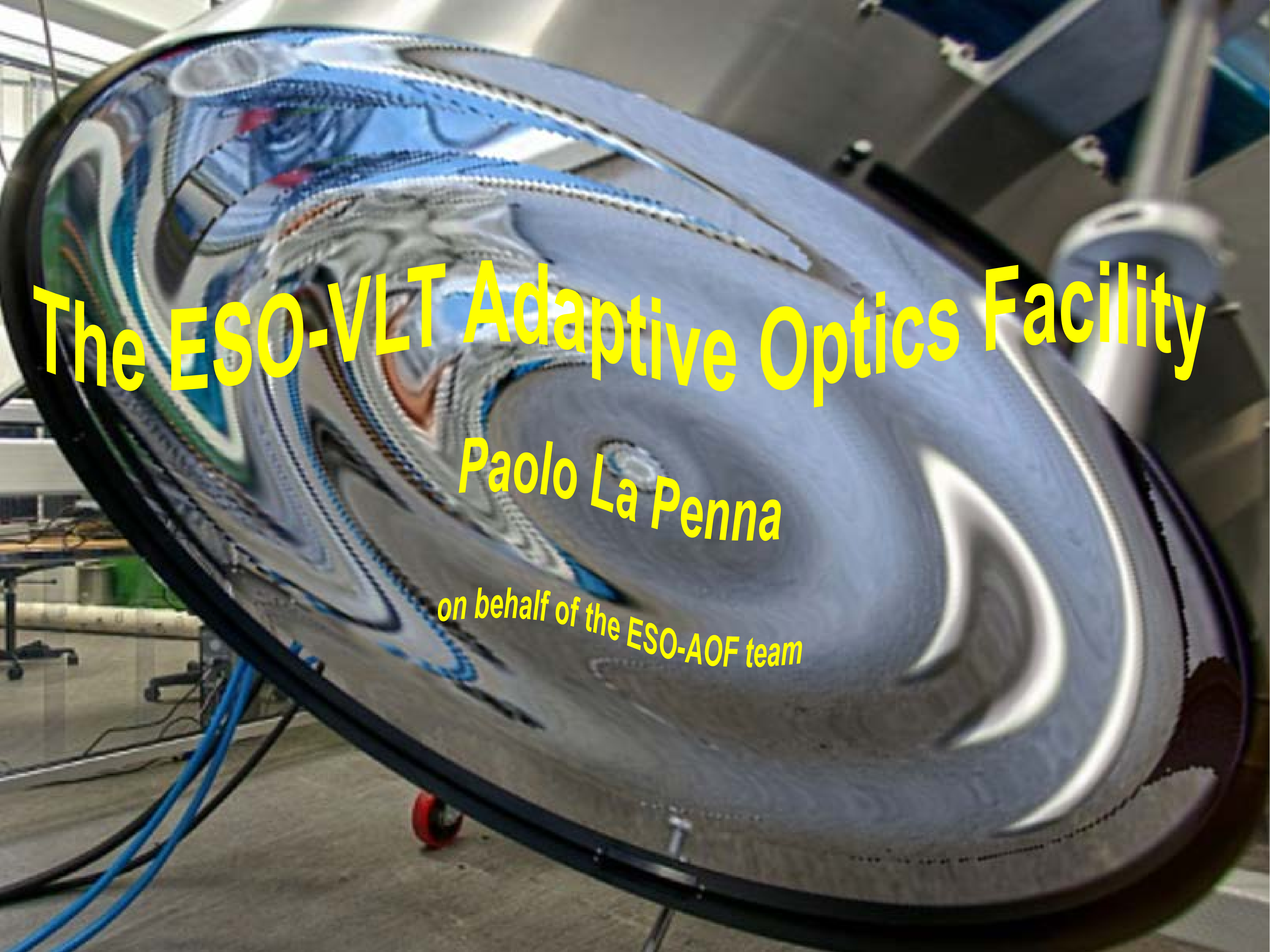


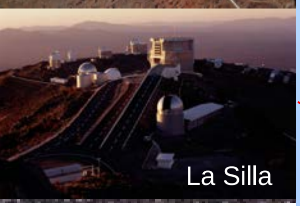
The ESO-VLT Adaptive Optics Facility

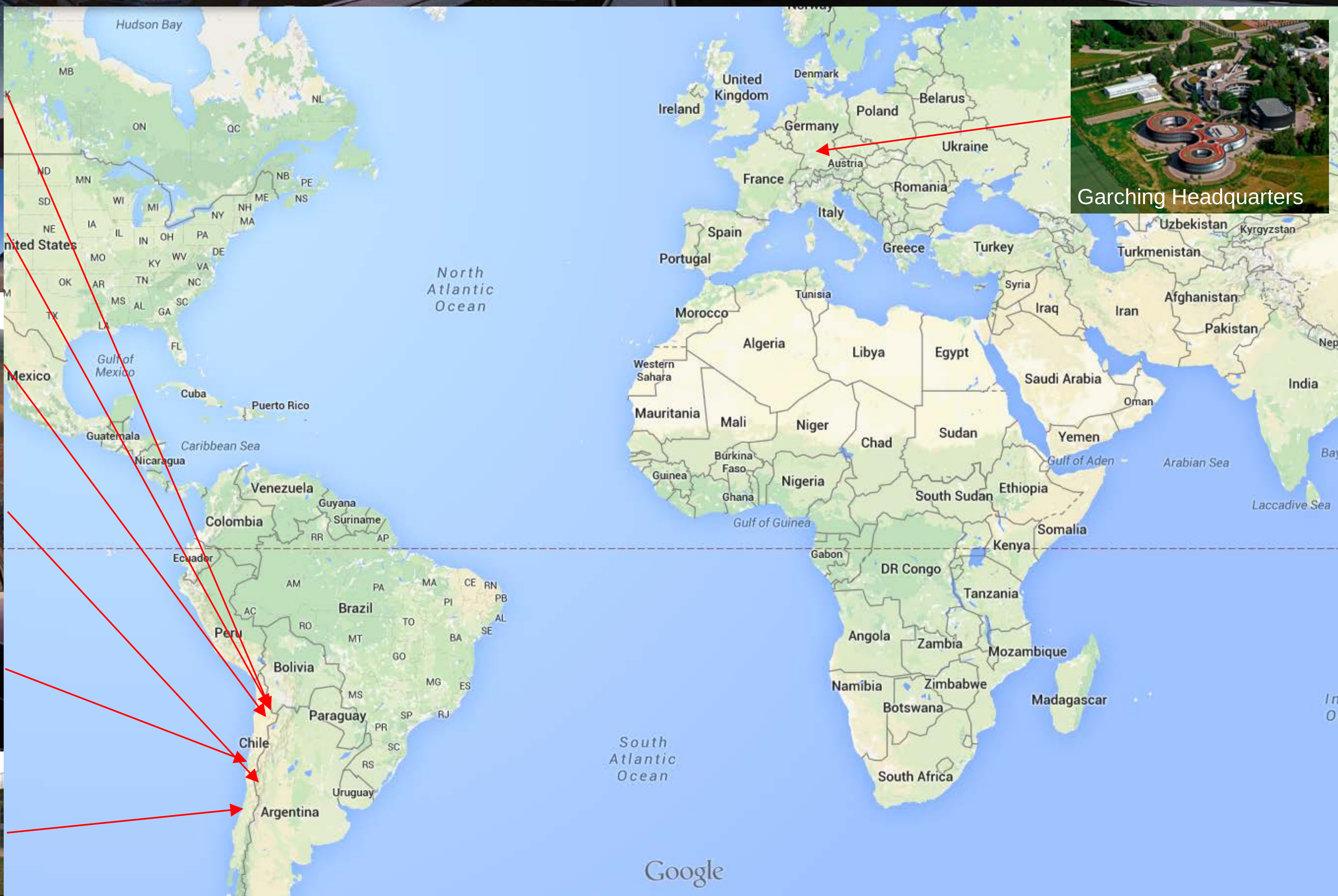
Paolo La Penna

on behalf of the ESO-AOF team

ESO: European Southern Observatory

14 (almost 16) states, 7 sites in Europe and Chile, many collaborations…





What does ESO

ESO is specialized in earth based astronomy. In particular: big telescopes.

Why telescopes have to be big?

The bigger the diameter, the higher the resolving power (diffraction limit $\cong \lambda/D$)
They collect a lot of light (collection power $\propto D^2$).

But, if you build a big telescope on earth your effort will be frustrated by:

If it is big: weight (gravity): flexures of heavy structure, mirrors, etc.
If it is on earth: Atmosphere: image deformation, absorption

These problems are solved by going to space (no weight, no atmosphere),

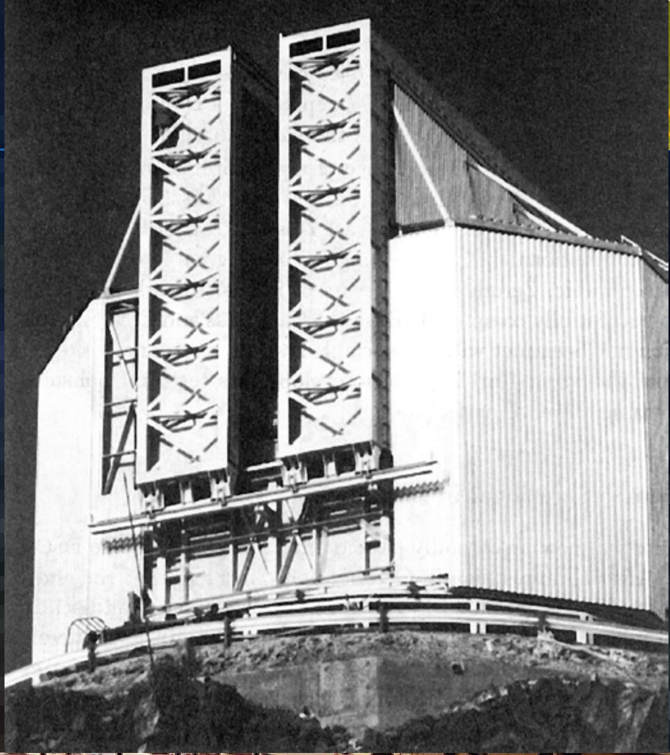
but:

Building things in space is expensive:

Spitzer: 0.85 m	>2.2 billion USD
Kepler: 0.95 m	> 600 million USD
Hubble: 2.4 m:	>2.5 billion USD
Herschel: 3.5 m	>1.4 billion USD
JWST (not yet launched): 6.5 m	>8.7 billion USD

Maintenance: known problems of Hubble and Kepler

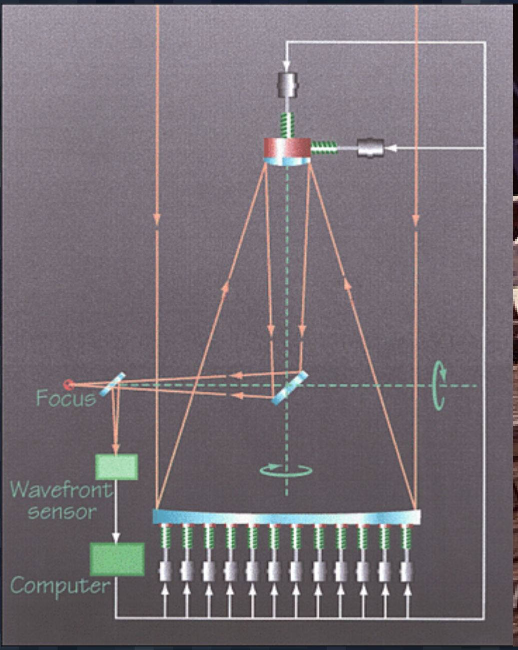
Gravity: Active Optics

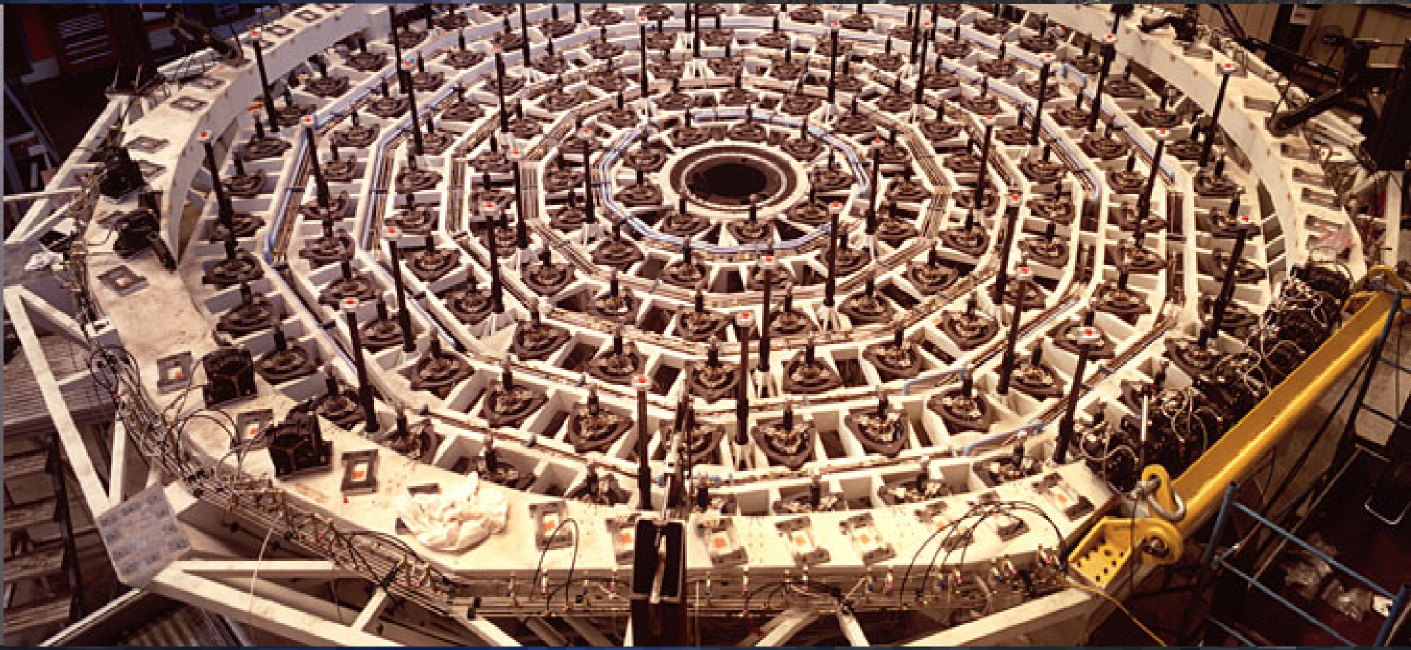


ESO was the first observatory using Active Optics
When changing the mirror orientation (following the sky), a big primary mirror will bend.

- Solution: act from behind the mirror to correct the shape: Active Optics (nvented at ESO by Ray Wilson in '80)
- First light: ESO NTT telescope at La Silla (3.5 m)
- Now on all big telescopes

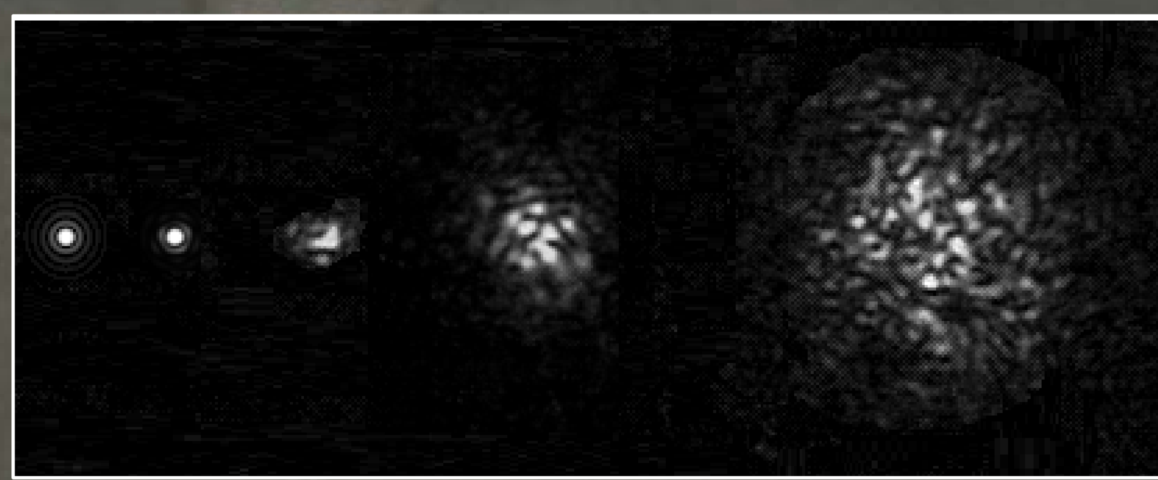
Active optics allows to build big telescopes





Dry air+height ≡ less distortion (that's why telescopes are in dry places, like on a mountain called Cerro Paranal, in the mid of the Atacama Desert…)

Seeing: spread of the theoretical Point Spread Function (PSF):
Theoretical PSF ≅ 0.010 asec
Observed ≅ 1 asec

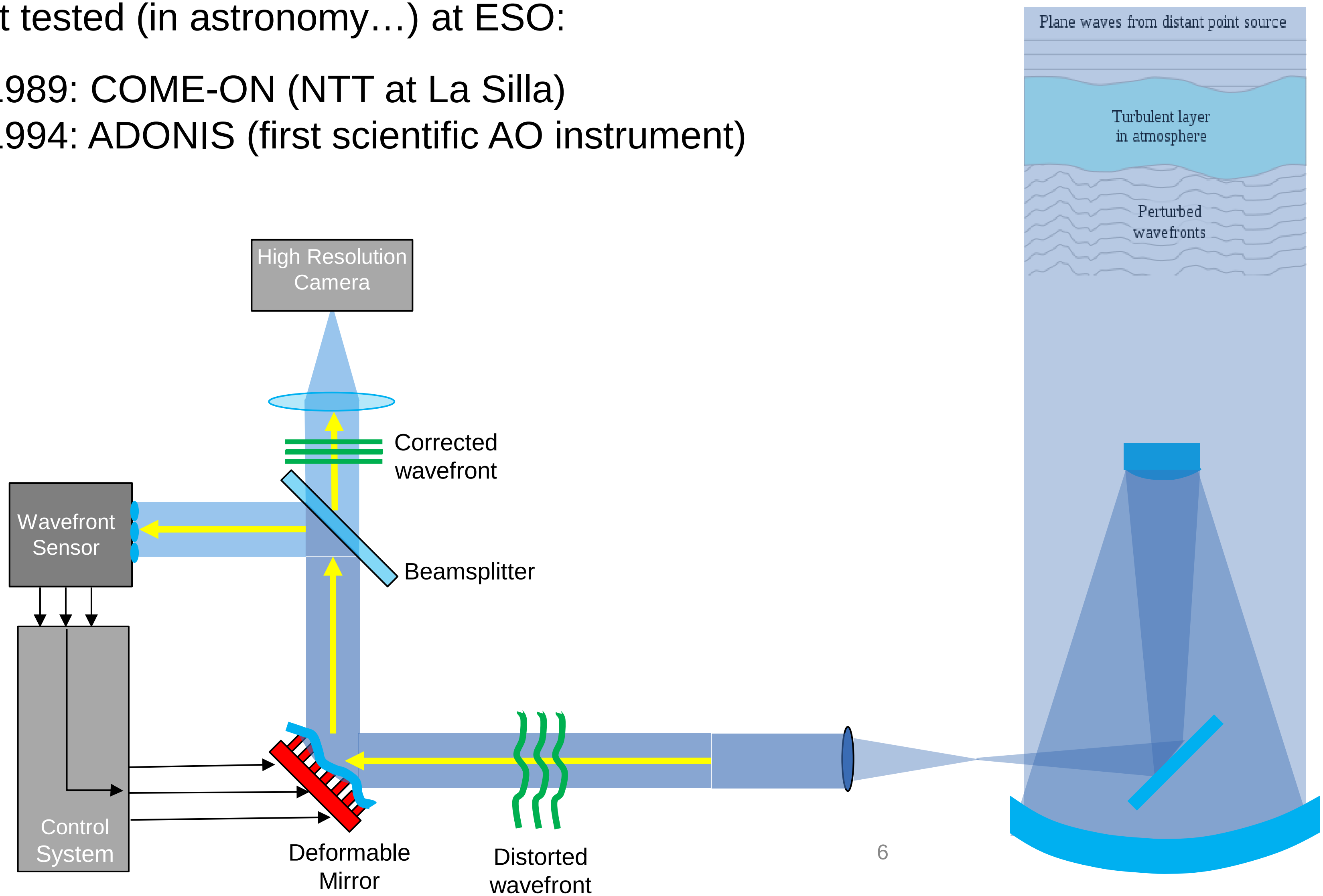


Atmosphere: Adaptive Optics

AO was first proposed by H.W. Babcock in 1953

First tested (in astronomy…) at ESO:

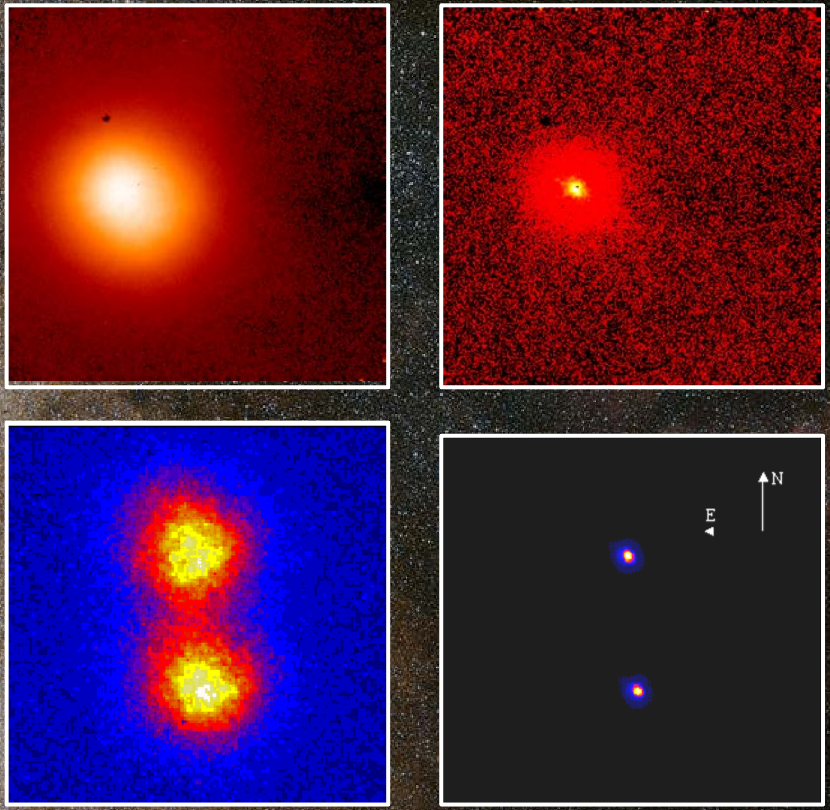
- 1989: COME-ON (NTT at La Silla)
- 1994: ADONIS (first scientific AO instrument)

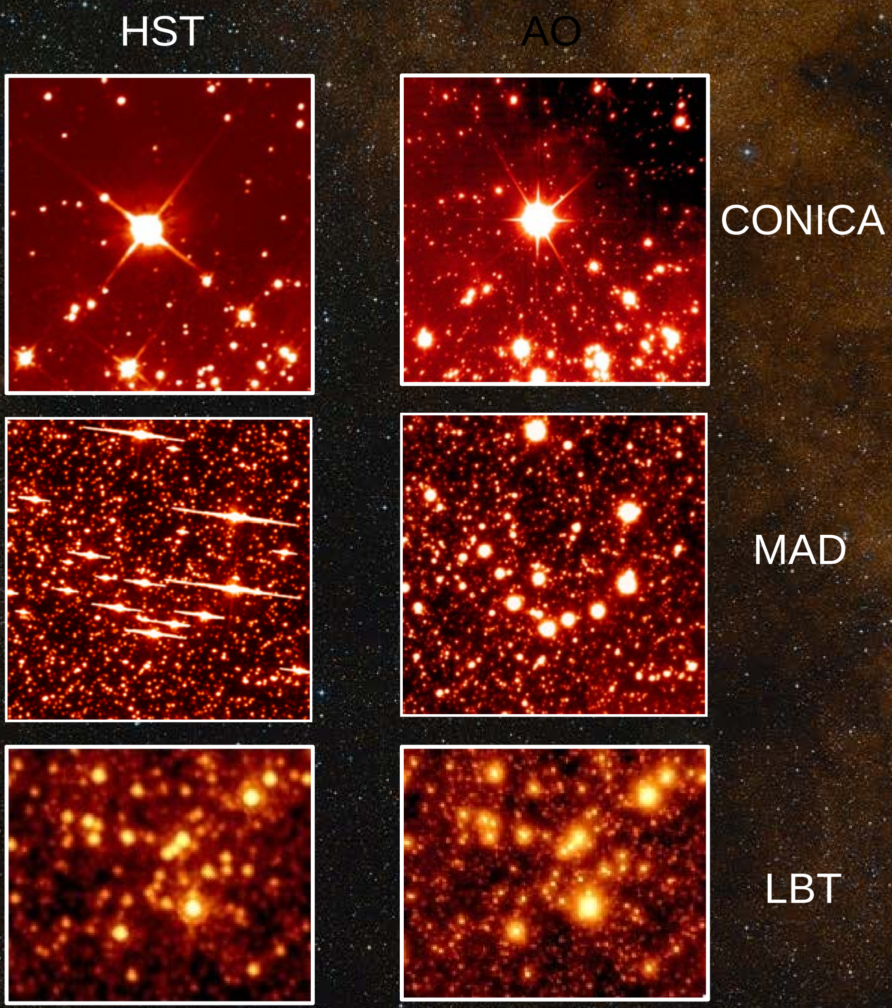


Results of Adaptive Optics

After Active Optics Adaptive Optics provides now a resolution comparable with space telescopes

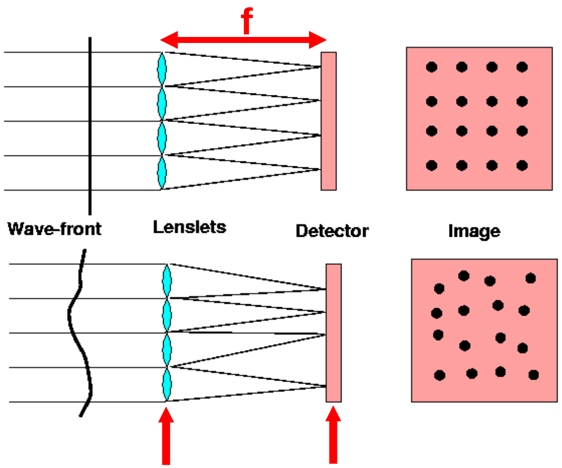
AO at Keck-II telescope:

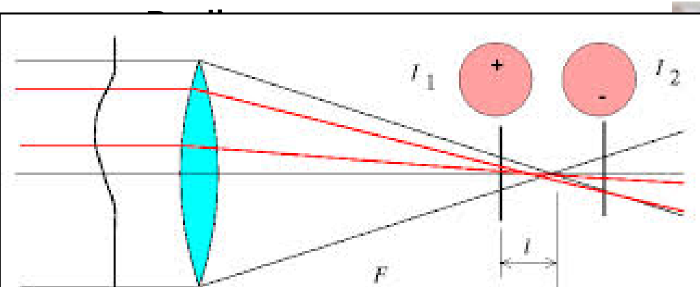


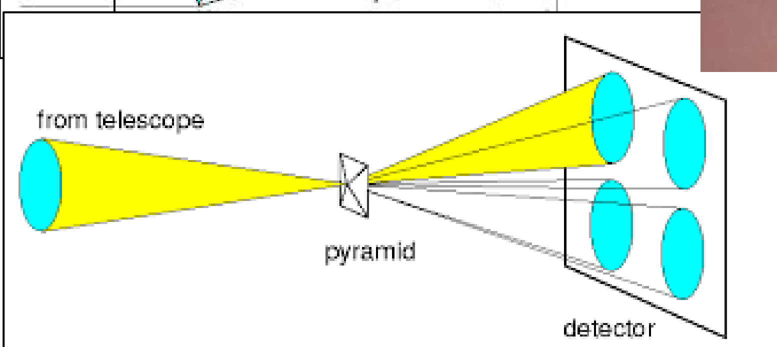


AO: sensors, mirrors, schemes

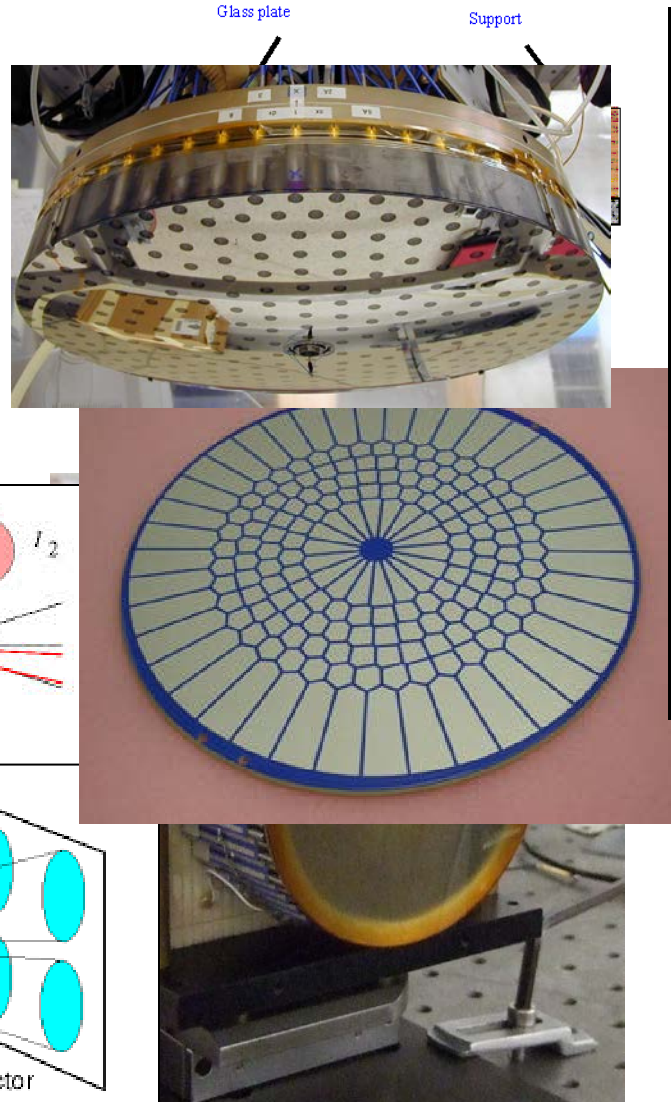
Sensor:



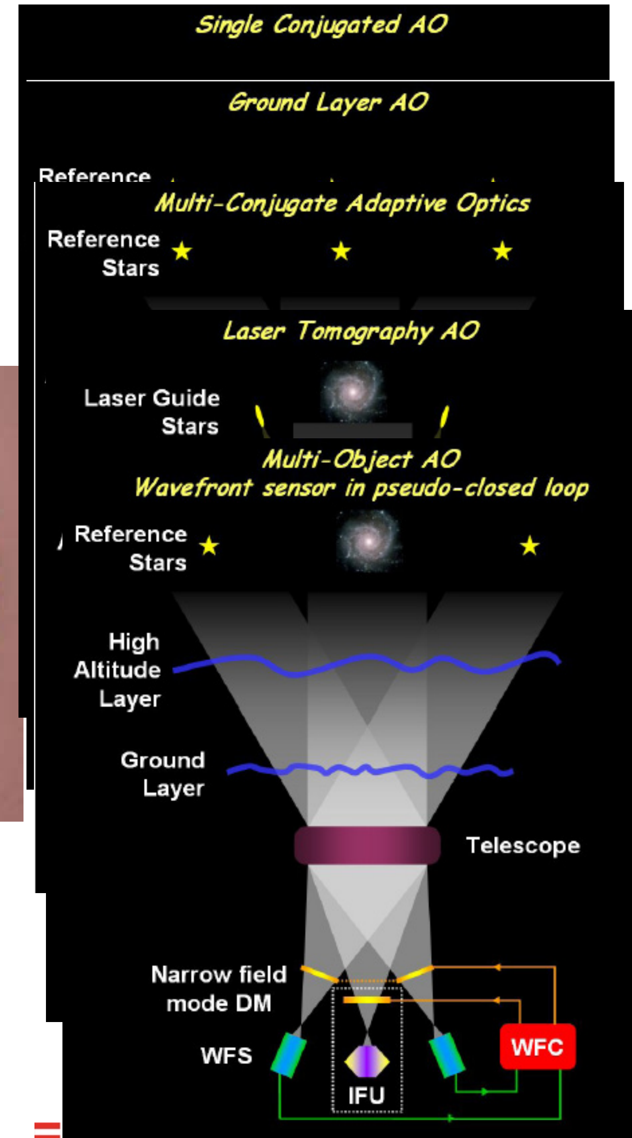




Actuator:
deformable mirror

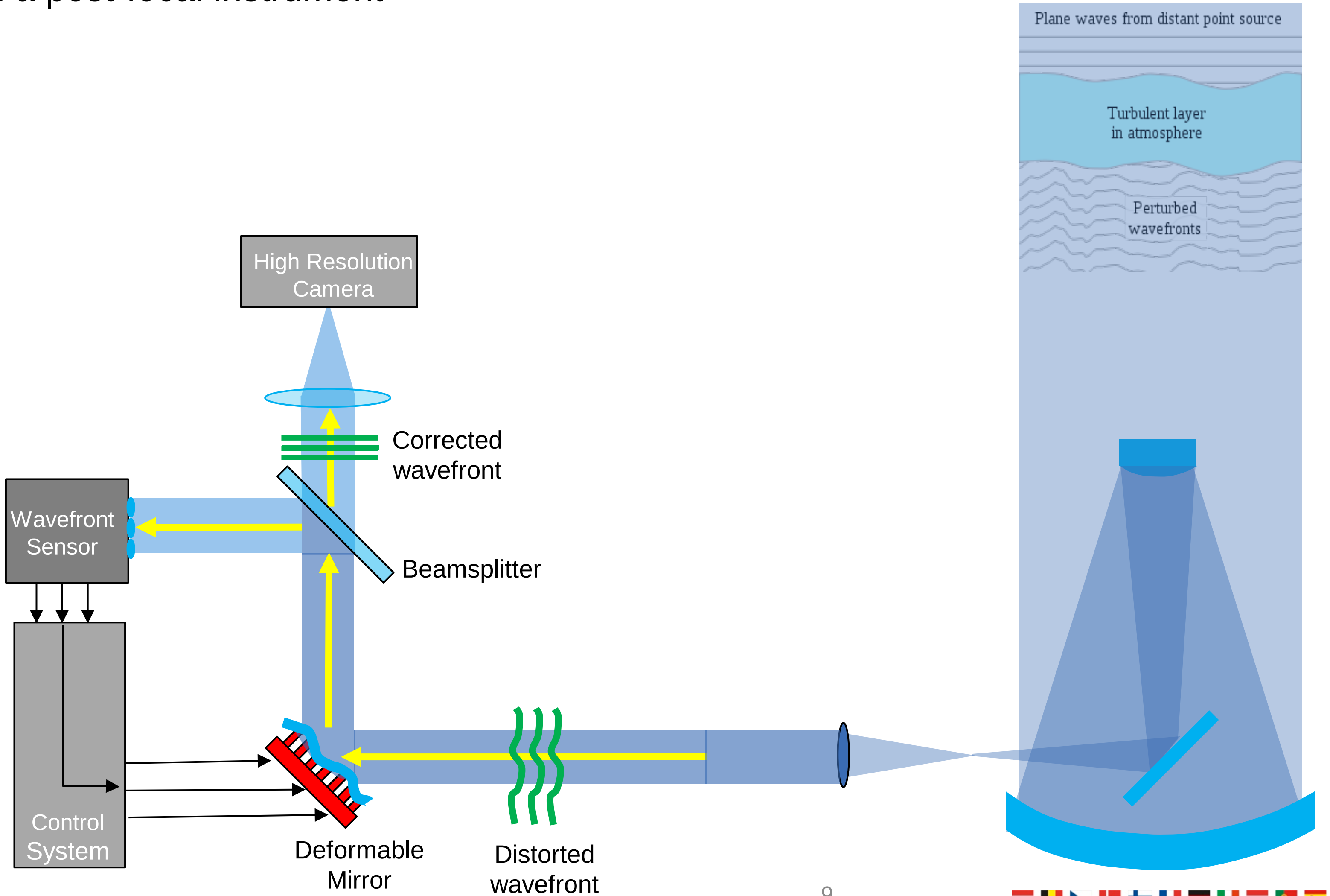


AO scheme:



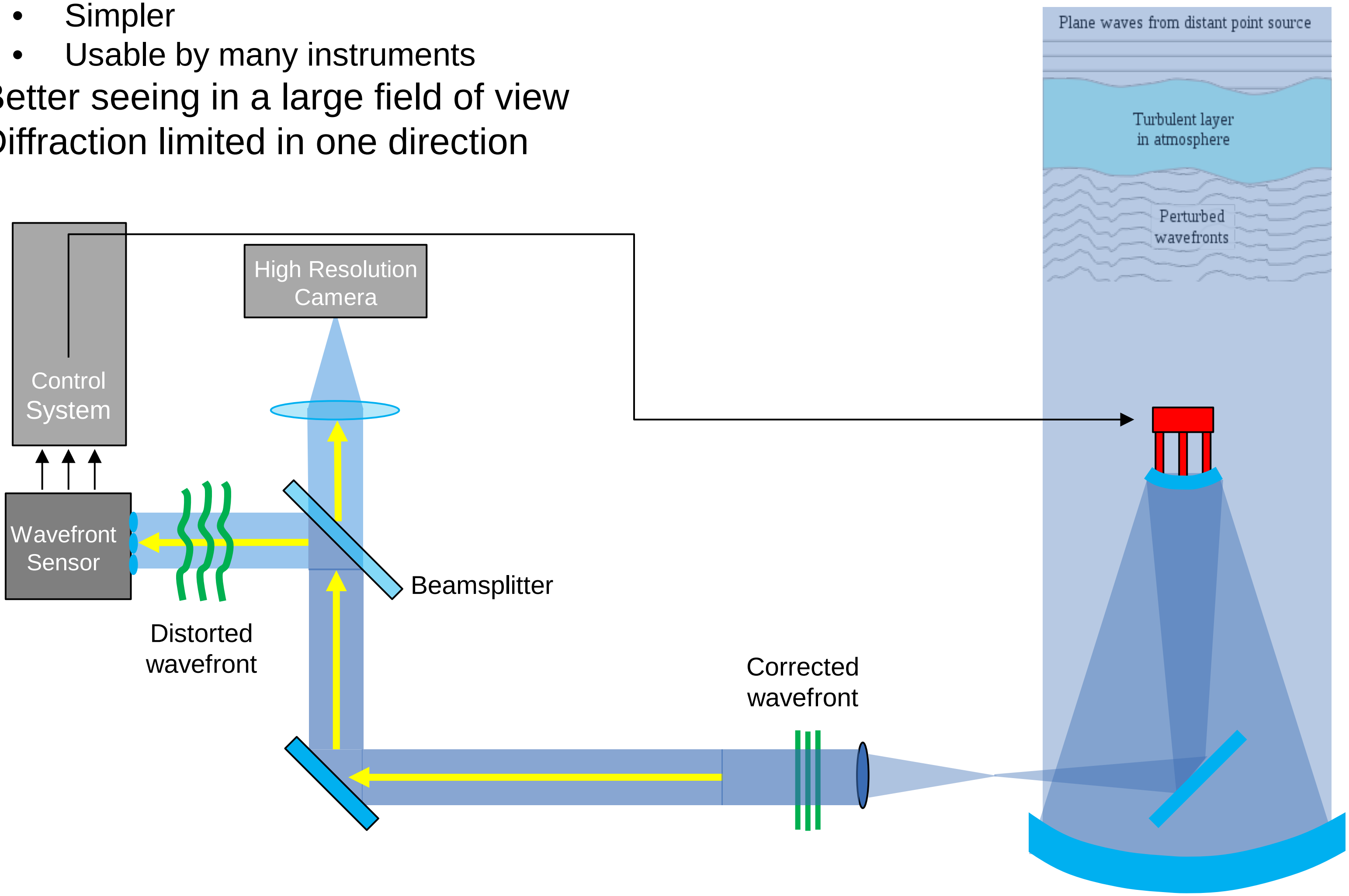
Up to now: Post-Focal Adaptive Optics

- Telescope delivering seeing limited wavefront
- Correction performed by an adaptive mirror
- In a post-focal instrument



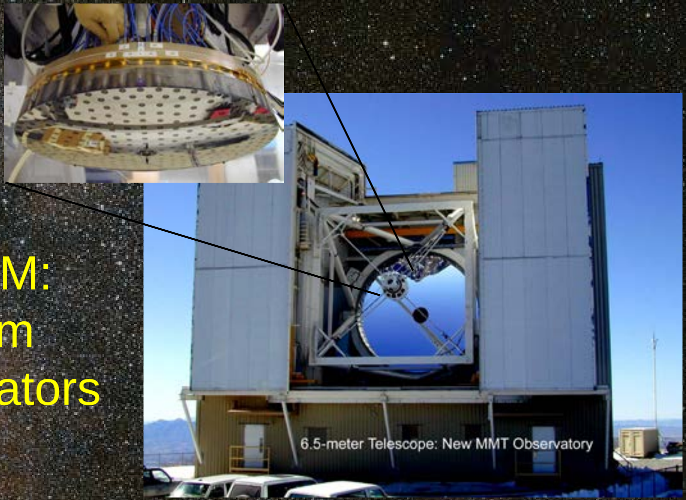
Adaptive Telescope

- Larger Adaptive Mirror: large number of actuators
  - High spatial frequency correction
  - Smaller sensitivity to actuator failure
- No post focal AO relay optics:
  - Simpler
  - Usable by many instruments
- Better seeing in a large field of view
- Diffraction limited in one direction

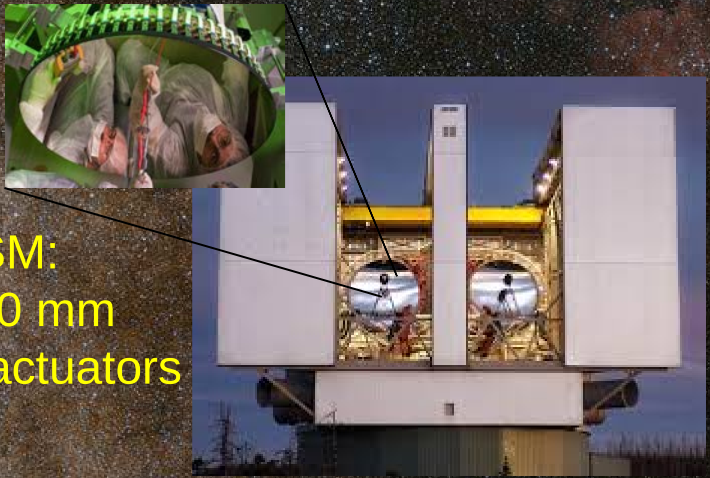


How may adaptive telescope

Existing



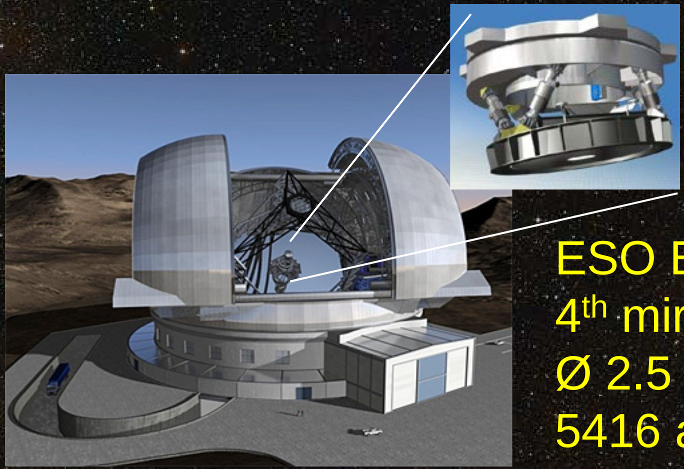
MMT DSM:
Ø 640 mm
336 actuators



LBT DSM:
2×Ø 910 mm
2×672 actuators

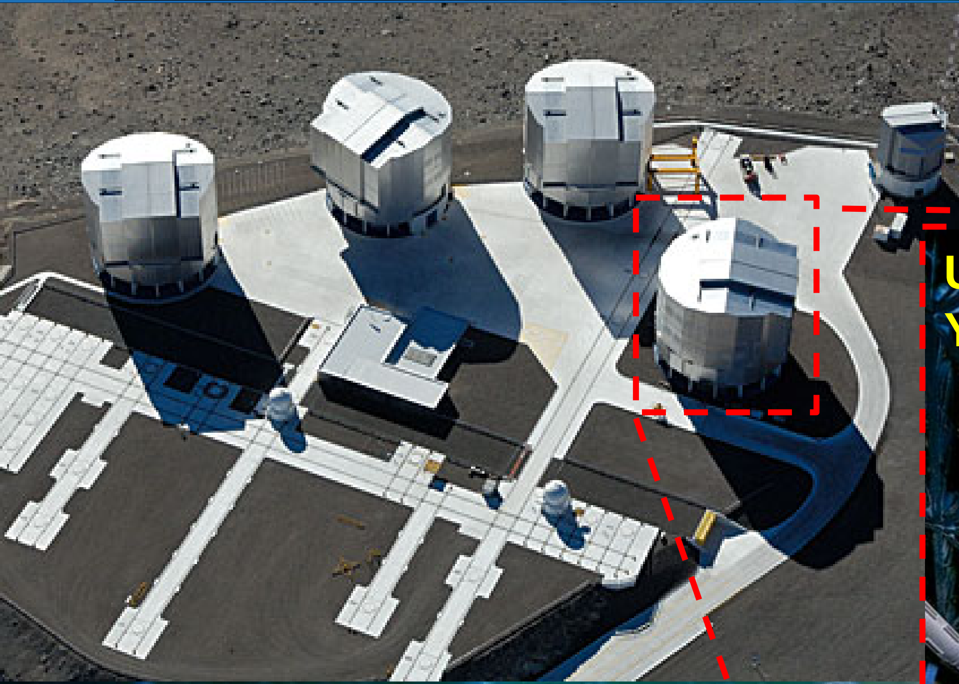
In construction

GMT DSM:
7×Ø 1.05 m
7×672 actuators

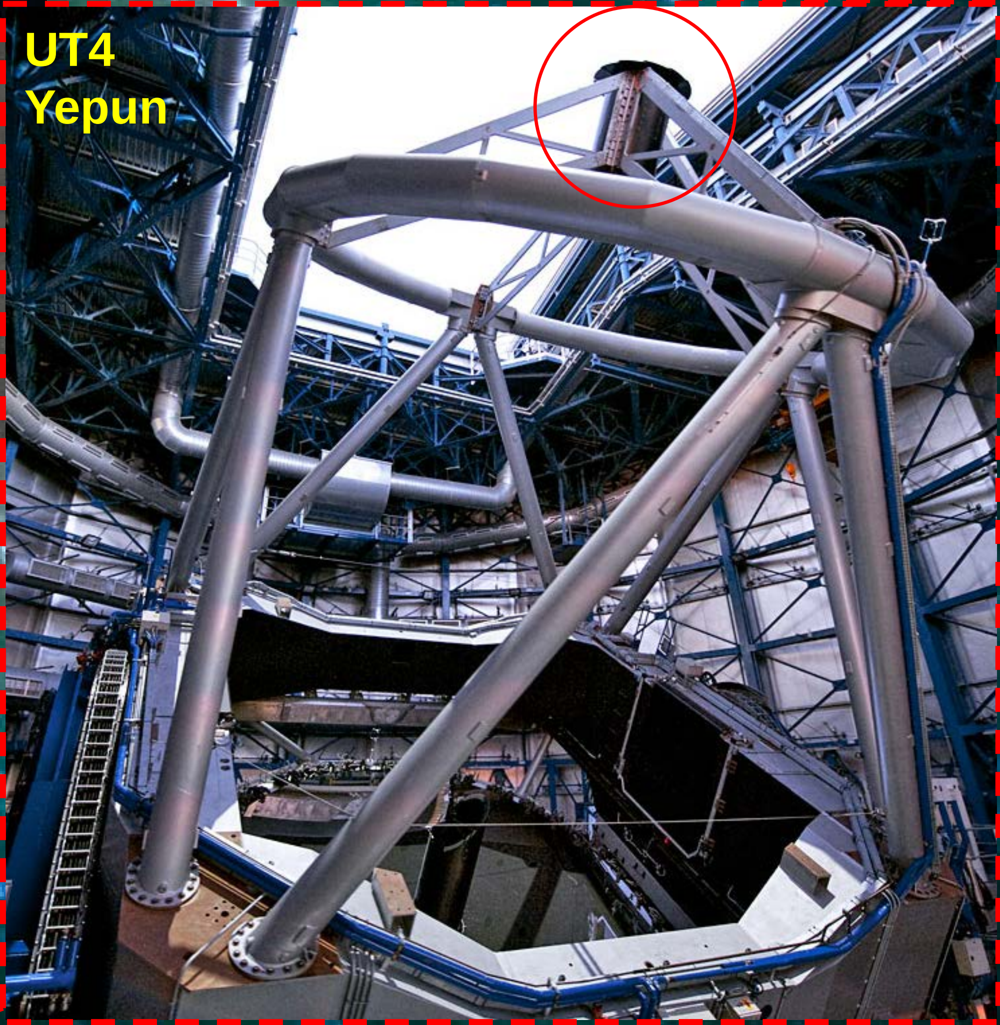


ESO E-ELT
4^{th} mirror:
Ø 2.5 m
5416 actuators

ESO: UT4 transformation



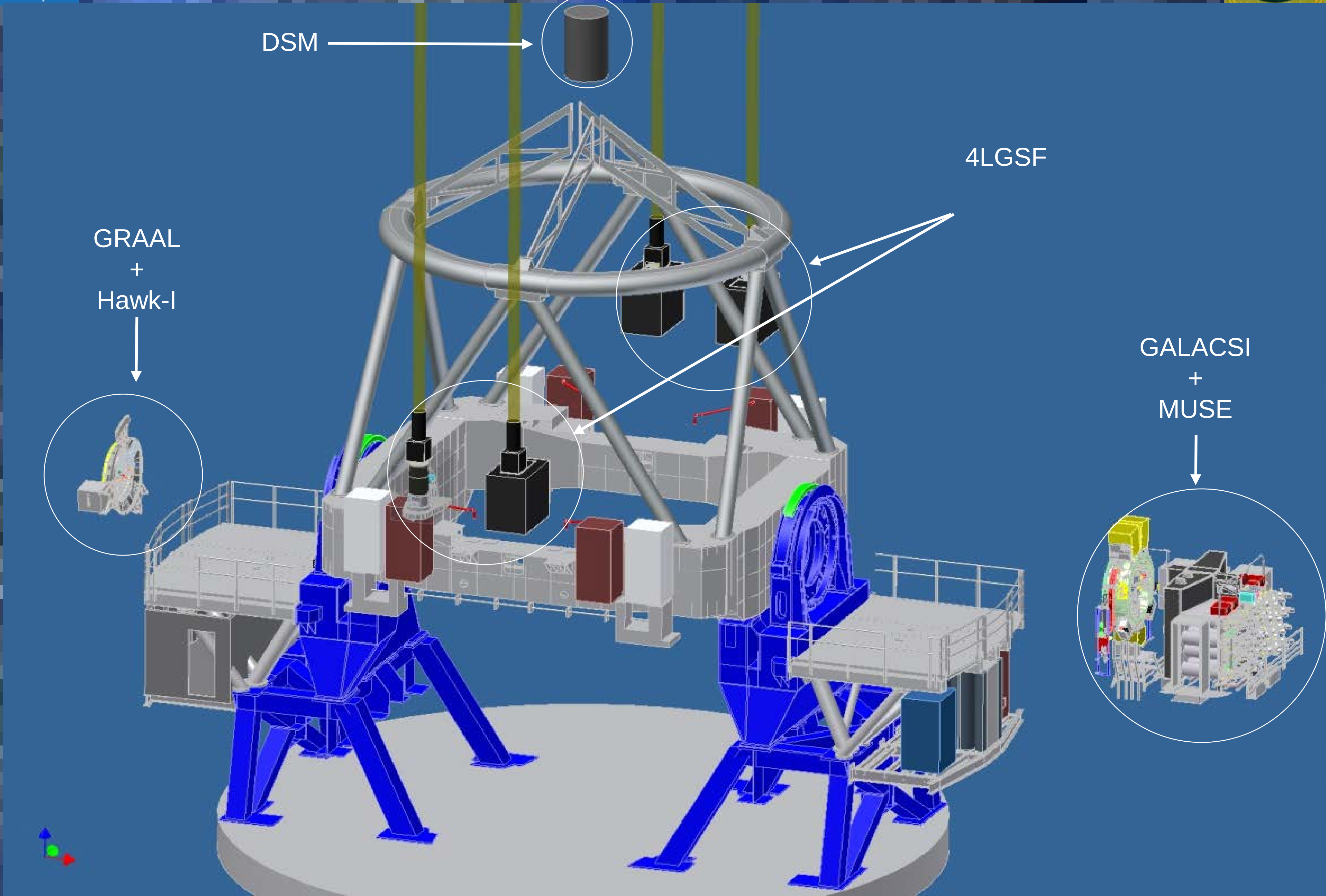
Why not so many adaptive telescopes? Turning-out a UT in an adaptive telescope it's not just adding a DSM



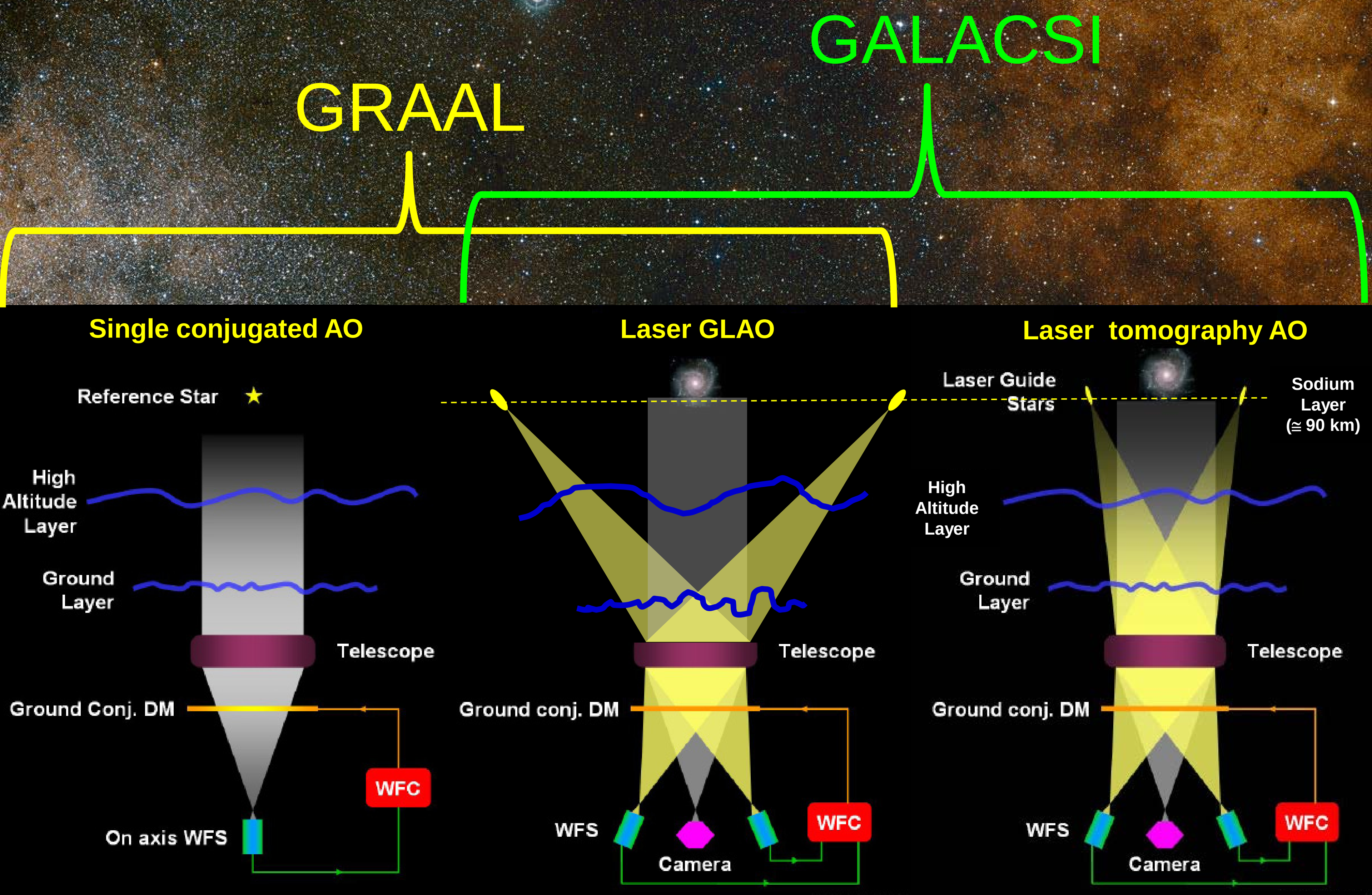
ESO UT4 transformation in an adaptive telescope implies:

- Replacement of the secondary
- mirror with a deformable one
- A multi Laser Guide Star facility
- Post focal AO modules to provide corrected wavefront to the instruments
- Test facilities

The Adaptive Optics Facility



AO Modes



GALACSI
GRAAL
Single conjugated AO
Laser GLAO
Laser tomography AO
Reference Star
High Altitude Layer
Ground Layer
Telescope
Ground Conj. DM
WFC
On axis WFS
Ground conj. DM
WFS
Camera
Laser Guide Stars
Sodium Layer (≅ 90 km)

Scientific goals

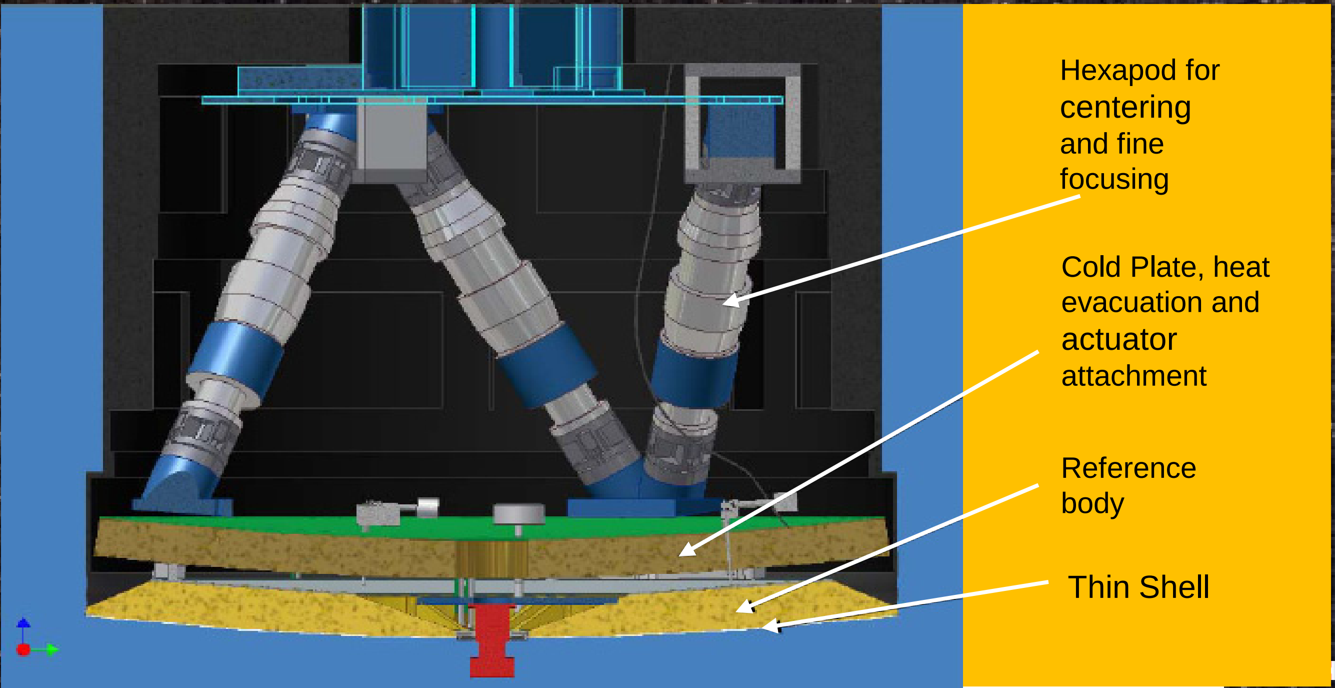
- Enable **more** observations and specifically surveys in high throughput (DM in telescope)

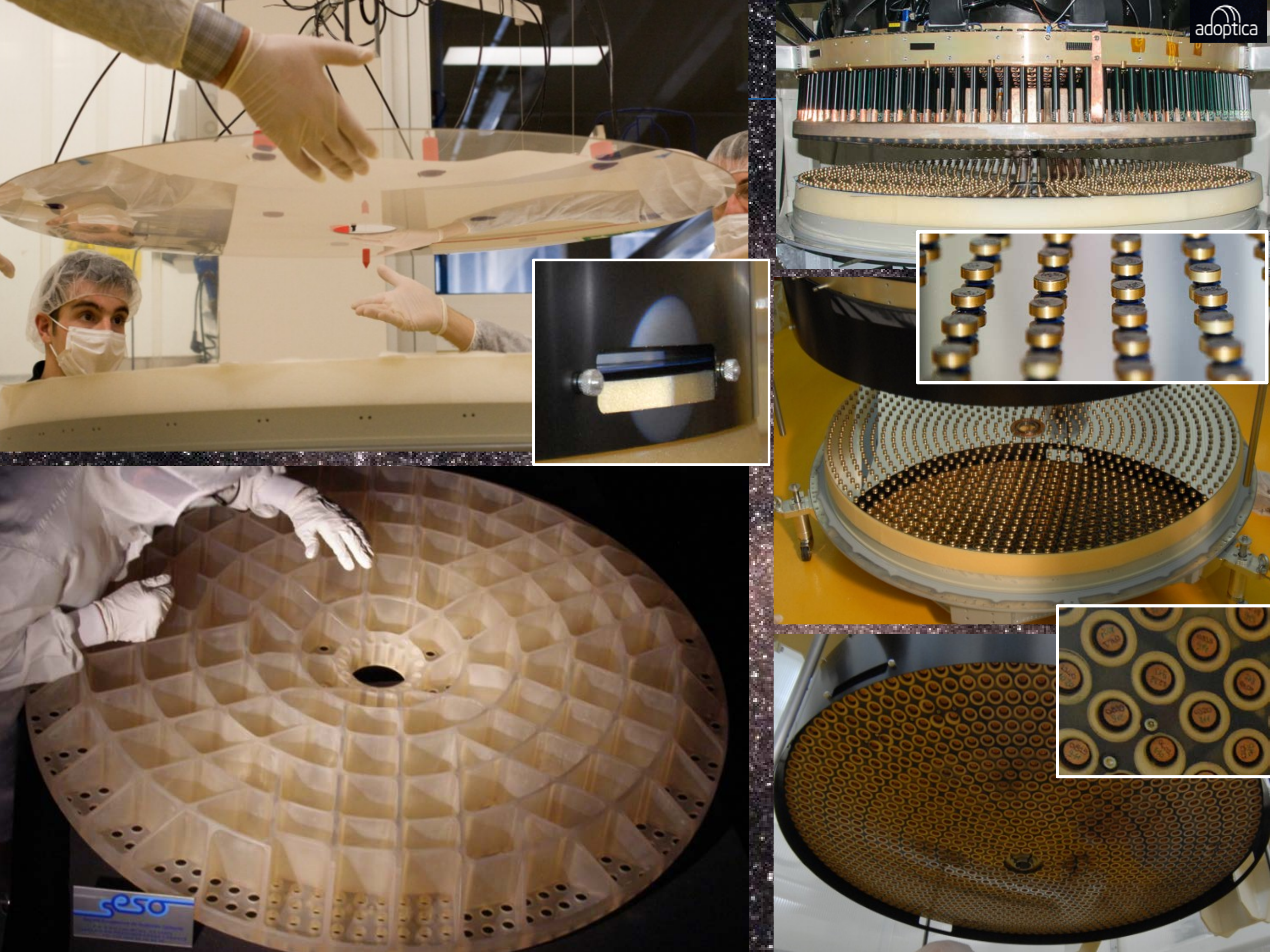
- In ***GLAO improved***
  - For MUSE: 50% ≤ seeing 0.45” at 750nm (EE-gain ≈ 2)
  - For Hawk-I: 50% ≤ seeing 0.3” at K-band
  - Fainter magnitude limits for point sources
  - Better spatial resolution for extended sources

- **In Laser Tomography Mode**
  - High Spatial Resolution dynamical studies (galaxies, Galactic Center…): for MUSE: 10% Strehl at 650 nm

The Deformable Secondary Mirror (DSM)

- Optical diameter = 1120 mm
- Curved (aspherical): R_{curv}=4.553 m
- Actions: Focus, centering, tilt/chop, AO
- 2 mm Zerodur thin shell, with magnets
- 1170 voice coil actuators
- DSM response time < 1 ms
- glued on
- Zerodur Reference Body
- Liquid cooled (1.5 kW)



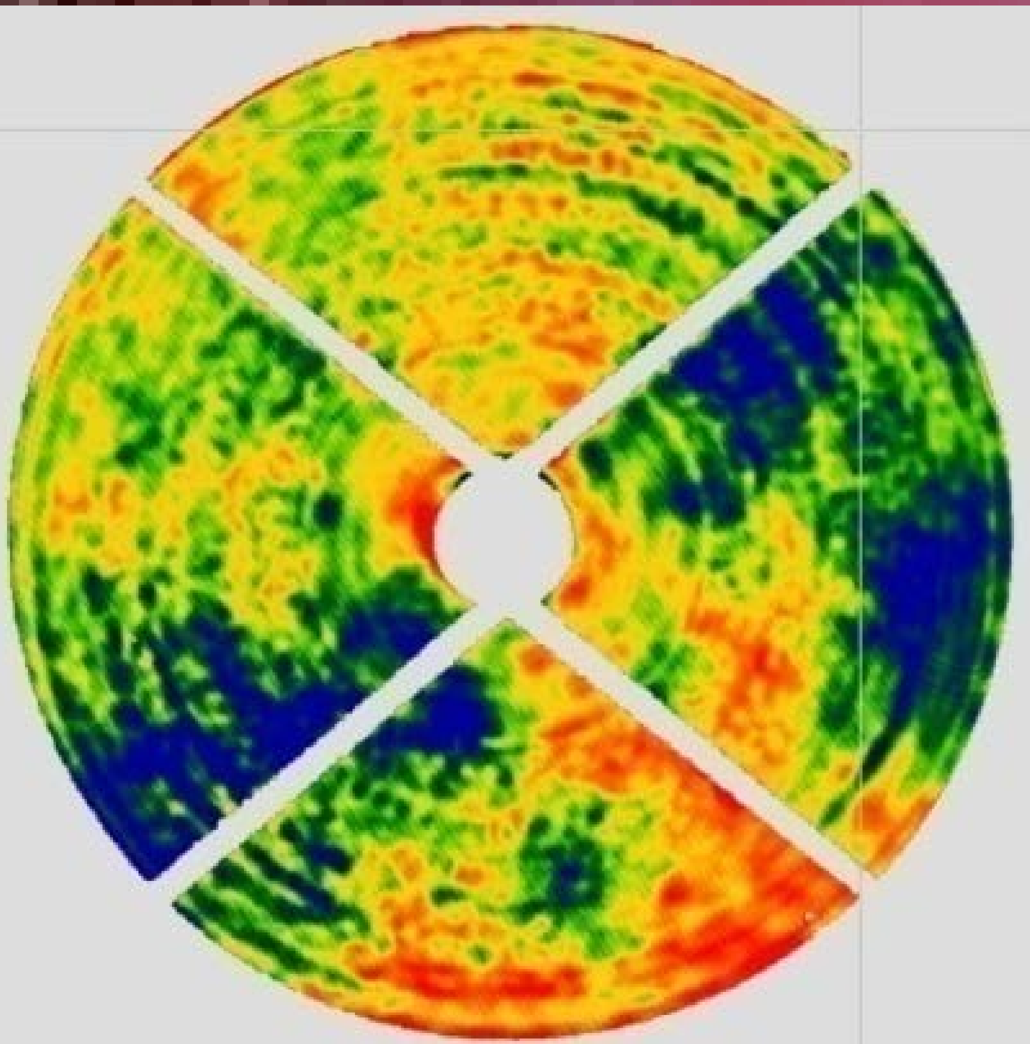

adoptica

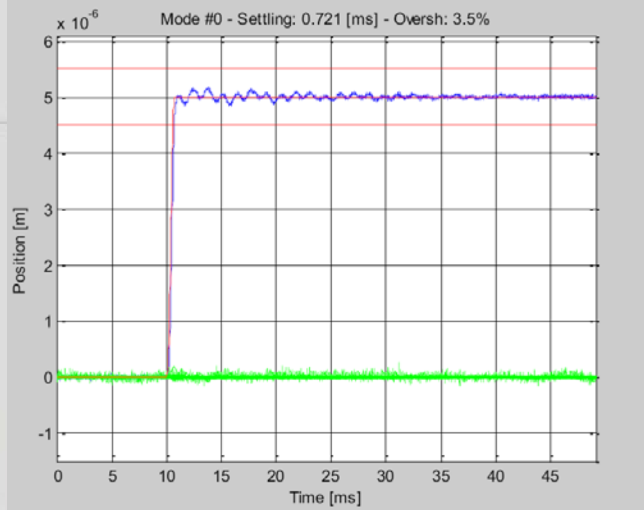
DSM shaping

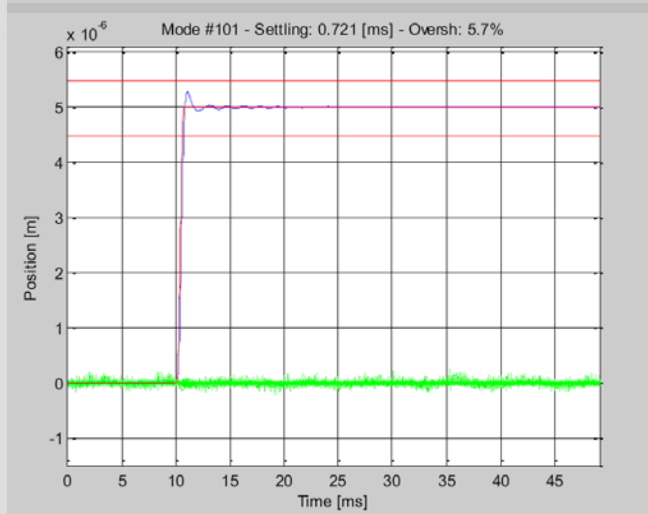
Best surface figure of the DSM

< 10 nm RMS

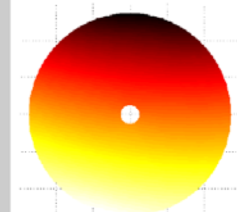
Settling time < 1 msec



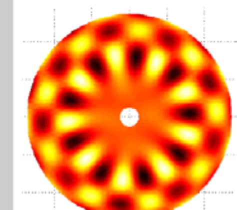




Mode#1 (tip)



Mode# 100

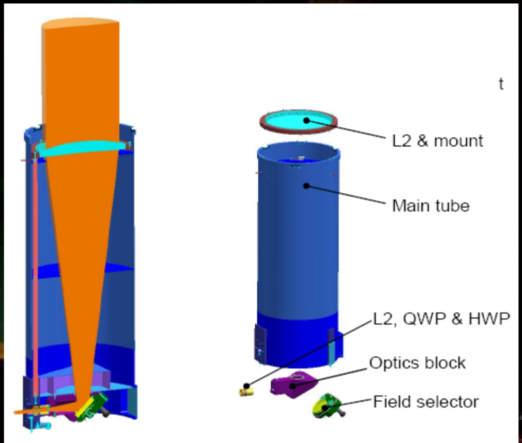


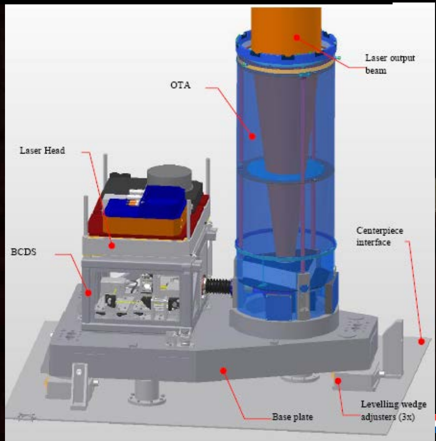
The LGS facility: 4 lasers stars at 90 km

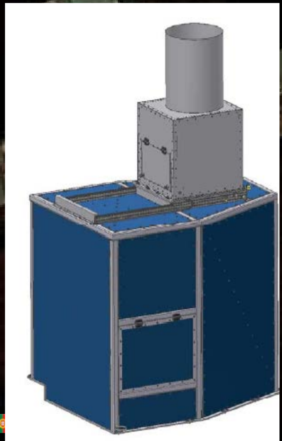
LGS: Laser beam excitation of sodium atoms at ~ 90 km altitude produced from the disintegration of meteors in the Earth's mesosphere: artificial star available everywhere (sky coverage).

- 4 identical LGS Unit, mounted on UT4 Center Piece
- One 40 cm diameter Launch Telescope (TNO)
- LGS spot of about 0.5 m diameter
- One Beam Control and Diagnostic System (ESO):
  - Control of focusing altitude (70 to 200 km)
  - Control of LGS position (0 to 6 arcmin from optical axis)
  - LGS jitter stabilization mirror (controlled by AO modules)
  - Safety devices (shutters), diagnostic tools (power meter, WFS, alignment camera)

L2: 50 mm thick, 300 mm diameter aspherical lens.

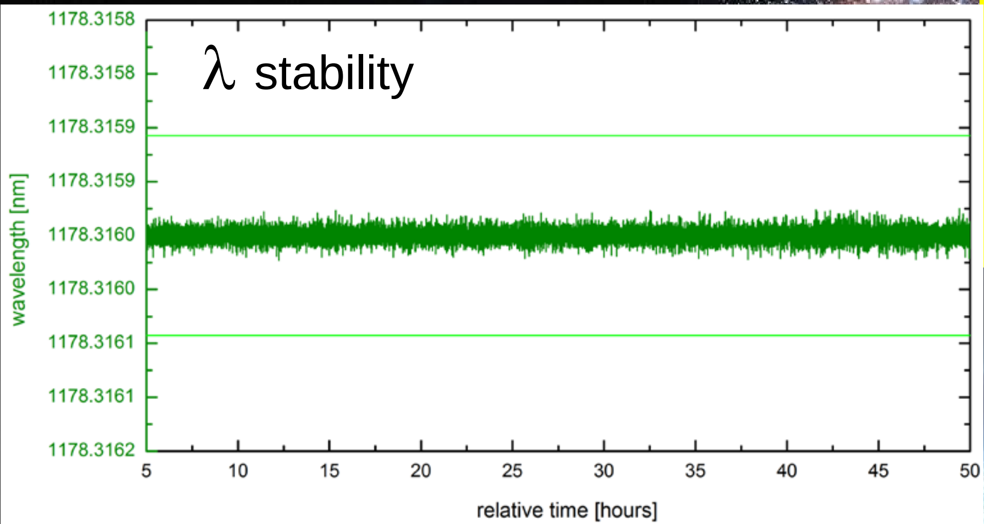


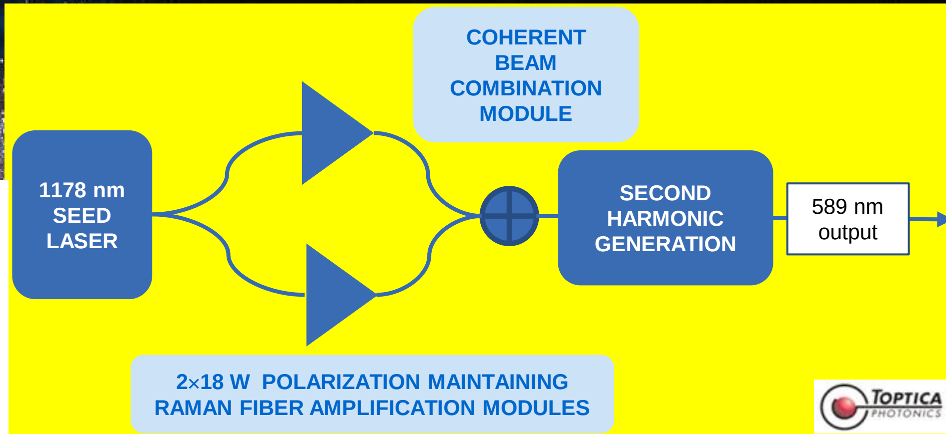


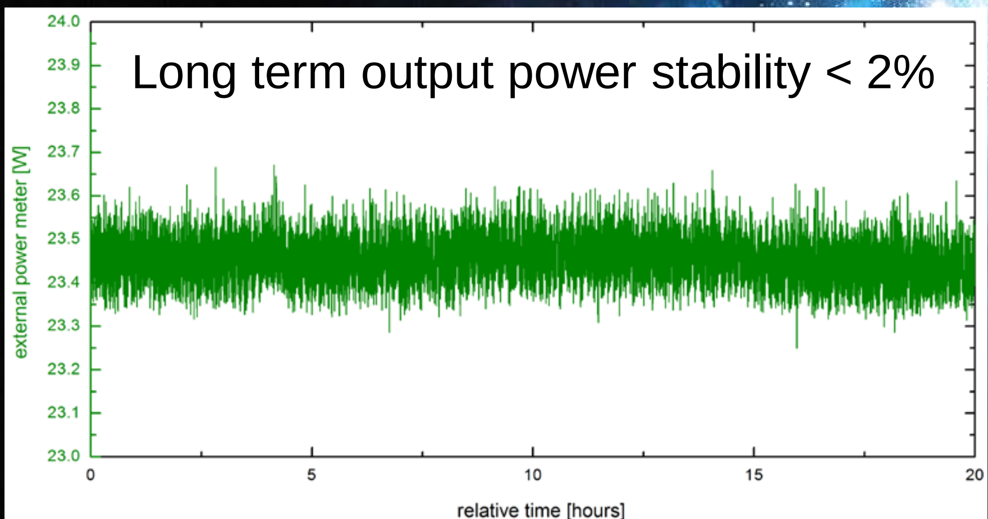


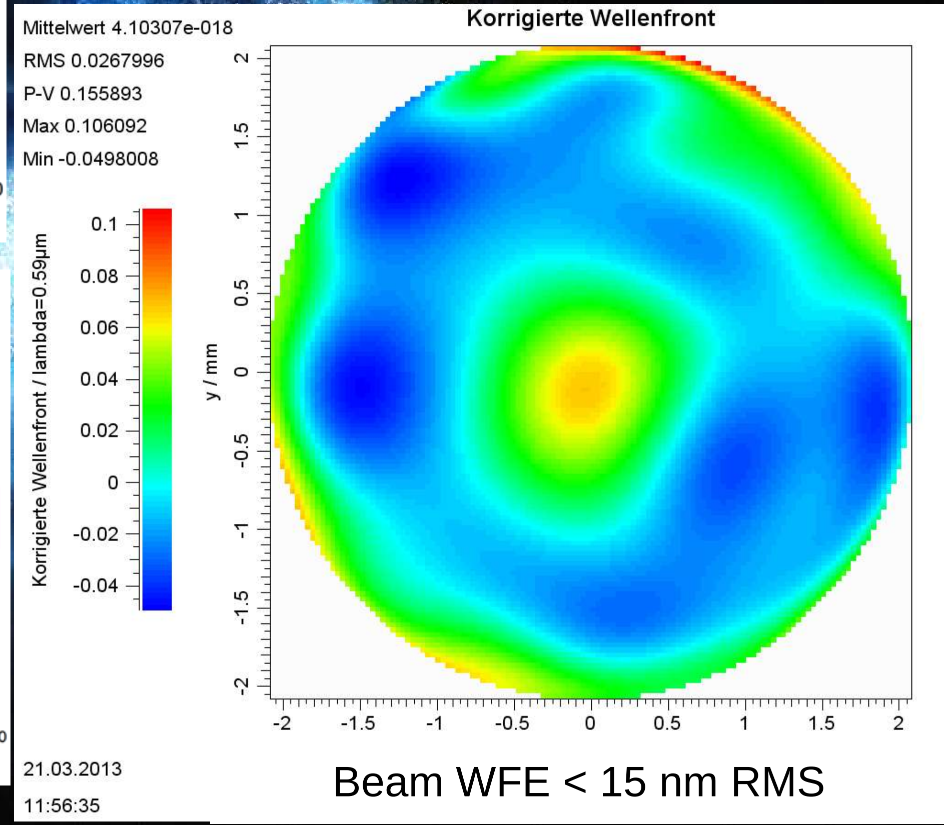
The lasers

Four 20 W CW dual line laser (TOPTICA & MPBC)
18 W in D_{2a} and 2 W in D_{2b} lines (back-pumping scheme)
Compact, efficient, reliable and maintainable laser



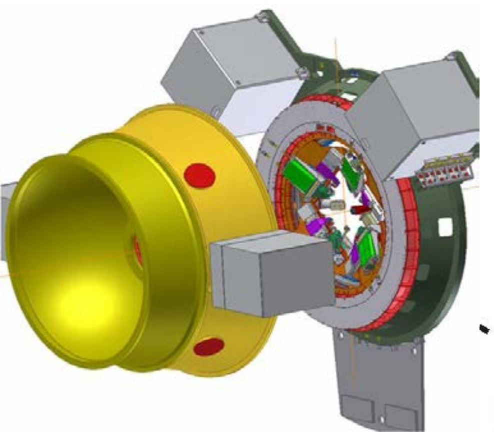


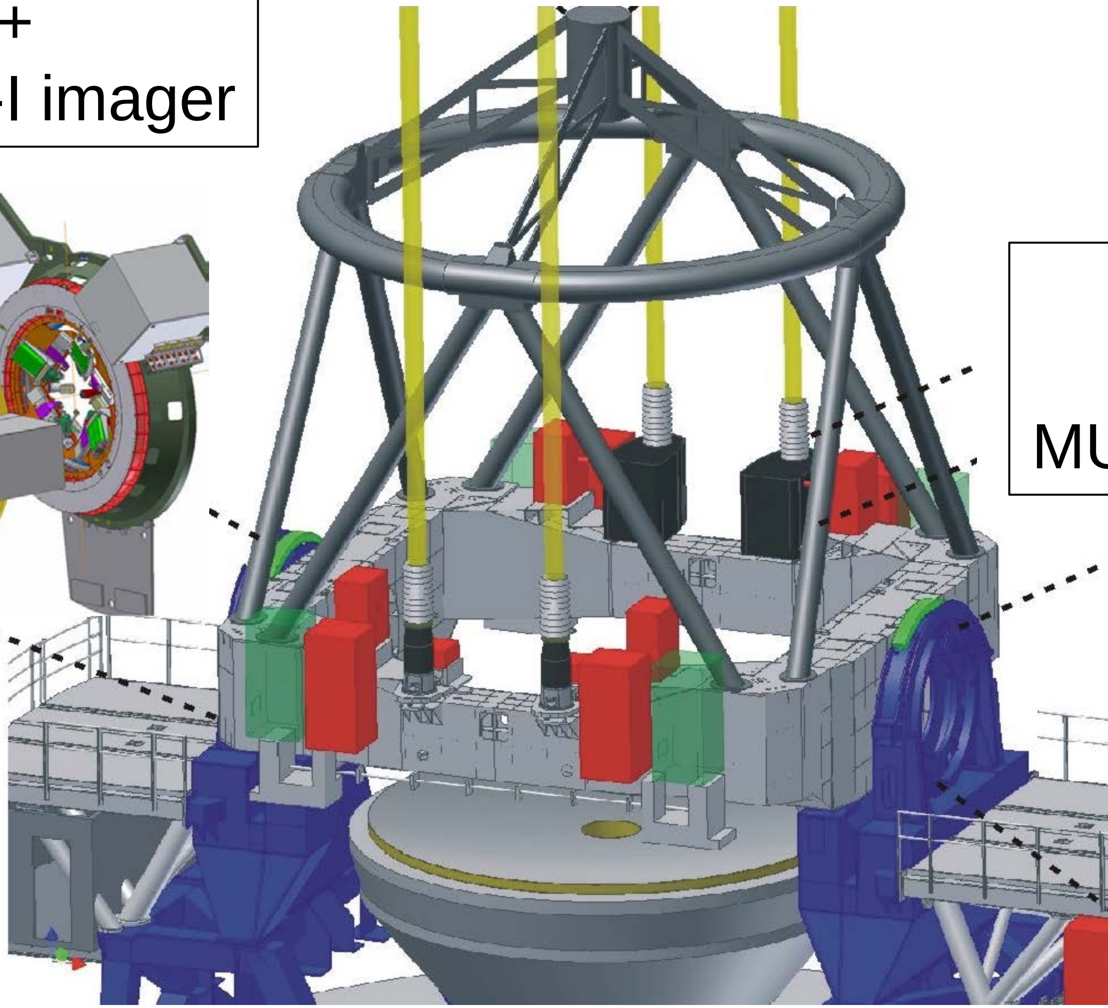




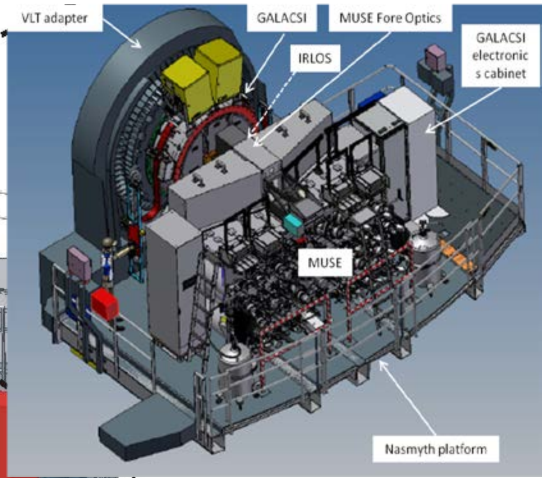
The instruments

GRAAL
+
HAWK-I imager

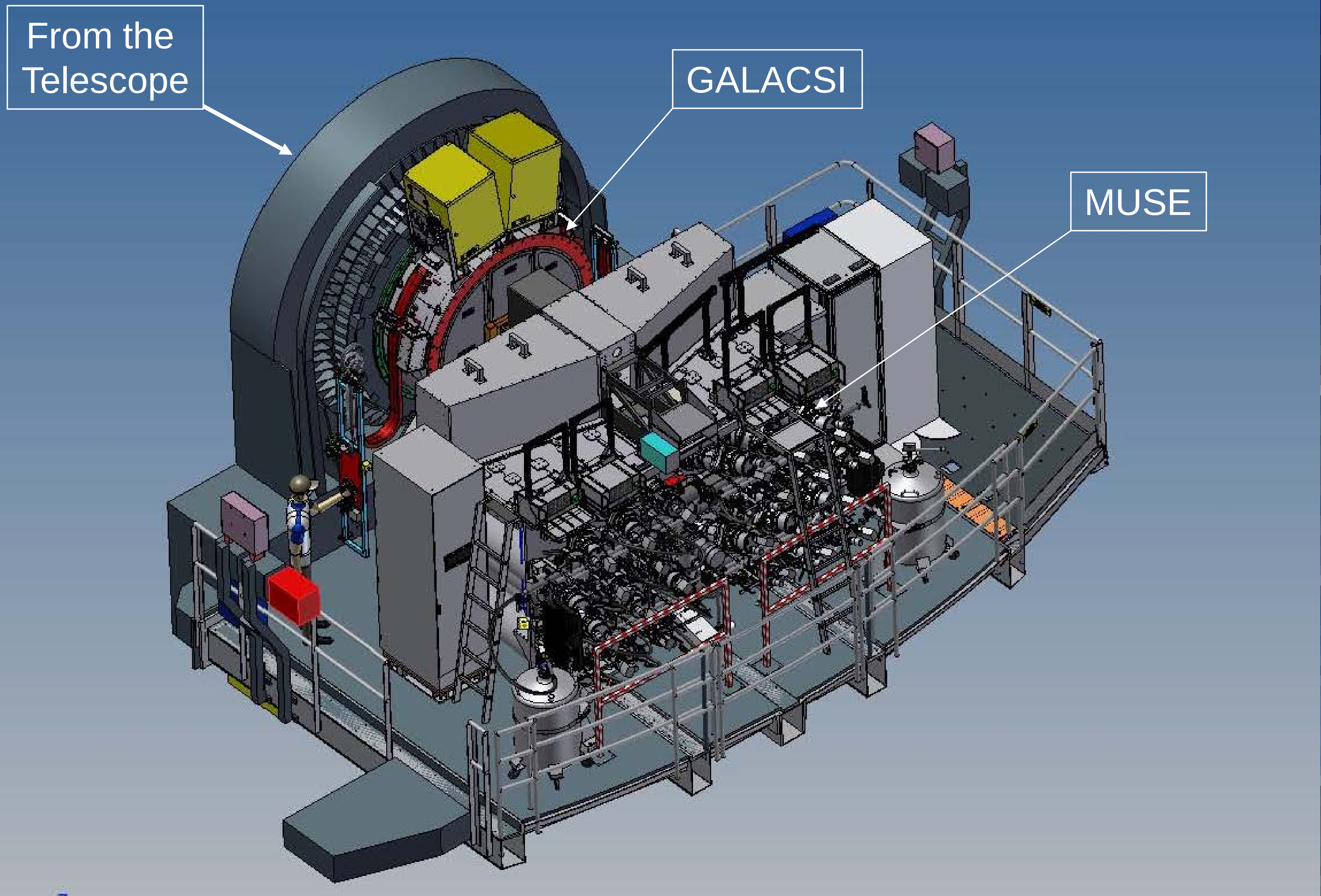


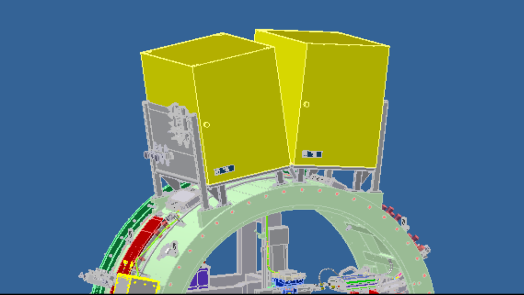


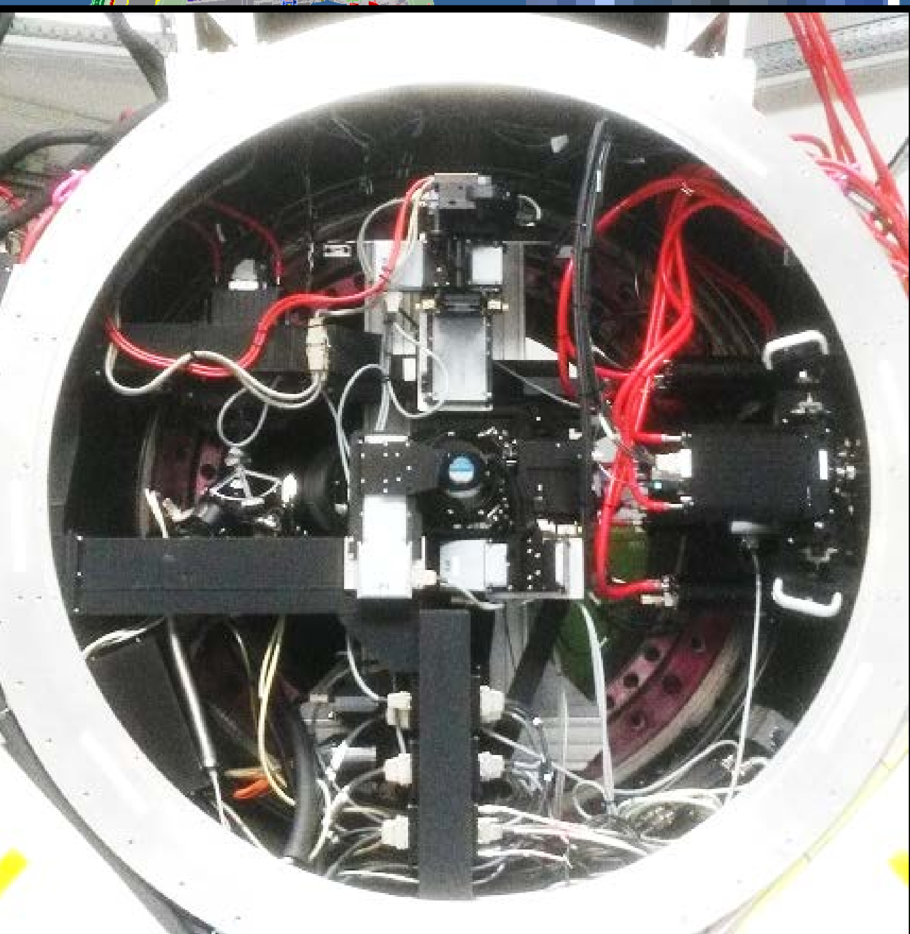
GALACSI
+
MUSE spectrograph

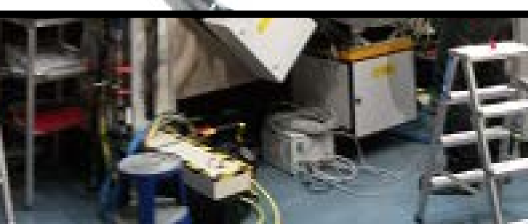


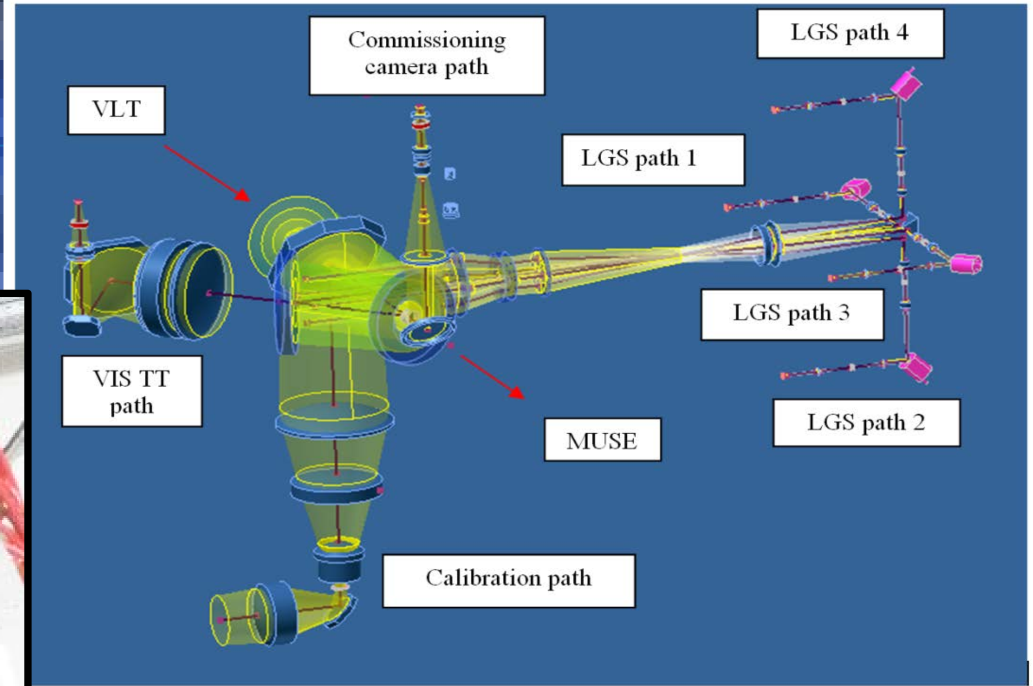
GALACSI: AO module for MUSE

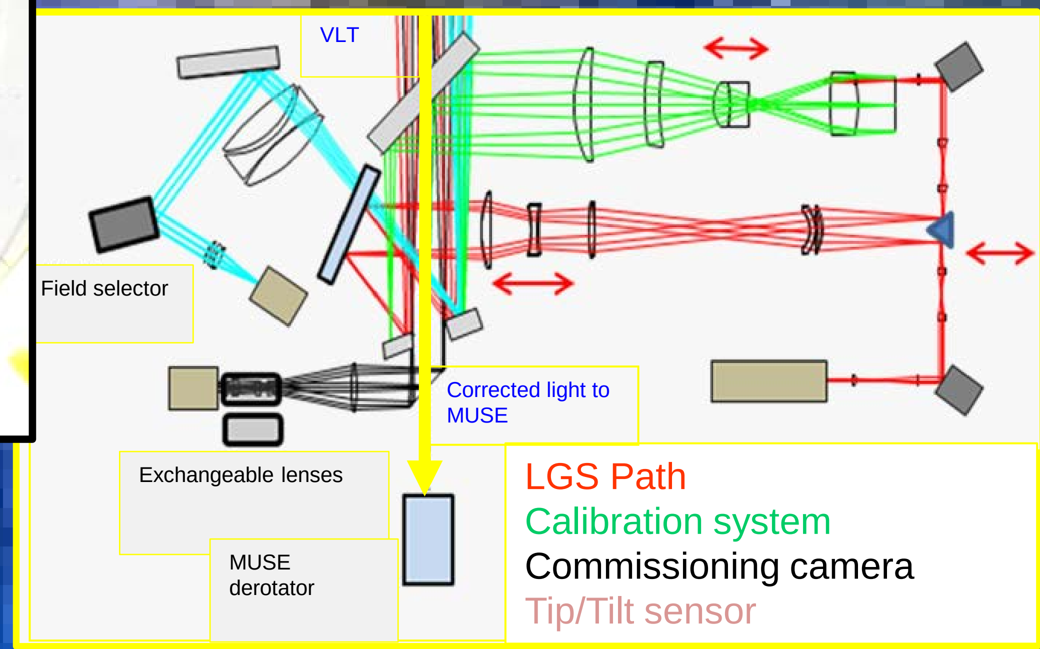




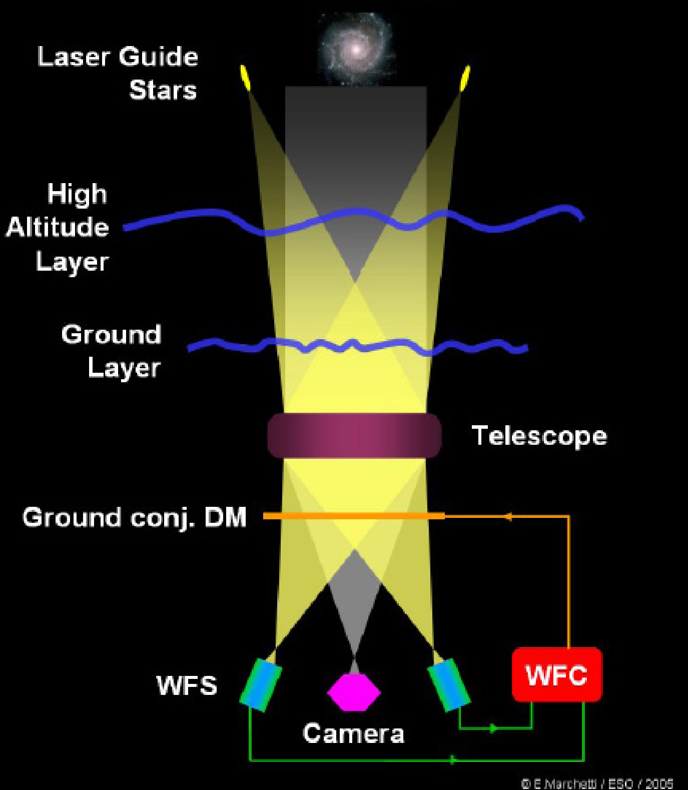




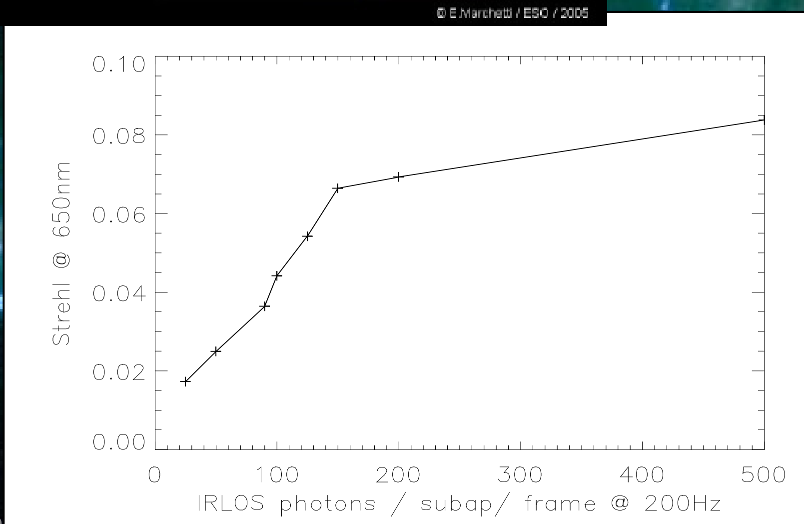

Commissioning camera path
LGS path 4
VLT
LGS path 1
LGS path 3
VIS TT path
MUSE
LGS path 2
Calibration path

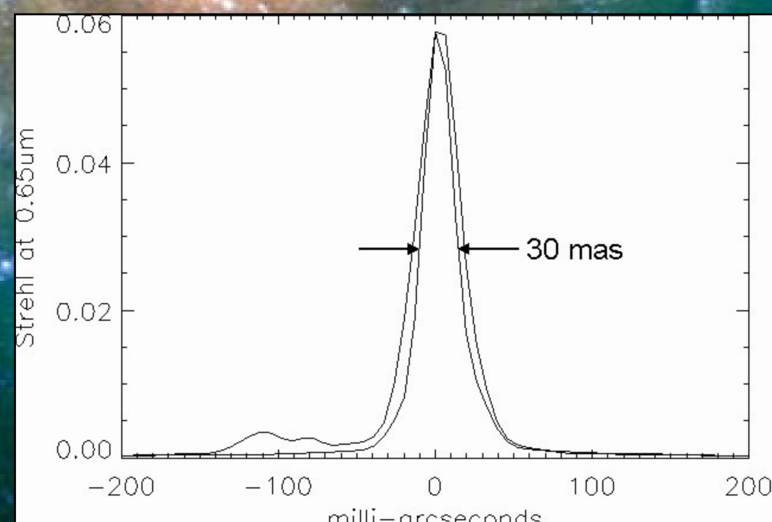

VLT
Field selector
Corrected light to MUSE
Exchangeable lenses
MUSE derotator
LGS Path
Calibration system
Commissioning camera
Tip/Tilt sensor

LASER TOMOGRAPHY: innovative on sky

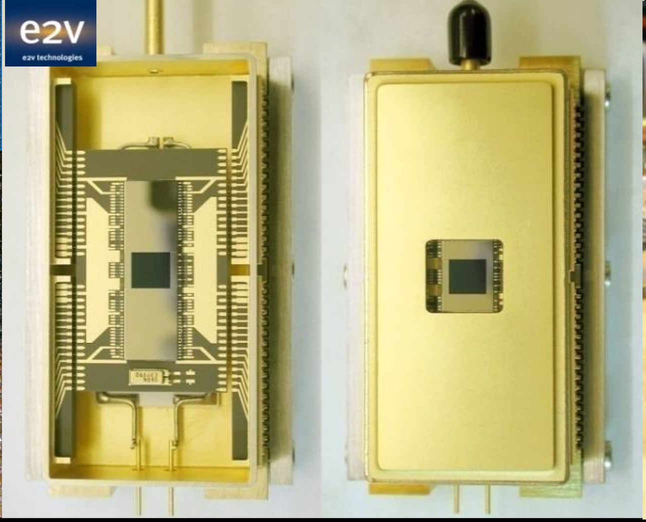


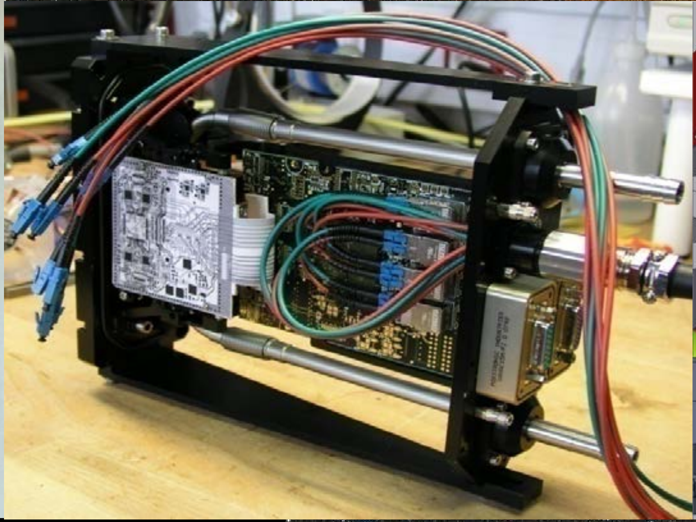
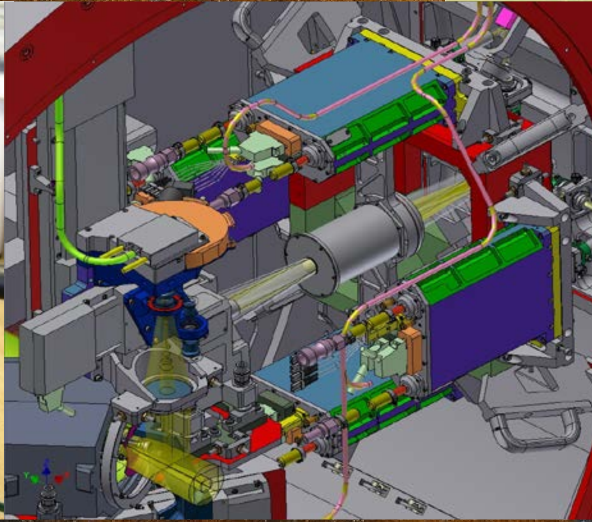
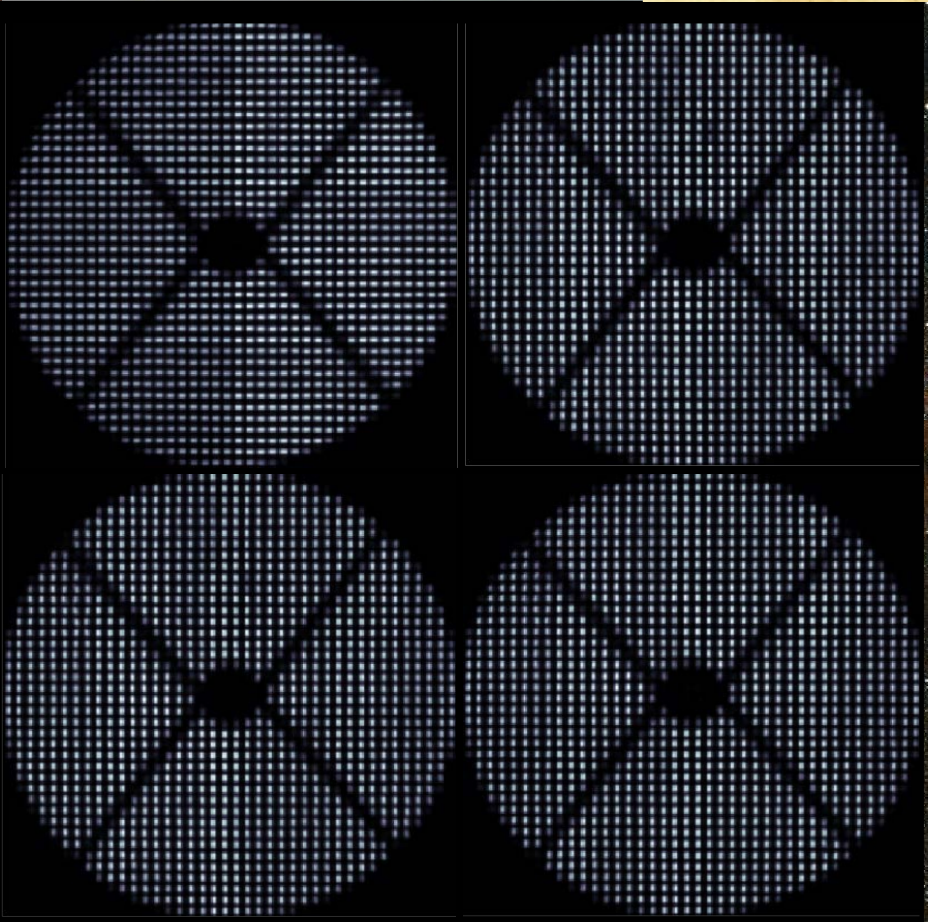
Field of view	1’ WFM (7.5” NFM)
Size of pixel	TT: 0.2” WFM (0.025” NFM); LGS: 0.83”/pixel
Instrument	Muse (VIS 3D-spectrograph)
Modes	GLAO, LTAO
Performance GLAO	×2 in ensquared energy (central pixel), 95% sky coverage
Performance LTAO	Strehl Ratio >5% @0.65µm
WFS	4 LGS L3-CCD (1 e^- Read out Noise) 1 TT L3-CCD 1 TT IR
Loop frequency	= 1 kHz
4LGSF	4 stars ∅2’/∅20” LTAO drives LGS power





Paolo



4-WFS detector and electronics.

E2V CCD 220/SH.

Shack-Hartmann sensor:

40×40 subapertures,

6×6 pixels/subaperture (pixel size: 24 μm).

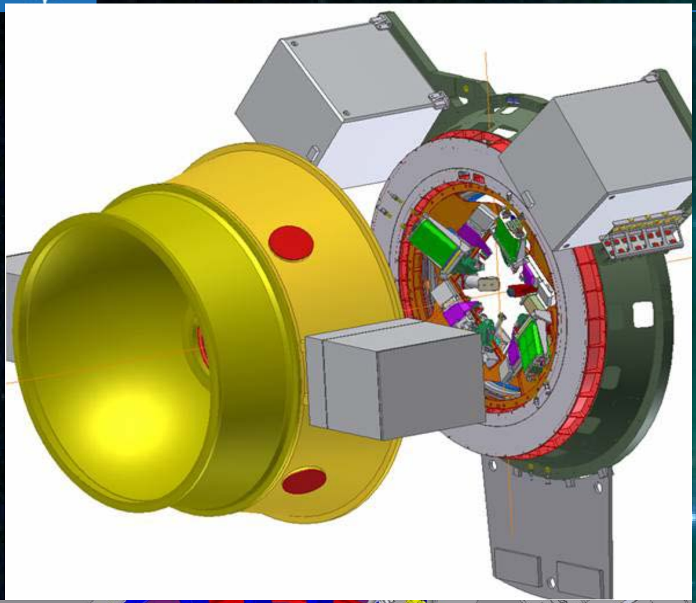
240x240 pixels

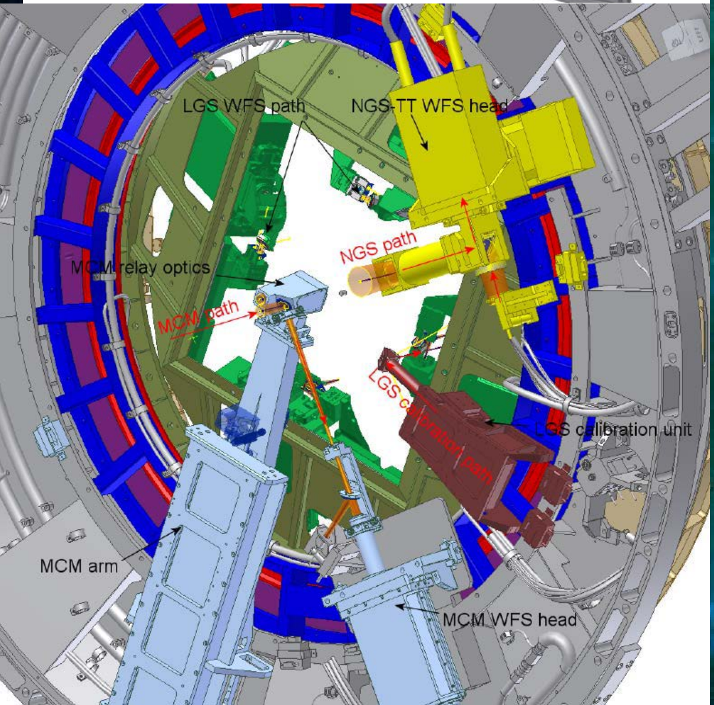
1000 frames/s

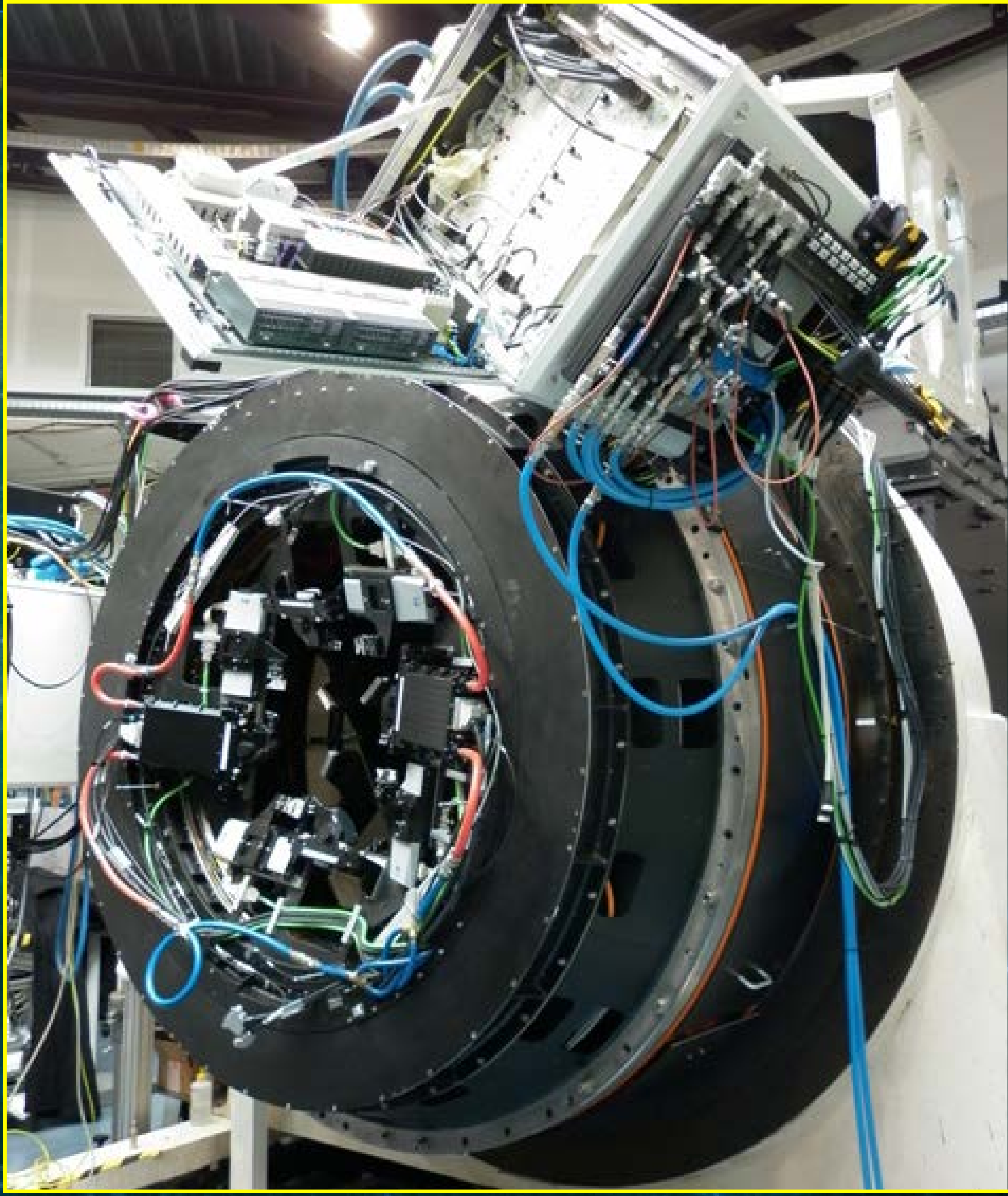
High QE: > 80% @ 589 nm

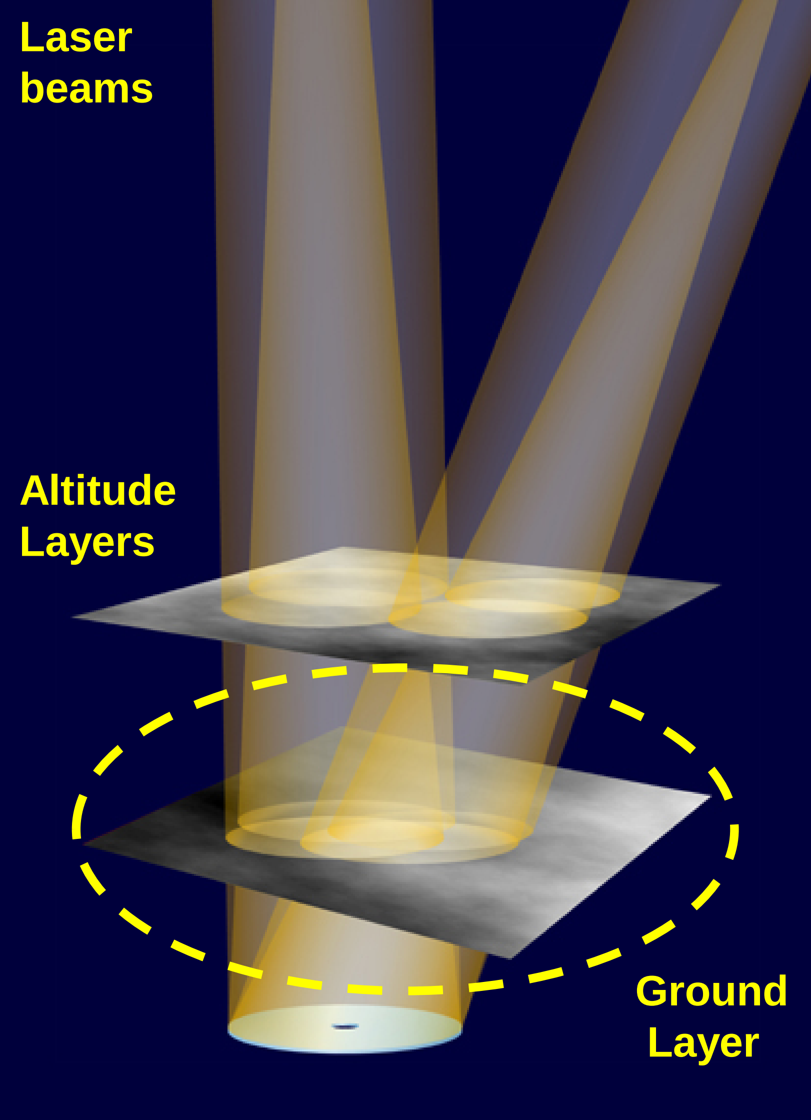
RoN: < 1e⁻/pixel/frame

GRAAL: the HAWK-I imager AO Module

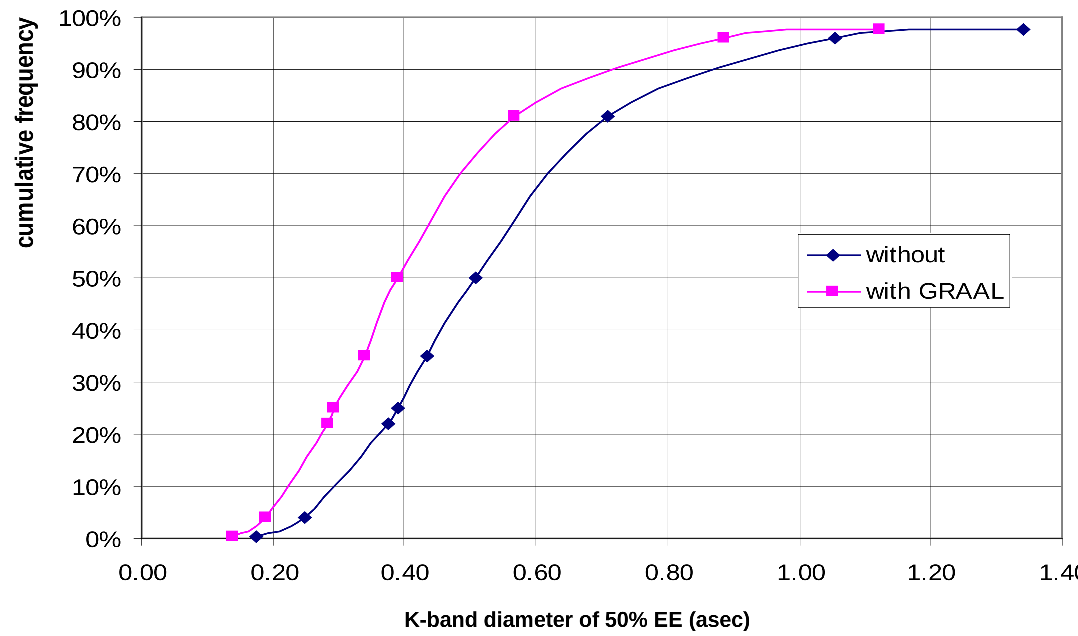






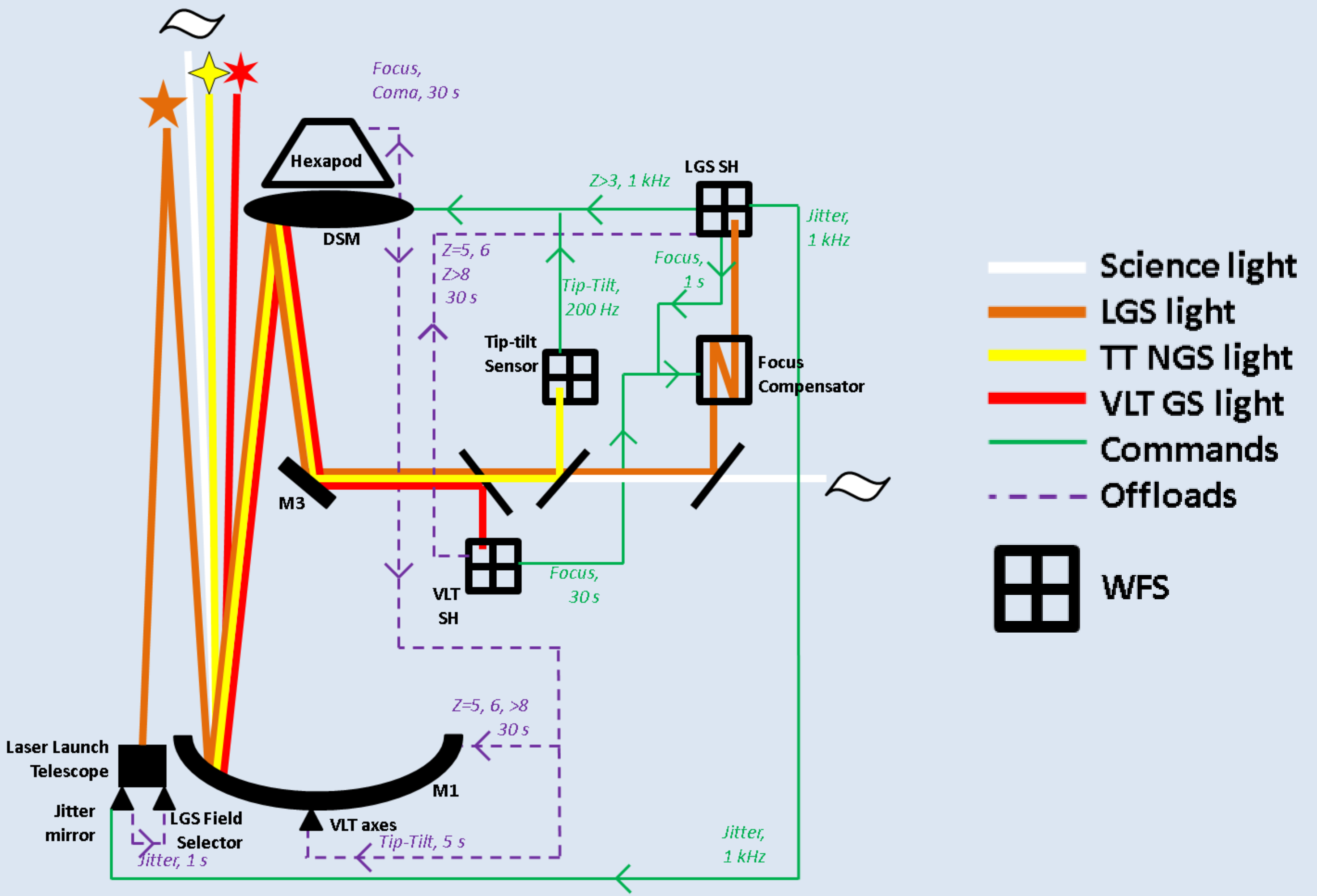


Field of view	7.5’ (10” MCM)
instrument	Hawk-I (IR imager)
modes	GLAO, SCAO
Performance GLAO	x1.7 (central pixel), 95% sky coverage
Performance SCAO	(80% in K-band)
WFS	4 LGS L3-CCD (1 e^- Read out Noise) 1 TT L3-CCD 1 NGS L3-CCD
Loop frequency	≥ 700 Hz
4LGSF	4 stars Ø12’



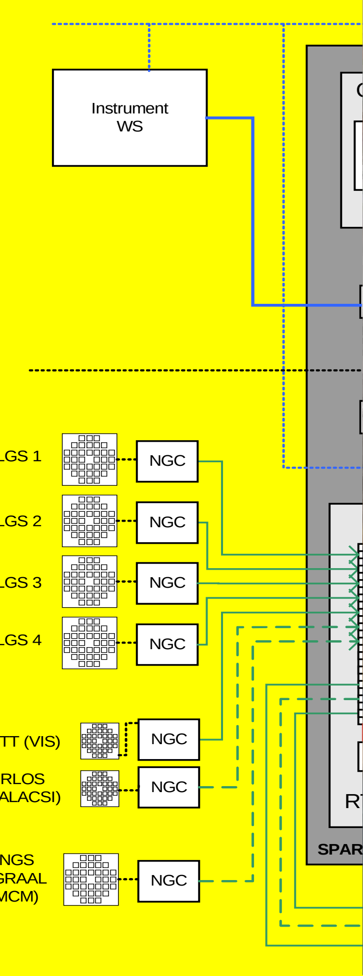
GLAO mode:
Seeing enhancer in
7.5 x 7.5 arcmin^2 FoV

A complex control scheme



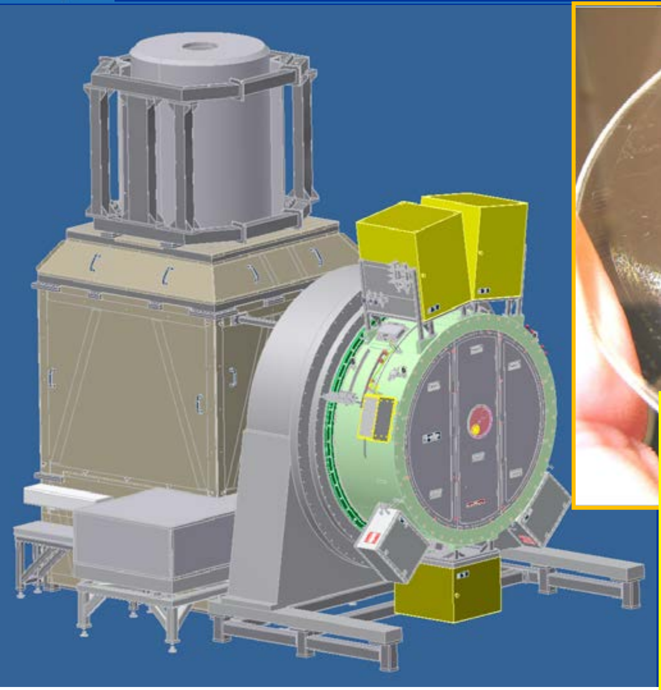
SPAR for AO control

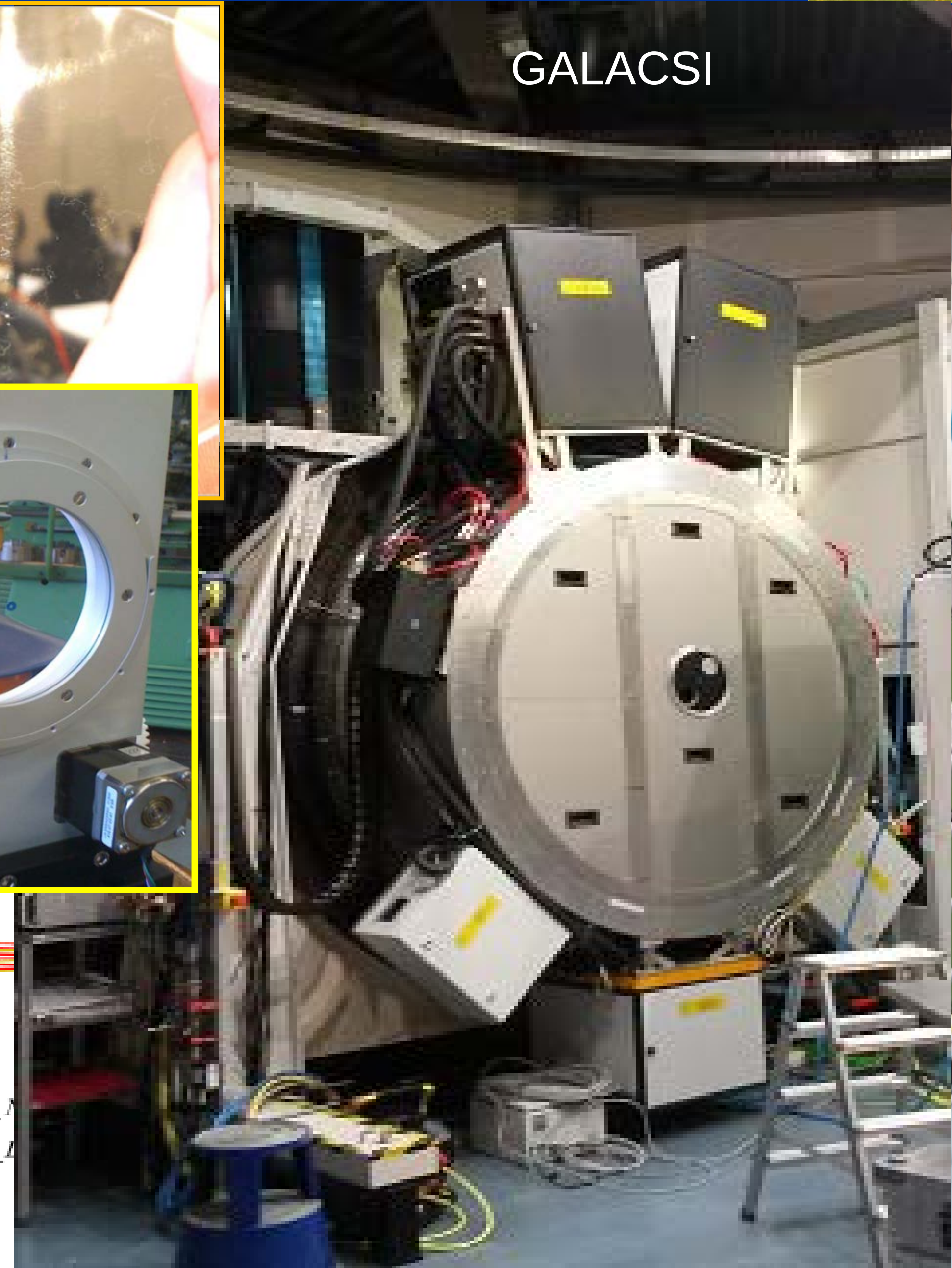
Inputs: 4 x p.) Shack-Hartmann
Outputs: 11

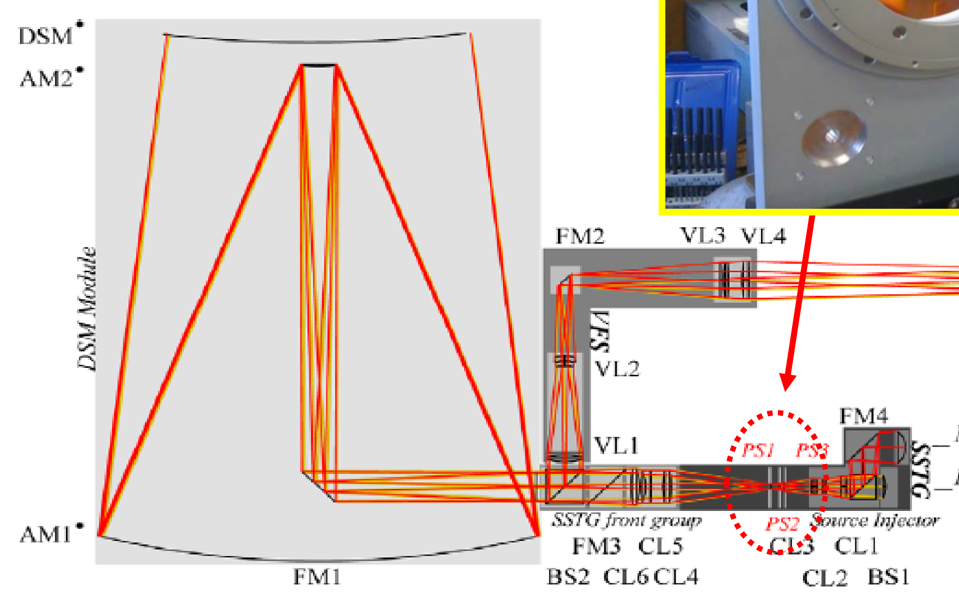


- *Control frequency: 1 kHz latency: 400 μs*
- *WFS measurement algorithm: WCoG*
- *Control algorithm: Matrix Vector Multiplication*

Tests in Europe: ASSIST

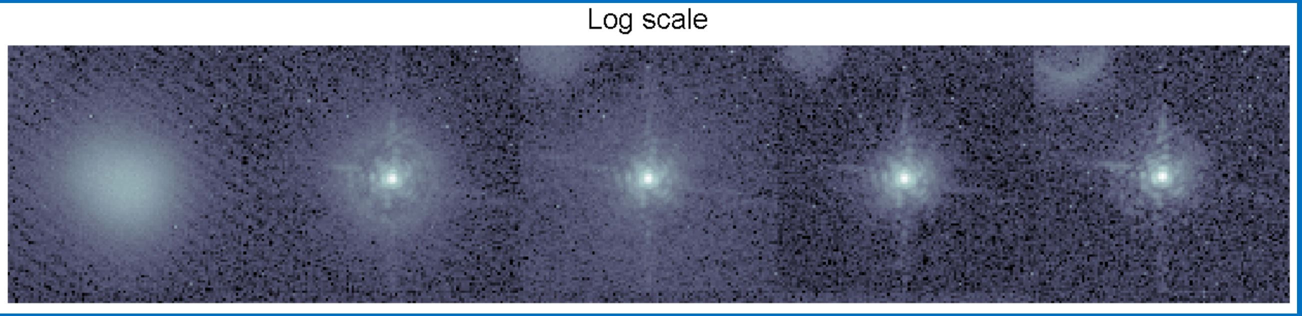


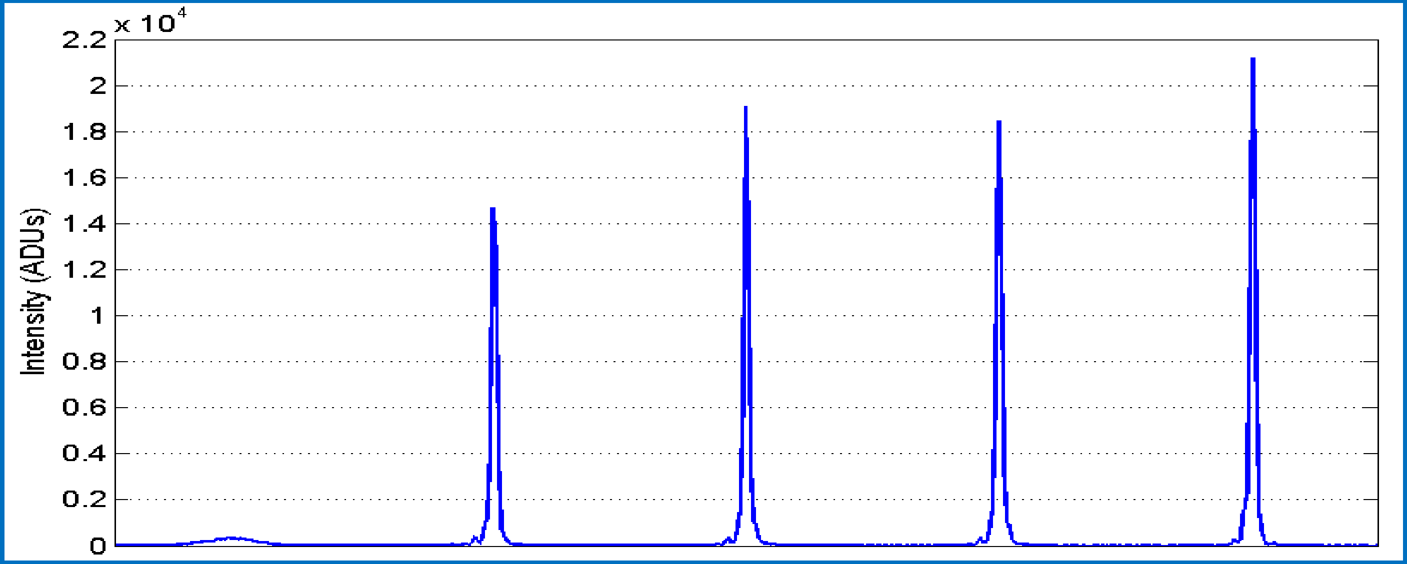




GRAAL closed loop on turbulence SCAO

GRAAL MCM closed loop on turbulence with 0.65" seeing (good seeing)



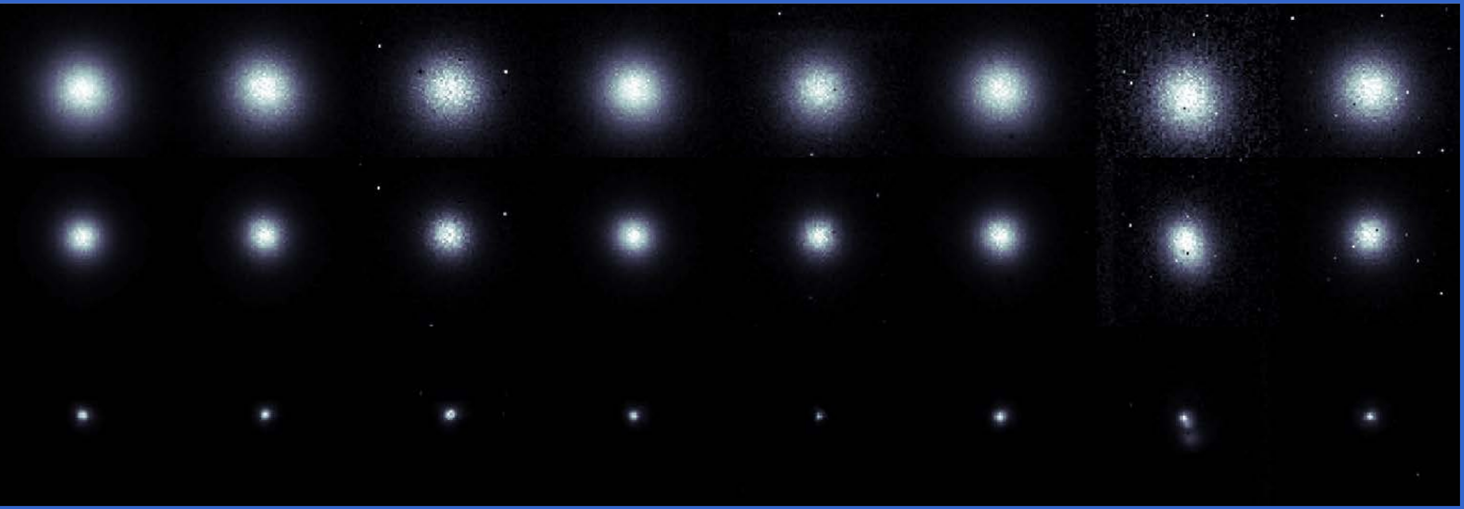


- Peak intensity increases: factor 60 w.r.t. the open loop.
- Estimated the Strehl: 65% in H band (76% on the fiber, no turbulence) ⇒ relative 85%.

Open loop	Closed Loop 150 modes	Closed Loop 550 modes	Closed Loop 950 modes	Reference image (no turbulence)

GRAAL GLAO closed loop on turbulence

λ=1600 nm



Open Loop

Closed Loop

Diffraction Limit

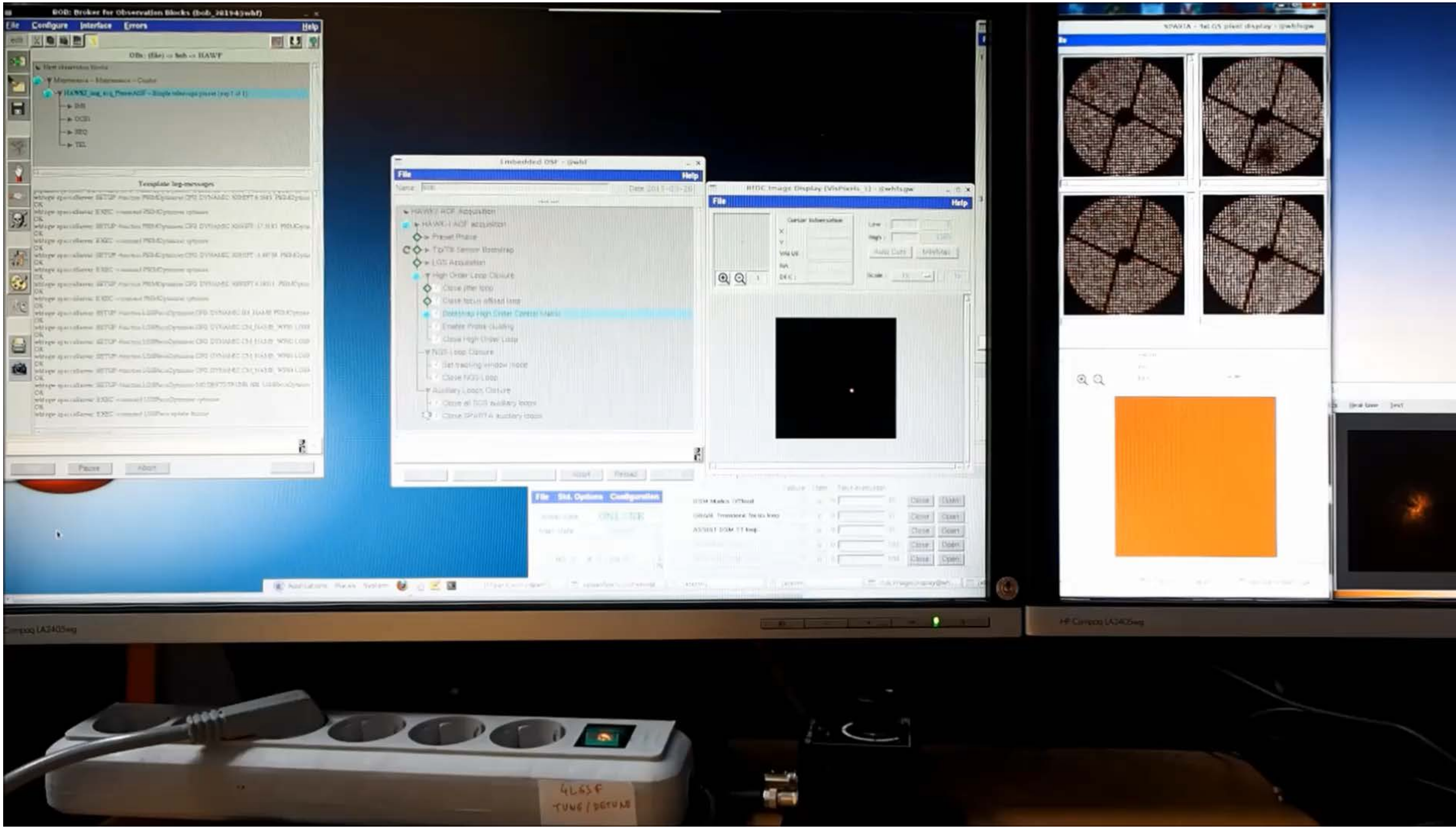
Open loop:

- FWHM = 620 mas (seeing ≅ 1.10 arcsec at 500 nm)

Closed loop:

- 600 modes corrected,G=0.3: FWHM = **355 mas**

gain in FWHM of a factor **1.75 ± 0.06.**


File
Configure
Interface
Errors
Help
Template log-messages

What and when?

- Now:
  - GRAAL has been tested in Garching and is now being integrated at Paranal
  - The first Laser Guide Star is installed and working on the telescope
  - GALACSI is being tested with the Deformable Mirror at Garching

- First mid of 2016:
  - GALACSI and the DSM will be shipped to Paranal
  - All the other LGS will be installed

- Summer 2016: stop for observation of galactic center event

- End 2016: DSM integrated in the telescope
- 2017: AOF commissioning

Credits

ESO

- Sub-Systems Responsible:
- J.Paufique, P.LaPenna, E.Vernet, J.-F.Pirard, W.Hackenberg
- AO Experts:
- M.LeLouarn, S.Stroebele, J.Kolb, N.Muller, A. Garcia-Rissmann, S. Oberti
- Laser Experts:
- D.Bonaccini Calia, T.Pfrommer, S.Lewis, J.L. Alvares
- Mechanics:
- R.Conzelmann, R.Guzman Collazos, M.Quattri, P.Jolley, R.Ridings, J.A.Abad, C.Frank, J.Quentin
- Optics: B.Delabre, B.Buzzoni
- Control & RTC: L.Petazzi, S.Babak, F.Gago, M . Suarez, E. Fedrigo
- Electronics: M.Duchateau, A.Jost, I.Guidolin, L.Kern, G.Fischer, A.Haimerl, C.Soenke, P. Gutierrez
- Detectors: M.Downing, J.Reyes, L.Mehrgan, G. Finger
- Software: M.Kiekebusch, M.Comin, R.Donaldson, P.Duhoux, J.Argomedo
- Integration:S.Tordo, J.-L.Lizon, C.Dupuy
- Operation: P.Amico, P. Haguenauer

- Project Office:
- R.Arsenault, H.Kuntscher, P.-Y.Madec, J.-F. Pirard
- Oversight: N. Hubin, M. Casali, L. Pasquini, S. Stanghelini

Contractors/Collaborations

Istituto Nazionale di Astrofisica
http://www.inaf.it/

Sterrewacht Leiden
http://www.strw.leidenuniv.nl/

Hextec
http://www.hextek.com/

ADS International
http://www.ads-int.com/

Microgate Engineering
http://www.microgate.it/engineering/default.asp

Schott
http://www.schott.com/

Winlight Optical System
http://www.winlight-system.com/

SILIOS Technologies
http://www.silios.com/

Array Electronics
http://www.array-electronics.com/

e2v
http://www.e2v.com/

NTE
http://www.nte.es/

Toptica Photonics
http://www.toptica.com/

MPB Communications Inc.
http://www.mpbc.ca/

Advanced Mechanical and Optical Systems
http://www.amos.be/

Laboratoire d'Astrophysique de Marseille
http://www.oamp.fr/infoglueDeliverLive/www/+LAM

Societé Européenne de Systèmes Optiques
http://www.seso.com/uk/

Sagem
http://sagem-ds.com/

MUSE consortium
http://muse.univ-lyon1.fr/http://sagem-ds.com/

Optical Infrared Coordination Network for Astronomy
http://www.astro-opticon.org/

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
http://www.tno.nl/

Calar Alto Observatory
http://www.caha.es/

Machinenfabriek Boessenkoo bv
http://www.boessenkool.com/

JDSU
http://www.jdsu.com/en-us/Pages/Home.aspx

Precision Optics Gera
http://www.pog.eu/en/products_os_00.html

SUSS MicroTec
http://www.suss.com/

mso jena Mikroschichtoptik GmbH
http://www.suss.com/

Physik Instrumente Piezo nano positioning
http://www.physikinstrumente.de/de/index.php

FASORtronics
http://www.fasortronics.com/FASORtronics/FASORtronics_LLC.html

Nederlandse Onderzoekschool voor de Astronomie
http://www.strw.leidenuniv.nl/nova/