AY257: Modern Observational Techniques

- This class is about
  - astronomical data and data reduction techniques
  - observing proposals, observing planning, efficient observing
  - instrumentation as it relates to the above
- Working through the homework problems is the best way to learn the material

Data Reduction Tools

- IRAF developed at NOAO soon after digital detectors became widespread
  - Lots of packages, well documented, good control of details, good statistical basis, all-in-one package except for publication-quality plots
- IDL has many well-developed astro-related routines ⇩
- Python has many well-developed astro-related routines ⇧
- Many observatories maintain data reduction pipelines
- Will use IRAF in many cases to demonstrate the principles of procedures, recommend that you use the Python equivalents

Data Reduction Literature

- Measuring the Universe (Rieke)
- Observational Astrophysics (Lena, Lebrun, Mignard)
- CCDs in Astronomy, ASP Conf Series 8
- Astronomical CCD Observing and Reduction Techniques, ASP Conf Series 23
- Electronic Imaging in Astronomy, Ian McLean

Class Outline

I. Telescopes
II. S/N calculations
III. Planning an observing run
    a) Proposal Writing
    b) Aircharts
    c) Calibration Frames
    d) Checks during the run
IV. Data Reduction
    i. Preliminary processing: overscan, bias, flat-fielding
    ii. Photometry
        a. Imaging cameras
        b. Point Sources
        c. Surface Photometry
        d. Star-galaxy separation
        e. calibration

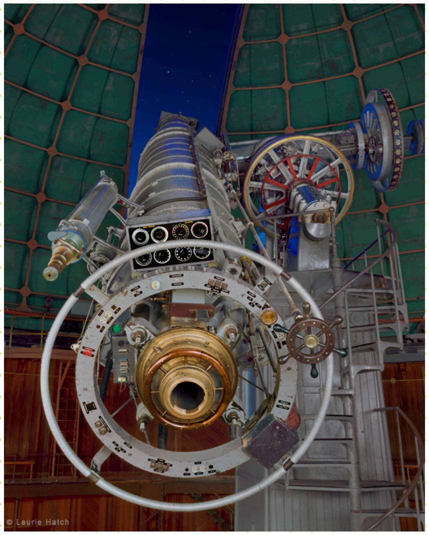
Outline cont.

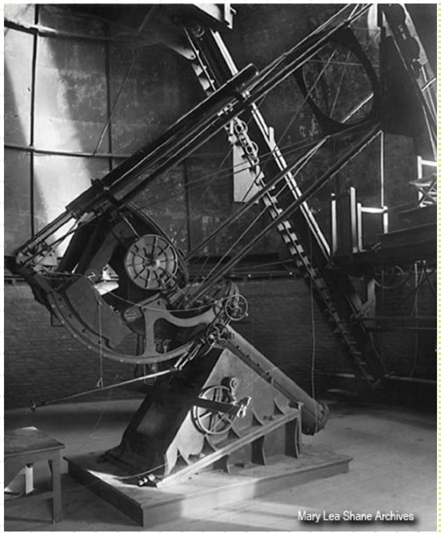
iii. Spectral data
  a. Spectrometer design
  b. Formats
  c. Extraction
  d. Radial velocity measurements
  e. Equivalent width measurements
  f. Indices
iv. IR (to 10μ)
v. Radio
vi. X-ray/gamma-ray astronomy
vii. Database astronomy

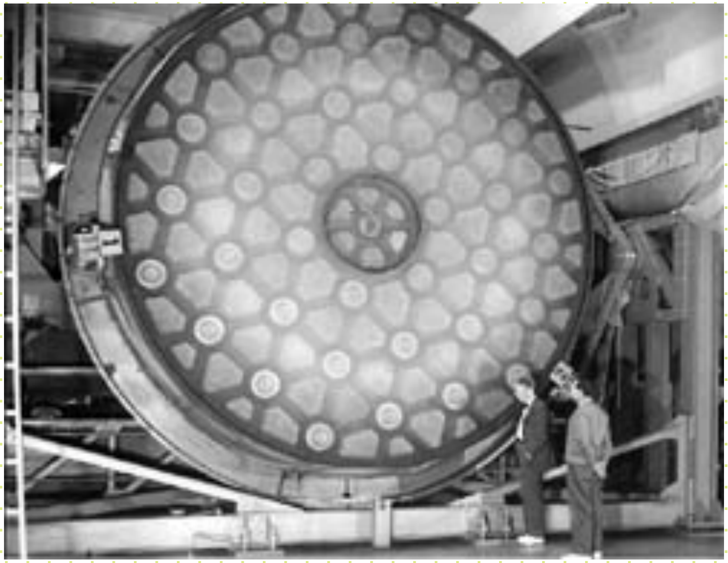
Homeworks

- Homework should be written up carefully using Latex/WORD with embedded figures. Purpose, ``howto'', results.
- Fine to work together, but everyone should do their writeups independently.
- Will need access to a computer with IRAF or Python, Latex or Word, plotting package (e.g. SM, Python) to do the homeworks and writeups.
- Learning to use these packages is a great side benefit of the class.

Telescopes in the last 400 years



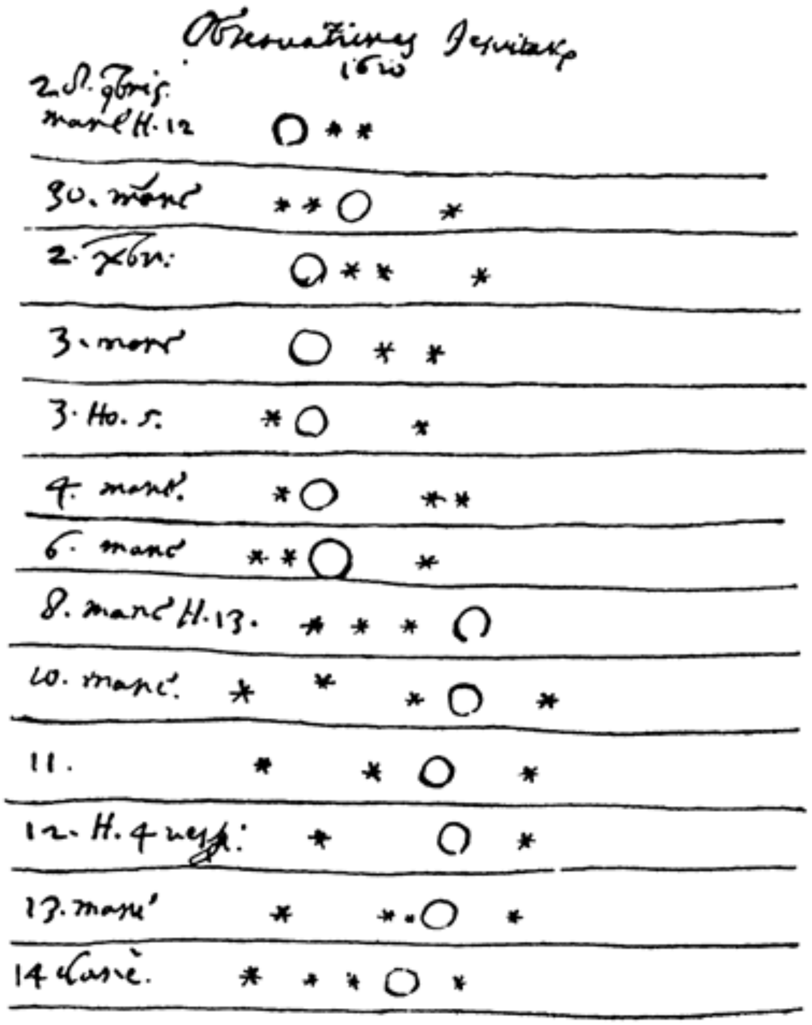




The Start: Galileo

- 1608 Hans Lippershey applied for a patent for "*seeing things far away as if they were nearby*"
- 1609 Galileo built a 1.5cm diameter refracting telescope with 33x magnification and made observations of celestial objects

Galileo’s Observations



Observationi Jesuitae
1610

2. S. Jouis: mane H. 12 O * *

30. mane * * O *

2. xbris: O * * *

3. more O * *

3. Ho. s. * O *

4. mane * O * *

6. mane * * O *

8. mane H. 13. * * * O

10. mane. * * * O *

11. * * O *

12. H. 4 vesp: * O *

13. mane' * * . O *

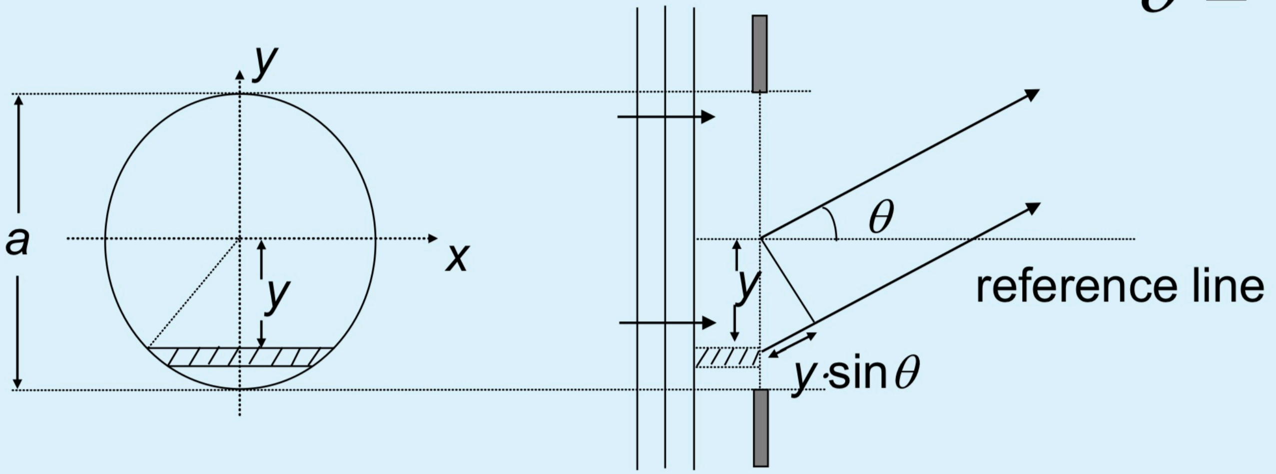
14 Carie. * * * O *

With his telescope he:

- Had more light-gathering capability and could see fainter objects
- Had higher spatial resolution because of magnification *and smaller diffraction limit than the unaided eye*

Reminder: ;Diffraction from a circular aperture

$$\delta = \frac{2\pi}{\lambda} y \sin\theta$$

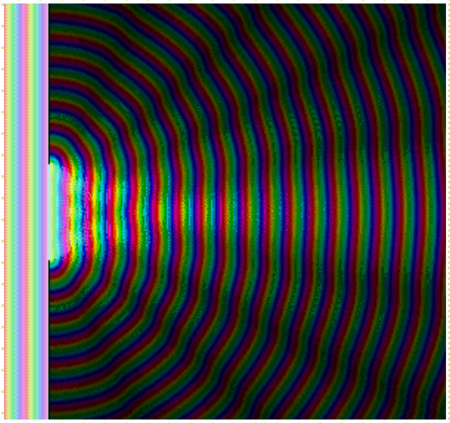


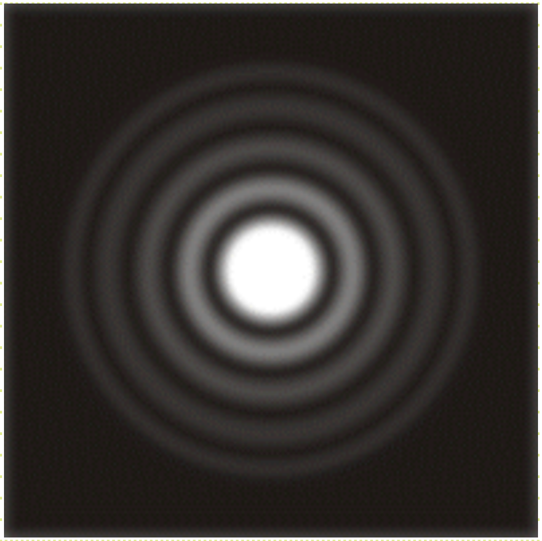
$$\frac{I(\theta)}{I(0)} = \left[\frac{2J_1(\rho)}{\rho}\right]^2$$

where $\rho = \left(\frac{2\pi\sin\theta}{\lambda}\right)\frac{a}{2}$

a – **diameter of the aperture**

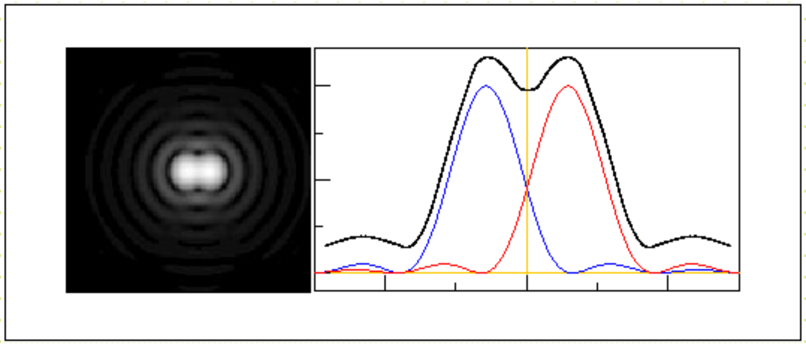
Diffraction Limit for circular aperture





- Rayleigh Criterion for difraction-limited resolution is when first Airy minimum coincides with second source maximum
- $\theta_R = 1.22\lambda/D$ where:

θ_R is separation of sources in radians, λ is the wavelength of light and D is the diameter of the aperture



Diffraction Limit for circular aperture

$$\theta_R=1.22\lambda/D$$

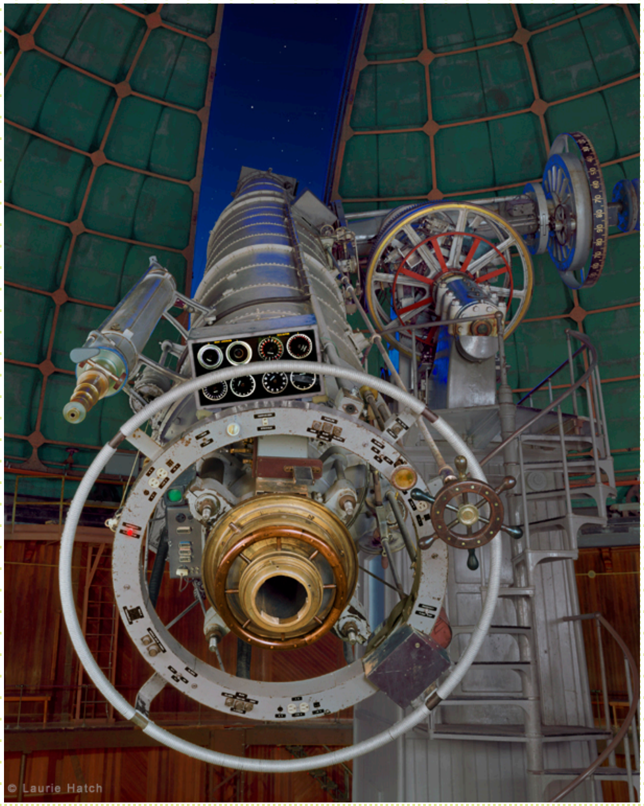
- For a given primary mirror diameter, the diffraction limit is smaller (i.e. can resolve finer detail) linearly with decreasing wavelength. So, HST images are 2x sharper at 500nm than they are at 1000nm assuming the mirror is diffraction limited at 500nm
- At a given wavelength, the diffraction limit is smaller for a larger mirror: inverse linear relationship. 30m diameter mirror can produce images that are 30/2.4 = 12.5x sharper than HST at wavelengths where the 30m can reach diffraction limit

- Human eye: D~5mm
  - θ_R~25 arcsec @550nm
- Galileo 1.5 inch = 38mm telescope:
  - θ_R~3.2 arcsec @550nm
- 5-inch telescope: θ_R~1 arcsec @550nm
- 10m Keck telescope:
  - θ_R~0.012 arcsec@550nm
- Moon is 30 arcmin in diameter, unaided eye can resolve big craters

Back to Galileo

- Galileo observed imperfections on the surface of the moon and the Sun
- Perhaps most importantly, with the improved spatial resolution of his telescopes, Galileo observed that Venus showed different phases

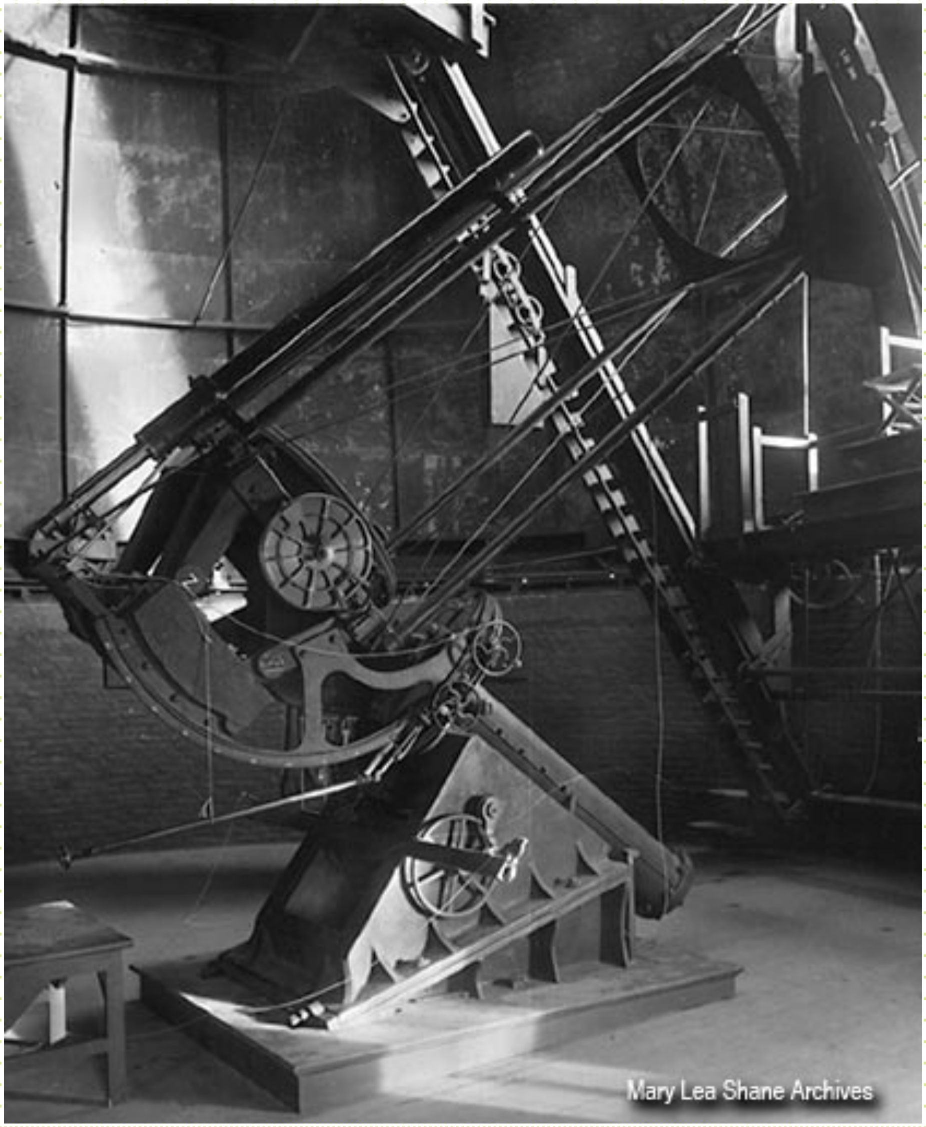
Refracting telescopes



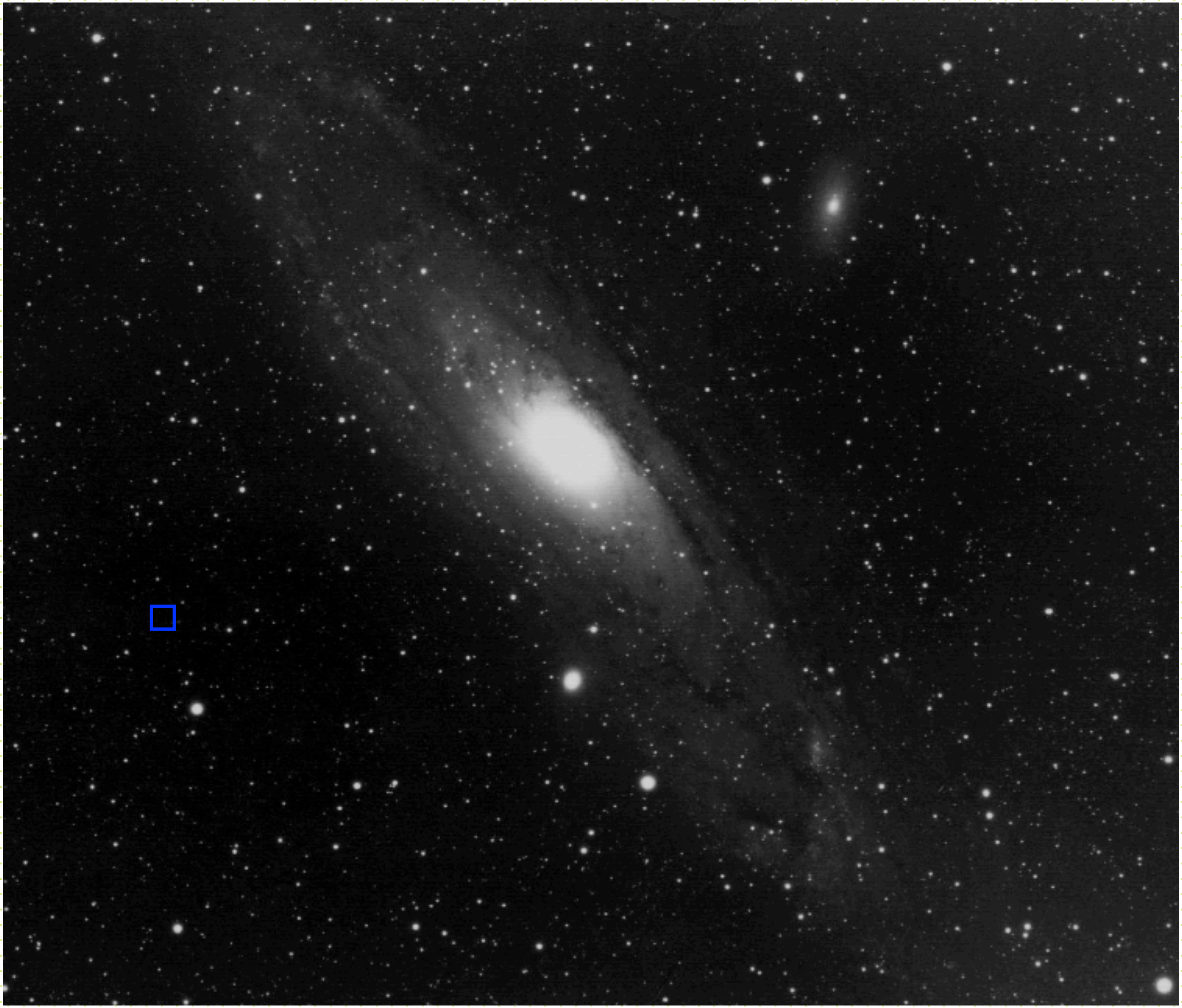
Lick Observatory Great Refractor 1-m diameter

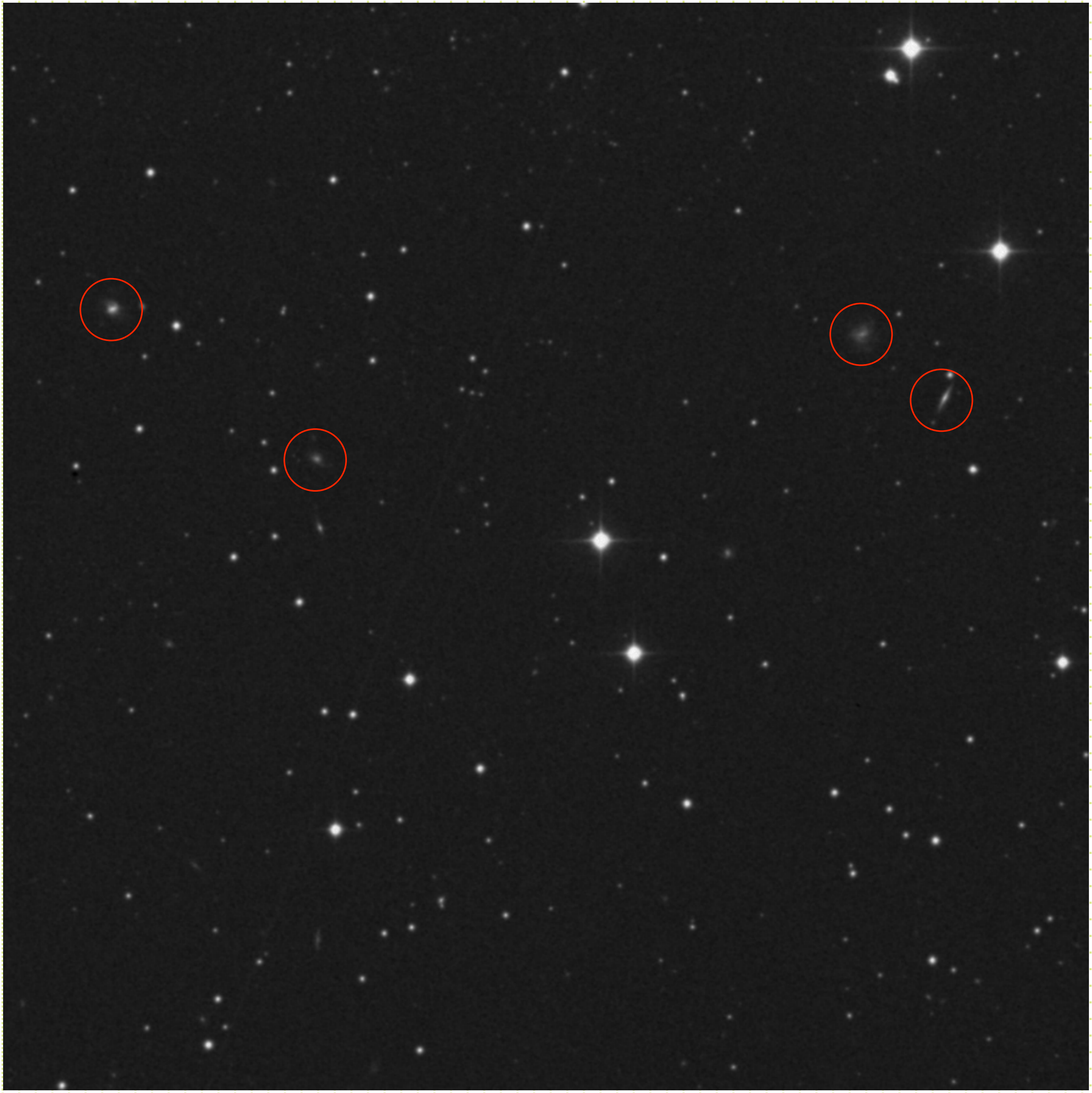
- Use a combination of glass lenses to focus light to a single focal plane. Compound lenses required to correction chromatic aberrations
- Refractors dominated up through late 1800s
- Limit to size set by mechanical stiffness of glass and requirement to support lenses at perimeter

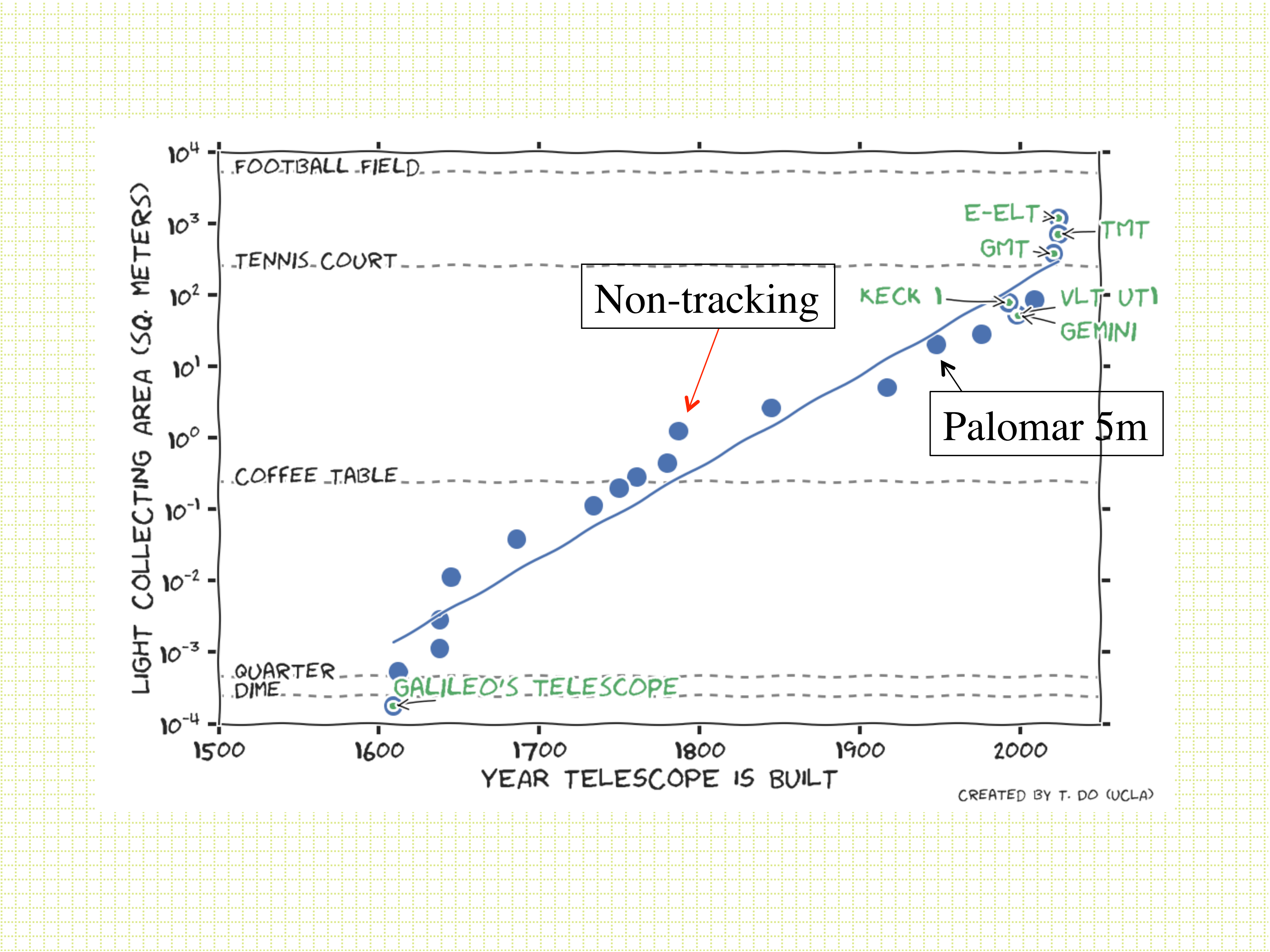
Photographic Plates and the Universe


Mary Lea Shane Archives

- 1896 the 36″ Crossley Reflecting Telescope arrived at Lick Observatory
- "faster" optics and possibilities of building larger and larger mirrors (can support mirrors from behind)
- Photographic plates allowed long exposures







Non-tracking

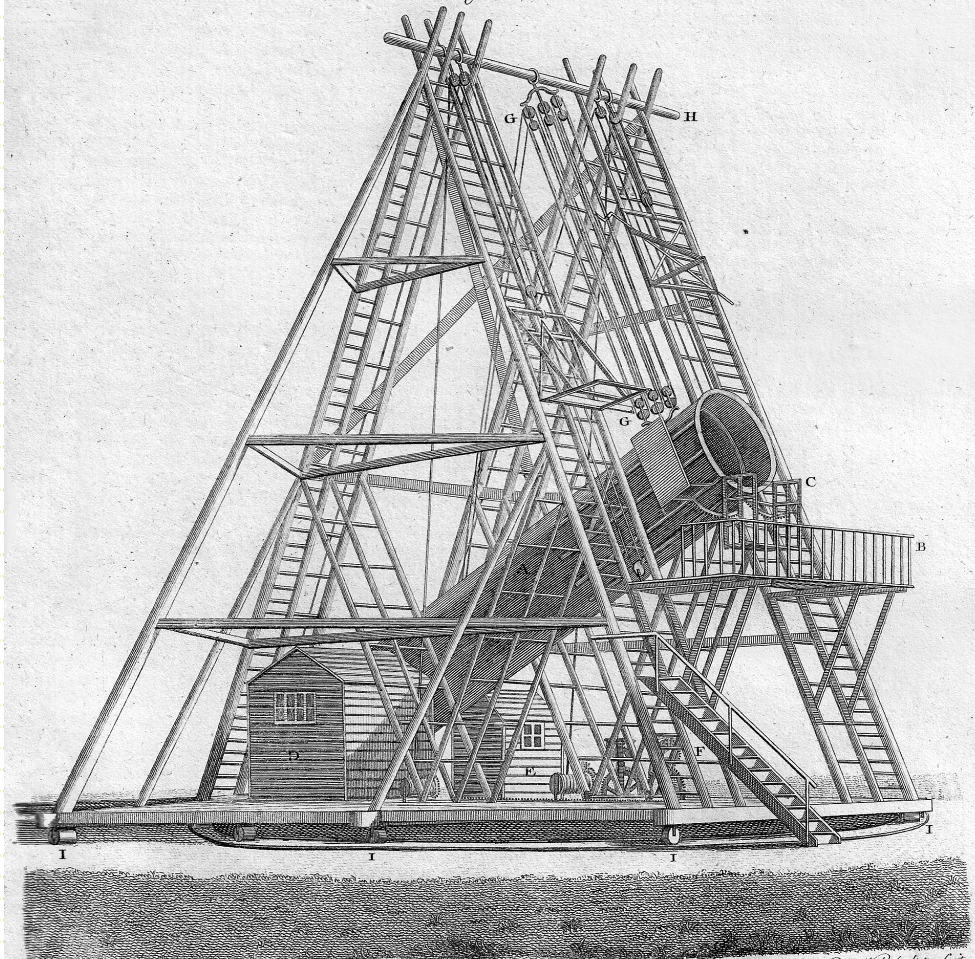
Palomar 5m

Herschels Grand

TELESCOPE,

Plate DV.

Fig. 24.



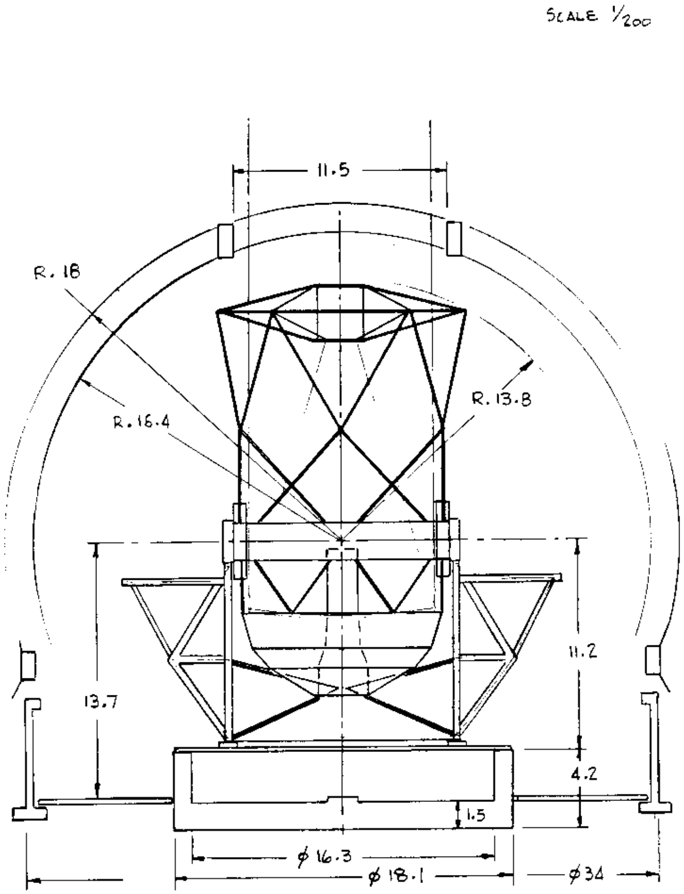
A. Bell Prin. Wal. Sculptor fecit.

Telescope mounts

Equatorial (example: Palomar 5m)

Equatorial only move in RA to track the sky. Alt-Az, move both axes at changing rates to track the sky, and field rotates. Payoff: N-platforms, 1-axis gravity deformation.

Alt-Az (example Keck)

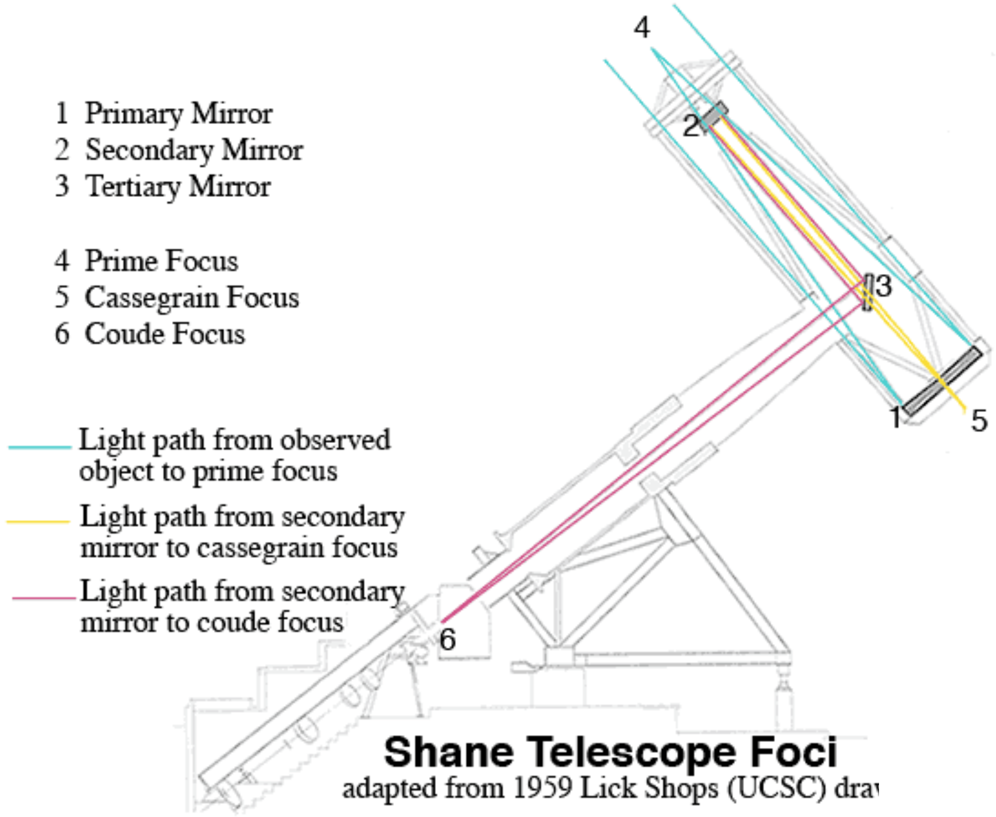


KECK 10m Telescope Facility
Figure 5.

Telescope foci

Powered optics (typically M2) change focal length and plate scale

Flat mirrors redirect beam at fixed FL



Shane Telescope Foci
adapted from 1959 Lick Shops (UCSC) dra

Prime focus requires correction

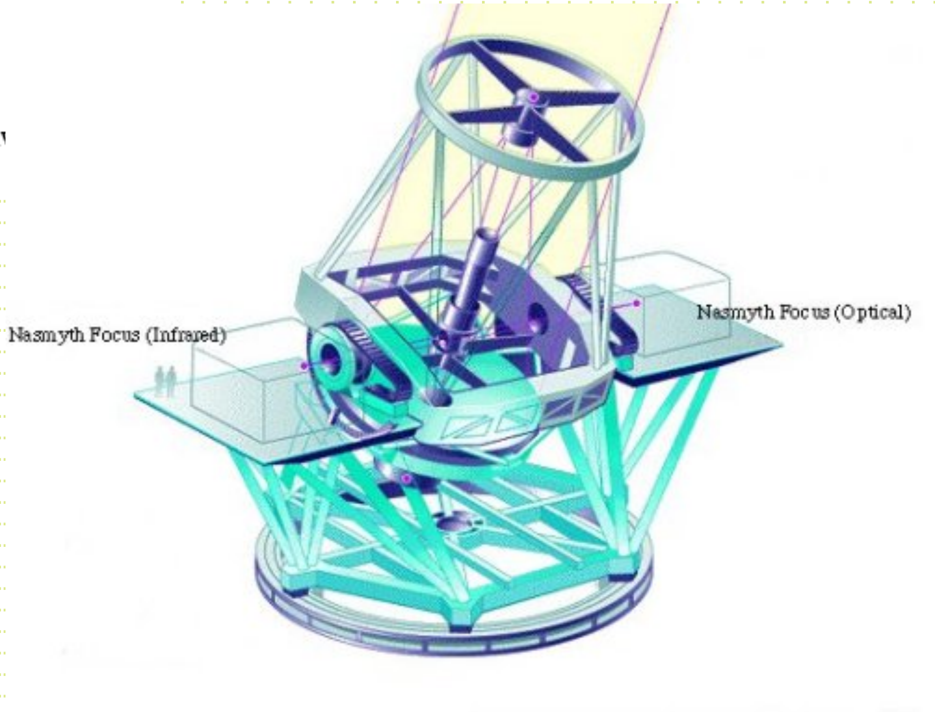
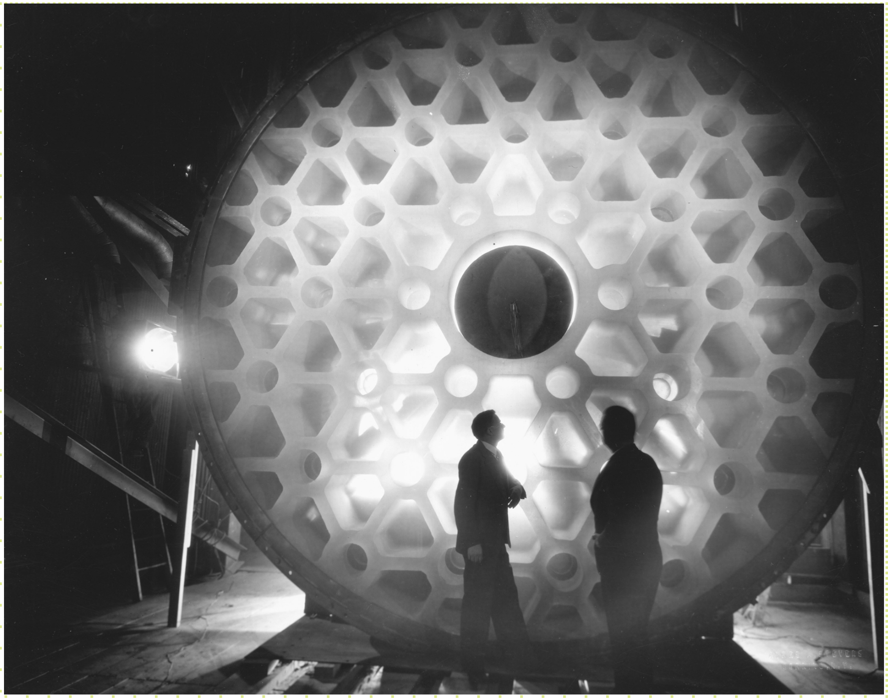


Illustration by Takaetsu Endo, taken from Nikkei Science 1996

What makes telescopes hard to build

- The optics need to be accurate on all spatial scales and stable (gravity vector, temperature, wind) to <10% of the wavelength of light:
  - 0.5μm is the center of the visible-light spectrum. Human hair has a typical diameter of 50μm
- The telescope structure needs to be very stiff and rigid to preserve the alignment of the optics and to point the telescope
  - Pointing accuracies and motion smoothness need to be <1´´
  - A highly-optimized 10m steel structure deforms ~ 1mm due to gravity forces, or 20,000 x larger than the optical tolerances
  - A 10m steel structure will deform 120μm for every °C change in temperature
  - It is very common to actively correct some of these errors with focus adjustments that are a function of temperature and pointing corrections that are a function of telescope position. Optics misalignments and non-elastic deformations are harder to correct.

The Trouble with Big Mirrors



- Palomar 5m Pyrex Mirror weighs 14.5 tons and the support structure almost the same
- Surface polished to ~ 50nm precision over 11 years of grinding
- Very difficult to maintain that exquisite figure for different orientations

For glass, deflection δ scales with radius (r) and thickness (h) as:

$$\delta \propto \frac{r^4}{h^2}$$

Moving beyond the 5-m limit

- Palomar 5m was completed in 1949, reigned for 40 years
- In the 1980s, two University of California physicists, Jerry Nelson and Terry Mast, proposed a new approach to building giant mirrors using hexagonal segments that fit together and are controlled very precisely

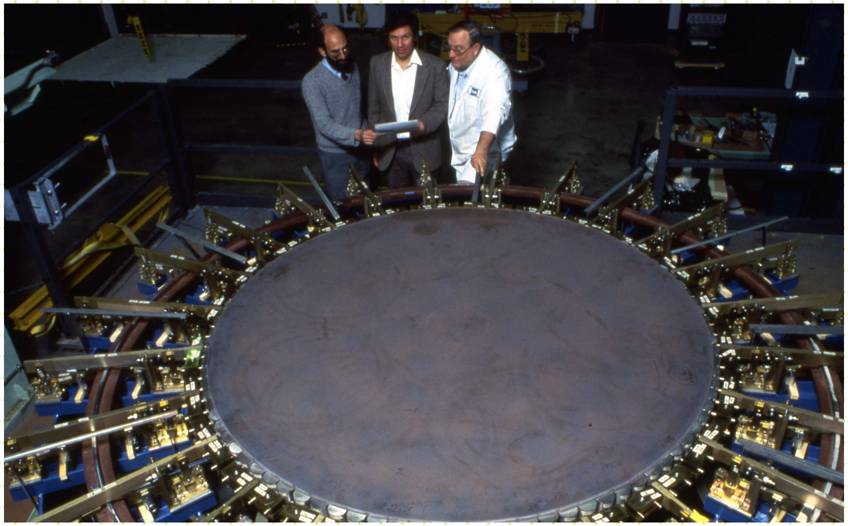
- Fabrication of off-axis segments
- Edge sensors good to ~5nm
- Actuators good to ~5nm
- Control algorithms

Segmented Mirrors

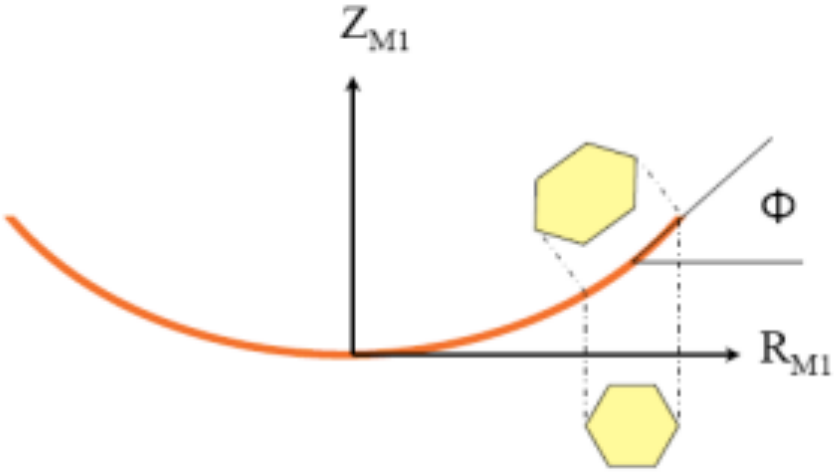
- Upsides of small segments
  - Individual segments are cheap: no single-point failure
  - Low thermal inertia
  - Intrinsic stiffness is high, requirements for support structure relaxed
  - Mirror weight is greatly reduced
  - Mirror coating vacuum chamber/handling fixturing small
  - Scalable technology
- Downsides of segments
  - Polishing of off-axis segments potentially difficult
  - Active control of segments required: in 1980s no position sensors or actuators existed that worked at the required ~5nm precision and no real-time computer codes existed

Stressed Mirror Polishing

- Developed by Nelson and Lubliner
  - Tension perimeter of a round blank
  - Polish a sphere
  - Release tension and the mirror is close to right figure
  - Cut to hexagon and improve figure
  - Ion-figure out residual errors
  - Add whiffle-tree passive support and warping harnesses adjusted at telescope
  - For Keck, 36 1.8m segments
  - 1% light loss from gaps, sharp edges

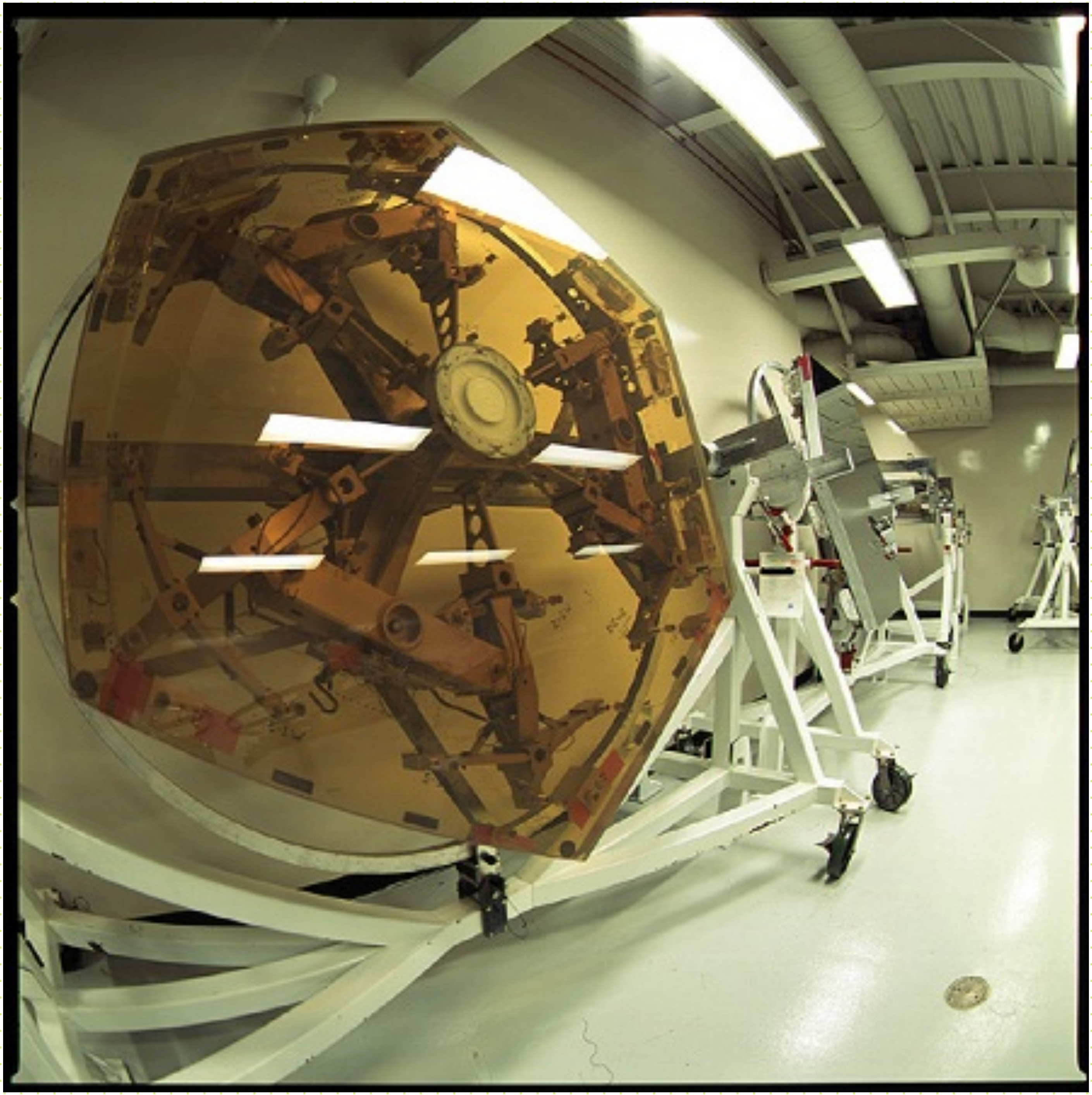


Small details count



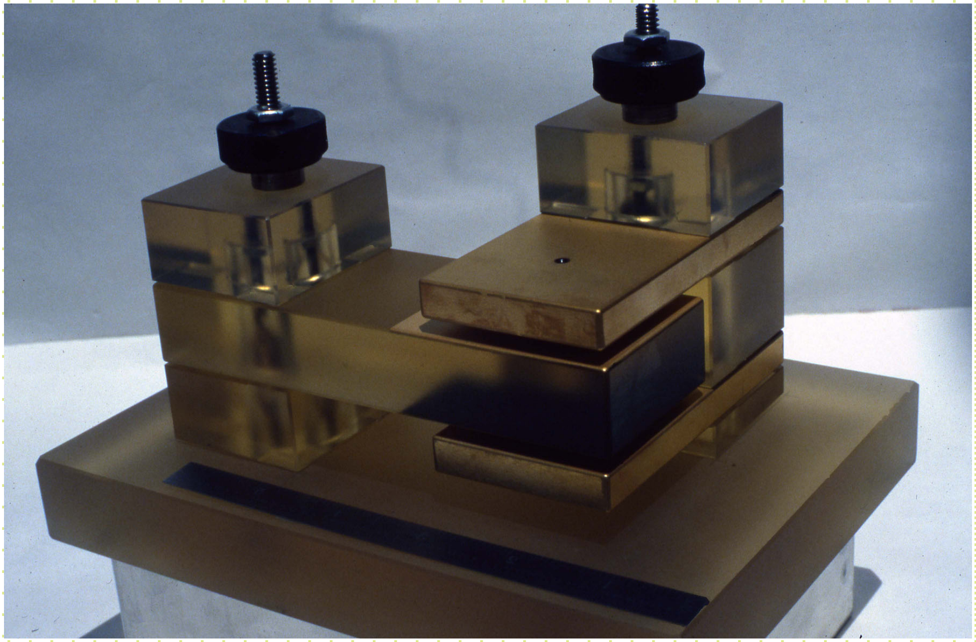
Mapping segments onto curved global M1 surface and maintaining uniform gap between segments means the segments get slightly elongated as a function of radial distance

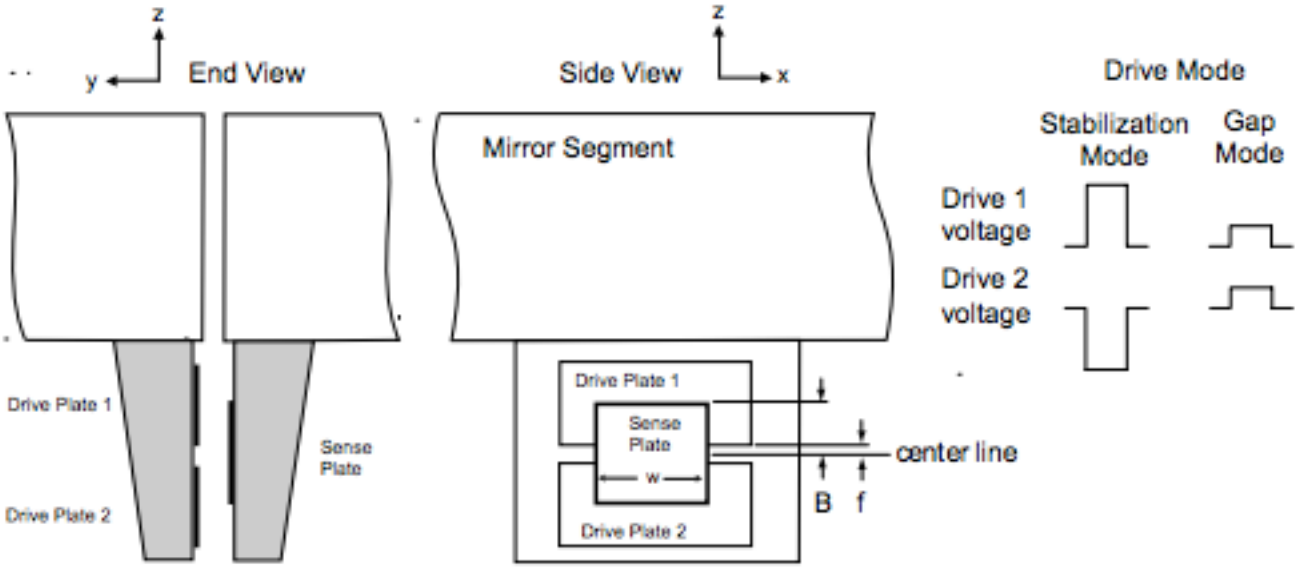
With Keck, small weights were glued to segments to enable the wiffle-tree support structures to be identical for all segments



Edge sensors

- 2 edge sensors per segment edge
- Differential capacitive sensors
- Measures height difference between adjacent segments
- Extreme stability needed (drift rates of ~20nm/week)
- Noise level ~ 1 nm





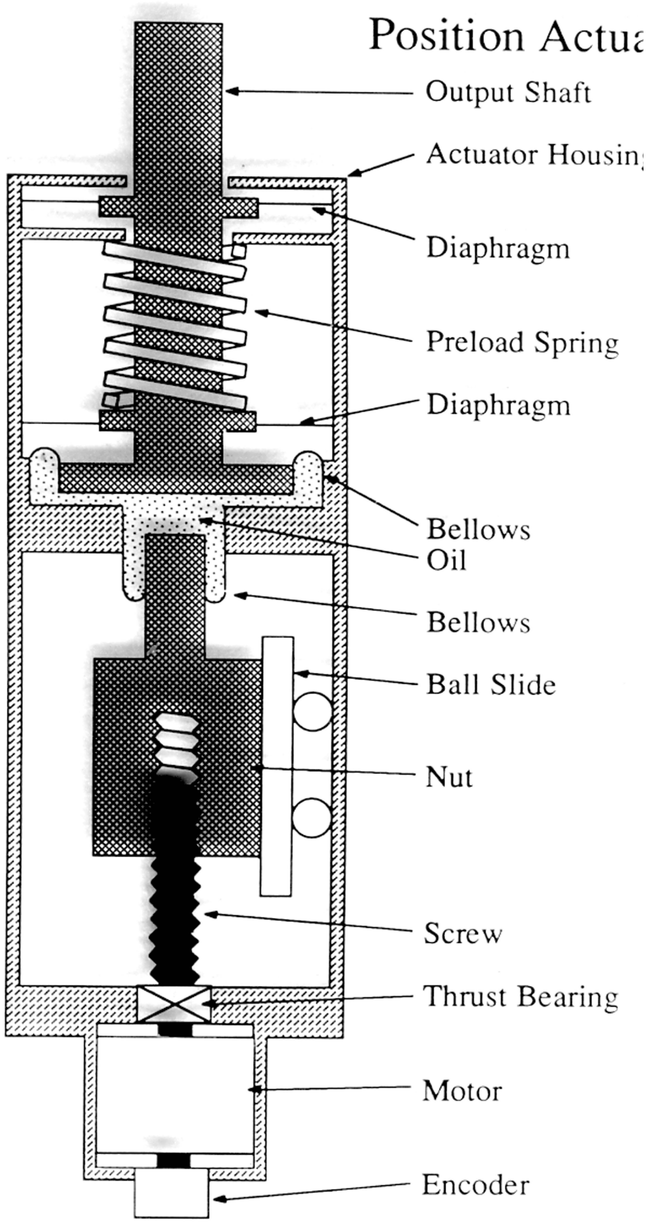
$$R = \frac{2\varepsilon_0 w V}{y}\left(-z - z^D + z^S - x\left(\theta_y + \theta_y^D\right) - y\theta_x^S + \frac{B^2 - f^2}{2y}\left(\theta_x + \theta_x^D - \theta_x^S\right)\right) \qquad (2)$$

The desired sensitivities are to height, z, and to dihedral angle, θ_x. The undesired sensitivities are to displacements x and y, and to installation error angles $\theta_x^D, \theta_x^S, \theta_y^D, \theta_y^S$, with separate bookkeeping for the drive (D) and sense (S) side.

For TMT optical system, there are ~12,000 degrees of freedom

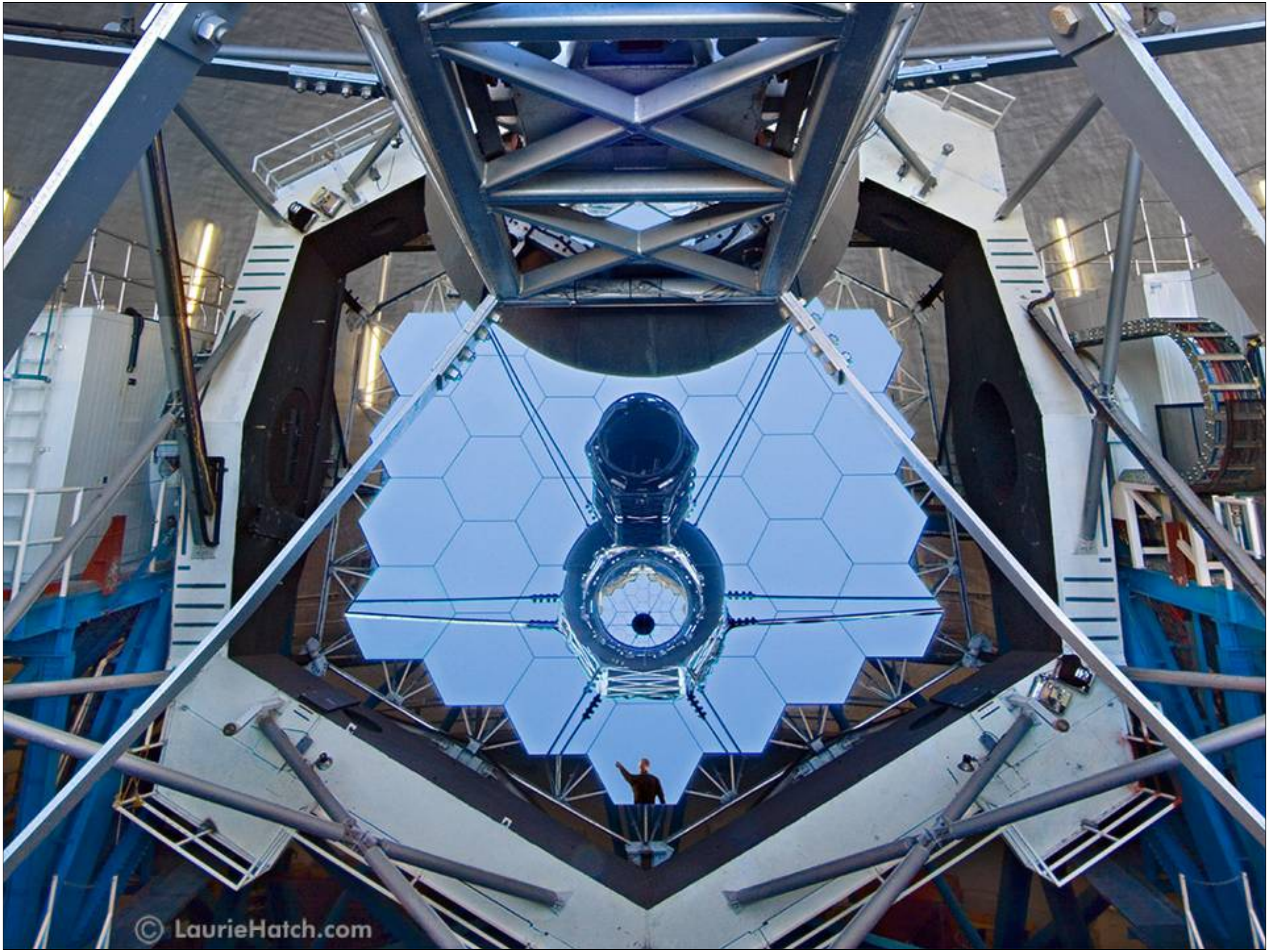
Displacement actuators

- 3 actuators per segment control piston tip/tilt
- Actuator range is 1.2 mm
- Motor driven roller screw and hydraulic reducer
- Since there is closed loop control, smoothness is needed but not high level of accuracy
- Actuator smoothness is ~ 4 nm

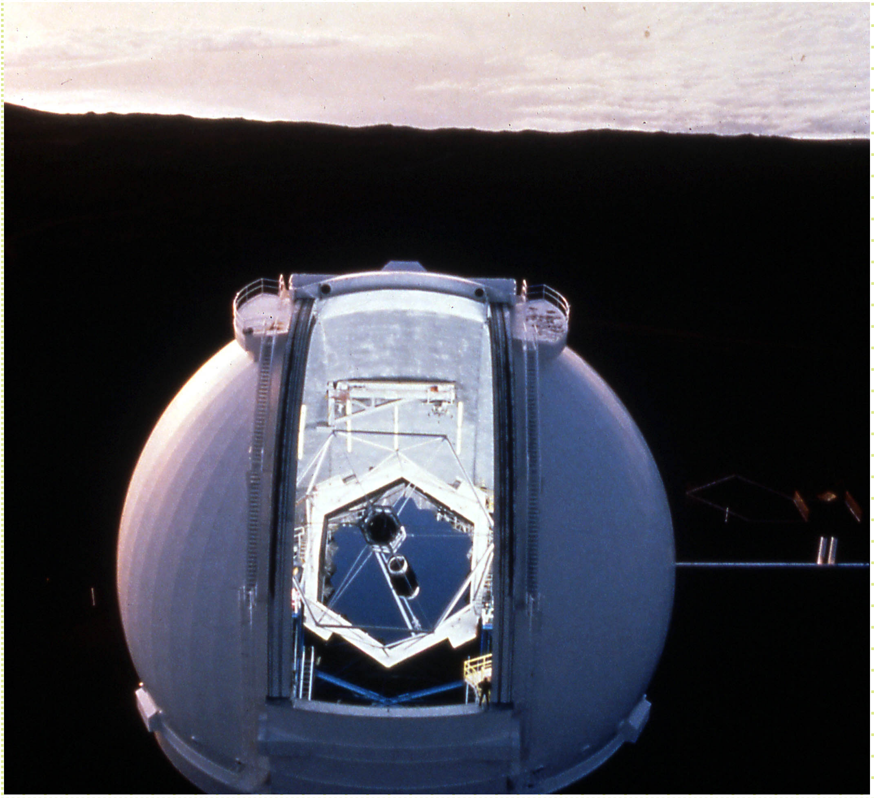


W.M. Keck Observatory

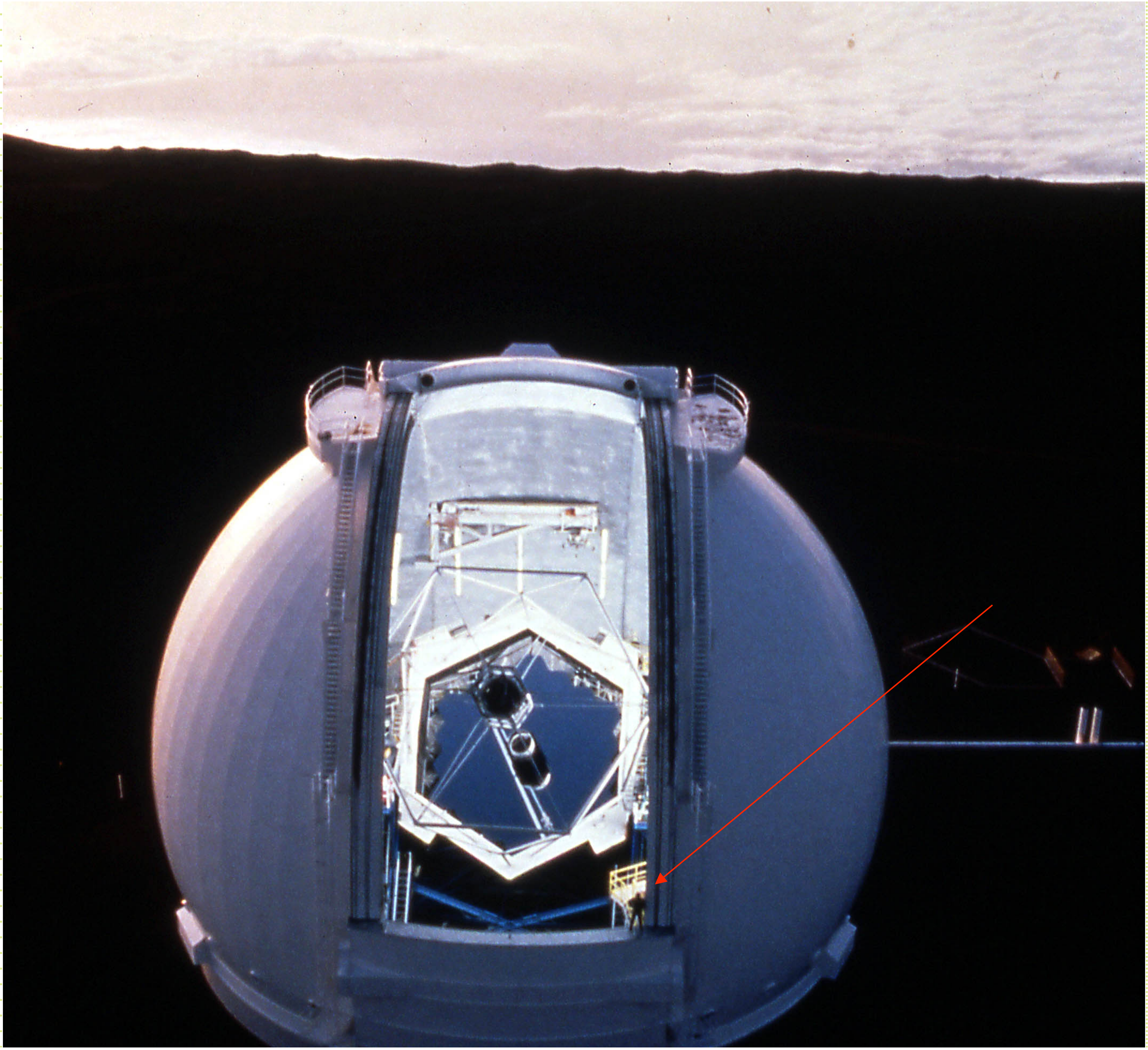
- Nelson/Mast concept became an observatory via gift from the Keck Foundation to Caltech and partnership between Caltech and the University of California
- "prototype" Keck 1 was a spectacular success
- One attractive aspect to segmented approach was scalability of the concept to even larger primary mirrors



W.M. Keck Observatory



- Twin 10m telescopes designed by UC astronomers in the 1980s.
- Capital funding from the Keck Foundation via a gift to Caltech ($180M)
- UC contributed ~$10M/year operations for equal-share partnership with CIT through 2018
- NASA came in as 1/6th partner as part of the funding of the second telescope



Big Telescope Aperture Advantage Reminder

- Seeing-limited observations and observations of resolved sources

$$\boxed{Sensitivity \;\propto\; \eta D^2 \quad (\sim 14 \times 8\text{m})}$$

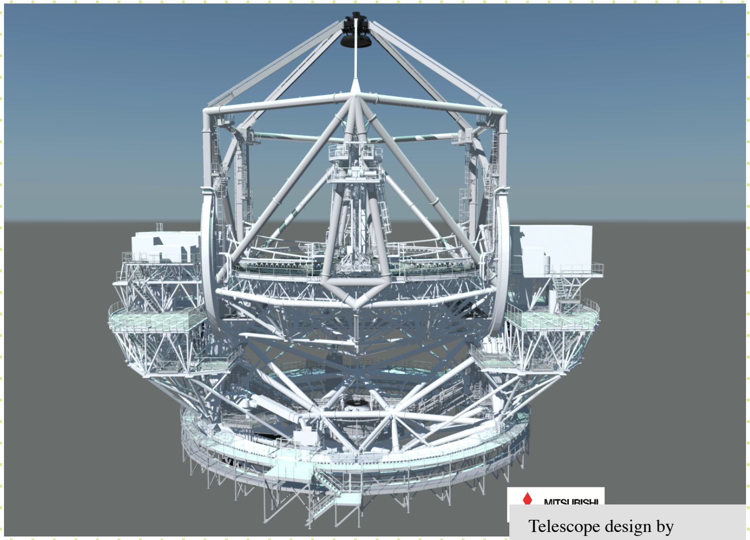
- Background-limited AO observations of unresolved sources

$$\boxed{Sensitivity \;\propto\; \eta S^2 D^4 \quad (\sim 200 \times 8\text{m})}$$

$Sensitivity = 1/$ time required to reach a given s/n ratio
$\eta =$ throughput, $S =$ Strehl ratio. $D =$ aperture diameter

The Thirty-Meter Telescope

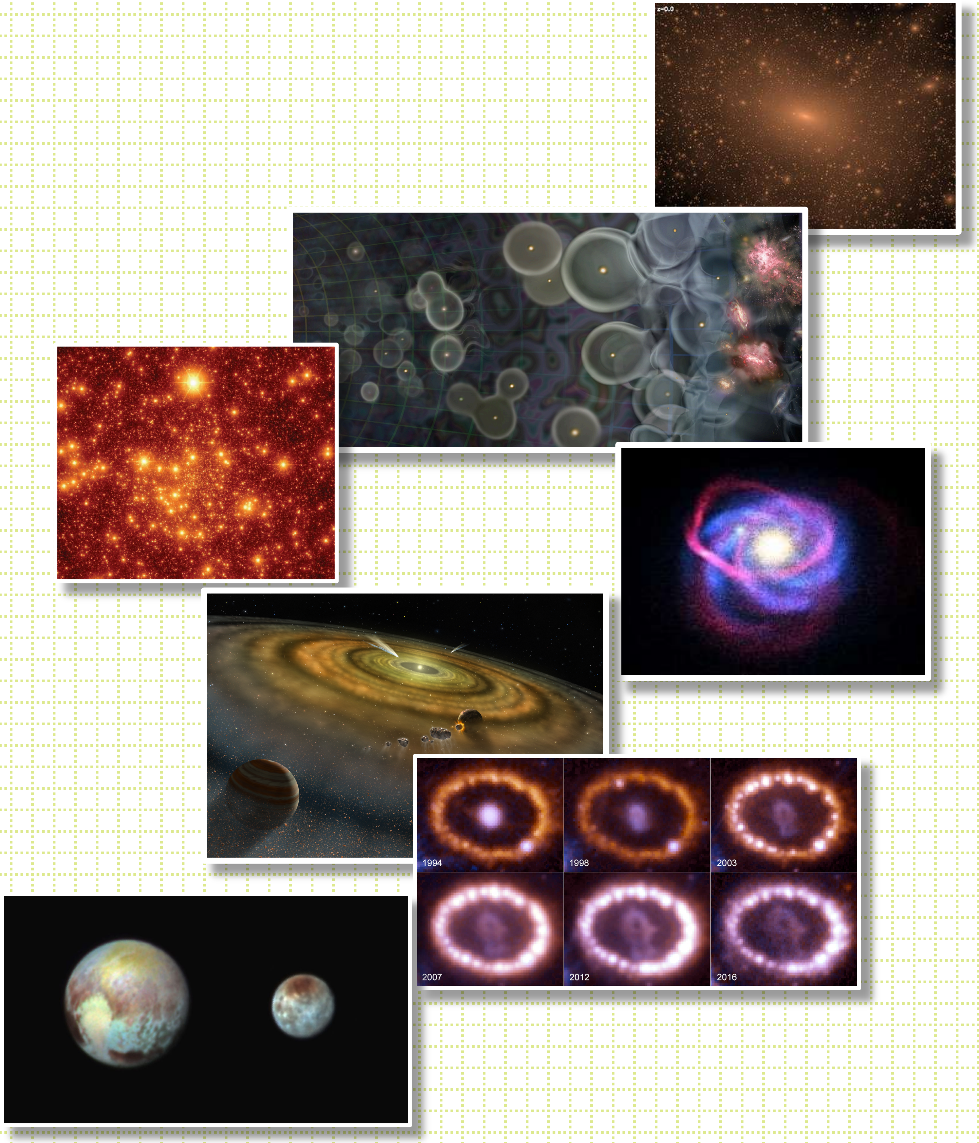
TMT - Overview



Telescope design by MELCO

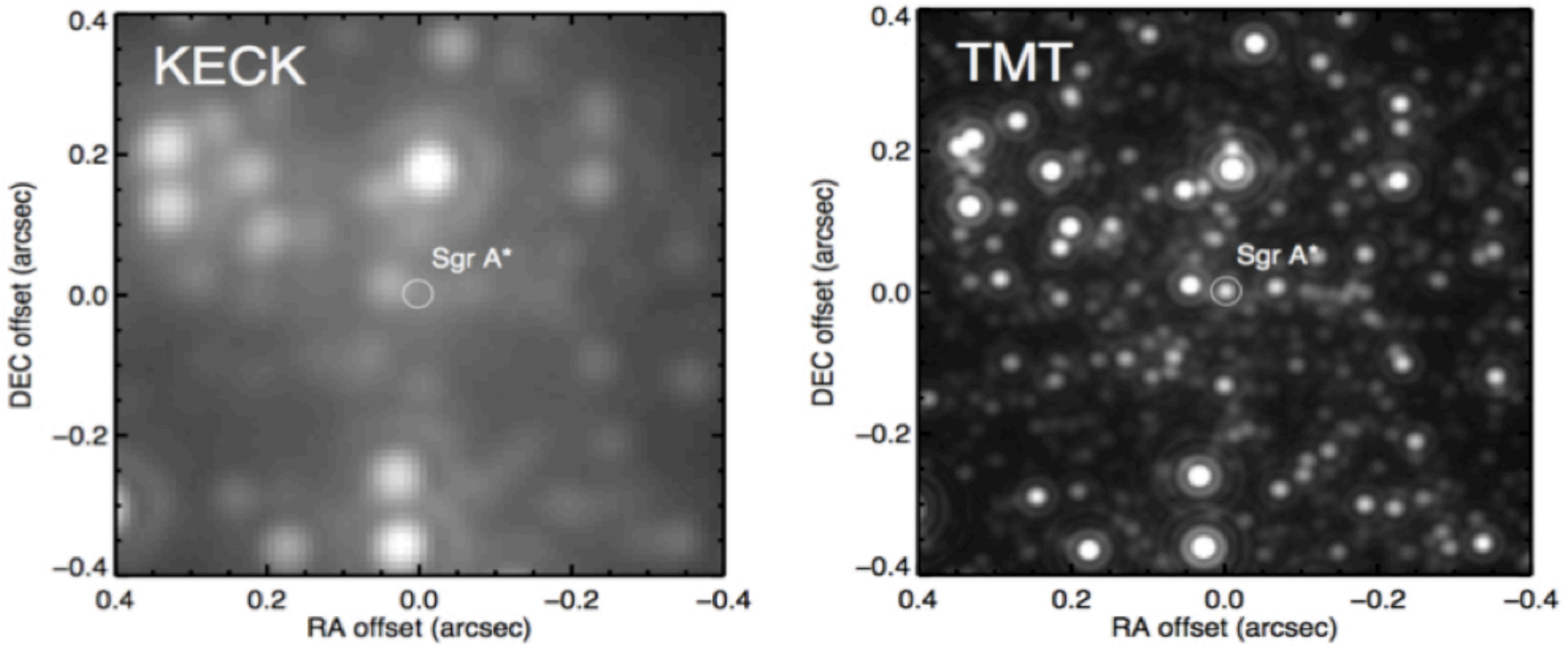
- 30m diameter primary aperture
- “Keck”-style
- 492-closed-pack segments
- Facility AO system for 1st light
- 0.007″ resolution at 1 micron with AO
- 20 arcmin-diameter field of view
- Tennis-court-sized Nasmyth platforms with articulated tertiary

TMT Science

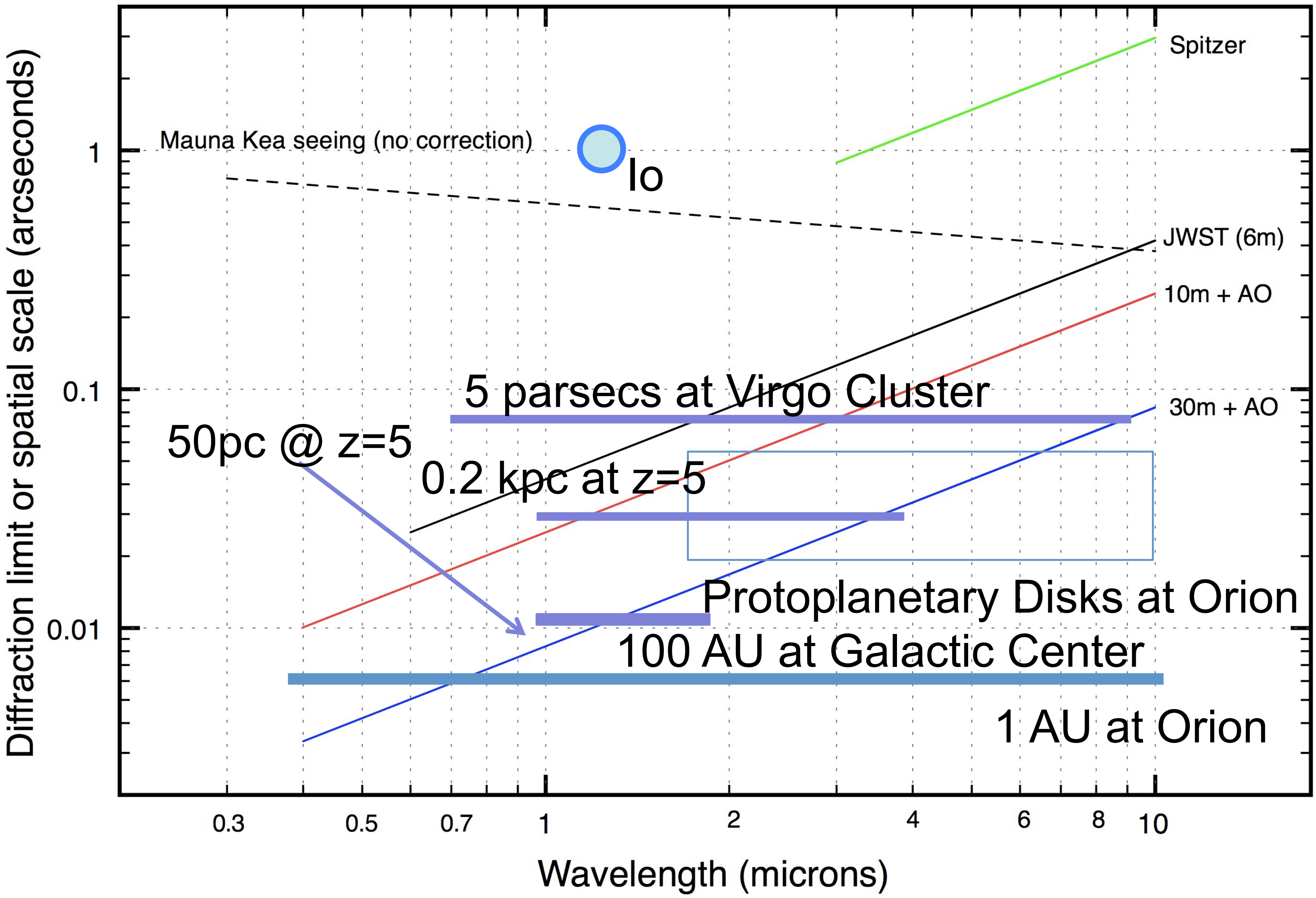


- TMT Science Case: Everything
  - Fundamental physics & cosmology
  - Early Universe & galaxy formation
  - Super massive black-holes
  - Exoplanet discovery and characterization
  - Nearby-galaxies & Milky-way
  - Time-domain science
  - Solar-system
- Synergies with GMT
  - All-sky coverage
  - Complementary instrumentation and capabilities

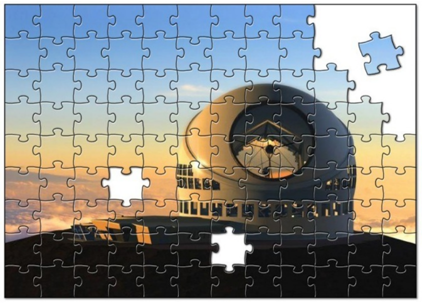
Adaptive Optics: NFIRAOS (NRC-Canada)



- Multi-laser tomography MCAO system (30´´ field)
- 187nm RMS wavefront error (1st light) k-band strehl~0.75
- Diffraction Limit: 0.007´´ @ 1μ (0.05kpc @ z=5)
- 50% sky coverage at Galactic Pole


Spitzer
Mauna Kea seeing (no correction)
Io
JWST (6m)
10m + AO
5 parsecs at Virgo Cluster
30m + AO
50pc @ z=5
0.2 kpc at z=5
Protoplanetary Disks at Orion
100 AU at Galactic Center
1 AU at Orion
1
0.1
0.01
Diffraction limit or spatial scale (arcseconds)
0.3
0.5
0.7
1
2
4
6
8
10
Wavelength (microns)

TMT and TIO



- In 2014, former members of the TMT Collaborative Board formed *TMT International Observatory LLC* (TIO).
- Caltech, Canada, China, India, Japan, University of California (see final slide for official participants)

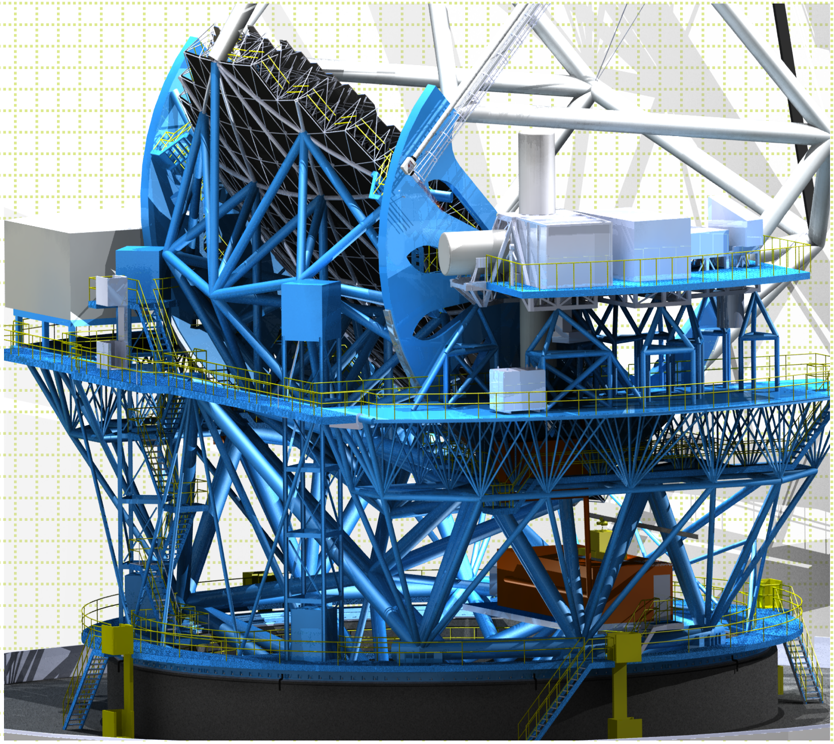
TMT Partnership

- After many international trips over five years, four countries selected TMT after considering the other ELT projects
  - Canada
  - Japan
  - China
  - India
- Workshare matrix agreed
- Complex partnership agreements in place

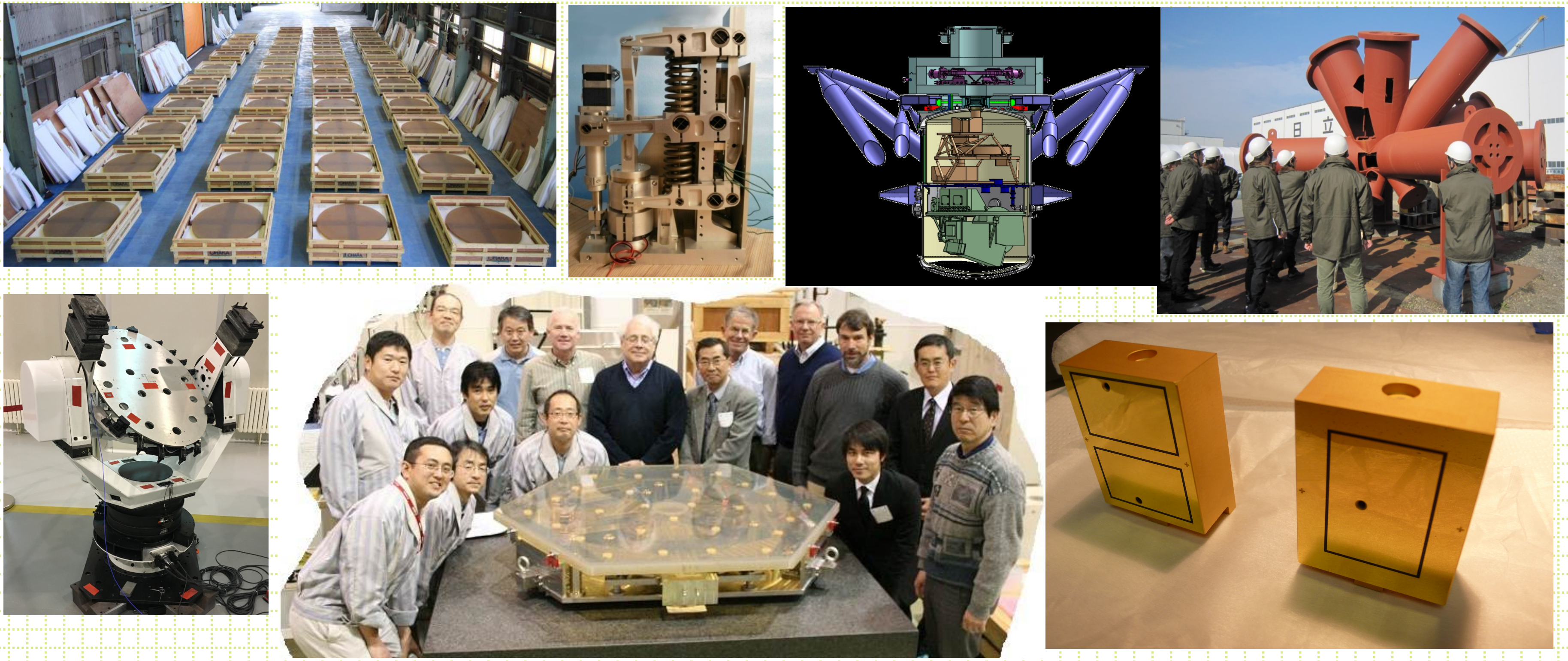
Partnership Formation


Thirty Meter Telescope Collaborative Board of Directors Meeting

TMT: Technical Status



- Design is at build stage for telescope, mirrors and control systems, enclosure and summit facilities
- Very rigorous project management procedures and tools in place
- Project has undergone multiple, extensive external reviews for technical readiness, and cost and contingency fidelity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Mauna Kea

- Mauna Kea is one of the few best sites for astronomy research in the world. Certainly the best in the northern hemisphere and within the US
  - altitude
  - dryness
  - stable, cool temperature
  - dark skies
  - *very stable air above site*

This is the big one--combination of the tropical inversion layer below the summit, topography of the mountain and location in the center of the ocean

Mauna Kea Issues

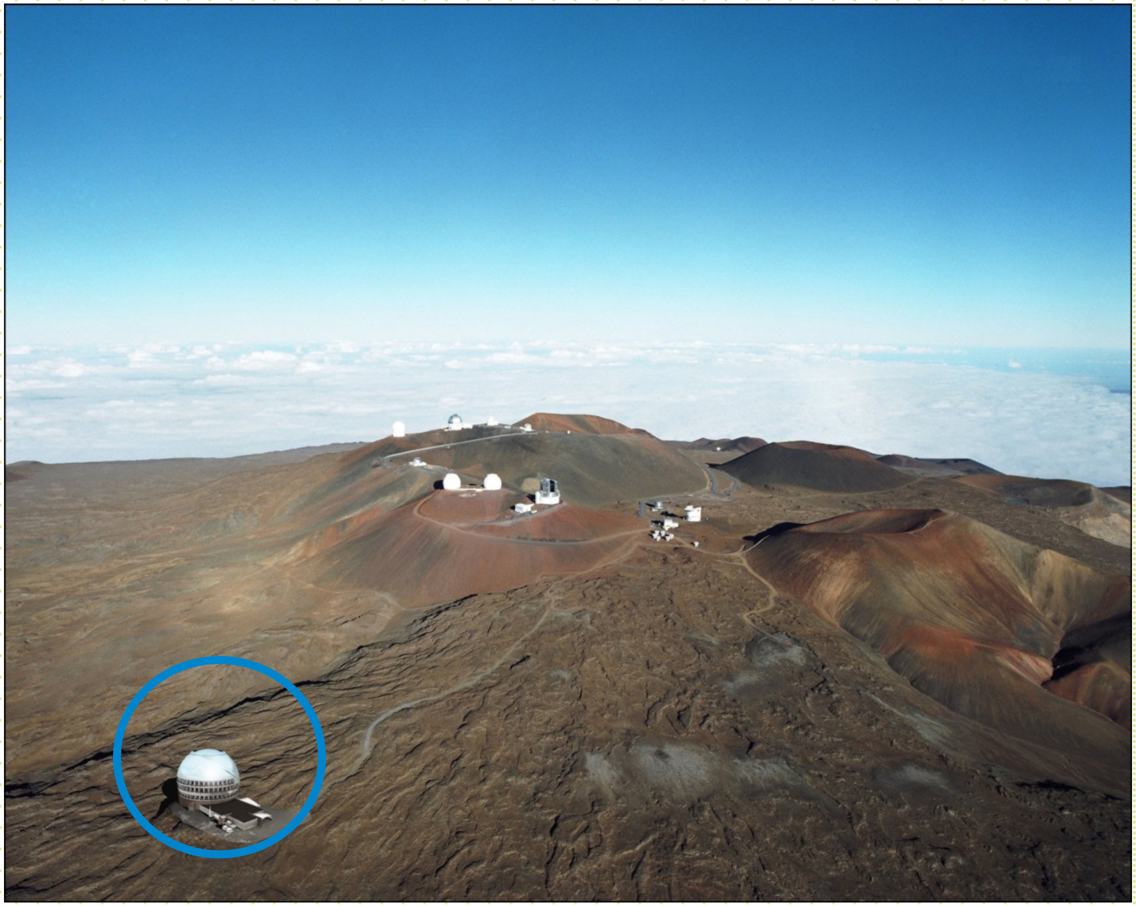
- Desecration of sacred place
  - Summit formations have religious significance
  - Burial areas and shrines
  - Access for traditional rituals
- Environmental concerns (wekiu bug, chemicals, stewardship problems)
- Continued growth in the last 30 years

Hawaii: short version of a long story

- Maunakea holds a special place in Hawaiian culture and it is a unique and very delicate environment
- Started the permitting process in 2007 with establishing a local presence on the Big Island and consulting with many stakeholders.
- Major issues: environmental stewardship, coexistence with cultural practices, shared economic benefits.
- Telescope site, lease payments to support stewardship of the mountain, greatly enhanced local benefits to Big Island communities are all the outcome of these conversations
- 30 Nov 2018 Hawaii Supreme Court ruled in favor of TMT

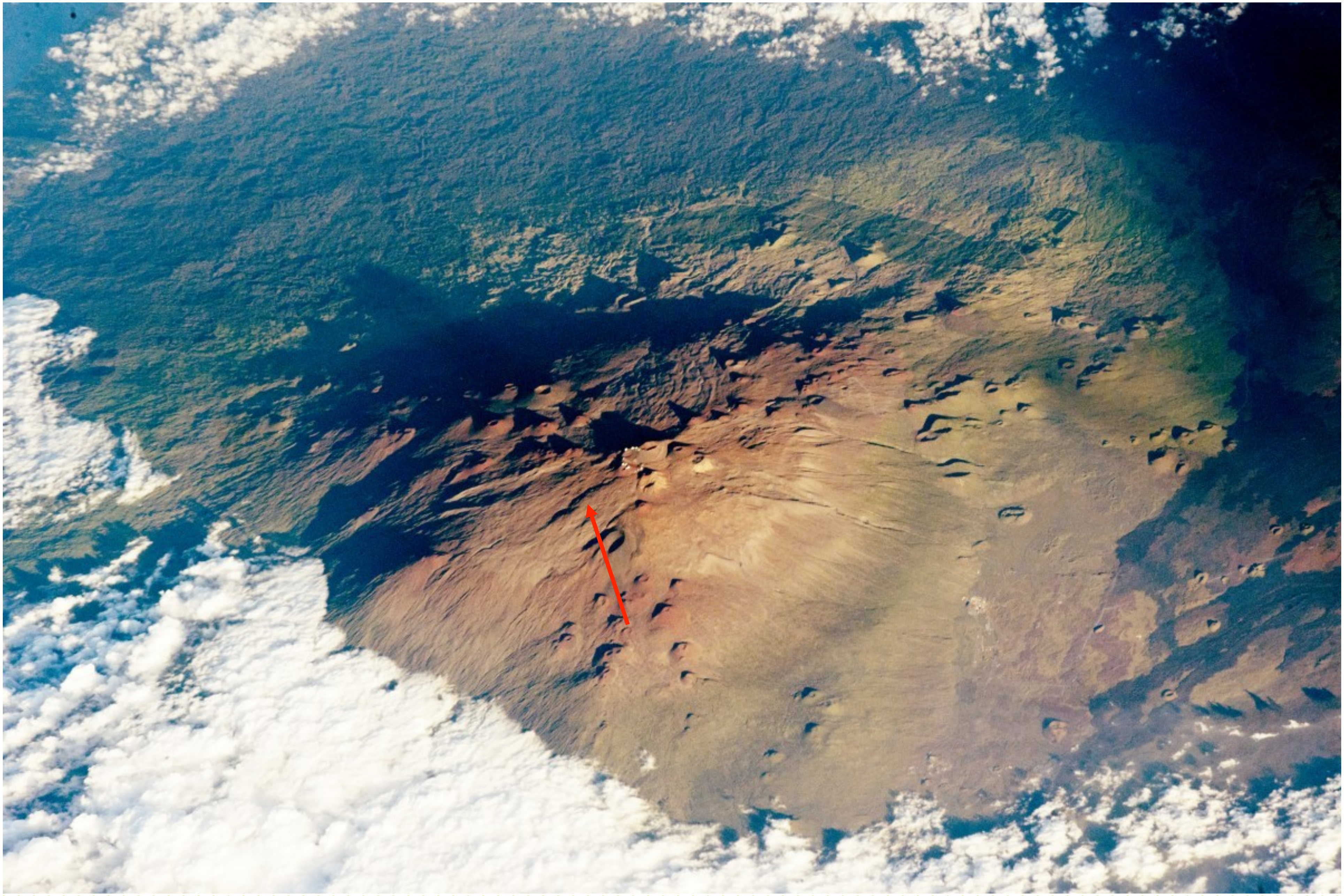
TMT site and arrangements

- Roughly 150m below the 4205m summit
- Visible from 15% of the coast
- No archeological finds
- Lease payments to support Maunakea stewardship
- STEM and workforce pipeline development programs on the Big Island



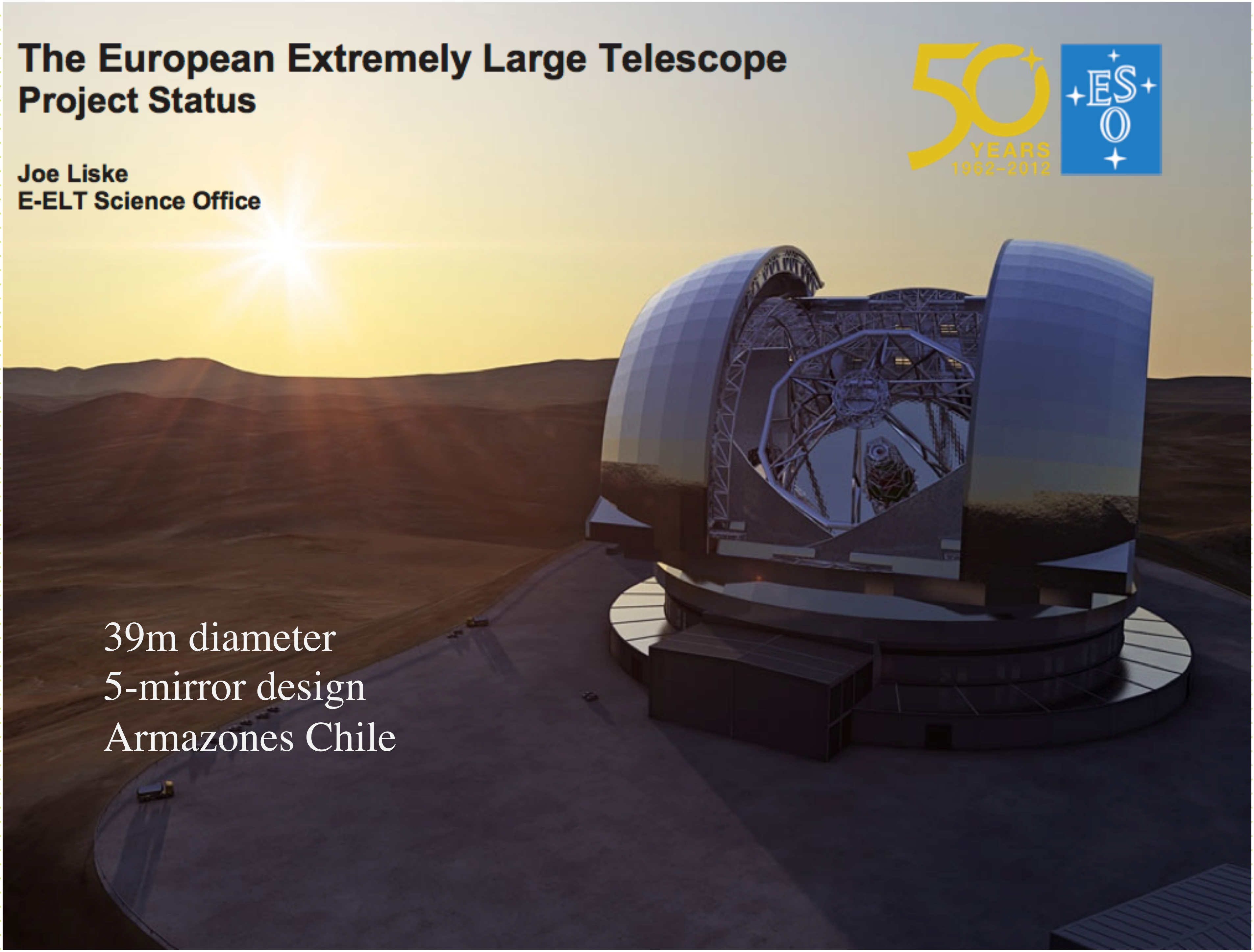
TMT Approach: Community Benefits

- STEM educational opportunities: THINK Fund
- Workforce Pipeline Development
- Resources for stewardship of Maunakea and OHA benefits
- Total of $3M annually for lifetime of observatory
- These plans came about via ~15 public meetings and many additional meetings with a broad range of stakeholders over five years
- Majority of Hawaiians (and of Native Hawaiians) support TMT, but not everyone



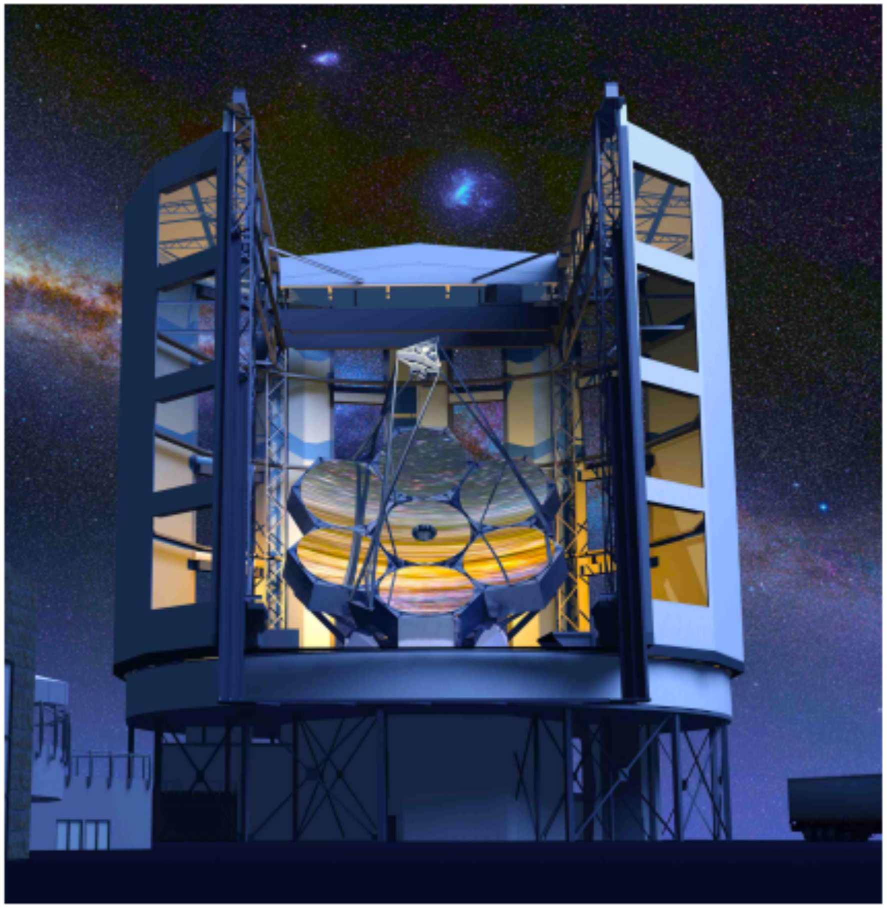
The European Extremely Large Telescope Project Status

Joe Liske
E-ELT Science Office



39m diameter
5-mirror design
Armazones Chile

GMT – Giant Magellan Telescope



- 21.9-m effective aperture
  - 7 mirrors / 8.4-m
  - 20’ FoV
- Early science mid-2019
  - With 4 mirrors
- All 7 mirrors and AO ~2022
- Located at Las Campanas

- First instruments
  - Optical MOS
  - Optical Echelle
  - Near-IR AO IFU/Imager

- Queue / Remote / Classical operating modes

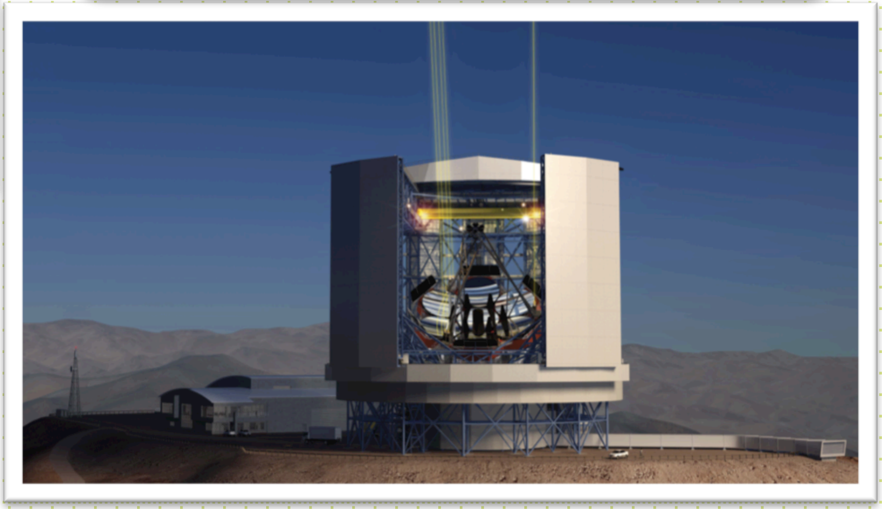
The Aspiration

Bi-hemispheric ELT system

Bold leadership for U.S.

- Bi-hemisphere access
- Broad instrument suite
- Key Science Programs
- Open Access, ≥ 25% at **both** facilities

Opportunity to significantly broaden U.S. public access to the next generation of ground-based optical-infrared telescopes

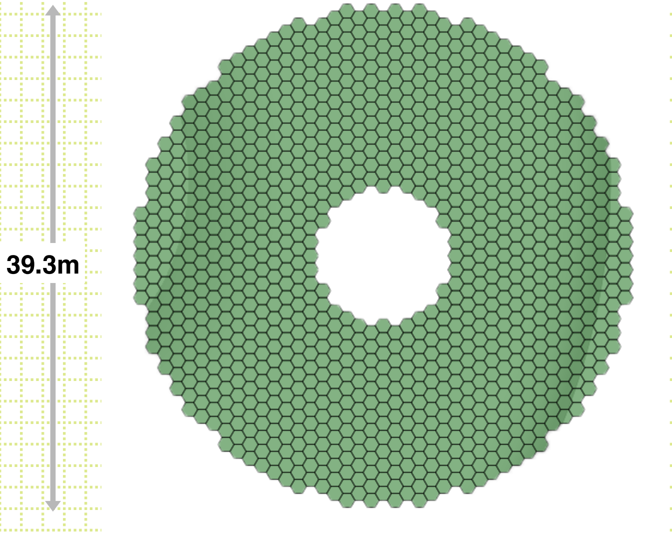


The Situation

Accessibility

Only the National Science Foundation can enable this collaborative effort

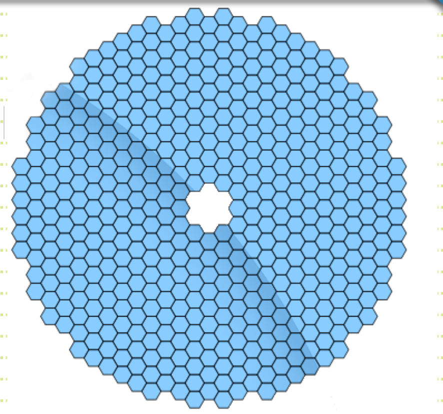
European Southern Observatory:



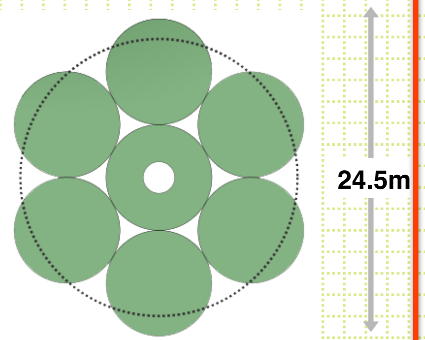
European Extremely Large Telescope

~ 3200 HRS/YR

No U.S. open access



Thirty Meter Telescope



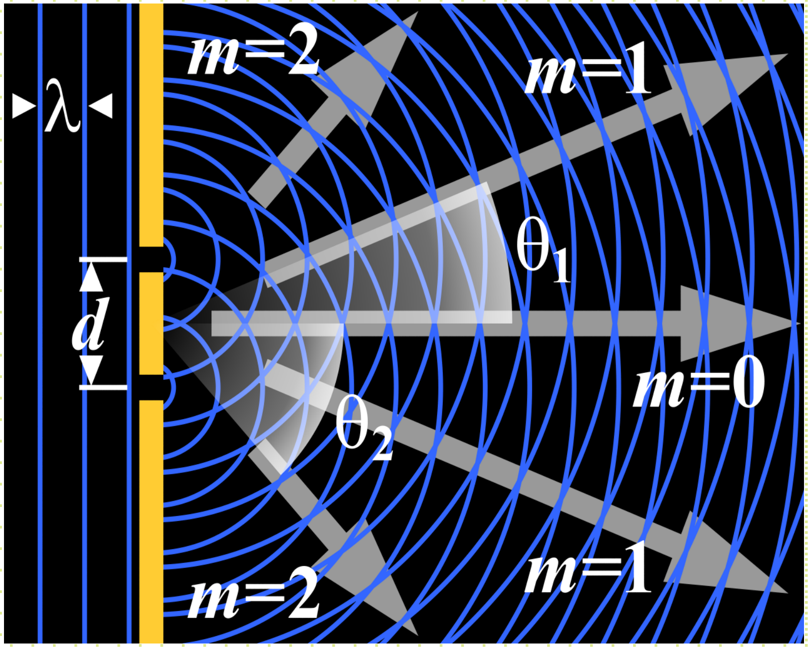
Giant Magellan Telescope

~ 6400 HRS/YR

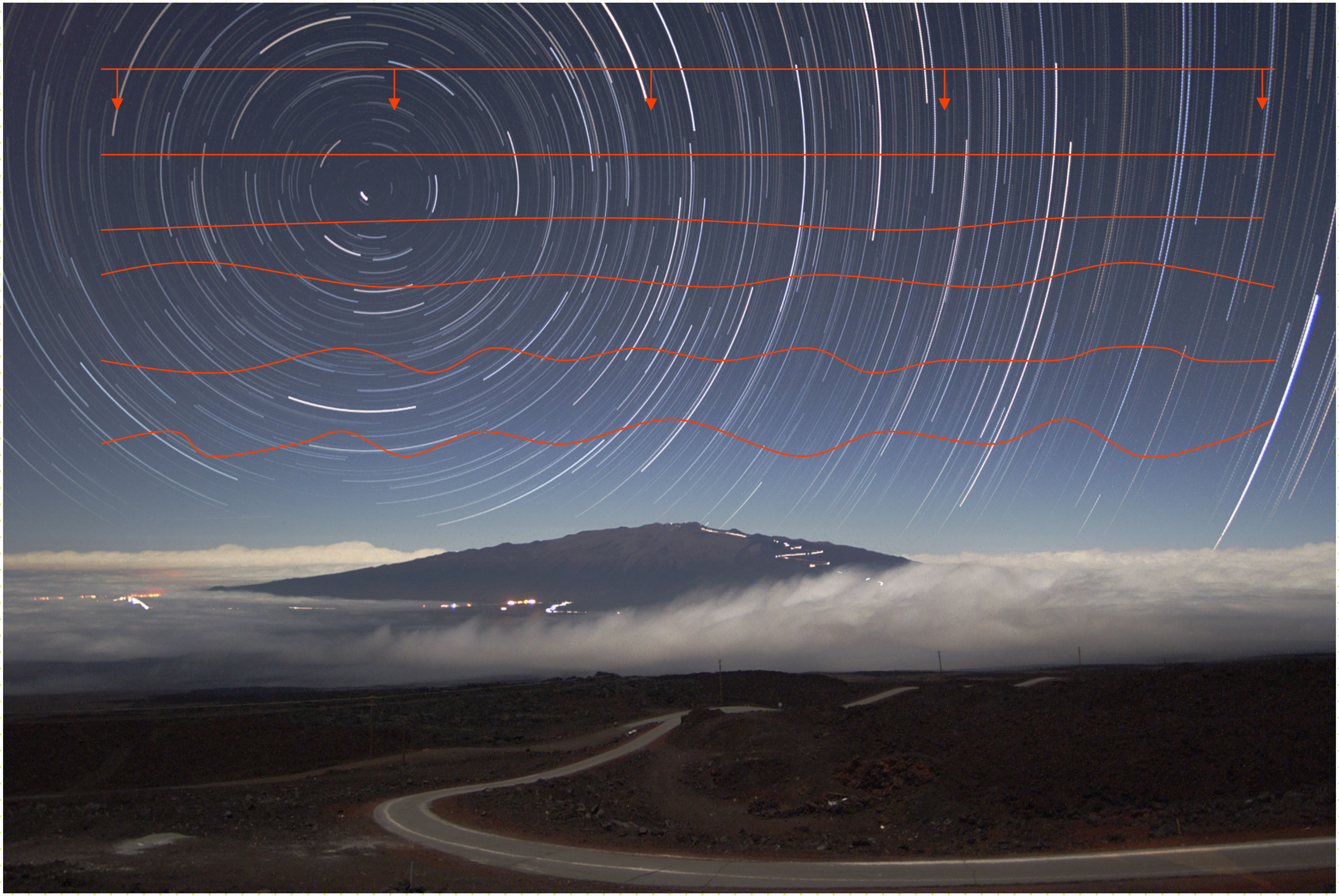
U.S. open access

TIO and the US-ELTP

The 3rd Revolution in Astronomy: Adaptive Optics

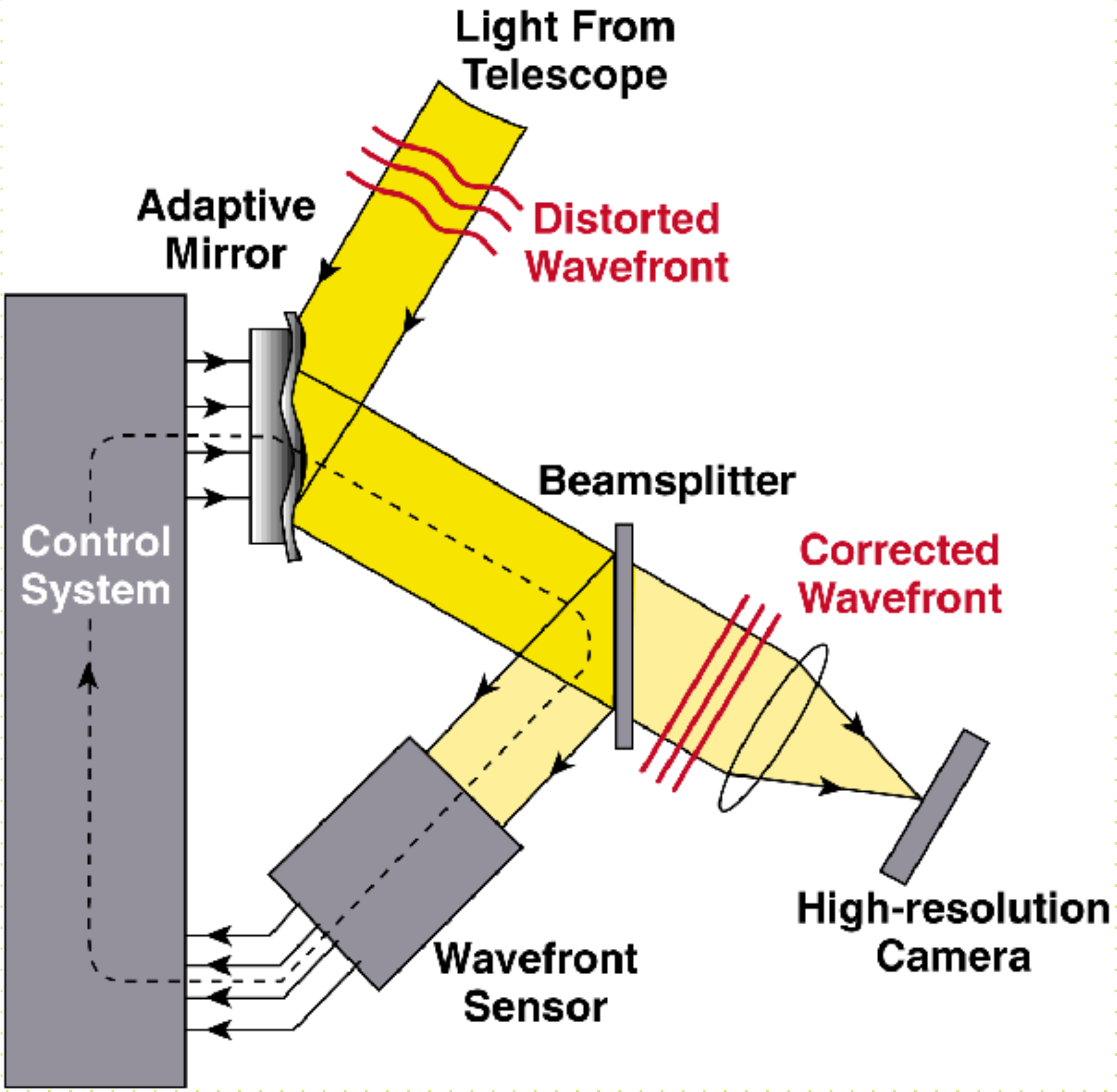


- Theoretical resolution is set by primary mirror diameter and diffraction properties of light
- For telescopes at the surface of the Earth, resolution is set by blurring of the atmosphere to ~1´´, equivalent to a 6-inch telescope



Adaptive Optics

Feedback loop: next cycle corrects the (small) errors of the last cycle



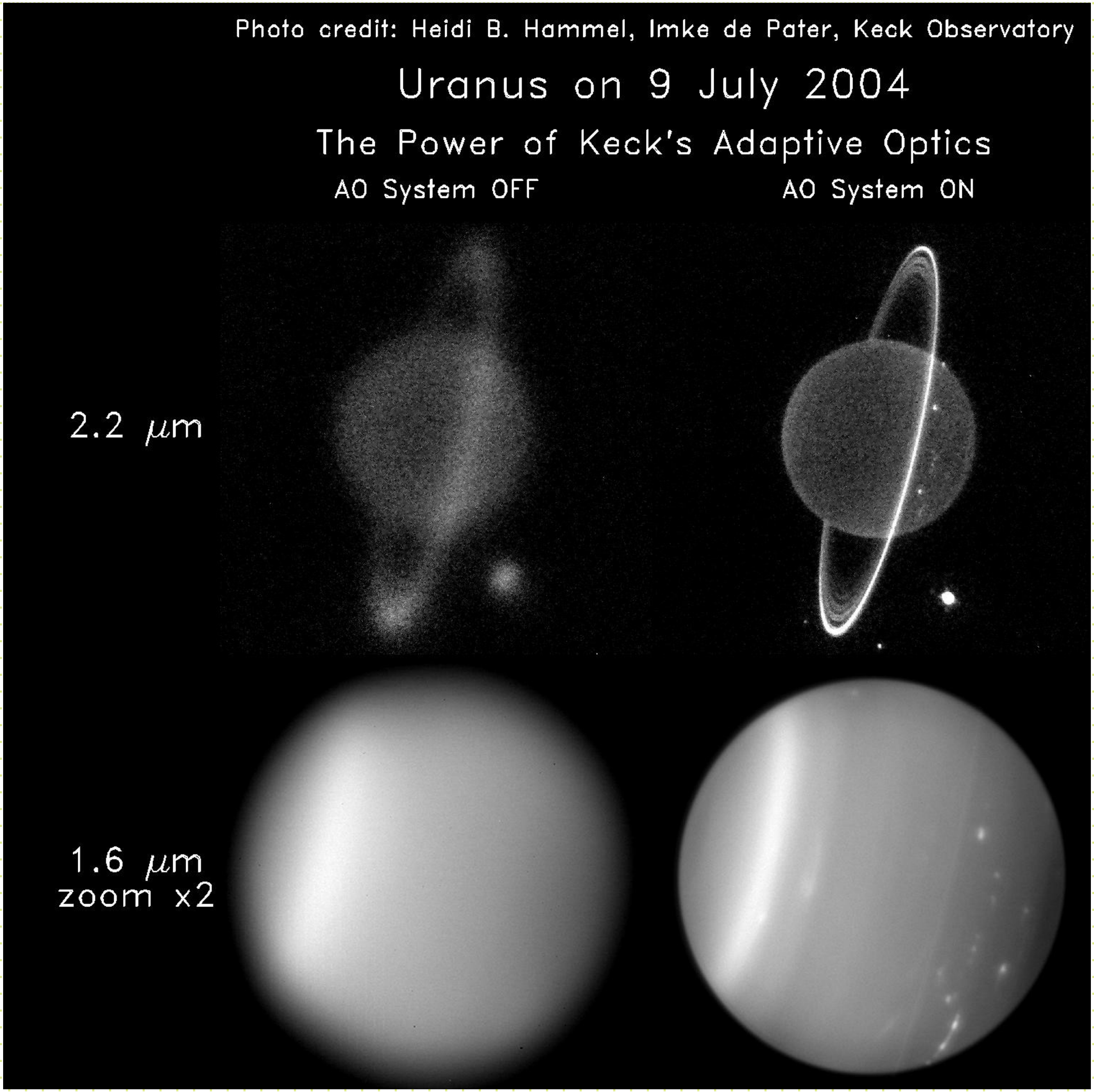
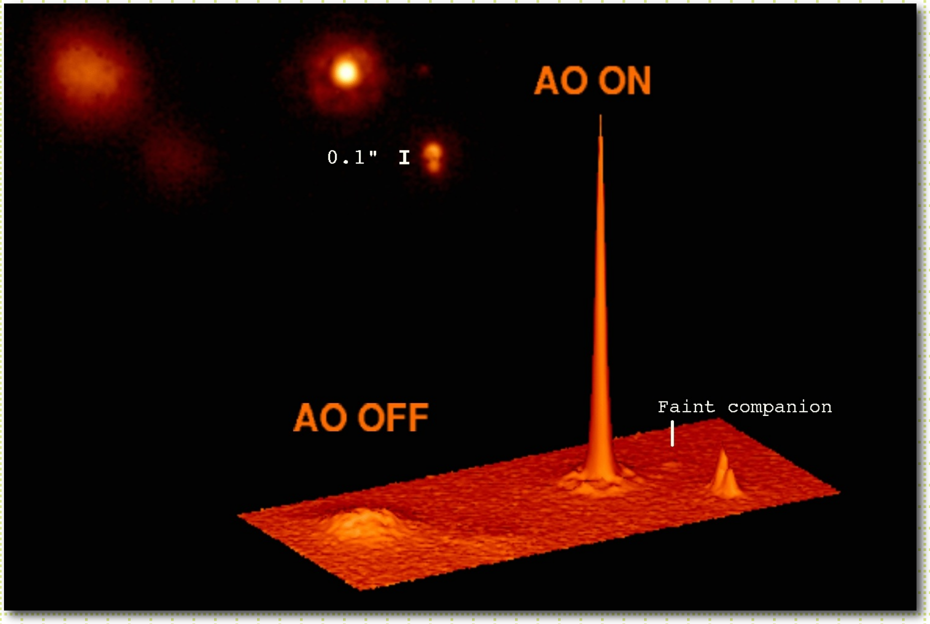


Photo credit: Heidi B. Hammel, Imke de Pater, Keck Observatory

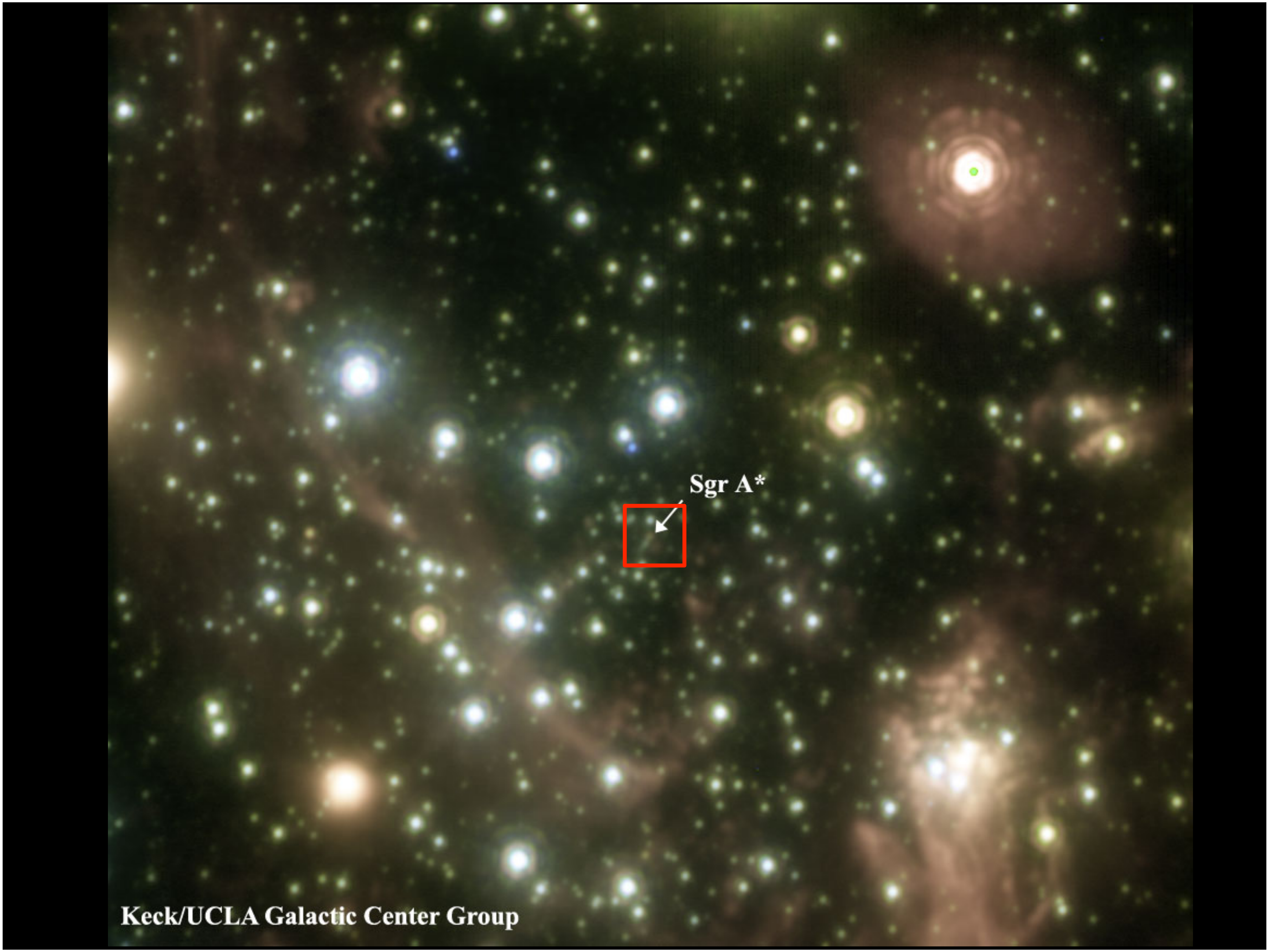
Uranus on 9 July 2004

The Power of Keck's Adaptive Optics

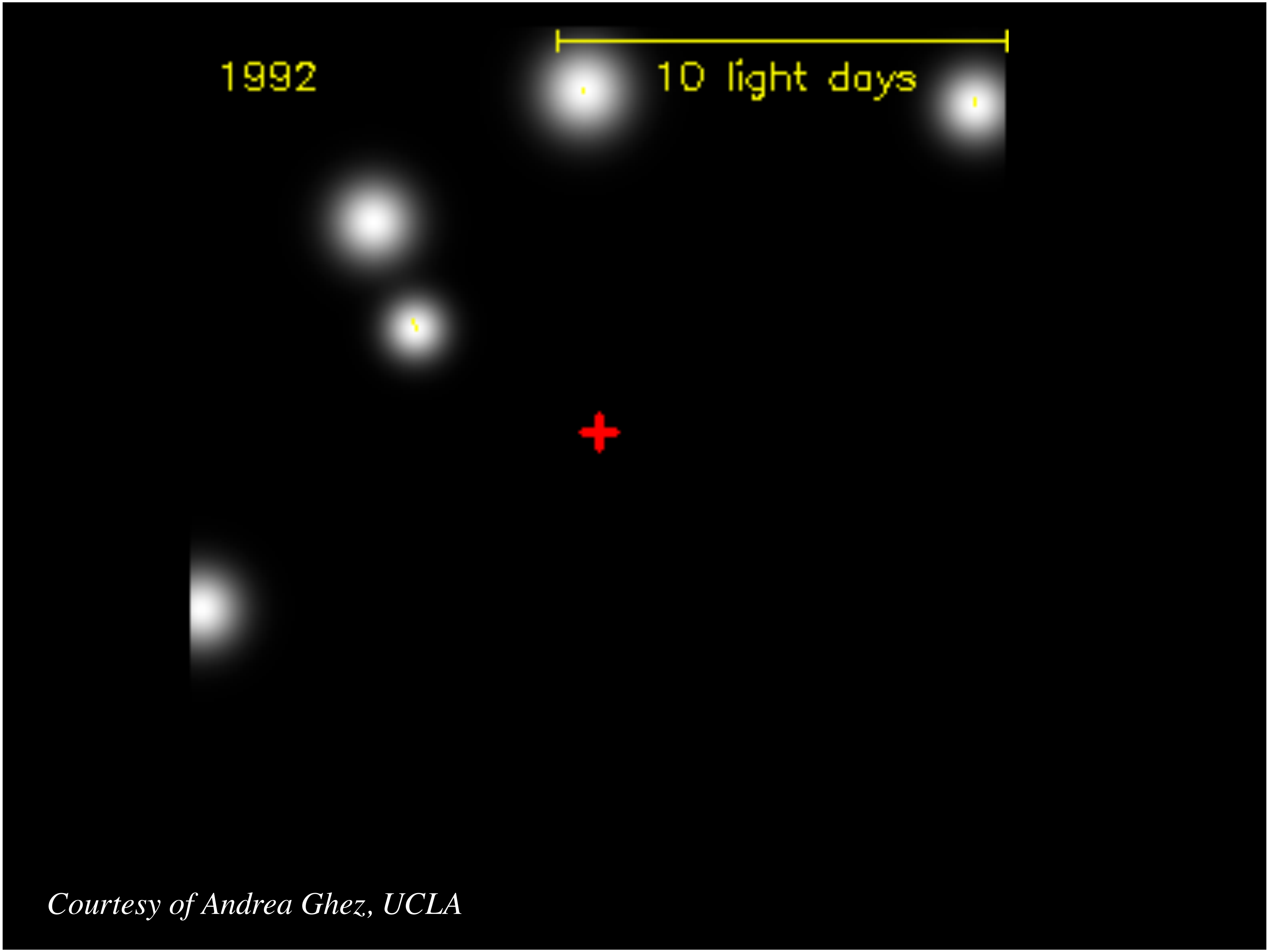
AO works



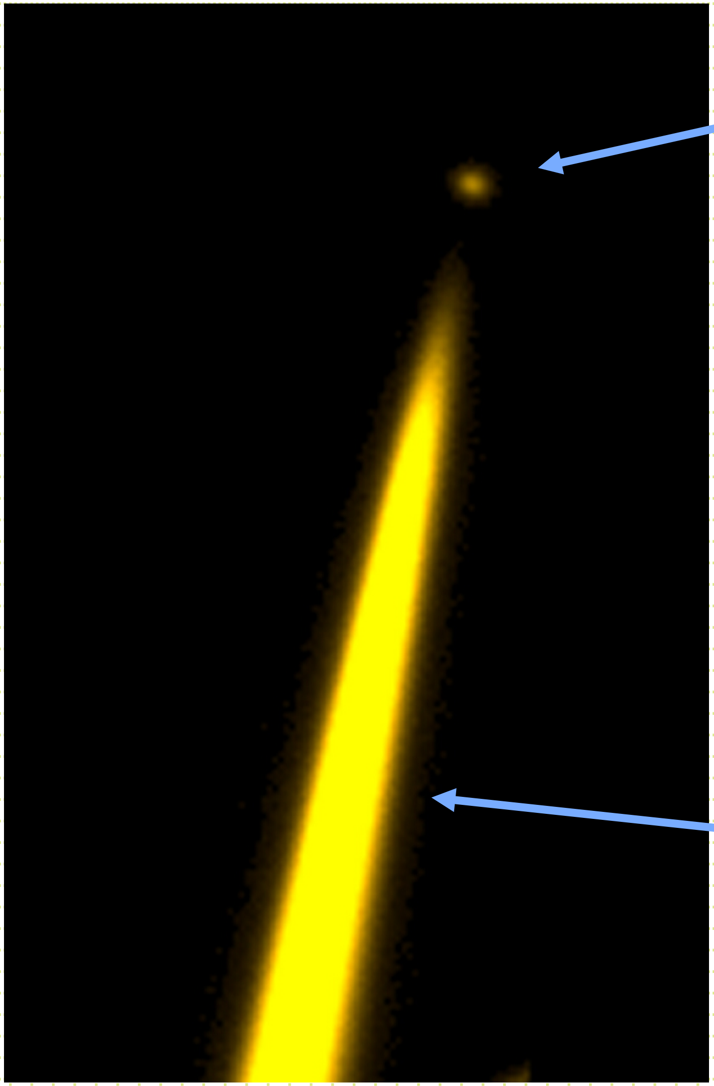
- Correction is easier and better for wavelengths > 1μ
- Need to correct at 50Hz or faster
- For 10m, diffraction limit is 0.02″ @ 1μ, for 30m it is 0.007″
- For many observations the sensitivity gain scales as D^4



Keck/UCLA Galactic Center Group



Courtesy of Andrea Ghez, UCLA



Guide star in sodium layer at ~ 90 km

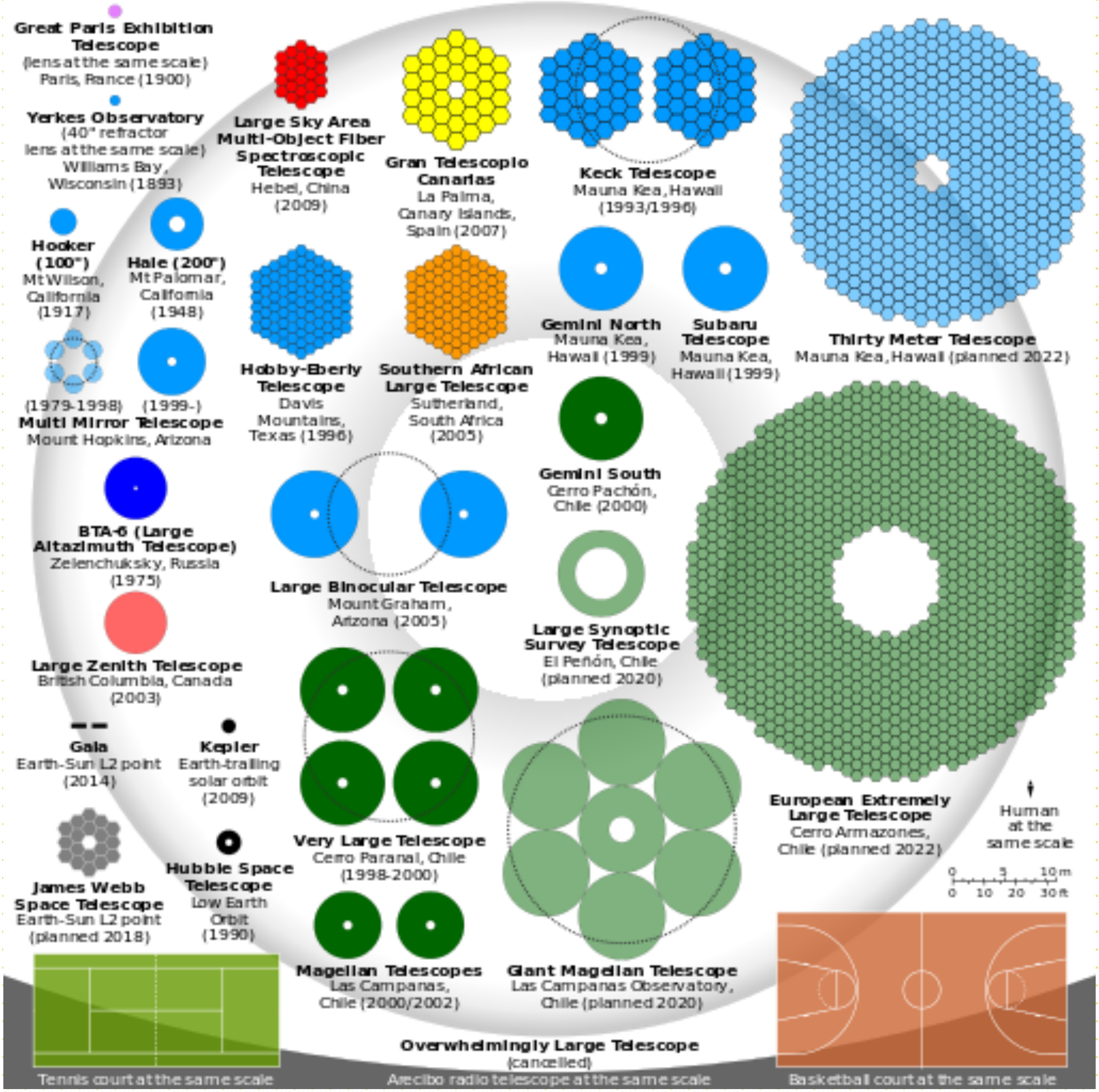
Scattered light from low in atmosphere

The Adaptive Optics Era is here

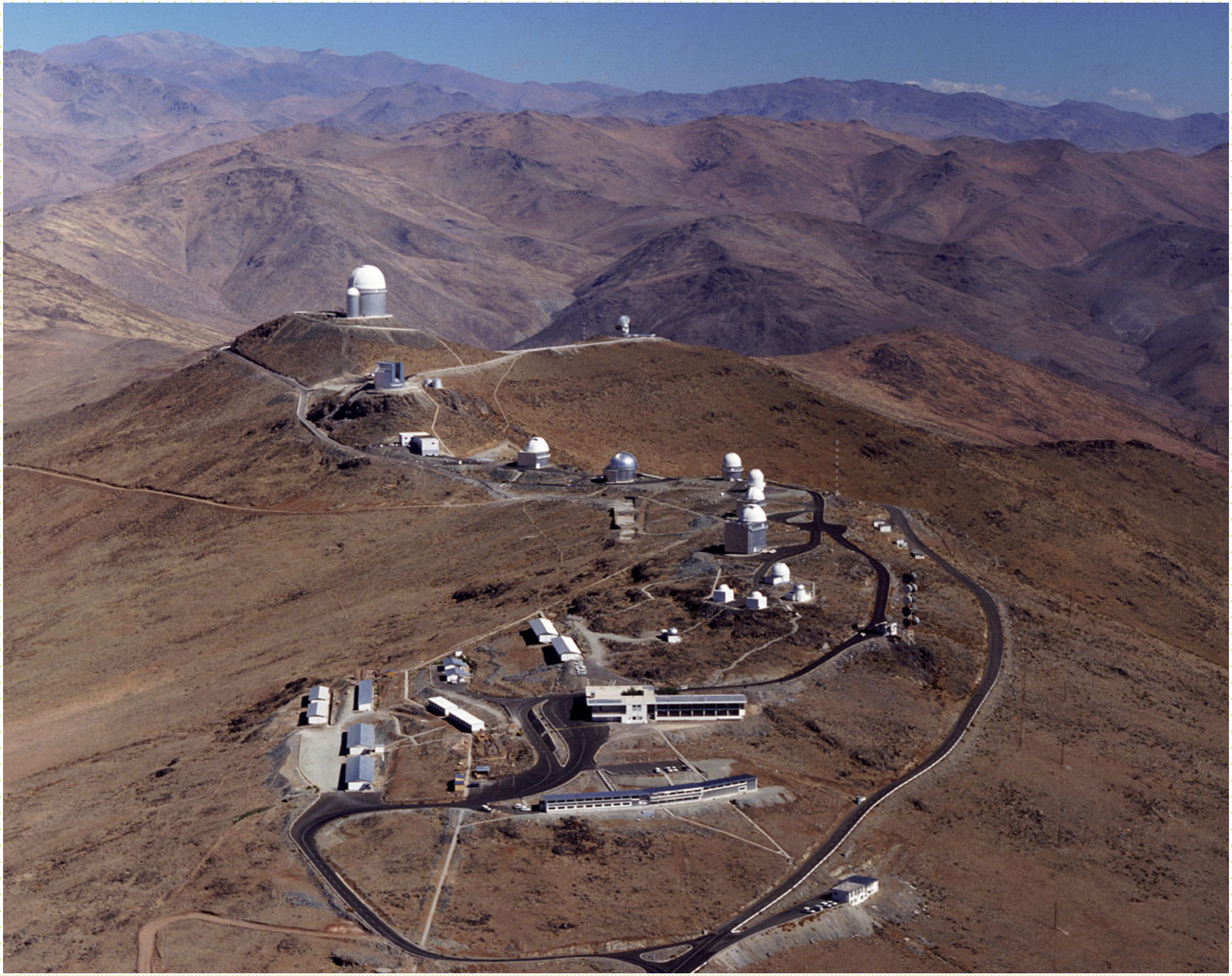
Keck 1 and 2, Subaru at Mauna Kea (photo credit: Dan Birchall)

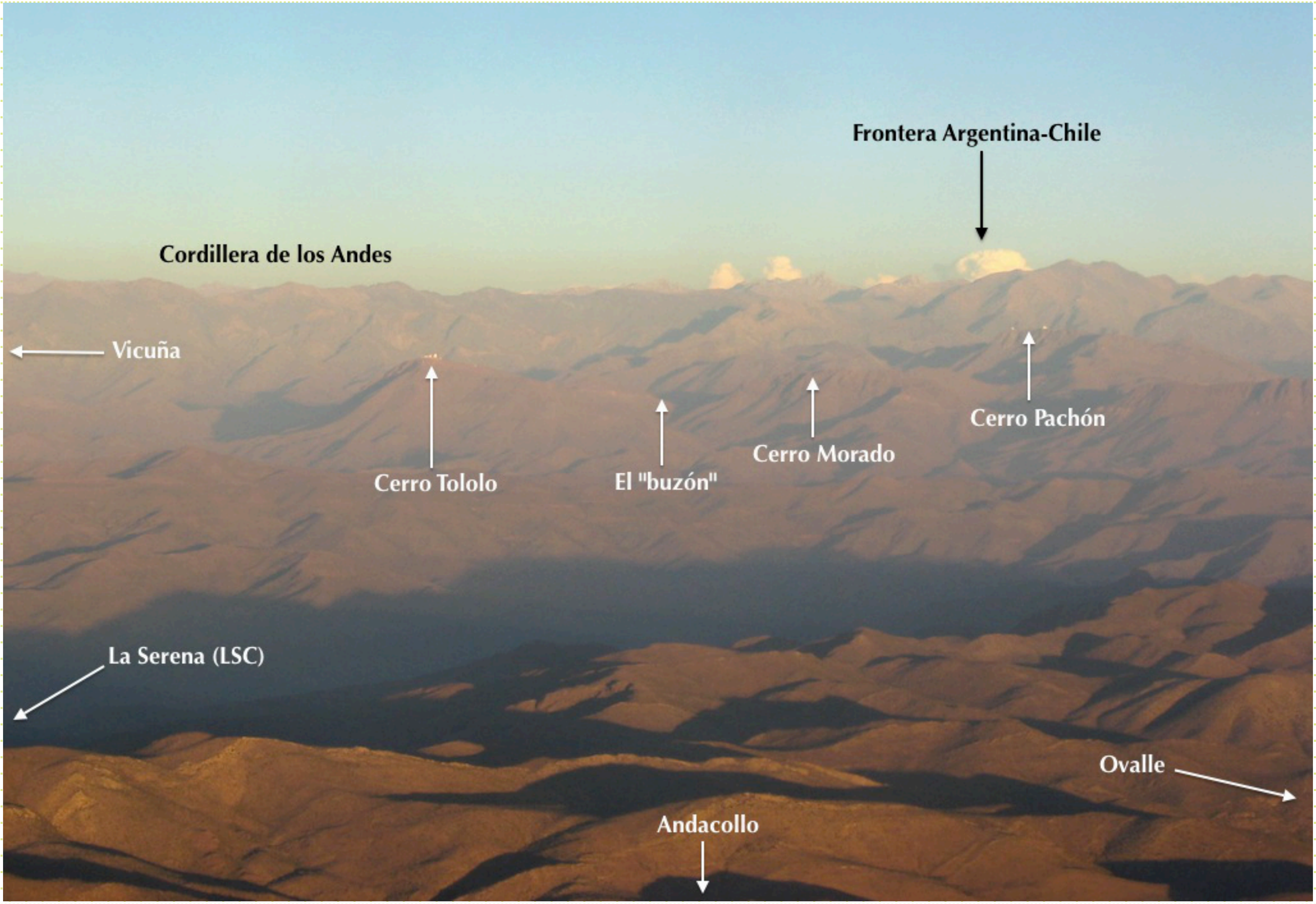
Telescope Cities

- Lots of ground-based telescopes around the world.
  - Some have open access, some are limited
  - Some have open access archives, some don't
- Lots of options for use
  - Travel to telescope for "PI-based" nights
  - Remotely access in PI mode
  - Robotic or queue mode
  - Survey mode with access to data or data products


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Hooker (100")
Mt Wilson,
California
(1917)
Hale (200")
Mt Palomar,
California
(1948)
Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)
Southern African Large Telescope
Sutherland,
South Africa
(2005)
Gemini North
Mauna Kea,
Hawaii (1999)
Subaru Telescope
Mauna Kea,
Hawaii (1999)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón,
Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Binocular Telescope
Mount Graham,
Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing
solar orbit
(2009)
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)
Human
at the
same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth
Orbit
(1990)
Magellan Telescopes
Las Campanas,
Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale


CSO
Subaru
Keck 10m
JCMT
UHH
UKIRT
UH 2.2m
IRTF
CFHT
Gemini N




Frontera Argentina-Chile
Cordillera de los Andes
Vicuña
Cerro Tololo
El "buzón"
Cerro Morado
Cerro Pachón
La Serena (LSC)
Ovalle
Andacollo

W.M. Keck Obs control room, Waimea, HI

What makes a good optical/IR site?

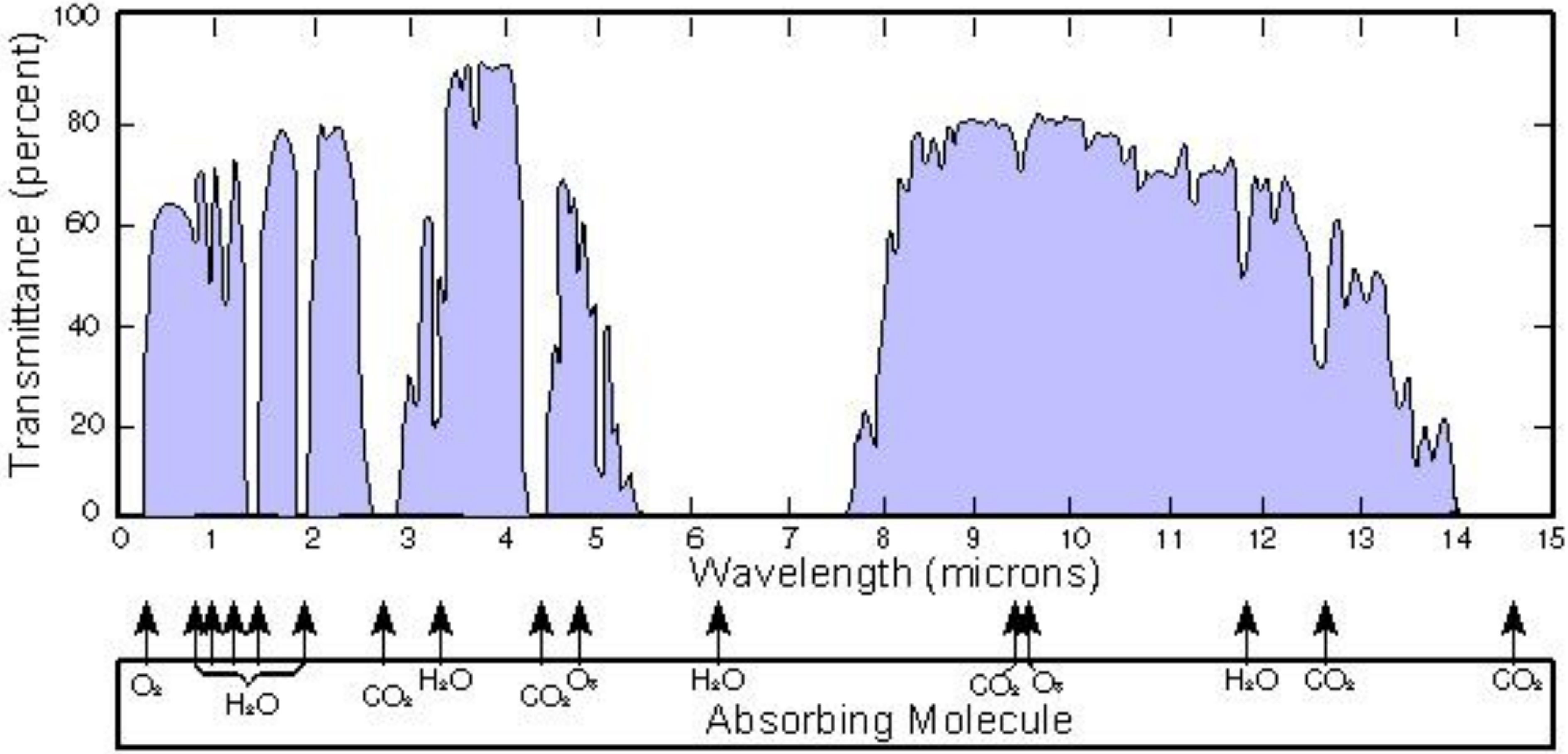
- Dark skies
  - Increasingly difficult!
- Clear (no clouds) weather
- High altitude
- Low precipitable water vapor
- Laminar wind flows
- Hawaii, northern Chile, islands off Europe

Radio Telescopes

- As we will talk about later, there are many different types of signals from the Universe.
- Radio telescopes are sensitive to long wavelength electro-magnetic radiation
- Surface figure and structure performance requirements much lower

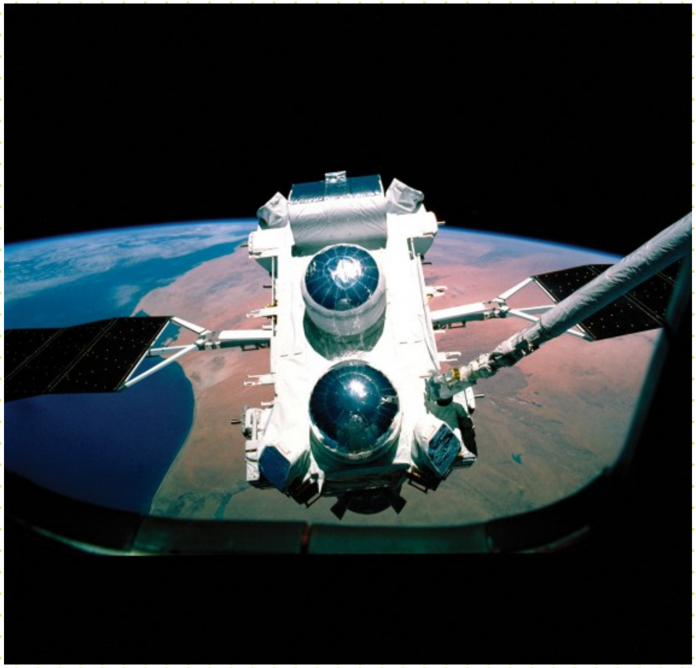
Space Telescopes

- No distortion from the atmosphere (can do wide-field high-quality imaging)
- No absorption or emission background from the atmosphere:
  - X-ray telescopes
  - far infrared telescopes
  - gamma-ray telescopes have to be in orbit
- A little pricey, can't always do upgrades

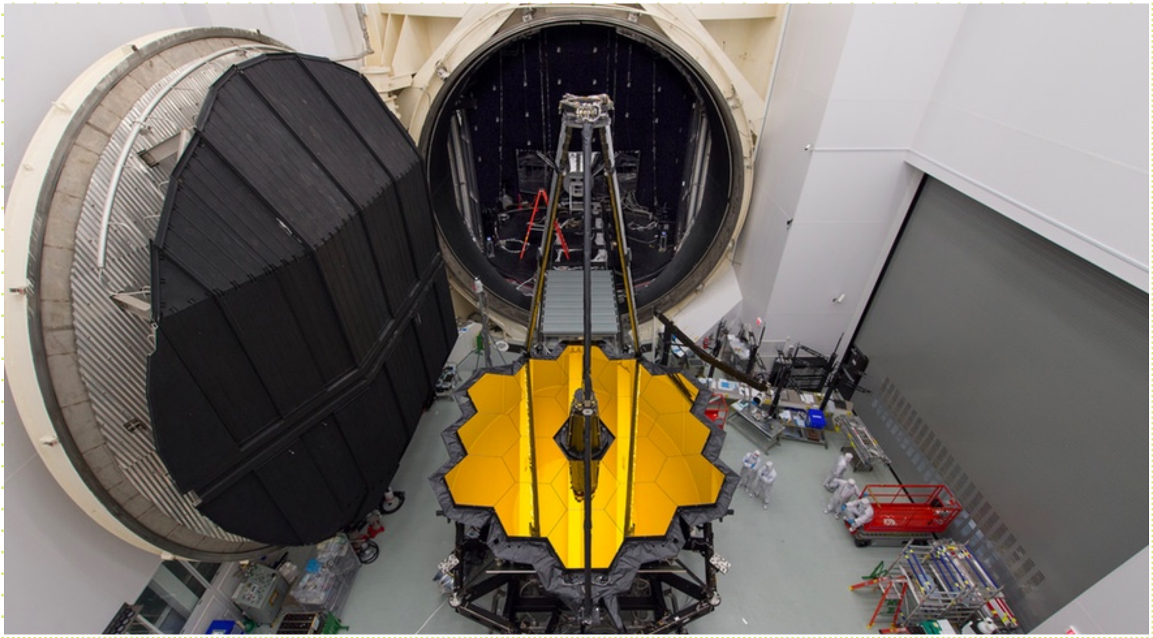

Transmittance (percent)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Wavelength (microns)
O₂
H₂O
CO₂
H₂O
CO₂
O₃
H₂O
CO₂
O₃
H₂O
CO₂
CO₂
Absorbing Molecule


Optical "window"
Radio "window"

The Space Age



James Webb Space Telescope



- Diffraction limited to 2μ
- Cooled to 30K
- 6.5m deployable mirror
- Launch date: ~~2010~~, ~~2014~~, ~~2018,~~ 2020
- Cost: ~~$1.4B, $5B, $8B~~
- Will make ground-based IR astronomy *almost* obsolete