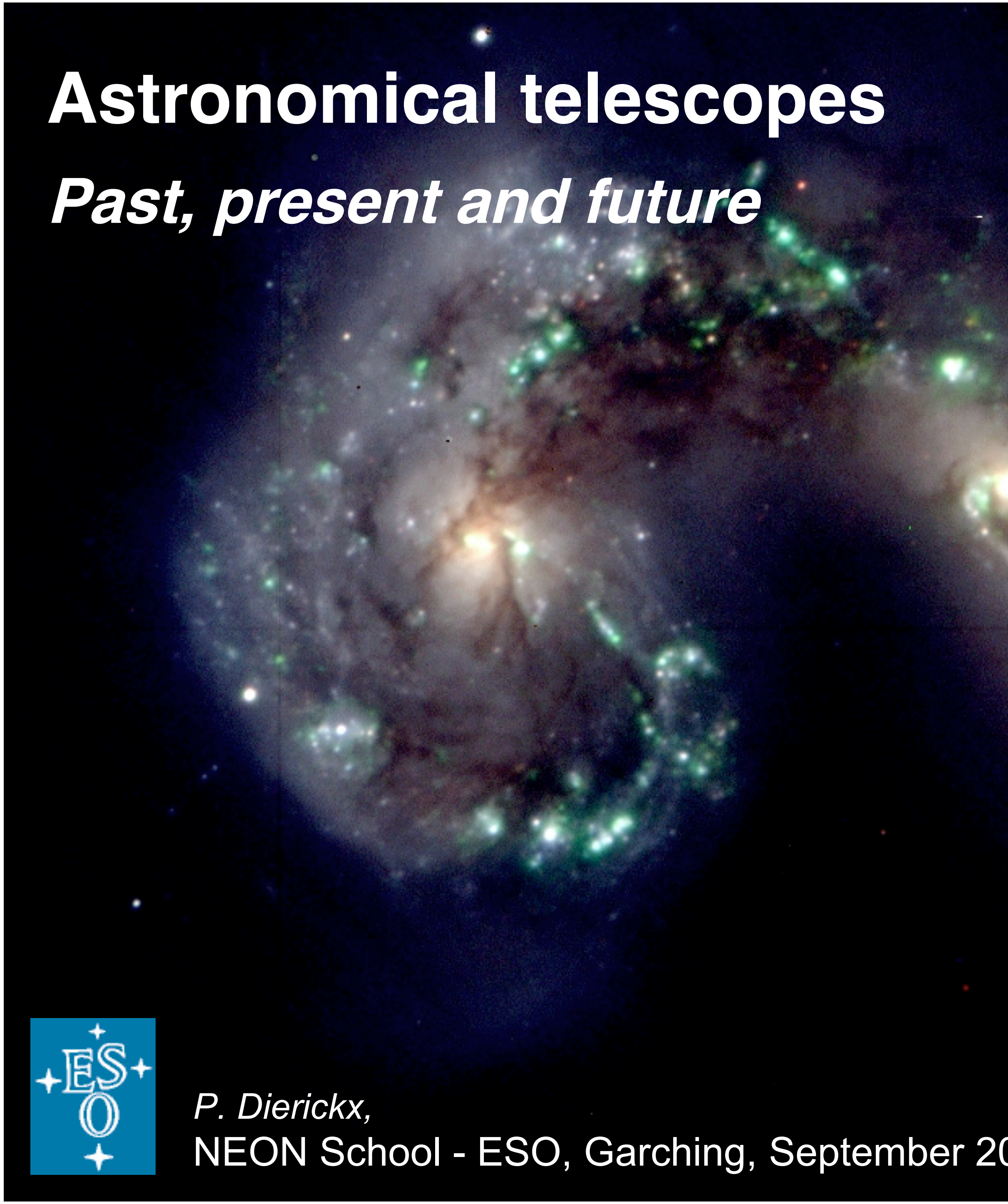
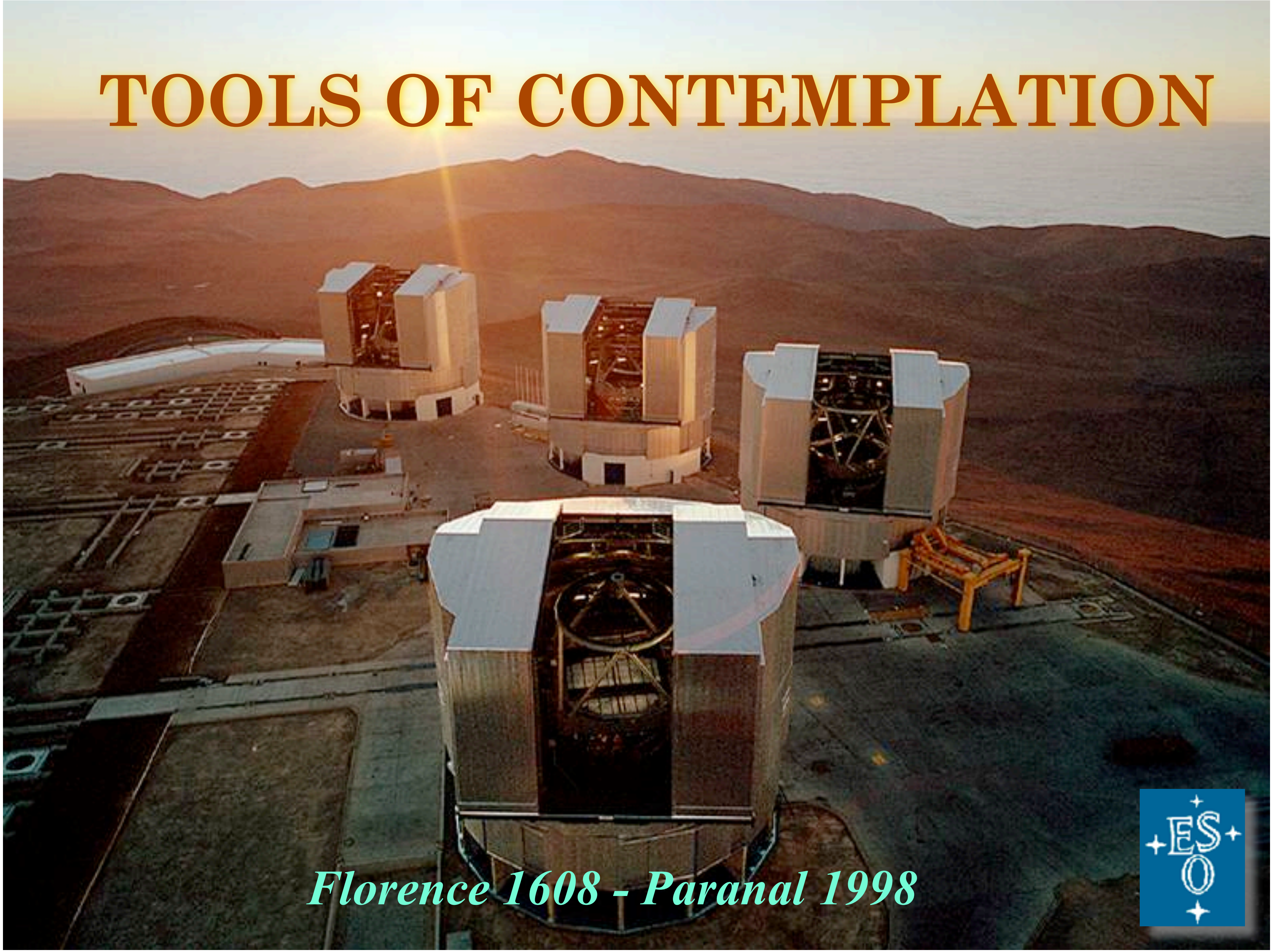
Astronomical telescopes

Past, present and future



P. Dierickx,

NEON School - ESO, Garching, September 2006


TOOLS OF CONTEMPLATION
Florence 1608 - Paranal 1998
ESO

TOOLS OF CONTEMPLATION

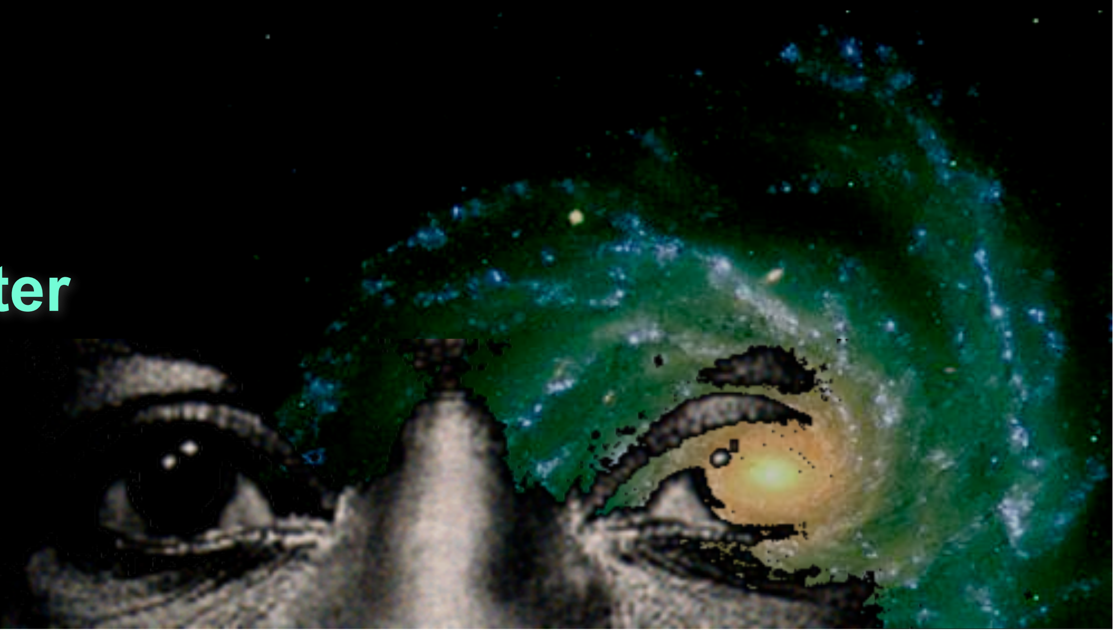
The human eye.

7 mm and a supercomputer

1 arc minute resolution

Extreme dynamic range

Limiting magnitude ~6

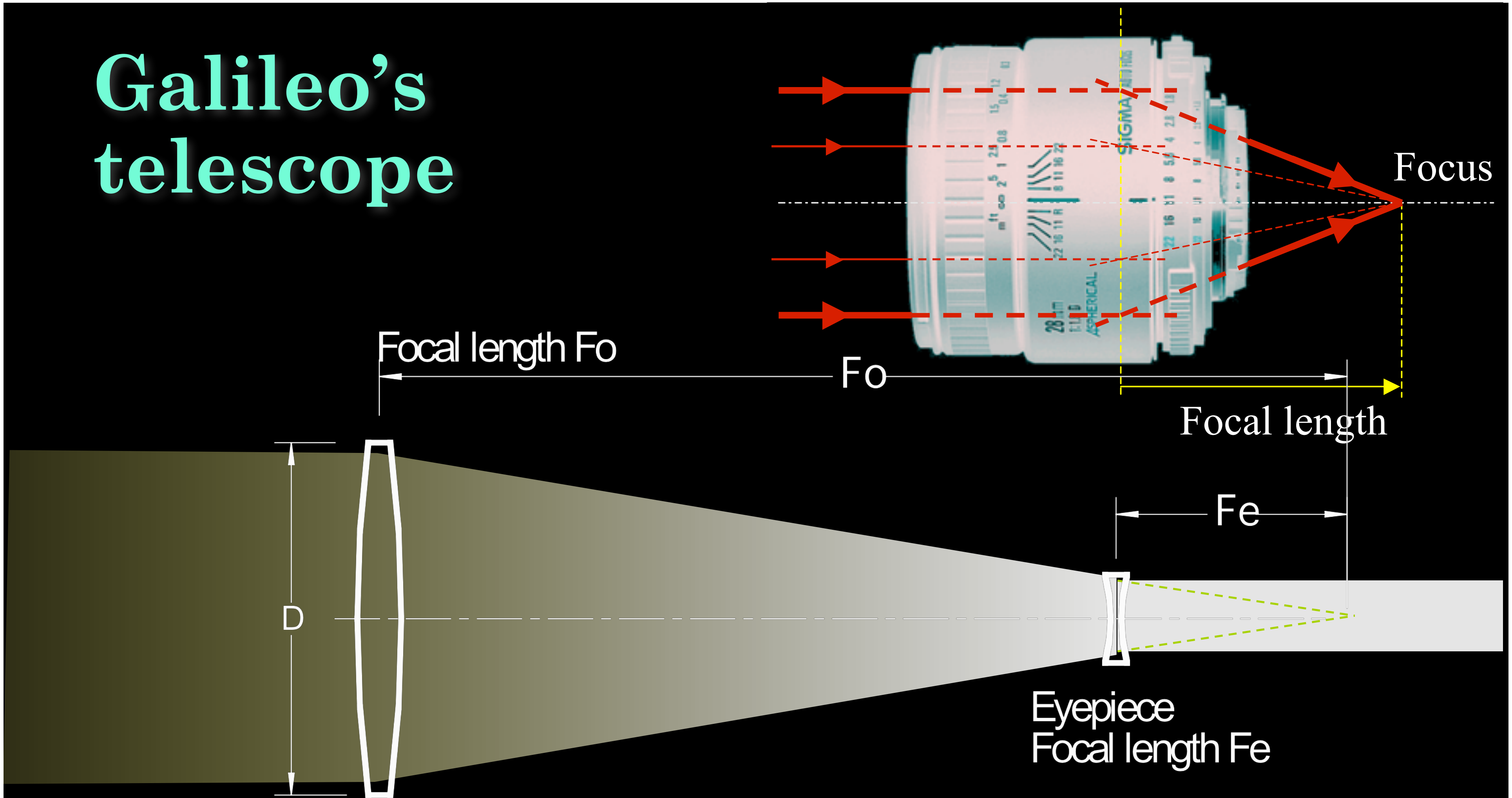


Galileo's telescope
Diameter 30 mm

Thomas Harriot
1609

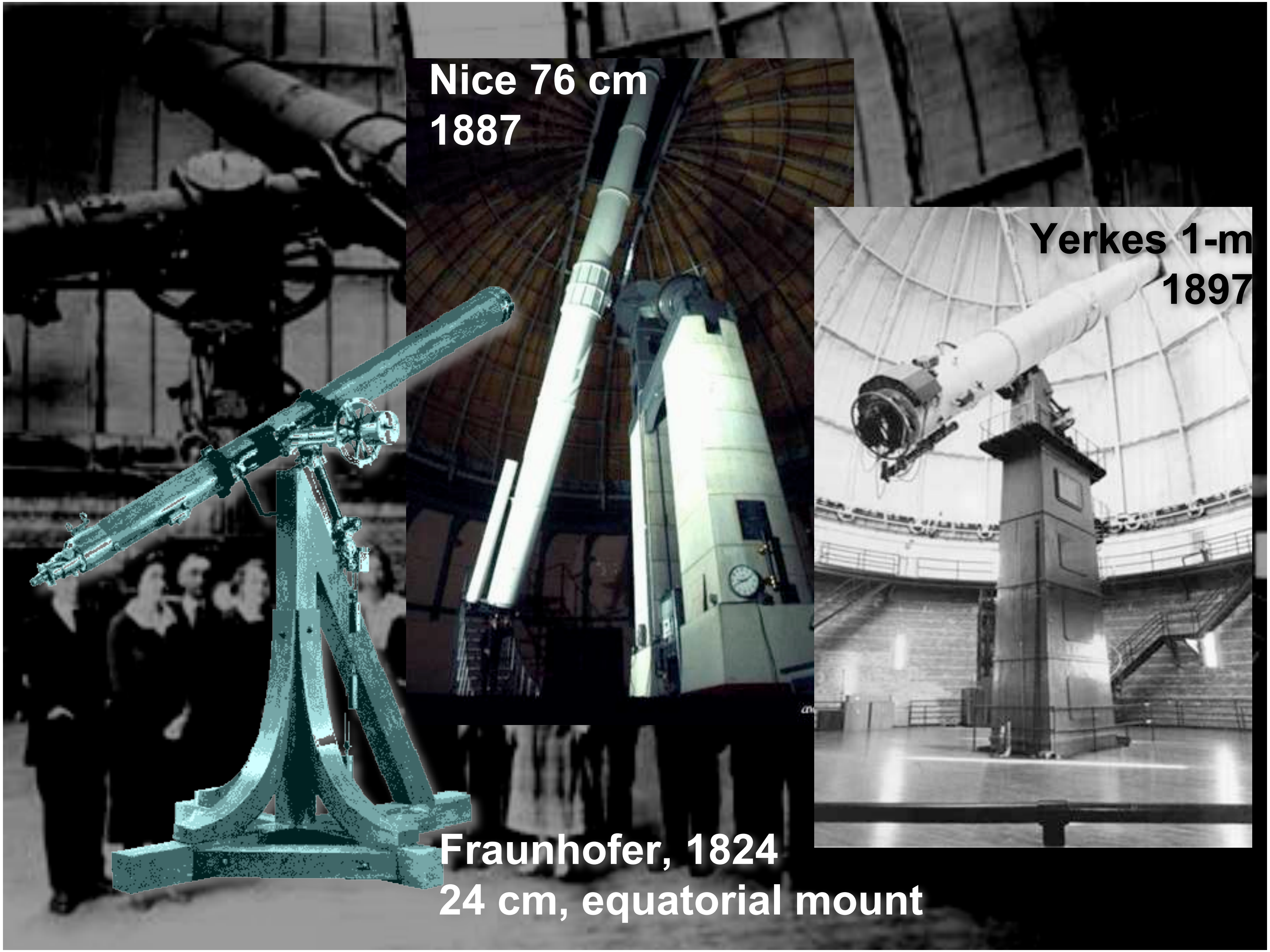
Venice, 1609.

Galileo's telescope



Angular magnification G=Fo / Fe

Focal ratio N=Fo / D

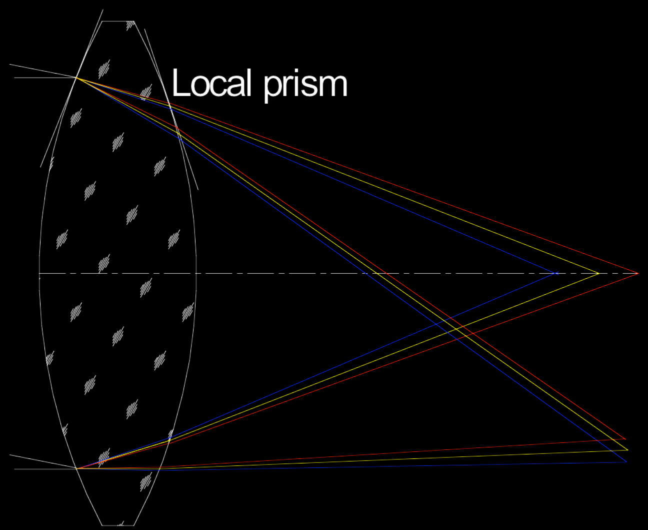

Nice 76 cm
1887
Yerkes 1-m
1897
Fraunhofer, 1824
24 cm, equatorial mount

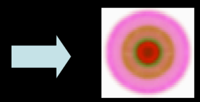
Refracting

- Chromatic aberrations
- Spherical & field aberrations

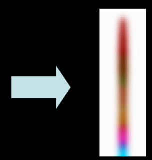
Reflecting

- Spherical & field aberrations
- 4 times tighter manufacturing tolerances



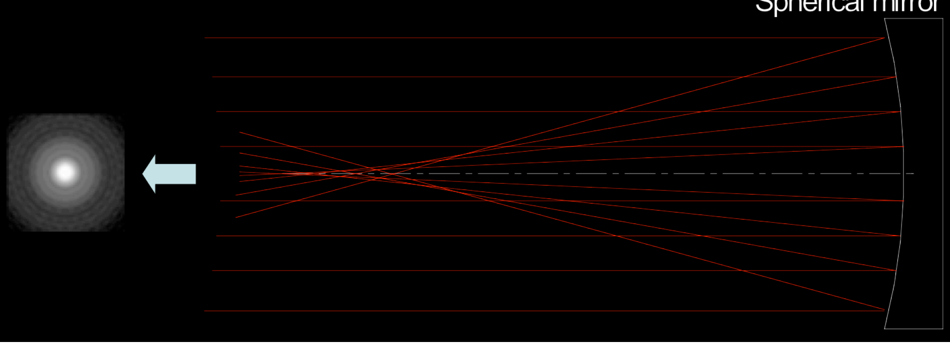


Axial chromatism



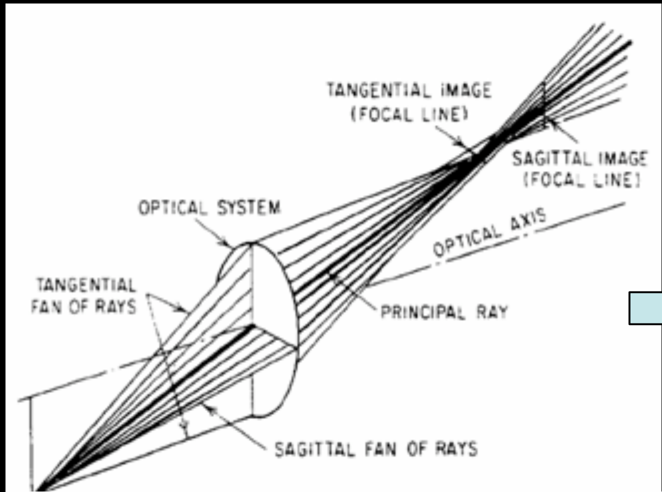
Lateral chromatism

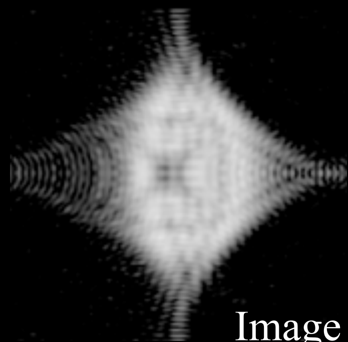
Spherical aberration



Field aberrations

Astigmatism

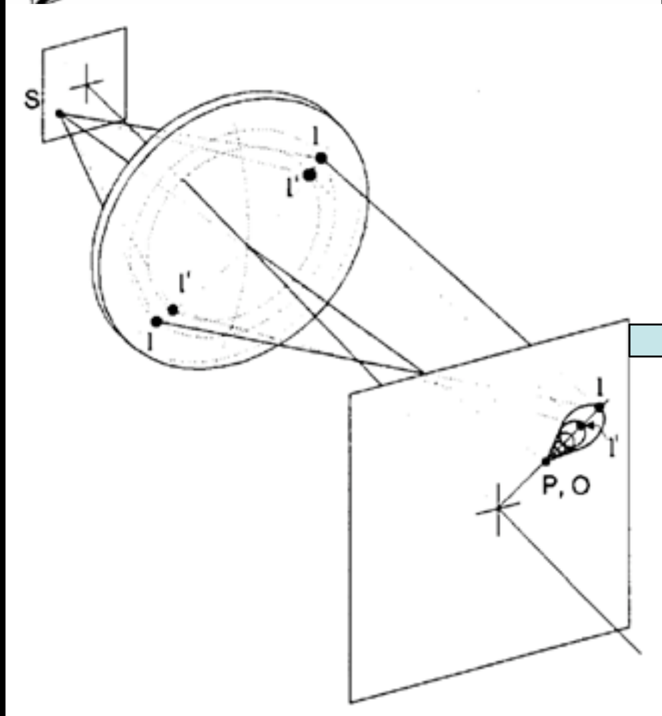


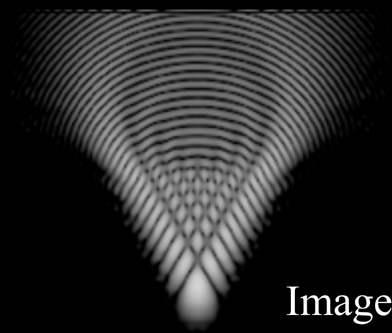


Image

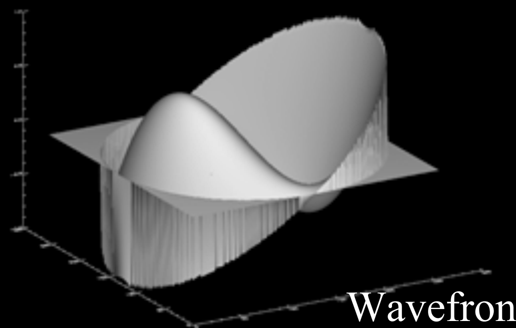
Wavefront

Coma



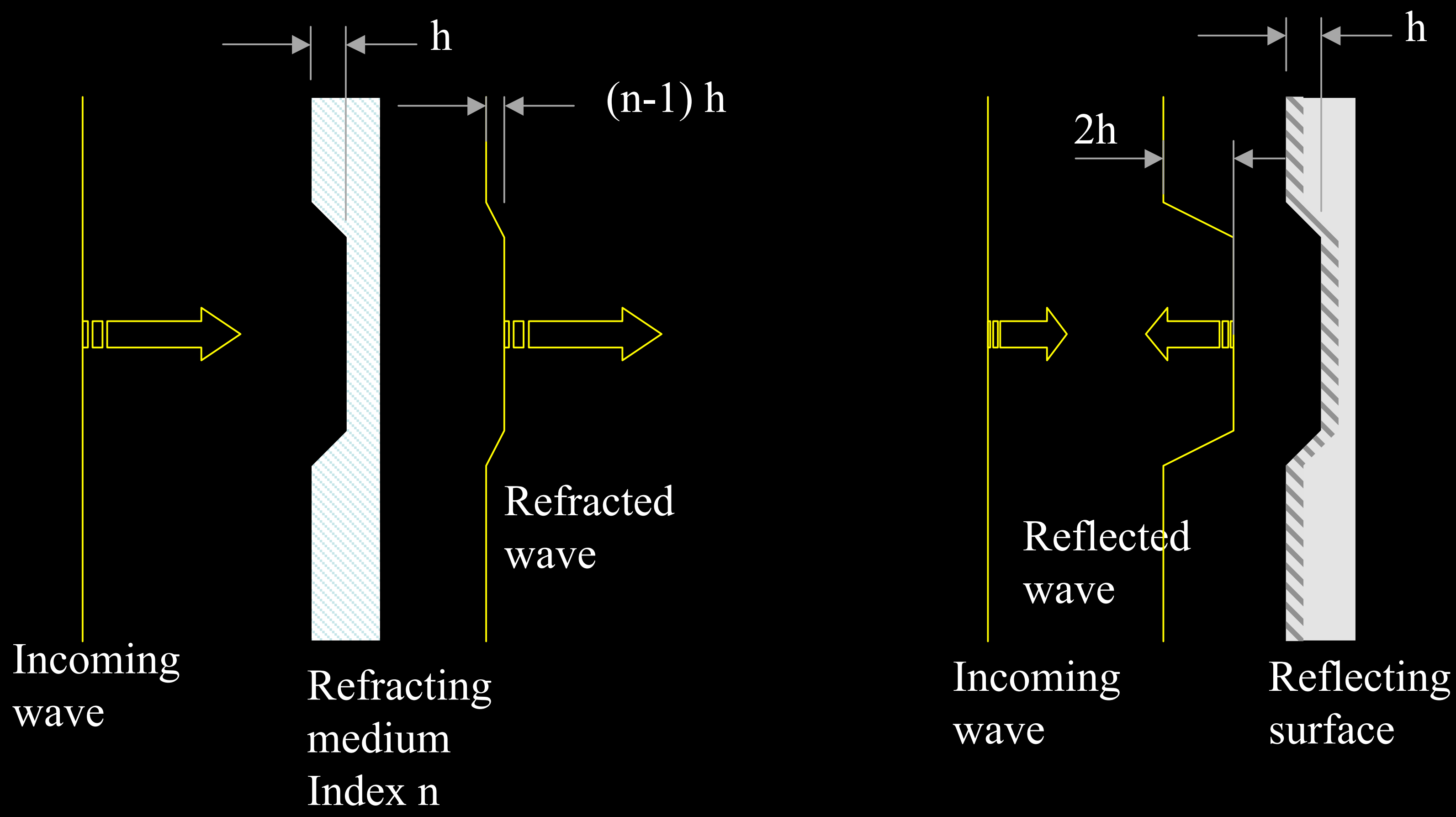


Image



Wavefront

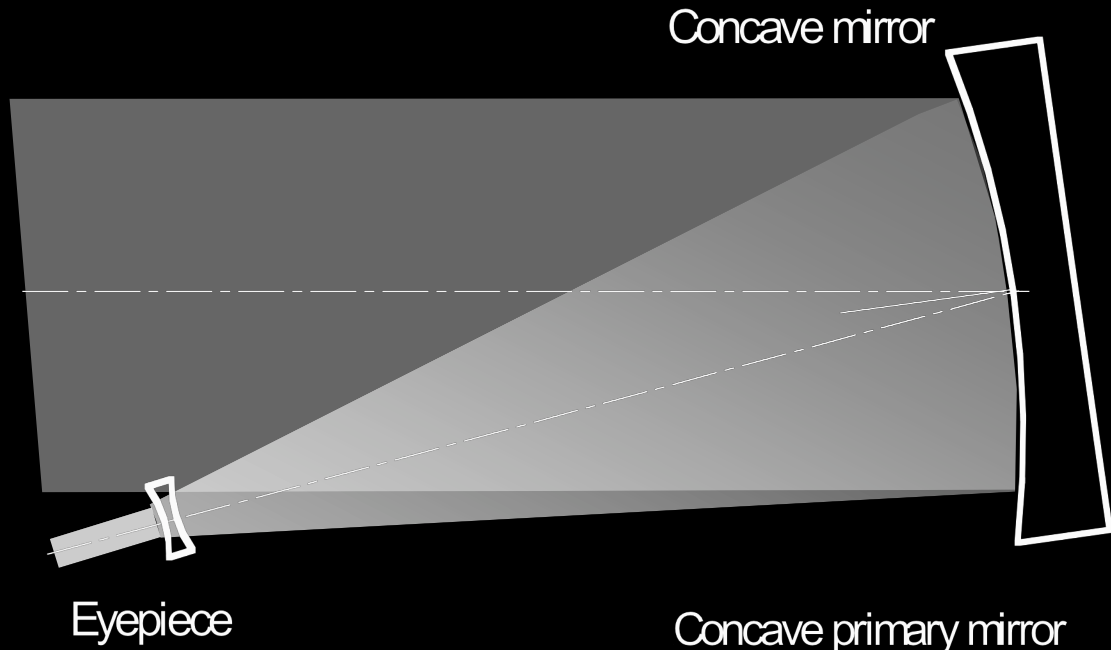
- Refractors
- Reflectors

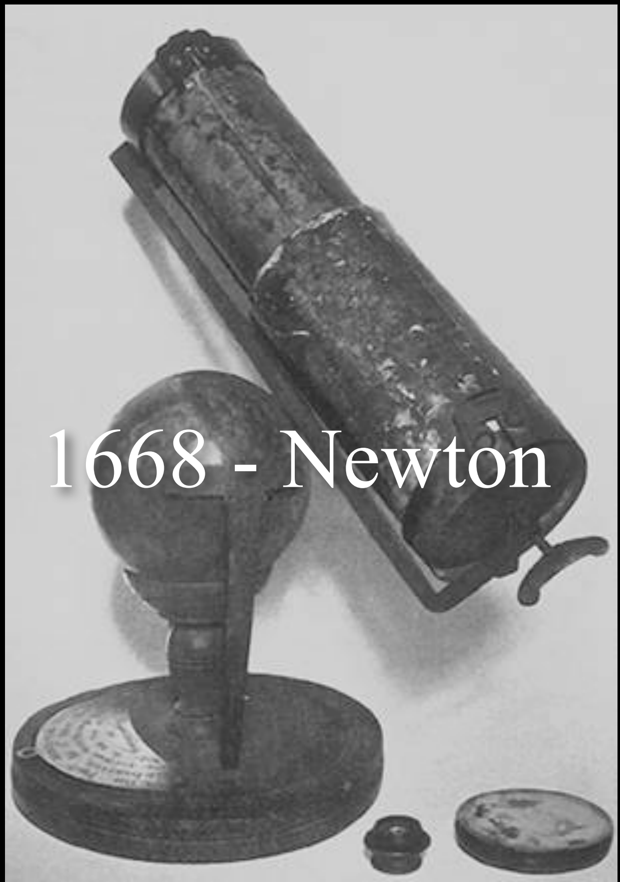


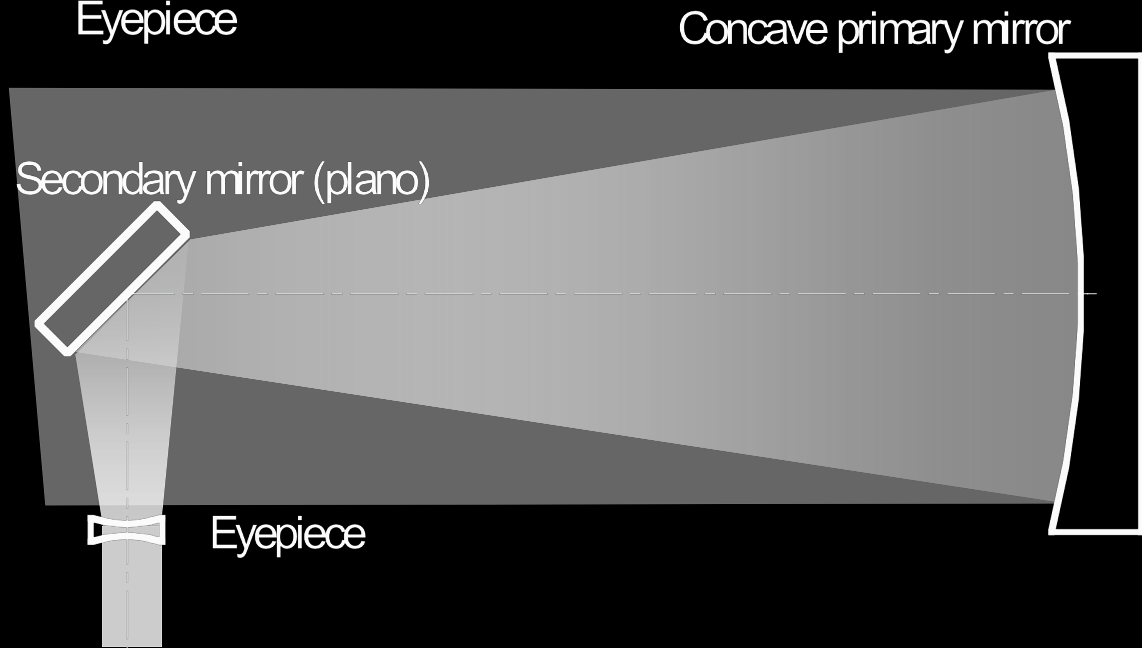
Surface quality requirement for a reflecting surface ~ 1/4th of surface quality requirement for a refracting one

Reflecting telescopes – the early years 1608-1672

1616 - Zucchi

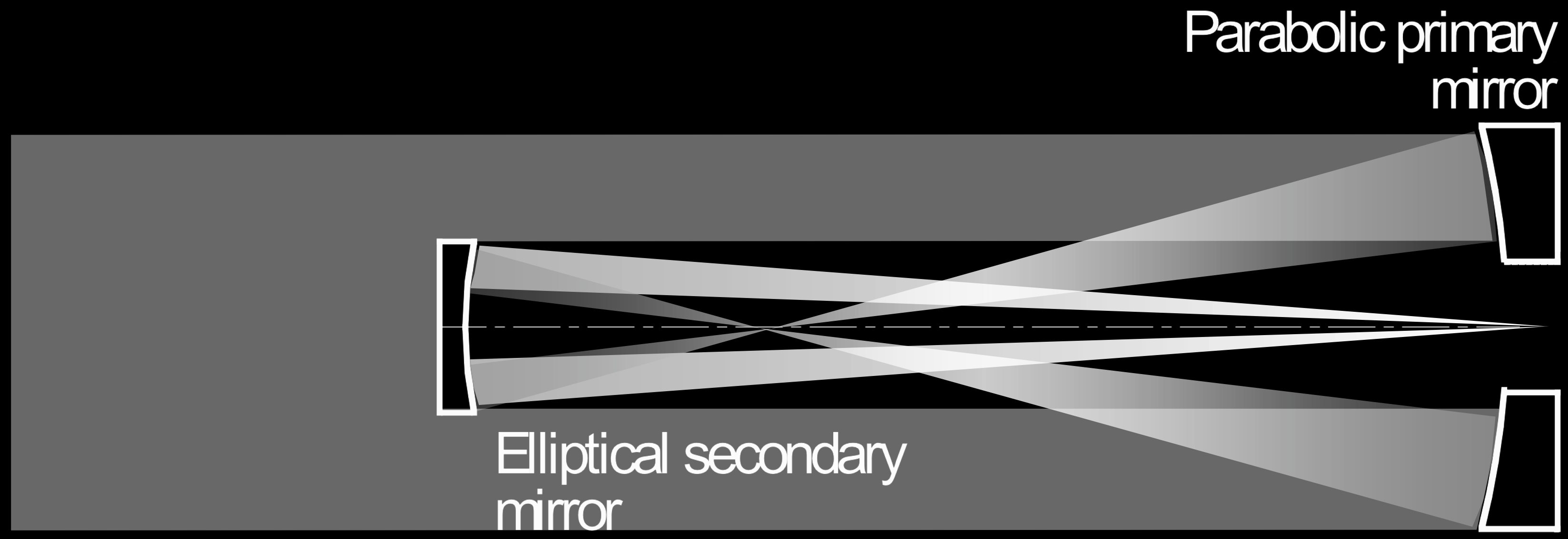






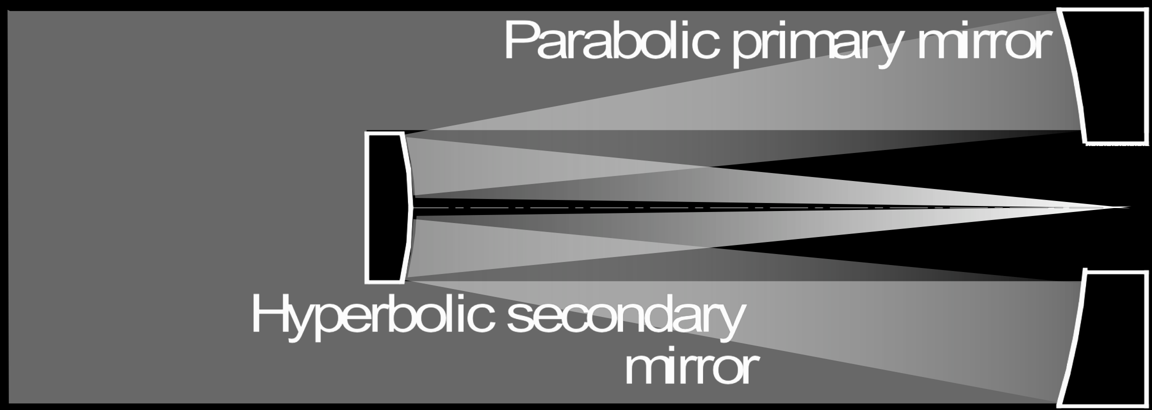
The early years 1608-1672

Gregorian



The early years 1608-1672

Cassegrain



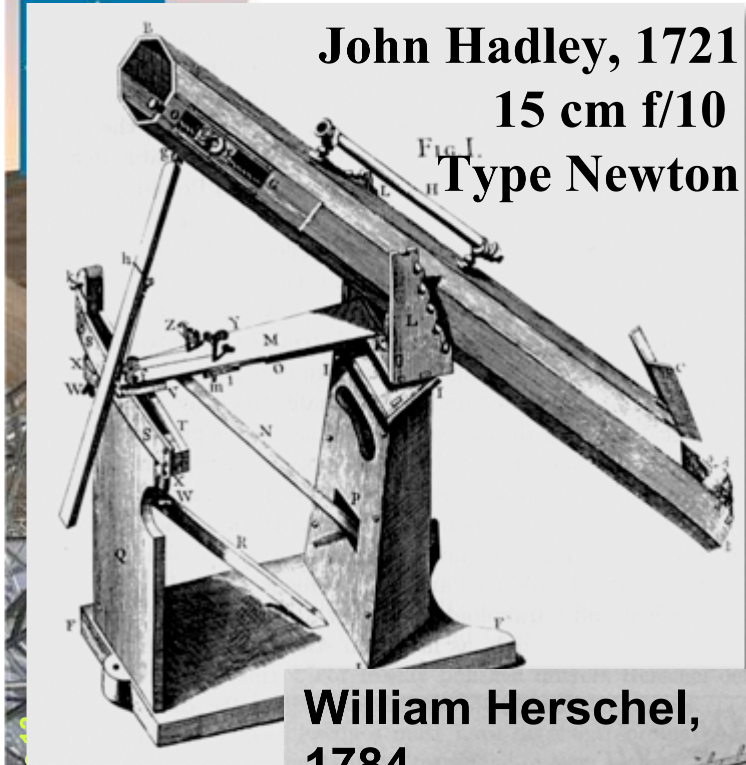
The theory of the reflecting telescope

(mirrors shape)

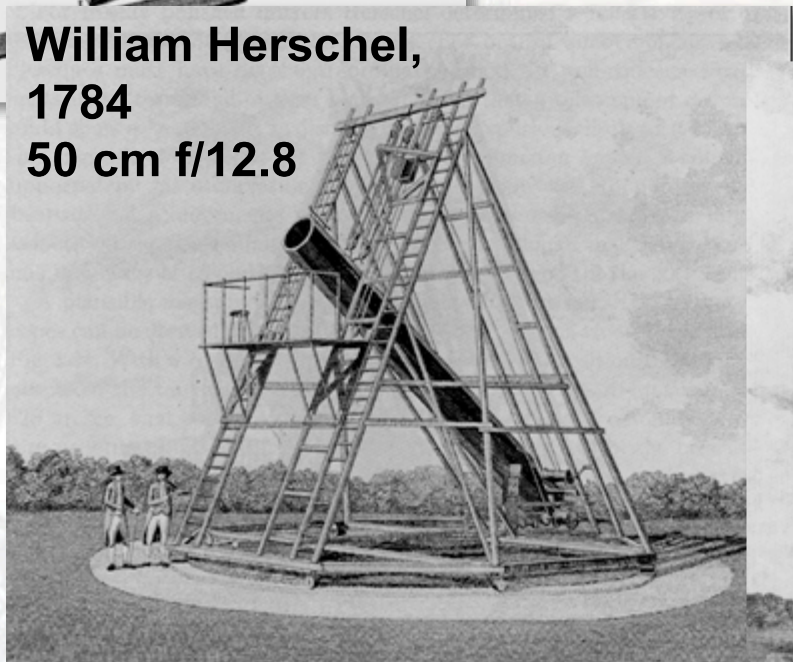
will remain unchanged until 1905.

Reflecting telescopes after 1672

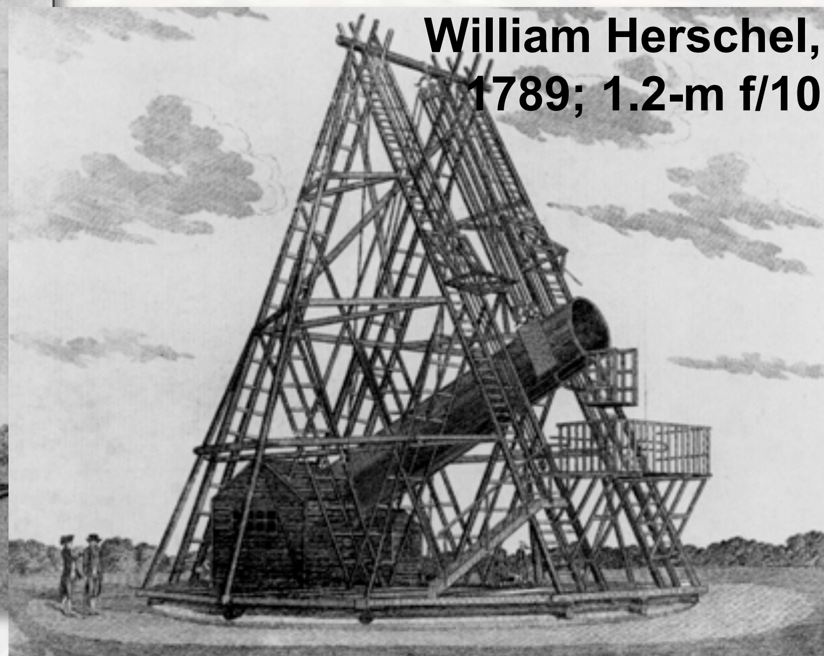
- Speculum mirrors
- Low efficiency (~60% / mirror)
- Need periodic re-polishing
- Large collecting area



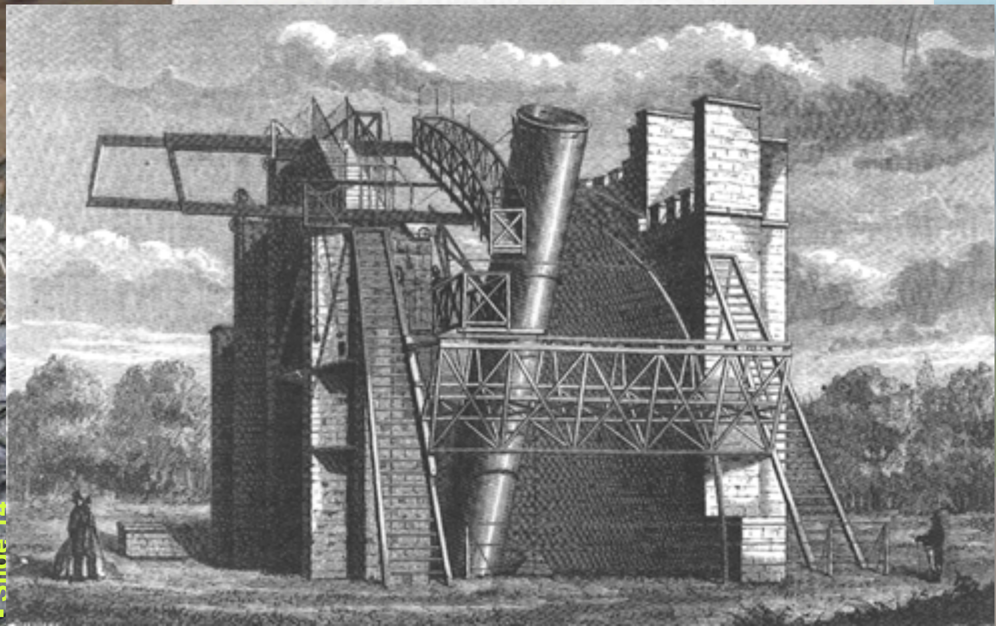
John Hadley, 1721
15 cm f/10
Type Newton



William Herschel,
1784
50 cm f/12.8



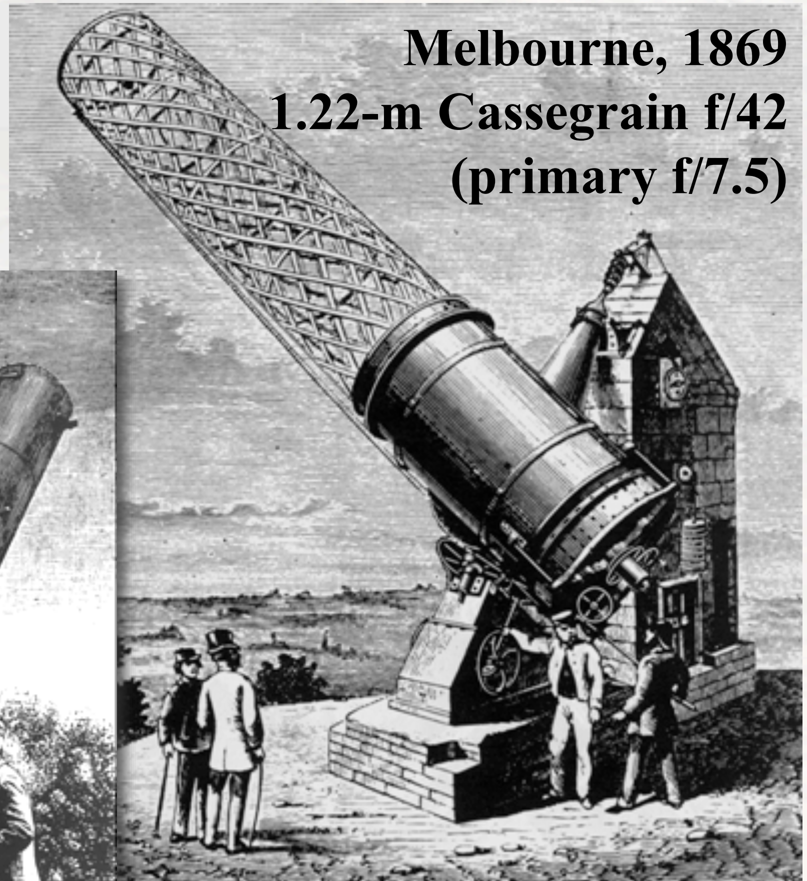
William Herschel,
1789; 1.2-m f/10



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

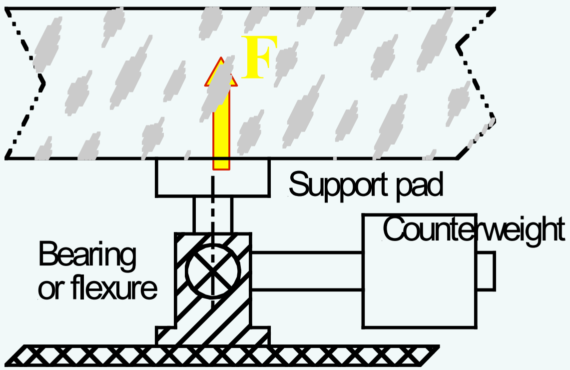
Reflecting telescopes after 1672

Lassel, 1861
Newton focus
1.22-m,
Malta

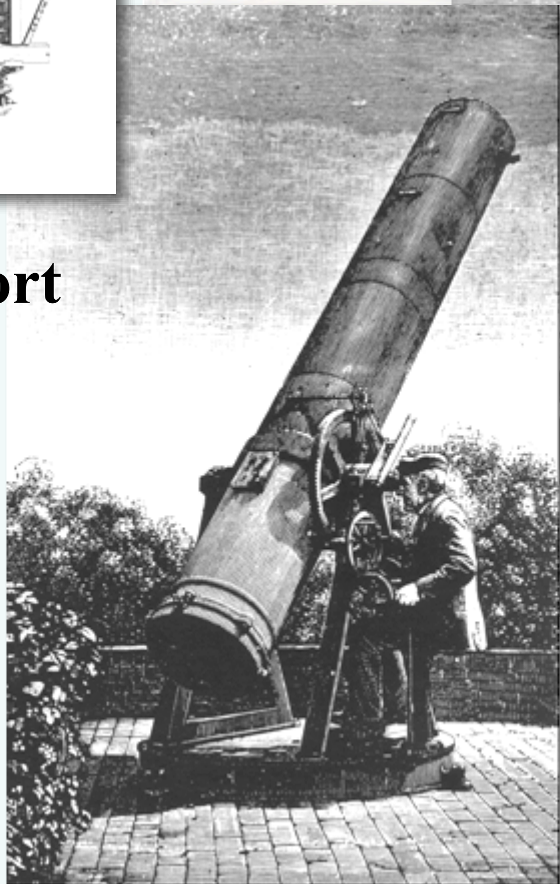


Melbourne, 1869
1.22-m Cassegrain f/42
(primary f/7.5)

Counterweight support

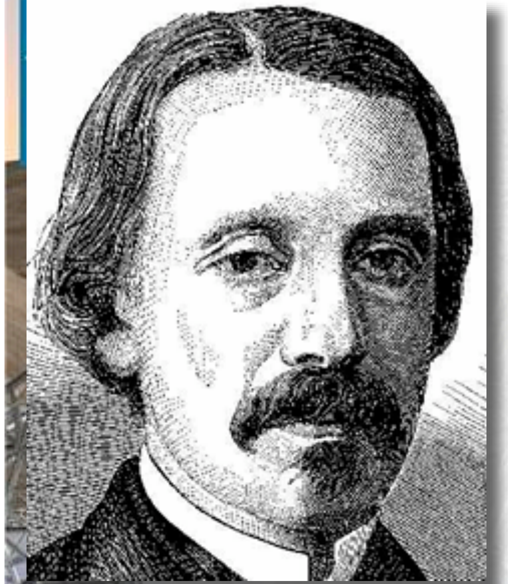


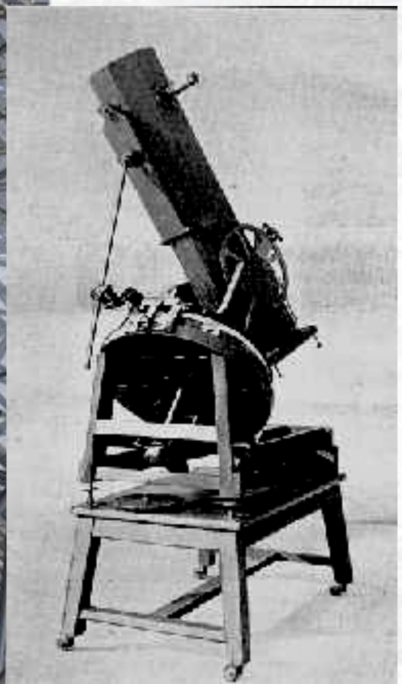
$F \propto \cos z$

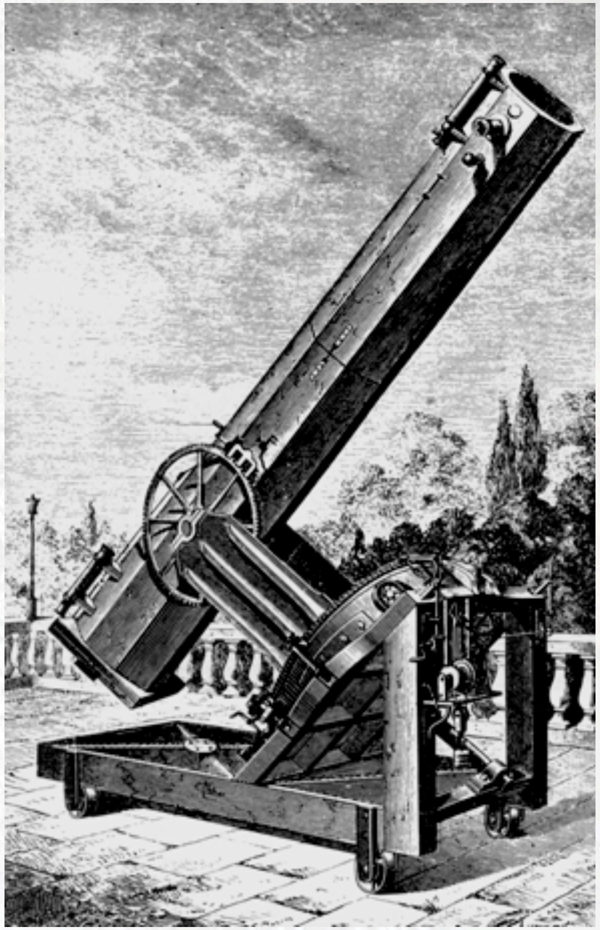


Nasmyth, 1845
50-cm

Glass mirrors





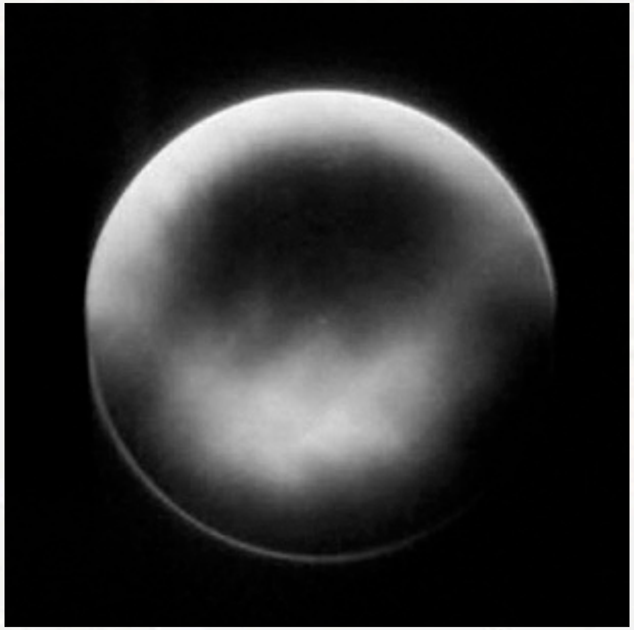


1862, 80 cm,
Silvered glass mirror

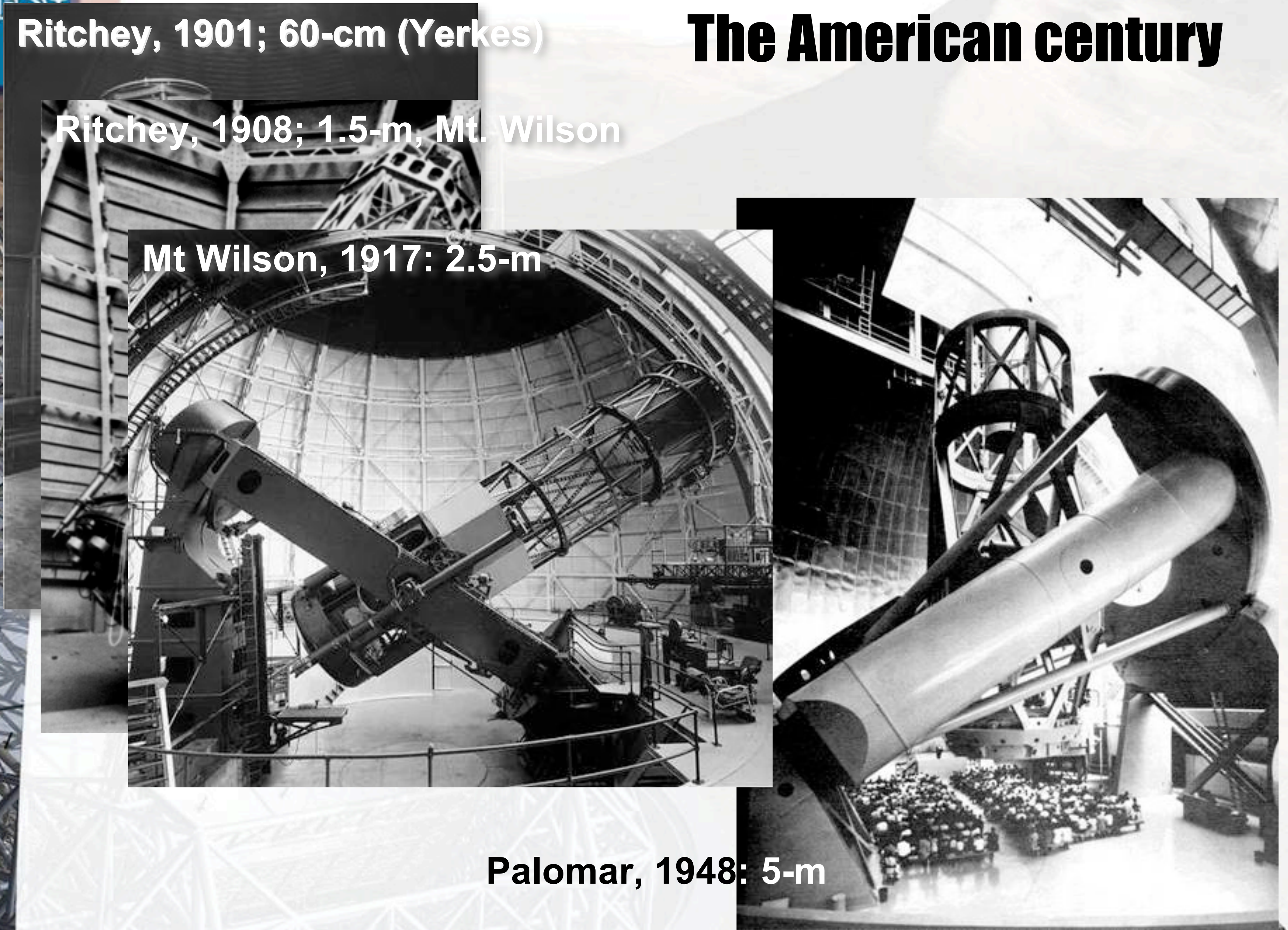
Foucault

1857: silver on glass

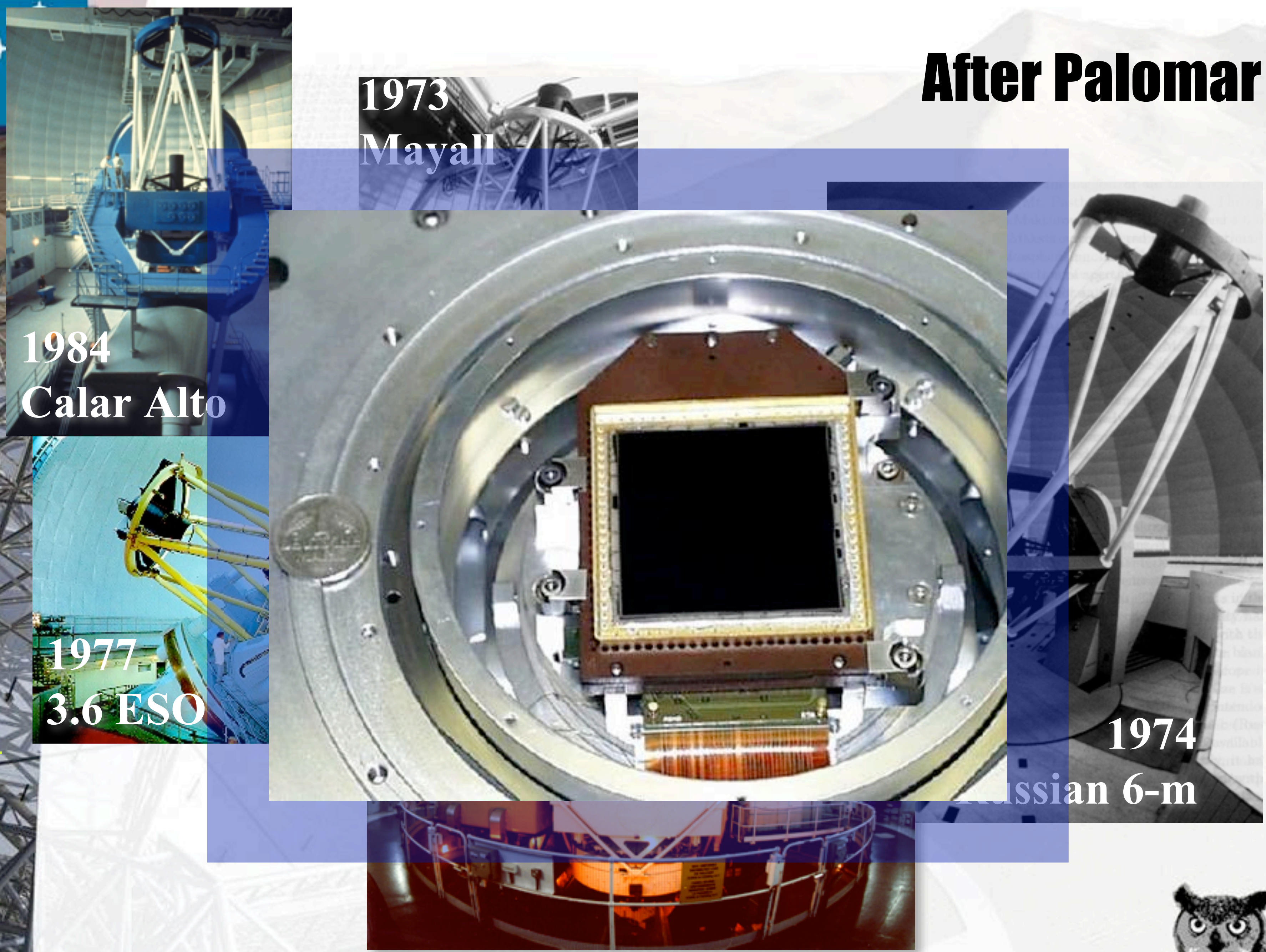
1859: Foucault test



The American century



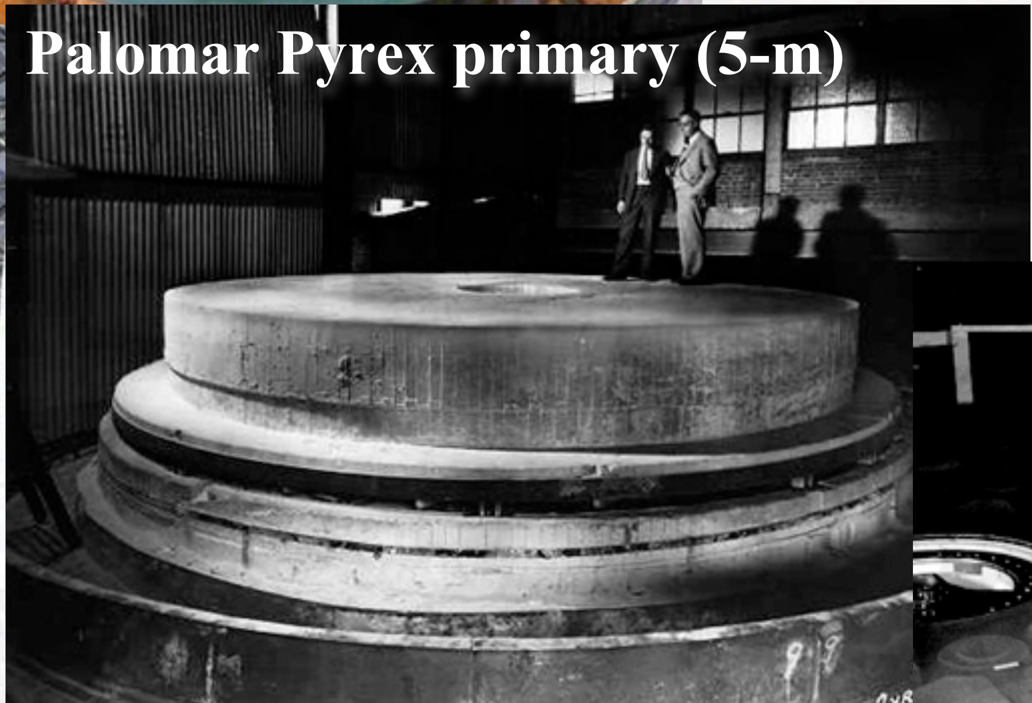
After Palomar



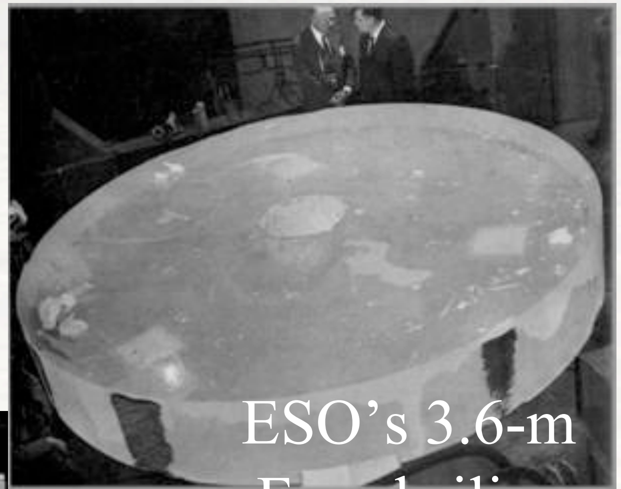
Slow progress

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

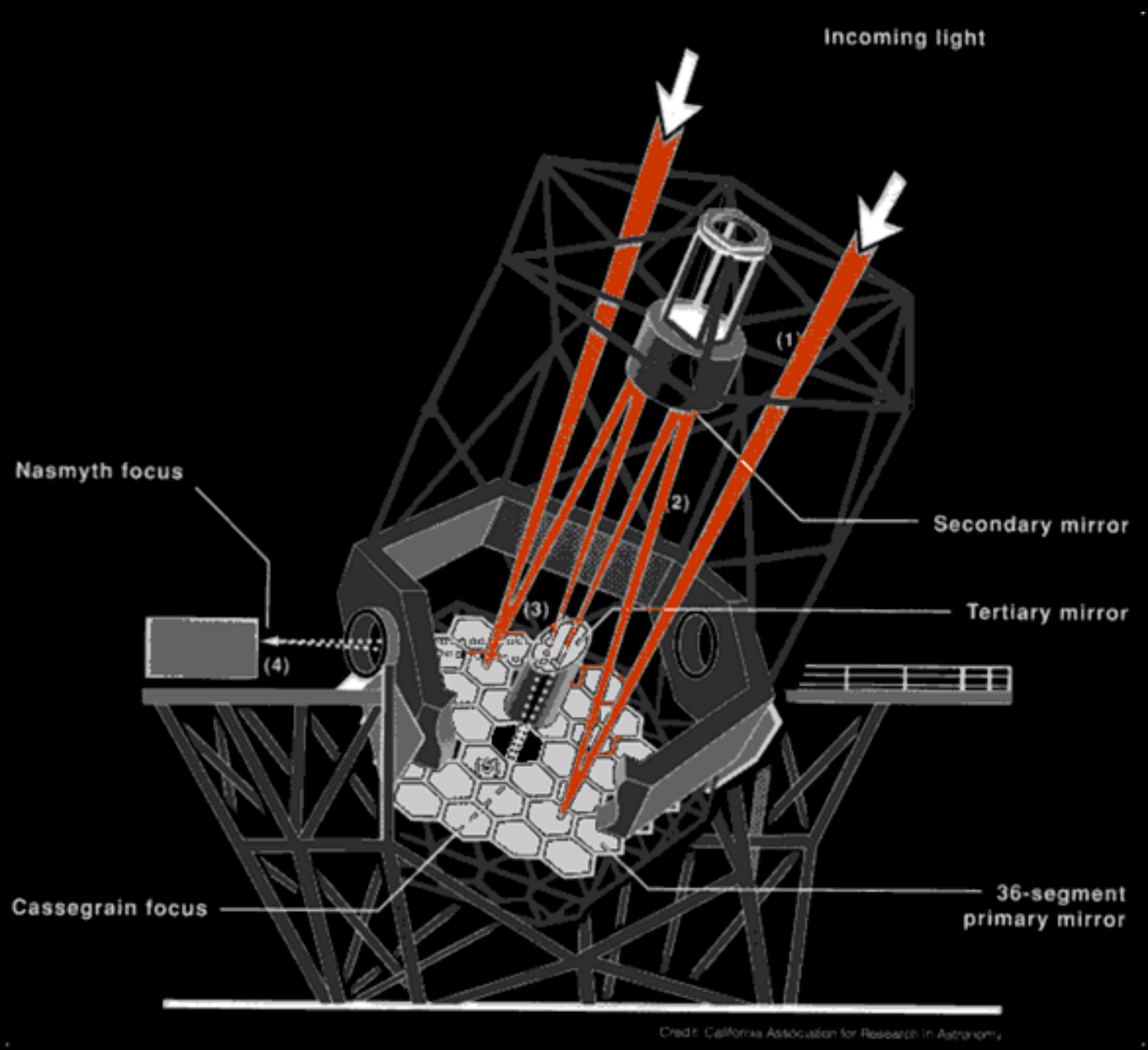
Hooker primary mirror (Mt Wilson 2.5-m)

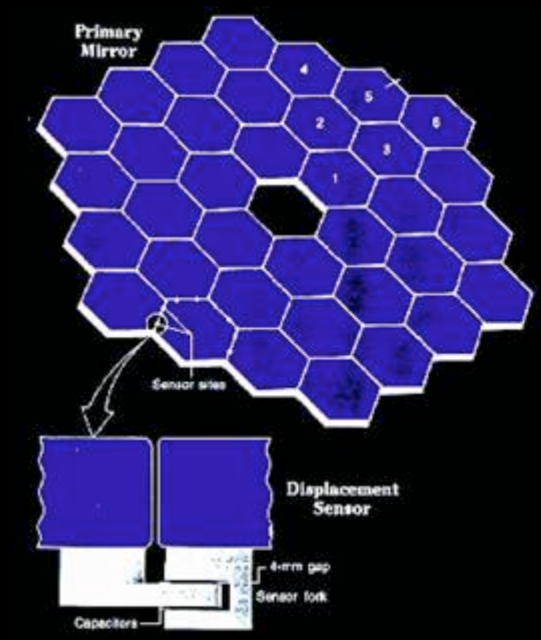


Palomar Pyrex primary (5-m)

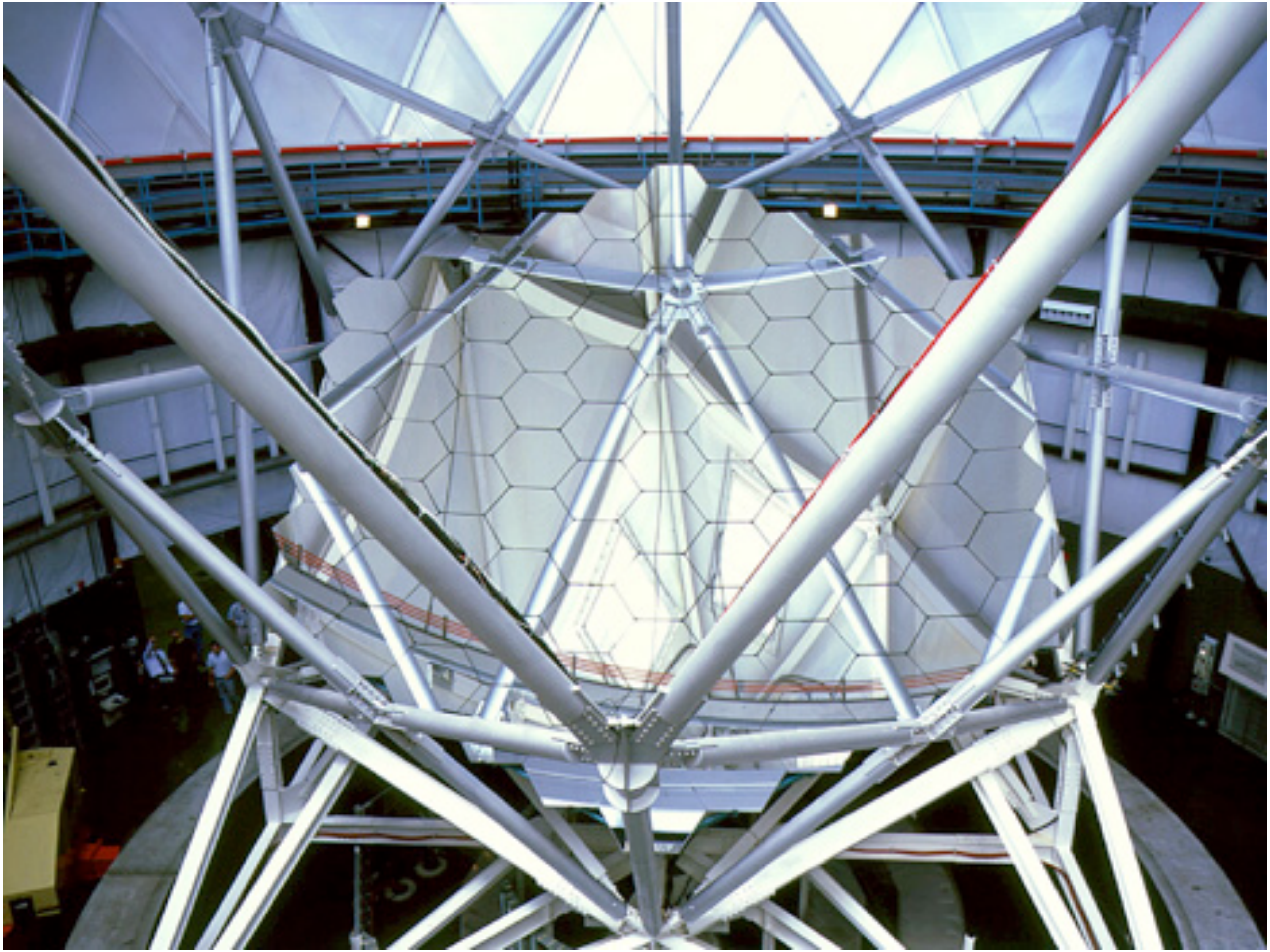


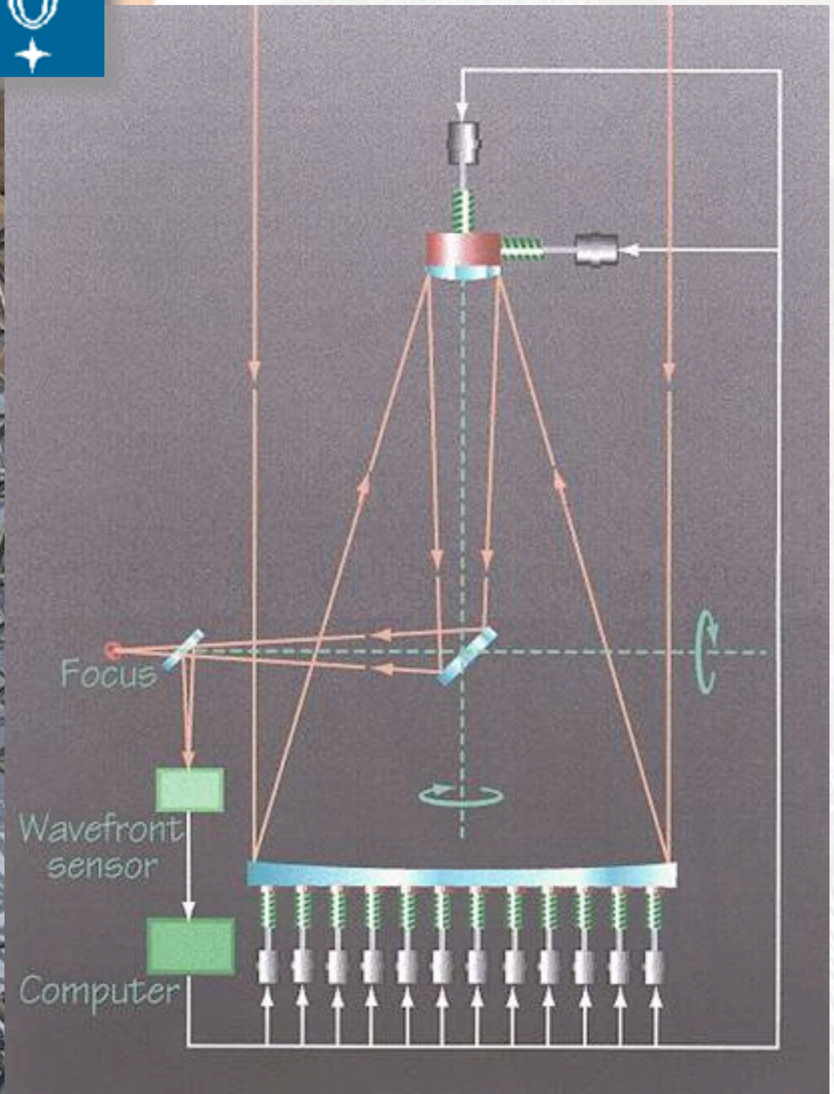
ESO's 3.6-m Fused silica

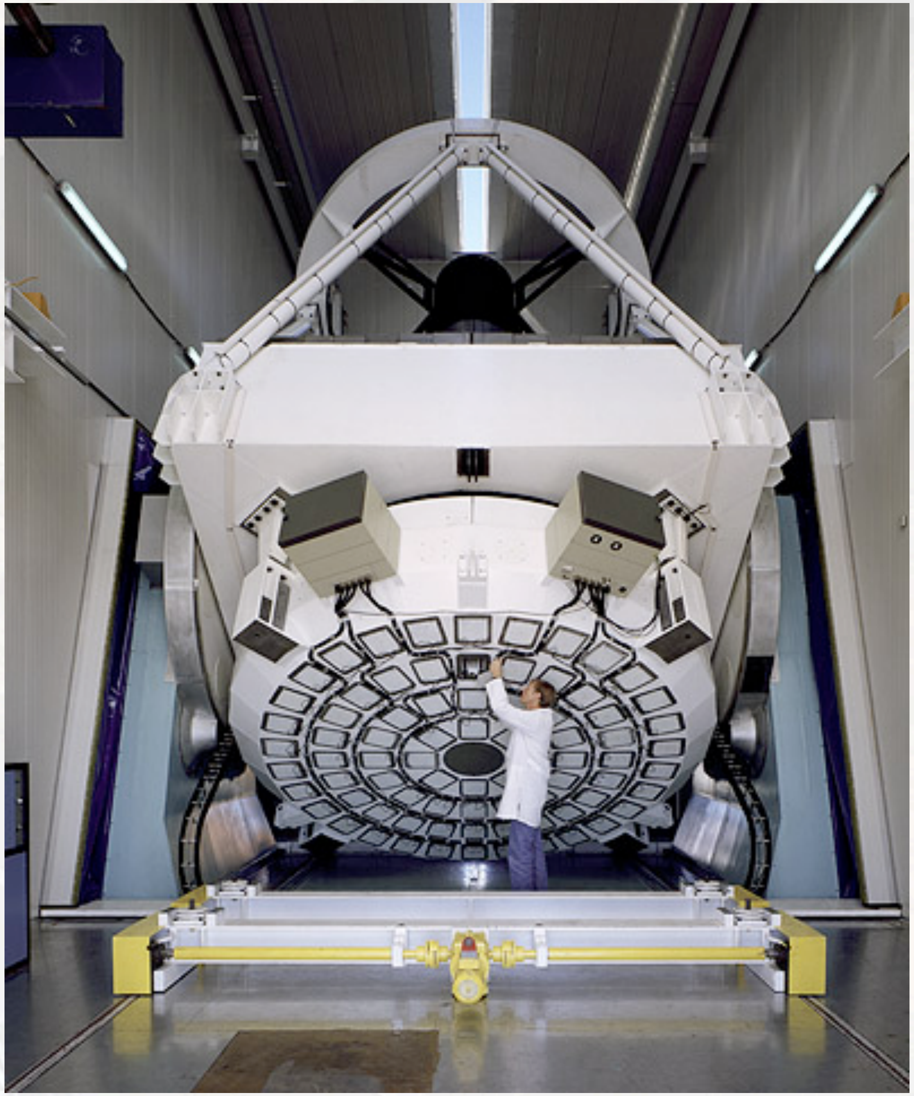


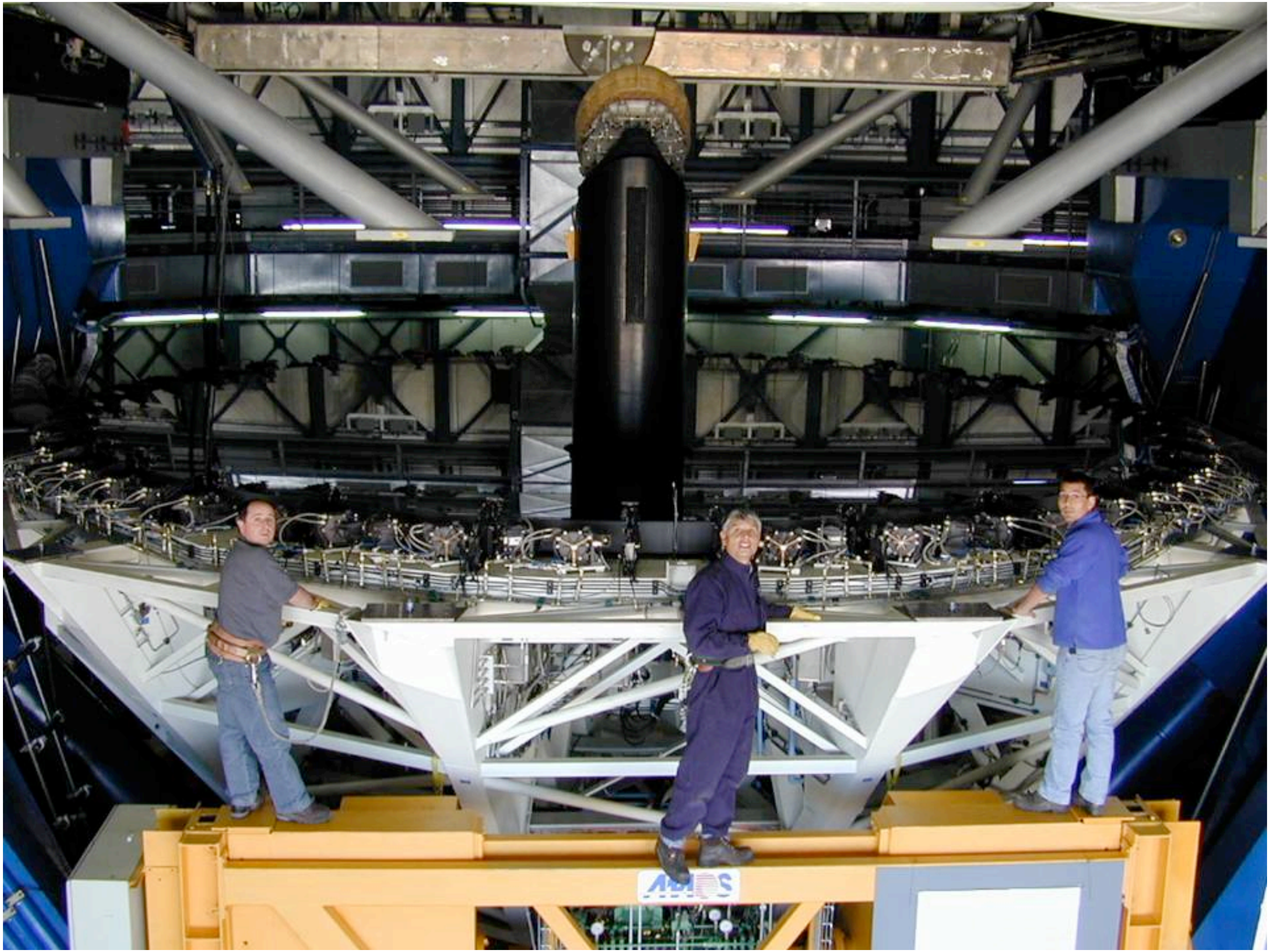


Segmentation – Keck 10-m telescopes



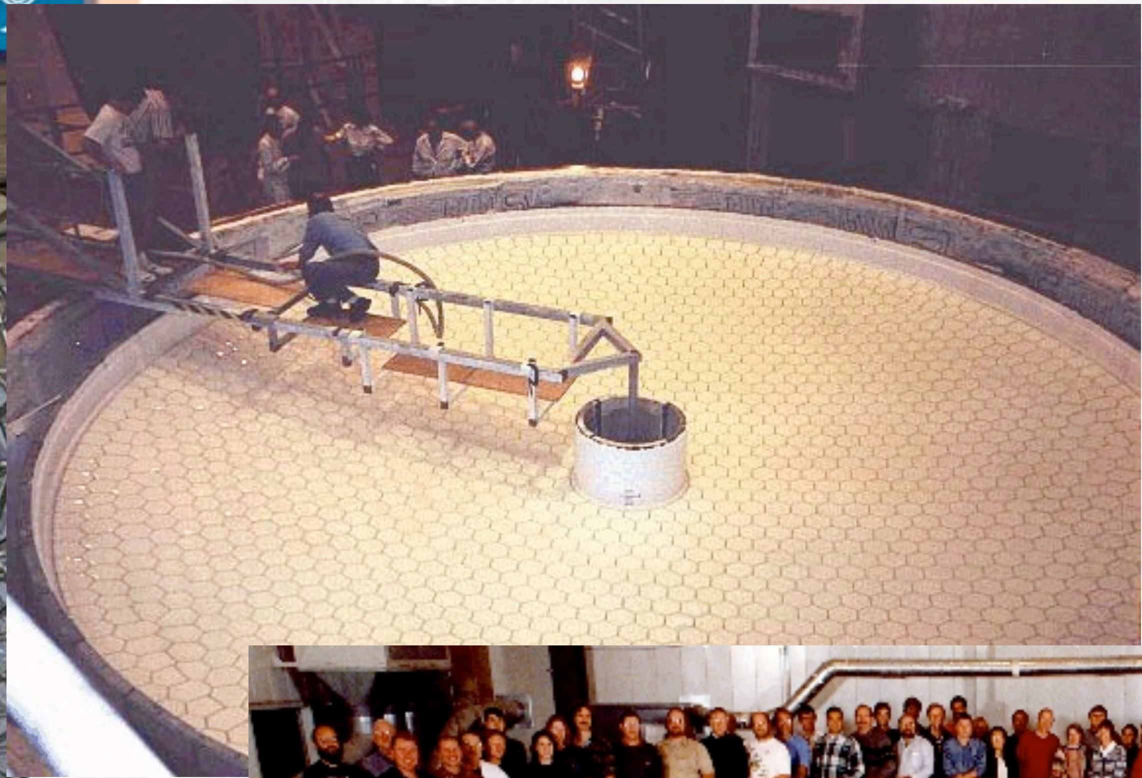

Focus
Wavefront sensor
Computer





VLT ACTIVE OPTICS

ROTATING CROSSES



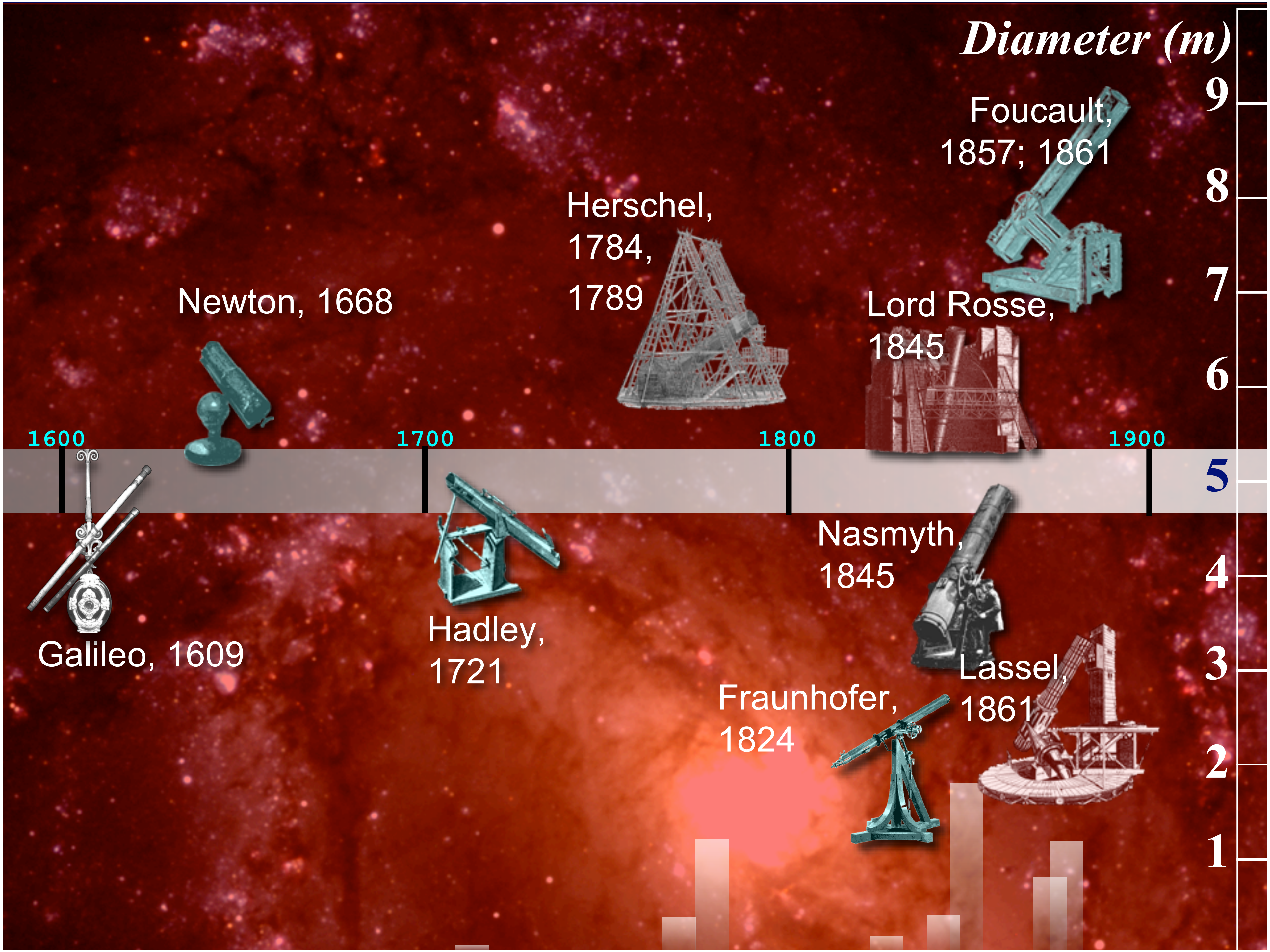
Lightweight borosilicate

“Palomar-like”

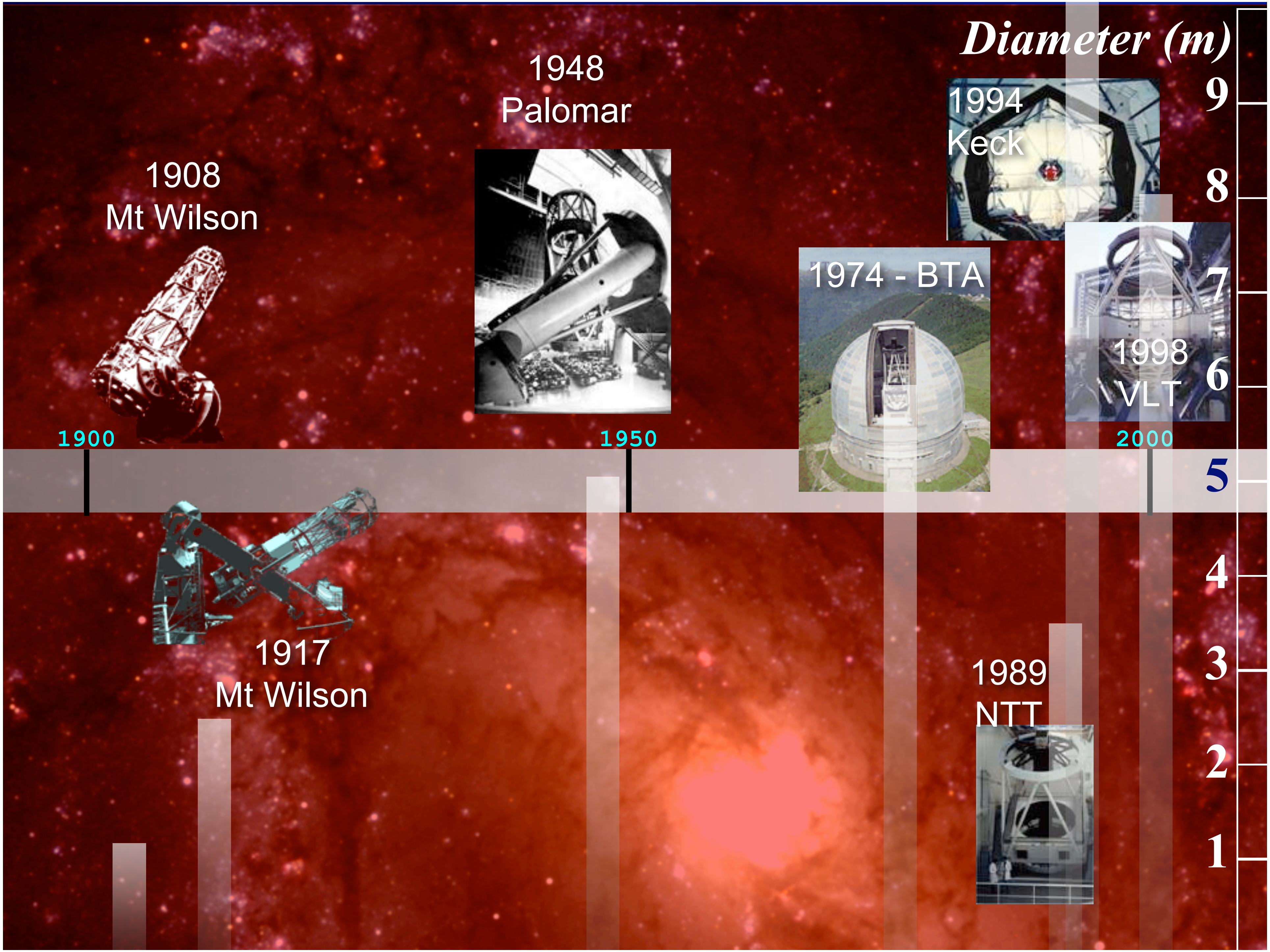
High thermal inertia

Non-zero thermal expansion

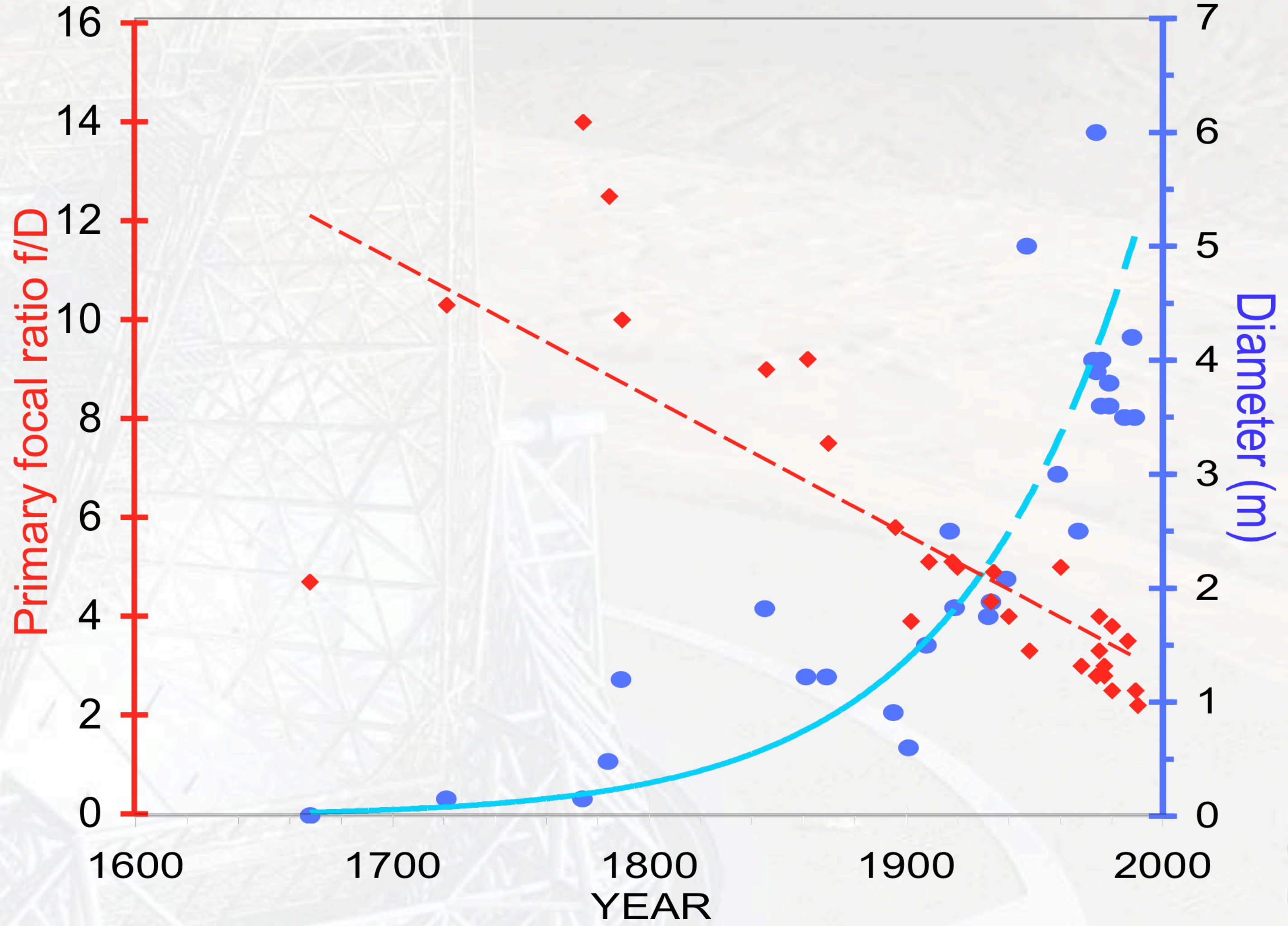
Requires active shape & thermal control



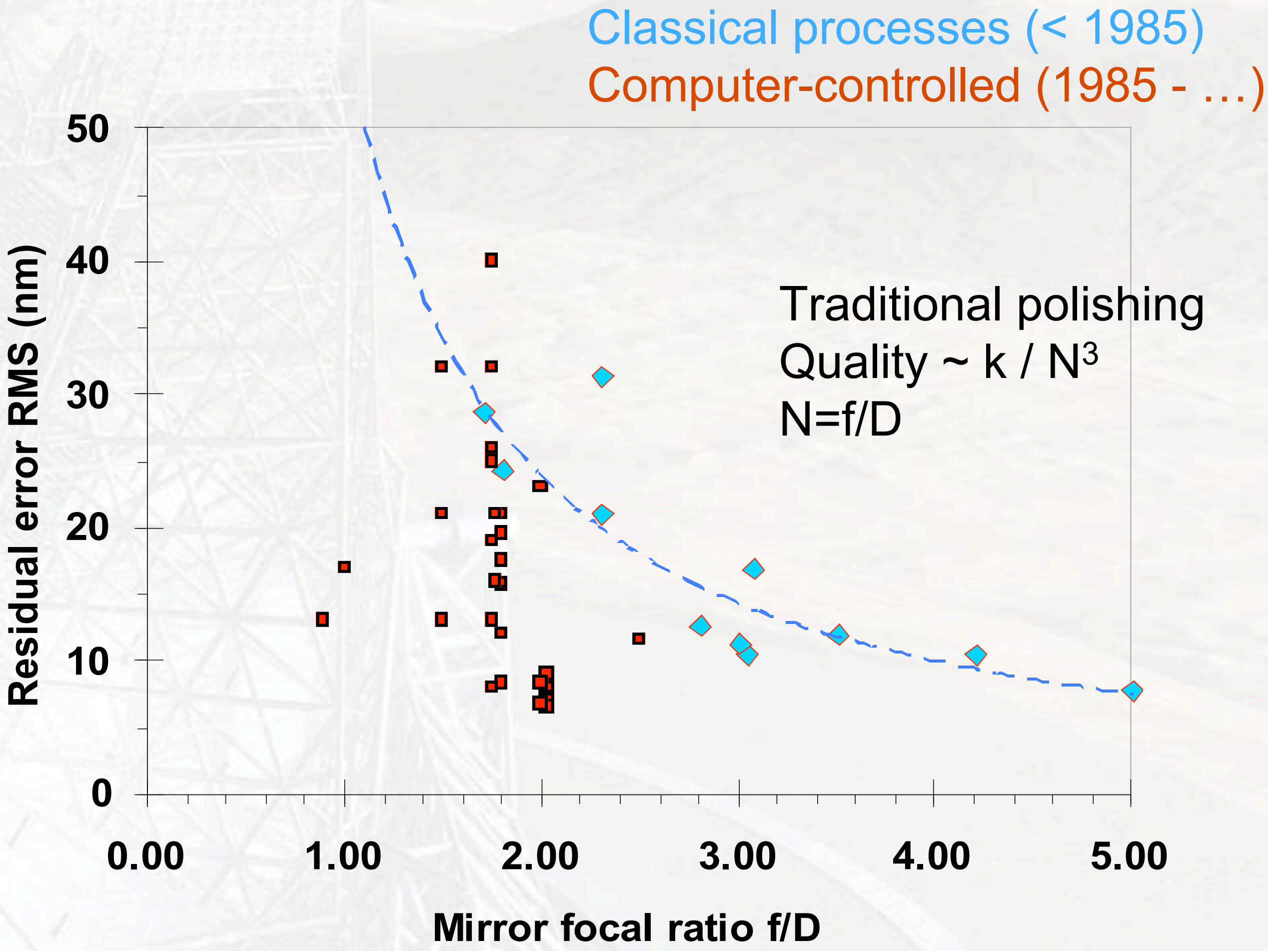
Diameter (m)
9
8
7
6
5
4
3
2
1
1600
1700
1800
1900
Foucault, 1857; 1861
Herschel, 1784, 1789
Newton, 1668
Lord Rosse, 1845
Nasmyth, 1845
Galileo, 1609
Hadley, 1721
Lassel, 1861
Fraunhofer, 1824


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

Larger and shorter

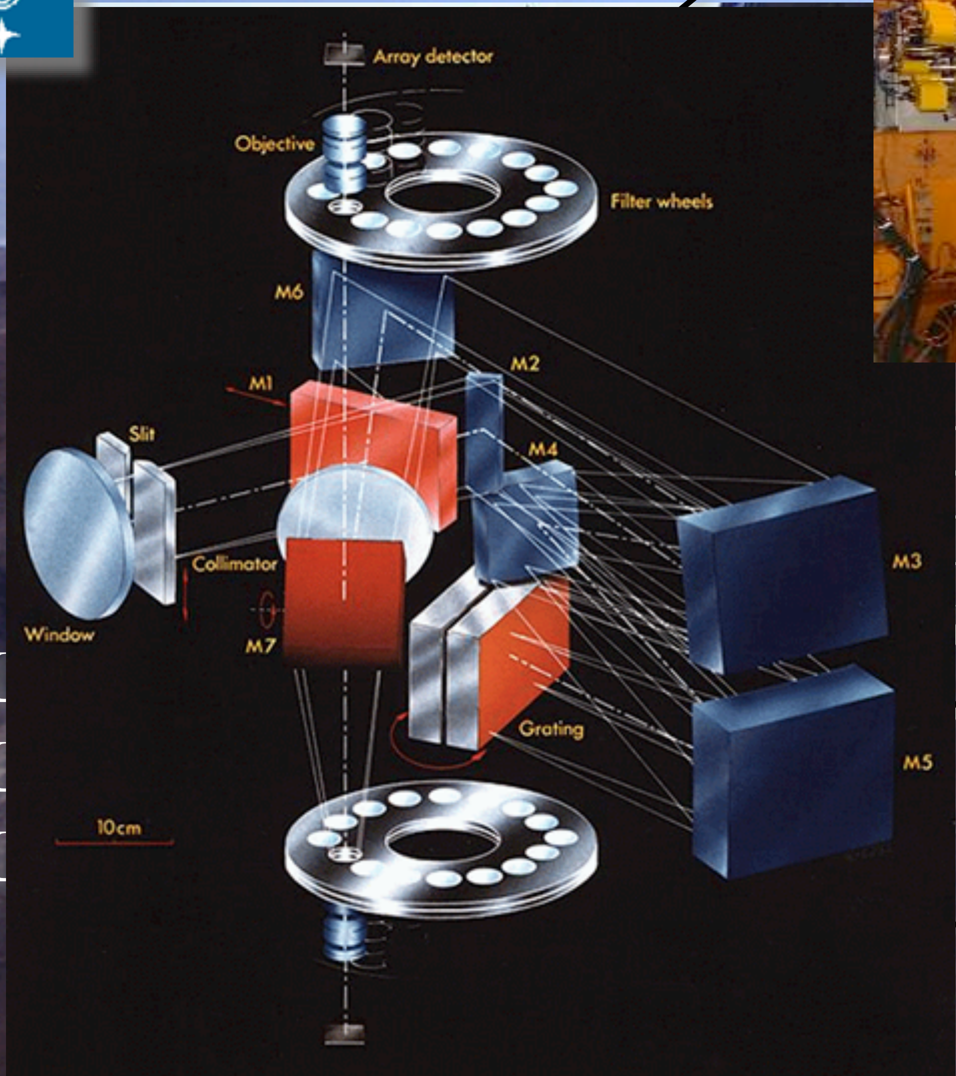


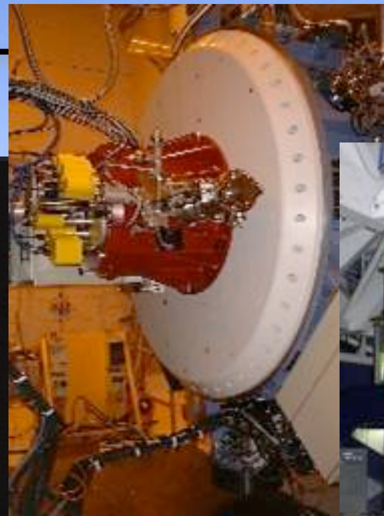
Shorter is more difficult

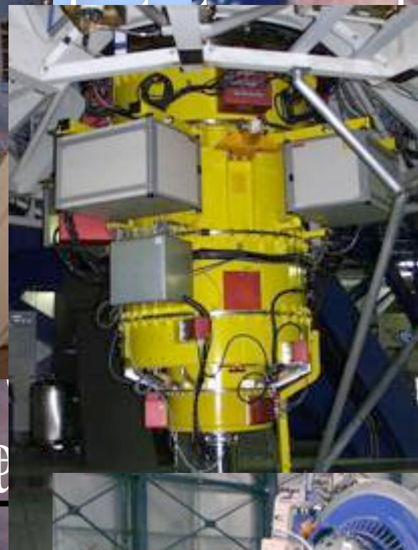


TODAY: IF YOU CAN MEASURE IT, YOU CAN DO IT
(BUT YOU MAY HAVE TO PAY A LOT …)

Paranal, a modern observatory







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Daytime c
Wind pern
Minimal h
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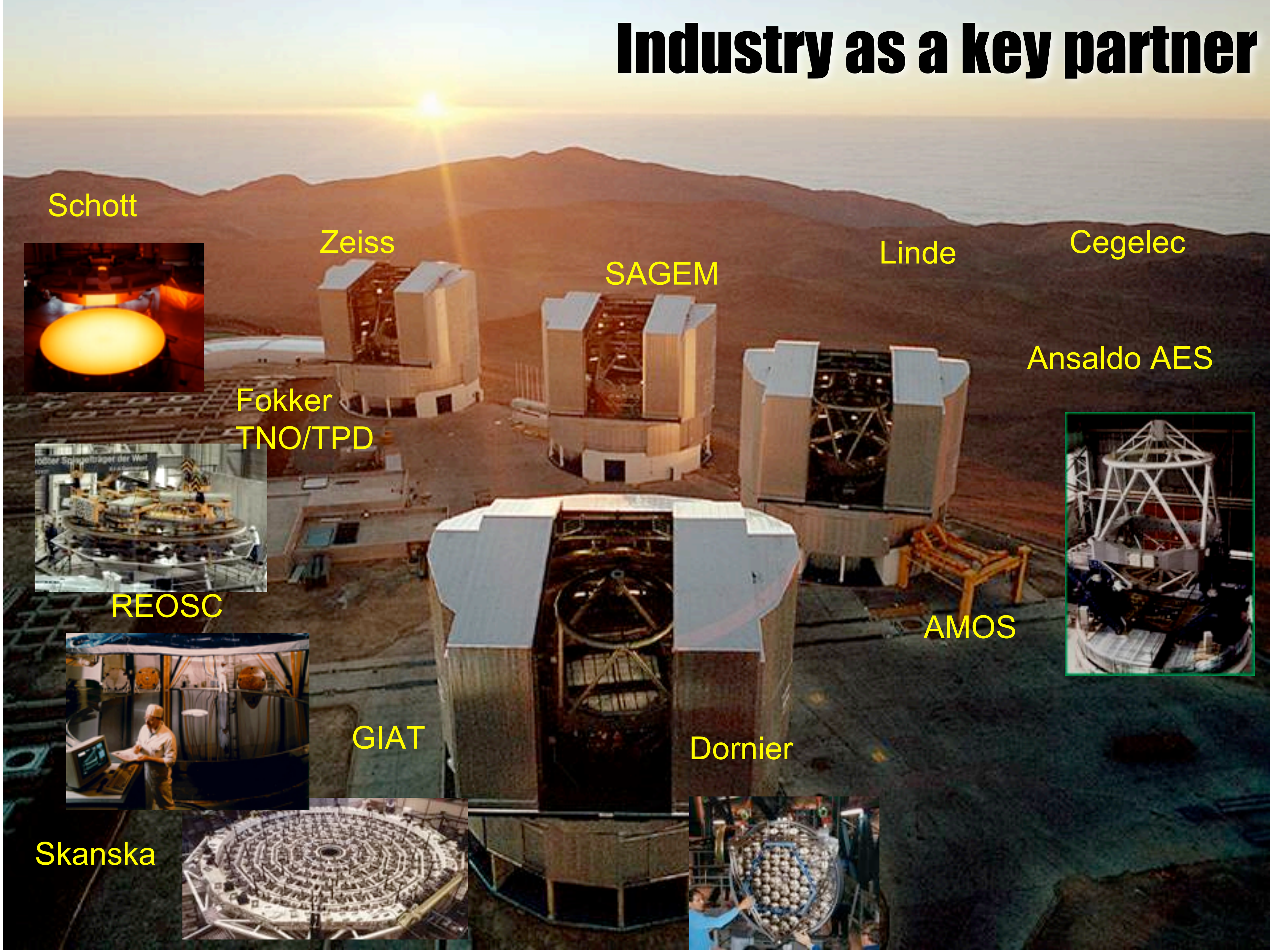
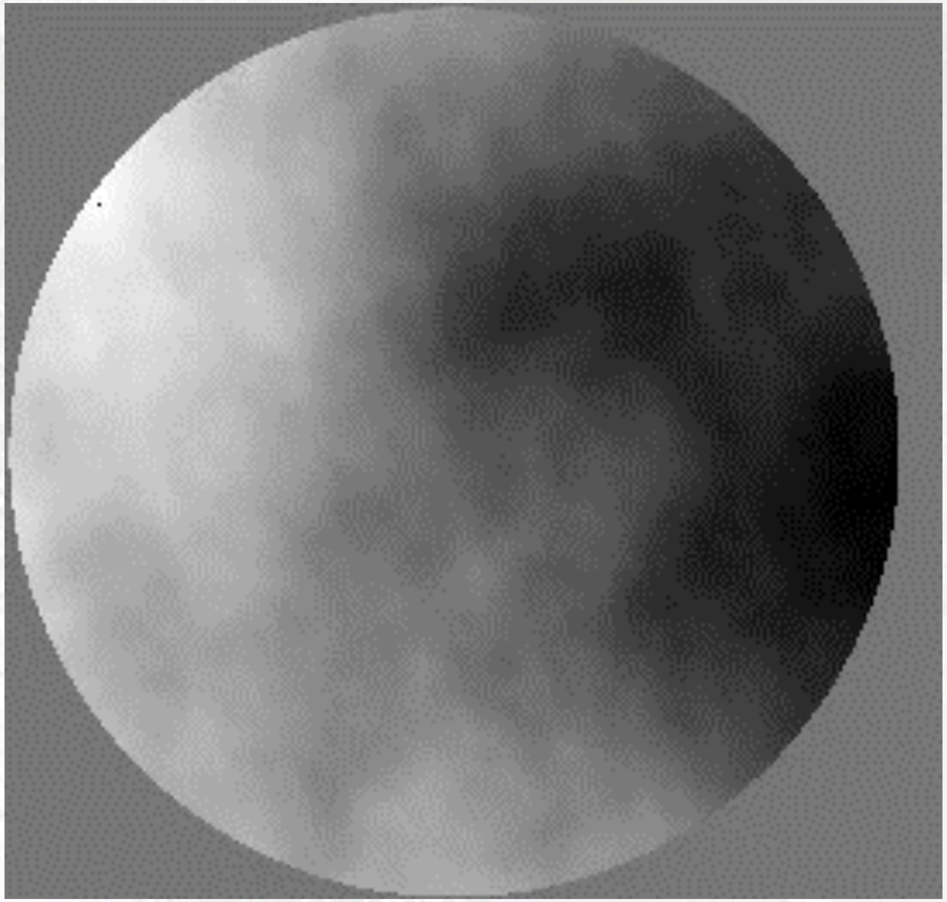
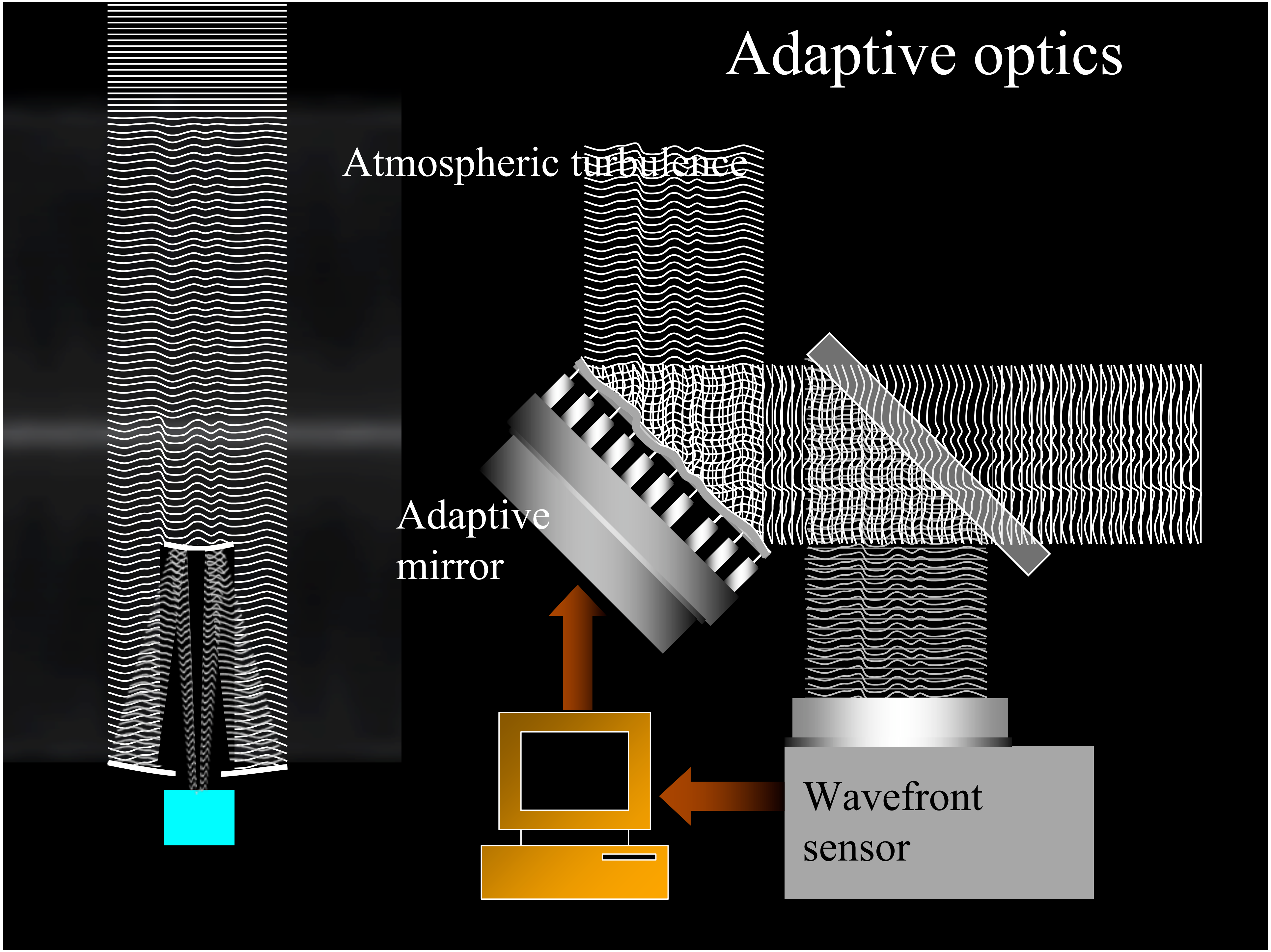
- I
- I

Active, deformable primary mirror


Industry as a key partner
Schott
Zeiss
SAGEM
Linde
Cegelec
Ansaldo AES
Fokker
TNO/TPD
REOSC
AMOS
GIAT
Dornier
Skanska

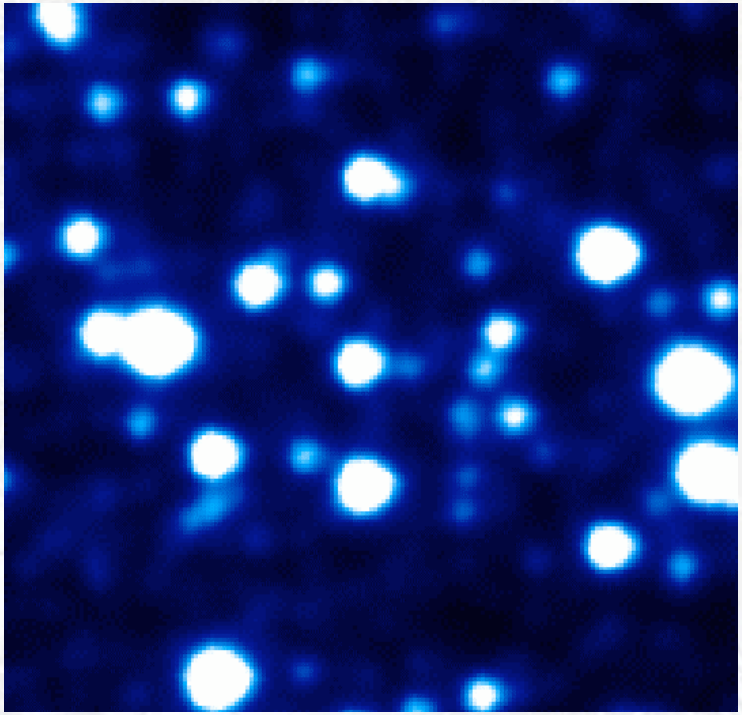


Atmospheric turbulence

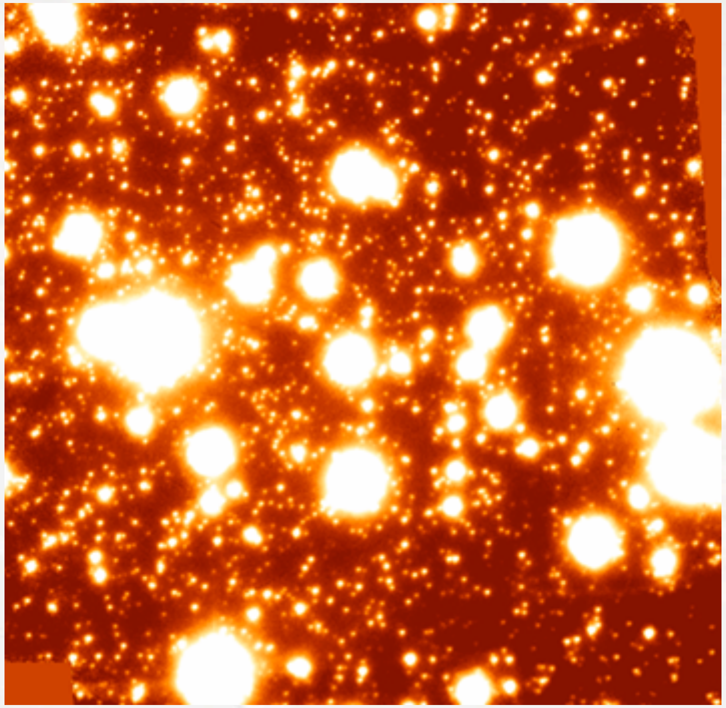

Adaptive optics
Atmospheric turbulence
Adaptive mirror
Wavefront sensor

Increase in resolution and sensitivity

Seeing-limited
(0.85 arc seconds)



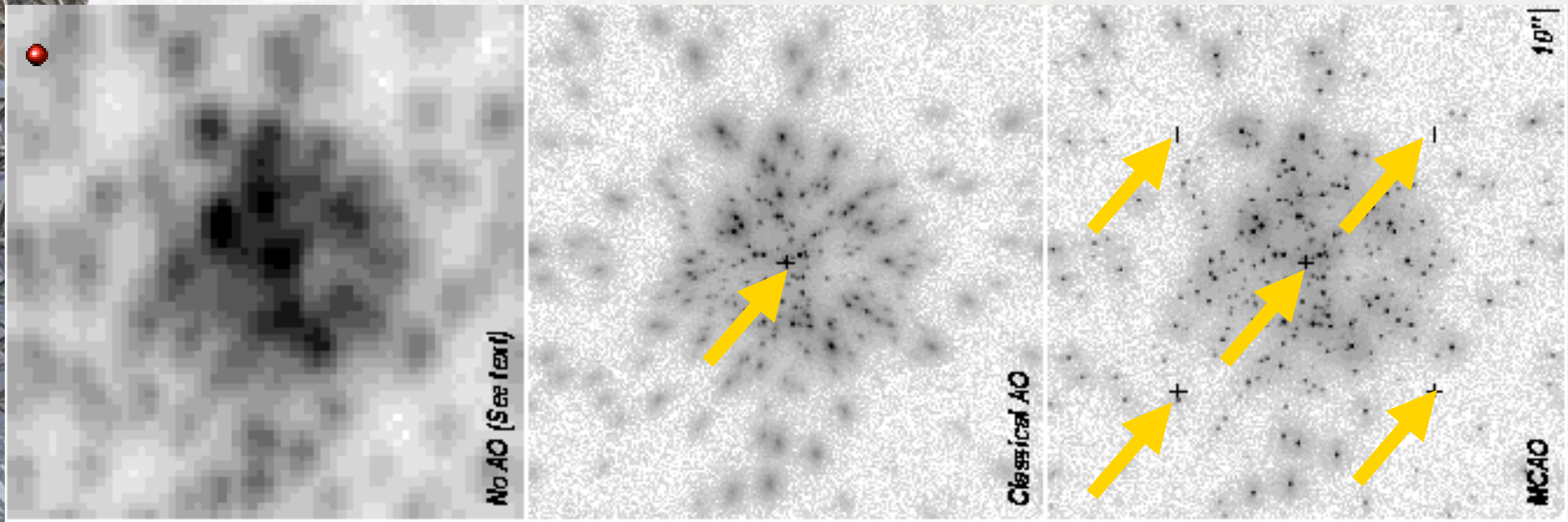
Hokupa'a+Quirc
0.092 arc seconds



Images: Gemini Observatory, Mauna Kea

Field limitations

Uncorrected | Single conjugate AO | Multi-conjugate AO



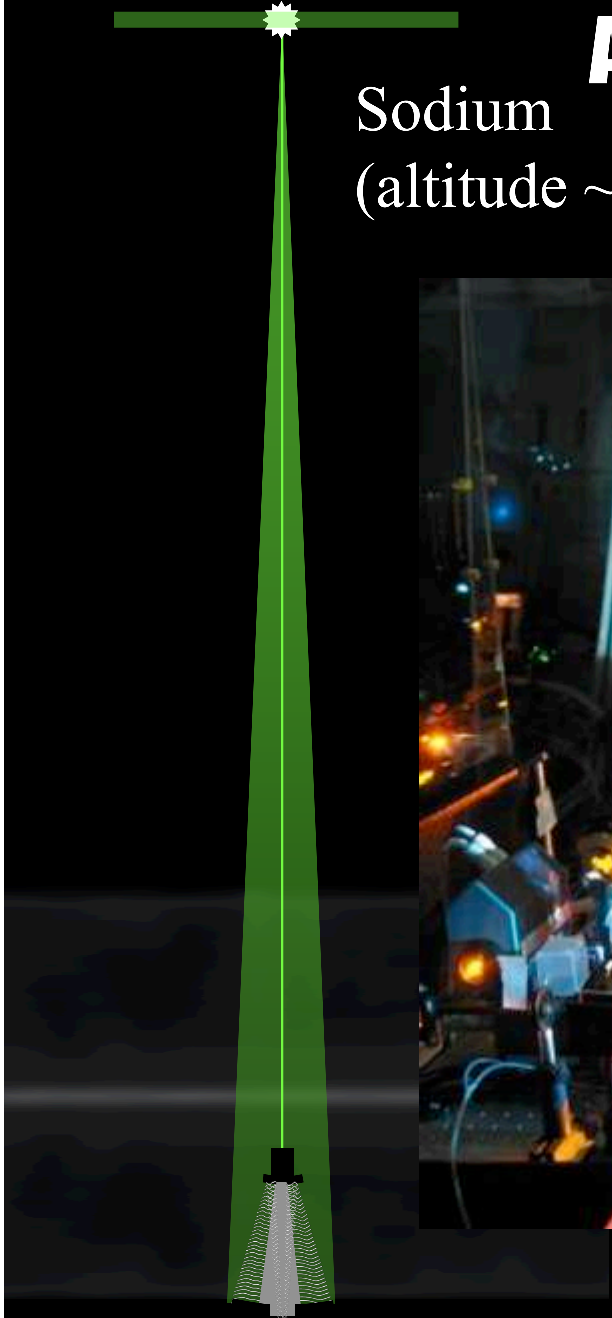
1 adaptive mirror
1 guide star

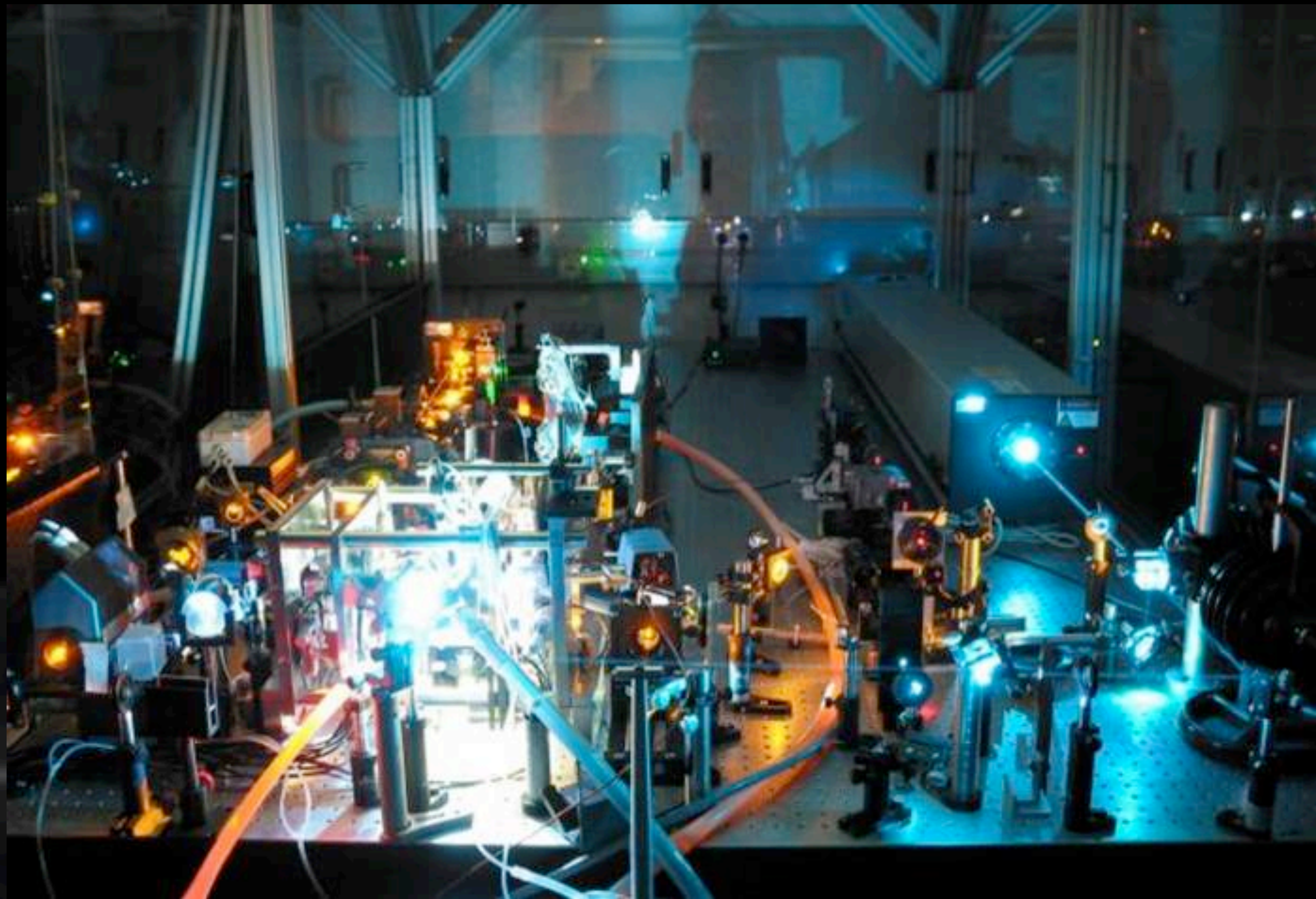
2 adaptive mirrors
5 guide stars

F. Rigaut, Gemini, 1999

Adaptive optics – Laser Guide Stars

Sodium
(altitude ~90 km)

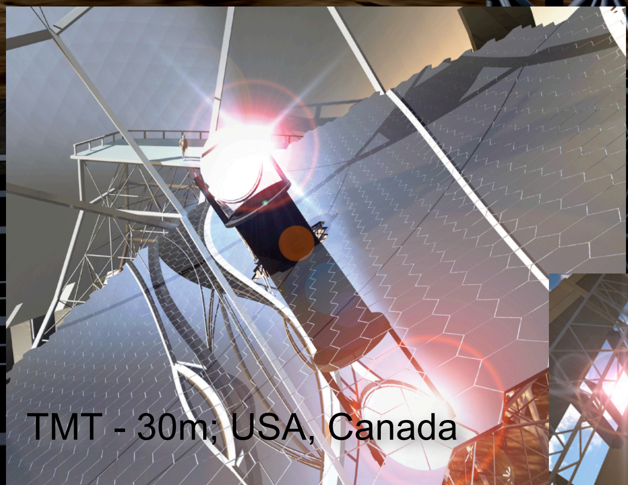




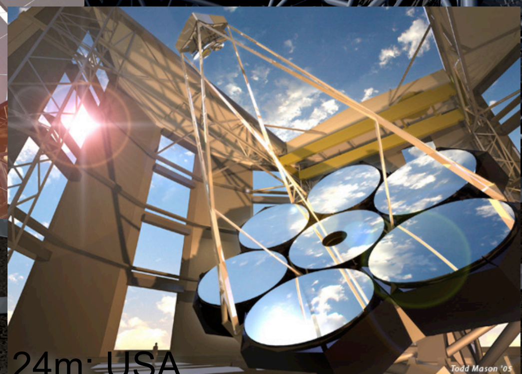
Towards the future

- Detectors have reached ~100% efficiency
  Maintaining science progress requires larger telescopes

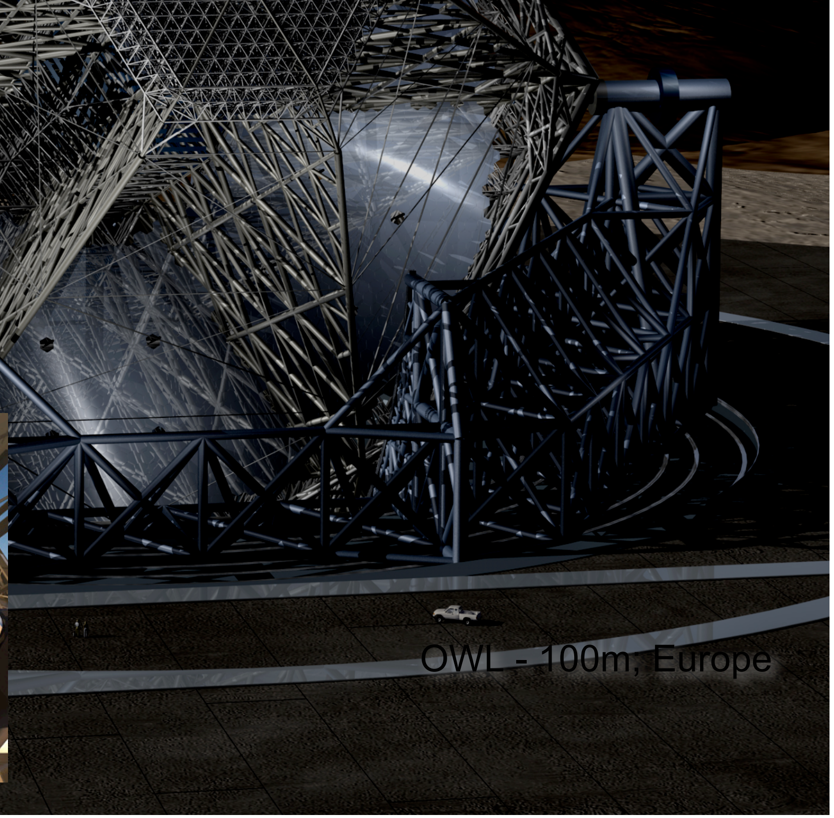
- Active optics - control of optical alignment and shape in real time
- Segmentation - optical fabrication scalable
- Adaptive optics - cancellation of atmospheric turbulence
  A giant telescope can be made and would be efficient (no light bucket)



TMT - 30m; USA, Canada



GMT - 24m; USA



OWL - 100m; Europe

Extremely Large Telescopes

- A brief history …
  - 1977: Meinel et al, 25-m feasible (but not very useful …)
  - 1989 … 25-m … 50-m concept proposed by Lund university
  - 1996: Mountain et al; HDF spectroscopy ⇨ 50-m MAXAT
  - 1997, Gilmozzi et al: is a 100-m telescope possible ? ⇨ OWL
  - 2000: ELT, GSMT, CELT, EURO-50, etc.; OWL phase A funded

- NO LIGHT BUCKETS ! Adaptive optics essential !!!

Geometrical étendue, pixel matching

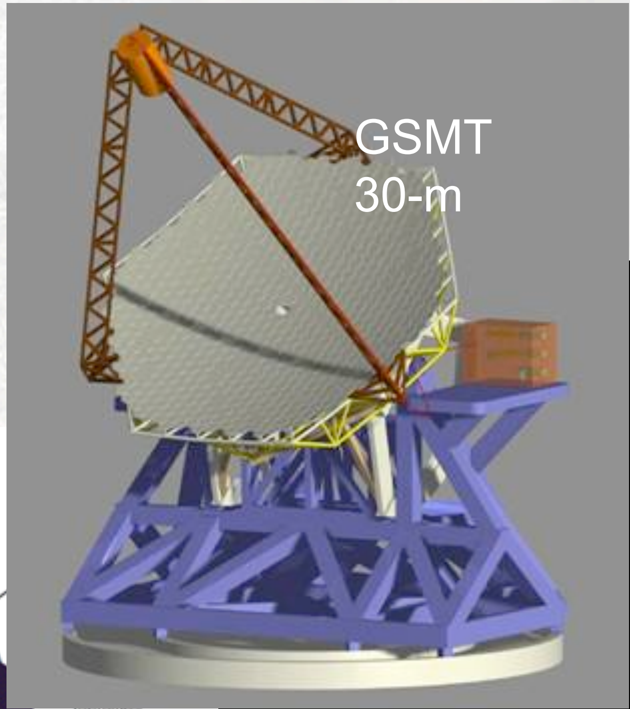
- Linear dimensions in focal plane

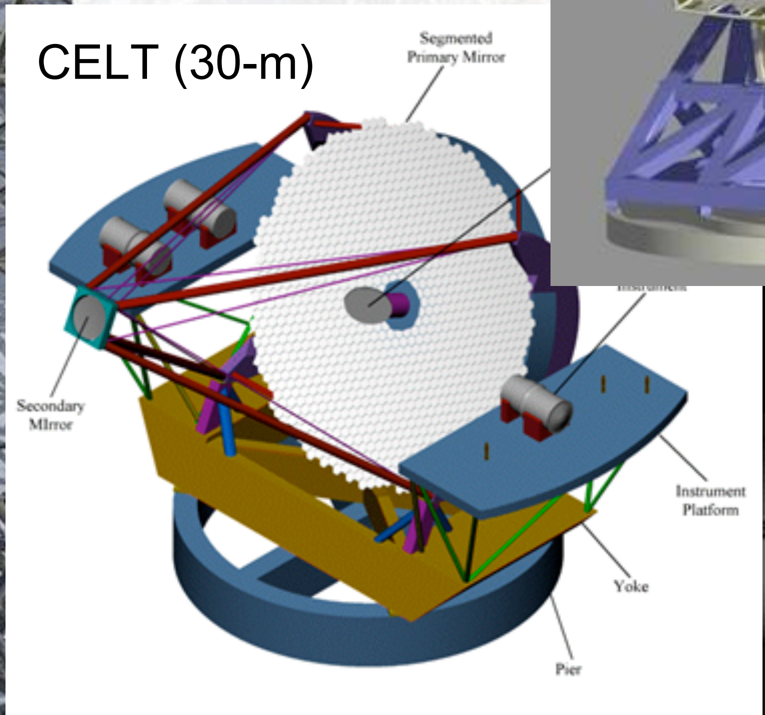
  y = f . θ

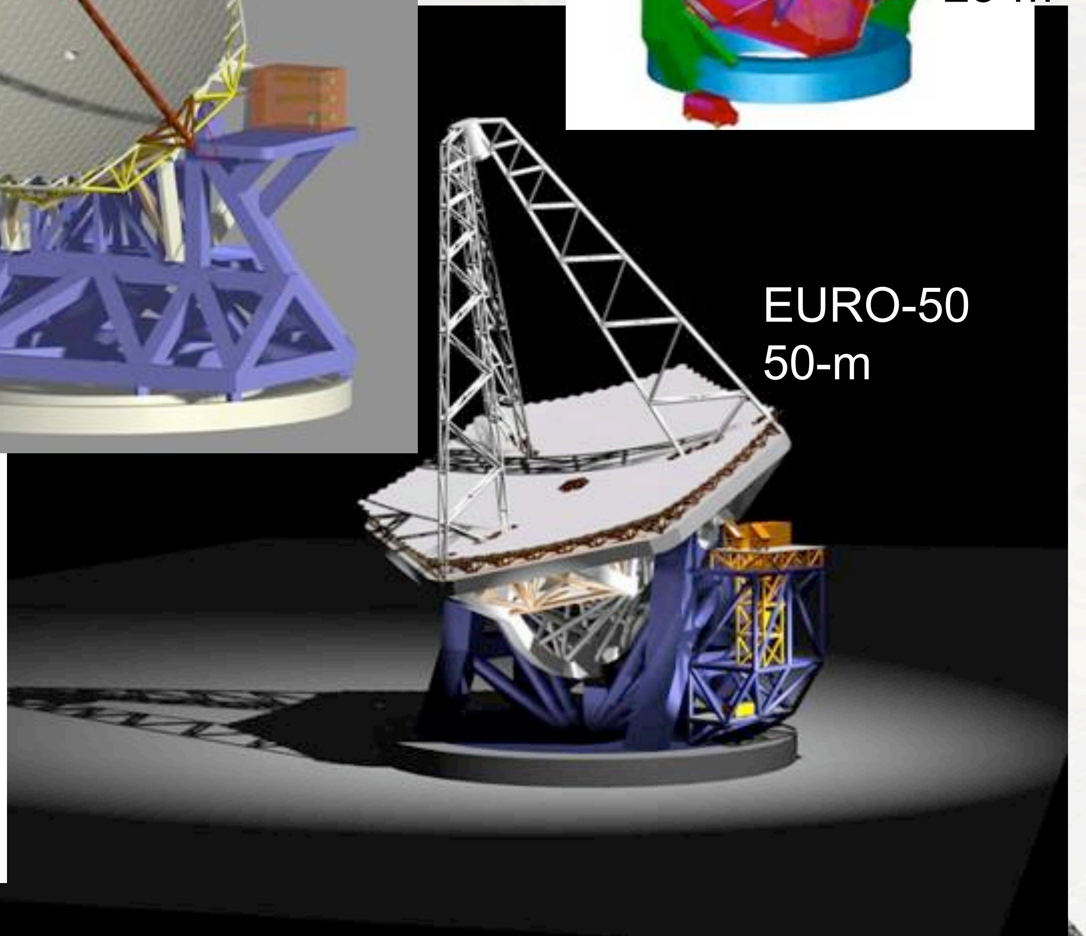
- If seeing-limited
  - Typically : 1 pixel ~ 0.2 arc seconds
  - 1 pixel ~ 20 microns ⇨ f ~ 20m
  - f/D ~ 0.5 on detector for a 40-m class telescope
  - Instrumentation extremely difficult
- If diffraction-limited
  - 1 pixel ~ λ/2D
  - f/D ~ 40 / λ (λ in microns)
  - BUT: long focal length ⇨ large linear field

    Example: 10 arc minutes, 42m, f/15 ⇨ field 1833 mm

Extremely Large Telescopes

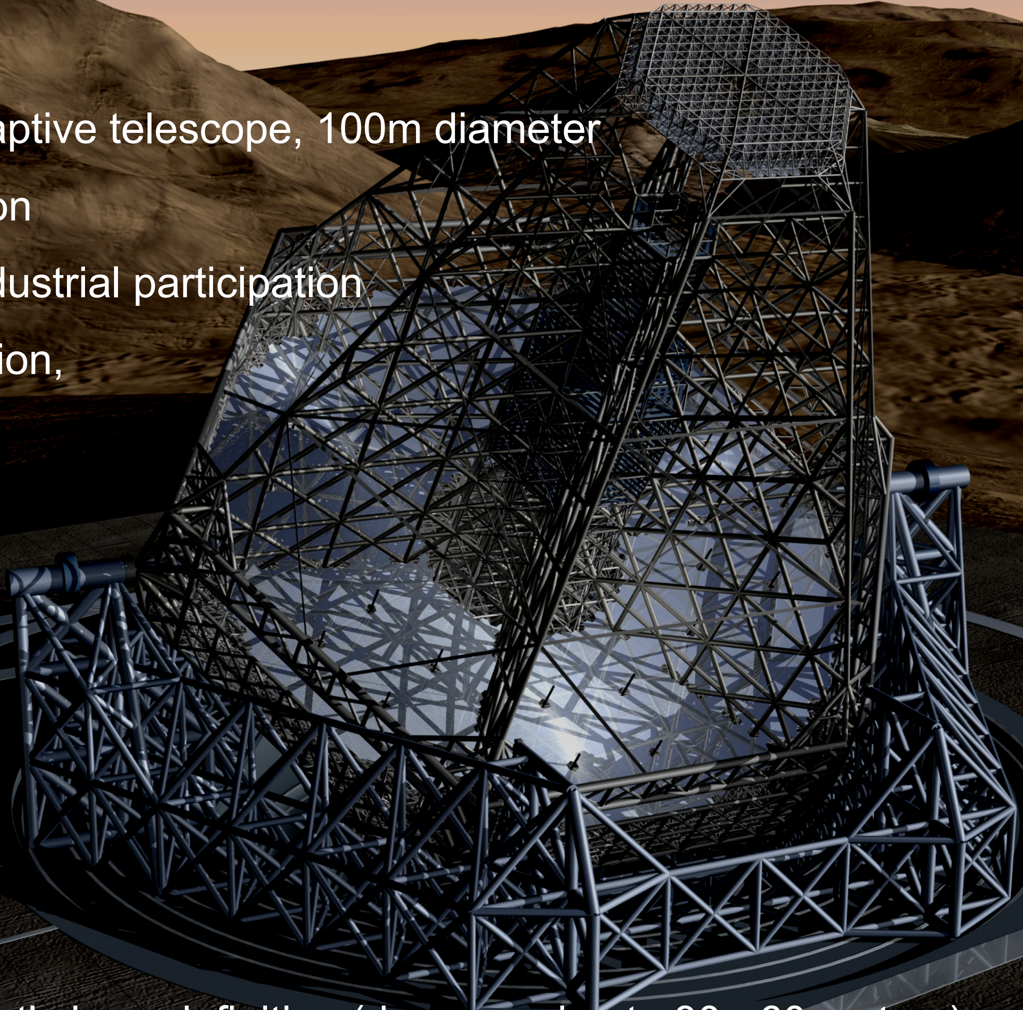






OverWhelmingly Large telescope (OWL)

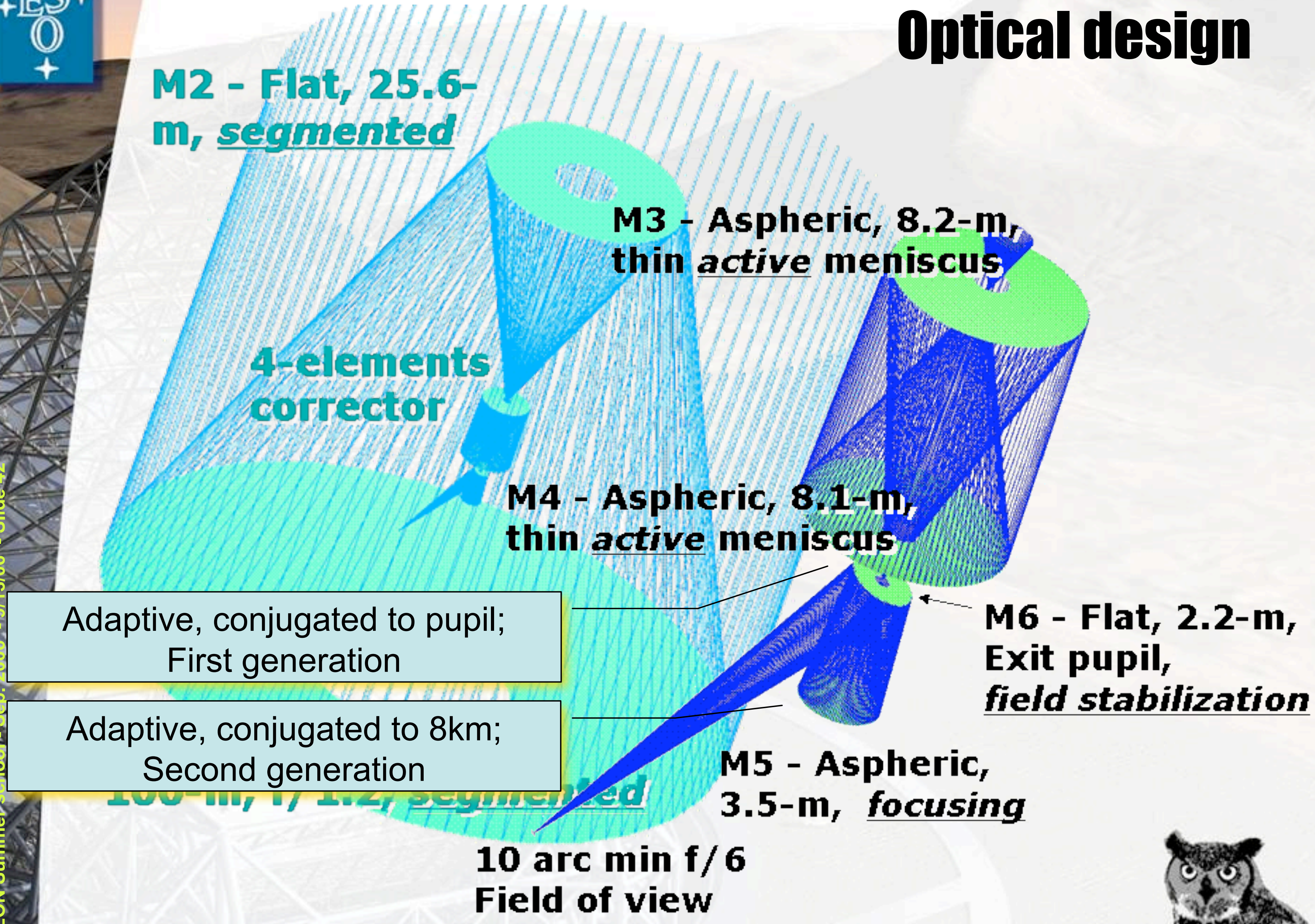
- An optical & infrared, active / adaptive telescope, 100m diameter
- Down 1 milli-arc second resolution
- 5 years concept study, strong industrial participation
- Concept based on serial production,
  proven subsystem technology
  wherever possible,
  low industrial risk
- First light 2015, completion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

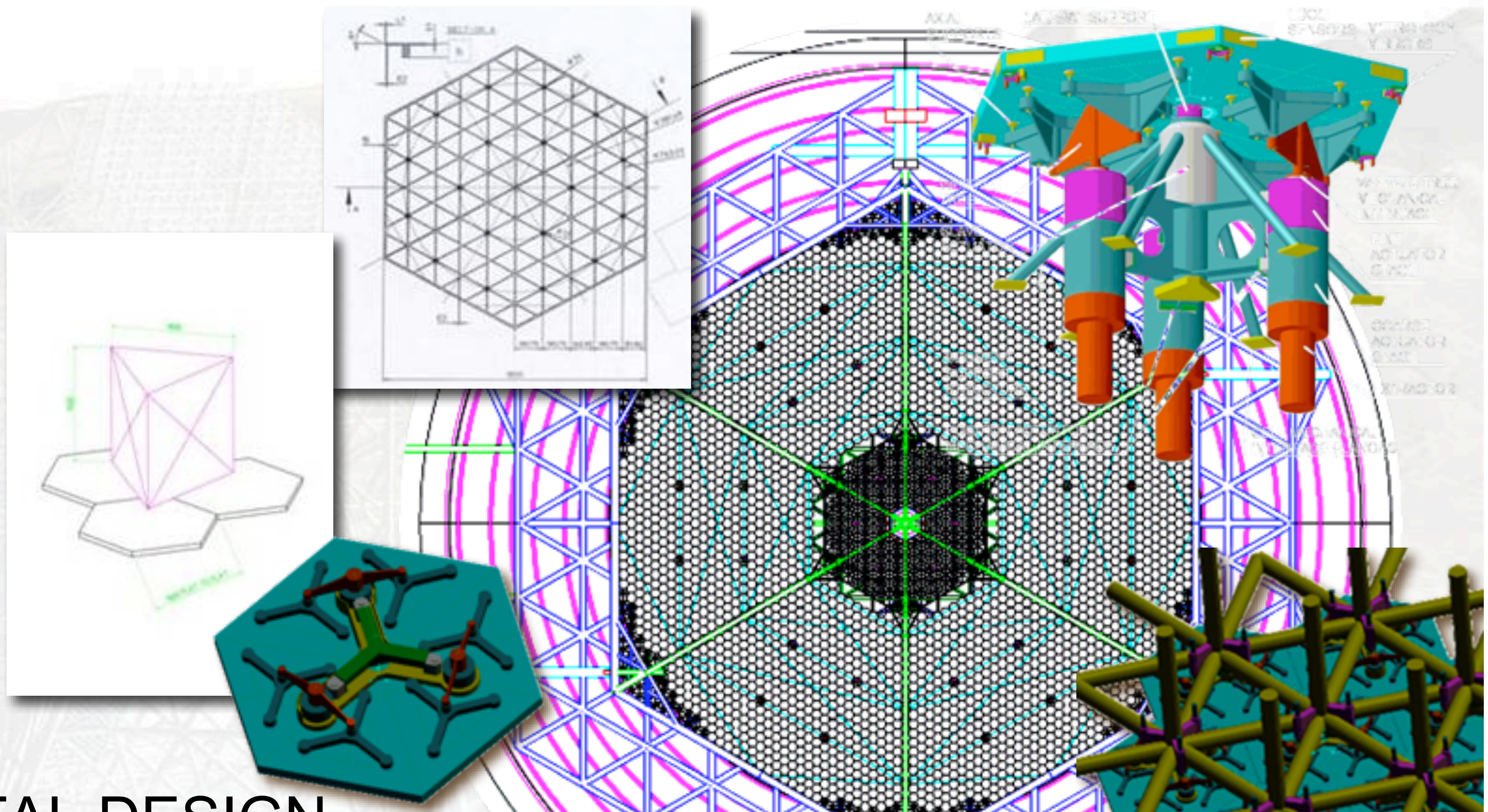


Phase A completed, currently in re-definition (downscoping to 30 - 60 meters).

A lost opportunity for Framework Programme 7 … Originally Was Larger ?

Optical design

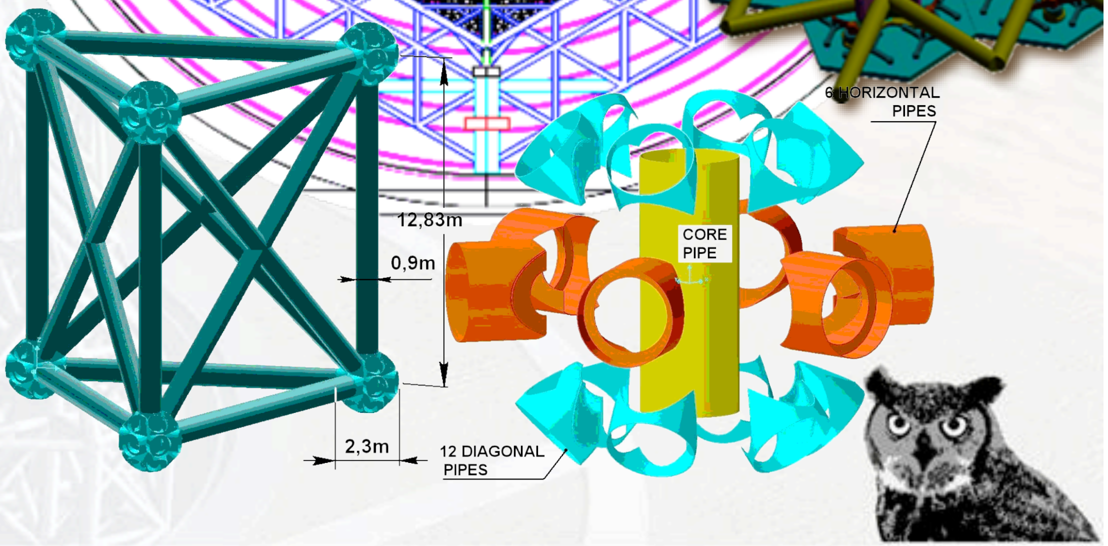




FRACTAL DESIGN

All dimensions as multiple of segment size

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



Cost estimate (capital investment)

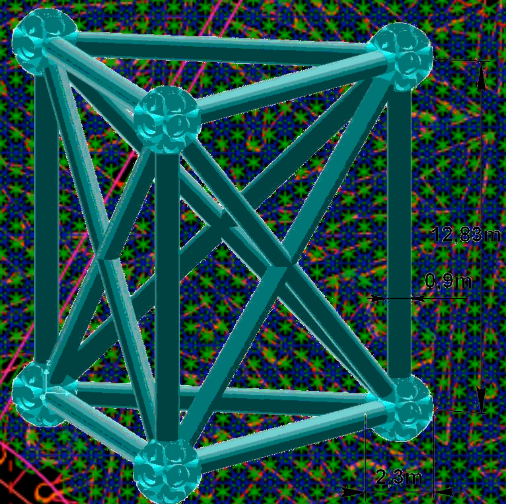
SUMMARY	MEuros	
OPTICS	**406**	
Primary & secondary mirror units		355.2
M3 unit		14.4
M4 unit		21.4
M5 temporary unit		5.3
M6 temporary unit		10.1
ADAPTIVE OPTICS	**110**	
M5/M6 design & prototypes		10
M6 AO unit		25
M5 AO unit		35
XAO units		20
LGS		20

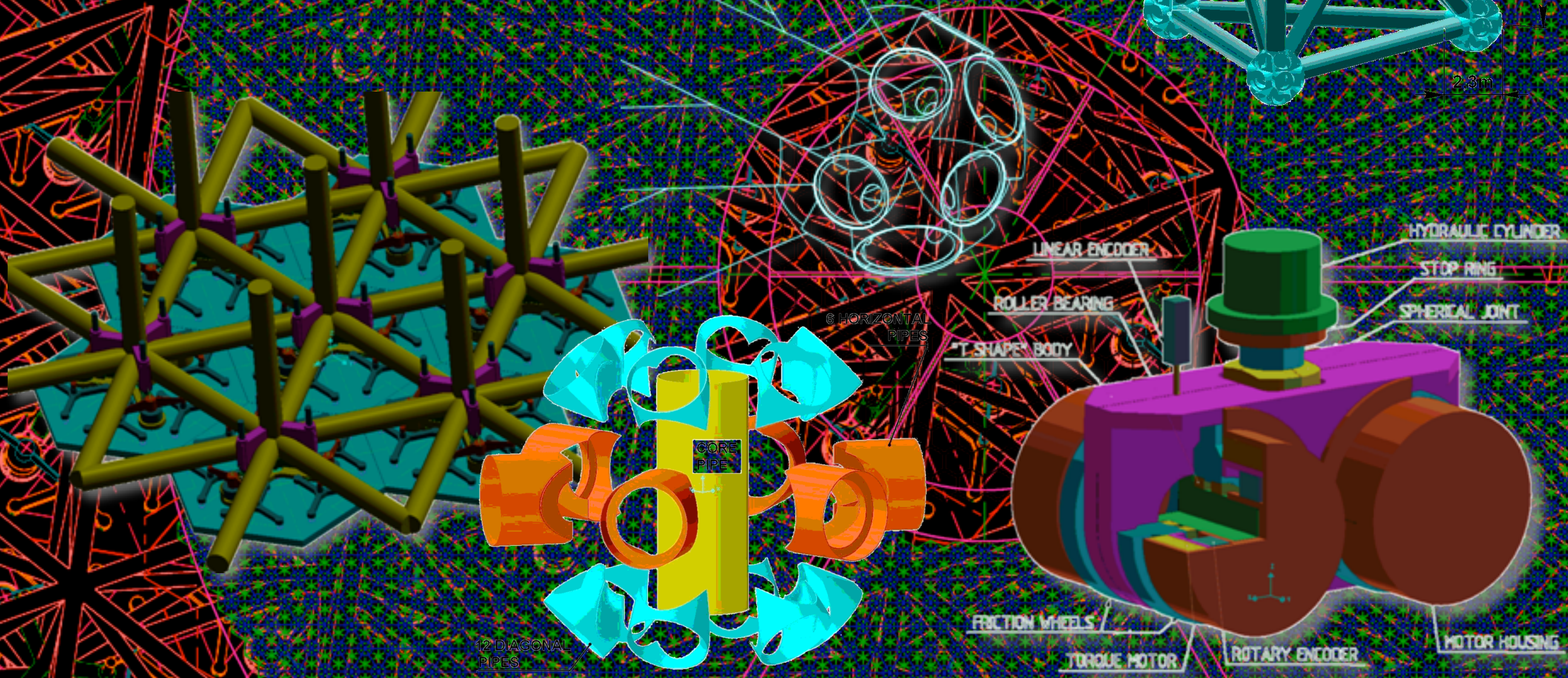
MECHANICS	**185**	
Azimuth		53.8
Elevation		34.9
Cable wraps		5.0
Azimuth bogies (incl. motors)		14.7
Altitude Bogies & bearings		5.7
Mirror shields		15.0
Adapters		6.0
Erection		50.0
CONTROL SYSTEMS (*)	**17**	
Telescope Control System		5.0
M1 Control System		8.0
M2 Control System		2.0
Active optics Control System		2.0
CIVIL WORKS	**170**	
Enclosure		40.4
Technical facilities		35.0
Site infrastructure		25.0
Concrete		70.0
INSTRUMENTATION	**50**	
INSTRUMENTATION		50
Total without contingency	**939**	*938.9*
(*) High level cs only; local cs included in subsystems		

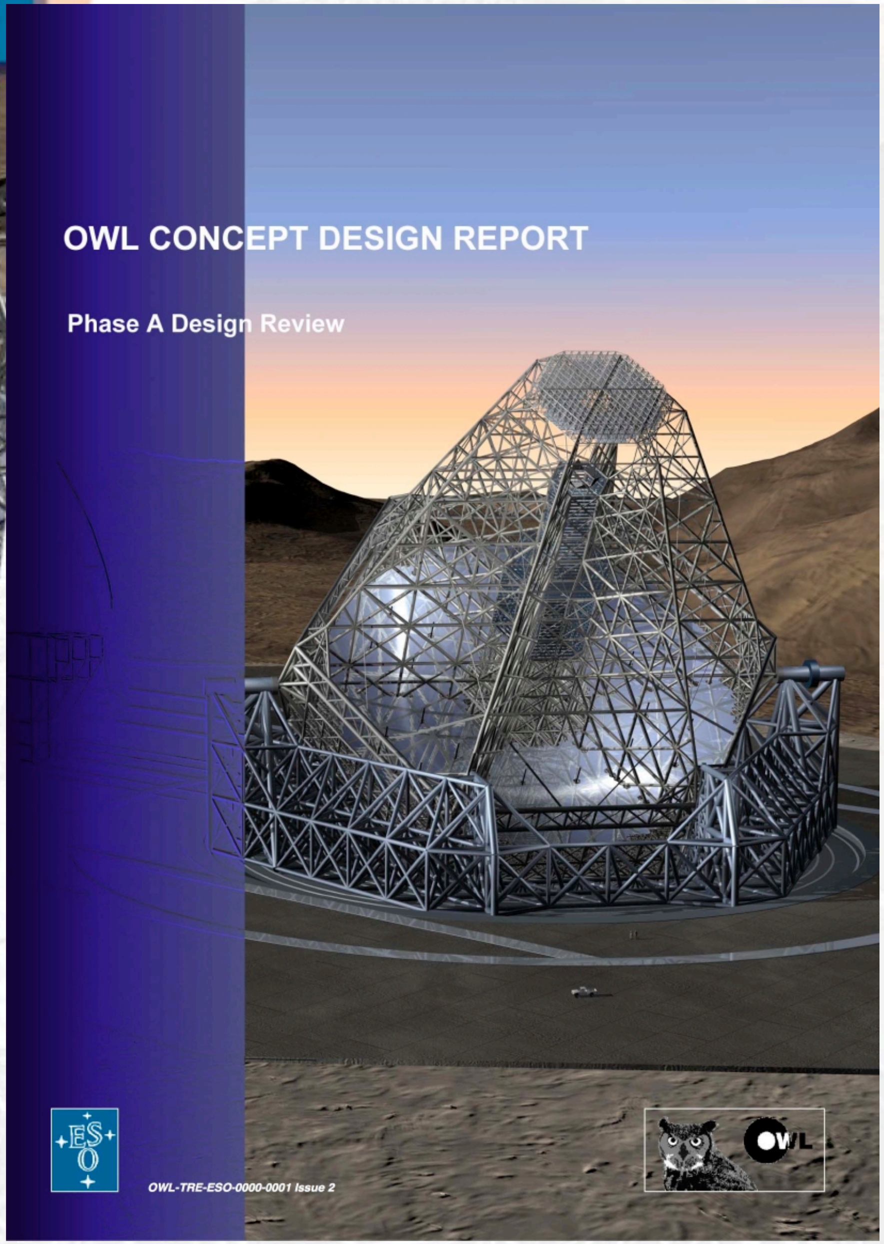
Assumes "friendly site"

- Seismically quiet
- Moderate altitude
- Average wind speed
- Moderate investment in infrastructures

- Optimized geometry (interface optics-mechanics)
- All parts fitting in 40-ft containers
- 1.6-m all-identical segments (~3000 units), single optical reference for polishing
- 12.8-m standard structural modules (integer multiple of segment size)
- Friction drive (bogies), hydraulic connection







More in …

OWL Blue Book

730 pages, 20 MB

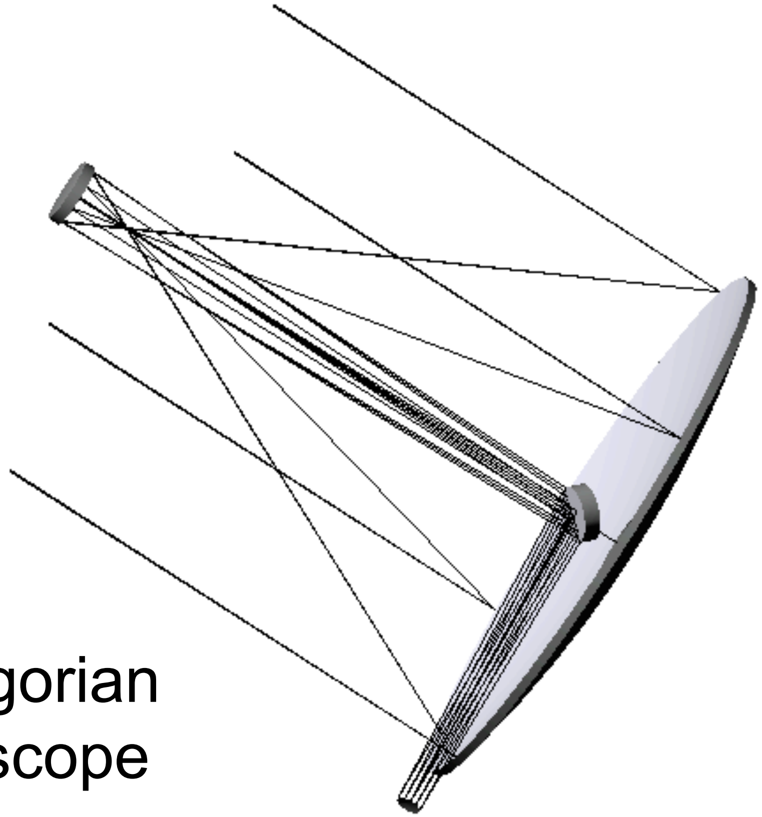
Public version does not include detailed cost estimates.

www.eso.org/projects/owl

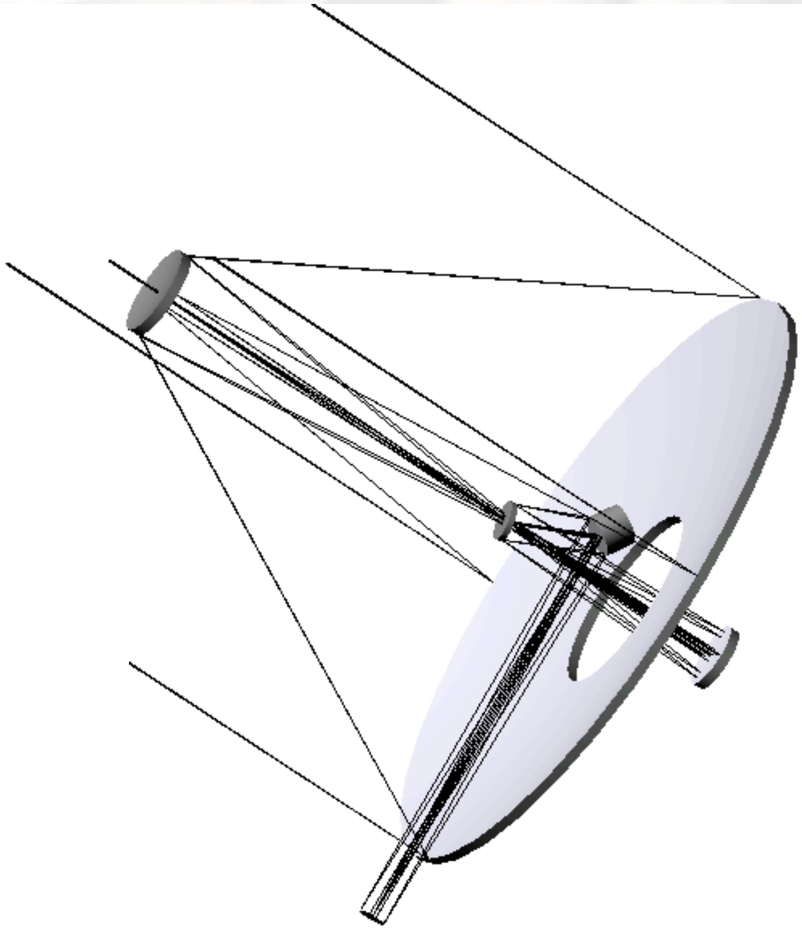
What now ?

- ESO Council resolution - 30 to 60m ELT is highest priority
- First half 2006 :
  - Extensive consultation with scientific community
    Working groups: science, site, instrumentation, AO, telescope design
  - Capture requirements
  - Identify plausible solutions
  - Narrow down to 2 “families” of designs
- Second half 2006
  - Define 2 Basic Reference Designs (Gregorian, 5-mirror)
  - Design & construction plans
  - Cost / schedule estimates

  … in progress
- 2007-2009 design phase
- 2010-2015 construction phase

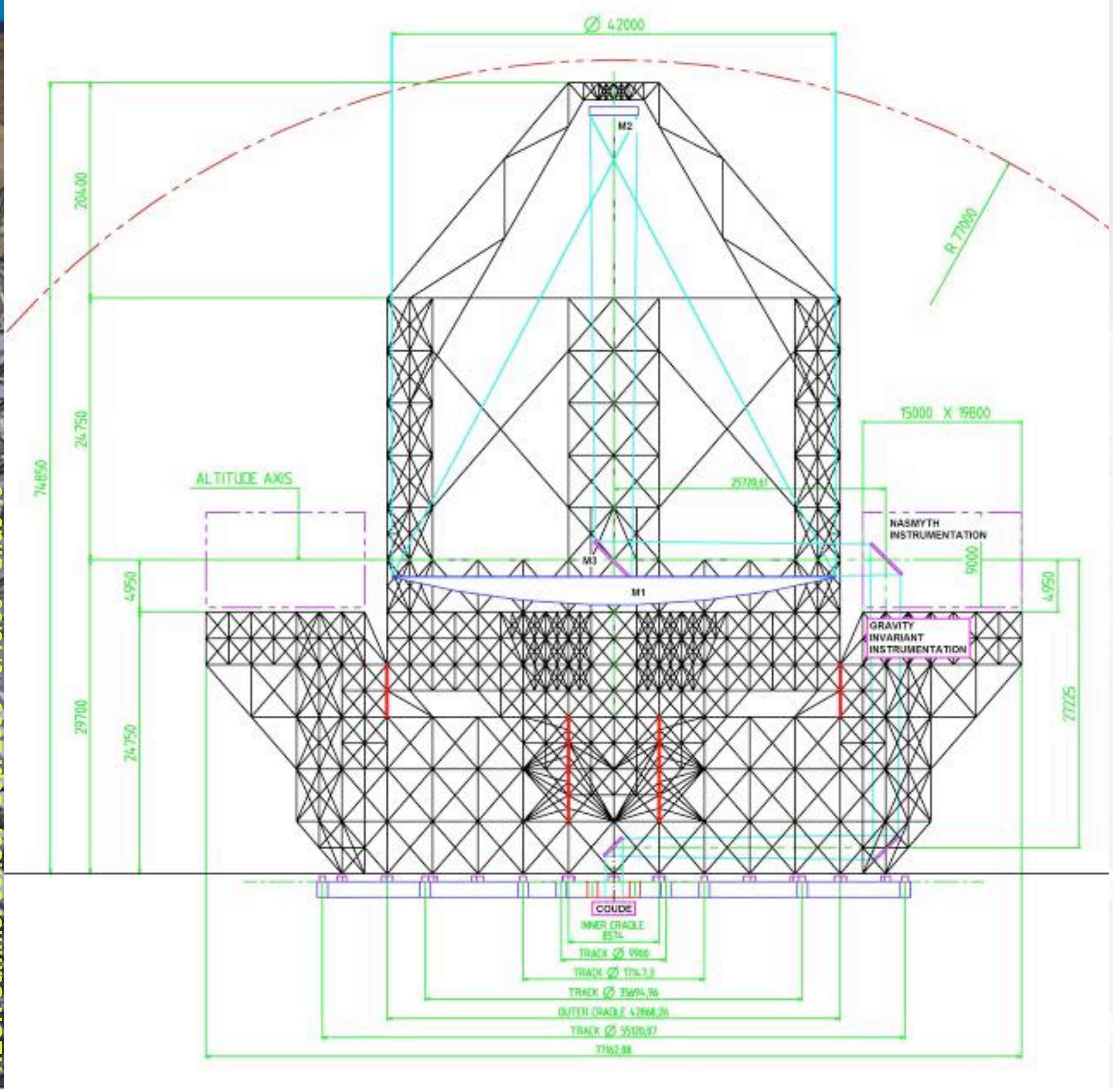


Gregorian telescope



5 Mirror telescope

3 MIRRORS DESIGN - GREGORIAN



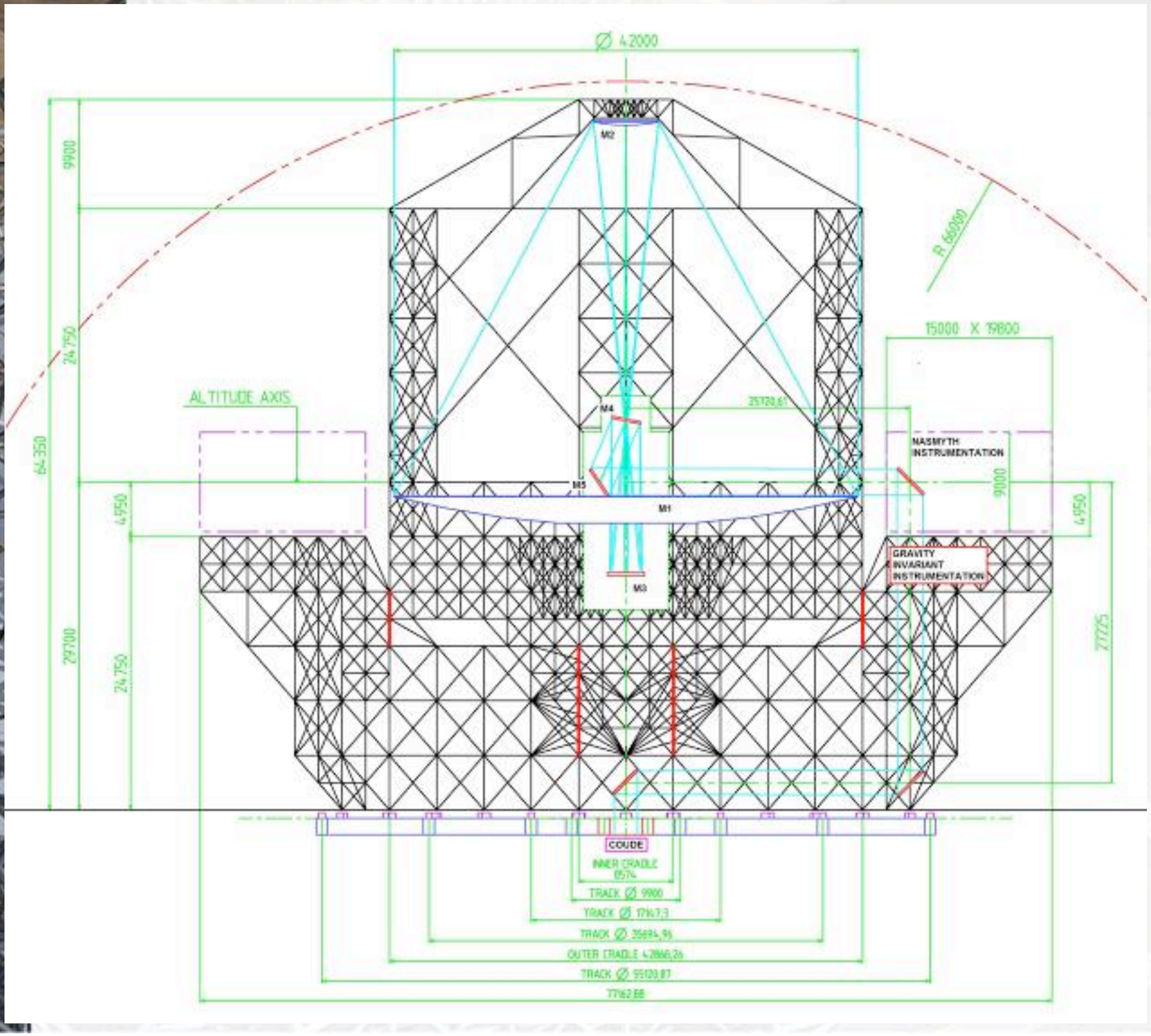
Azimuth structure

- 4 Tracks 370 m
- Direct Drive 92 m (R 27,5m)
- 42 Axial bearings
- 1 Central radial bearing
- Mass 2500 tons

Altitude structure

- 4 Cradles 227 m
- Direct Drive 62 m (R 22,5m)
- 44 Radial bearings
- 44 Axial bearings
- Mass 2800 tons
- M1 Mass 243 tons

5 MIRRORS DESIGN (& Ritchey Chretien)



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- Direct Drive 62 m (R 22,5m)
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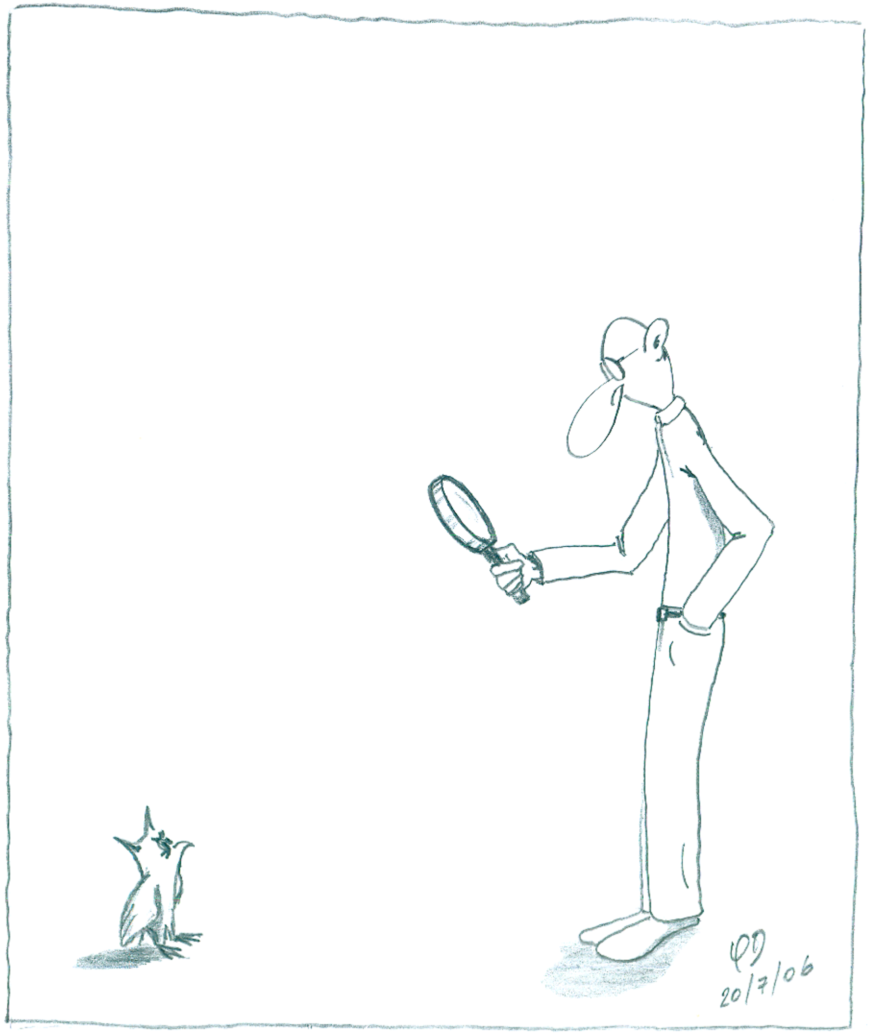
- 44 Axial bearings
- Mass 2800 tons
- M1 mass 224 tons

OWL vs EELT

- EELT
  - instrumentation-friendly
  - LGS-friendly (5-mirror design)
  - AO mirror simpler (not smaller, but does not have to do the tip-tilt)
- EELT less cost-effective
  - Aspherical M1 (daydreaming is over)
  - Nasmyth and Coudé foci expensive
  - Reduced freedom for the positioning of the altitude axis
    - ⇨ Increase of total mass
    - ⇨ Reduction of stiffness
  - Mass-production effect significantly reduced

NOT the Return of the OWL !!!



The return of the OWL