

WATCHERS OF THE SKY

Philip Hughes

Department of Astronomy

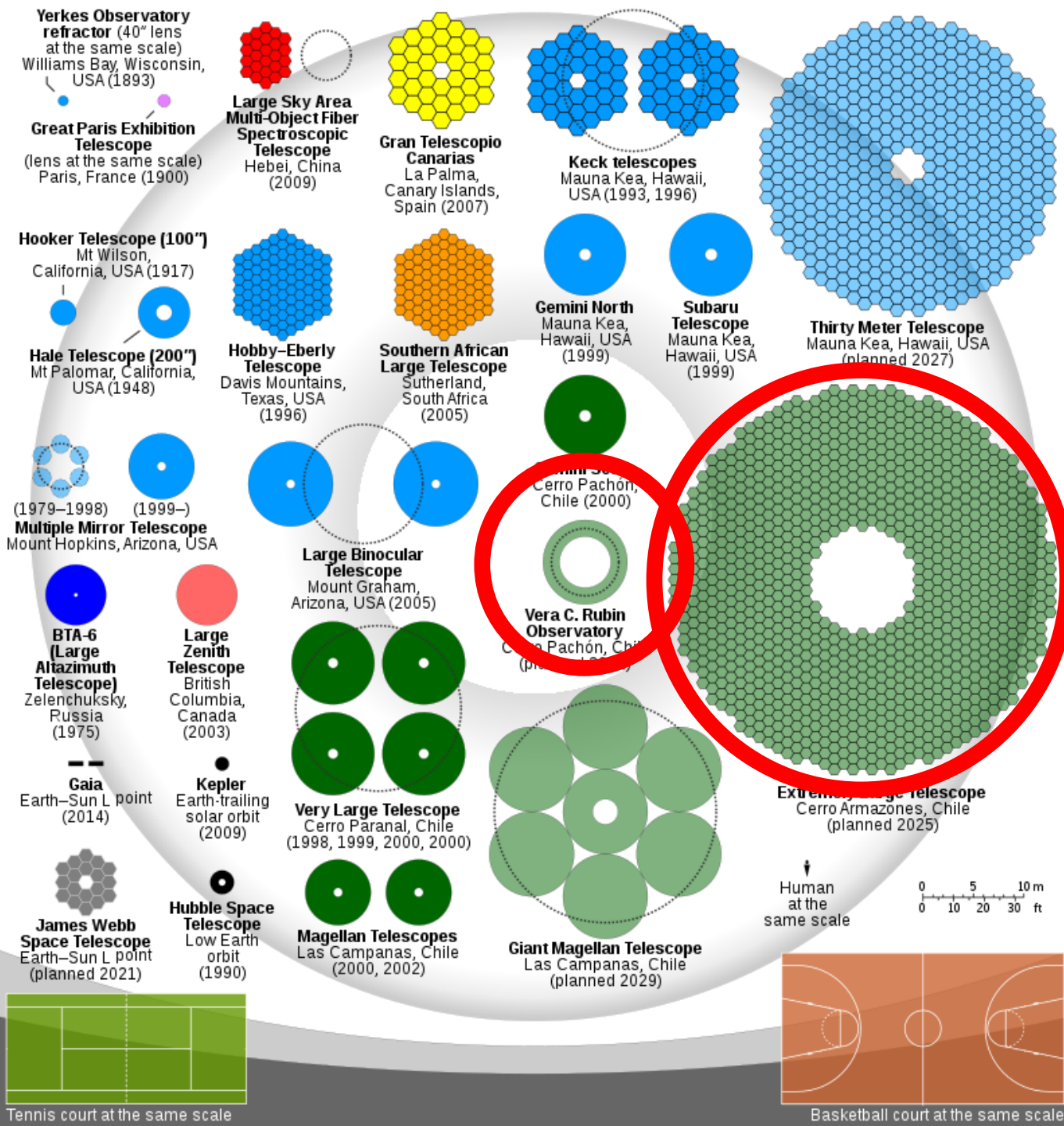
University of Michigan

phughes@umich.edu

www-personal.umich.edu/~phughes/

Overview

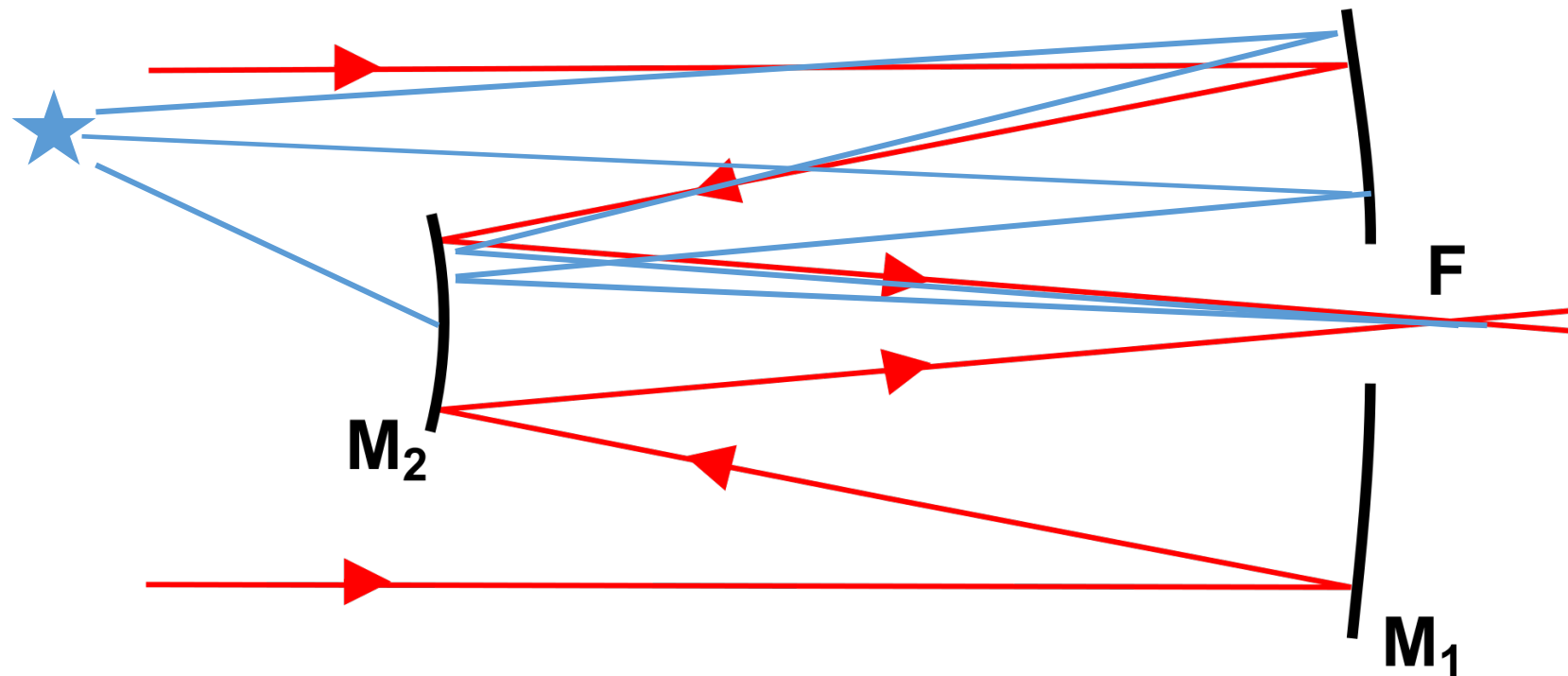
- Background
 - Astronomy
 - Physics
 - Technology
- Facts & Figures
 - What makes this unique?
 - Gee whiz factors
- Science Goals



Primary Mirror

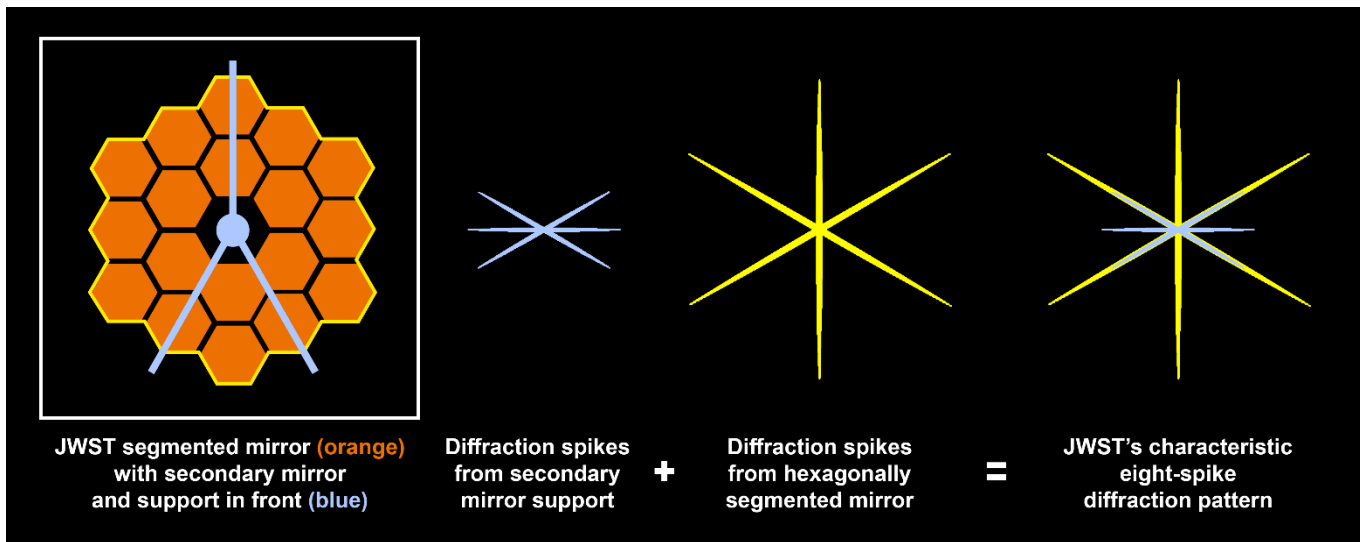
- You **cannot** cast a 39 meter primary mirror
- The giant primary is made up of 798 individual hexagonal segments
- Doesn't this impact the image?
- No & Yes!!

Recap: Reflecting Telescopes



EW 2023: JWST

- Secondary: held by 3 struts
- Contributes to “iconic” diffraction spike pattern

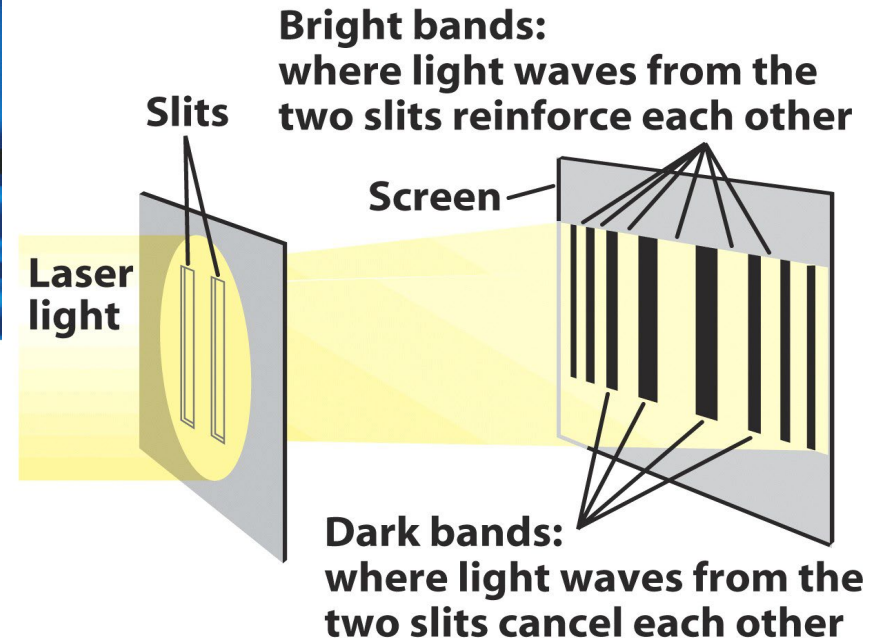
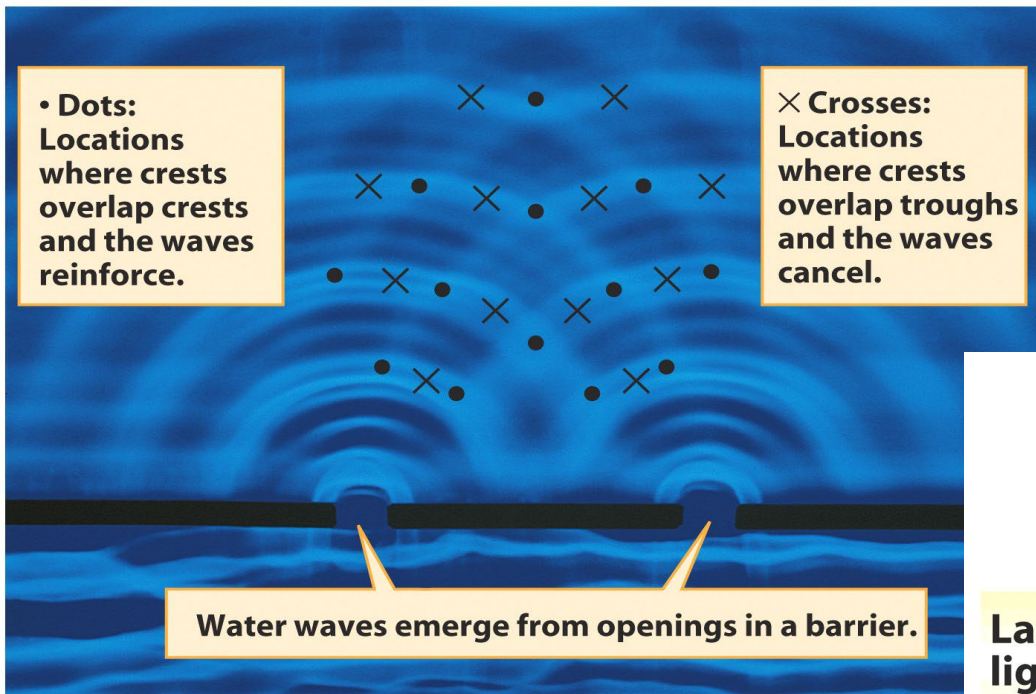


Alignment

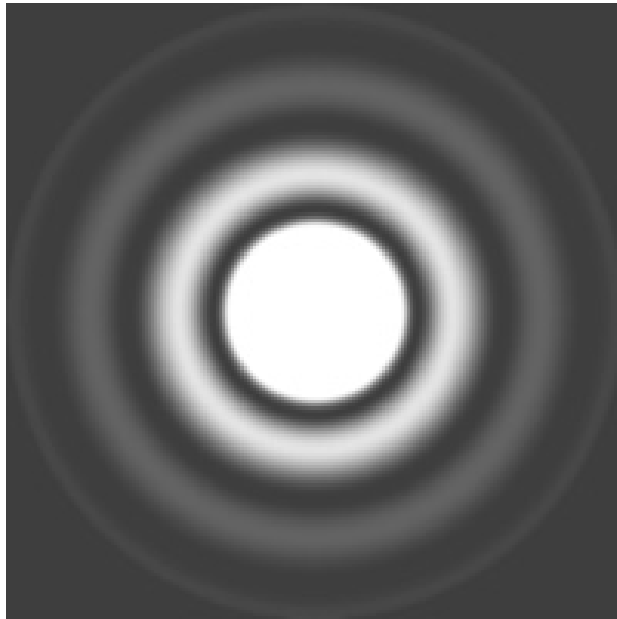
- In a multi-segment design like this, a lot of work has to go into ensuring alignment
- Edge sensors on each segment monitor its position
- Actuators (typically 3 on each segment) make adjustments
- The mirror support system is critical: this is designed to evenly distribute stresses, and provide a “warping harness” to slightly change mirror shape in response to gravitational/thermal effects
- A computer system monitors and controls all this

Atmosphere: Adaptive Optics

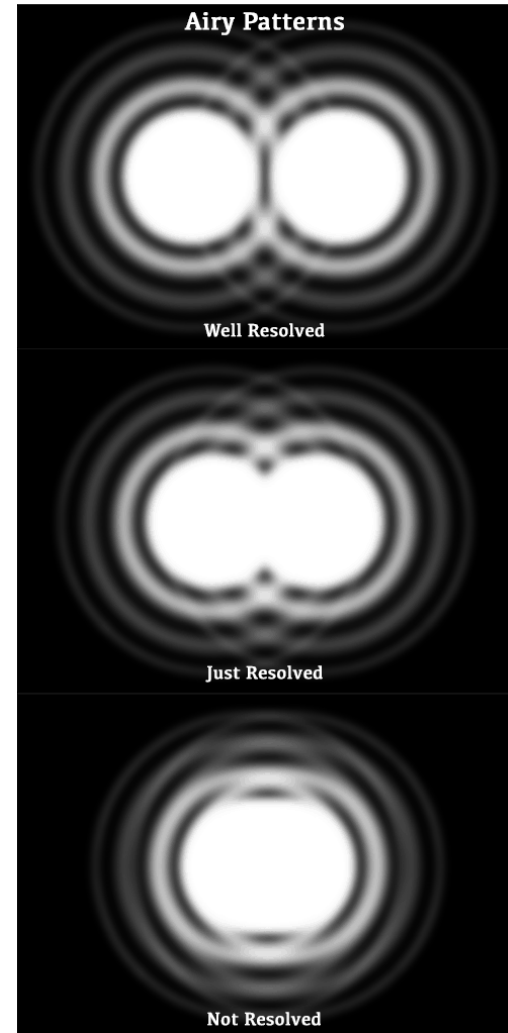
➤ Young's slit experiment (1801)



Diffraction

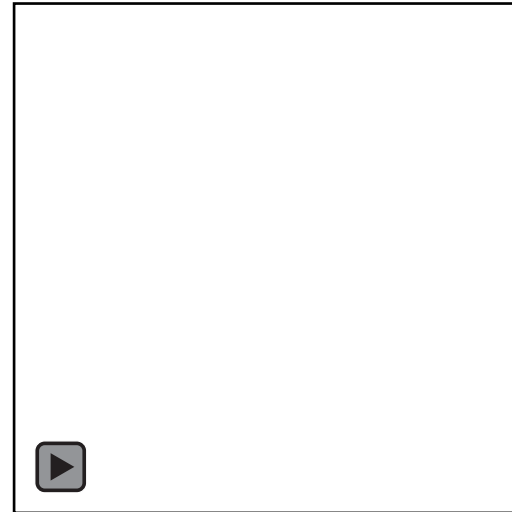
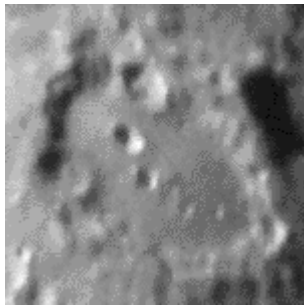


- “Diffraction Limit” is the goal!

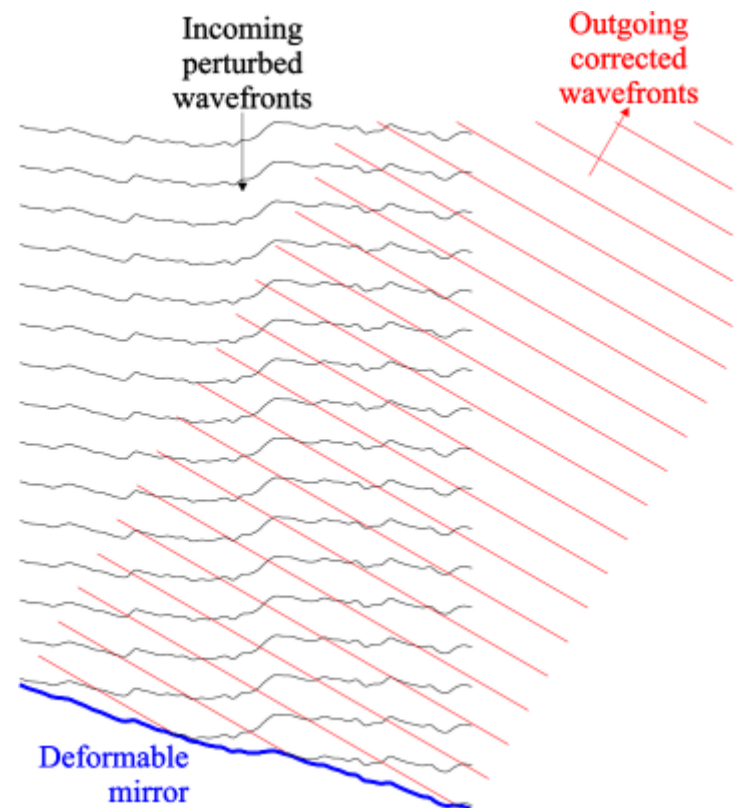
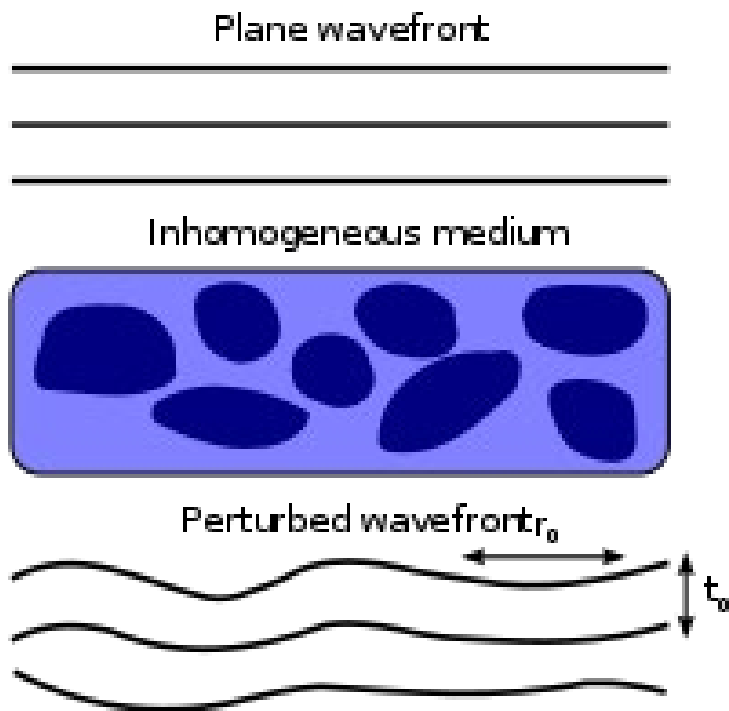


Adaptive Optics

- Wavefronts are distorted by inhomogeneity in intervening medium

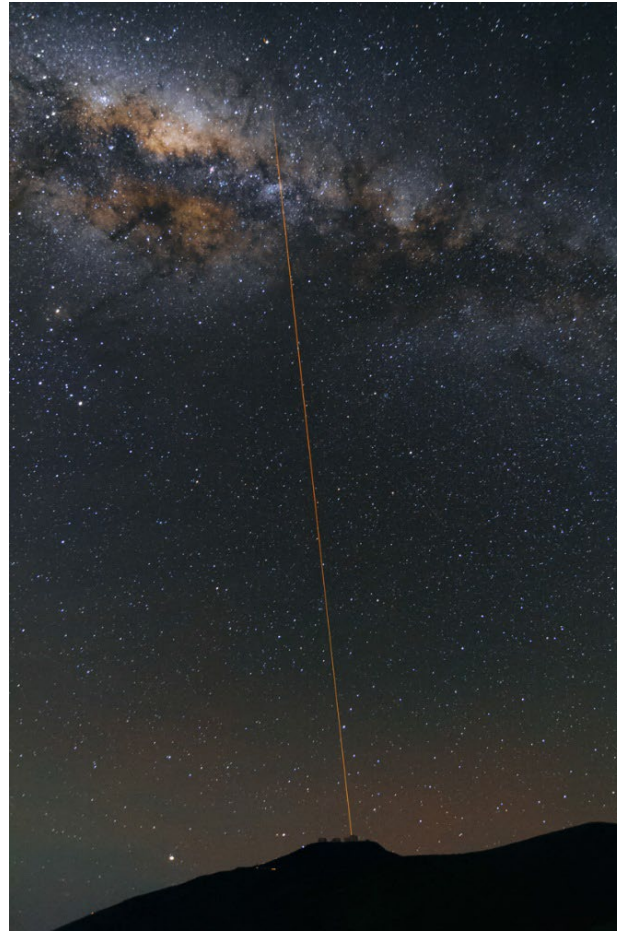


- Wavefronts are corrected by mirror – arbitrarily deformable in an ideal world



A Practical Approach...

- Bright star or laser – sample incoming wavefronts

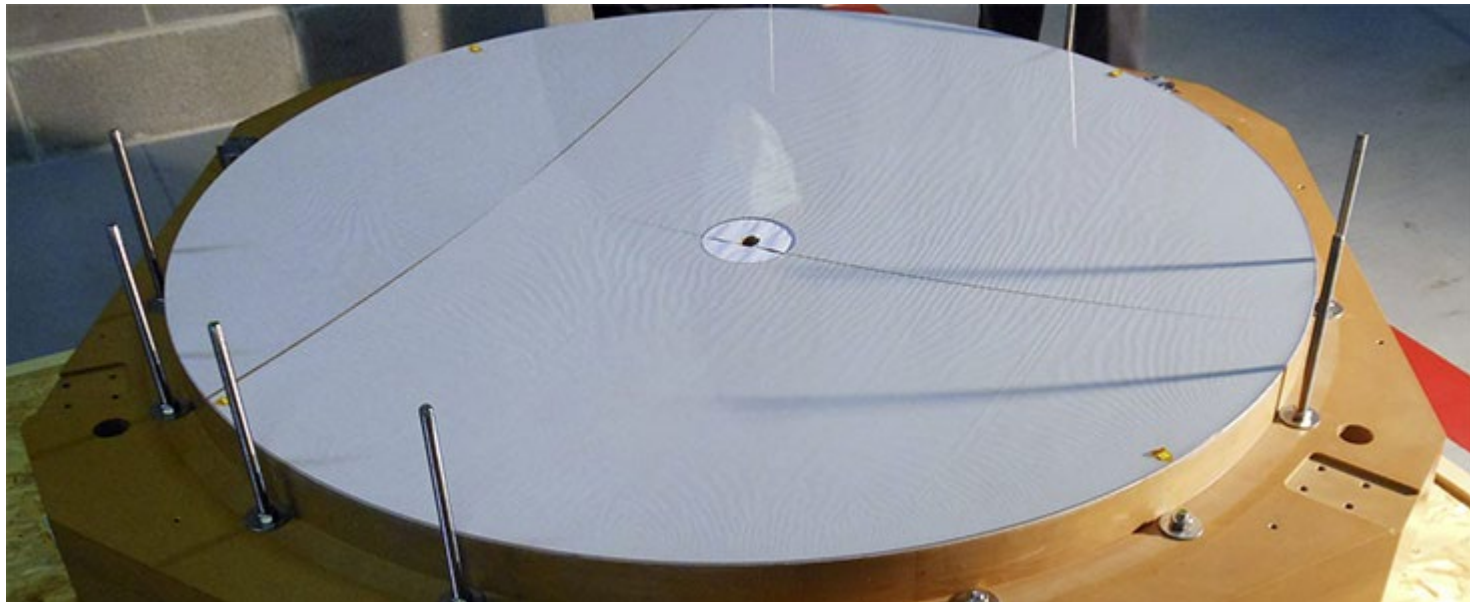
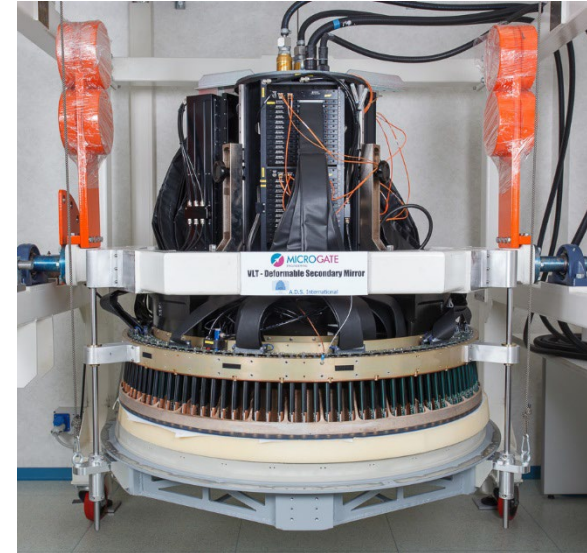


- A tuned laser excites atoms in the mesospheric sodium layer at about 90km altitude, causing fluorescence
- The sodium results from the vaporization of cosmic dust

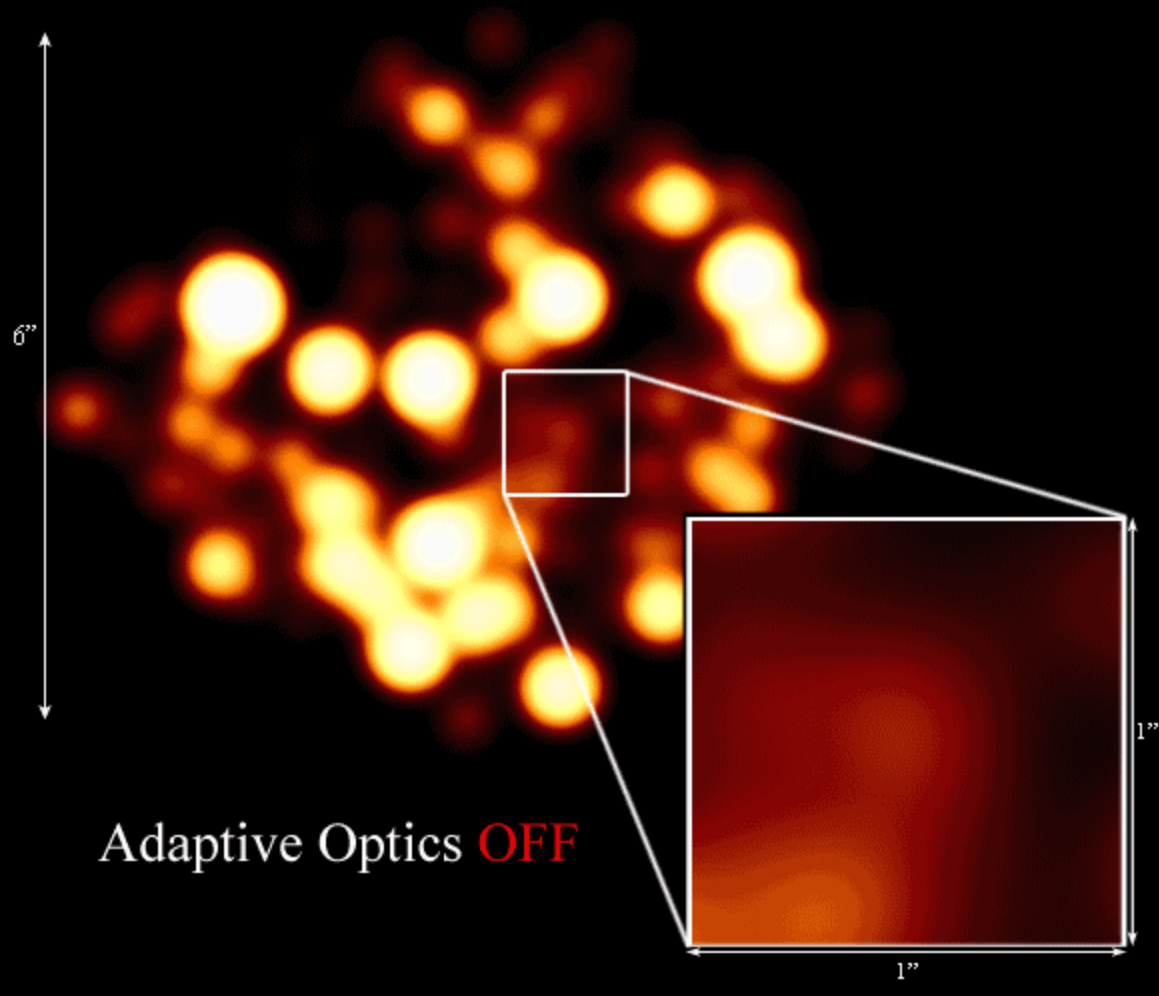
ESO VLT, Paranal, Chile

A Practical Approach...

- Deformable mirror
 - eg, ESO shell mirror
 - 1.2m diameter, 2mm thick, deformed > 1000 times per second by > 1000 actuators

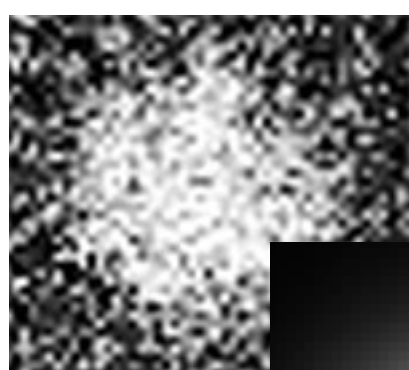


The Galactic Center at 2.2 microns

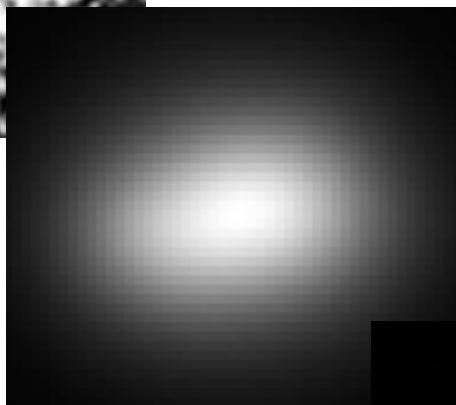


Atmosphere: Lucky Imaging

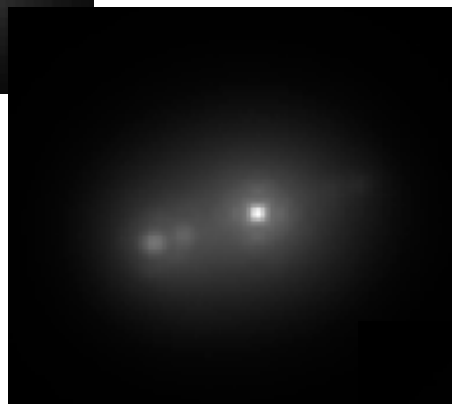
- High speed camera (and bright object!) with exposure time less than 100 ms
- During any one frame change in Earth's atmosphere is minimal
- Select a subset (10%) least influenced by atmosphere, shift and add
- Example shows triple star system with 50,000 images, 40 images per second



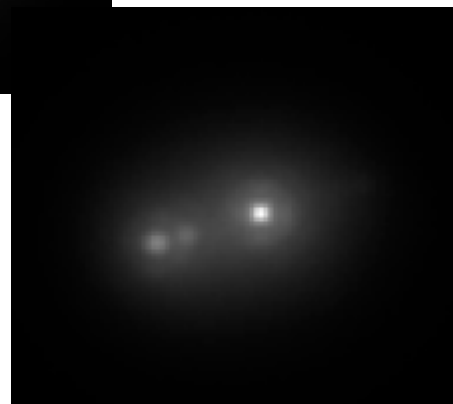
single exposure, low
image quality



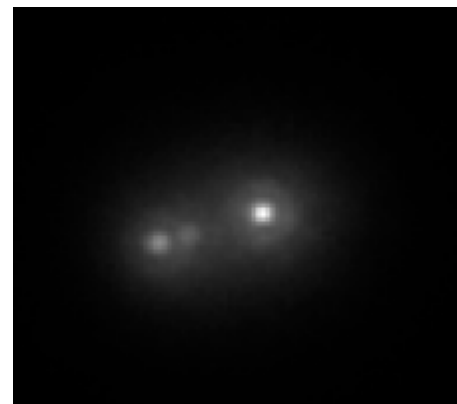
100%



50%



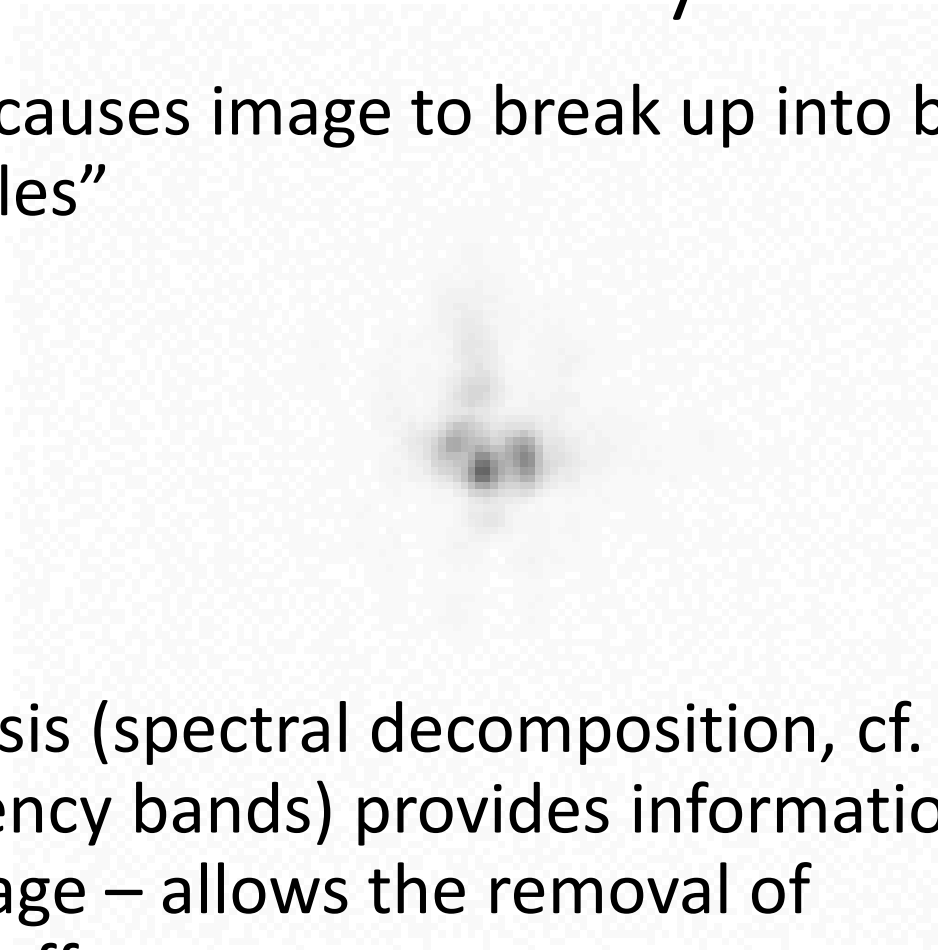
10%



1% of all 50,000 frames

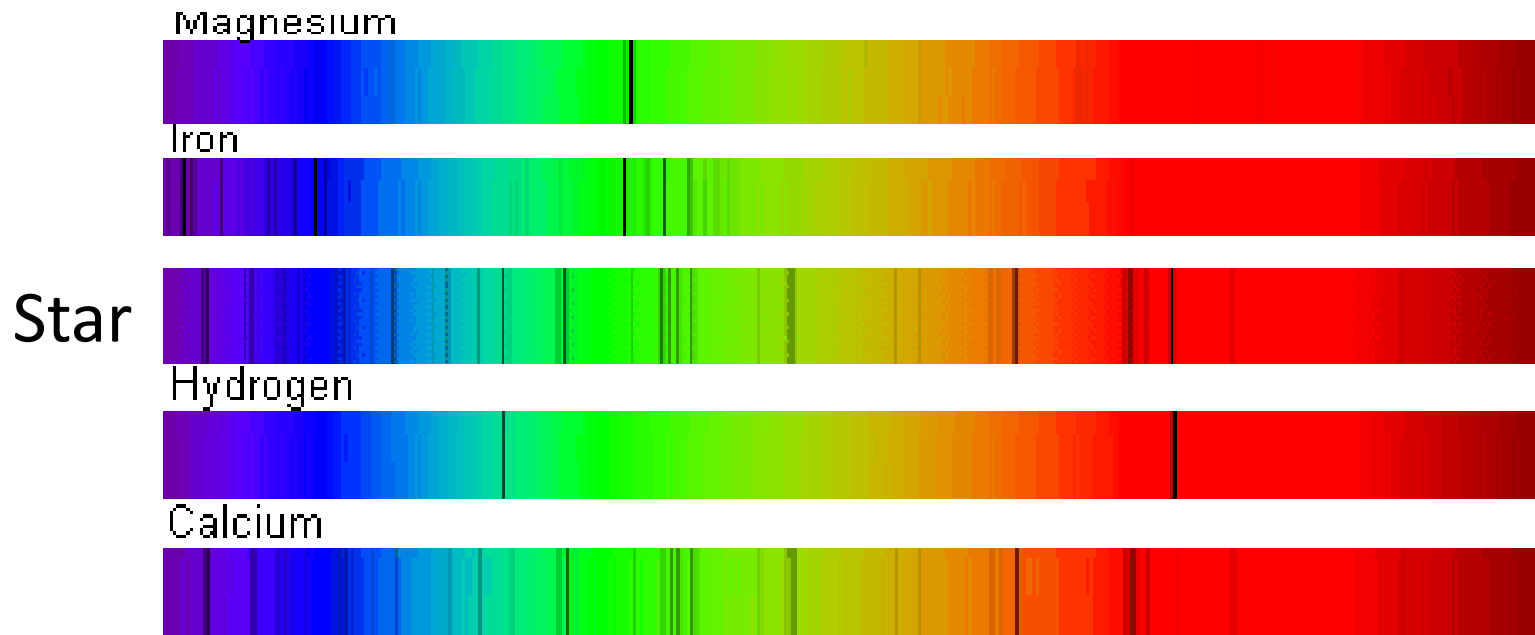
Atmosphere: Speckle Interferometry

- Atmosphere causes image to break up into blobs called “speckles”



- Fourier analysis (spectral decomposition, cf. sound across frequency bands) provides information on “original” image – allows the removal of atmospheric effects

Recap: Spectroscopy Is Important!



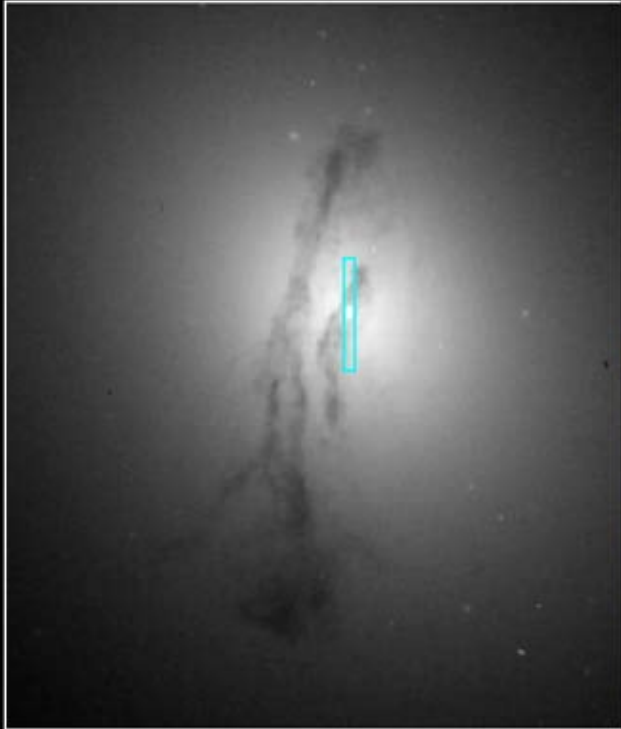
Which elements are seen in the spectrum of this star?

- a) All 4 b) Fe + H c) H + Ca d) Fe, H & Ca

Hydrogen and Calcium are strong

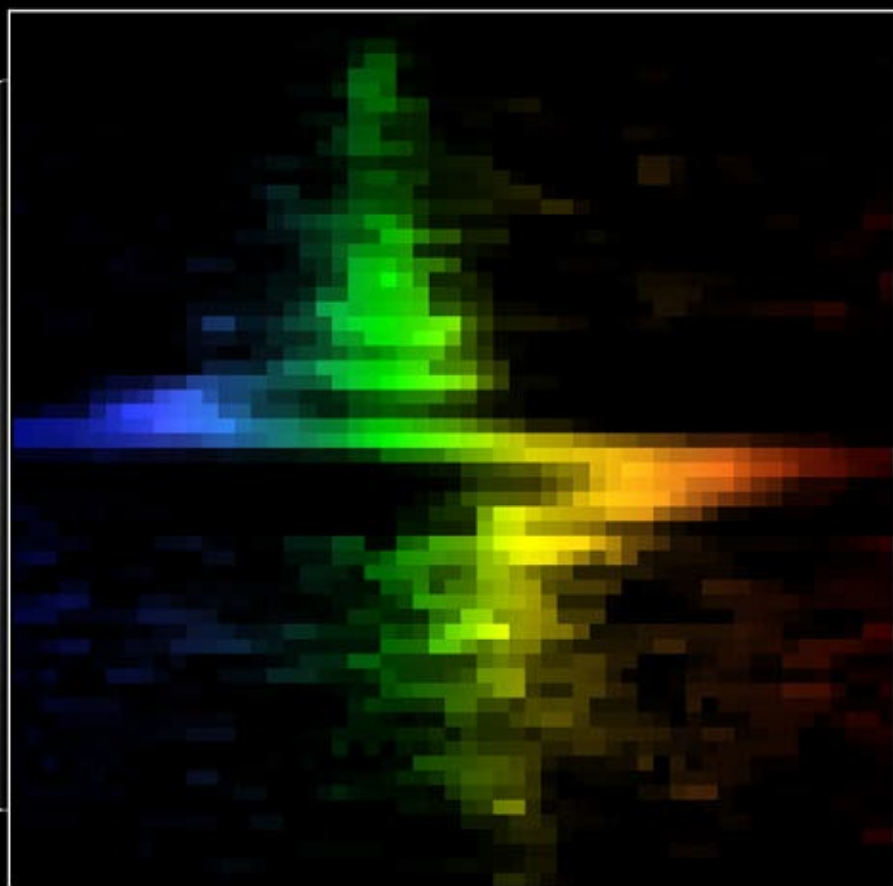
Spectroscopy: Slit

Galaxy M84 Nucleus



WFPC2

Hubble Space Telescope



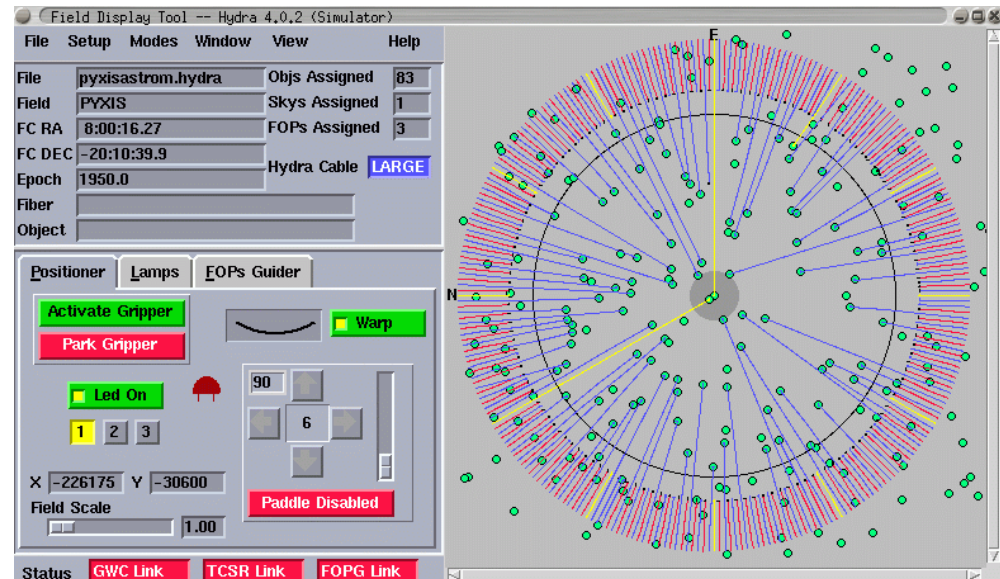
Spectrum of
ionized
Hydrogen
and Nitrogen
taken with
STIS

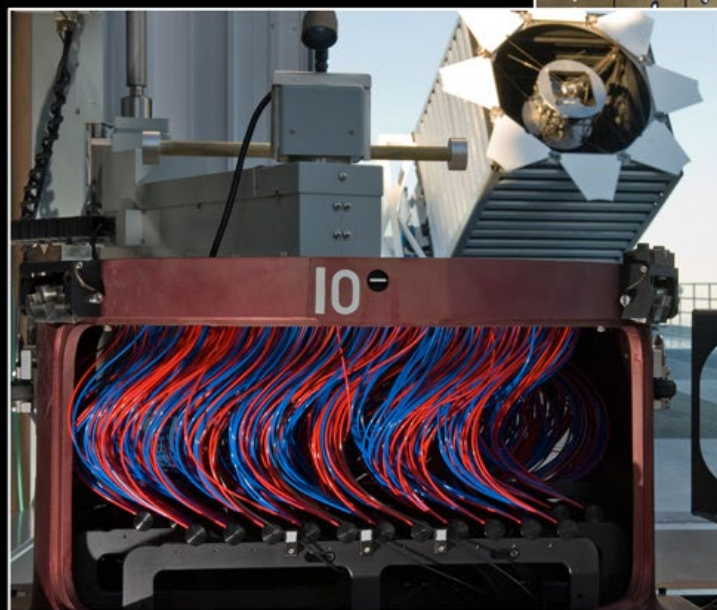
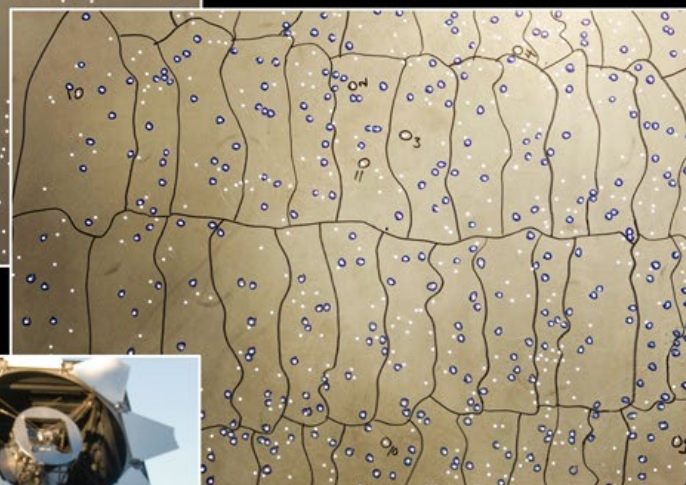
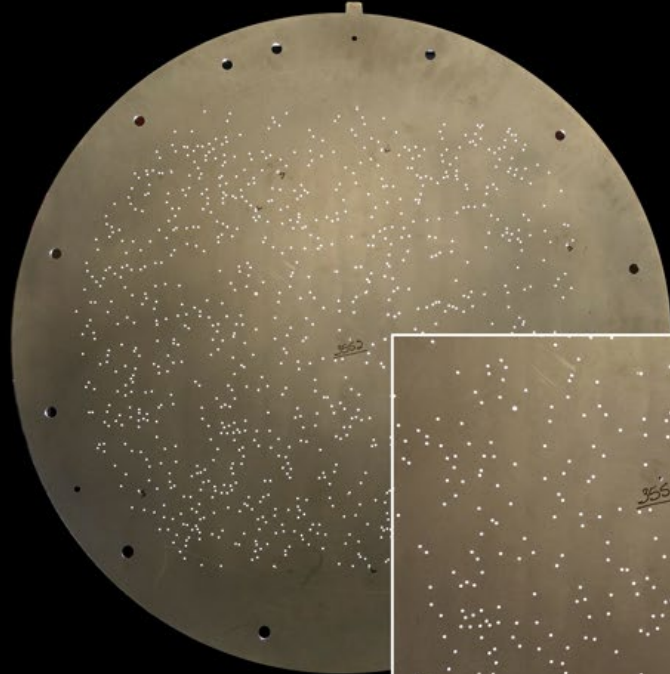
STIS

PRC97-12 • ST ScI OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

Spectroscopy: Multifibers

- Example shows BOSS plug plate with 1000 fiber holes; 2000 plates in the whole project
- Get simultaneous spectra of all 1000 objects in the field making otherwise impossible projects possible
- Each plate must be plugged manually or by robot – need care to avoid tangles/collisions!



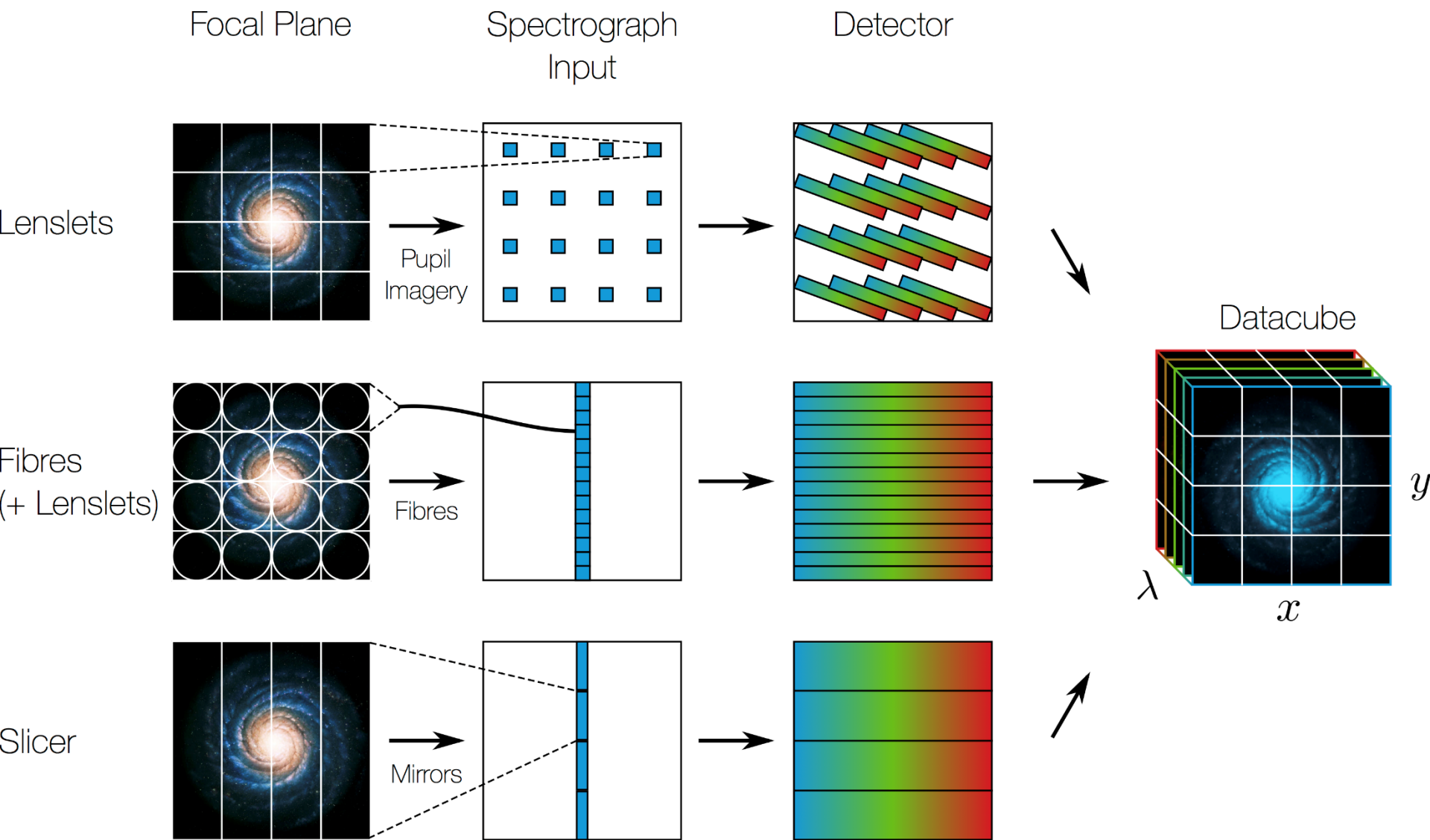


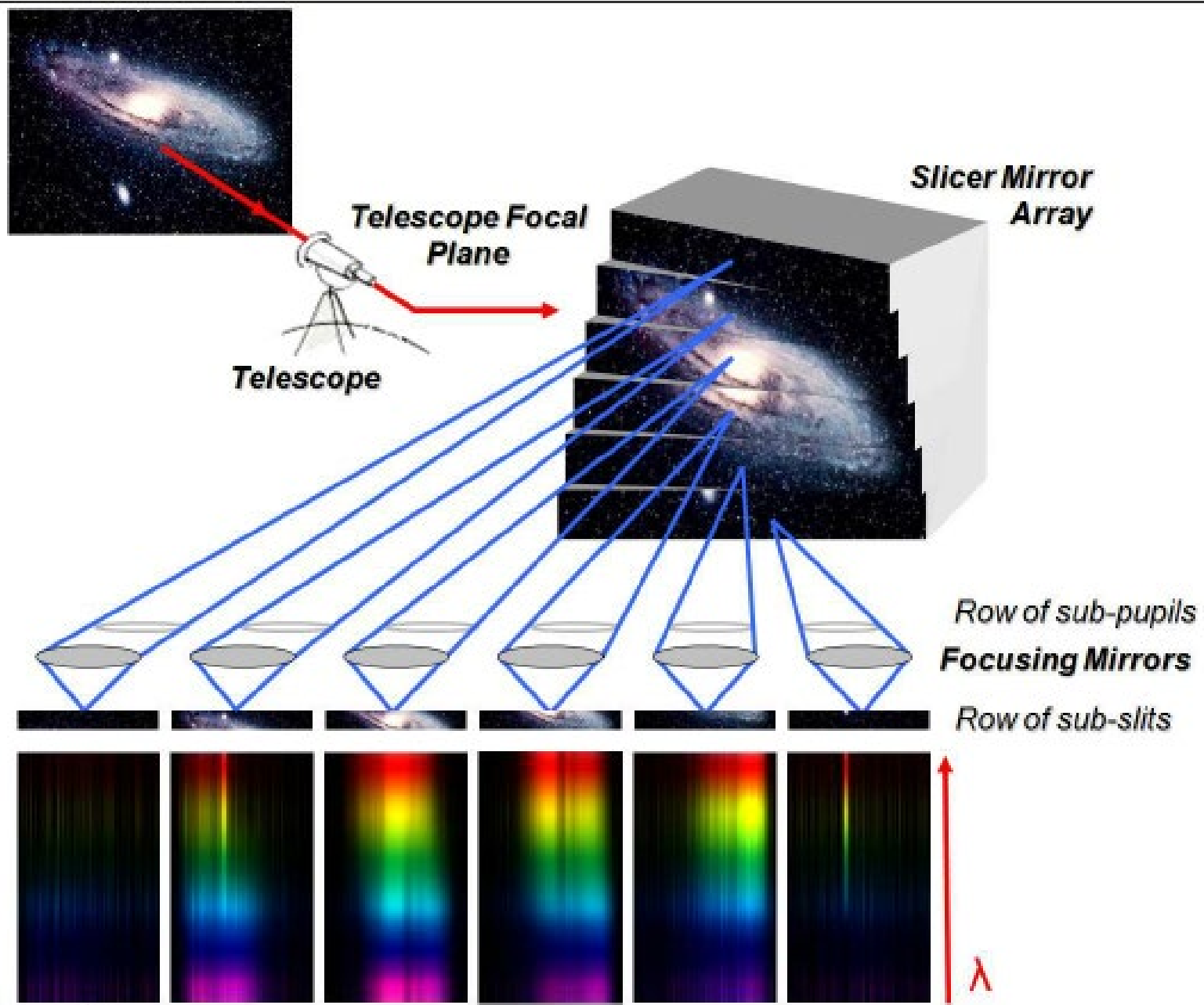
Spectroscopy: Integral Field



Wavelengths →

Computer reconstructed image

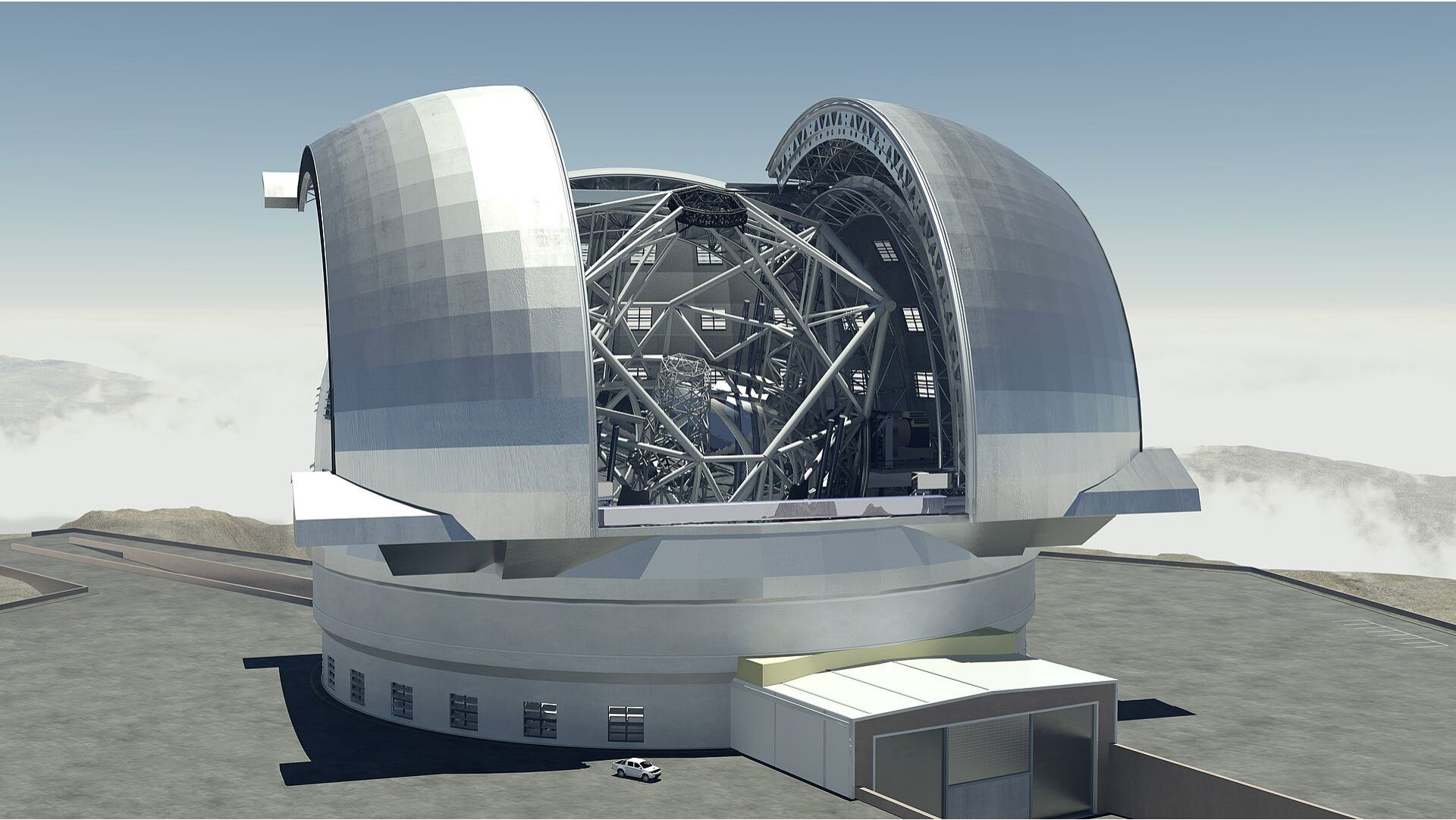


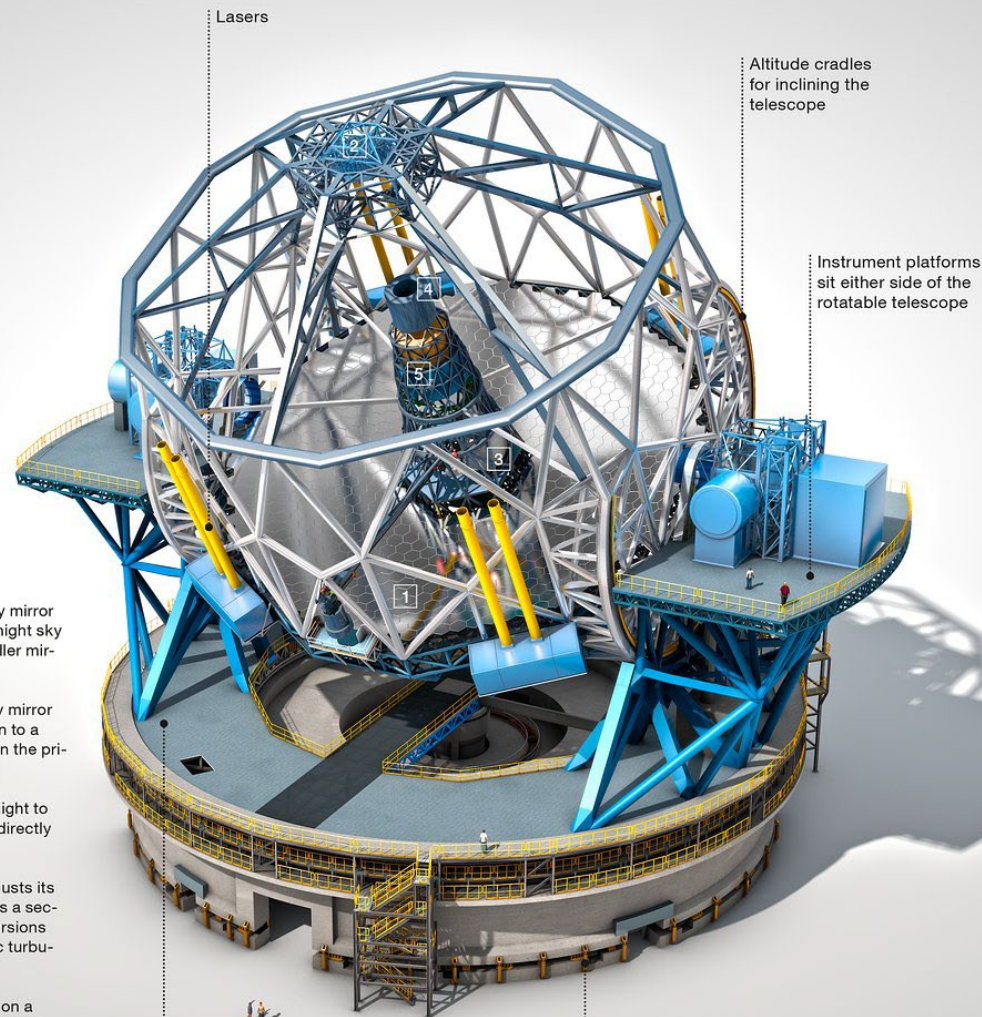


Location

- Management: European Southern Observatory, Garching, Germany
- ELT Observatory: Cerro Armazones, Chile
- Construction & Operation: many organizations and consortia, including companies and universities





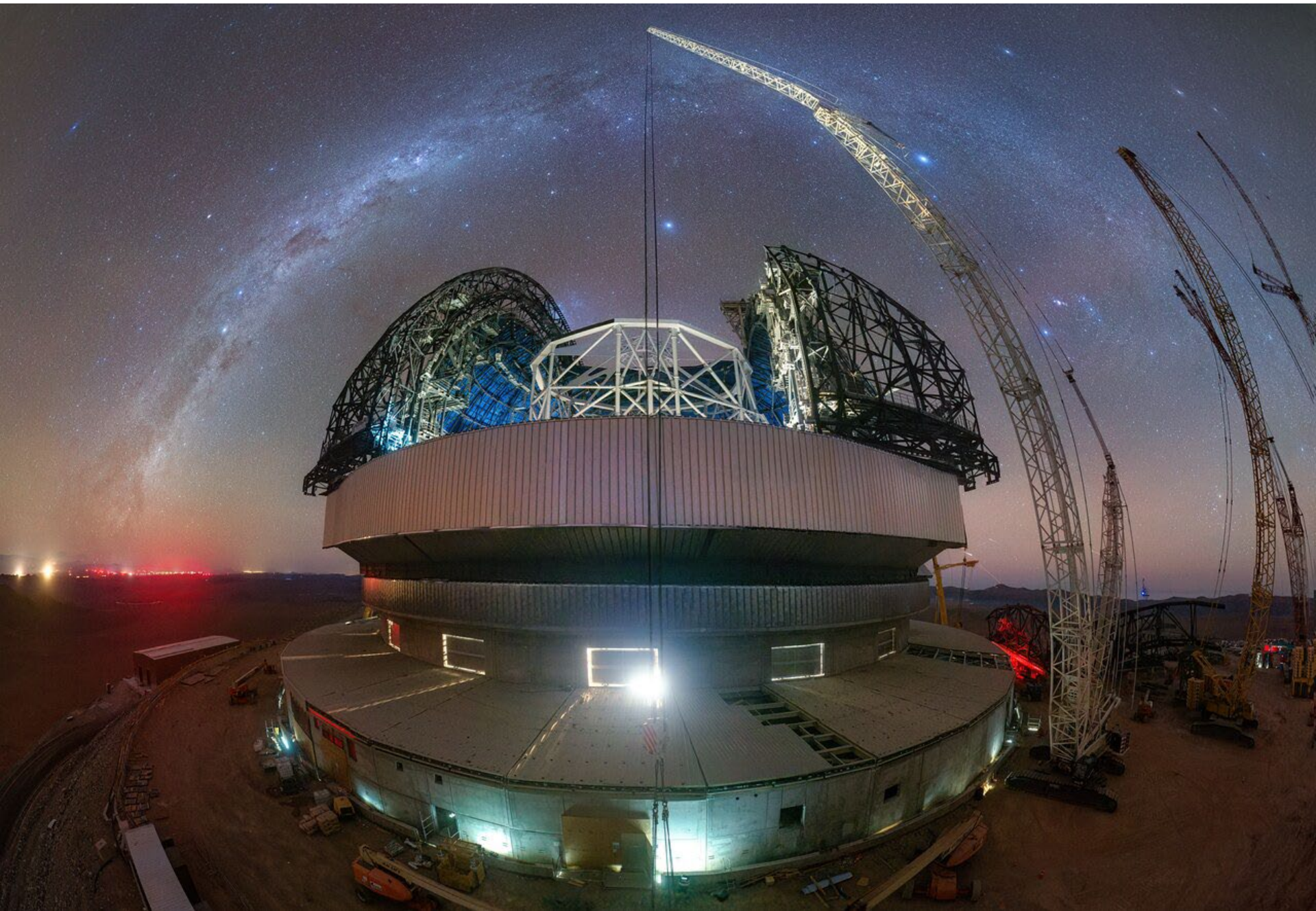


Five-mirror design

1. The 39.3-metre primary mirror collects light from the night sky and reflects it to a smaller mirror located above it.
2. The 4-metre secondary mirror reflects light back down to a smaller mirror nestled in the primary mirror.
3. The third mirror relays light to an adaptive flat mirror directly above.
4. The adaptive mirror adjusts its shape a thousand times a second to correct for distortions caused by atmospheric turbulence.
5. A fifth mirror, mounted on a fast-moving stage, stabilises the image and sends the light to cameras and other instruments on the stationary platform.

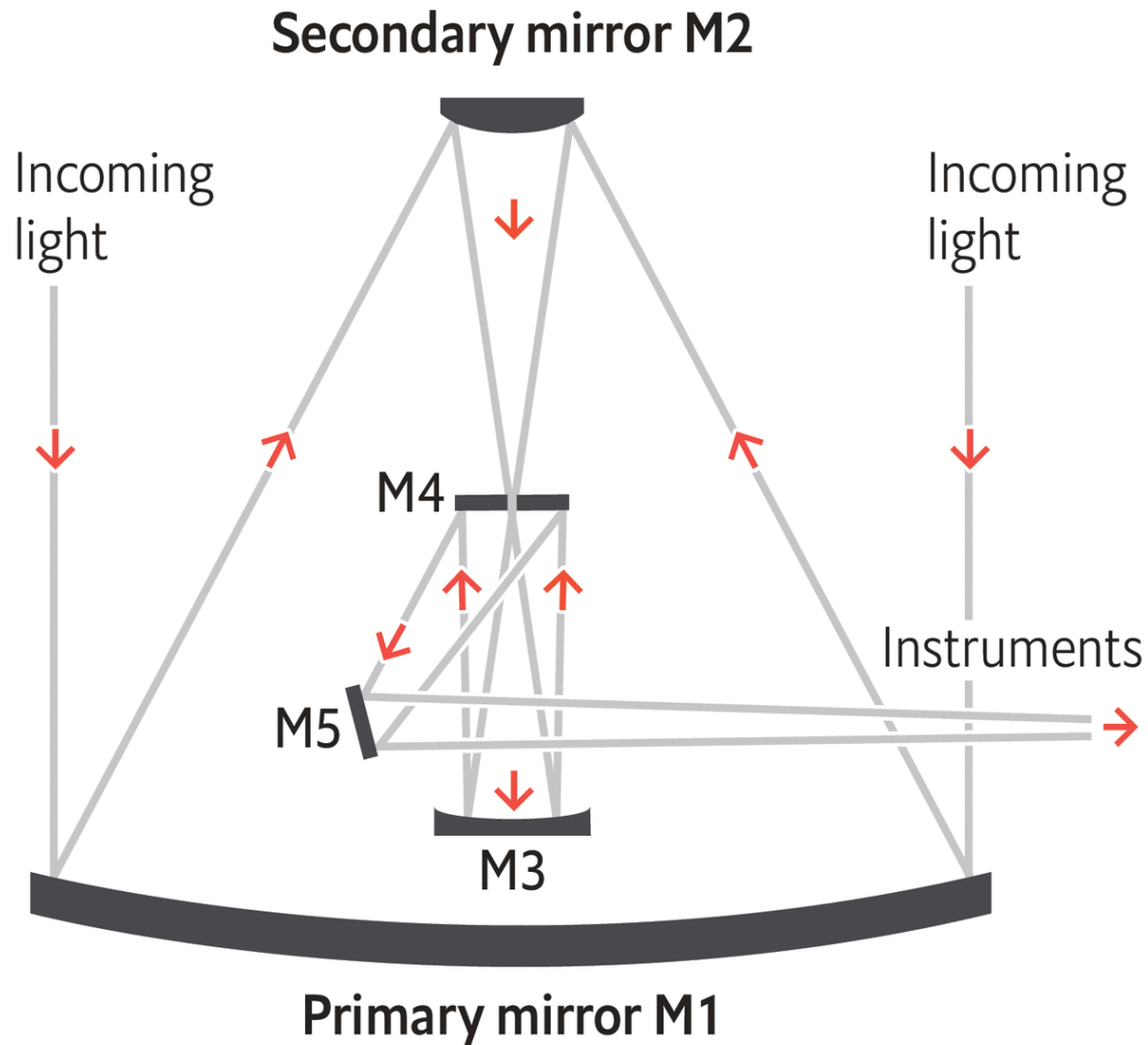
The 2800-tonne telescope system can turn through 360 degrees

- Seismic isolators



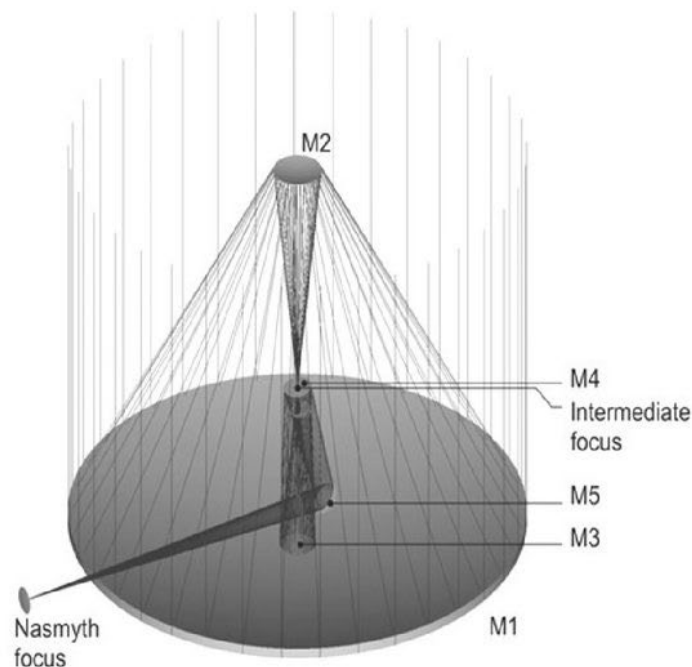
April 2025

ELT Mirror Design



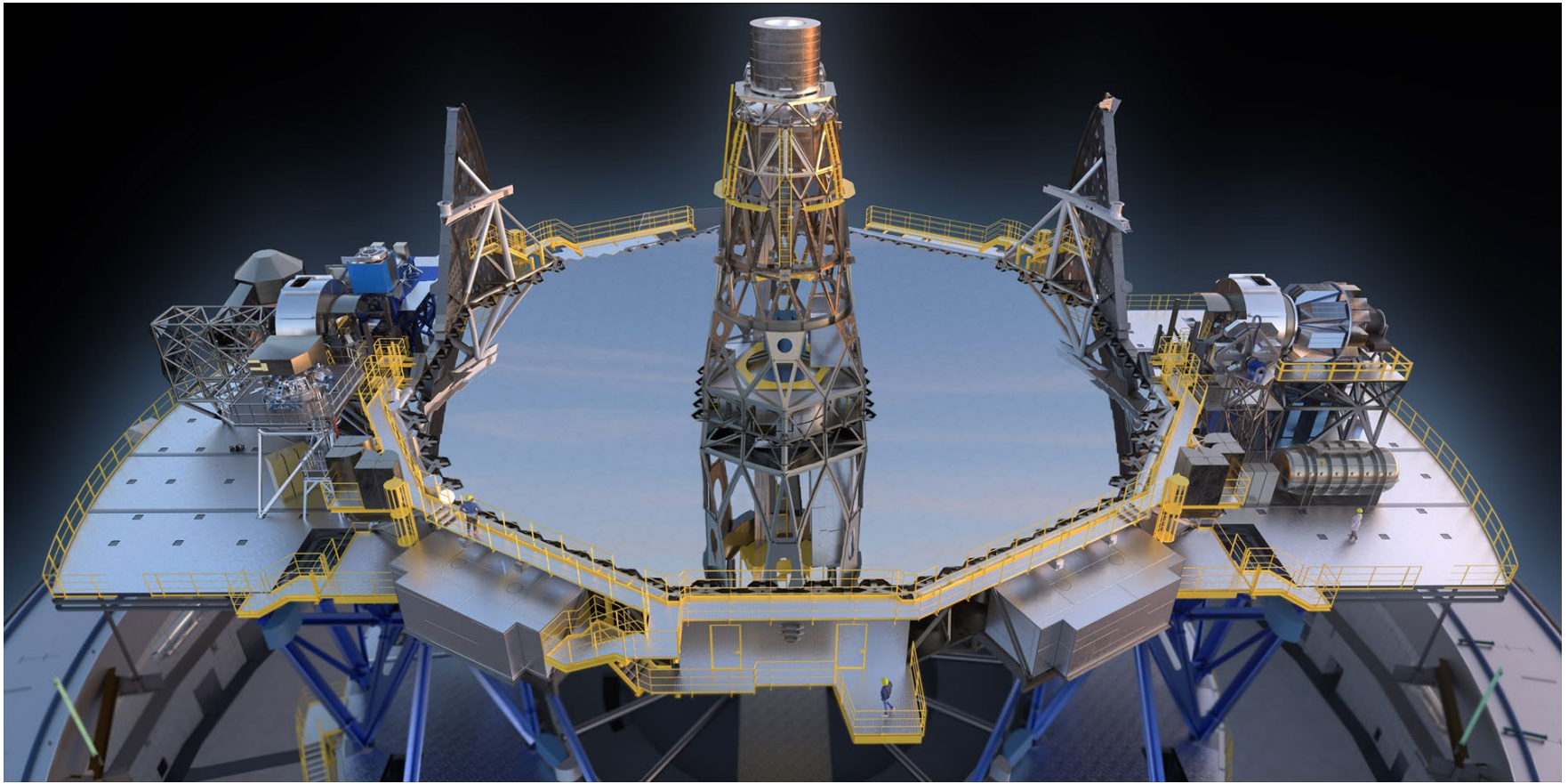
Nasmyth Focus

- James Nasmyth, 1808-90 – Scottish engineer
- Facilitates attachment of massive/complex instrumentation – no need to “hang” it below the Cassegrain focus



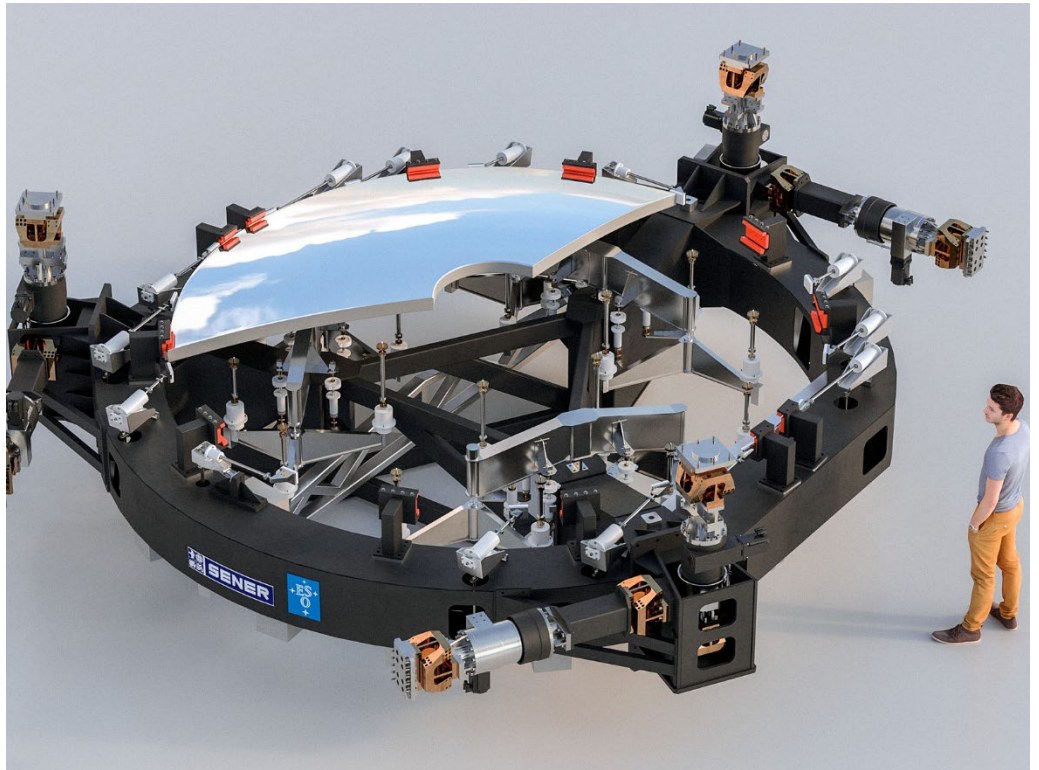
ELT Mirror M1

- The giant primary mirror:
- 39m diameter, 798 hexagonal segments, each 1.4m across; position/shape controlled to 10s nm



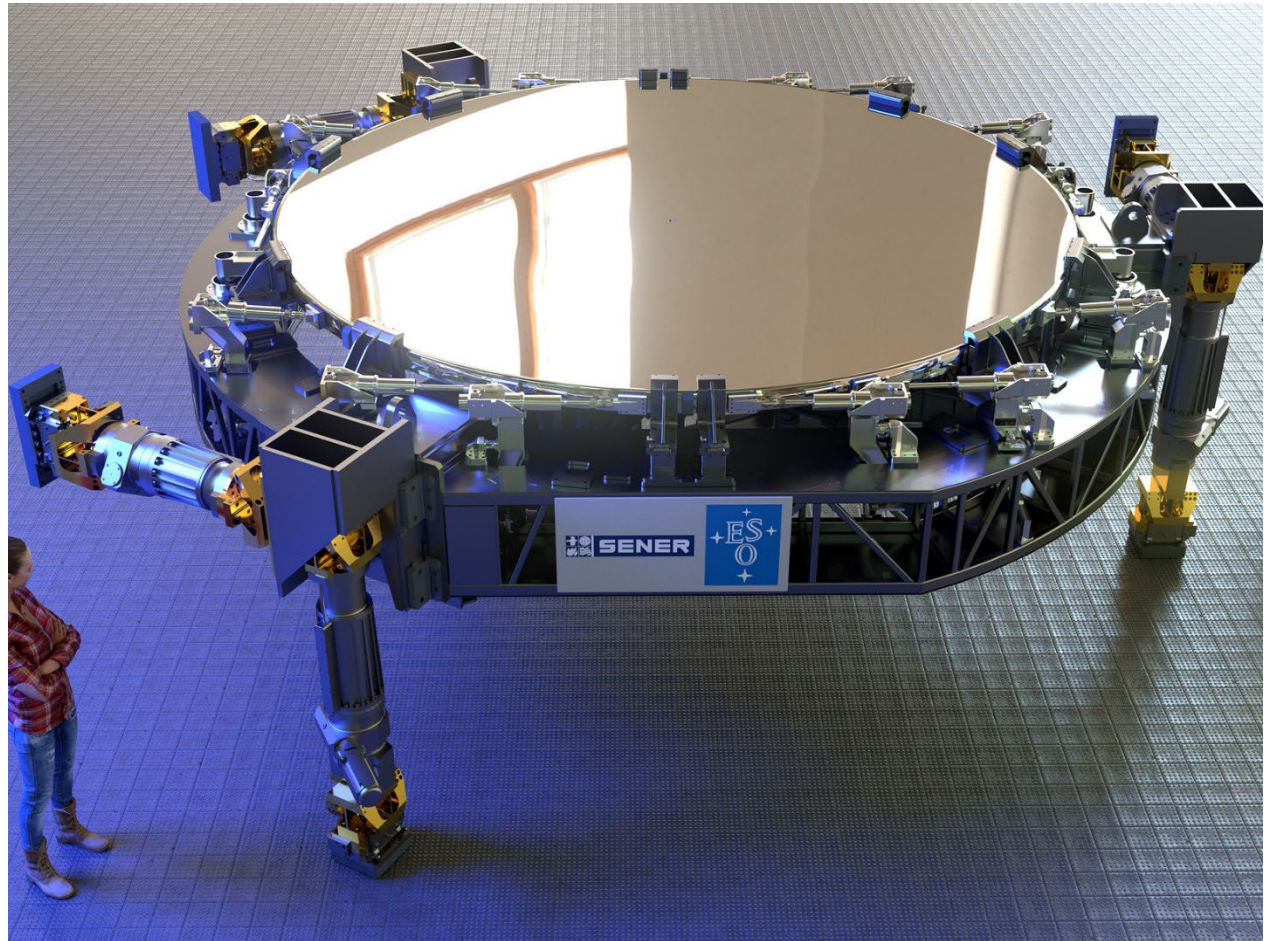
ELT Mirror M2

- 4.25m diameter, the largest secondary ever built
- Mirror weighs 3 tonnes, and with cell and structure 12 tonnes
- Anchored to the telescope main structure, 60m above ground



ELT Mirror M3

- 4m diameter
- Mirror weighs 3 tonnes, and with cell and structure 12 tonnes



ELT Mirror M4

- At 2.4m diameter, the largest adaptive optics mirror ever built

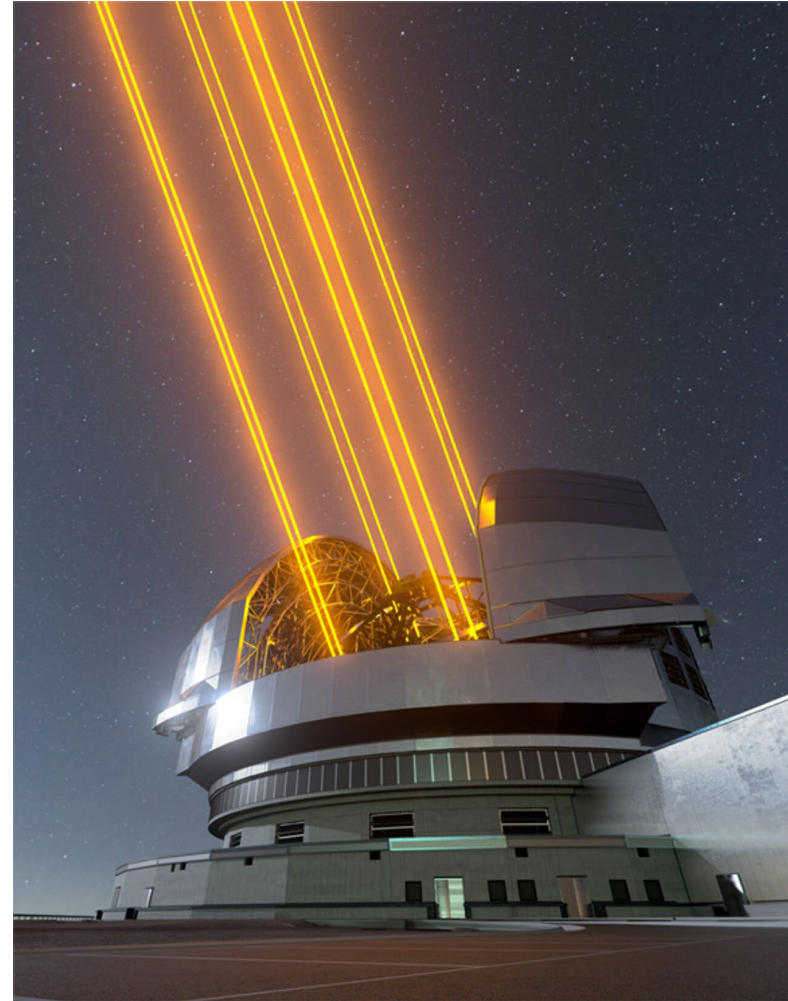


ELT Mirror M4

- At 2.4m diameter, the largest adaptive optics mirror ever built
- Made of 6 “petals”, less than 2mm thick
- More than 5000 actuators [linear motors with magnet-coil assembly] change the mirror shape by up to 50 microns, up to 1000 times per second, to allow for atmospheric turbulence and residual telescope vibration
- Sensors co-located with actuators measure position 70,000 times per second with accuracy 10s nm

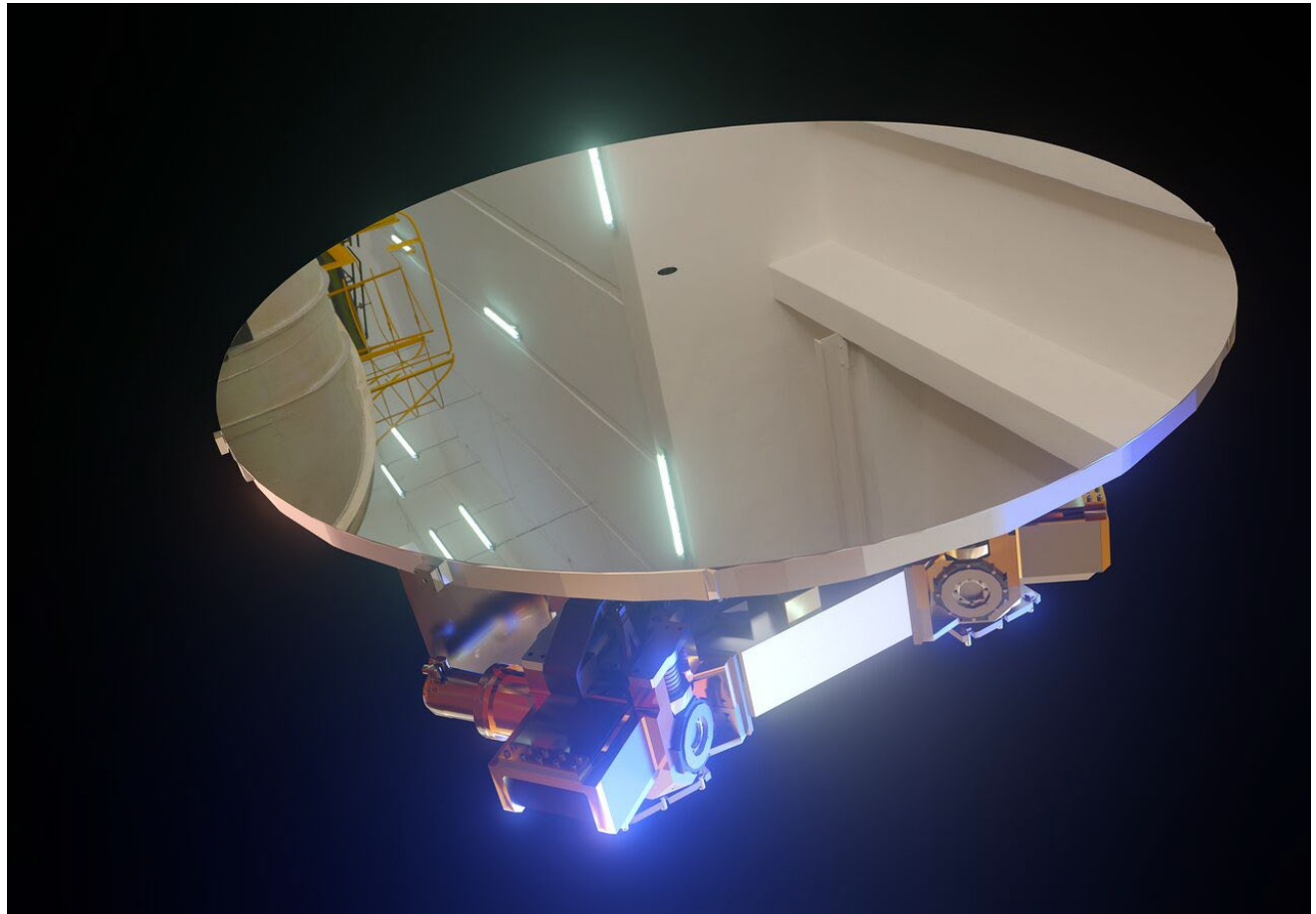
ELT Laser Guide Stars

- Up to 8 guide star 22W lasers (not all necessarily in use at once)
- Used with 3 complementary wavefront sensing cameras:
 - ALICE optical/natural
 - LISA optical/laser
 - FREDa ir/laser
- Computers analyze the signals in real time – 500 times per second – and feed information to the actuators to deform the mirror



ELT Mirror M5

- At 2.2x2.7m this is the largest flat, rigid, tip-tilt mirror ever built – part of the adaptive optics system



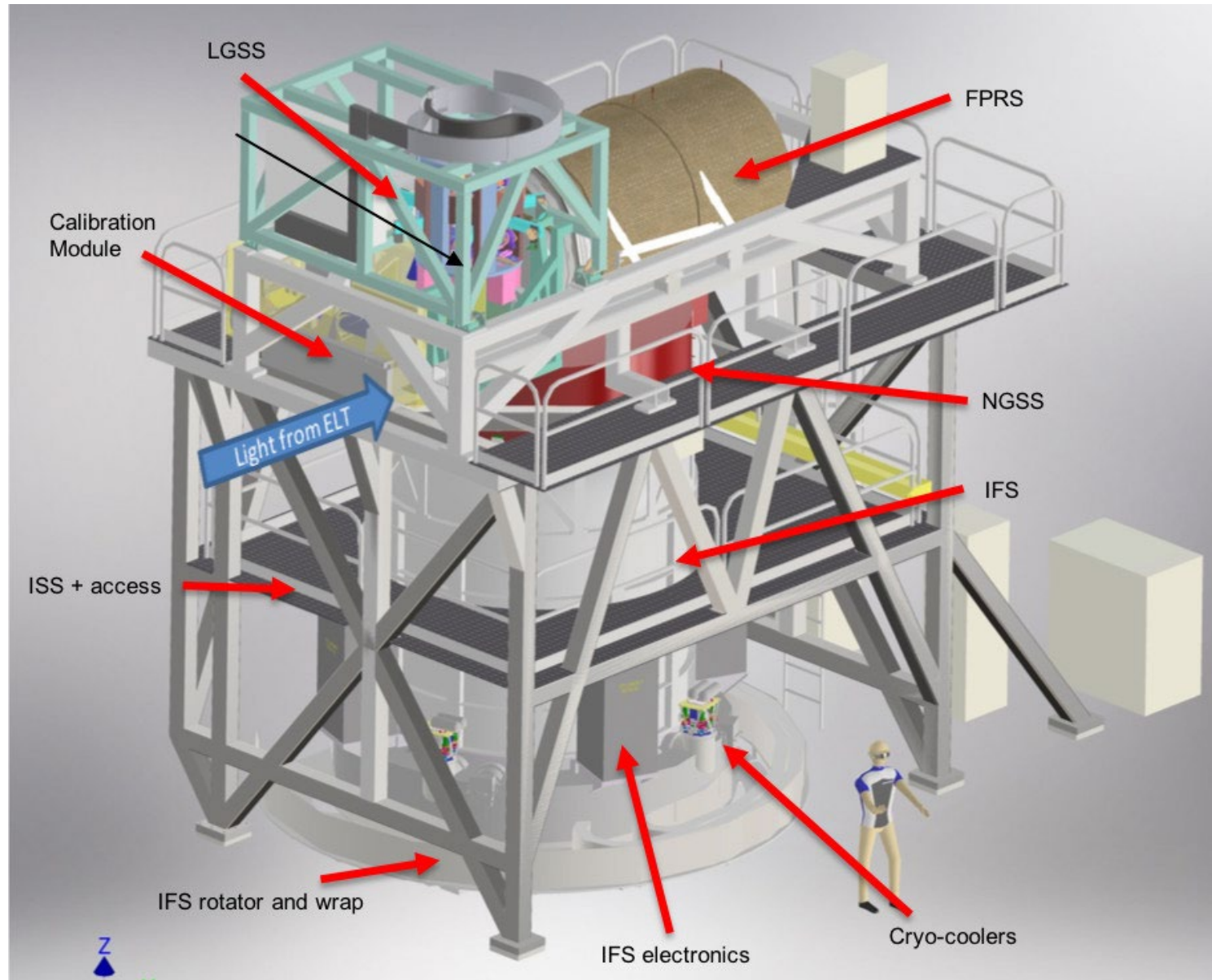
ELT Mirror M5

- At 2.2x2.7m this is the largest flat, rigid, tip-tilt mirror ever built
- Also made of 6 “petals” brazed together
- Part of the adaptive optics system, but also has a switching mechanism to feed the appropriate Nasmyth platform

Instrumentation

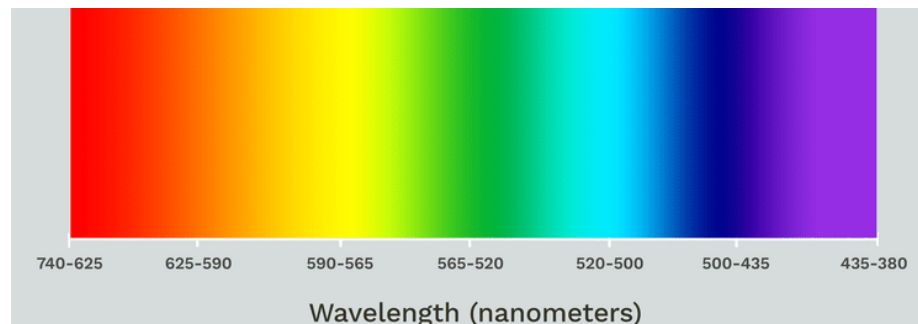
- HARMONI: High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph
- MICADO: Multi-adaptive optics Imaging Camera for Deep Observations
- *METIS: A mid-infrared imager & spectrograph*
- *MOSAIC: A multi-object spectrograph*
- *HIRES: A high resolution spectrograph*
- *PCS: A dedicated planetary camera & spectrograph*

HARMONI



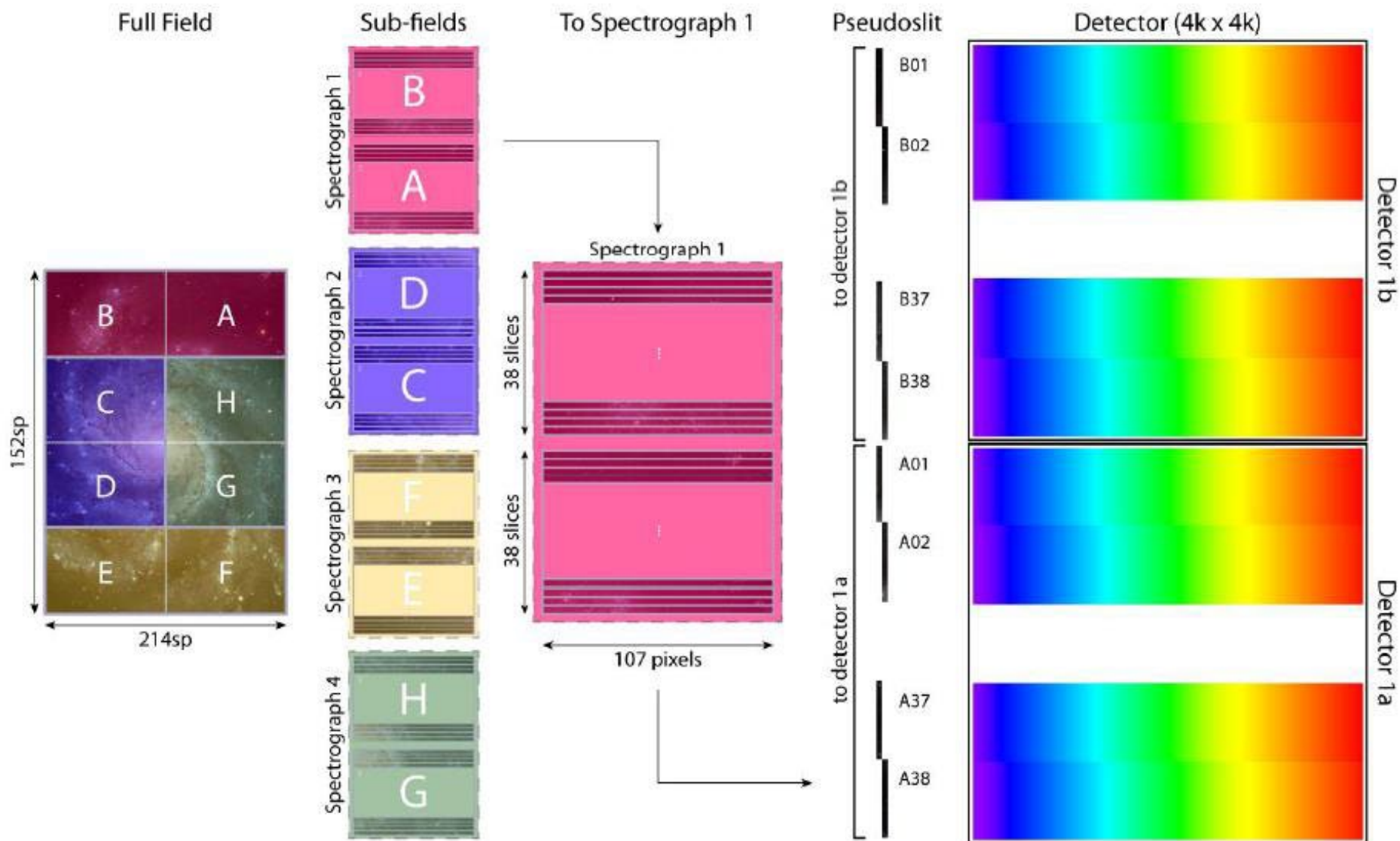
HARMONI

- A flexible integral field spectrograph – does “image slicing” to provide a 3D data cube
- The “slicer” divides an image into many “spatial pixels” called spaxels
- The user can choose between 4 spaxel scales (between 4mas and 60mas): smaller scale has smaller field of view but higher *spatial resolution*
- The user can choose from a range of *spectral resolutions* spanning 450 to 2450 nm

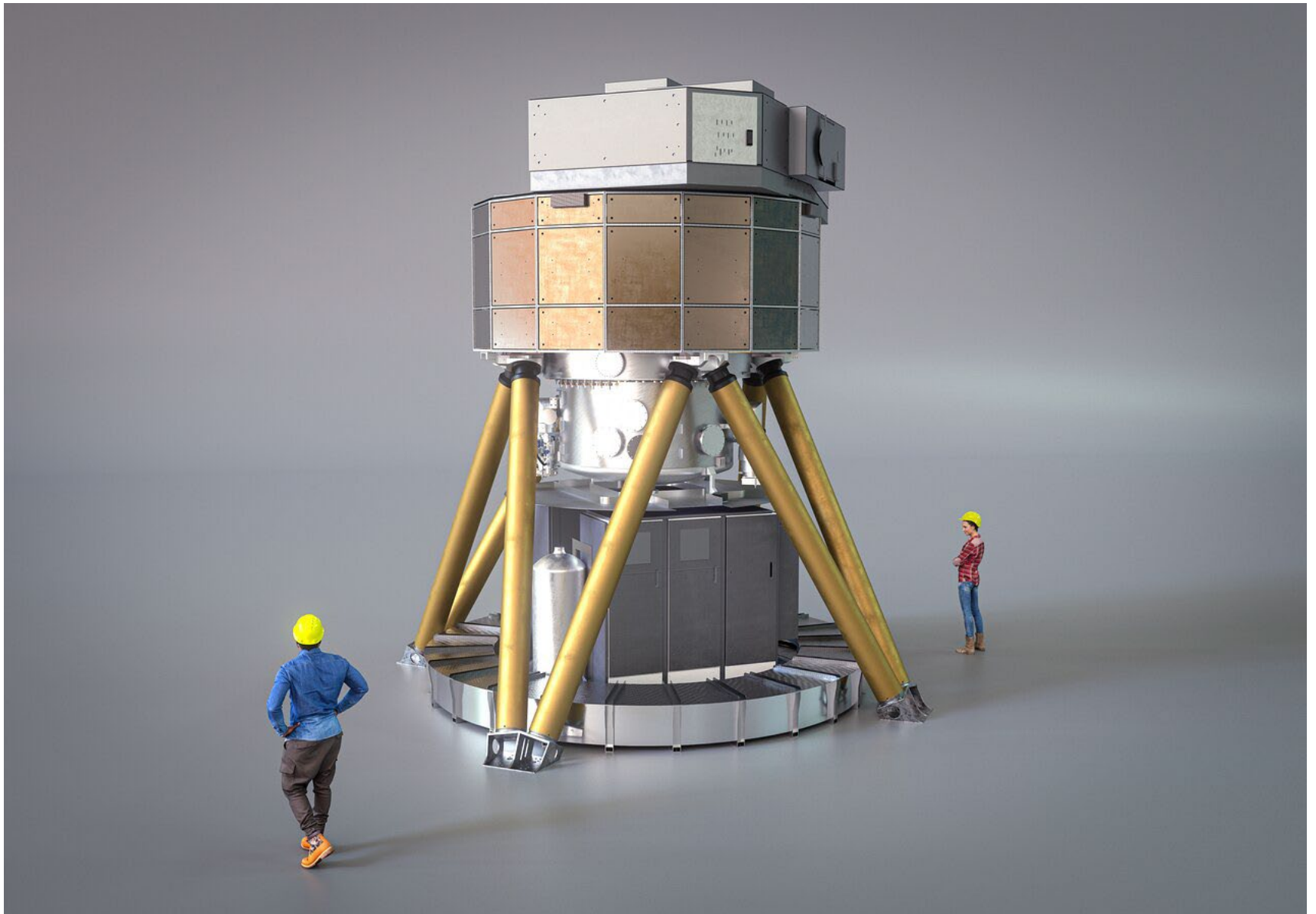


Spaxels? You're Kidding Me!

- The rectangular field is 214x152 “pixels”, so about 31,000 “pixels”; these are the “spaxels”
- This field of view is split into 8 subfields
- Each of the subfields is sliced into 38 narrow strips
- Subfields are paired, and the 2x38 slitlets are arranged into a long “pseudo-slit” and send to one of four spectrographs
- Each spectrograph has 2 detectors
- **Yes – an image would help clarify this!!**

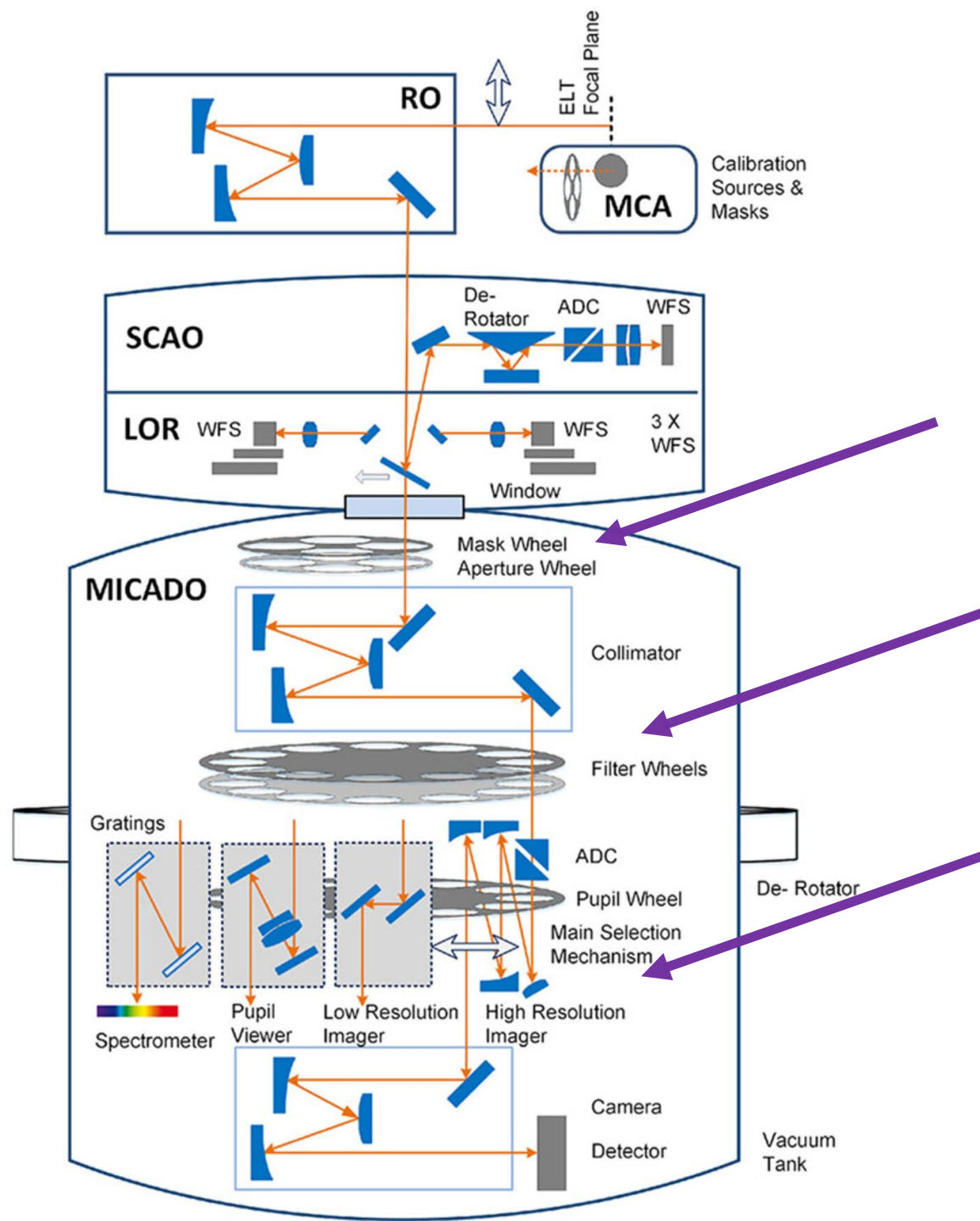


MICADO



MICADO

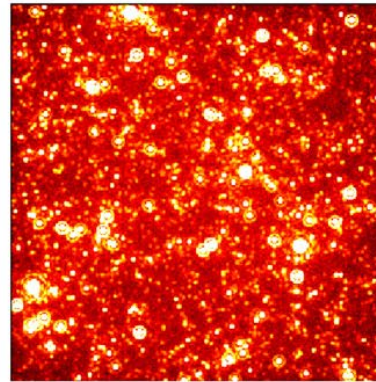
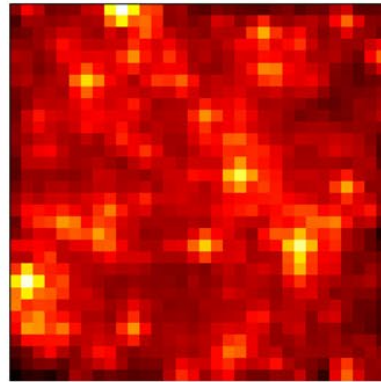
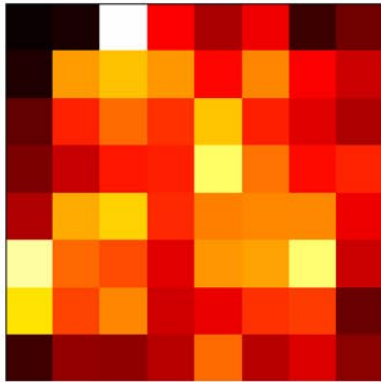
- A camera providing sensitive imaging and high resolution spectroscopy in the near infra-red
- Camera has an array of 3x3 detectors, each with 4096x4096 pixels
- Notable: will produce the highest resolution images ever achieved in astronomy
- Notable: will allow astrometry with precision of 50 microarcseconds
- Notable: has “built in” adaptive optics
- Notable: has “built in” coronagraph to block star-light and reveal exoplanets



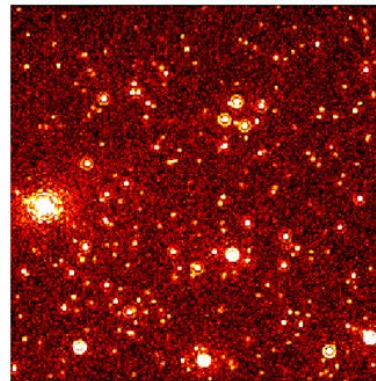
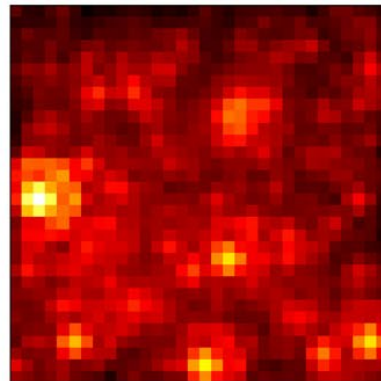
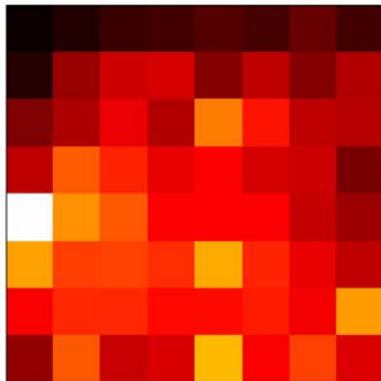
HST / WFC3

JWST / NIRCam

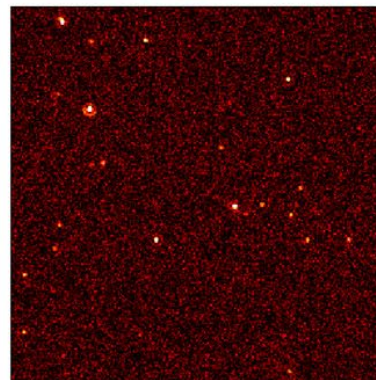
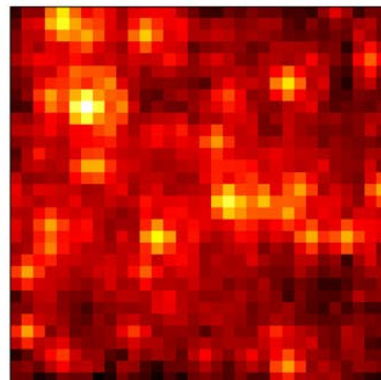
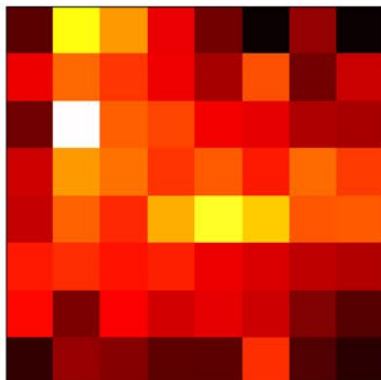
ELT / MICADO



$\mu=19.6$
(10^6 stars/arcsec ^{2})



$\mu=22.0$
(10^5 stars/arcsec ^{2})



$\mu=25.2$
(10^4 stars/arcsec ^{2})

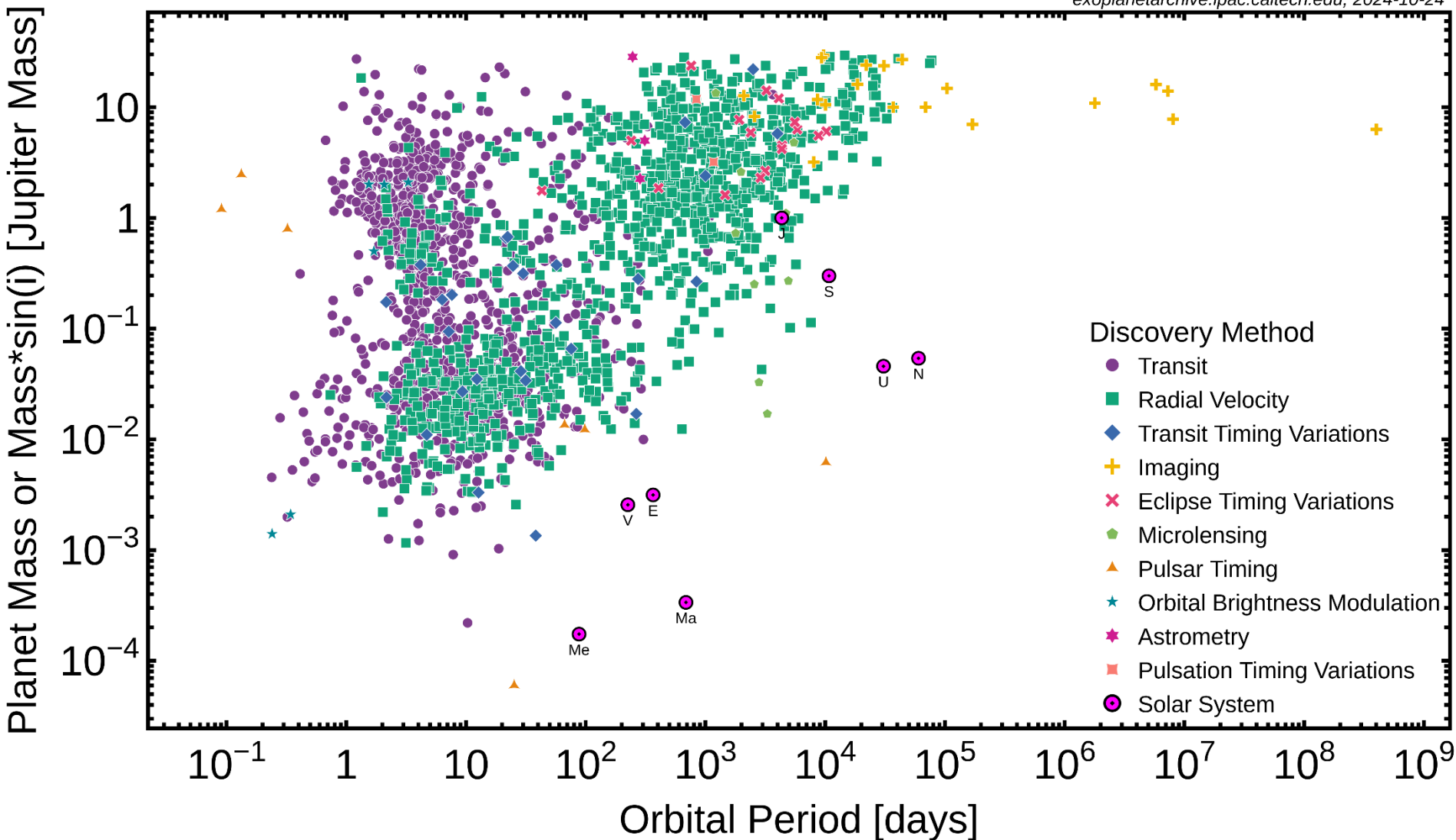
ELT Science Goals 1

- **Exoplanets**
- Characterize atmospheres of potentially habitable exoplanets, looking for biosignatures such as methane & oxygen
- Study planet formation through protoplanetary and debris disks

Exoplanet Demographics

Planet Mass or Mass* $\sin(i)$ vs Orbital Period

exoplanetarchive.ipac.caltech.edu, 2024-10-24

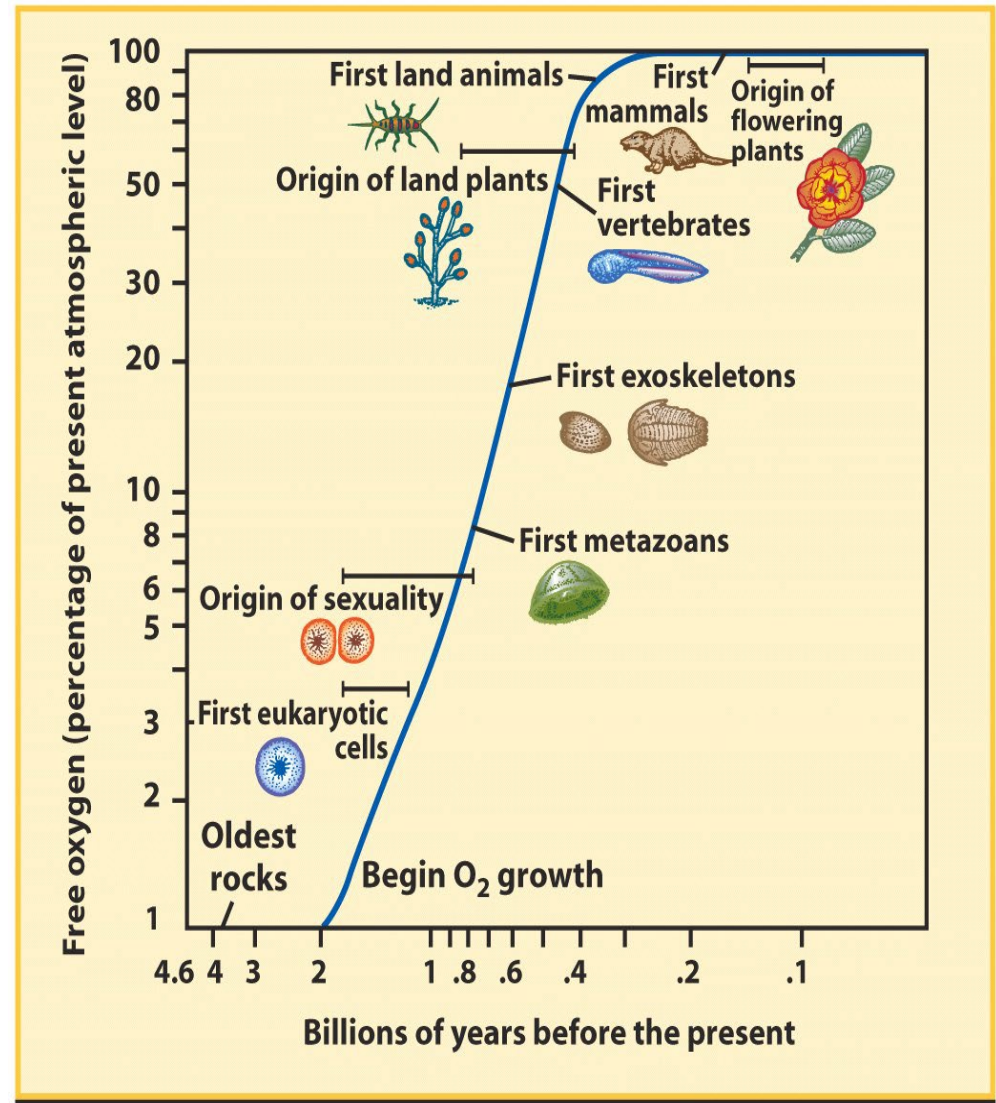


The Rise Of Oxygen

- In the Earth's early, Oxygen-free atmosphere, simple organisms would have been anaerobic; they were probably
 - chemoautotrophs – getting energy from inorganic compounds
 - modern Archaea in hot springs get their energy from H/S/Fe compound reactions
- Photosynthesis evolved from light absorbing pigments, that eventually allowed
 - photohetero(auto)trophs – getting energy from sunlight
 - “blue-green” algae release oxygen

The Rise Of Oxygen

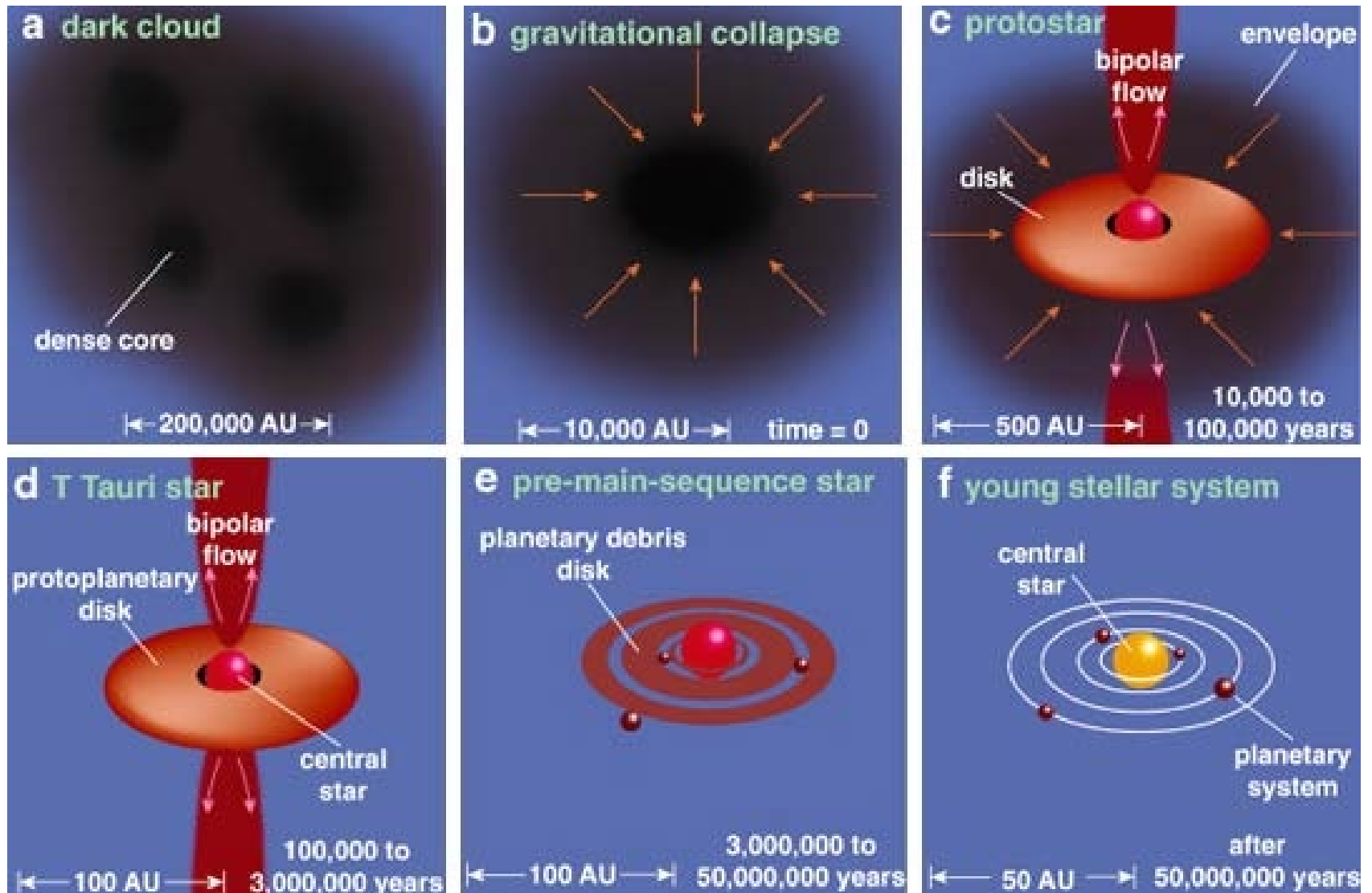
- Oxygen is **highly reactive**:
 - Oxidizes surface rock & Fe minerals in oceans
 - Rocks > 2 billion years old have only 1% modern oxygen levels
 - No more than 10% current until about 1 billion years ago
 - Then reaches current levels
- **Oxygen needs life!**
 - O_2/O_3 in exoplanet atmosphere is a promising indication of life



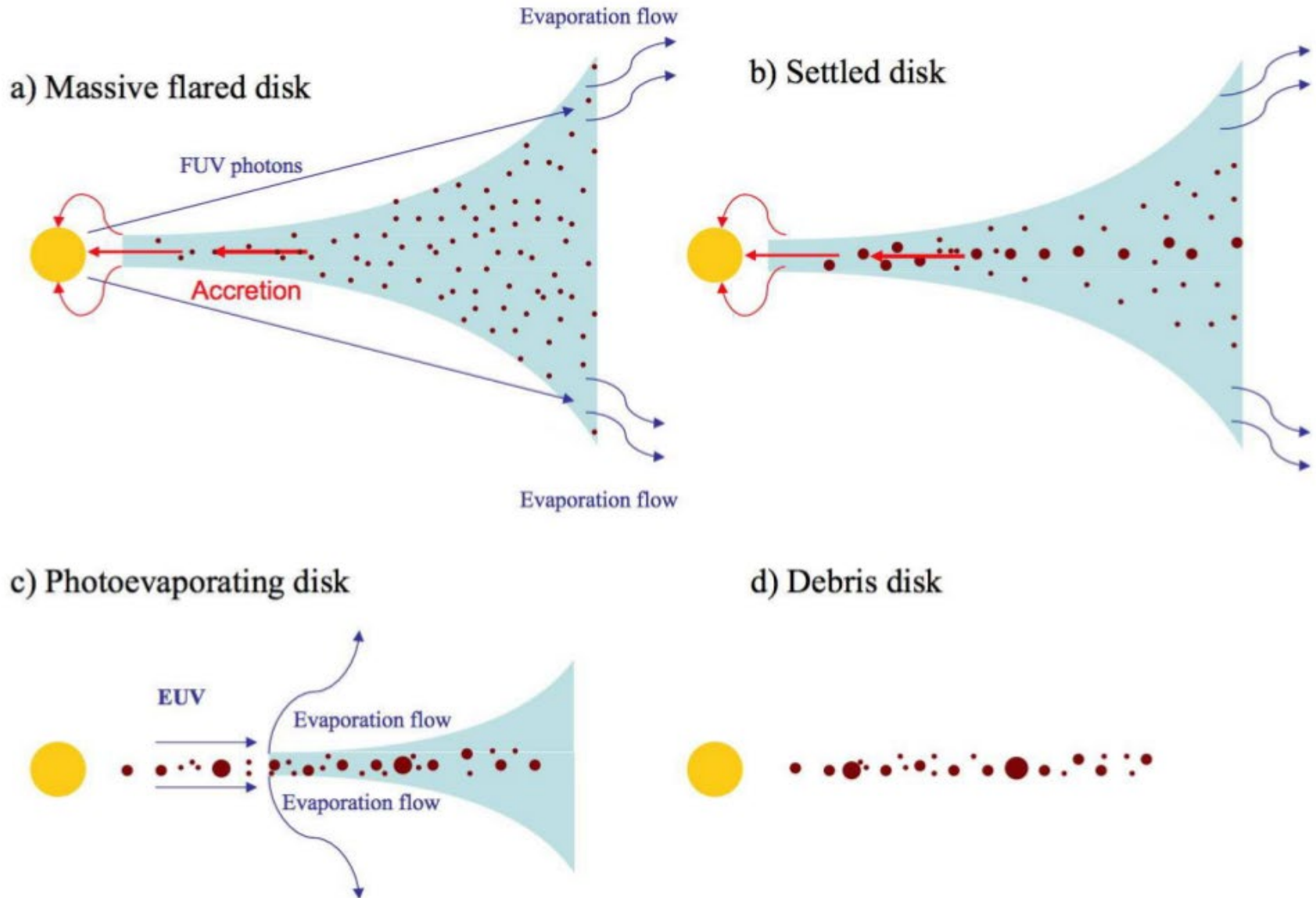
Exoplanet Atmospheres

- As of early 2025, 249 atmospheres have been studied
- We are probing *structure*, as for planets in our Solar System:
 - day/night temperature and latitude differences, circulation and clouds
- We are beginning to probe *composition*; 60 different molecules have been found, including
 - TiO, CO, H₂O, CO₂, CH₄

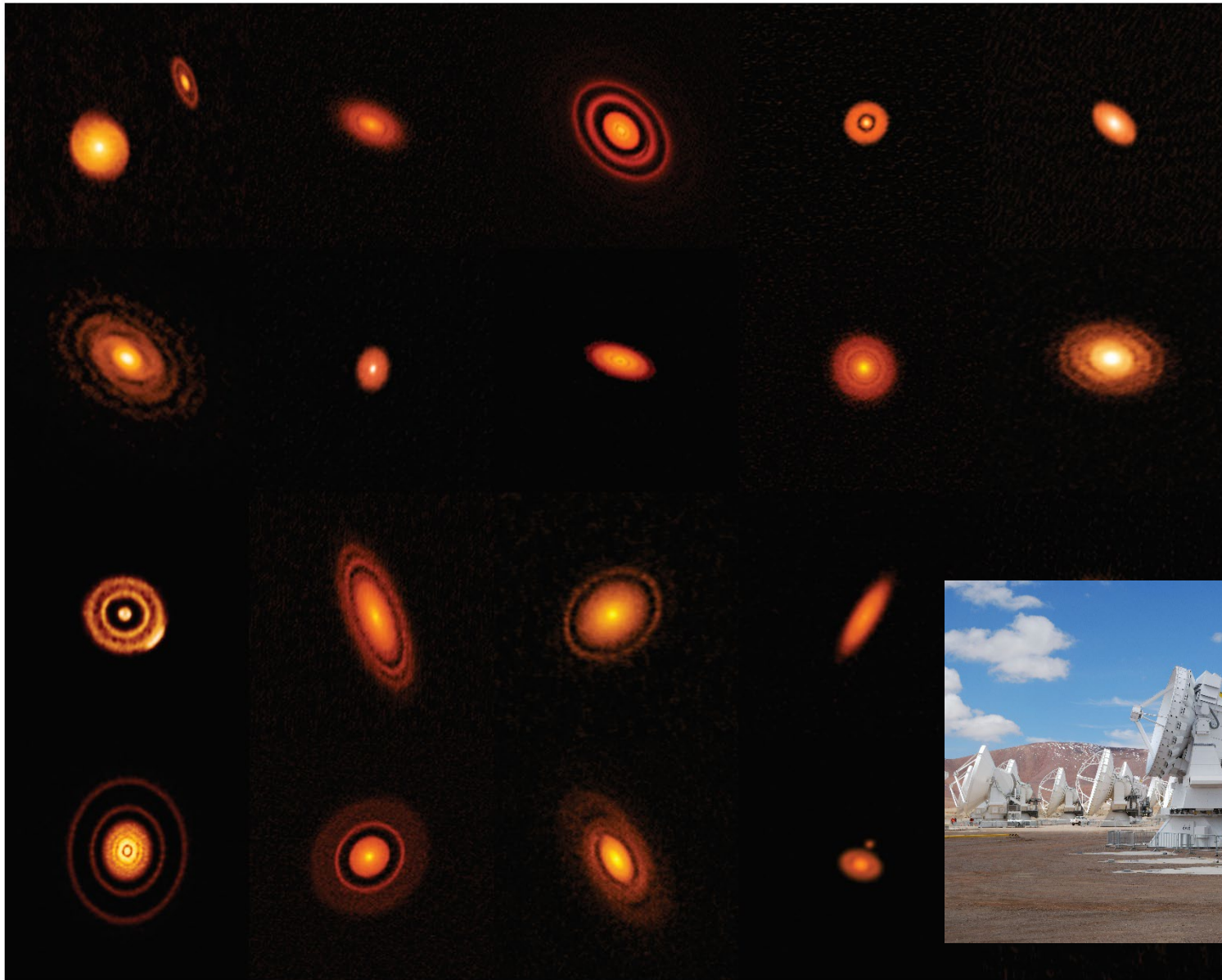
Planet Formation



Planet Formation



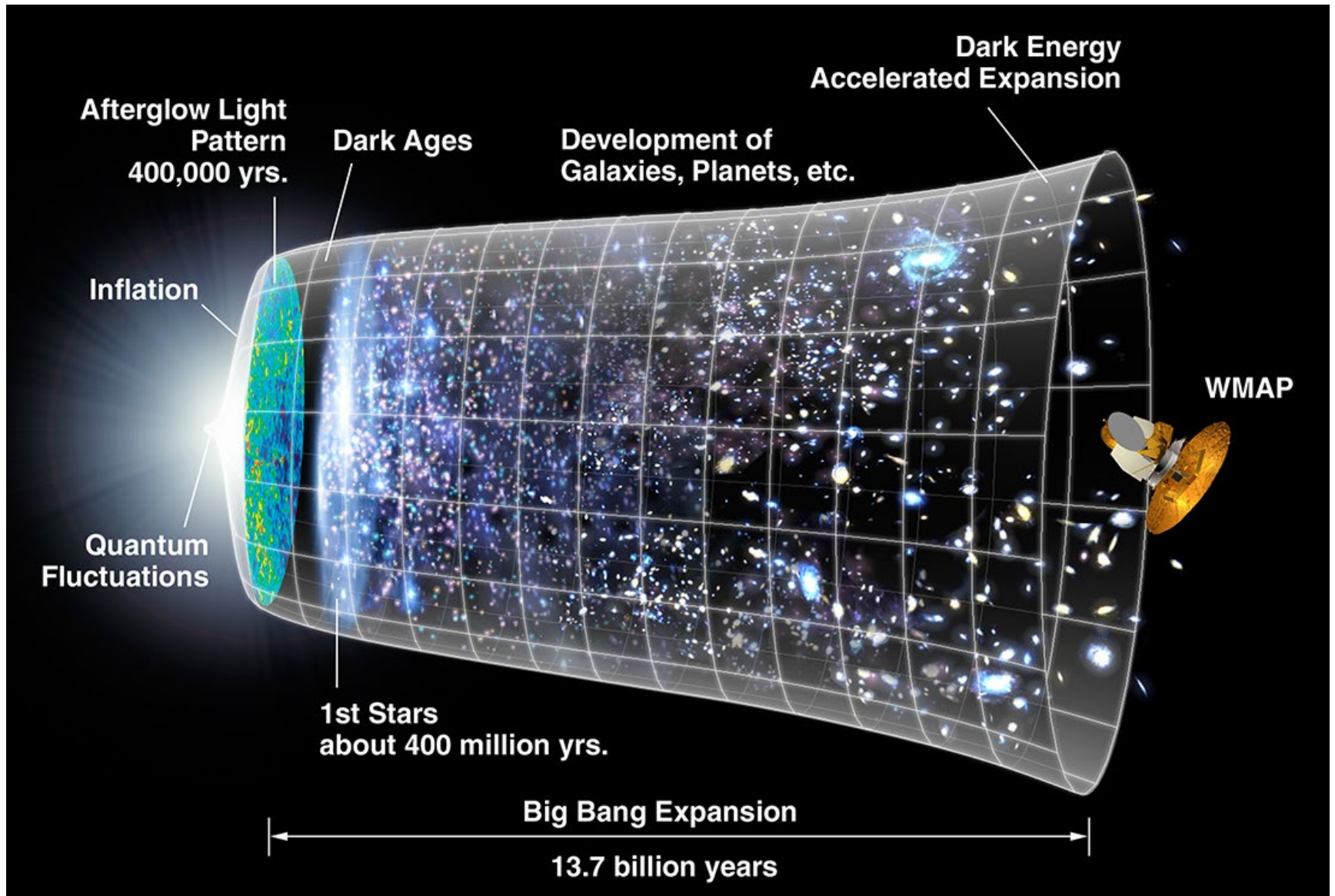
ALMA



ELT Science Goals 2

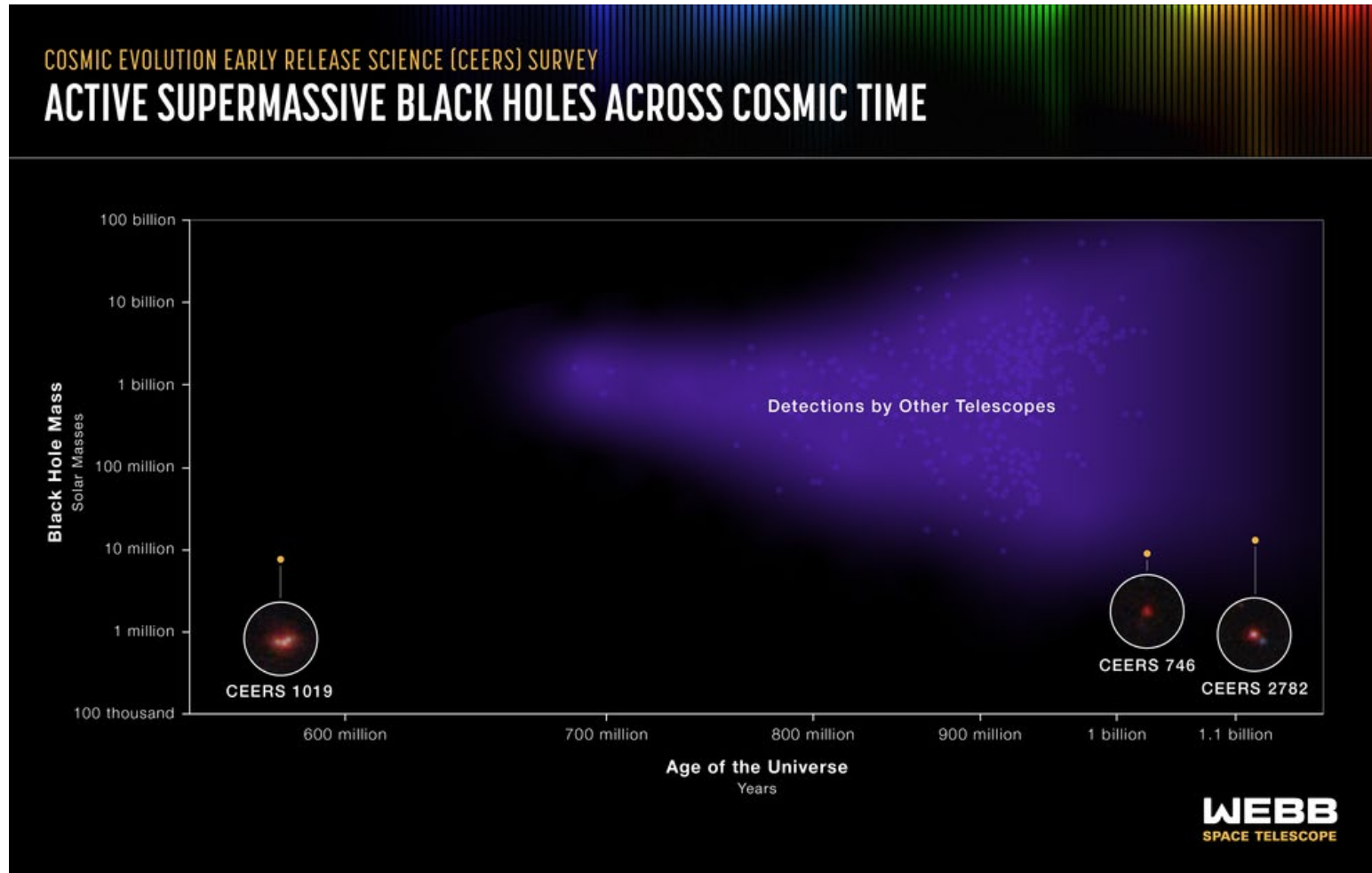
- **The First Galaxies**
- When did the 1st galaxies form?
- What was the rate of star formation, and what did the early stellar populations look like?

A Compact History



A Potential Problem

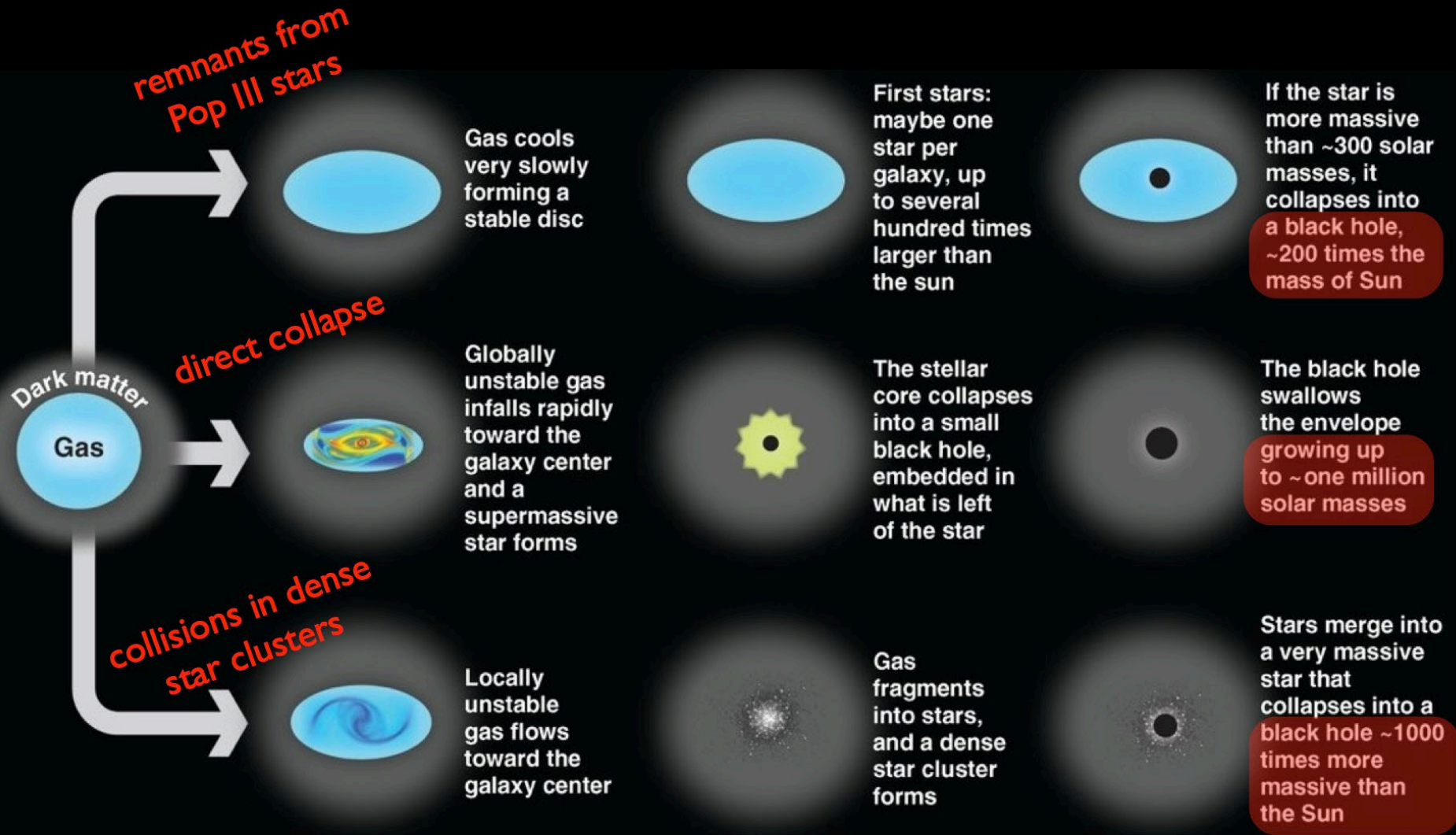
- Supermassive Black Holes/Galaxies exist only 100s millions of years after the Big Bang



A Potential Problem

- **It is unlikely that they have time to grow by accretion from few solar mass stellar seeds**
- At some point in cosmic time black holes with a mass up to a million solar masses had to exist to provide the seeds for those of greater than a billion solar masses
- **How are the intermediate mass seeds created?**

What is the origin of supermassive black hole “seeds”?



ELT Science Goals 3

- **Dark Matter & Dark Energy**
- *See last week on the Rubin Observatory*
- *This is a study of fundamental physics; but that's not all...*

ELT Science Goals 4

- **More Fundamental Physics**
- Observations across a range of objects and distances can test whether constants such as the “fine structure constant”*, proton-to-electron mass ratio, etc. are the same from place to place and time to time [through subtle changes in spectral line positions]
- By observing orbits about black holes, we can test the validity of General Relativity

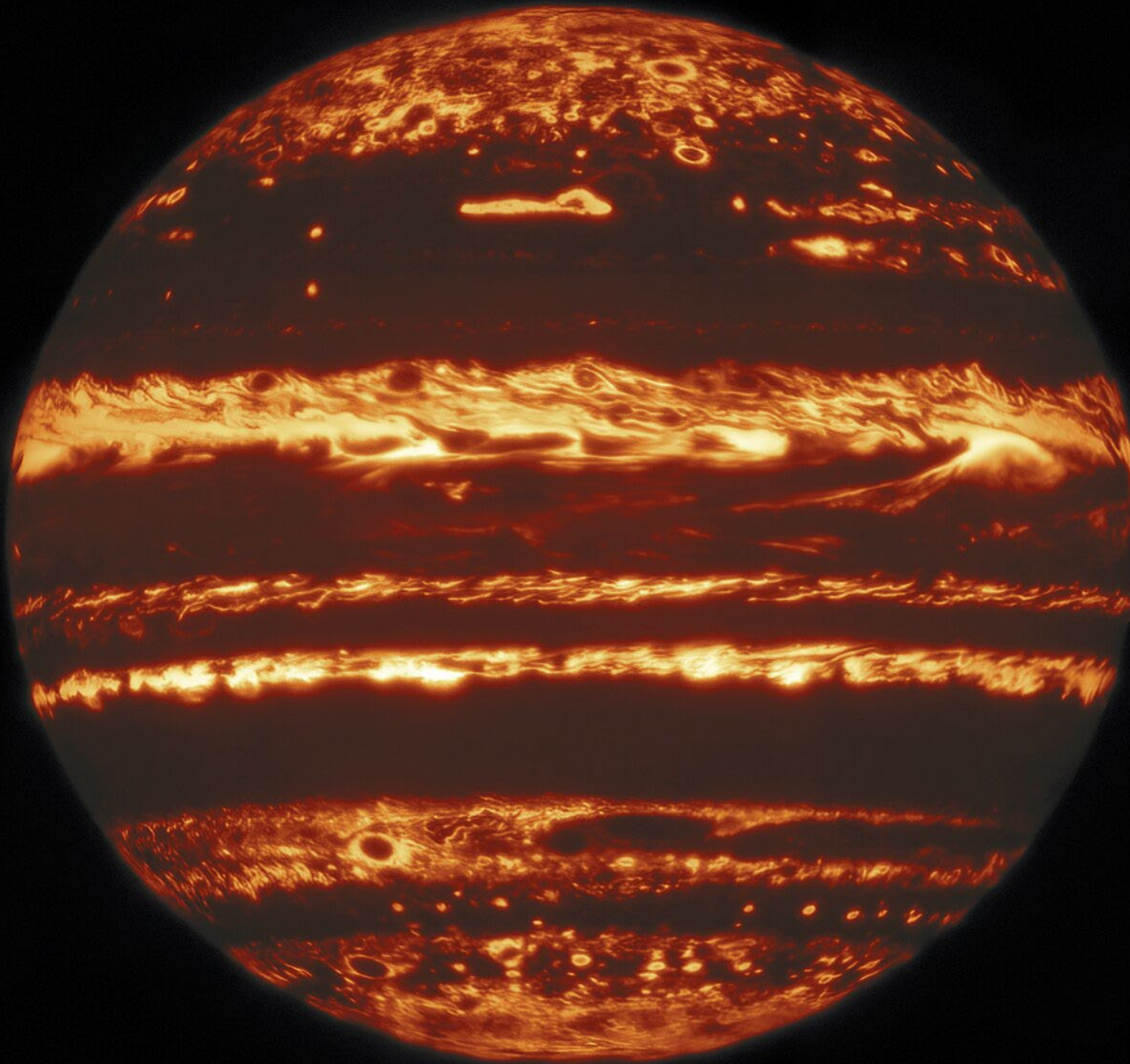
*Measures how strongly charged particles interact electromagnetically

ELT Science Goals 5

- **Solar System Objects**
- *See last week on the Rubin Observatory, plus....*
- Study the atmospheres of the gas giants
- Study (cryo-)volcanism on the gas giant's moons

Giant Planet Atmospheres

- High resolution spectroscopy will determine chemical composition
- Doppler imaging will probe global circulation & dynamics; we will better understand the 3-D structure of these atmospheres – temperature structure, cloud cover and wind patterns
- Repeated observations will probe short & long term changes in chemical make up, temperature and winds
- All the above will provide a crucial baseline for comparison with exoplanet atmospheres



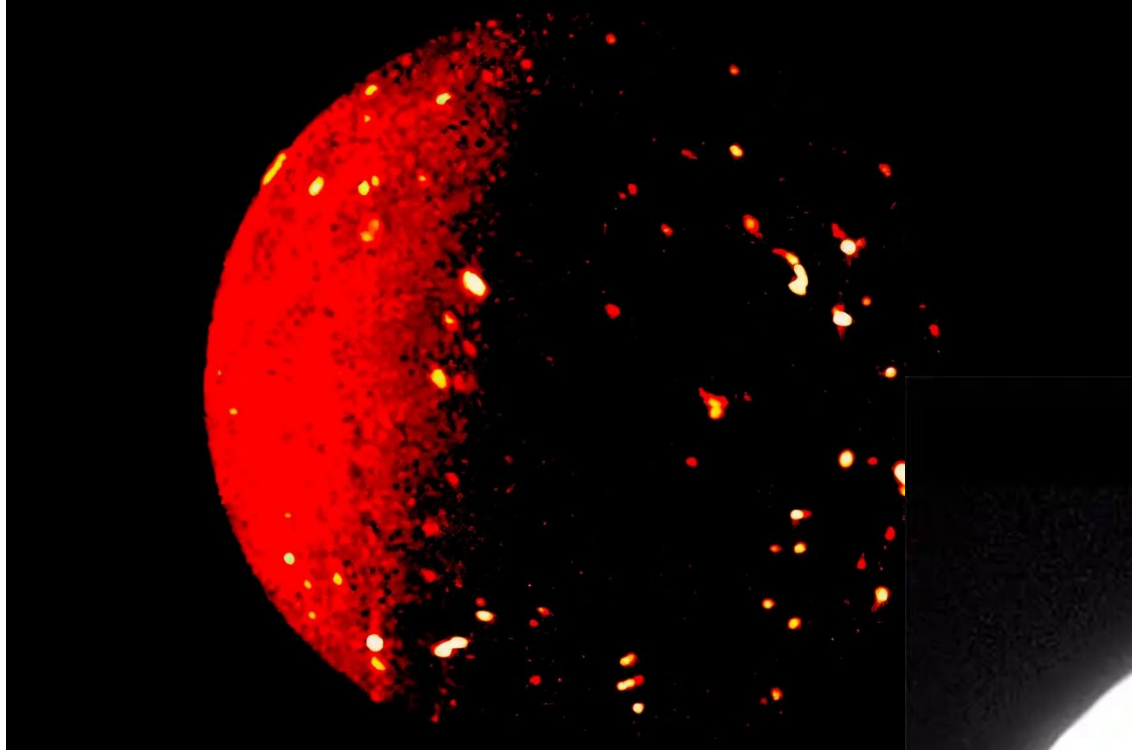
Jupiter

International Gemini
Obs. /
NOIRLAB

Lucky
imaging!

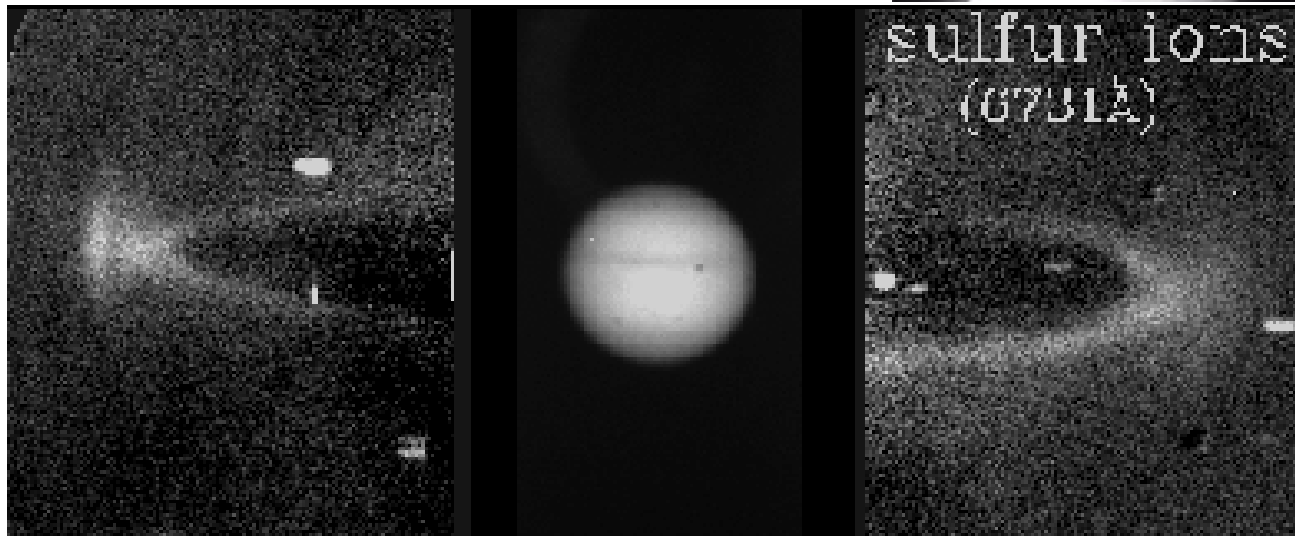
(Cryo-)Volcanism On Moons

- High resolution imaging will reveal overlapping debris fields, and thus identify individual volcanoes and changes
- This will tell us how the moon's surface is sculpted and inform comparative planetology
- High resolution spectroscopy will probe chemical composition of ejecta & plumes
- Study of plumes will probe how they interact with the planetary magnetic field / produce a plasma torus

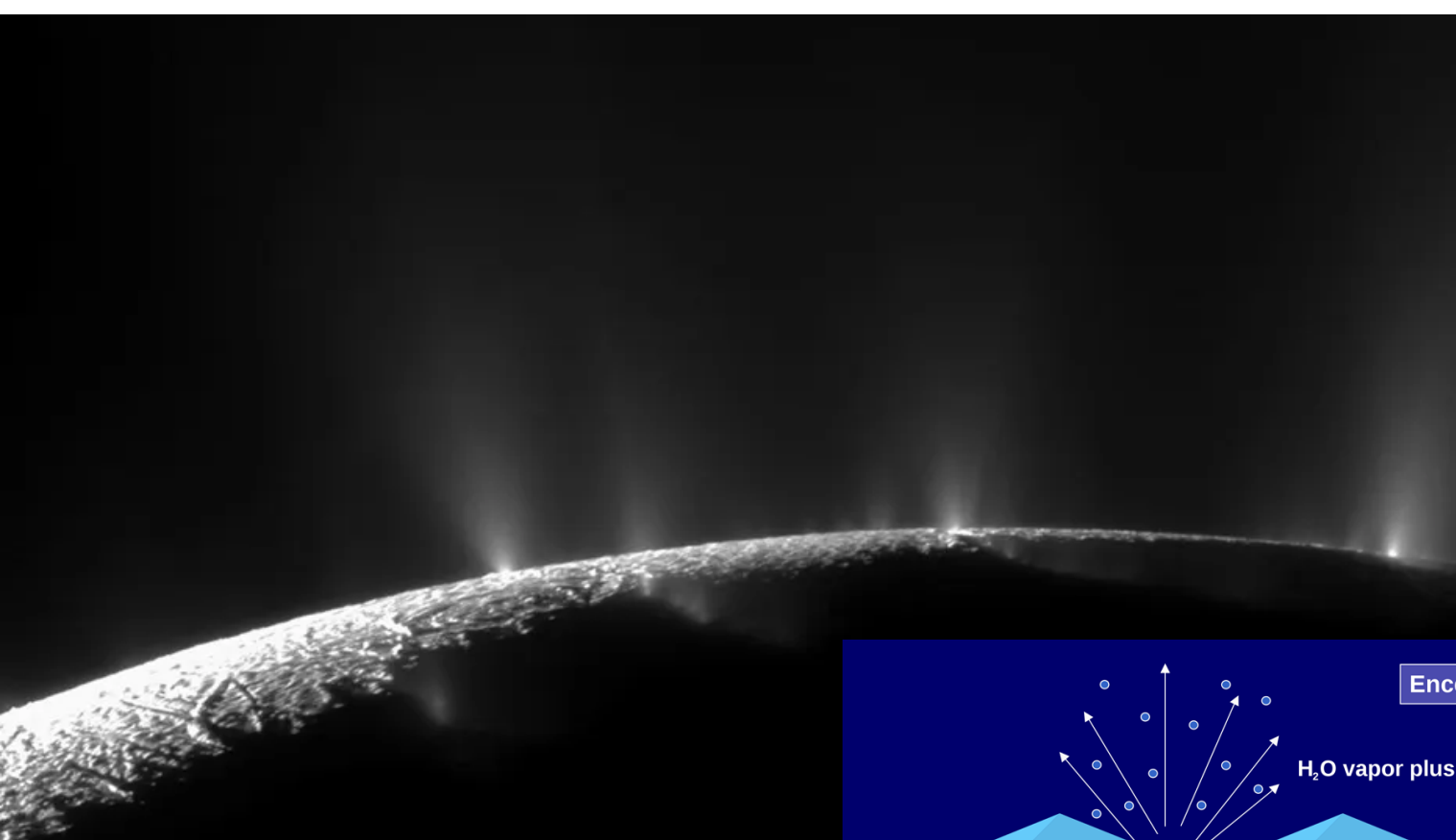


IR image of Io from Juno probe

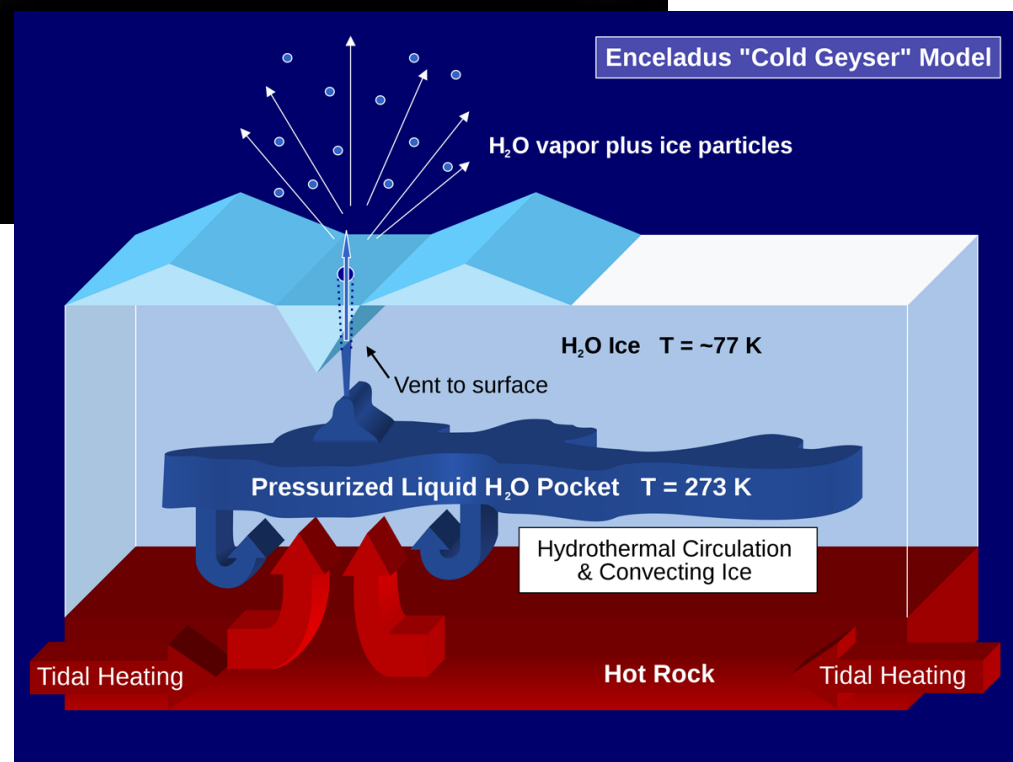
Image of Io plume from New Horizons probe



Io plasma torus from Earth



Enceladus water
plumes / Cassini:
Cryovolcanism





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University of Michigan ELT Postdoctoral Fellowship

The Department of Astronomy at the University of Michigan invites applications for our ELT Postdoctoral Prize Fellowship, focused on transformational science with Extremely Large Telescopes (ELTs).

Our department is currently the only U.S. institution participating in the instrumentation program for ESO's groundbreaking 39-meter ELT, through active membership in the HARMONI, METIS, ANDES, and MOSAIC consortia, as well as their Science Working Groups.

This fellowship is intended for junior scientists in all areas of astronomy who aspire to define ambitious research goals for the next generation of telescopes and make full advantage of the unparalleled capabilities of ELTs, including the European ELT, Giant Magellan Telescope, and Thirty Meter Telescope. You will have the opportunity to establish independent research that addresses scientific questions uniquely enabled by 30-meter-class telescopes. While experience with instrumentation is valued, this position emphasizes projects that utilize existing observational facilities and/or theoretical modeling and simulations to help shape the next generation of ground-based astronomy. Bring your boldest ideas, set the scientific agenda, and help chart the future of ELT discoveries with Michigan.

Is It Worth It?

- Construction cost: about \$1.5 billion (provided by ESO member states)
- Annual operations: \$54 million
- First light: March 2029
- Thoughts?