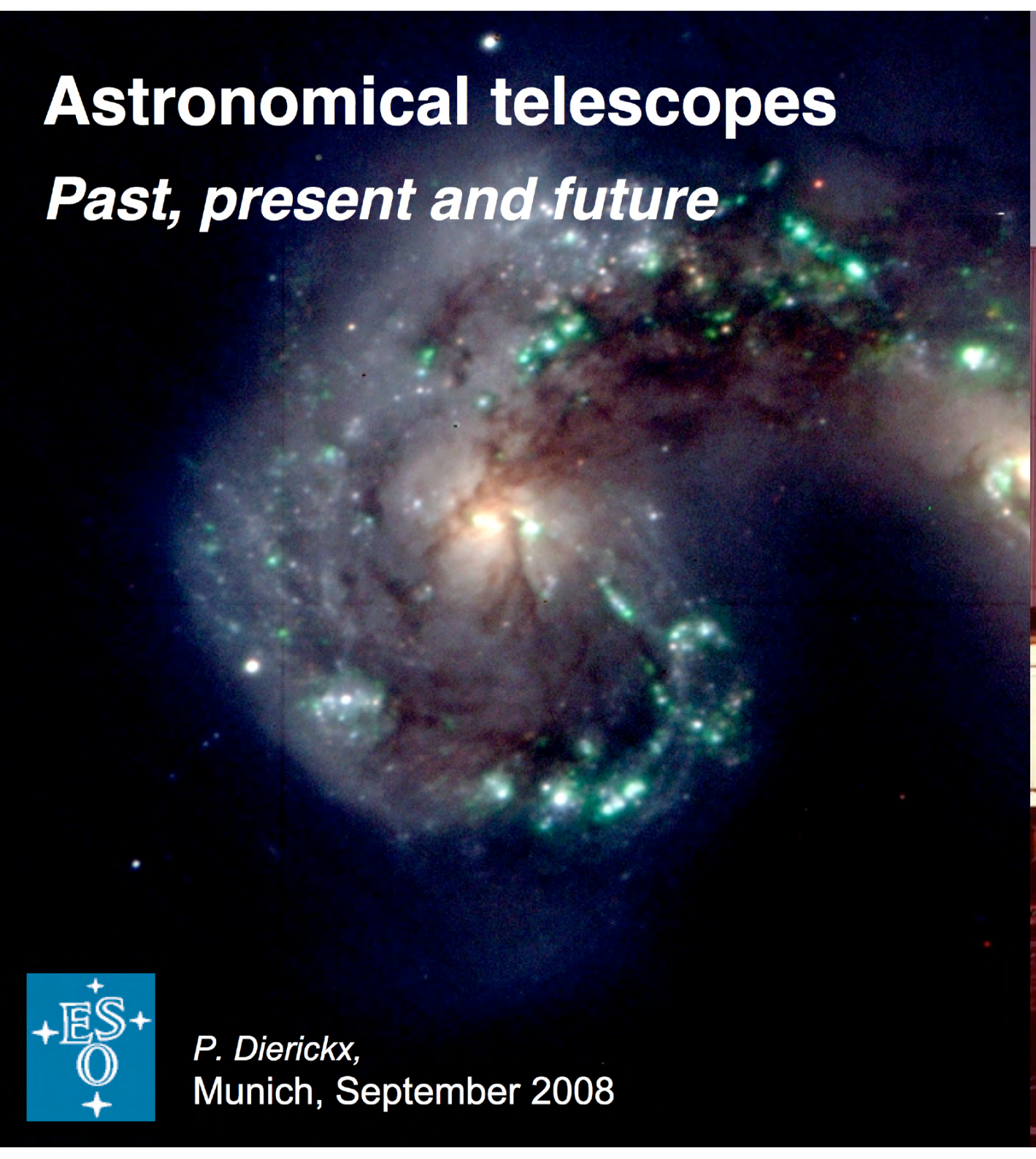
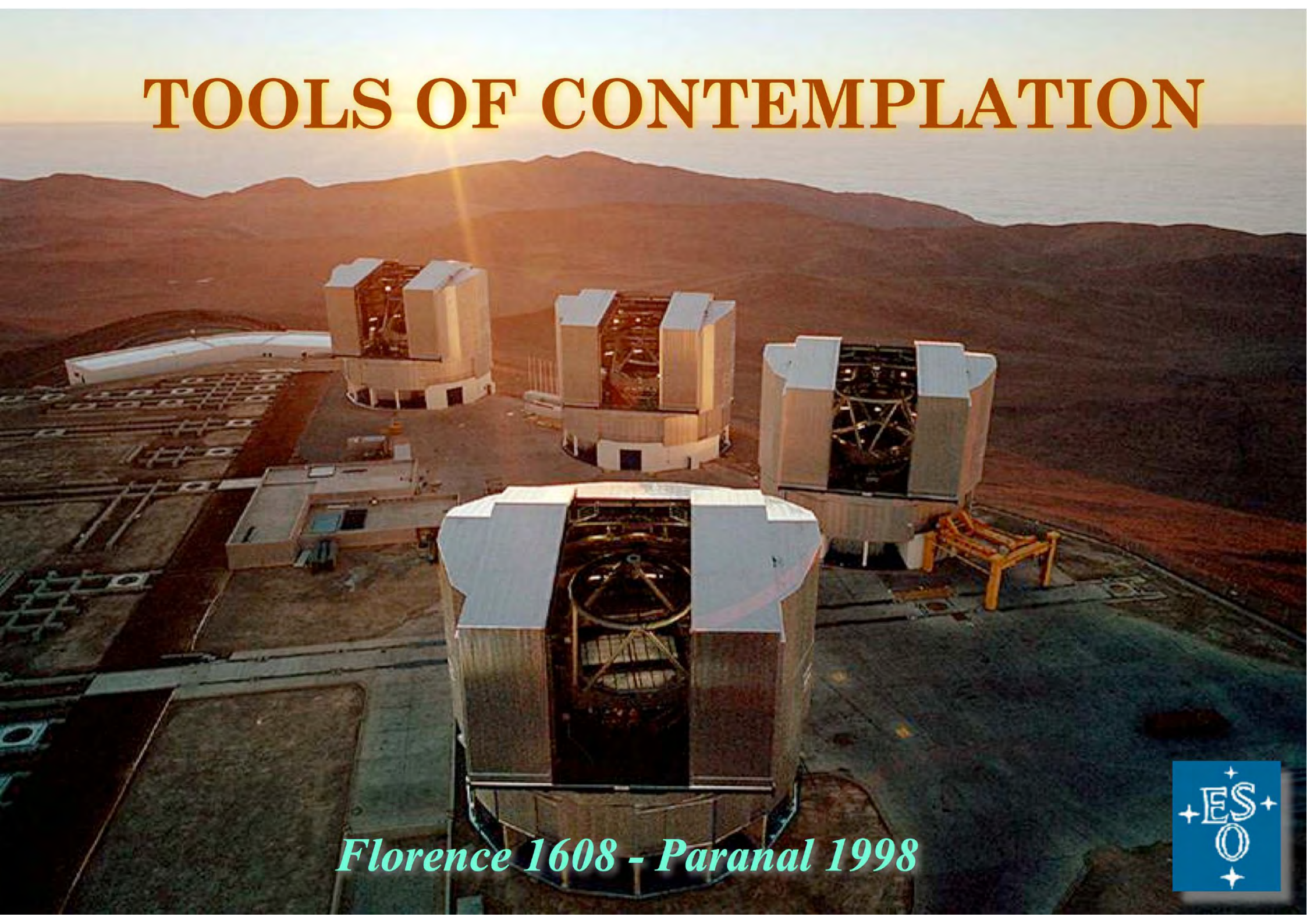
# Astronomical telescopes

## *Past, present and future*



*P. Dierickx,*
Munich, September 2008

# TOOLS OF CONTEMPLATION



*Florence 1608 - Paranal 1998*

# TOOLS OF CONTEMPLATION

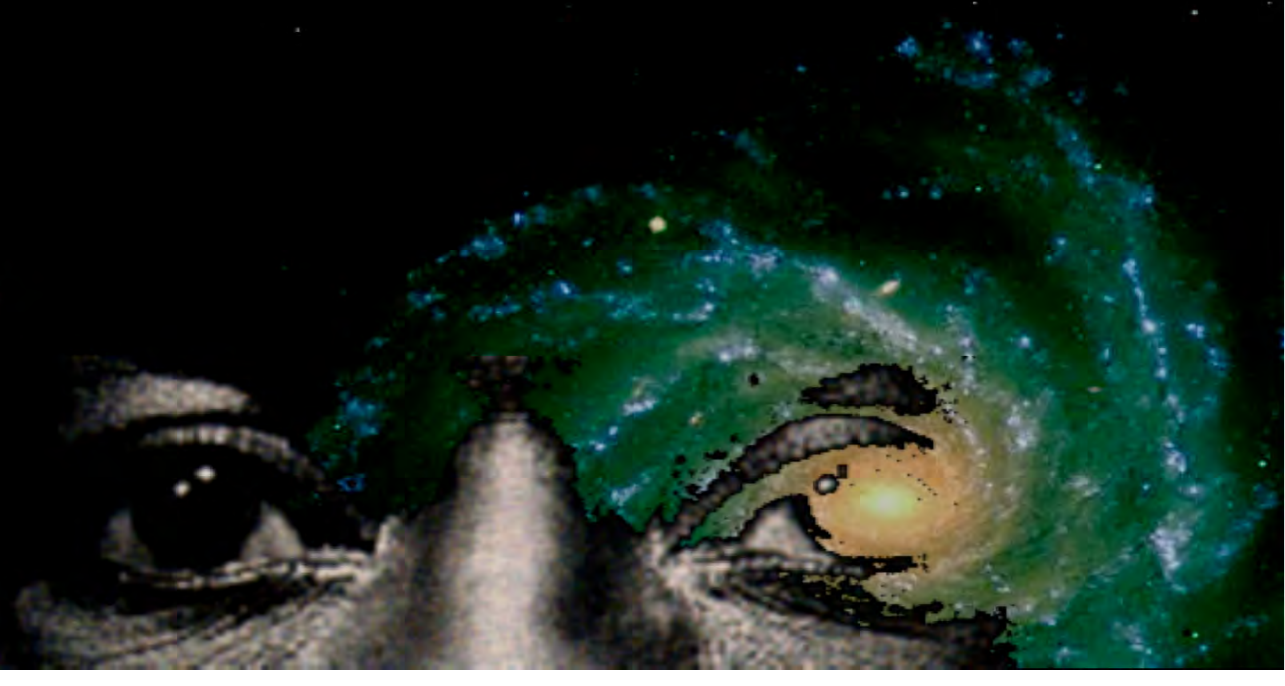
The human eye.

7 mm and a supercomputer

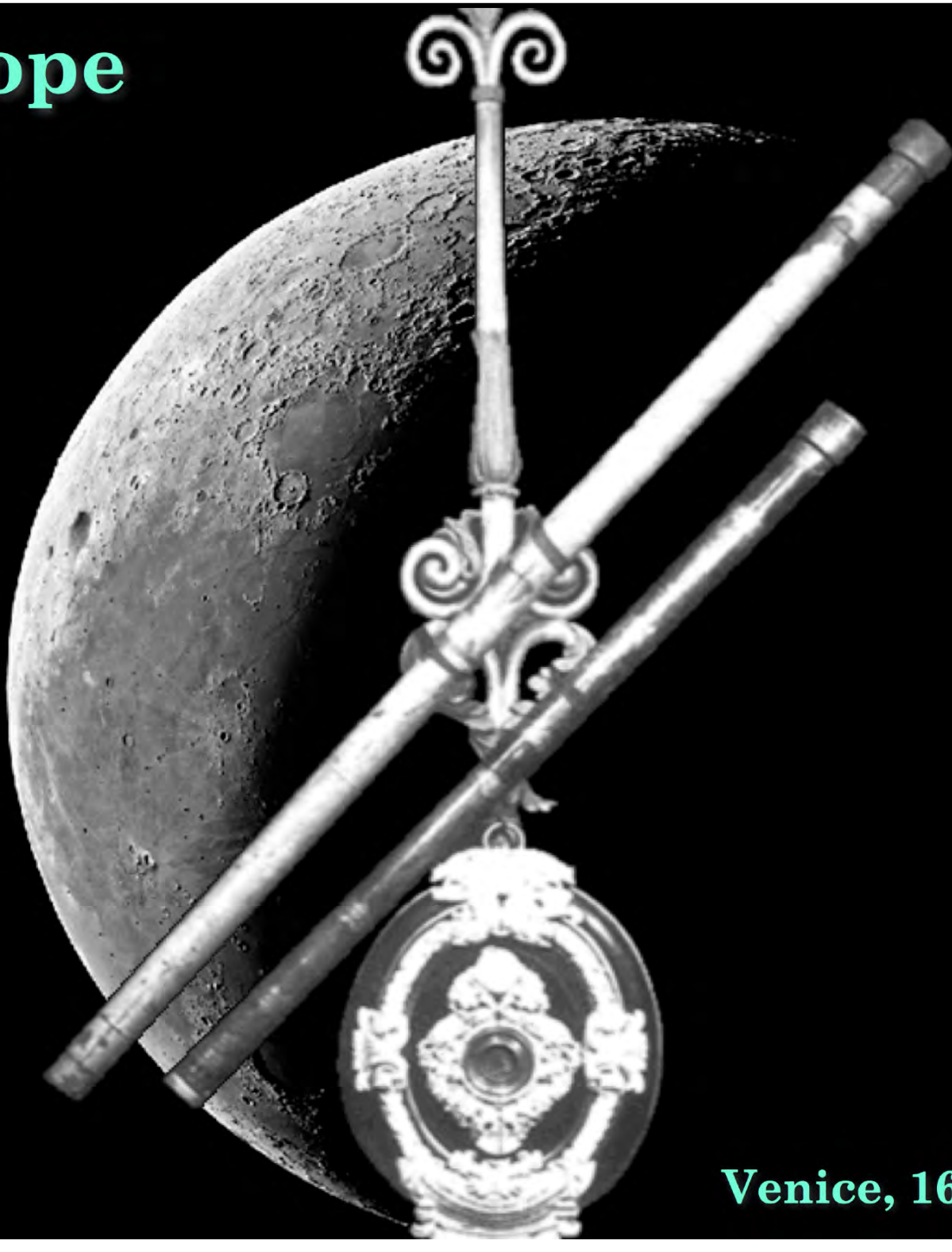
1 arc minute resolution

Extreme dynamic range

Limiting magnitude ~6



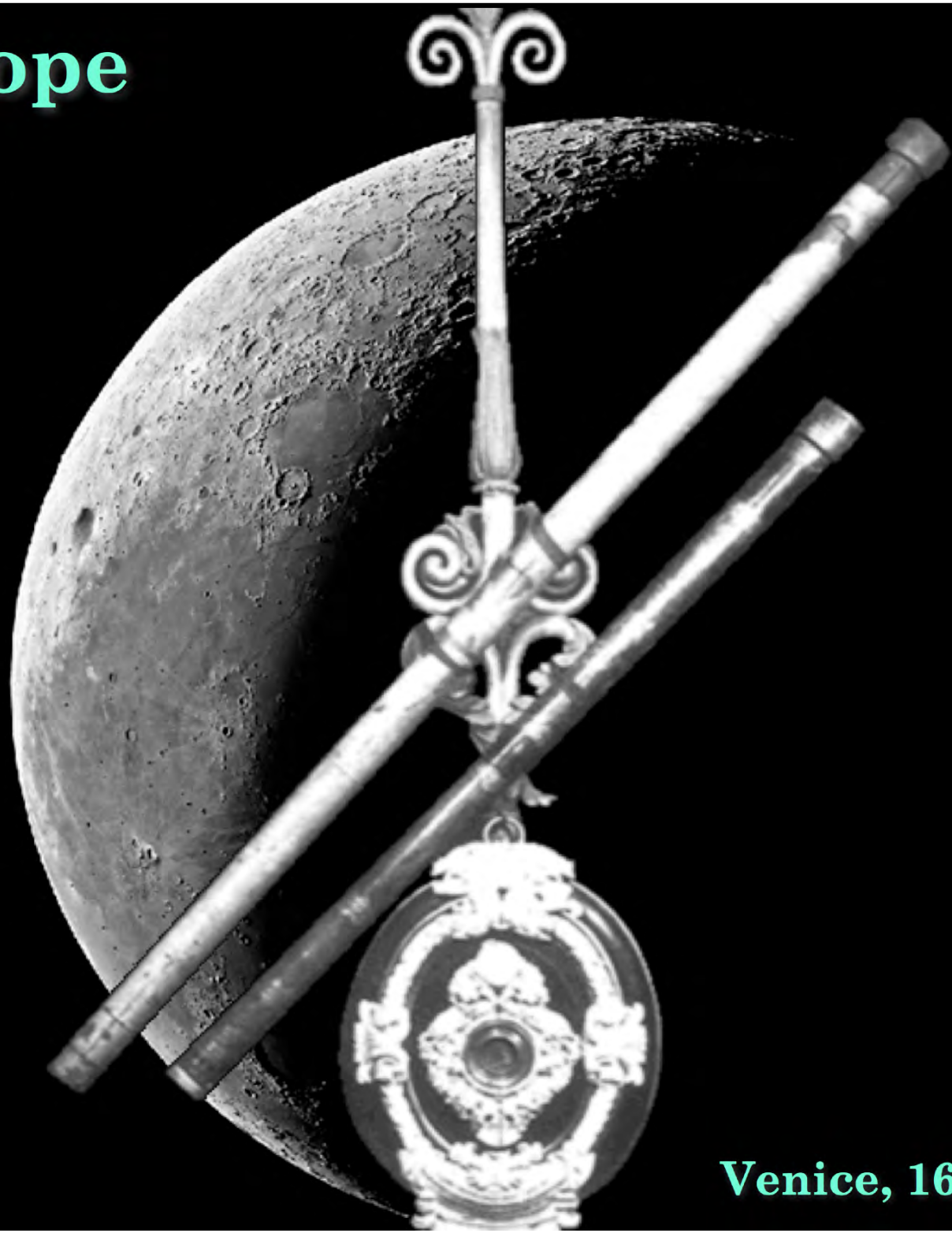
# Galileo's telescope
## Diameter 30 mm



Venice, 1609.

# Galileo's telescope
# Diameter 30 mm

Thomas Harriot, 1609



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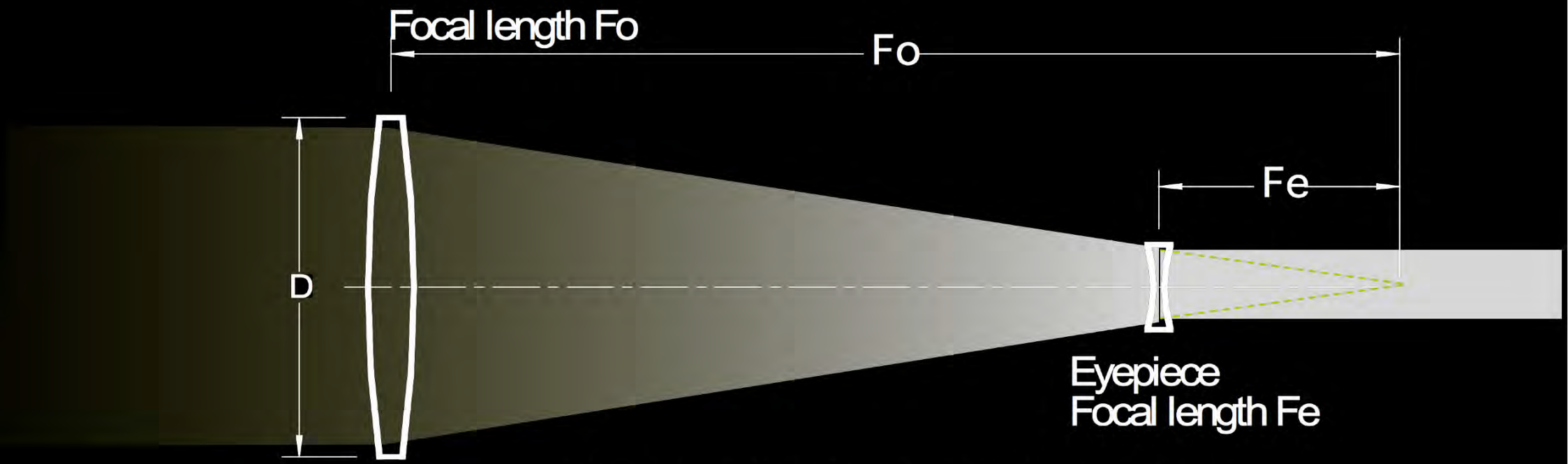
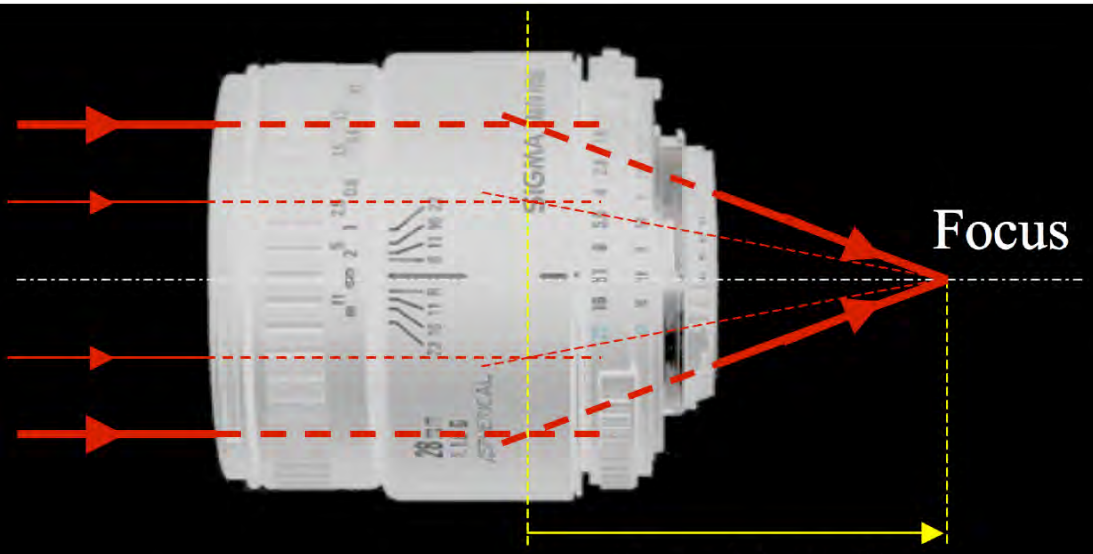


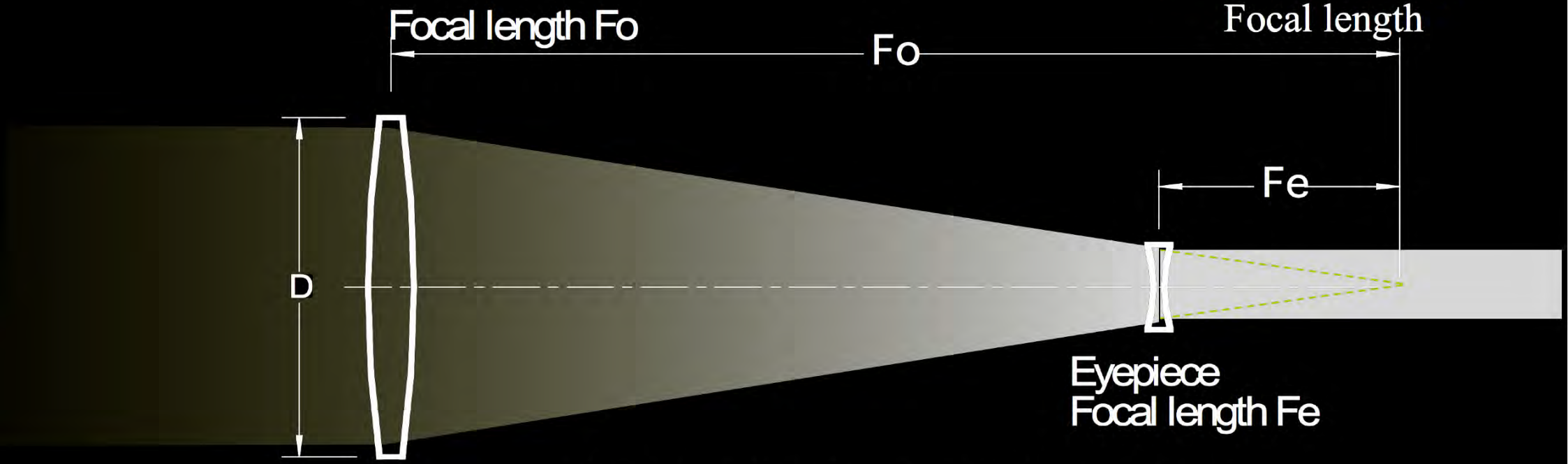

Afocal system for visual observation

Angular magnification $G = F_o / F_e$

**Focal ratio of a component or of a system N = F / D ⇨ optics, mechanics**

# Galileo's telescope

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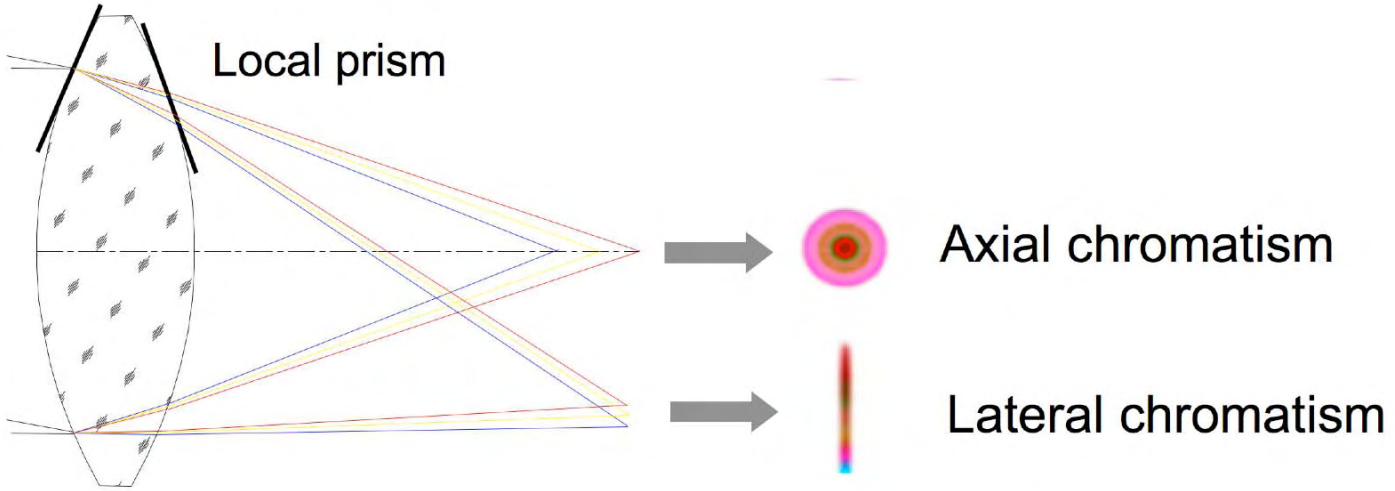
- Chromatic aberrations (refractive telescopes only)
  - 1729, Moor Hall (theory); 1758, John Dollond: first achromatic objective
  - 1761, Clairaut, modern form



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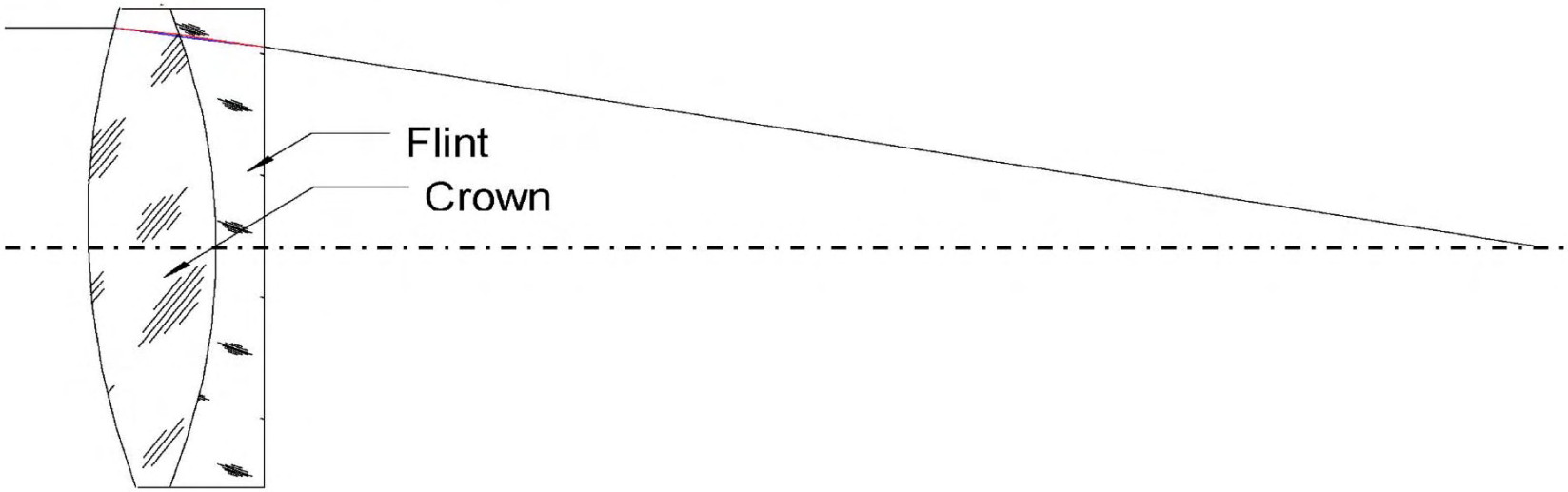

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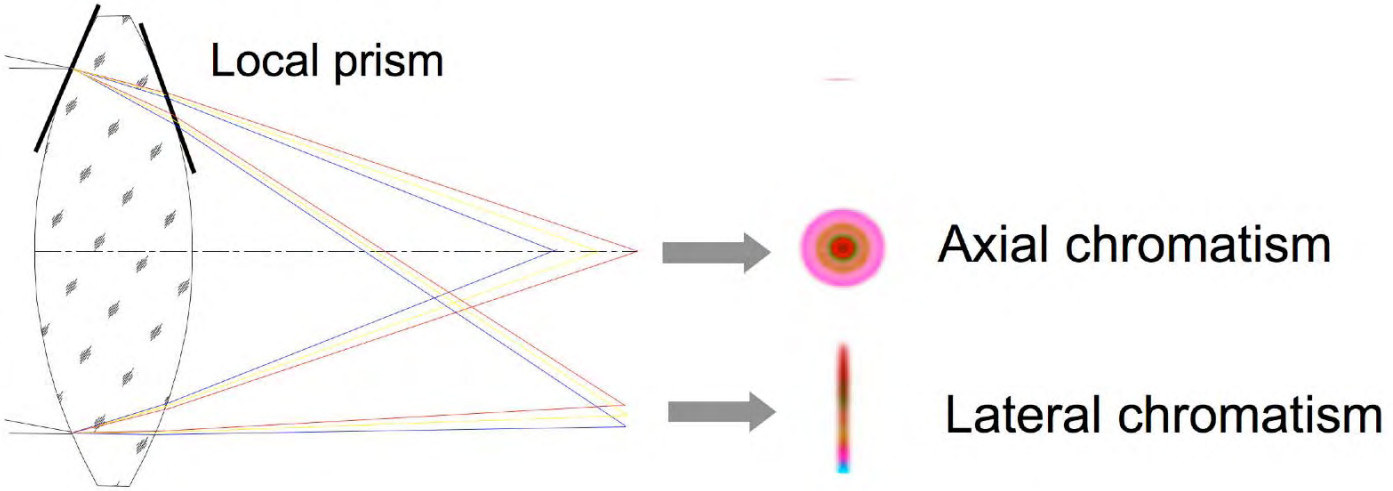
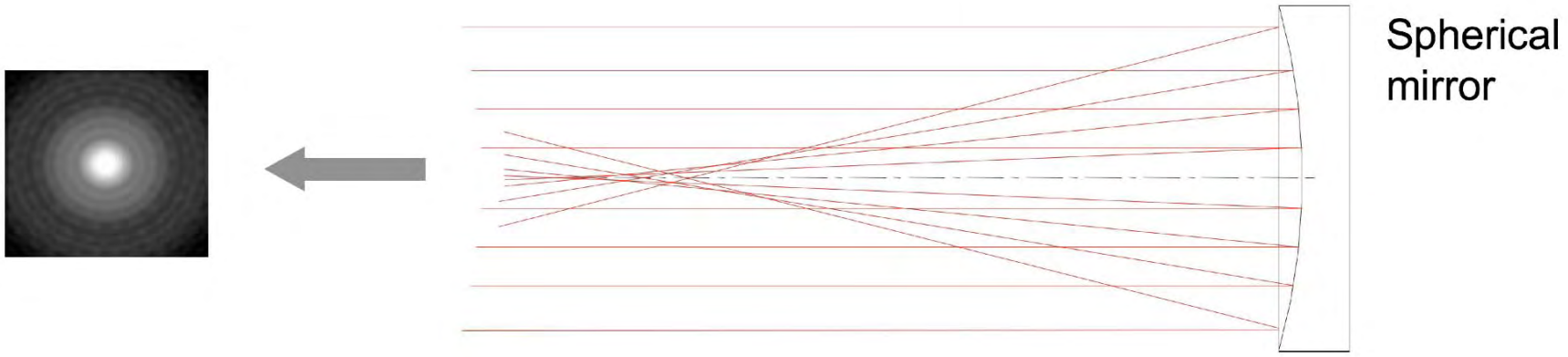
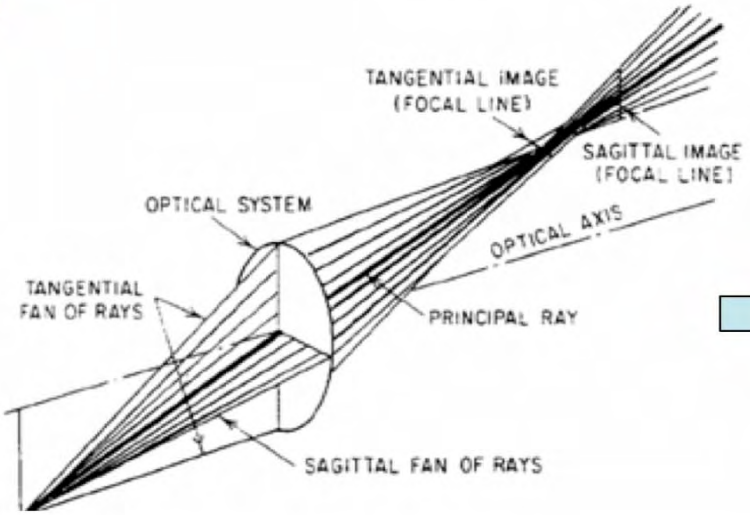


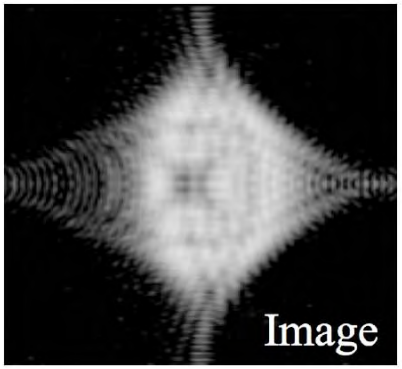

- Spherical aberration (refractive and reflective telescopes)
  - Descartes, 1636 (theory) - Aberrations ~ non-linear terms in the Taylor expansion of $n \sin i = n' \sin i'$ (n: indices of refraction)

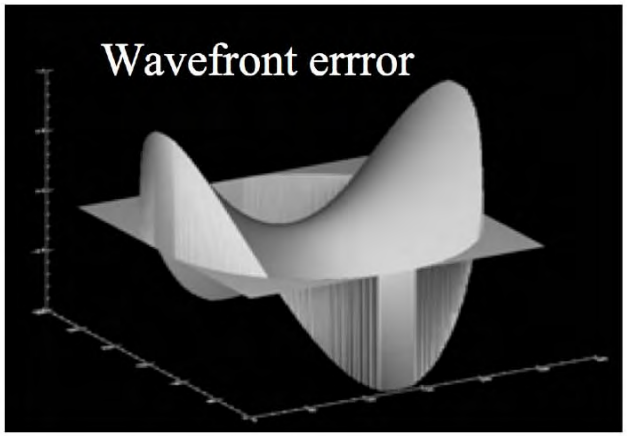


# Field aberrations

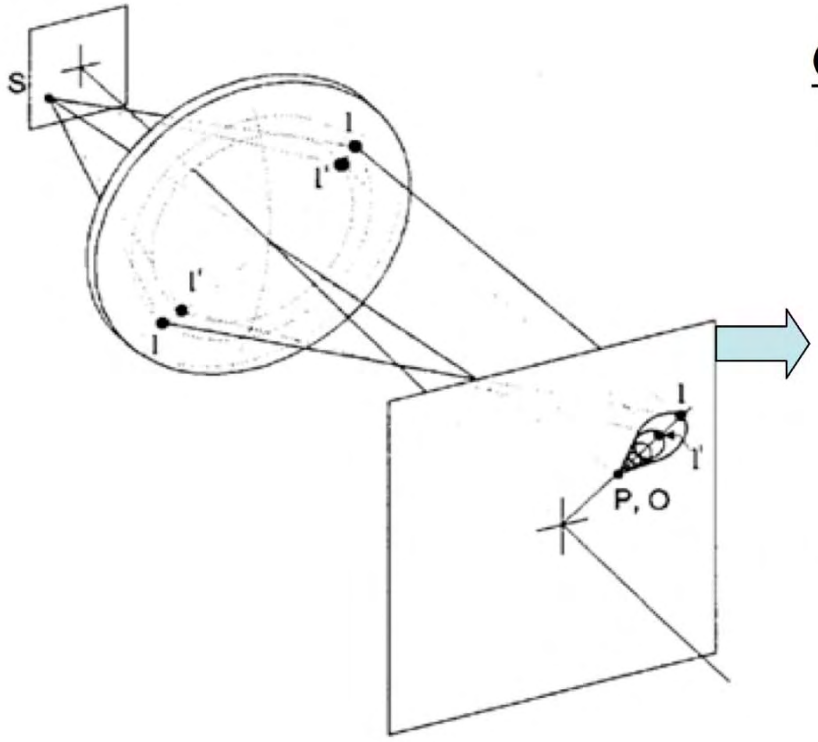
## Astigmatism

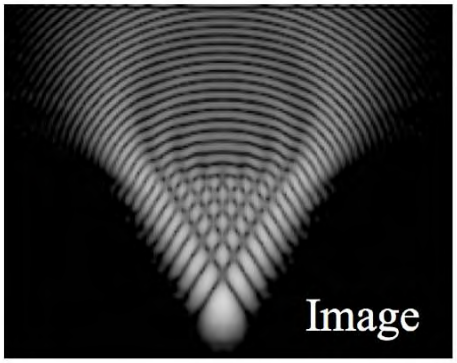


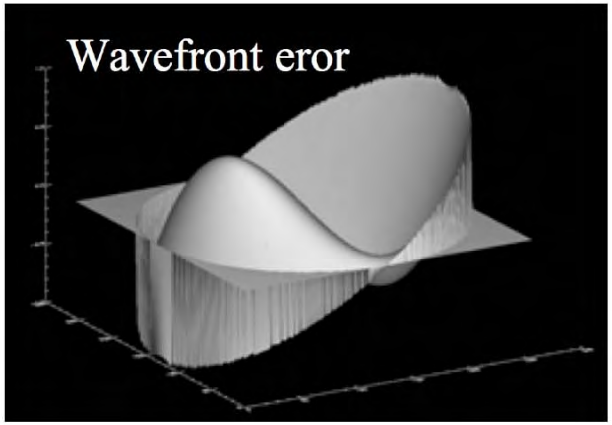



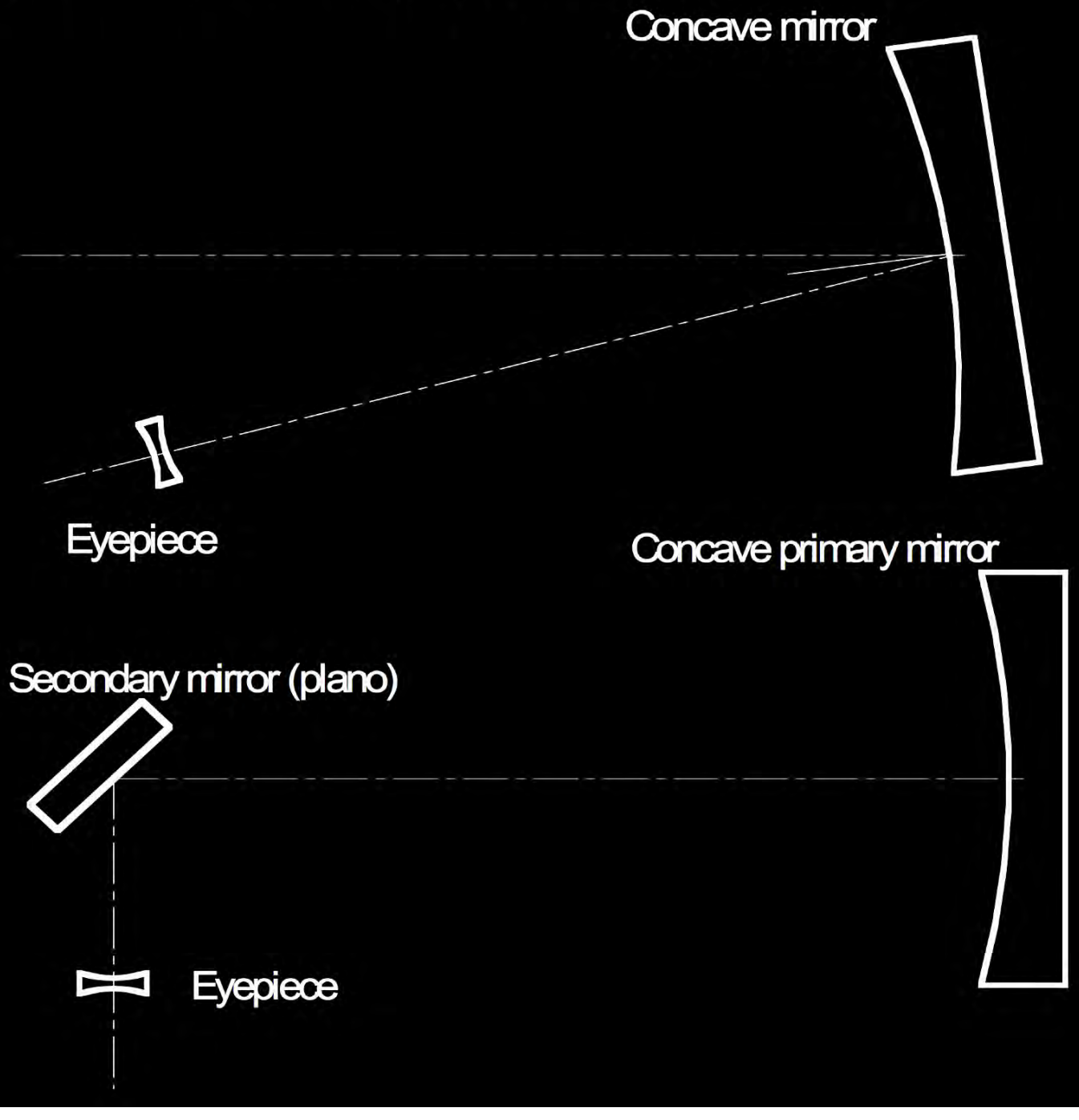

## Coma



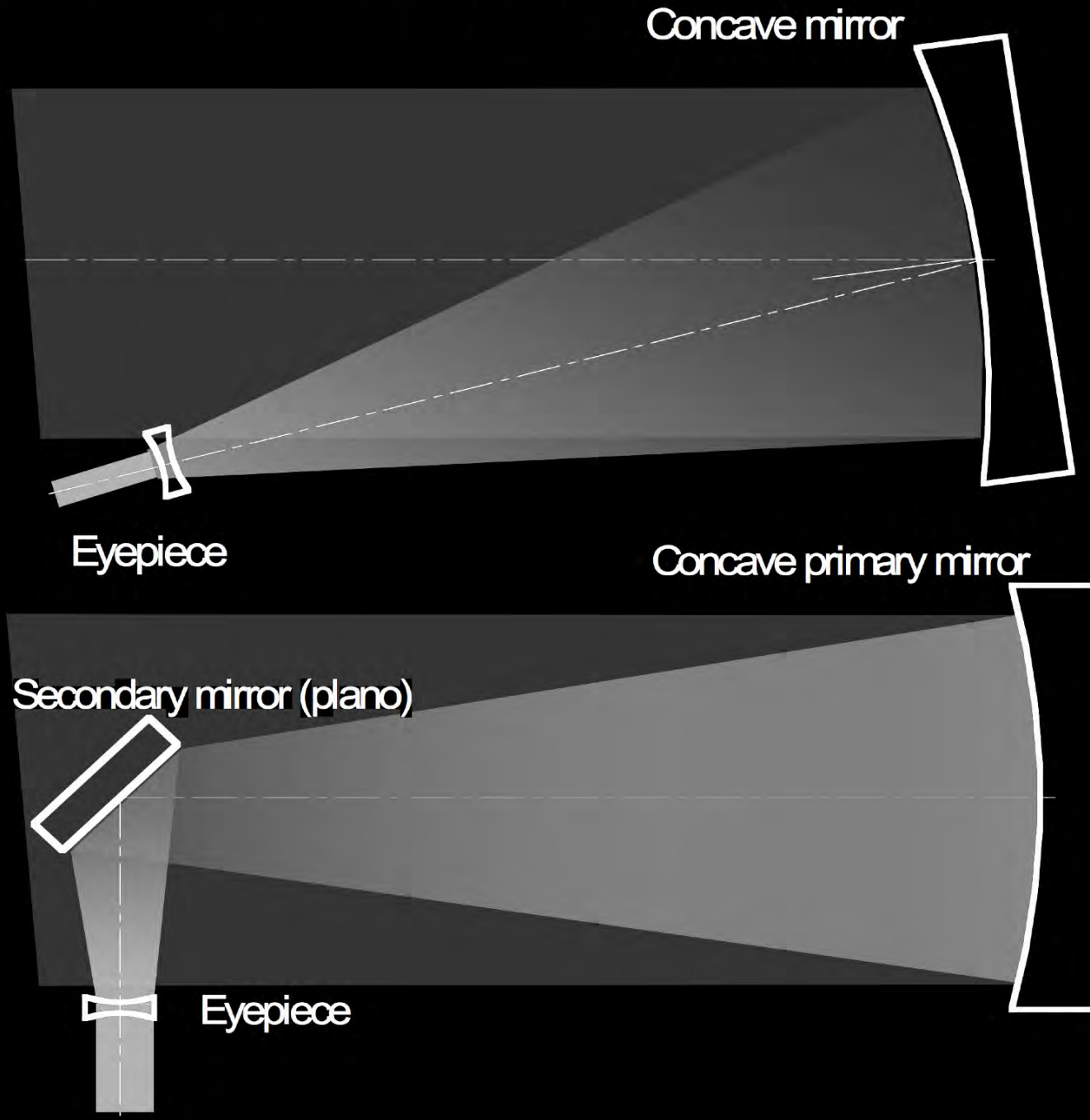
# Reflecting telescopes – the early years 1608-1672



# Reflecting telescopes – the early years 1608-1672

## 1616 - Zucchi

## 1668 - Newton



# The early years 1608-1672

## Gregorian

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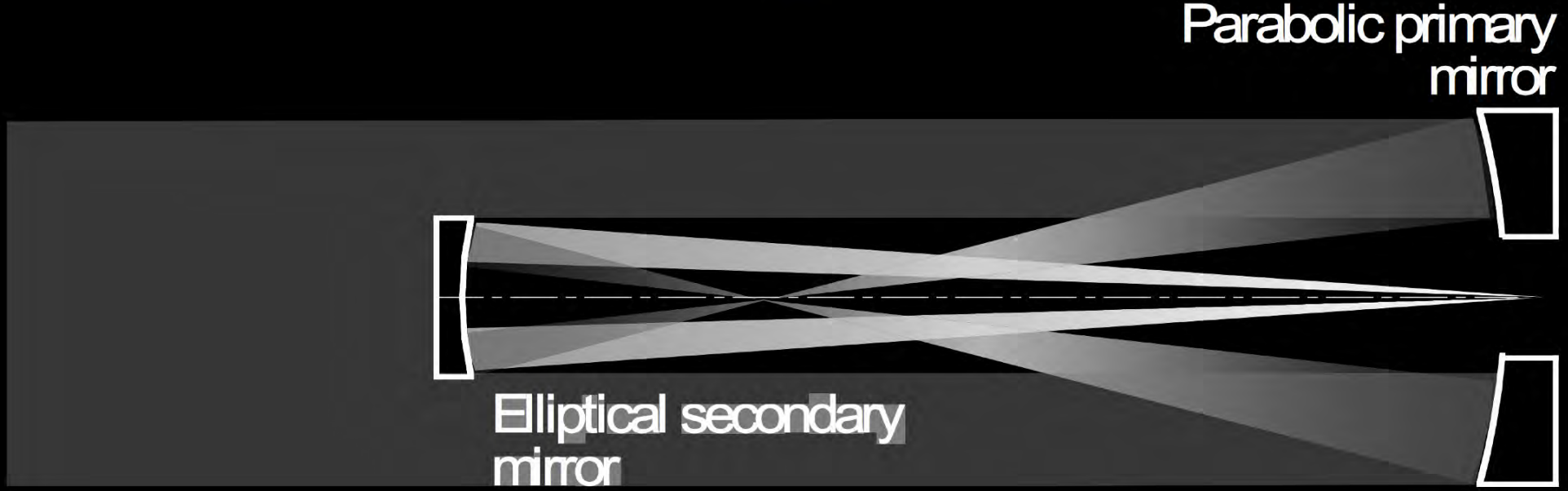
## Gregorian

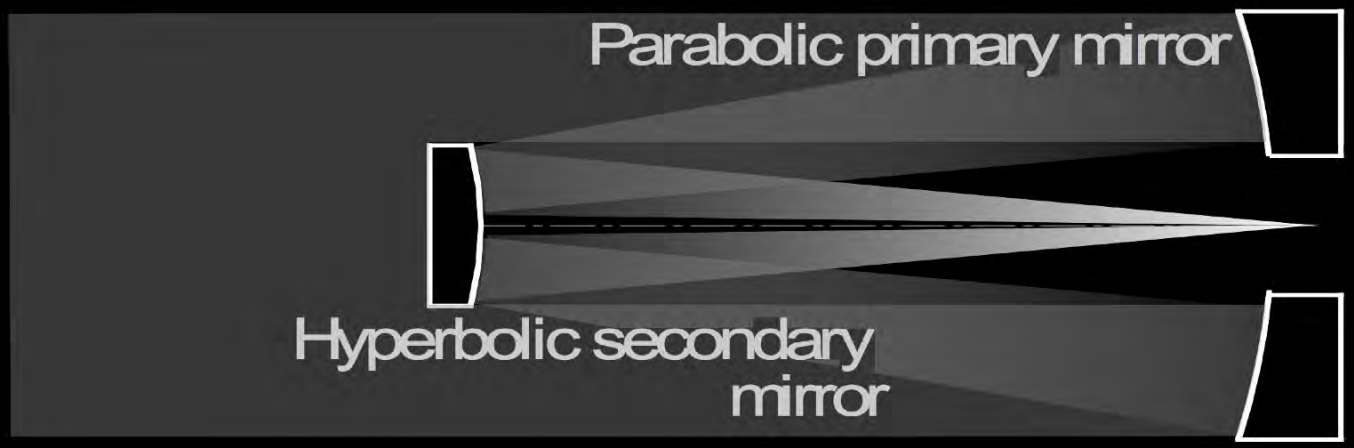


The early years 1608-1672

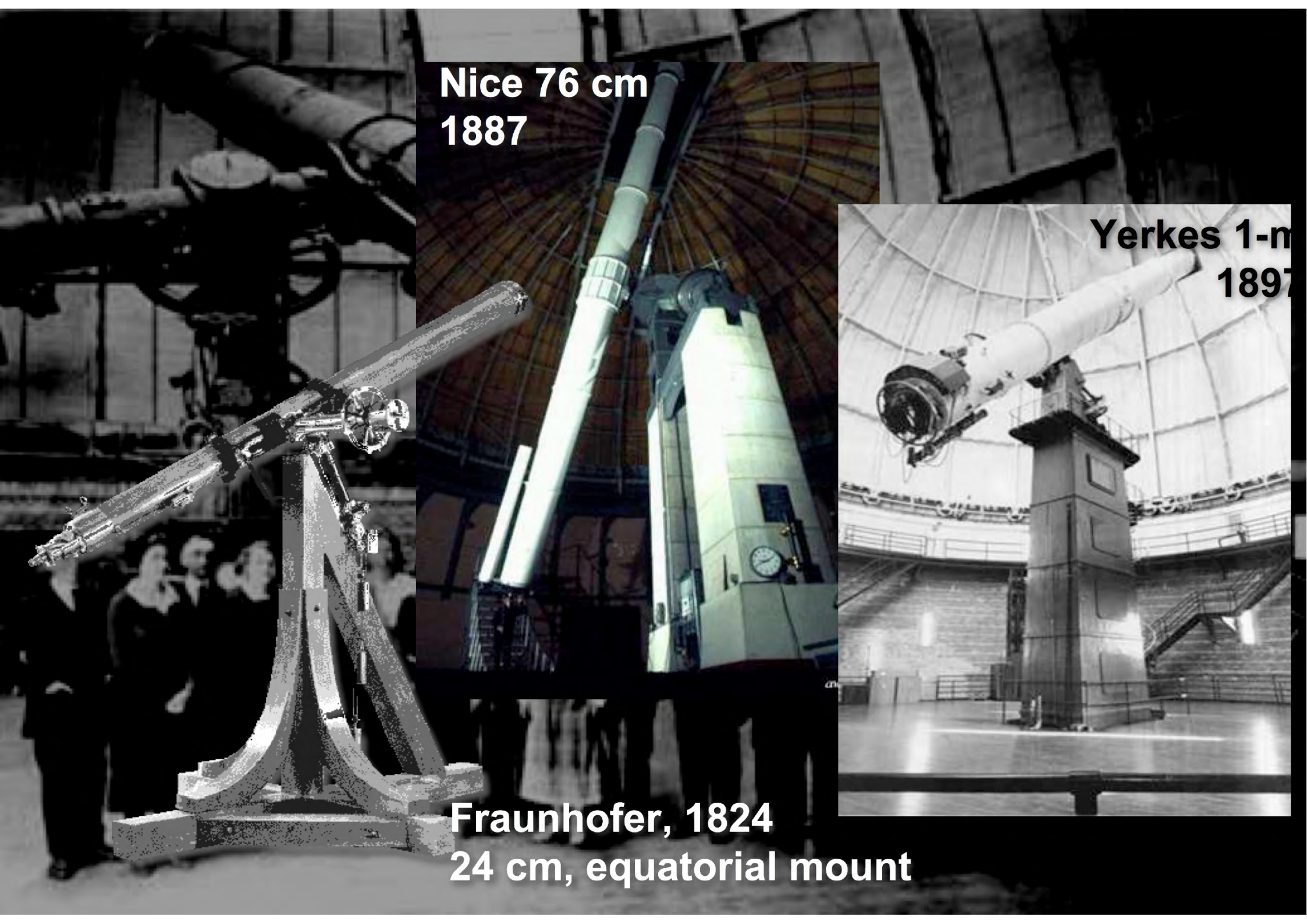
# Cassegrain

The early years 1608-1672

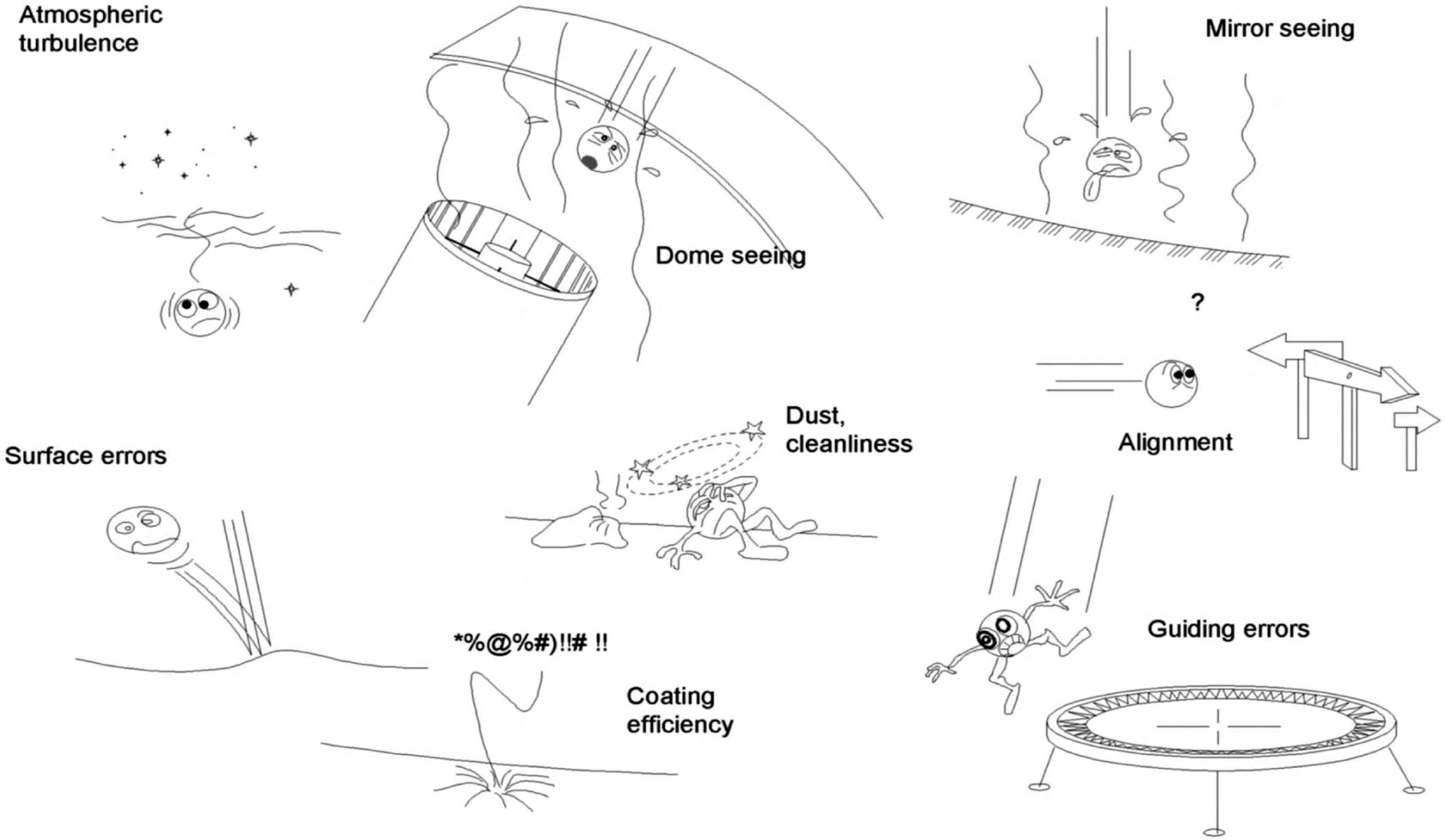
# Cassegrain



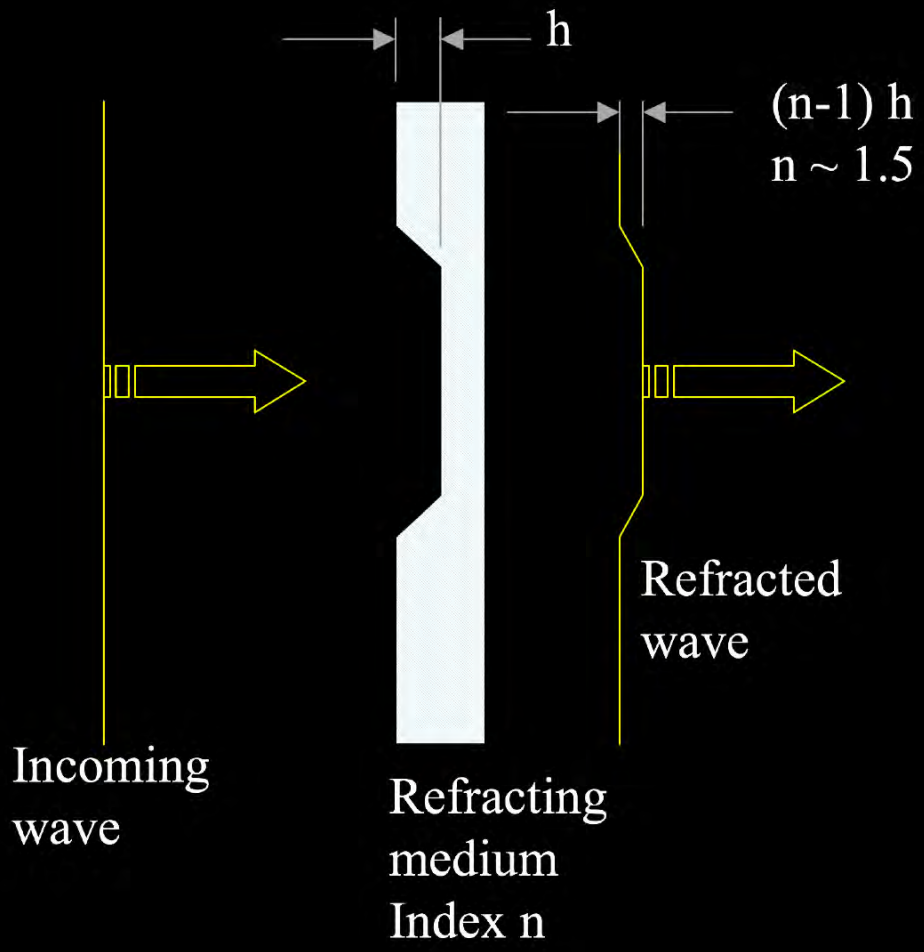

The theory of the reflecting telescope will remain unchanged until 1905.


Nice 76 cm
1887
Yerkes 1-m
1897
Fraunhofer, 1824
24 cm, equatorial mount

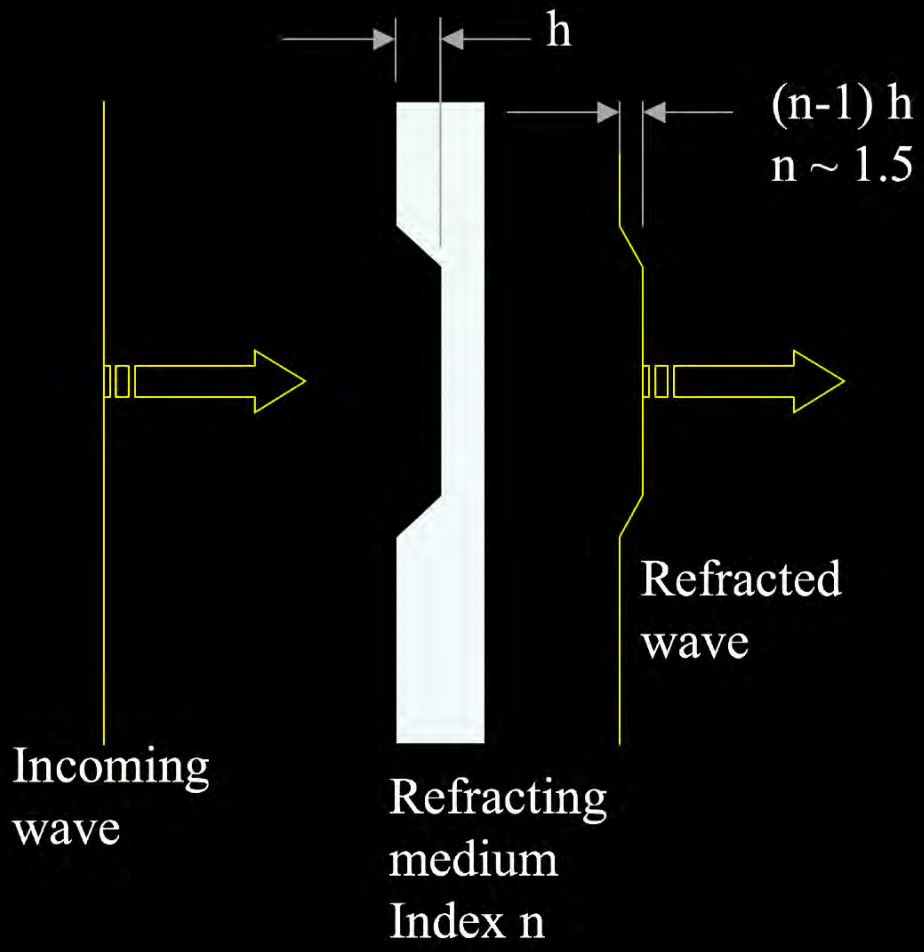
# The hazards of a photon life



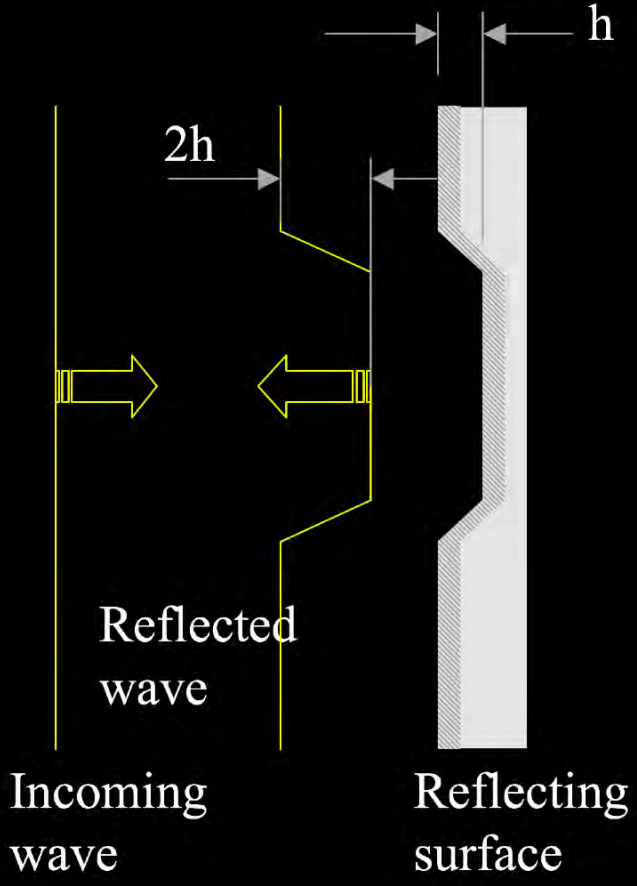
- Refractors


h
(n-1) h
n ~ 1.5
Refracted
wave
Incoming
wave
Refracting
medium
Index n

- Refractors




- Reflectors

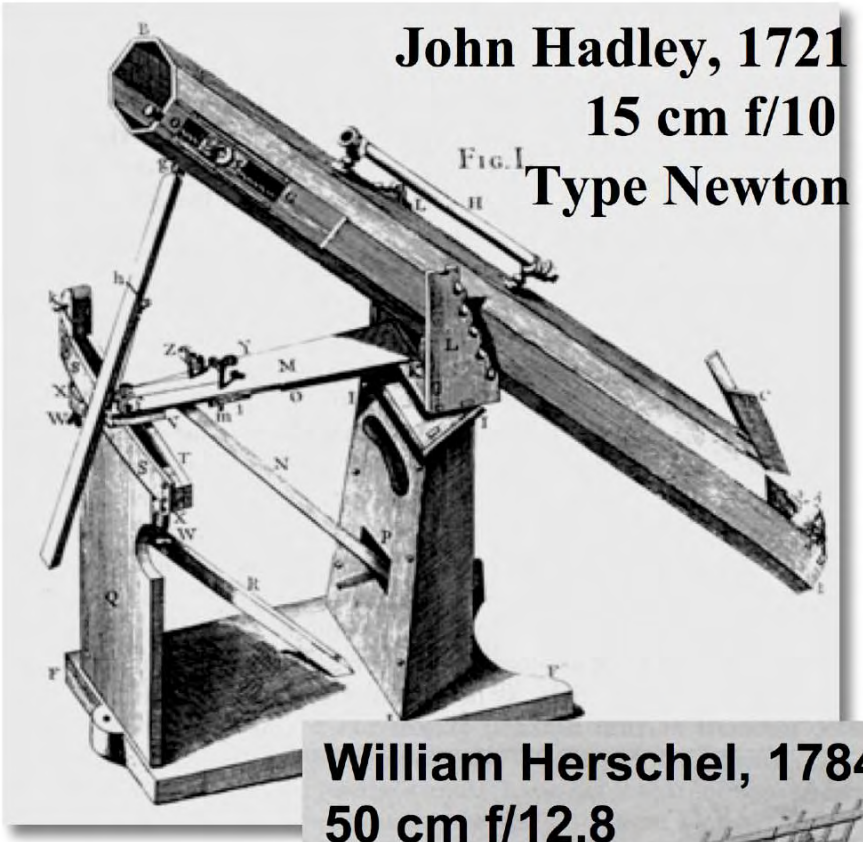



Surface quality requirement for a reflecting surface ~ 1/4$^{th}$ of surface quality requirement for a refracting one

# Reflecting telescopes after 1672

- **Speculum mirrors**
- **Low efficiency (~60% / mirror)**
- **Need periodic re-polishing**
- **Large collecting area**

# Reflecting telescopes after 1672

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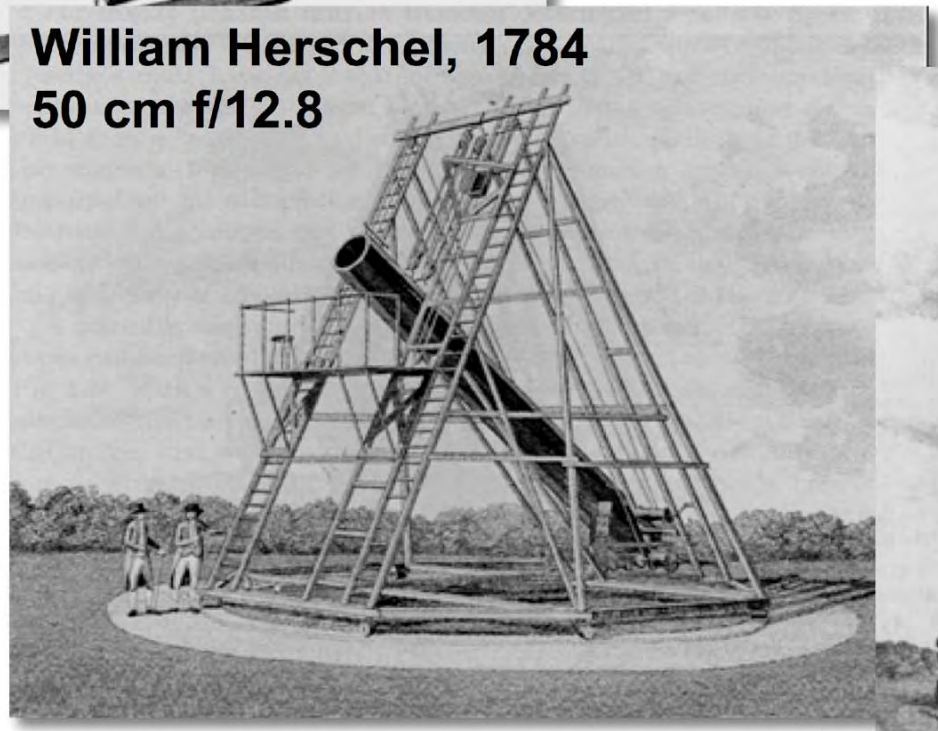
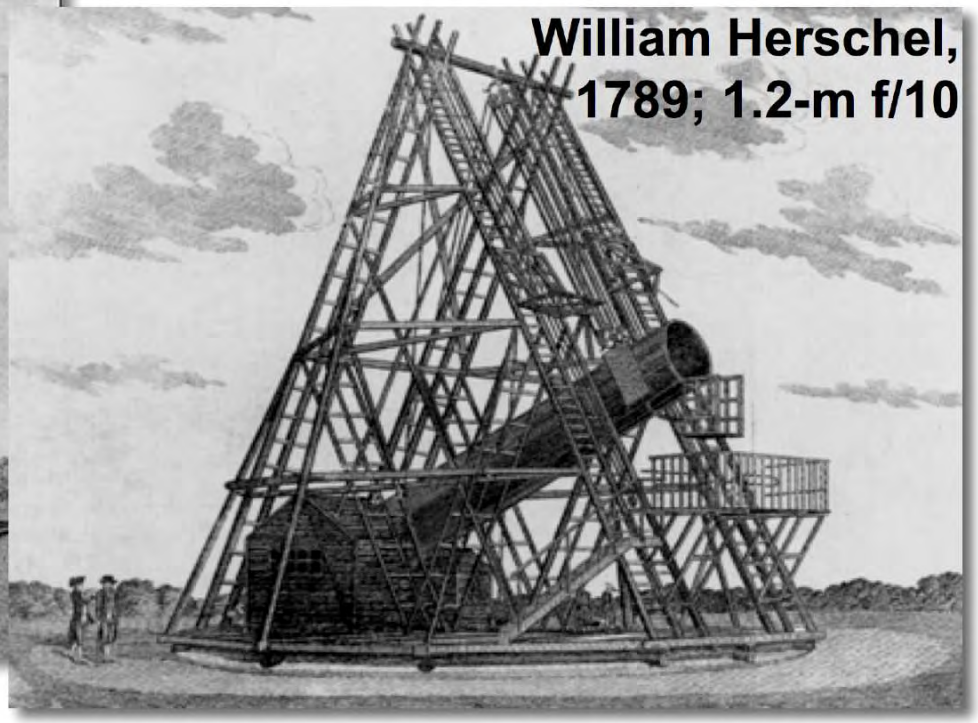
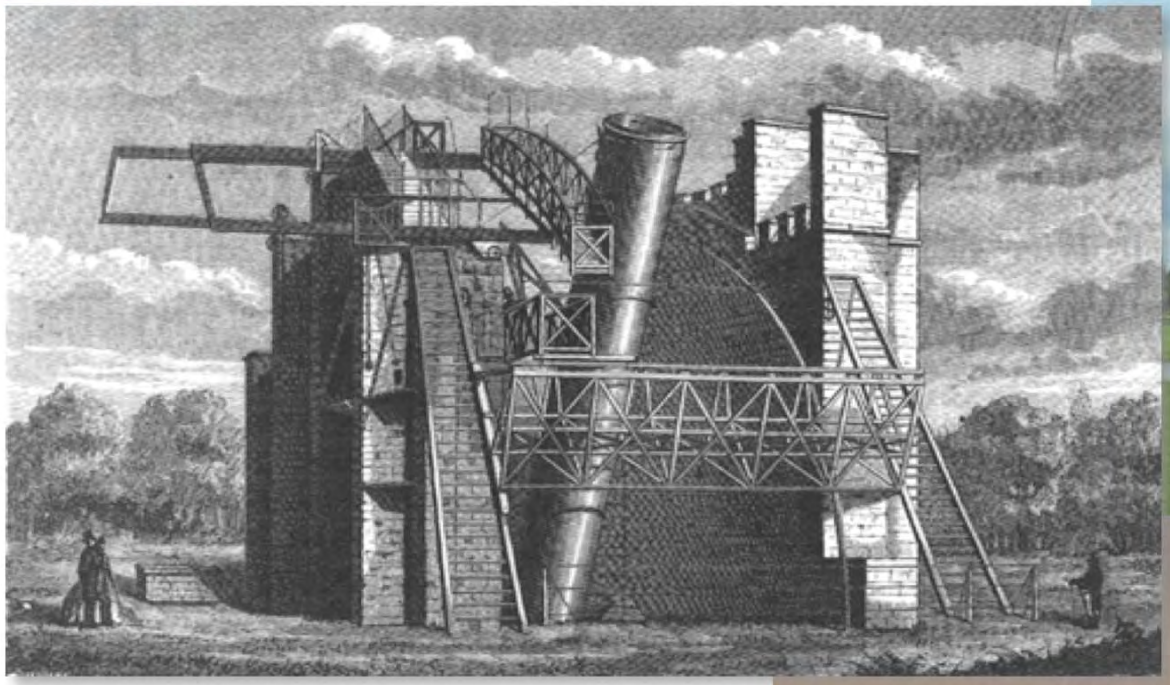


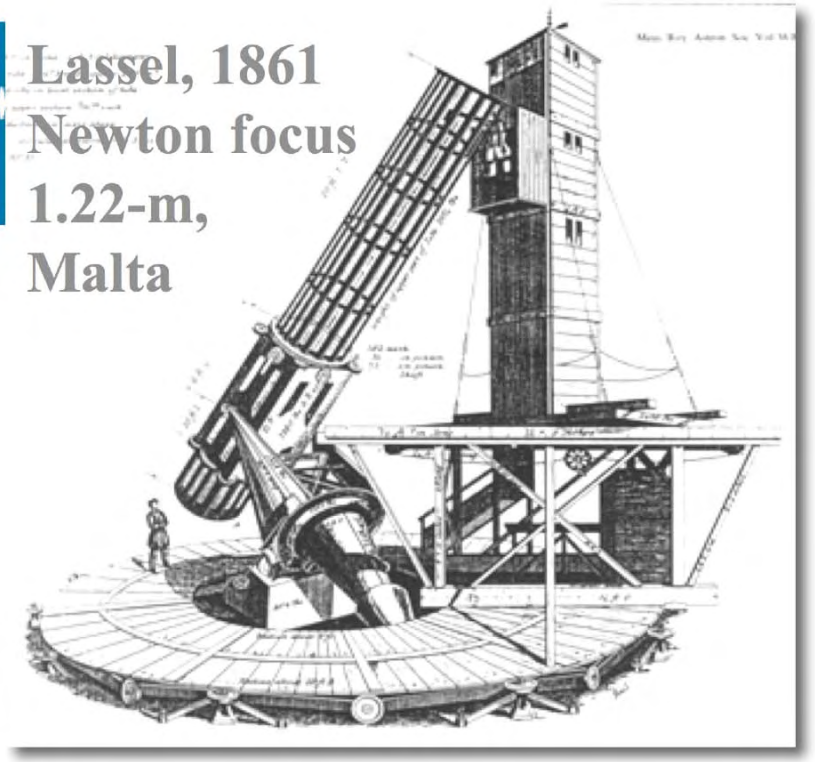





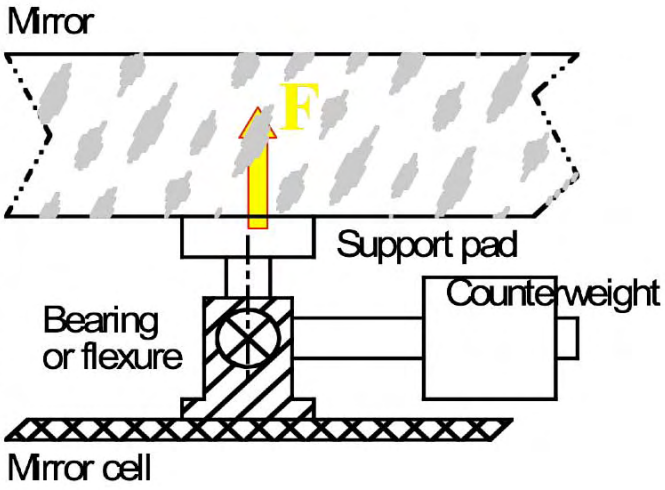
Lord Rosse 1.82-m, 1845
F/9 Newton focus
Astatic supports
Byrr Castle, Ireland

# Reflecting telescopes after 1672

Lassel, 1861
Newton focus
1.22-m,
Malta



## Counterweight support




$F \propto \cos z$

# Reflecting telescopes after 1672

Lassel, 1861
Newton focus
1.22-m,
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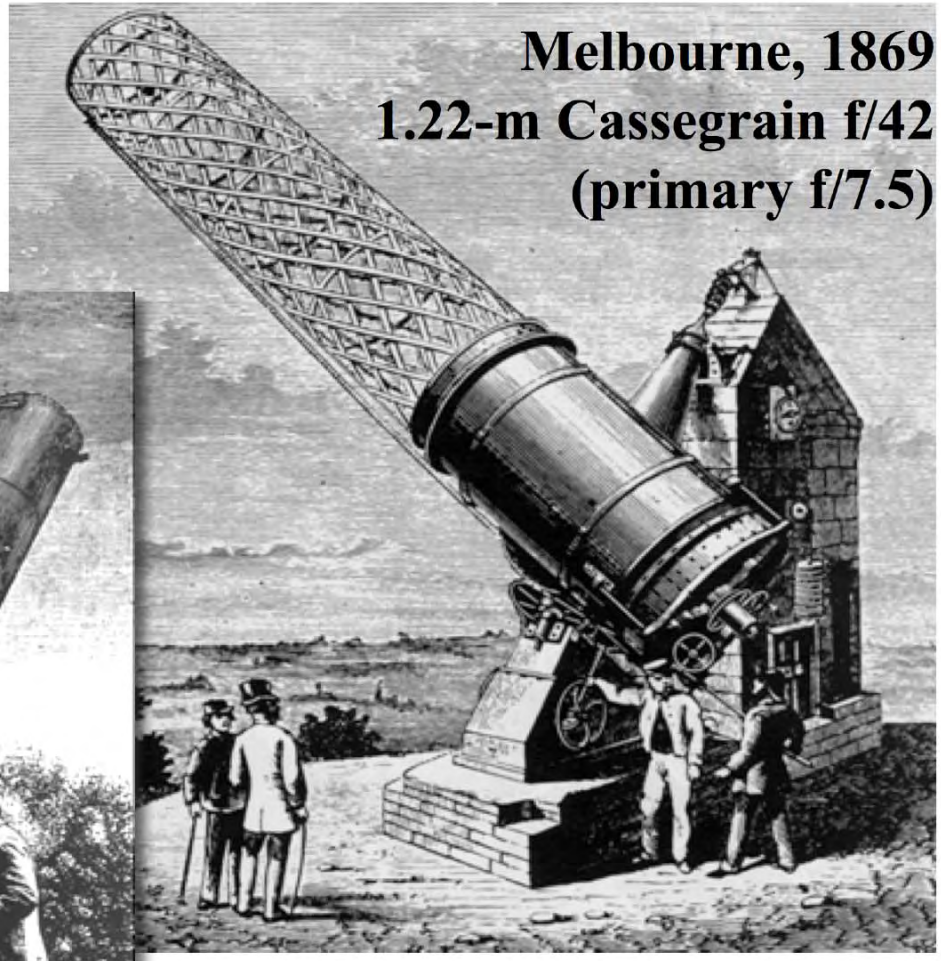
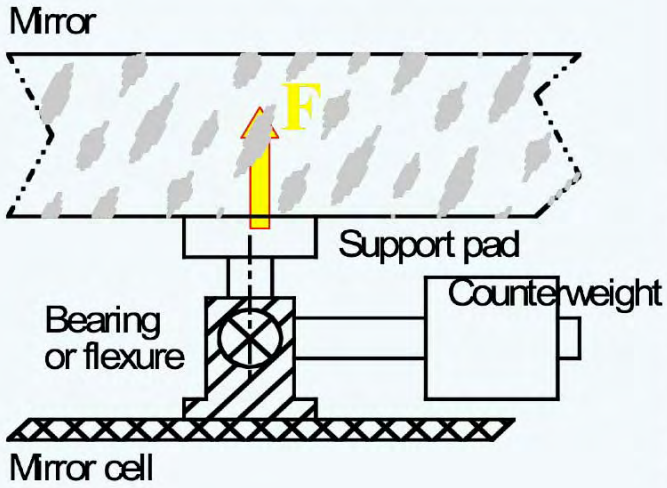


Melbourne, 1869
1.22-m Cassegrain f/42
(primary f/7.5)

Nasmyth, 1845
50-cm

## Counterweight support




$F \propto \cos z$

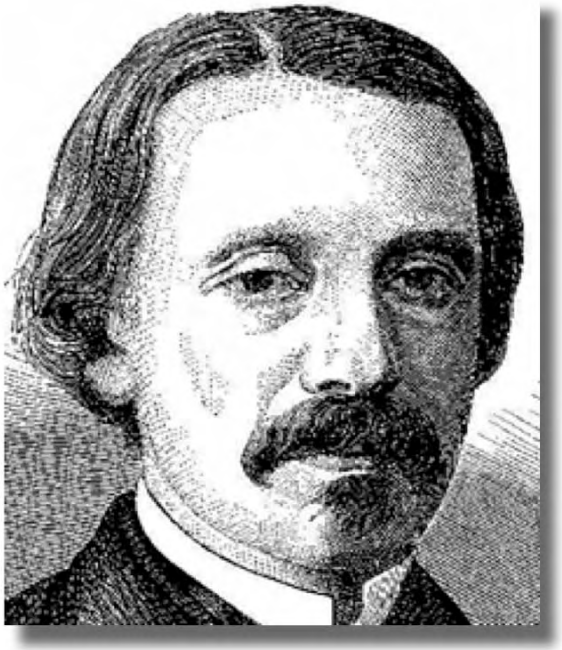
# Glass mirrors

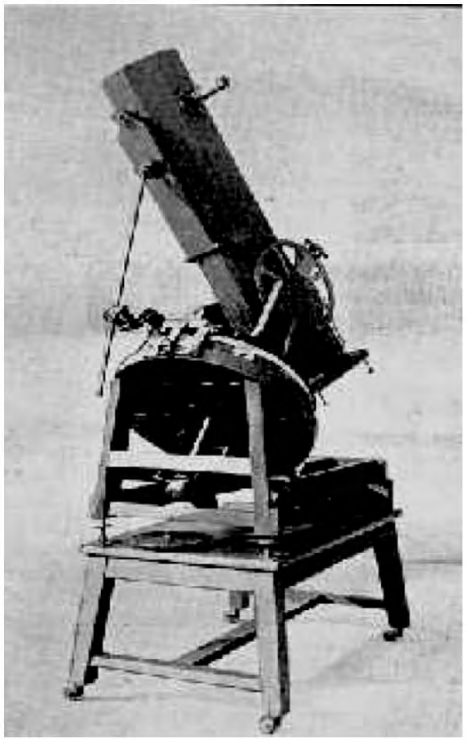
***Foucault***

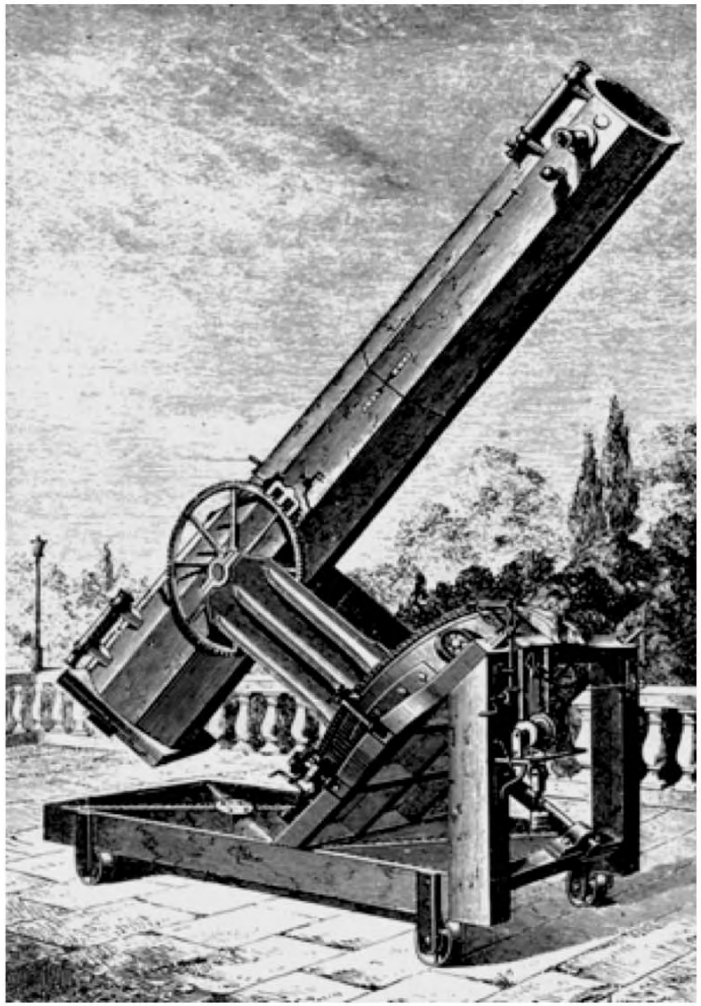
1857: silver on glass

1859: Foucault test

# Glass mirrors





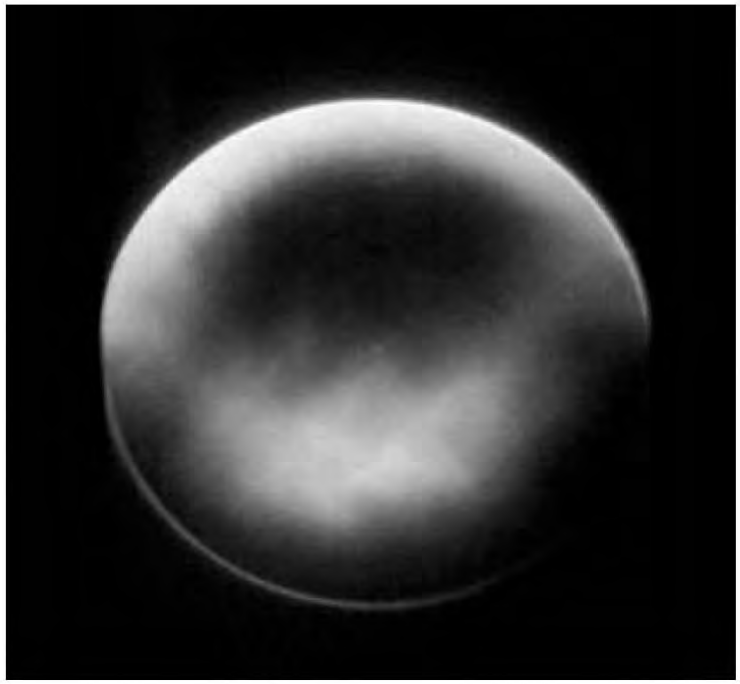


1862, 80 cm,
Silvered glass mirror

***Foucault***

1857: silver on glass

1859: Foucault test



# The American century

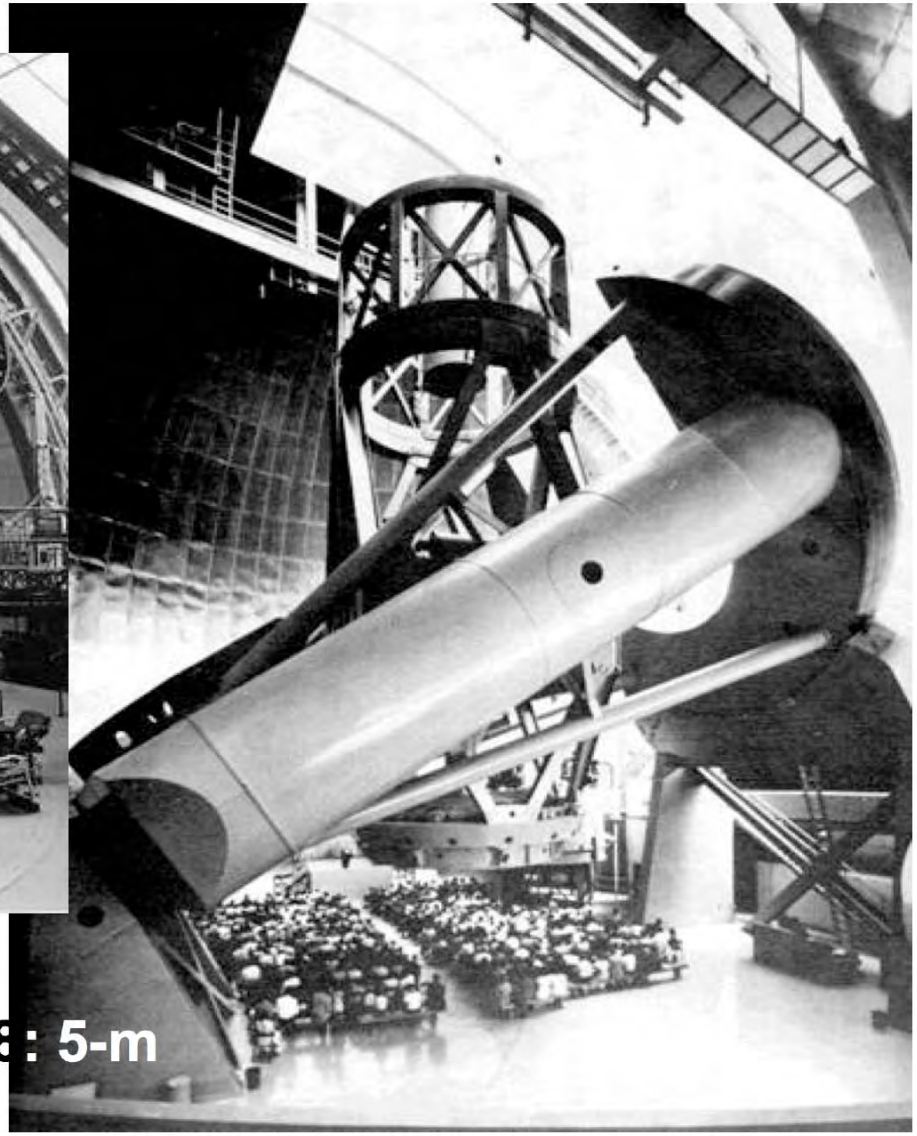
# The American century

Ritchey, 1901; 60-cm (Yerkes)

Ritchey, 1908; 1.5-m, Mt. Wilson



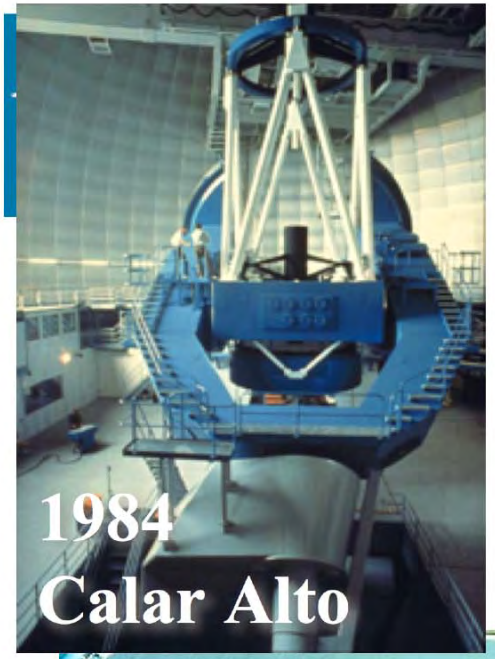
Mt Wilson, 1917: 2.5-m

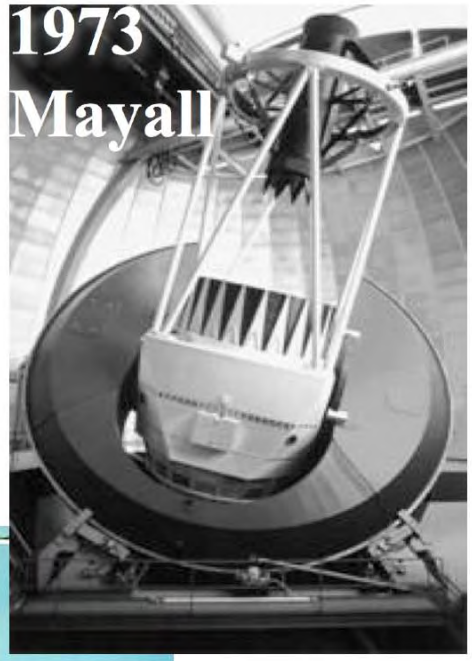


Palomar, 1948: 5-m

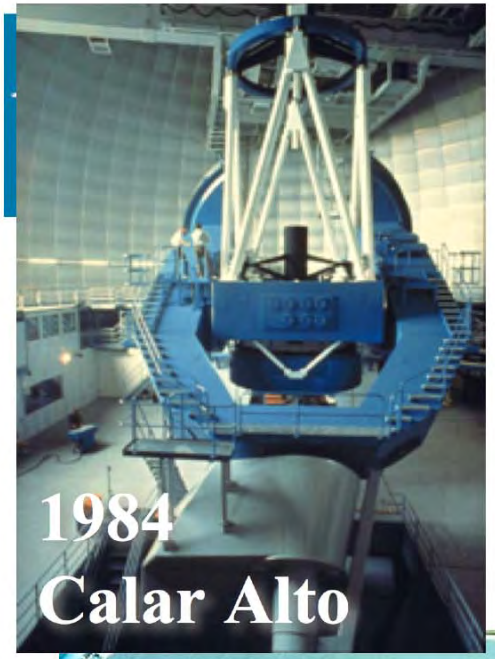
# After Palomar

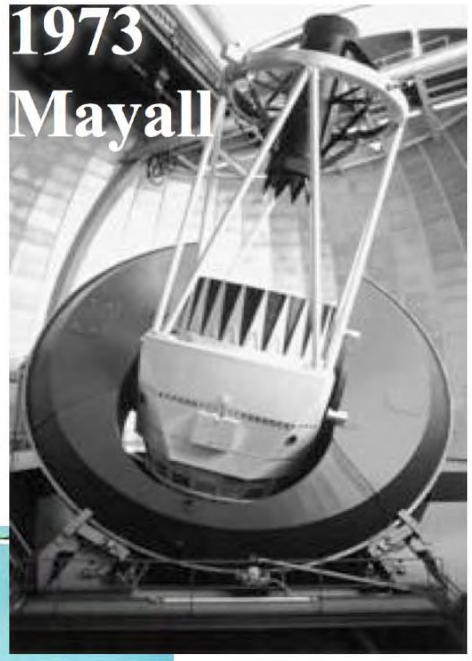
# After Palomar

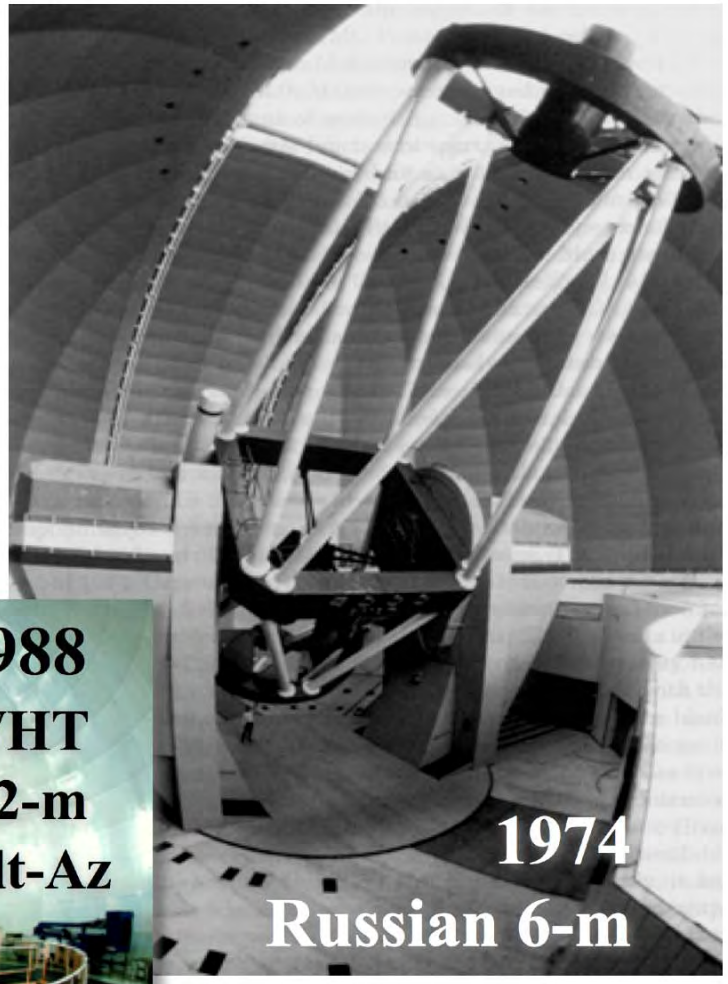


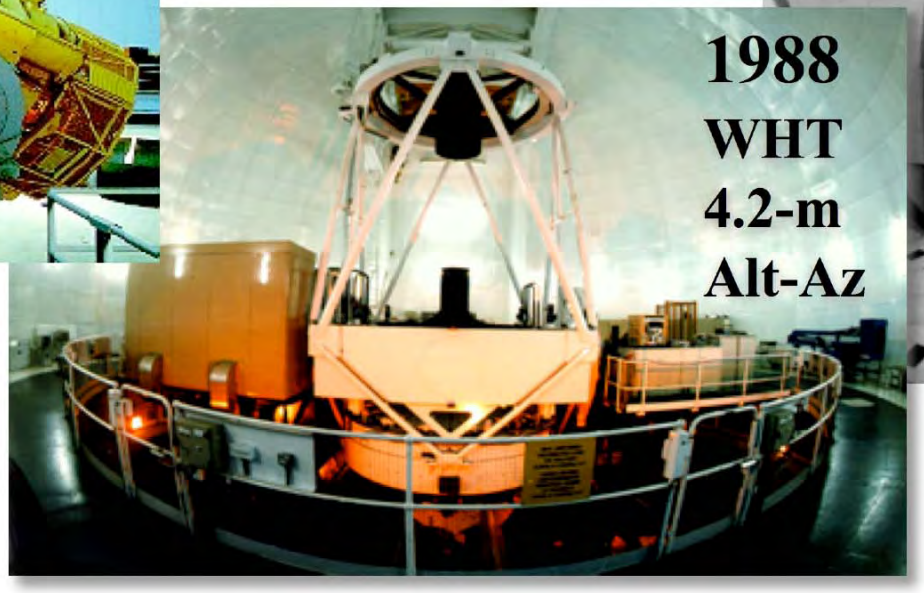

# After Palomar







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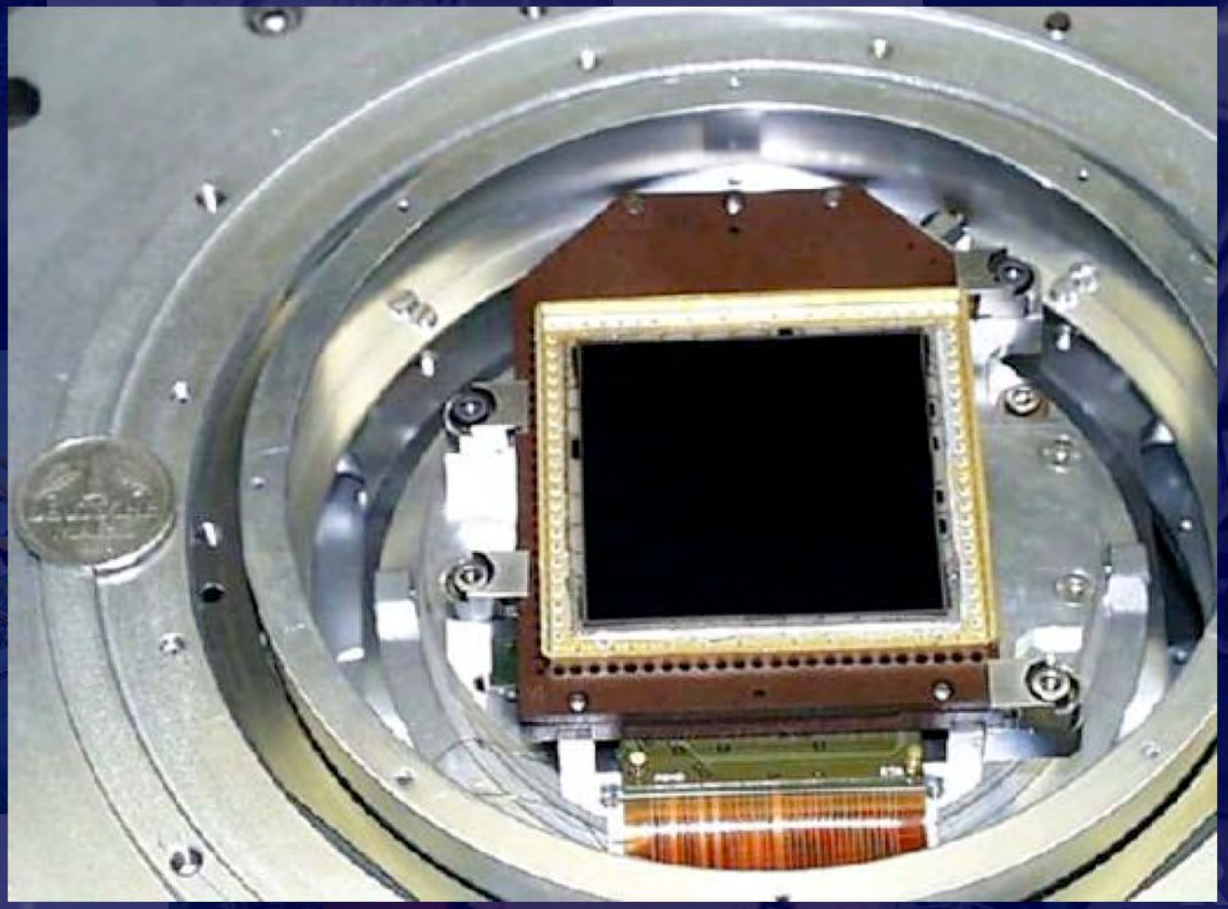

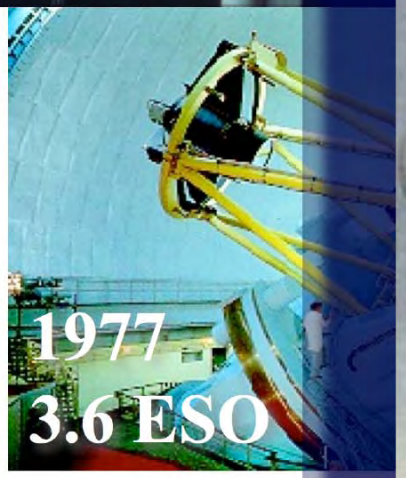


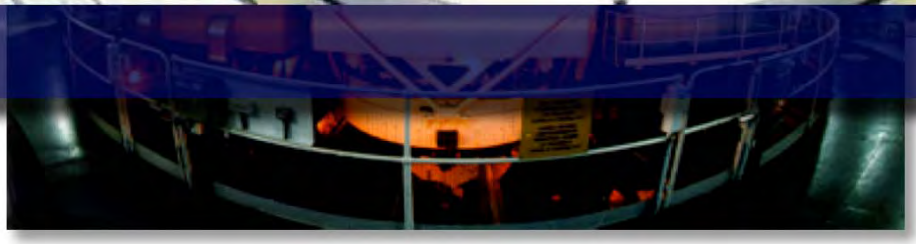

Slow progress

- Casting large homogeneous slabs,
- Polishing incl. metrology
- Support systems


Slow progress

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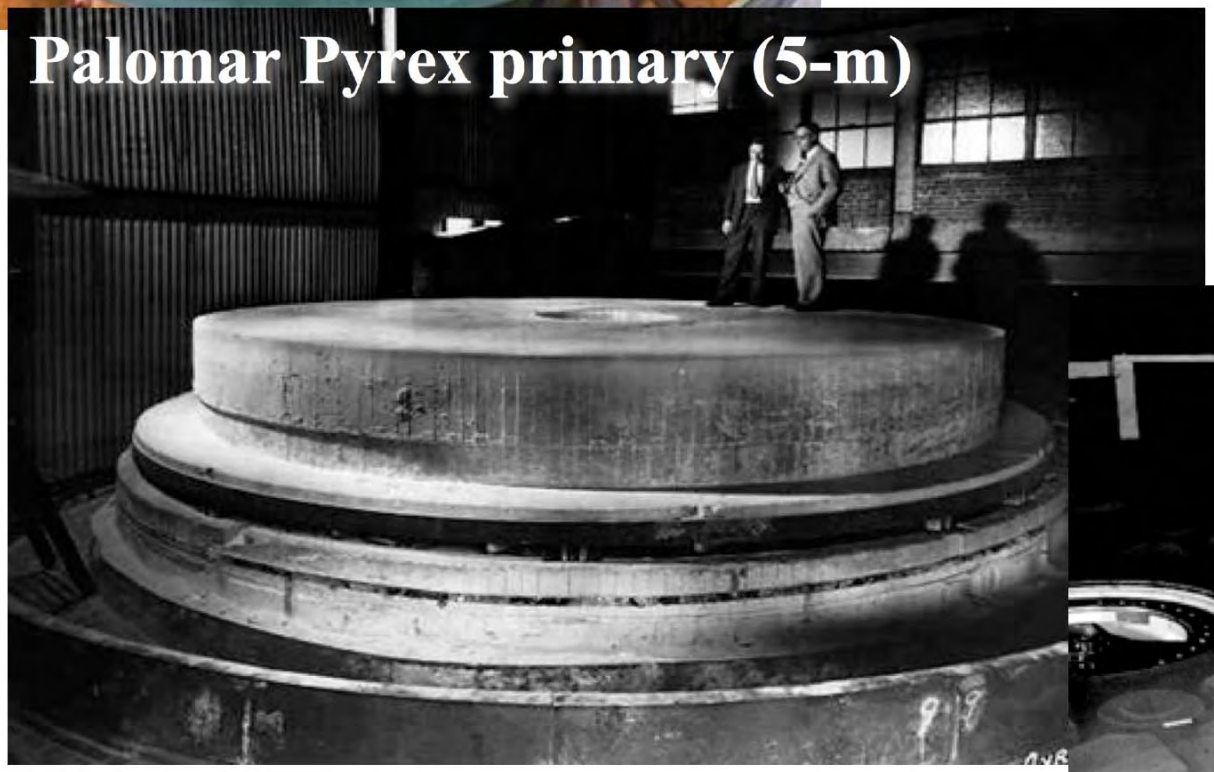
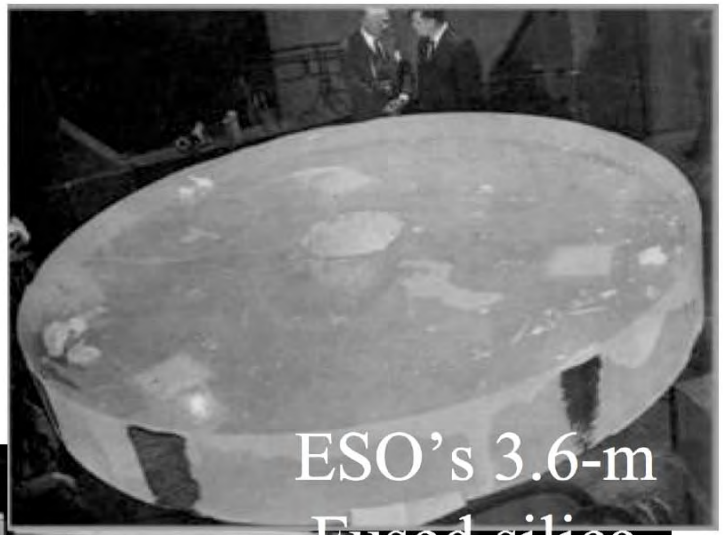
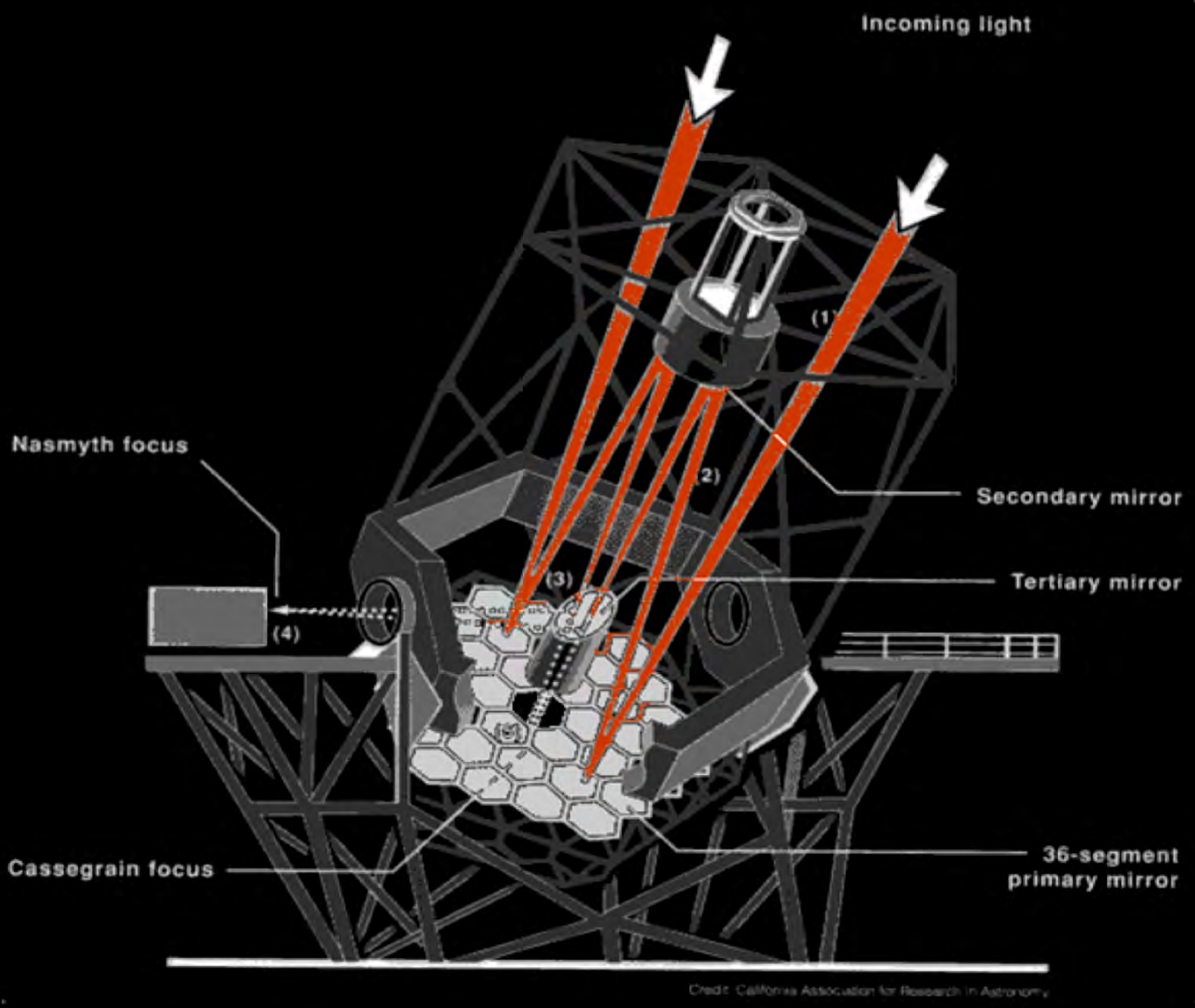
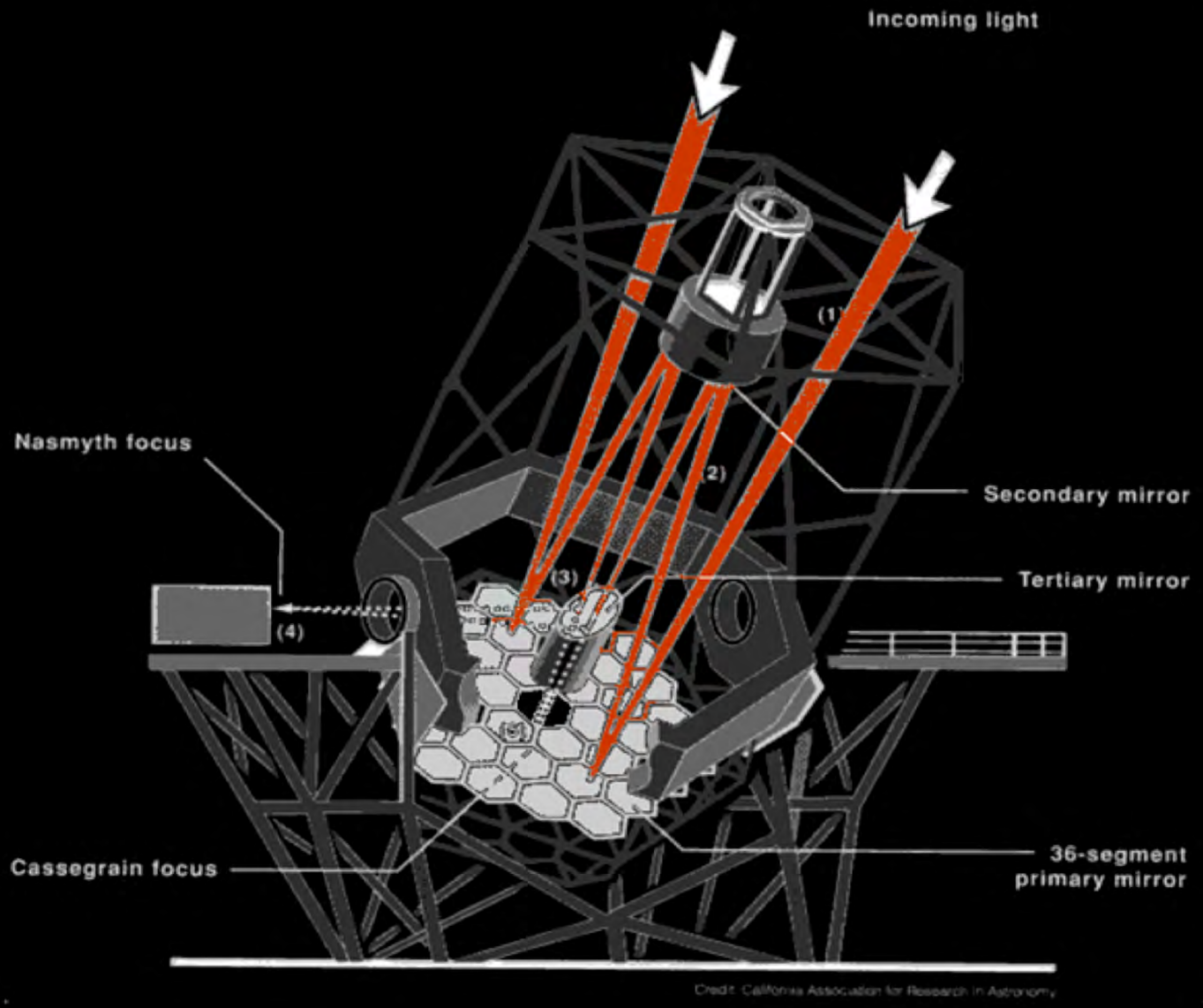
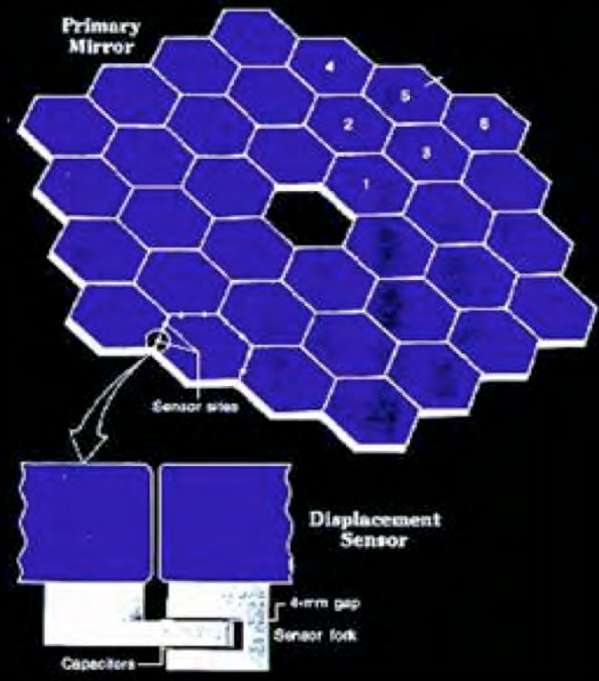




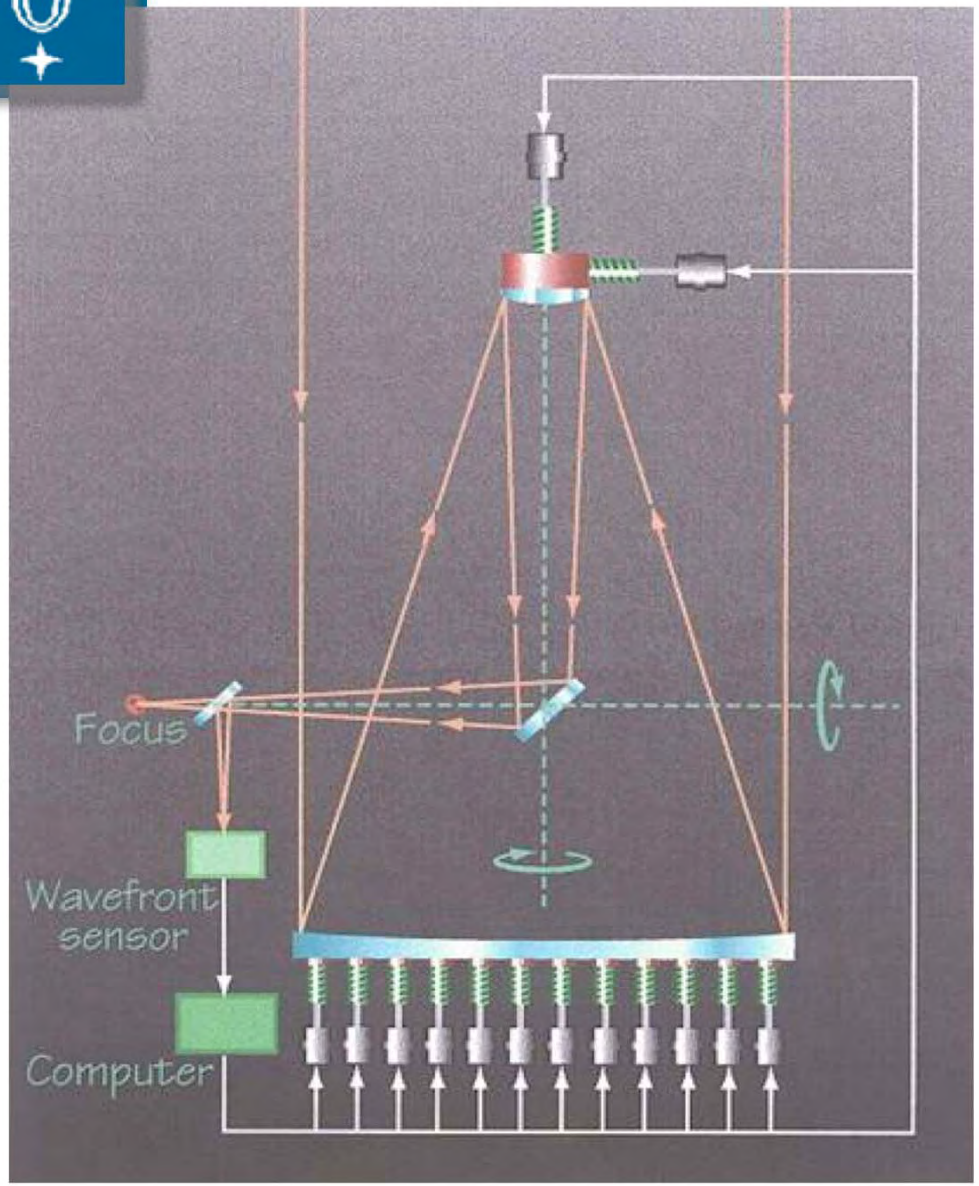

# Segmentation – Keck 10-m telescopes



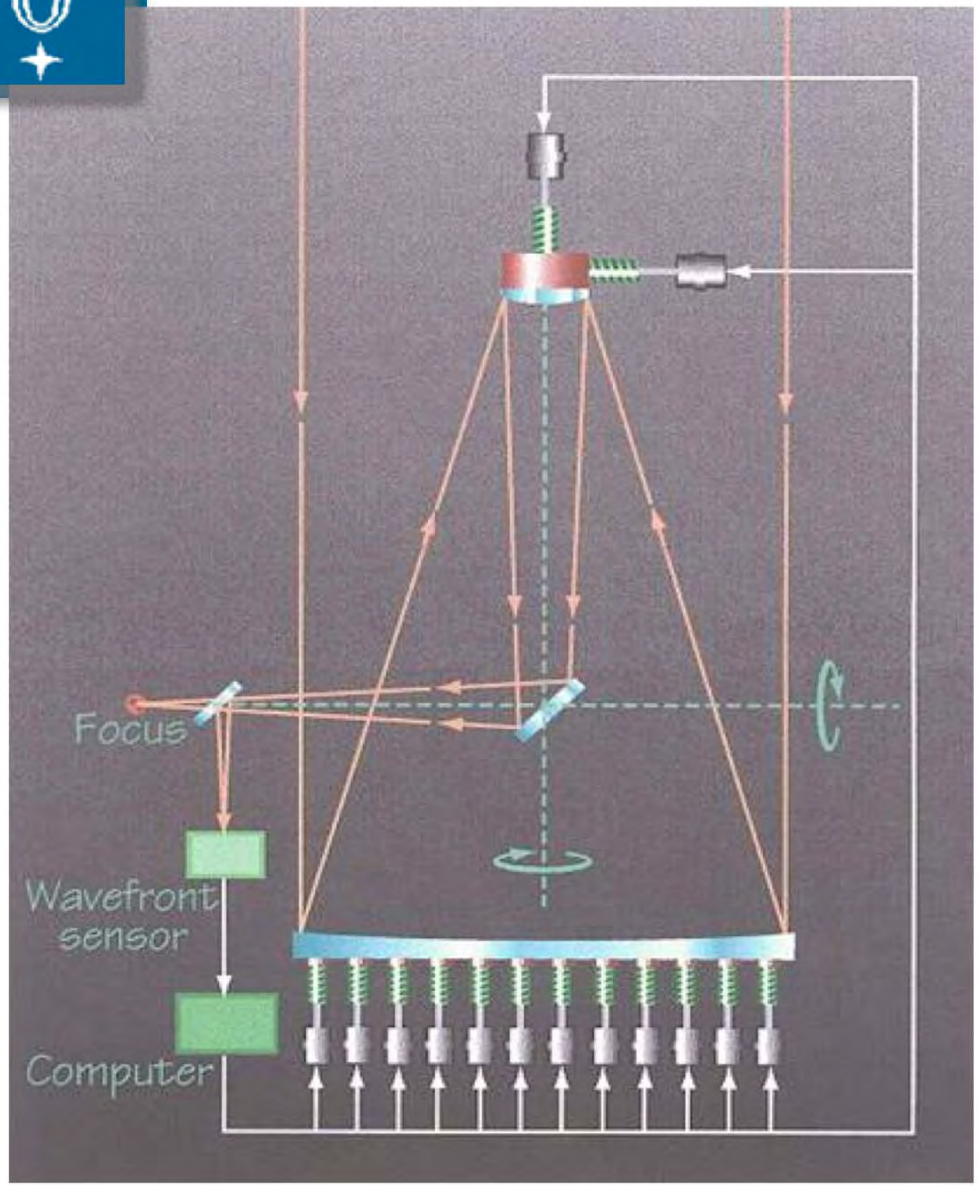

# Segmentation – Keck 10-m telescopes


11-m Southern African Large Telescope (SALT)




Active Optics - ESO, 1989

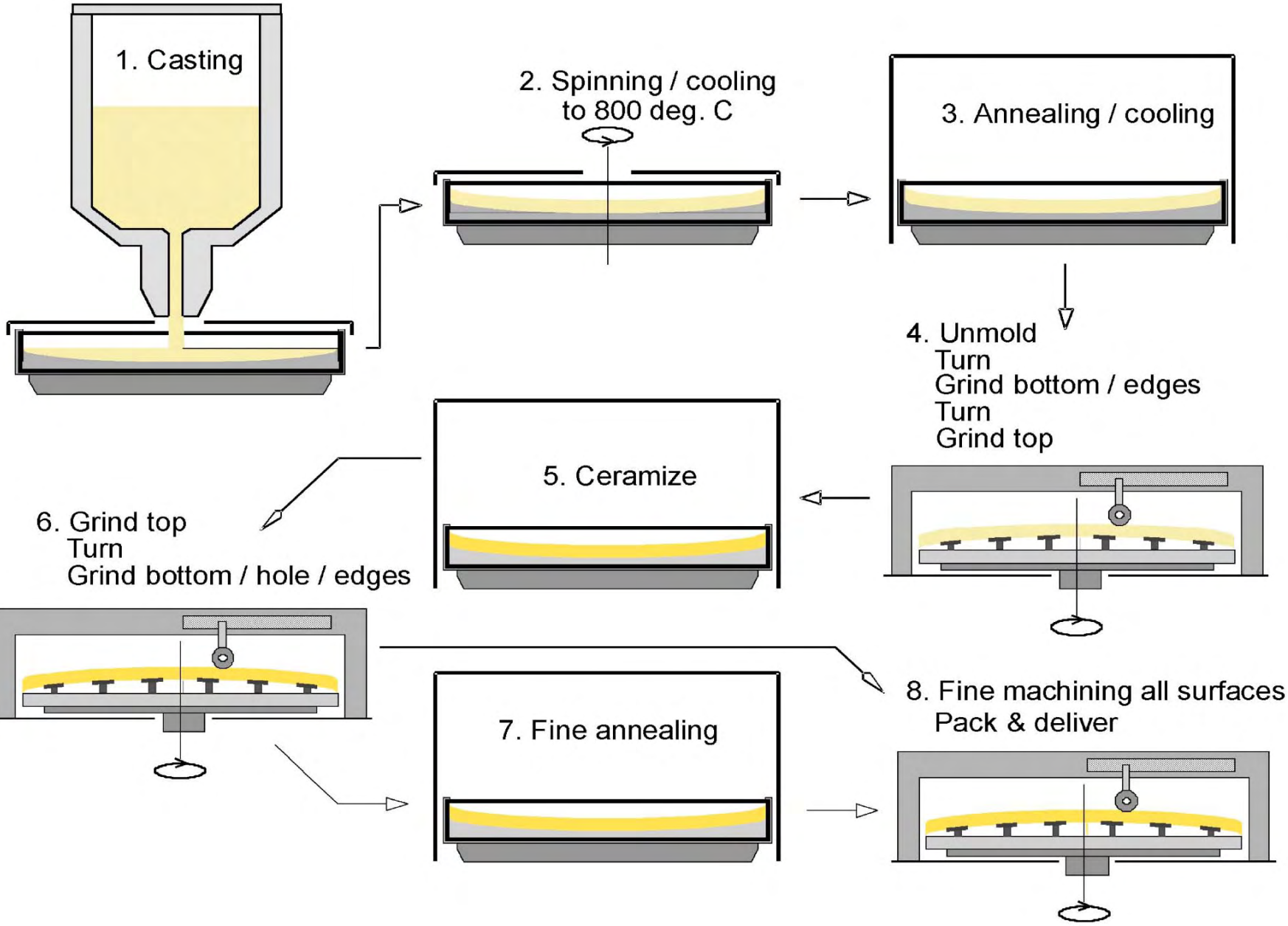
3.5-m New Technology Telescope



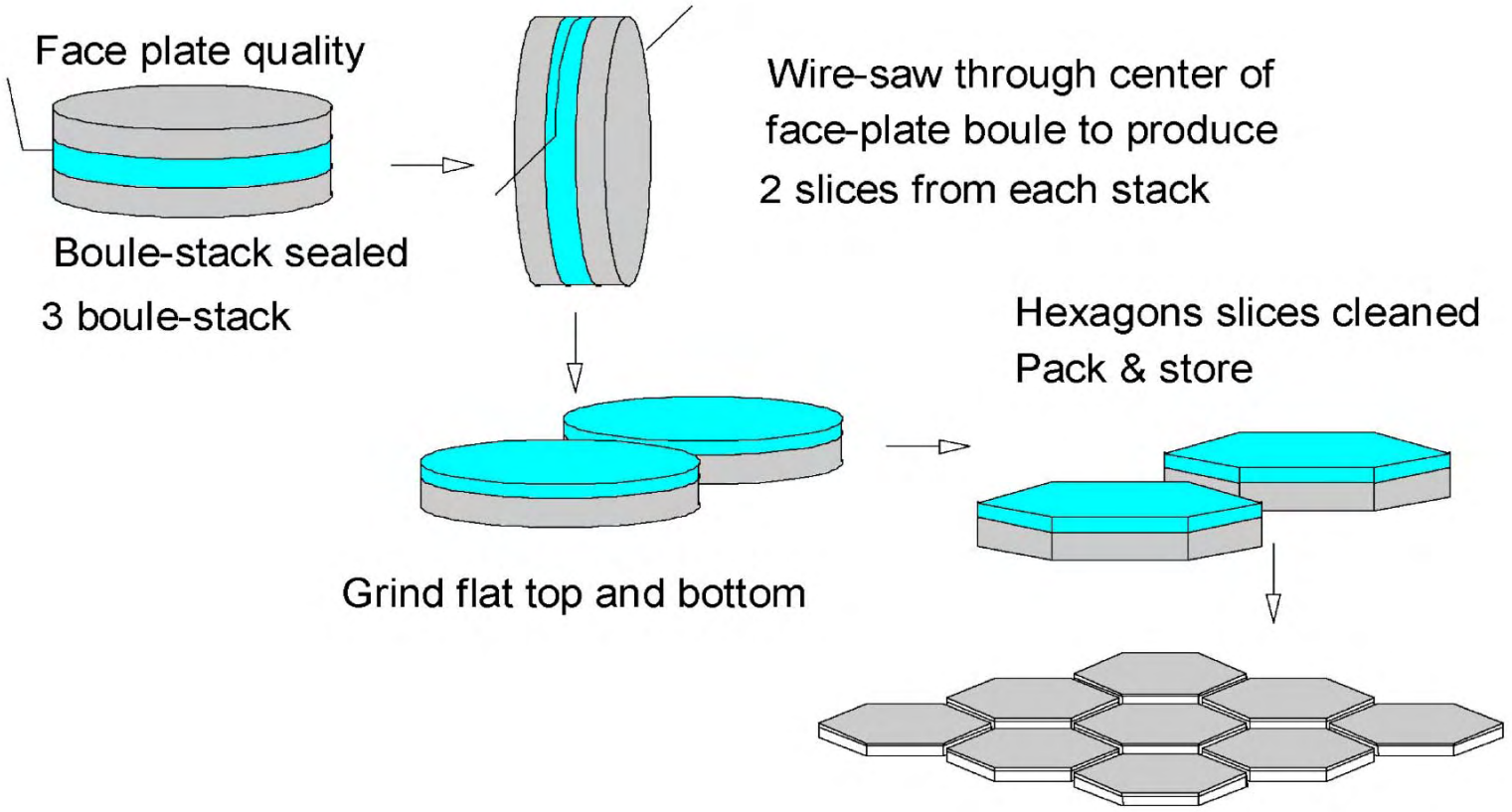

Active Optics - ESO, 1989

3.5-m New Technology Telescope

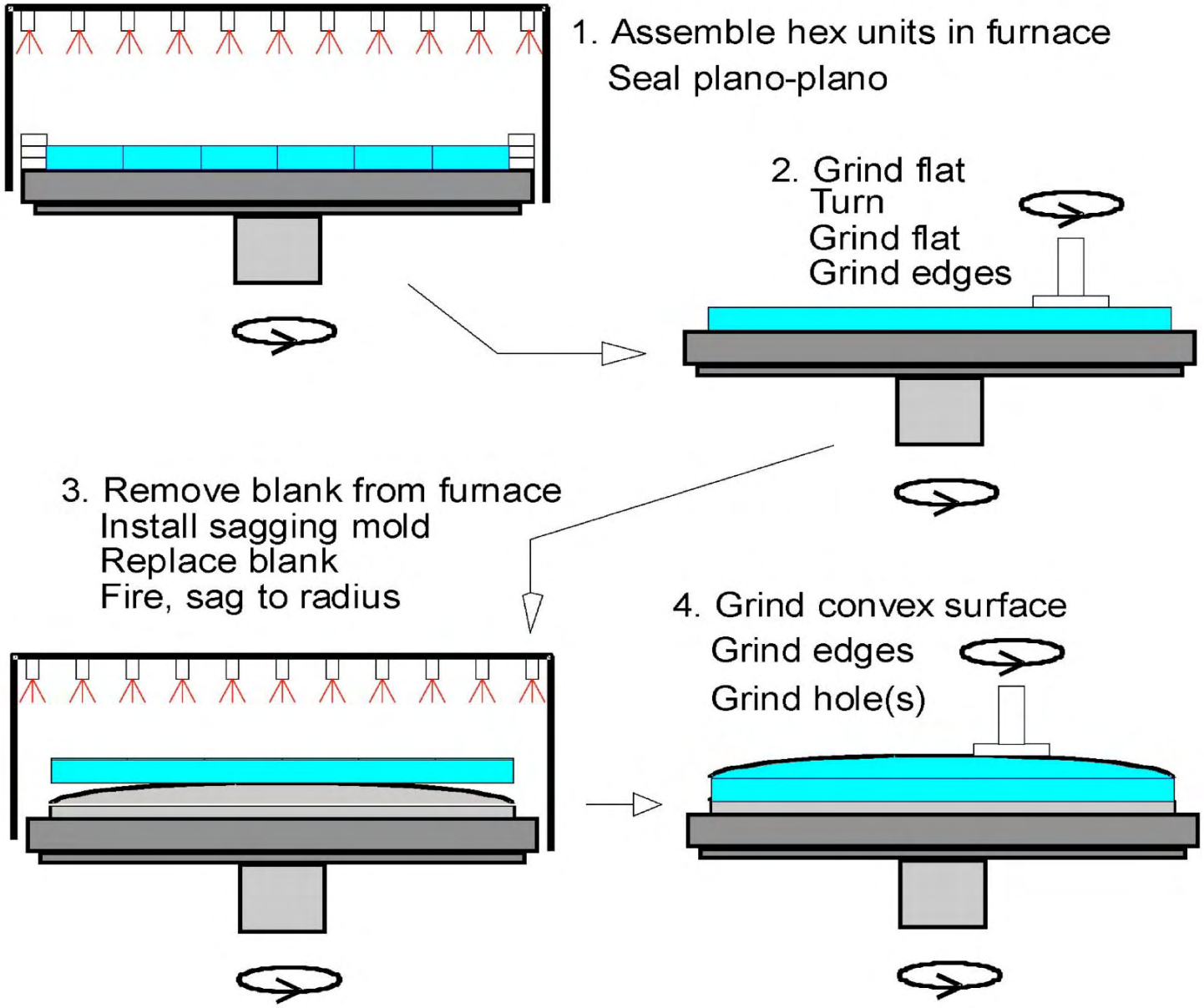
# Spin-casting (SCHOTT Zerodur, Germany)



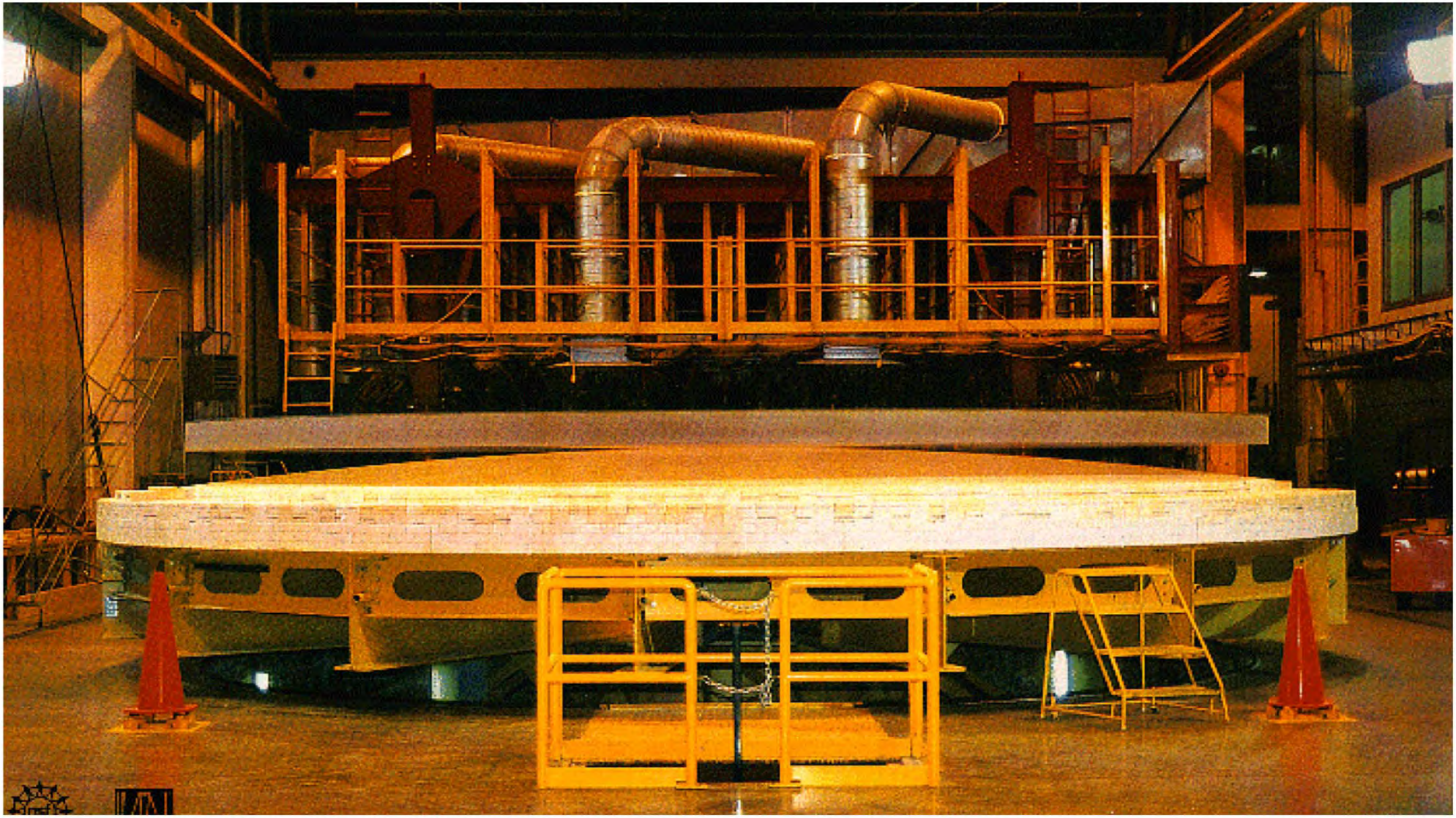
# Ultra-Low Expansion Glass (Corning, US)



# Ultra-Low Expansion Glass (Corning, US)



# Gemini 8.1-m ULE mirror blank at Corning



# ACTIVE OPTICS AT THE VLT

No. of active, axial supports:
150

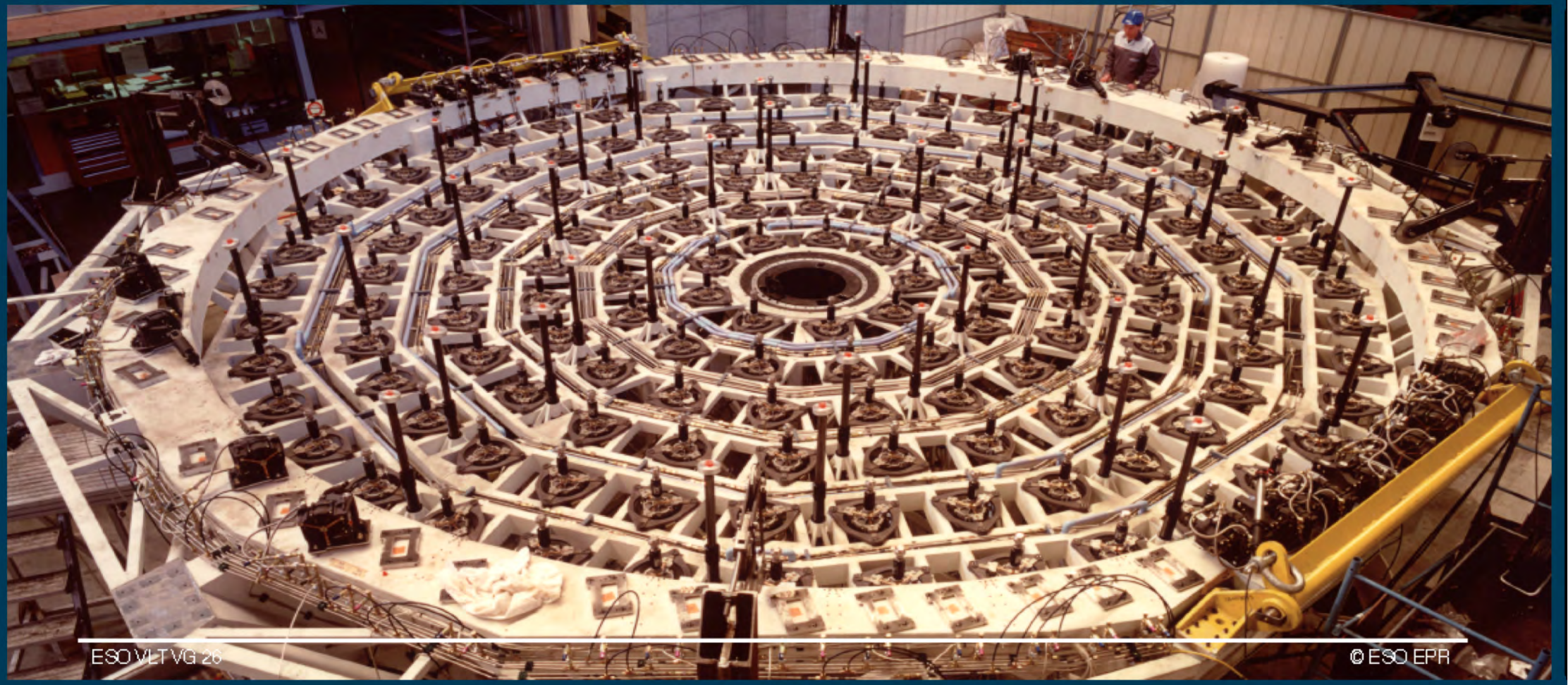
No. of lenslets in WFS:
30x30

Update interval:
30 sec (typ.)

Wavefront Sensor (WFS):
Shack-Hartmann

Correction scheme:
Modal

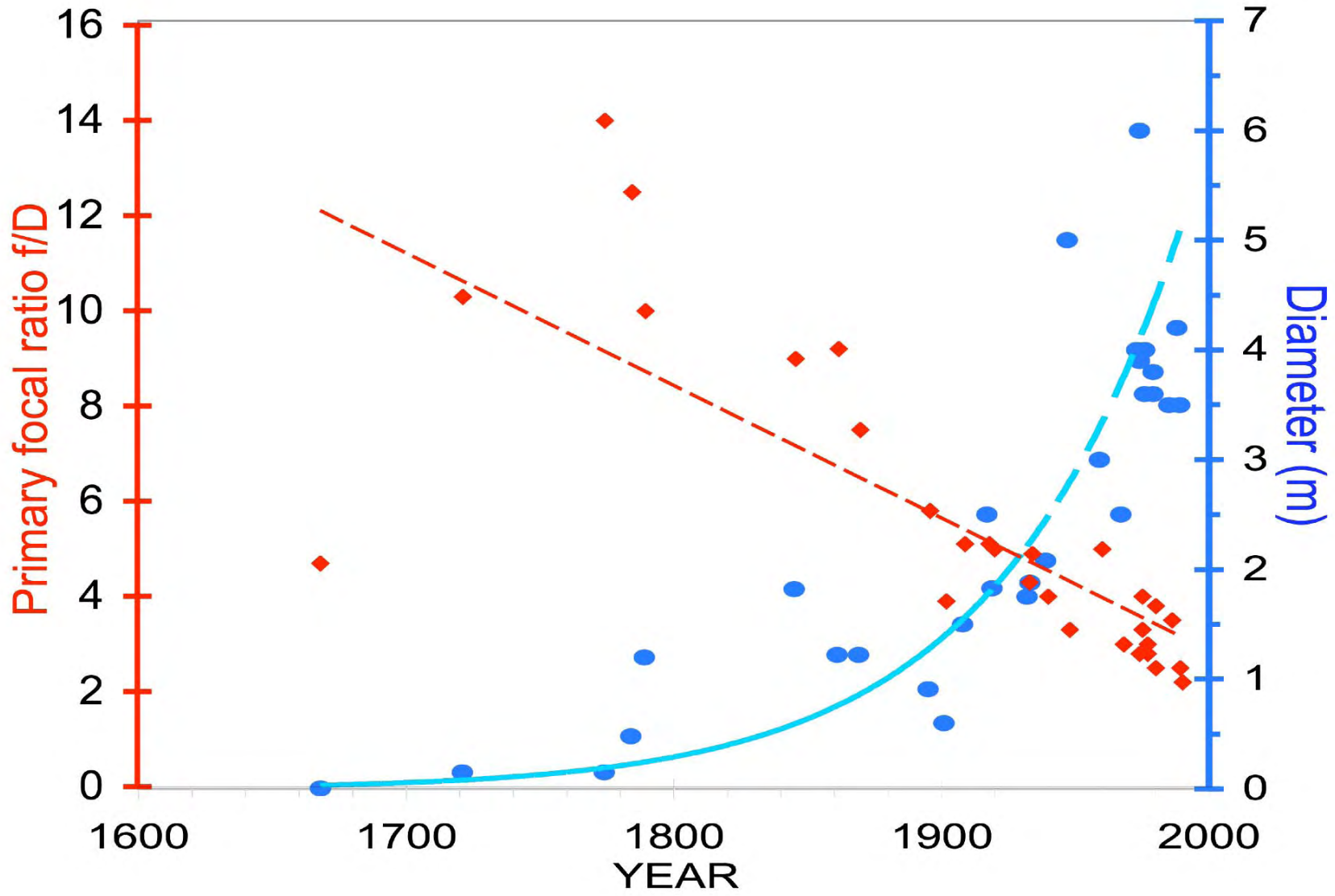
Coma and focus correction:
on M2



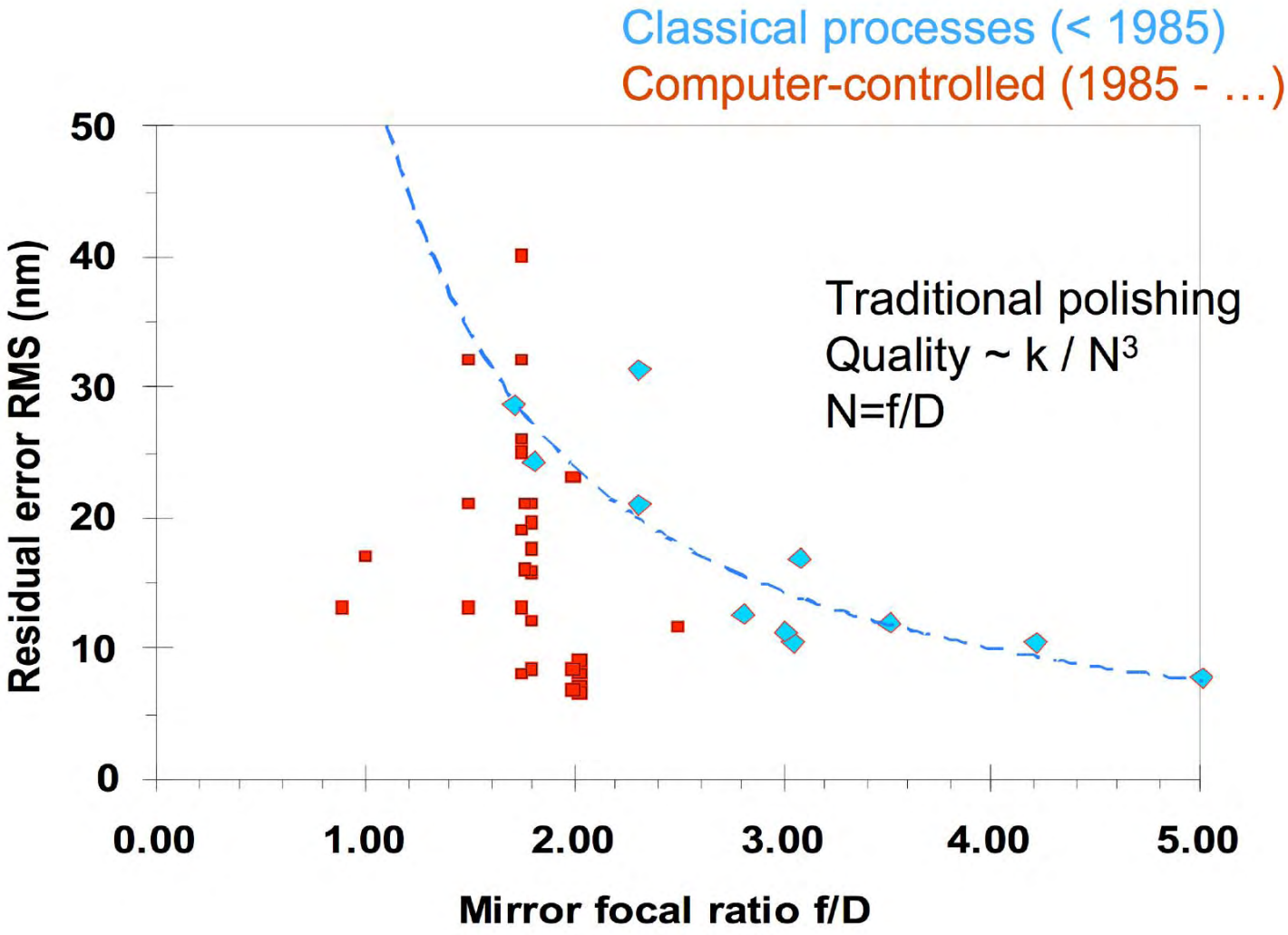
8.2-m Very Large Telescopes (ESO)

# Larger and shorter

# Larger and shorter

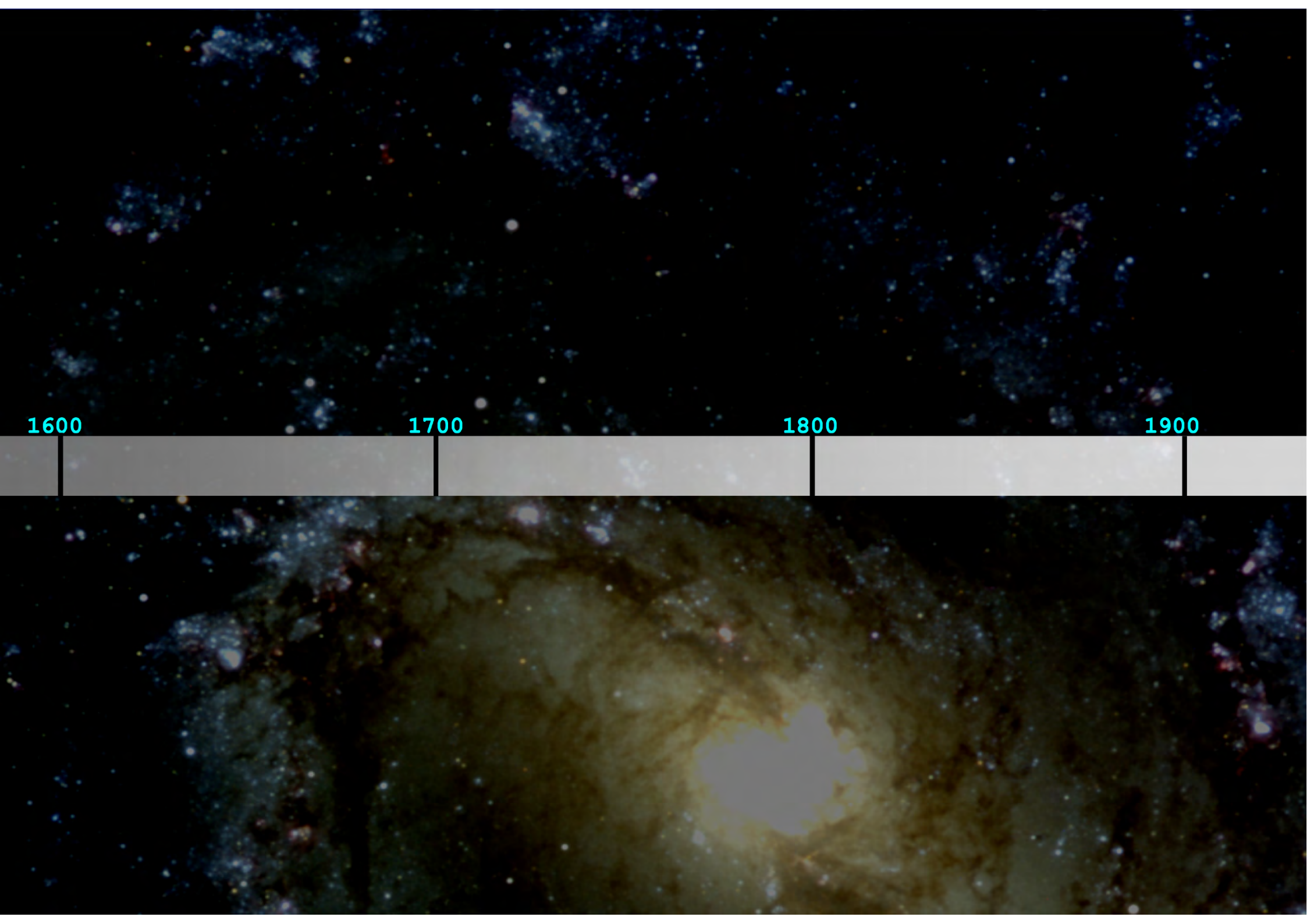


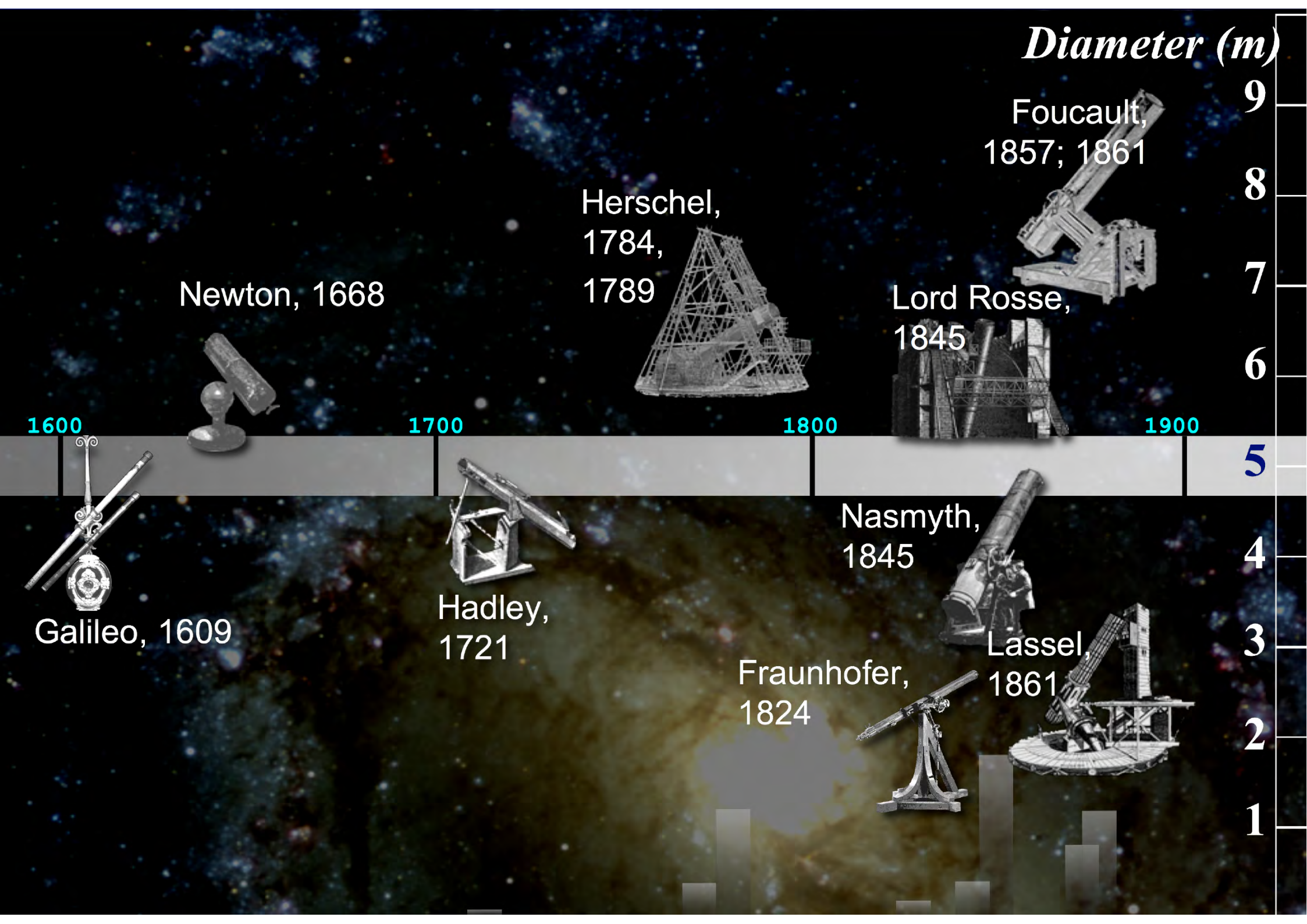
# Shorter is more difficult

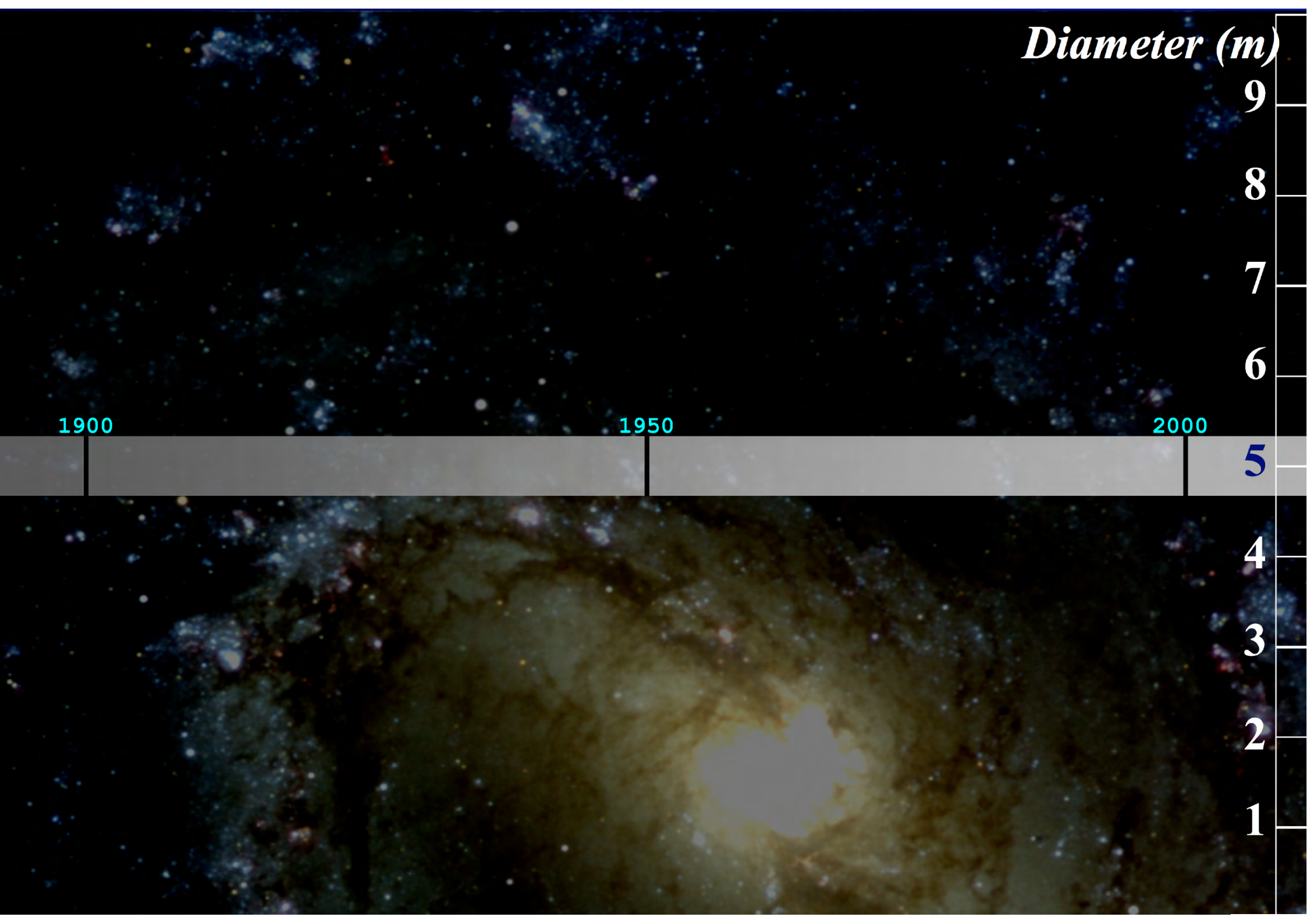


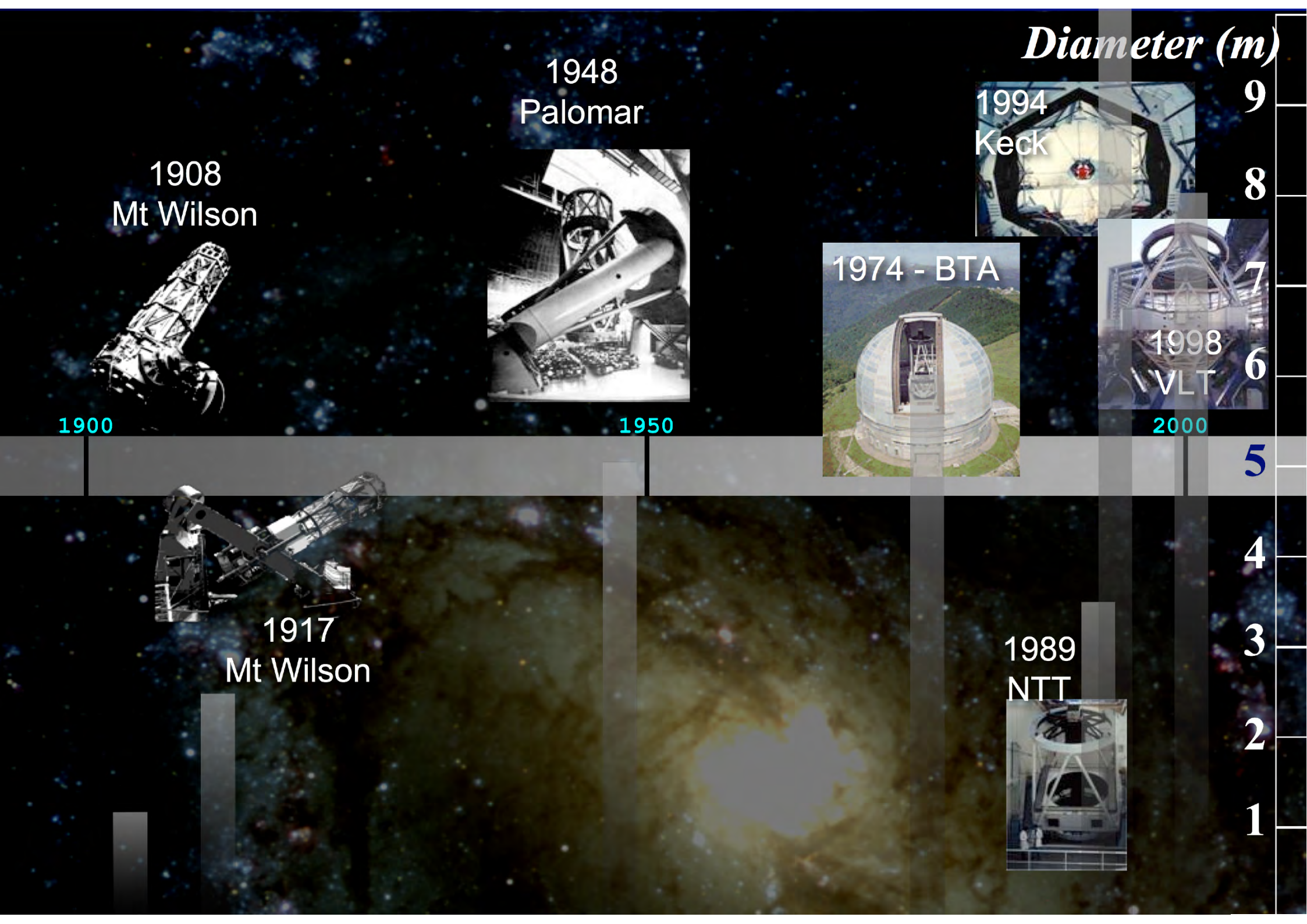

TODAY: IF YOU CAN MEASURE IT, YOU CAN DO IT
(BUT YOU MAY HAVE TO PAY A LOT …)

VLT primary Mirror. 50 $m^2$.
8,5 nm RMS surface error

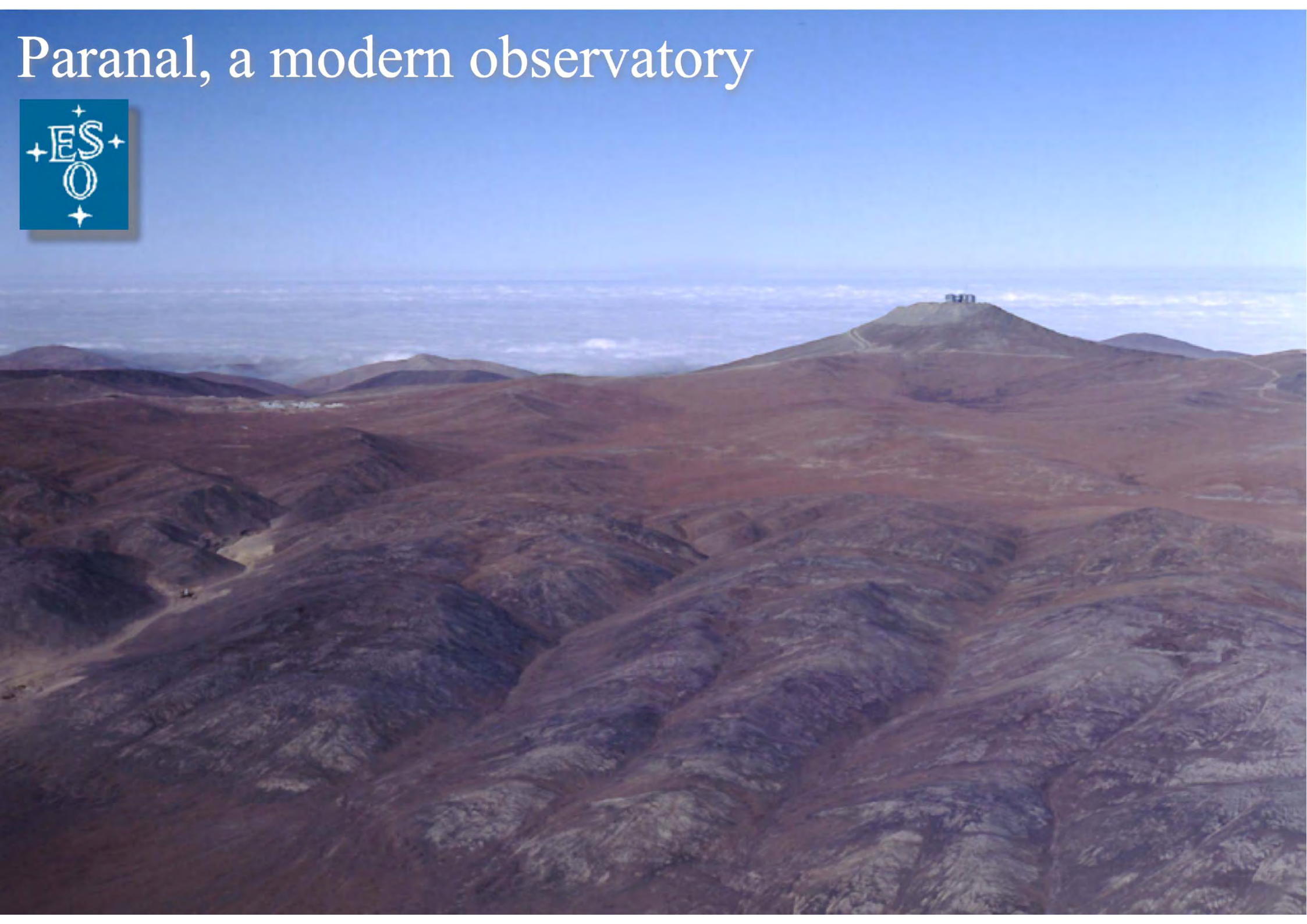

1600
1700
1800
1900


Diameter (m)
9
8
7
6
5
4
3
2
1
1600
1700
1800
1900
Galileo, 1609
Newton, 1668
Hadley, 1721
Herschel, 1784, 1789
Lord Rosse, 1845
Foucault, 1857; 1861
Nasmyth, 1845
Fraunhofer, 1824
Lassel, 1861

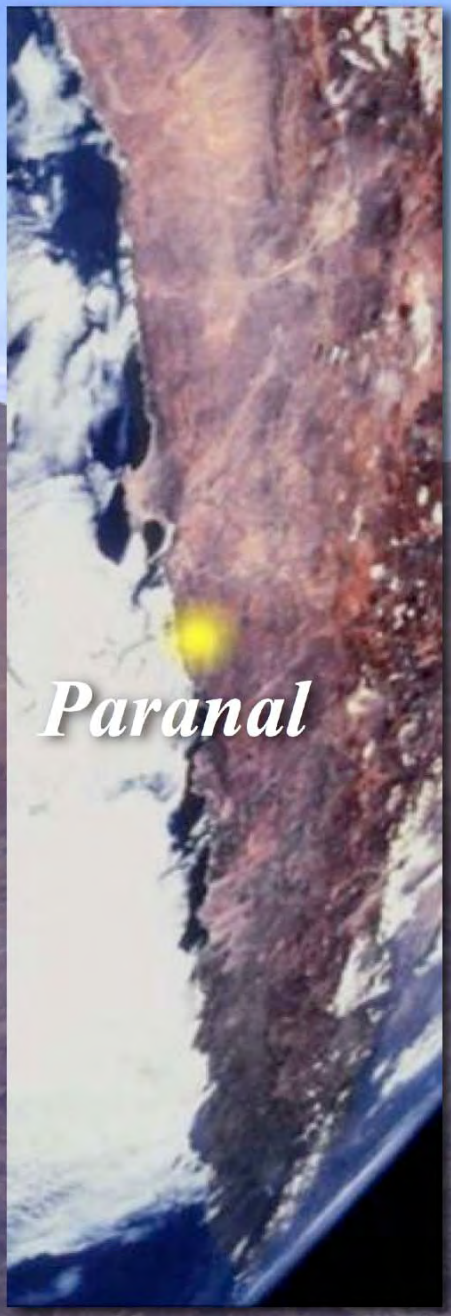

Diameter (m)
9
8
7
6
5
4
3
2
1
1900
1950
2000


Diameter (m)
9
8
7
6
5
4
3
2
1
1900
1950
2000
1908
Mt Wilson
1917
Mt Wilson
1948
Palomar
1974 - BTA
1989
NTT
1994
Keck
1998
VLT

# Paranal, a modern observatory



# Paranal, a modern observatory




- Low water vapor content
- Low cloudiness
- Low atmospheric turbulence

# Paranal, a modern observatory

- Compact enclosure
- Daytime cooling
- Wind permeability
- Minimal human presence

# Paranal, a modern observatory

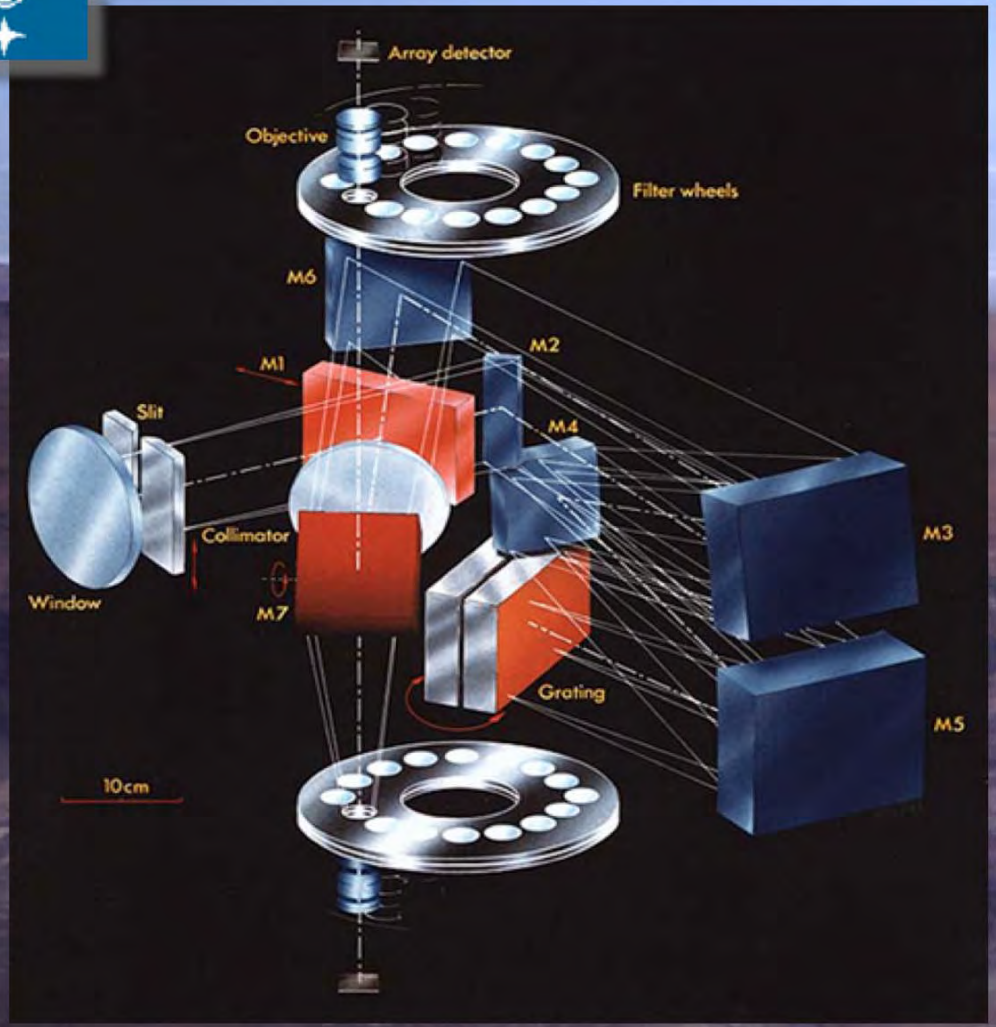
Lightweight secondary mirror; fast steering for field stabilization, active focusing & centering

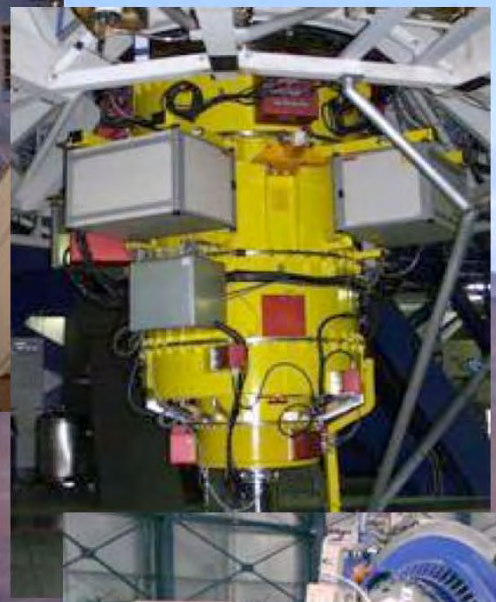
Nasmyth & Cassegrain foci, on-sky metrology

Alt-az fork mount

Active, deformable primary mirror

# Paranal, a modern observatory



**VERY HIGH RELIABILITY - LESS THAN 3% DOWNTIME**

# Industry as a key partner

# Industry as a key partner

Schott

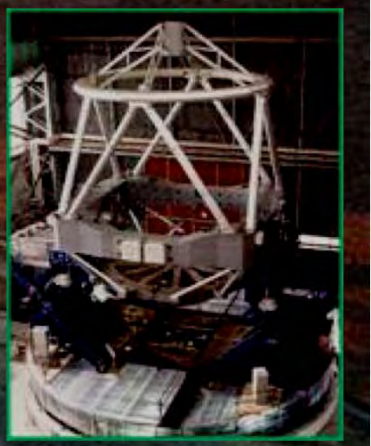
Zeiss

SAGEM

Linde

Cegelec

Ansaldo AES



Fokker
TNO/TPD

REOSC

AMOS

GIAT

Dornier

Skanska

# Armospheric turbulence

**Characteristic size**

**~λ/D**

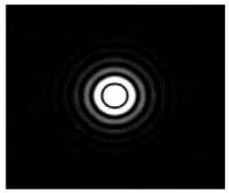
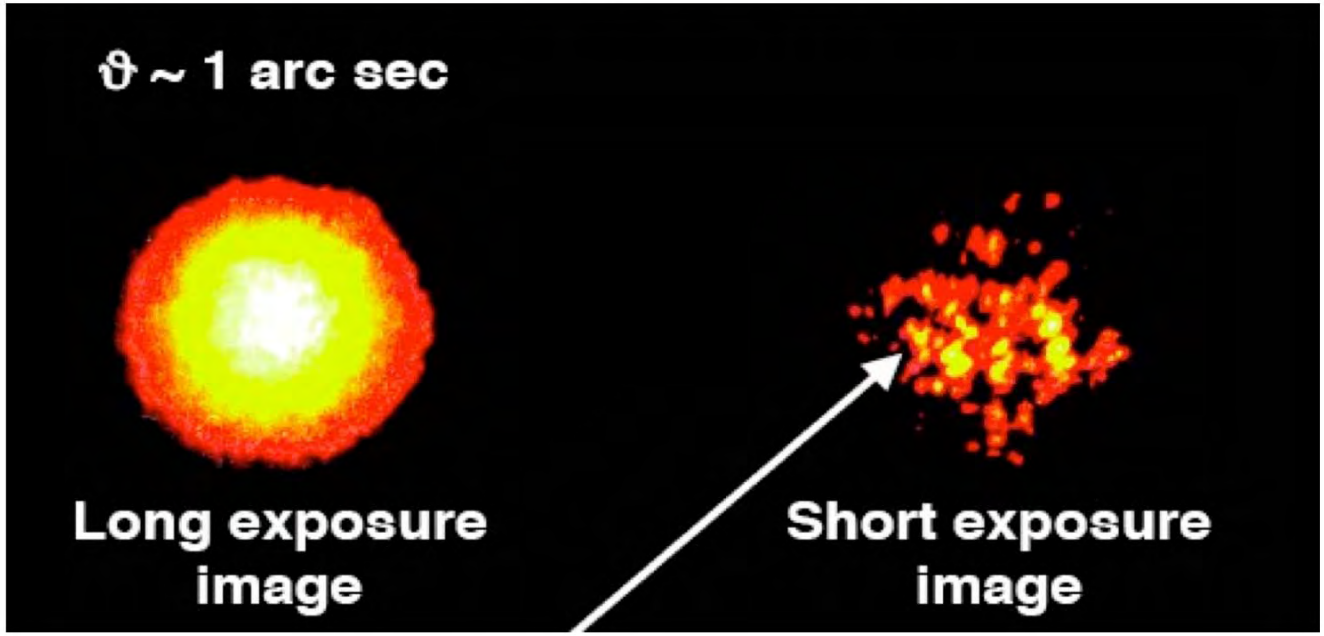
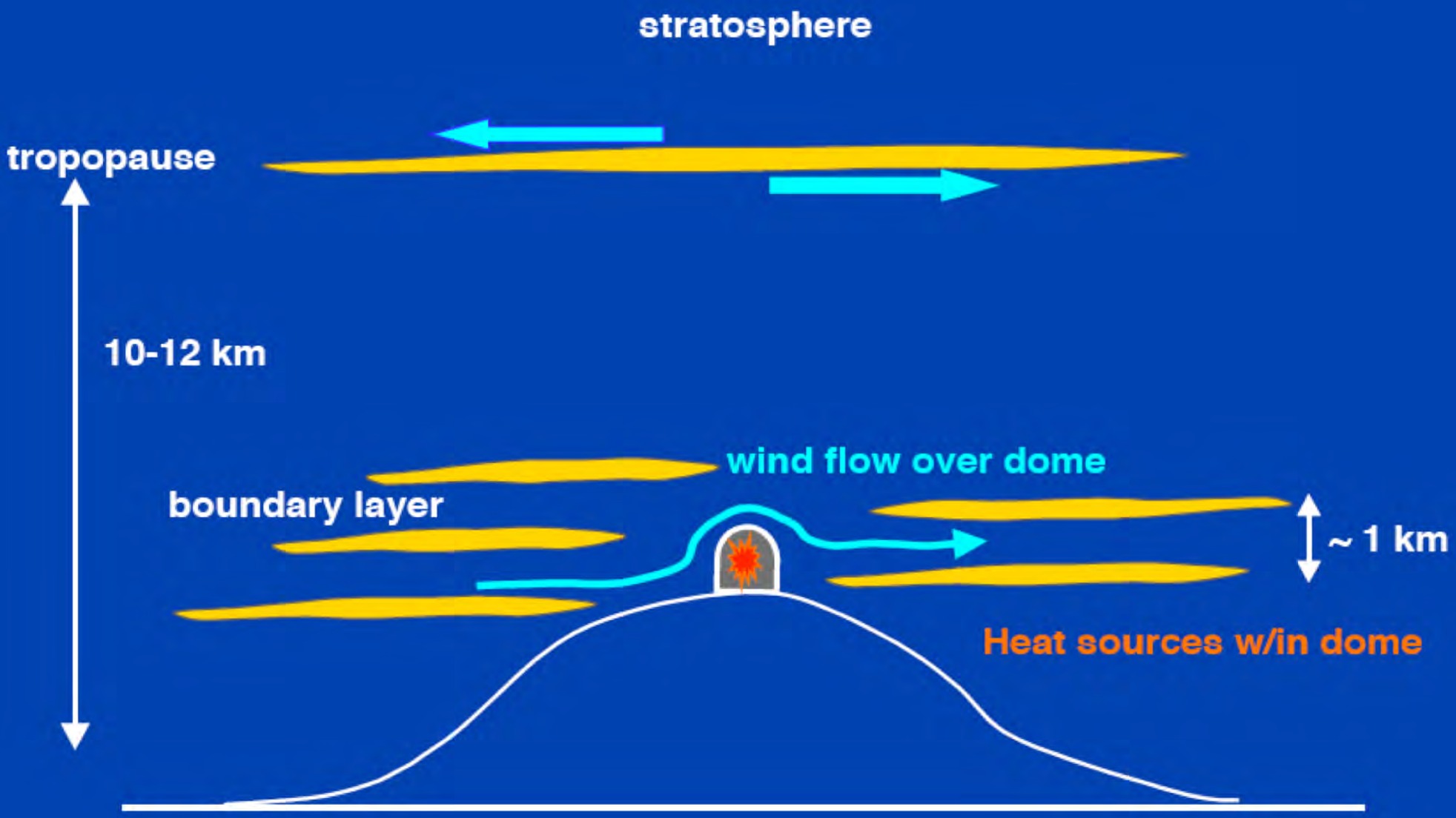


Image: Lick Observatory, 1-m telescope



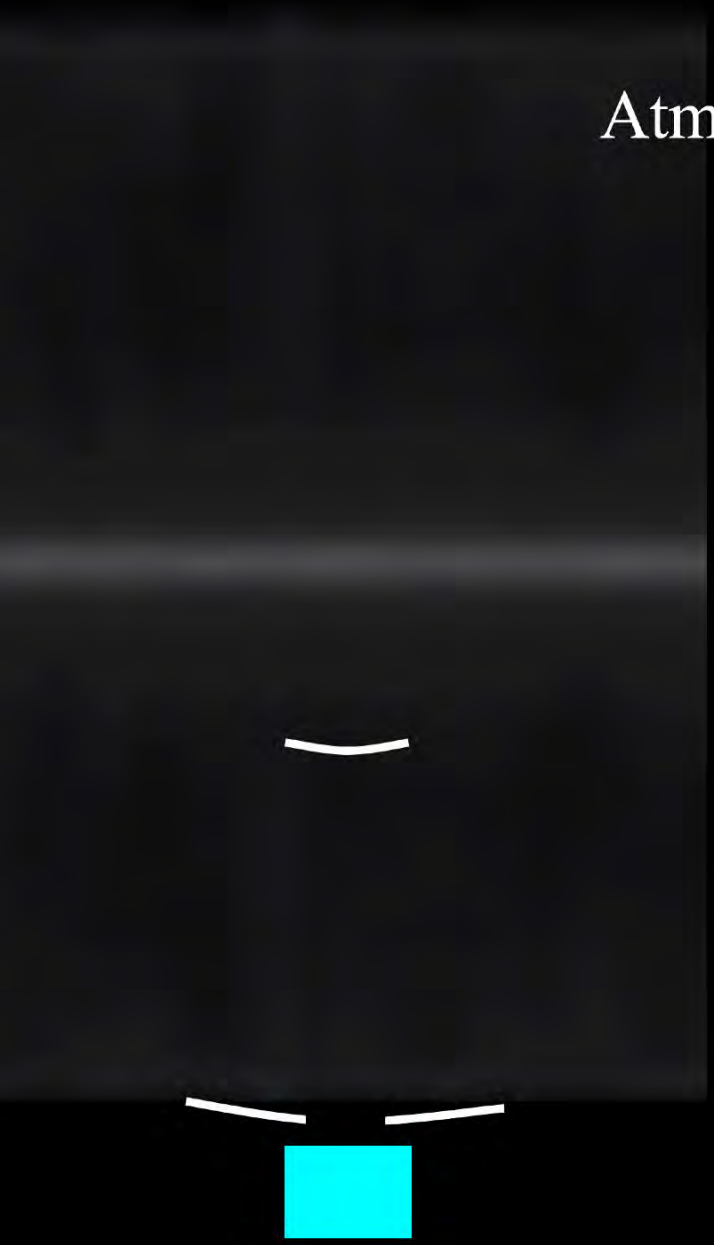

Speckle

# Turbulence arises in several places

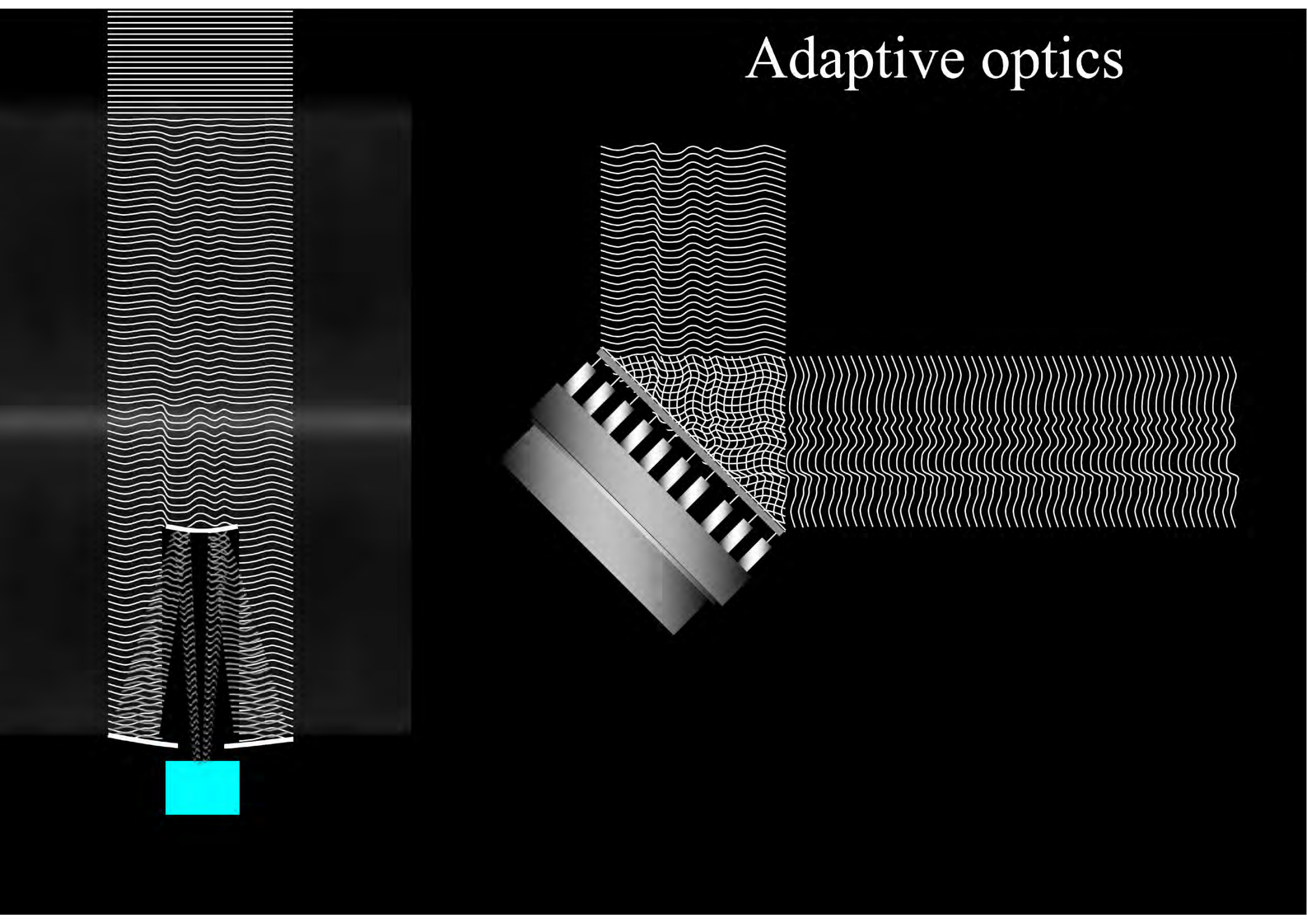


# Adaptive optics

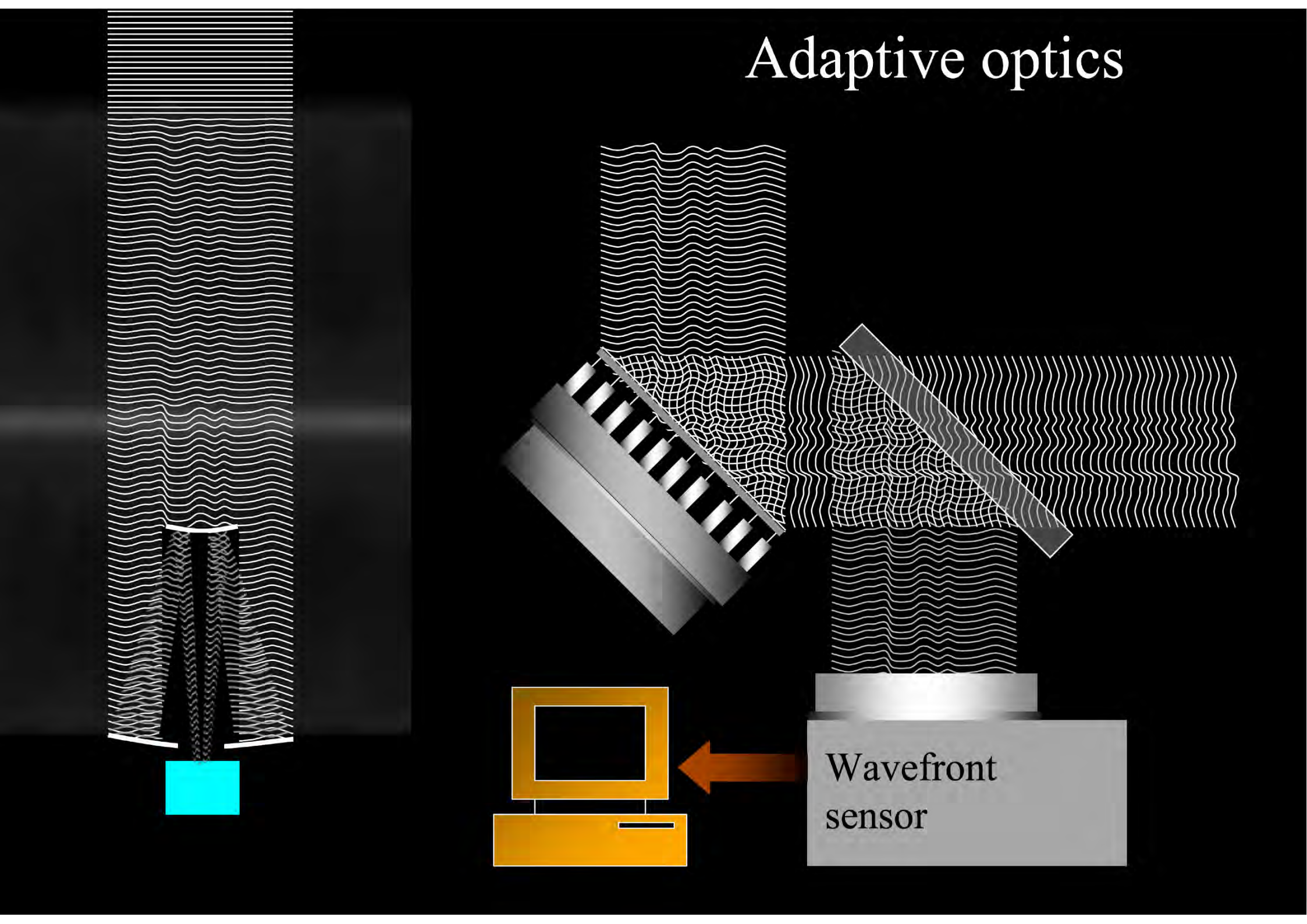
Atmospheric turbulence

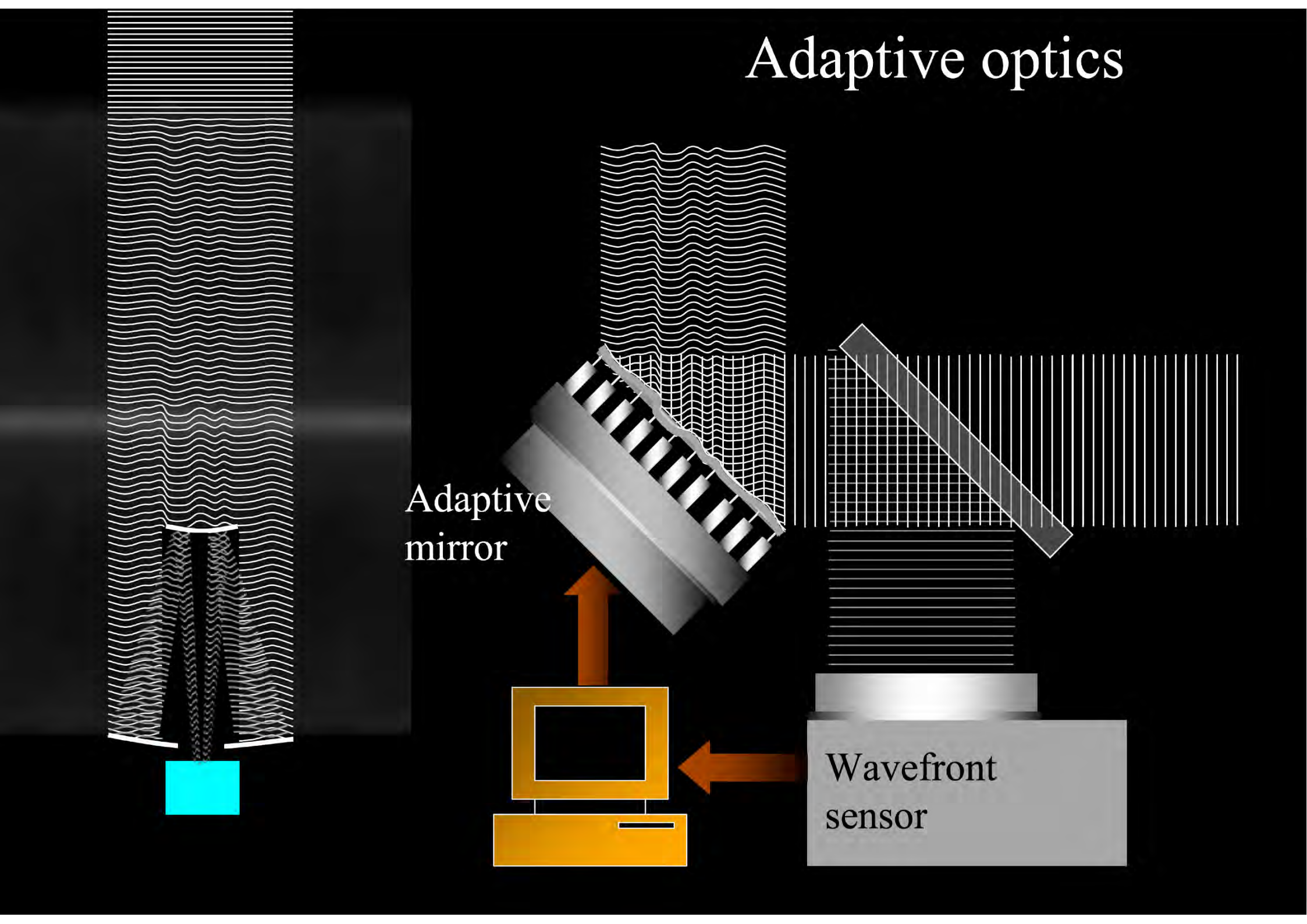


# Adaptive optics

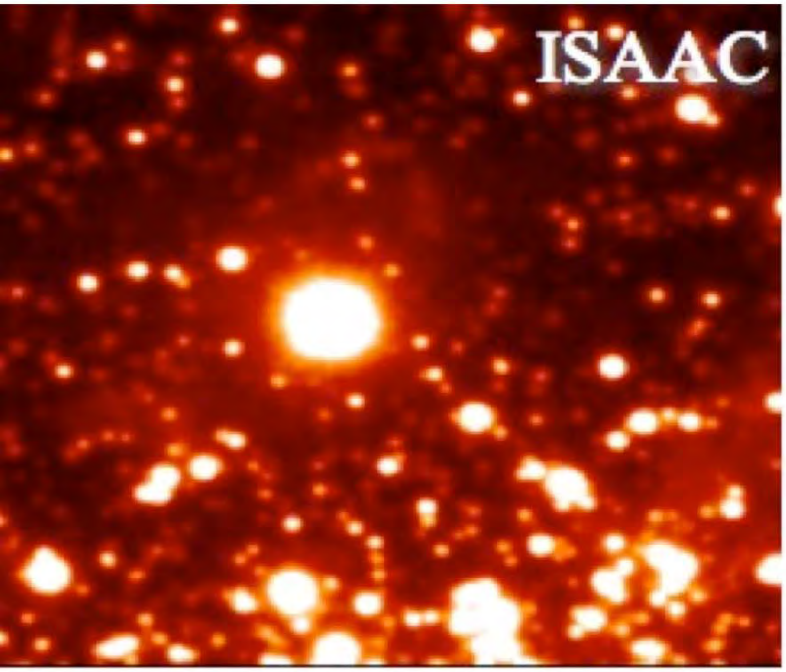


# Adaptive optics



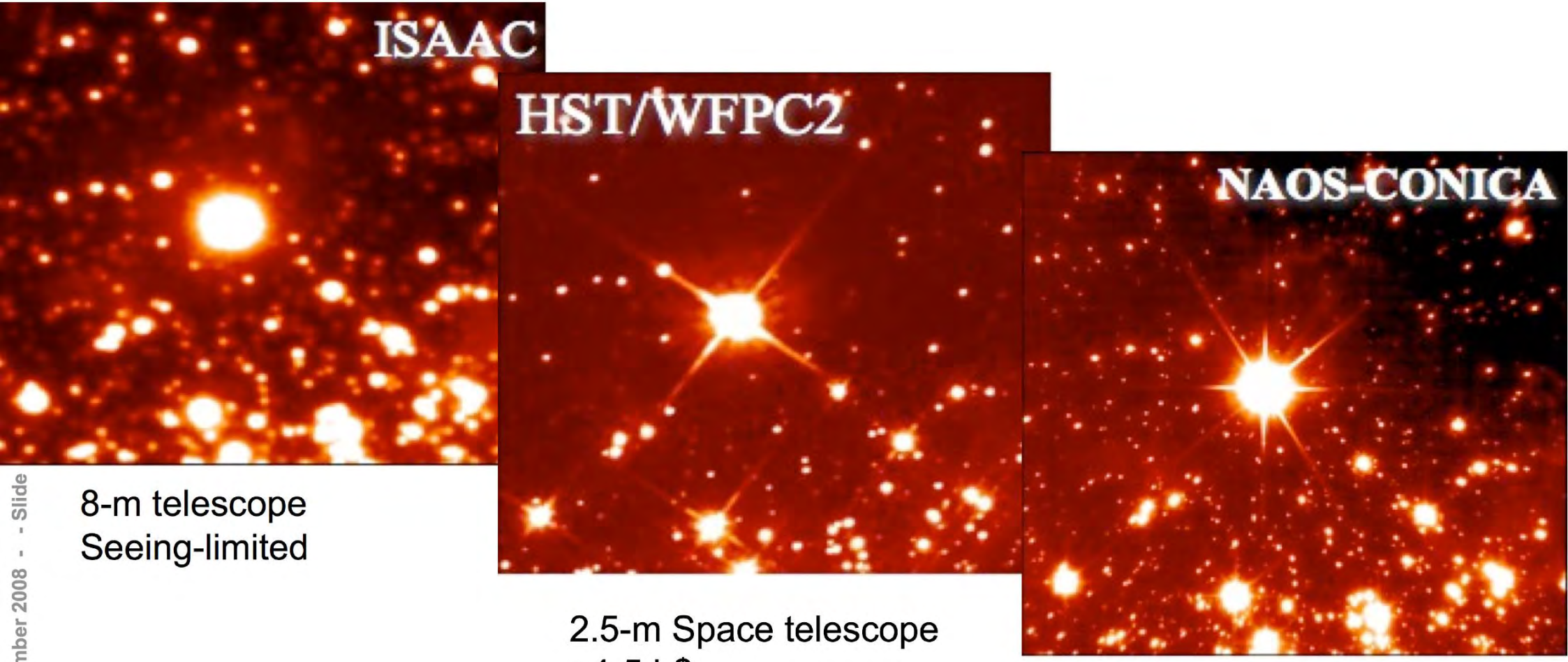

Adaptive optics
Adaptive mirror
Wavefront sensor

# High resolution: from the ground !




8-m telescope
Seeing-limited

# High resolution: from the ground !




8-m telescope
Seeing-limited

2.5-m Space telescope
~4-5 b$

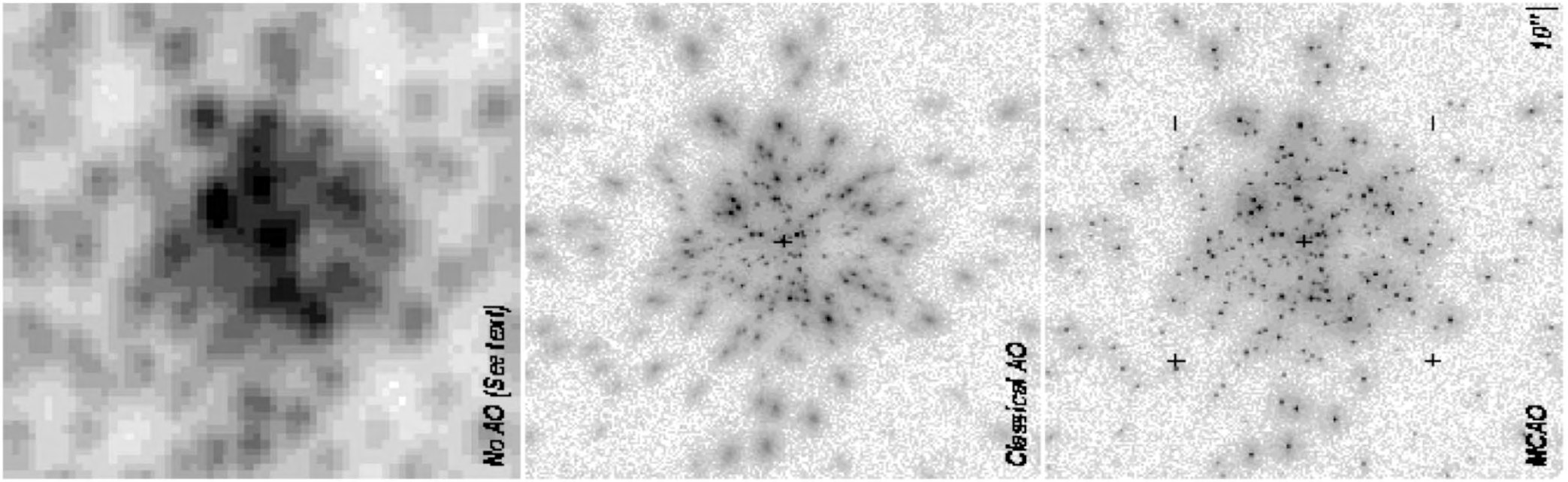
8-m telescope +
Adaptive optics
~0.15 b$

Where is the snag? (There must be one)

# Field limitations, sky coverage

*Images courtesy F. Rigaut, Gemini, 1999*

Uncorrected | Single conjugate AO | Multi-conjugate AO



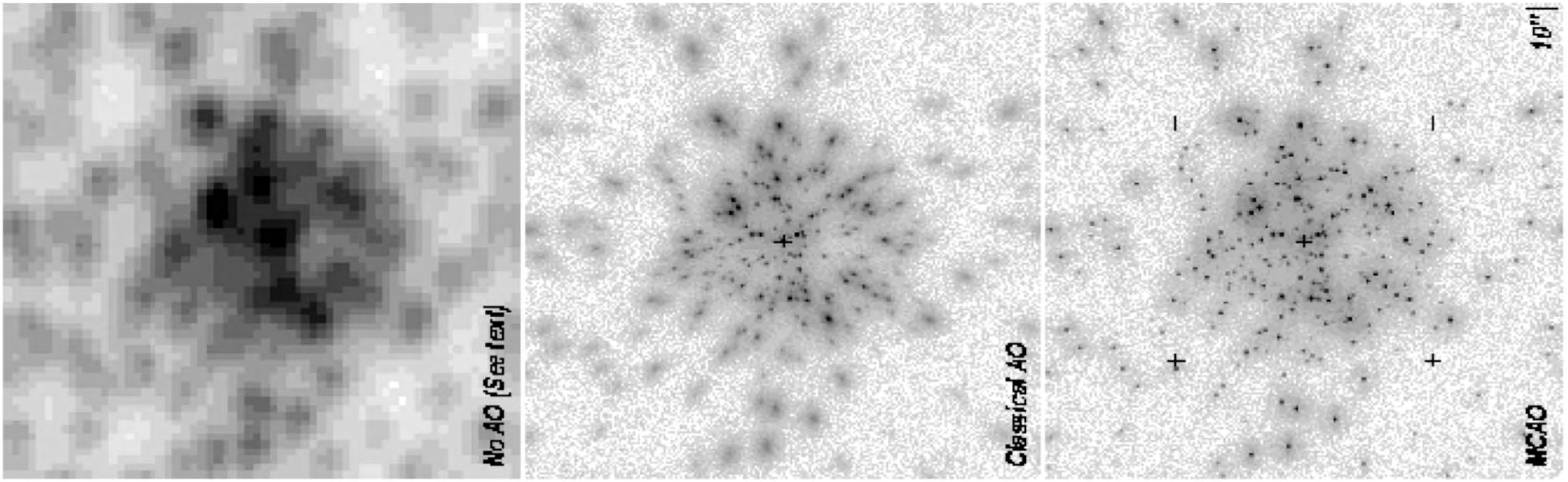

1 adaptive mirror
1 guide star

2 adaptive mirrors
5 guide stars

# Field limitations, sky coverage

*Images courtesy F. Rigaut, Gemini, 1999*

Uncorrected | Single conjugate AO | Multi-conjugate AO




1 adaptive mirror
1 guide star

2 adaptive mirrors
5 guide stars

Guide star(s) must be close to science target and bright enough
⇨ Poor sky coverage

# Field limitations, sky coverage

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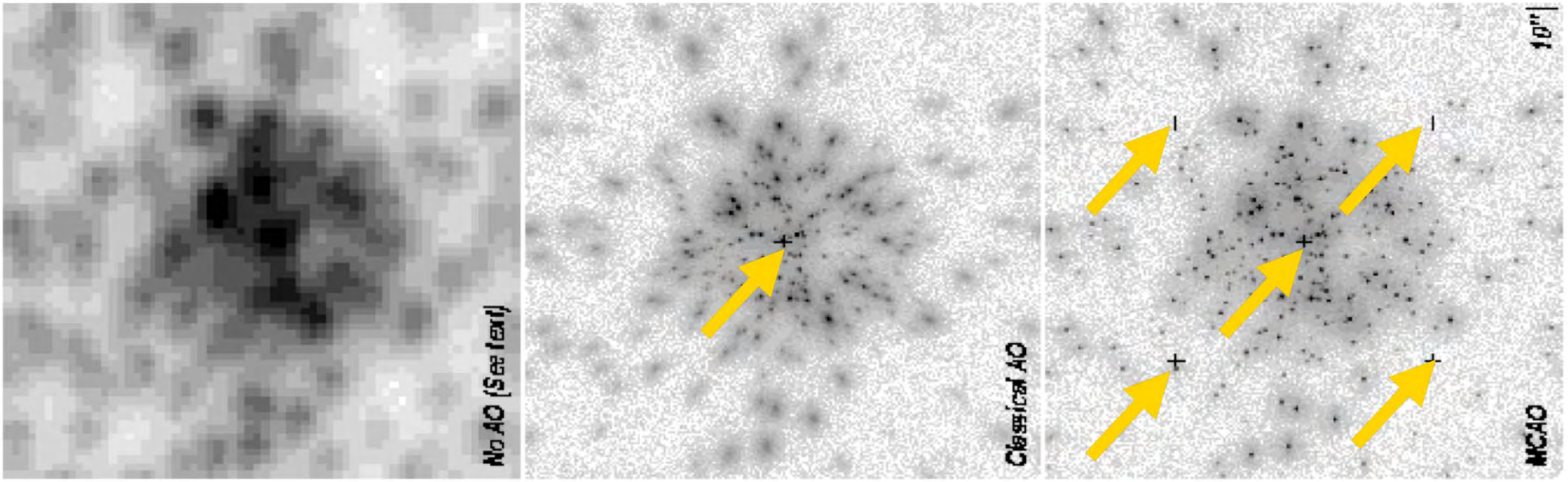


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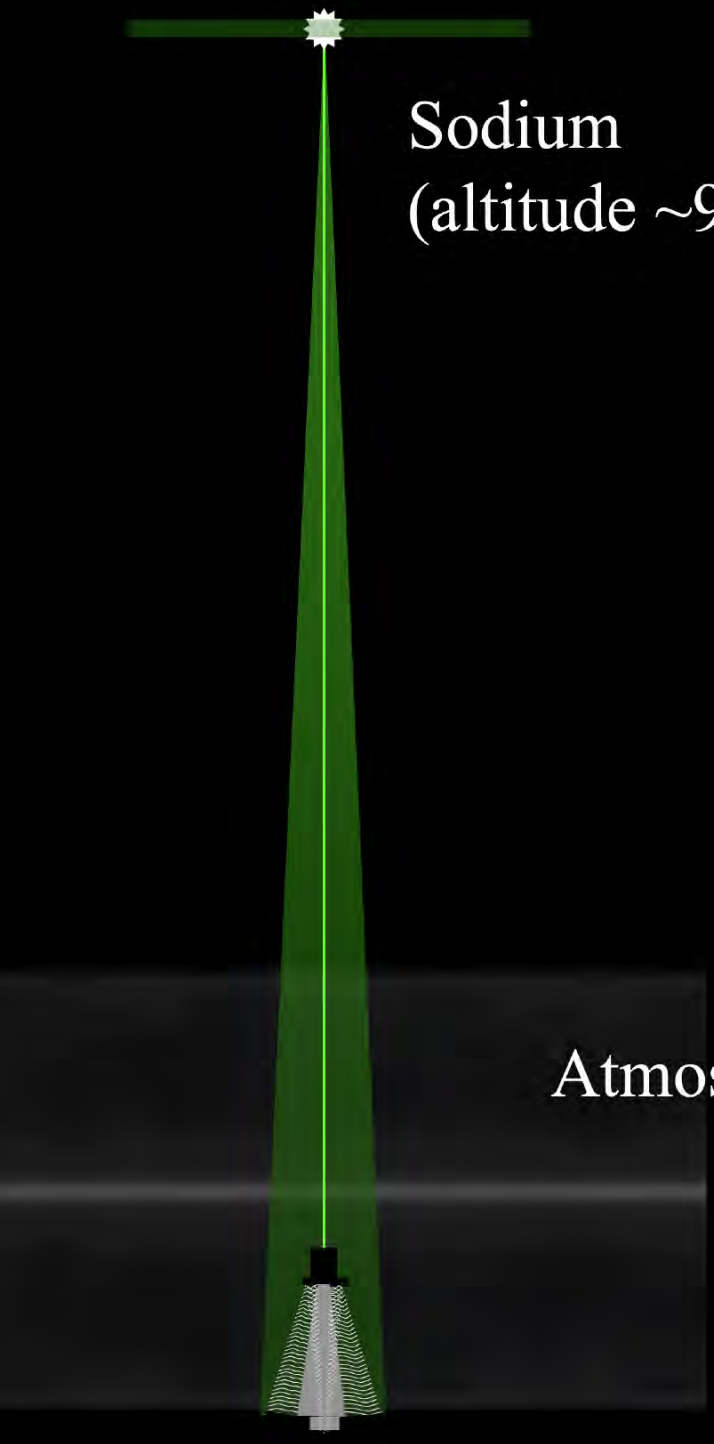
# Adaptive optics – Laser Guide Stars

Sodium
(altitude ~90 km)

Atmospheric turbulence

# Adaptive optics – Laser Guide Stars



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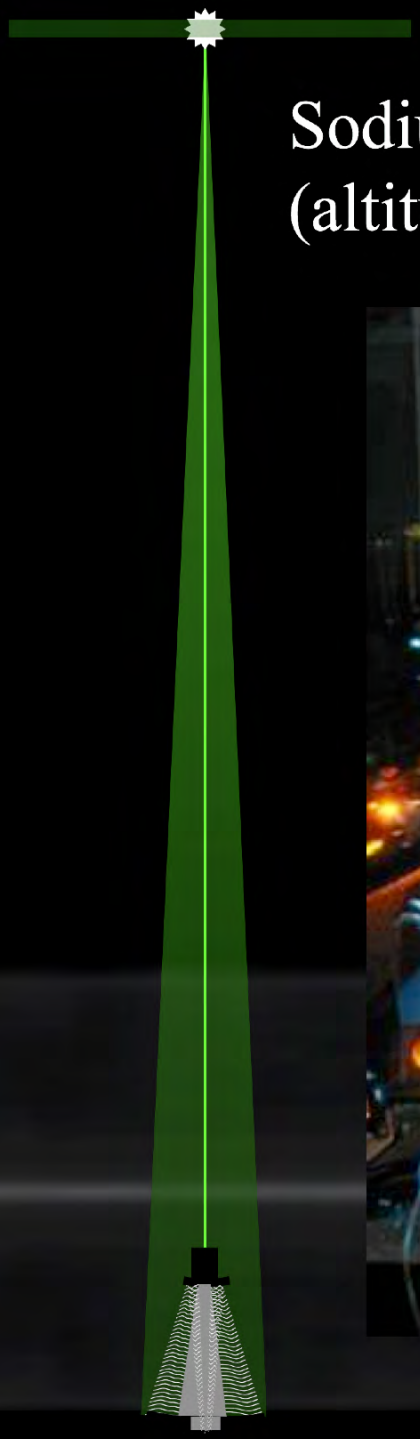
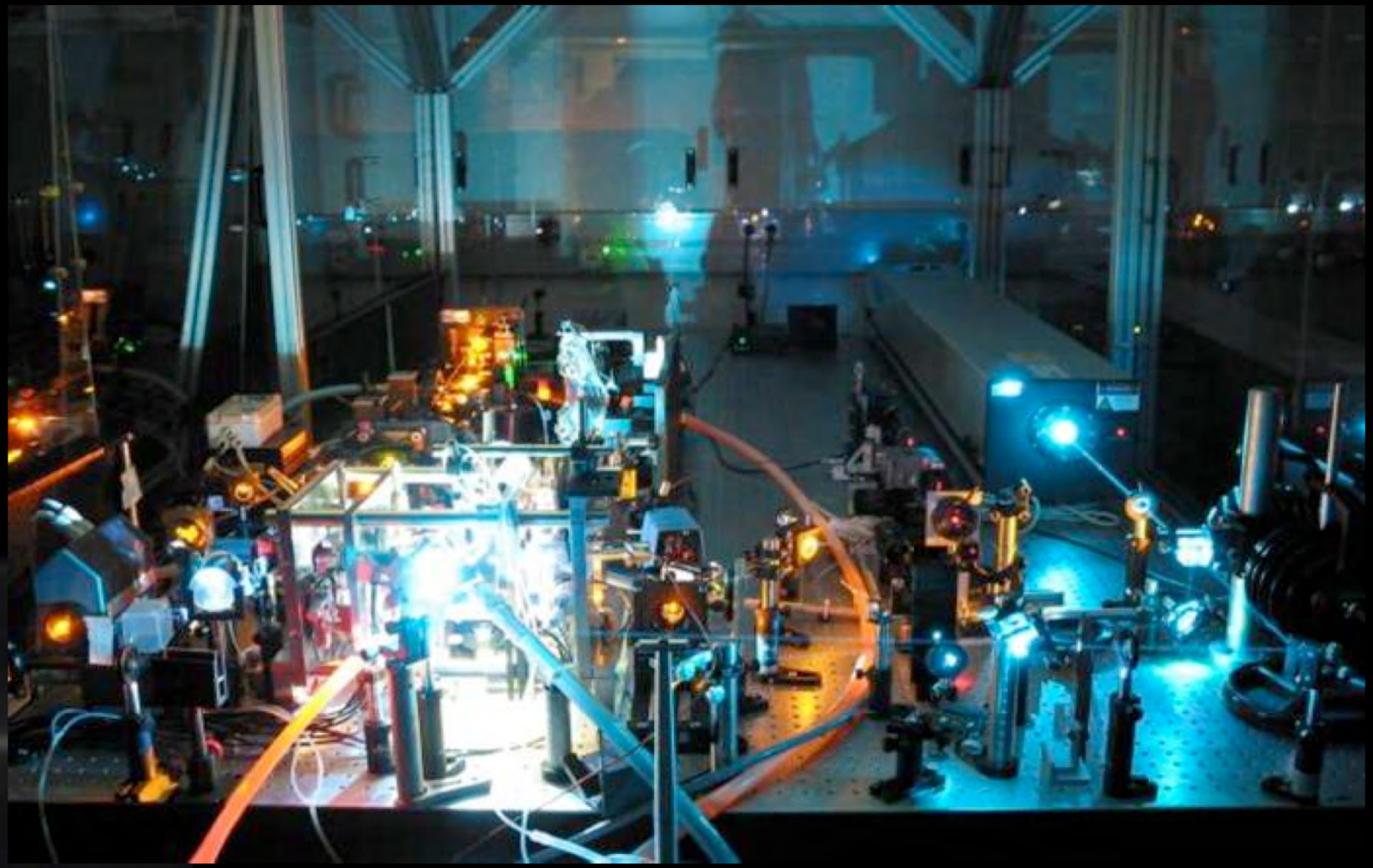
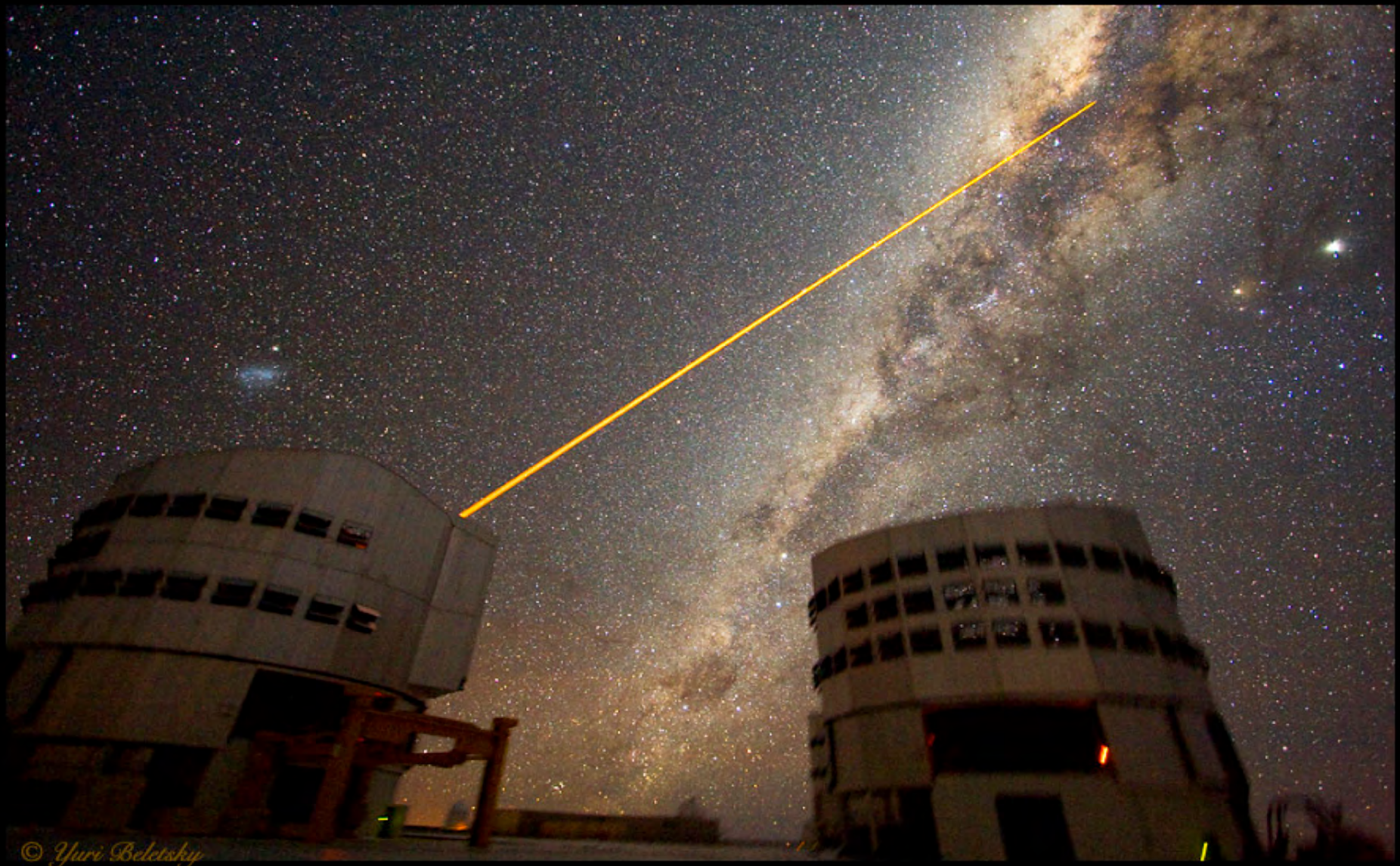


Sodium
(altitude ~90 km)




© Yuri Beletsky

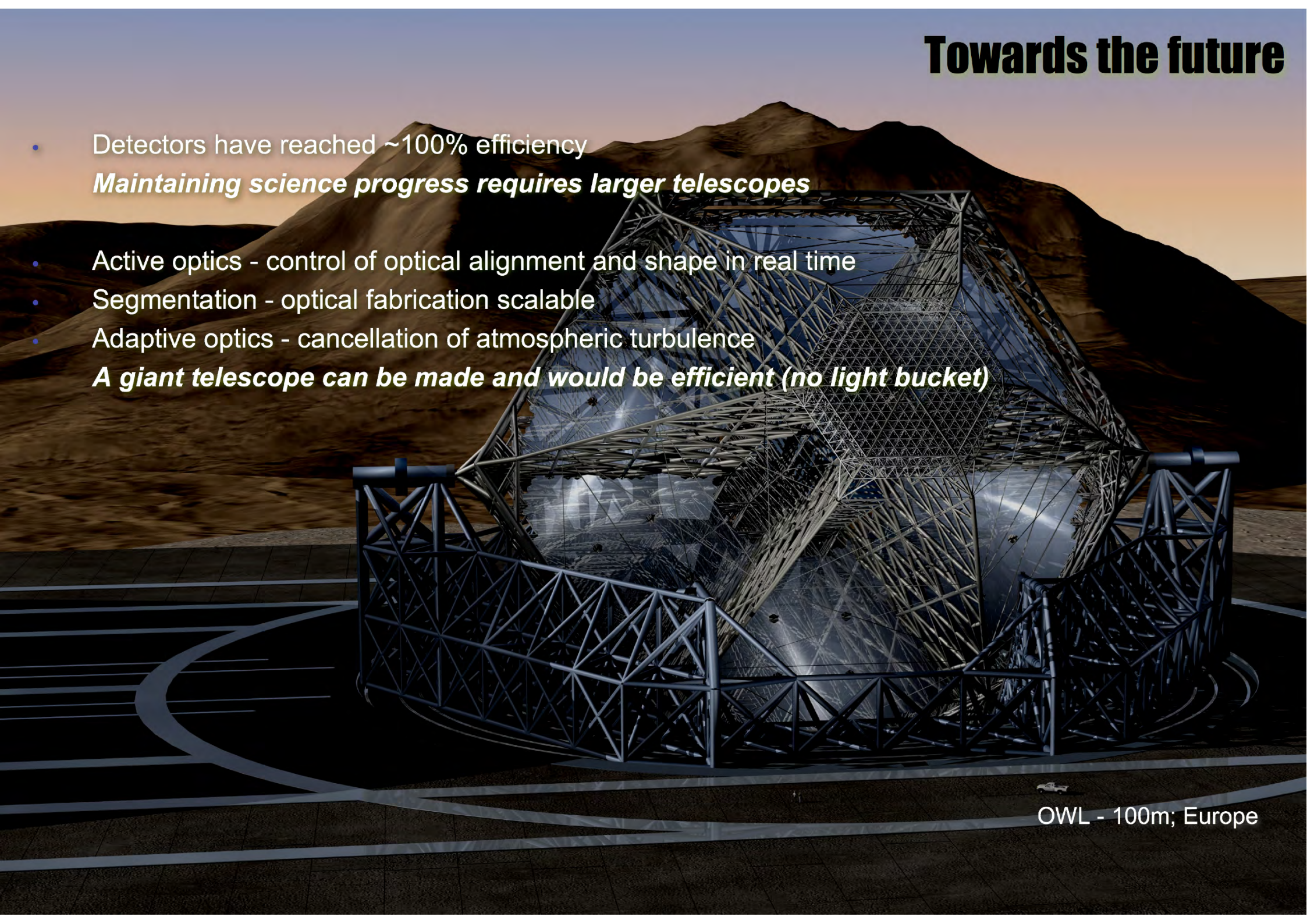
# Towards the future

- Detectors have reached ~100% efficiency

***Maintaining science progress requires larger telescopes***

- Active optics - control of optical alignment and shape in real time
- Segmentation - optical fabrication scalable
- Adaptive optics - cancellation of atmospheric turbulence

***A giant telescope can be made and would be efficient (no light bucket)***



OWL - 100m; Europe

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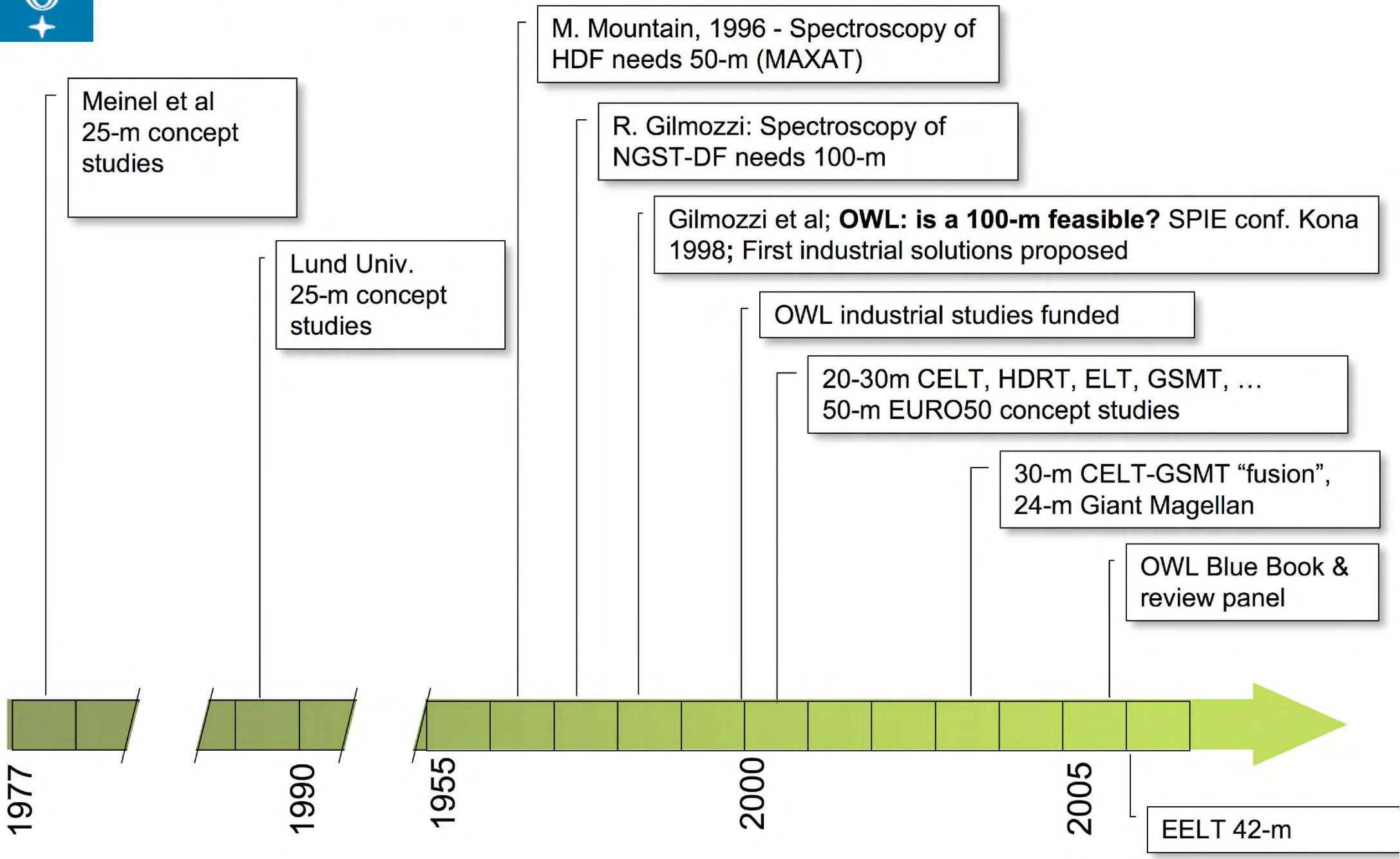
TMT - 30m; USA, Canada

GMT - 24m; USA

OWL - 100m; Europe

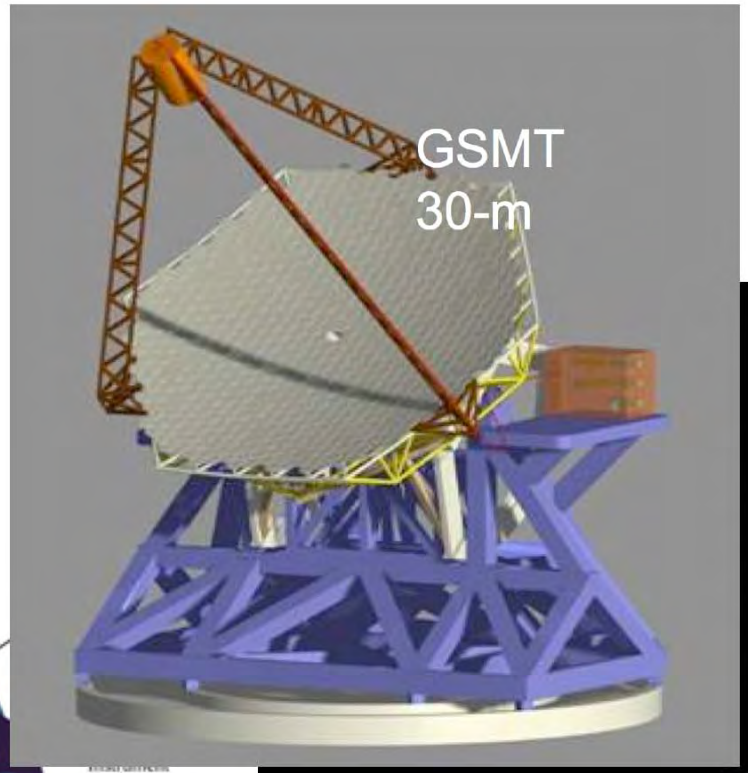
# A brief history of the future … ?



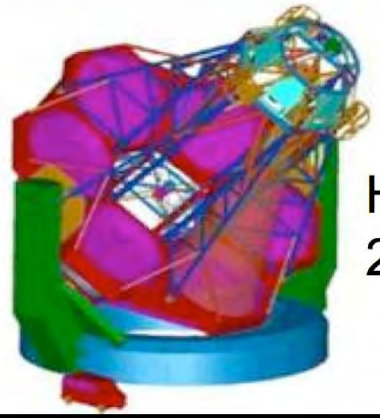
# Extremely Large Telescopes

# Extremely Large Telescopes

LPT (20-m)

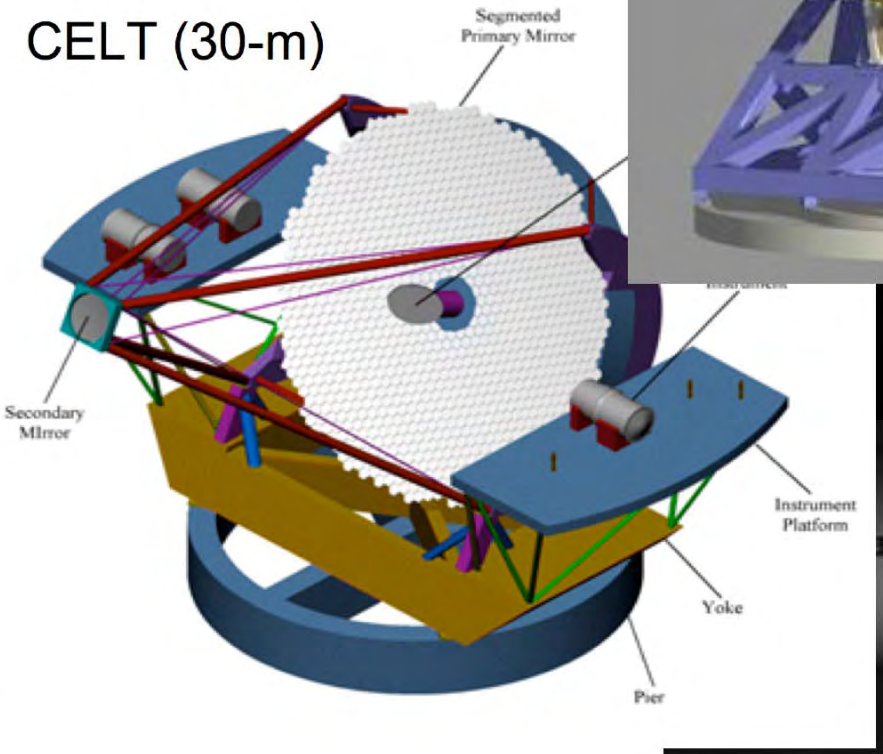


GSMT
30-m



HDRT
25-m

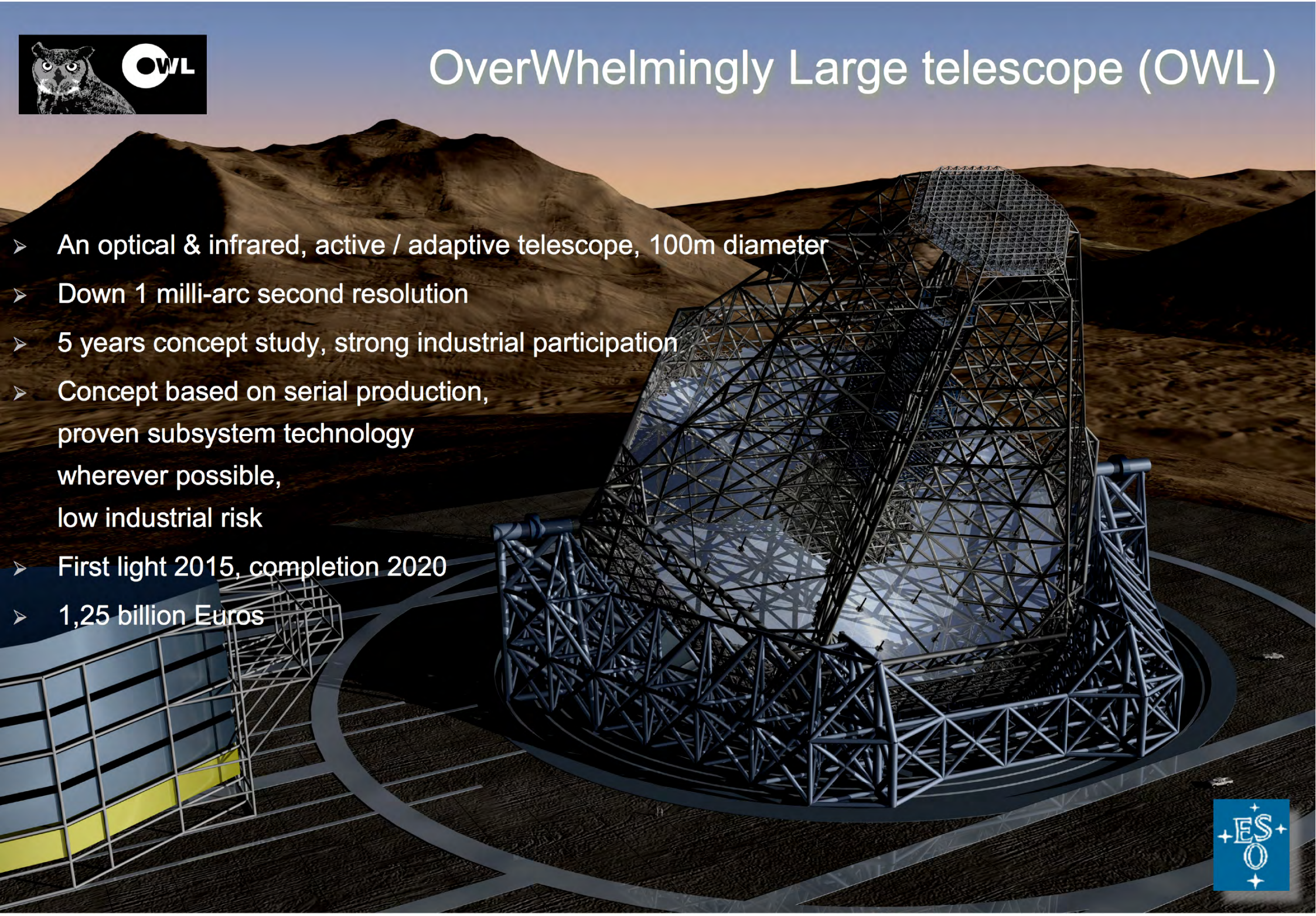
CELT (30-m)






EURO-50
50-m

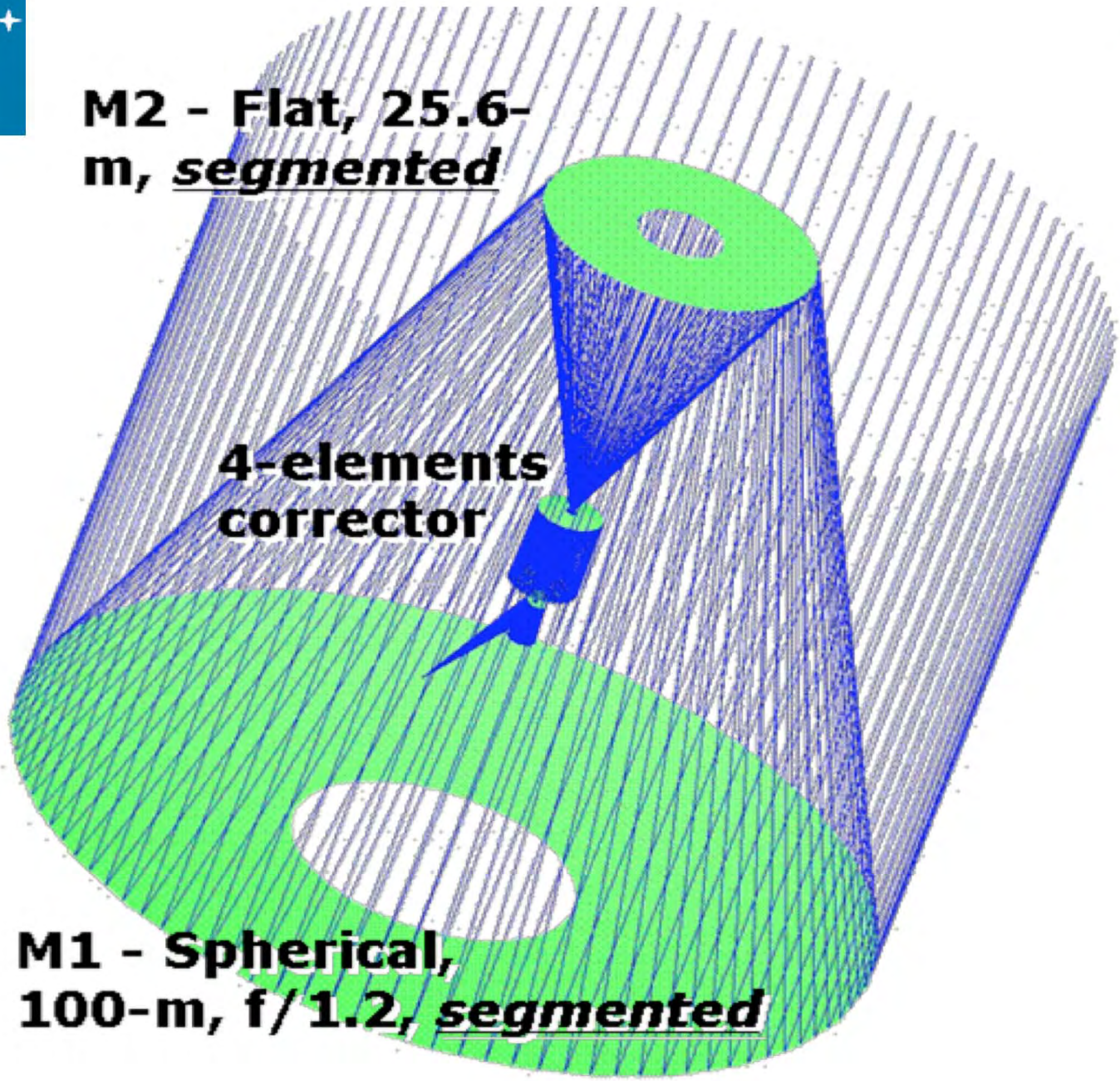
# OverWhelmingly Large telescope (OWL)



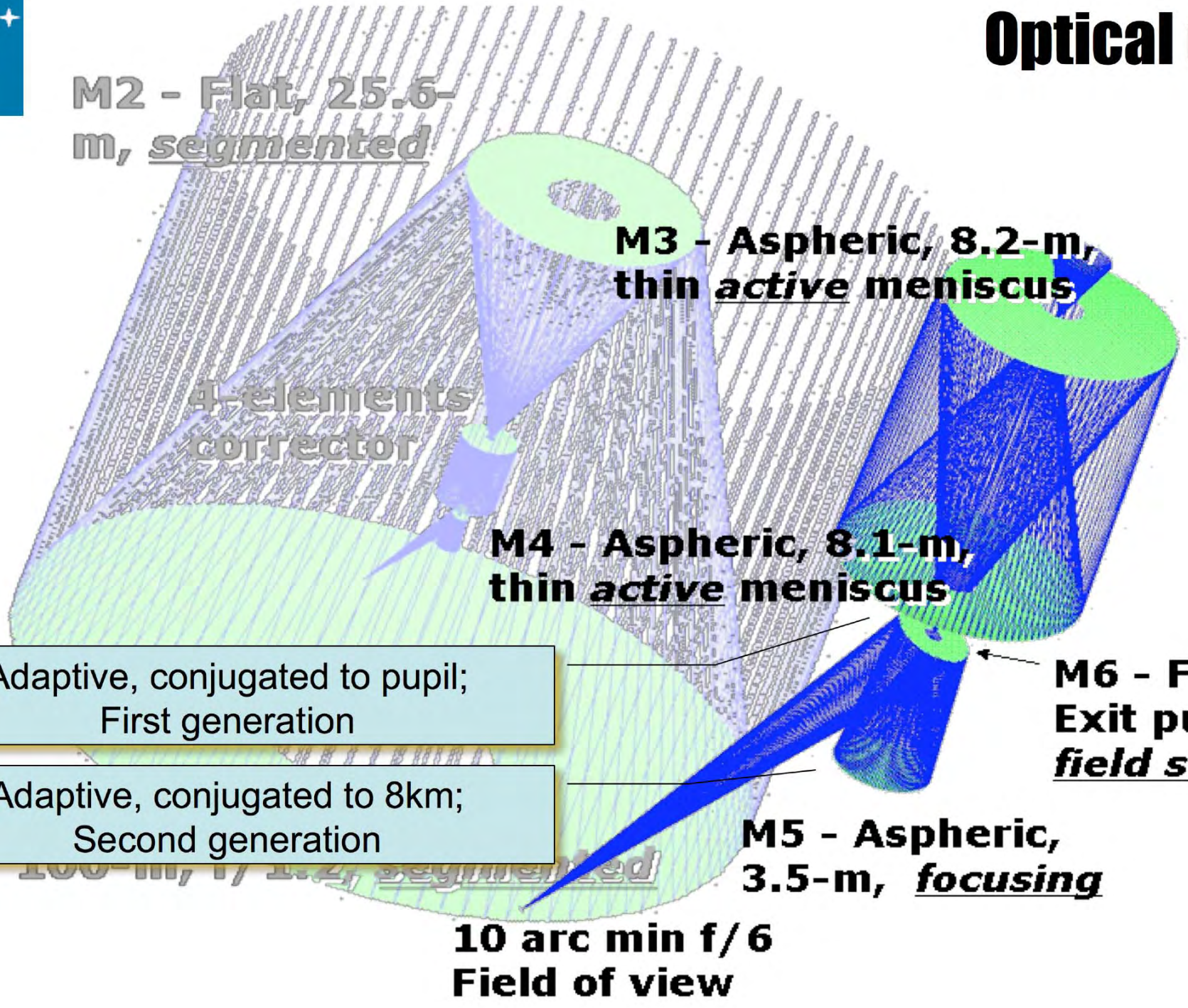
- An optical & infrared, active / adaptive telescope, 100m diameter
- Down 1 milli-arc second resolution
- 5 years concept study, strong industrial participation
- Concept based on serial production,
  proven subsystem technology
  wherever possible,
  low industrial risk
- First light 2015, completion 2020
- 1,25 billion Euros

# Optical design

# Optical design

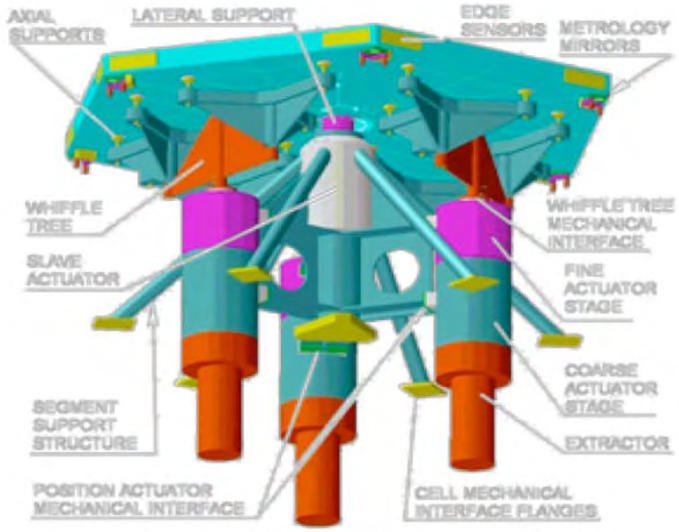


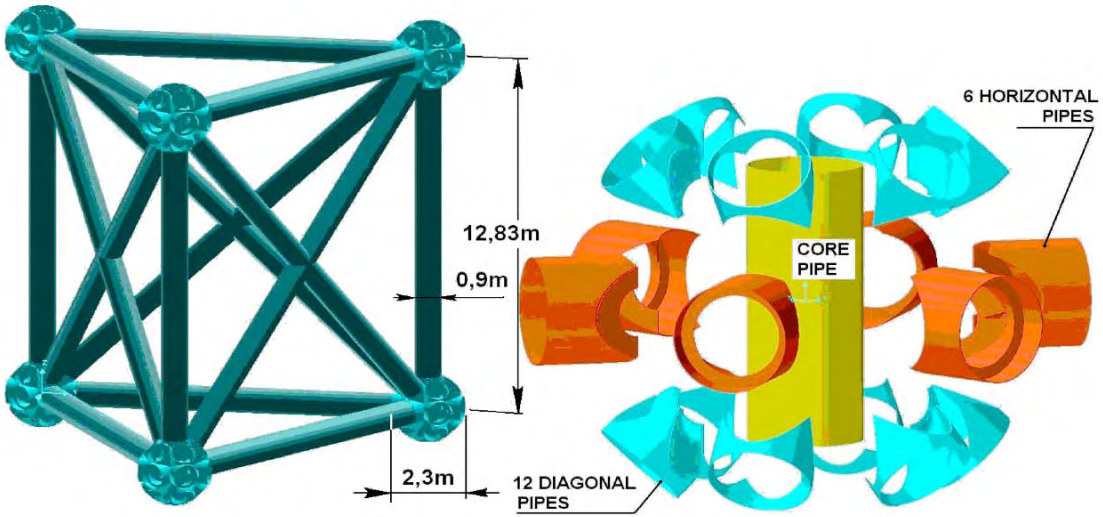
# Optical design



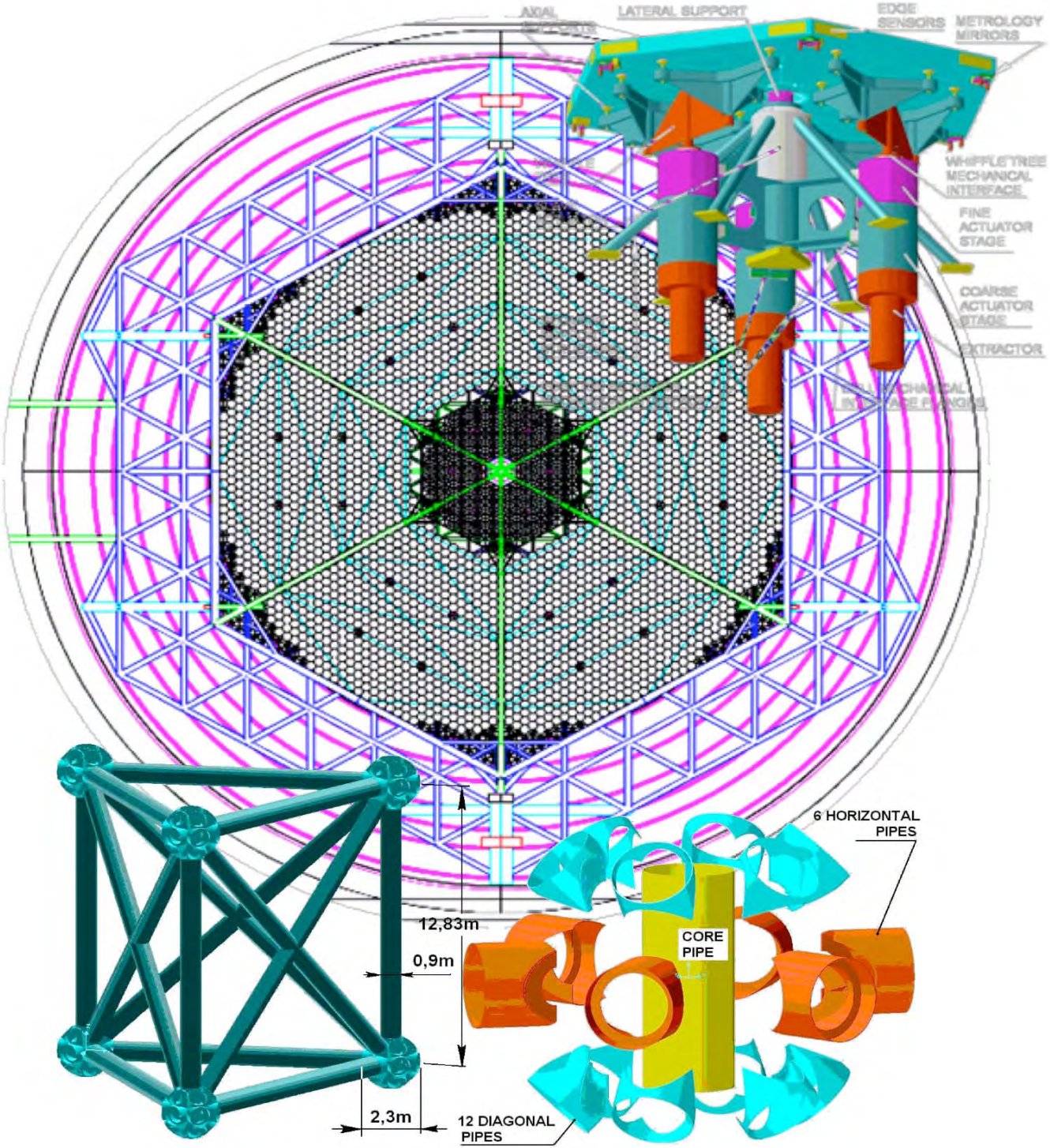

Adaptive, conjugated to pupil; First generation

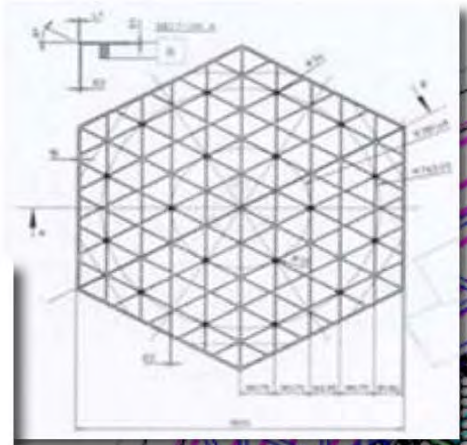
Adaptive, conjugated to 8km; Second generation

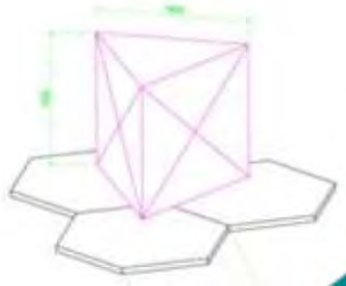

AXIAL SUPPORTS
LATERAL SUPPORT
EDGE SENSORS
METROLOGY MIRRORS
WHIFFLE TREE
WHIPPLE TREE MECHANICAL INTERFACE
SLAVE ACTUATOR
FINE ACTUATOR STAGE
COARSE ACTUATOR STAGE
SEGMENT SUPPORT STRUCTURE
EXTRACTOR
POSITION ACTUATOR MECHANICAL INTERFACE
CELL MECHANICAL INTERFACE FLANGES

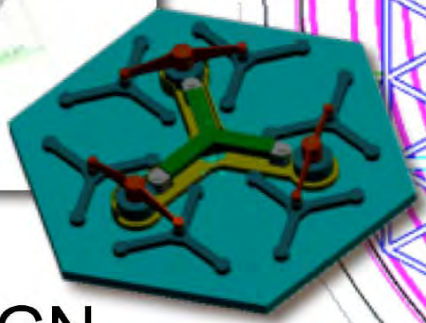

12,83m
0,9m
2,3m
6 HORIZONTAL PIPES
CORE PIPE
12 DIAGONAL PIPES

# FRACTAL DESIGN



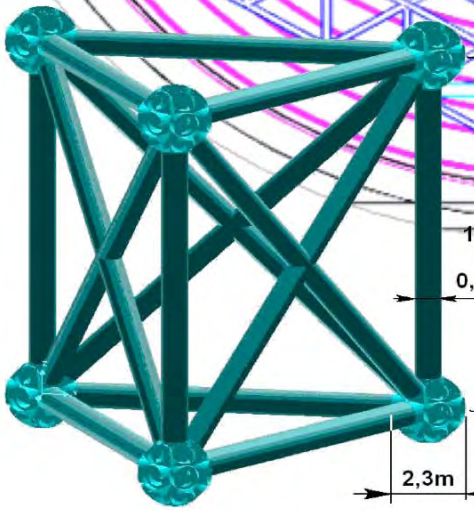


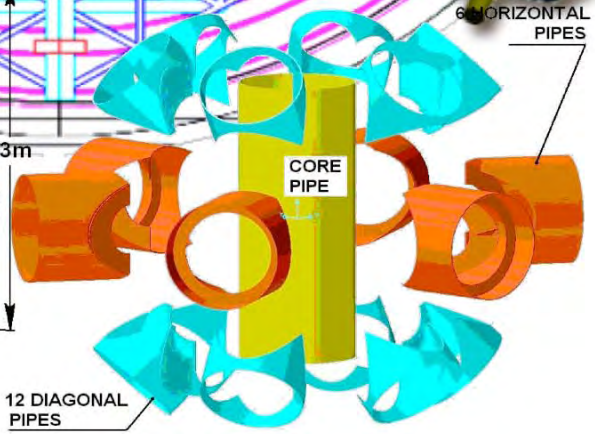








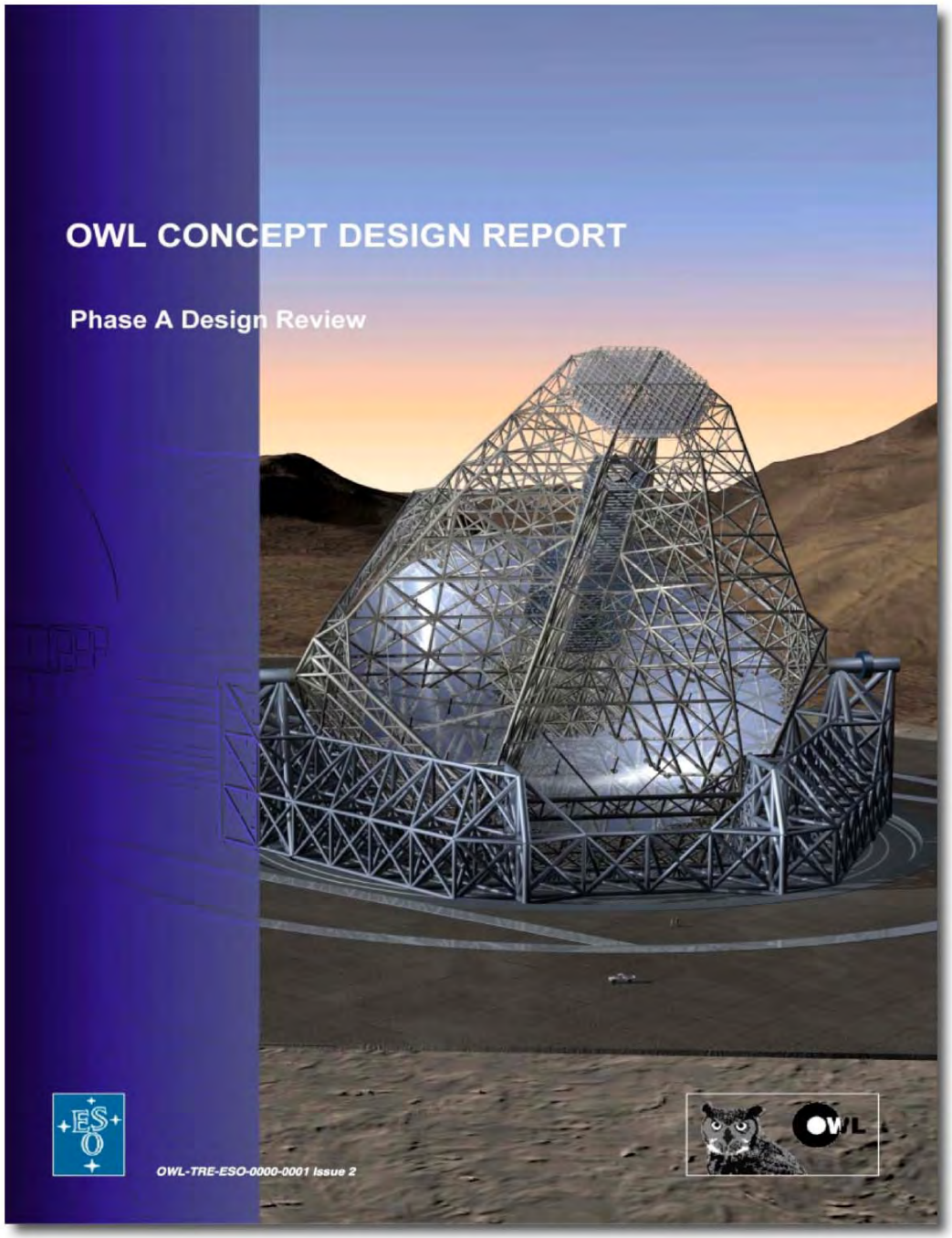




# FRACTAL DESIGN

All dimensions as multiple of segment size

- Standardization
- Ease of integration
- Ease of maintenance
- Optimal loads transfers




More in …

***OWL Blue Book*** (730 pages)

Public version does not include detailed cost estimates.

www.eso.org/projects/owl

# What next ?

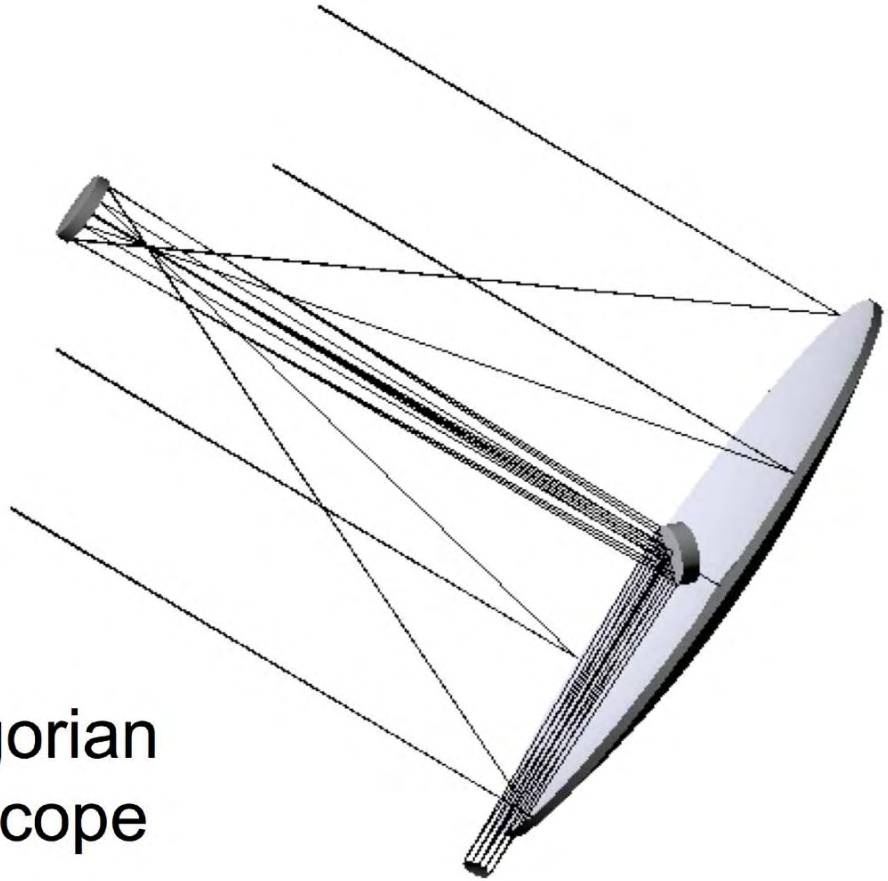
**OWL review panel, Dec. 2005:**

*"[OWL] made a plausible case that a 100-m telescope is feasible and can be operated."*

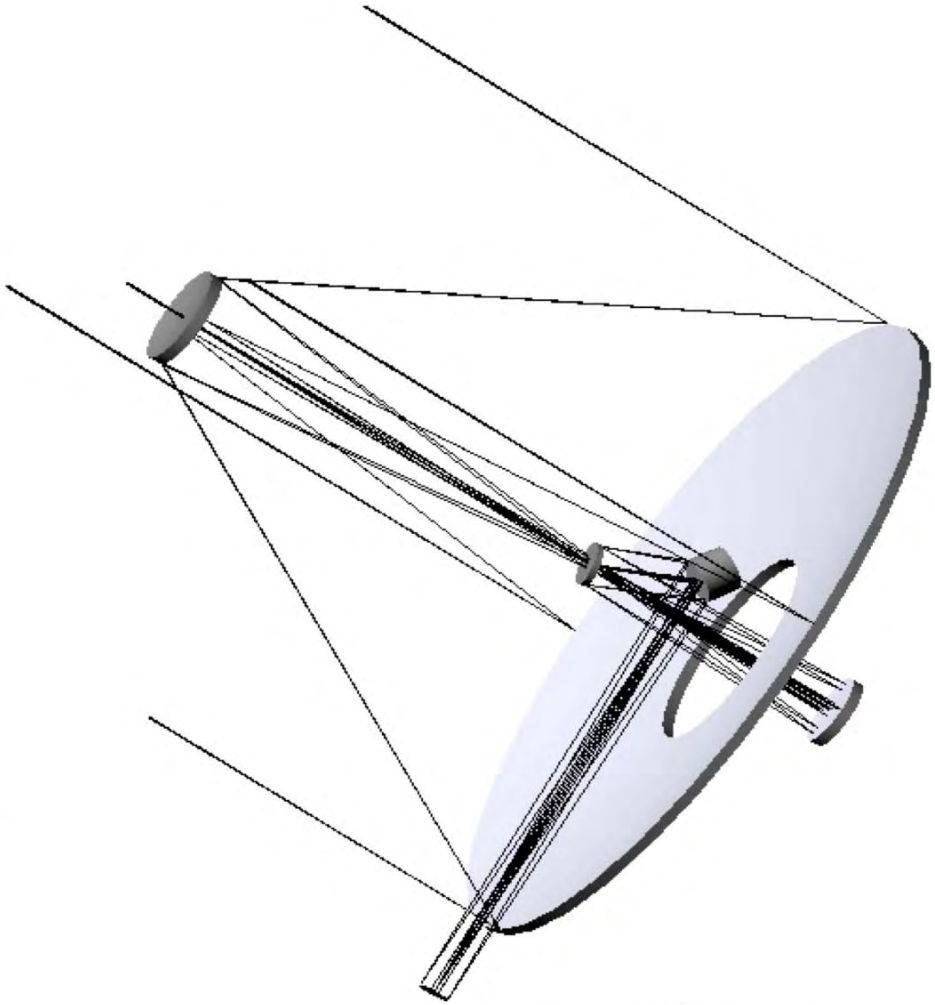
But … High schedule risk, will miss NGST window.

- 2006:
  - Extensive consultation with the scientific community
  - Options for a 30 to 60-m telescope
  - Crystallization around a 42-m telescope, anastigmatic solution

- 2007-2009 design phase, 2010-2015 construction phase



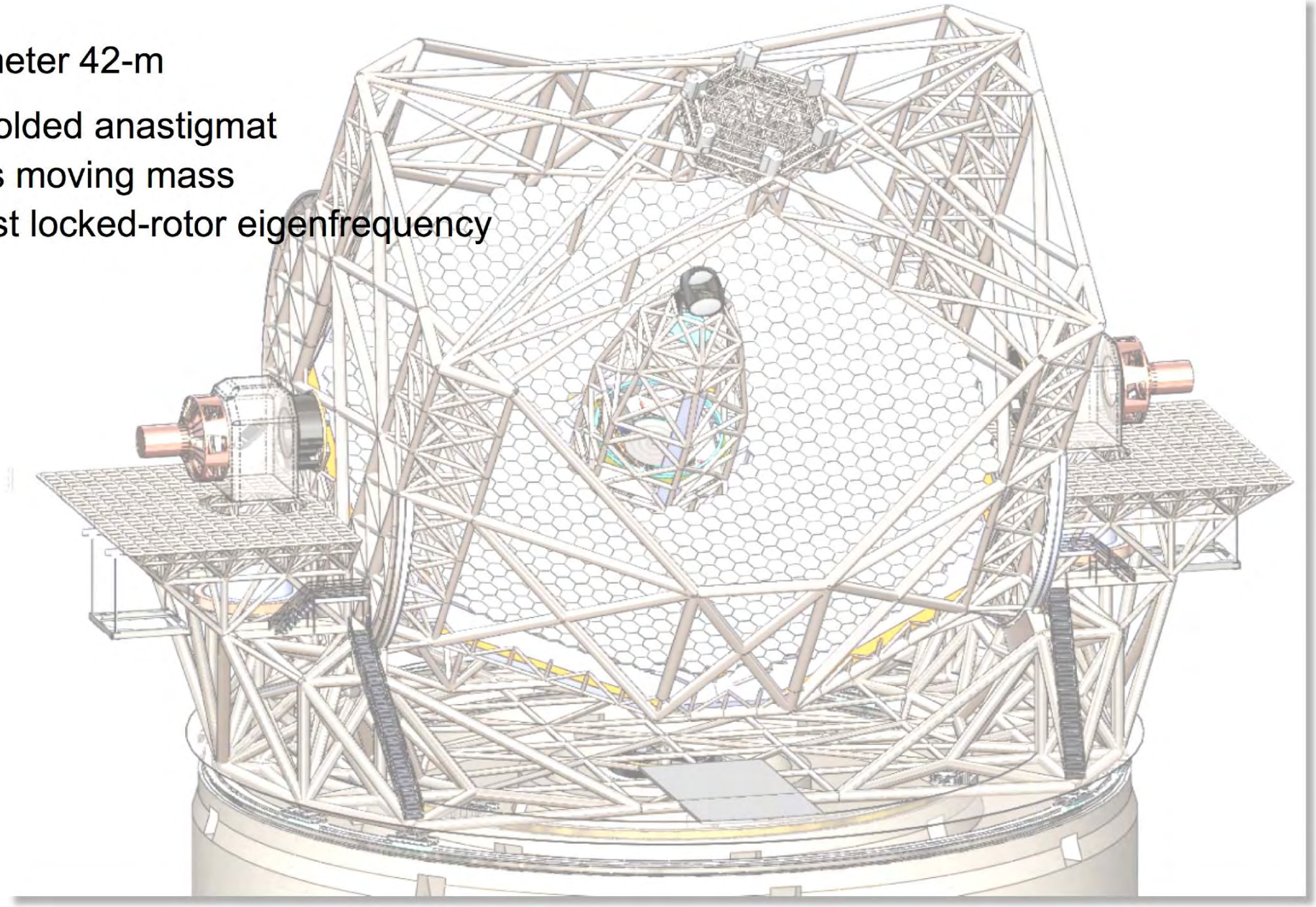
Gregorian telescope

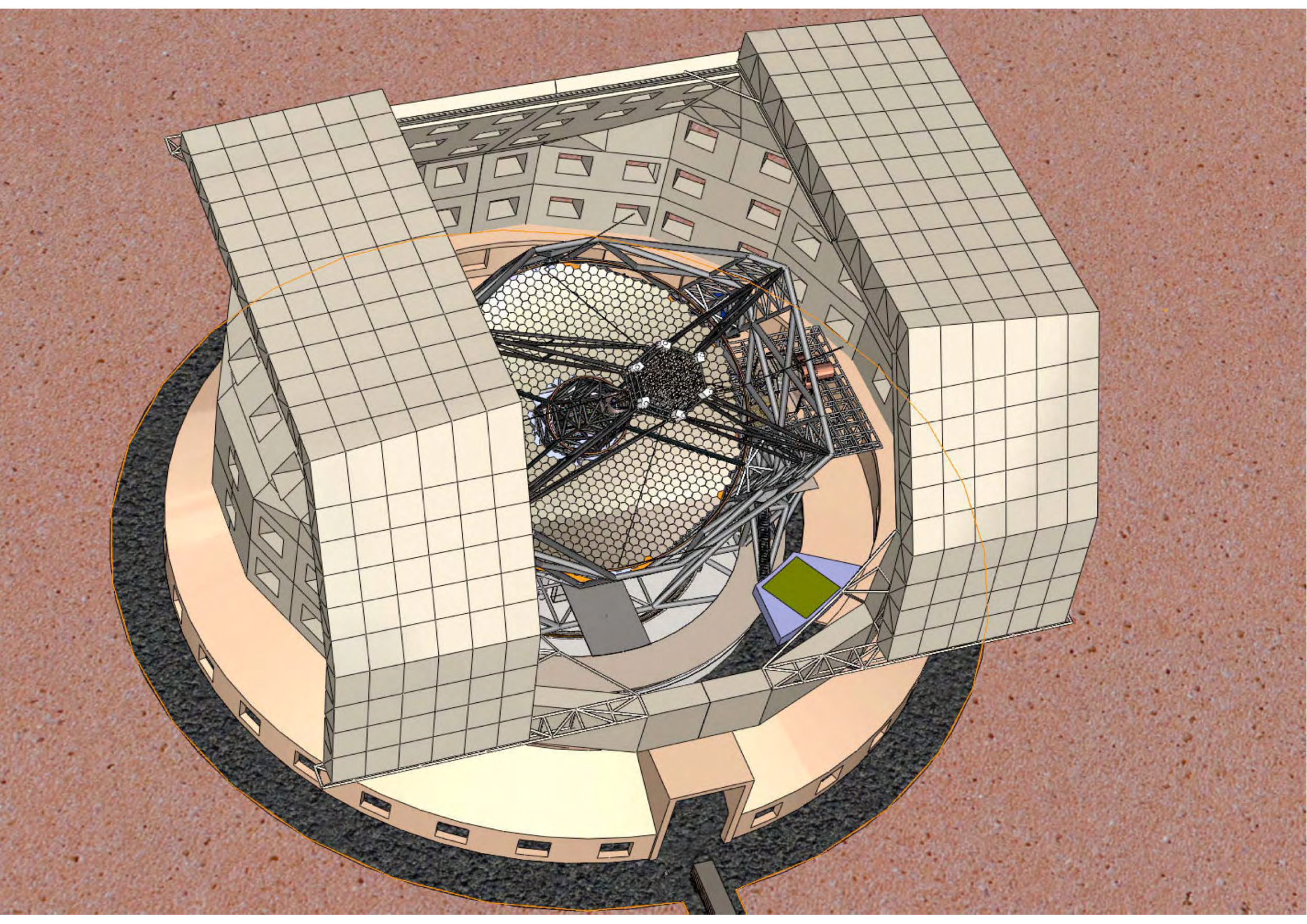


5 Mirror telescope

EELT, diameter 42-m

- 5-mirror folded anastigmat
- 5300 tons moving mass
- 2.6 Hz first locked-rotor eigenfrequency

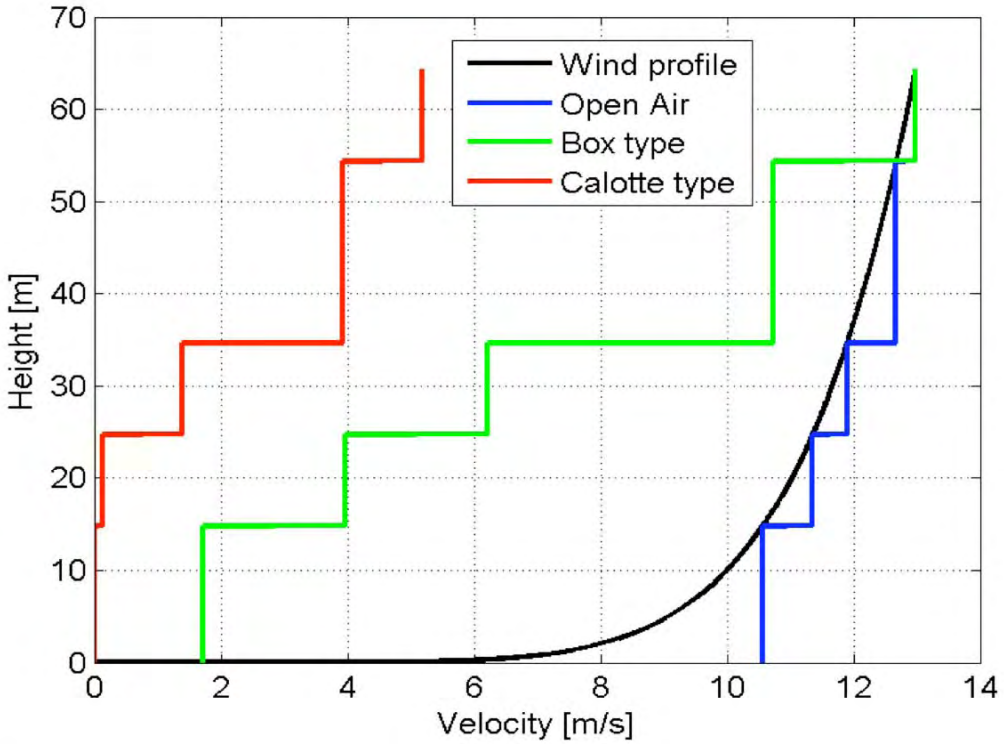




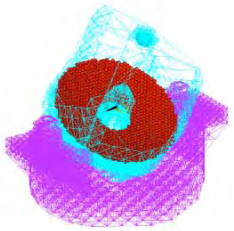

Not small. You could get lost in there …

# Wind Disturbance Assumptions

- External wind speed at 10 m height: 10 m/s
- 3 Enclosure configurations
- Wind speed profile (5 levels)
- Von Karman PSD spectra (correlated/uncorrelated)




**Open air**



**Box type Dome**

VLT wind load assumptions and measurements

**Calotte type Dome**

TMT wind load assumptions

**(20 % larger dome, dome seeing)**

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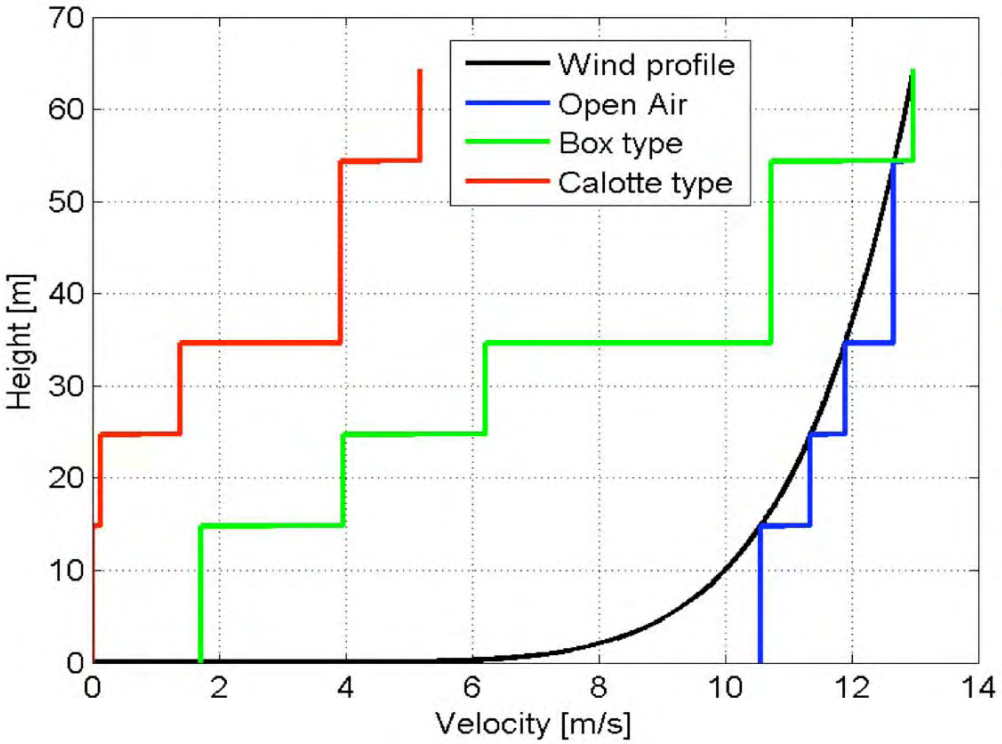


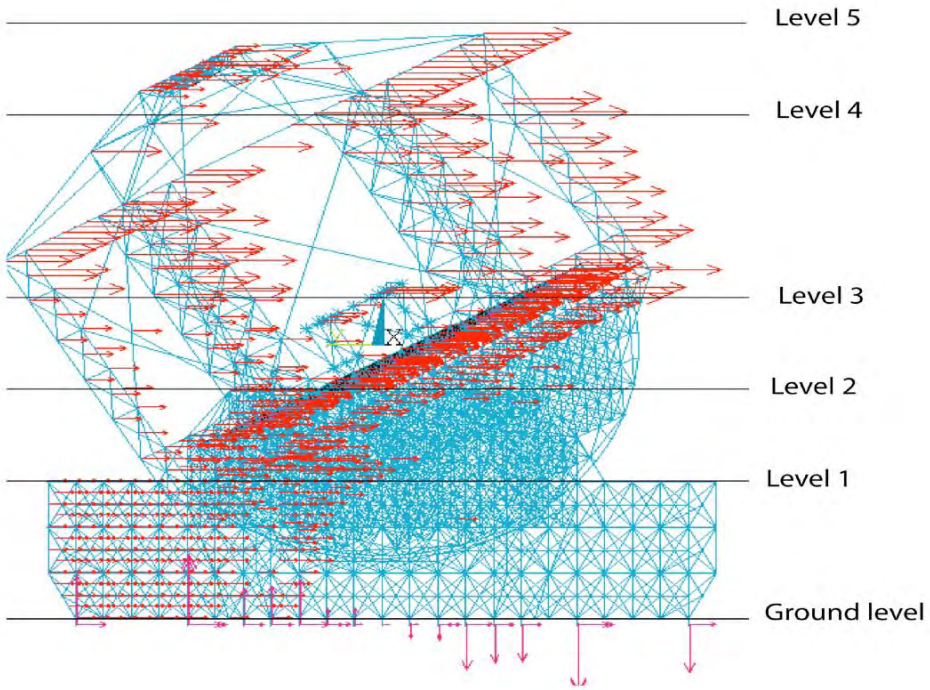

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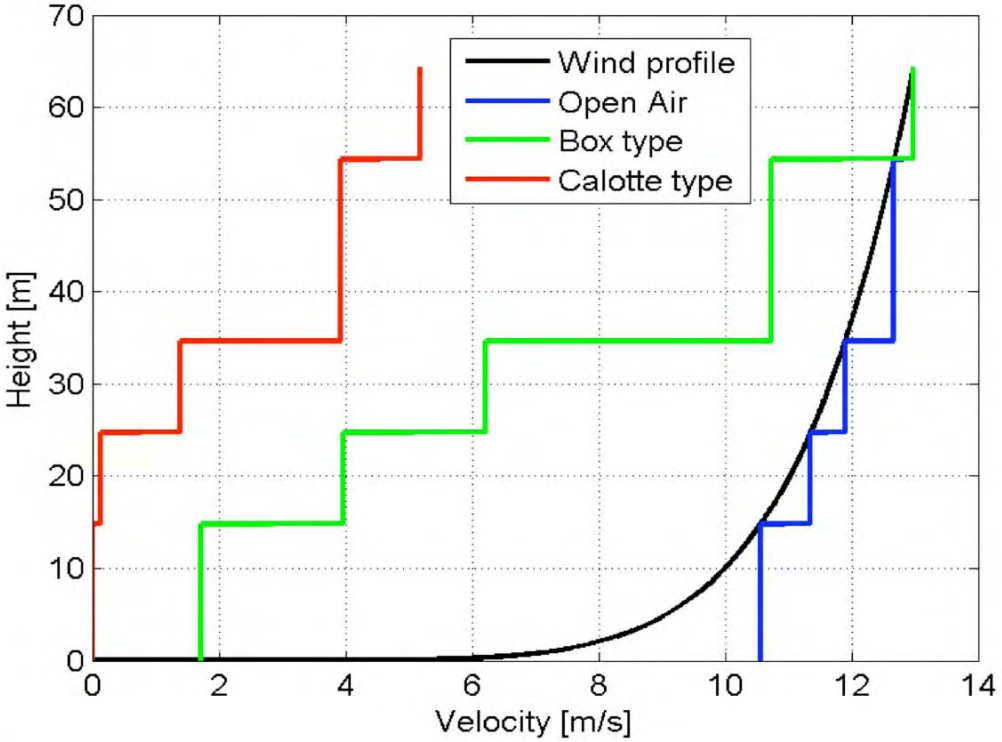
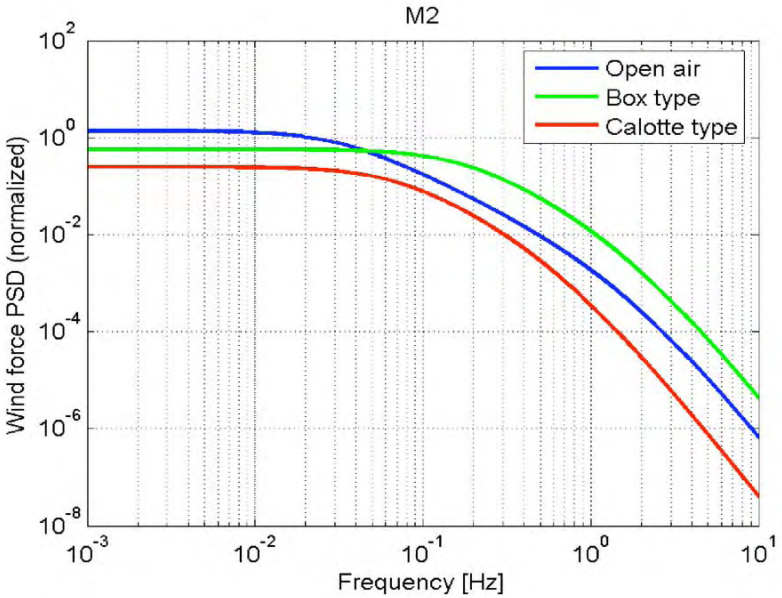
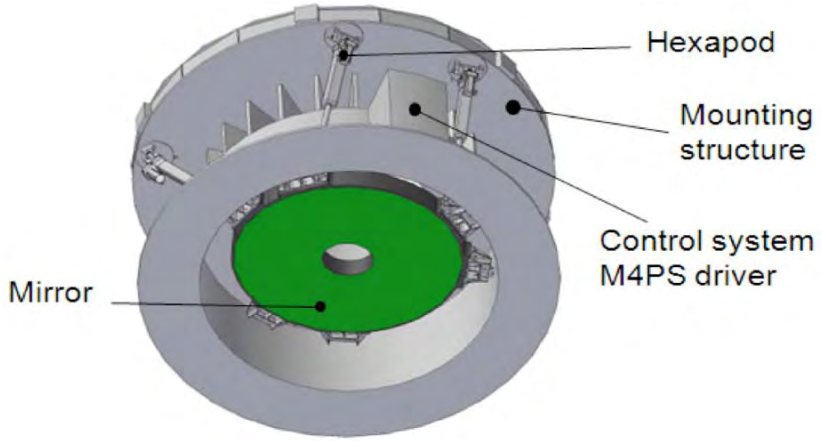
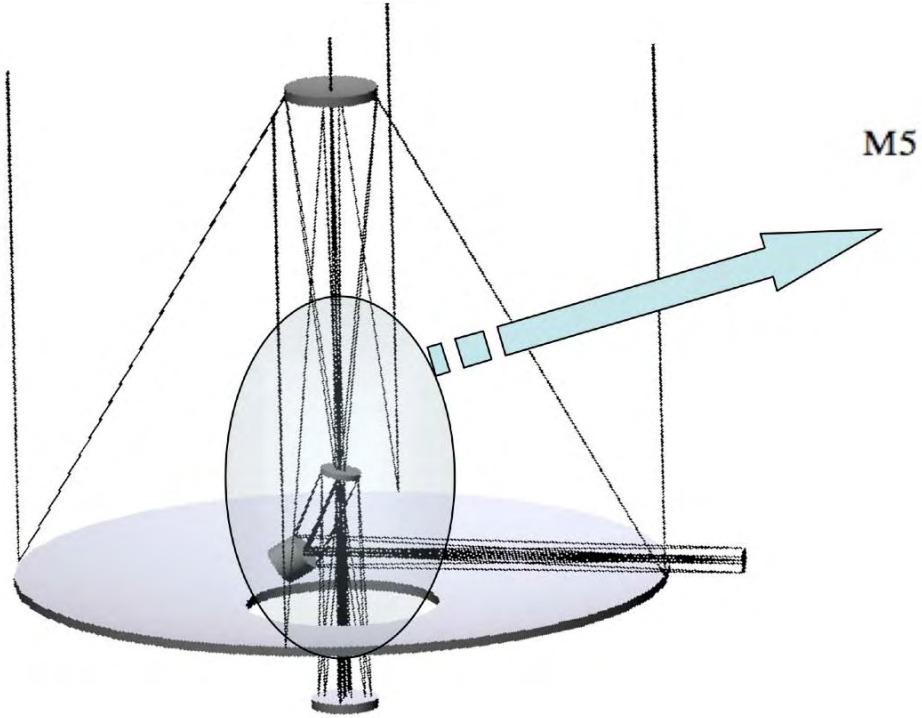
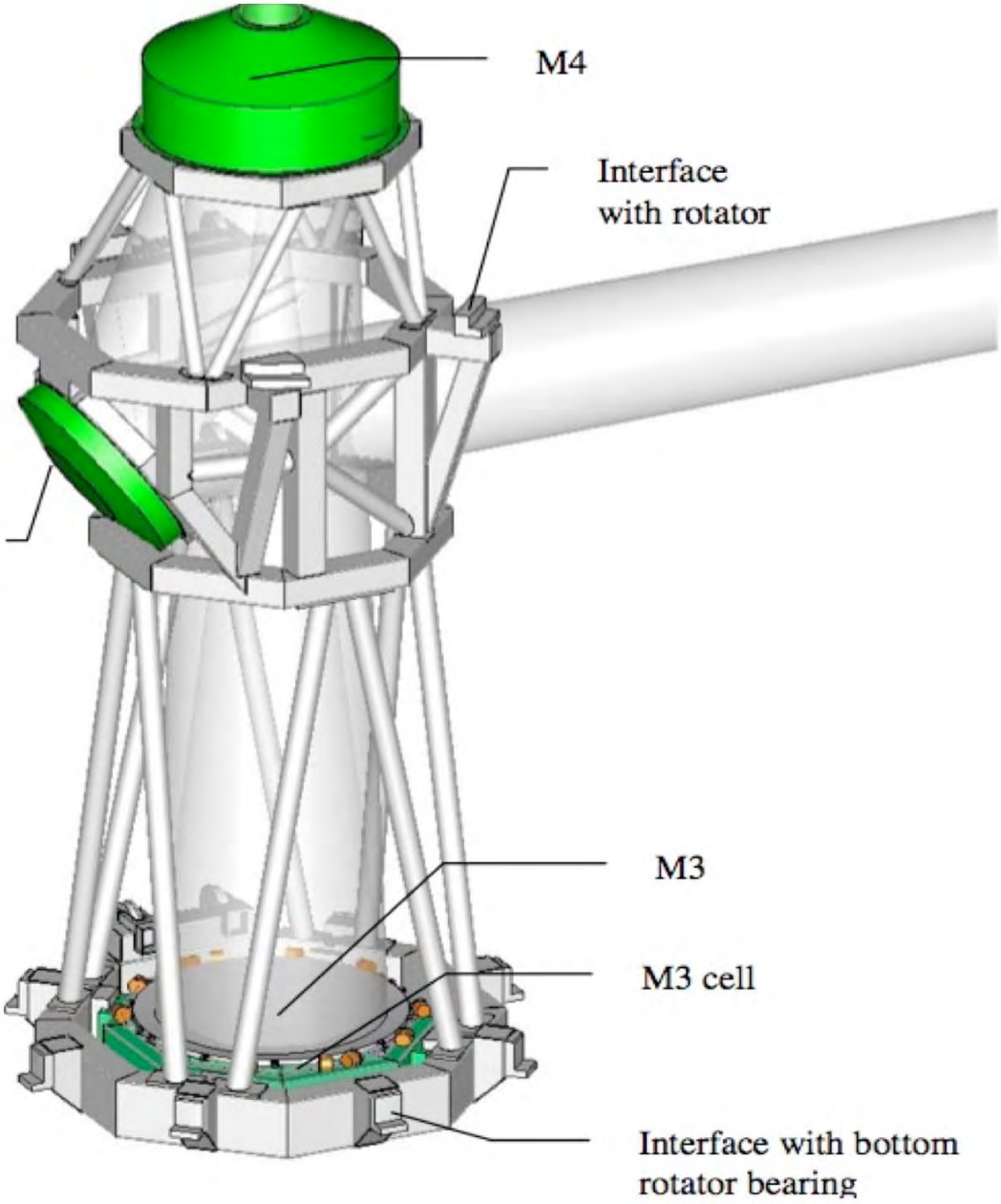


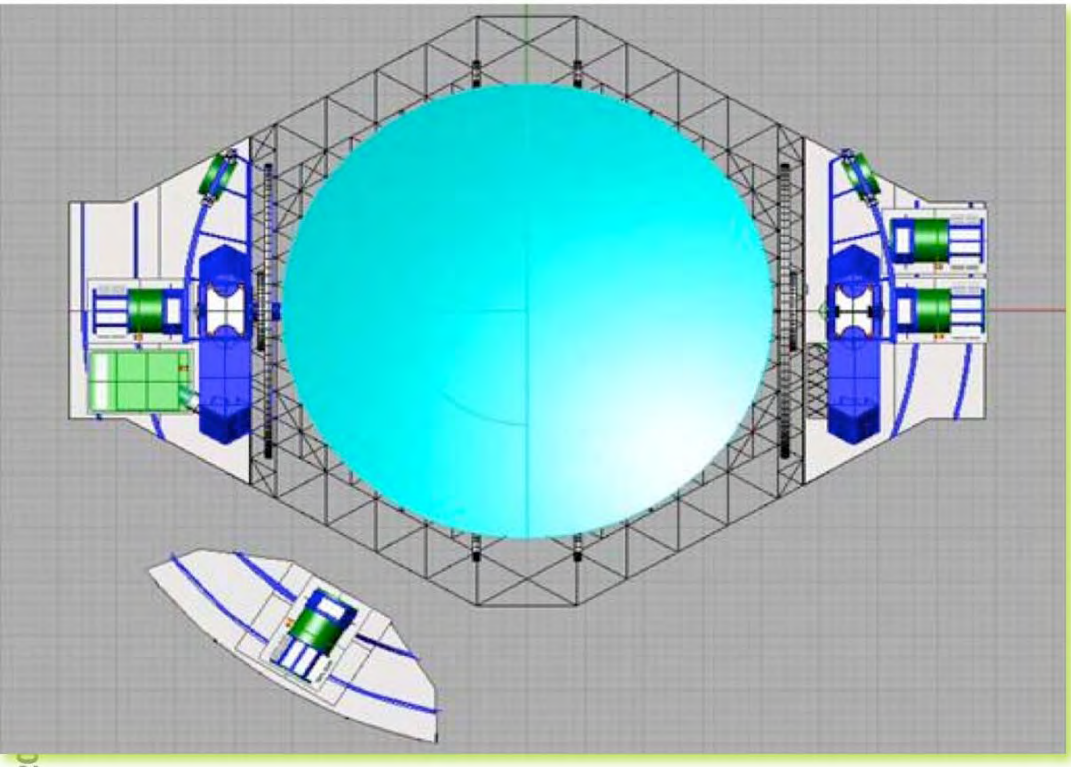
# An Adaptive Telescope

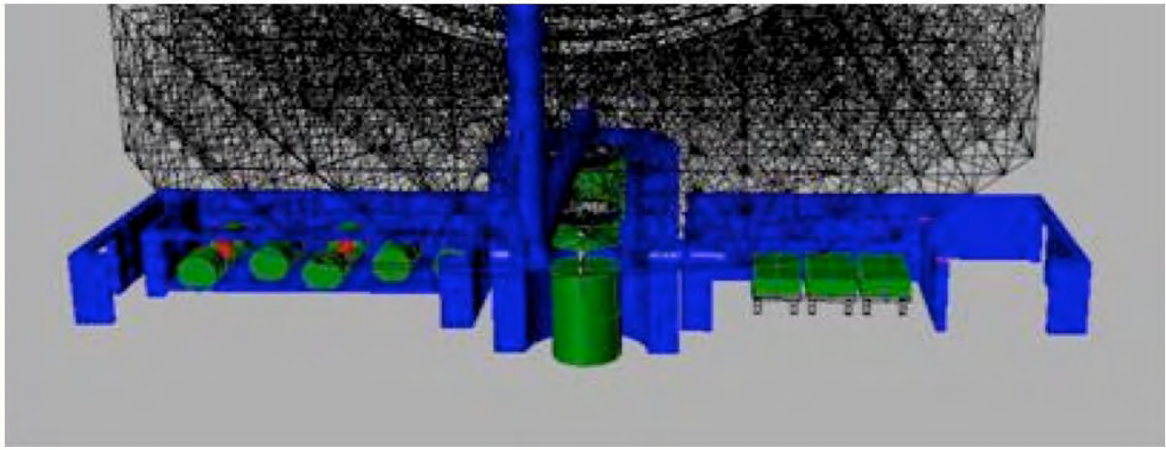


# A telescope with places to put both big and small instruments and with a coude





# The Science Case

# The Science Case


***Science case*** a set of mythical scientific objectives that turn irrelevant once they become attainable.

# If you ever build a telescope ...

***Telescope*** an empty tube with a hole inside, that generally points upwards. Telescopes are very accurate. ***Astronomers believe they know how to build them, and engineers believe they know what they are used for.***

Specify what you want, and how it will be operated.

Do not write the error budget but understand and control it.

Understand risks.