Extremely Large Telescopes and Extreme AO

Markus Kasper (ESO)

Overview of the talk

Why big telescopes? Need for Adaptive Optics

Extremely Large Telescopes

ELT generation instruments

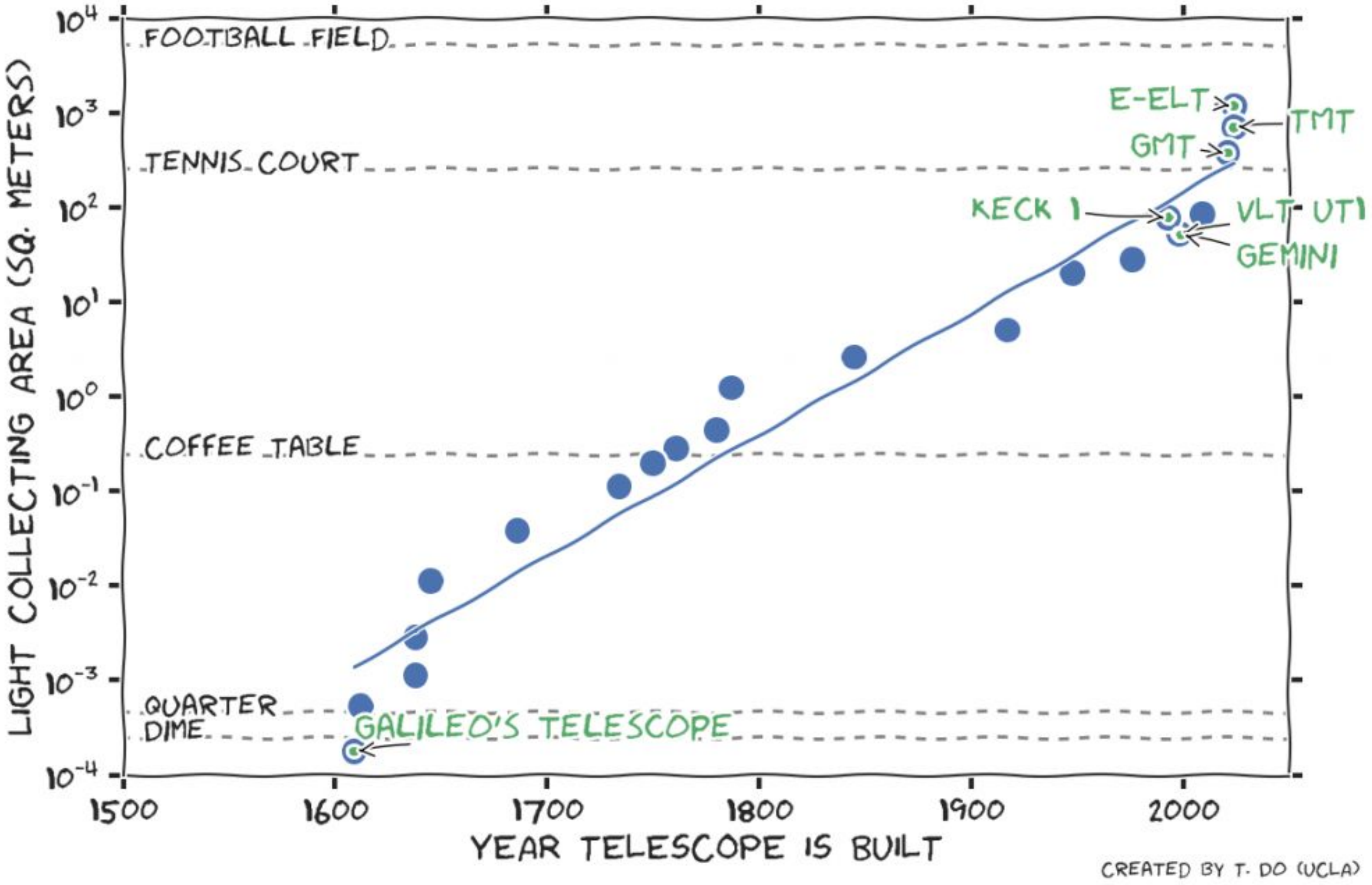
Planetary Camera & Spectrograph (PCS) and XAO

Why build larger (aperture) telescopes?

Resolving power $\propto 1.22\frac{\lambda}{D}$

Light gathering power $\propto D^2$

Speed point sources $\propto D^4$



ELT vs VLT: The power of large telescopes

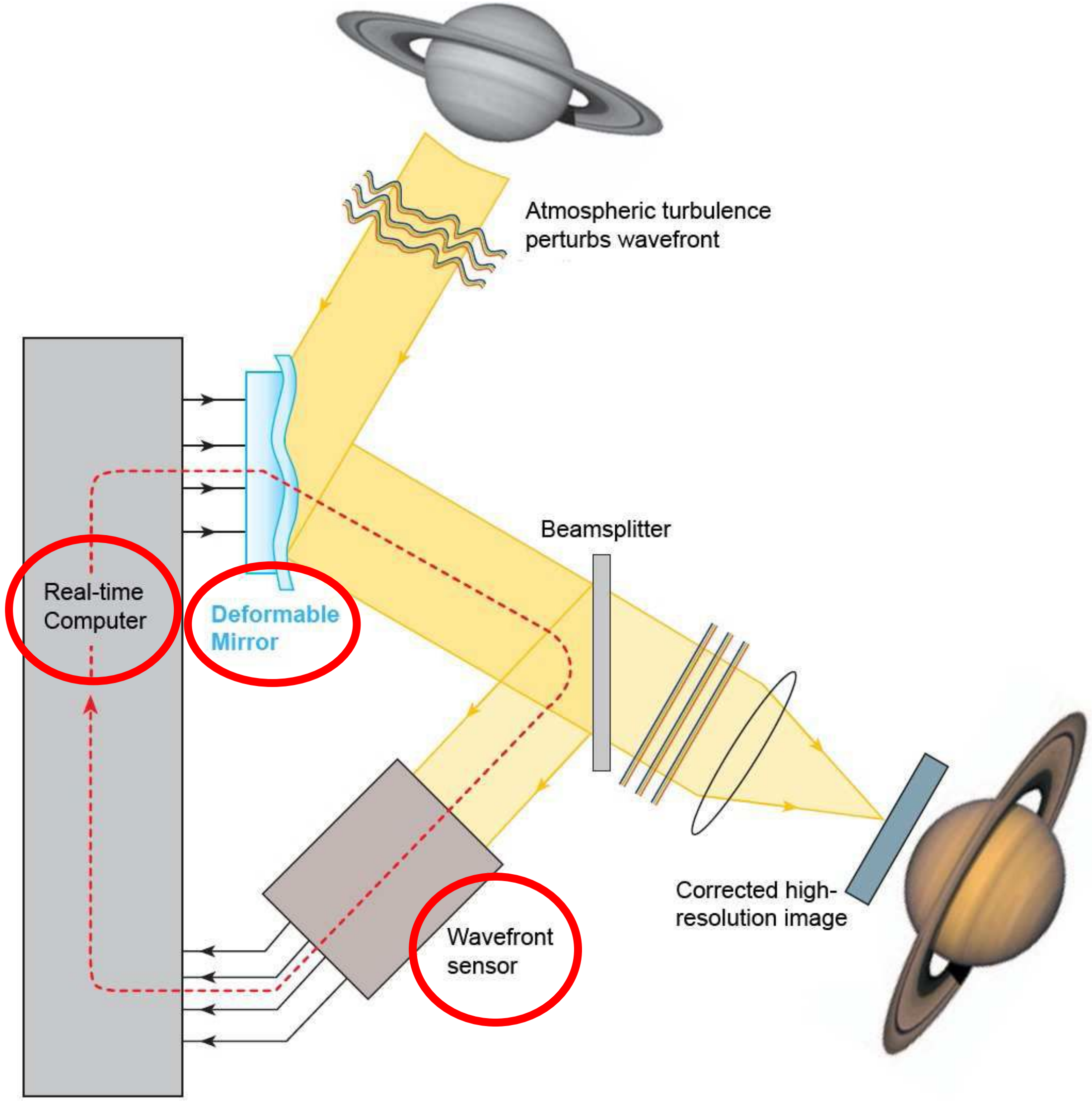
- Big telescopes collect more flux ($S \propto D^2$)
- AO concentrates flux onto a smaller patch on the sky ($\propto 1/D^2$)
- Sky noise stays constant (flux increase is compensated by patch size decrease)

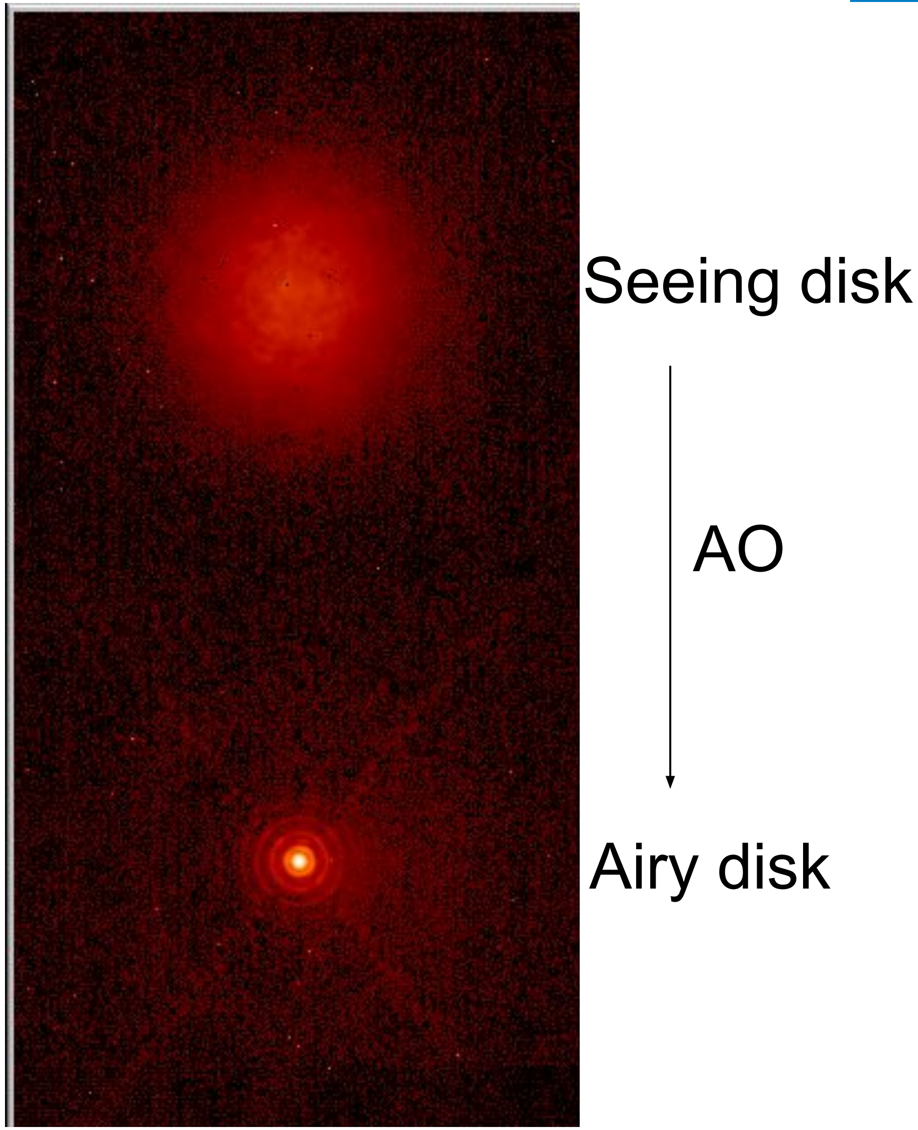
$$SNR \propto D^2 \times \sqrt{t} \qquad \Rightarrow \qquad t_{SNR} \propto D^{-4}$$

A 40-m telescope can do an observation $5^4 = 625$ times faster than an 8-m

magnitude limit/hr increases by $5^2 = 25$ (e.g., from ~23 mag to ~26.5 mag)

Adaptive Optics (AO) makes ground-based telescopes diffraction limited





Large apertures show more detail

HST

2.4 m diameter

VLT+AO

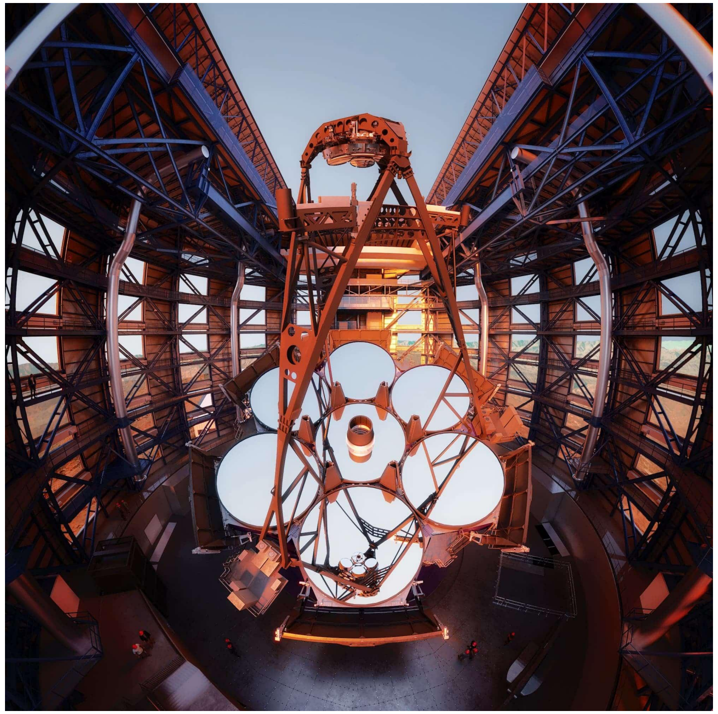
8 m diameter

ELT

39 m diameter

US Extremely Large Telescope Projects: Giant Magellan and Thirty Meter Telescopes (GMT & TMT)

- Both projects have headquarters in Pasadena, CA
- GMT will be located in the southern hemsisphere (Las Campanas, Chile)
- TMT in the northern hemisphere



Giant Magellan Telescope (www.gmto.org)

In Final Design Phase.
1st light early to mid 2030s

In manufacturing or testing:

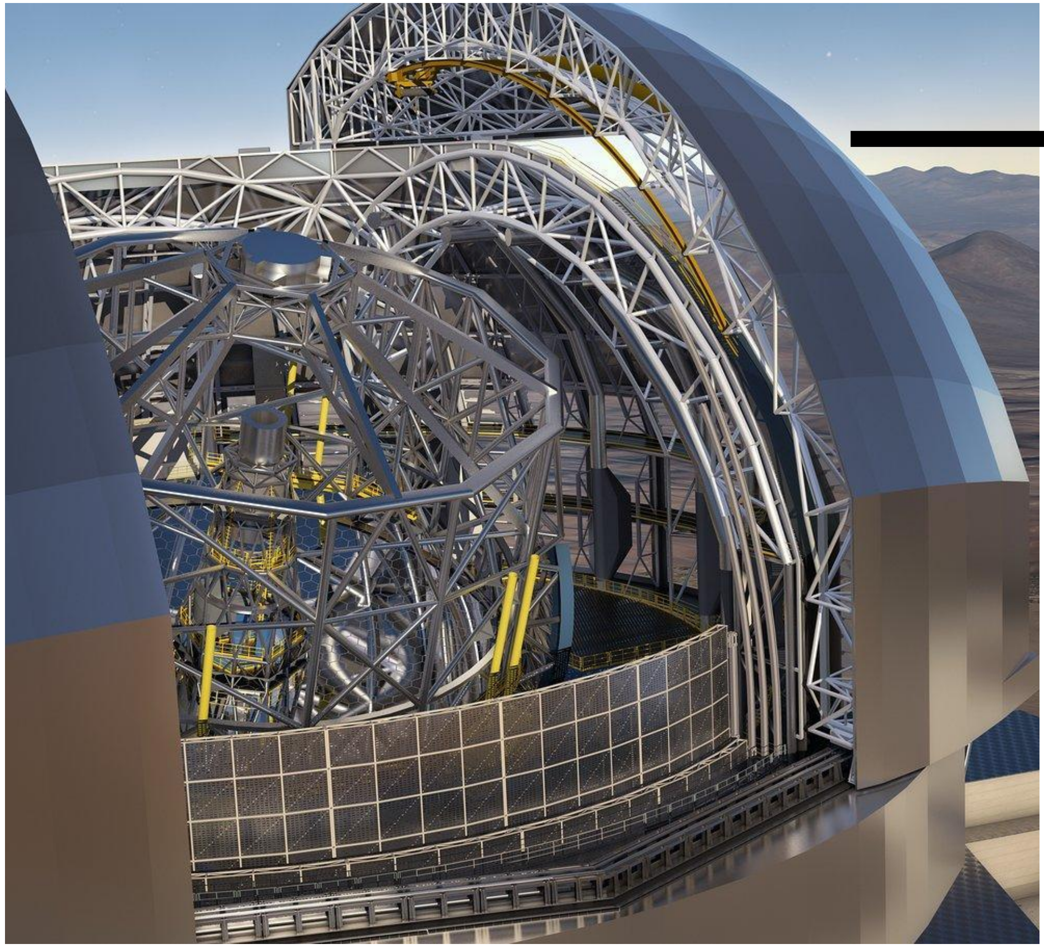
primary mirrors,
AO DSMs,
science instruments,
telescope mount

Completed site work:

hard rock excavation, utilities,
roads, foundation for the enclosure.

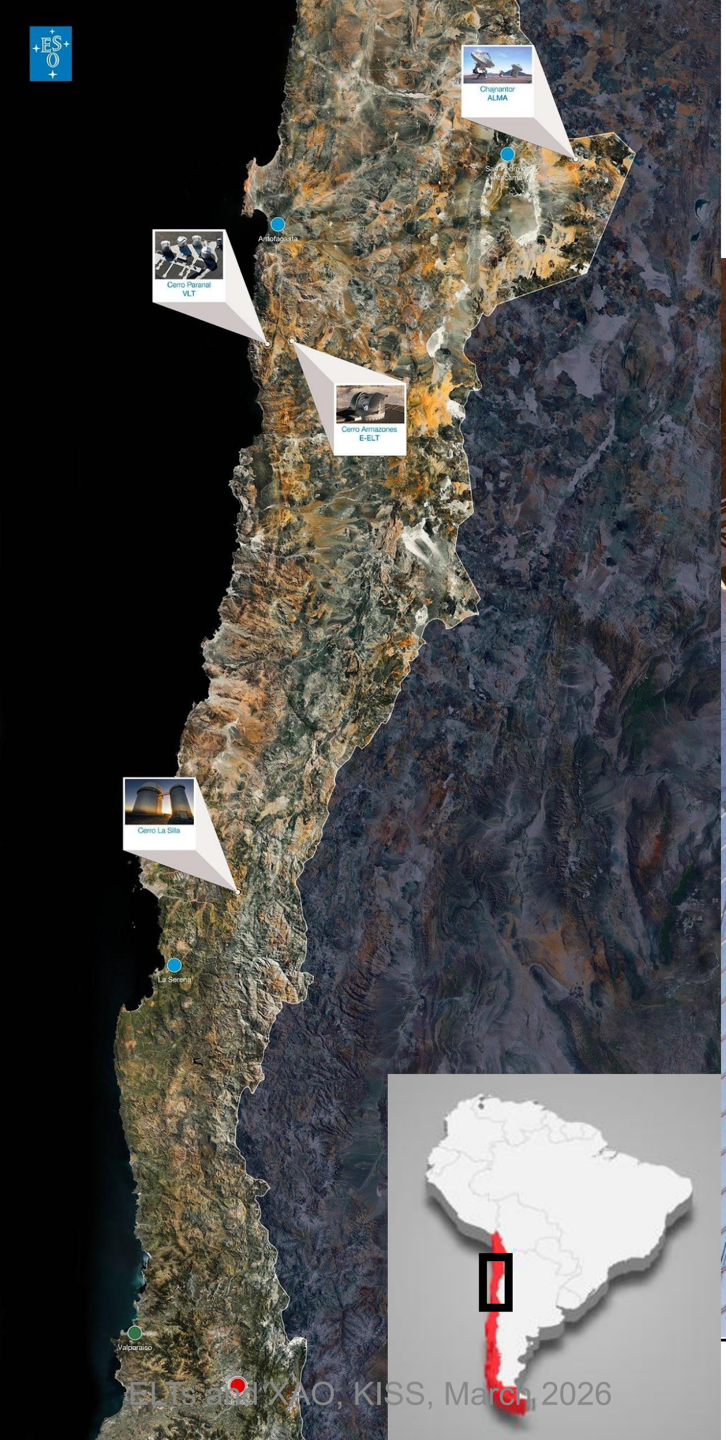
The Thirty Meter Telescope (www.tmt.org)

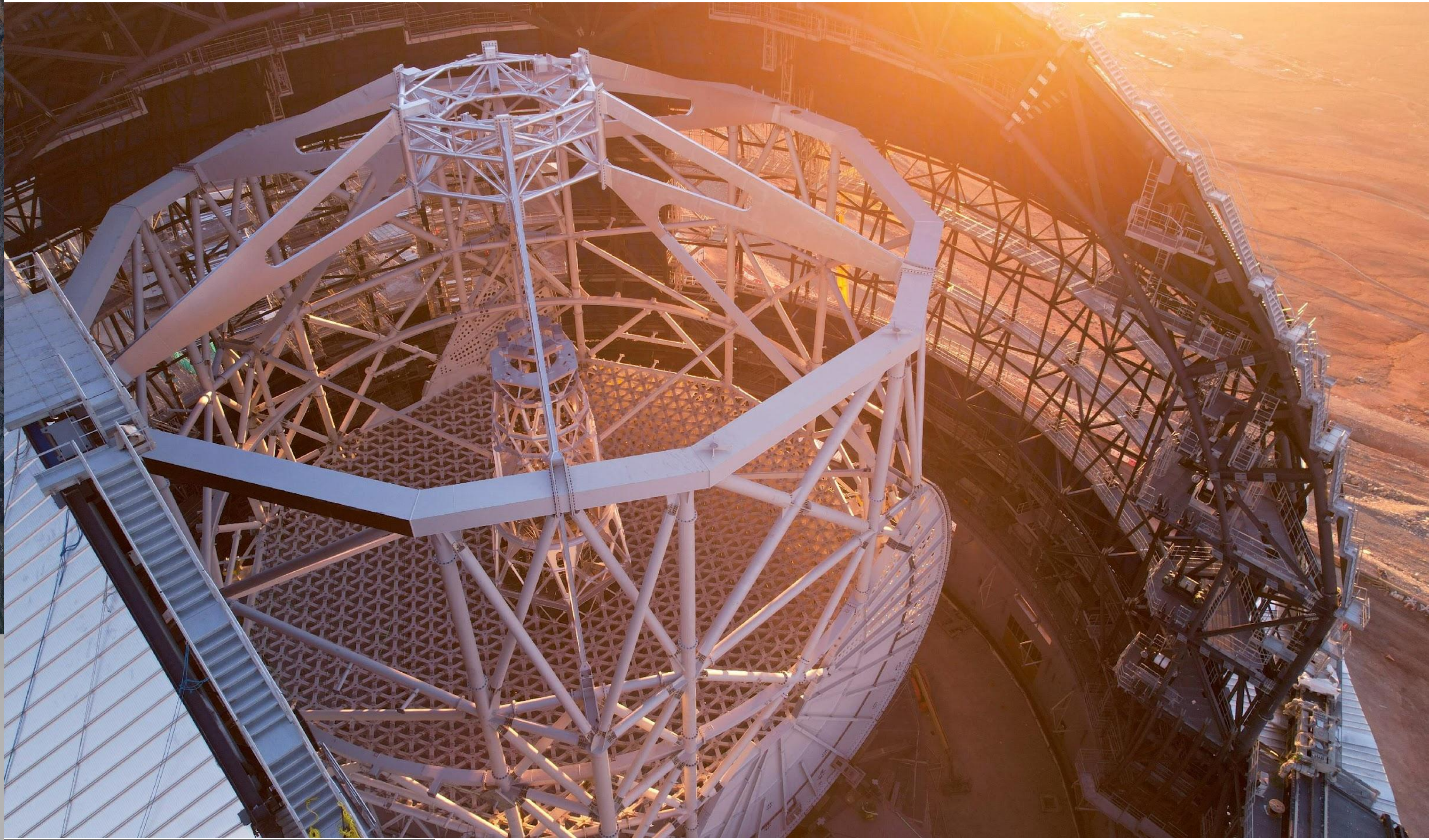
The Extremely Large Telescope



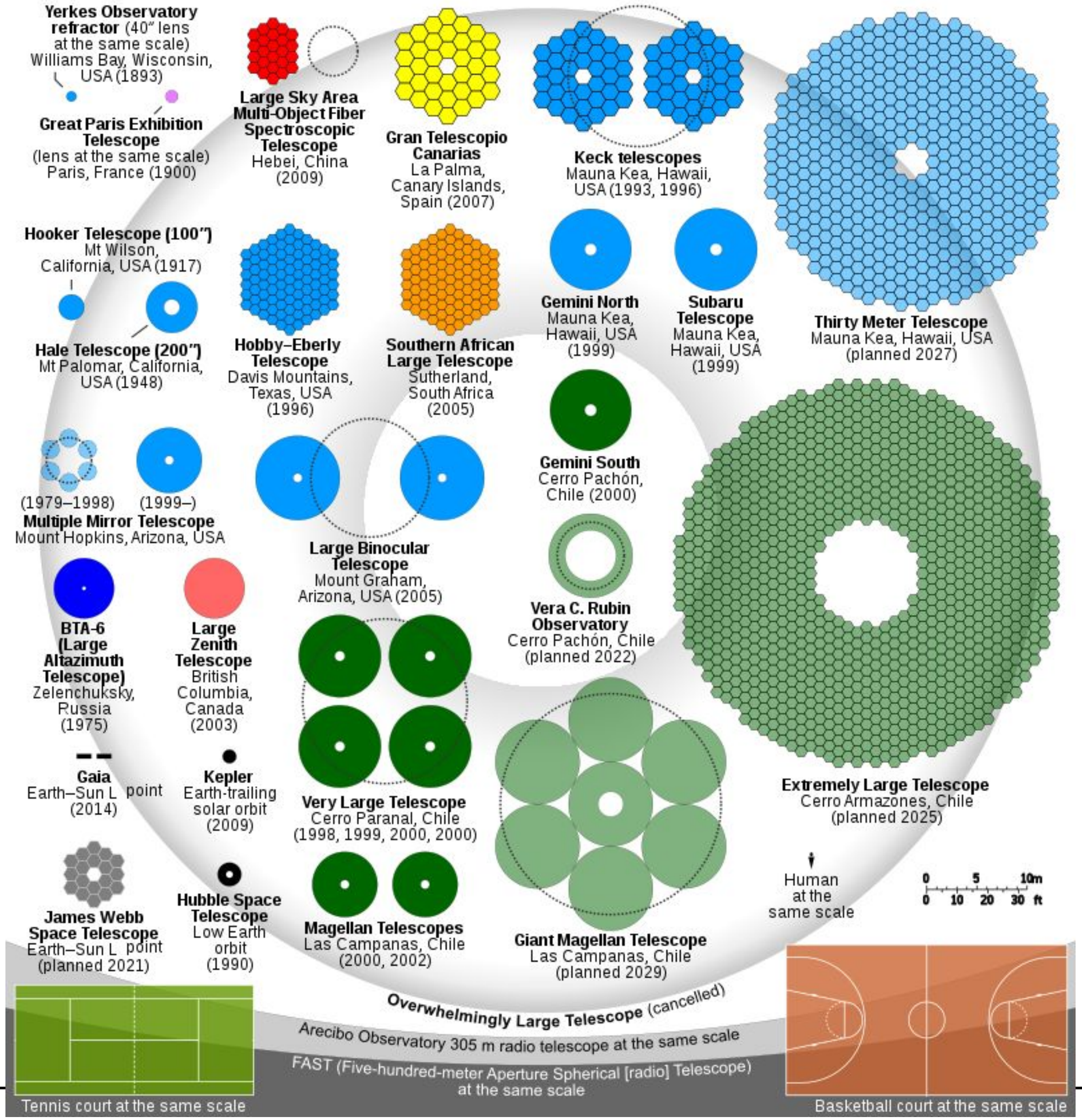
https://xkcd.com/1294/

ELT and other ESO sites in Chile





Why build extremely large telescopes?



Astronomers today have access to a variety of telescopes, on the ground- and in space

Not just for visible light, but X-ray, radio ….

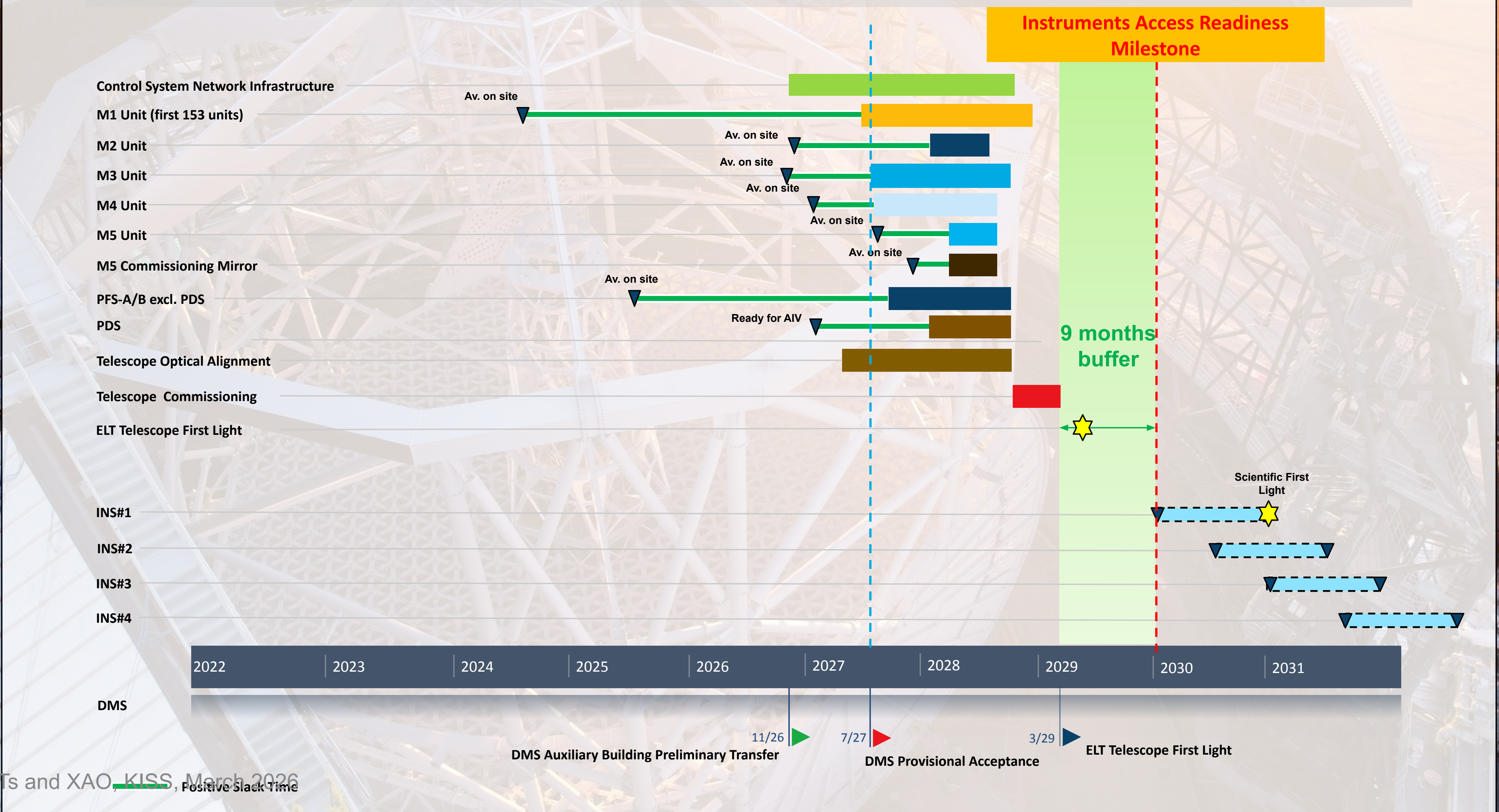
The biggest telescopes no longer have of a monolithic circular aperture

Mirror segmentation makes ELTs possible

Things are moving

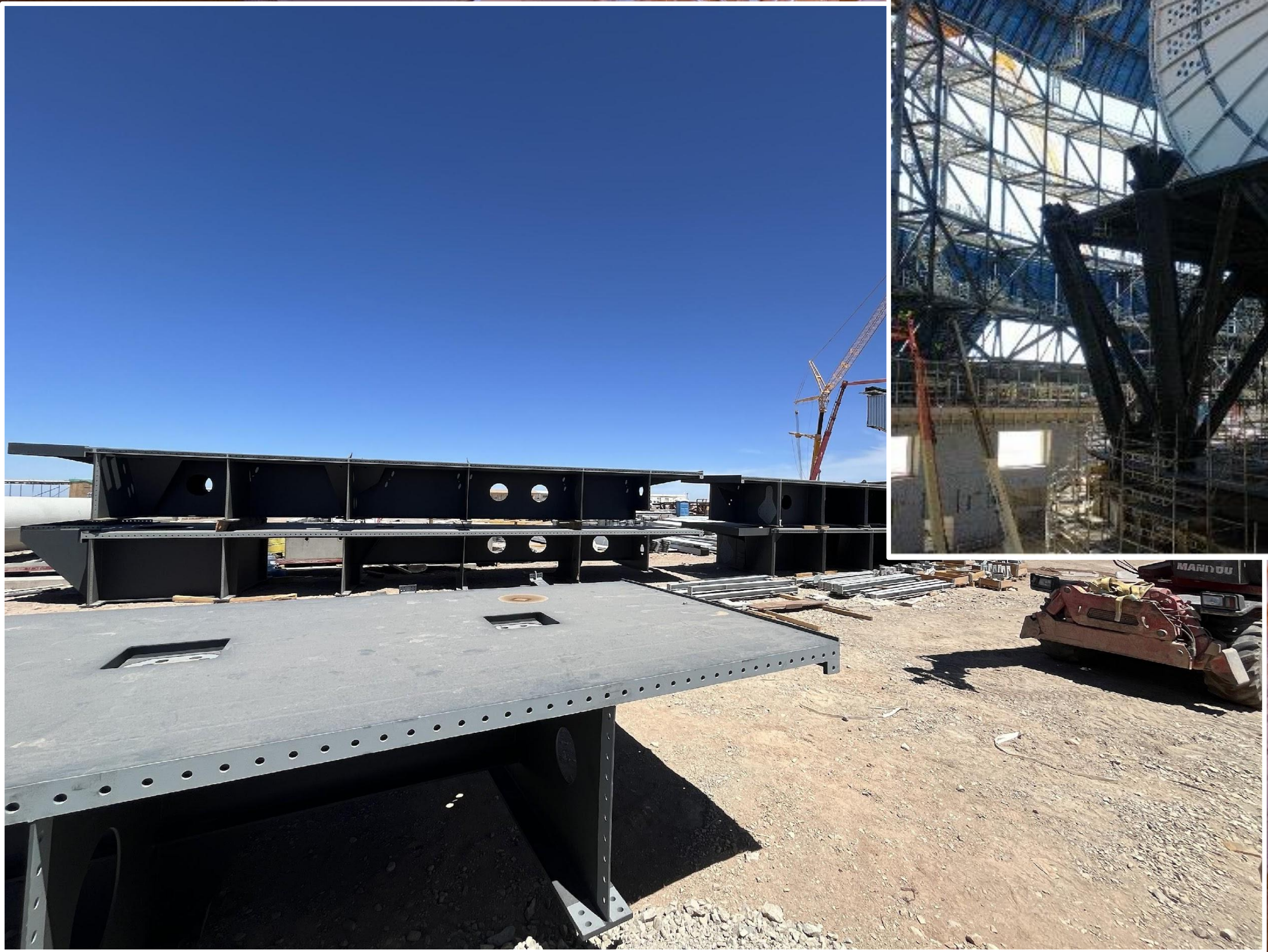
https://www.eso.org/public/images/potw2605a/

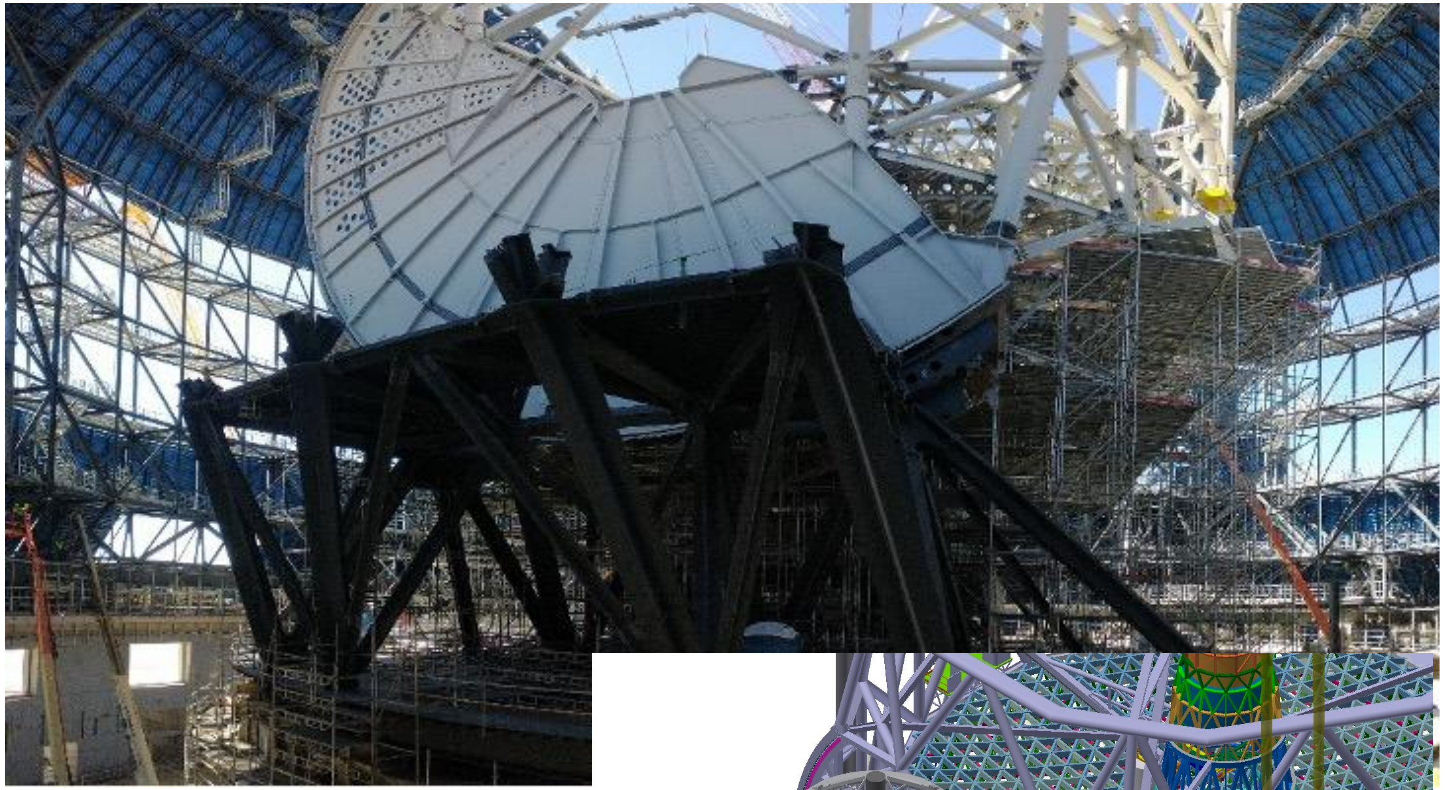
ELT Schedule

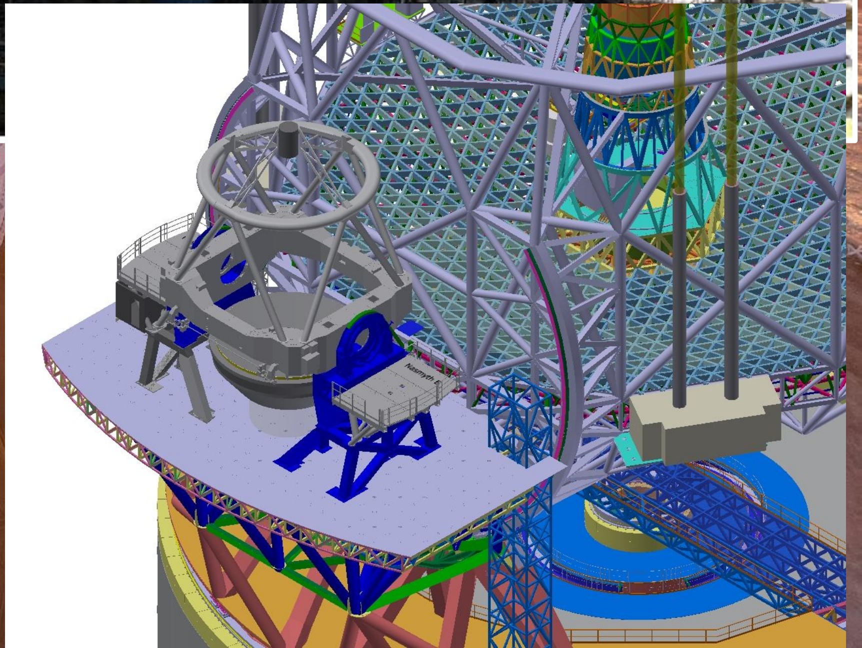


Nasmyth Platforms are enormous

Area ~basketball court each

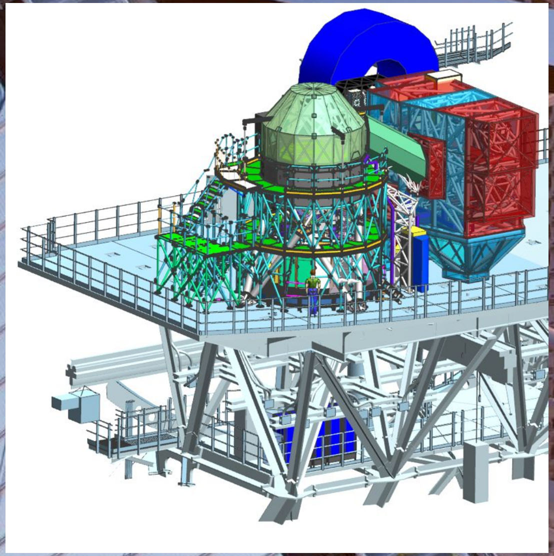


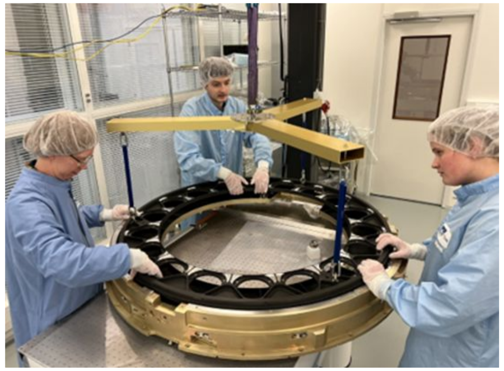




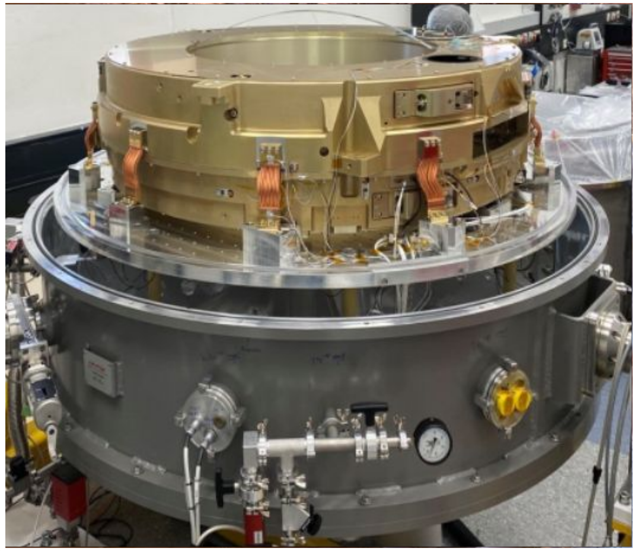
Instruments: MICADO

- NIR imager and spectrograph
- SCAO and MCAO with MORFEO
- In full construction phase



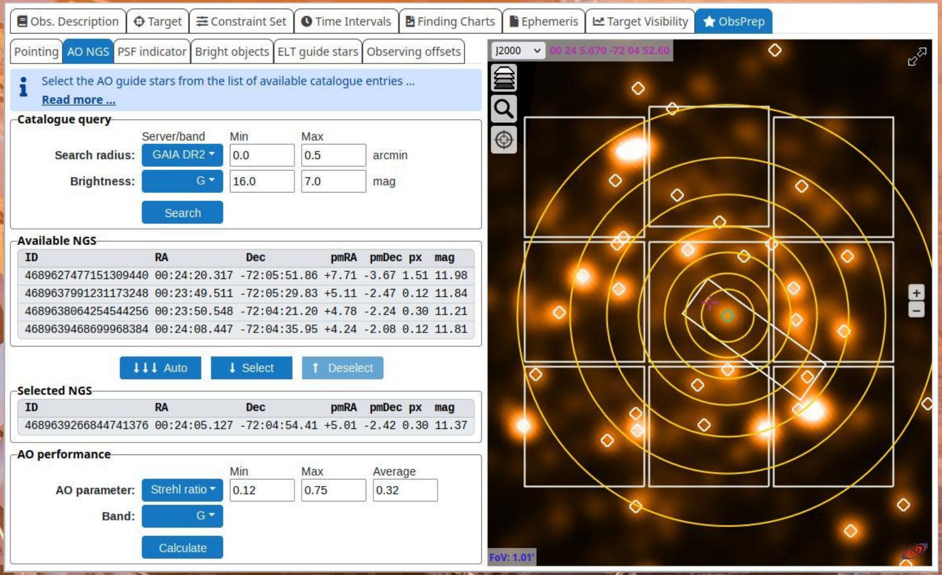


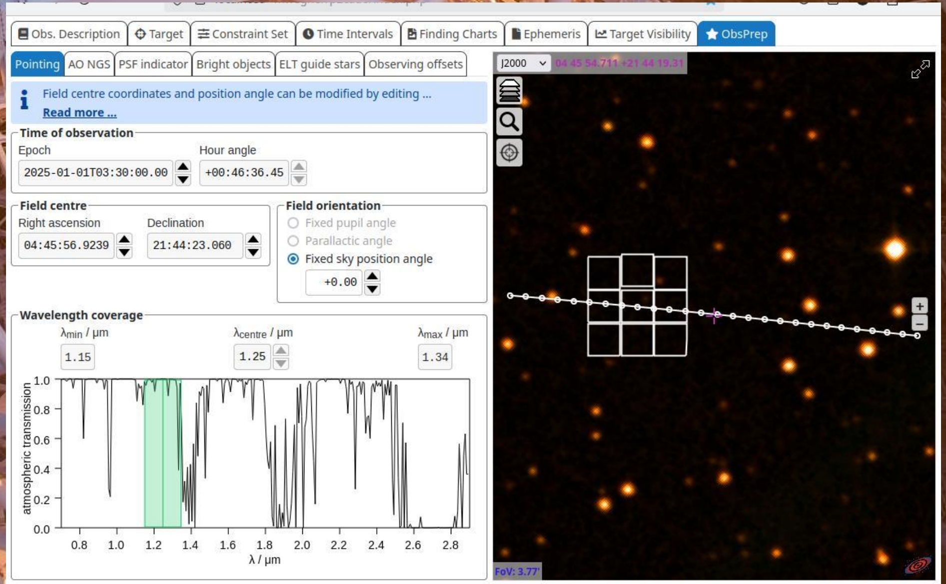
Central wheel mechanism



Instruments: MICADO

- NIR imager and spectrograph
- SCAO and MCAO with MORFEO
- In full construction phase
- Observation preparation tools in development

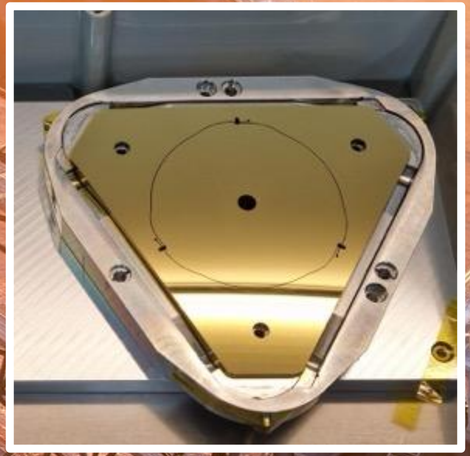




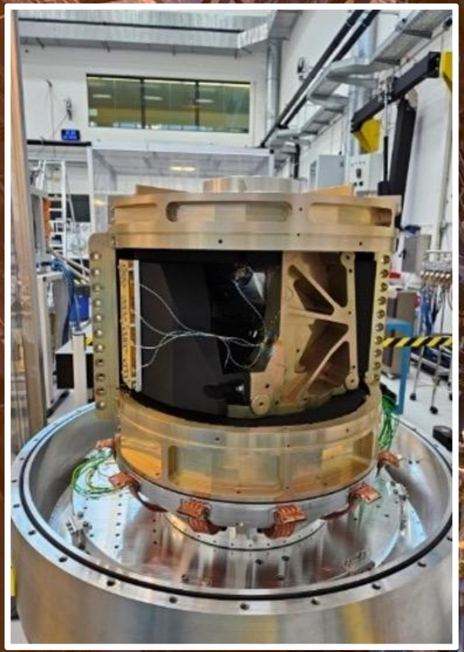
Instruments: METIS

- Mid-IR imager and spectrograph
  - 3-13.3 μm
  - Imgaging FoV 10” x 10” LM and N band with slit spectroscopy (few thousand in LM and few hundreds in N band)
  - High resolution (R~100,000) IFU spectroscopy in LM band.
  - SCAO + HC
- In full construction phase

Cryostat



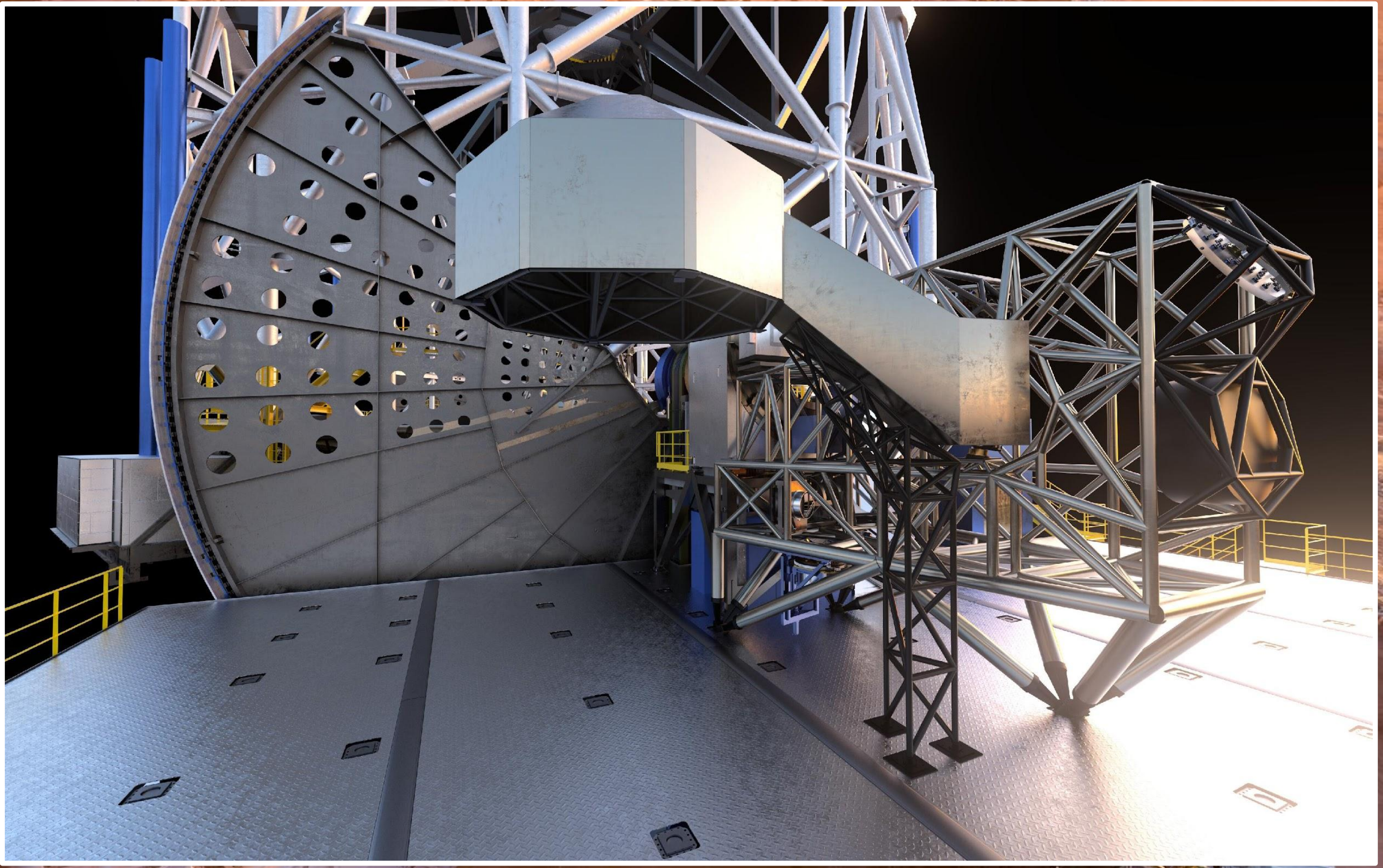
Chopper



Derotator

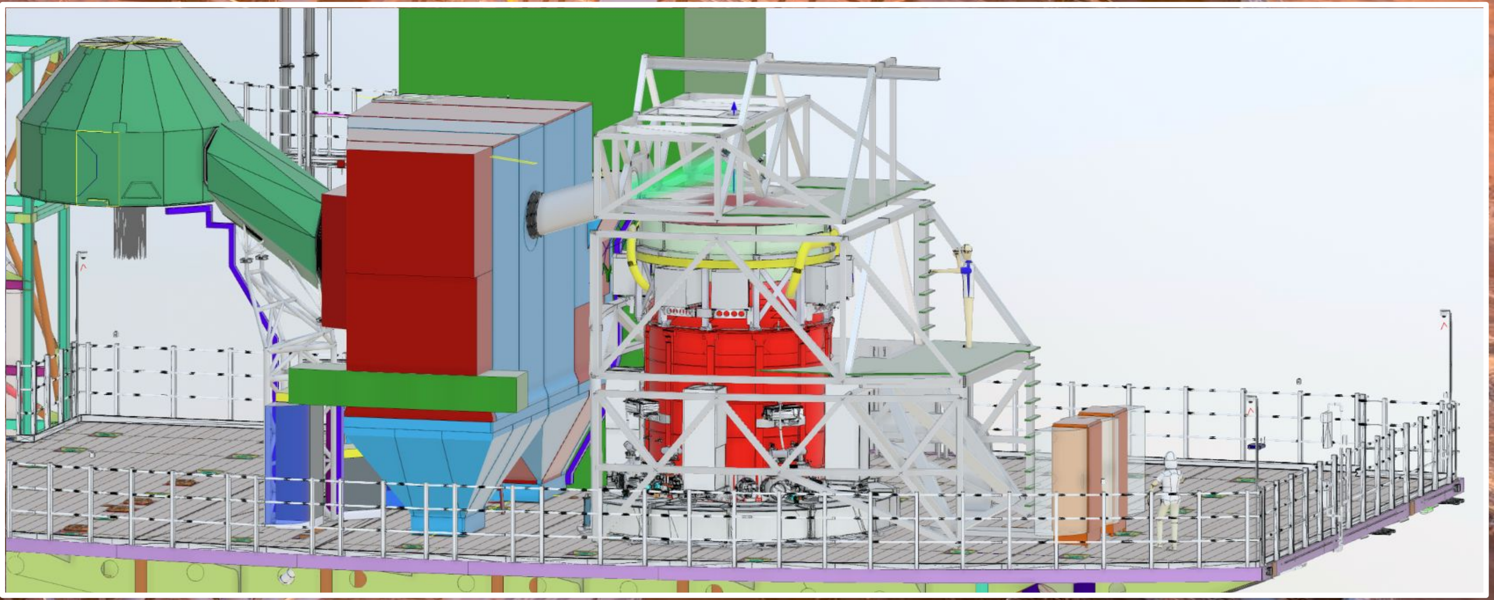
Instruments: MORFEO

- MCAO module
  for MICADO and HARMONI
- Passed optics FDR
  large optics being procured
- Two large (>1m) DMs ordered
- FDR started last month



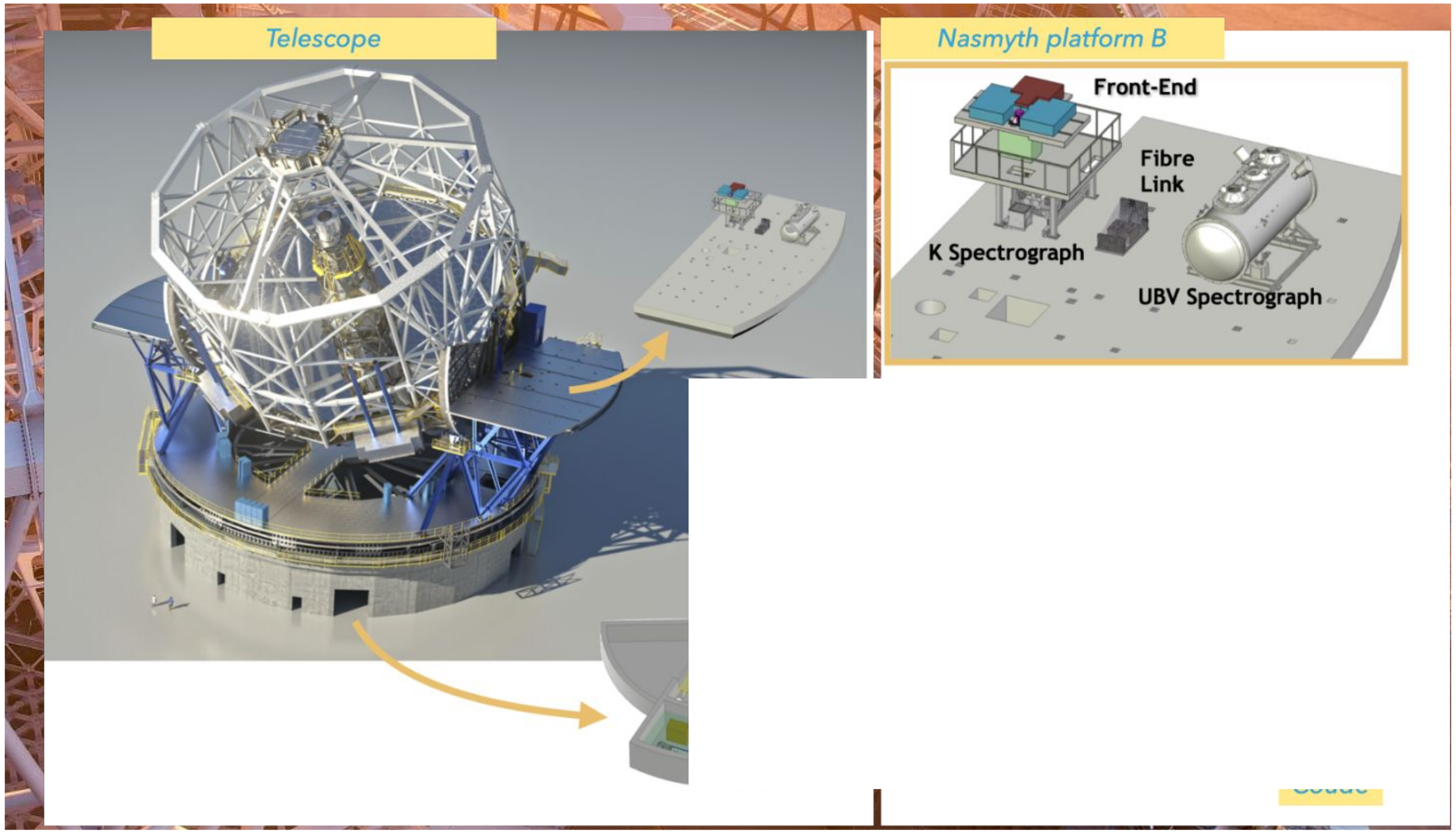
Instruments: HARMONI

- Near-IR diffraction limited IFU
- In rescoping phase:
  - 0.8 – 2.5 μm
  - 6 mas and 25 mas plate scale
  - R~3000 and ~7000
- Fed by MORFEO MCAO + SCAO and High contrast



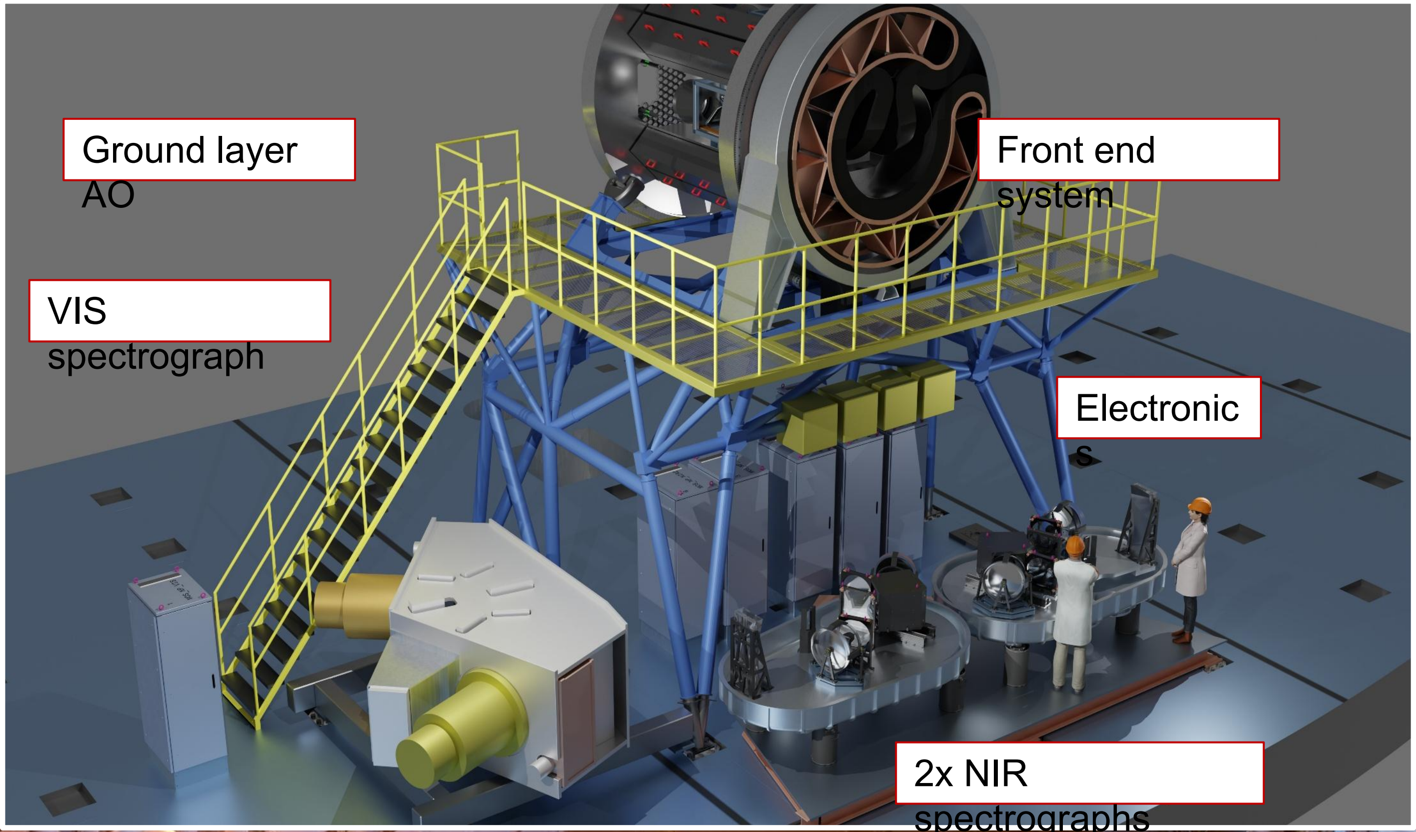
Instruments: ANDES

- High resolution visible and near-IR spectrograph
  - Simultaneous wavelength coverage: 0.4-2.4 μm (4 spectrographs, IFU)
  - R~100.000, at least 4 pixels for resolution element
  - Wavelength calibration precision and 24h stability of 1m/s
  - AO provide difflim in NIR
- Sub-system PDRs on-going, preparing for PDR ~mid 2026



Instruments: MOSAIC

- Vis and near-IR MOS
  - VIS LR (R~4000) : 138 mplex
  - VIS HR (R~19,000): 60 mplex
  - NIR (R~4000 & R~18,000) : 180 mplex
  - 8 IFUs
  - $\lambda \approx 0.4\mu m$ □ $1.8\mu m$
  - GLAO correction
- System Architecture Review
- Contract for construction signed on 1 December 2025



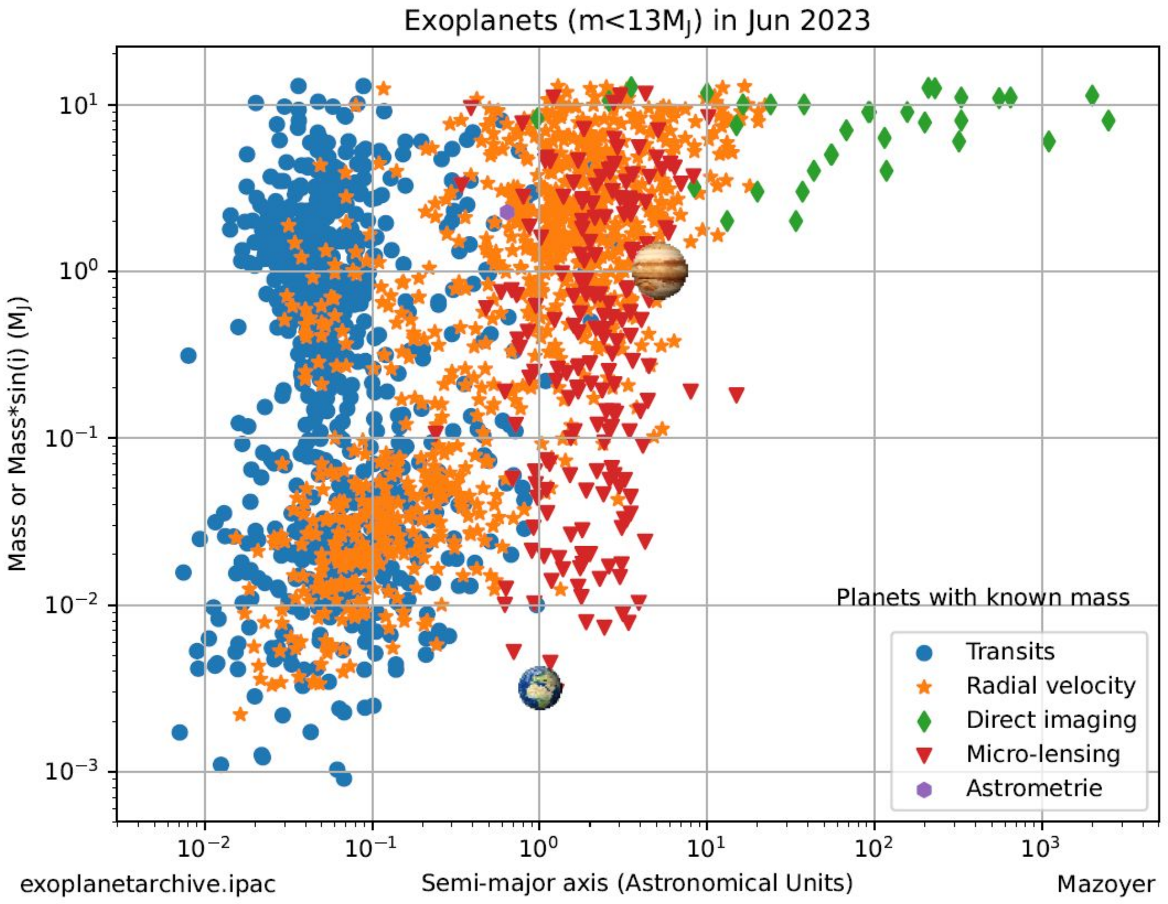
MOSAIC CONSORTIUM

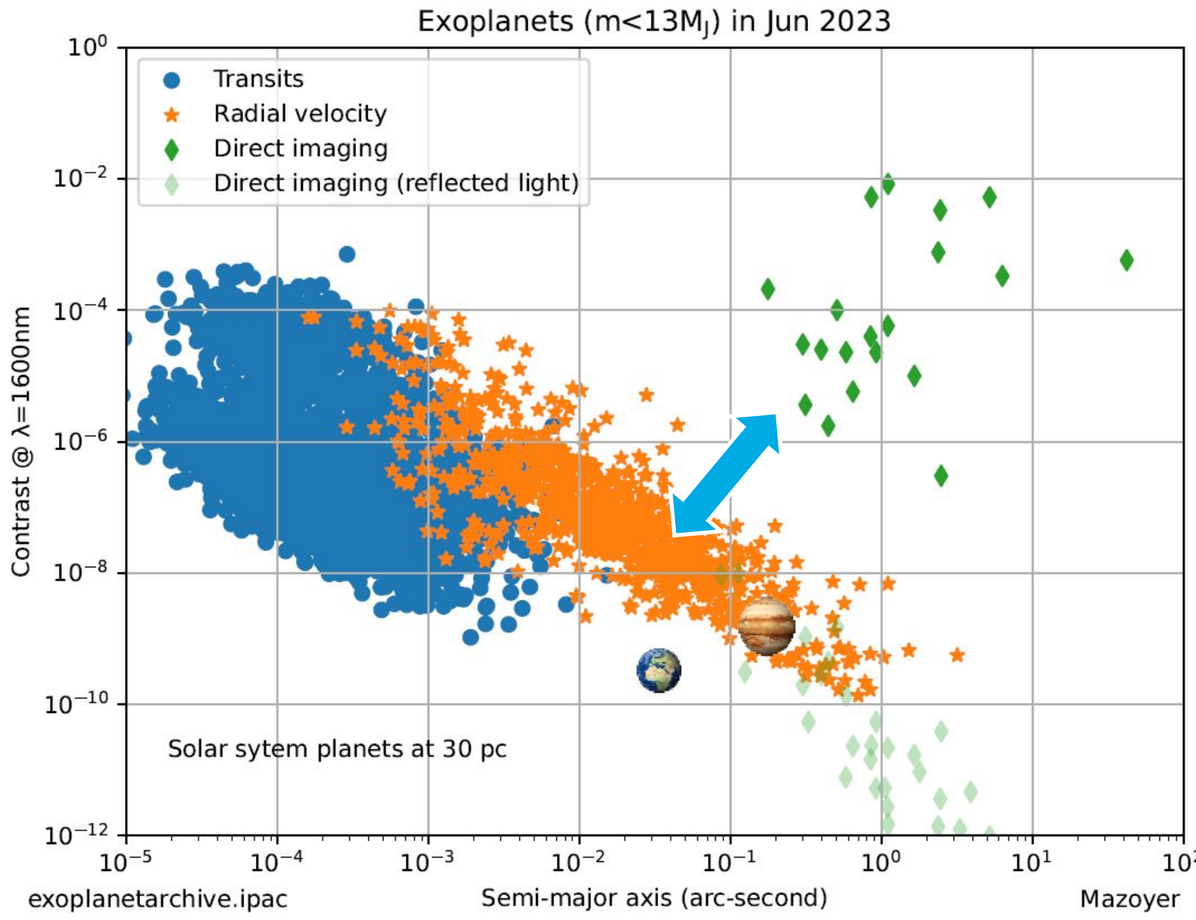
PCS is the next ELT instrument to be launched

Instrument	Main specifications			Schedule				
	Field of view/slit length/ pixel scale	Spectral resolution	Wavelength coverage (μm)	Phase A	Project start	PDR	FDR	First light
MICADO	Imager (with coronagraph) 50.5″ × 50.5″ at 4 mas/pix 19″ × 19″ at 1.5 mas/pix	*I, Z, Y, J, H, K* + narrowbands	0.8–2.45	2010	2015	2019	2024	
	Single slit	*R* ~ 20 000						
MORFEO	AO Module SCAO – MCAO		0.8–2.45	2010	2015	2023		
HARMONI + LTAO	IFU 4 spaxel scales from: 0.8″ × 0.6″ at 4 mas/pix to 6.1″ × 9.1″ at 30 × 60 mas/pix (with coronagraph)	*R* ~ 3 200 *R* ~ 7 100 *R* ~ 17 000	0.47–2.45	2010	2015	2018		
METIS	Imager (with coronagraph) 10.5″ × 10.5″ at 5 mas/pix in *L, M* 13.5″ × 13.5″ at 7 mas/pix in *N*	*L, M, N* + narrowbands	3–13	2010	2015	2019	2024	
	Single slit	*R* ~ 1400 in *L* *R* ~ 1900 in *M* *R* ~ 400 in *N*						
	IFU 0.6″ × 0.9″ at 8 mas/pix (with coronagraph)	*L, M* bands *R* ~ 100 000						
ANDES	Single object	*R* ~ 100 000	0.4–1.8 simultaneously	2018	2024			
	IFU (SCAO)							
	Multi object (TBC)	*R* ~ 10 000						
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	*R* ~ 5 000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5 000–20 000	0.8–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

1 milliarcsecond (mas) = 0.001″

How to increase directly imaged planet yield?





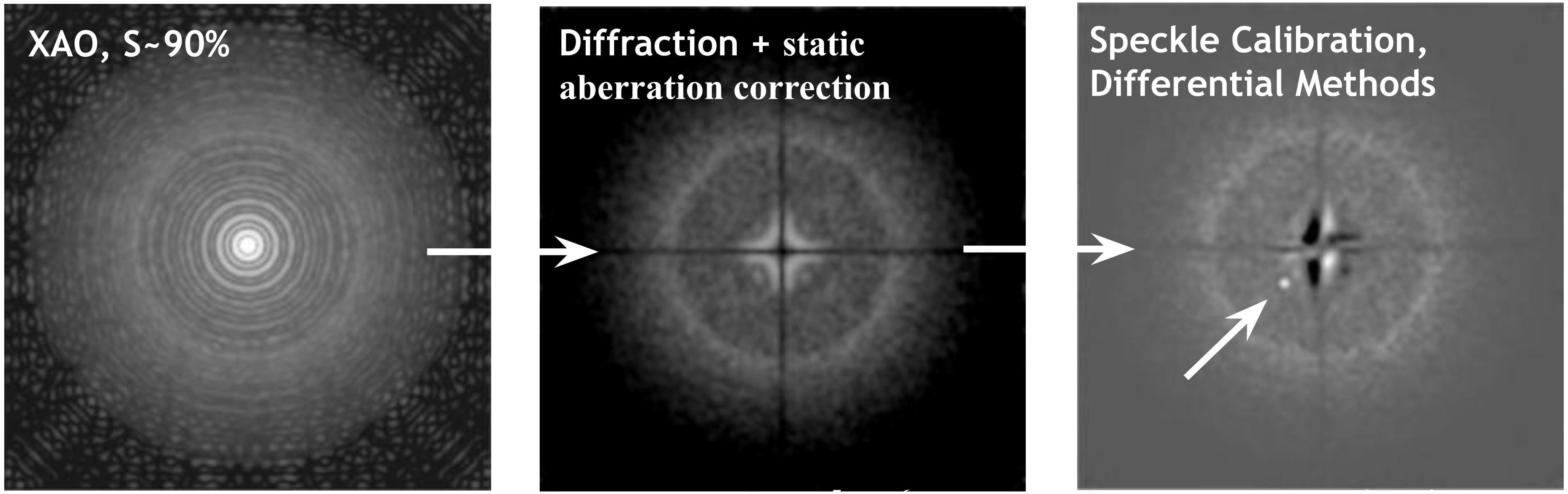
By courtesy of Johan Mazoyer

Push **inner working angle and contrast** to observe Exoplanets in reflected light
Need 10^{-8} contrast at 10-50 mas separation

How to achieve high imaging contrasts

3-step process

1. XAO corrects atmospheric turbulence effects (Seeing)
2. Diffraction residuals are reduced by coronagraphy
3. Residual imperfections are calibrated by differential methods



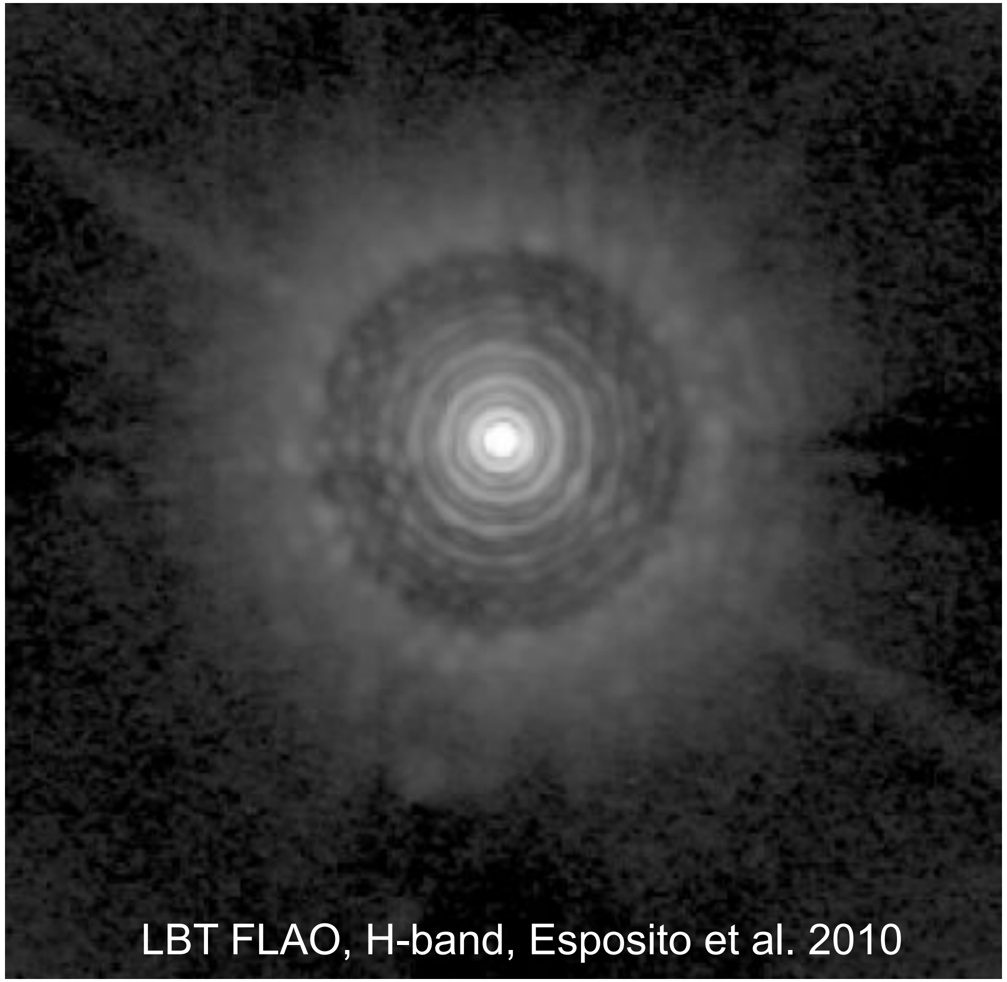
eXtreme AO (XAO)?

CFAO webpage: "*…scientifically driven by the need to achieve* ***high-contrast imaging*** *and spectroscopic capabilities to enhance the detection and characterization of* ***extra-solar planetary systems****…*"

Goal 1: High Strehl ratio (enhance planet signal)

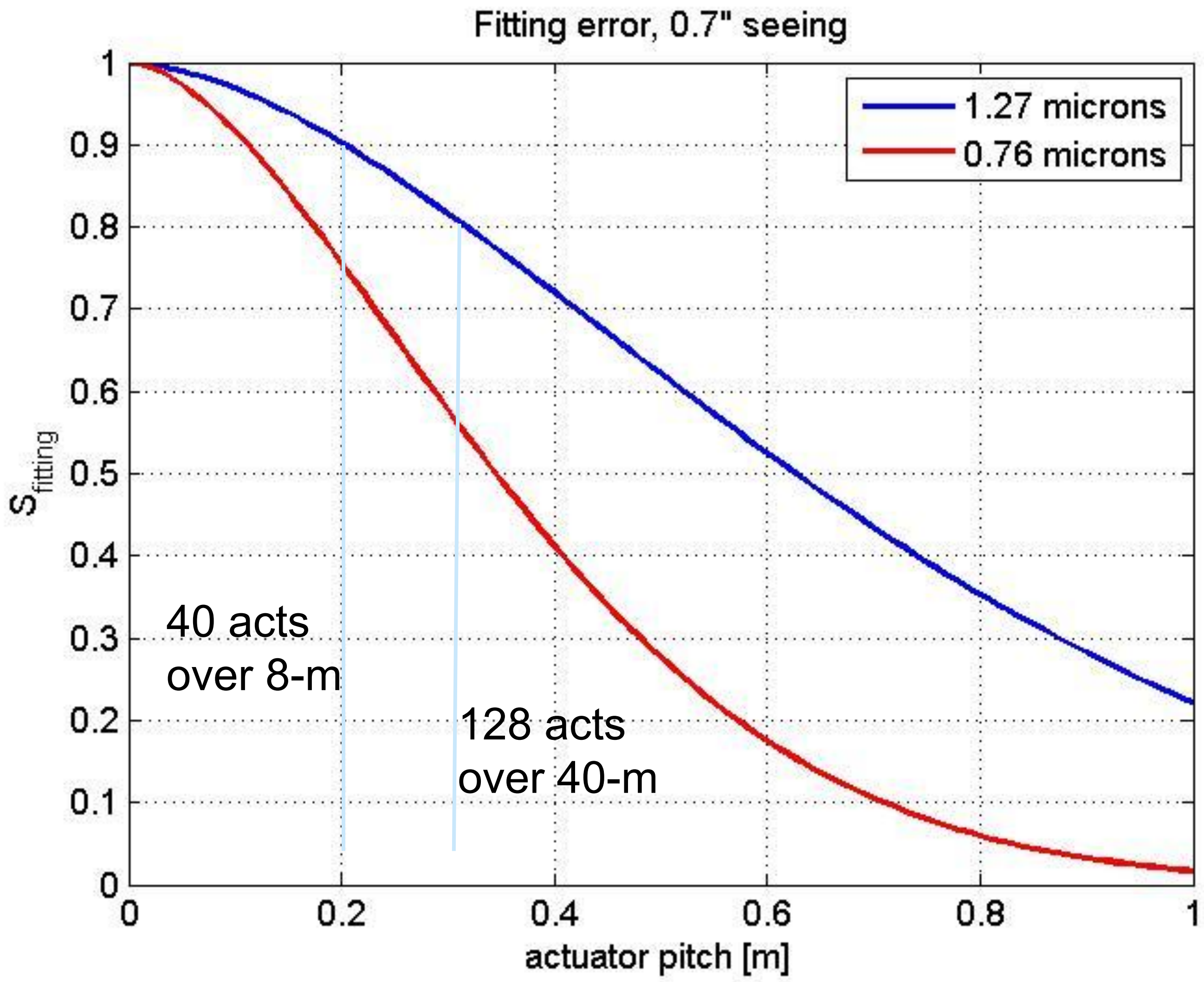
Goal 2: Suppress stellar residual halo (reduce noise)

Conceptually just a powerful single-conjugate AO



LBT FLAO, H-band, Esposito et al. 2010

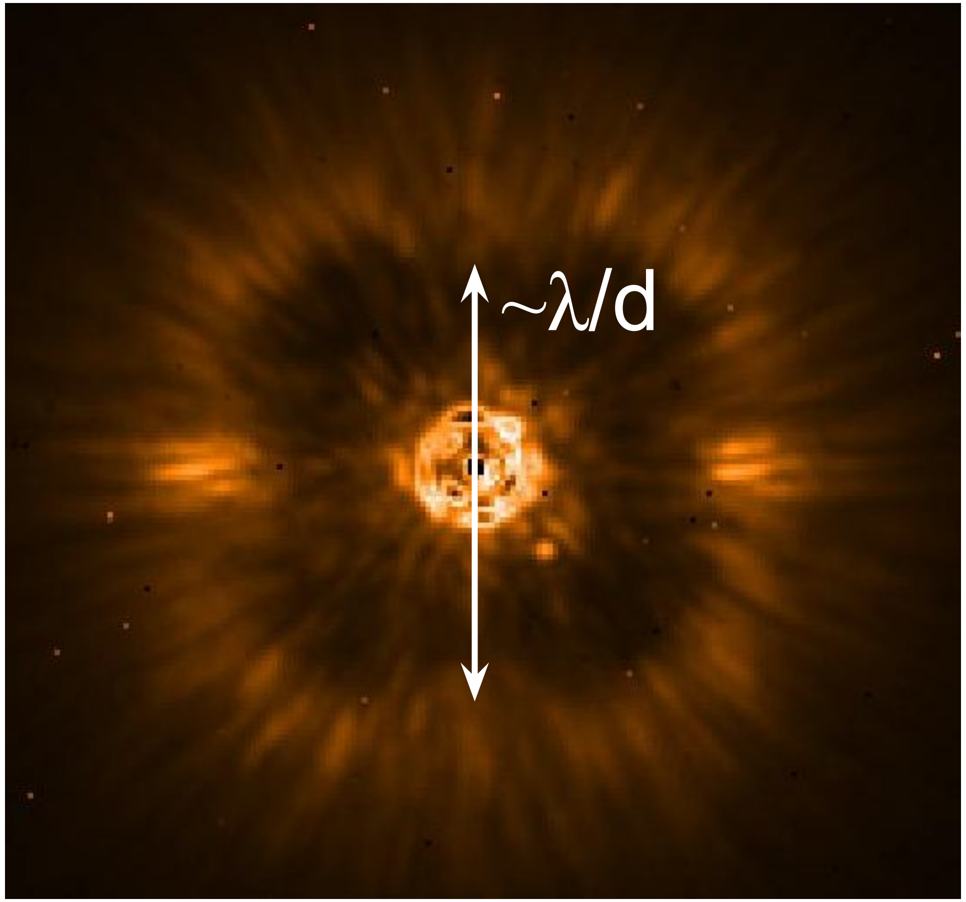
More DM actuators: high Strehl at Science wavelength



Planet signal ~SR

VLT-SPHERE DM, 20 cm pitch
⇒ 40 actuators across 8-m
⇒ 1377 actuators total

More DM actuators: Larger correction area



SPHERE coronagraphic on-sky PSF

Example VLT-SPHERE

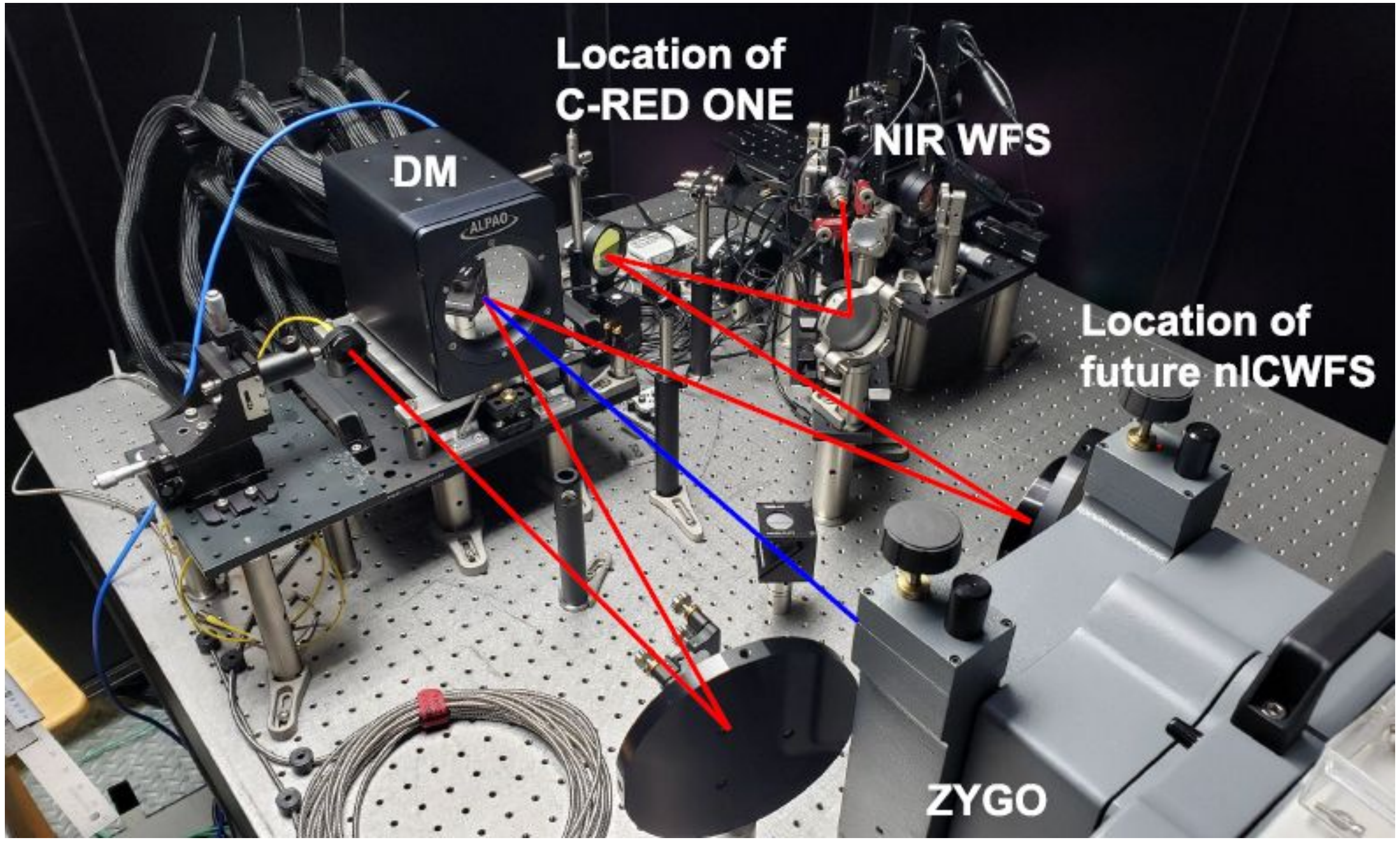
Actuator pitch $d = \frac{8\,m}{40} = 0.2\,m$

Wavelength $\lambda = 1.6\,\mu m$

=> DM correction diameter $\frac{\lambda}{d} = 1.6''$

XAO DMs off-the-shelf today

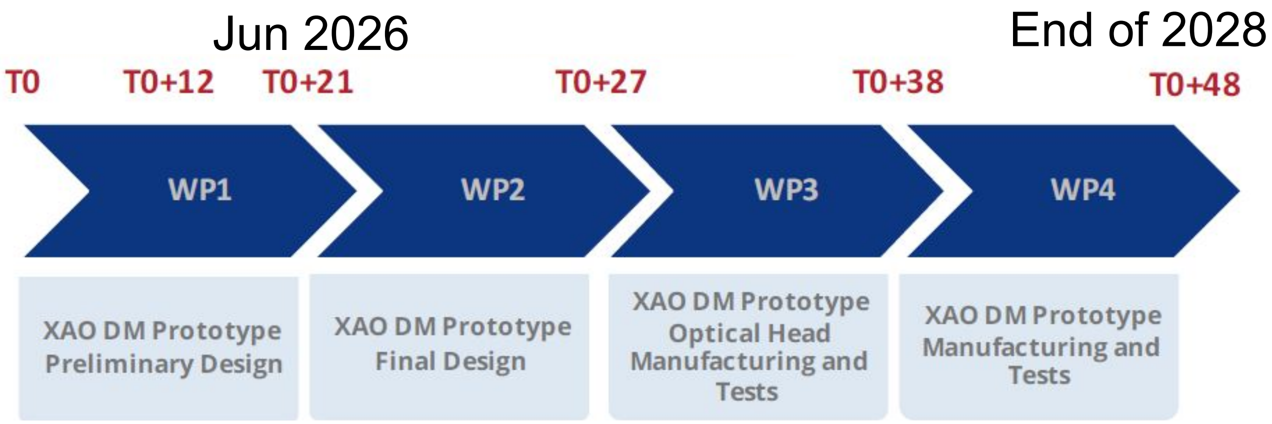
Bertin-ALPAO 64x64 @ Subaru (Lozi et al. 2022)



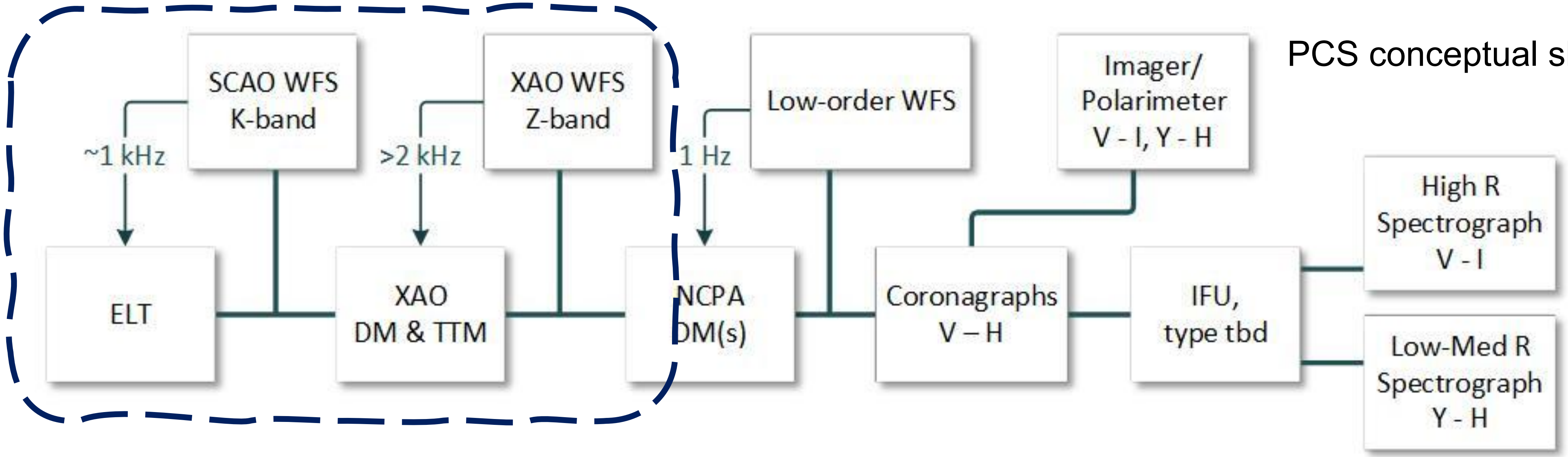
BMC 4K-3.5 with 64 across

XAO DM development for PCS

- ESO (S. Stroebele) development with Bertin-ALPAO
  - Many actuators: > 13000, >128 across pupil
  - High speed: small stroke settling < 300 us
  - ±3μm Stroke @ 0.2 nm resolution
  - Integrated drive electronics



XAO: The unique selling point of PCS



PCS conceptual sketch

- High framerate and predictive control for minimization of dominating temporal delay error
- XAO DM with > 13k actuators for high Strehl ratio in the optical (~60% at 750 nm)

PCS roadmap community collaboration, started early 2025

Clear understanding of the PCS instrument's scientific objectives

Draft instrument concept addressing these scientific objectives

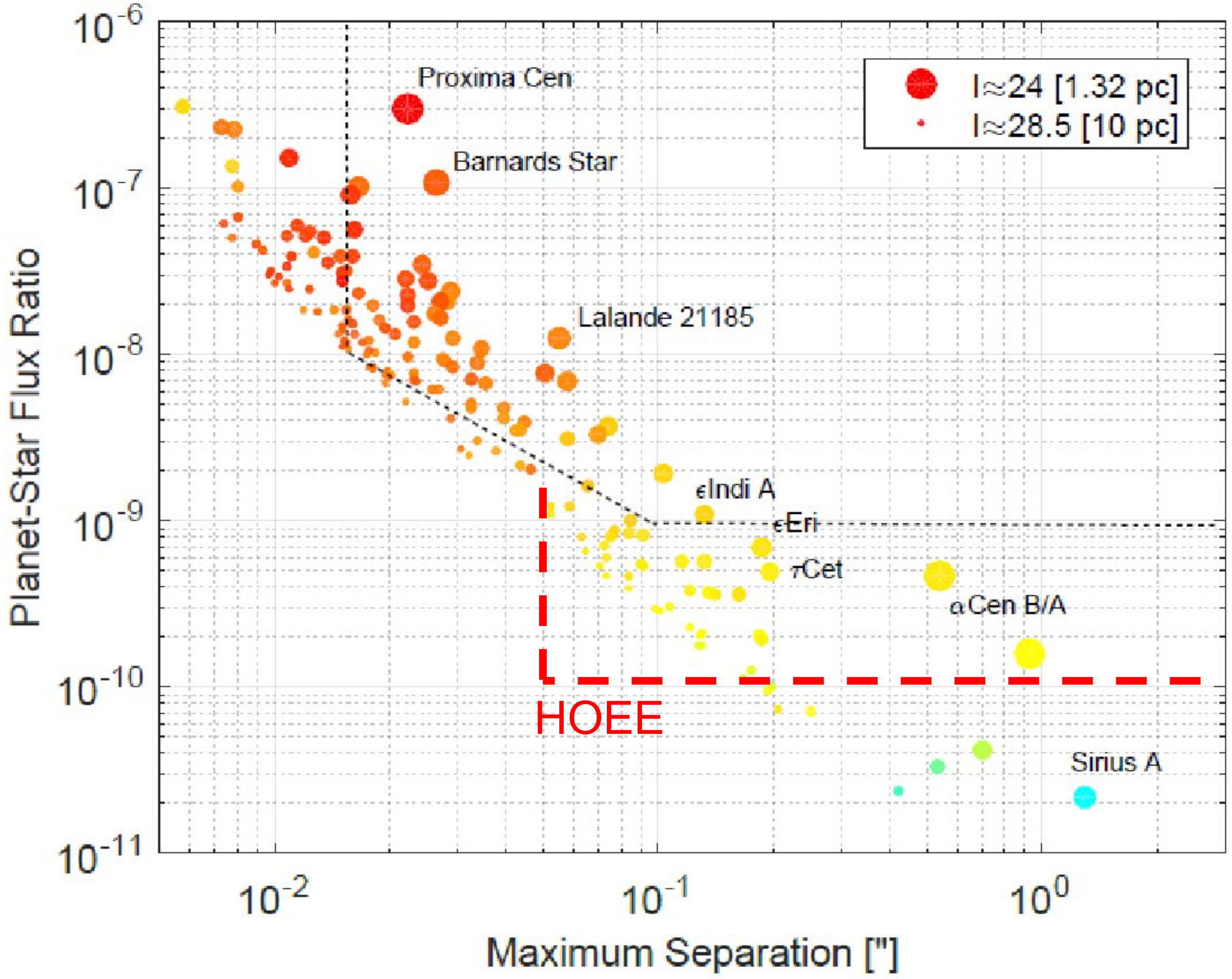
Rough estimates of important instrument budgets (volume, weight, transmission, power, cost)

Analysis of scientific capabilities of the proposed concept

Summary in a white paper early 2028

Establish training opportunities for graduate students and fellows in the field of high-contrast imaging

PCS science goal



For more info on PCS XAO…

see Jalo's poster (or talk to us ☺)

Take aways

ELTs with AO provide superior spatial resolution, sensitivity and speed

Three projects: ELT (1st light ~2030), GMT (1st light early to mid 2030), TMT (1st light tbd)

The ELT instrumentation suite is being developed starting with MICADO and METIS at 1st light

The XAO planet imager PCS is in pre-phase-A. The 13k actuators DM is being developed (prototype late 2028) and will provide for Strehl ratios around 50%-60% in at red optical wavelengths

Connect with ESO

Thank you!

Here your name
and your contact details
Final slides include our flag row

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PCS science

Rocky planets: detection, orbit determination and inclination, habitability - presence of (liquid) H_2O, biosignatures (O_2, CH_4), variation in atmospheric composition, connection to dust/debris

Sub-Neptunes – Giant Planets: characterization in reflected light, orbits, compositions

Planet formation: Hα (656 nm) imaging at very high contrast and small IWA, accreting Exoplanets in transitional disks. Synergy with ELT 1st light instruments observation in NIR

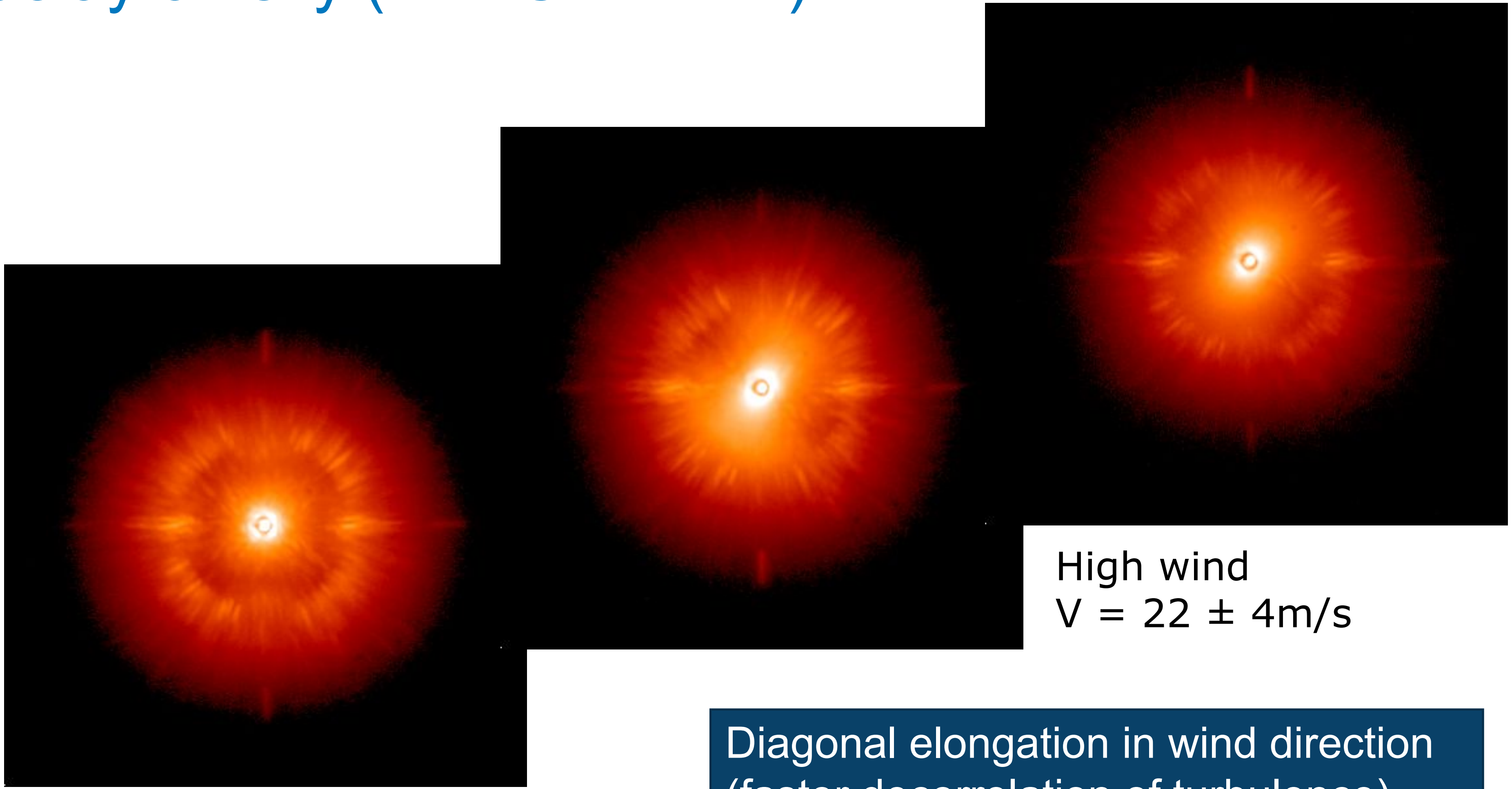
Young Giant Exoplanets: High S/N enables studies of precise photometric variability, Doppler imaging

Exomoons: detection by RV, transits, imaging

Circumstellar disks and dust (incl. exozodiacal): Imaging at ~5 mas resolution with 15 mas IWA Synergies with ALMA (similar spatial resolution at mm wavelengths)

…

AO delay on sky (VLT-SPHERE)

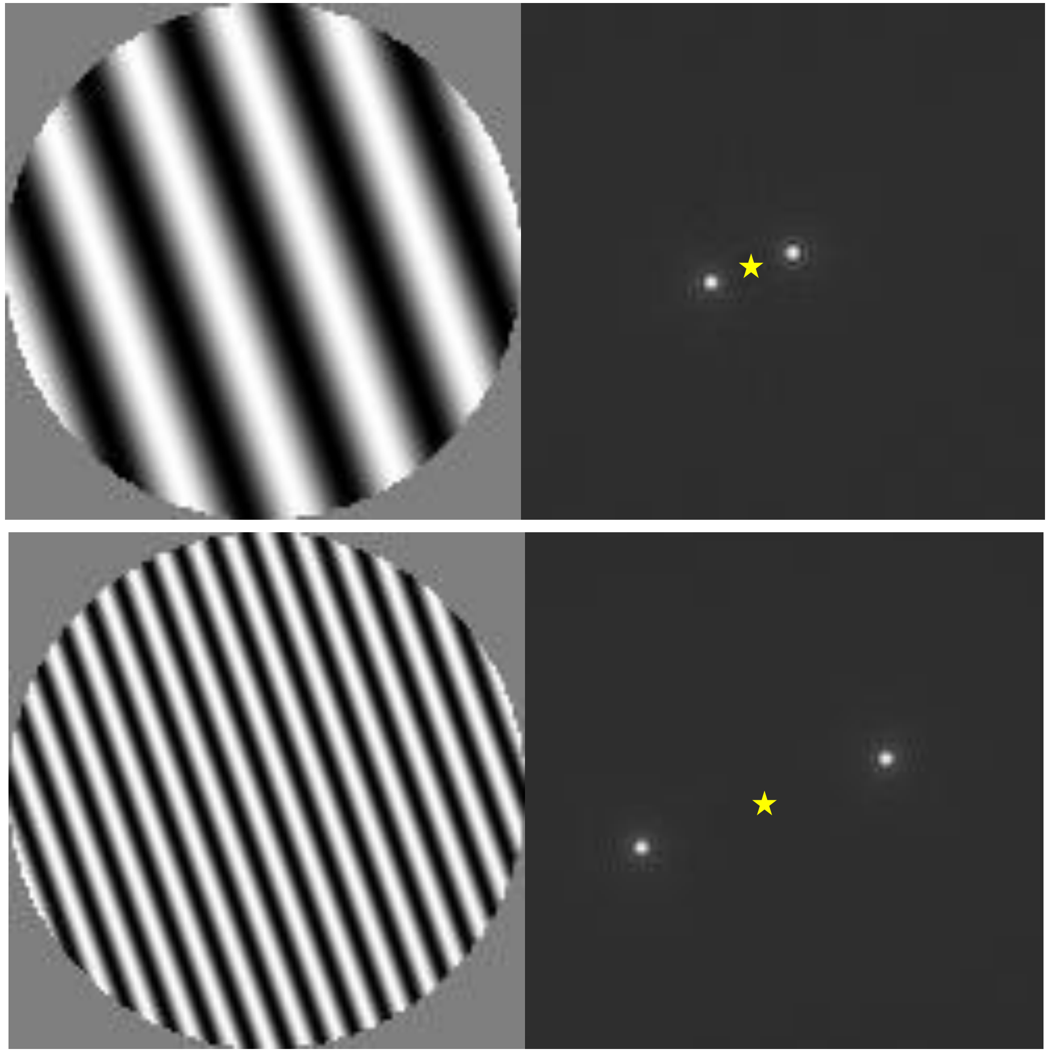


Low wind
V = 3 m/s ± 1 m/s

High wind
V = 22 ± 4m/s

Diagonal elongation in wind direction
(faster decorrelation of turbulence)

Speckles



$$I_{speckle} = (2\pi a/\lambda)^2/4$$

$\lambda = 760$ nm:
$a = 0.25$ nm for $I_{speckle} = 10^{-6}$

A good optical surface introduces a few nm rms

SPHERE:

- ~25 surfaces between wavefront sensor and science detector
- Lightbeam drifts over surfaces during the observation (flexure, refraction, …)
- Speckle field slowly variable

Aberration spatial frequency sets speckle location

$$E_a(x) = \exp[i(a\sin(2\pi x f + \alpha) - ib\sin(2\pi x f + \beta))]$$
$$= 1 + i(a\sin(2\pi x f + \alpha) - ib\sin(2\pi x f + \beta)).$$

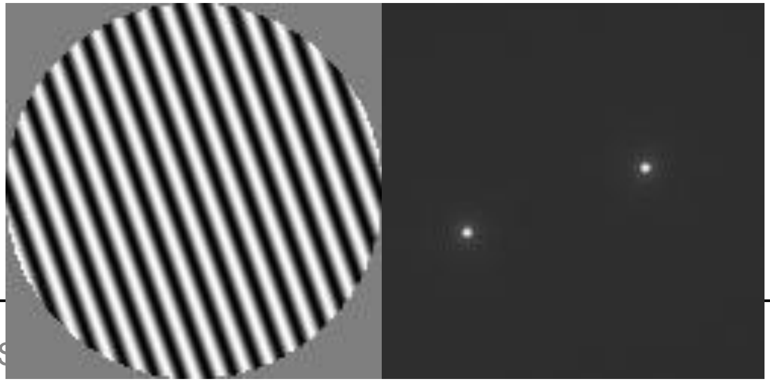
Phase ripple   Amplitude ripple

Far-field

FT

$$E_i(\theta) = E_{i,0}(\theta) + 0.5[a\exp(i\alpha) - b\exp(i(\beta + \pi/2))]E_{i,0}(\theta + f\lambda) \quad (1.33)$$
$$+ 0.5[a\exp(-i(\alpha - \pi)) - b\exp(-i(\beta + \pi/2))]E_{i,0}(\theta - f\lambda).$$

$I_i = E_i E_i^*$ = Airy(0) + Airy($\theta \pm f\lambda$) + cross-terms (pinned speckles)



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