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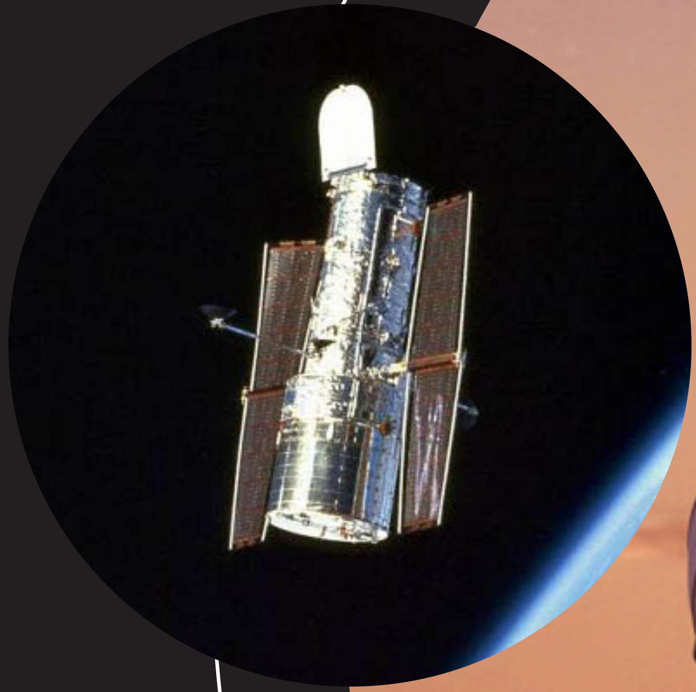

Telescope Fundamentals

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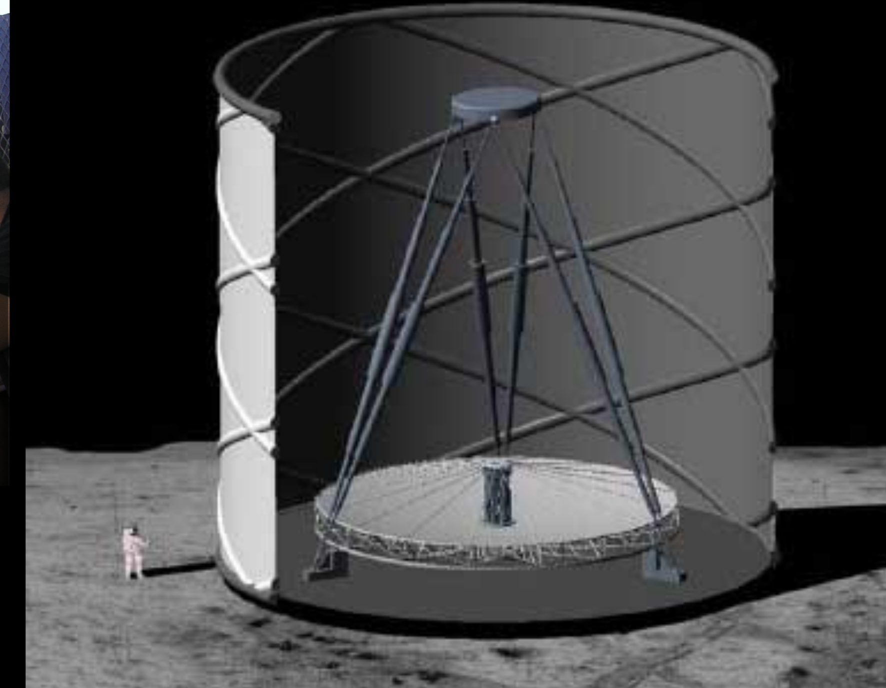
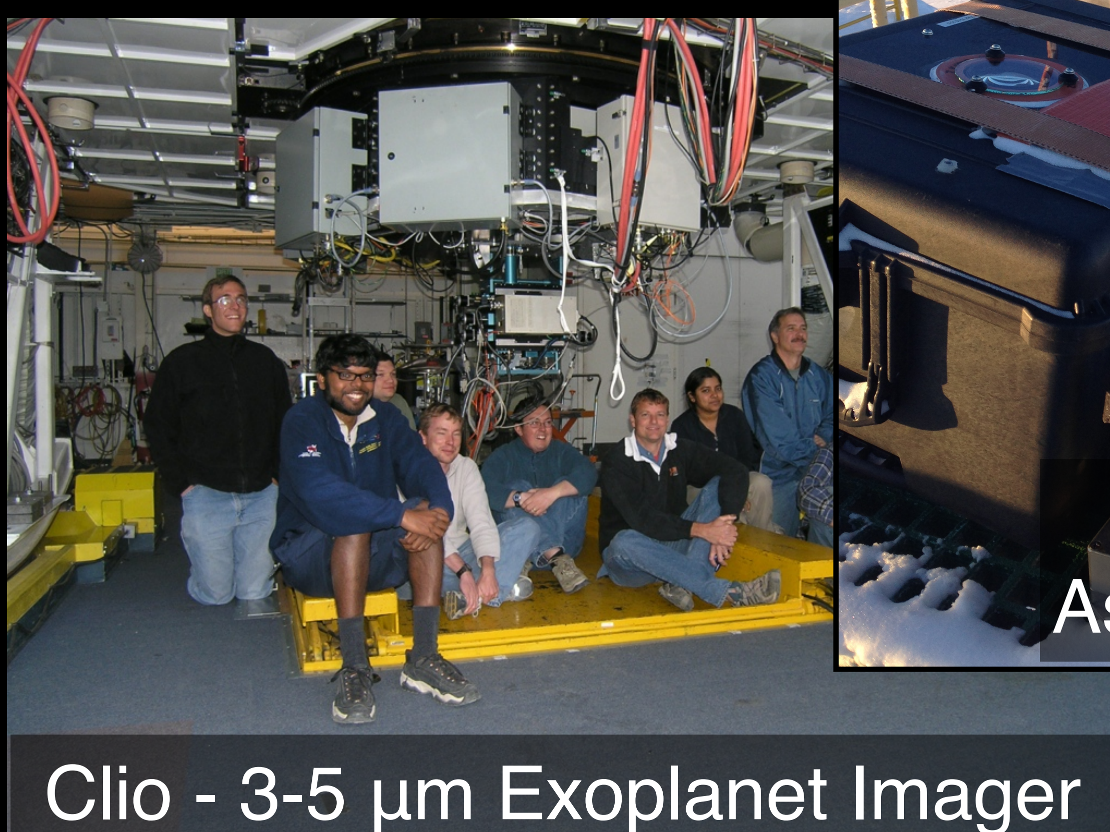
6m Large Zenith Telescope

High Concentration Solar Power Generator

20-100m Lunar Liquid Mirror Telescope

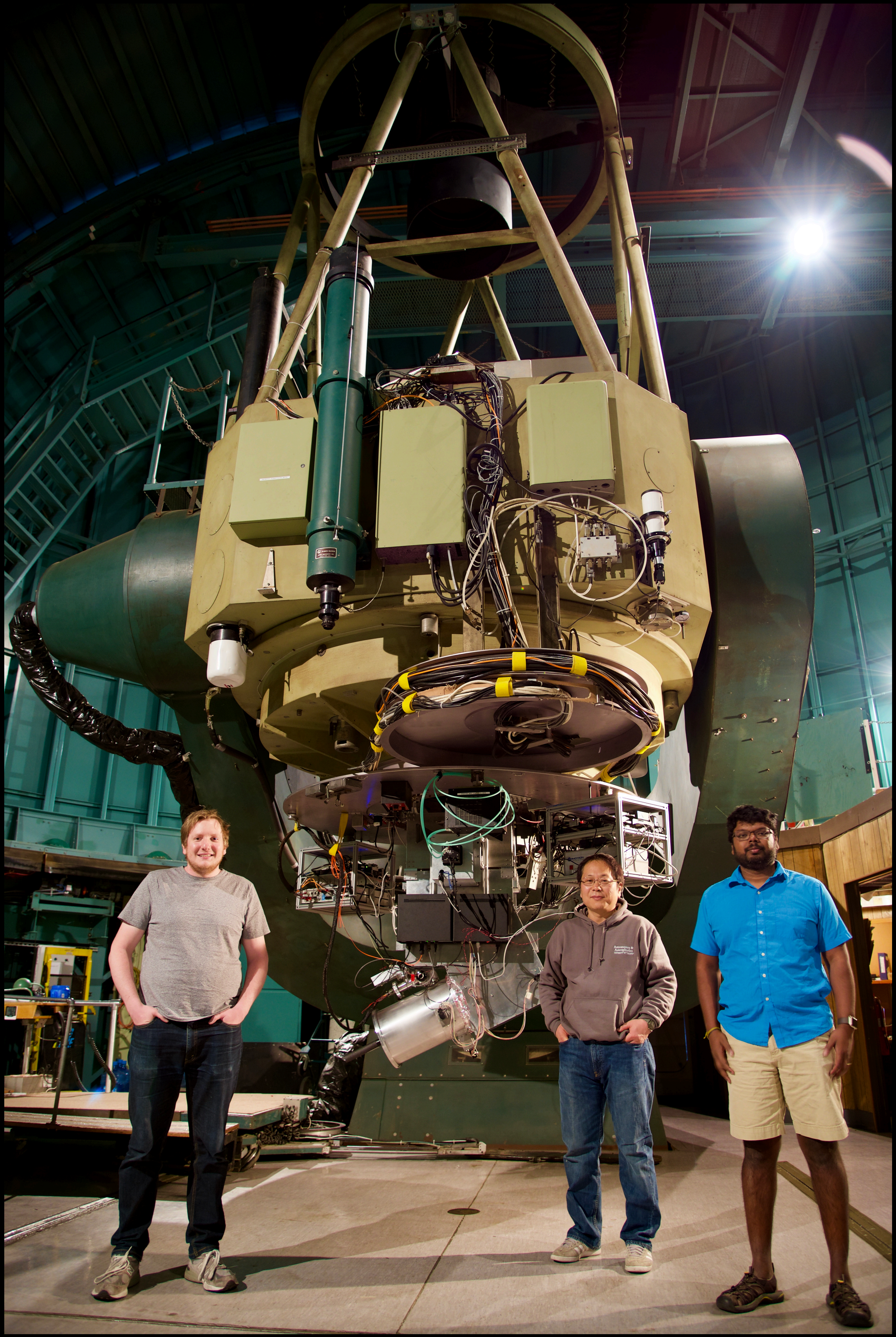




Clio - 3-5 µm Exoplanet Imager

Arctic Astronomy

Lockheed Arizona IR Spectrometer



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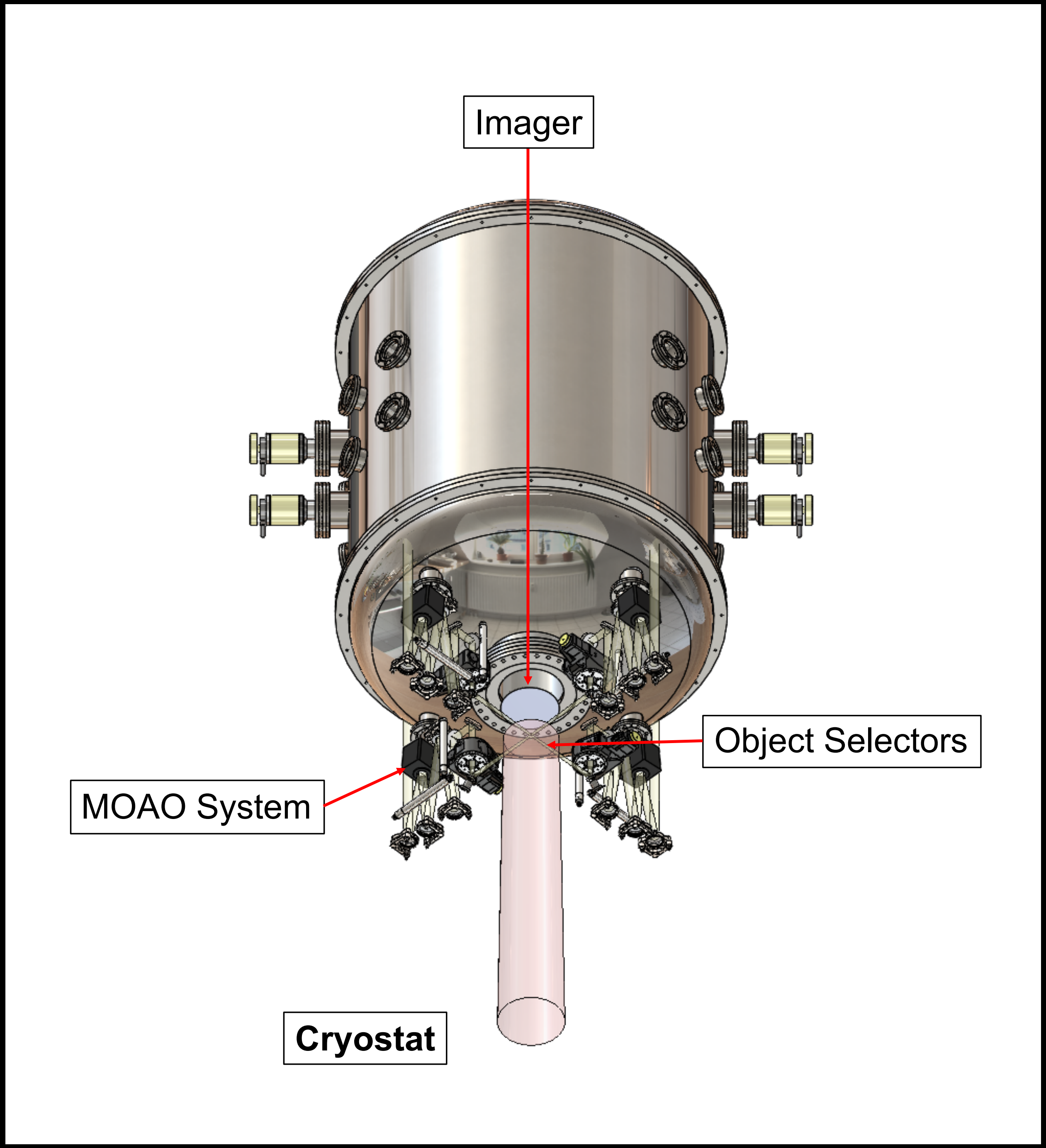
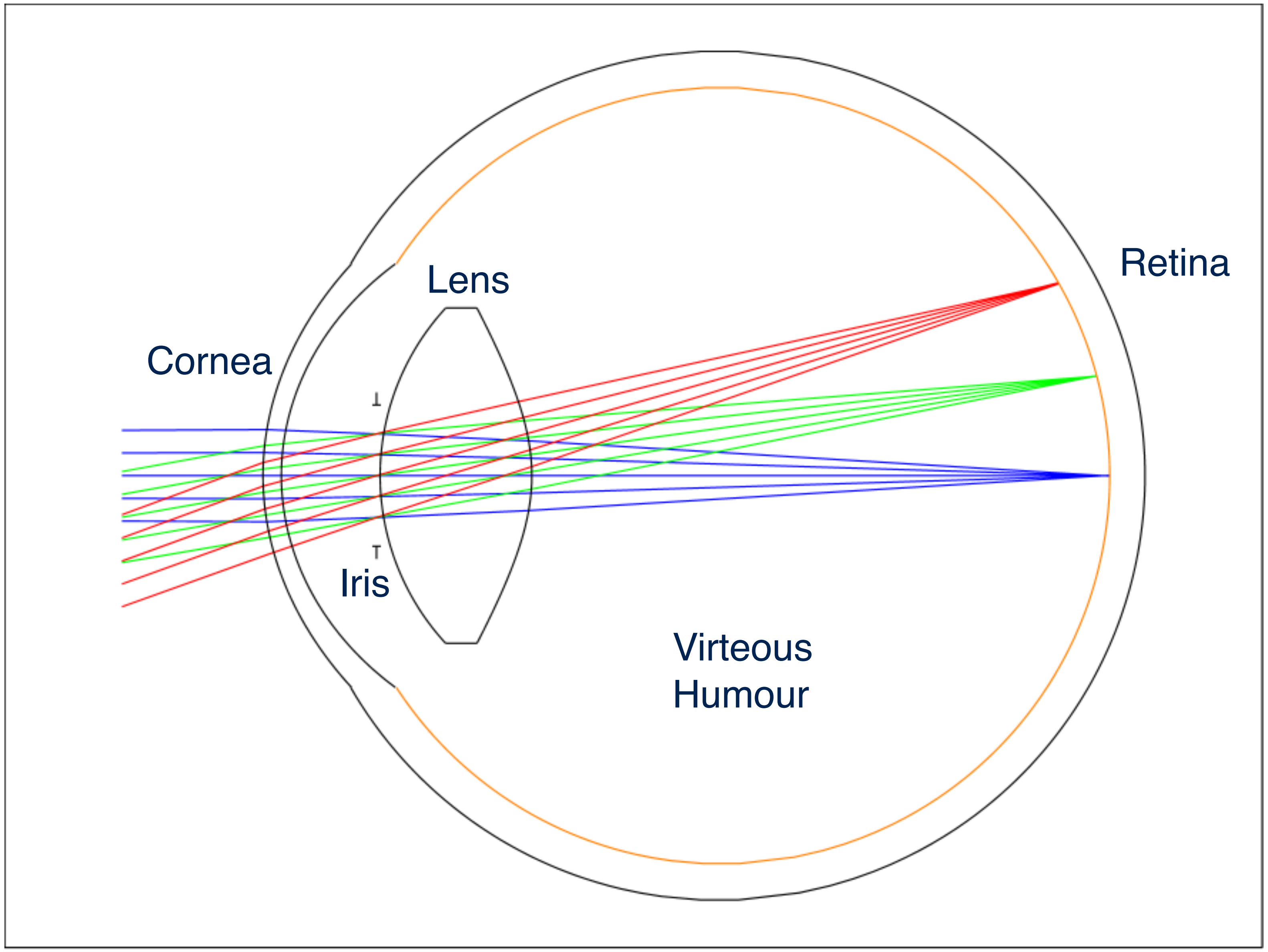


GIRMOS

Outline

- What does a telescope do?
  - Properties and Goals
- The development of the telescope
  - Refractive and Reflective Approaches
- Modern telescope and features
- Telescope Optical Design
  - Aberrations
  - Design Examples

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

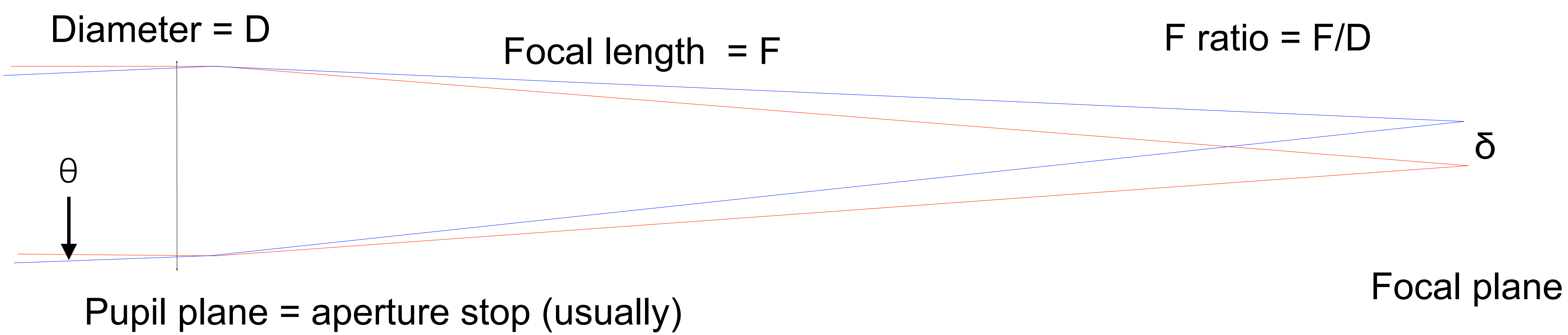
$1 CAD
Loonie

Purpose of a Telescope

- Form an image of a scene at infinity.
    - “Simple” Optics.
- Resolve closely spaced objects.
    - Larger “baselines” are needed for this.
- Detect faint objects.
    - Larger collecting area is needed for this.
- Form images of many objects at once.
    - Multiplexing advantage.

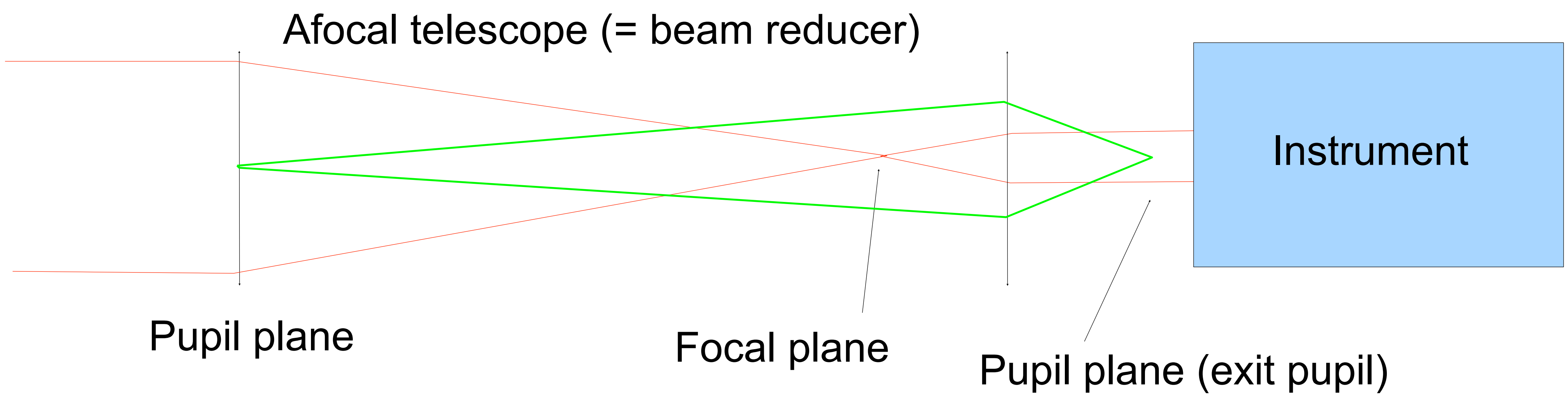
- Be a platform for a broad range of research instruments.

Telescope Principles



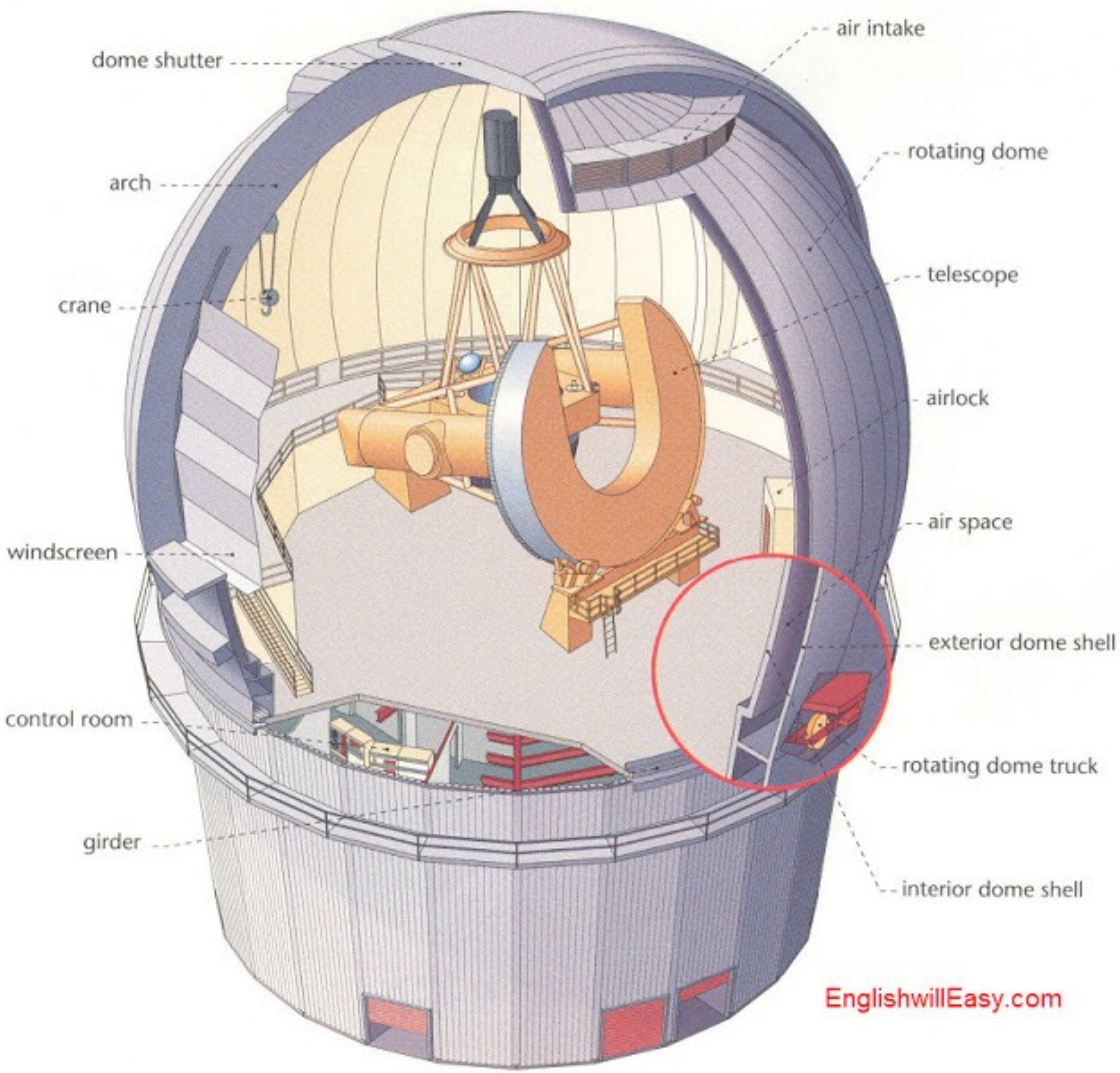
- F determines the pixel scale at the focal plane (the ratio between the angle on the sky and the physical dimension on the detector)
  - $\delta = \theta \times F$ (Suppose at 8.4-meter with an f/15 focal ratio, what is F?)
- The focal ratio gives the size of the diffraction limit on the focal plane/detector.
  - $x = F/D \times \lambda$

Mating Telescopes with Instruments

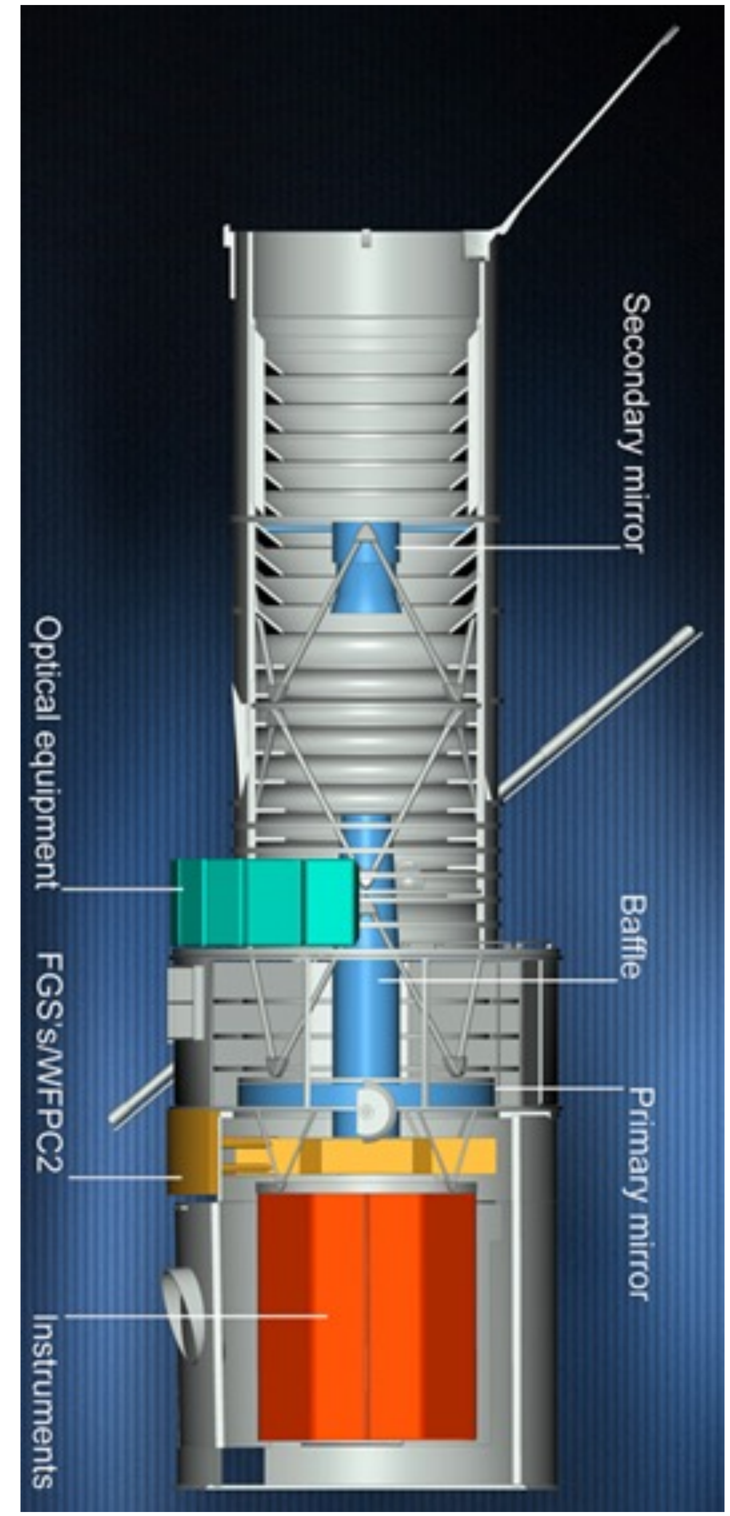


- Telescopes are often just the first stage in a more complex optical system (the instrument).
- Initial telescopes were designed to use the human eye as an instrument so they had an afocal design.

Primary Components for Telescopes



Canada France Hawaii Telescope



Hubble Space Telescope

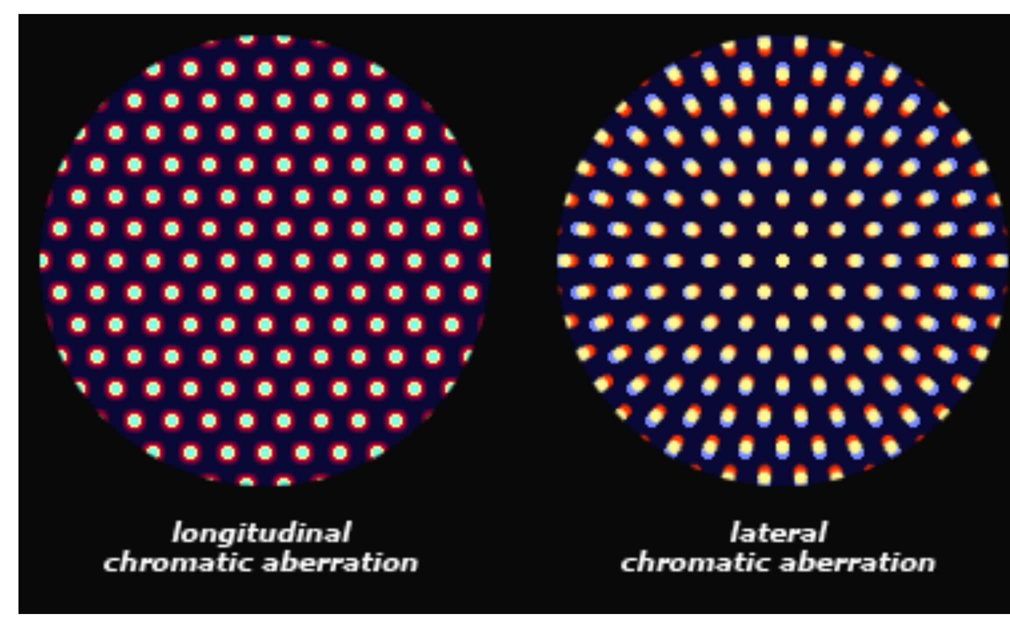
Telescope Development

Galileo's telescope (1609)

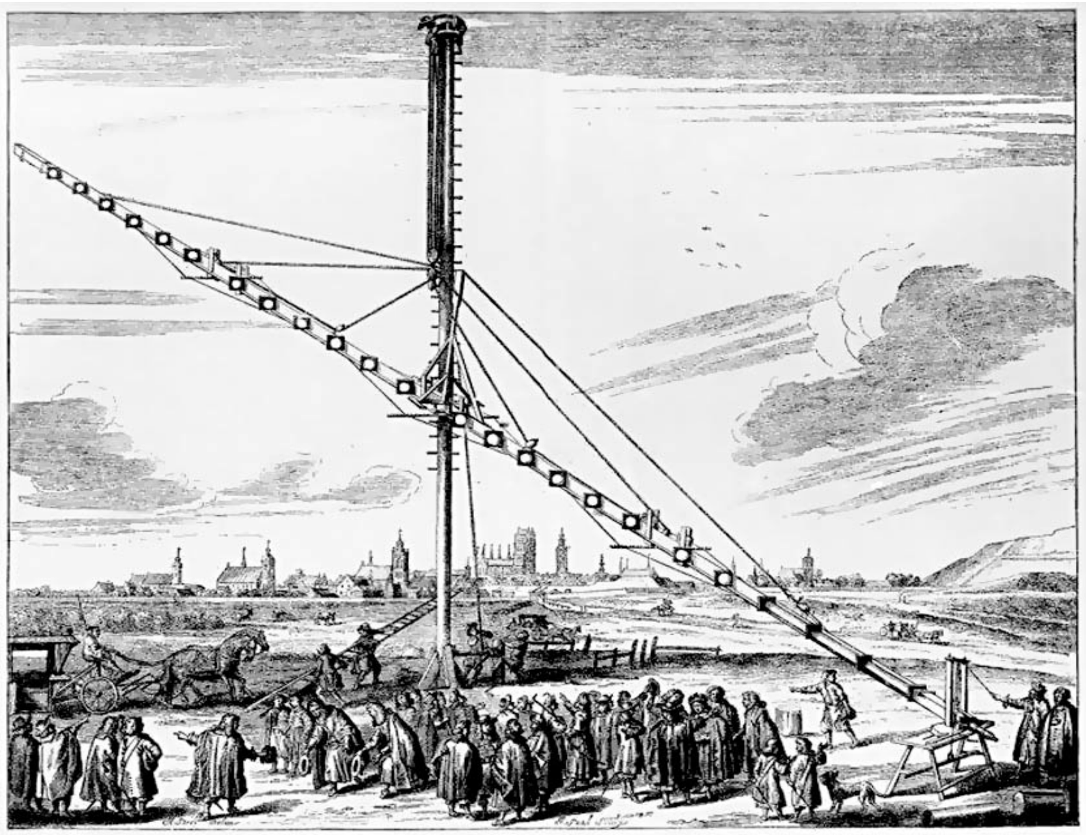
D=37 mm
m=20

Yerkes obs. refractor (1-m diameter, 1900)

- Easiest small telescopes to make are lens-based.
- Chromatic effects limit their usefulness.
  - Achromatic design can increase coverage somewhat.
- Large Refractors become difficult.
  - Edge mounting of lenses makes large (>1 m) optics challenging to hold.
  - The large optic needs to be at the top of a mount -> top heavy.



Lens-Based Telescopes



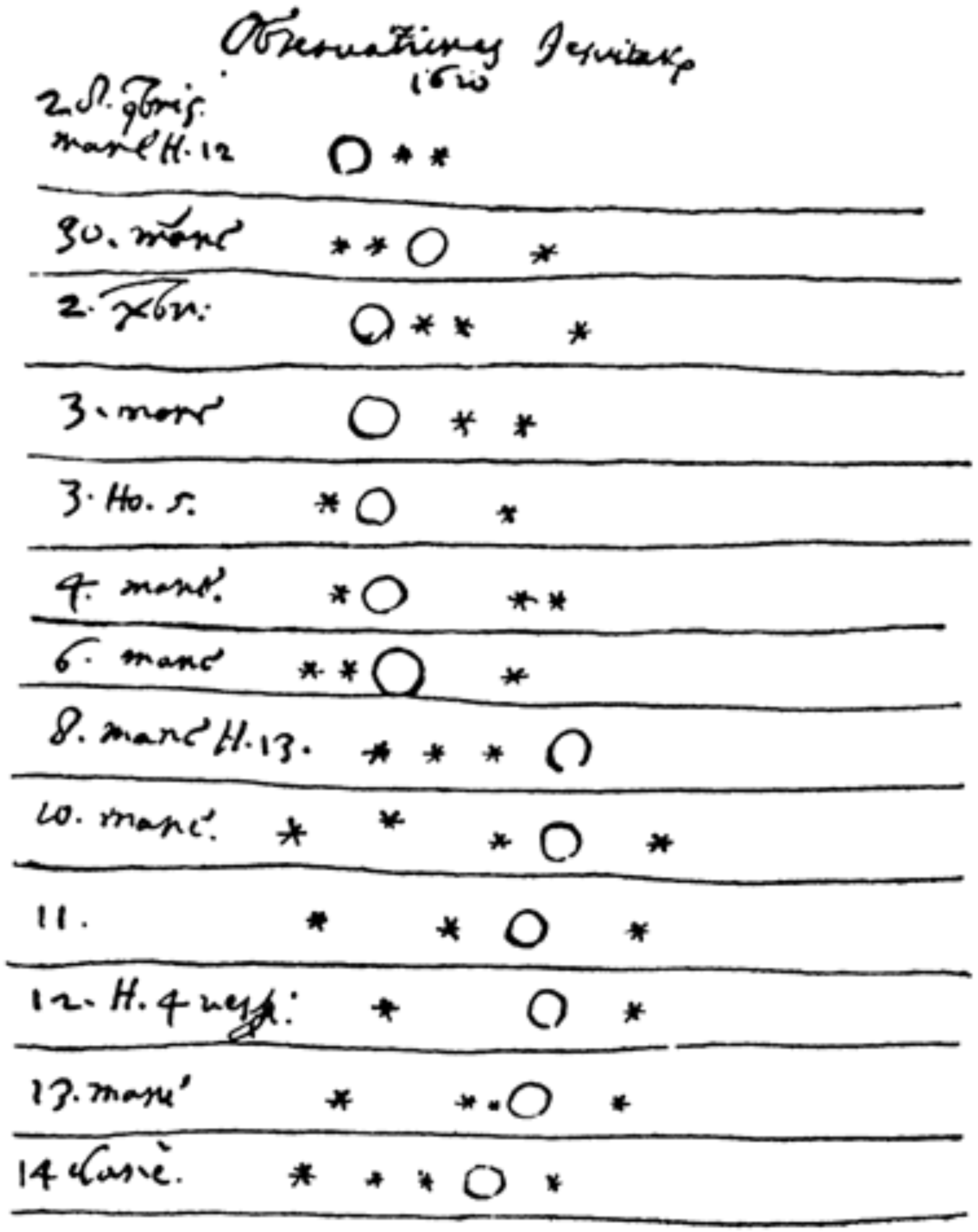
Johann Hevelius 45m long telescope (1673)

Modern wide angle lens

Dragonfly Telescope Array

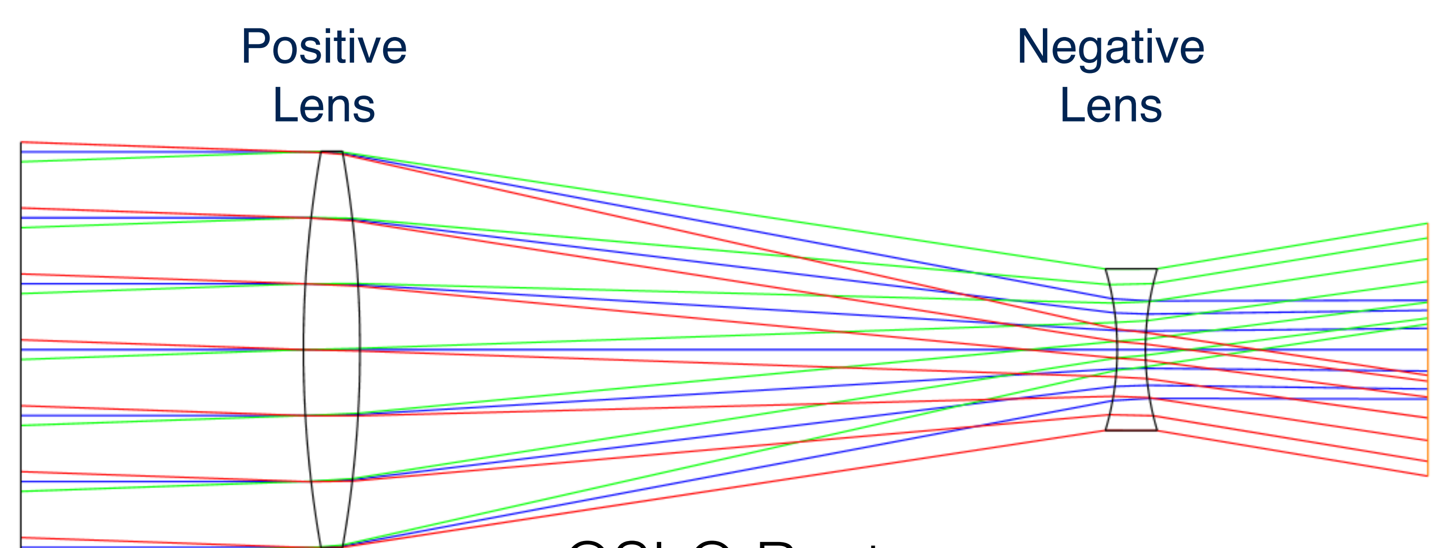
- Chromaticity problem can be mitigated by adopting long focal length.
    - Refracting telescopes used to be very long and narrow field of view
- More recently, developments in lens design and manufacturing technology have led to high quality short refractors
    - Refractors are still used in astronomy for wide field small diameter systems, and the same technology is used to correct for aberrations in wide field reflecting telescopes.

Galilean Telescope



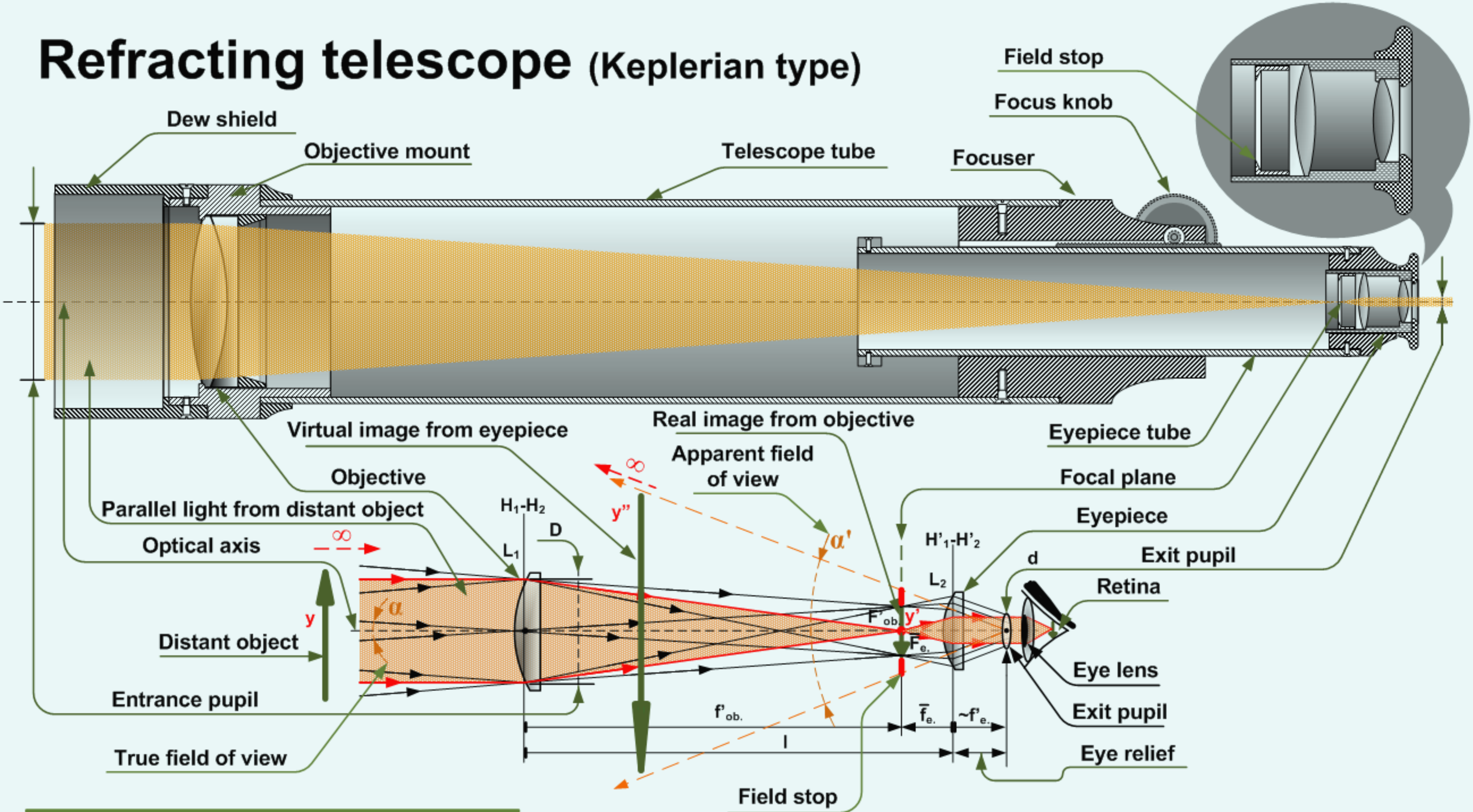
Sketches from Galileo's Notebook
(c. 1610 AD)

- Jupiter's largest moons maximum separation ~2-10 arcminutes; difficult to discern by eye
- Used Galilean afocal telescope to magnify (up to 30x) the Jovian system
- Optical performance relatively poor, but could see phases of Venus, craters on the Moon, and Jupiters moons



OSLO Raytrace

Refracting telescope (Keplerian type)

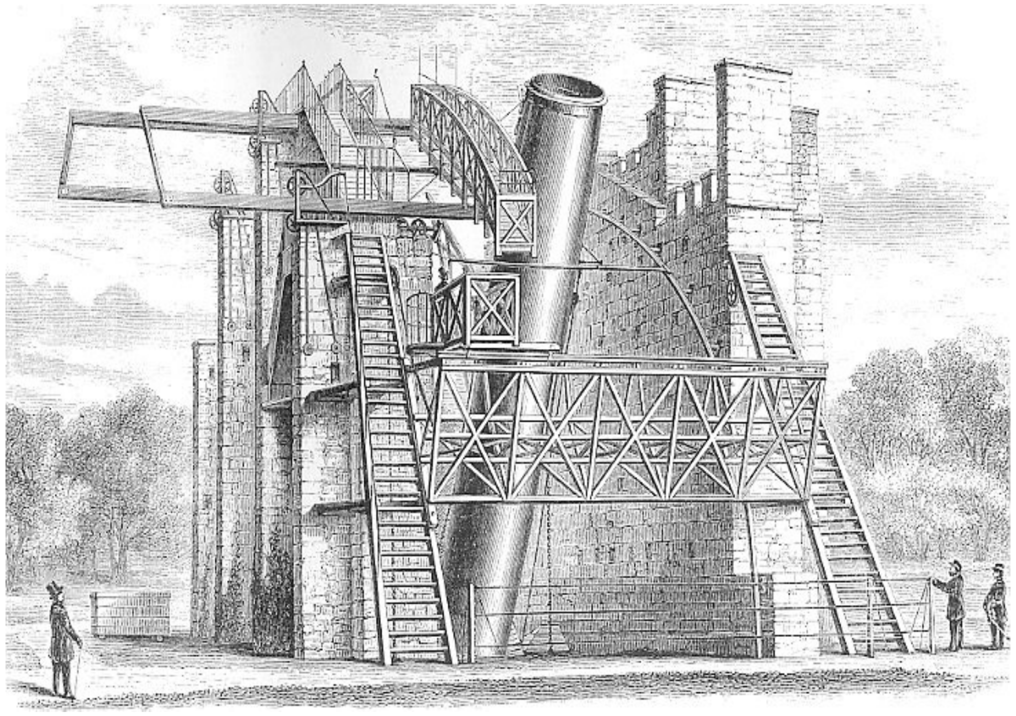


Telescope magnification: $M = \frac{tg\alpha'}{tg\alpha} = \frac{f'ob.}{fe.} = \frac{D}{d}$

Reflecting Telescopes

Newton's telescope (1668-1672)

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



- Reflecting Telescopes have a similarly long history.

Reflecting Telescopes

★ **Challenges:**

- Light bounces back toward the object.
  - Either the focal plane is in front or you need a secondary mirror as well.
- Mirrors have ~4x tighter tolerances than lenses.
  - A bump on a mirror creates: 2h error for a mirror but only h(n-1) error for a lens.
- Mirrors need to be made reflective for high throughput
  - Metal mirror or metal deposited on glass.

★ **Advantages:**

- Achromatic by design.
  - More broadly usable than refractors.
- Scales better to larger apertures. Mirrors have ~4x tighter tolerances than lenses.
  - Mirrors can be held from the bottom and can be made thin with active supports.
  - All the weight is at the bottom of the tube.
  - A single element system can be made relatively short allowing for smaller enclosures…

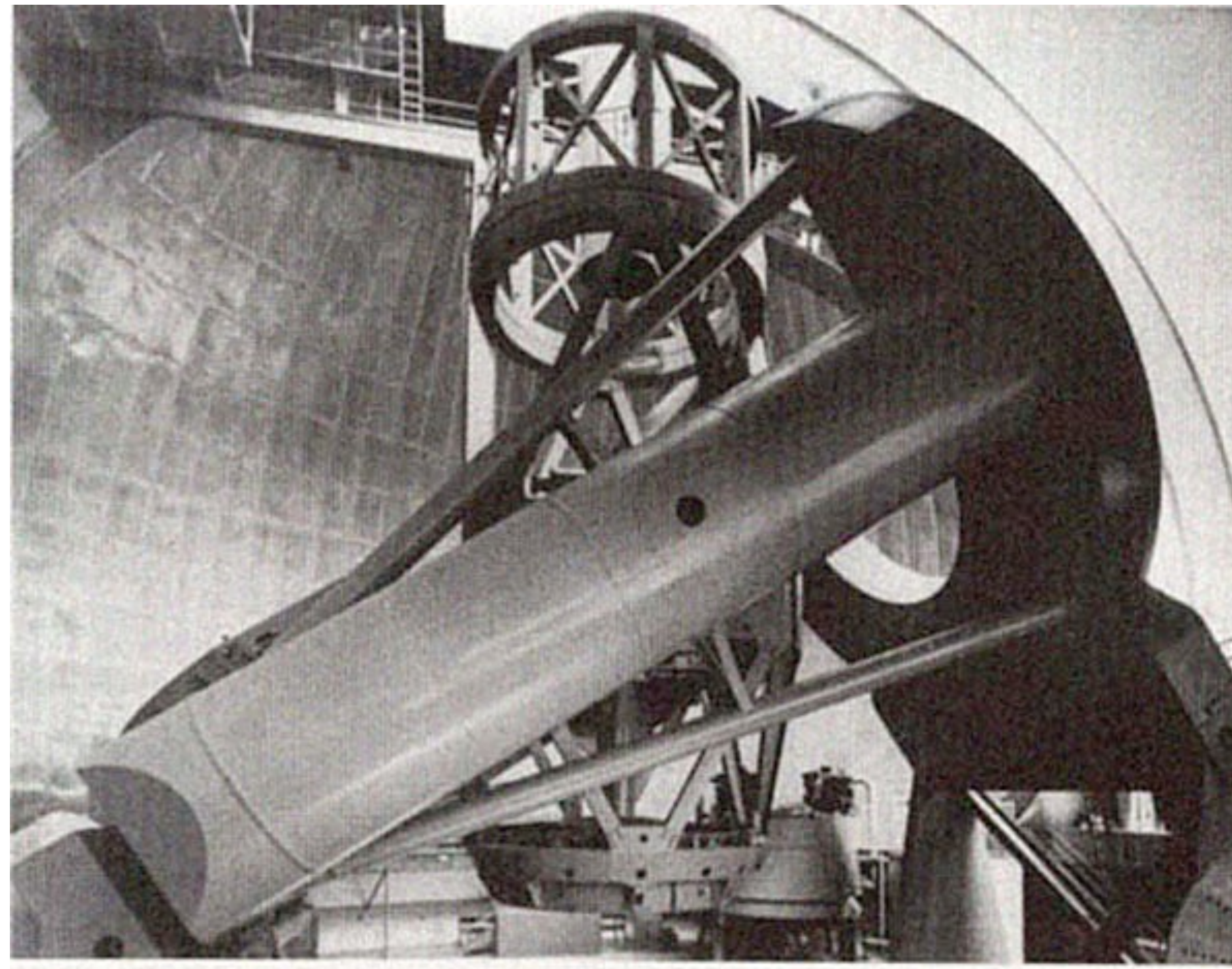
Tracking the Stars

Long exposures require a mount that can track the stars across the sky.

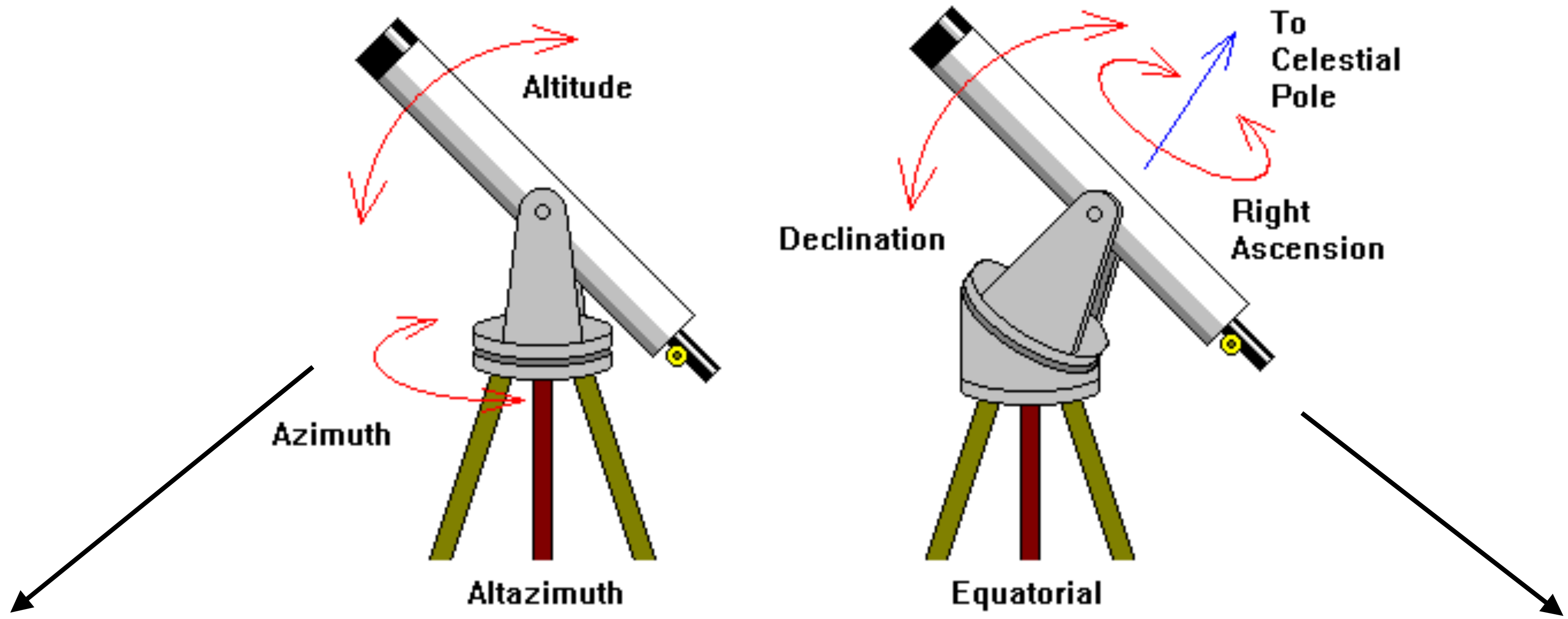
Early-mid 20th century telescopes were all equatorial mounts.

Almost all modern large telescopes are elevation-azimuth mounts.

Telescopes can often track within <0.1” with a closed-loop guiding system



Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.


Altitude
Azimuth
Altazimuth
Declination
To Celestial Pole
Right Ascension
Equatorial


Keck 10-meter Telescopes
Hale 5-meter Telescope
Domes Shown To Scale!

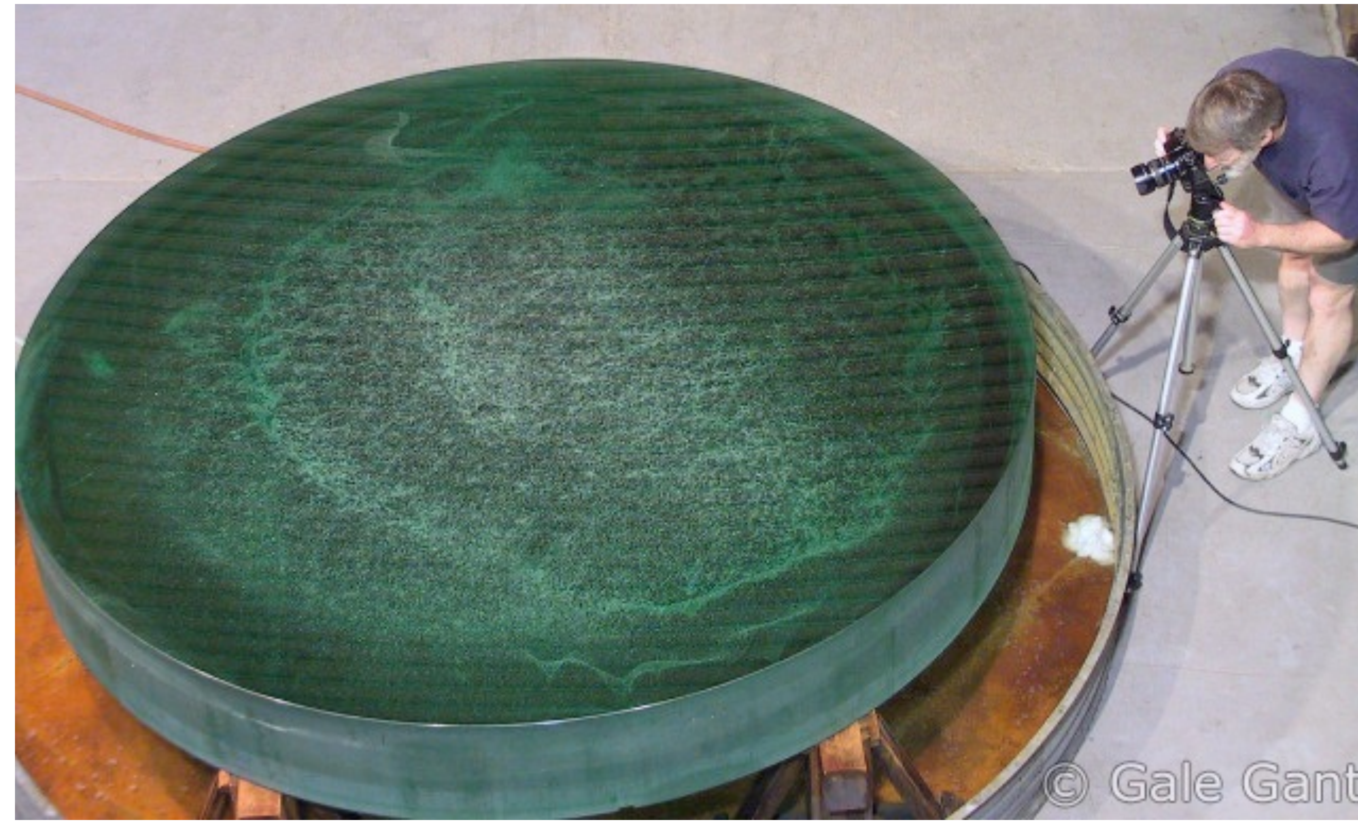
Primary Mirror: Big and Fast

The primary mirror size determines how many photons a telescope receives.

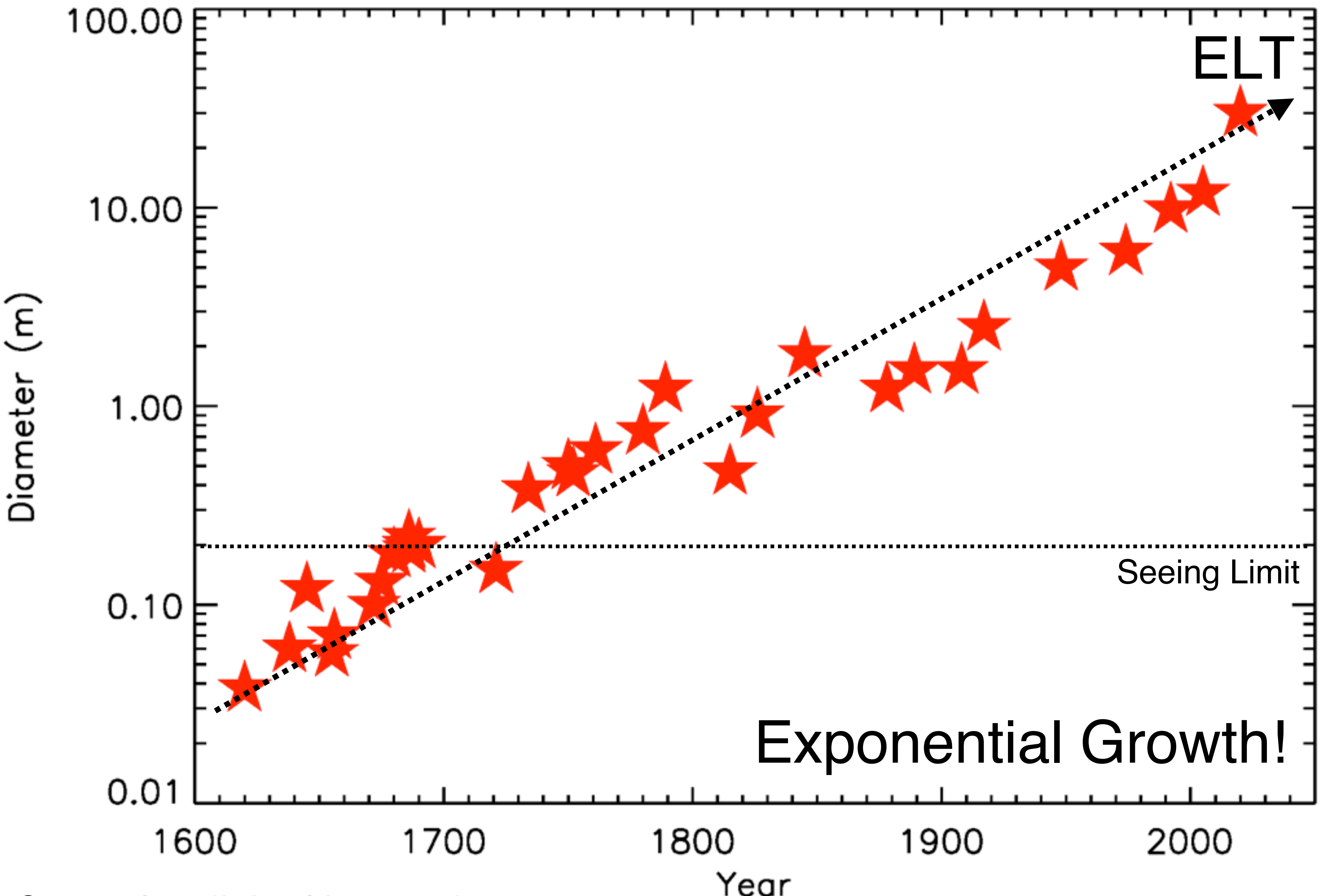
A larger telescope can also (in principle) form a sharper image.

Diffraction limit:

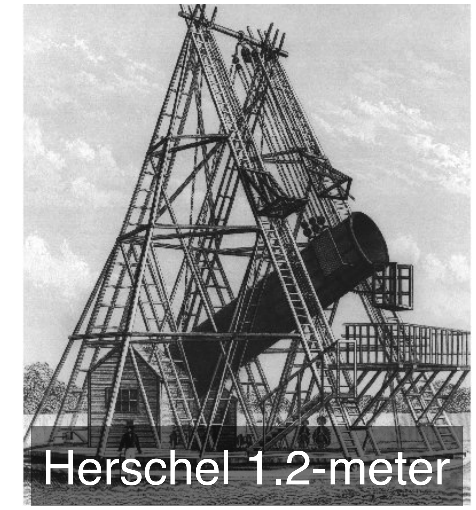
$\theta \sim \lambda/D$

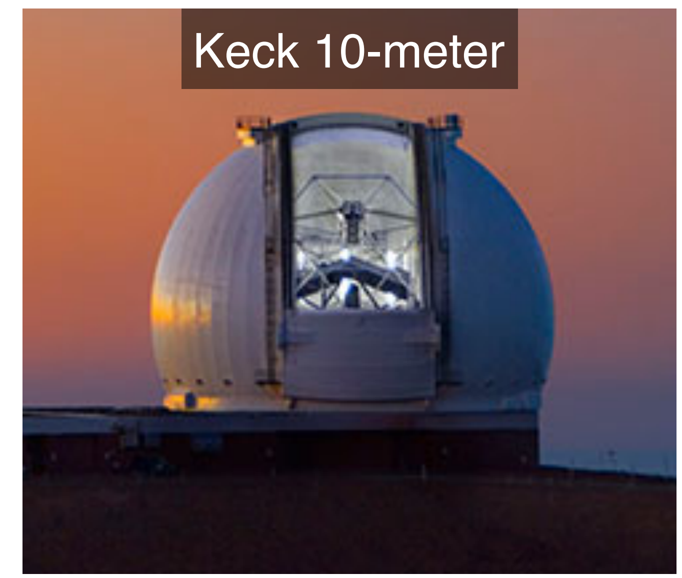


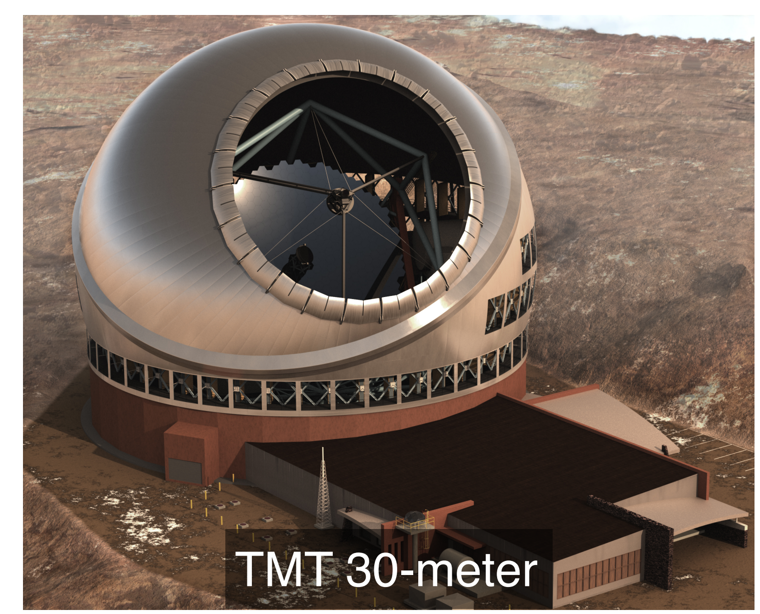
Explosive Growth in Ground-Based Optical/Infrared Telescopes



Source: http://stjarnhimlen.se/

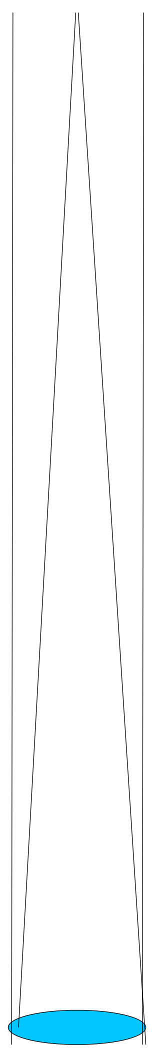




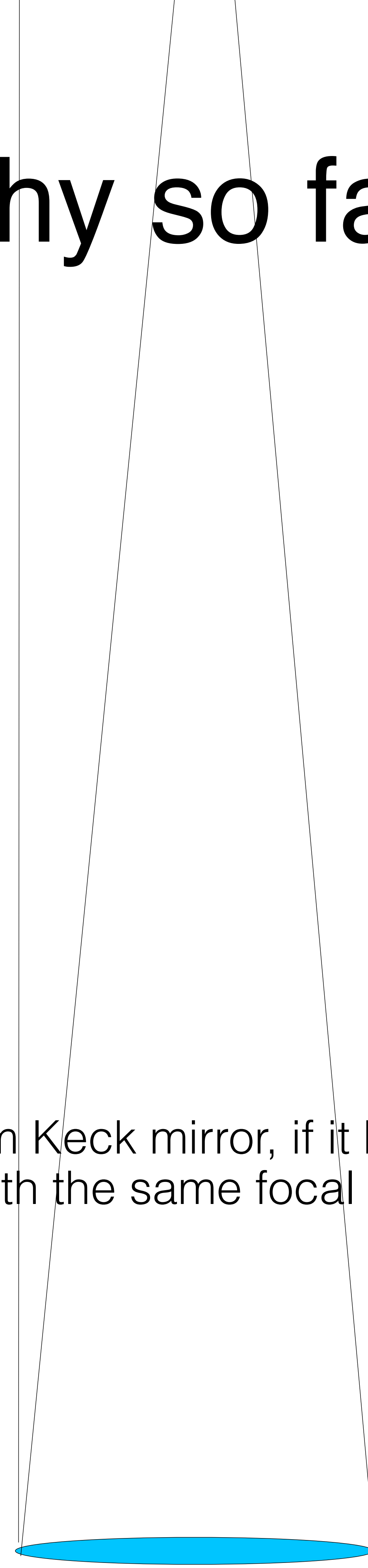


Why so fast?

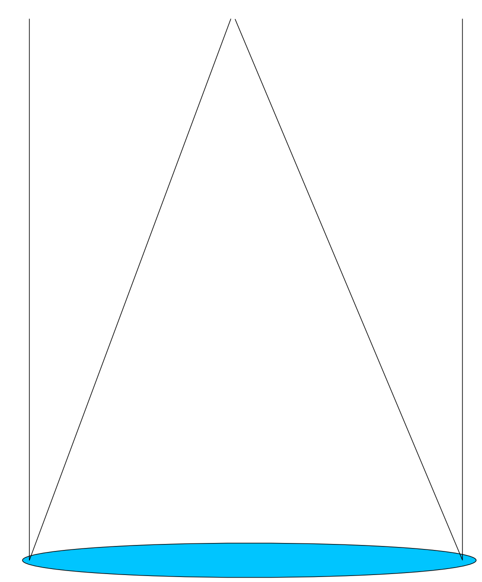
The Hooker 2.5 m with an f/5 Primary mirror.



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

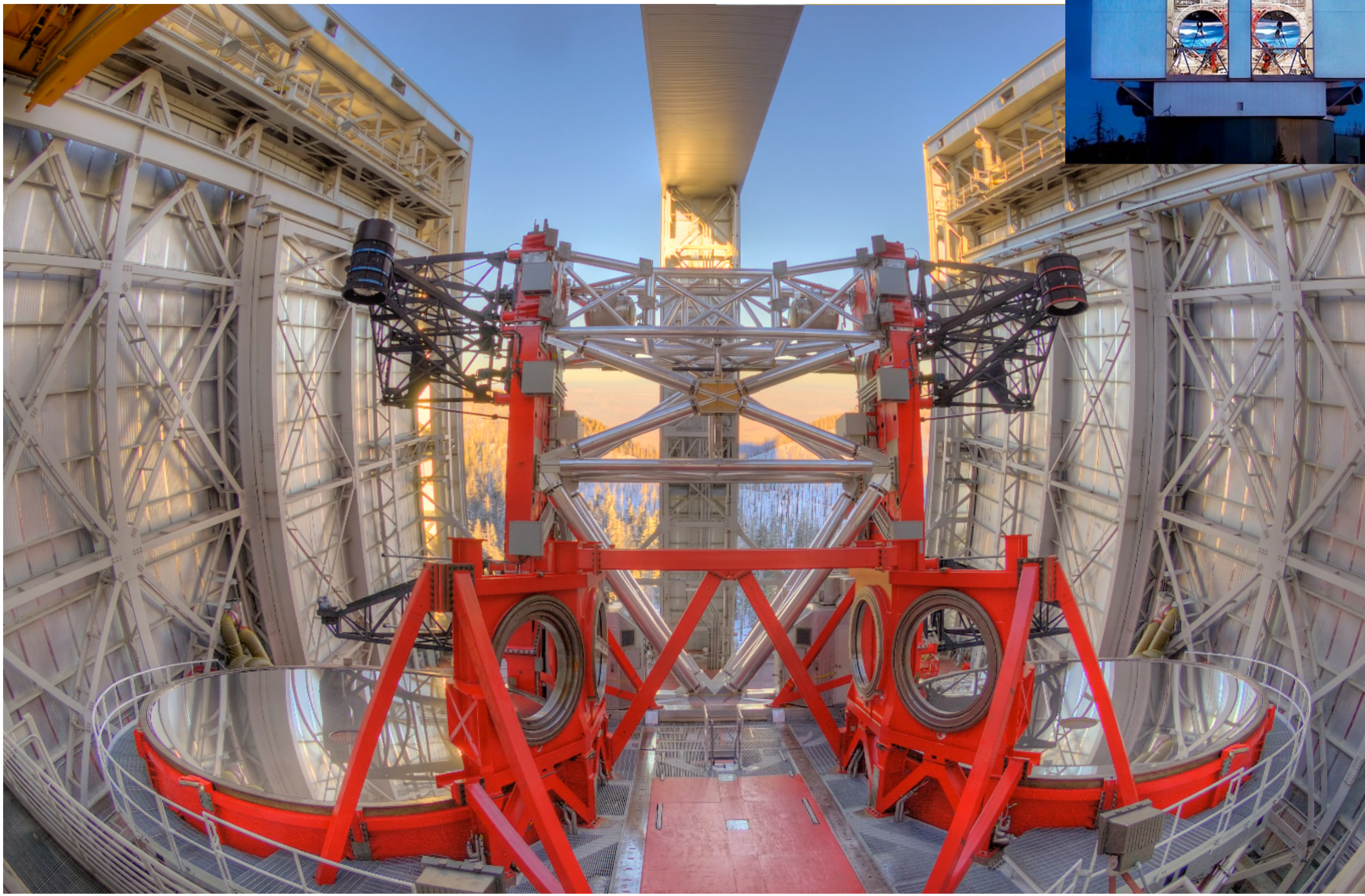


The Keck mirror, as designed with an f/1.75 primary.



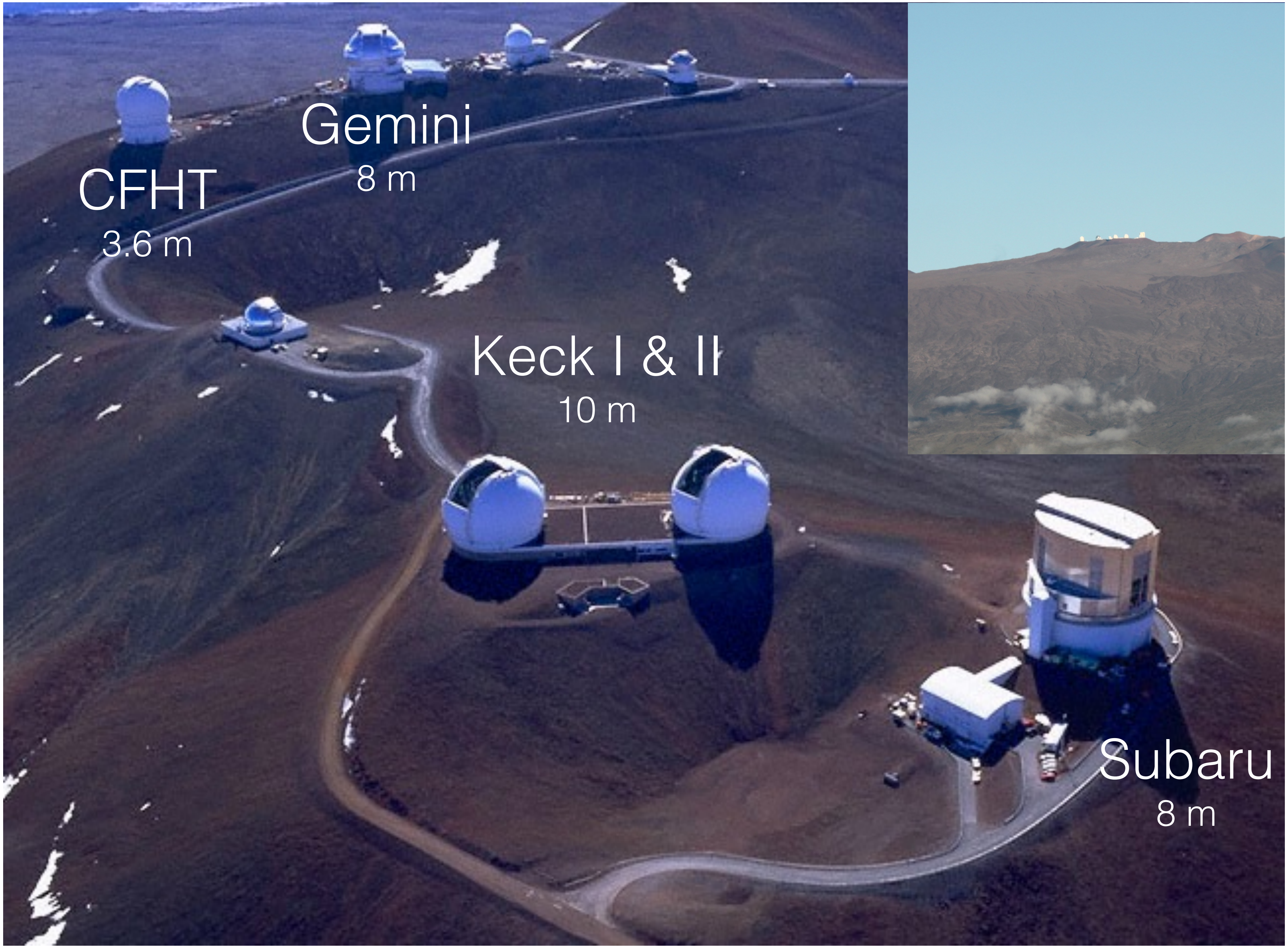

Keck 10-meter Telescopes
Hale 5-meter Telescope
Domes Shown To Scale!

Modern reflecting telescopes (glass mirrors)



Large Binocular Telescope (LBT) @ Mt. Graham, AZ, USA: 2 x 8.4 m

Very Large Telescope (VLT) @ Paranal, Chile : 4x 8 m + 1.8m aux. telescopes

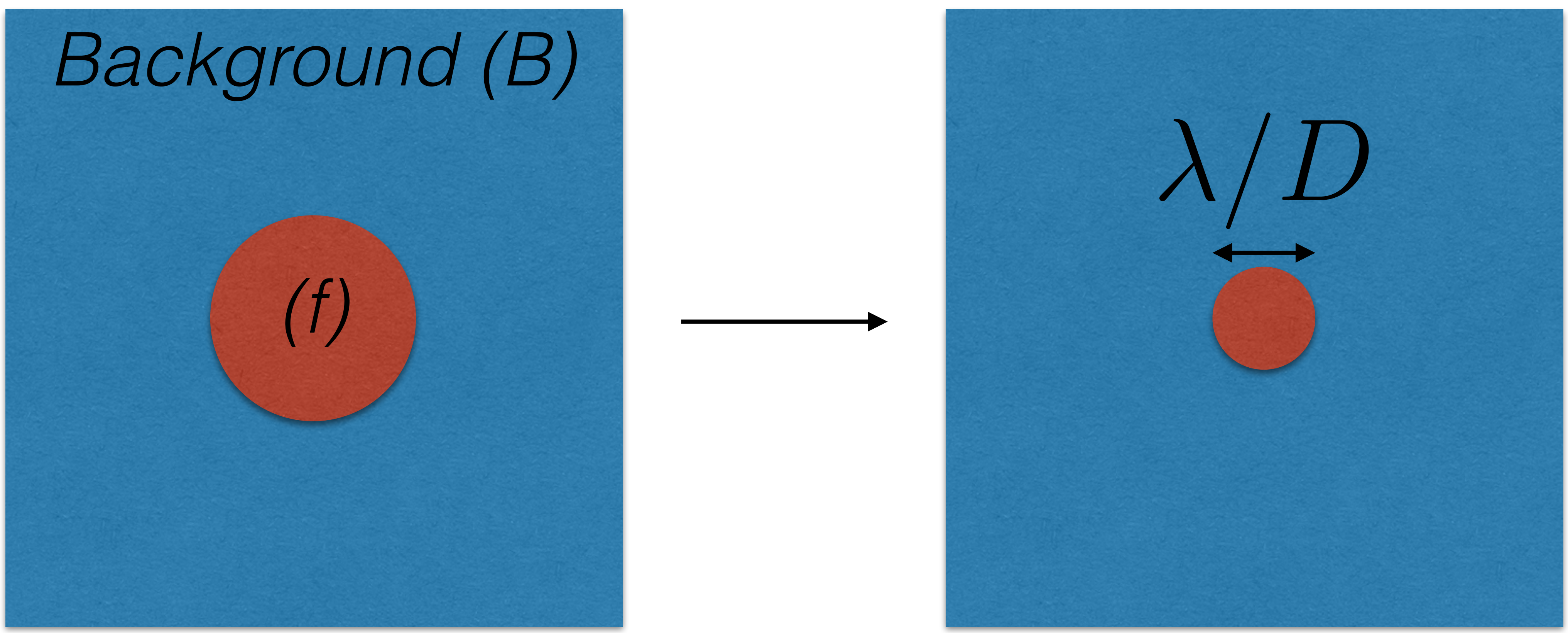


Mauna Kea, Hawaii, USA

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

Why build large telescopes?

Consider the diffraction limit of telescopes



Telescope 2x bigger

$$SNR = \frac{f * A_{tel} * t}{\sqrt{A_{tel} * t * (f + B * A_{src})}}$$

Background-limited case

$$t \propto 1/D^4$$

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/adaptive optics 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

Challenges associated with large telescopes: Thermal issues for a large primary mirror

A difference in temperature between the mirror and ambient air is bad for astronomy: it creates turbulence just above the mirror and makes the image less sharp

PROBLEM: the air temperature is constantly changing, and the mirror needs to follow it closely
→ thermal time constant for the mirror needs to be short
→ thick massive mirrors are problematic!

SEEING AT CFHT 1027

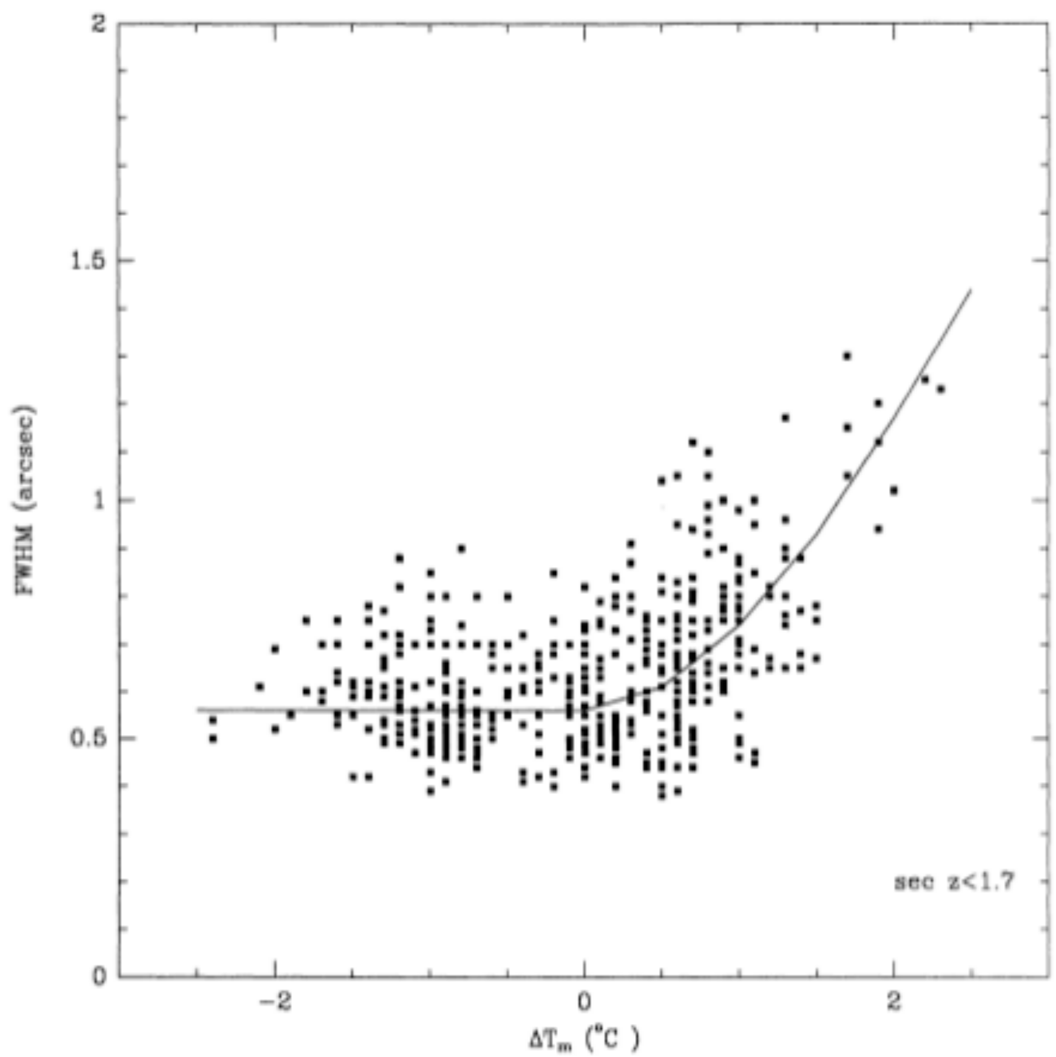


FIG. 6–Image spread as a function of the mirror-to-air temperature difference. The line is the expected relation for a spread of 0$''$.56 due to optics and average natural seeing and a mirror seeing of 0$''$.40/°C$^{.65}$ when $\Delta T_m > 0$.

Racine et al. 1991 (3.6-m Canada France Hawaii Telescope)

Larger size telescopes were made possible by fundamental changes in the primary mirror design

Honeycomb mirrors

Honeycomb stiffness:

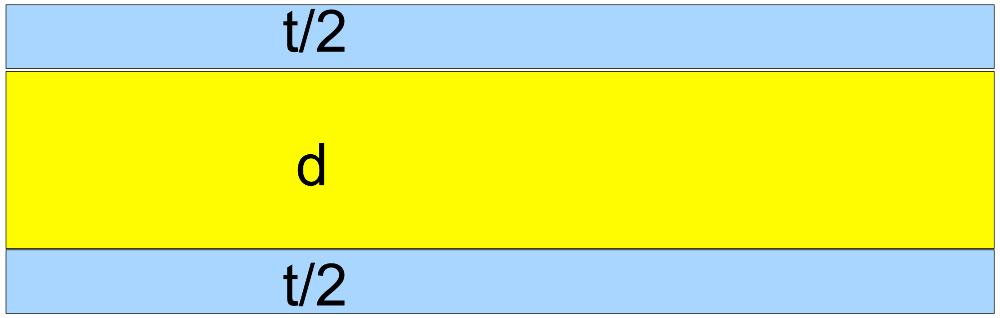
$\underline{D} \sim E/(1-v^2)\ \ x\ \ ((2/3)x(d/2+t/2)^3 - d^3/12)$

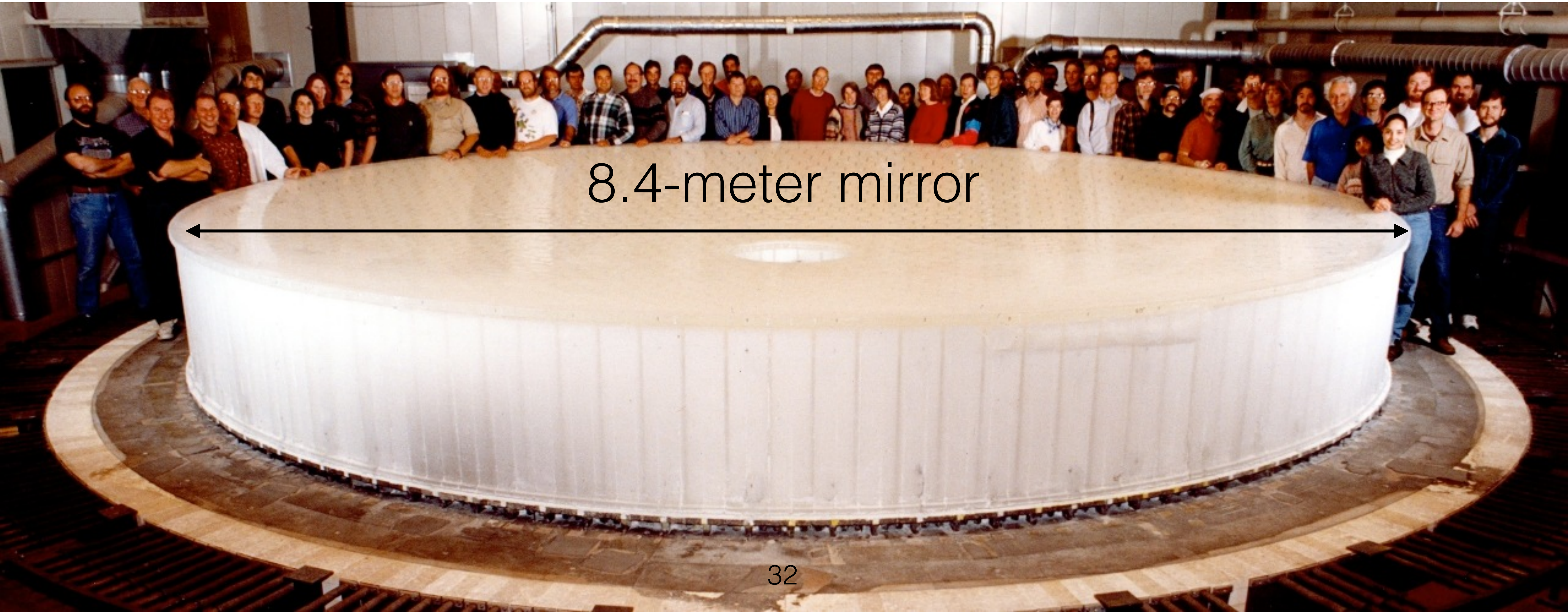
t/2 = top plate thickness = bottom plate thickness

d = core thickness

→ allows high stiffness without increasing mass

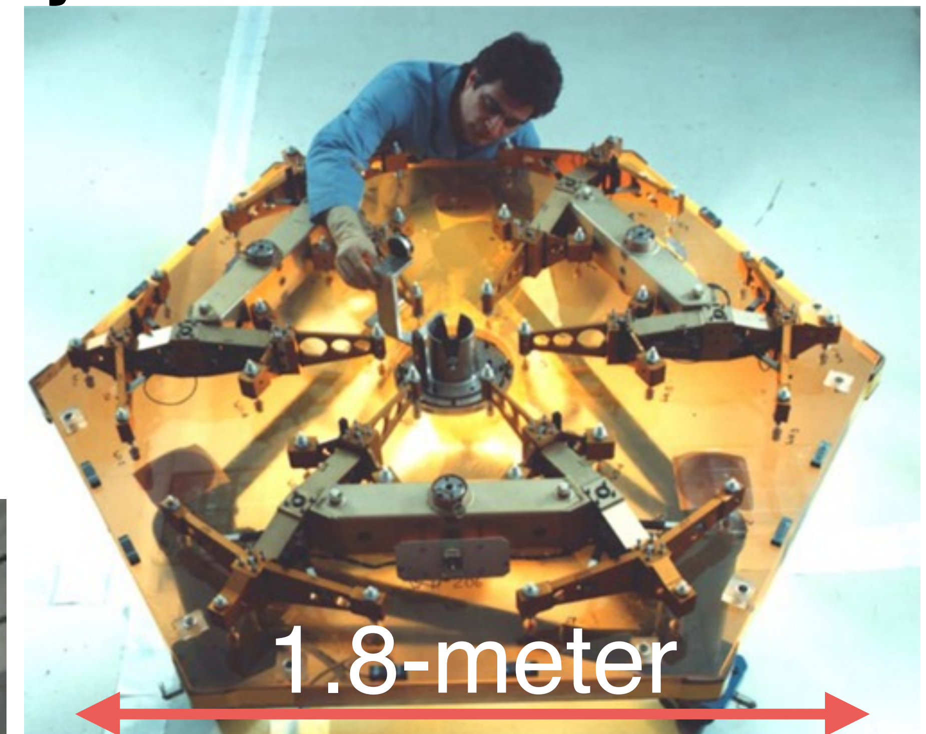
→ reduced thermal time constant by circulating air inside the mirror





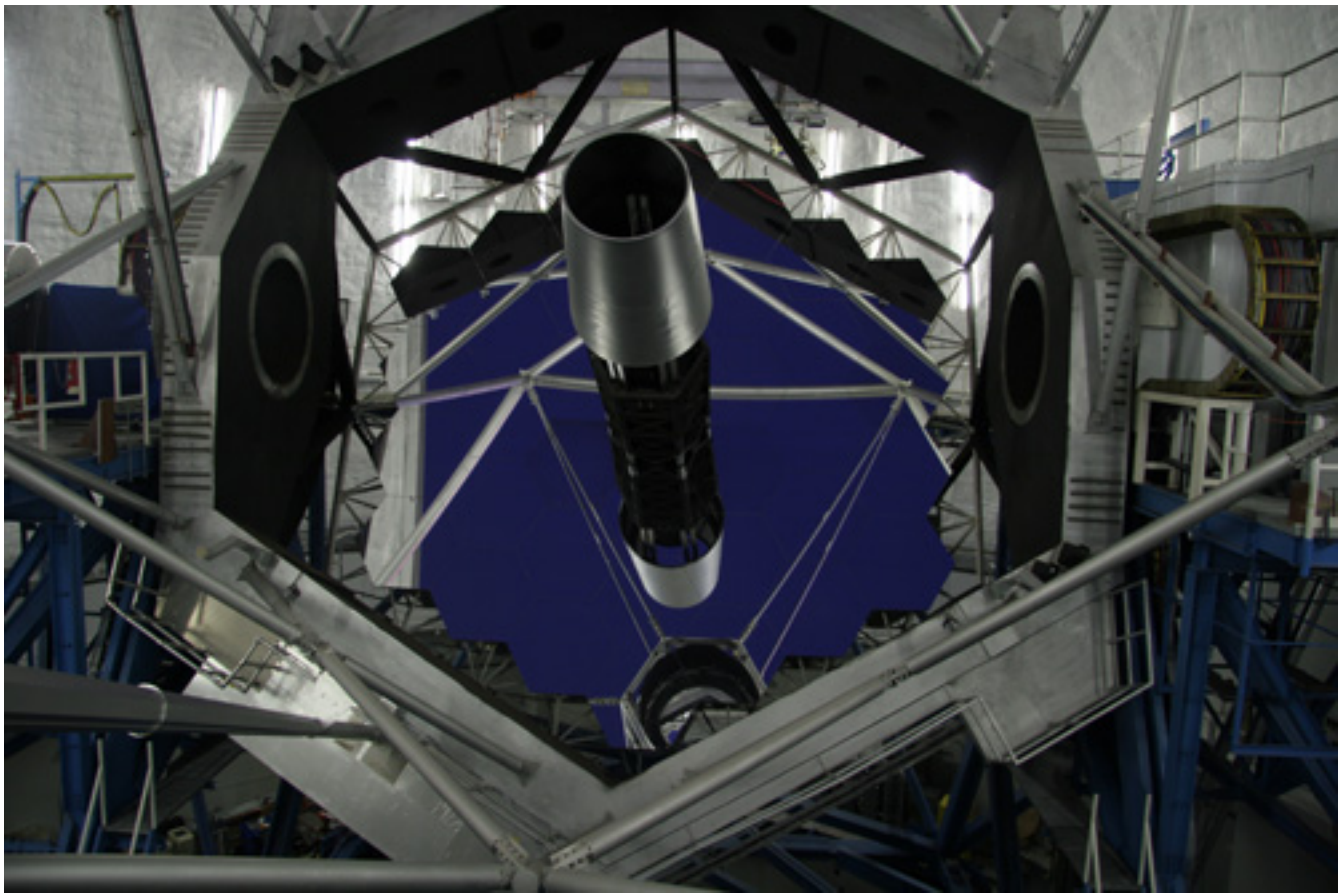
University of Arizona
Mirror Lab

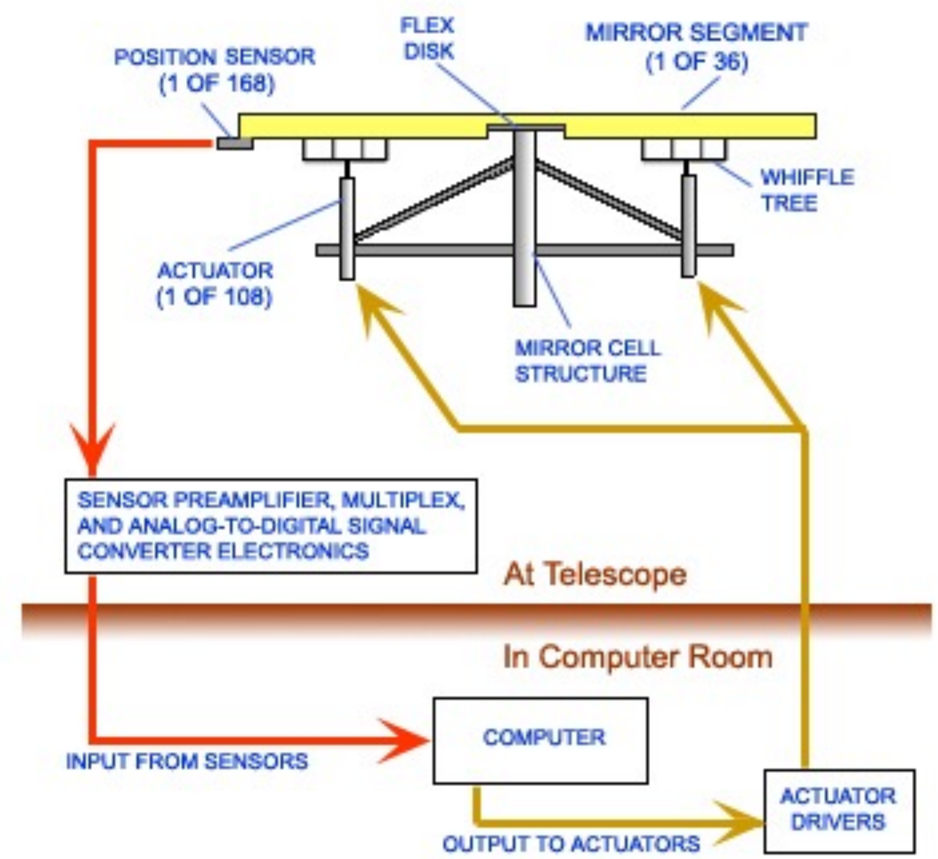
Larger size telescopes were made possible by fundamental changes in the primary mirror design



Segmented mirrors

The mirror is made of segments individually controlled in position





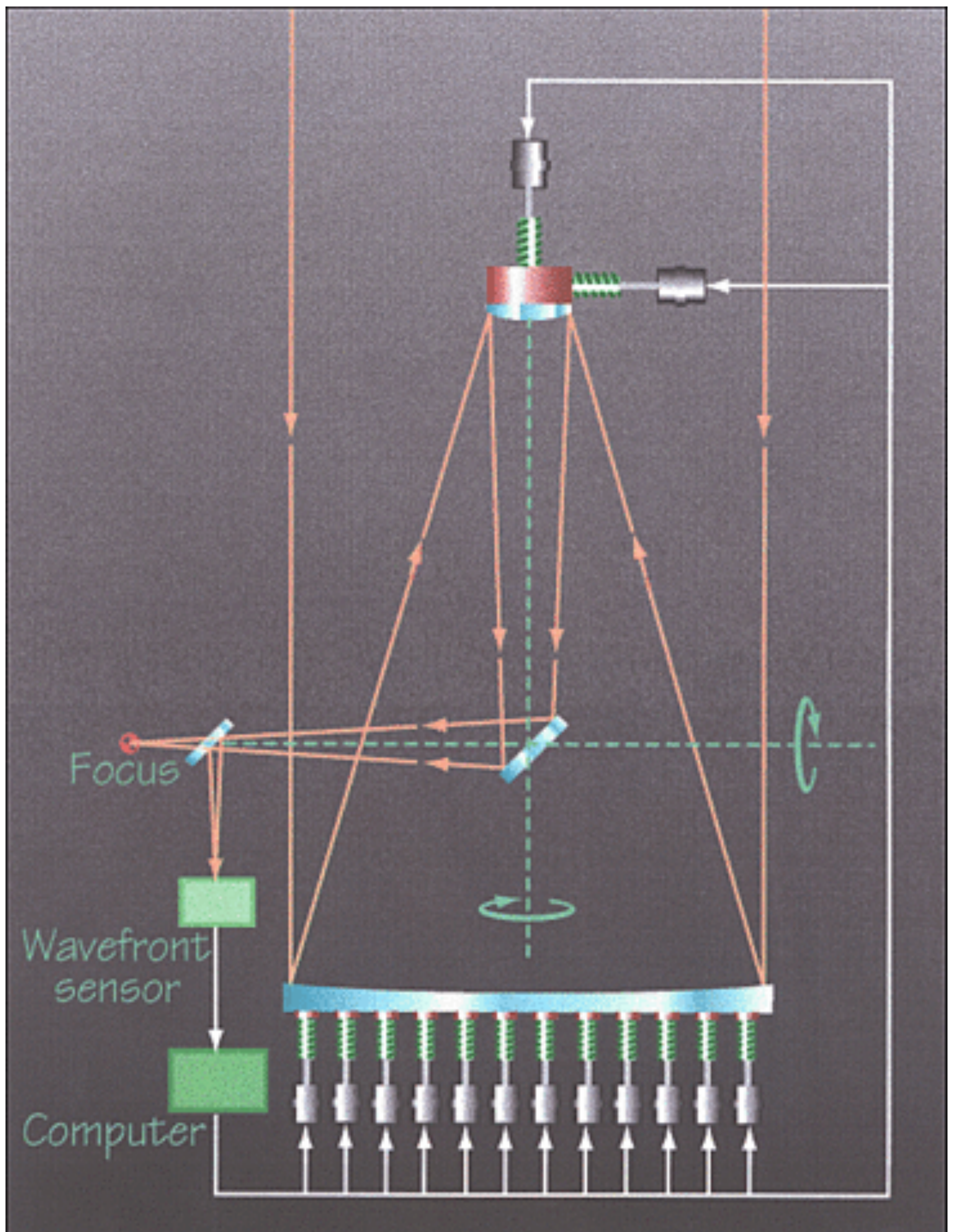
Simplified Control System Diagram

Keck telescope: 36 hexagonal segments form the primary mirror

Same Design for TMT: 492 hexagonal segments 1.44-m diameter

Larger size telescopes were made possible by fundamental changes in the primary mirror design

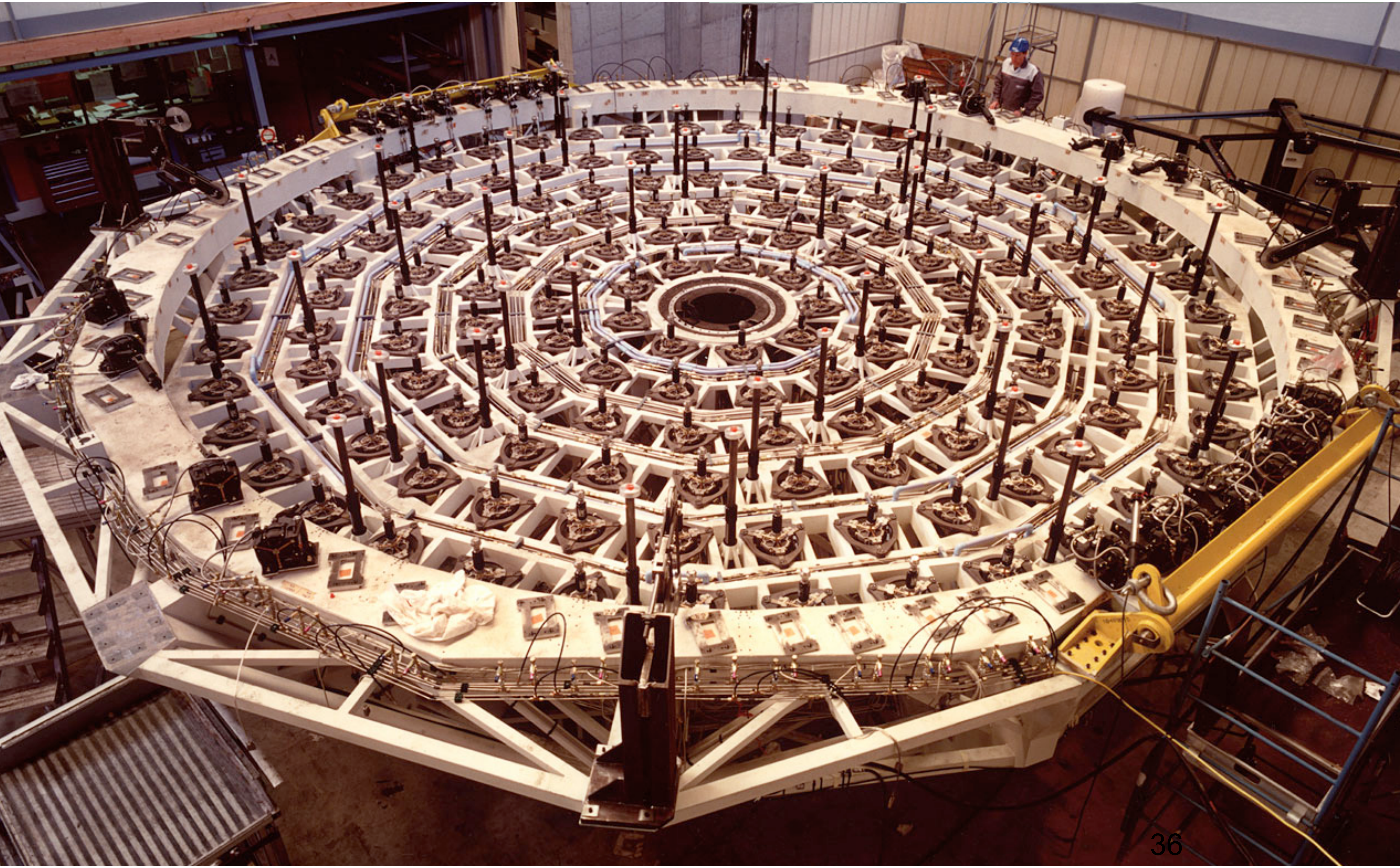
Active optics to enable thin mirror telescopes
The telescope mirror shape is actively controlled by computers driving force actuators
→ thinner mirrors can be used



Courtesy of ESO

Gemini Telescope mirror: 8m diameter, 20cm thick

All large modern telescope include computer-controlled active optics



 VLT mirror cell for 8m mirror, ~20cm thick

Vibrations, Dome

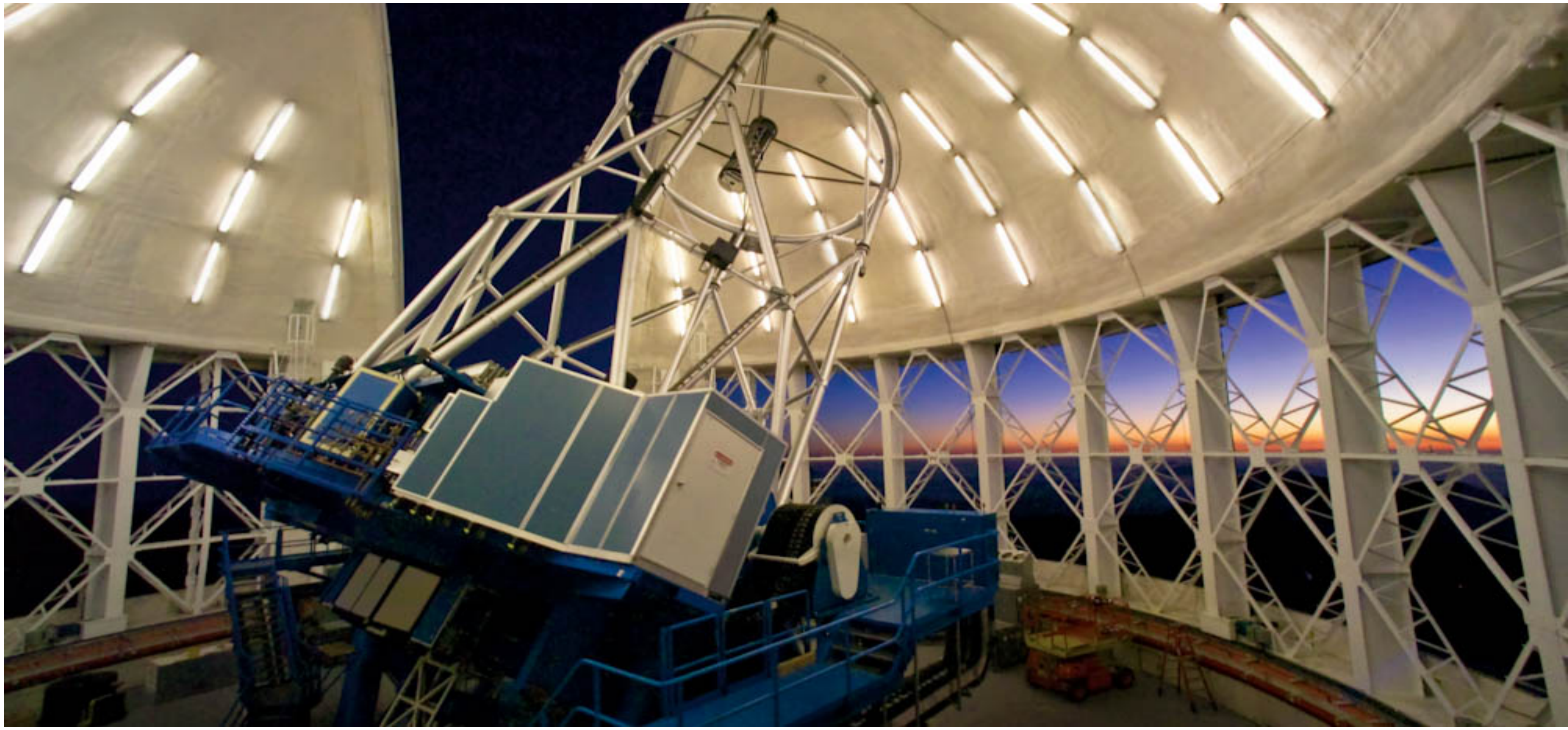
Vibrations are mostly introduced by wind, but can also be generated by telescope drive motors.

The telescope structure must be as stiff as possible
stiff = high frequency resonances = small amplitude resonances

Lowest resonance frequencies on large telescopes are ~10 Hz
Active correction is possible (vibrations can be measured optically or with accelerometers)
Dome must be carefully designed:

Dome must let air flow through telescope to avoid temperature gradients
Dome must block wind before it excites telescope structure resonances

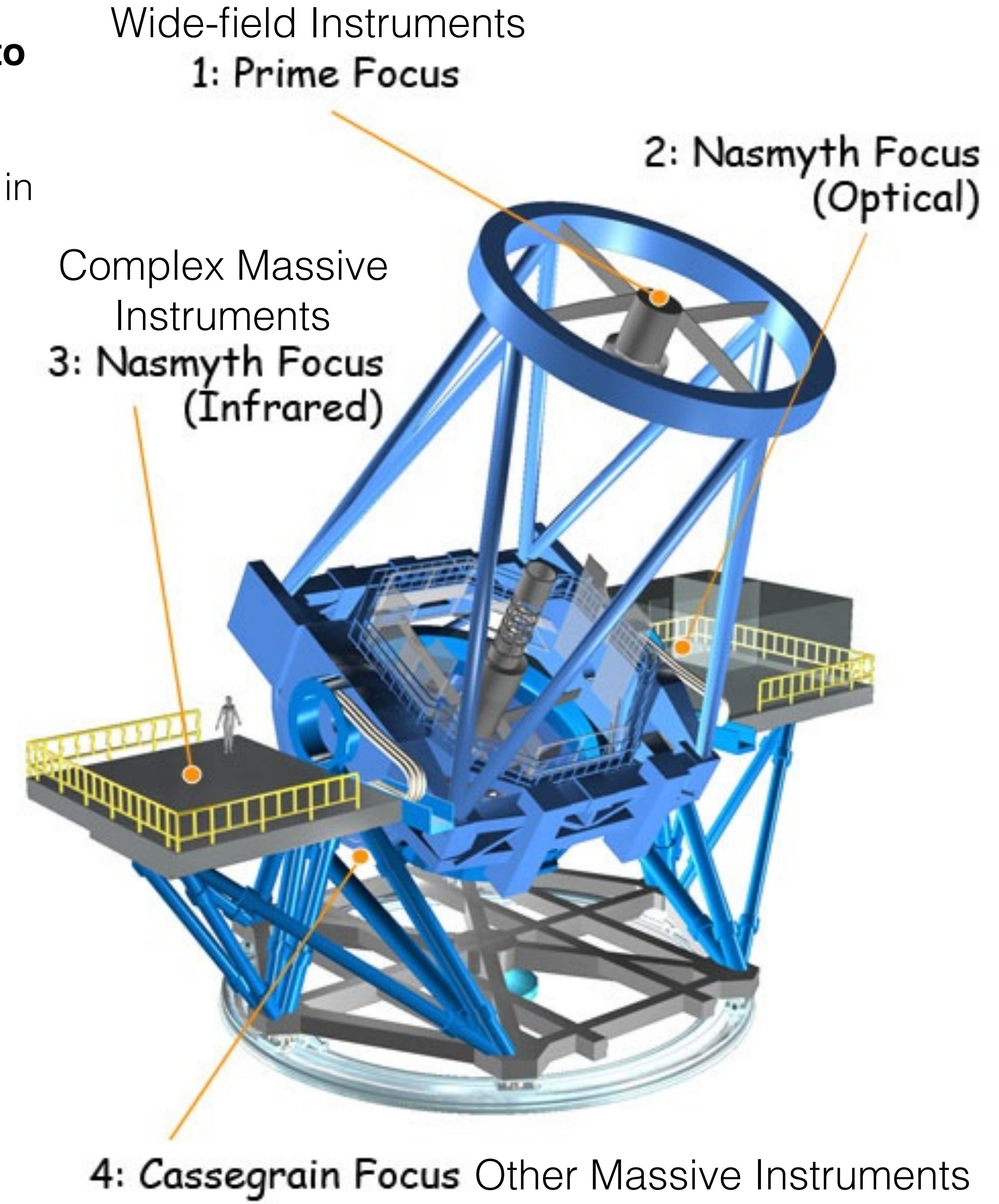
Gemini Telescope dome includes side vents
low wind: open
high wind: closed



Location of focus & instrument(s) is key to telescope design

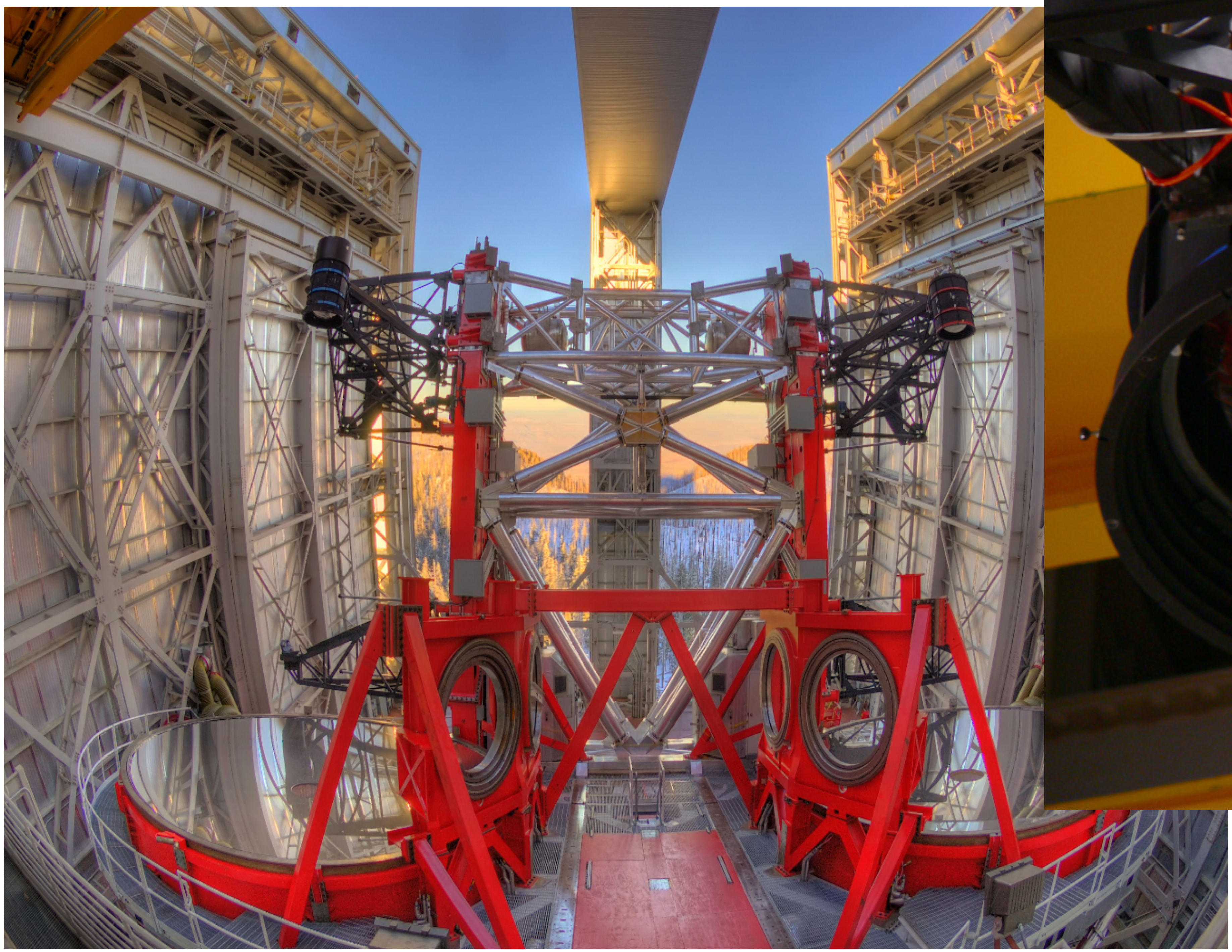
Telescopes are designed with instrument(s) in mind.

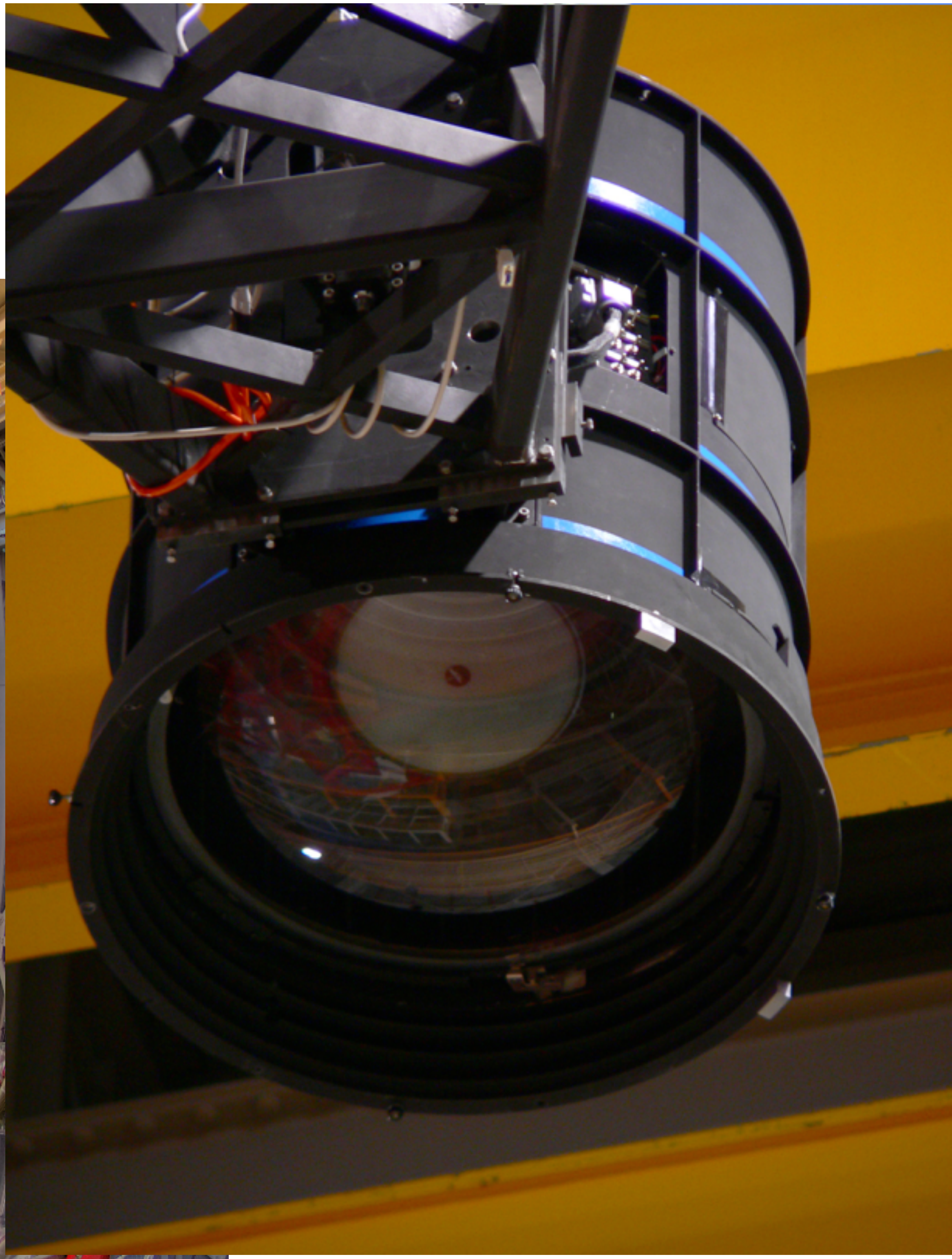
Sometimes, a specialized telescope + instrument are designed together.



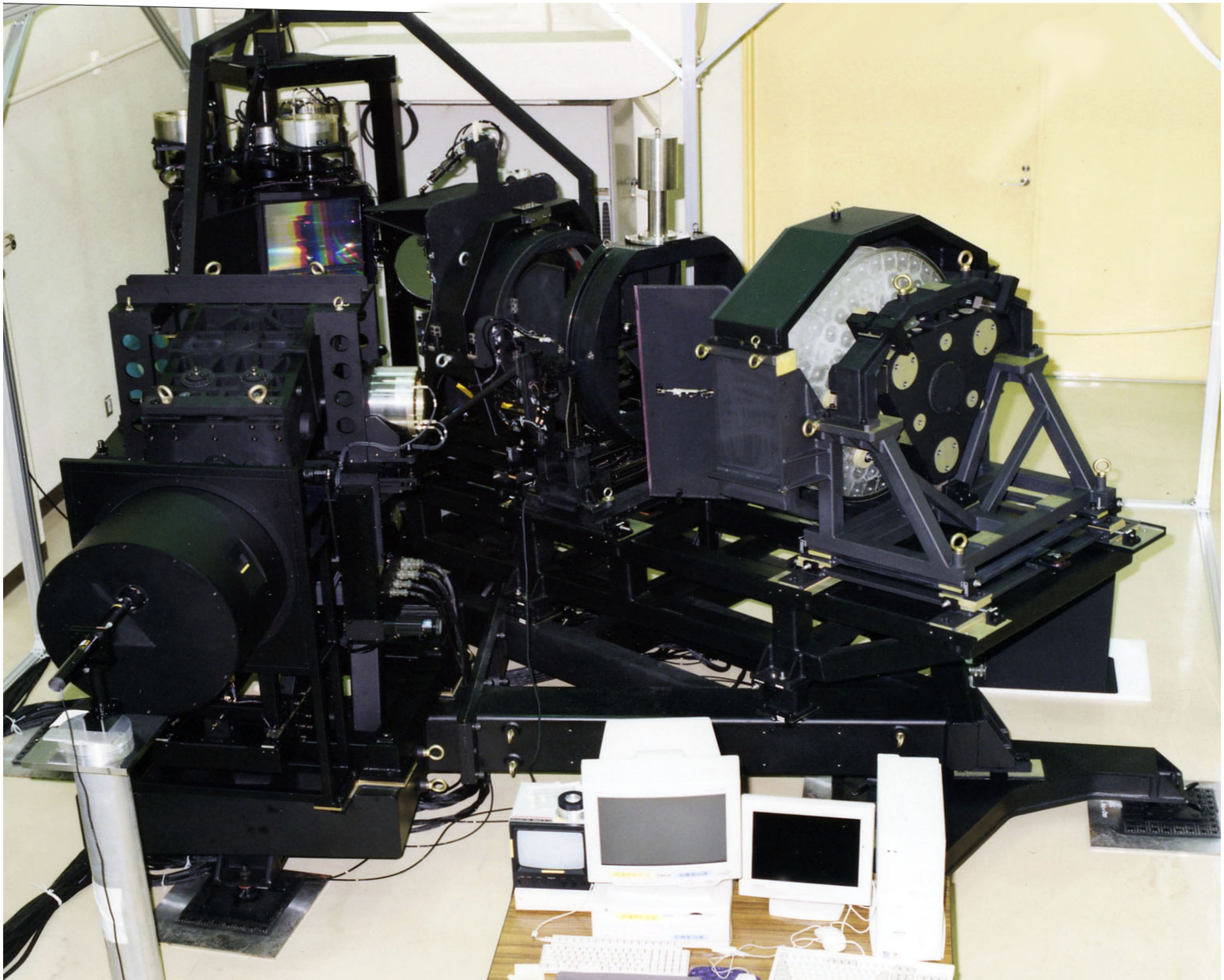
Subaru telescope (8.2m): location of the 4 telescope focii

Large Binocular Telescope's wide field cameras
@ prime focus

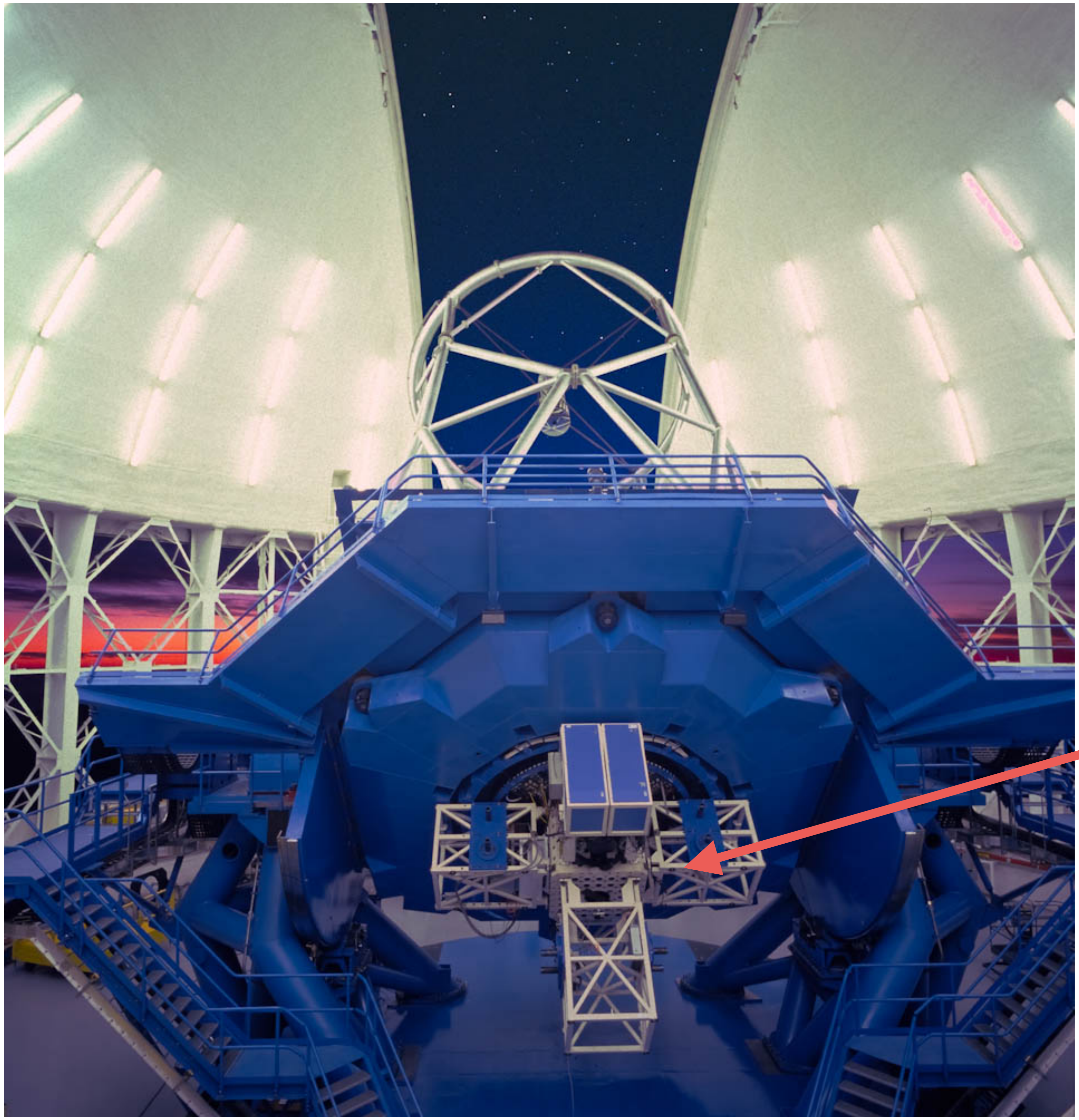




Subaru High Dispersion Spectrograph
@ Nasmyth focus, 6 metric tons

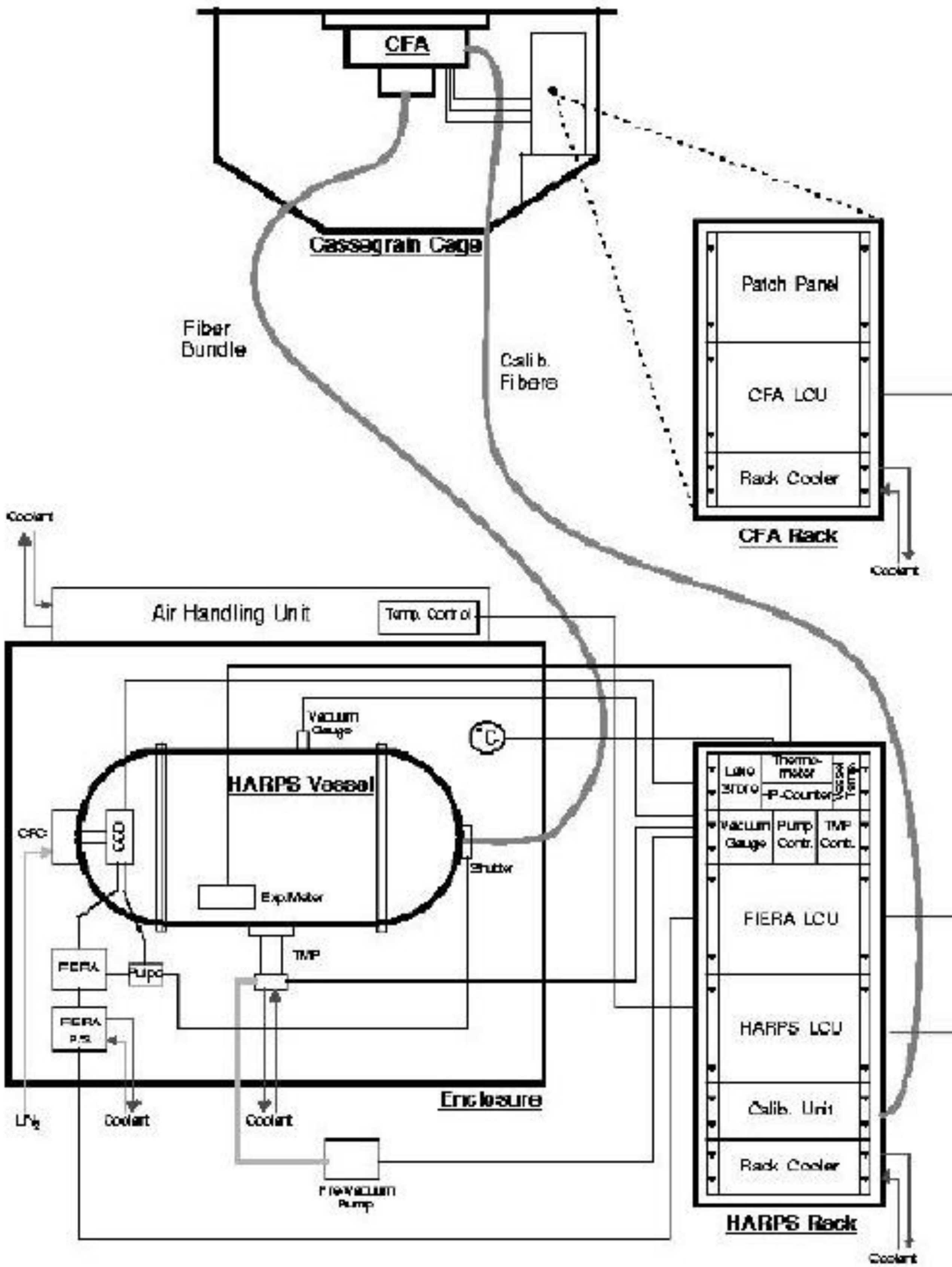


Gemini Instruments
@ Cassegrain focus



Cassegrain Focus

HARPS spectrograph at ESO's 3.6m
High Accuracy Radial velocity Planet Searcher



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Telescope Optical Design

Types of aberrations in optical systems: Seidel aberrations

Seidel aberrations are the most common aberrations:

Spherical aberration

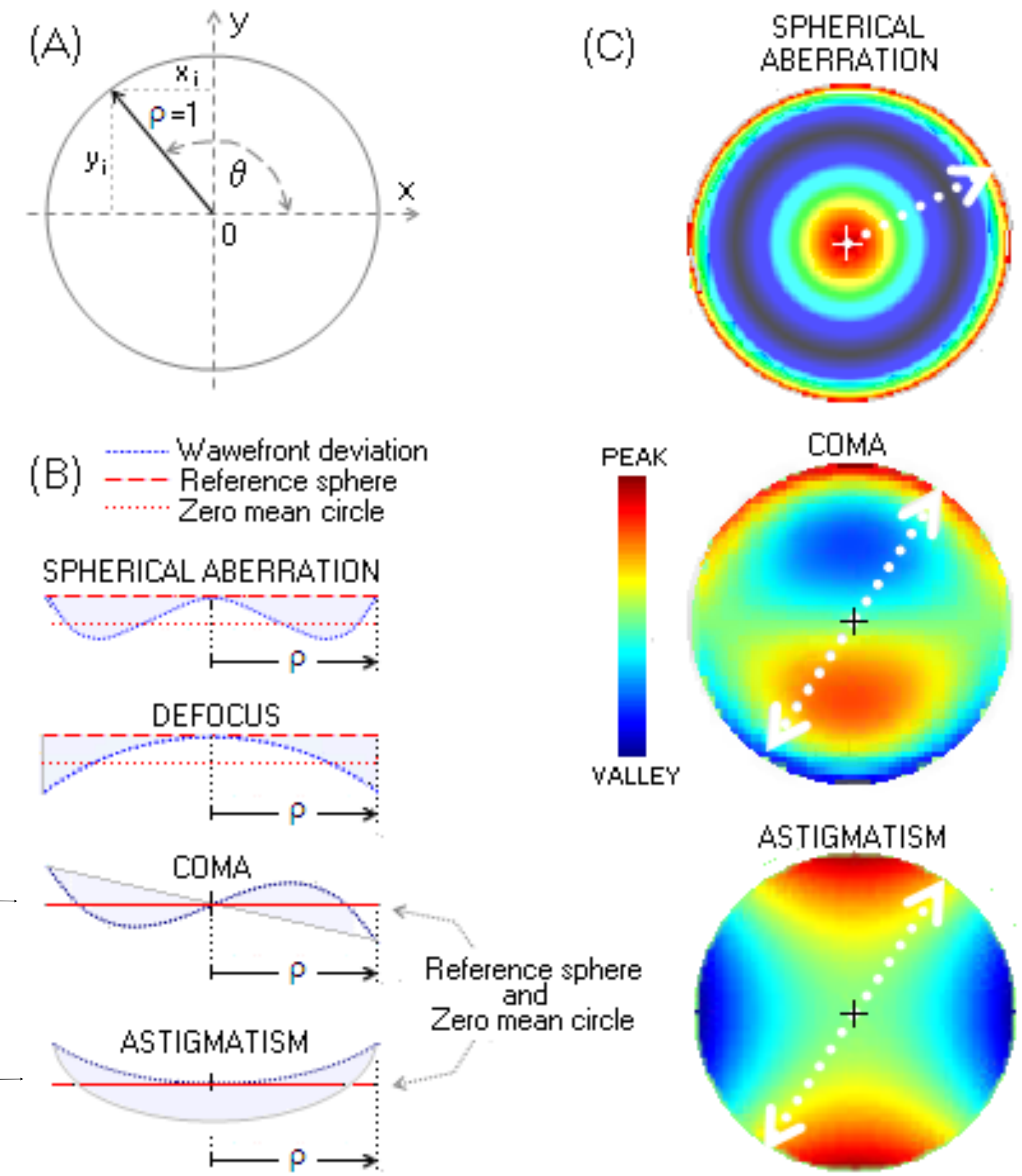
Coma

Astigmatism

Field curvature

Field distortion

Types of aberrations in optical systems



Wavefront errors

Spherical aberration

On-axis aberration, difference between a sphere and a parabola. Telescope focus is function of radius in pupil plane

Coma

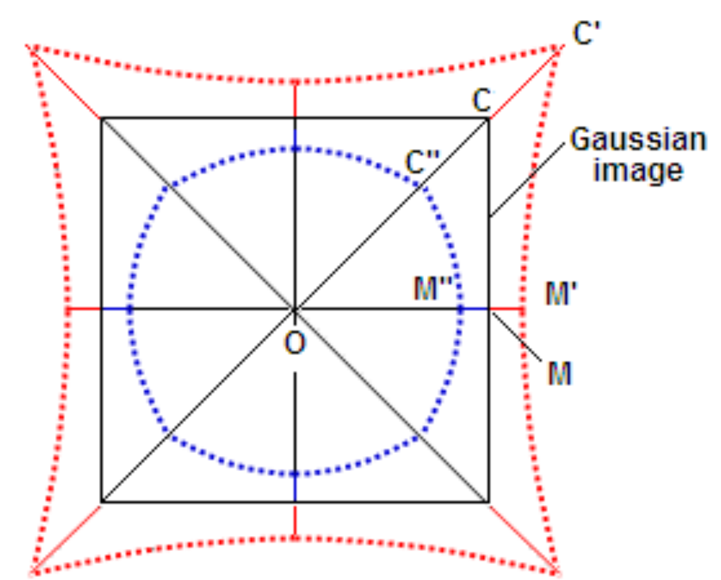
Off-axis aberration

Astigmatism

Off-axis aberration. Focal length is different along x and y axis

Field curvature

Sharpest image surface is not a plane, it is curved → a flat detector will not be in focus at all distances from optical axis



Field distortion

Chromatic aberration

www.telescope-optics.net

Design considerations

Wavefront errors should be minimized by the telescope design and can also be reduced with a field corrector (usually refractive optics). Systems with very large field of views all have refractive field correctors, as the number of optical surfaces required to achieve suitable correction is too large for an all-reflective design to be practical.

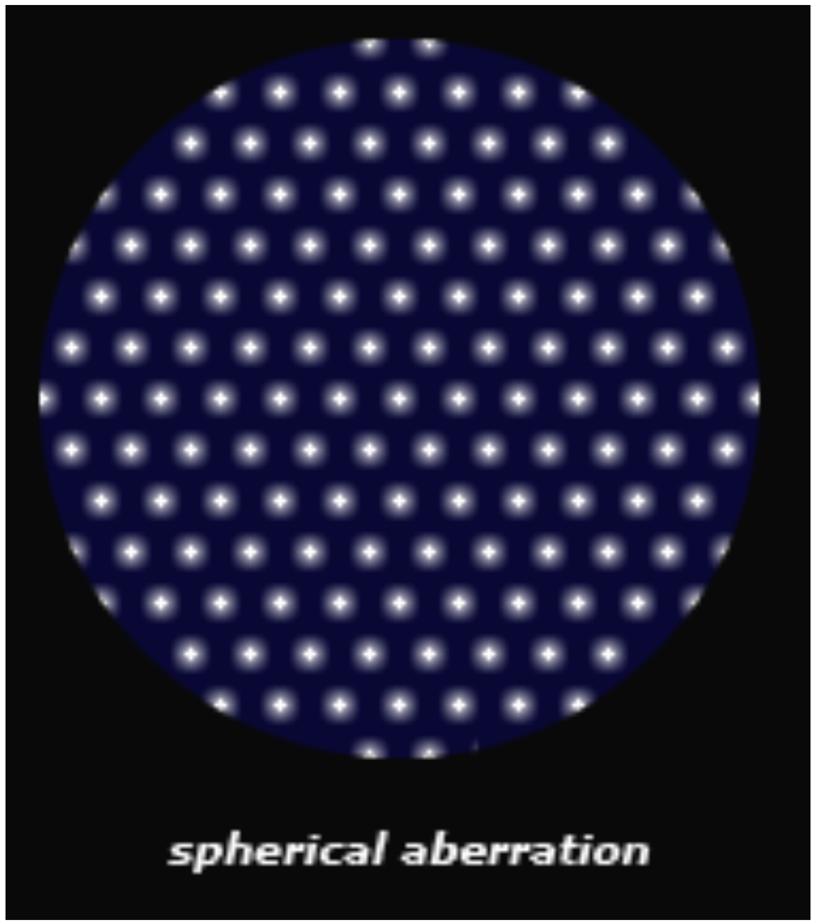
Field curvature can be minimized by a refractive corrector. Sometimes, it is simpler to build a curved focal plane detector than optically correct field curvature (see previous slide)

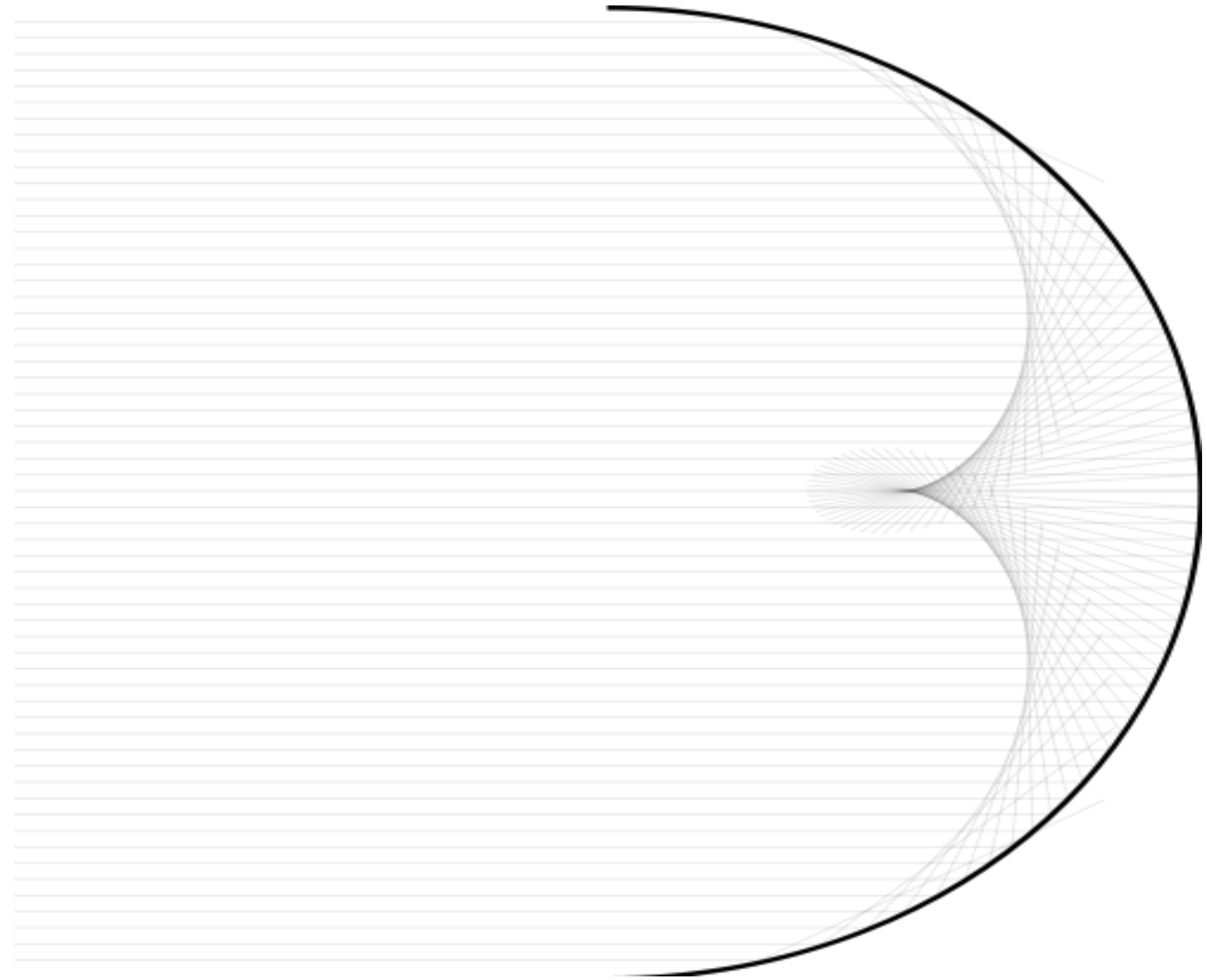
Field distortion is usually not a concern, as it is known and can be accounted for in the analysis of the images.

Chromatic aberration is not an issue with reflecting telescopes, but is a design constraint for refractive wide field correctors.

Having to simultaneously minimize wavefront errors, field curvature, (field distortion?) and chromatic aberrations over a wide field of view requires careful optical design and usually complex multi-element refractive correctors and/or unusual optical designs.

Spherical Mirrors Produce Poor Image Quality

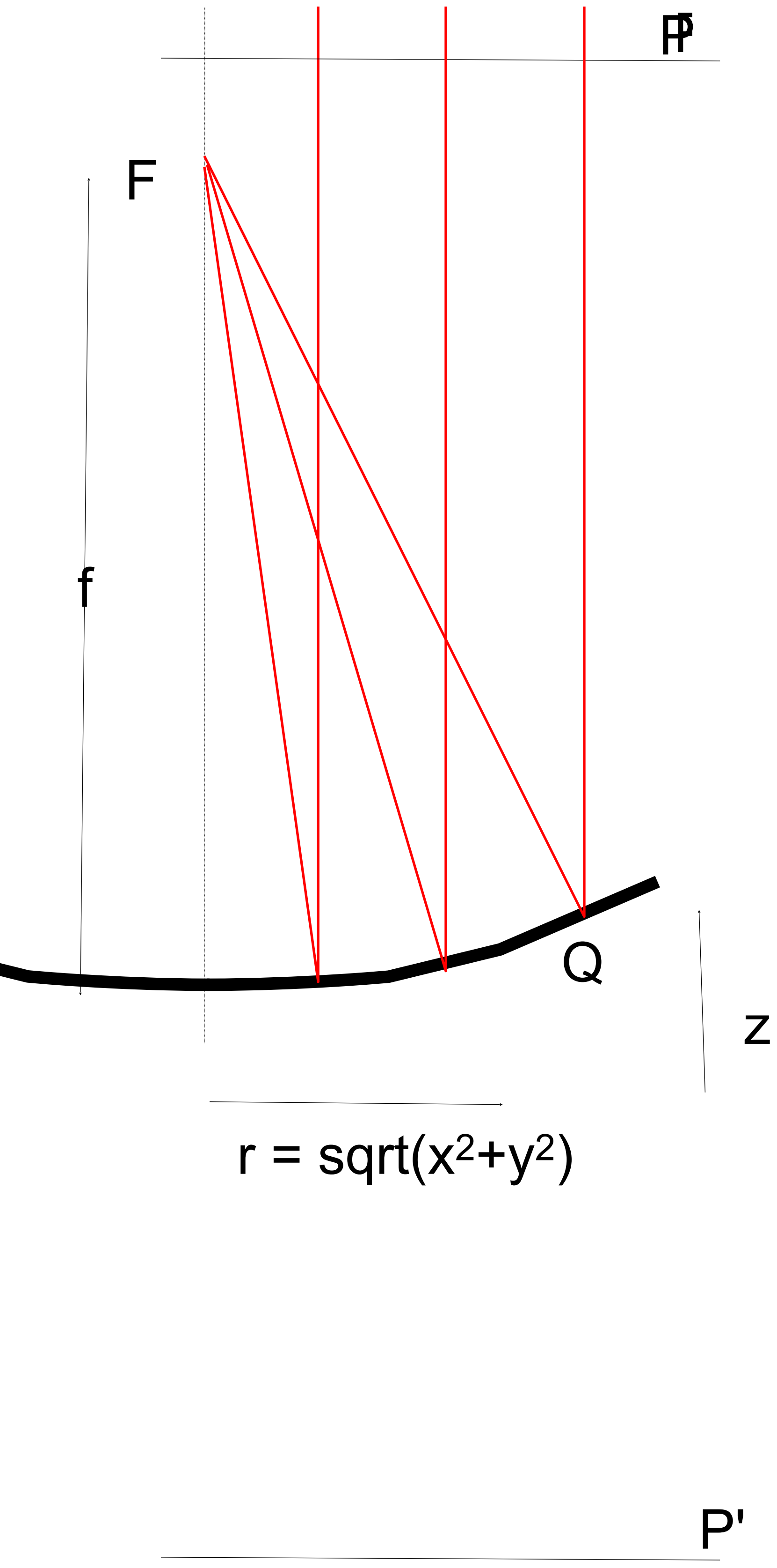




Spherical mirror

This issue gets worse the faster the mirror is!

Parabola



A parabola is the **ONLY** continuous shape that will focus starlight to a point with a single mirror

$z(x,y) = (x^2+y^2) / (4f)$

Why is there only one solution to this problem ?
Why is that solution a parabola ?

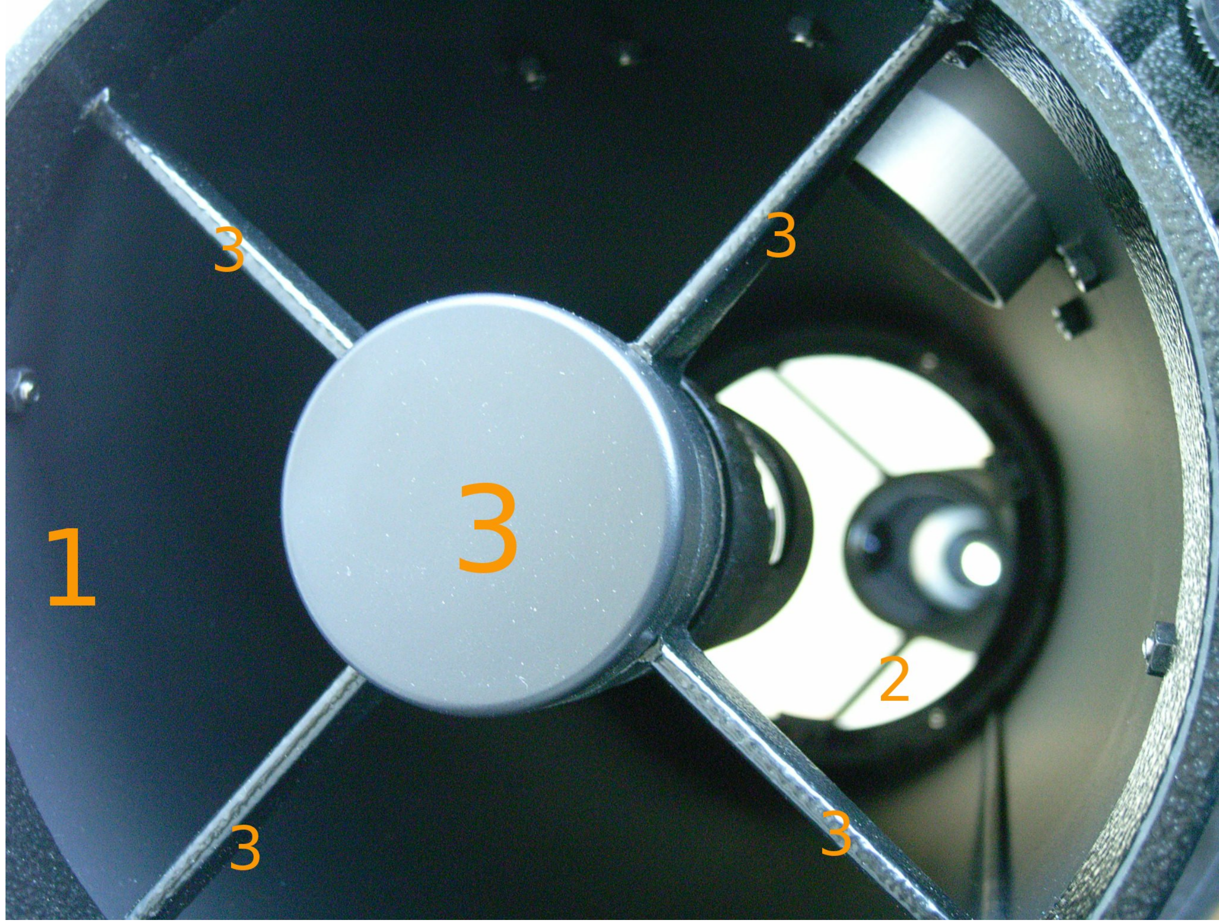
Fermat's principle: Light rays follow shortest path from plane P to focus F. With OPD(x,y) the distance from the object to focus (= distance from plane P to point F):
d OPD(x,y) / dx = d OPD(x,y) / dy = 0

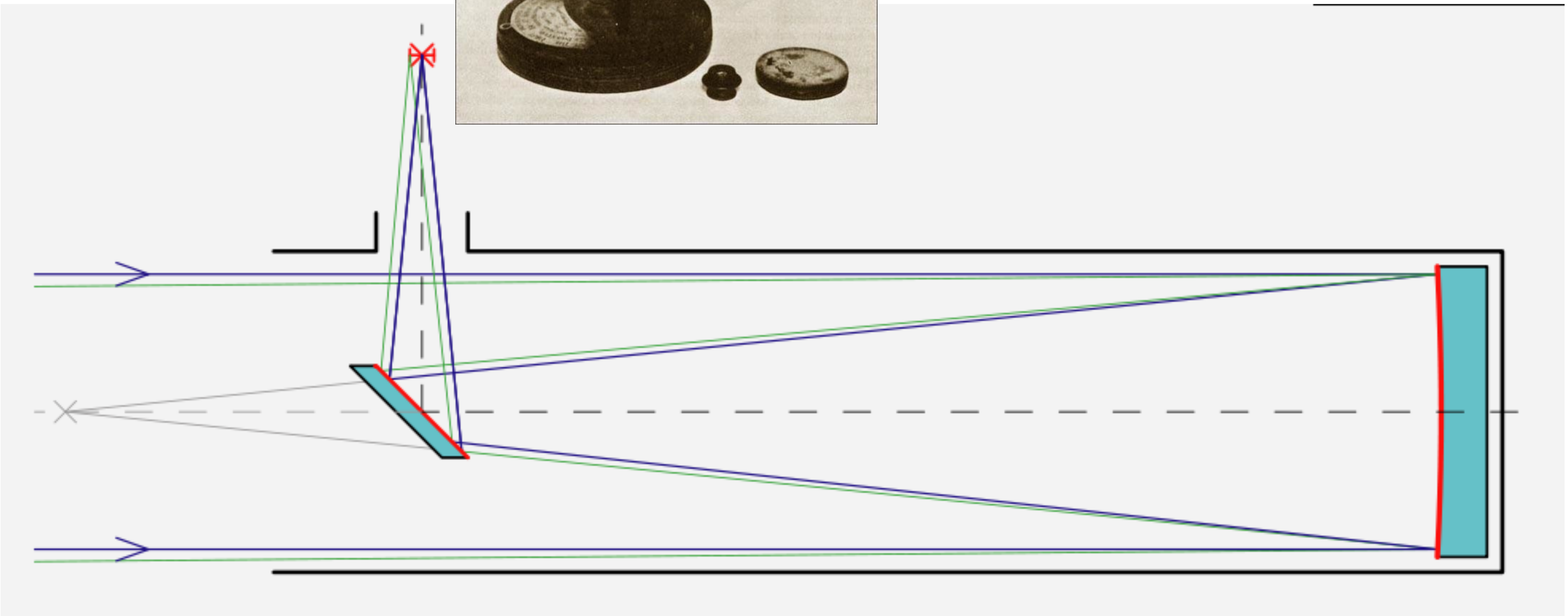
Parabola is surface of equidistance between a plane P' and a point (with the plane below the mirror on the figure on the left): distance (FQ) = distance (QP')
with : (QP') + (QP) = (P'P) = constant
→ (FQ) + (QP) = (QP') + (QP') = constant
Parabola obeys Fermat's principle

Why is the solution unique ?
If building the mirror piecewise, with infinitively small segments, working outward from r=0 (optical axis), the constraint that light ray must hit focal point F is a constraint on the local slope of the mirror
→ dz/dr = function_of(r,f,z)
→ mirror shape can be derived by integrating this Eqn.

Newtonian Telescope

Parabolic mirror + flat secondary mirror to move image out of the incoming beam





**Field of view problem with parabola:
Coma aberration**

Coma is the main aberration for an parabolic mirror observing off-axis sources

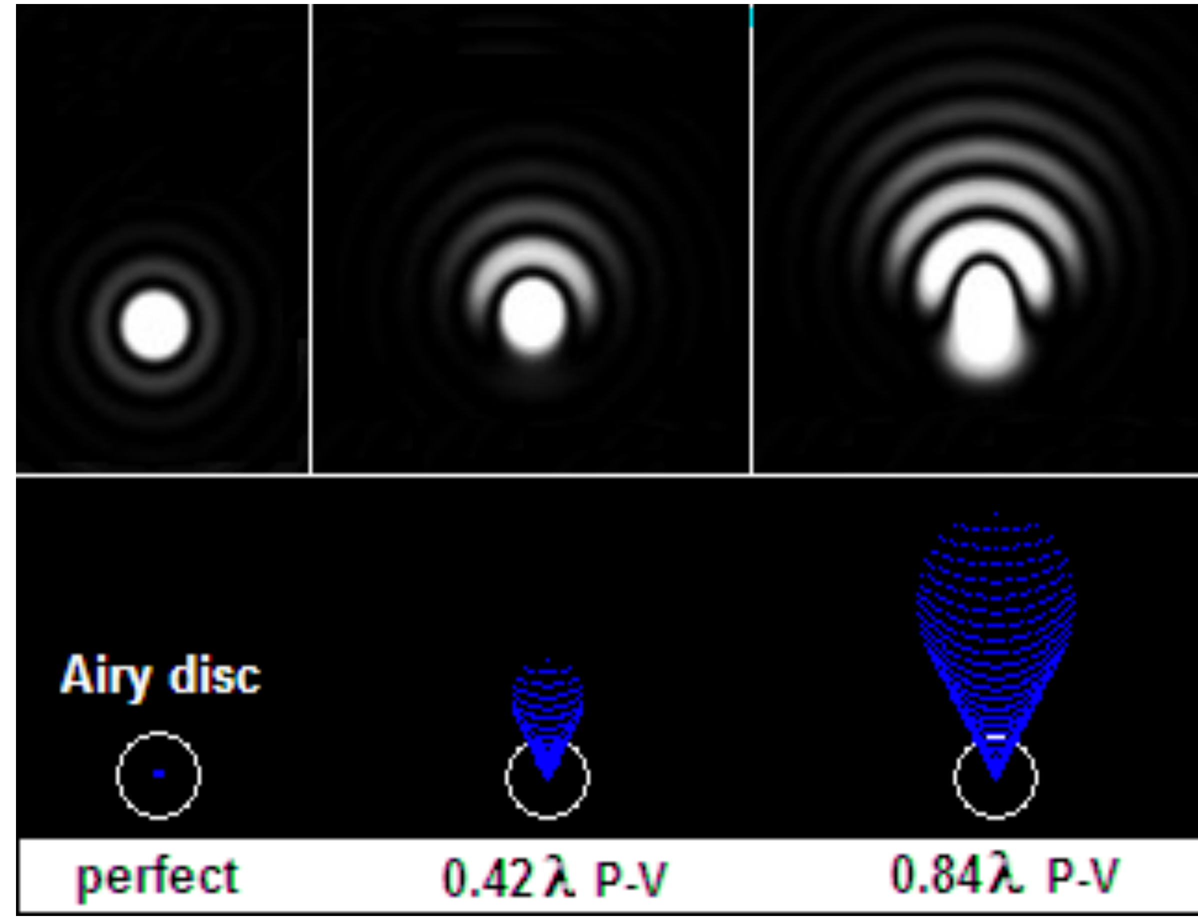
For a source offset α [rad], the RMS geometrical blur radius due to coma is:

$\mathbf{r_{COMA}[arcsec] = 0.051\ \alpha/F^2}$

Examples:
for F = f/D = 10 telescope
r < 0.1” (0.2” diameter spot)
—> α=3.3’

for F = 5
r < 0.1”
—> α=49”

Parabolic mirror telescopes are not suitable for wide field imaging



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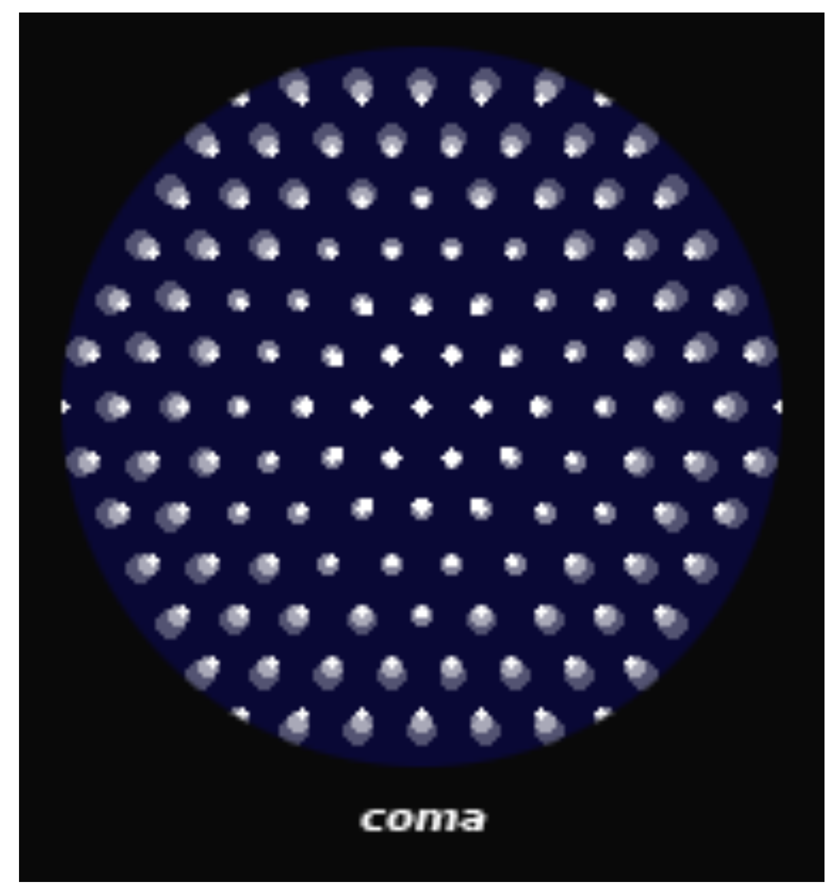
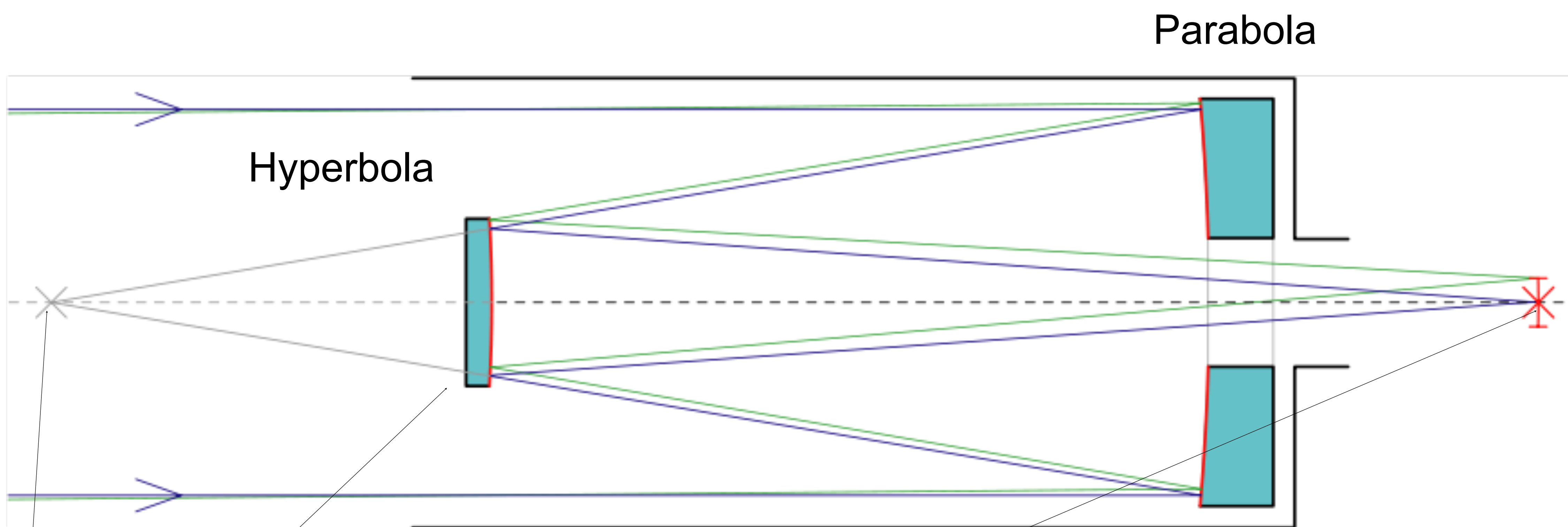
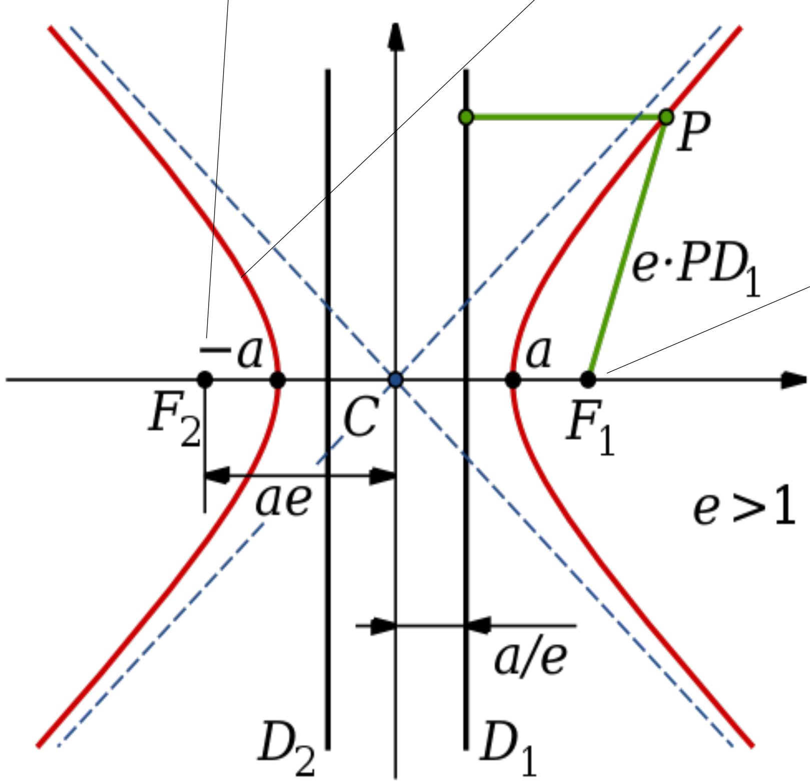


Classical Cassegrain Telescope

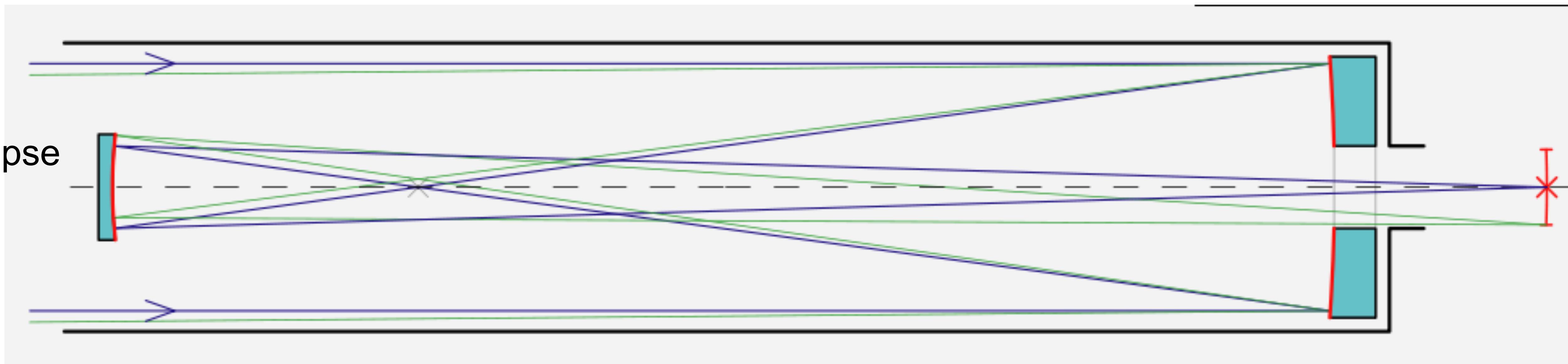




If secondary mirror is flat, then focus is inside telescope (not practical)

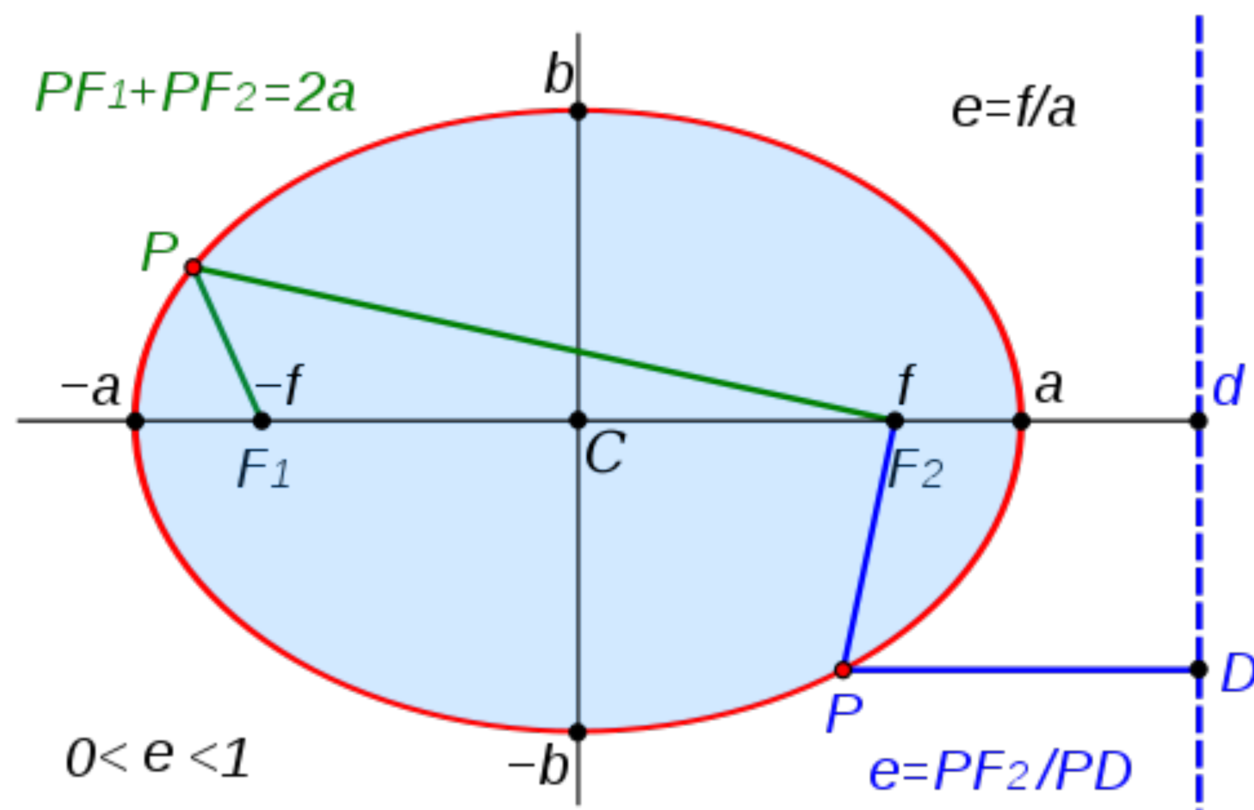
Hyperbola is curve/surface for which difference between distances to two focii (F1 and F2) is constant (=2a).
Fermat's principle → hyperbola

Gregorian Telescope

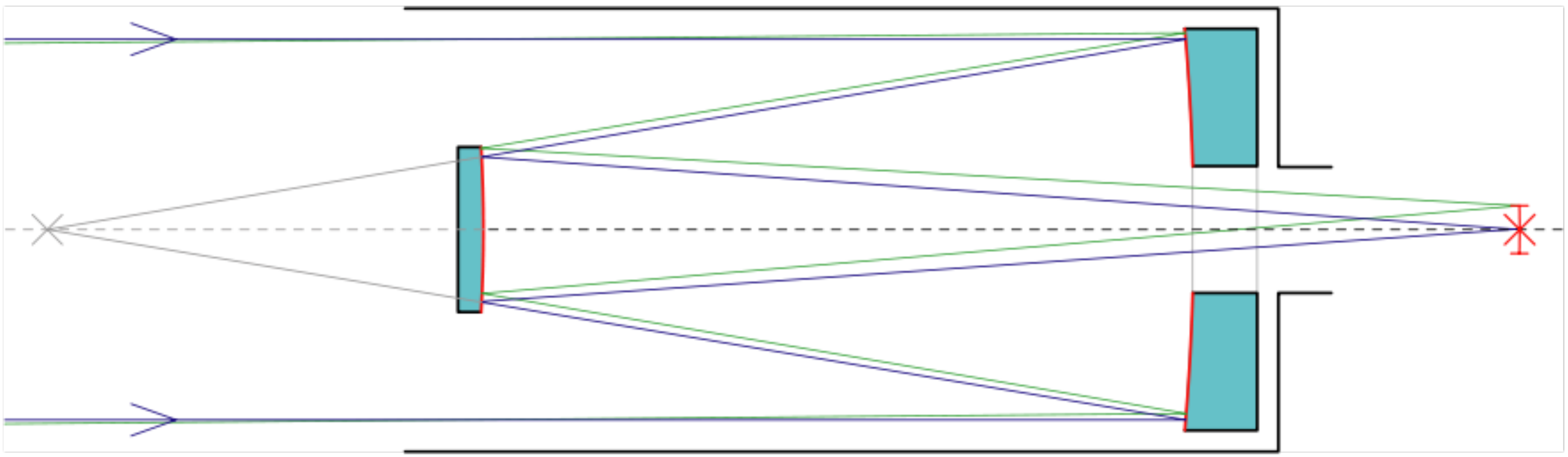


If secondary mirror is flat, then focus is inside telescope (not practical)

Ellipse is curve/surface for which sum of distances to two focii (F1 and F2) is constant (=2a).
Fermat's principle → Ellipse

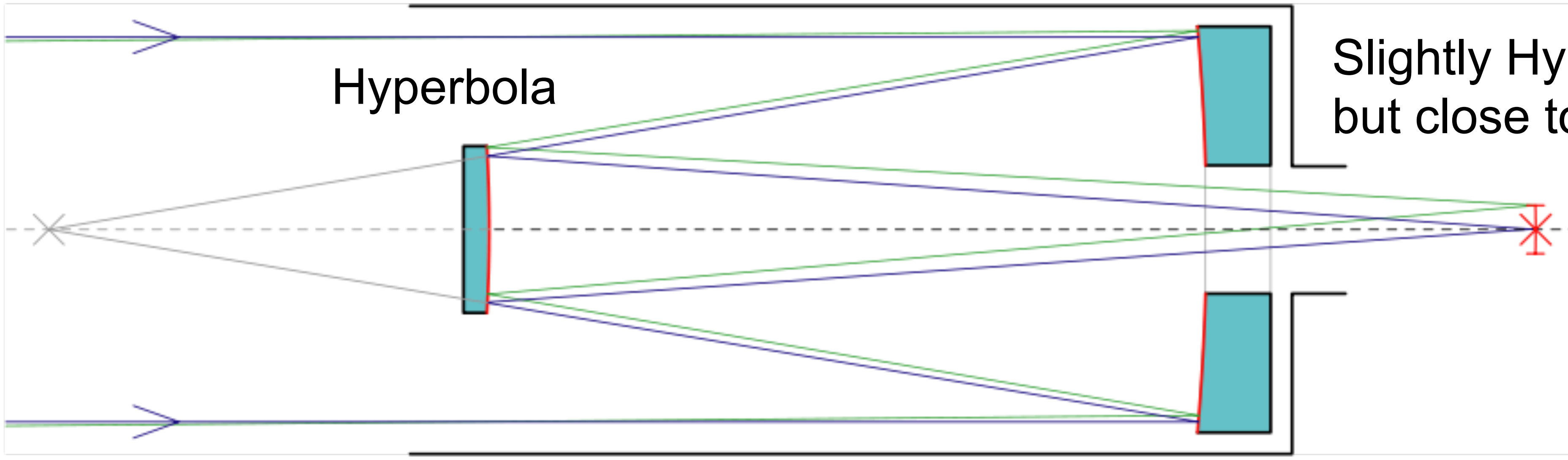


Solution to the field of view problem: >1 optical surface



With 2 mirrors, there is now an infinity of solutions to have perfect on-axis image quality.
For ANY primary mirror shape, there is a secondary mirror shape that focuses on-axis light on a point
→ shape of one of the 2 mirrors becomes a free parameter that can be used to optimize image quality over the field of view.

Ritchey-Chrétien Telescope



Primary and secondary mirror are hyperbolas

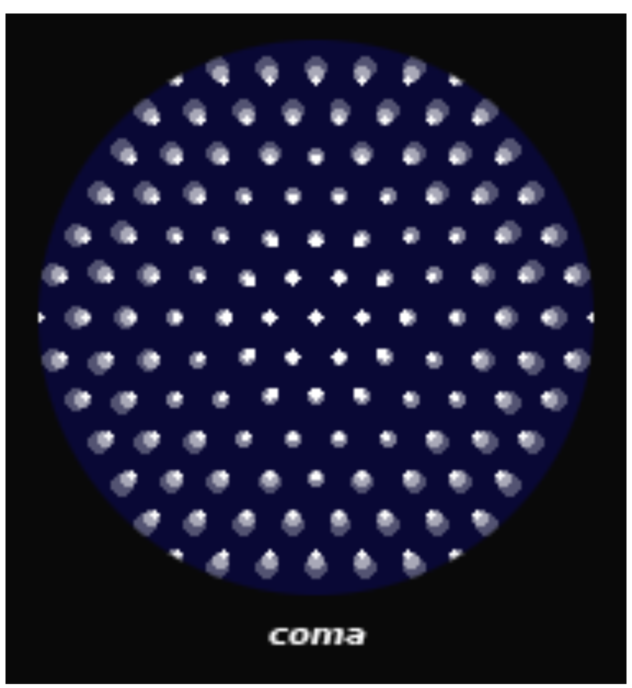
Spherical and Coma can be removed by choice of conic constants for both mirrors

→ field of view is considerably larger than with single parabola

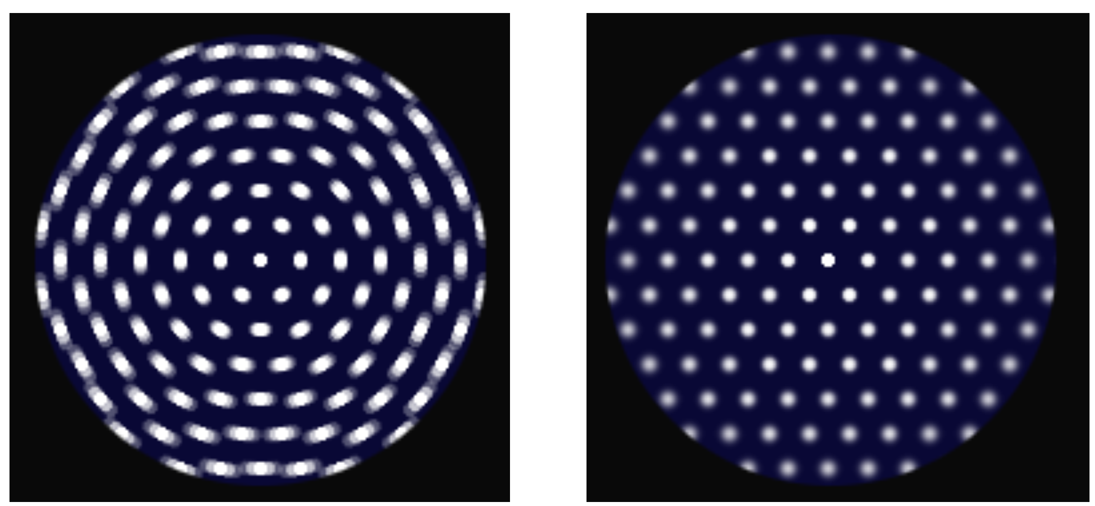
→ satisfies the Abbe sine condition (no coma)

Most modern large telescopes are RC (example: Hubble Space Telescope, Keck, TMT)

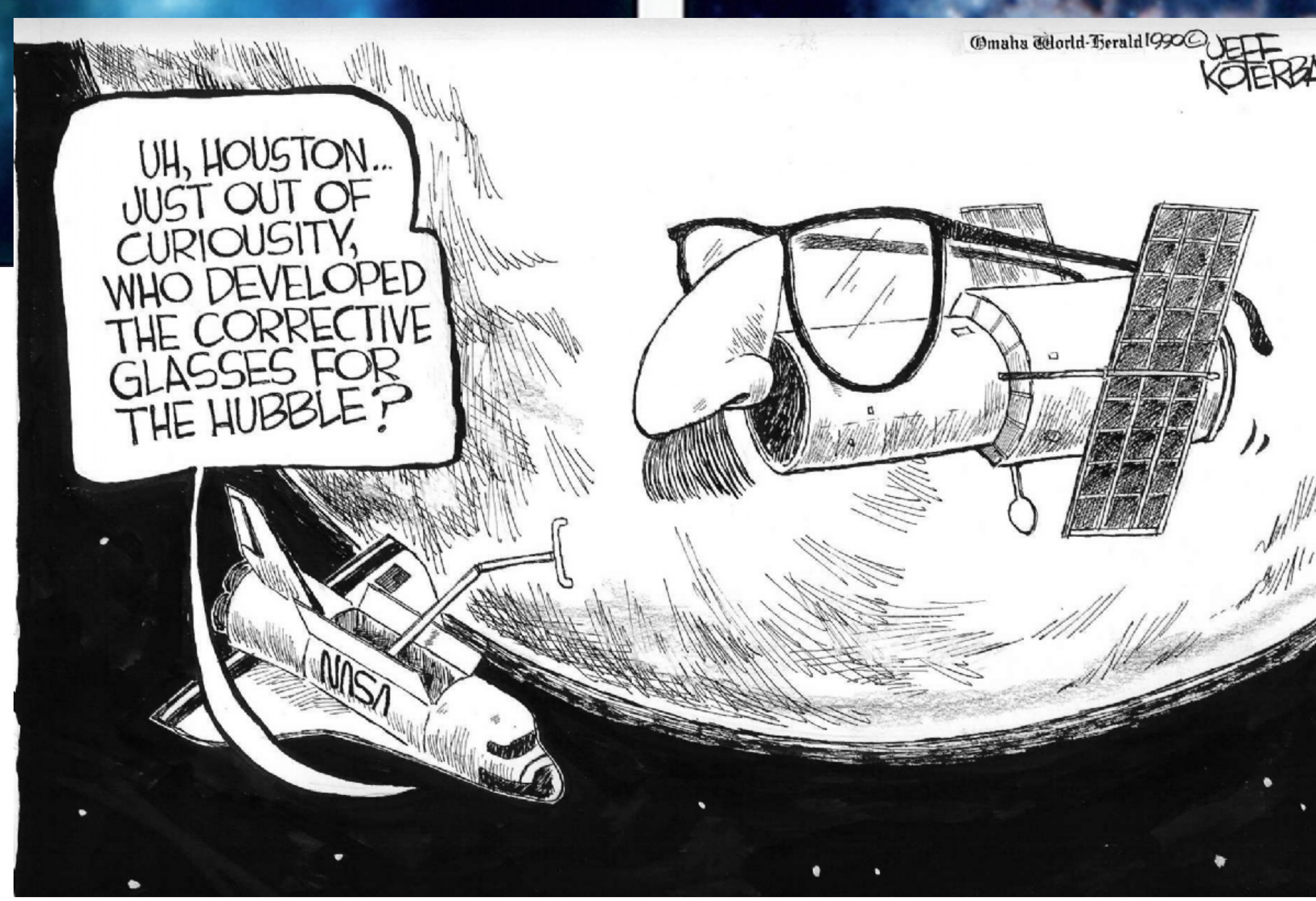
Cassegrain

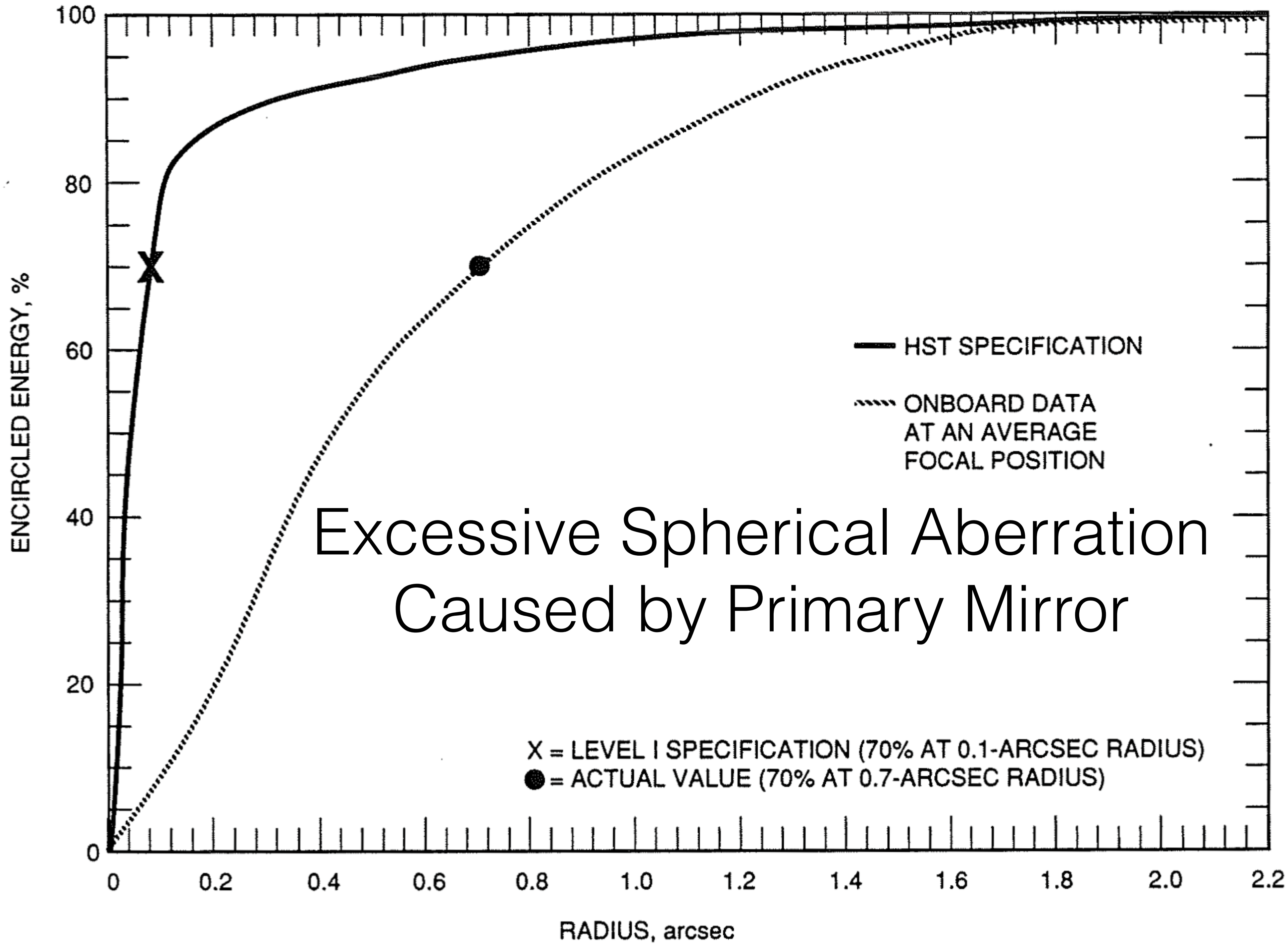


R-C Design



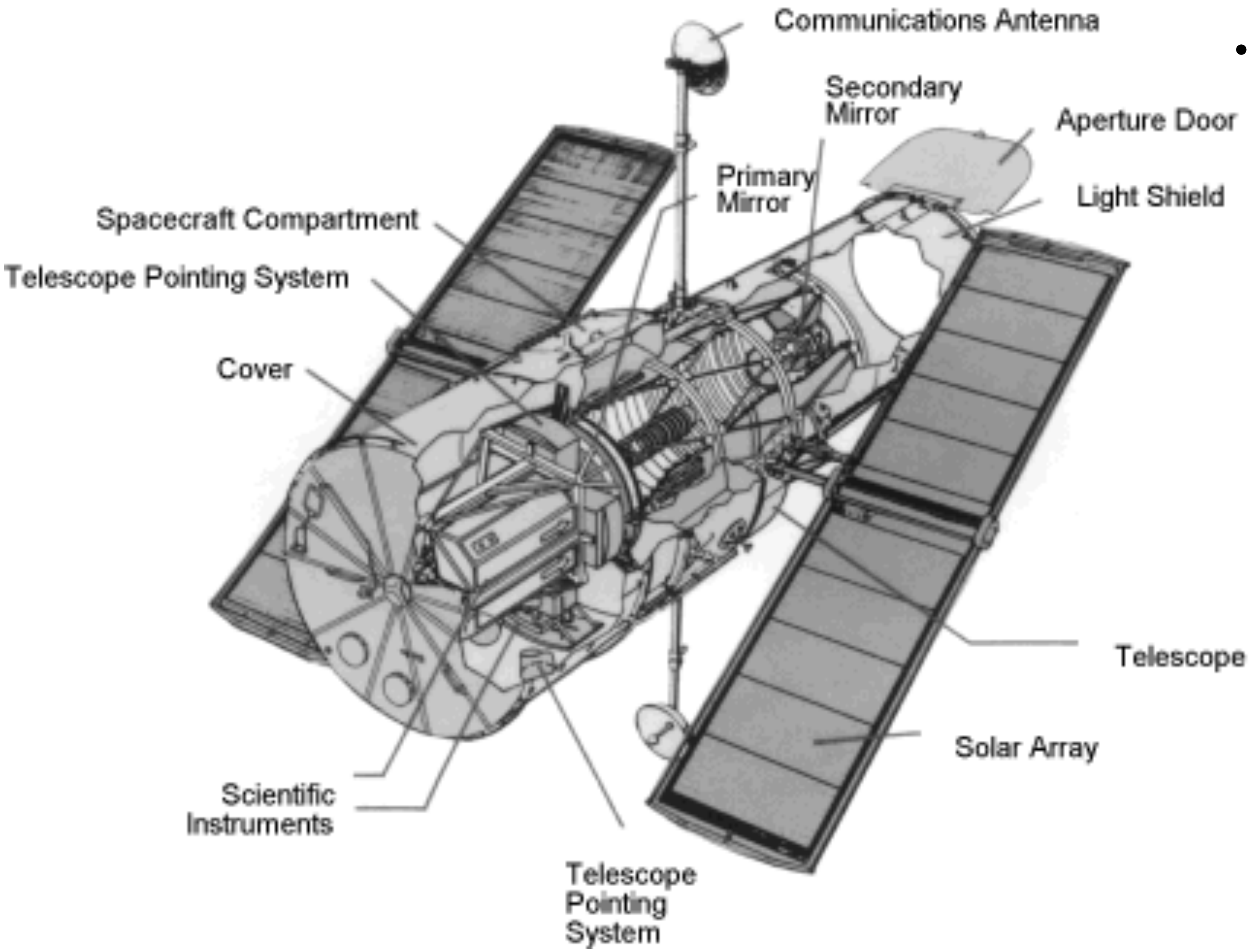
Residual Astigmatism and Field Curvature


Omaha World-Herald 1990 © JEFF KOTERBA
UH, HOUSTON... JUST OUT OF CURIOUSITY, WHO DEVELOPED THE CORRECTIVE GLASSES FOR THE HUBBLE?
NASA

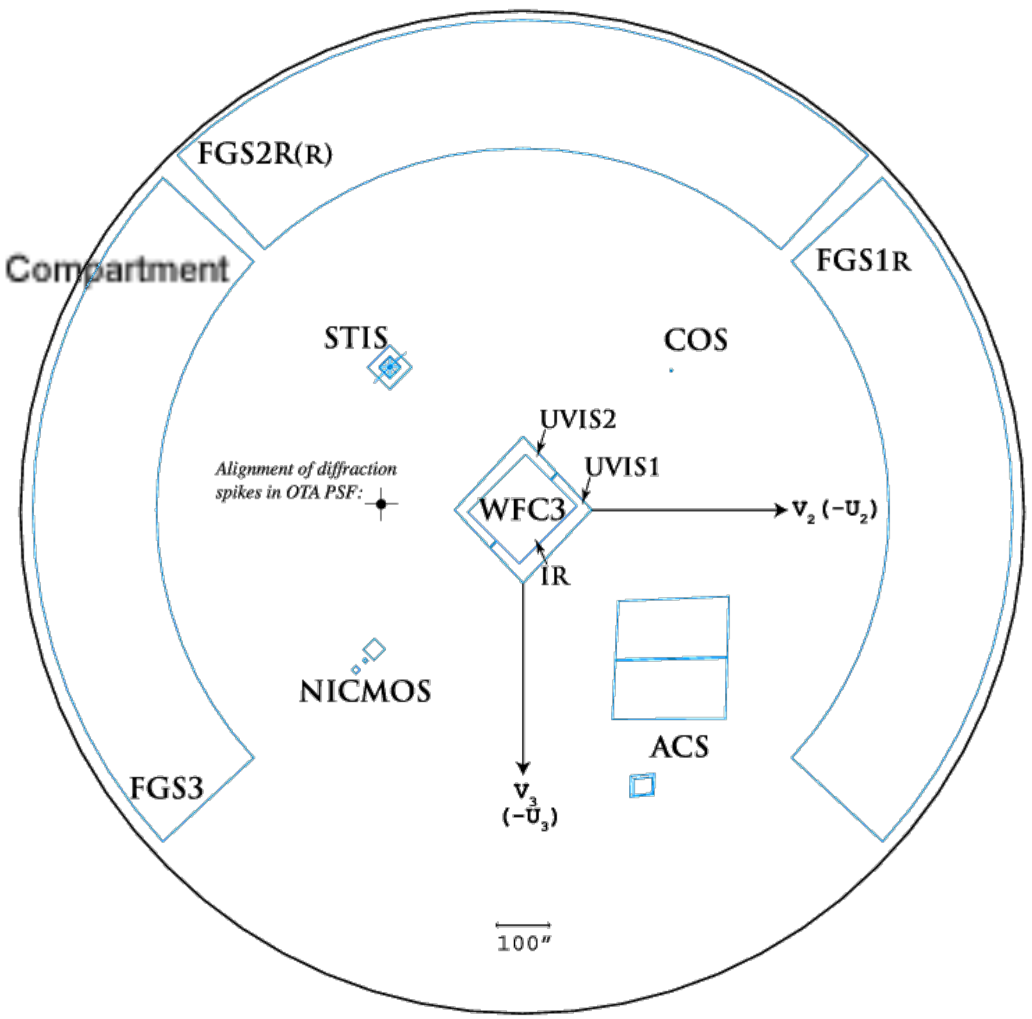


The Hubble Space Telescope Optical Systems Failure Report

Hubble Space Telescope

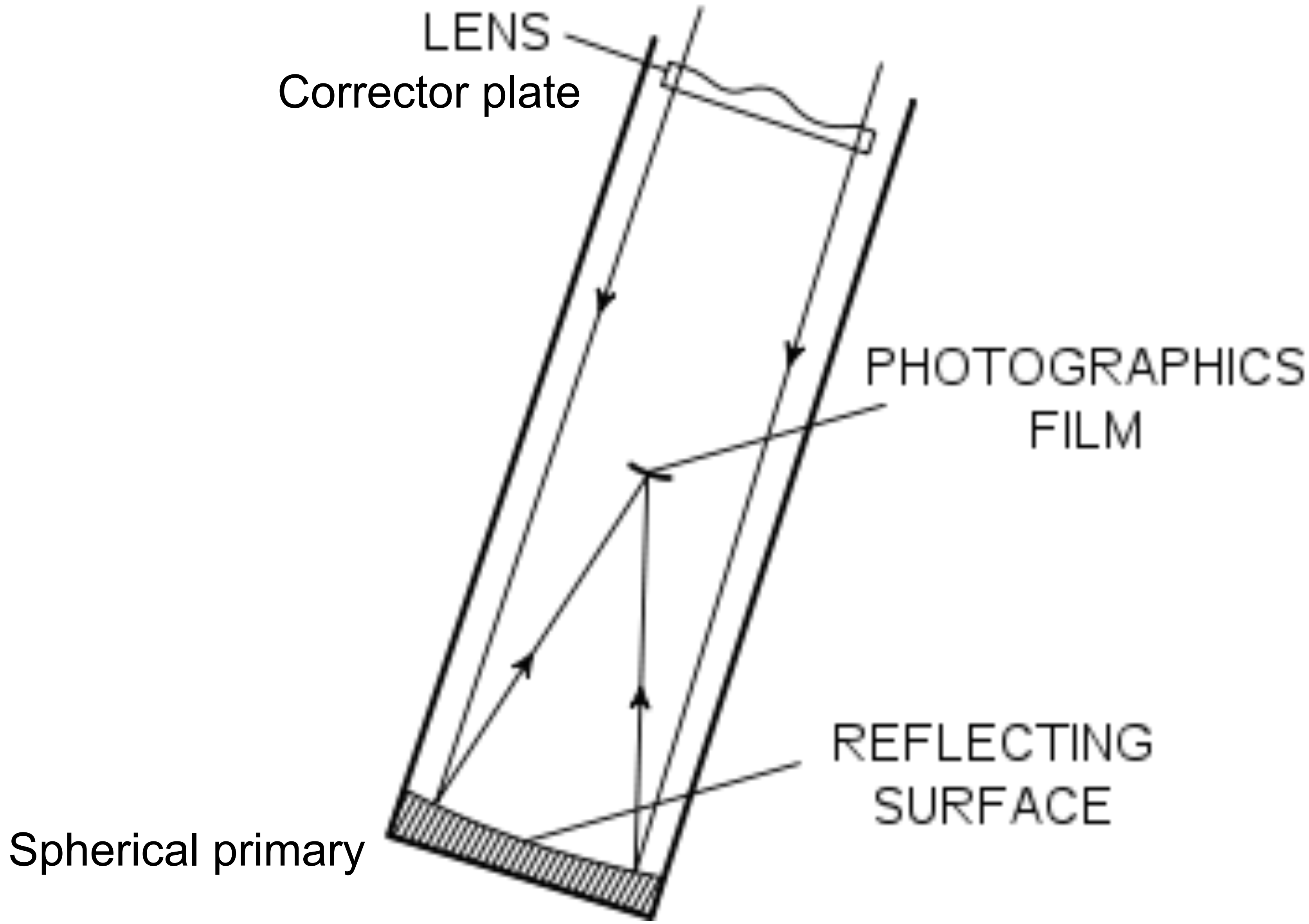


- Ritchey-Chrétien design
  - Residual field curvature limits the field-of-view of HST



Schmidt Telescope (Wide-field Telescopes)

A Schmidt design is a Catadioptric (Lens+Mirror) system : uses both refraction and reflection



Aspheric corrector plate removes spherical aberration

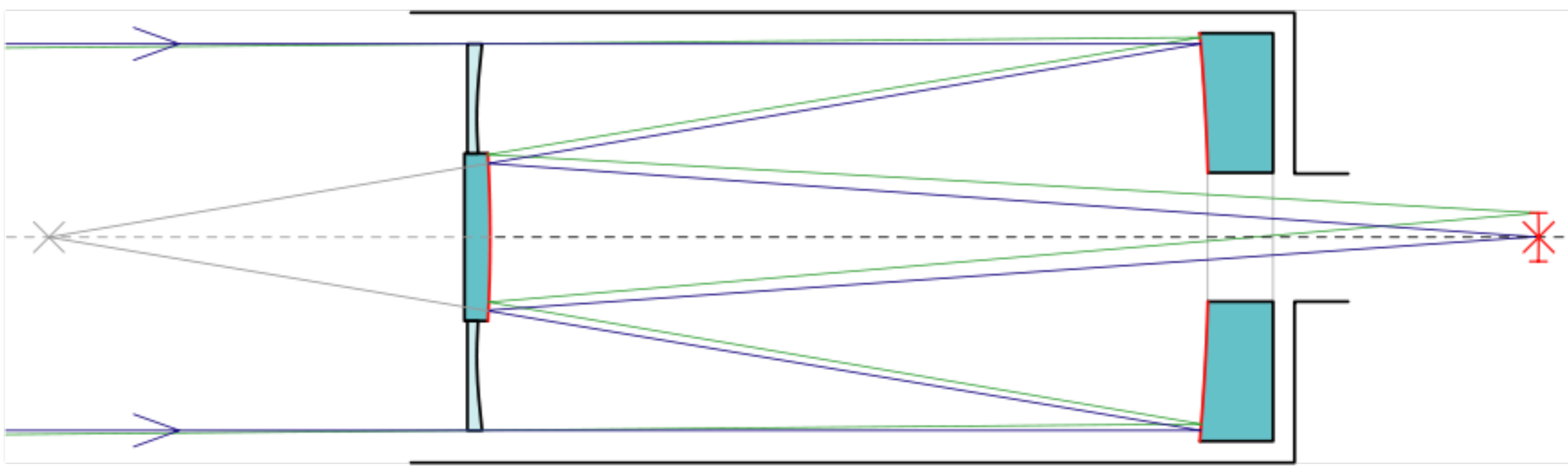
Spherical aberration is field independent with a spherical mirror
→ Correction is valid over a wide field of view
→ Modest image quality

Schmidt-Cassegrain Telescope

Easier access to focal plane.

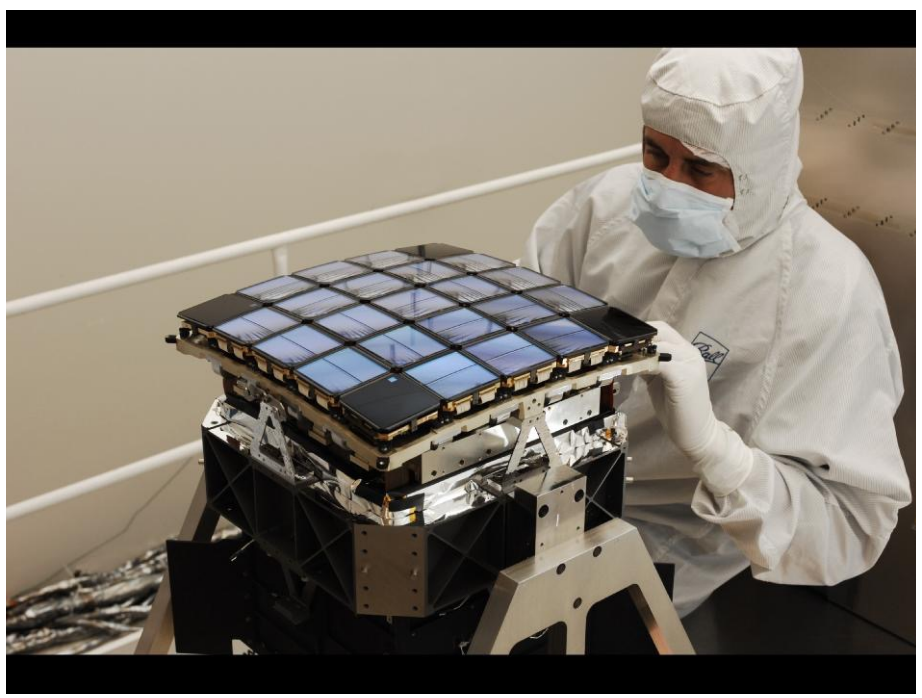
Spherical primary

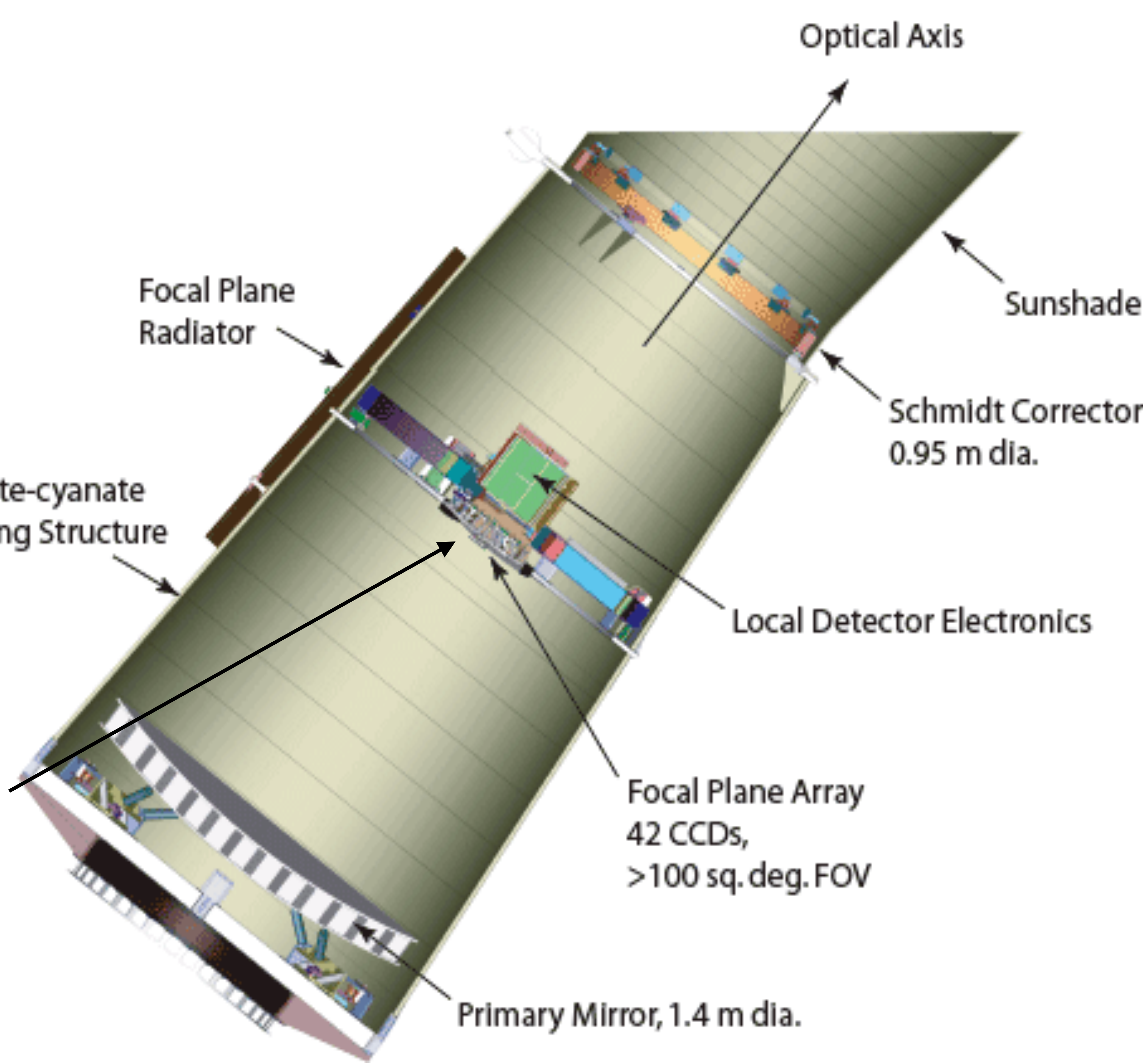
Corrector plate



Secondary mirror can flatten the field with proper choice of radius of curvature

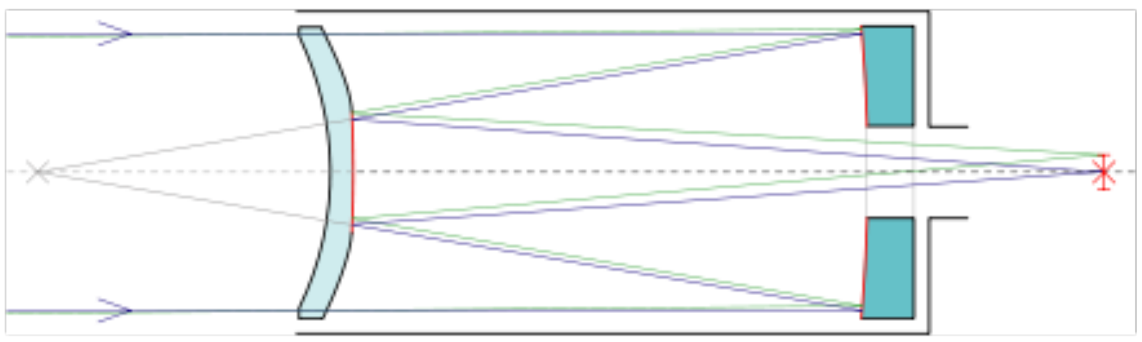
Schmidt Telescope: Kepler optical design



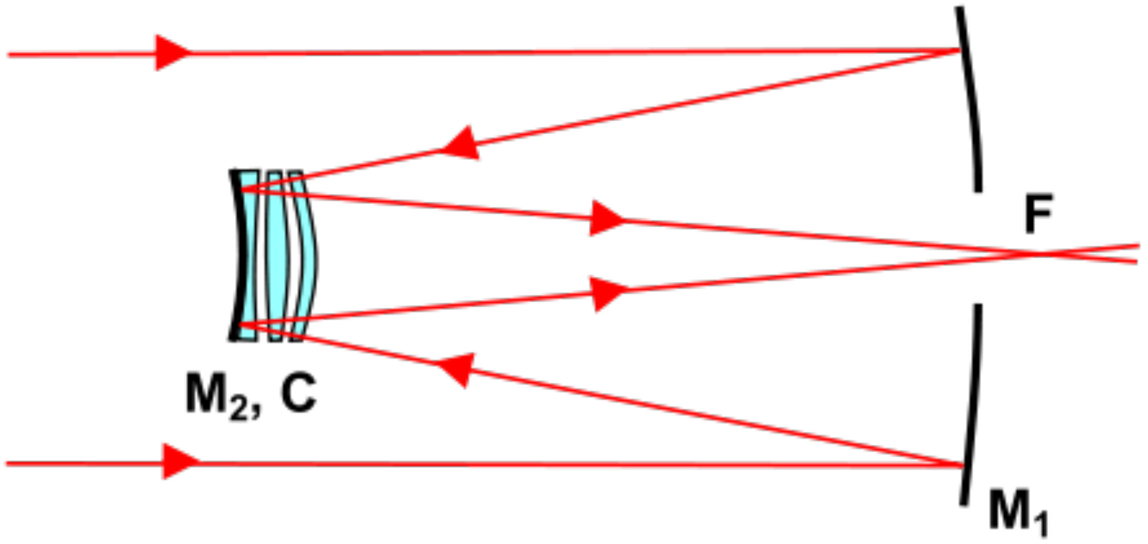


Kepler optical design: Schmidt camera for large field of view detector at prime focus.
→ no field flattening effect of secondary mirror
→ strong field curvature (corrected for by curving the focal plane!)
Note that PM is larger than corrector plate. Effective diameter is set by corrector.

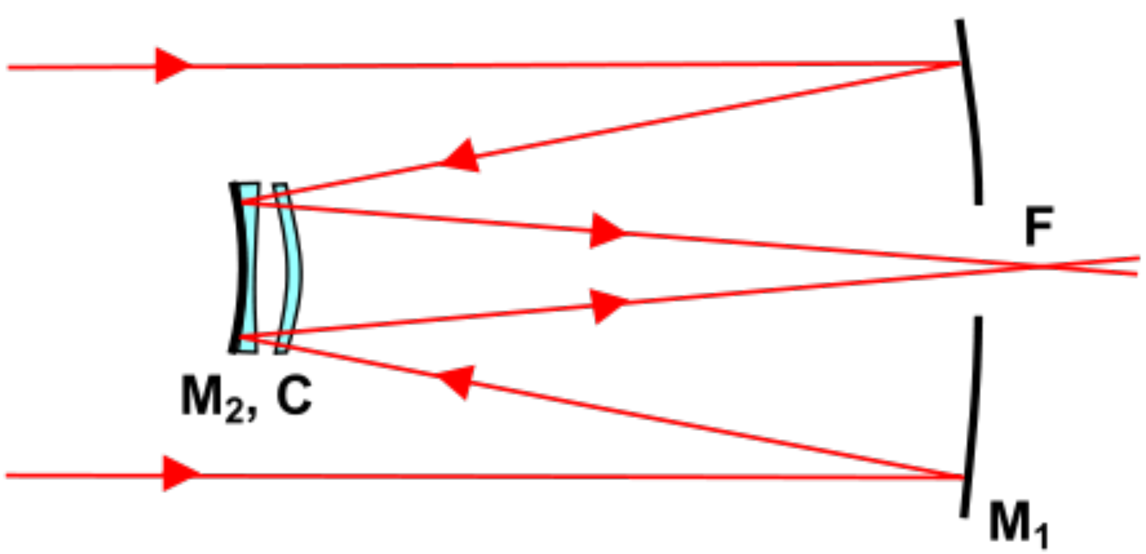
Other Catadioptric telescope designs



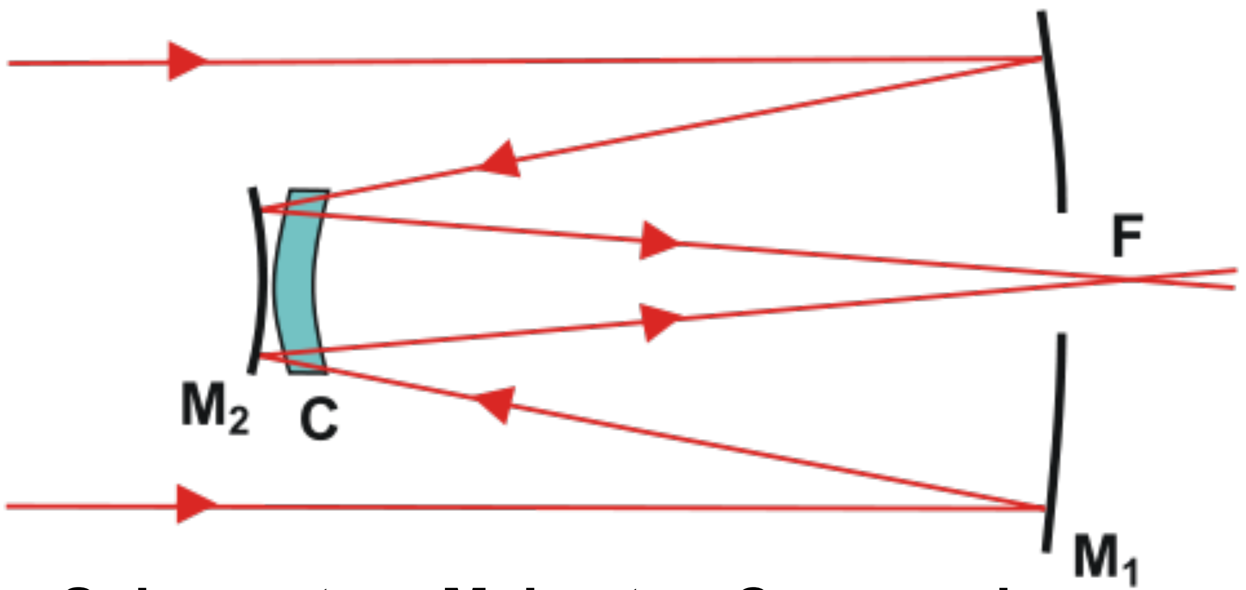
Maksutov-Cassegrain



Argunov-Cassegrain



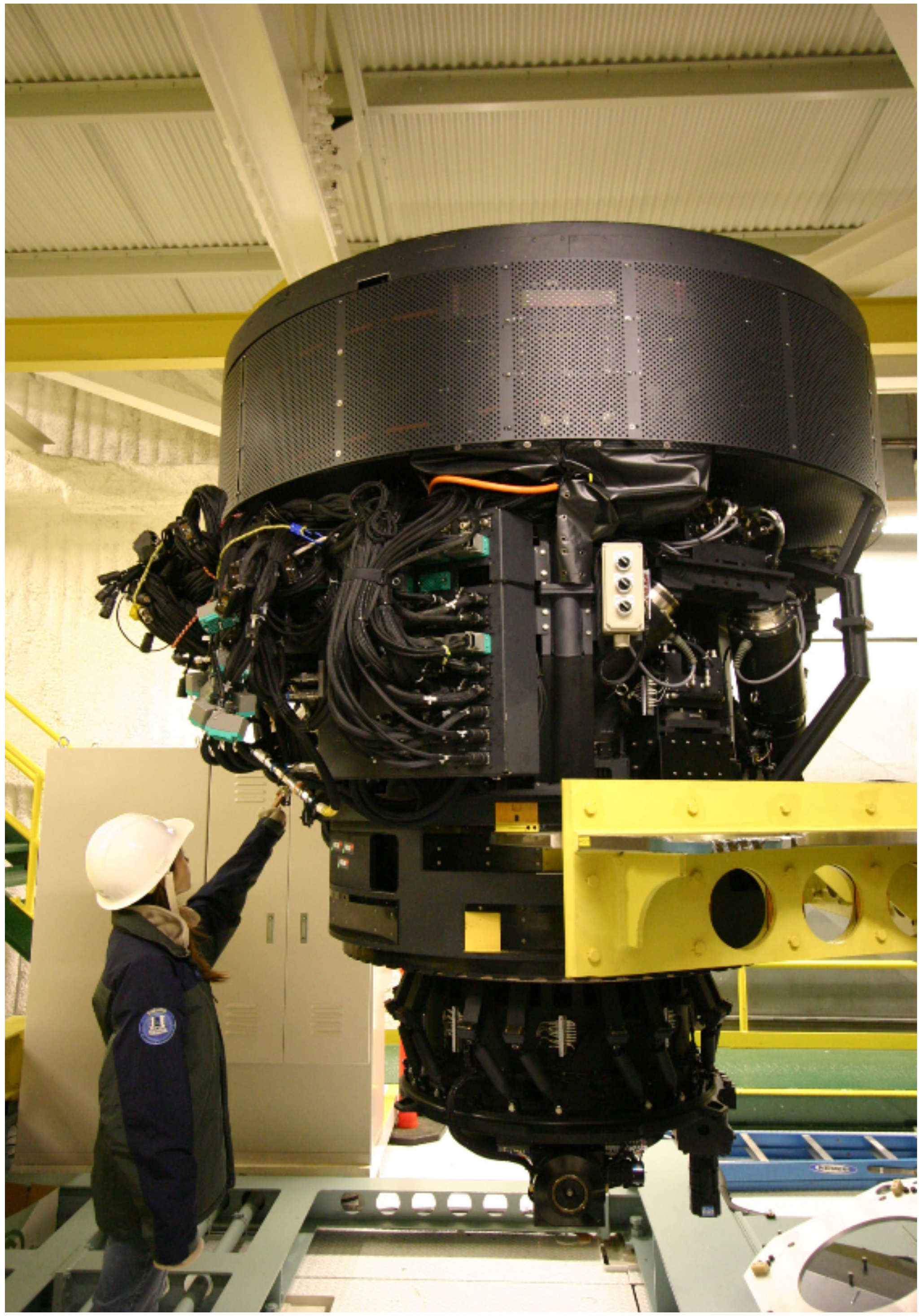
Klevtsov-Cassegrain



Sub-aperture Maksutov-Cassegrain

SuprimeCAM corrector (Subaru Telescope)

Possible to extend field of existing telescopes



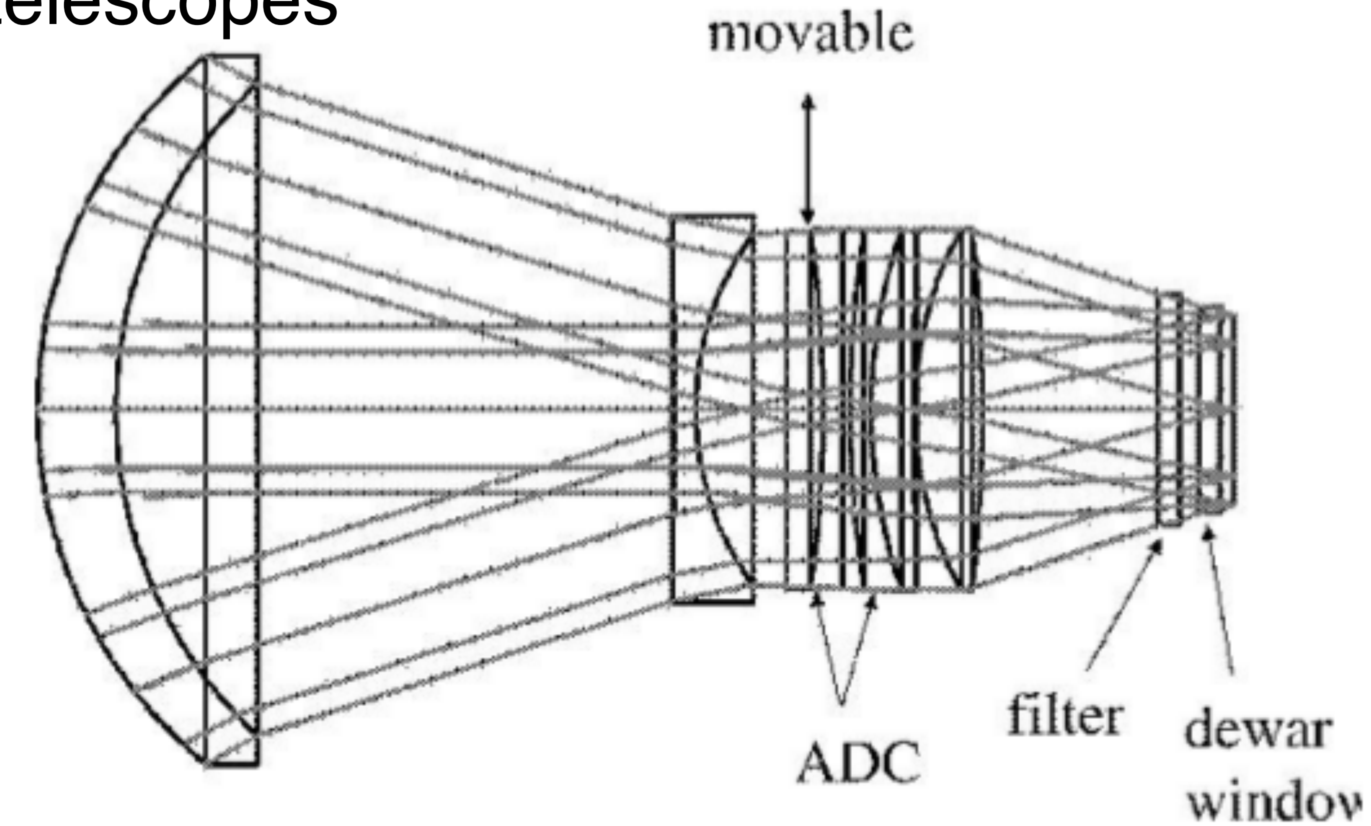
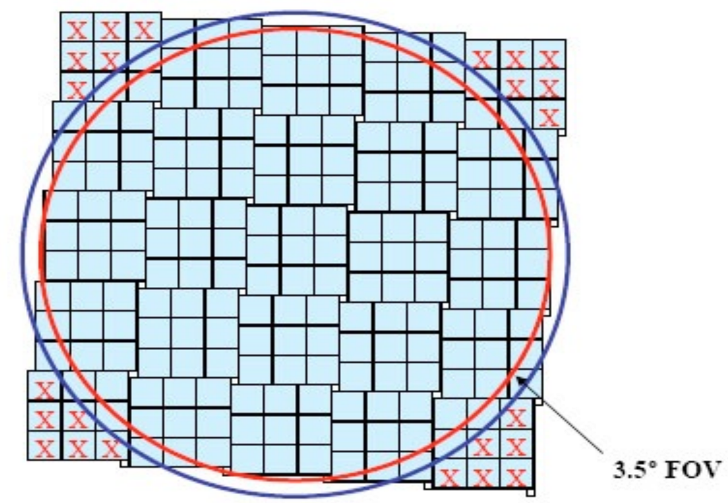


Fig. 14. Prime-focus corrector for Suprime-Cam based on a three-lens corrector design (Wynne 1965), but optimized with additional optical components for ADC.

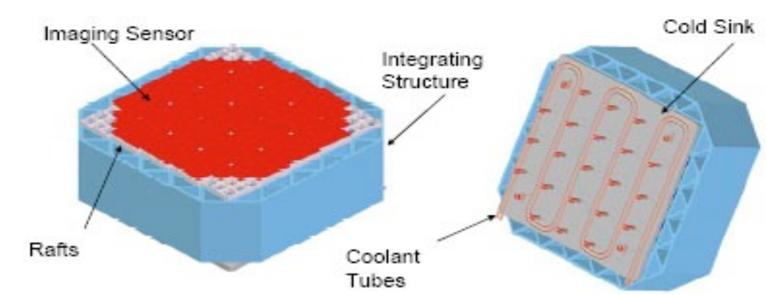
Large Synoptic Survey Telescope

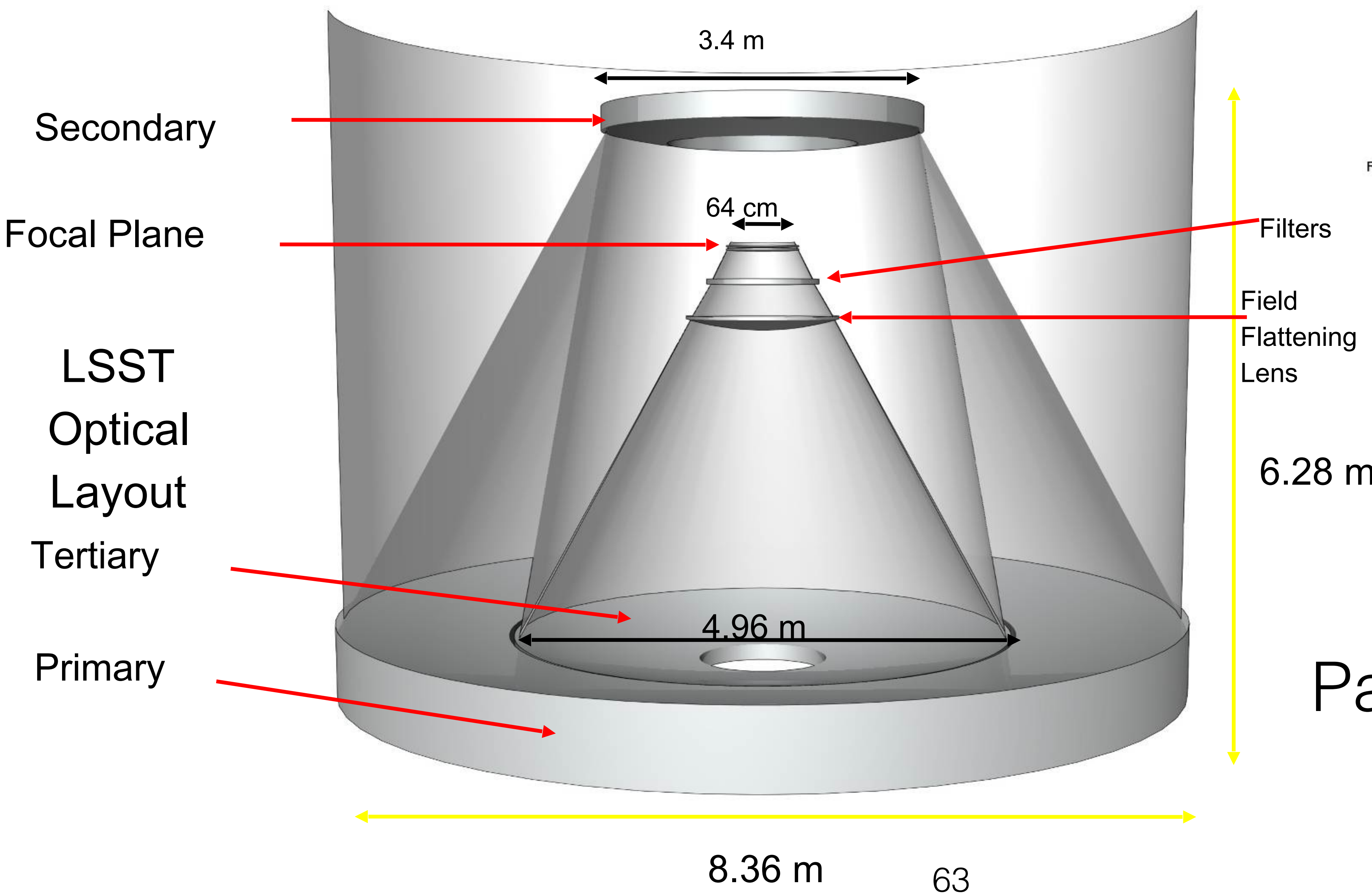
200 4k x 4k detectors



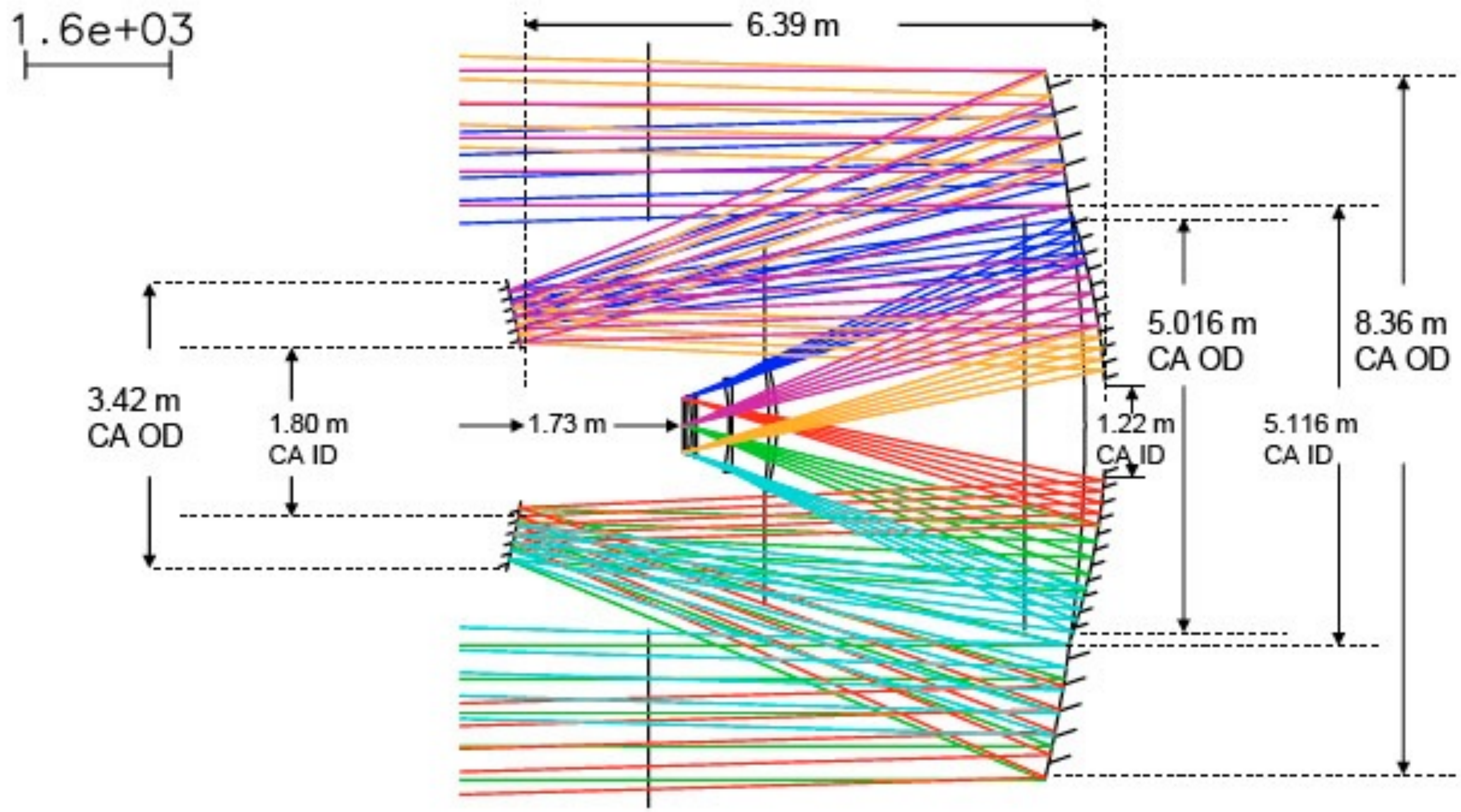
3.5° field of view for all-sky survey

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

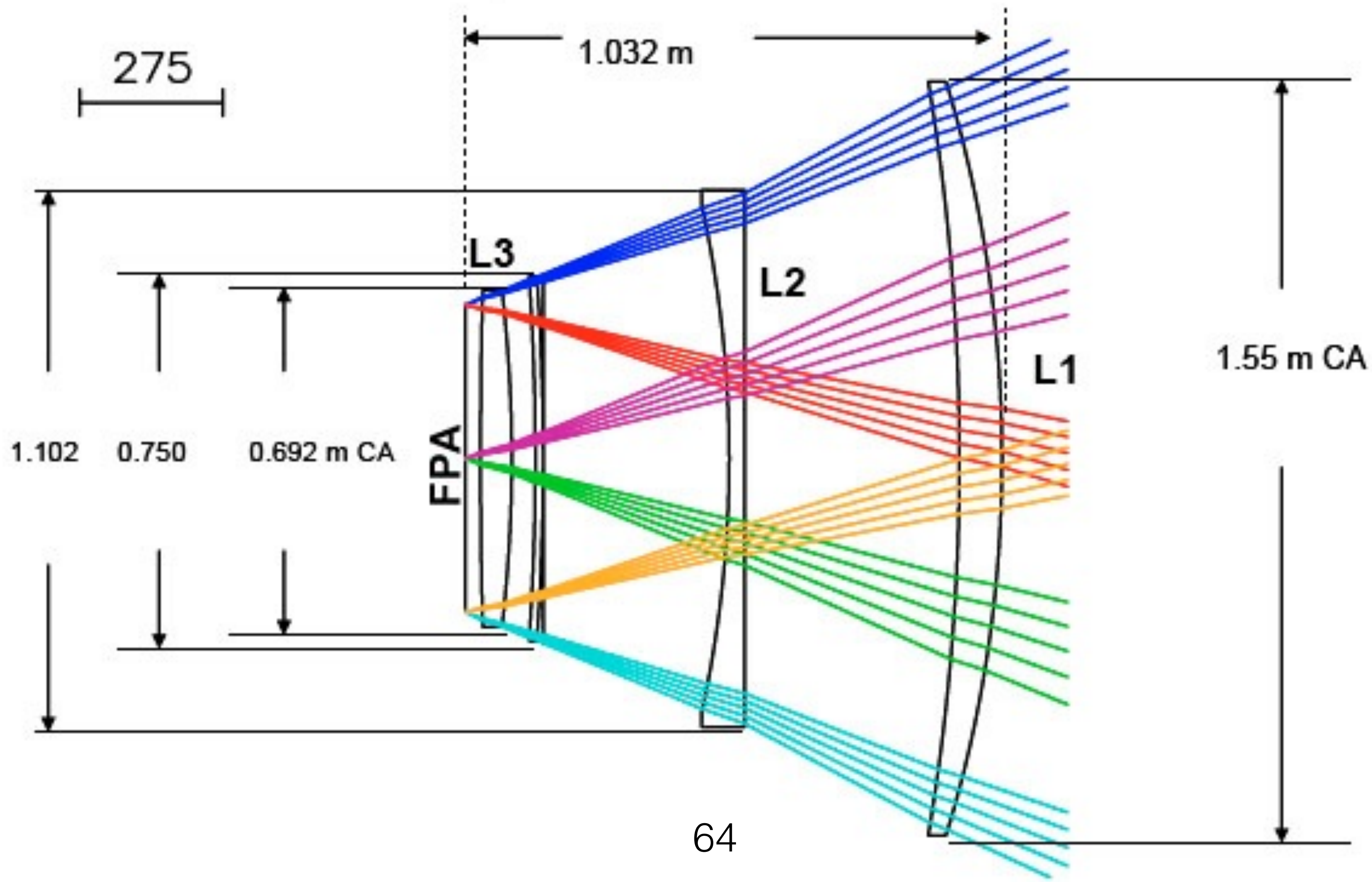




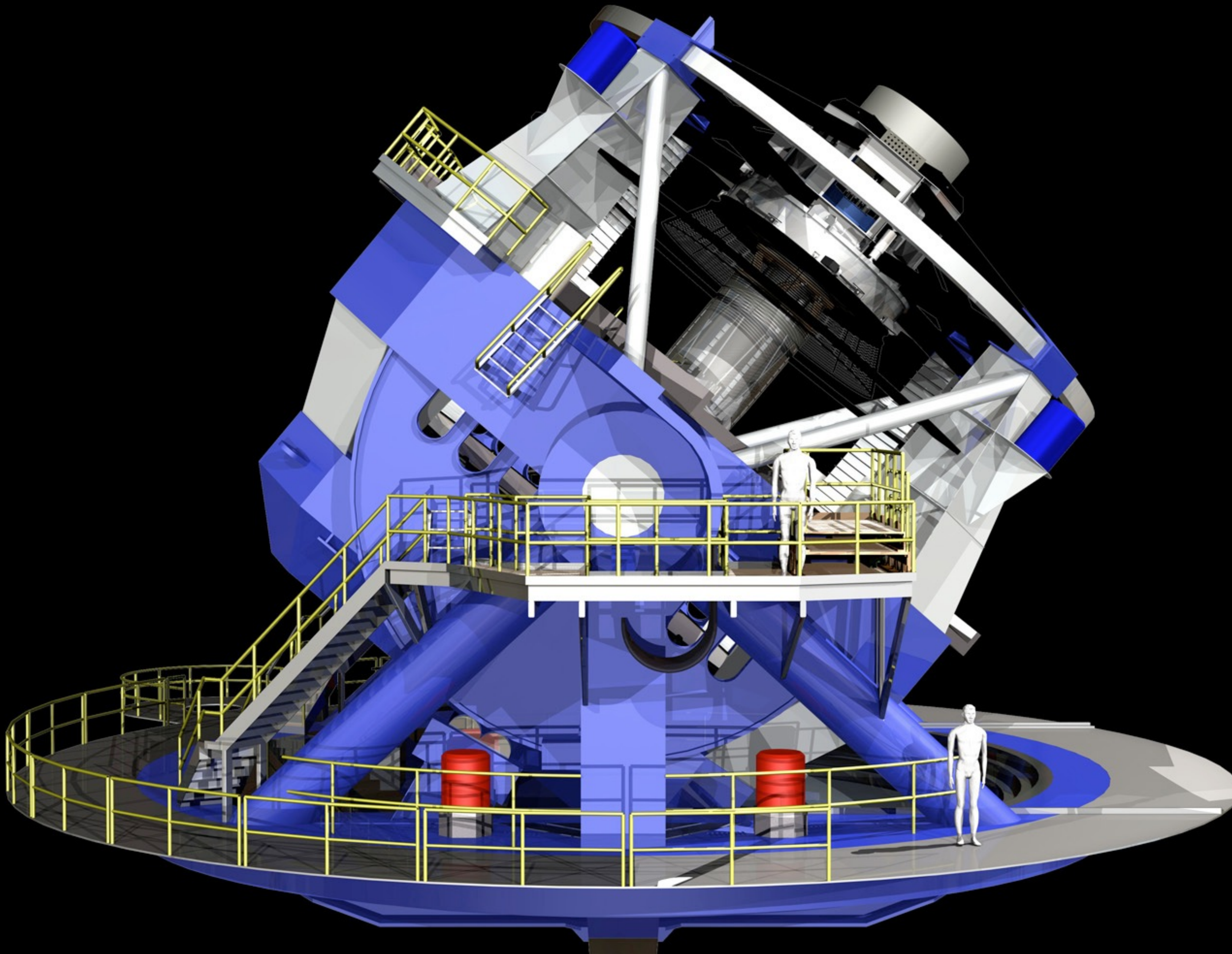
Paul-Baker Design



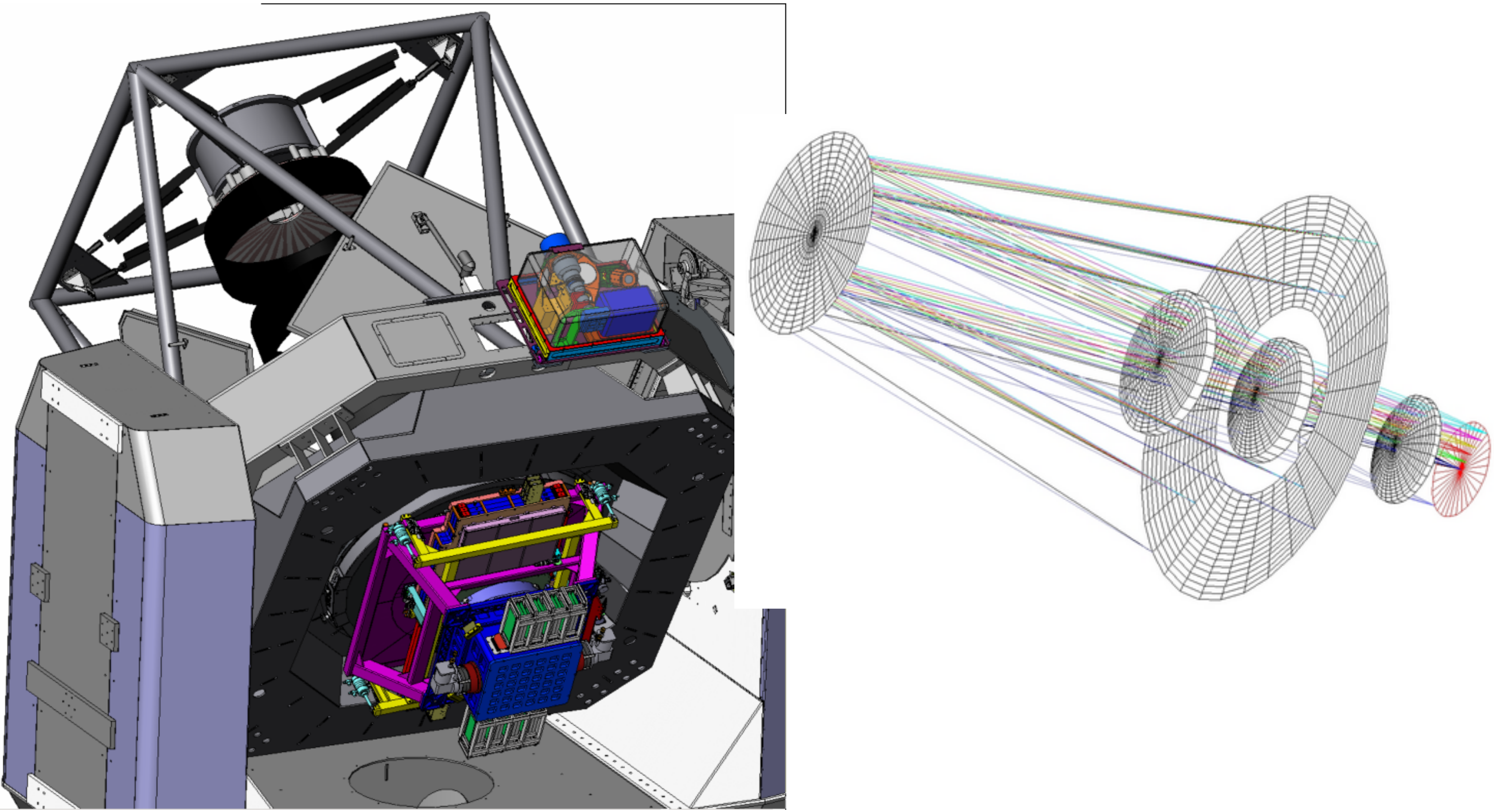
1.6e+03
6.39 m
5.016 m
CA OD
8.36 m
CA OD
3.42 m
CA OD
1.80 m
CA ID
1.73 m
1.22 m
CA ID
5.116 m
CA ID



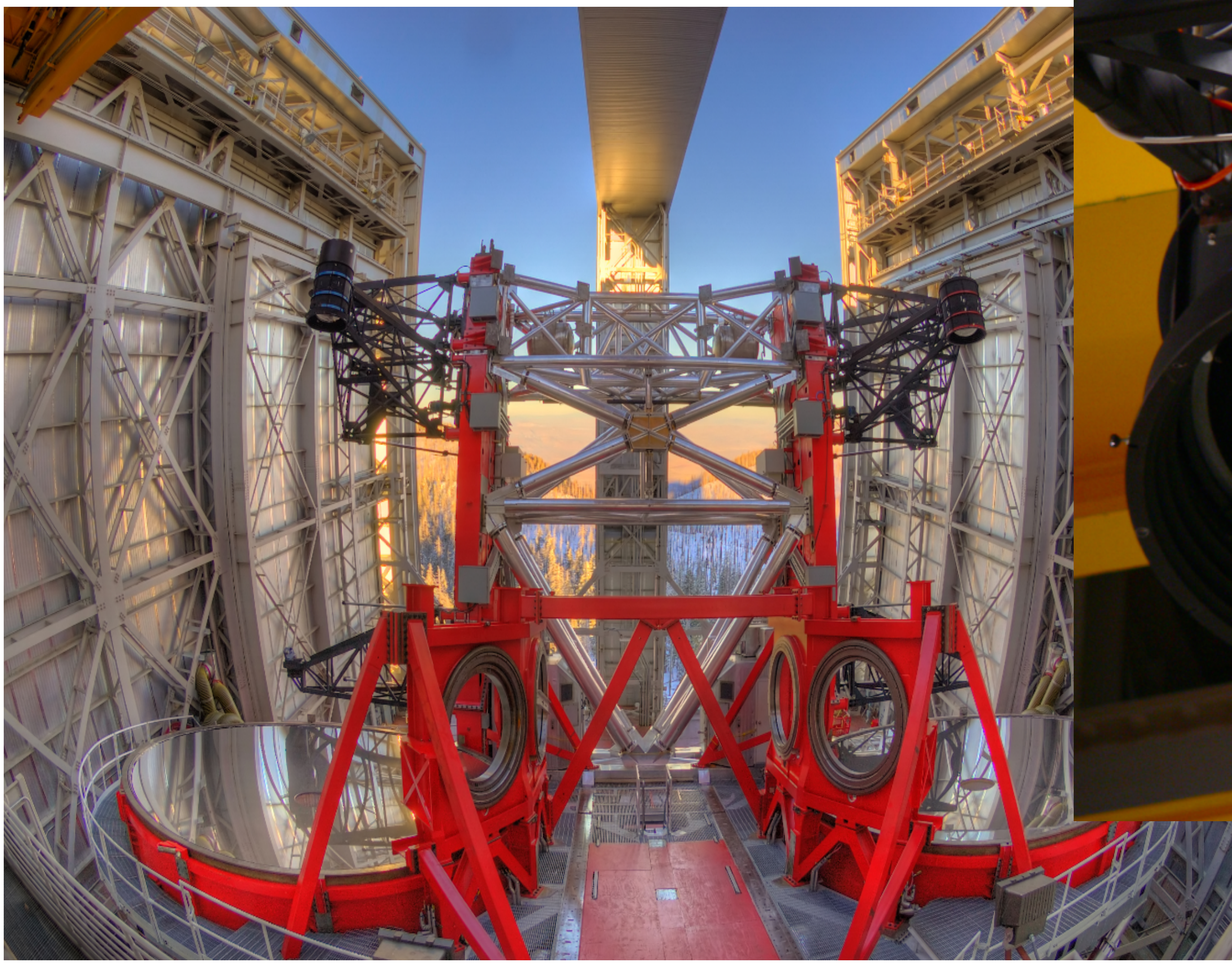
275
1.032 m
L3
L2
L1
1.55 m CA
1.102
0.750
0.692 m CA
FPA

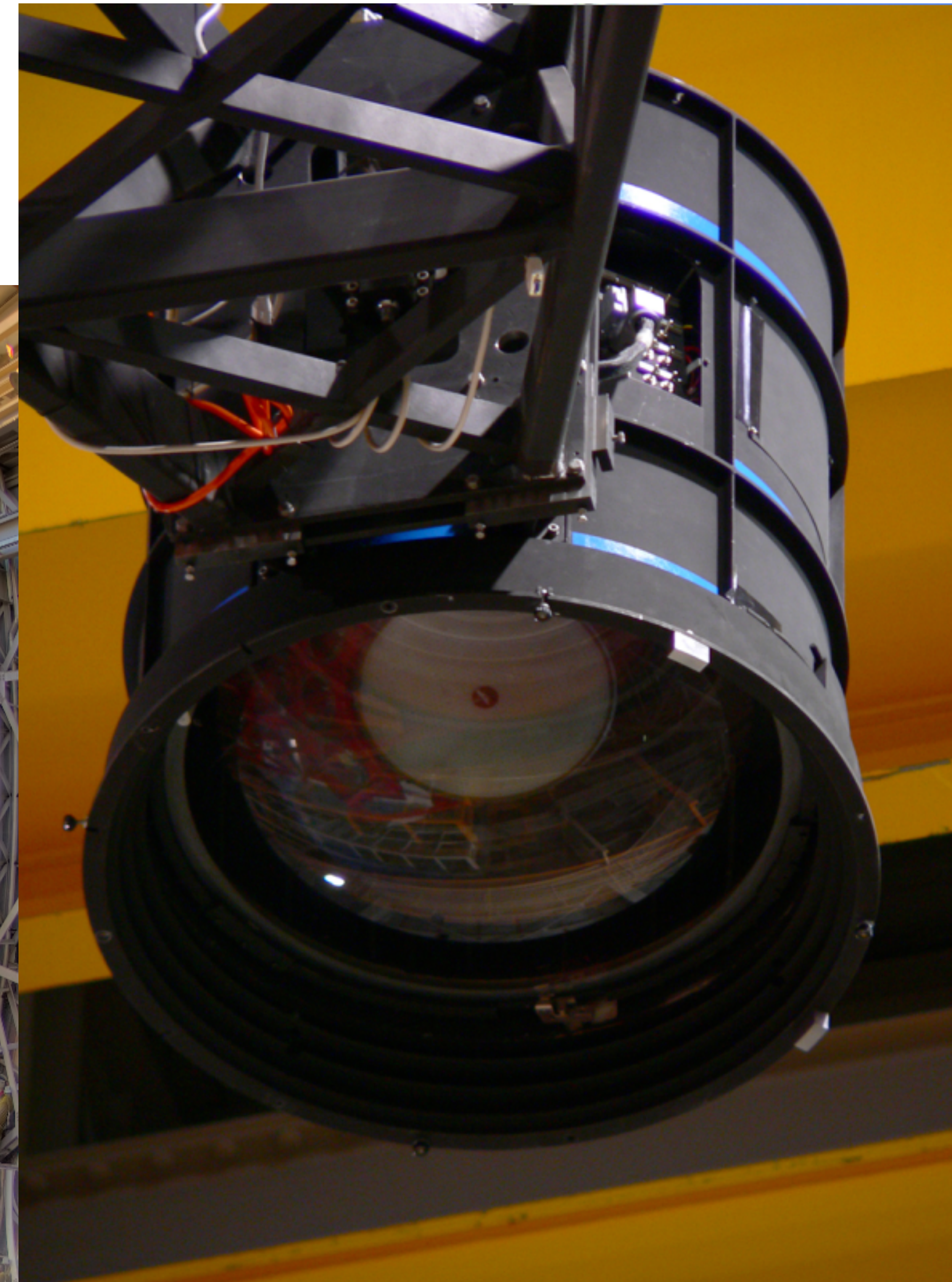


Pan-STARRS : 1.8m diameter telescope, 3 deg. diameter FOV



Large Binocular Telescope's (8.4 meter)
Wide field cameras ~ 0.4 deg. on a side





Survey Speed

If the cameras are the same for Pan-STARRS and LBC, which can survey a large patch of sky to a certain depth in a given amount of time?

LBC requires $(3/0.4)^2$ pointings to survey the field Pan-STARRS gets in a single pointing. 56 times worse.

However, it collects the same number of photons in $(1.8/8.4)^2$ of the time. 22 times faster.

Conclusion: Pan-STARRS would be more effective for observing a large FOV. However, for areas < 20-30’ LBC would be preferred.

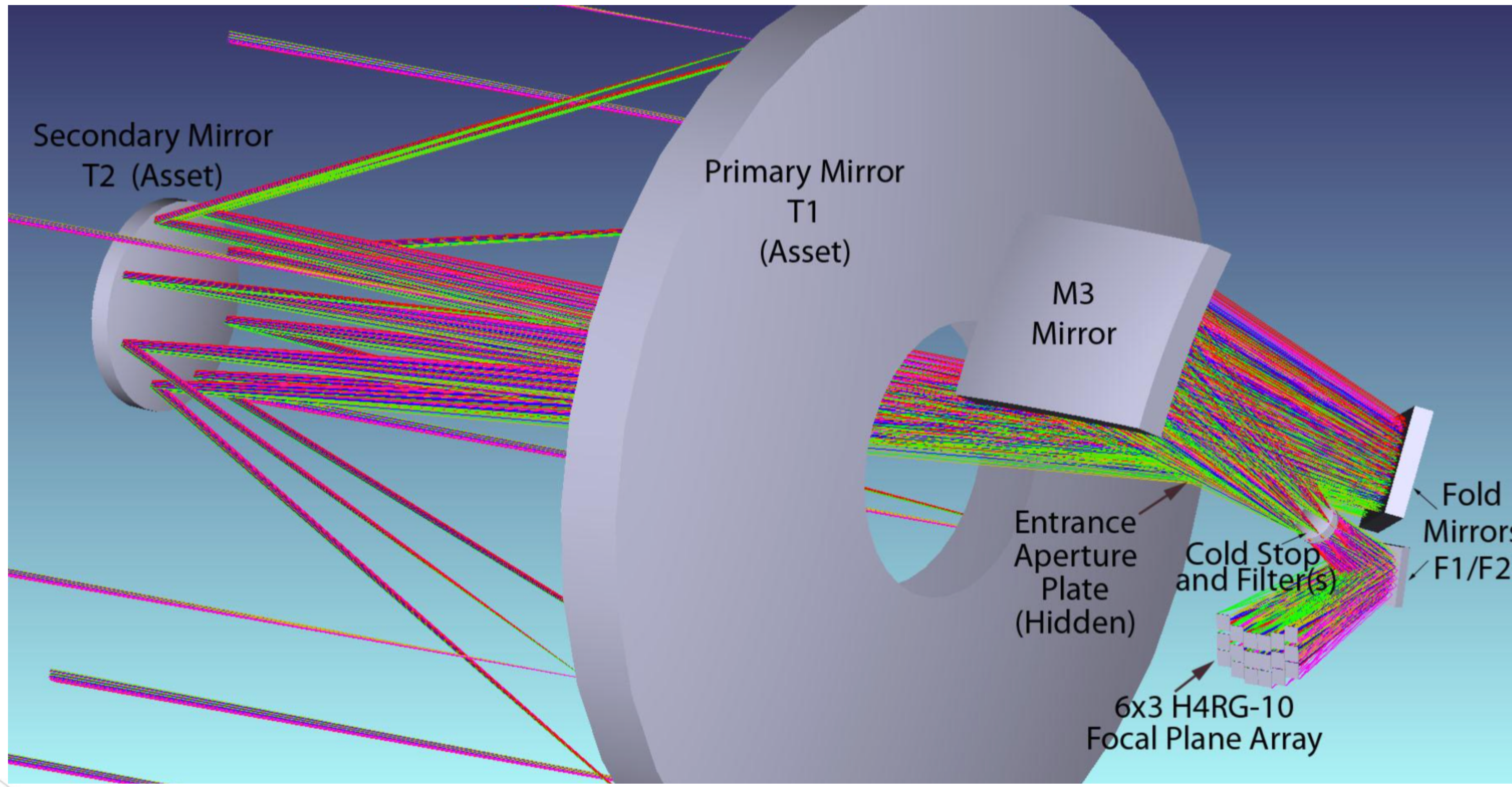
The parameter most important for survey efficiency is called **étendue**, or AΩ product:

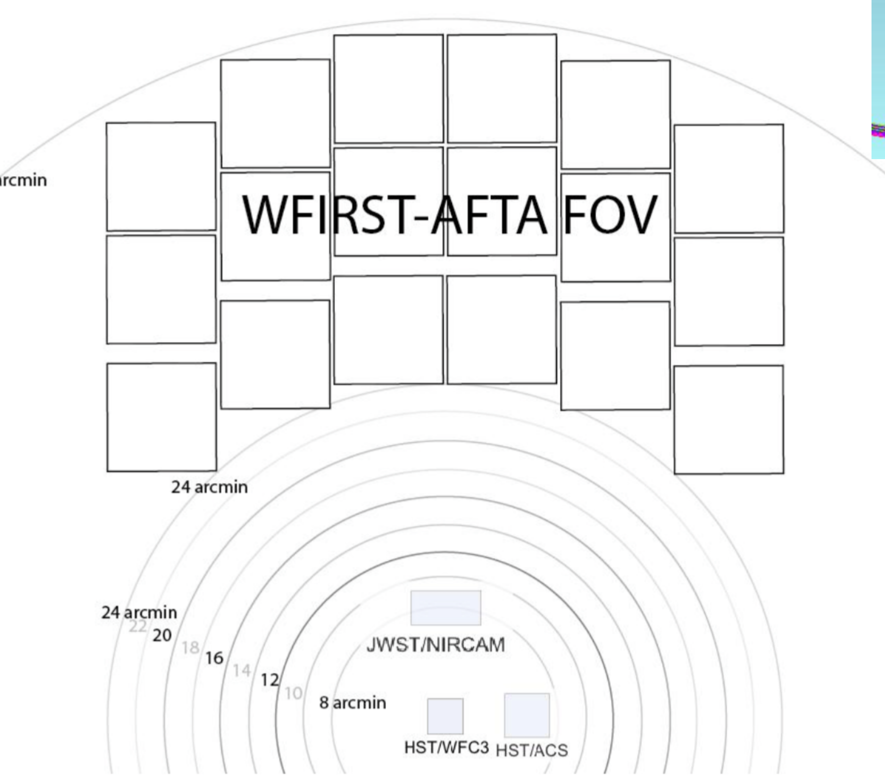
AΩ = collecting area [m²] x field of view [sq. deg]

Survey time = 1/AΩ

TMA (Three Mirror Anastigmat)

WFIRST, annular FOV, 0.28 sq degrees,
2.4 m aperture, 0.8-2.0 µm bandpass





Moon (average size seen from Earth)

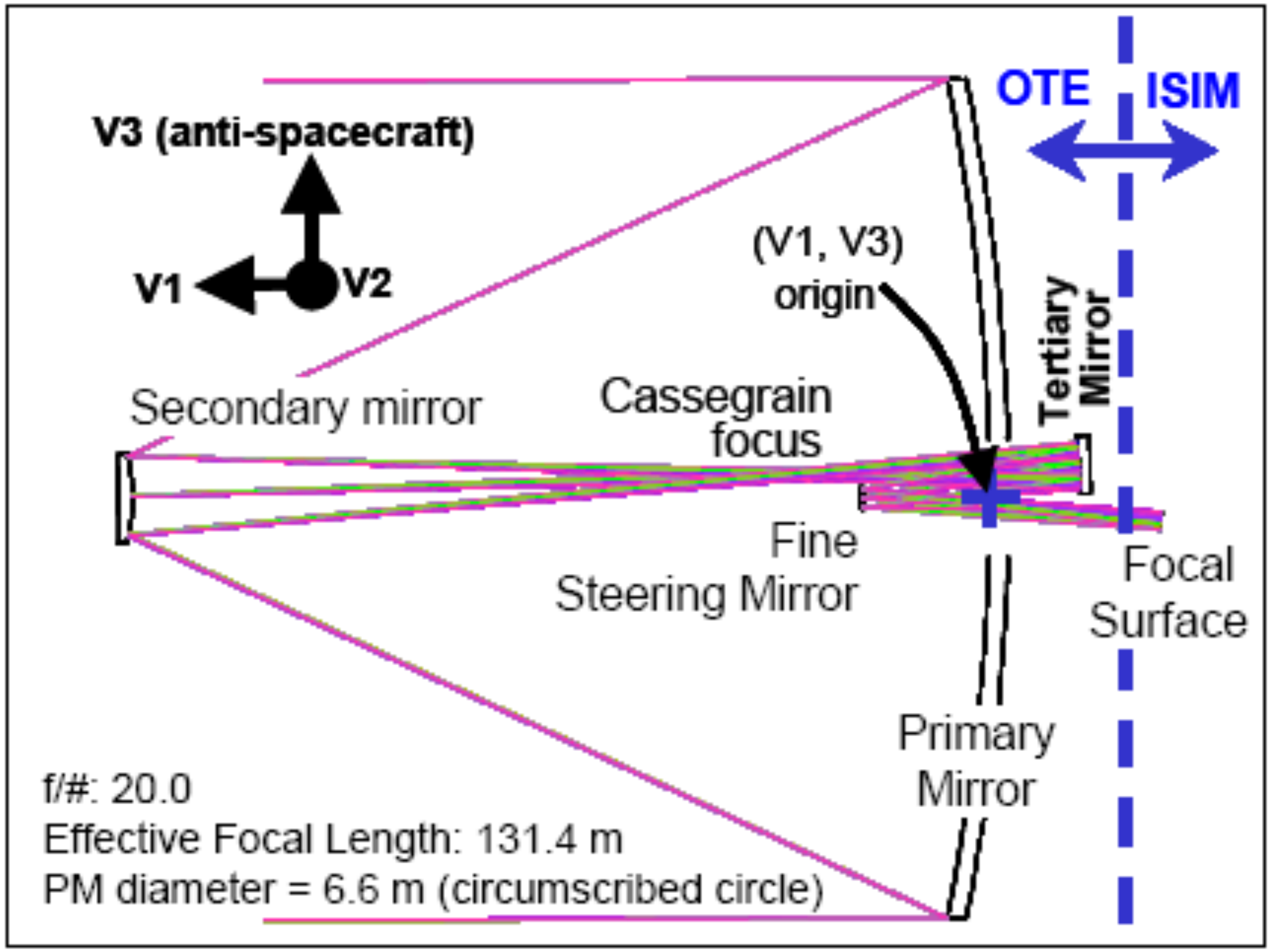
Multiple Instruments:

Wide-field Camera

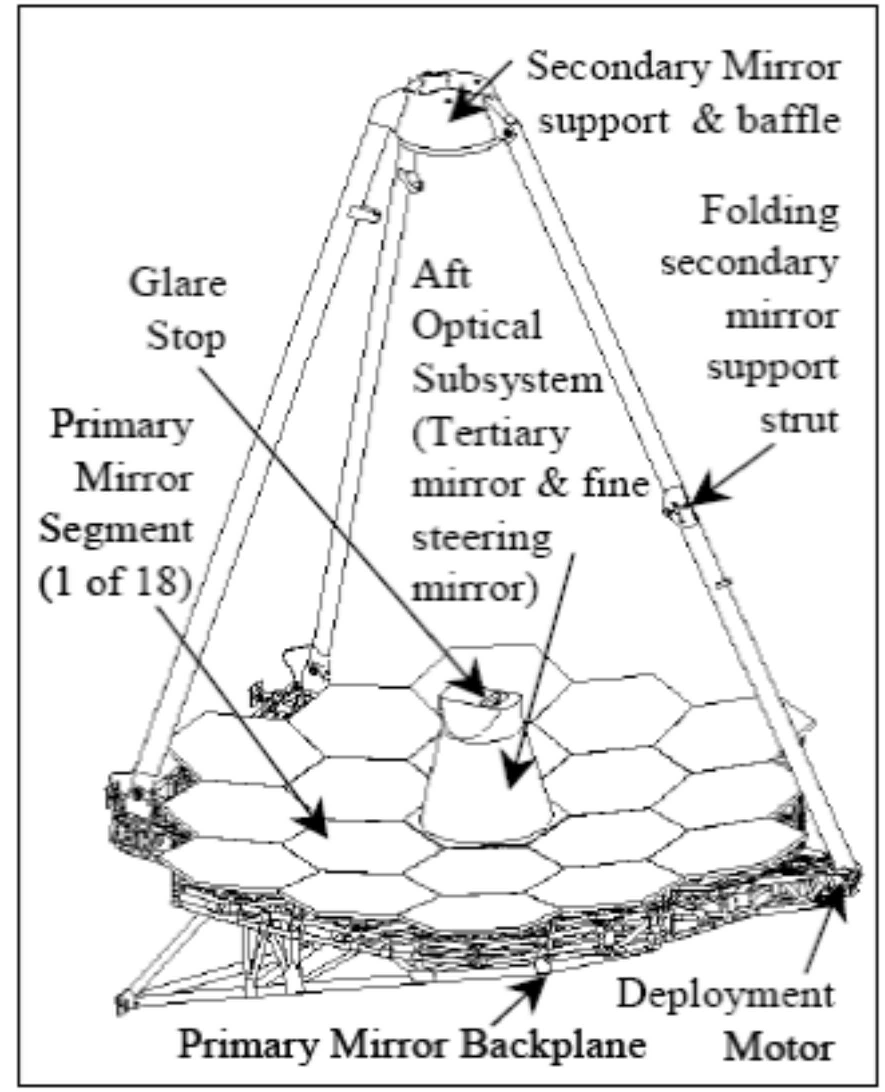
High Contrast Exoplanet Imager

Integral-Field Spectrograph

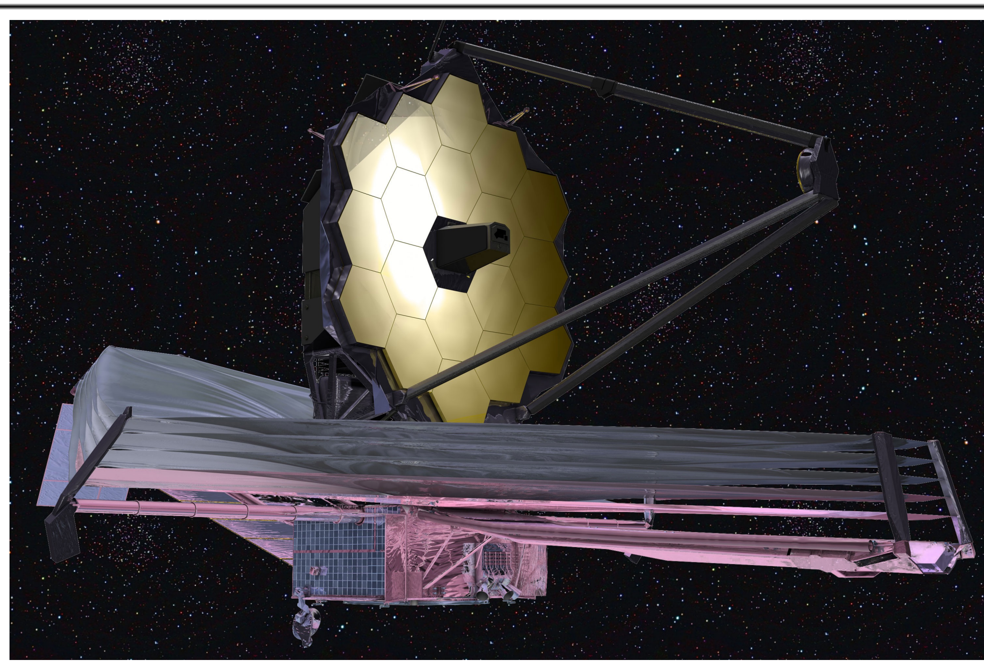
JWST TMA

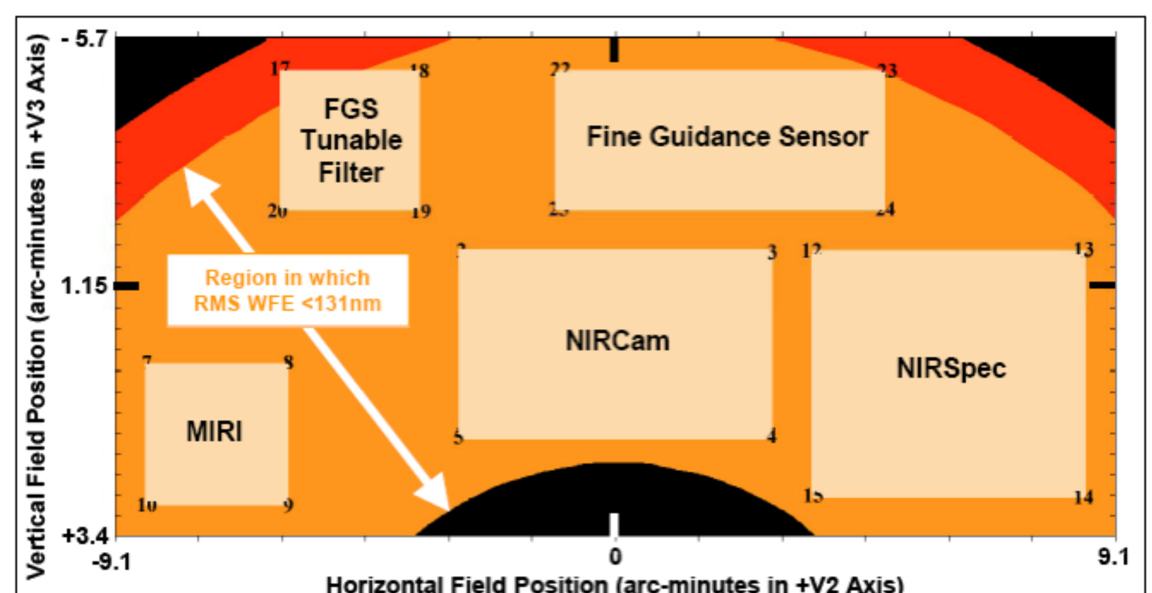


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

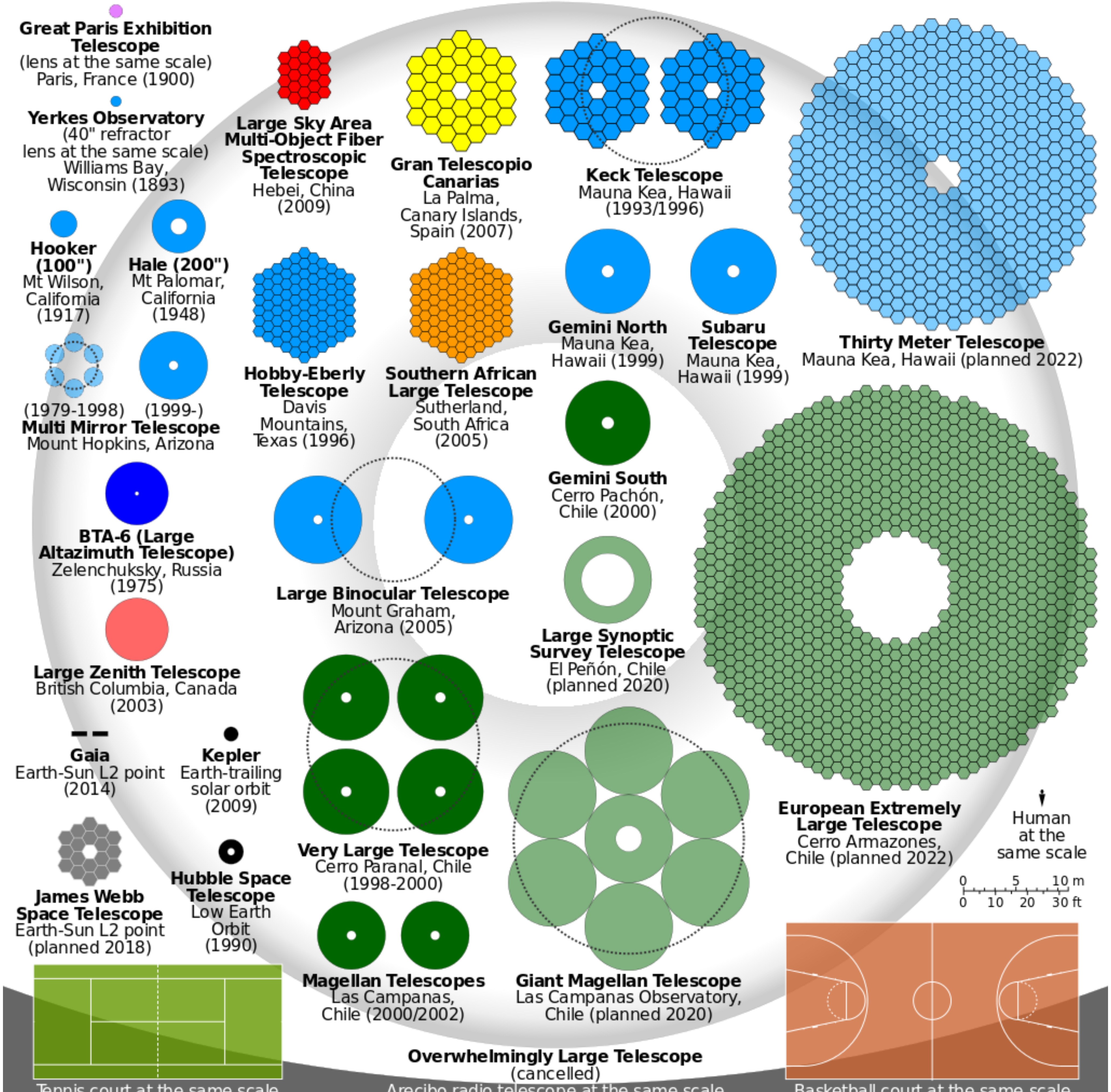


Secondary Mirror
support & baffle
Folding
secondary
mirror
support
strut
Glare
Stop
Aft
Optical
Subsystem
(Tertiary
mirror & fine
steering
mirror)
Primary
Mirror
Segment
(1 of 18)
Deployment
Motor
Primary Mirror Backplane



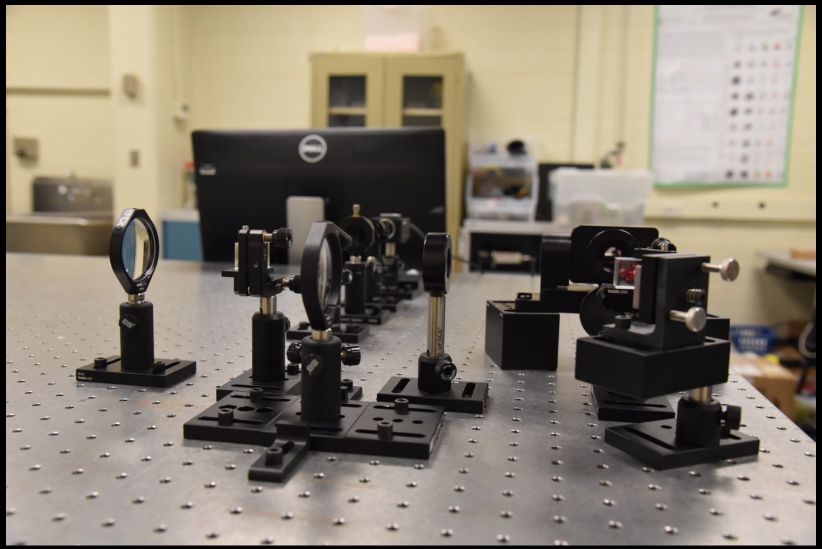


FGS
Tunable
Filter
Fine Guidance Sensor
Region in which
RMS WFE <131nm
NIRCam
NIRSpec
MIRI
Vertical Field Position (arc-minutes in +V3 Axis)
- 5.7
1.15
+3.4
-9.1
0
9.1
Horizontal Field Position (arc-minutes in +V2 Axis)



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)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchukskу, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
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)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
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)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

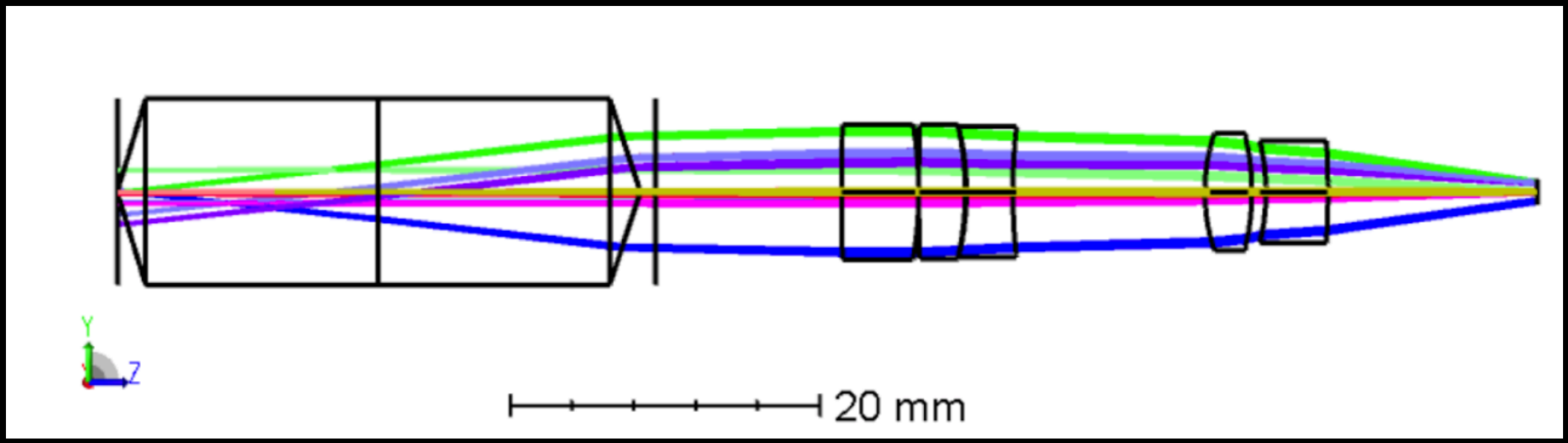
Our Lab


Adaptive Optics Testbed

Pillars:

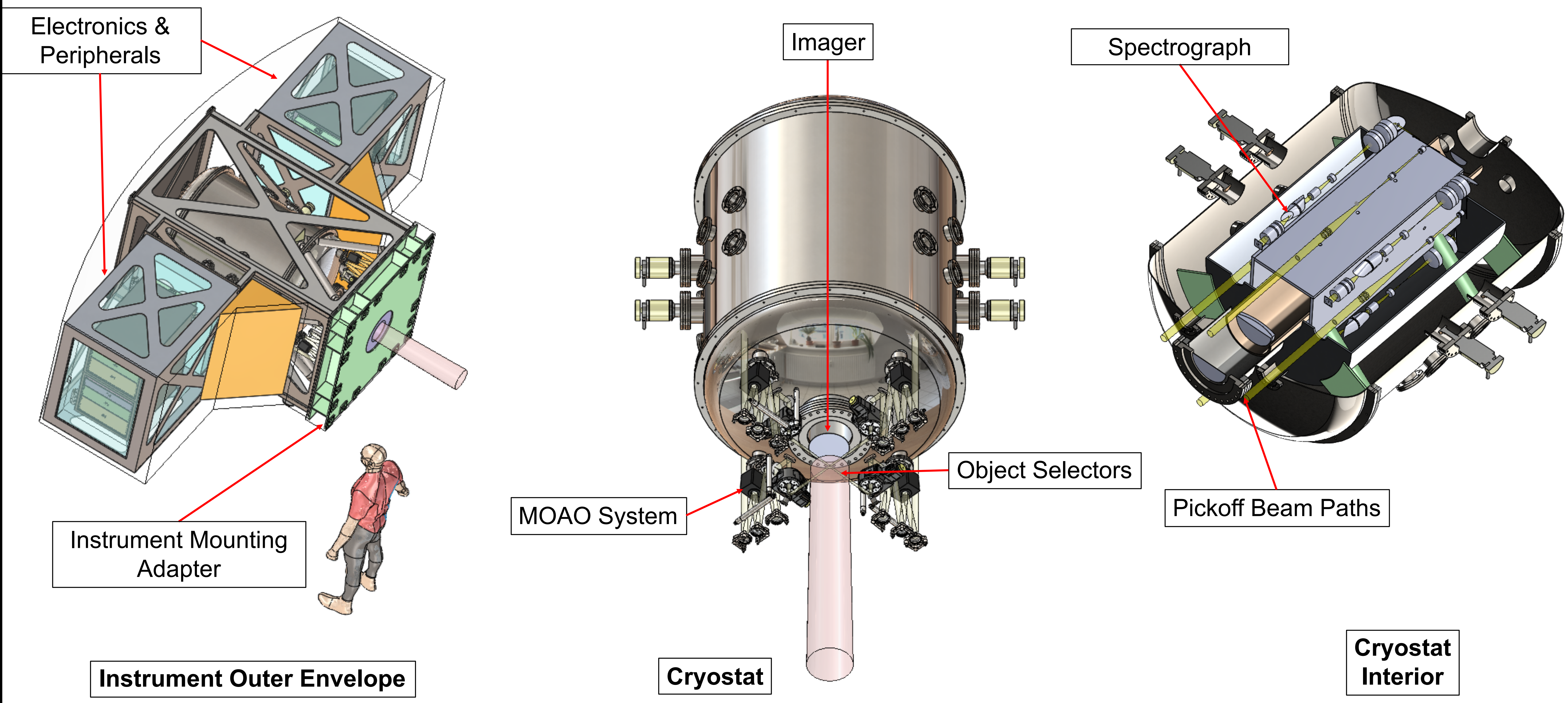
1. Adaptive Optics
2. Multiplexed Spectroscopy
3. Astrophotonics


DMD Test Bench (Credit: Dunlap Institute)



IR Pyramid Wavefront Sensor (Credit: Shaojie Chen)

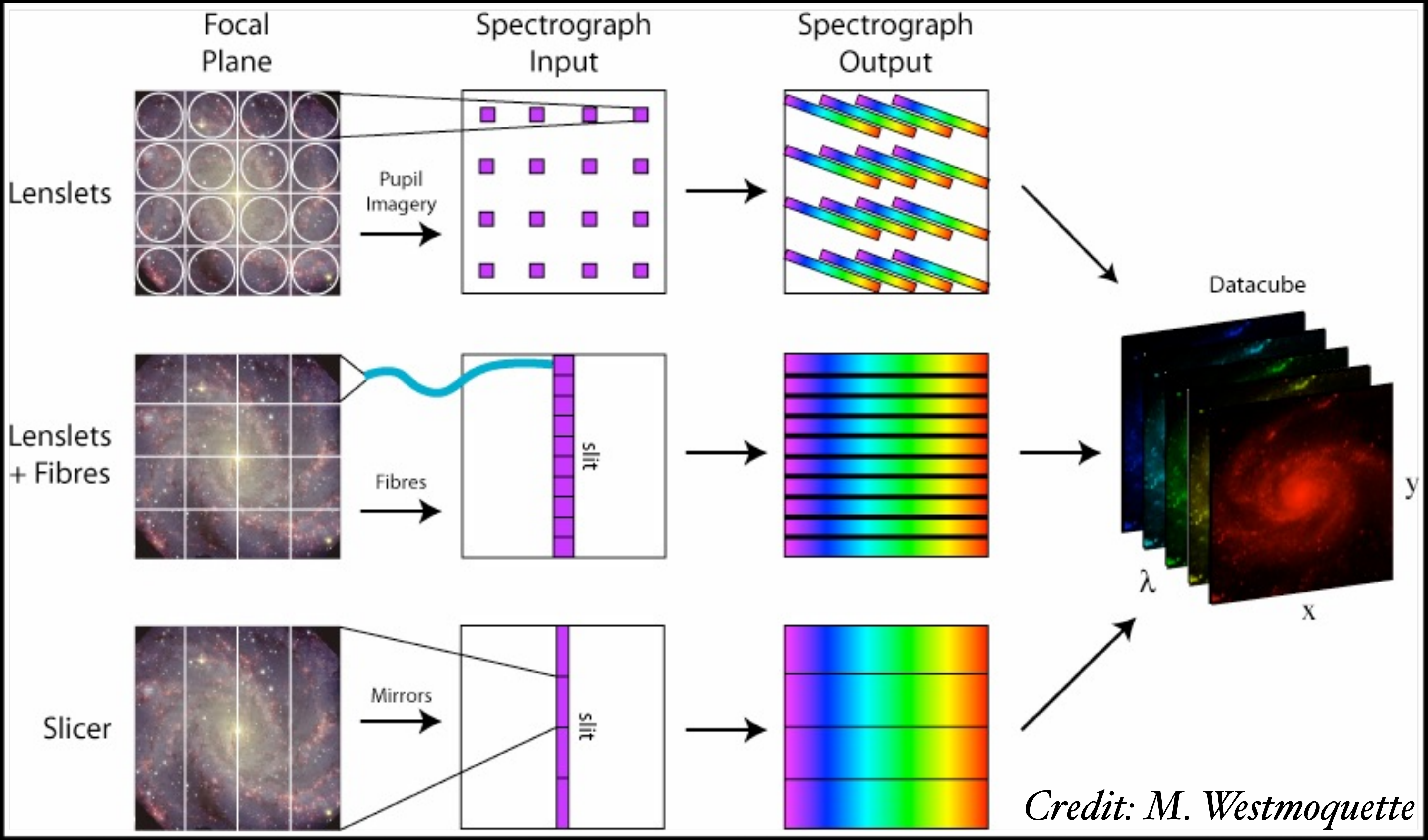
Next Generation Instrument & Pathfinder



Gemini Infrared Multi-Object Spectrograph

Multi-Object AO + Imaging Spectroscopy

What is Integral-Field Spectroscopy?

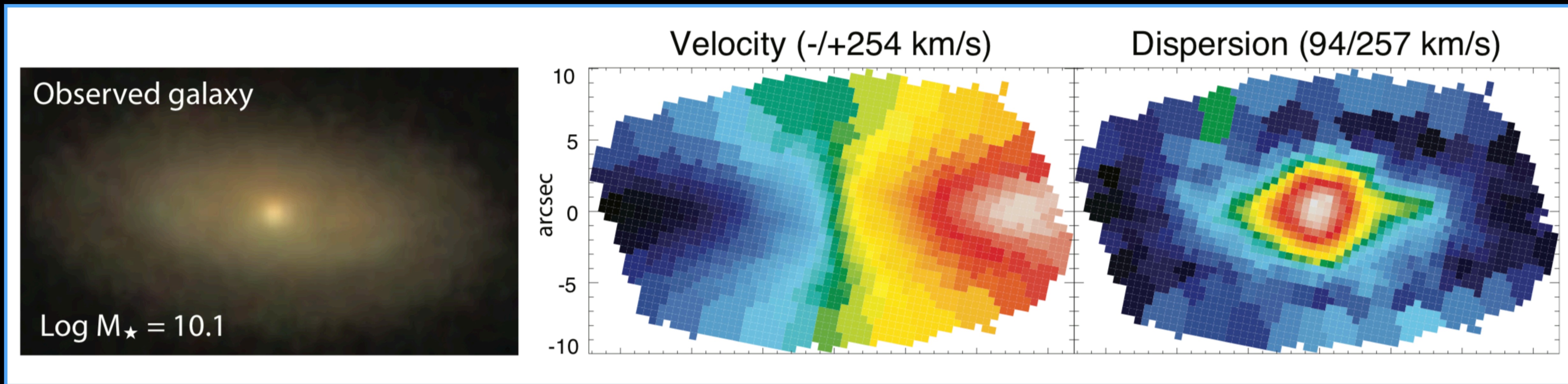


Require a method to reformat the telescope field into the spectrograph

Individual lenslets and fibres to not preserve spatial information

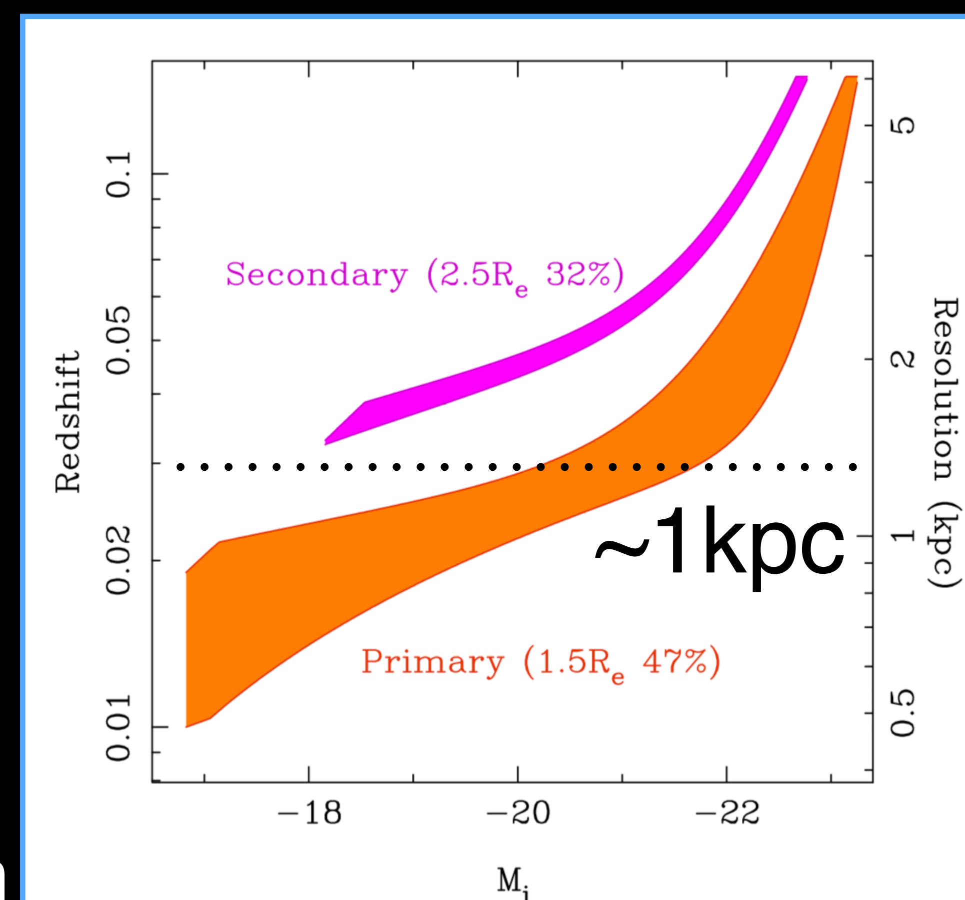
Individual slices do preserve spatial information in one direction

Age of Integral Field Spectroscopy of Nearby Galaxies



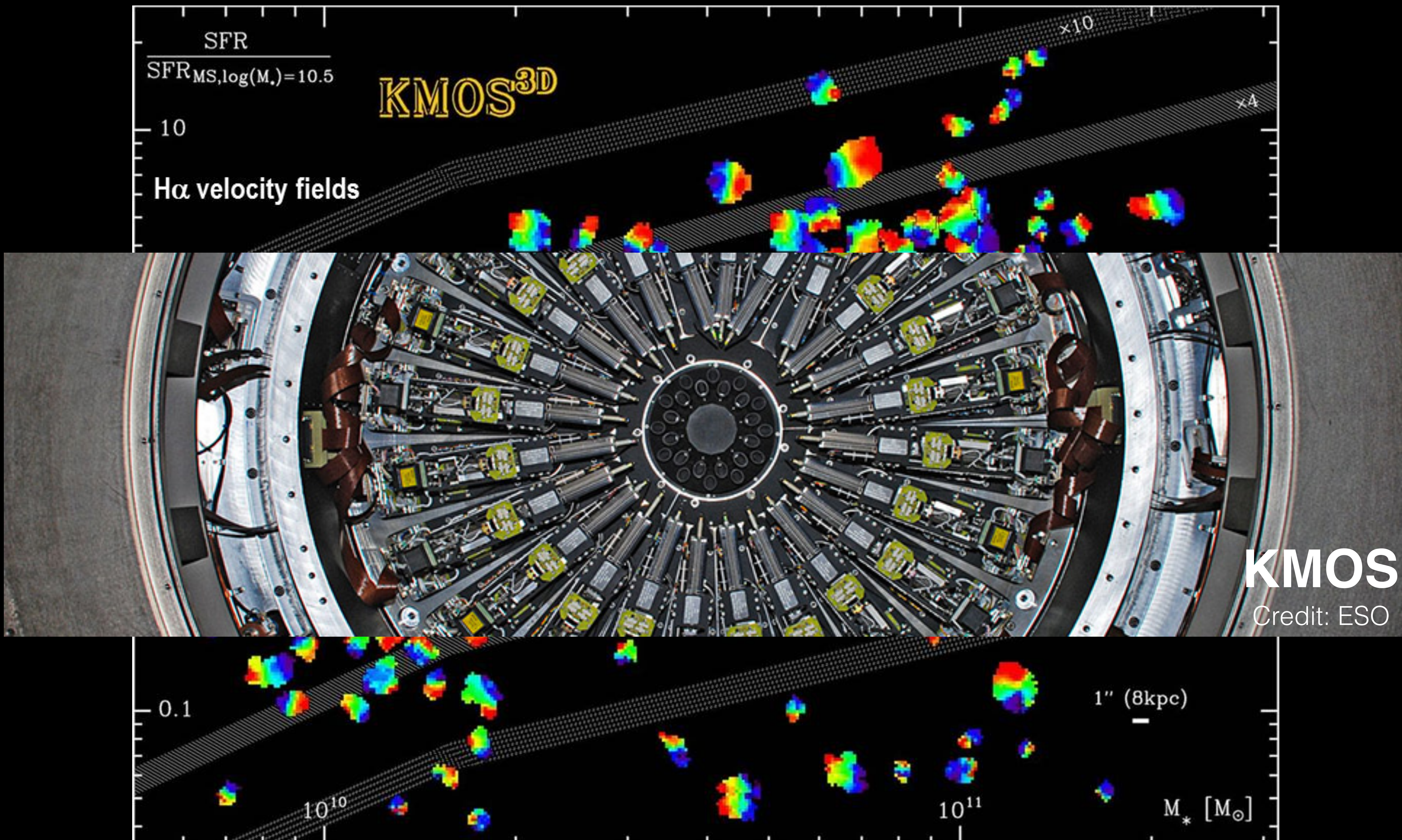
1. **How do galaxy disks grow?**
2. **How do bulges and ellipticals grow?**
3. **What affects star formation?**
4. **How have galaxies assembled and what are the relative contributions of their components?**

MaNGA Bundy et al. (2015)



Spatial Resolution

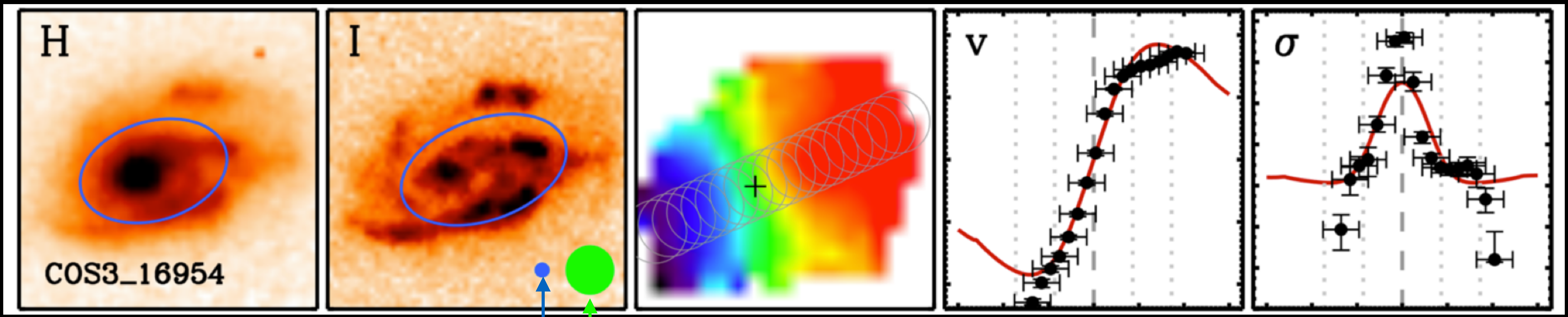
Age of High-z Integral Field Spectroscopy



Wisnioski et al. (2014)

The Need for High Angular Resolution and High Sensitivity

HST **KMOS**



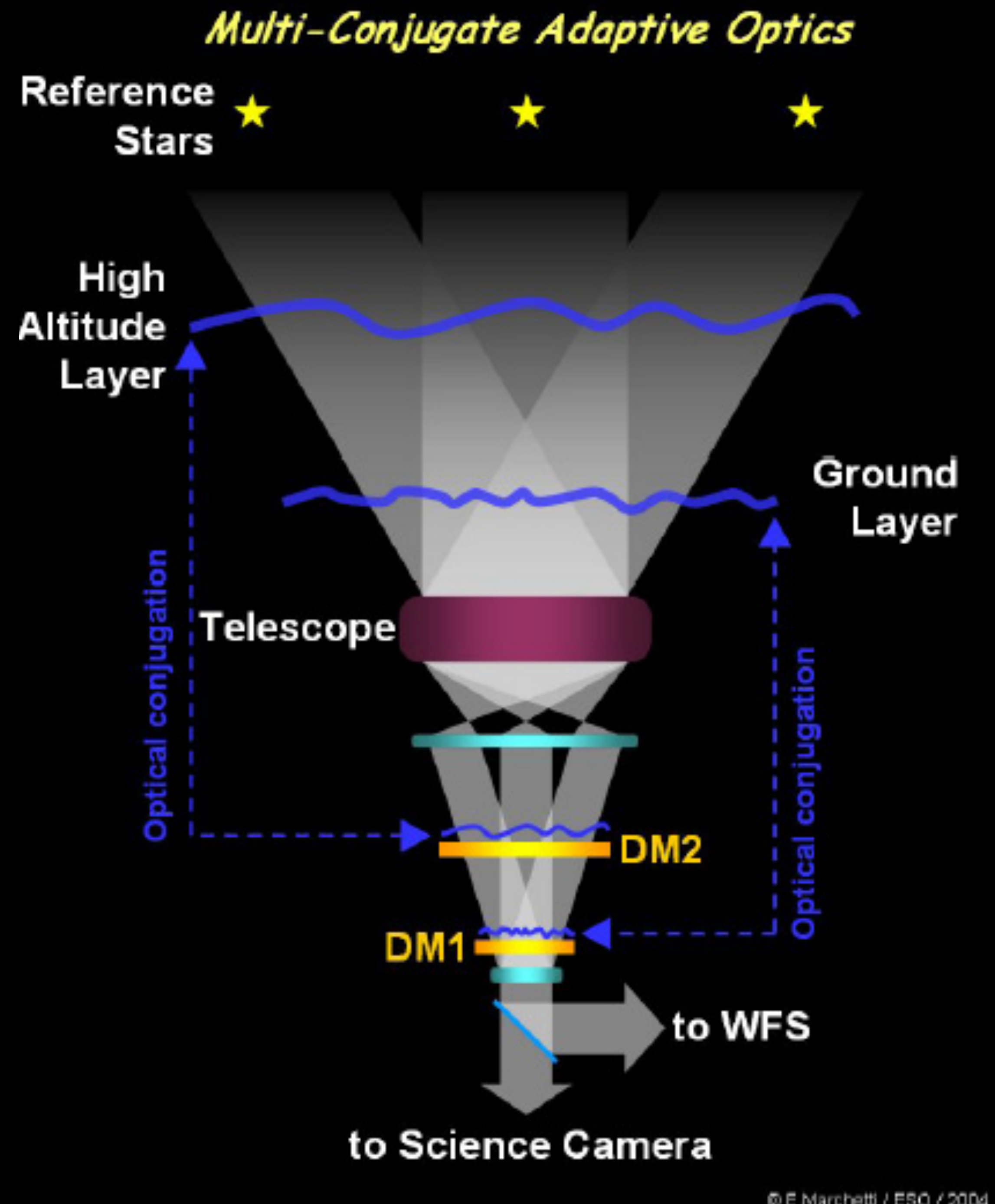
3"

GIRMOS/KMOS
spatial resolution

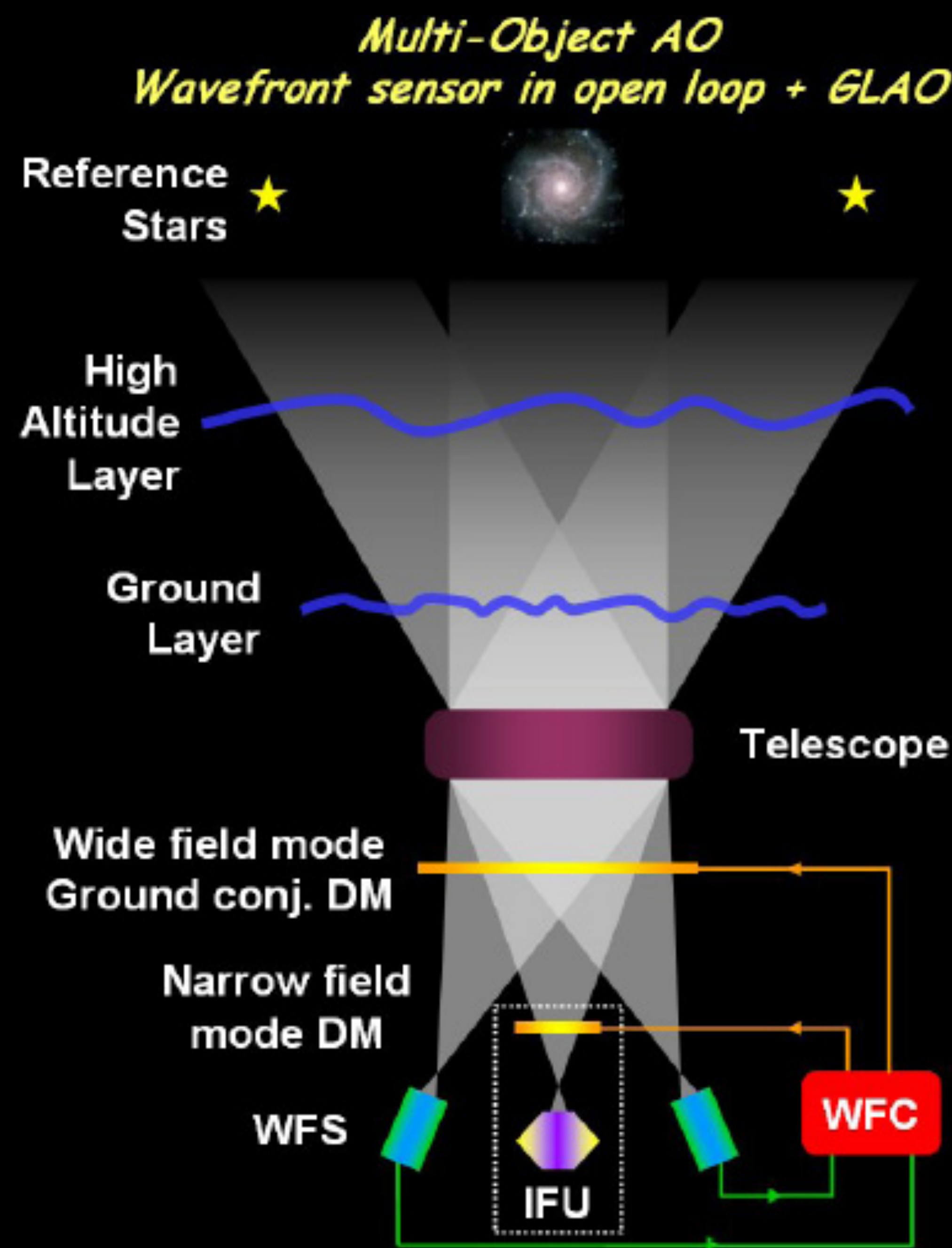
High-z galaxy
Wuyts, S. et al. (2016)

- **Existing Multi-IFU instrument (KMOS) does not have sufficient spatial resolution to resolve high-z galaxies in detail**
  - **SINFONI SINS survey a benchmark for high-z galaxy science**
- **Increased spatial resolution can resolve individual HII regions at increased sensitivity so long as system throughput is sufficient**

MCAO

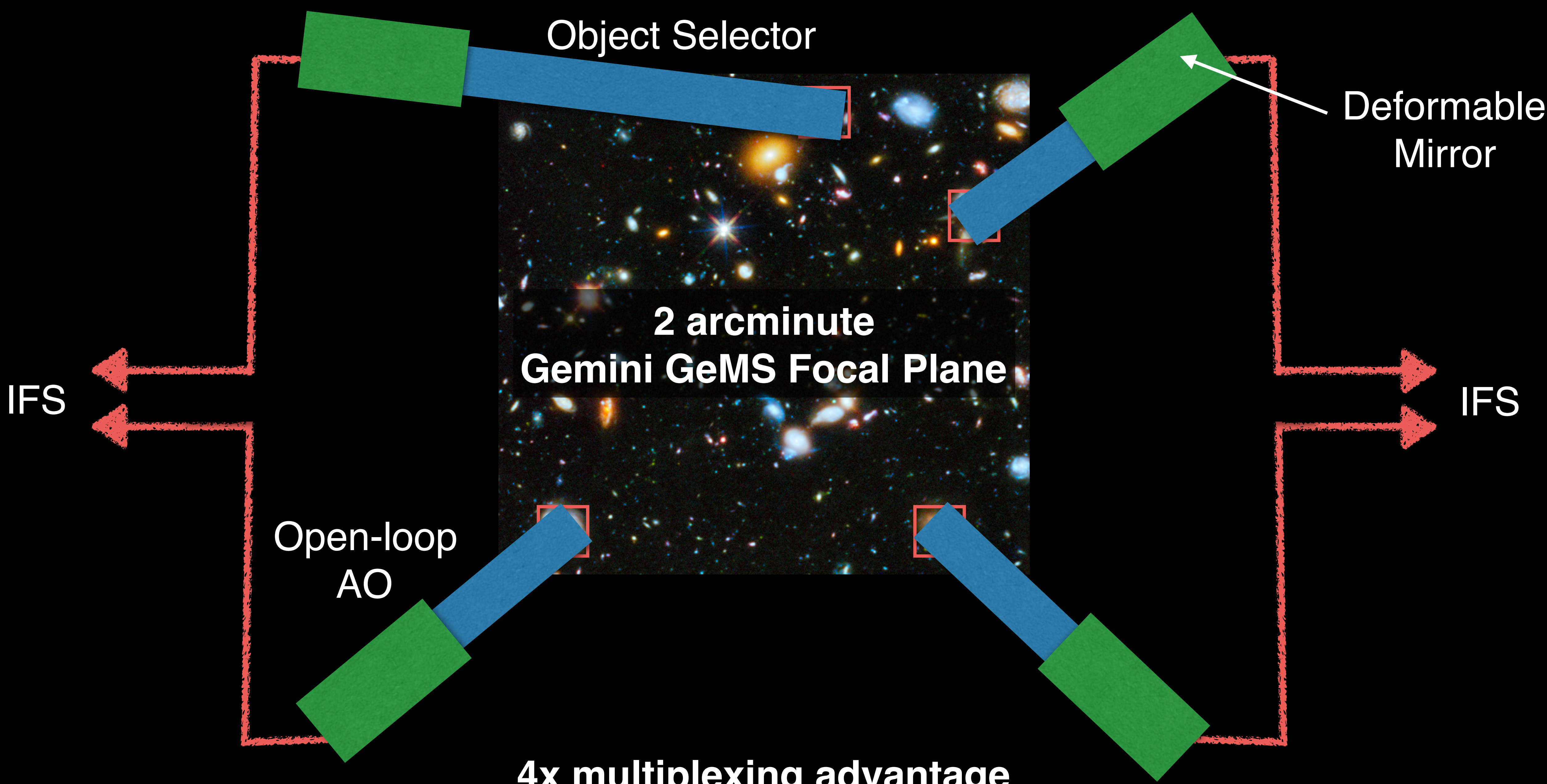


MOAO



Credit: ESO

System Architecture

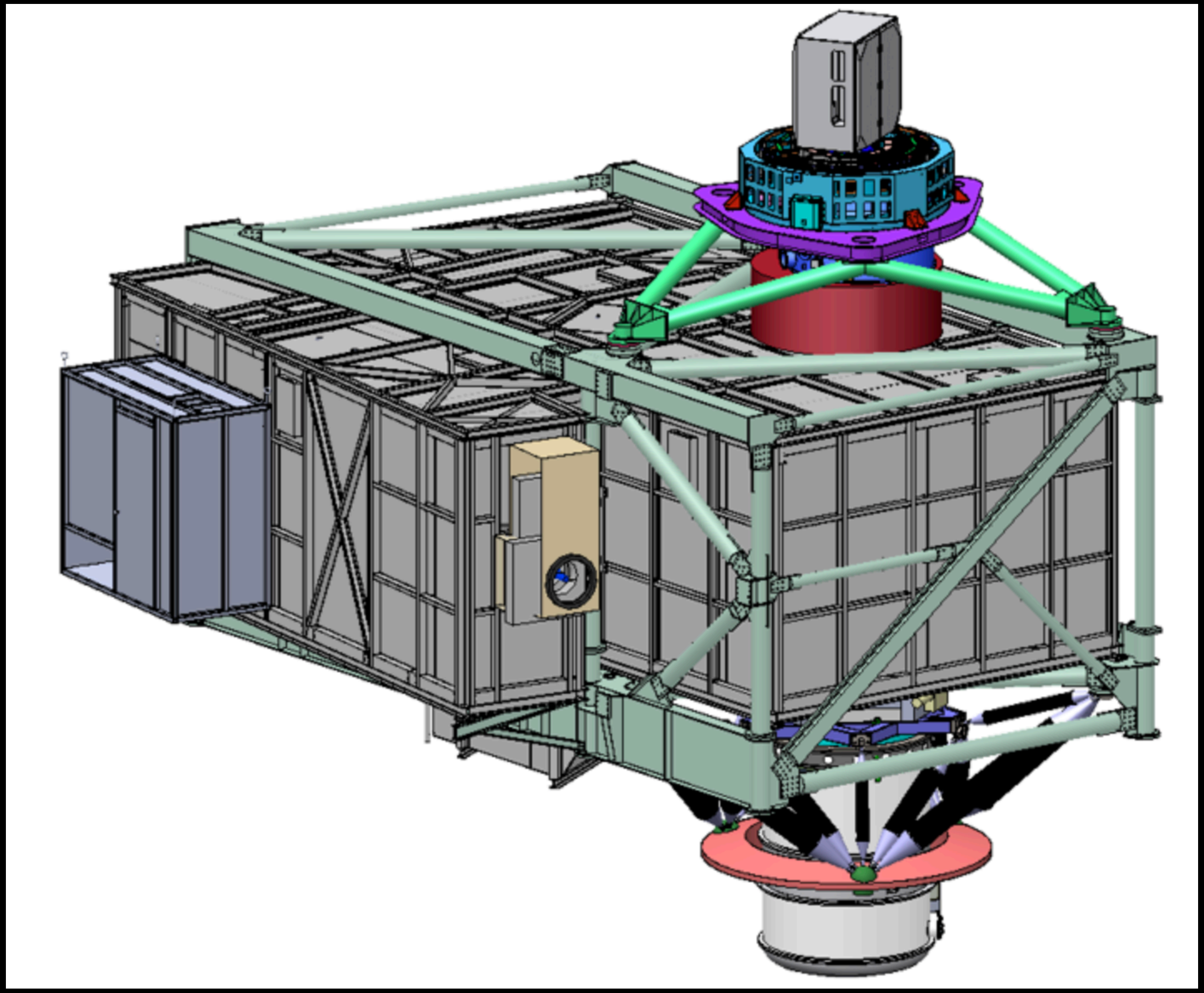


4x multiplexing advantage over similar instruments

10x survey efficiency

Path to TMT early light instrument

- **TMT IRMOS (TIRMOS) will be based on the same architecture as Gemini IRMOS**
- **Leverage already existing AO system at TMT (NFIRAOS) by including additional MOAO correction**
- **Quick path to TMT second generation instrument without need for additional observatory infrastructure**



TMT NFIRAOS (Credit: TMTO)

JWST

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