



The Era of Extremely Large (Optical) Telescopes

Exploring the Universe at
Unprecedented Scales

ELT • TMT • GMT • Vera C. Rubin
Observatory

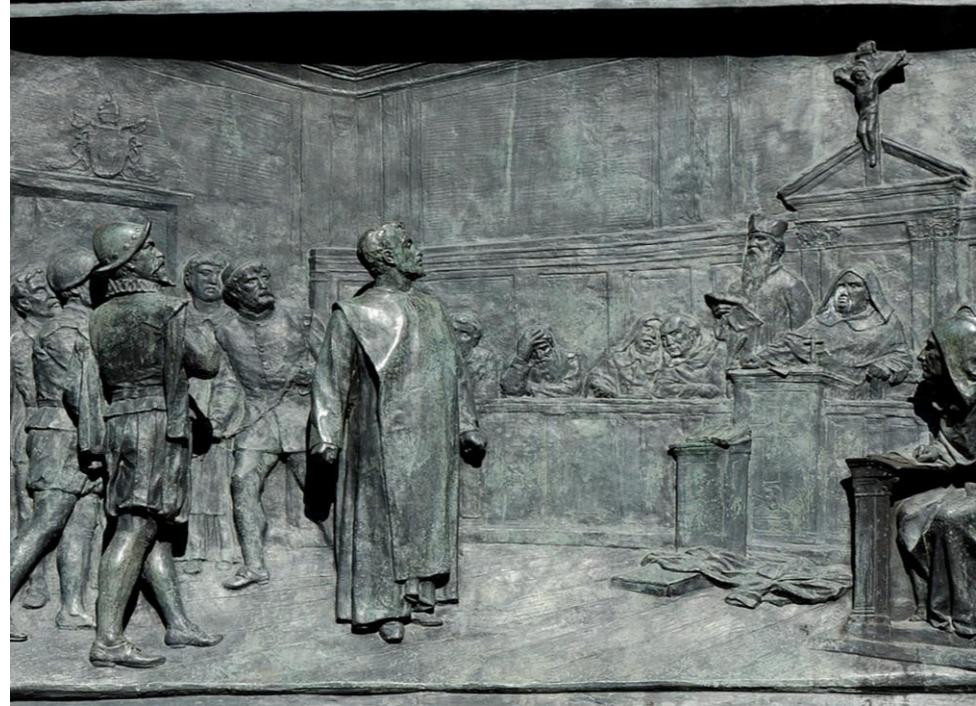
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A Martyr for Free Thought

- **Giordano Bruno** : death February 17, 1600, in Rome's Campo de' Fiori. After a seven-year trial by the Roman Inquisition, he was executed for his radical theological views—including pantheism and denial of core doctrines—and his cosmological belief in an infinite universe. He proposed that the stars were distant suns surrounded by their own planets (exoplanets), and he raised the possibility that these planets might foster life of their own, a cosmological position known as cosmic pluralism. He also insisted that the universe is infinite and could have no centre.
- The Inquisition found him guilty, and he was burned at the stake in Rome's Campo de' Fiori in 1600. After his death, he gained considerable fame, being particularly celebrated by 19th- and early 20th-century commentators who regarded him as a martyr for science.



A Brief History of the Telescope Apertures

The Refractor Era (1609 – c. 1750)}

- Galileo (1609): 1.5~in — first telescopic views of Jupiter's moons, lunar craters.
- Huygens (c. 1655): 5~in — long, tubeless 'aerial' telescopes.

The Great Refractor & Early Reflector Era (c. 1750 – 1910)

- William Herschel (1789): 1.2~m metal-mirror reflector
- Leviathan of Parsonstown (1845): 1.8~m metal mirror
- Yerkes Refractor (1897): 1.02~m — largest successful refractor ever built

The Modern Glass-Mirror Reflector Era (c. 1900 – 1990)

- Hooker Telescope (1917): 2.54 m — proved galaxies exist beyond the Milky Way .
- Hale Telescope (1948): 5.08 m — ruled for 45 years; discovered quasars; monolithic mirror limit approached
- Soviet BTA-6 (1976): 6.0 m — plagued by engineering issues; demonstrated practical limit of single-piece mirrors

The Segmented Mirror & Adaptive Optics Era (c. 1990 – 2010)

- Keck Telescopes (1993, 1996): 10 m (36 segments, 3 actuators ACS, optical interferometry) — broke the monolithic barrier; template for all future ELTs.
- Very Large Telescope (VLT, 1998–2000): Four 8.2 m units; interferometry mode achieves virtual 130 m resolution.
- Adaptive Optics (1990s–present): Deformable mirrors correct atmospheric blur in real time.

The Extremely Large Telescope (ELT) Era (2020s – Future)

- Current Record Holders: Gran Telescopio Canarias (10.4 m, 2009); Hobby-Eberly Telescope (11 m x 10 m, upgraded 2015).

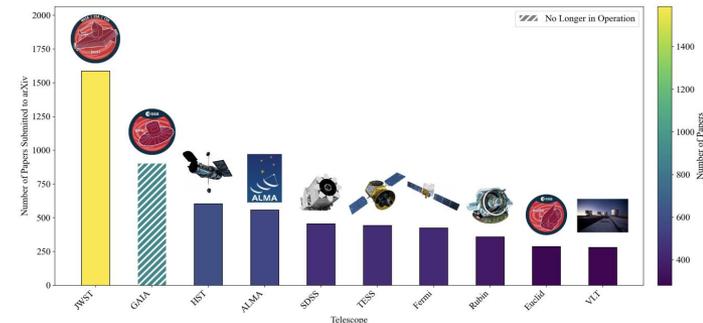
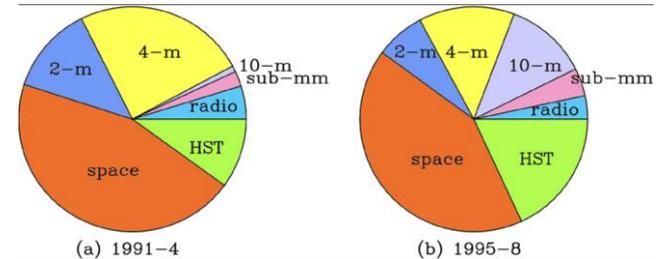
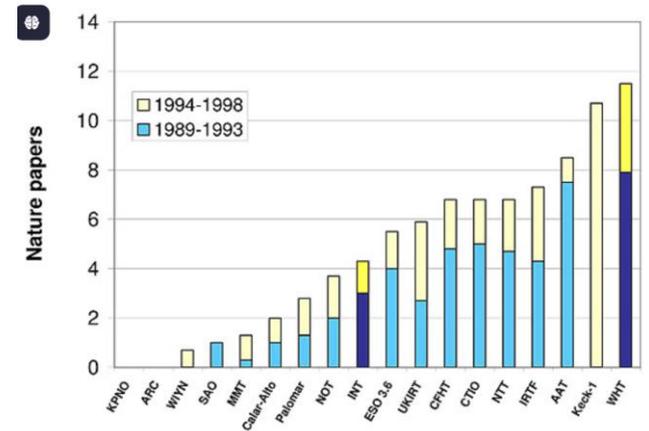
Under Construction:

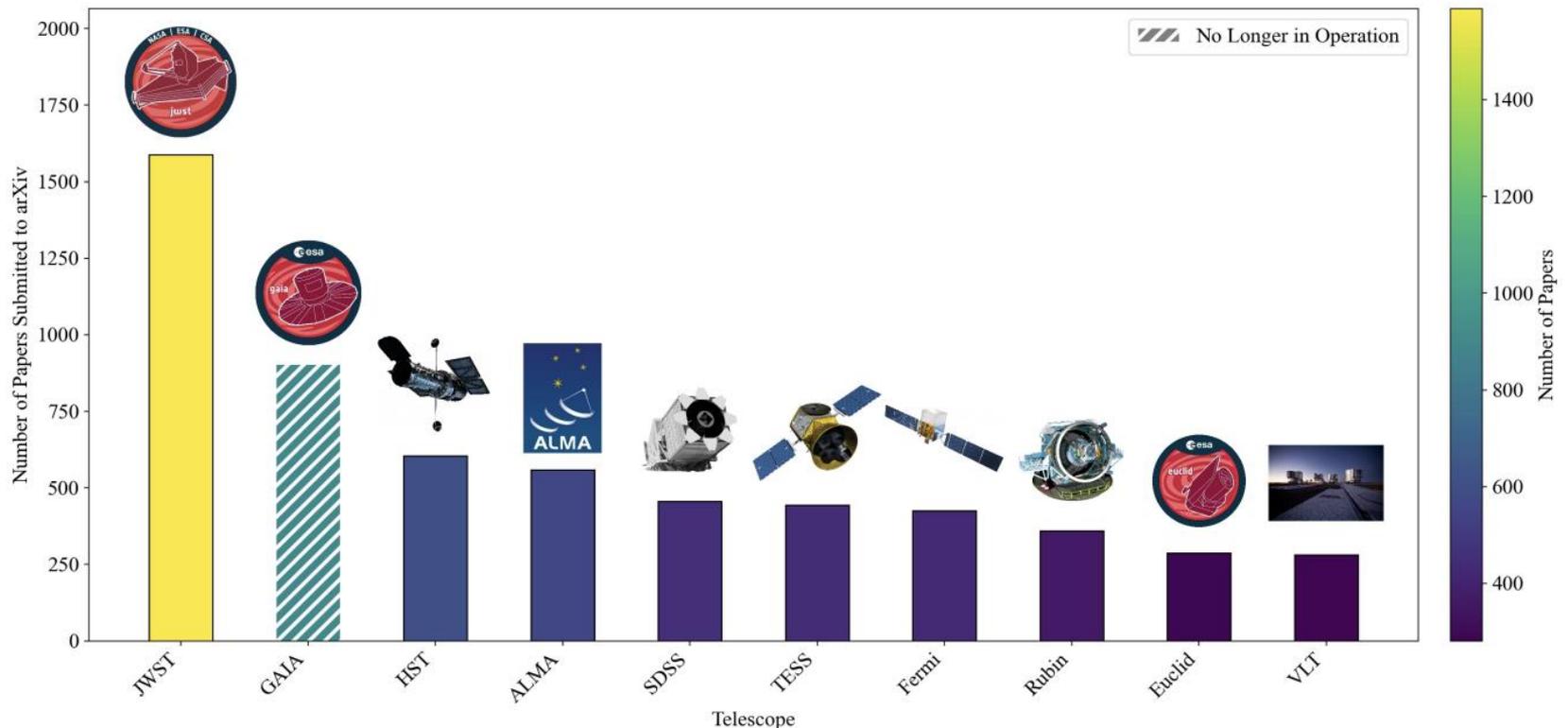
- Giant Magellan Telescope (GMT): 25.4 m effective aperture (seven 8.4 m monolithic mirrors)
- Thirty Meter Telescope (TMT): 30 m segmented (492 pieces). Site pending.
- European Extremely Large Telescope (ELT): 39 m segmented (798 pieces). First light ~2028.
- The Vera C. Rubin Observatory, located on Cerro Pachón in Chile, is a revolutionary astronomical facility designed to conduct the 10-year Legacy Survey of Space and Time (LSST). Featuring an 8.4-meter telescope and the world's largest 3,200-megapixel digital camera, it will image the entire southern sky every few nights to study dark matter, dark energy, and transient cosmic events.

Why Large Telescopes?

- Bigger aperture: Bigger bucket- fainter sources of light
- Bigger aperture: Better Resolution $R=1.22 \lambda/D$ where λ is wavelength, D is the diameter of the objective, and R is the resolution in seconds of arc. HST (2.4 m) $R = 134/2400 = 0.06''$ arcseconds or 60 milliarcseconds
- However, Field of View (FOV) decreases.

This is given by: Real FOV = Eyepiece FOV/Magnification. So, to observe the full moon ($\$0.5^{\{0\}}\$$) for a telescope with eyepiece with a FOV of $60'$, the magnification will need to be 120X





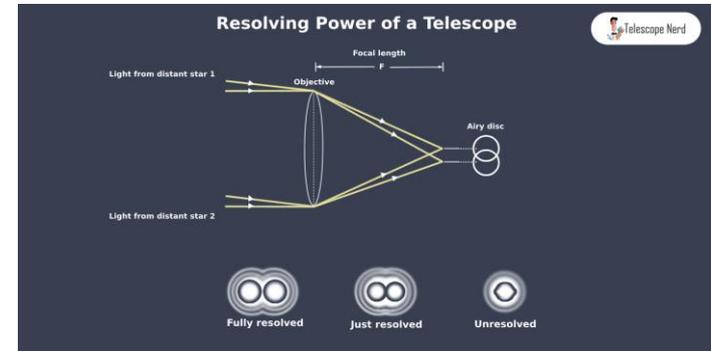
Top 10 Most Mentioned Telescopes in 2025 arXiv papers. The number of papers are represented both as the relative height of the bars and as a colour map for readers with different visual preferences for interpreting data

Resolution

Resolution $R=1.22 \lambda/D$

Other key steps to enhance resolution include:

- **Using shorter wavelengths:** Observing in shorter wavelengths (e.g., blue or ultraviolet light) increases the resolving power.
- **Improving optical quality:** Using high-quality optics reduces image distortion, thereby increasing the effective resolution.
- **Using Adaptive Optics:** For ground-based telescopes, implementing adaptive optics corrects for atmospheric turbulence, improving image sharpness.
- **Reducing "atmospheric seeing":** Placing telescopes at high altitudes or in space minimizes atmospheric interference.



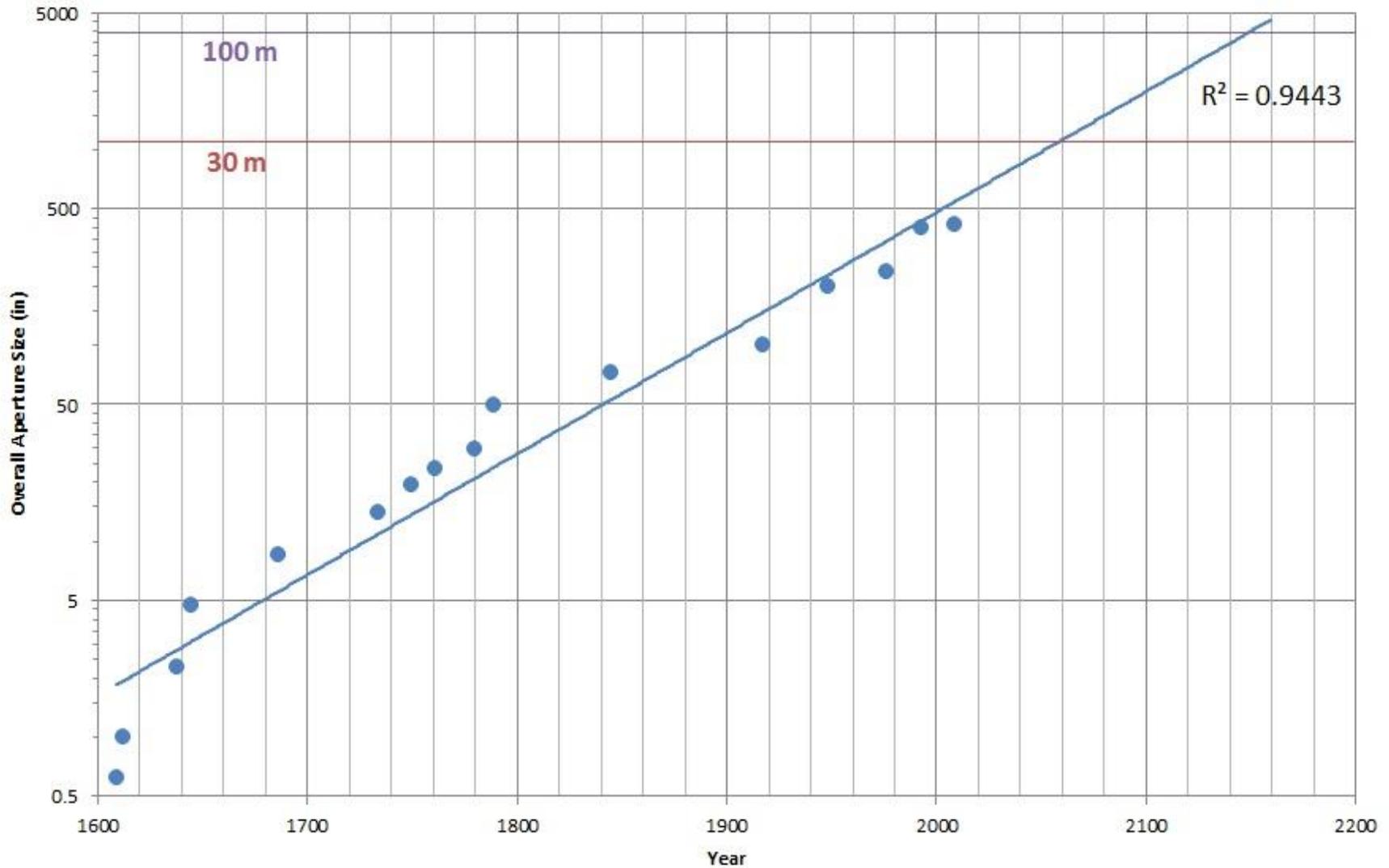
Is big always better?

TABLE 1. High-Impact Observatories

Rank	Facility	Citations	Participation
1	SDSS	1892	14.3%
2	Swift	1523	11.5%
3	HST	1078	8.2%
4	ESO	813	6.1%
5	Keck	572	4.3%
6	CHFT	521	3.9%
7	Spitzer	469	3.5%
8	Chandra	381	2.9%
9	Boomerang	376	2.8%
10	HESS	297	2.2%

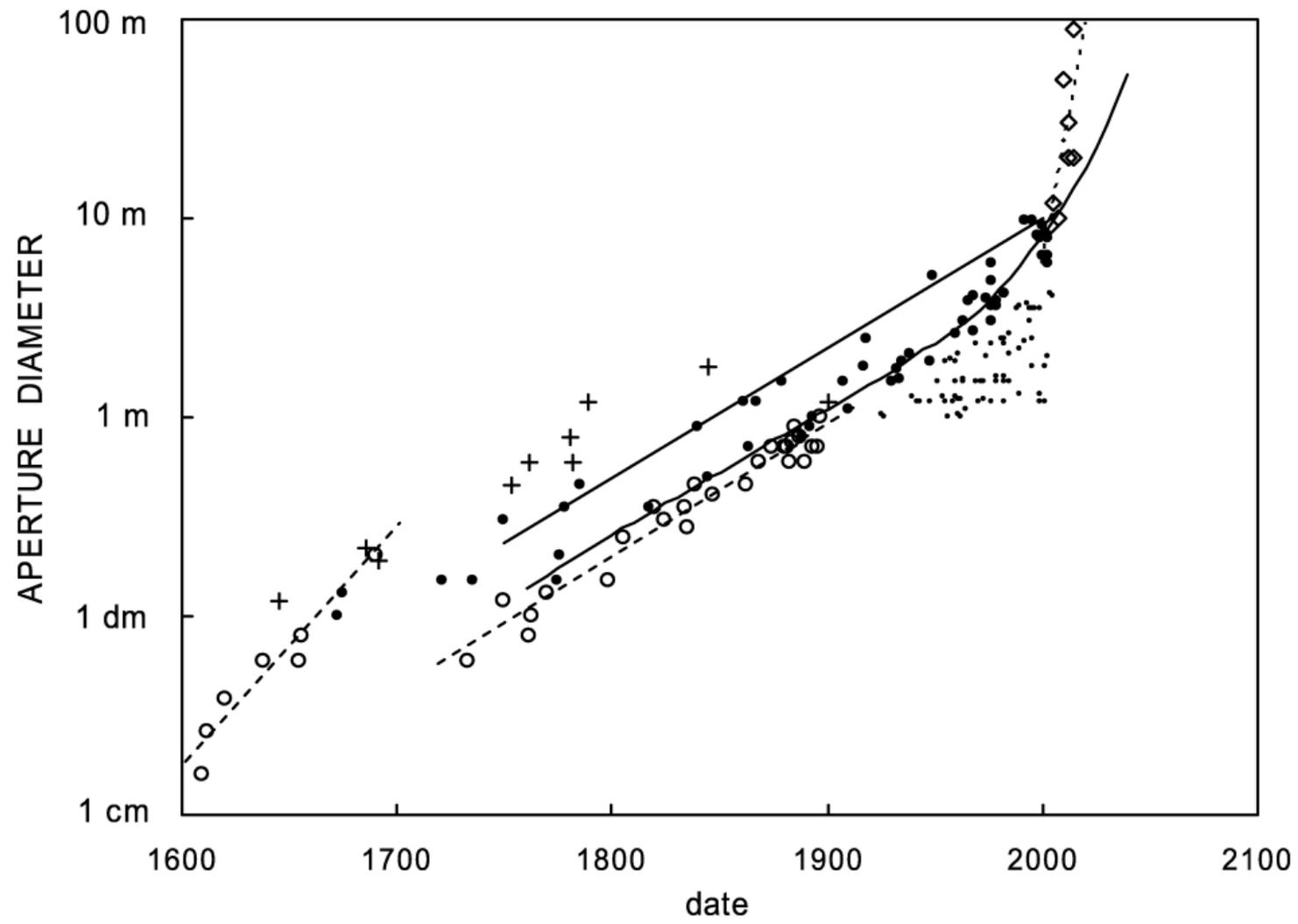
Based on 2006 data, Madrid 2006

Largest Optical Telescopes



Size doubles every 40 years!!

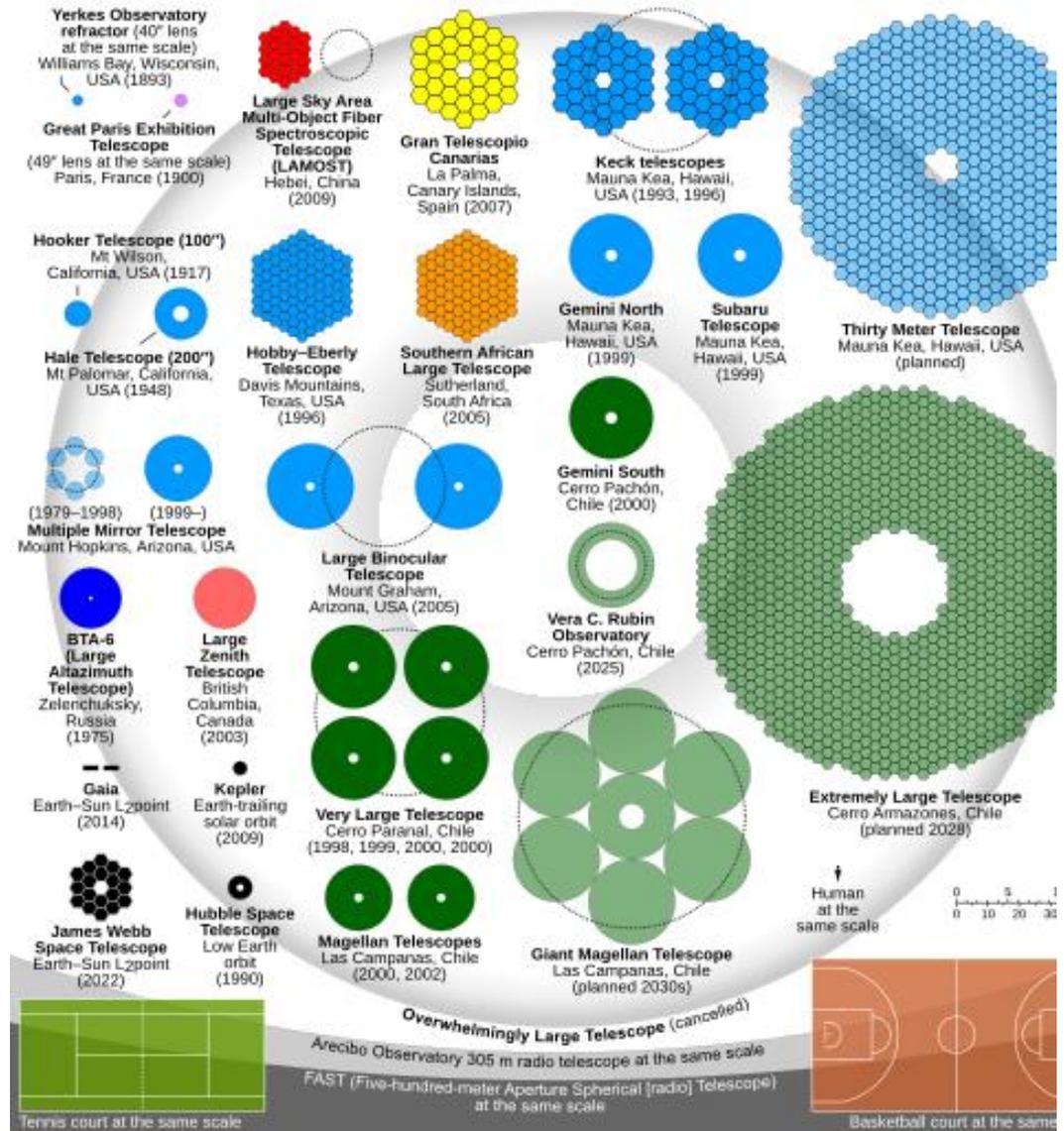
The trend line posits a TMT around 2060. OWL is around 2150 *Racine(2004)*



Why Bigger Telescopes?

- Light-gathering power scales with mirror size
- Higher resolution reveals finer cosmic details
- Access to fainter and more distant objects
- Key to studying early universe and exoplanets

The aperture doubling time has hovered around 40-50 yr for 4 centuries, and the transitions from one technology to the next did not spectacularly break the trend! (Racine 2006)



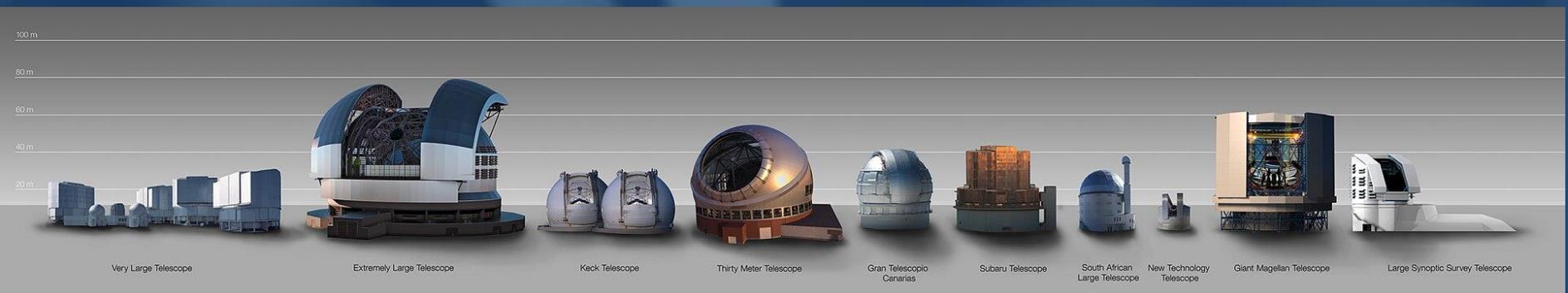
What Are Extremely Large Telescopes (ELTs)?

- Optical–infrared telescopes with mirrors >20 m

- Use segmented primary mirrors

- Advanced adaptive optics systems

- Ground-based but rival space telescopes

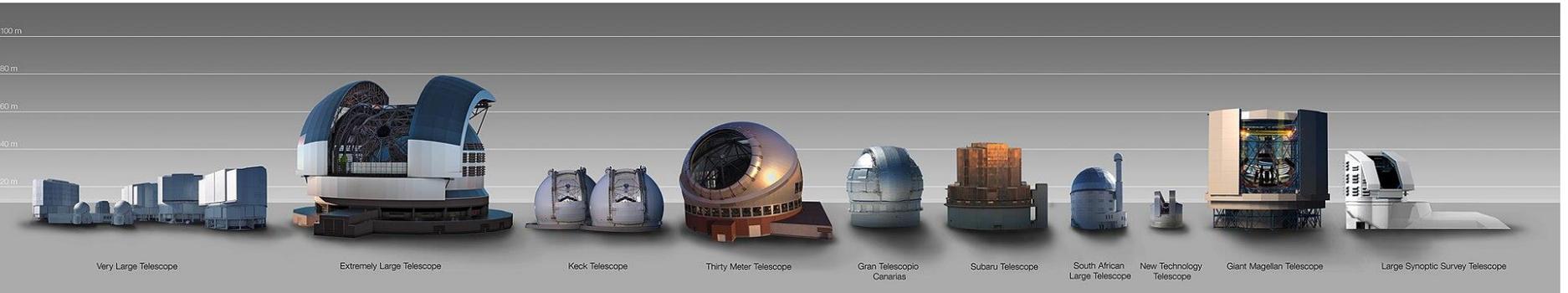


Projects

Some of these projects have been cancelled, or merged into ongoing extremely large telescopes.

- GSMT:^[22] **Giant Segmented Mirror Telescope**, merged into TMT
- OWL:^[23] **Overwhelmingly Large Telescope**, passed over in favor of ELT
- VLOT:^[24] **Very Large Optical Telescope**, merged into TMT
- LAT:^[25] **Large Atacama Telescope**
- EURO50:^[26] **European 50-metre Telescope**, merged into ELT
- LPT:^[27] **Large Petal Telescope**
- Magellan 20: merged into **GMT**
- HDRT:^[28] **High Dynamic Range Telescope**
- JELT:^[29] **Japanese ELT Project**; Japan joined the TMT project in 2008
- CELT:^[30] **California Extremely Large Telescope**, became/merged into TMT
- MAXAT:^[31] **Maximum Aperture Telescope**

Name	Cost (est. USD)	Alternate
Extremely Large Telescope (ELT)	\$1590 million	€1300 million ^[17]
Thirty Meter Telescope (TMT)	\$1400 million	\$3600 million ^{[18][12]}
Giant Magellan Telescope (GMT)	\$1000 million	\$2540 million ^[18]
Large Binocular Telescope (LBT)	\$120 million	



The Extremely Large Telescope (ELT)

- 39-meter primary mirror (ESO, Chile)
- Largest optical telescope ever built
- Focus: exoplanets, first galaxies, dark matter
- First light expected later this decade



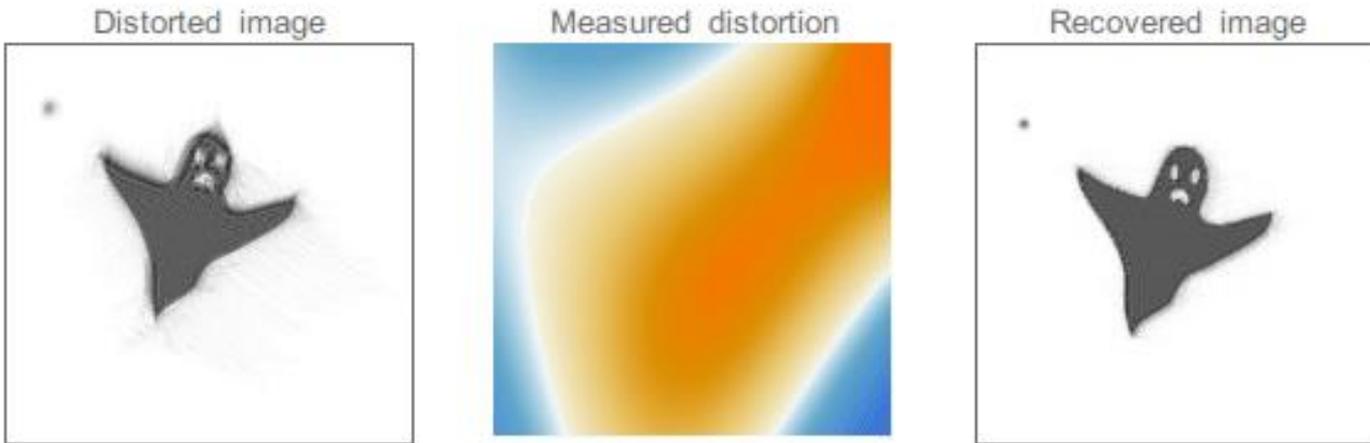


The Extremely Large Telescope (ELT)

- When completed, it will be the world's largest optical and near-infrared extremely large telescope.
- European Southern Observatory (ESO)
- Cerro Armazones in the Atacama Desert of northern Chile, 23 km from the existing facilities at Paranal Observatory.

- Reflecting telescope, 39.3-m-diameter **segmented primary mirror** and a 4.25 m (14 ft) diameter secondary mirror.
- **adaptive optics**, six **laser guide star** units, and various large-scale scientific instruments
- 100 million times more light than the human eye,
- 10 times more light than the largest **optical telescopes** in existence as of 2025
- ability to correct for atmospheric distortion.
- 250 times the light-gathering area of the HST, images 15 times sharper than those from Hubble.

Adaptive optics



- Atmosphere blurs astronomical images
- Adaptive optics correct distortions in real time
- Laser guide stars create artificial reference stars
- Achieves near-space resolution from the ground

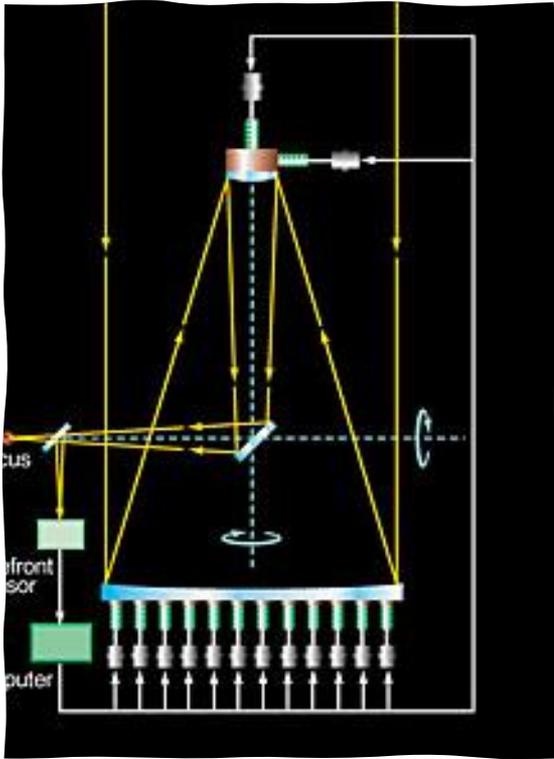
Adaptive Optics: Beating Earth's Atmosphere

- Atmosphere blurs astronomical images

- Adaptive optics correct distortions in real time

- Laser guide stars create artificial reference stars

- Achieves near-space resolution from the ground



Active Optics

Compensates for slow deformations caused by gravity, temperature changes, and wind, allowing for the use of thin, flexible, or segmented mirrors.

Key Differences:

Active Optics (Structural/Slow): Maintains the primary mirror's optimal shape against gravity and thermal changes, allowing for larger, thinner mirror construction. It compensates for slow (roughly 1 Hz) distortions.

Adaptive Optics (Atmospheric/Fast): Uses deformable mirrors to correct high-frequency (100–1000 Hz) image distortions caused by atmospheric turbulence. It enables ground-based telescopes to reach diffraction-limited resolution.

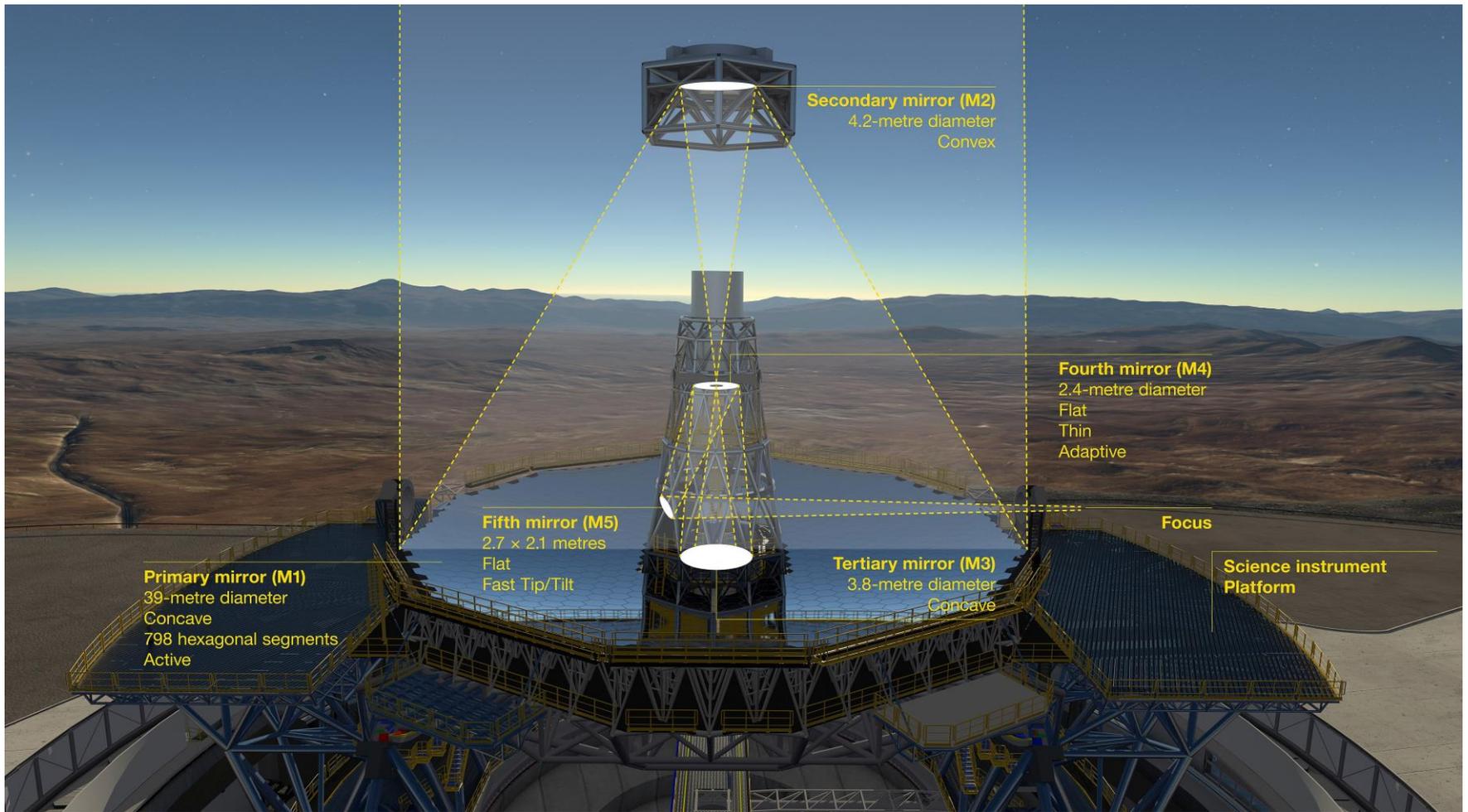
Correction Speed: Active optics is slow; Adaptive optics is very fast.

Scale of Errors: Active optics deals with large-amplitude, low-frequency errors, while adaptive optics manages small-amplitude, high-frequency errors.

Application: Active optics is standard on most large modern telescopes to maintain shape, whereas adaptive optics is used for real-time atmospheric compensation.

ELT Construction

- Construction work on the ELT site started in June 2014. By December 2014, ESO had secured over 90% of the total funding and authorized construction of the telescope to start, estimated to cost around one billion [euros](#) for the first construction phase. The first stone of the telescope was ceremonially laid on 26 May 2017, initiating the construction of the dome's main structure and telescope.
- The telescope passed the halfway point in its development and construction in July 2023, with the expected completion and [first light](#) set for March 2029
- [Here](#)

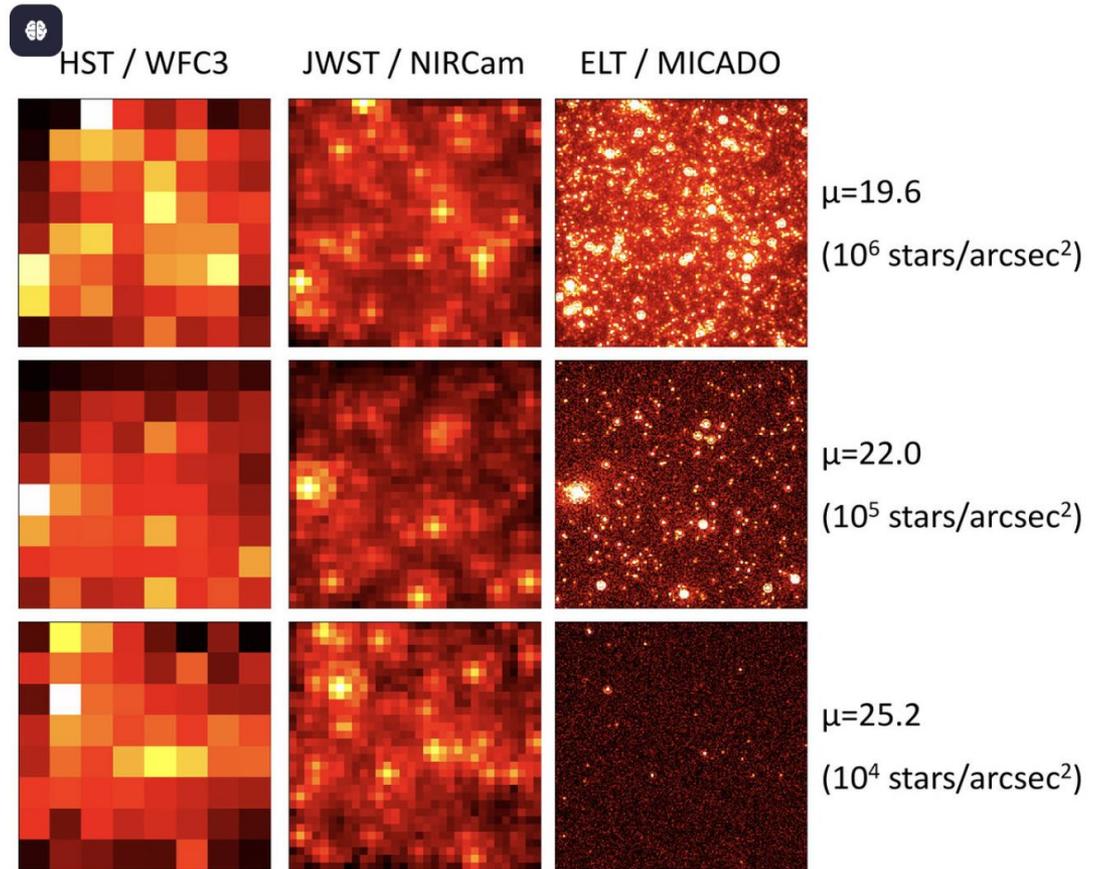


The M1 Cell: The massive frame that holds the 798 segments of the primary mirror.
The M2 Assembly: A 3.5-ton secondary mirror suspended 60 meters (20 stories) above the primary mirror by six colossal steel beams.
The Central Tower: Housing the complex suite of M3, M4, and M5 mirrors. [Path](#)

First-generation instruments

- MICADO: A powerful near-infrared camera to capture ultra-sharp images and hunt for faint exoplanets.
- HARMONI: A spectrograph to dissect the light of stars and galaxies, revealing their composition and motion.
- METIS: A mid-infrared camera/spectrograph to peer through dust and study the birth of stars and planets.
- MOSAIC: A multi-object spectrograph capable of analyzing hundreds of galaxies simultaneously, mapping the universe in 3D.
- ANDES: An ultra-precise spectrograph designed to search for chemical biosignatures in the atmospheres of Earth-like exoplanets.

What to expect?



Comparison of how crowded stellar fields would appear when observed by the Hubble Space Telescope (HST, left), the James Webb Space Telescope (JWST, centre), and ELT's MICADO instrument (right) for three different stellar densities.

Credit: ESO/MICADO consortium

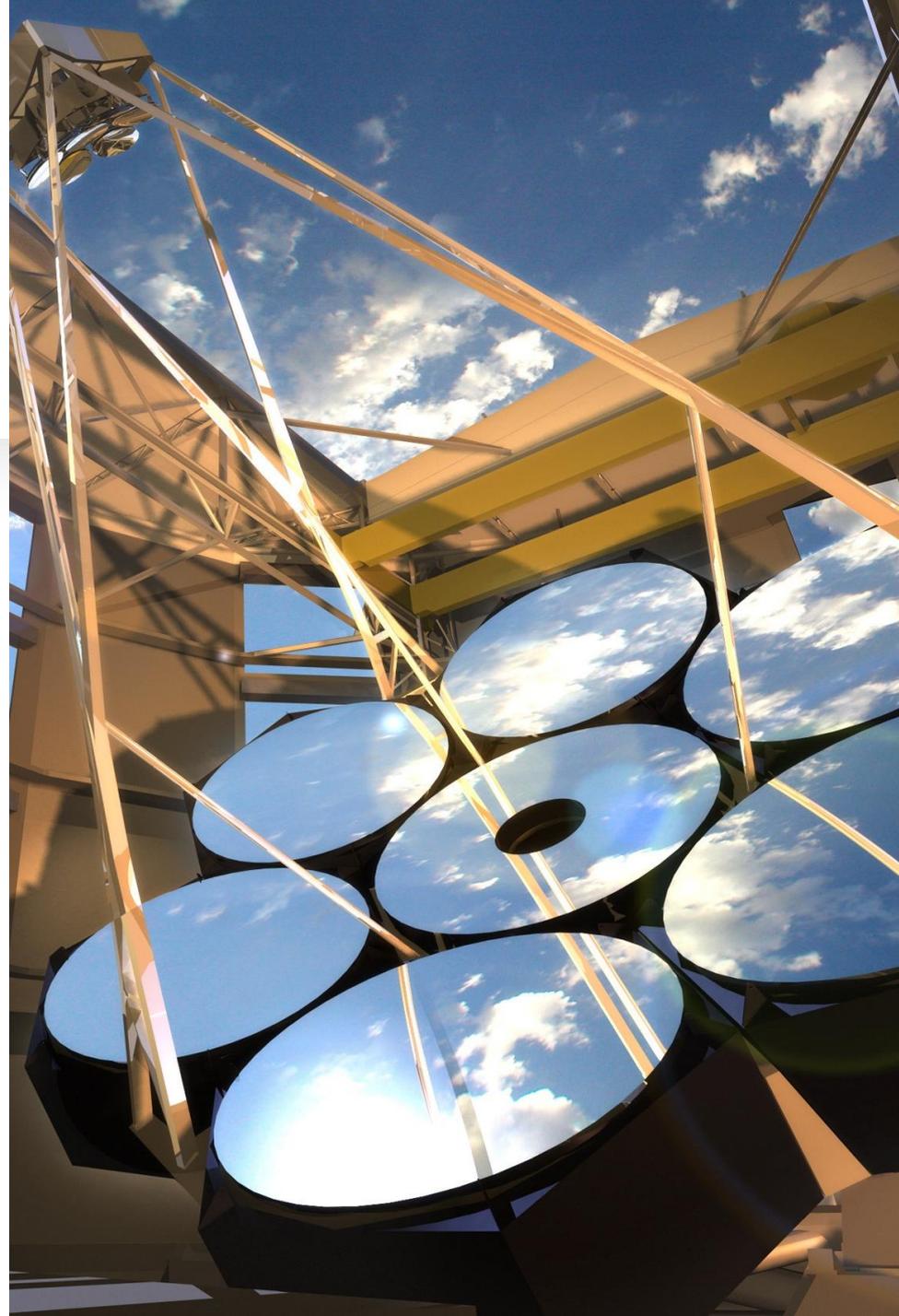
The Giant Magellan Telescope (GMT)

- Effective aperture: 24.5 meters
- Seven giant monolithic mirrors
- High-resolution spectroscopy
- Southern hemisphere advantage

Special low-expansion glass is loaded into a honeycomb mould and placed inside a spinning furnace. Heated to 1,200°C, the glass melts as the furnace spins, naturally forming a perfect parabolic shape. A three-month, painstakingly slow cooling process follows.

The result? A mirror that's 80% hollow and weighs just 20 tons.

[Casting](#)



- [Video](#)
- The GMT adaptive optics system is made up of actuators that warp the telescope's thin, flexible secondary mirrors and deform them thousands of times per second to cancel out atmospheric blur in real time. The GMT will house the most advanced adaptive optics system ever built. With this, the GMT, with its immense aperture and adaptive optics, will push all the way to its diffraction limit —the fundamental physical limit of its sharpness.



The Giant Magellan Telescope is a \$2.6 billion project led by a consortium of 16 universities and research institutions from the United States, Chile, Australia, Brazil, Israel, South Korea, and Taiwan.

Key Construction Milestones:

(Primary Mirrors): All seven 8.4-meter primary mirror segments are cast at the University of Arizona. The first mirror was polished in 2012, and the seventh was cast in 2023.

(Ground-breaking): Official groundbreaking for the site in Chile.

(Site Infrastructure): Completion of utilities and foundation excavation for the pier and enclosure.

(Enclosure Final Design): The 65-meter-tall, 5,000-metric-ton enclosure passed its final design review and is ready for construction.



(Site Preparation): First blast to level the mountain peak at Las Campanas Observatory in Chile.

(Management): WSP awarded the contract to manage construction.

(Mount Fabrication): Ingersoll Machine Tools finished the manufacturing facility for the 39-meter-tall telescope mount in Illinois.

(Advanced Phase): The project advanced to the National Science Foundation (NSF) Final Design Phase.



Located at Las Campanas Observatory,^[16] which is also home to the [Magellan Telescopes](#). The observatory is situated approximately 115 km (71 mi) north-northeast of [La Serena](#), and 180 km (112 mi) south of [Copiapó](#), at an altitude of 2,516 m

Performance specifications [\[edit \]](#)

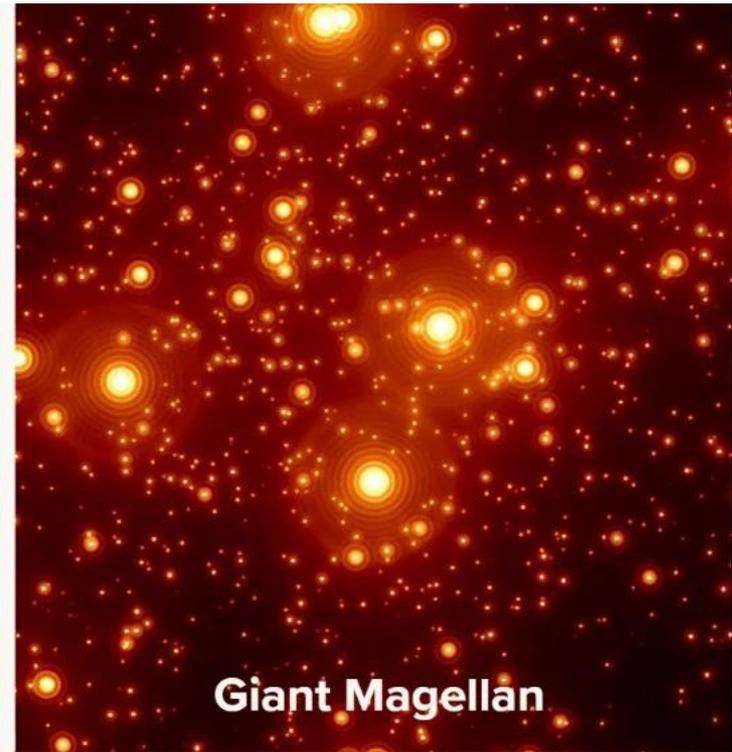
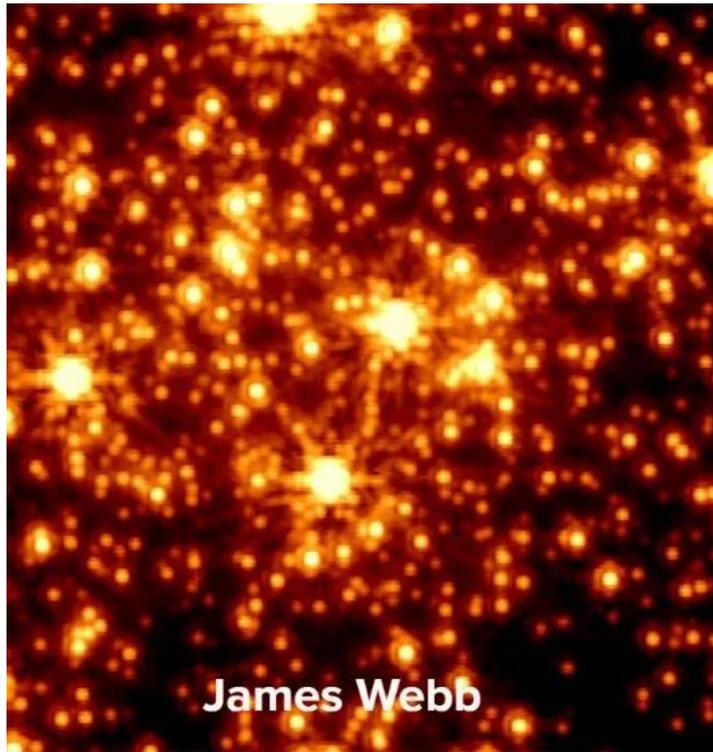
Optical Prescription	Aplanatic Gregorian
Focal Plane Scale	0.997 arcseconds/mm
Wavelength Range	0.32–25 μm
Field of View	20 arcminute diameter
Primary Mirror Diameter & Collecting Area	25.4 m, 368 m ²
Primary Mirror f/#	0.71
Mirror f/#Final f/# (with Wide Field Corrector)	8.16 [8.34]
Diffraction-limited Angular Resolution	0.01 arcsecond at 1 μm



Instruments

- GMT-Consortium Large Earth Finder (G-CLEF) – an optical-band echelle spectrograph
- GMT Multi-object Astronomical and Cosmological Spectrograph (GMACS) – a visible multi-object spectrograph
- GMT Integral-Field Spectrograph (GMTIFS) – a near-IR IFU and AO imager
- GMT Near-IR Spectrograph (GMTNIRS) – a near-IR spectrograph
- The Many Instrument Fiber System (MANIFEST) – a facility fiber system

What to expect?



The Thirty Meter Telescope (TMT)

- 30-meter segmented mirror
- International collaboration
- Powerful adaptive optics
- Ideal for exoplanet atmospheres and stellar populations

Mauna Kea, on the island of Hawai'i.

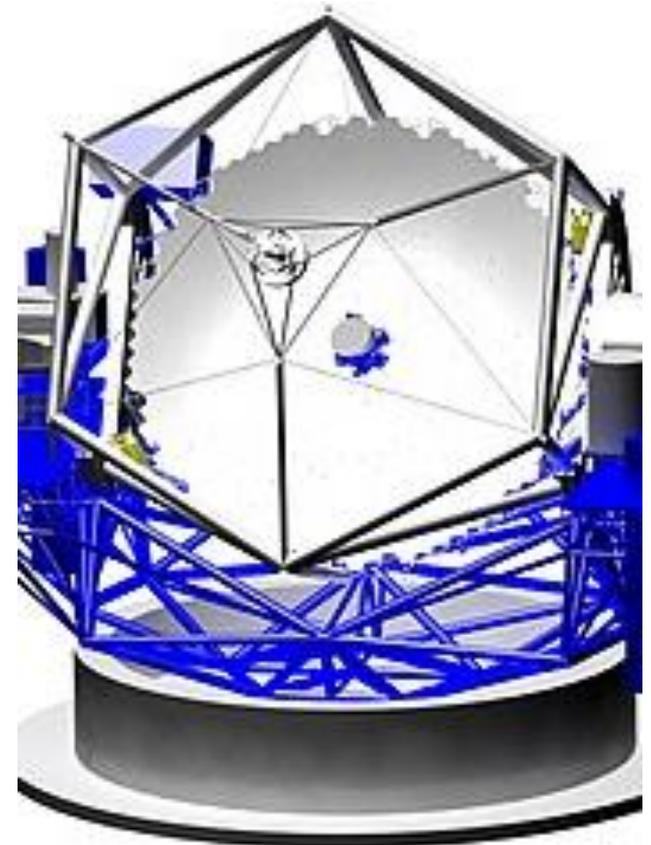


Ritchey-Chrétien telescope with a 30-metre
(98 ft) diameter primary mirror.

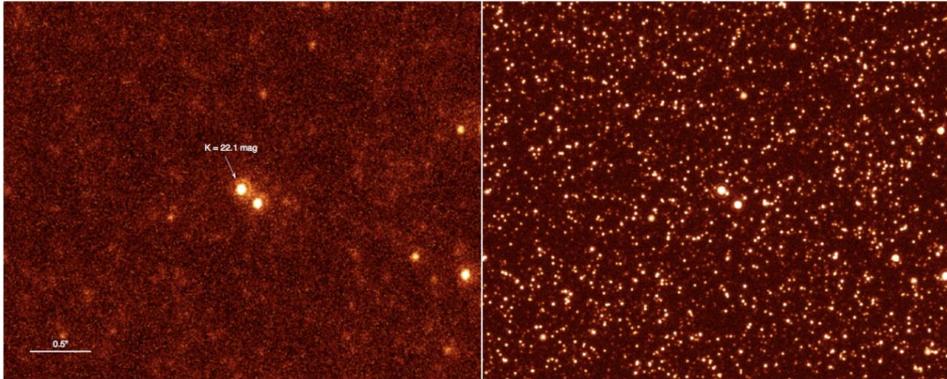
492 segments, 1.4

The shape of each segment, as well as its
position relative to neighboring segments,
will be controlled actively

[Light path](#)

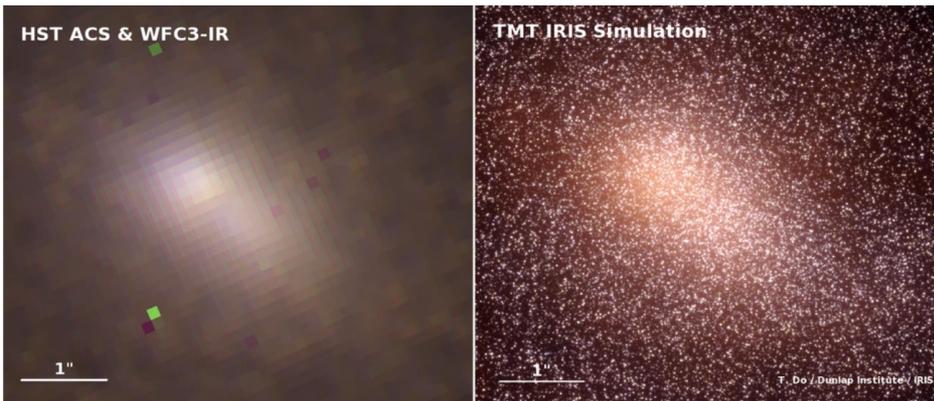


What to expect?



Resolving stellar populations in Virgo Galaxies

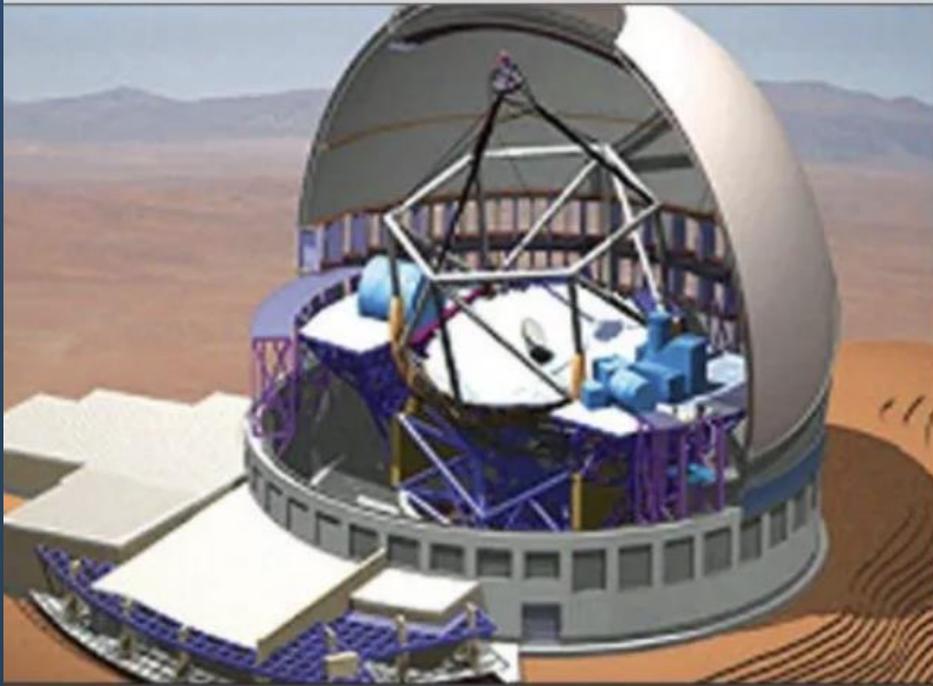
Simulations of a field within a spiral galaxy in the Virgo Cluster. The field contains an old, metal-rich population in an area with a surface brightness of 22 mag arcsec⁻², assuming a total exposure time for 3 hours in K. The left hand panel shows the field as it would appear if viewed with the Keck AO system, while the right hand panel shows the field as it would appear if viewed by IRIS+NFIRAOS. Only the very brightest asymptotic giant branch (AGB)-tip stars are detected in the Keck image. However, stars that are fainter than the red giant branch (RGB) tip are detected with TMT. The detection of stars on the AGB and the upper portions of the RGB will allow the age and chemical evolution of Virgo galaxies to be probed in a direct manner.



M31

TMT will be a revolutionary instrument that will be able to resolve individual stars at the center of Andromeda. On the left shows a three color image of the current capabilities using HST ACS (F814W) and WFC3 (F110W, F160W). On the right a three color image (Z, J, and K bands) using TMT's first light instrument IRIS with the NFIRAOS adaptive optics system. TMT and IRIS will provide the necessary sensitivity and spatial resolution for understanding the dynamics, stellar population, and supermassive black hole at M31's center.

THIRTY METER TELESCOPE



India's Participation in Thirty Meter Telescope (TMT) project was approved by the NDA Government at a total cost of Rs.1299.8 crores in September 2014.

The Department of Science and Technology on behalf of Government of India executed TMT international Observatory partnership documents becoming a full member in the project on 2nd December 2014.

The other participating countries in the TMT project are USA, Canada, China and Japan.



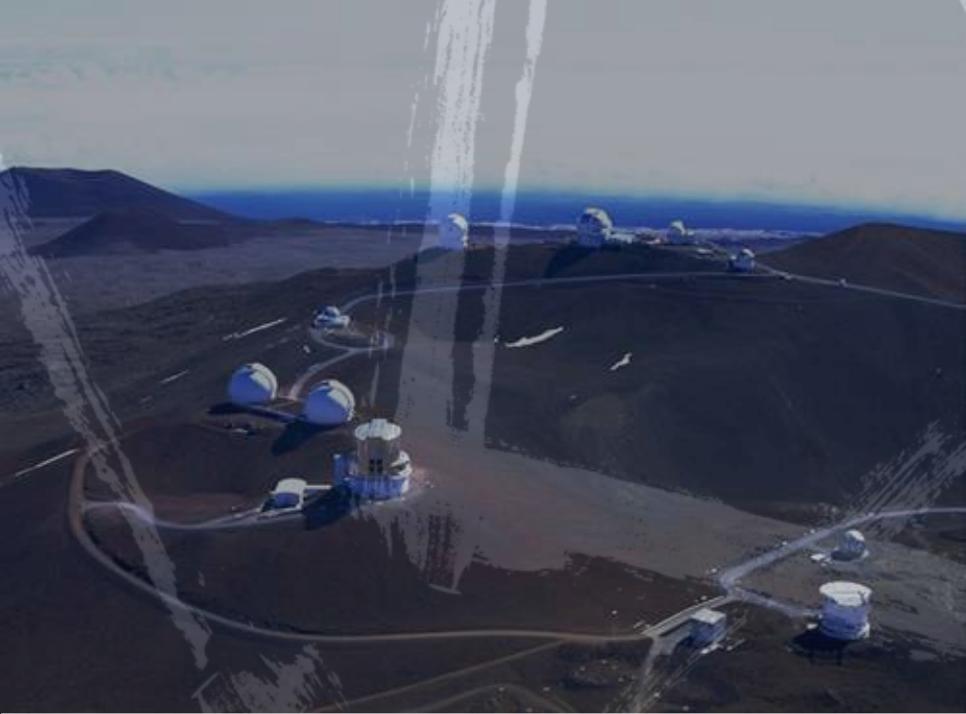
Brand-new India-TMT Optics Fabrication Facility (ITOFF) at CREST campus, IIA, December 2020.



Early-light capabilities

Three instruments are planned to be available for scientific observations:

- *Wide Field Optical Spectrometer (WFOS)* provides a seeing limit that goes down to the **ultraviolet** with optical (0.3–1.0 μm wavelength) imaging and spectroscopy capable of 40-square arc-minute field-of-view. The TMT will use precision cut focal plane masks and enable long-slit observations of individual objects as well as short-slit observations of hundreds of different objects at the same time. The spectrometer will use **natural (uncorrected) seeing images**.
- *Infrared Imaging Spectrometer (IRIS)* mounted on the observatory MCAO system, capable of **diffraction-limited** imaging and integral-field **spectroscopy** at near-infrared wavelengths (0.8–2.5 μm). Principal investigators are James Larkin of UCLA and Anna Moore of Caltech. Project scientist is Shelley Wright of UC San Diego.
- *Infrared Multi-object Spectrometer (IRMS)* allowing close to diffraction-limited imaging and slit spectroscopy over a 2 arc-minute diameter field-of-view at near-infrared wavelengths (0.8–2.5 μm).

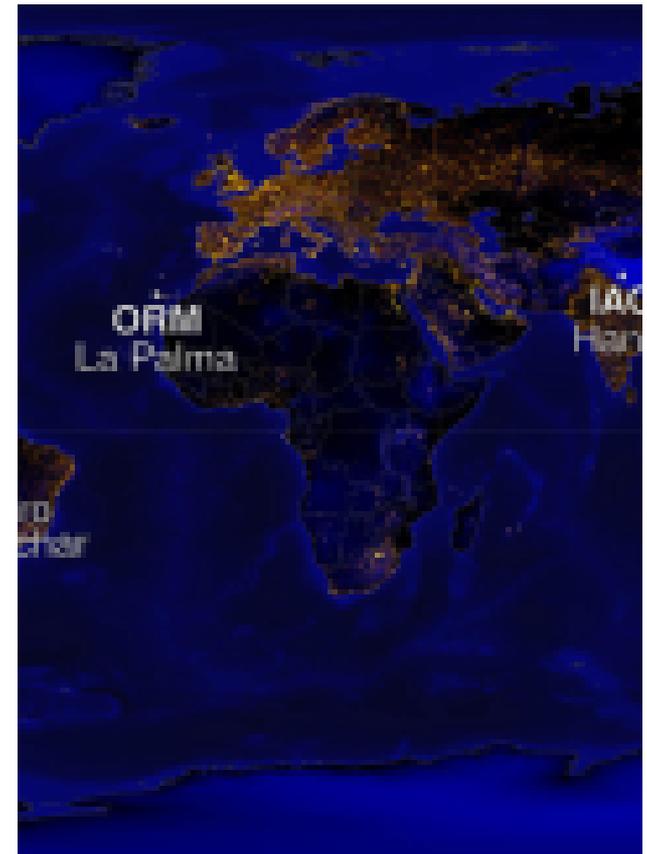


Protests...



Where will the TMT be?

- In cooperation with [AURA](#), the TMT project completed a multi-year evaluation of six sites:
- [Roque de los Muchachos Observatory, La Palma, Canary Islands, Spain](#)
- [Cerro Armazones, Antofagasta Region](#), Republic of Chile
- Cerro Tolanchar, Antofagasta Region, Republic of Chile
- Cerro Tolar, Antofagasta Region, Republic of Chile
- [Mauna Kea, Hawaii](#), United States (This site was chosen and approval was granted in April 2013)
- [San Pedro Mártir, Baja California](#), Mexico
- [Hanle, Ladakh](#), India





Vera C. Rubin Observatory

- 8.4-meter telescope (Chile)
- Largest digital camera ever built
- Legacy Survey of Space and Time (LSST)
- Maps the dynamic universe every few nights

January 2026 - Record-Breaking Asteroid Discovery: Early data was used to identify a highly active, fast-rotating asteroid, the first peer-reviewed scientific discovery from the observatory.

Lets Compare...

- In the near-UV/blue, TMT fills a crucial niche. It uses a protected silver coating with a near-UV enhancement, allowing sensitivity down to 310 nm. GMT uses aluminum for excellent blue performance but sacrifices in the infrared. The European ELT's five-mirror design with standard protected silver results in lower throughput at these shorter wavelengths. For multi-object spectroscopy in the blue, TMT's efficiency and site conditions make it highly competitive.
- In the optical, the `WFOS' instrument leverages the `sweet spot' design to use a pure refractive (lens-based) system, maximizing throughput. Comparisons with the European ELT's `MOSAIC' instrument show the two telescopes are highly competitive, with TMT's higher throughput balancing ELT's larger area.
- In the near-infrared, AO performance with TMT is excellent. The TMT point-spread function has a higher concentration of light in the central core due to our simpler optical layout and fewer gaps.
- In the mid-infrared (future instruments), TMT's site on Maunakea provides a major advantage: lower temperature and lower water vapor mean lower background and better transmission through atmospheric windows.
- The European ELT is excellent, but TMT is a highly complementary, competitive observatory that will enable unique and frontier science.

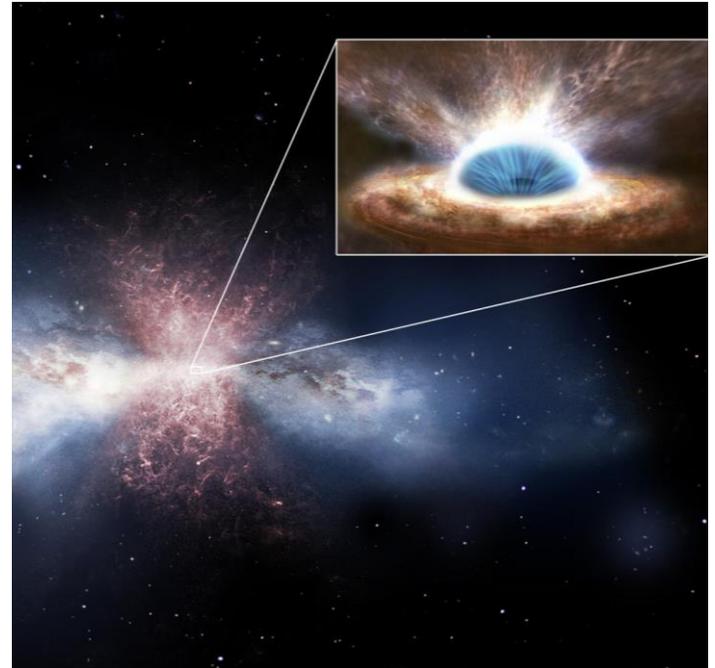
ELTs vs Vera Rubin: Complementary Science

- ELTs: deep, high-resolution, targeted studies
- Rubin: wide-field, time-domain surveys
- Rubin discovers → ELTs follow up
- Together enable precision cosmology



Key Science Goals

- First stars and galaxies
- Exoplanet detection and atmospheres
- Black holes and galaxy evolution
- Dark matter and dark energy



A New Era of Discovery

- From imaging Earth-like exoplanets
- To testing fundamental physics
- Astronomy enters the era of precision and scale
- The universe revealed in unprecedented detail



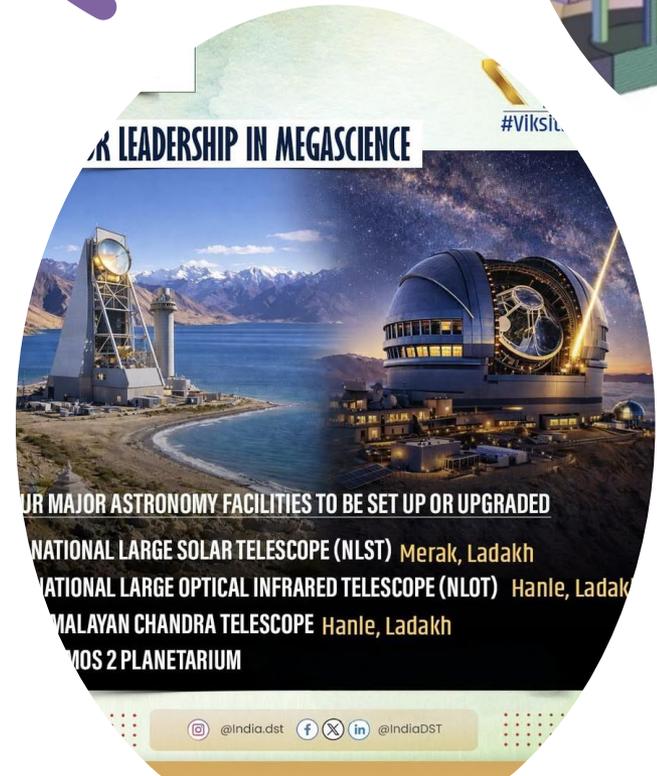
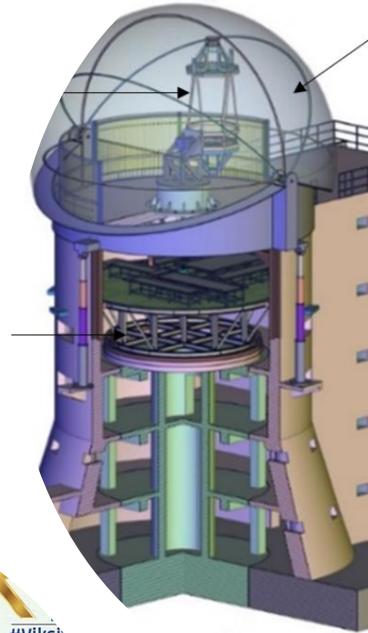
Name	Aperture diameter (m)	Collecting area (m²)	First light
Extremely Large Telescope (ELT)	39.5	978	2029
Thirty Meter Telescope (TMT)	30	655	2026 ^[55]
Giant Magellan Telescope (GMT)	25.4	368	2031
Very Large Telescope (VLT)	4 x 8.2	200	1998–2000
Southern African Large Telescope (SALT)	11.1 × 9.8	79	2005
Keck Telescopes	10.0	76	1990, 1996
Gran Telescopio Canarias (GTC)	10.4	74	2007

Note: future dates for first-light are provisional and are likely to change.

Table 1: Highlight science cases for a 50–100-m Extremely Large Telescope.

Are there Terrestrial planets orbiting other stars?	Are we alone? Direct detection of earth-like planets in extra-solar systems and a first search for bio-markers (e.g water and oxygen) becomes feasible.
How typical is our Solar System? What are the planetary environments around other stars?	Direct study of planetary systems during their formation from proto-planetary disks will become possible for many nearby very young stars. In mature planetary systems, detailed spectroscopic analysis of Jupiter-like planets, determining their composition and atmospheres, will be feasible. Imaging of the outer planets and asteroids in our Solar System will complement space missions.
When did galaxies form their stars?	When and where did the stars now in galaxies form? Precision studies of individual stars determine ages and the distribution of the chemical elements, keys to understanding galaxy assembly and evolution. Extension of such analyses to a representative section of the Universe is the next great challenge in understanding galaxies.
How many supermassive black holes exist?	Do all galaxies host monsters? Why are supermassive black holes in the nuclei of galaxies apparently related to the whole galaxy? When and how do they form and evolve? Extreme resolution and sensitivity are needed to extend studies to normal and low-mass galaxies to address these key puzzles.
When and where did the stars and the chemical elements form?	Can we meet the grand challenge, to trace star formation back to the very first star ever formed? By discovering and analysing distant galaxies, gas clouds, and supernovae, the history of star formation, and the creation history of the chemical elements can be quantified.
What were the first objects?	Were stars the first objects to form? Were the first stars the source of the ultraviolet photons which re-ionised the Universe some 200 million years after the Big Bang, and made it transparent? These objects may be visible through their supernovae, or their ionisation zones.
How many types of matter exist? What is dark matter? Where is it?	Most matter is transparent, and is detectable only through its gravitational effect on moving things. By mapping the detailed growth and kinematics of galaxies out to high redshifts, we can observe dark-matter structures in the process of formation.
What is dark energy? Does it evolve? How many types are there?	Direct mapping of space-time, using the most distant possible tracers, is the key to defining the dominant form of energy in the Universe. This is arguably the biggest single question facing physical science.
Extending the age of discovery	In the last decades astronomy has revolutionised our knowledge of the Universe, of its contents, and the nature of existence. The next big step is likely to be remembered for discovering the unimagined new.

- 1) The National Large Solar Telescope (NLST), 2-m
- (2) The National Large Optical–Near Infrared Telescope (NLOT) 13.7-m 90 hexagonal segments
- (3) Upgradation of the Himalayan Chandra Telescope at Hanle
- (4) A state-of-the-art planetarium capable of creating stunning visuals of the universe, and project them real time as well as from archival data of our telescopes.





Conclusion

- ELT, TMT, GMT redefine observational astronomy
- Vera Rubin reshapes time-domain science
- Together they form the backbone of 21st-century astronomy
- The future of cosmic exploration is here