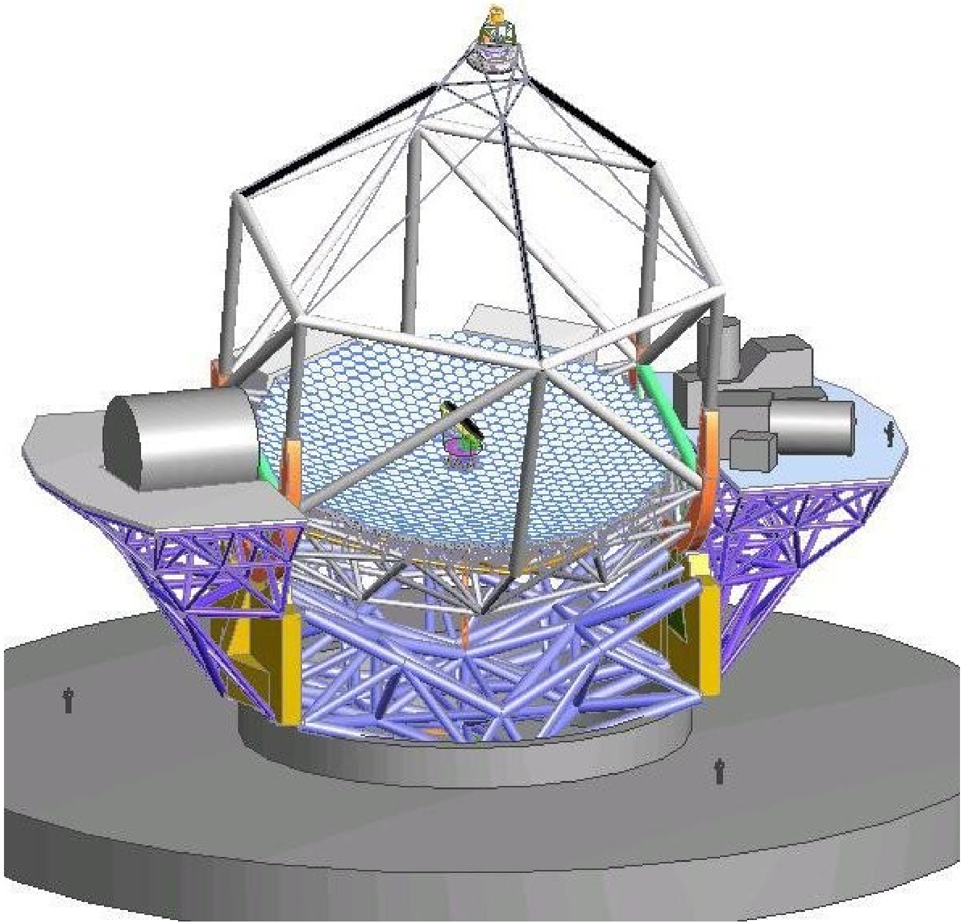
(Credit: ESO)

Questions?

(Credit: Shutterstock)

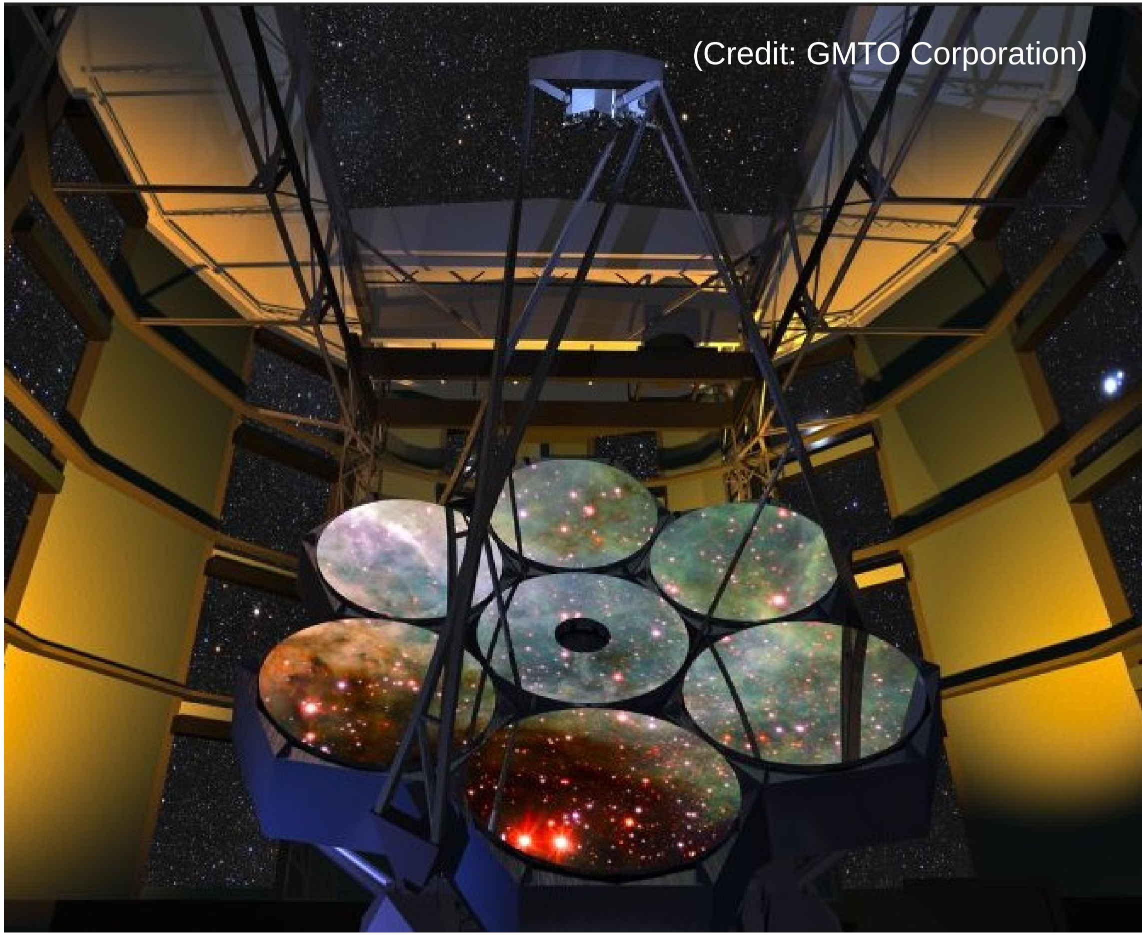
Thirty Meter Telescope (TMT)

- A folded Ritchey-Chrétien design with 3 mirrors
- Primary has 30m aperture with 492 segments
- Primary an secondary are hyperboloids
- The tertiary (flat) mirror folds the beam to eight instruments on the two Nasmyth platforms.
- Focal ratio ~ f/15
- Near-ultraviolet to mid-infrared (0.31 to 28 μm) with adaptive optics
- Mauna Kea is the preferred site, with Roque de Los Muchachos on the Canary Islands as secondary option



Giant Magellan Telescope (GMT)

- Primary: 7x8.4m honeycomb segments
- Secondary: 7x1.05m segments (adaptive mirrors)
- Gregorian design
- Area equivalent to 22m aperture
- Mirrors of borosilicate glass
- Near-ultraviolet to mid-infrared (0.32 to 25 μm) with adaptive optics
- Las Campanas Observatory, Chile, site of the Magellan telescopes



ELT in Comparison

- ELT:
  - Larger collecting area and better spatial resolution
  - Smaller field of view, 5 reflections
  - Optimized for diffraction-limited
- GMT:
  - Smaller collecting area
  - Wide field of view, seeing limited observations
  - Might host multi-object, survey instruments
- TMT:
  - Adaptive optics with a MCAO system
  - Wide field of view
  - Seeing limited observations

REFERENCES

- Baker 1969 (ITAES, 5, 261)
- Carrol & Ostlie 2017 (An Introduction to Modern Astrophysics)
- Cayrel 2012 (Proc. SPIE, 8444, 84441X)
- Davies et al. 2010 (Proc. SPIE, 7735, 77352A)
- Eyer et al. 2012 (Proc. IAUS 282, 33)
- Hill et al. 1998 (Proc. SPIE, 3352, 172)
- Ivezic et al. 2019 (ApJ, 873, 111)
- Juric et al. 2017 (ASPC 512, 279)
- Maiolino et al. 2013 (arXiv:1310.3163)
- McLean 2008 (Electronic Imaging in Astronomy)
- Neill et al. 2016a (Proc. SPIE, 9906, 99060Q)
- Neill et al. 2016b (Proc. SPIE, 9906, 990667)
- Olivier et al. 2012 (Proc. SPIE, 8446, 84466B)
- Spano et al. 2006 (AN, 327, 649)