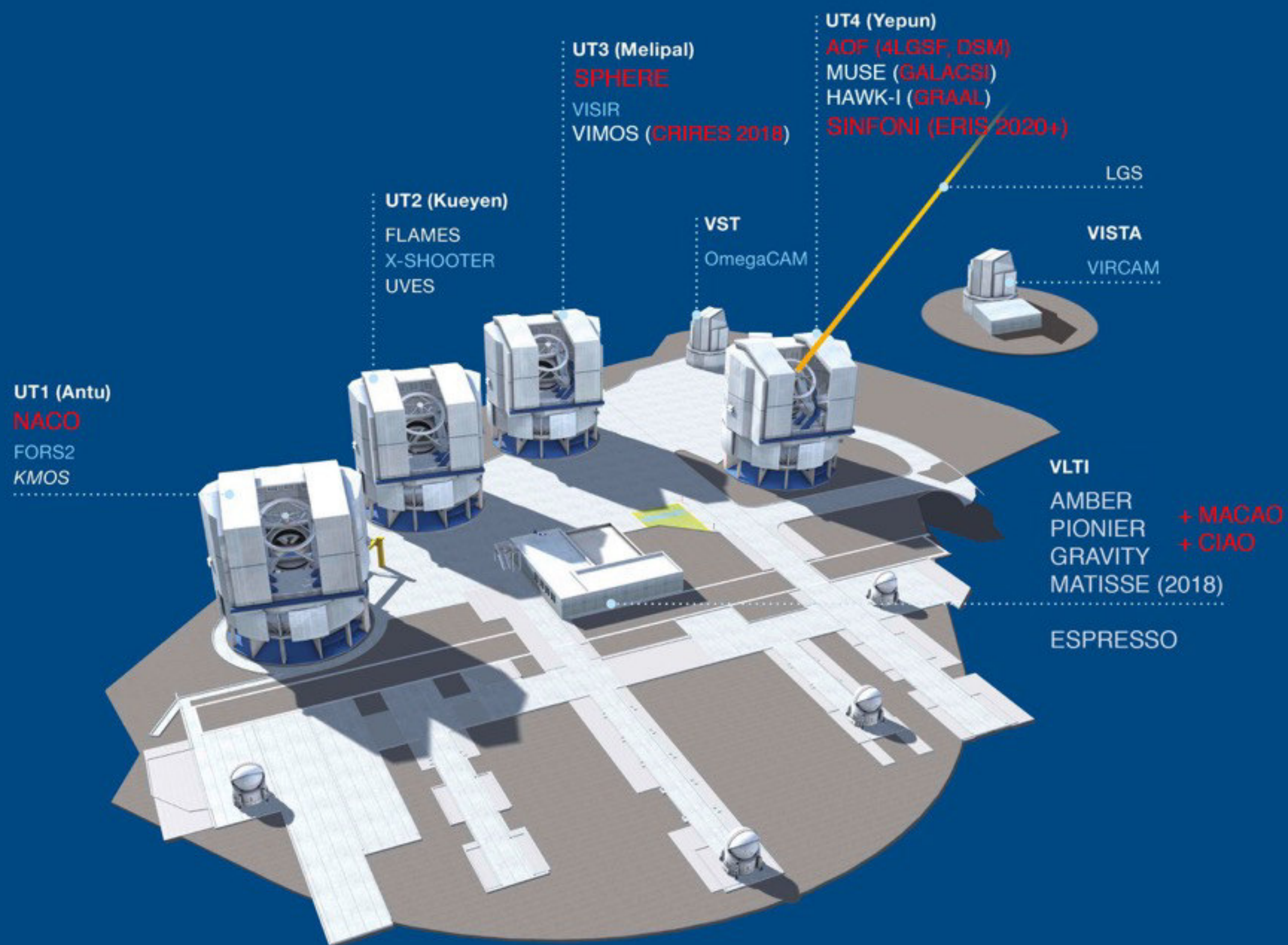
Paranal/VLT Adaptive Optics Instruments 2016+



VLT

NACO	**NA**OS - **CO**NICA [**N**asmyth **A**daptive **O**ptics **S**ystem - **Co**udé **N**ear-**I**nfrared **Ca**mera]
FORS2	**Fo**cal **R**educer **S**pectrograph (#2)
KMOS	**K**-band **M**ulti-**O**bject **S**pectrograph
FLAMES	**F**ibre **L**arge **A**rea **M**ulti-**E**lement **S**pectrograph
X-SHOOTER	Wide range [UV - H-band] point source spectrograph
UVES	**U**v **V**isual **E**chelle **S**pectrograph
SPHERE	**S**pectro-**P**olarimetric **H**igh-contrast **E**xoplanet **Re**search
VISIR	**V**LT **I**mager and **S**pectrometer in the **I**nfra**r**ed
VIMOS	**Vi**sible **M**ulti-**O**bject **S**pectrograph
AOF	**A**daptive **O**ptics **F**acility
MUSE	**M**ulti **U**nit **S**pectroscopic **E**xplorer
GALACSI	**G**round **A**tmospheric **L**ayer **A**daptive Opti**C**s for **S**pectroscopic **I**maging (AOF)
HAWK-I	**H**igh **A**cuity **W**ide field **K**-band **I**mager
GRAAL	**GR**ound-layer **A**daptive optics **A**ssisted by **L**asers (AOF)
SINFONI	**S**pectrograph for **In**tegral **F**ield **O**bservation in the **N**ear-**i**nfrared

In prep:

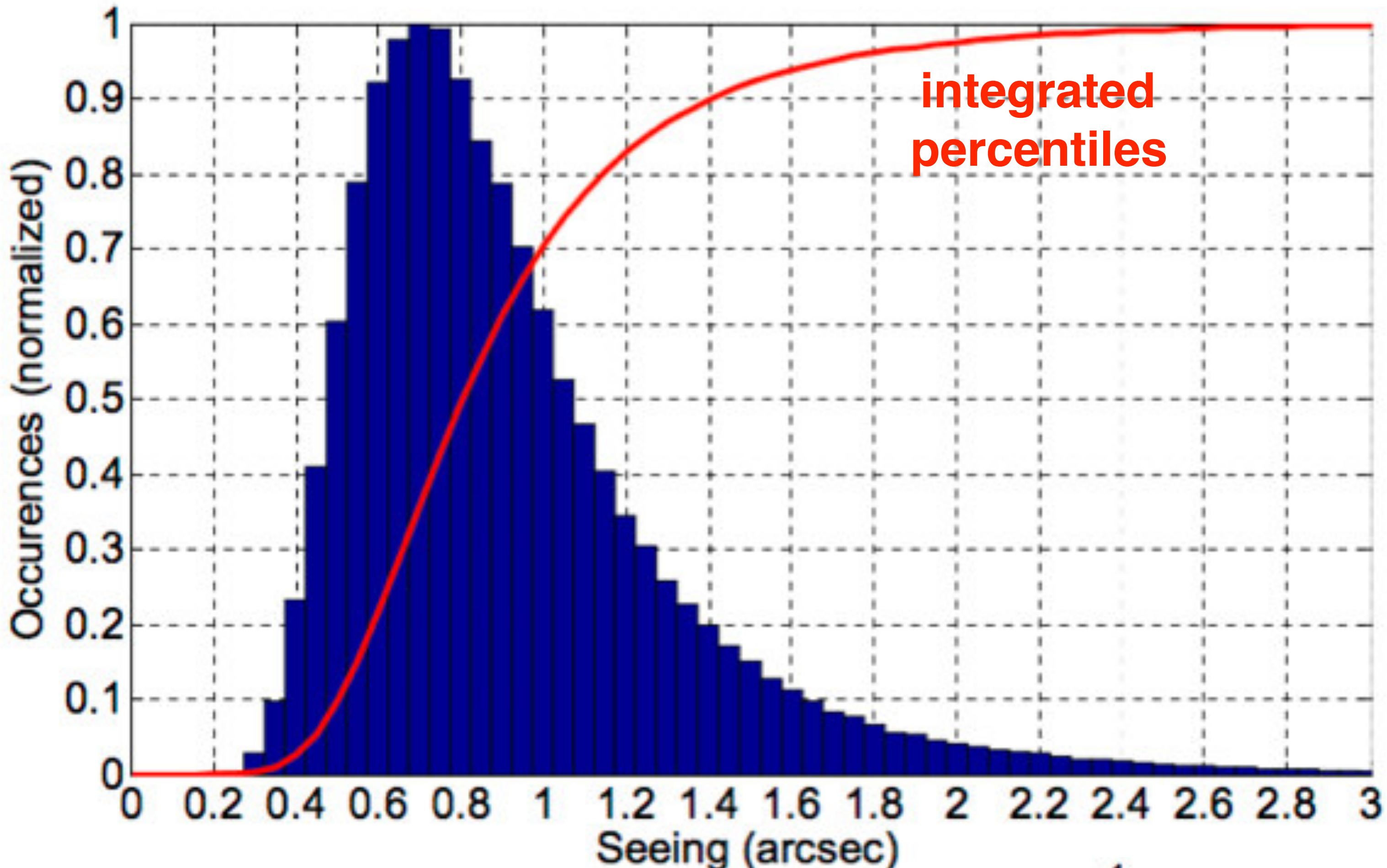
CRIRES+	**Cr**yogenic high resolution **I**nfra**re**d **S**pectrograph (upgrade)
MOONS	**M**ulti-**O**bject **O**ptical and **N**ear-infrared **S**pectrograph
ERIS	**E**nhanced **R**esolution **I**mager and **S**pectrograph

VLTI

ESPRESSO	**E**chelle **Sp**ectrograph for **R**ocky **E**xoplanet and **S**table **S**pectroscopic **O**bservations
AMBER	**A**stronomical **M**ultiple **Be**am **R**ecombiner
PIONIER	**P**recision **I**ntegrated-**O**ptics **N**ear-infrared **I**maging **E**xpe**r**iment H-band, 4-beam imaging combiner (ATs only)
GRAVITY &	**G**eneral **R**elativity **A**nalysis via **V**LT **I**nterferome**try**
CIAO	**C**oudé **I**nfrared **A**daptive **O**ptics
MATISSE	**M**ulti **A**per**t**ure Mid-**I**nfrared **S**pectro**s**copic **E**xperiment (2017/2018)

VISTA

4MOST	**4**-metre **M**ulti-**O**bject **S**pectroscopy **T**elescope



Paranal DIMM data
1999 - 2007

Median seeing: 0.85”
Seeing ~ λ/r_0
λ = 500 nm
=>
Median r_0 = 12.1 cm

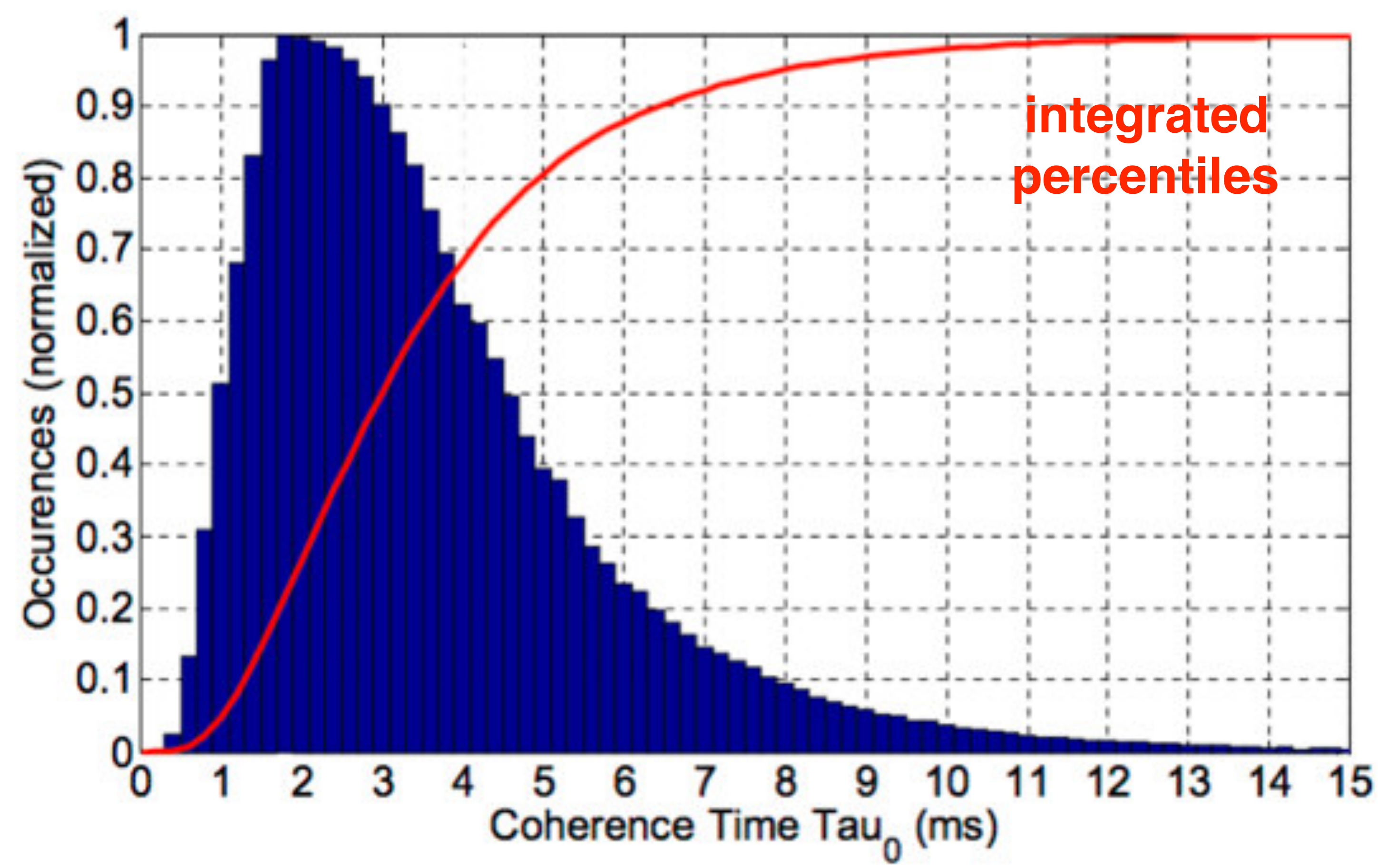


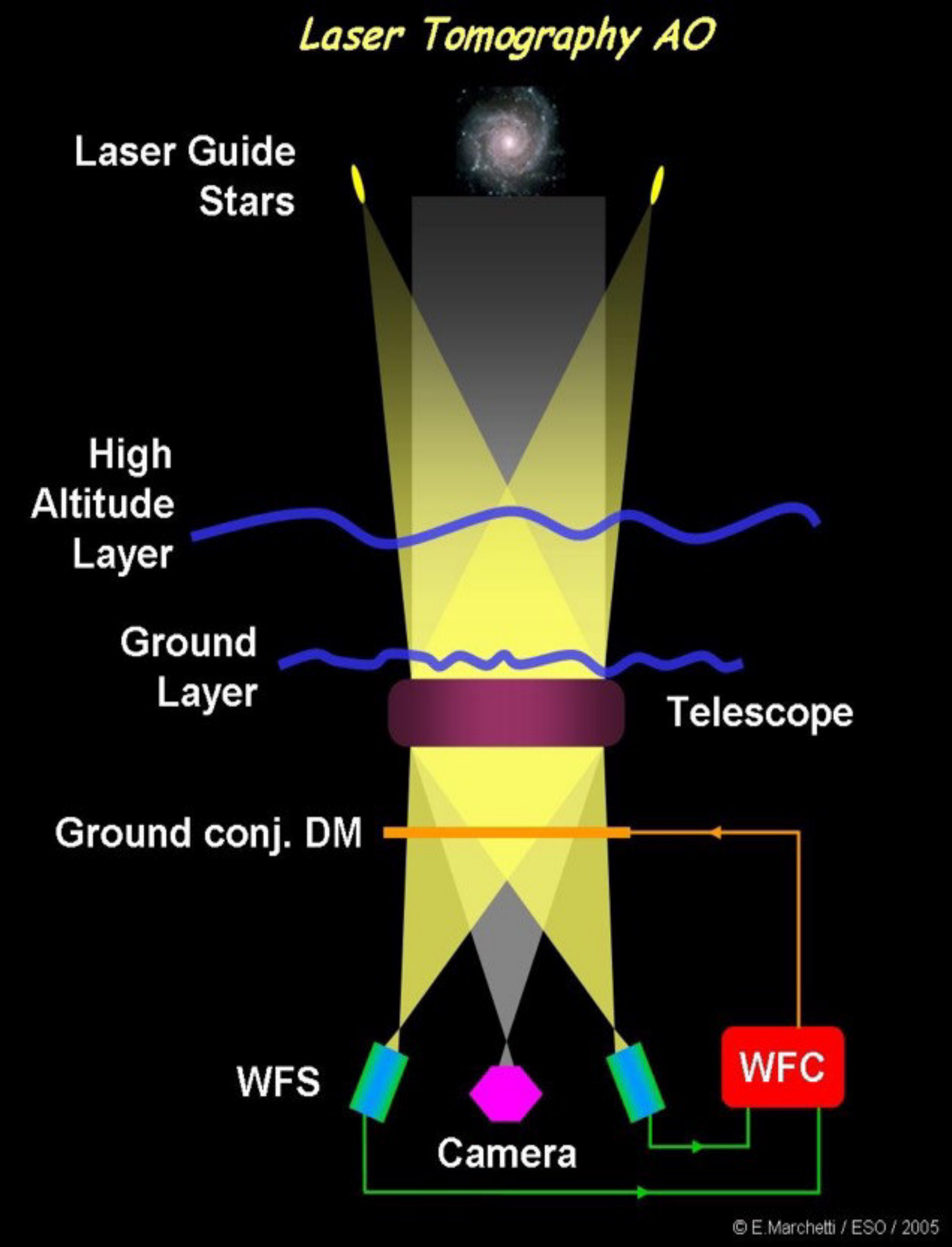
Figure 1: DIMM measurements in Paranal during the period 1999-2007. Histograms (blue bars) and Integrated percentile curves (red) [Top] Seeing at 0.5 microns [Bottom] Coherence time

Median t_0 = 3.1 ms

Site characteristics drive AO design, i.e.
spatial and temporal wavefront sampling

AO Types

- SCAO:
  - 1 Natural guide star, 1 WFS
  - WFS measures Turbulence
  - correction by the DM
- AOF GLAO with Laser guide stars:
  - 4 Laser guide stars, 4 WFSs
  - 1 Natural guide star, 1 TT Sens.
  - Average WFS signal→ High order DM command + tip tilt meas.
- AOF LTAO:
  - 4 Laser guide stars, 4 WFSs (closer together)
  - 1 Natural guide star, 1 low order sensor
  - WFS signal + Tomography Algorithm → high order DM command + tip tilt + focus meas.
  - correction by the DM



ESO Paranal VLT AO Instrumentation

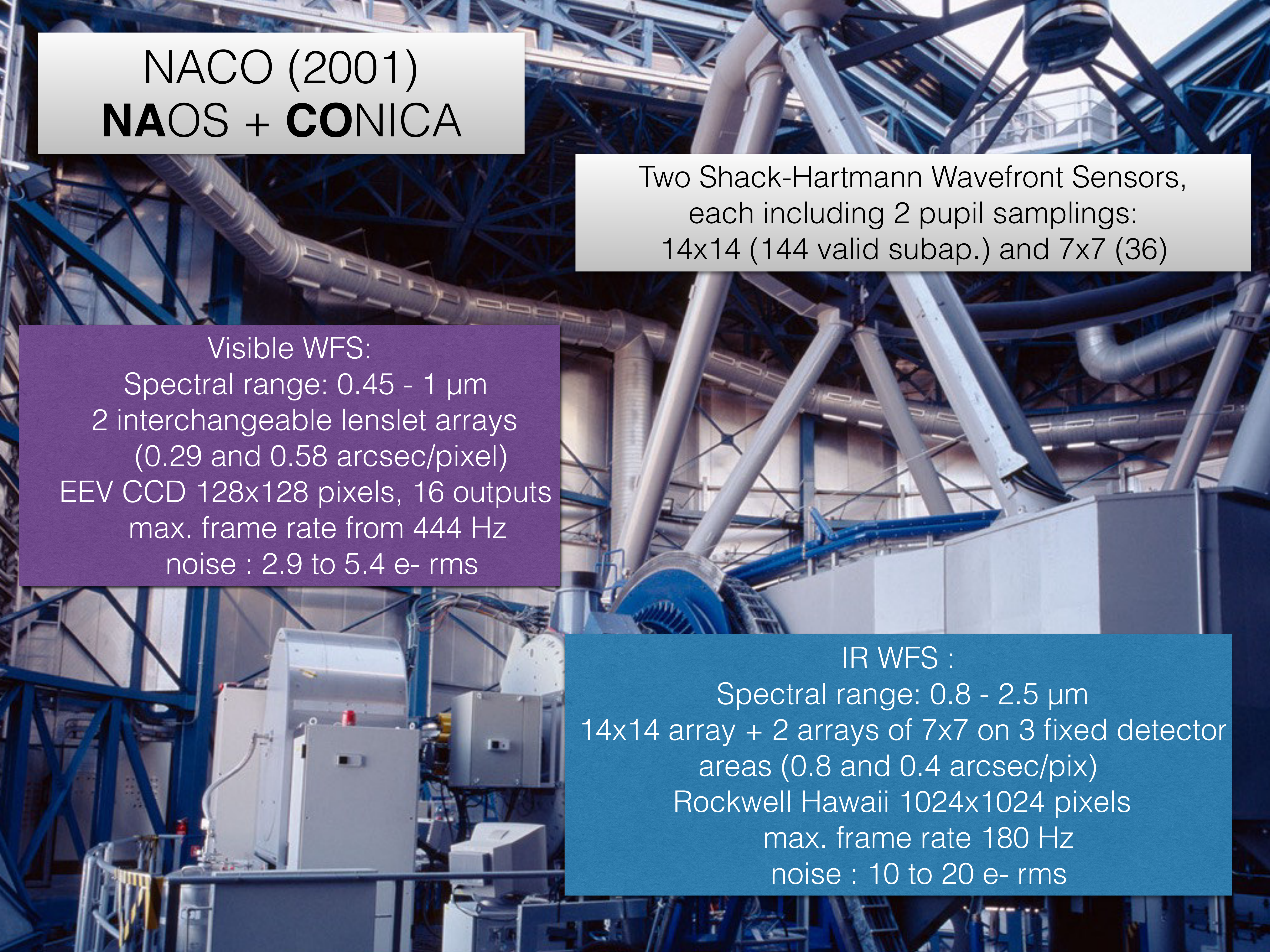
Instrument	NACO - NAOS	SPHERE - SAXO	AOF MUSE- GALACSI HAWK-I - GRAAL	SINFONI - MACAO	VLTI - MACAO	GRAVITY - CIAO
AO “type”	SCAO	XAO	GLAO, LTAO, SCAO	SCAO	SCAO	SCAO
Spectral band of AO	VIS, NIR	VIS, NIR (TT)	VIS	VIS	VIS	NIR
Wavefront sensing	Shack-Hartmann, 7x7, 14x14	Shack-Hartmann, 40x40	4 x Shack-Hartmann, 40x40	Curvature Sensor, 60 elements	Curvature Sensor, 60 elements	Shack-Hartmann, 9x9
Wavefront correction, high order	Piezo stack, 185 actuators	Piezo stack mirror, 41x41 actuators	Voice coil adaptive secondary, 1170 actuators	Bimorph mirror, 60 actuators	Bimorph mirror, 60 actuators	Bimorph mirror, 60 actuators
Max. AO speed	500 Hz	1200 Hz	700-1000 Hz	420 Hz	420 Hz, 1050 Hz	500 Hz
Artificial reference source	Sodium LGS (Parsec)	no	4 x Sodium LGS (4LGSF)	Sodium LGS (Parsec)	no	no
Low-order AO with LGS	STRAP (VIS)	no	LTAO: 2x2 SHWFS (IR), GLAO: VISIBLE WFS	STRAP (VIS)	no	no

GRAAL- GALACSI Comparison

Parameter	GRAAL		GALACSI	
Instrument	Hawk-I (IR imager) ESO		Muse (VIS 3D-spectrograph) Lyon	
Mode	Maintenance mode	GLAO	Wide Field Mode	Narrow Field Mode
Field of view	10”	7.5’	1’	7.5”
AO mode	SCAO	GLAO	GLAO	LTAO
Performance	(S.R. ~ 80% in K-band)	x1.7 EE gain	x2 EE gain	S.R. >5% (10% goal) @650nm
Natural Guide Stars	On axis, ~ 8 mag	R-mag 14.5 within 6.7’ to 7.7’ radius	R-mag <17.5 within 52” to 105” radius	On Axis, NIR, Jmag 15 Low Order sensing
Sky coverage	Close to “bright” stars	95%	>90%	Science target = TT reference
4LGSF config.	NGS only	Ø12’	Ø2’	Ø20”
WFS	1 NGS L3-CCD (40*40 sub app.)	4 LGS L3-CCD (40*40 sub app.) 1 TT L3-CCD	4 LGS L3-CCD (40*40 sub app.) 1 TT L3-CCD	4 LGS L3-CCD (40*40 sub app.) 1 IR Low Order
Loop frequency	HO loop: ≥ 700 Hz	HO loop: ≥ 700 Hz TT loop: 250Hz	HO loop: 1 kHz TT loop: 200Hz	HO loop: 1 kHz LO loop: 200-500Hz

Credit: Stefan Ströbele

NACO (2001)
NAOS + **CO**NICA



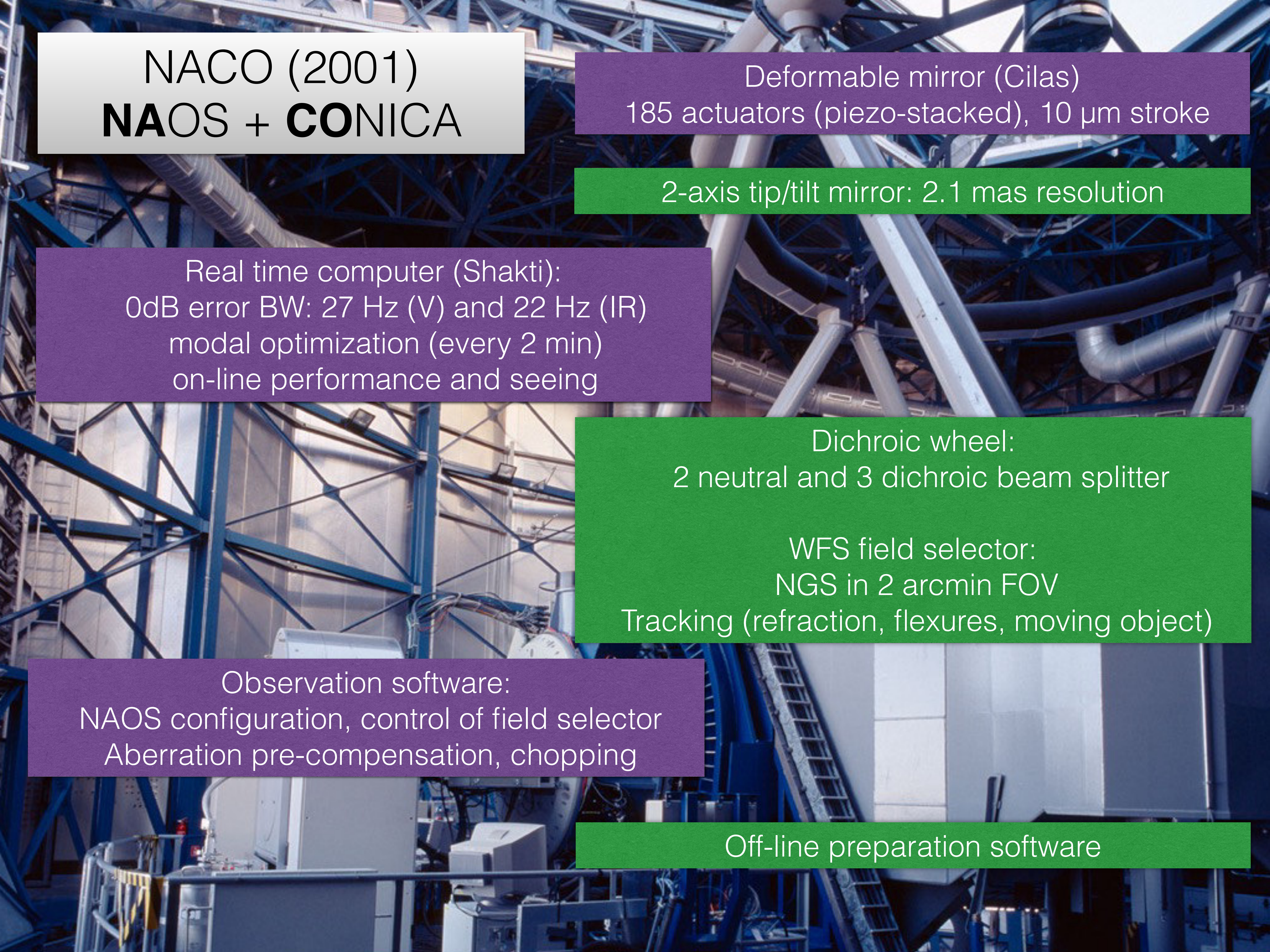
NACO (2001)
NAOS + **CO**NICA

Two Shack-Hartmann Wavefront Sensors,
each including 2 pupil samplings:
14x14 (144 valid subap.) and 7x7 (36)

Visible WFS:
Spectral range: 0.45 - 1 µm
2 interchangeable lenslet arrays
(0.29 and 0.58 arcsec/pixel)
EEV CCD 128x128 pixels, 16 outputs
max. frame rate from 444 Hz
noise : 2.9 to 5.4 e- rms

IR WFS :
Spectral range: 0.8 - 2.5 µm
14x14 array + 2 arrays of 7x7 on 3 fixed detector areas (0.8 and 0.4 arcsec/pix)
Rockwell Hawaii 1024x1024 pixels
max. frame rate 180 Hz
noise : 10 to 20 e- rms

NACO (2001)
NAOS + **CO**NICA



Deformable mirror (Cilas)
185 actuators (piezo-stacked), 10 μm stroke

2-axis tip/tilt mirror: 2.1 mas resolution

Real time computer (Shakti):
0dB error BW: 27 Hz (V) and 22 Hz (IR)
modal optimization (every 2 min)
on-line performance and seeing

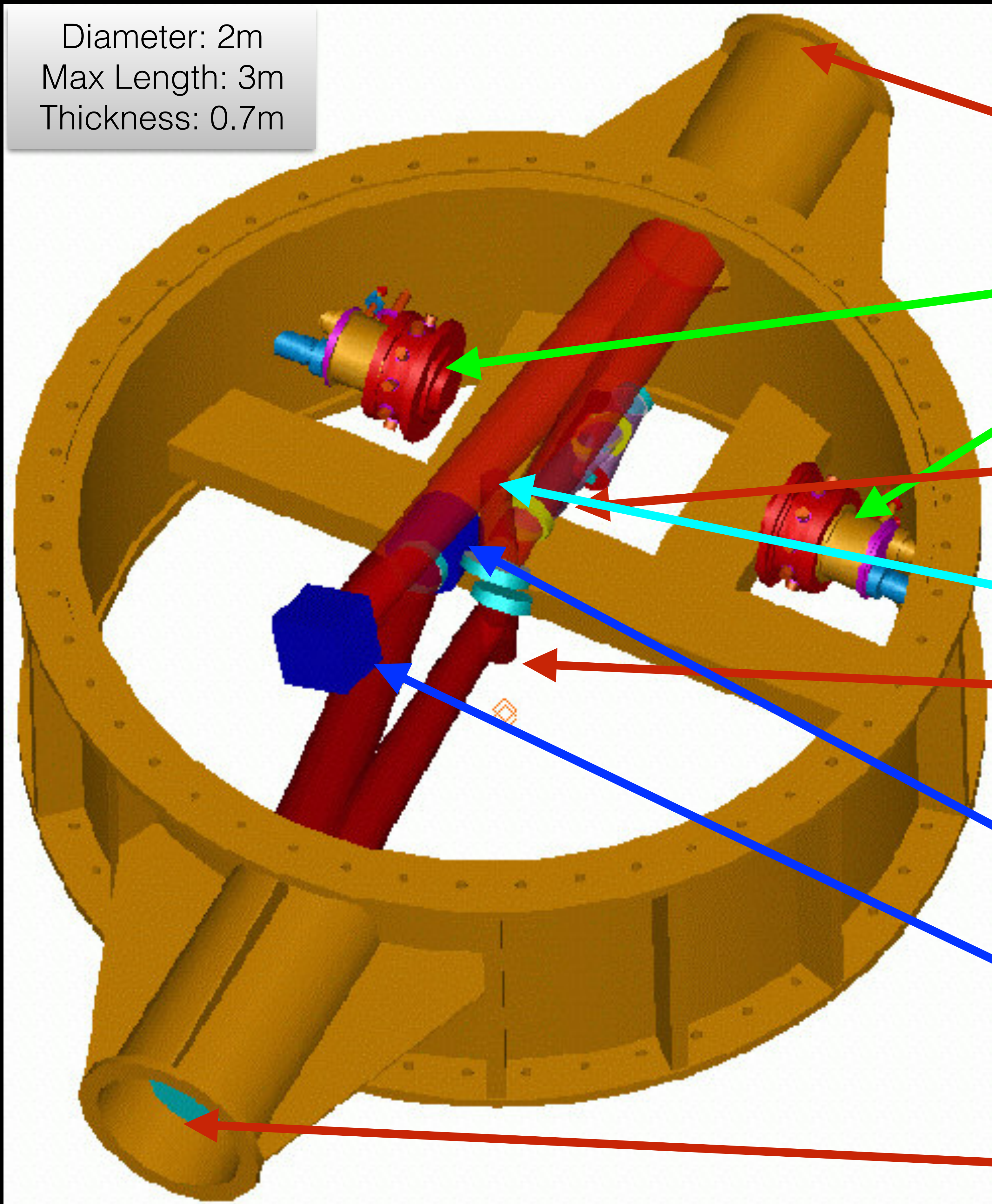
Dichroic wheel:
2 neutral and 3 dichroic beam splitter

WFS field selector:
NGS in 2 arcmin FOV
Tracking (refraction, flexures, moving object)

Observation software:
NAOS configuration, control of field selector
Aberration pre-compensation, chopping

Off-line preparation software

NAOS Opto-Mechanical Design



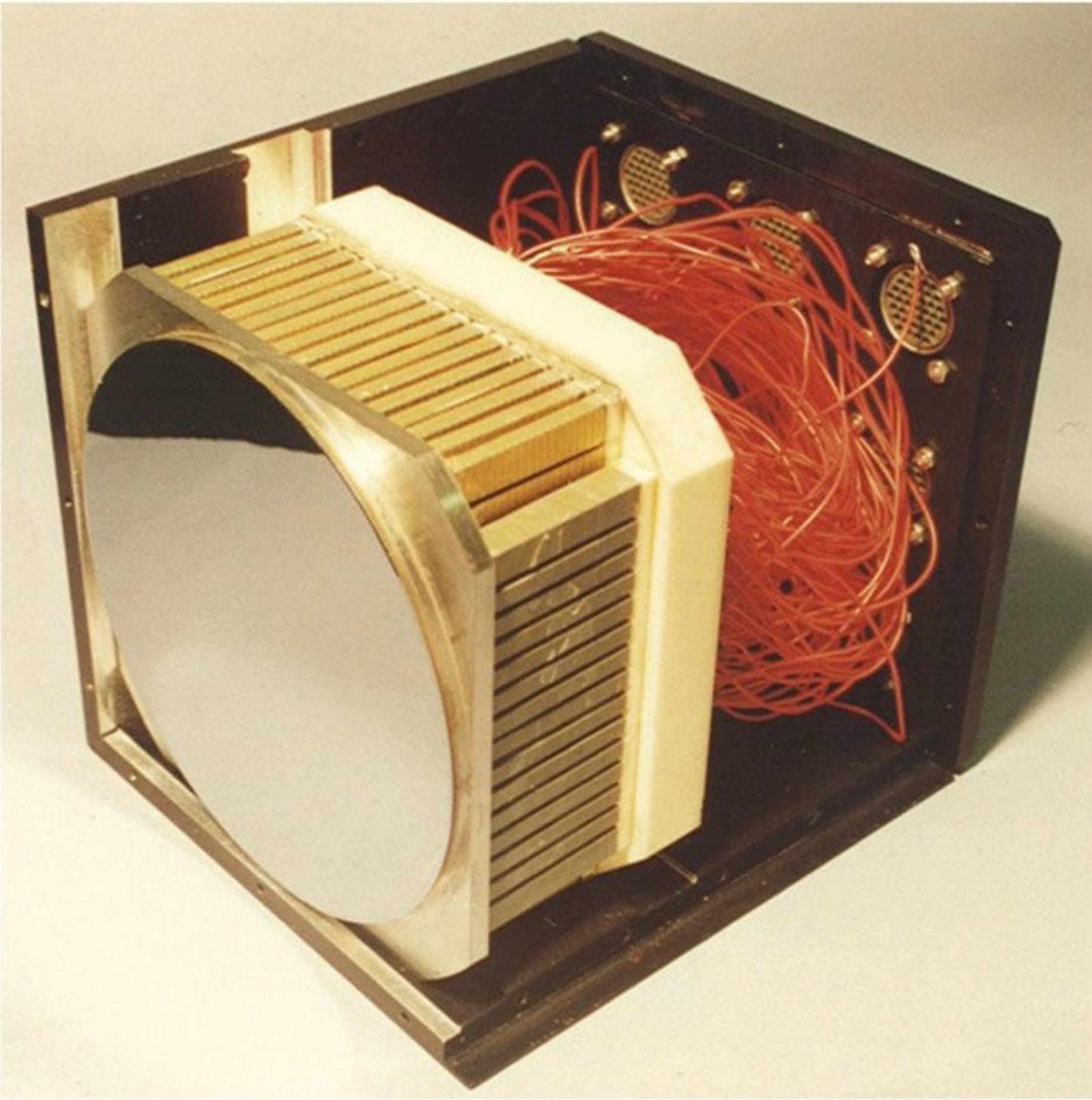
Wavefront measurement and correction in the pupil plane

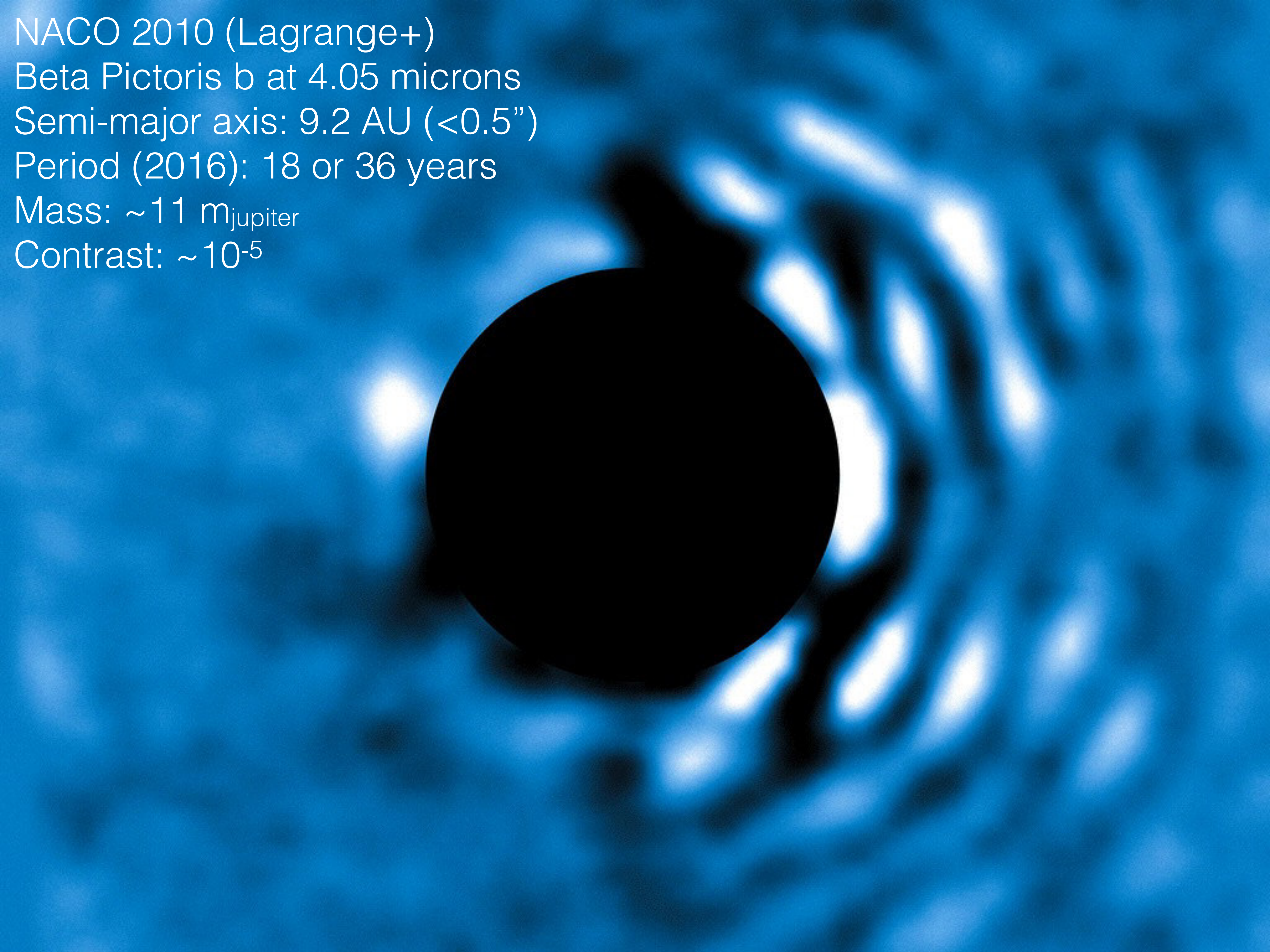
Telescope pupil

185 active actuators

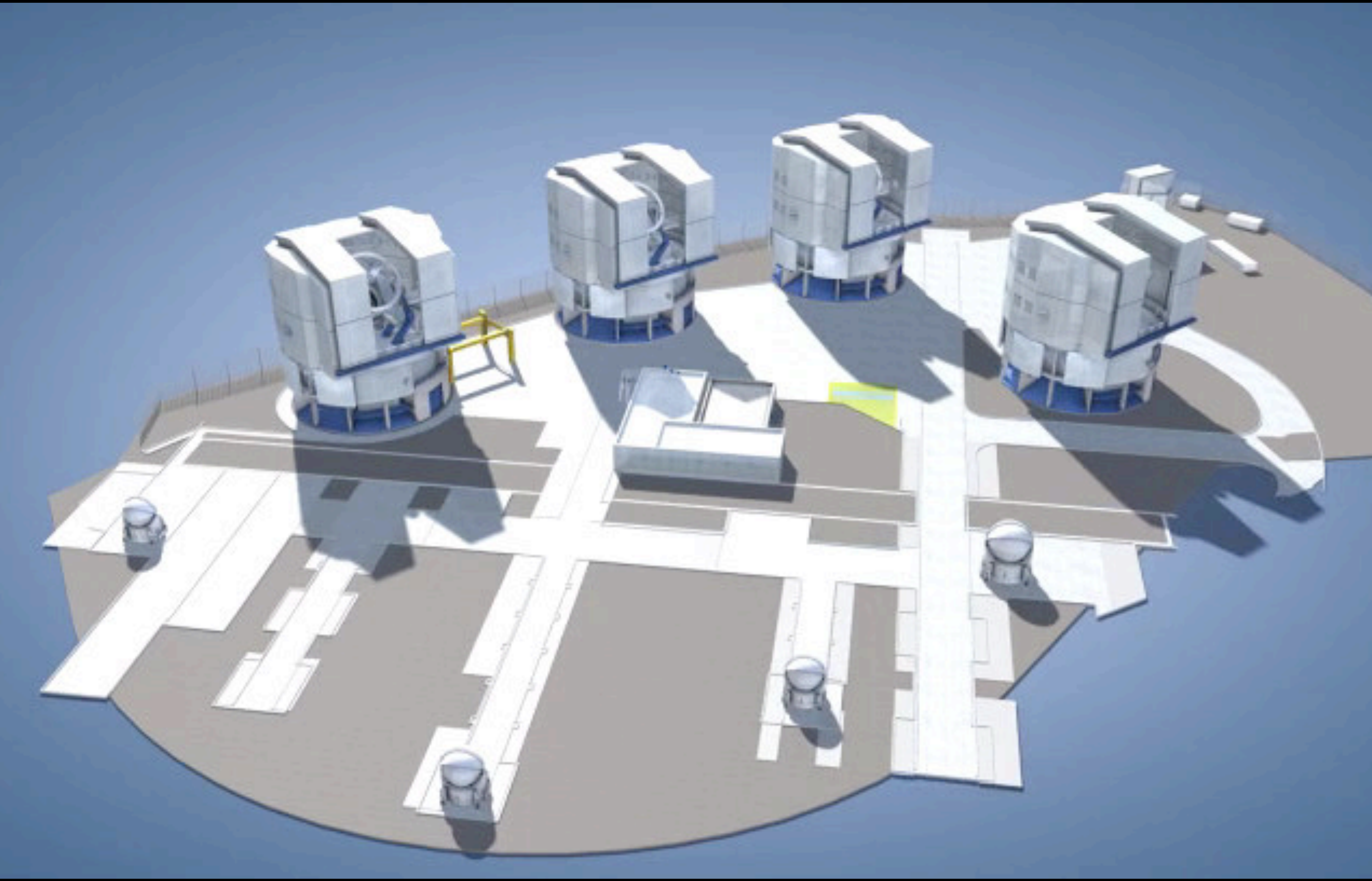
144 active sub-apertures

Central obscuration



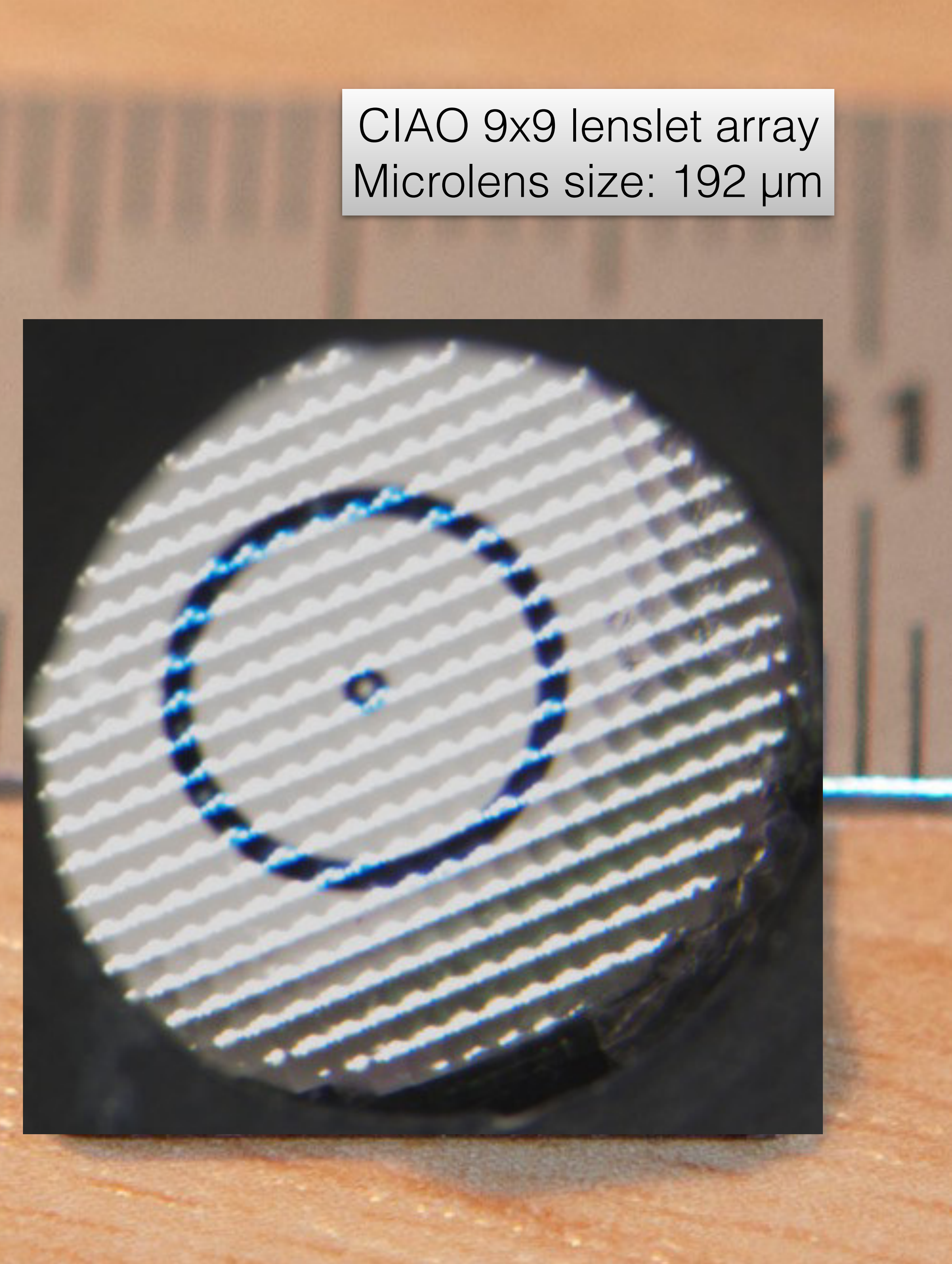

NACO 2010 (Lagrange+)
Beta Pictoris b at 4.05 microns
Semi-major axis: 9.2 AU (<0.5”)
Period (2016): 18 or 36 years
Mass: ~11 $m_{jupiter}$
Contrast: ~10^{-5}

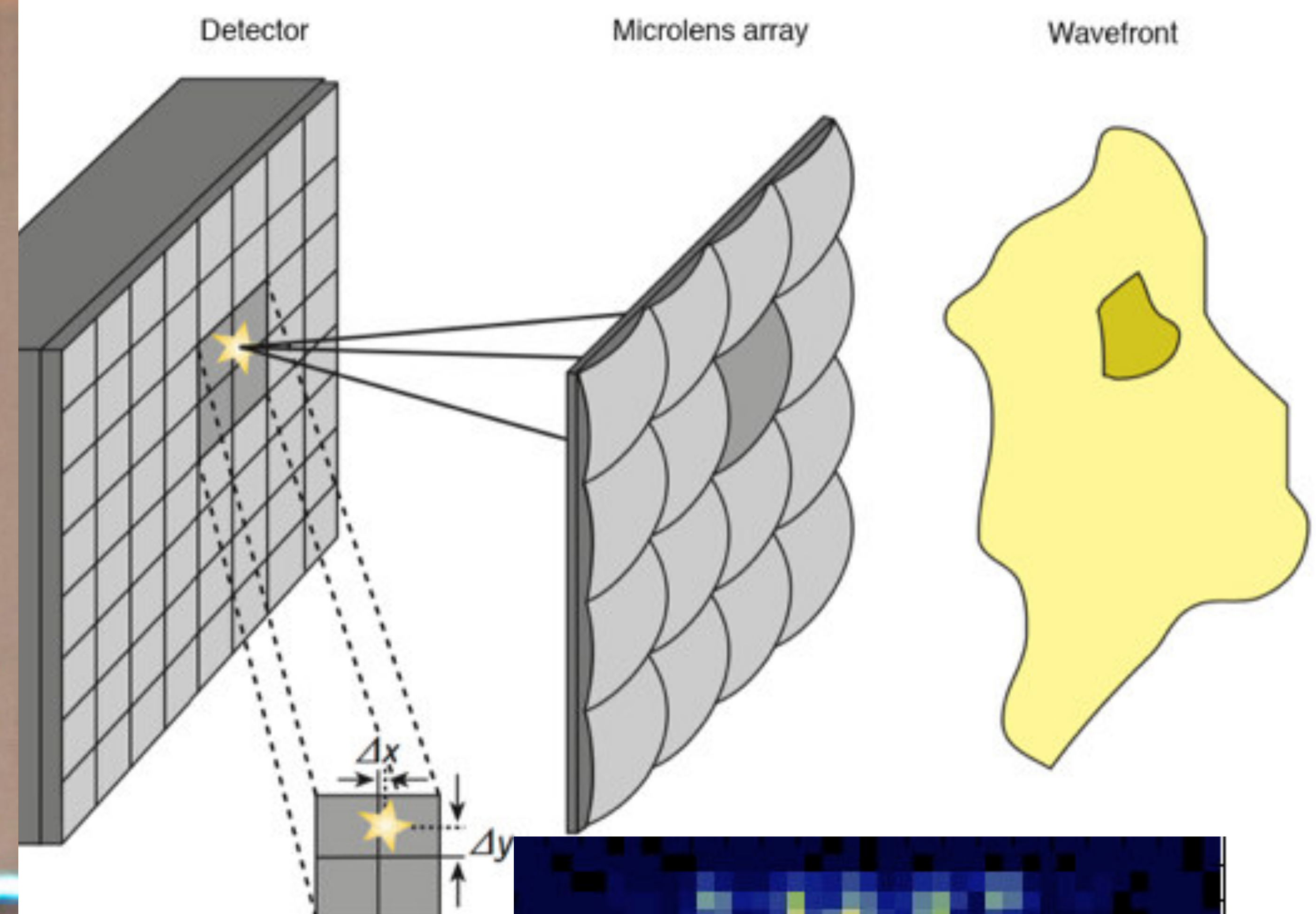
GRAVITY: Interferometry with Adaptive Optics CIAO

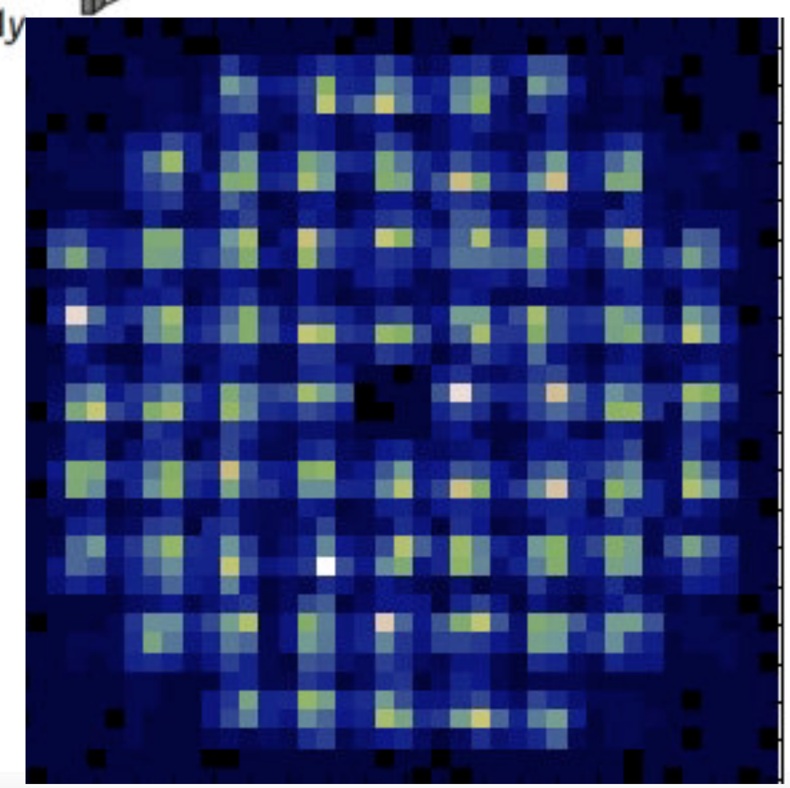


Video: ESO

front sensor in a nutshell

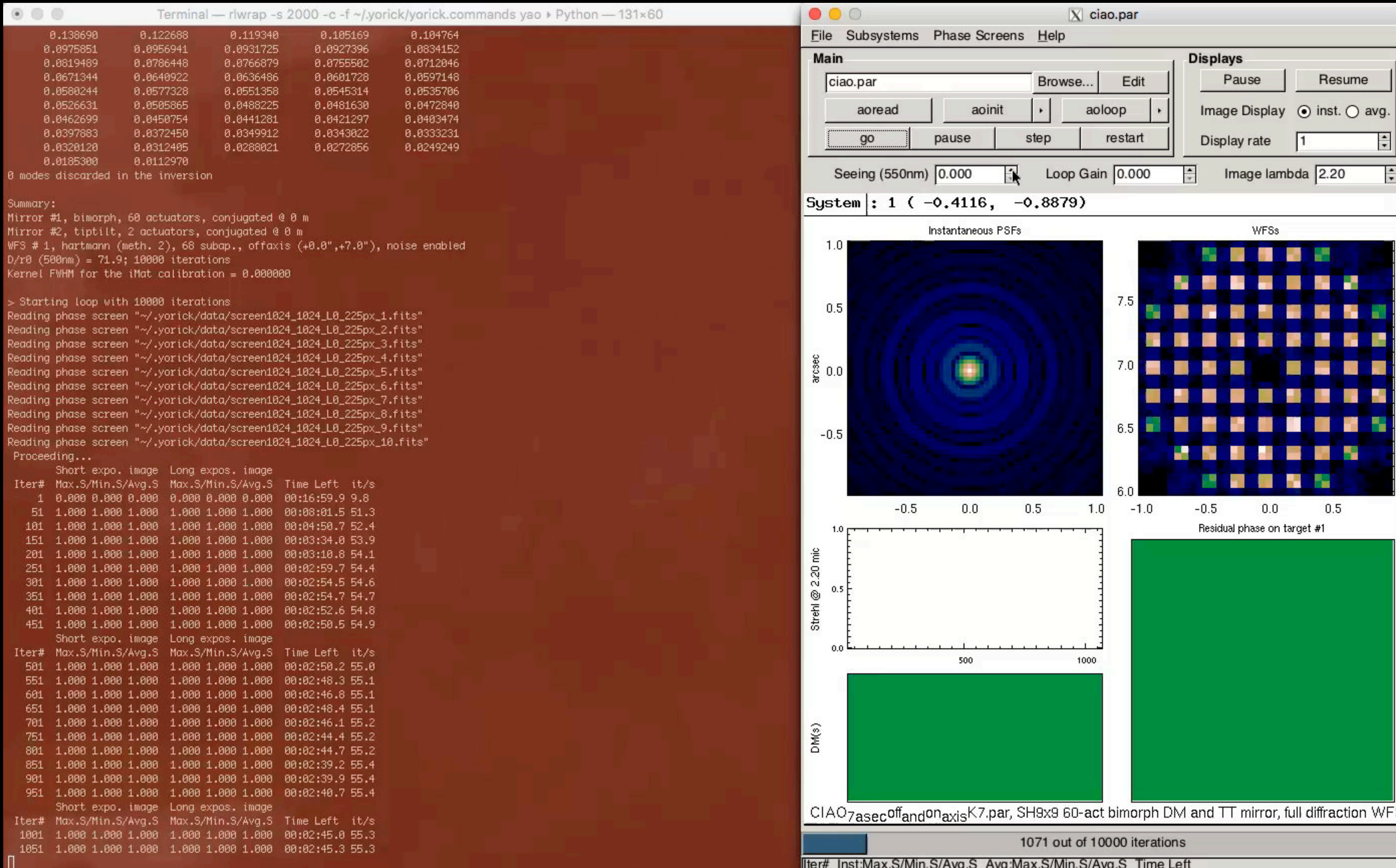


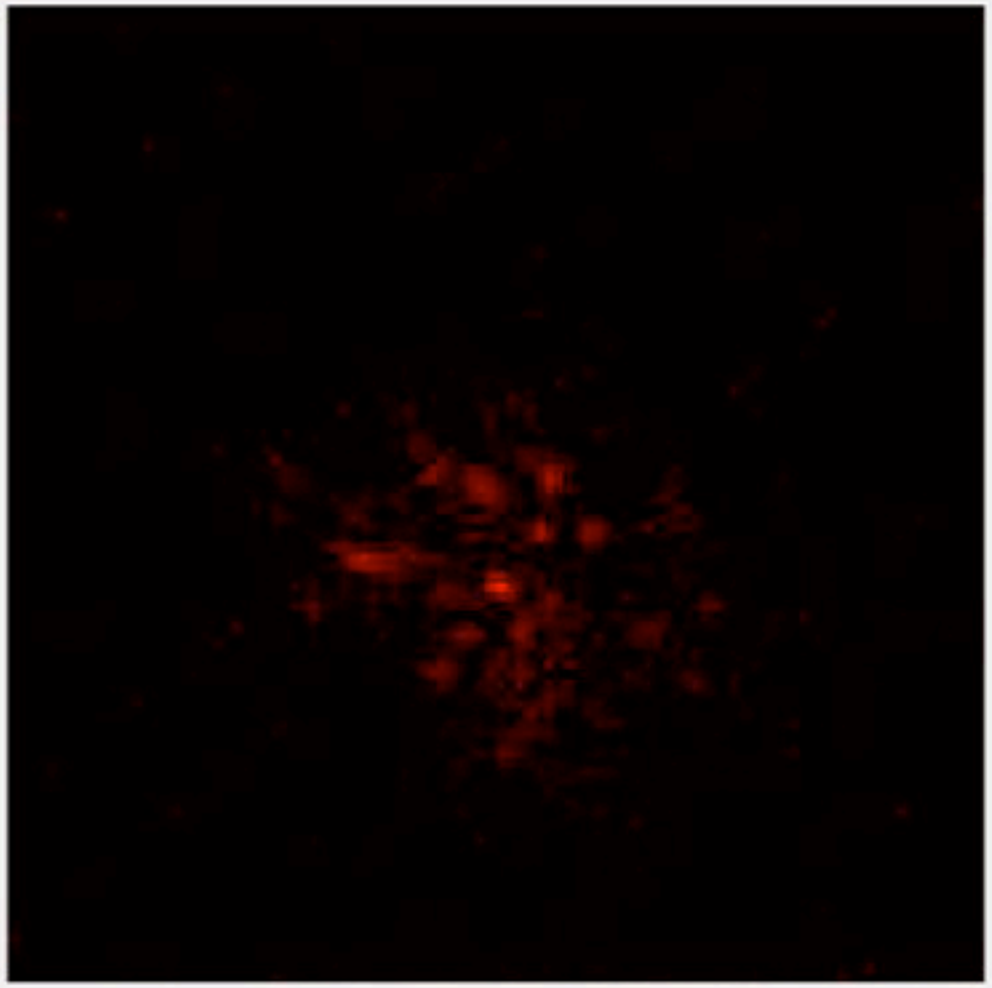




SH WFS is a pupil plane measurement of local wavefront slopes (first derivative of the wavefront) within a sub-aperture defined by a lenslet array.

CIAO Simulation with yao

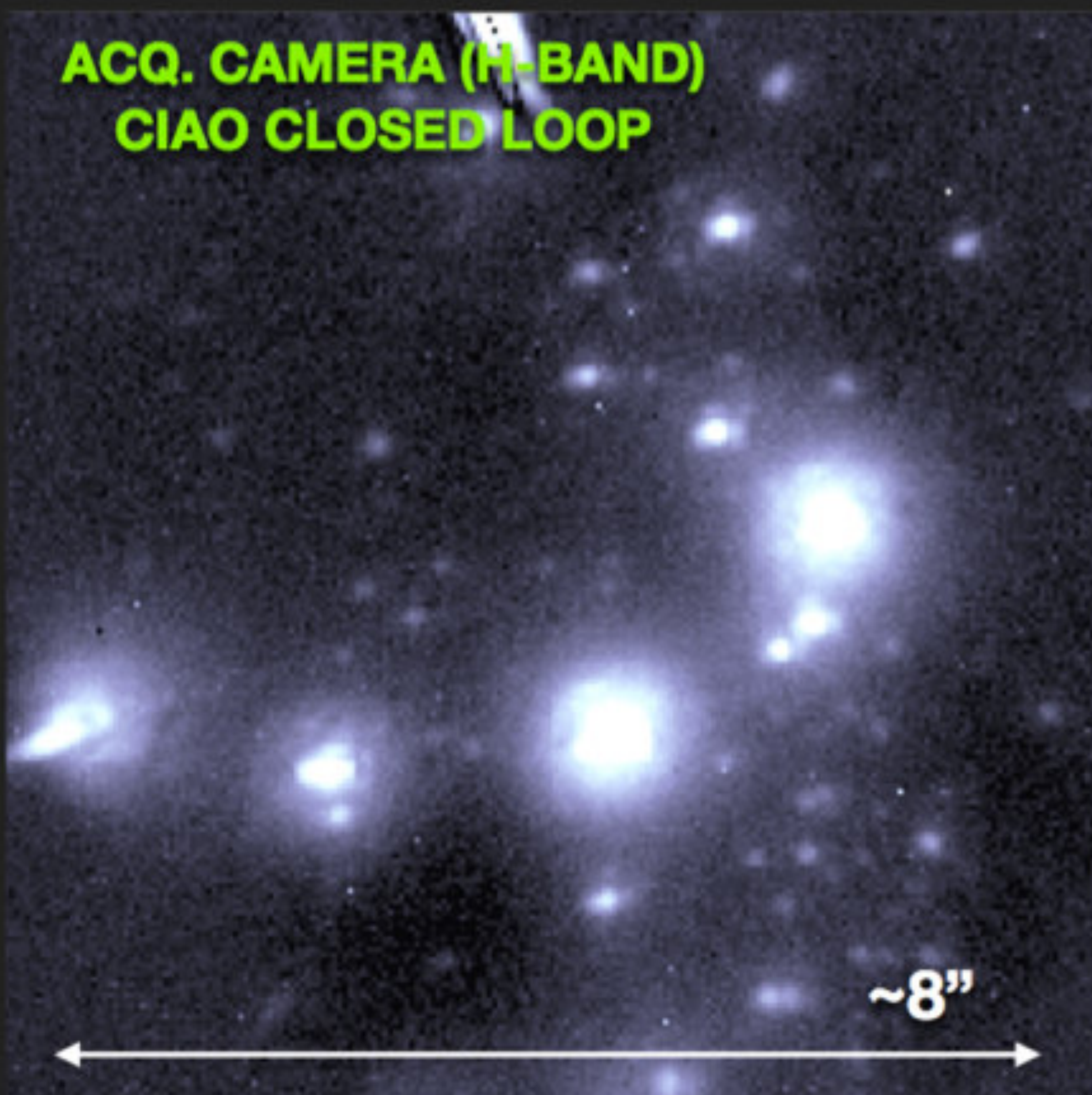


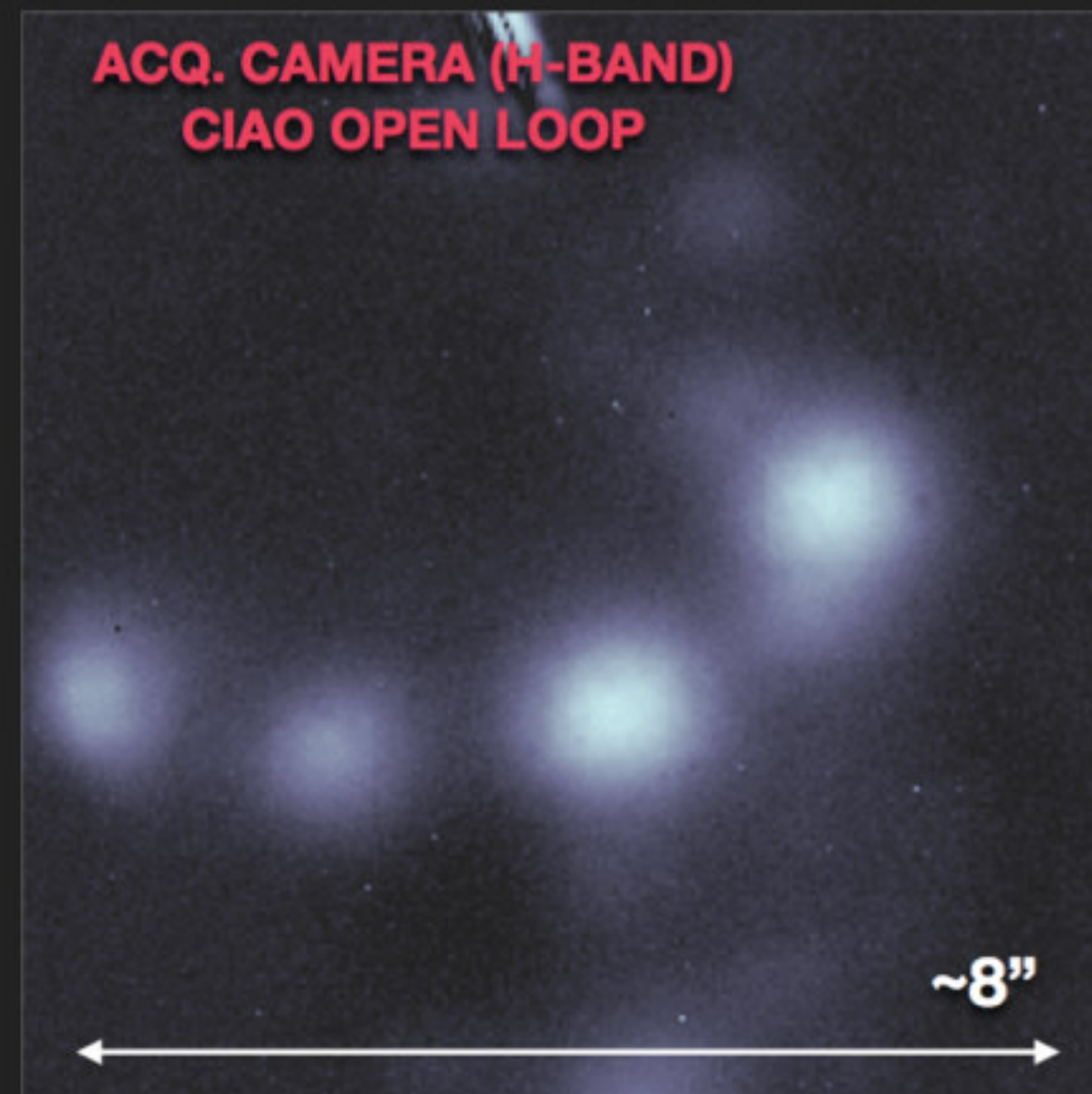


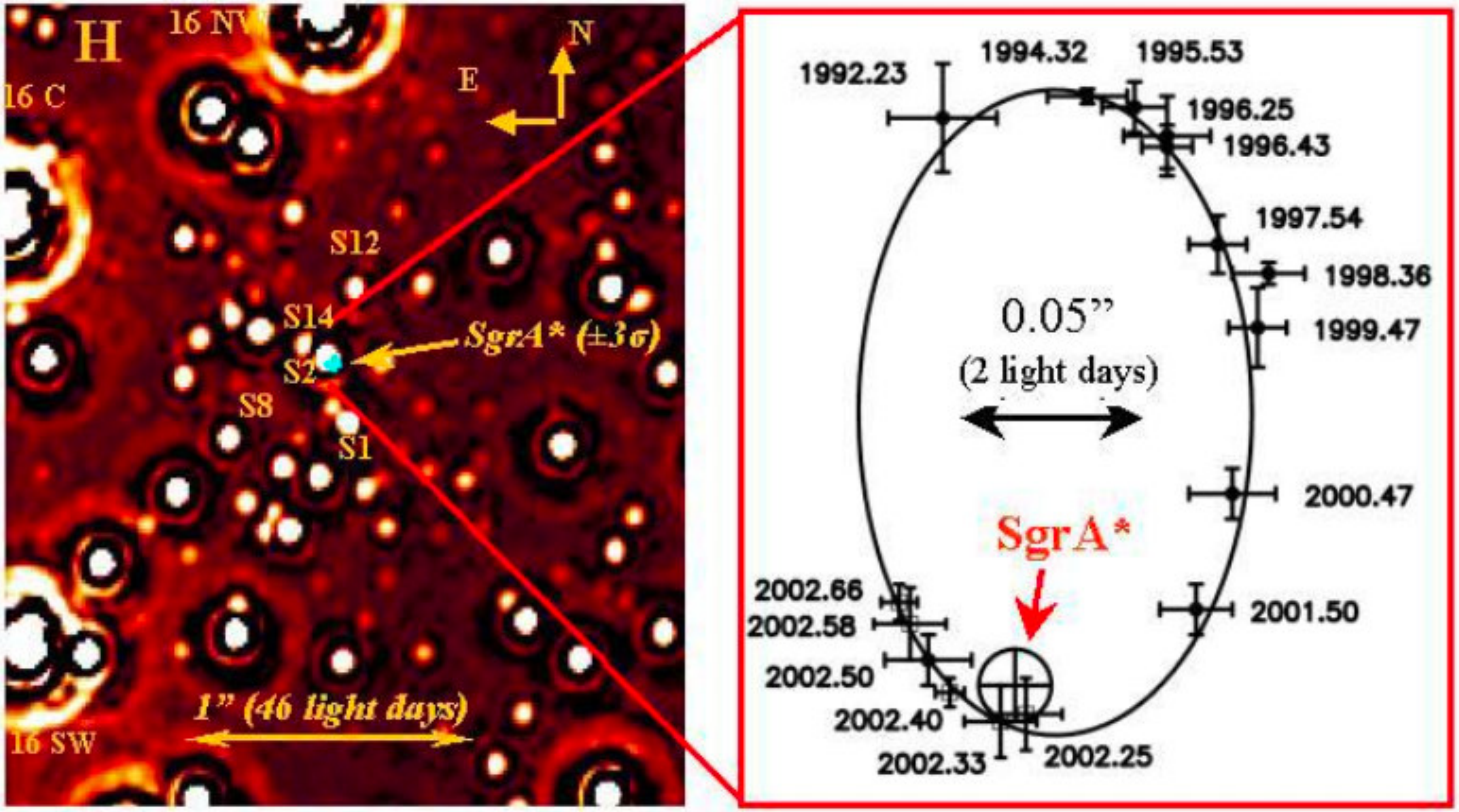
CIAO #1 first light
April 2016

PSF on MACAO TCCD,
800nm, ~4% AO Strehl
[>40% at 1.6 microns]

GRAVITY/CIAO looking at the Galactic Center





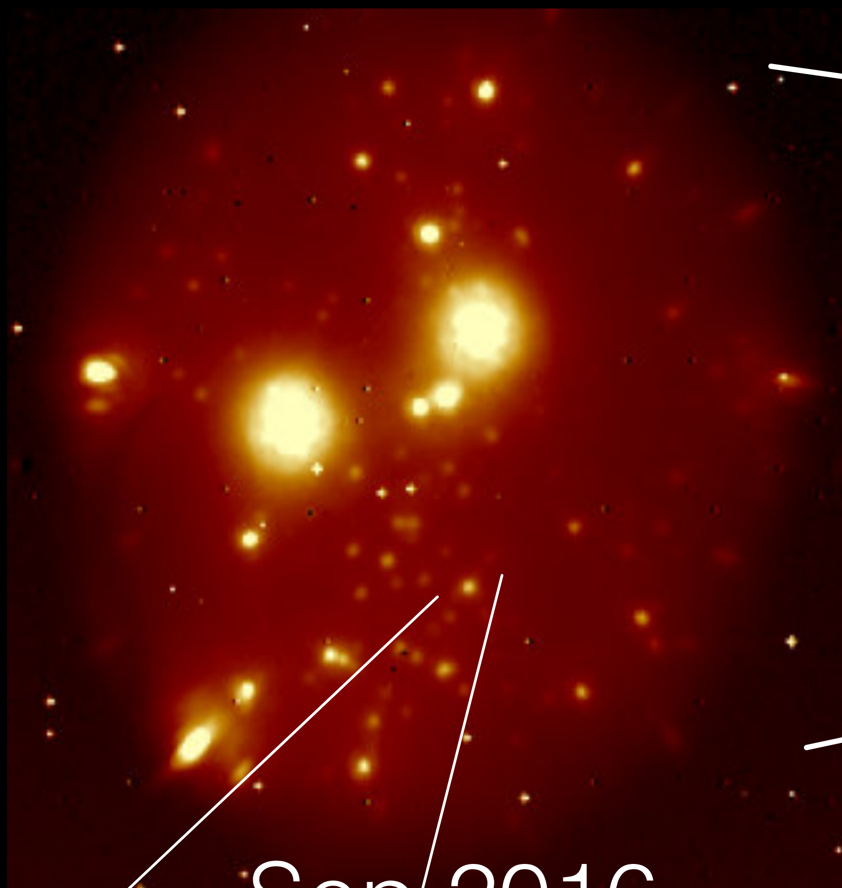


S2 estimated period: 15.5 years
Periastron: ~120 AU

Figure 4. Orbit of the star S2 around SgrA* (from Schödel et al. 2002, 2003). Left: Wiener filtered, H-band NAOS/CONICA image (40 mas resolution) of the central 2". The light blue cross denotes the position of SgrA*, and its 3σ error bar. Several of the blue 'S'-stars in the SgrA*-cluster are marked, as well as three of the bright IRS16 stars. The right inset shows the orbital data and best keplerian fit of S2 around the position of Sgr* (circle with cross). Filled circles are measurements with the SHARP speckle camera on the 3.5m NTT, and open squares are the new NAOS/CONICA measurements. Error bars are conservative estimates, including systematic uncertainties.

First light for GRAVITY and its Adaptive Optics and First Optical Interferometry of SgrA*

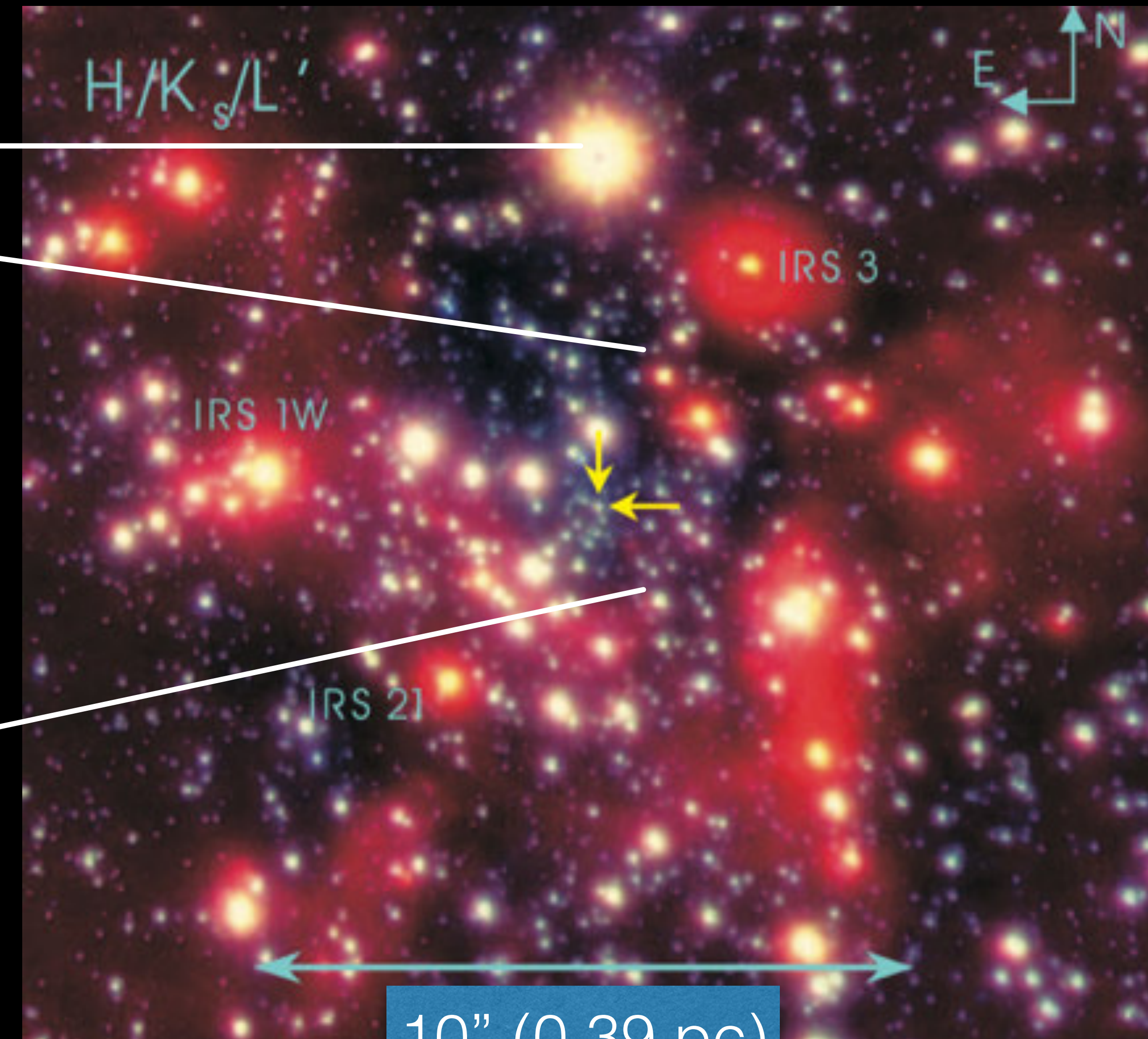
CIAO corrected image on GRAVITY



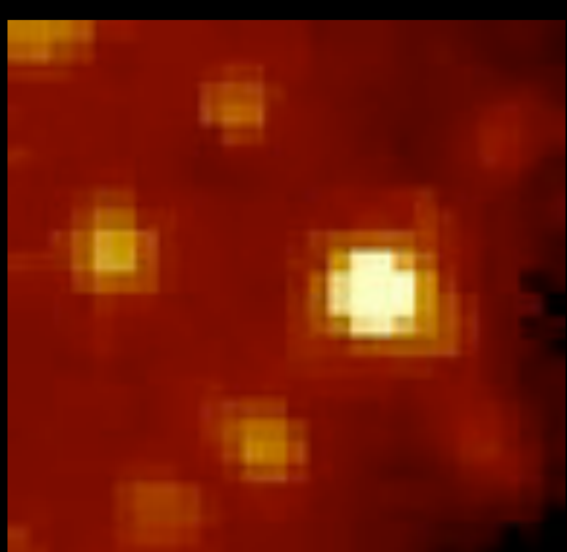
Sep 2016

IRS7, K=6.5

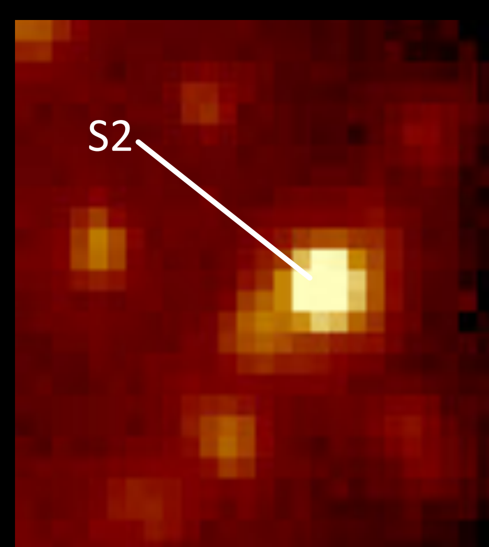
Genzel 2003



10" (0.39 pc)

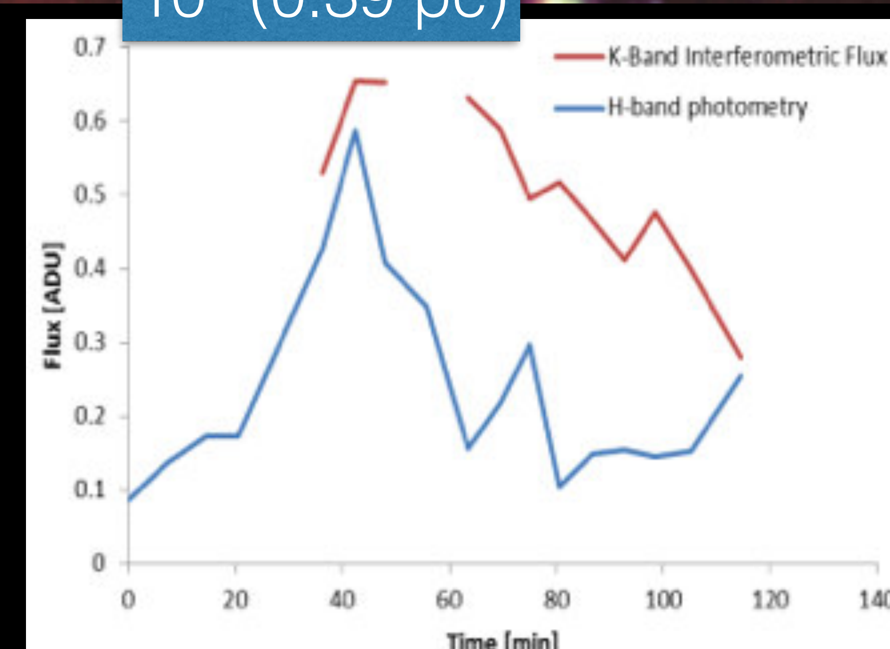


Movie from 18 frames
of 5 minutes each



Weak Flare

Lightcurve



Outline

- What is Adaptive Optics (AO) good for?

- VLT AO systems:
NACO, MACAO, PARSEC, MAD, SPHERE, *CIAO*, *AOF*, ….

- E-ELT AO systems:
SCAO, MCAO, LTAO

- Summary

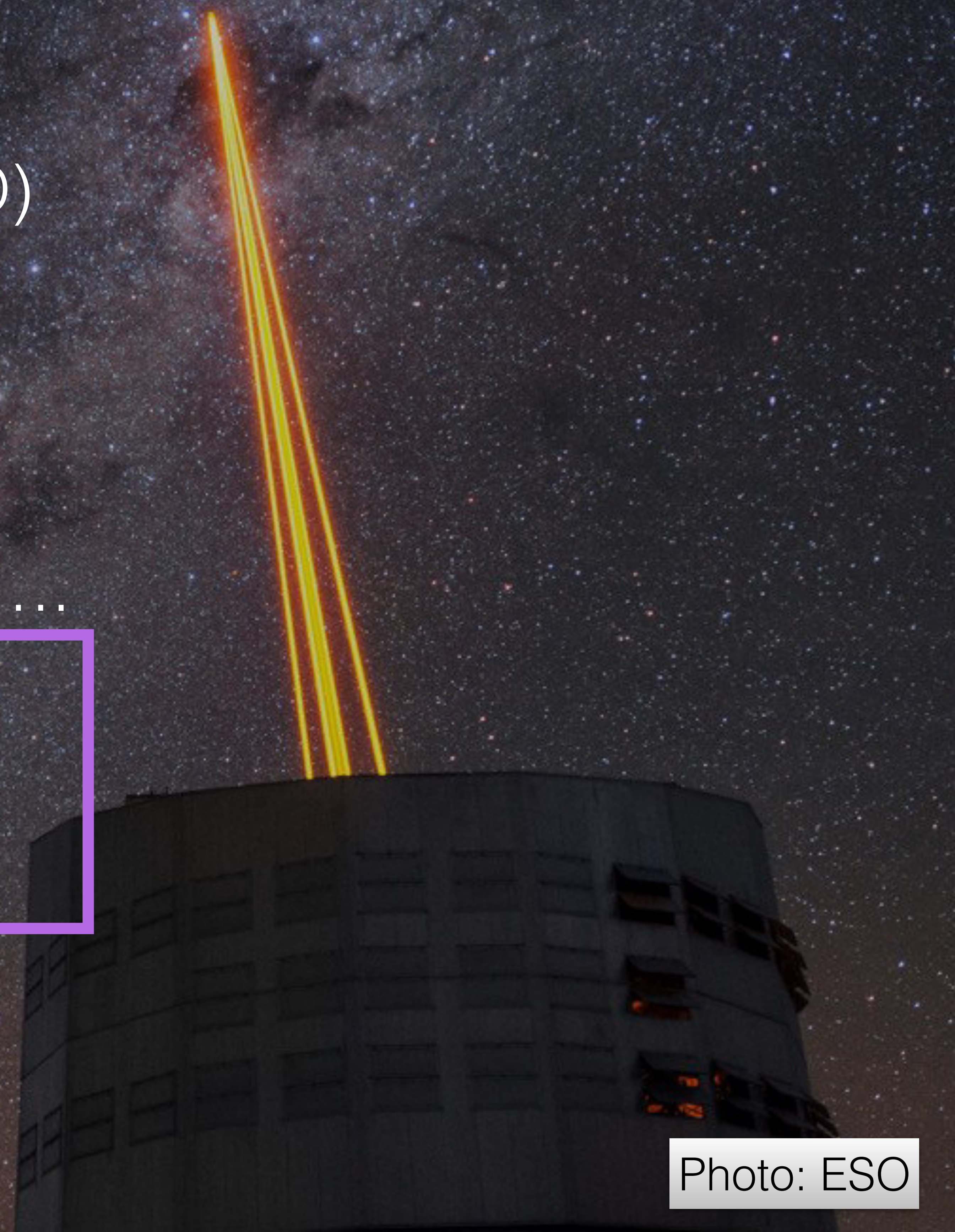


Photo: ESO


The E-ELT on Cerro Aramzones
Credit: ESO

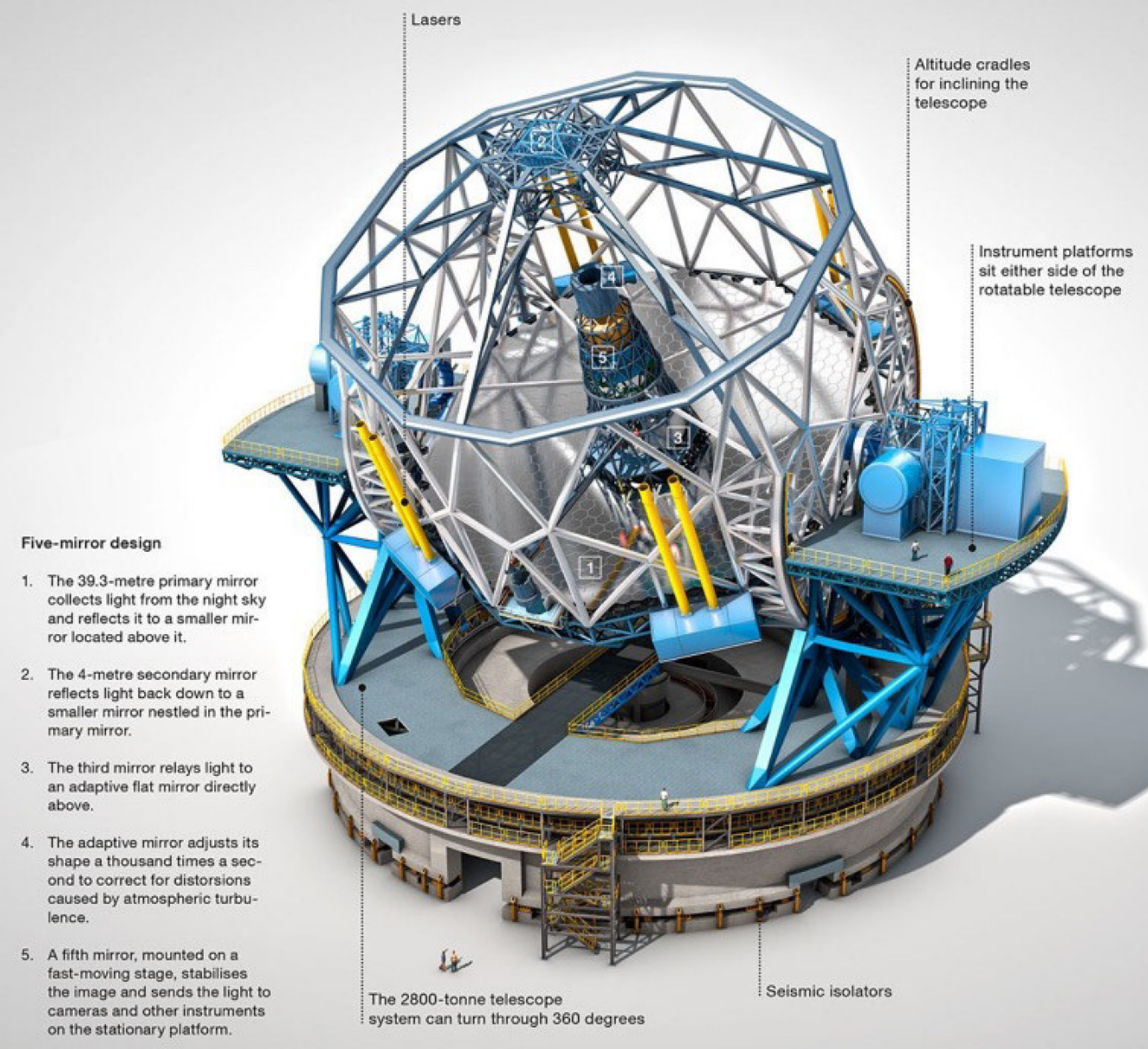
Angular resolution boost with the E-ELT

“NGC 3603 moved to ~35 kpc“

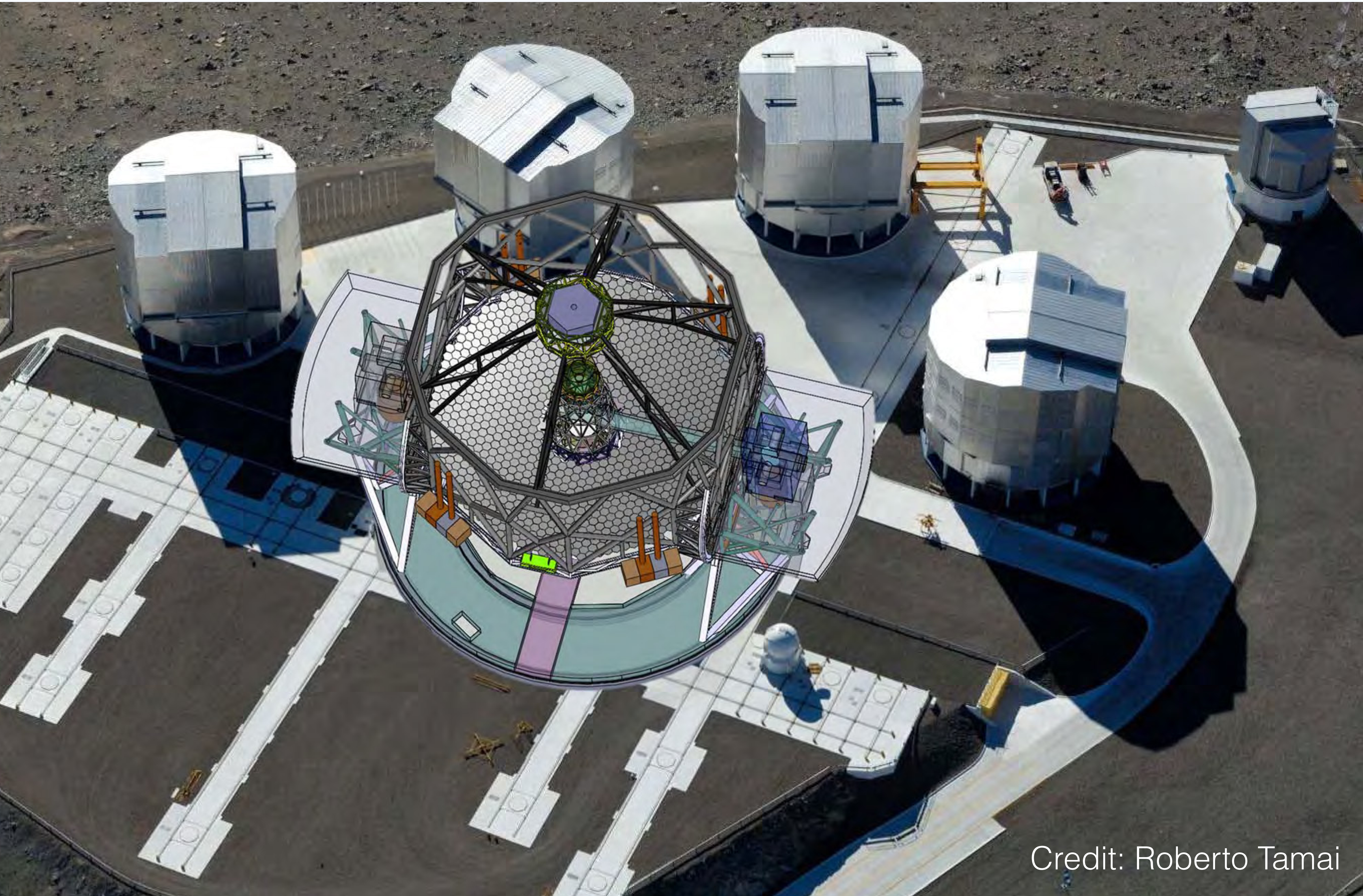
Image: Brandl, Brandner et al.

The E-ELT

- 40-m class telescope: largest optical-infrared telescope in the world.
- Segmented primary mirror.
- Active optics to maintain collimation and mirror figure.
- Adaptive optics assisted telescope.
- Diffraction limited performance.
- Wide field of view: 10 arcmin.
- Mid-latitude site (25 deg) (Armazones in Chile).
- Fast instrument changes.
- VLT level of efficiency in operations.

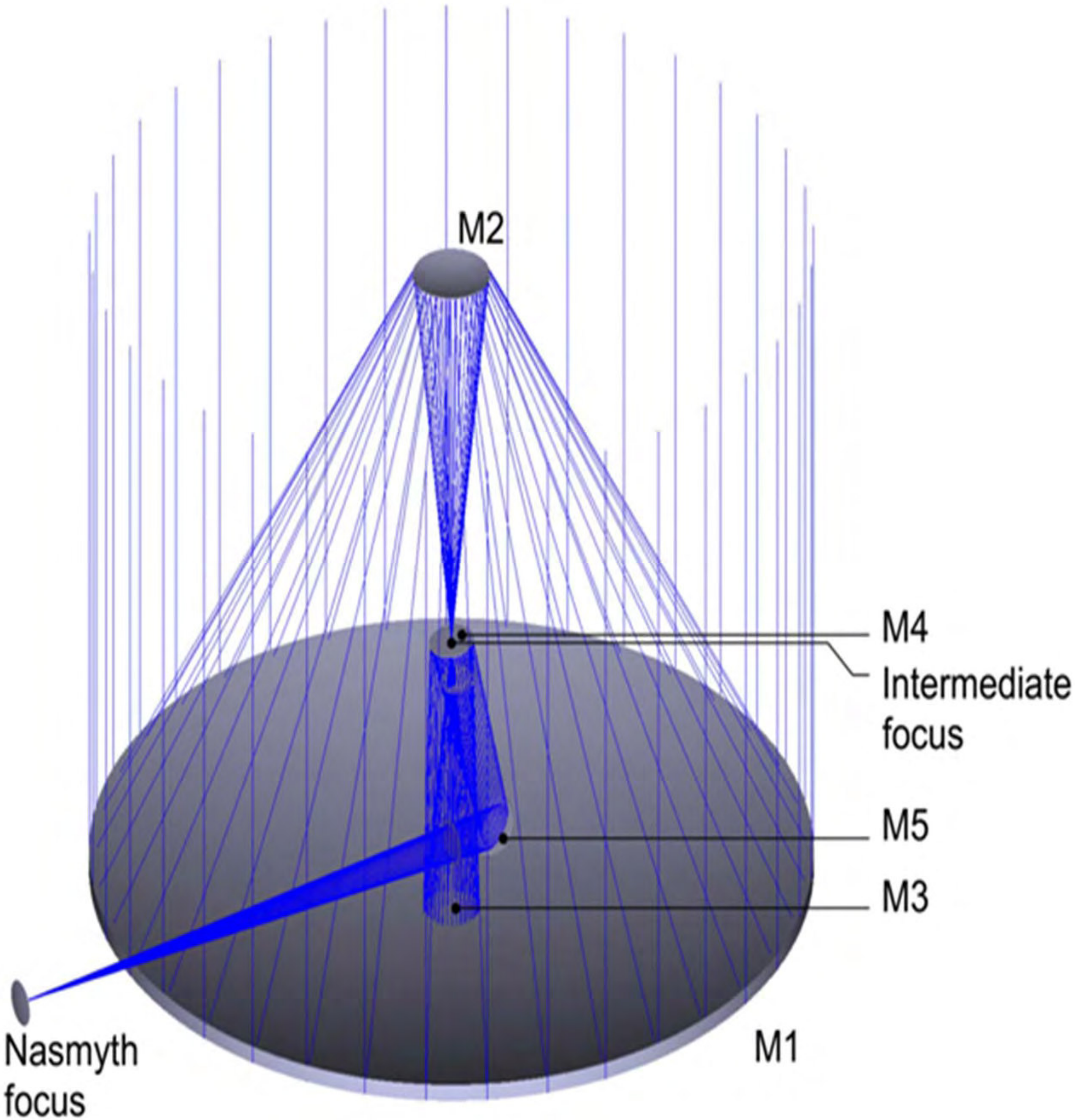


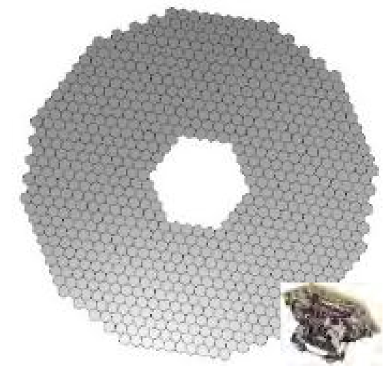
E-ELT vs VLT



Credit: Roberto Tamai

E-ELT Optomechanics





M1 Unit
39-m
Concave – Aspheric f/0.9
Segmented (798 Segments)
Active + Segment shape Control

M2 Unit
4-m
Convex Aspheric f/1.1
Passive + Position Control

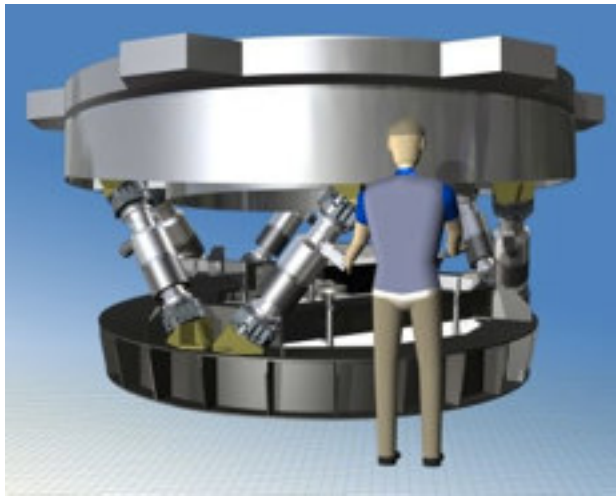
M3 Unit
4-m – Concave – Aspheric f/2.6
Active + Position Control

M4 Unit
2.4-m
Flat
Segmented (6 petals)
Adaptive + Position Control

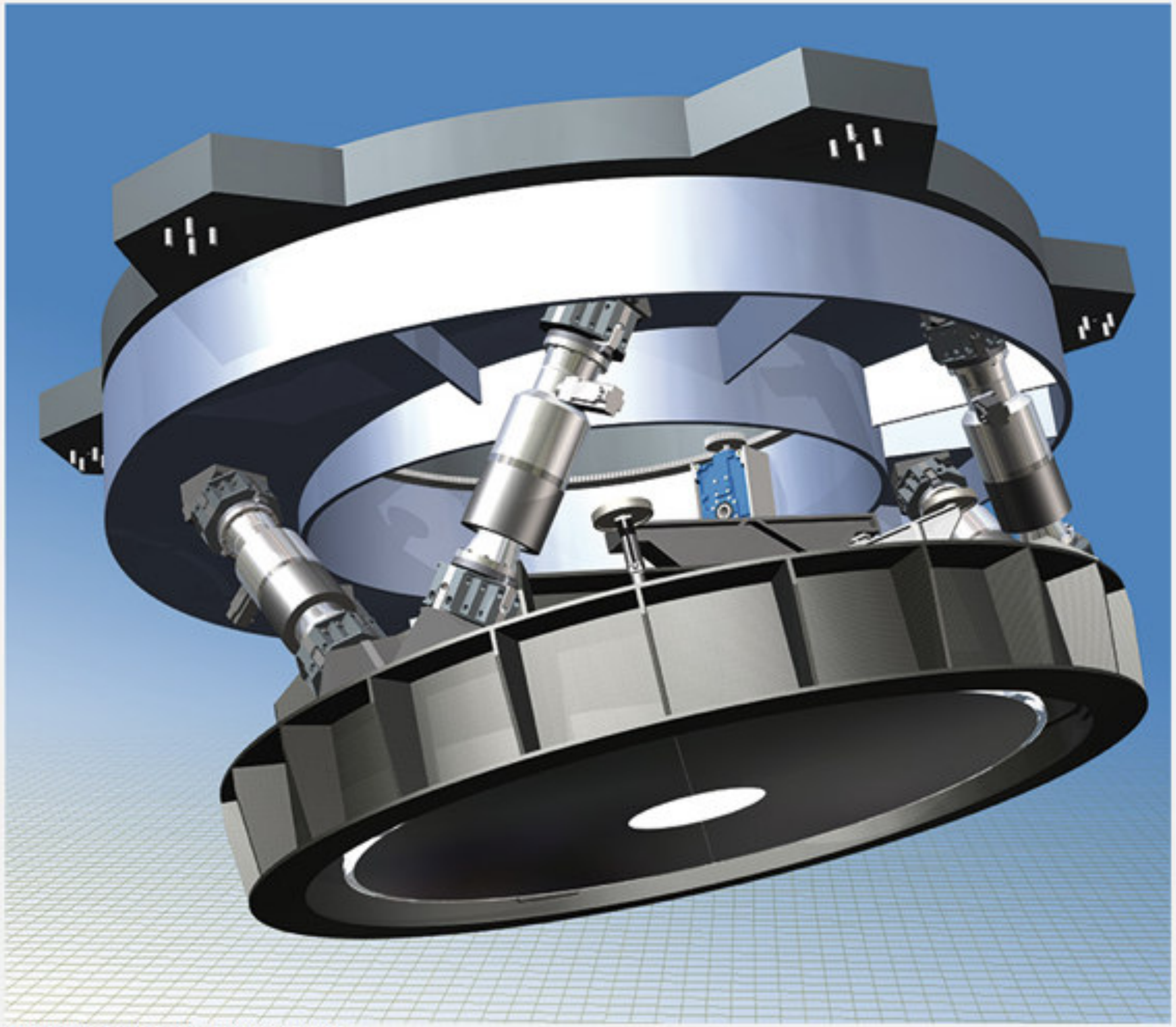
M5 Unit
2.7x2.1-m
Flat
Passive + Fast Tip/Tilt

Credit: Roberto Tamai

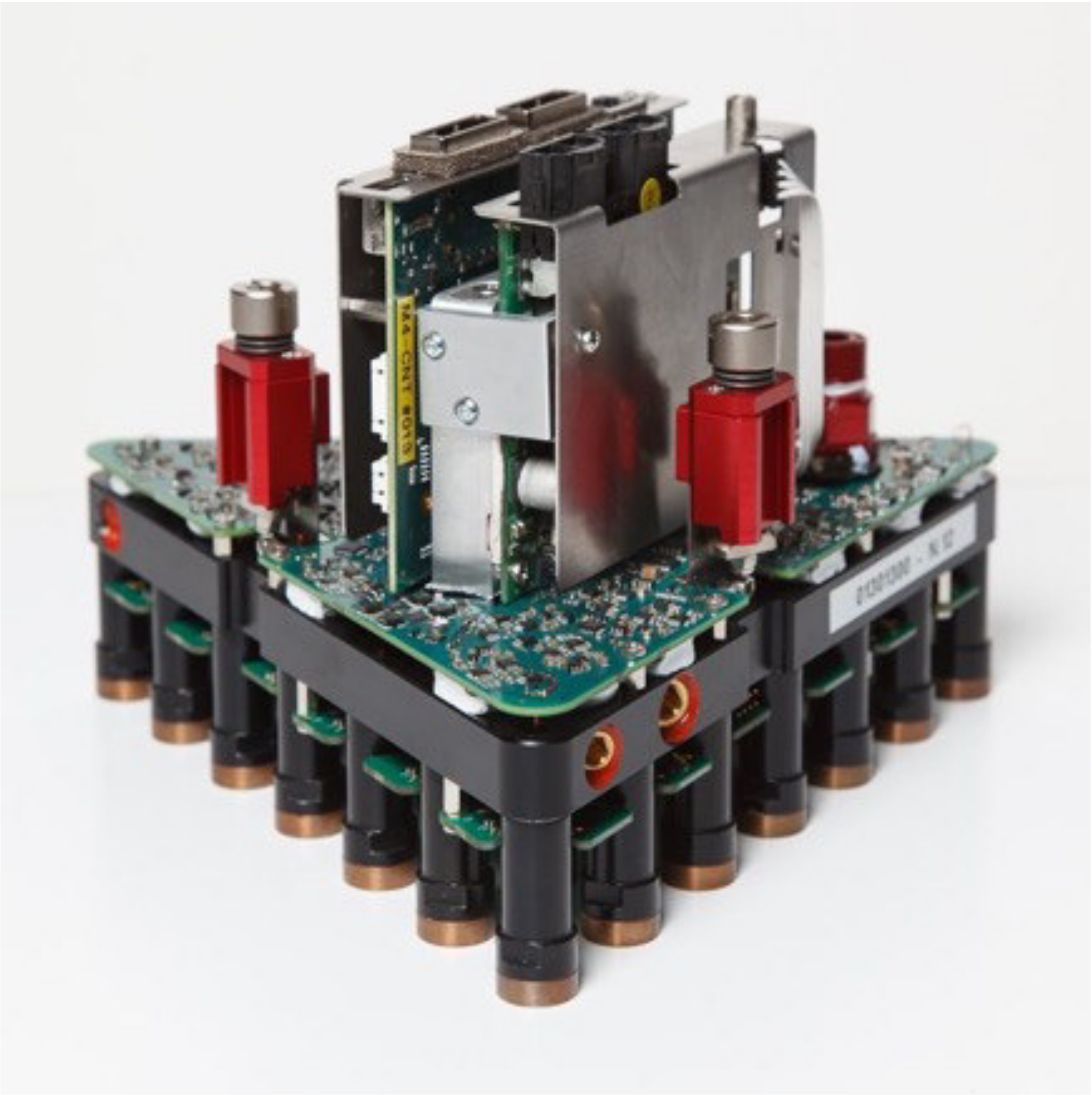
E-ELT M4 unit



- 2.4-m flat adaptive mirror – 6 thin-shell petals only 1.95mm thick
- ~5300 contactless actuators driving the mirror shape at 1 kHz
- Preliminary design study contract completed
- Contracts for final design and manufacturing: awarded to AdOptica



Rendering by ADS International & ESO



M4 animation (AdOptica)

METIS kick-off: October 2015

The E-ELT Instrument Roadmap

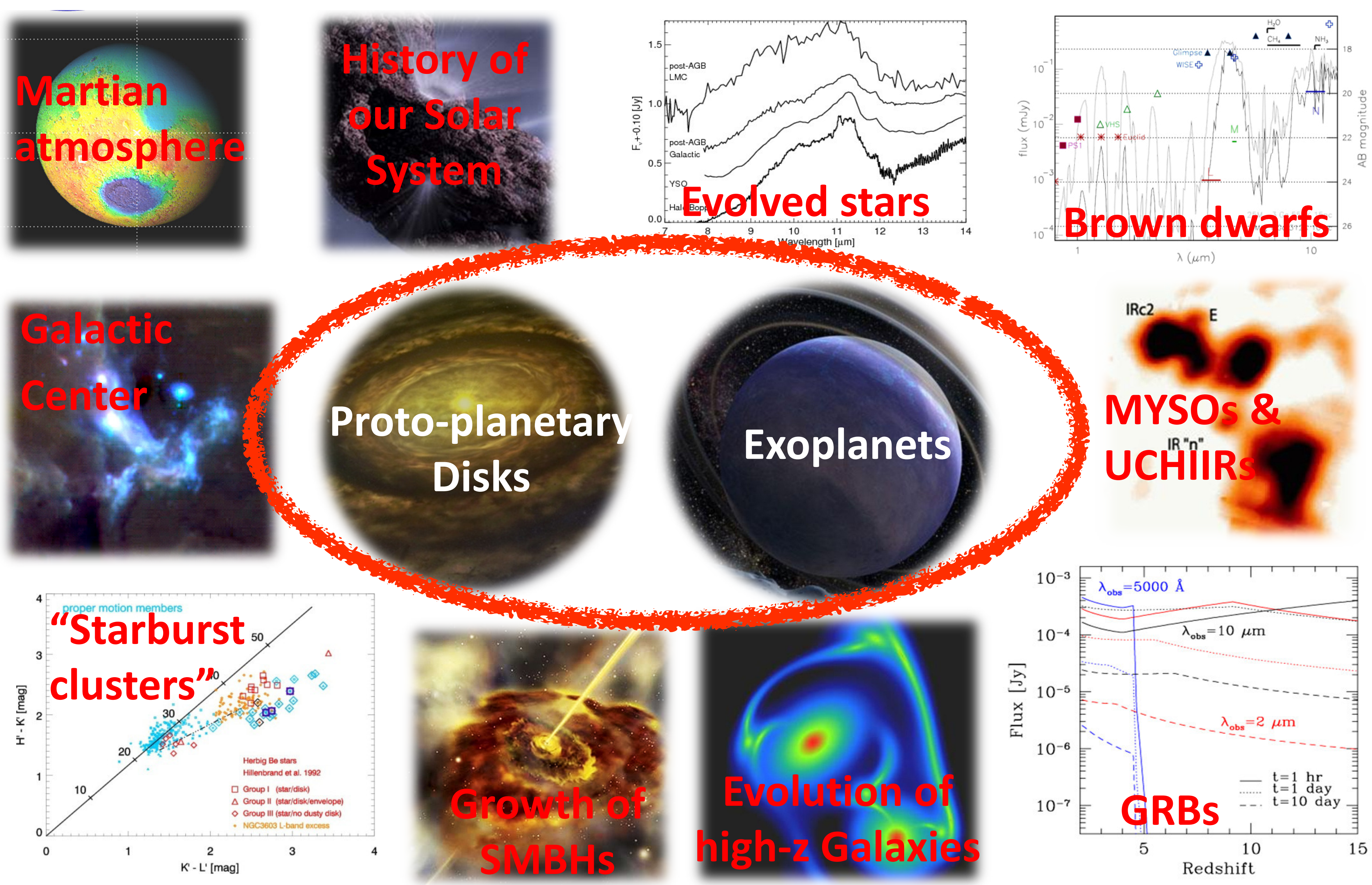
- Instruments selected in consultation with the ESO committees and community, based on
  - Scientific impact, return, flexibility
  - Complementarity to JWST, existing facilities
  - A plan to cover all observing conditions
- ELT-MIR: METIS

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-MOS	ELT-HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Cal for Proposals Start Phase A			
2016				Consortium Selection for construction		Call for proposals	
2017							
2018							TRL check
2019						Selection	Start when ready
2020							
2021							
2022							
2023							
2024							

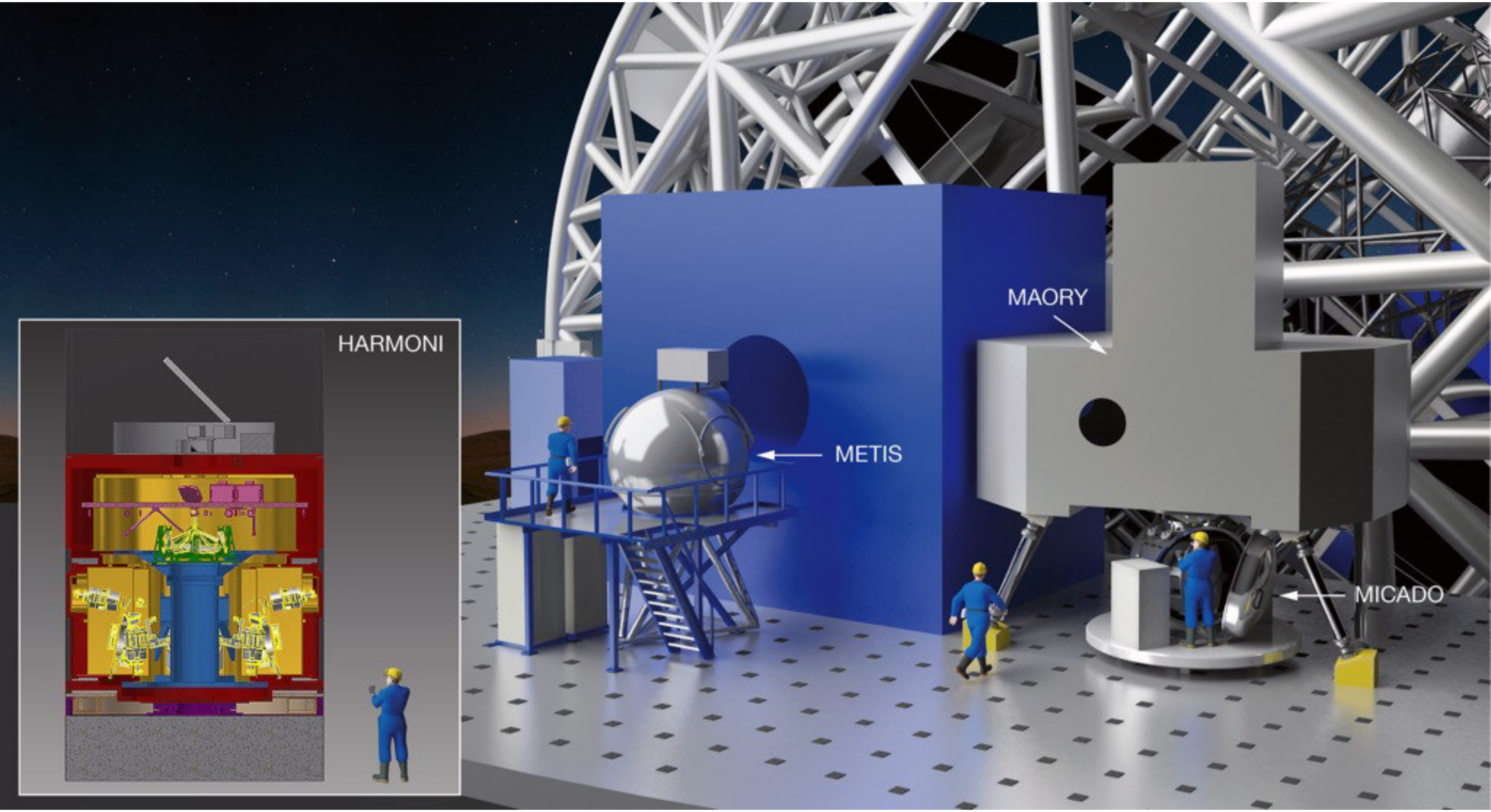
(grey)	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
(yellow)	Decision point
(green)	Development of Technical Specifications, Statement of Work, Agreement, Instrument Start.

28.9.2015:Agreement Signed for METIS Instrument for E-ELT

METIS science themes -
a multi-purpose instrument for the E-ELT

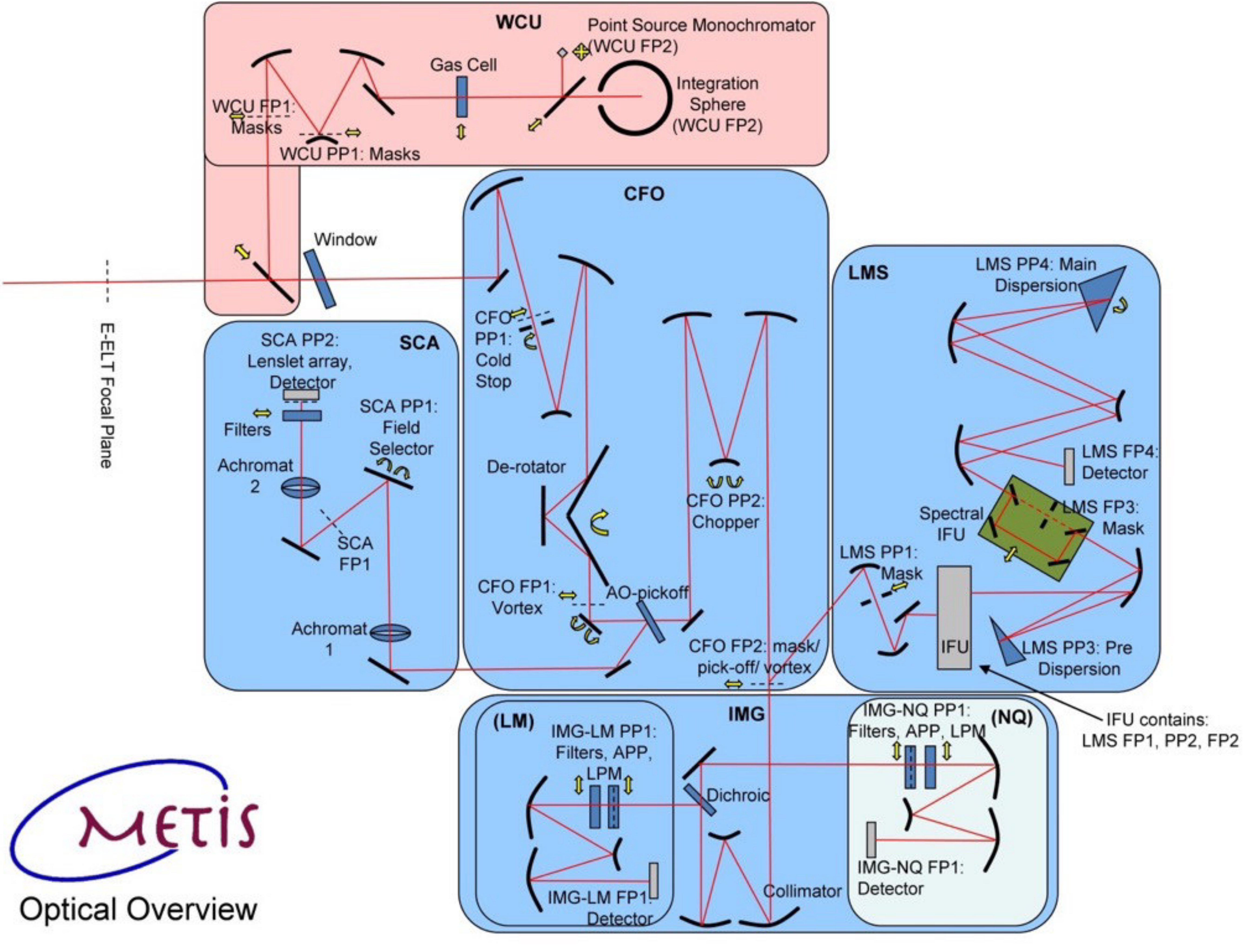


METIS, MICADO, MAORY, and HARMONI in 2009

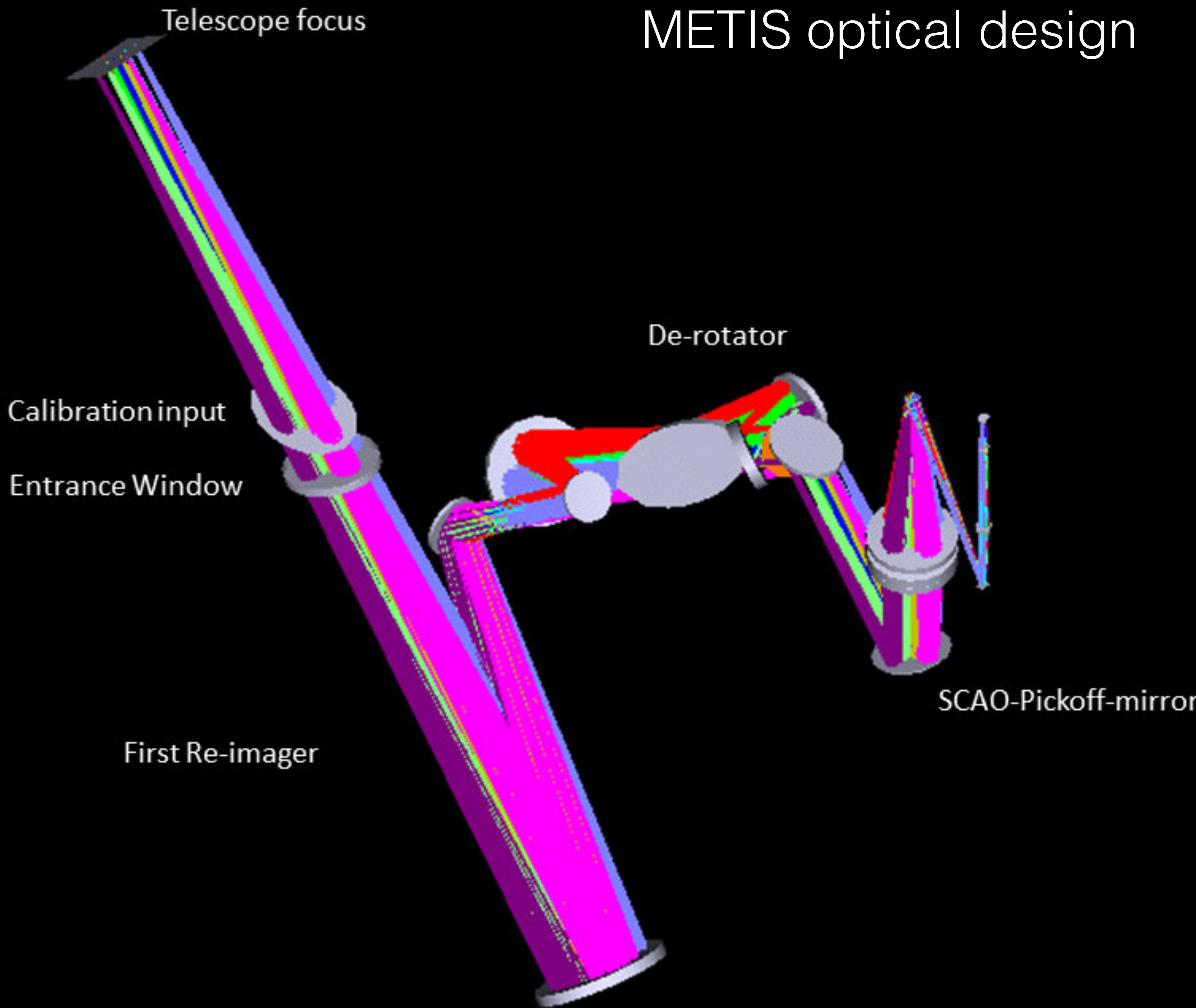


METIS: SCAO+LTAO, MICADO: SCAO+MCAO, HARMONI: GLAO, LTAO, SCAO

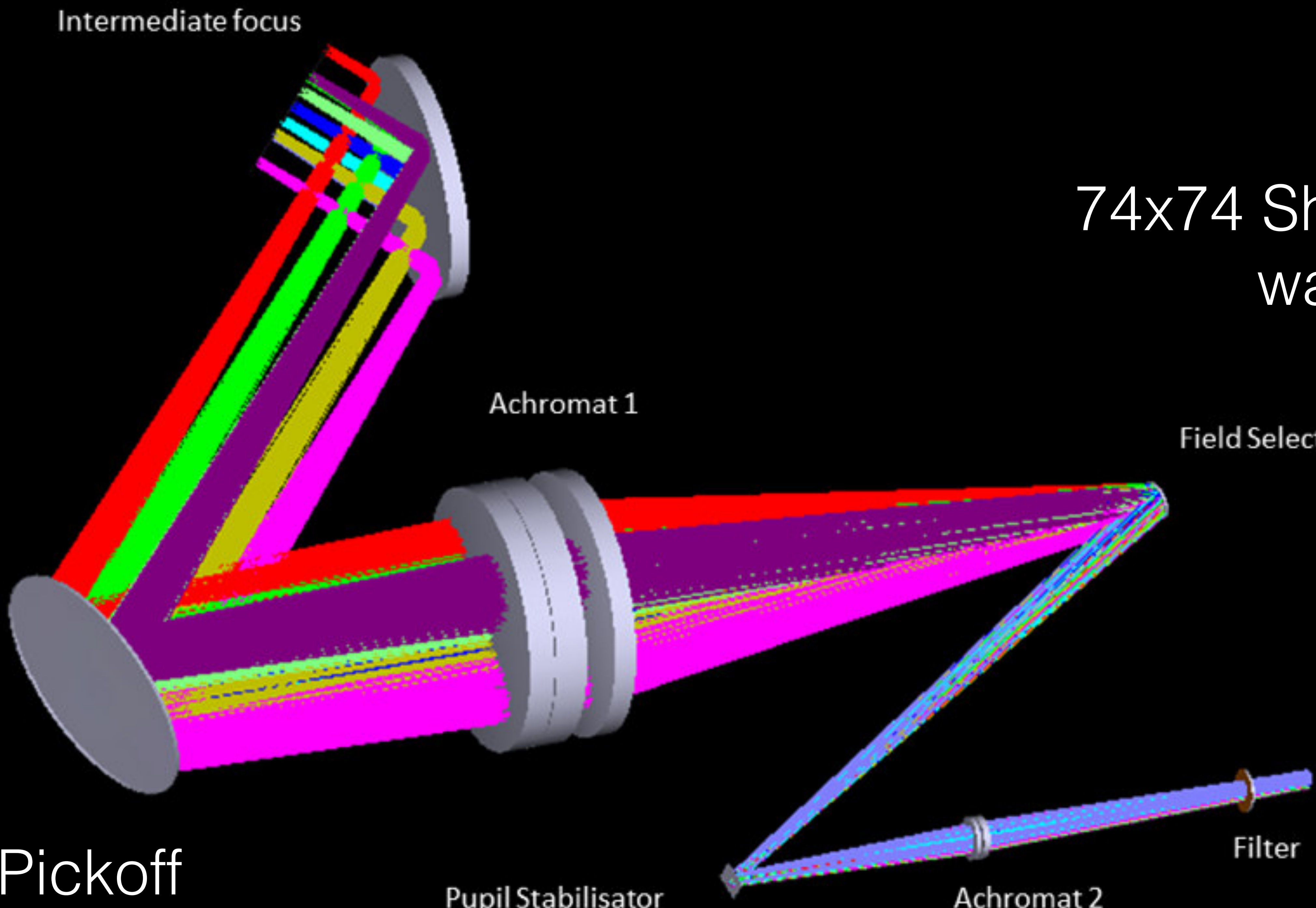
METIS 2016


WCU
Point Source Monochromator
(WCU FP2)
Gas Cell
Integration
Sphere
(WCU FP2)
WCU FP1:
Masks
WCU PP1: Masks
CFO
Window
E-ELT Focal Plane
CFO
PP1:
Cold
Stop
LMS
LMS PP4: Main
Dispersion
SCA
SCA PP2:
Lenslet array,
Detector
Filters
SCA PP1:
Field
Selector
Achromat
2
SCA
FP1
De-rotator
CFO PP2:
Chopper
LMS FP4:
Detector
Spectral
IFU
LMS FP3:
Mask
LMS PP1:
Mask
CFO FP1:
Vortex
AO-pickoff
Achromat
1
CFO FP2: mask/
pick-off/ vortex
IFU
LMS PP3: Pre
Dispersion
IFU contains:
LMS FP1, PP2, FP2
IMG
(LM)
IMG-LM PP1:
Filters, APP,
LPM
IMG-NQ PP1:
Filters, APP, LPM
(NQ)
Dichroic
IMG-NQ FP1:
Detector
Collimator
IMG-LM FP1:
Detector
METIS
Optical Overview

METIS optical design

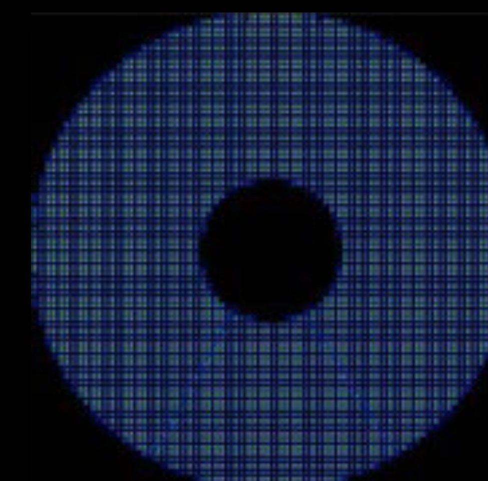


METIS SCAO optical design



Pickoff
mirror

74x74 Shack-Hartmann wavefront sensor



Pupil image
with lenslet array
and detector

METIS SCAO Configurations and Performances

yao configuration directory	BEST_GUESS3	BEST_GUESS2	BEST_GUESS	BASELINE_6x6px	BASELINE_4x4px	BASELINE_2x2px
yao grid size (sim.pupildiam)	370	300	300	370	370	370
SH WFS sub-aperture geometry	37 x 37	50 x 50	60 x 60	74 x 74	74 x 74	74 x 74
Active sub-apertures (_nsub)	924	1708	2472	3816	3816	3816
Pixel per sub-aperture	4 x 4	4 x 4	4 x 4	6 x 6	4 x 4	2 x 2
Desired pixel scale (0.8 * diff limit @ 2.2 microns, origpixsize) [“/px]	0.36	0.49	0.59	0.73	0.73	0.73
yao pixel scale (pixsize) [“/px]	0.43	0.46	0.69	0.85	0.85	0.85
DM actuator geometry (nxact)	75 x 75	75 x 75	75 x 75	75 x 75	75 x 75	75 x 75
Active actuators (_nact)	2964	4032	4036	4008	4008	4008
Performane results R-MET-111	**R-MET-111:** Minimum Strehl Ratio: METIS and its associated SCAO (NGS) system shall deliver at least **93% Strehl (goal: 95%) at 10µm, and at least 60% (goal: 80%) Strehl at 3.7µm**. These numbers are based on nominal E-ELT optics, a median **V-band seeing of 0.65′′**, a **zenith angle of 30 degrees**, a natural guide star with **mK = 10 mag**. This performance shall be provided continuously over at least 15 minutes under nominal telescope operating conditions.					
Strehlnumbers at 2.2, 3.7, and 10 microns	0.274 0.6 0.932	0.603 0.834 0.975	0.536 0.823 0.973	0.534 0.799 0.969	0.534 0.799 0.969	0.564 0.816 0.972
Strehlnumbers with 250nm static aberrations on WFS		0.579 0.824 0.974	0.521 0.794 0.969	0.417 0.734 0.959	0.417 0.734 0.959	0.559 0.814 0.972
FWHM at 2.2, 3.7, and 10	13.1	n/a	n/a	12.5	12.5	12.4

Outline

- What is Adaptive Optics (AO) good for?
- VLT AO systems:
  NACO, MACAO, PARSEC, MAD, SPHERE, *CIAO*, *AOF*, ….
- E-ELT AO systems:
  SCAO, MCAO, LTAO
- Summary

Photo: ESO

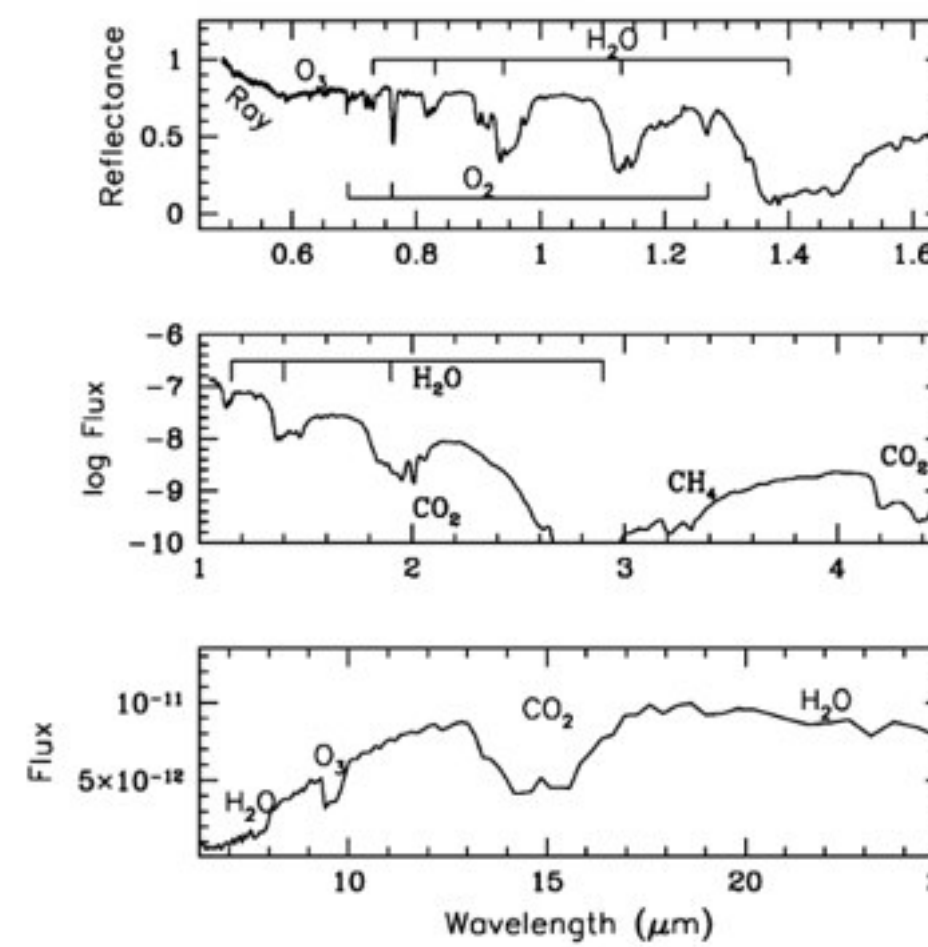
Signs of Alien Life Will Be Found by 2025, NASA's Chief Scientist Predicts

By Mike Wall, Space.com Senior Writer | April 7, 2015 04:50pm ET

MORE

Recent observations by planetary probes and telescopes on the ground and in space have shown that water is common throughout our solar system and the broader Milky Way galaxy.

Credit: NASA



Earth as Exoplanet (Seager 2014)

Humanity is on the verge of discovering alien life, high-ranking NASA scientists say.

"I think we're going to have strong indications of life beyond Earth within a decade, and I think we're going to have definitive evidence within 20 to 30 years," NASA chief scientist Ellen Stofan said Tuesday (April 7) during a panel discussion that focused on the space agency's efforts to search for habitable worlds and alien life.