Astro 426/526

Fall 2019

Prof. Darcy Barron

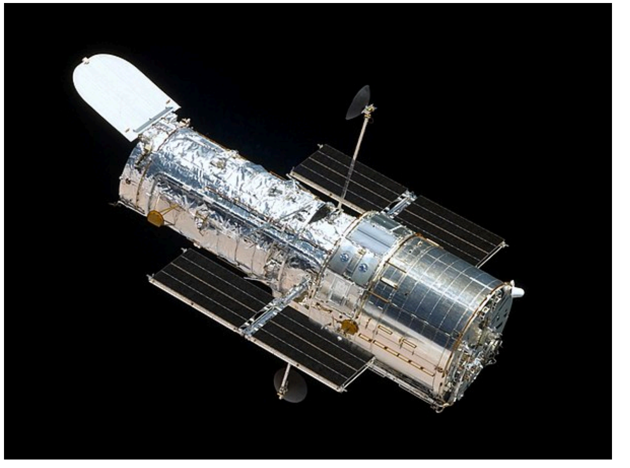
Lecture 7: Optical telescopes

Reminders

- Expect HW 2 to come out next week, due date ~ Sept 25
- Mid-term exam Oct 2
- For next two weeks: detectors, statistics, and noise
  - Summarized in Section 1.4.2 (Detectors: Basic Principles) and Section 1.5 (Statistics and noise) of *Measuring the Universe*
  - For next week: read chapter 3 of Measuring the Universe (Detectors for the ultraviolet through infrared)
  - For the week after (Sept 23): read chapter 3 of *Practical Statistics for Astronomers*

Hubble Space Telescope

- Ritchey-Chretien telescope
  - 2.4 meter primary mirror
  - 57.6 meter focal length
  - Focal ratio f/24 (big and slow)
- Four main instruments observe in near infrared, visible, and ultraviolet wavelengths
  - All share one primary mirror
- Launched in 1990 to low-earth orbit
  - Could last a few more decades
  - Only telescope designed to be maintained by astronauts



Hubble Space Telescope Design

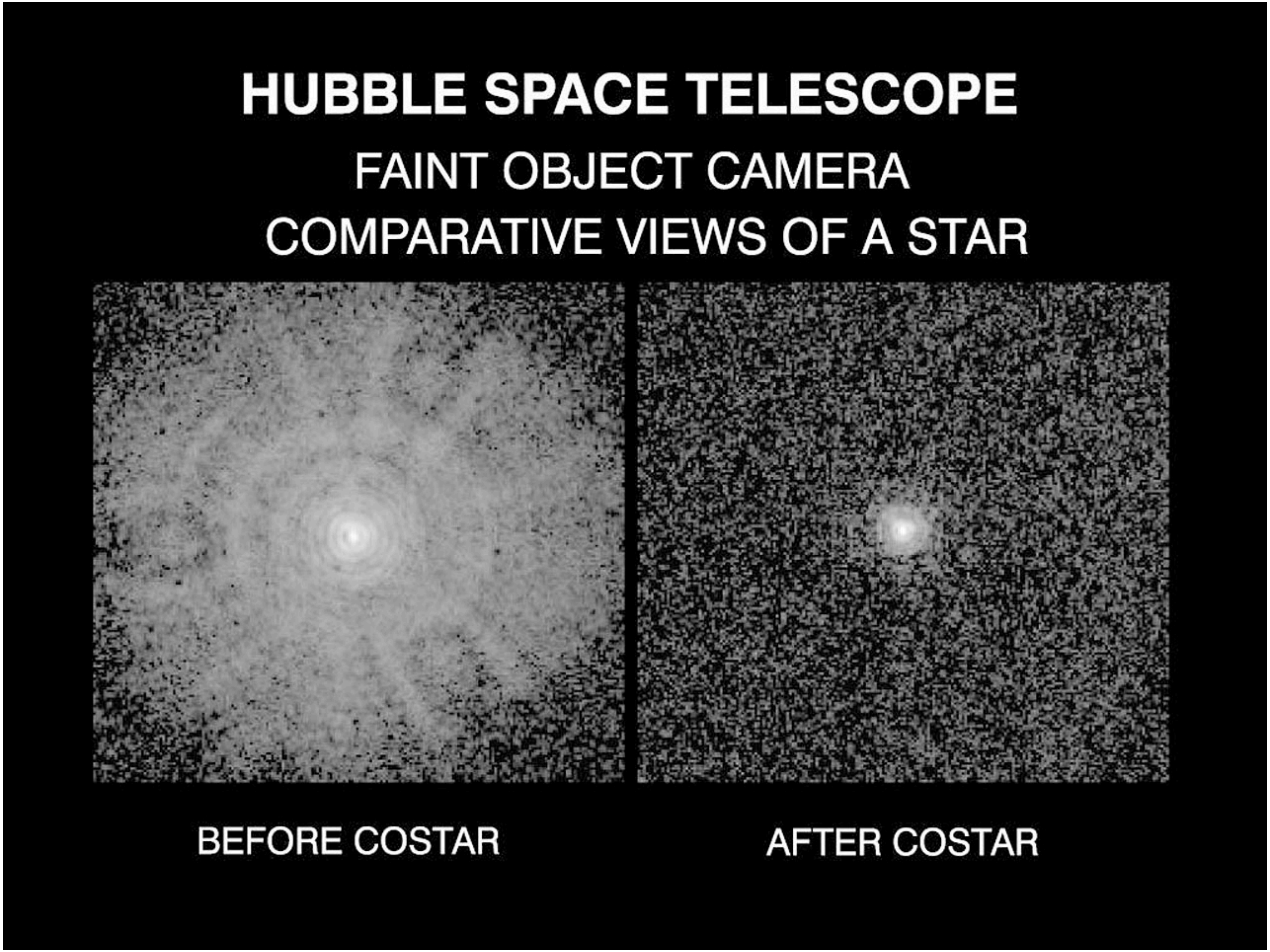
- Why space?
  - Can observe at infrared and ultraviolet
  - Resolution on the ground was limited to ~ 1 arcsecond due to atmospheric seeing
- Why a 2.5 meter primary?
- Why f/24?
- Why low-earth orbit?
  - First complicated space telescope, wanted to be able to go up and fix problems and swap in instruments
  - Timed with the space shuttle program which provided frequent access to low earth orbit

Hubble Space Telescope Design

- Why space?
  - Can observe at infrared and ultraviolet
  - Resolution on the ground was limited to ~ 1 arcsecond due to atmospheric seeing
    - What size aperture do you need to get 1 arcsecond diffraction limited resolution?
    - Why was anything ground-based bigger (pre-adaptive optics)?
- Why a 2.5 meter primary?
- Why f/24?
- Why low-earth orbit?
  - First complicated space telescope, wanted to be able to go up and fix problems and swap in instruments
  - Timed with the space shuttle program which provided frequent access to low earth orbit

What happened with Hubble?

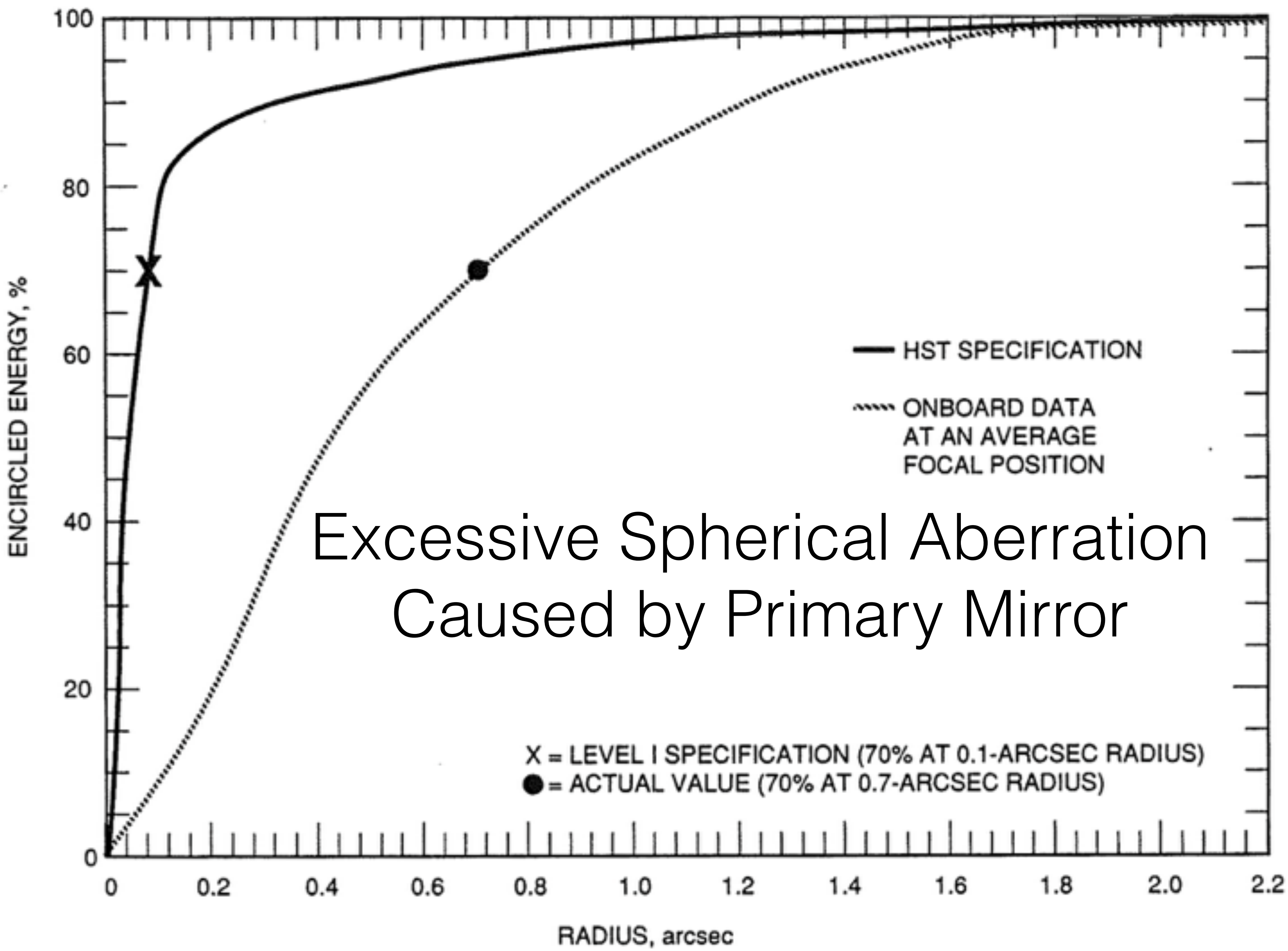
- On initial commissioning, Hubble was found to have very bad **spherical aberration**
- This resulted in blurry images and a resolution that was 10x worse than expected



https://www.spacetelescope.org/images/opo9408a/

What happened with Hubble?

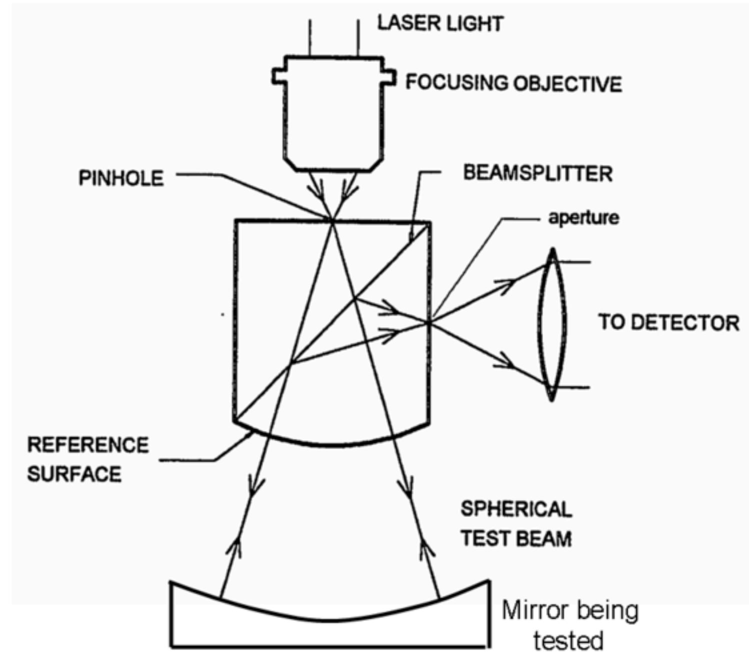
- The mirror had been ground extremely precisely, especially since it needed to be good enough to observe ultraviolet wavelengths
- Demonstrator mirror that this level of finishing was even possible is in storage at UNM (Prof. McGraw)
  - Smooth to 10 nm - If Hubble's primary mirror were scaled up to the diameter of the Earth, the biggest bump would be only six inches tall.
- The edge of the mirror was too flat, by 2200 nm



The Hubble Space Telescope Optical Systems Failure Report

What happened with Hubble?

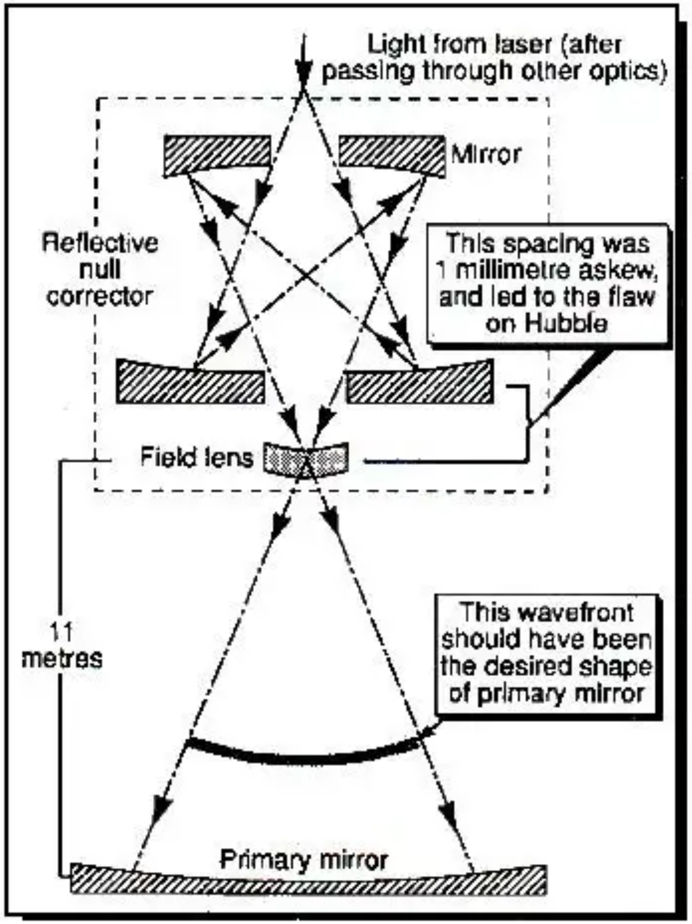
- Many different methods to test the shape of a mirror, and complex mirrors require more complex methods
- Nulling interferometry requires complex equipment but has results that are straightforward to understand
- Checks the deviation from a perfect spherical surface, to sub-wavelength precision



https://en.wikipedia.org/wiki/Null_corrector

What happened with Hubble?

- Aspherical surfaces can be tested using a null corrector
  - Setup for Hubble mirror shown at right
- Complicated setup of null corrector must be correct, to give the right surface figure to follow
- Hard to double-check if this is the only way to verify the figure
  - The company ignored problems with a coarser measurement since it wasn't supposed to be 'accurate'

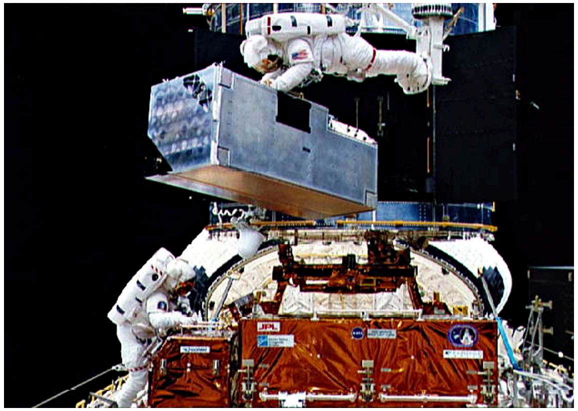


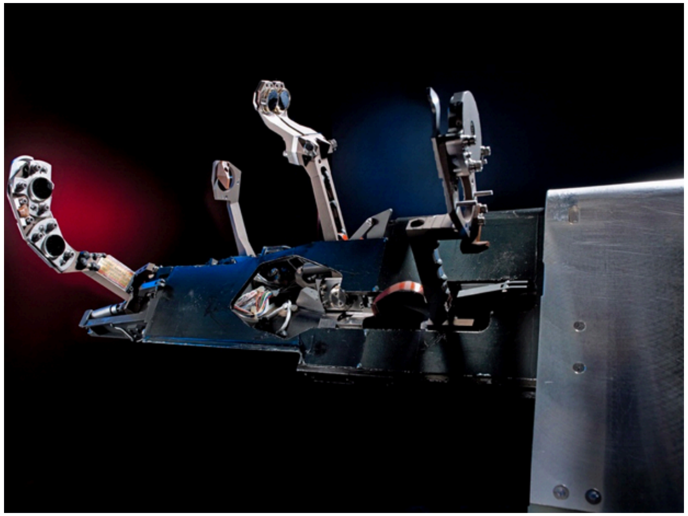
https://www.newscientist.com/article/mg12717301-000-the-testing-error-that-led-to-hubble-mirror-fiasco/

How was Hubble fixed?

- COSTAR: Corrective Optics Space Telescope Axial Replacement (COSTAR)
- 10 small mirrors on motorized arms corrected for the aberration on each of Hubble’s instruments
- Instruments have been replaced and upgraded to correct for aberration, so COSTAR is no longer in use
    - Is on display at the Smithsonian

https://www.spacetelescope.org/about/general/instruments/costar/



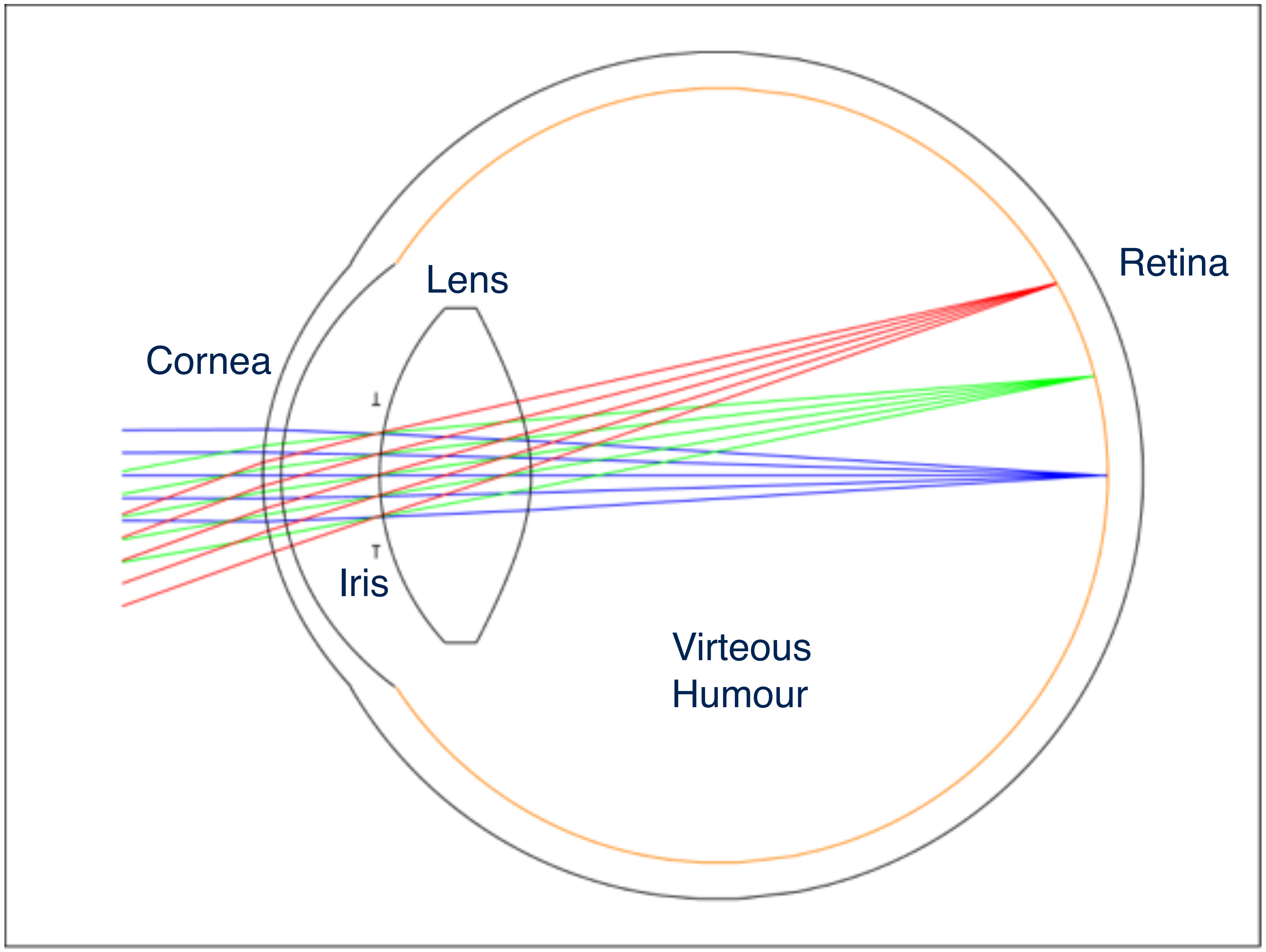


Examples of **Optical** Telescope Design

- Sections ~ 2.4 and 2.5 of Measuring the Universe
- Principles of Astronomical Telescope Design (Jingquan Cheng)
- Telescope Fundamentals by Suresh Sivanandam http://www.dunlap.utoronto.ca/wp-content/uploads/2016/08/Telescope-Fundamentals.pdf

- An important distinction when considering design: **user facility** vs. **shared** vs. **dedicated instrument**

First Astronomical Instrument - Human Eye



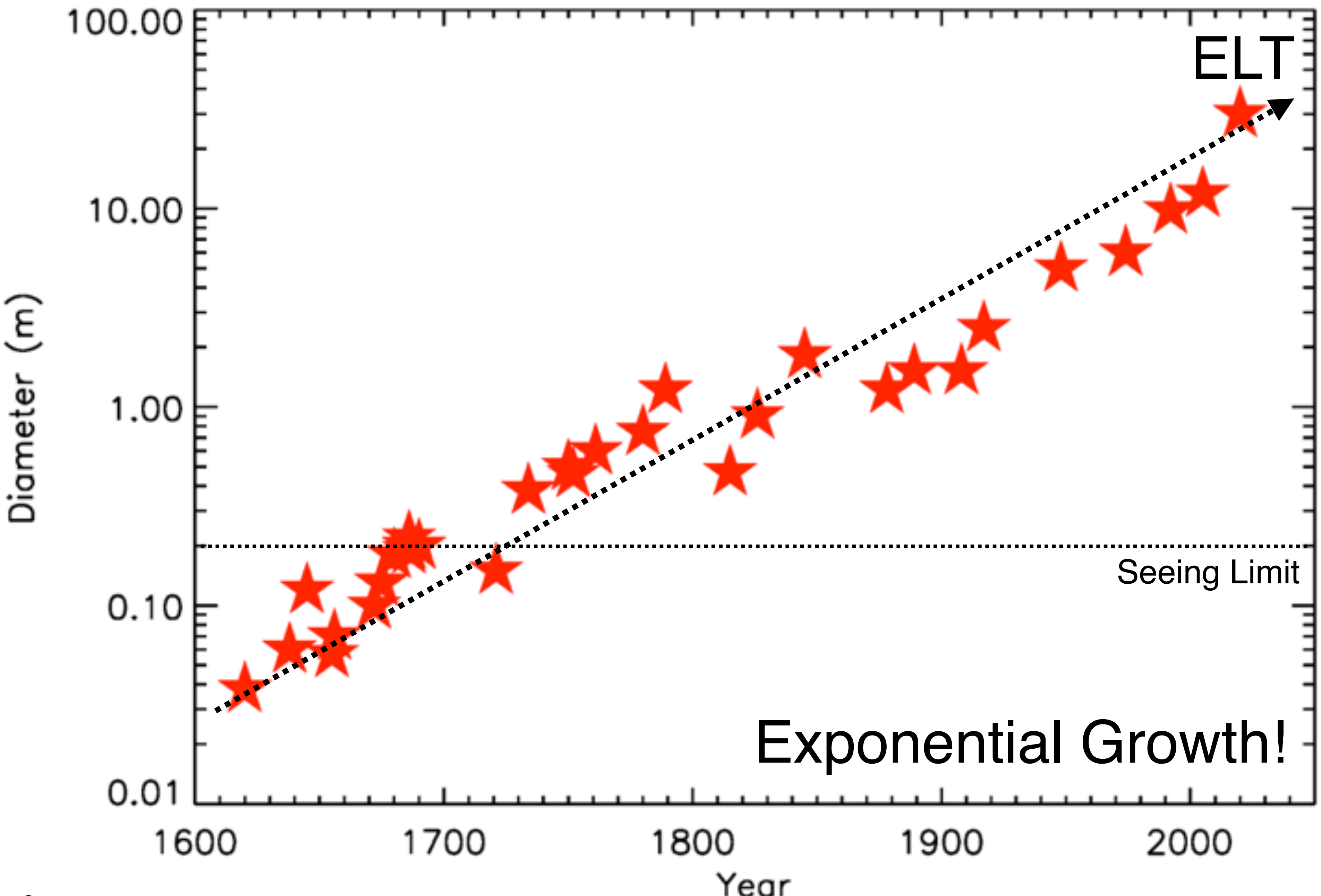
Zemax Optical Raytrace of Human Eye

Field-of-view	~100 deg ~10 deg (fovea)
Angular Resolution	~1-2 arcmin
Focal Length	17 mm (relaxed)
f/# Range	f/2-f/8
Dynamic Range	10^{12}
Quantum Efficiency	0.5% (bright) 5% (dark)

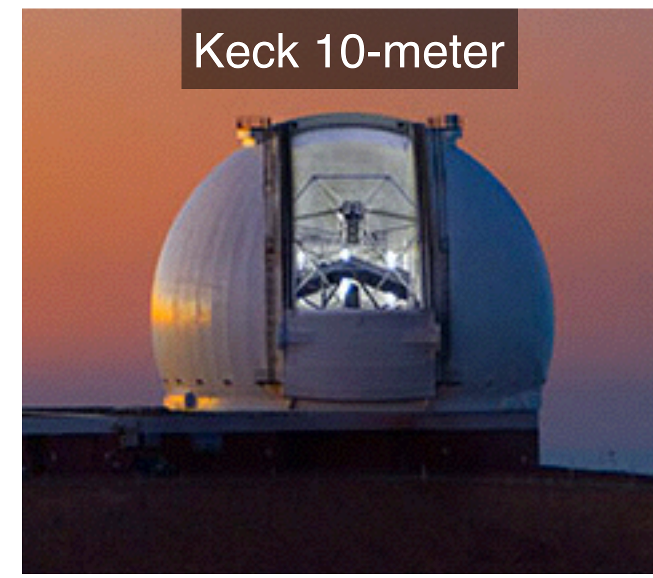
1 arcminute = 1/60 degree
$1 CAD seen at 100 meters
1 arcsecond = 1/60 arcminute
$1 CAD seen at 6 km

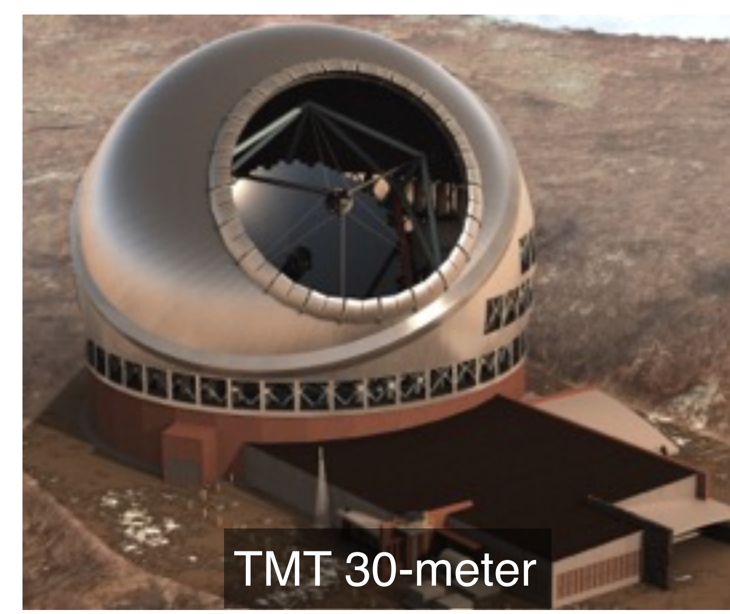
$1 CAD
Loonie

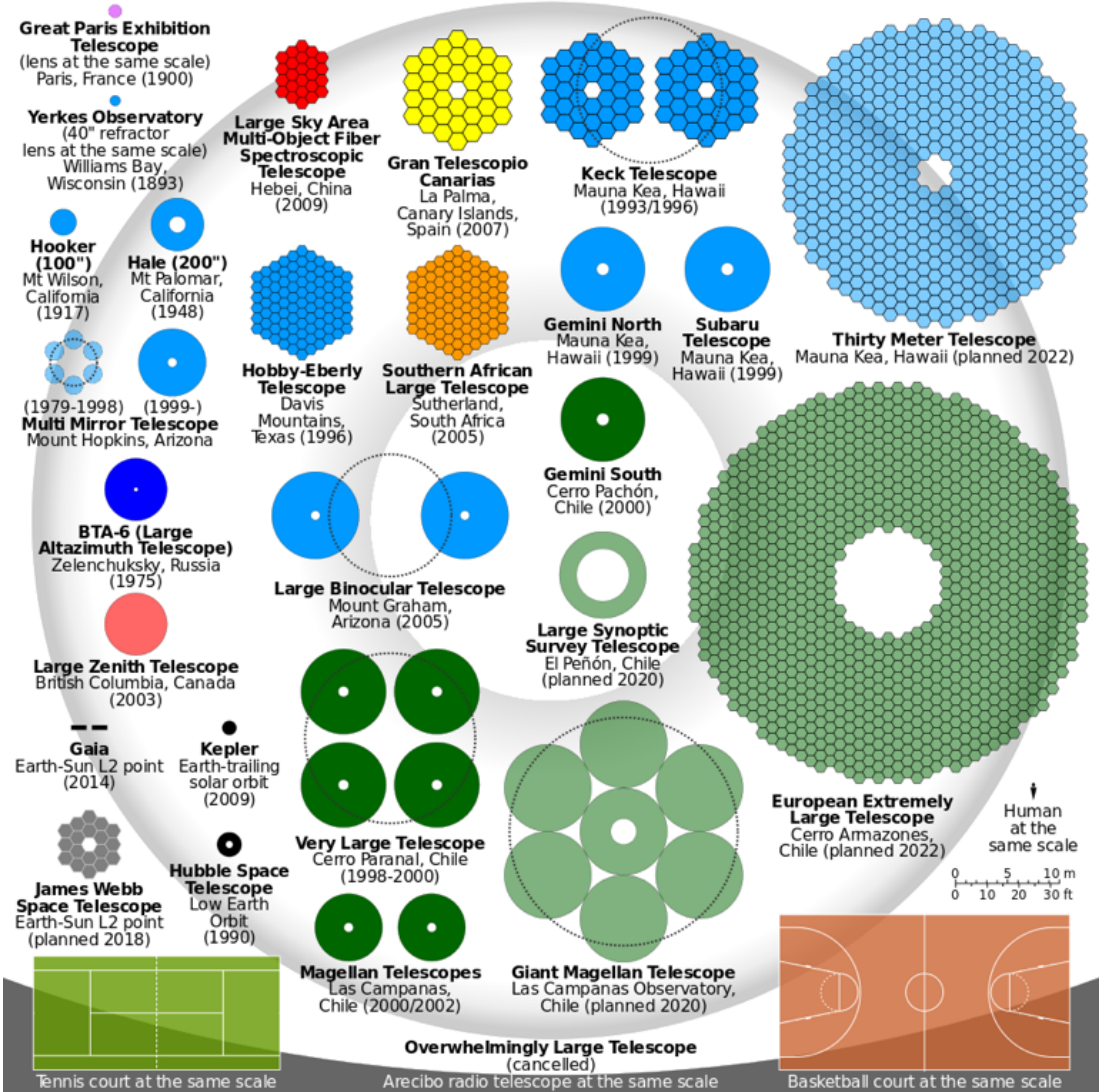
Explosive Growth in Ground-Based Optical/Infrared Telescopes



Source: http://stjarnhimlen.se/

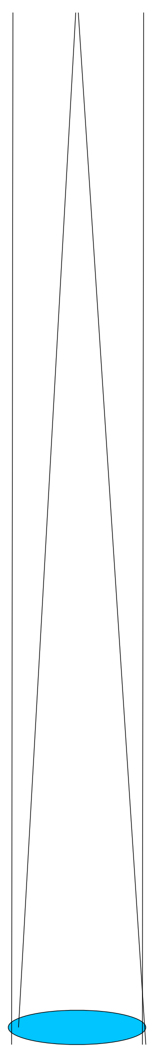


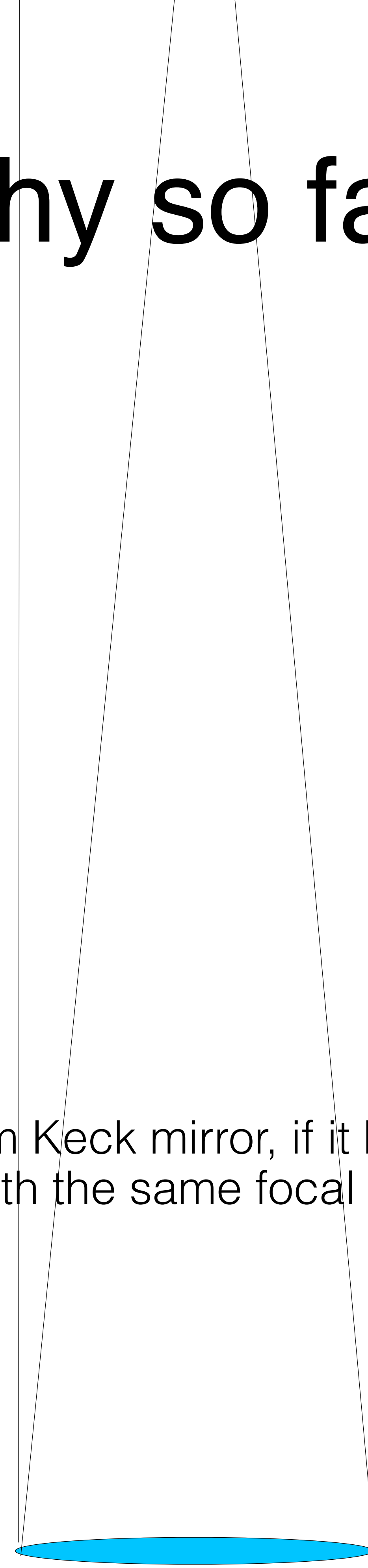



Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (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)
Zelenchukskya, 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

Why so fast?

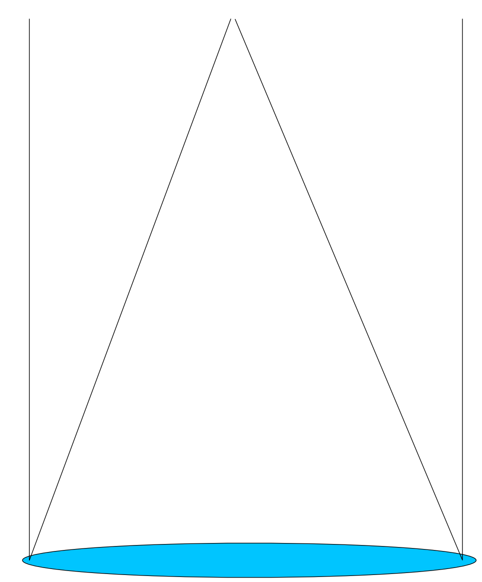
The Hooker 2.5 m with an f/5 Primary mirror.

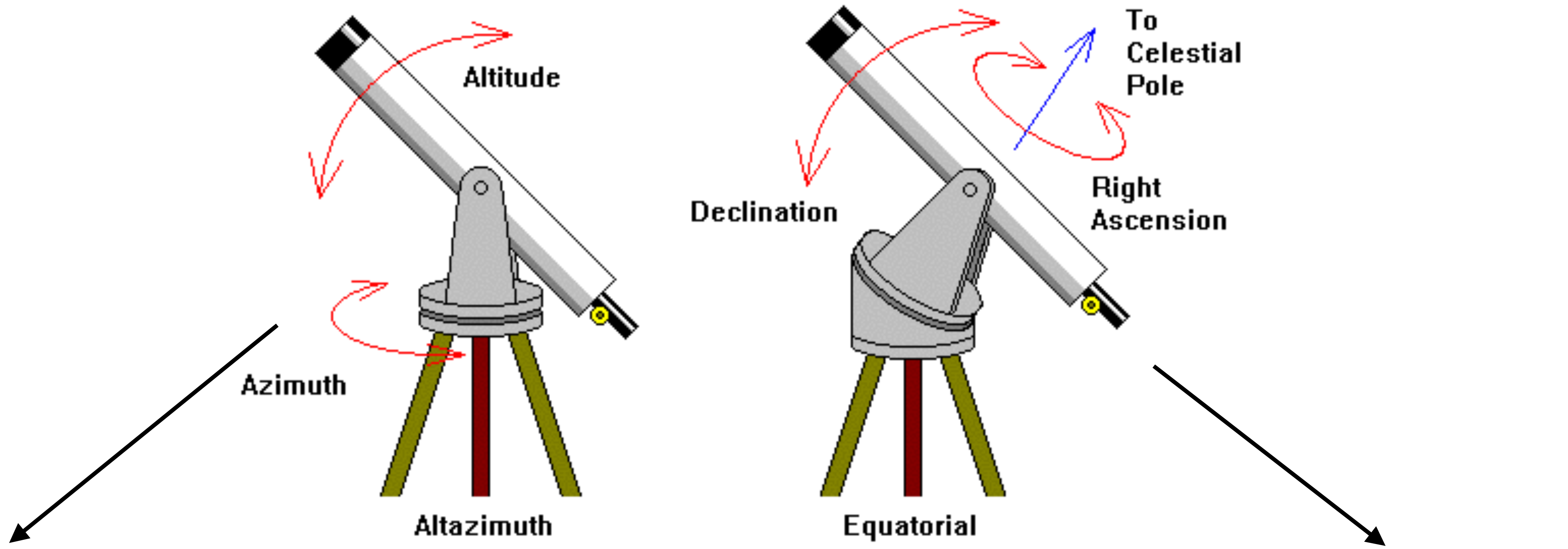




The 10 m Keck mirror, if it had been made with the same focal ratio.

The Keck mirror, as designed with an f/1.75 primary.

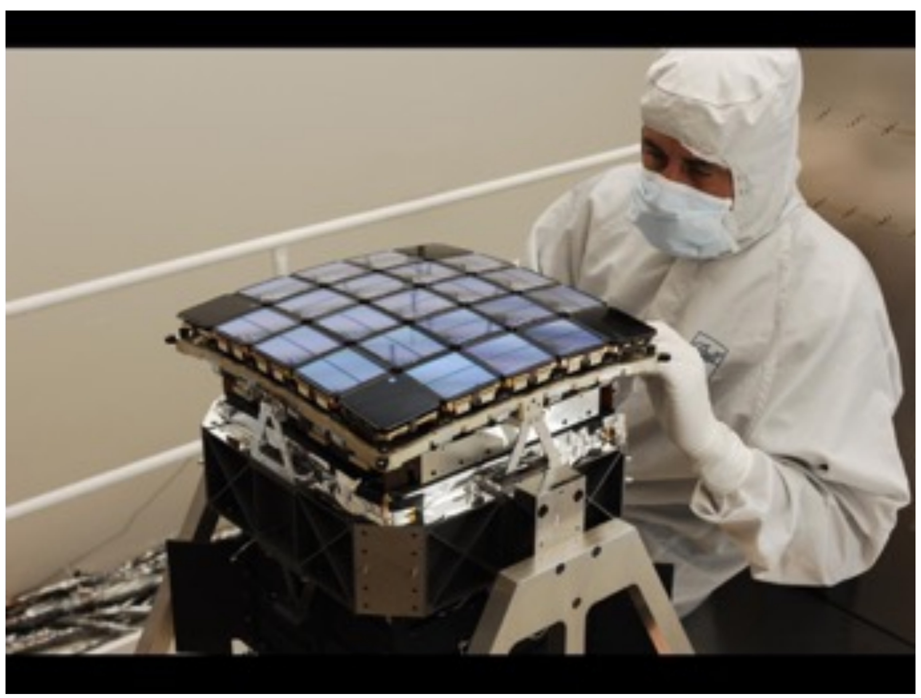


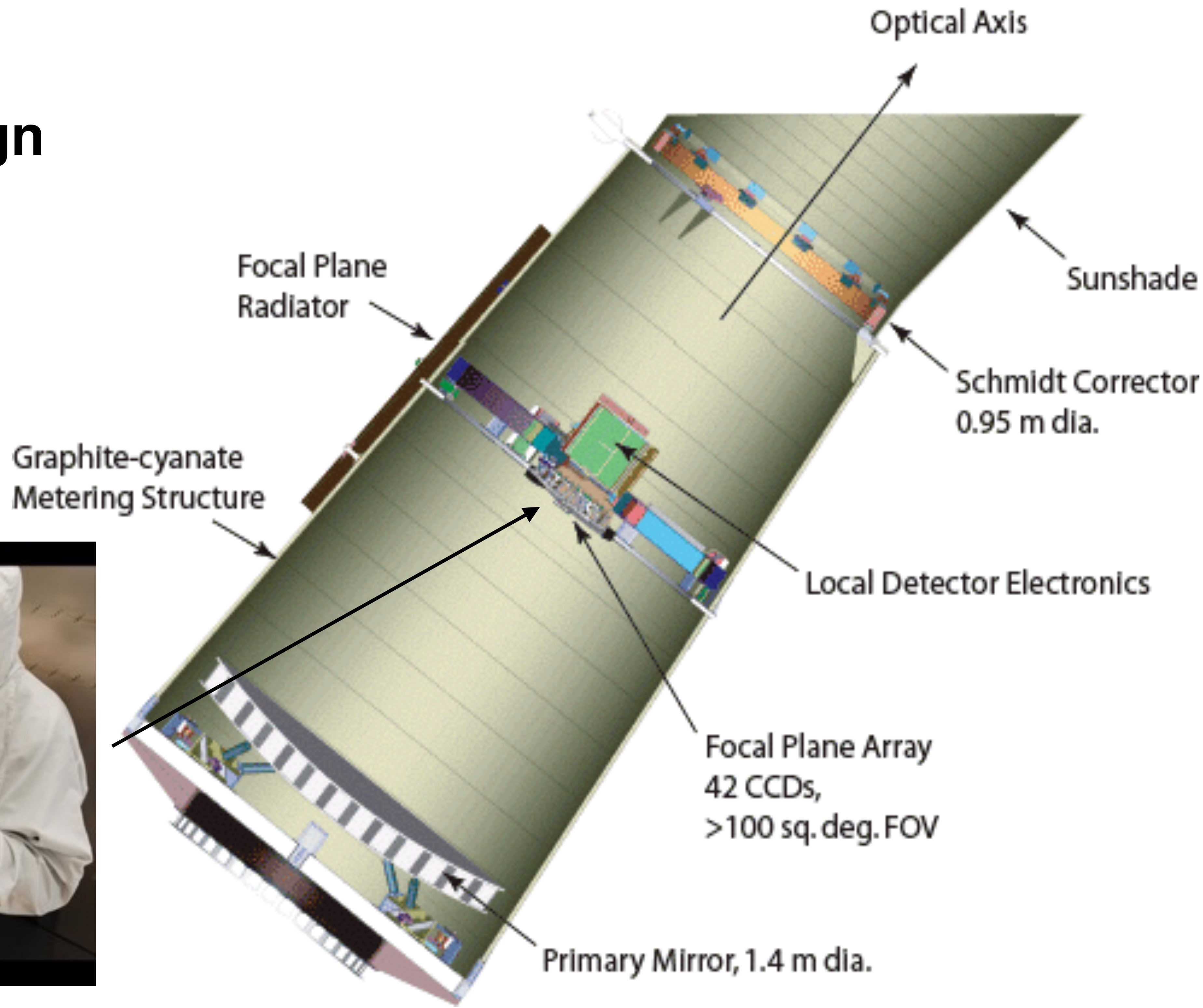

Altitude
Azimuth
Altazimuth
To
Celestial
Pole
Declination
Right
Ascension
Equatorial


Keck 10-meter Telescopes


Hale 5-meter Telescope
Domes Shown To Scale!

Schmidt Telescope:
Kepler optical design



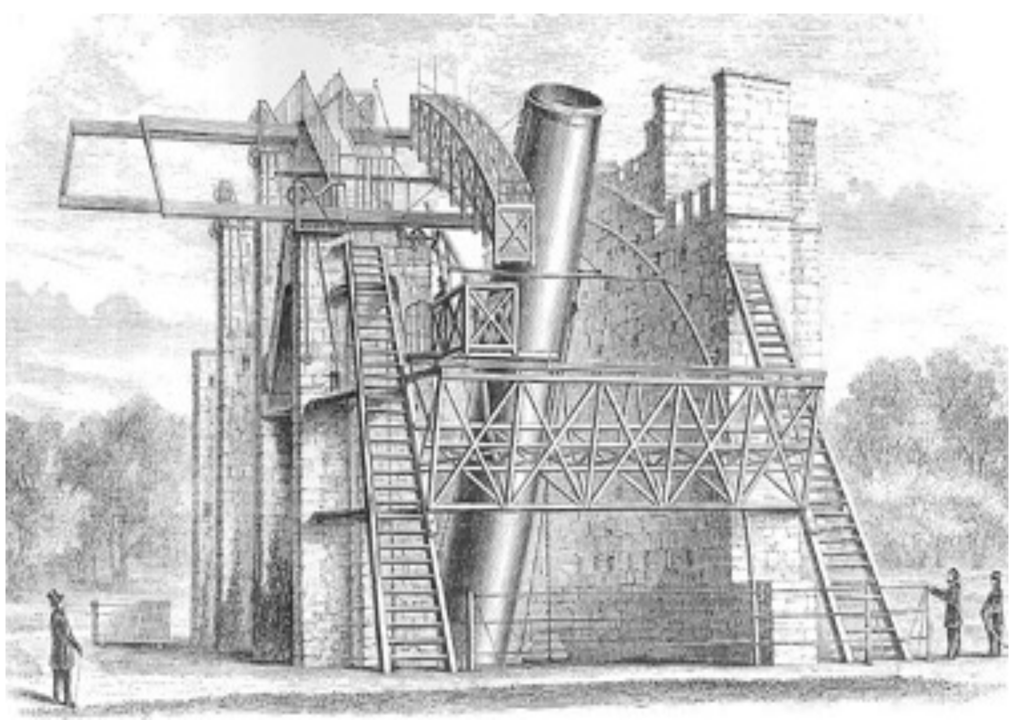


Kepler optical design: Schmidt camera for large field of view detector at prime focus.
→ no field flattening effect of secondary mirror
→ strong field curvature (corrected for by curving the focal plane!)
Note that PM is larger than corrector plate. Effective diameter is set by corrector.

Reflecting Telescopes

Newton's telescope
(1668-1672)

Herschel's telescope
primary mirror (1.26m)
(1875-1879)

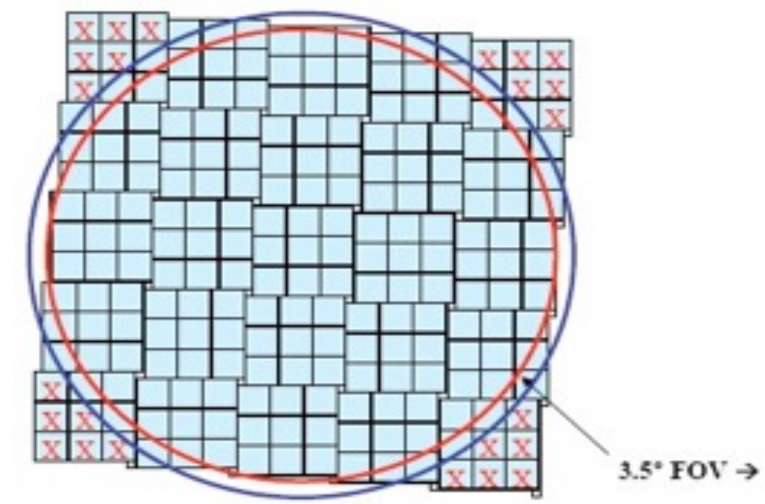


- Reflecting Telescopes have a similarly long history.

30-meter telescope TMT
f/1 primary!
Location: TBD

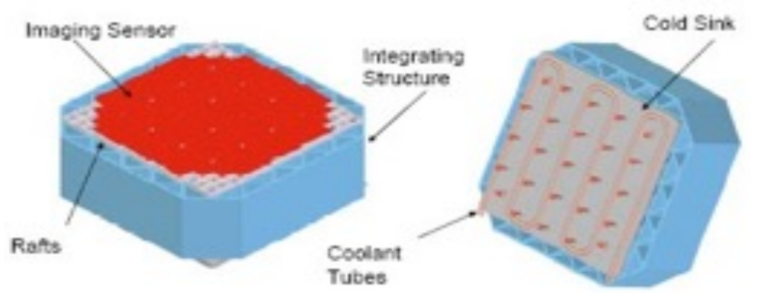
Large Synoptic Survey Telescope

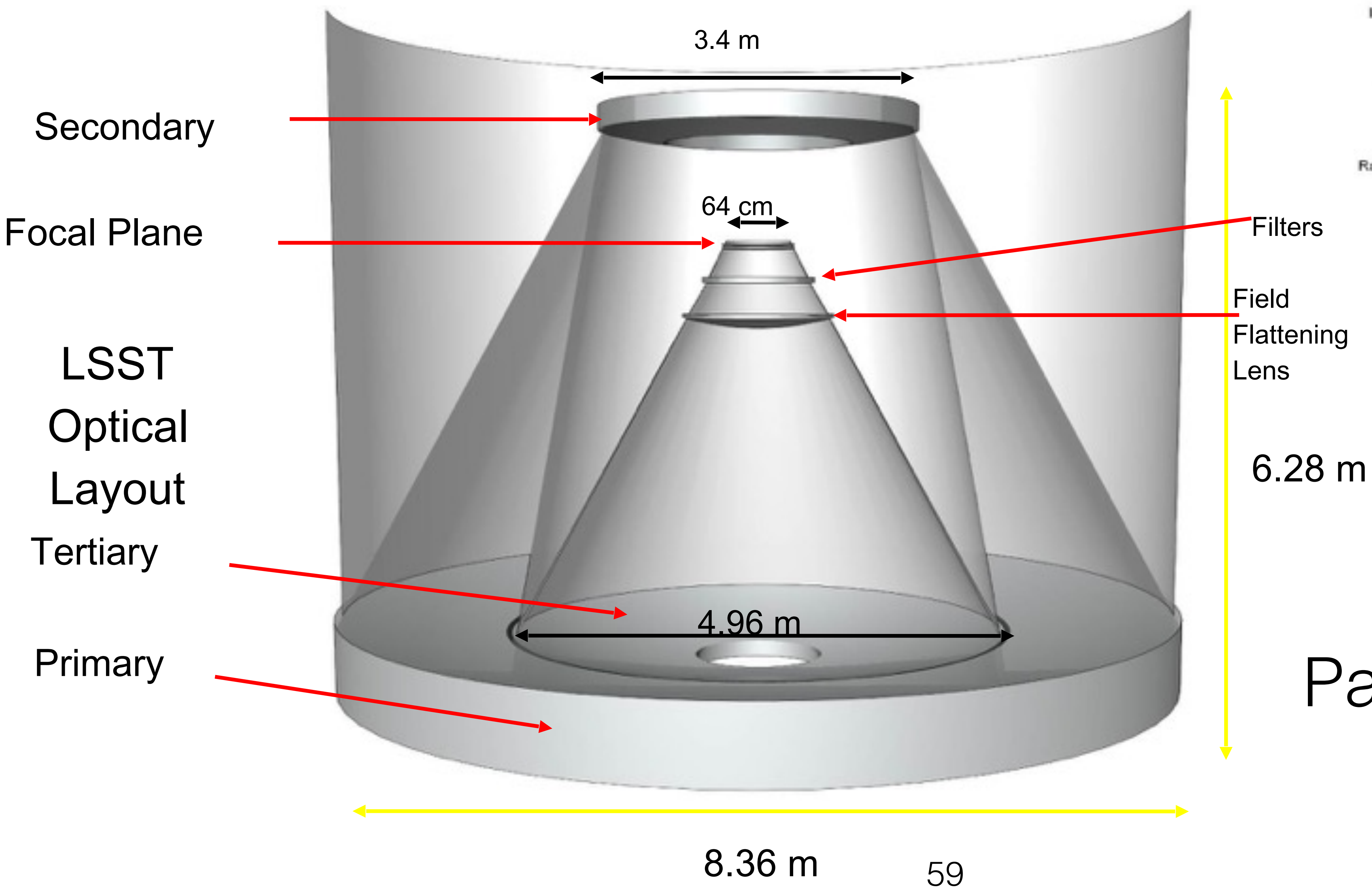
200 4k x 4k detectors



3.5° field of view for all-sky survey

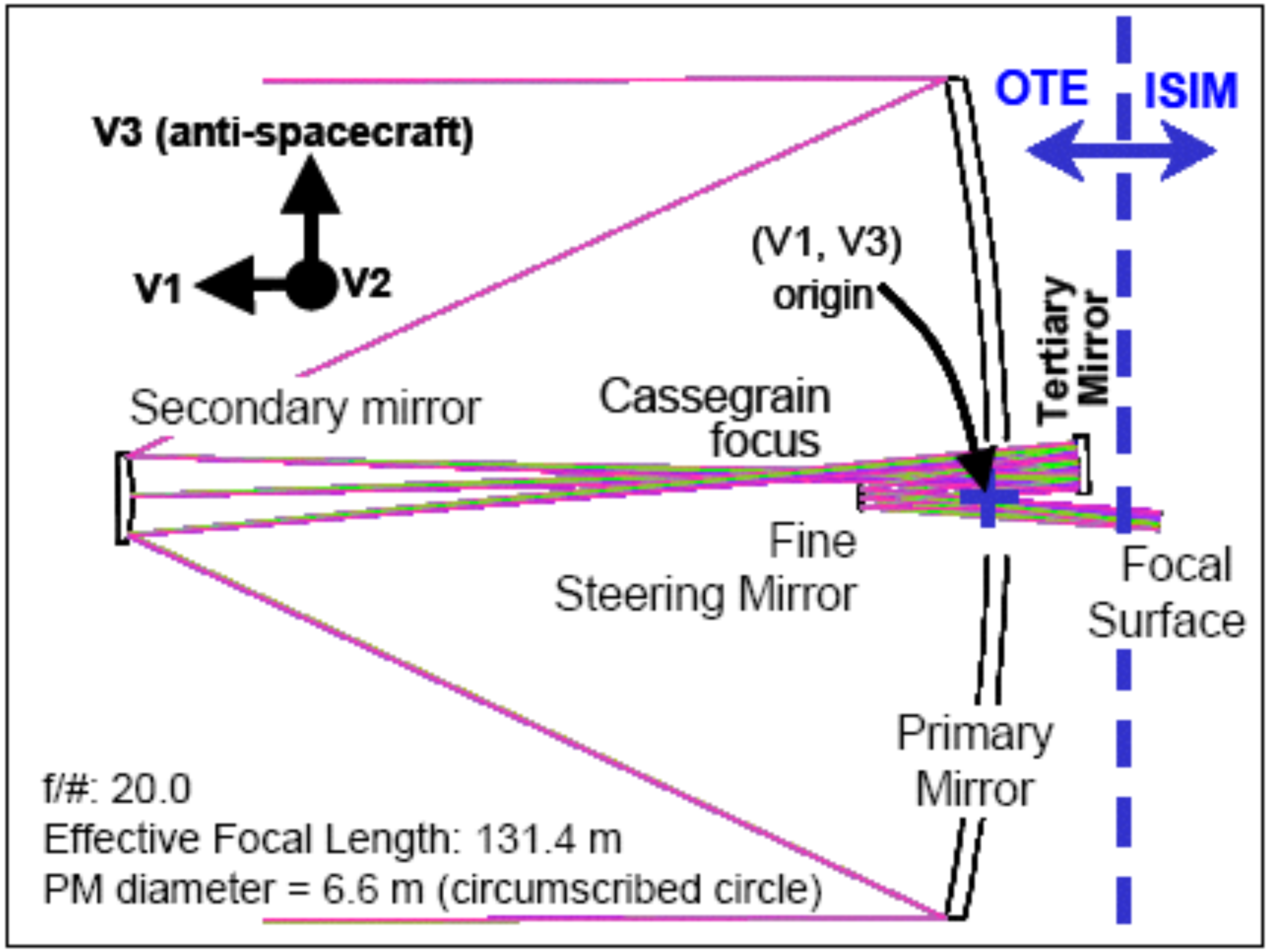
Primary and Tertiary mirrors to be made at Arizona *on the same substrate*



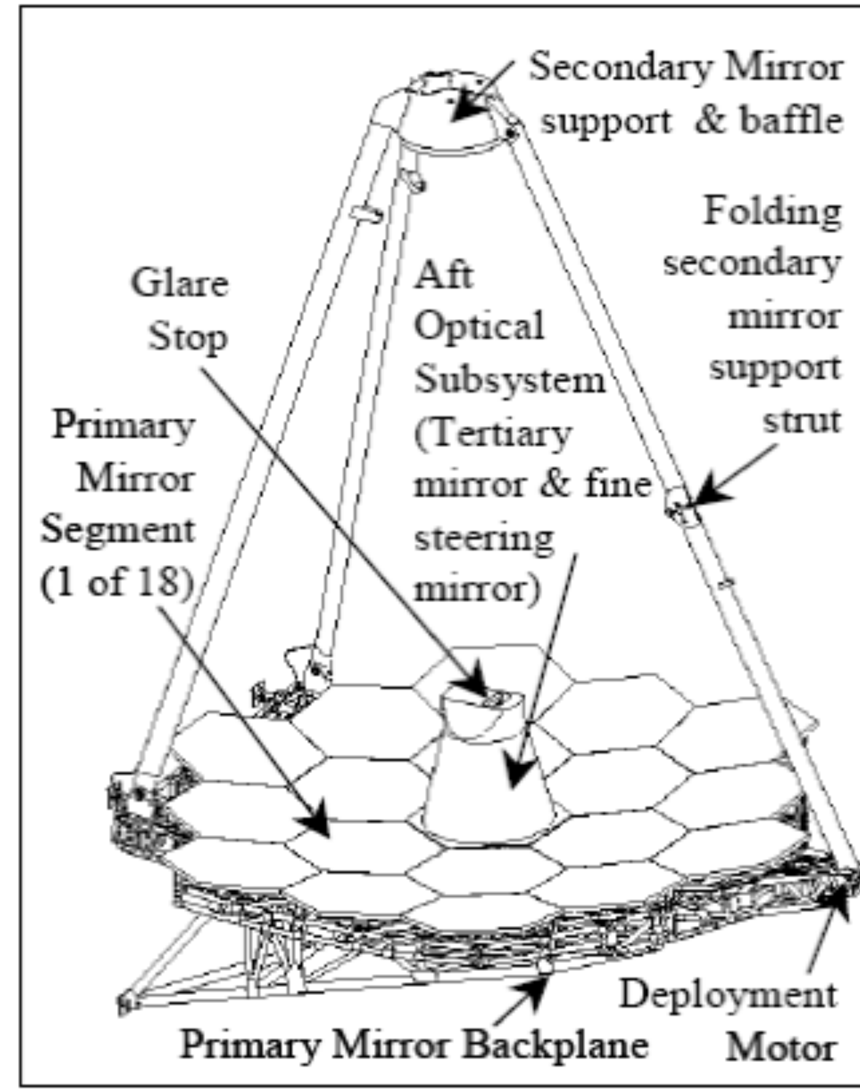


Paul-Baker Design

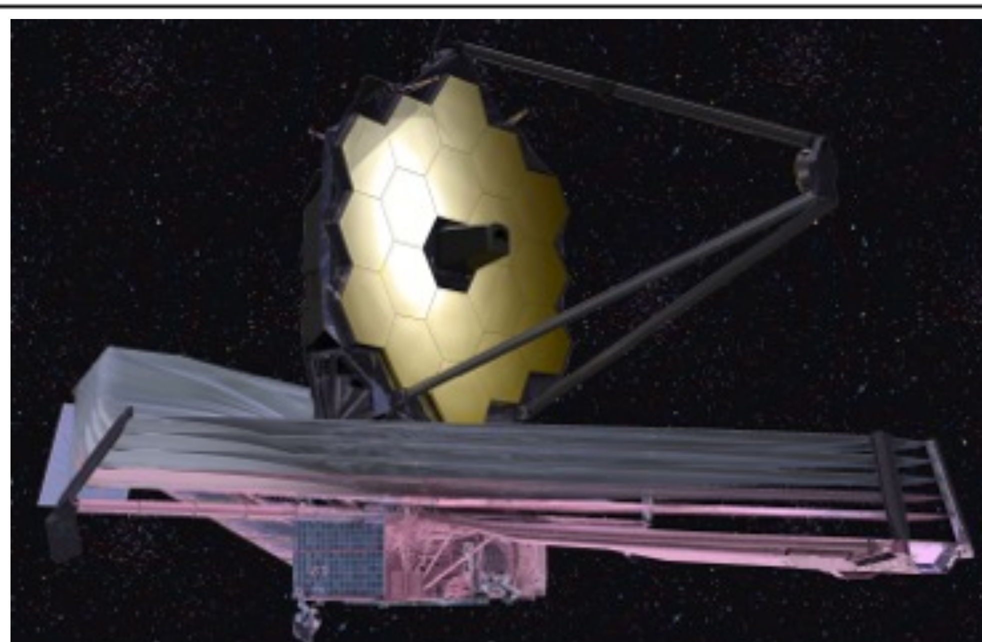
JWST TMA

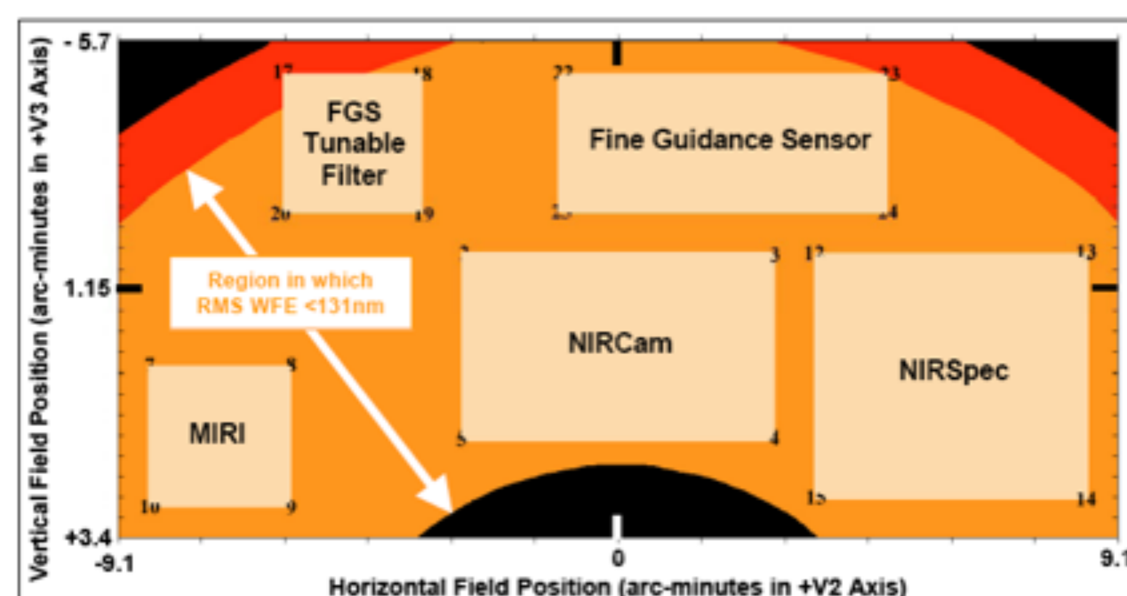


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)



Secondary Mirror
support & baffle
Folding
secondary
mirror
support
strut
Glare
Stop
Aft
Optical
Subsystem
(Tertiary
mirror & fine
steering
mirror)
Primary
Mirror
Segment
(1 of 18)
Deployment
Motor
Primary Mirror Backplane





FGS
Tunable
Filter
Fine Guidance Sensor
Region in which
RMS WFE <131nm
NIRCam
NIRSpec
MIRI
- 5.7
1.15
+3.4
-9.1
0
9.1
Vertical Field Position (arc-minutes in +V3 Axis)
Horizontal Field Position (arc-minutes in +V2 Axis)

Optical quality ↔ Image quality

How good does the telescope primary mirror need to be ?

Ground-based telescopes:
Optics need to produce an image which is sharper that the atmosphere delivers
In optical, very good site / very good night: seeing = 0.3”
On large telescope (8m), this is equivalent to ~1 μm of wavefront error (0.5 μm on the mirror surface)
→ Primary mirror surface should be good to ~100nm
for high spatial frequencies, this is achieved through figuring and polishing of the surface
for low spatial frequencies, this is achieved by active optics

Space-based telescopes:
Optics need to produce a diffraction limited image
In optical, mirror surface should ideally be ~1/40 of a wave (1/20 of a wave wavefront) ~ 10nm

Note: for some applications (wide field imaging for example), the telescope may not be required to reach diffraction limit
Example: Kepler telescope (NASA), 0.95m aperture, but 10” size image. Does high precision photometry of stars to detect planetary transits.

Challenges associated with large telescopes:
Maintaining optical surface on large primary mirror

Larger size requires fundamental changes in the telescope design
Maintaining good optical surface on large telescopes cannot be achieved passively, as it used to be done on small telescopes

Plate stiffness:

$\underline{D} = E/(1-v^2) \times (t^3 / 12)$
E = Young's modulus
t = plate thickness
v = Poisson's ratio

Mirror surface deformation is proportional to $q\ (N/A)^{-2}\ \underline{D}^{-1}$
$q = \rho t$ = areal density (proportional to t for simple plate)
N/A = actuator density (number of support points N per unit area A)

For a simple plate and a fixed number of support points:
N/A goes as power -2 of telescope diameter D
$\underline{D}$ goes as t^3 → deformation goes as : $D^4 \times t^{-2}$

Keeping the deformation constant requires $t \sim D^2$
A **1m diameter mirror, 10cm thick** would have the same deformation as a **5m diameter mirror with a 2.5m thickness**
Large mirror mass → even larger telescope structure mass