30-m telescopes

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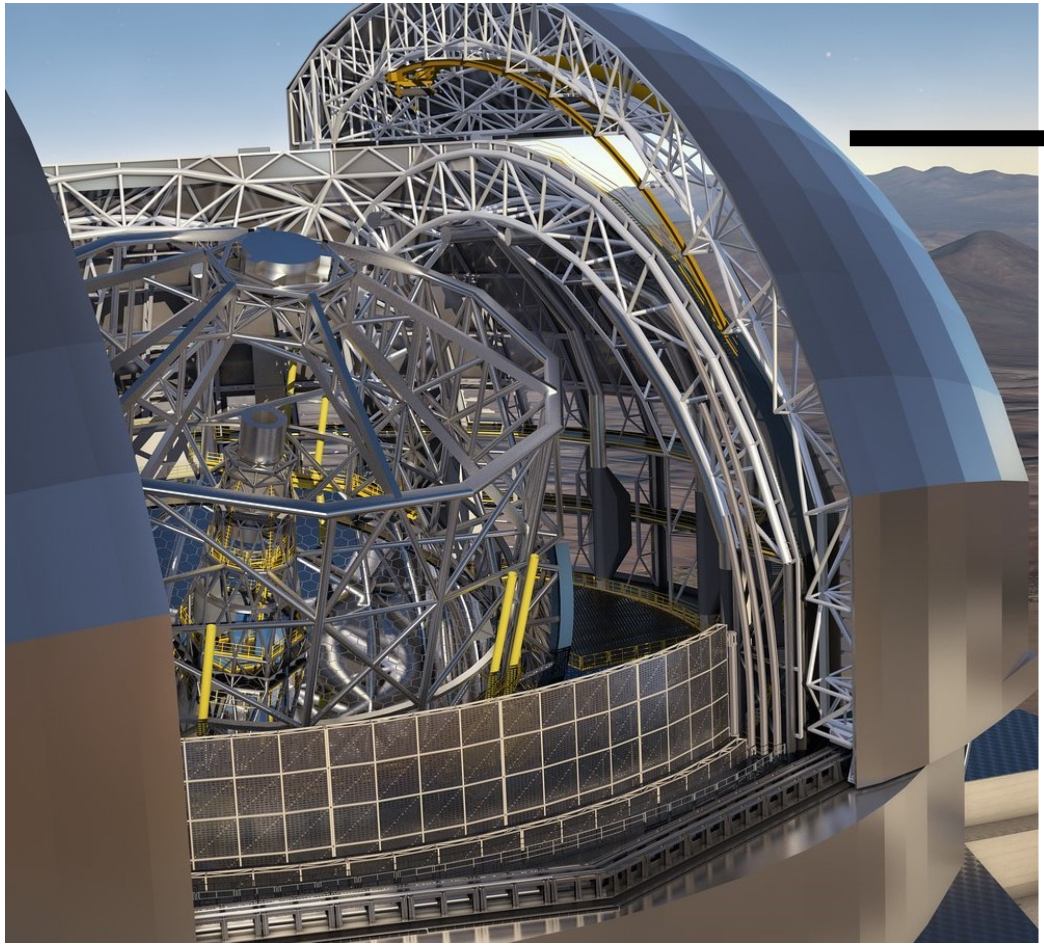
With inputs from S. Ramsay, R. Davies, N. Thatte and B. Brandl

Overview of the talk

- Why big telescopes?
- Extremely Large Telescopes
- ELT 1st generation instruments: MICADO/MAORY, HARMONI, METIS
- Planetary Camera & Spectrograph (PCS) – 2nd gen, tbc

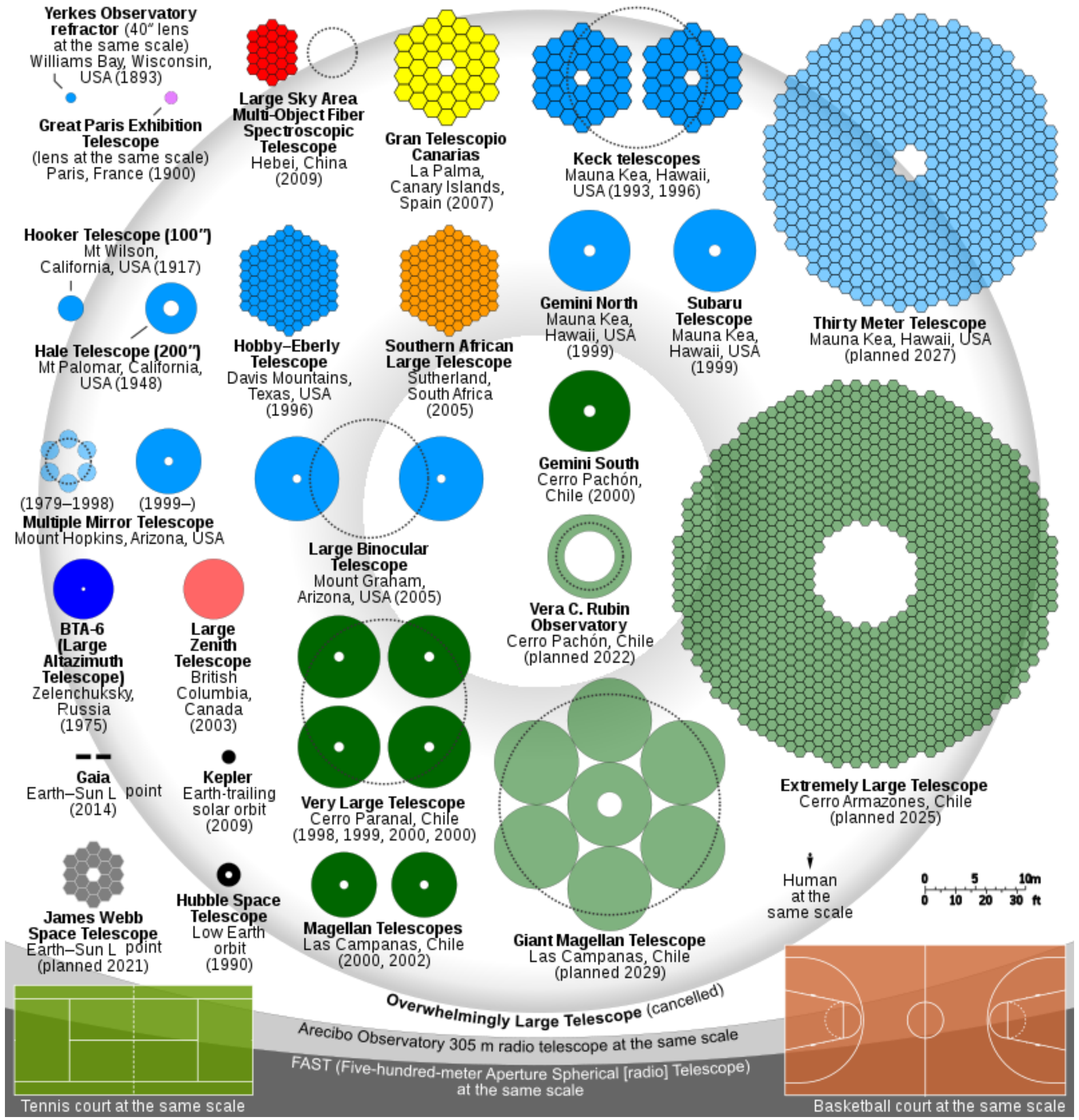
Disclaimer: This is a Euro-centric presentation, US 30-m telescopes are progressing on similar time-scale with similar instruments

The Extremely Large Telescope



https://xkcd.com/1294/

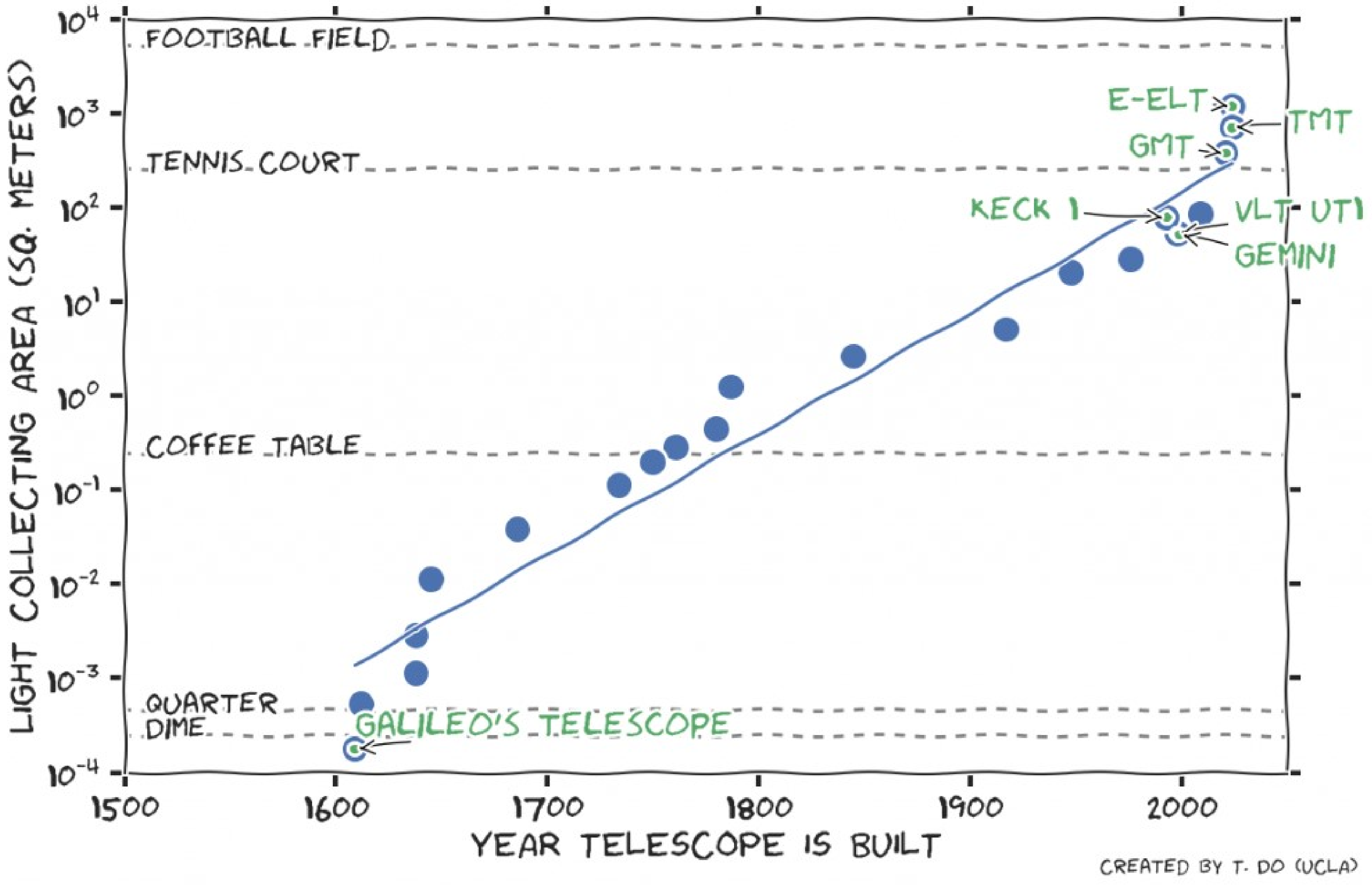
Why build an extremely large telescope?



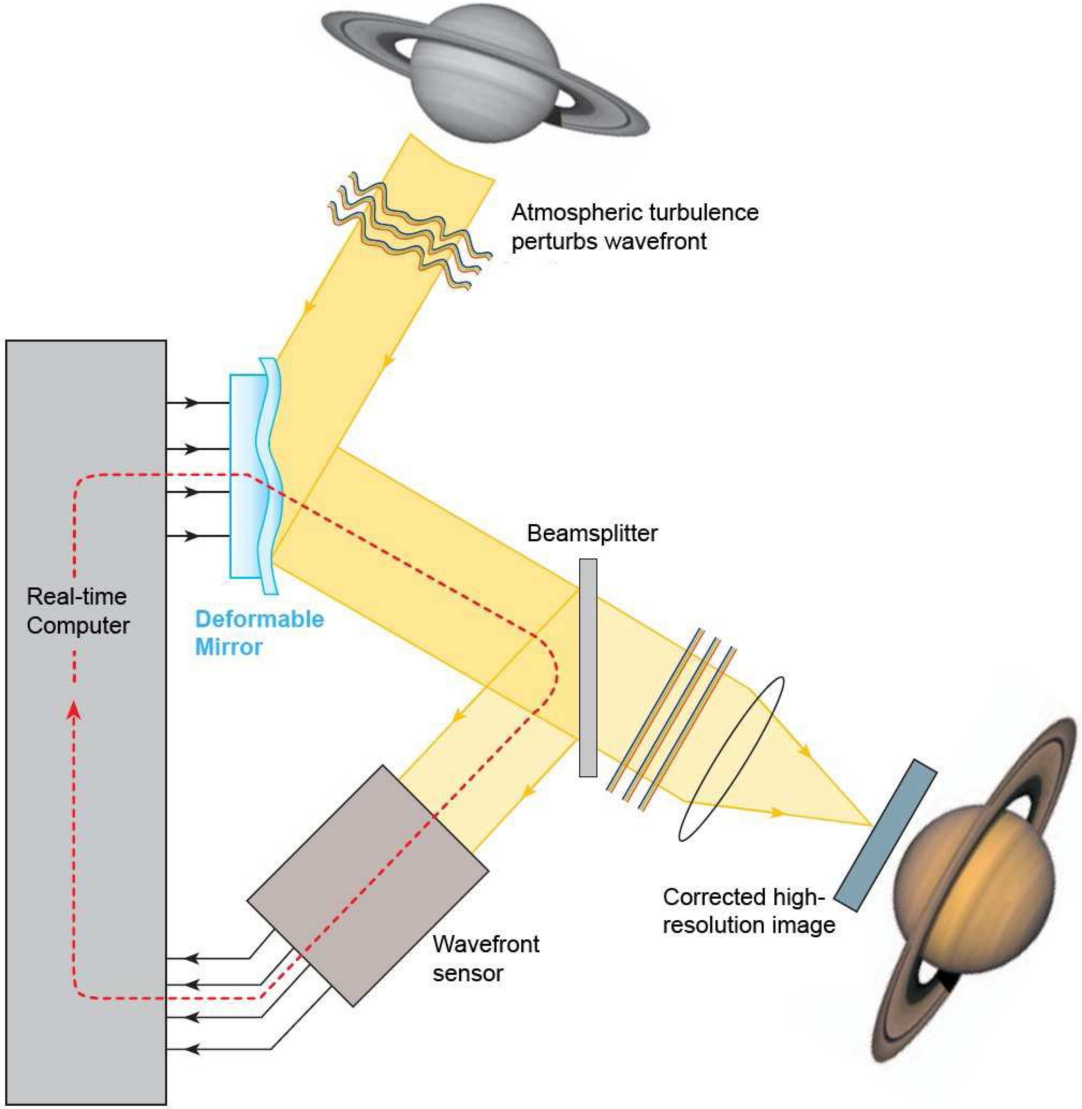
- Astronomers today have access to a huge number of telescopes
- On the ground and in space
- Not just for visible light, but X-ray, radio ….
- The biggest telescopes no longer have of a monolithic circular aperture
- Mirror segmentation makes large telescopes possible

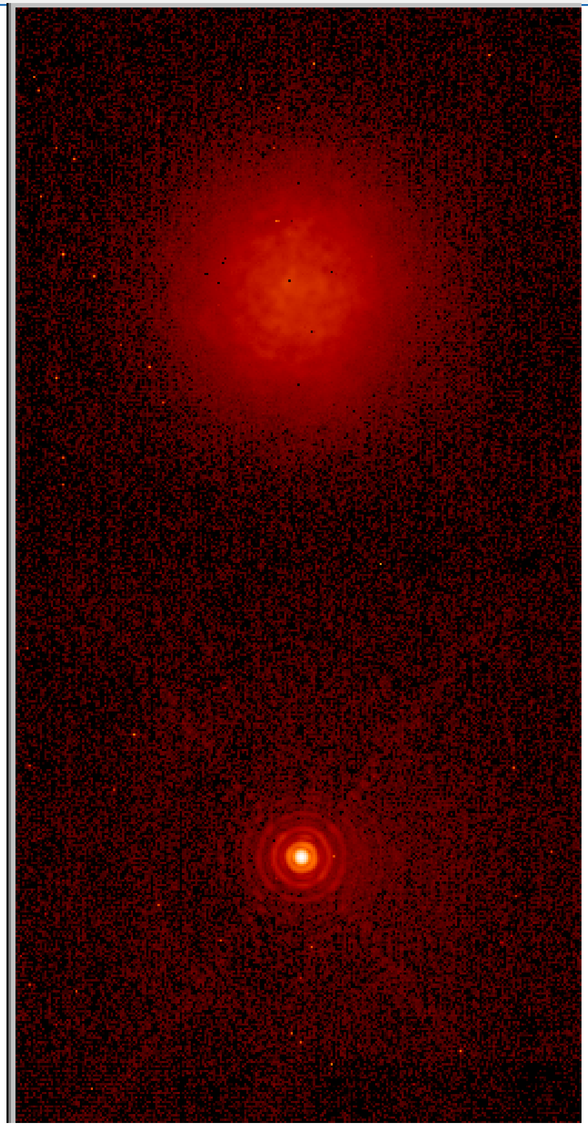
Why build larger (aperture) telescopes?

- Resolving power $\theta \simeq 1.22 \frac{\lambda}{D}$
- Light gathering power ~ $A \propto D^2$
- Imaging speed for point sources $\propto D^4$



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





Seeing disk

AO

Airy disk

The effect of telescope size

The Hubble Space Telescope
2.4m diameter

The Very Large Telescope
8m diameter

The Extremely Large Telescope
39m diameter

ELT vs VLT:
The power of large telescopes

- Big telescopes collect more flux ($\propto D^2$)
- Consider diffraction limited point source (Airy pattern area)
  - Collected point source flux $\propto D^2$
  - 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)

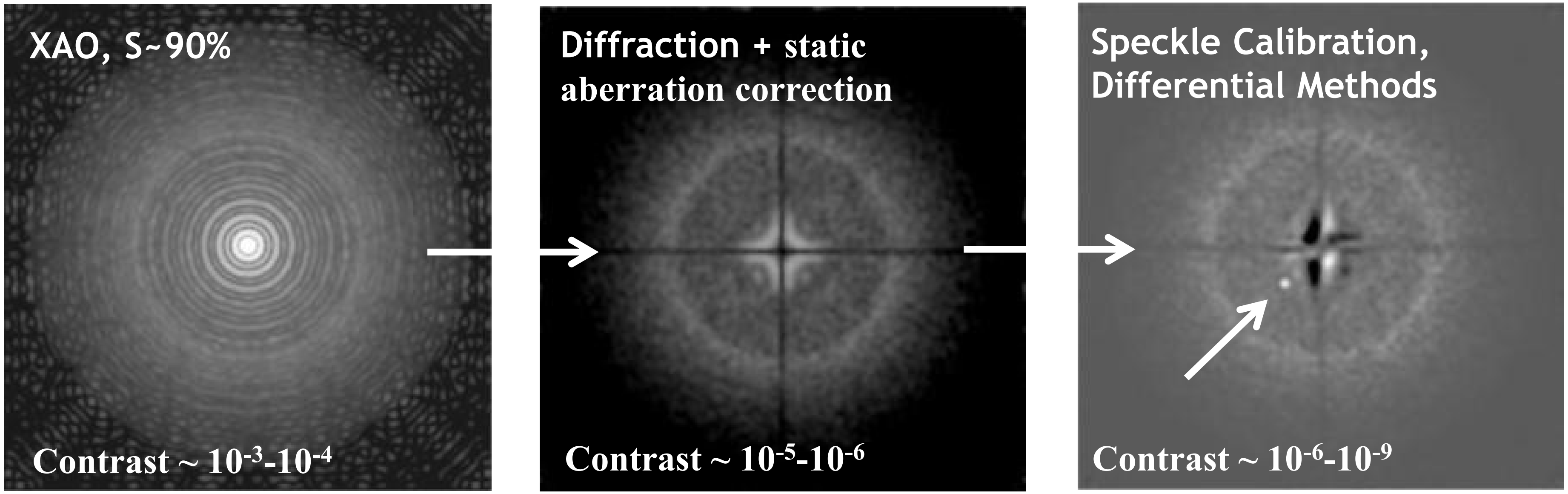
$$SNR \propto D^2 \times \sqrt{t} \qquad \Rightarrow \qquad t_{SNR} \propto D^{-4}$$

A 40-m telescope can do an observation $5^4 = 625$ times faster than an 8-m, NIR magnitude limit/hr increases by $5^2 = 25$ (from ~23 mag to ~26.5 mag)

How to achieve high imaging contrasts

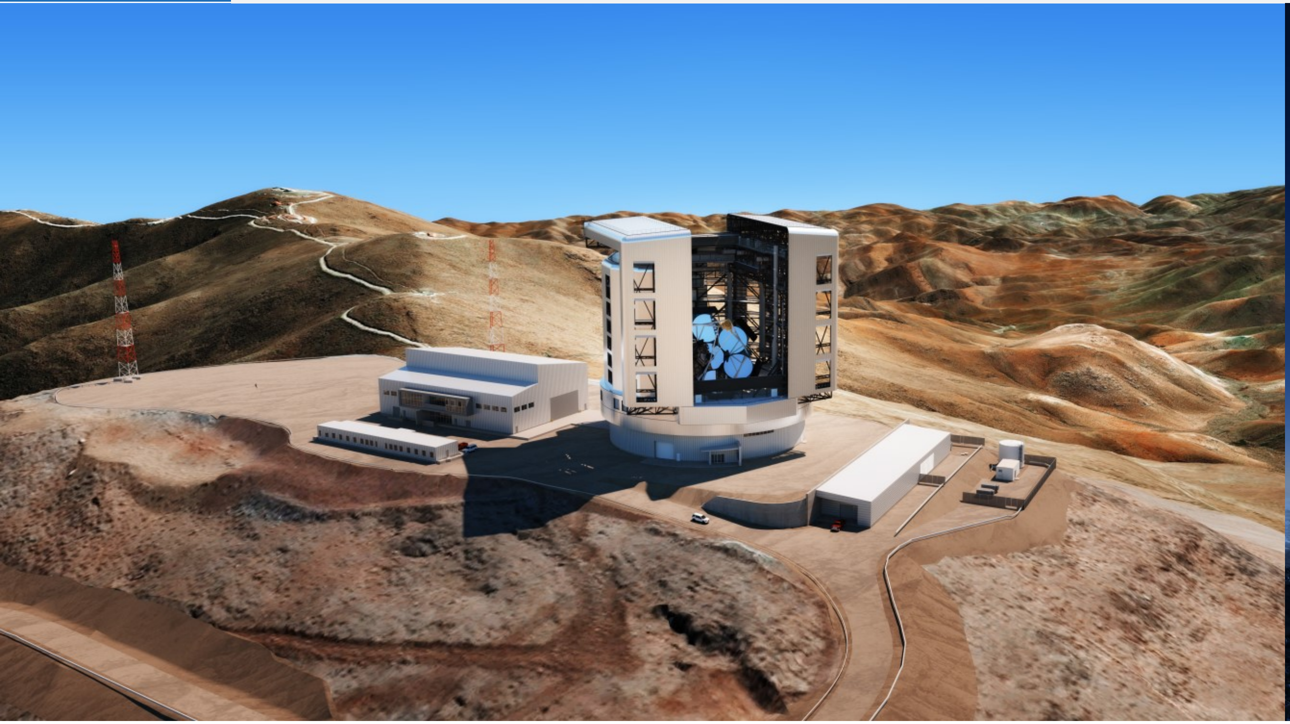
3-step process

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



EXTREMELY LARGE TELESCOPES

Extremely Large Telescope Projects

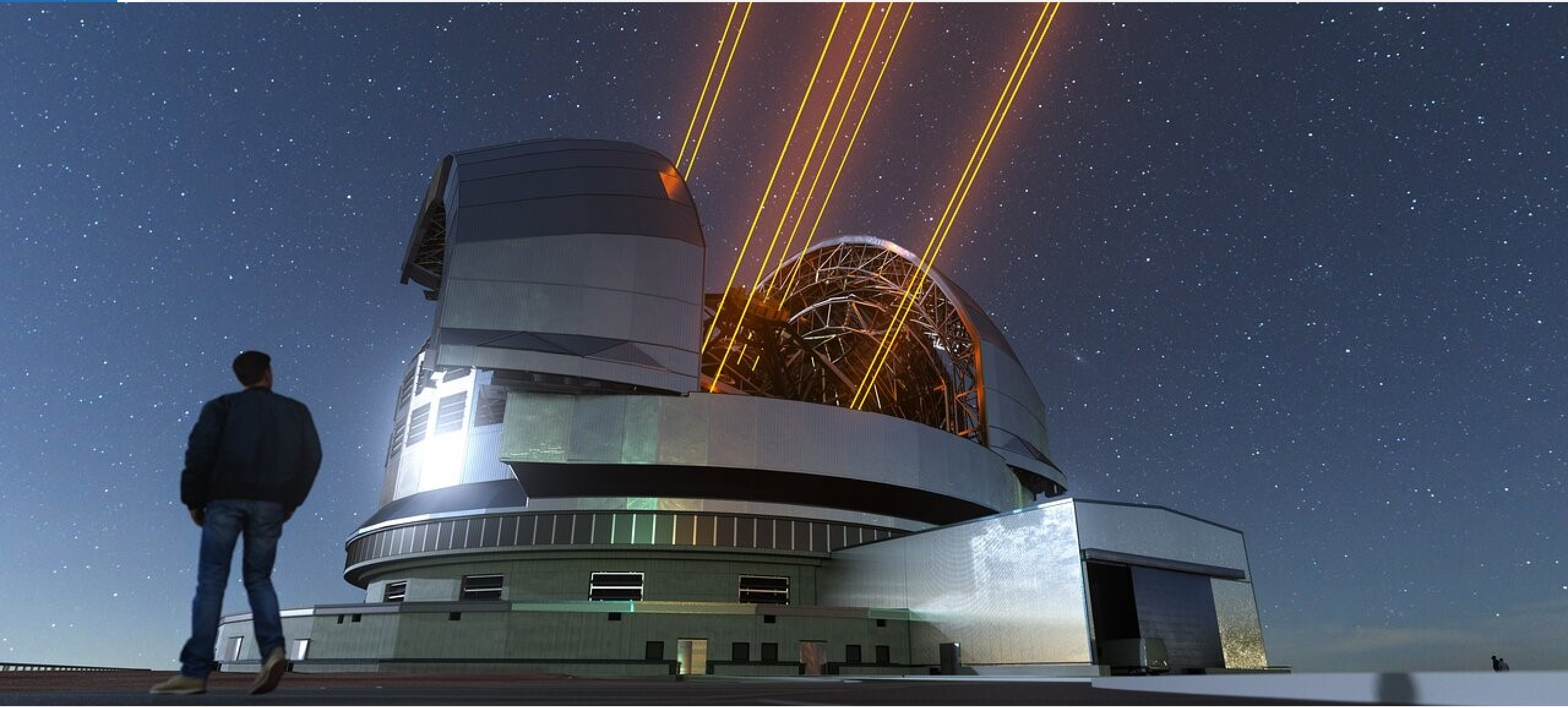


The 25-m Giant Magellan Telescope (www.gmto.org)

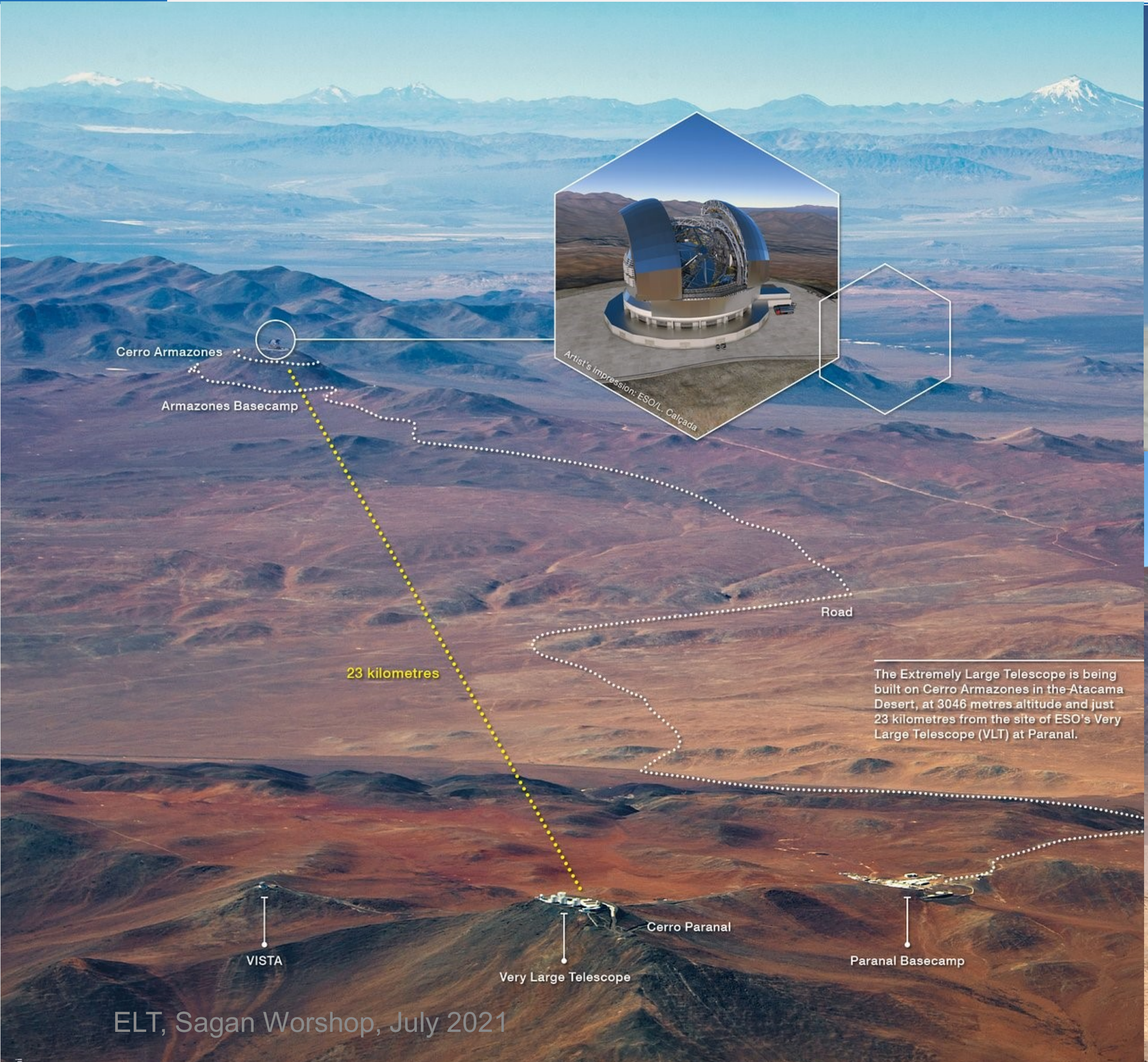
The Thirty Meter Telescope (www.tmt.org)

- The GMT and TMT projects have headquarters in Pasadena, CA
- Involve partners in the USA and around the world.
- GMT will be located in the southern (Chile) and TMT in the northern (likely Hawaii) hemispheres providing observations over the whole sky.

ESO's Extremely Large Telescope



A new mountain top for a new telescope



June 2014
Flattening the peak of Cerro Armazones

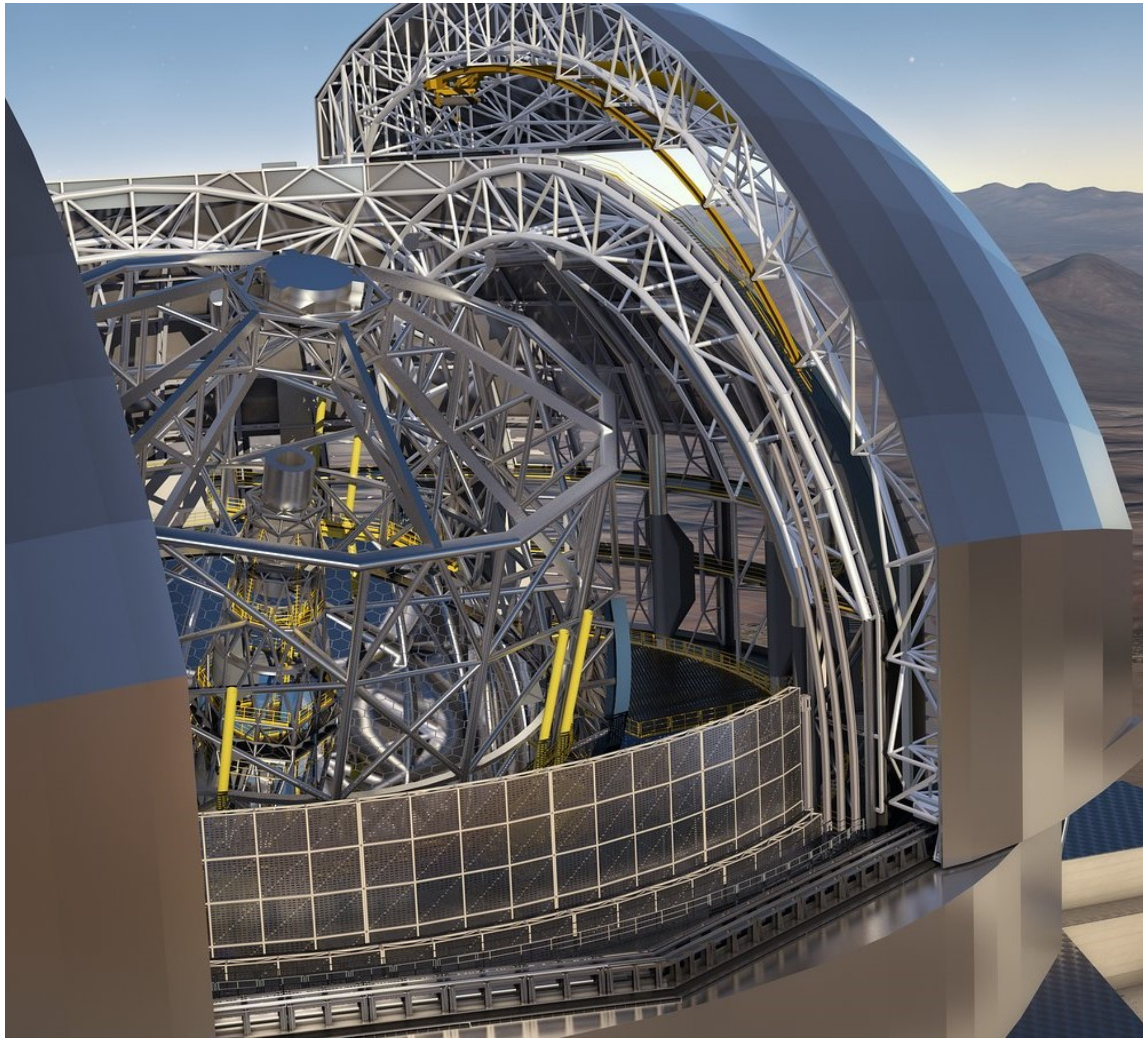
August 2014
Construction of the new road.

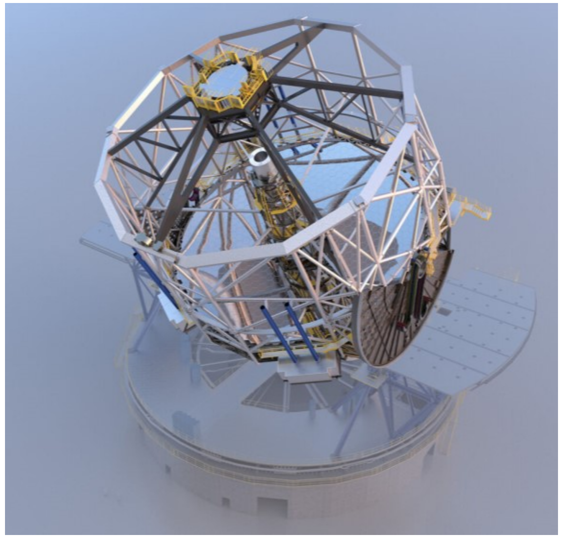
The site today

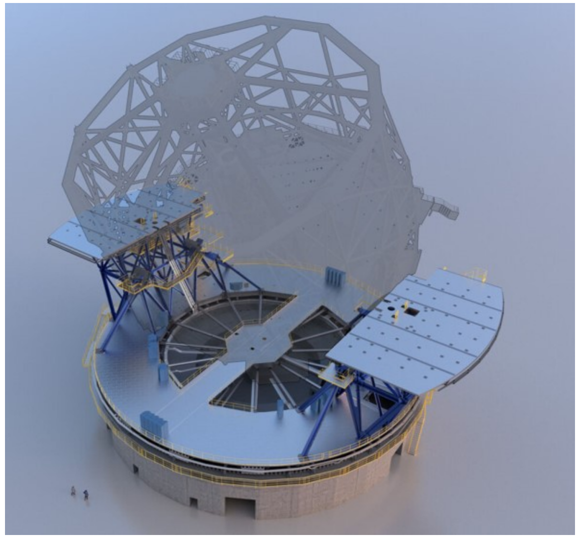
ELT DOME

- 80m (262 feet) high
- 88m diameter
- >6000 metric tonnes of rotating mass
- 30mins to walk from the entrance to the top

Telescope structure

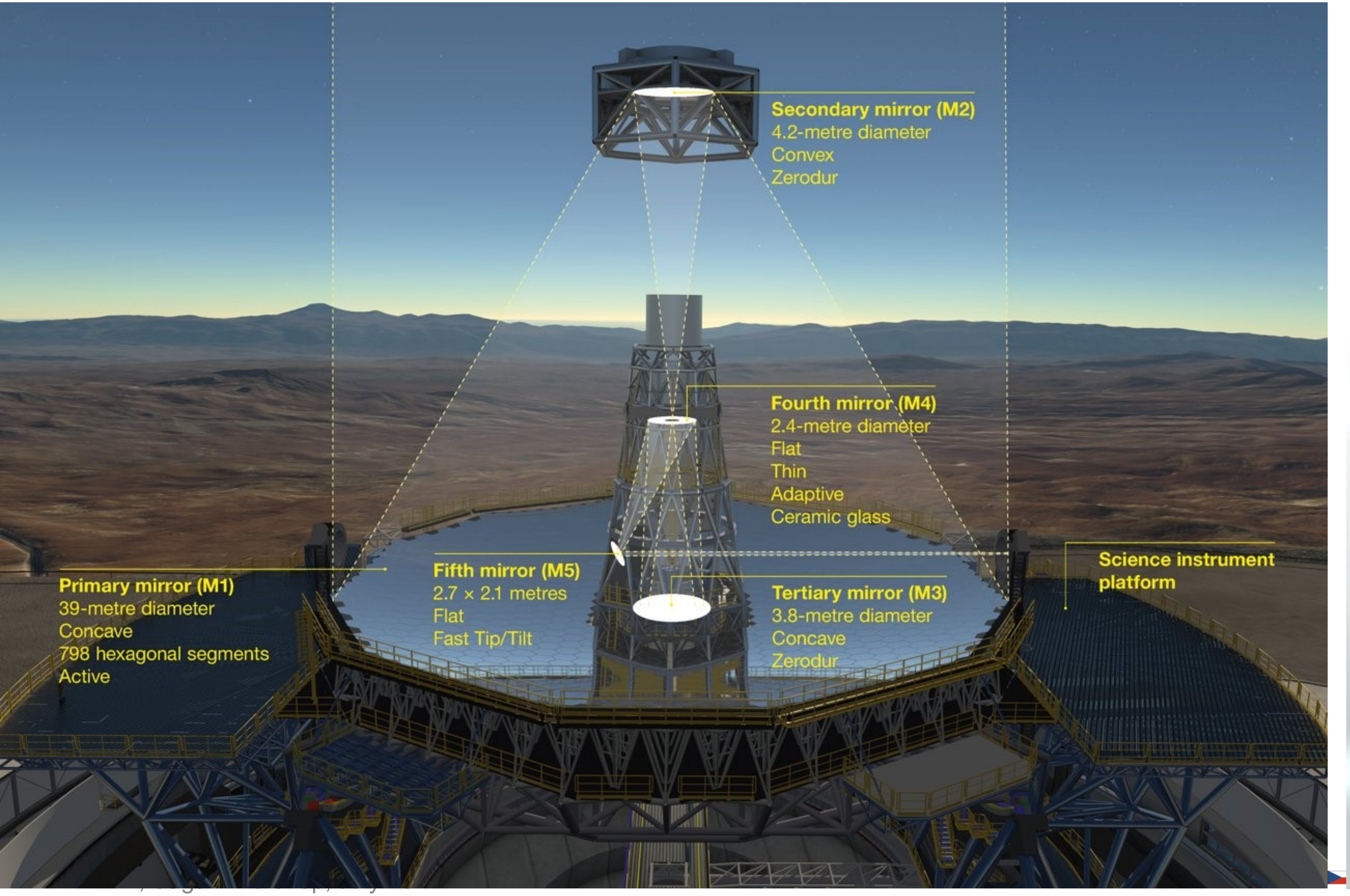




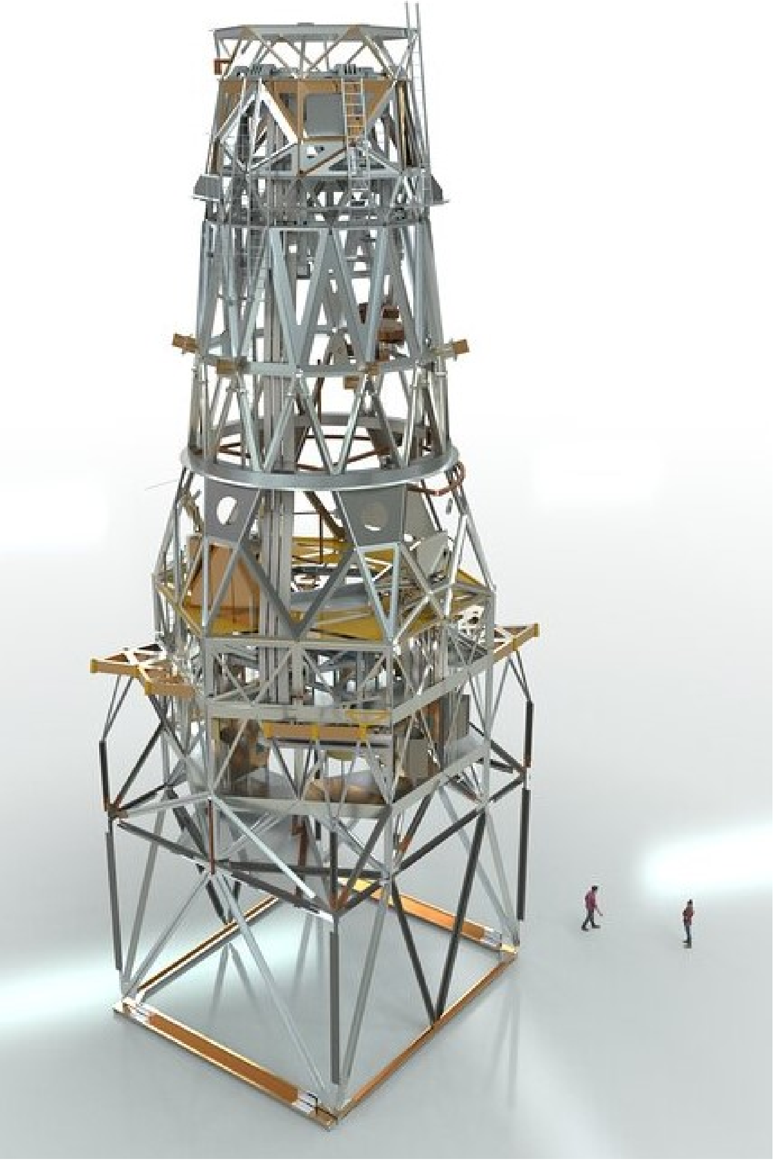


- Telescope rotates on oil bearings (largest 50m dia.)
- ~3700 tons incl mirrors and instruments
- Instrument (Nasmyth) platforms are 27-m above ground, 15m x 30m (or ~2 tennis courts !)

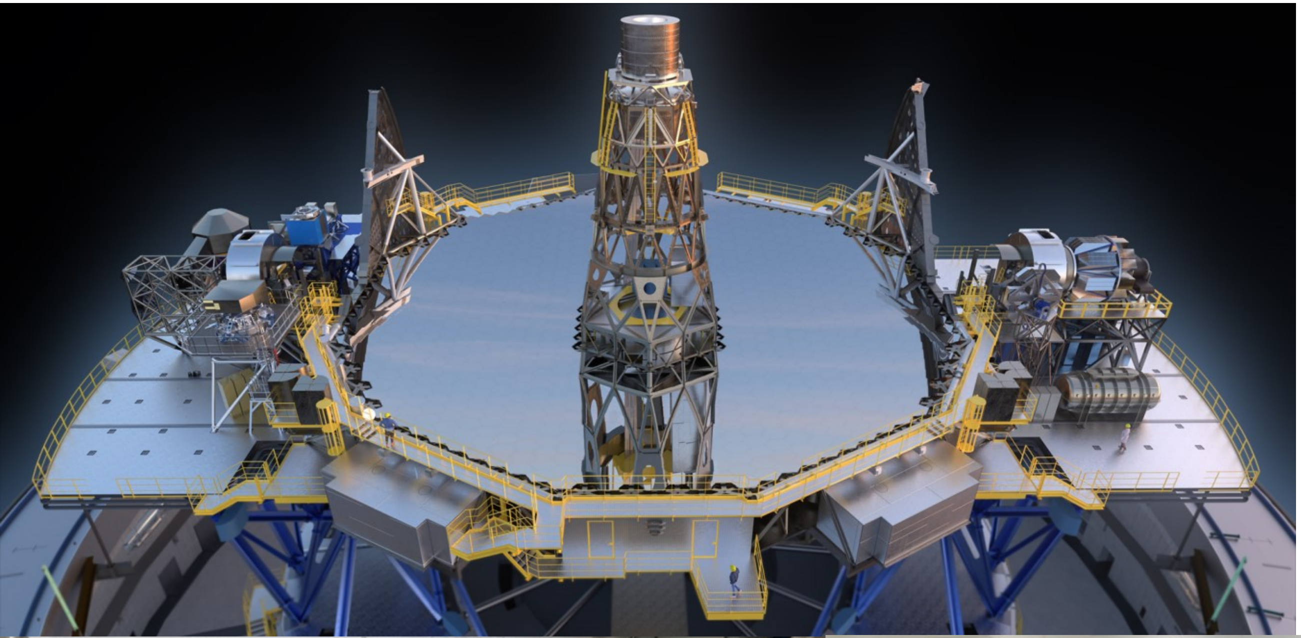
ELT optics



Secondary mirror (M2)
4.2-metre diameter
Convex
Zerodur
Fourth mirror (M4)
2.4-metre diameter
Flat
Thin
Adaptive
Ceramic glass
Science instrument platform
Primary mirror (M1)
39-metre diameter
Concave
798 hexagonal segments
Active
Fifth mirror (M5)
2.7 × 2.1 metres
Flat
Fast Tip/Tilt
Tertiary mirror (M3)
3.8-metre diameter
Concave
Zerodur



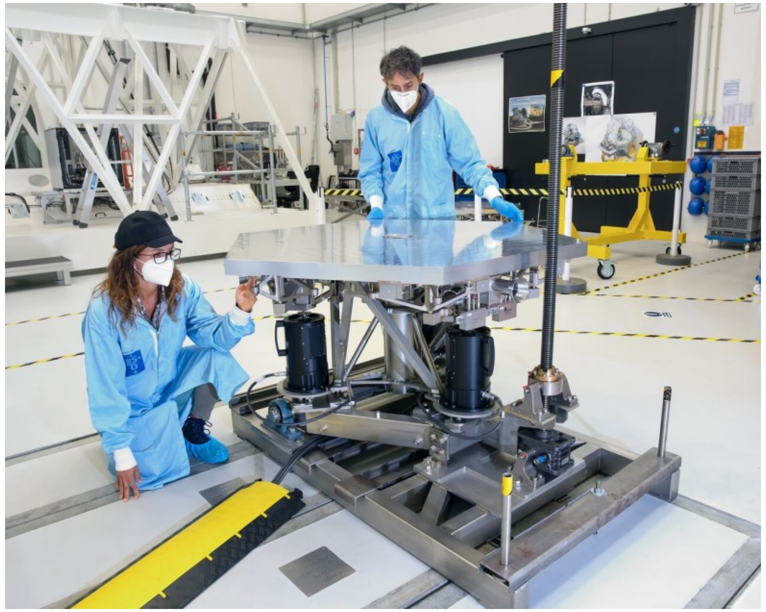
M1 – the ELT primary mirror

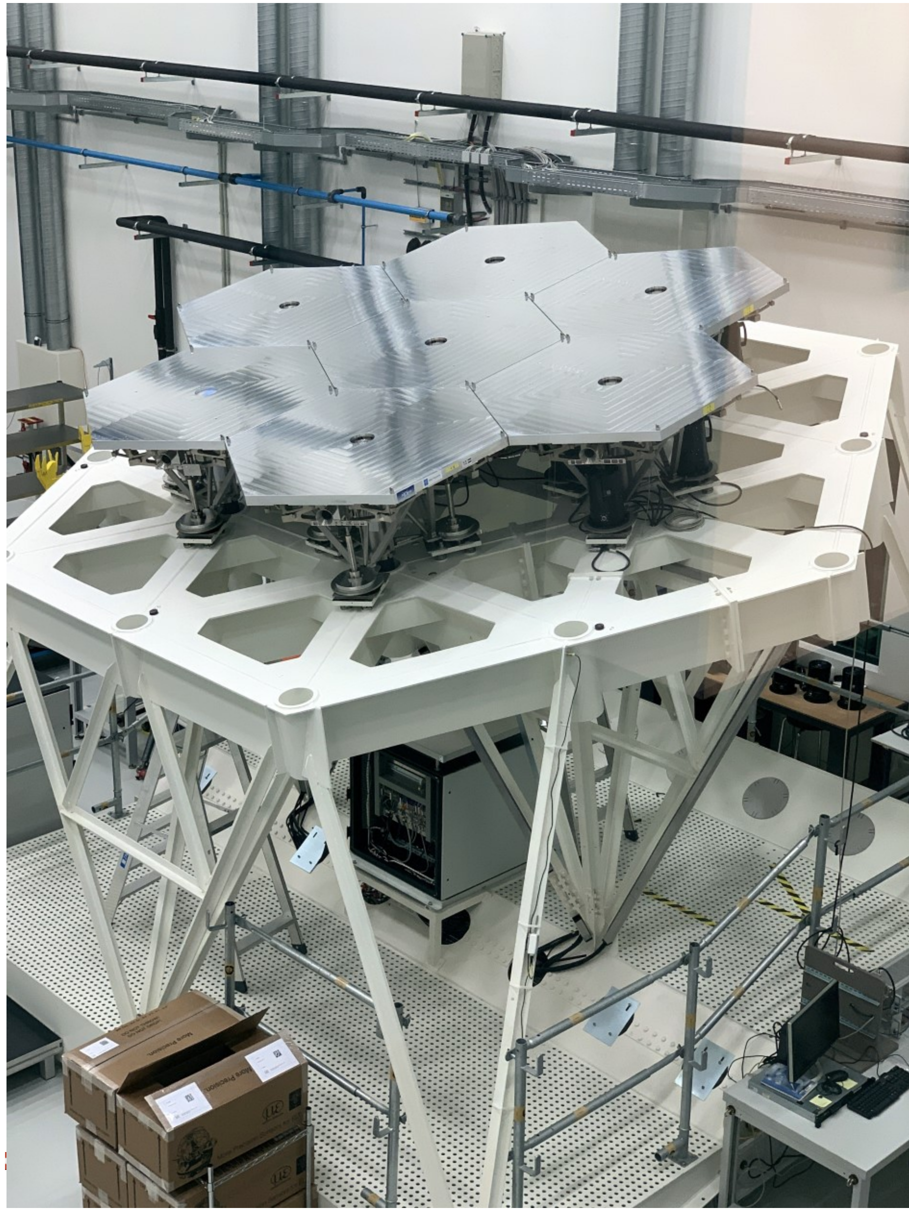


- M1 consists of 798 hexagonal segments 1.4m in ‘diameter’
- 6(+1) identical sectors with 133 different segments types each.
- Circular mirror “blanks” are made by Schott (De) and cut+polished by SAFRAN-REOSC (Fr)

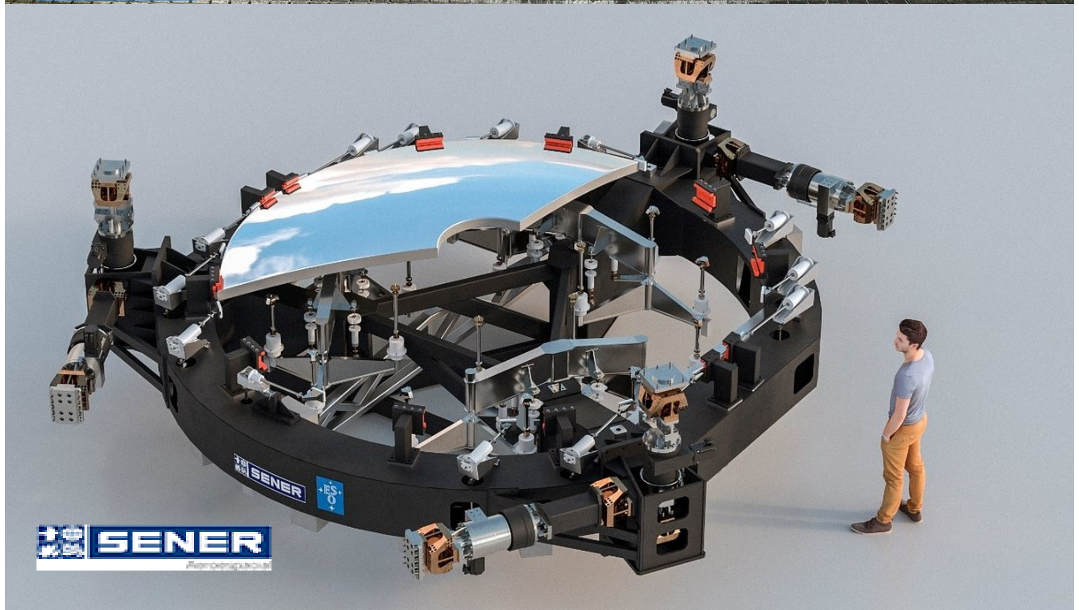
M1 – the ELT primary mirror

- The 798 mirrors are ‘phased’ to act as a single mirror
- The position is achieved by measuring and adjusting the mirrors using the support structure
- Accuracy is 10s of nanometers – 10 000 times smaller than a human hair
- Testing and developing this procedure takes place in ESO’s labs in Garching





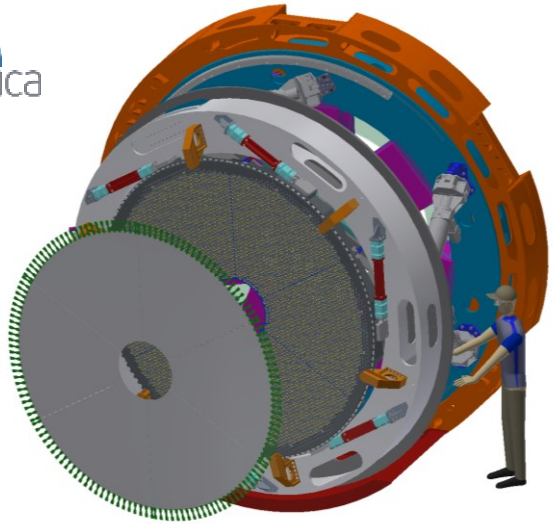
M2 and M3



- Casting of the 4-m mirrors at Schott (De)
- M2 largest convex mirror ever (4.2m)
- M3 starts from a similar “blank” but is 3.8m and concave
- They are made from Zerodur, a ceramic material which does is very stable with temperature (low-expansion) and weigh ~3000kg
- Mirrors will be polished by SAFRAN-REOSC (Fr) and mounted in a cell made by SENER (Es)
- Silver coating

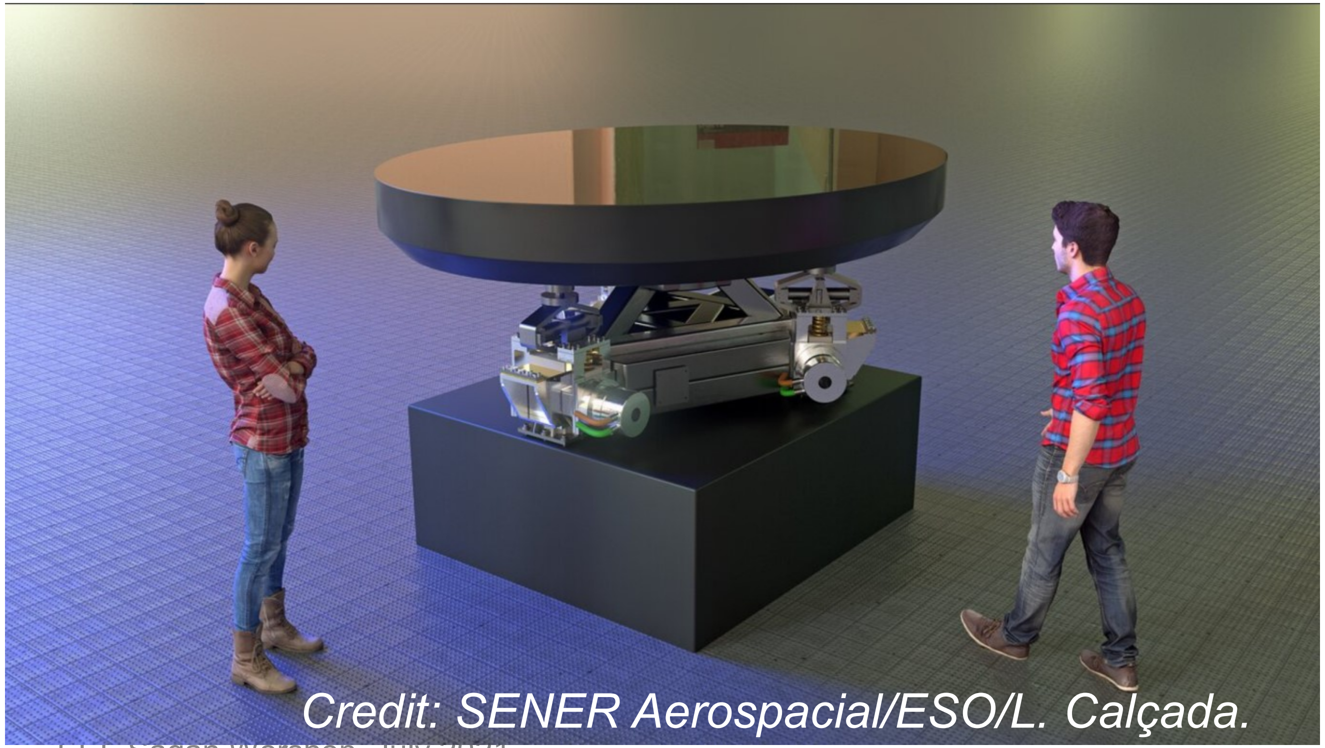
M4

- M4 is an adaptive mirror built by AdOptica (It) and SAFRAN-REOSC (shells, Fr)
- 6 thin “shells” are mounted on 5352 actuators change the mirror shape as fast as 1000 Hz

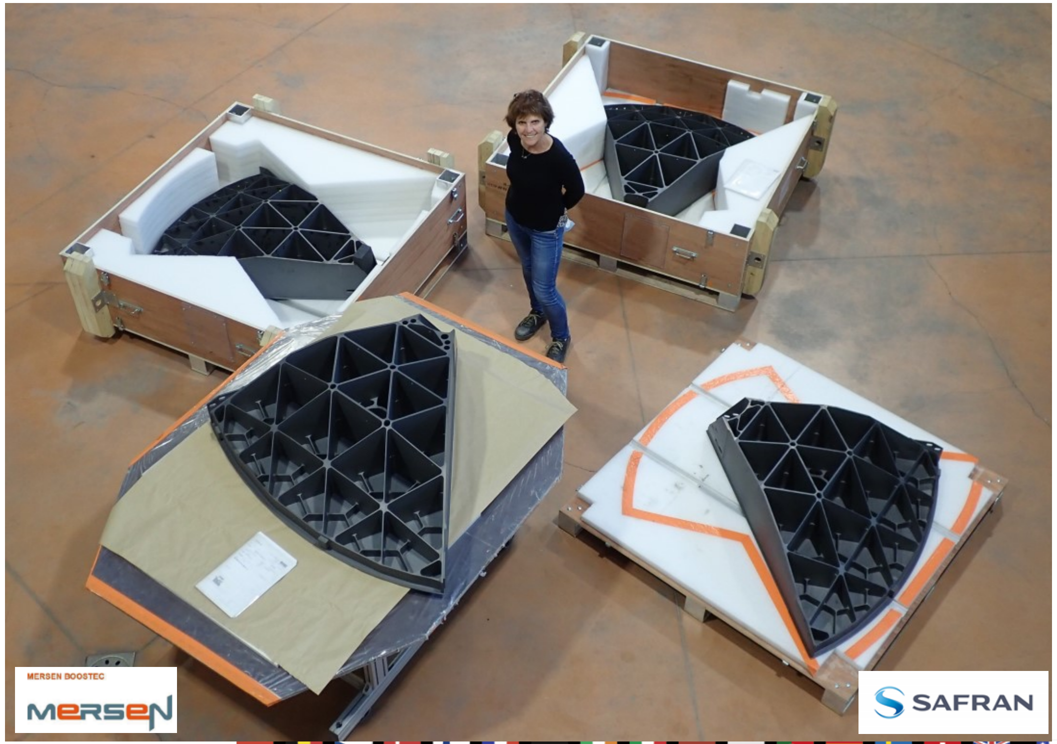


M5

- M5 also helps correct for the atmospheric turbulence “tip-tilt” (image stablisation) up to 10 Hz
- 2.7m x 2.2m flat, 440 kg, Silicon carbide mirror (Safran-Reosc and Mersen Boostec) mounted on a cell by Sener Aerospatiale

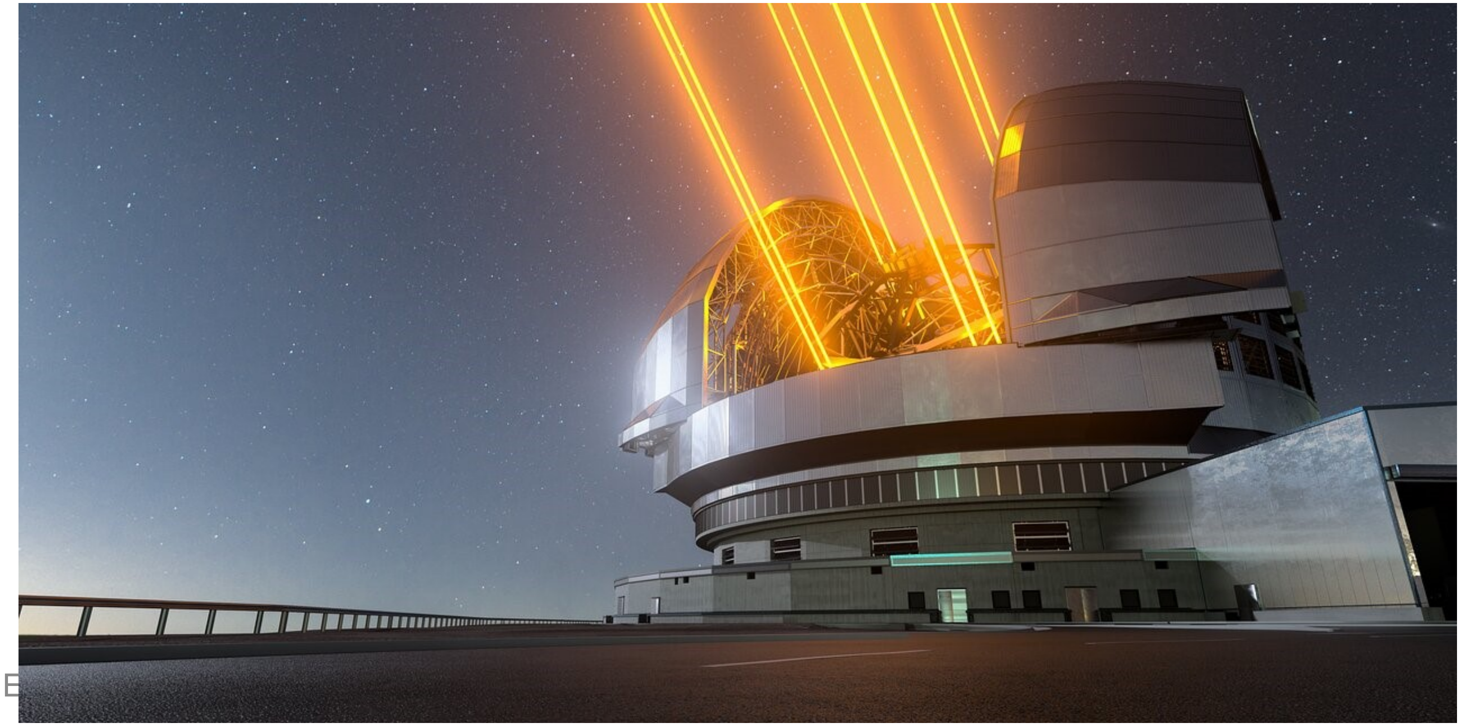


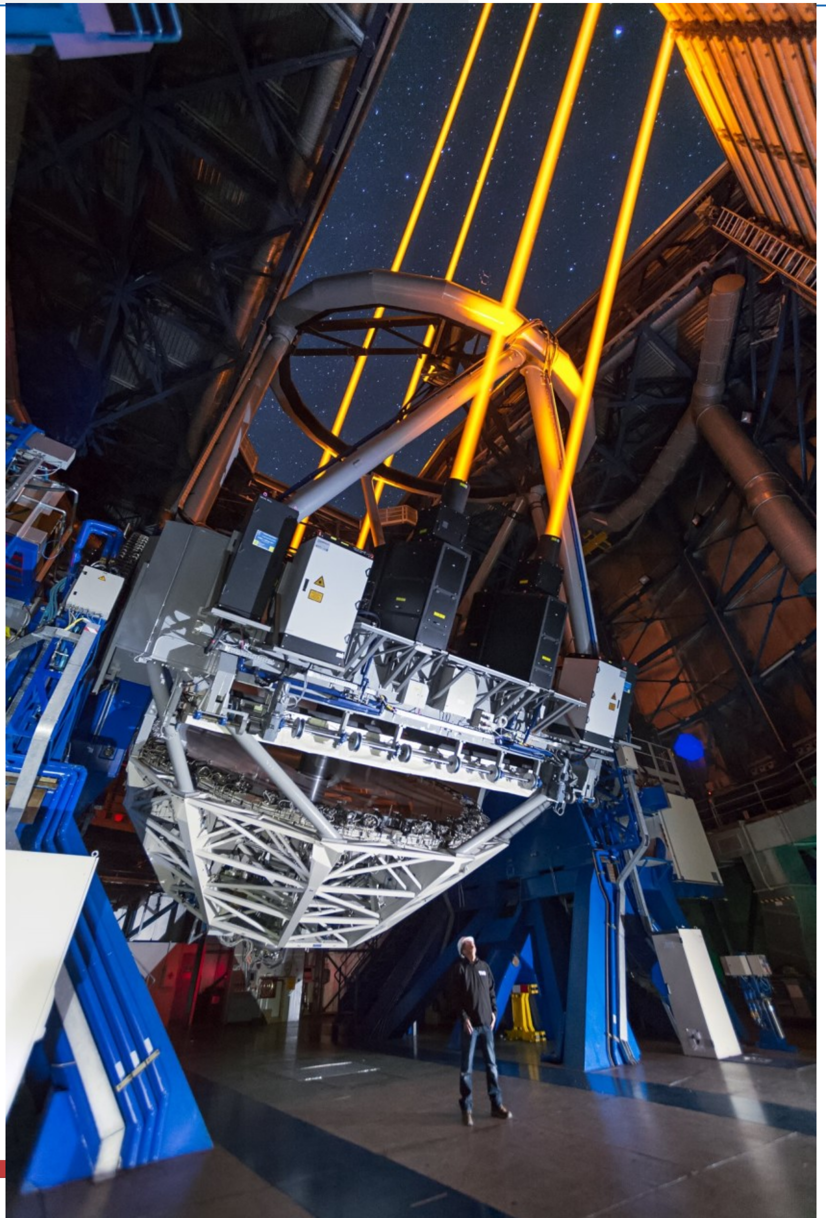
Credit: SENER Aerospacial/ESO/L. Calçada.



Laser guide stars

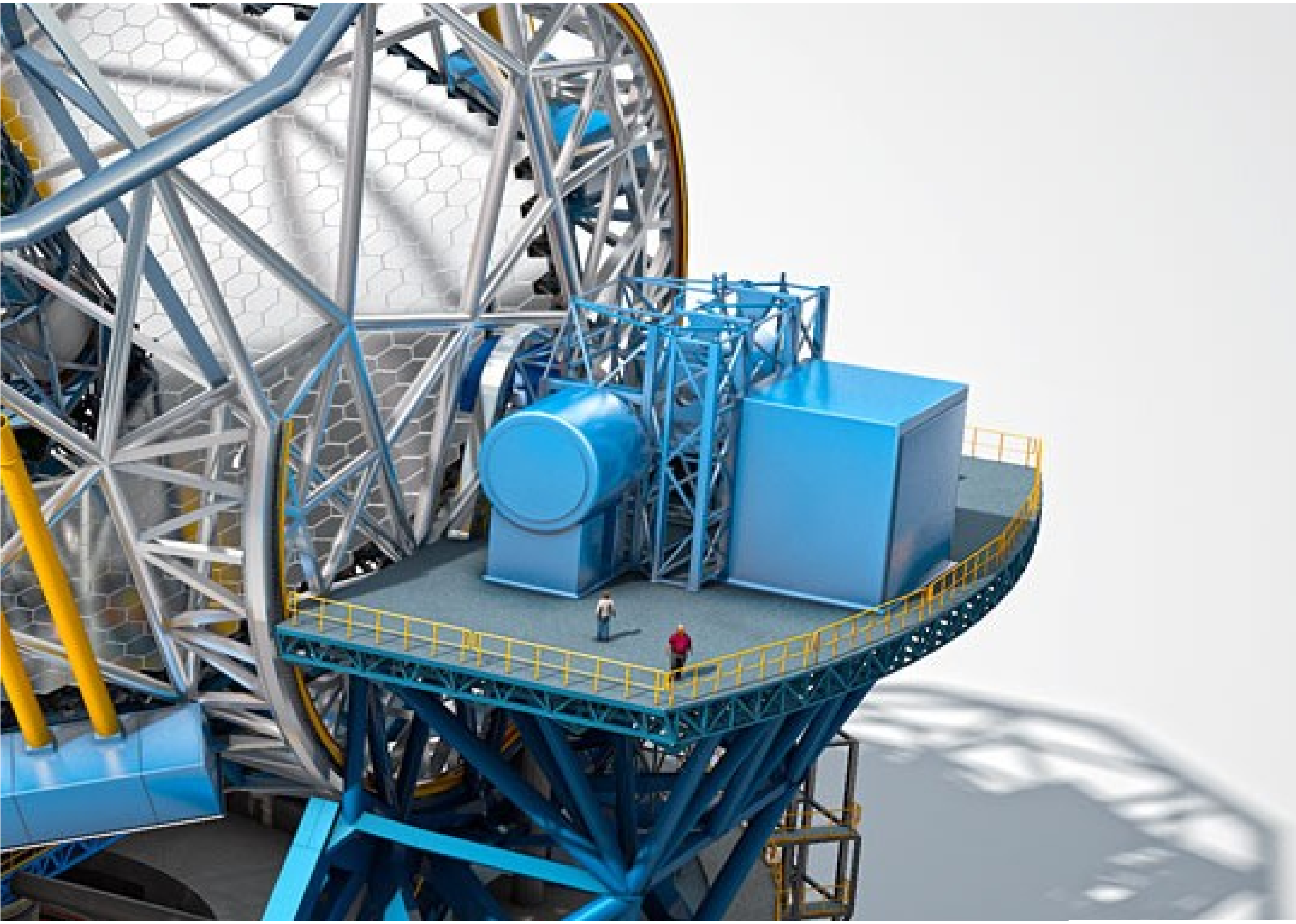
- AO needs bright “guide” star near the astronomical target. Sky coverage with NGS is only a few percent
- To observe the whole sky with AO, Artificial guide stars created by lasers exciting Sodium atoms at 90 km height
- Produced by Toptica (De) as for the VLT





ELT INSTRUMENTS

The ELT Nasmyth platform



James Nasmyth
(1808-1890)

By Lock & Whitfield - [1], Public Domain,
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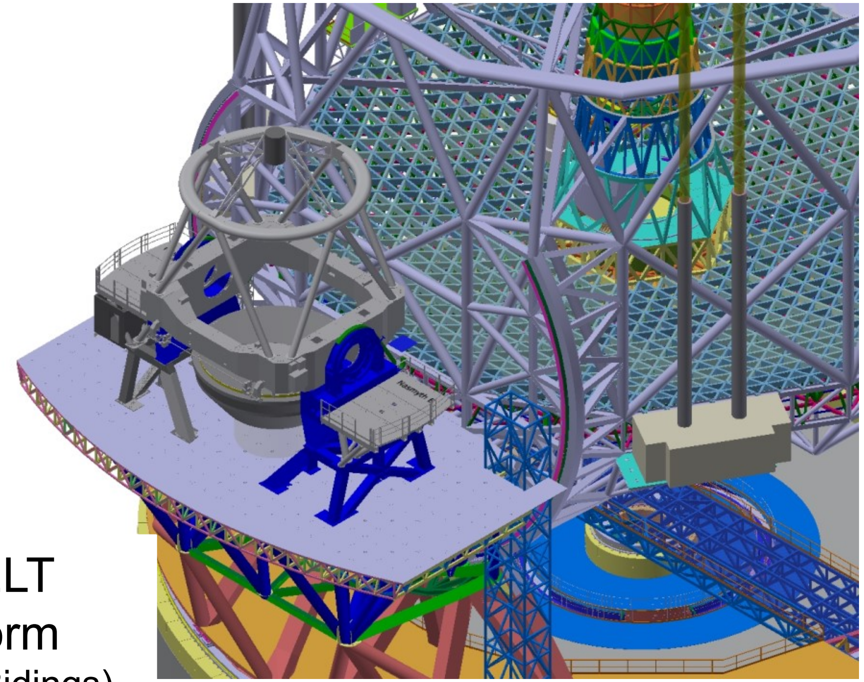


A VLT on the ELT
Nasmyth platform
(credit: ESO/Rob Ridings)

Big telescope → big instruments

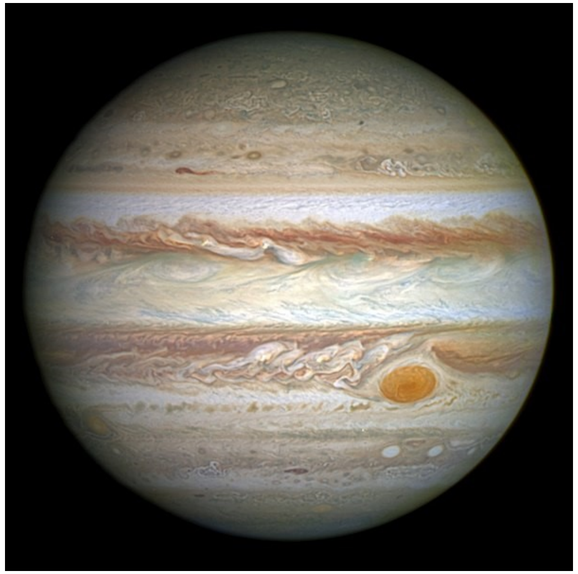
$$x = f\theta$$

- At the focus of the 39-m ELT ($f = 680\ m$):
  1" on the sky = $3.3\ mm$
- At the focus of the 8-m VLT ($f = 120\ m$):
  1" on the sky = $0.58\ mm$
- At the focus of the 4-m NTT ($f = 38\ m$):
  1" on the sky = $0.186\ mm$

- The diffraction limited spot size stays about the same ($\theta = \lambda/D$)
- A diffraction limited ELT instrument with a small FoV can be (relatively) small

Jupiter ~ 40 arcsecs

132mm at the focus of the ELT



23mm on VLT

7mm on NTT

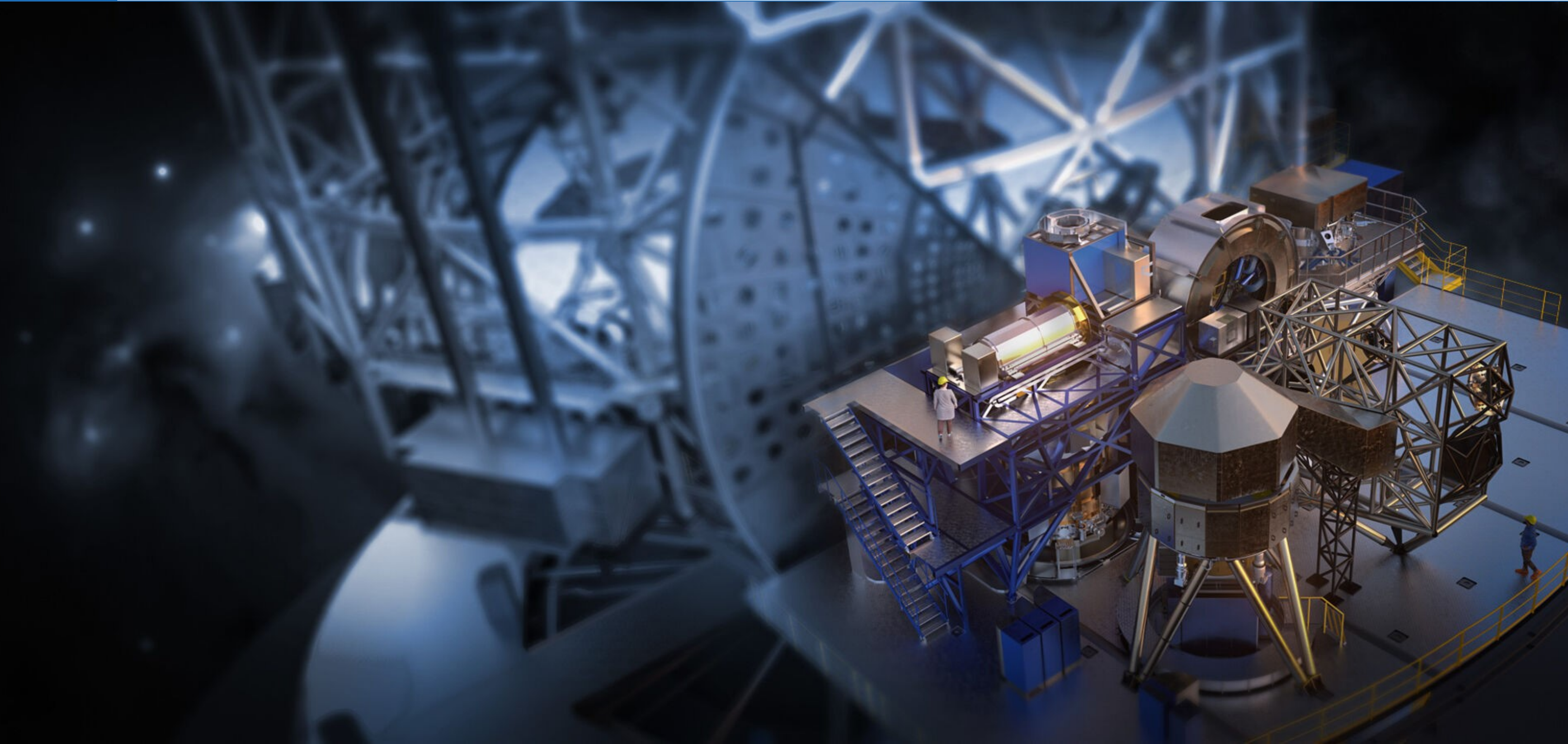
Extremely Large Teams

MAORY Kick-off 2016

- ESO instruments are often built by teams from ESO community institutes and universities.
- ESO often participates in these teams
- ESO always follows the development with a team of engineers and scientists

HARMONI Preliminary Design Review 2017

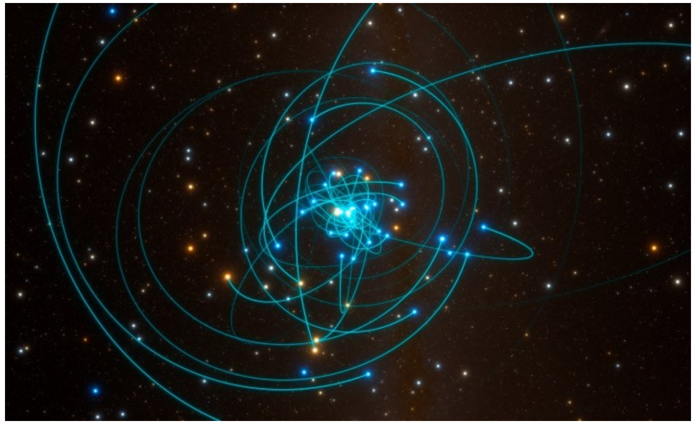
The ELT Nasmyth platform, view of ~2028



ELT 1st gen Instruments: MICADO & MAORY

- MICADO camera (~2027, SCAO)
- Versatile NIR imager/spectrograph, with lots of observing modes

- MAORY multi-conjugate AO using laser guide stars (~2028)
- Provides MICADO with sharp images over a large FOV (~1')



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Reinhard Genzel

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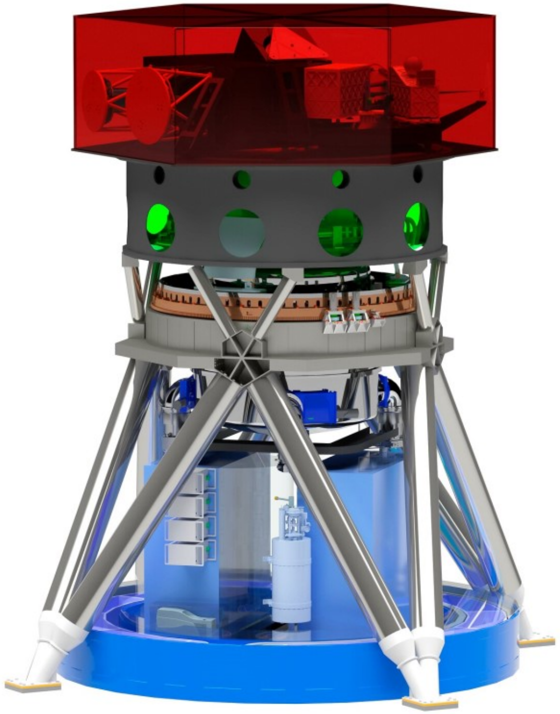
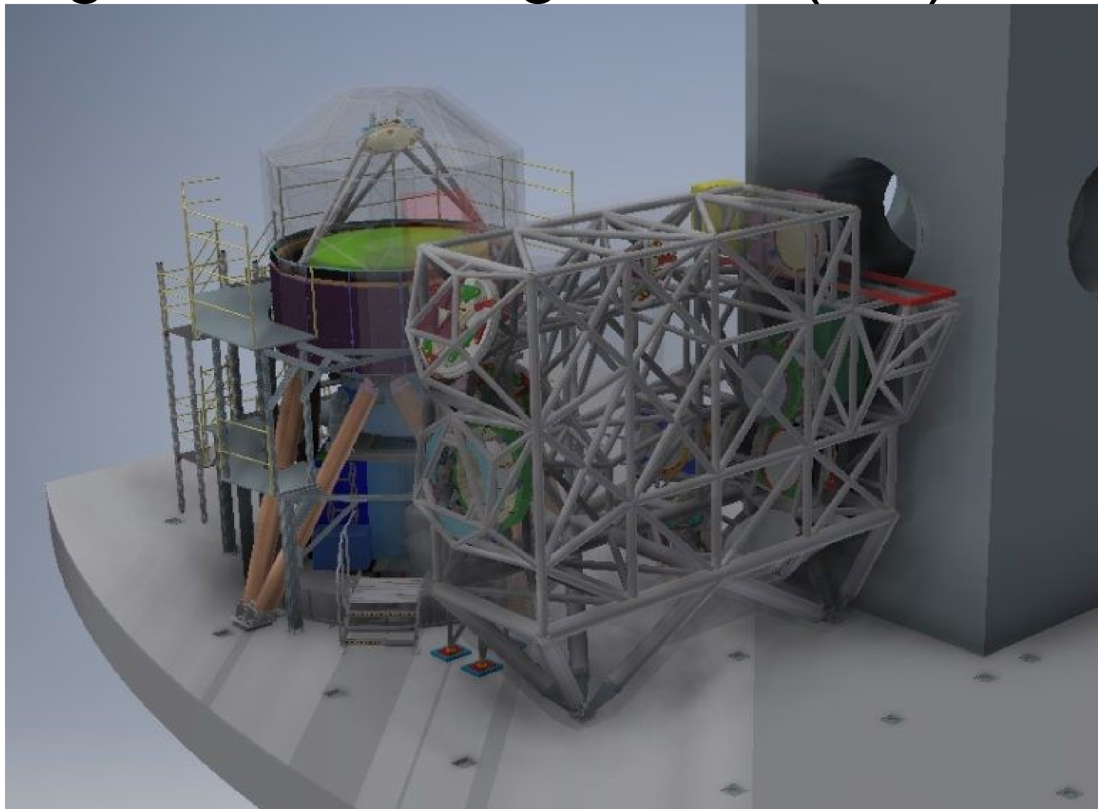
Andrea Ghez





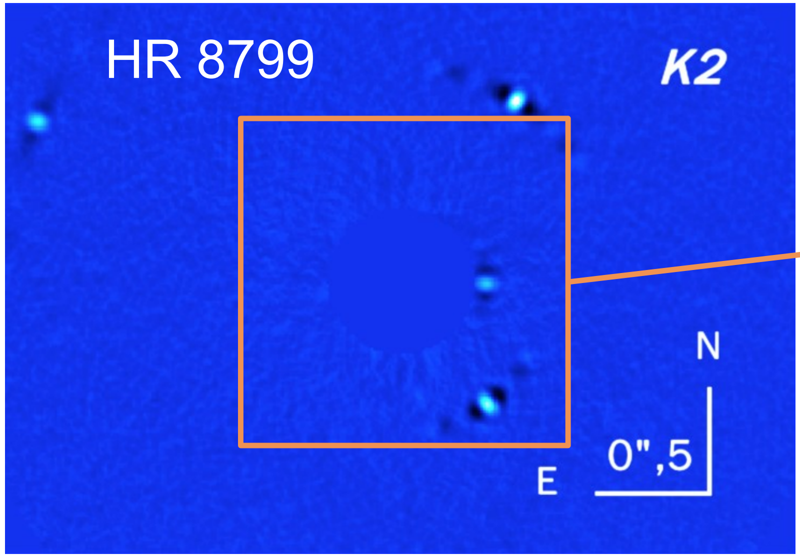
MICADO required capabilities

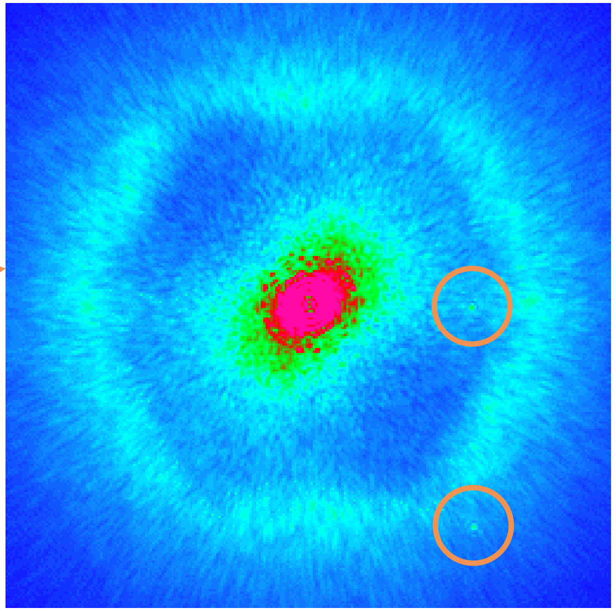
- ❑ Imaging
- ❑ Astrometric imaging
- ❑ High Contrast imaging
- ❑ Spectroscopy

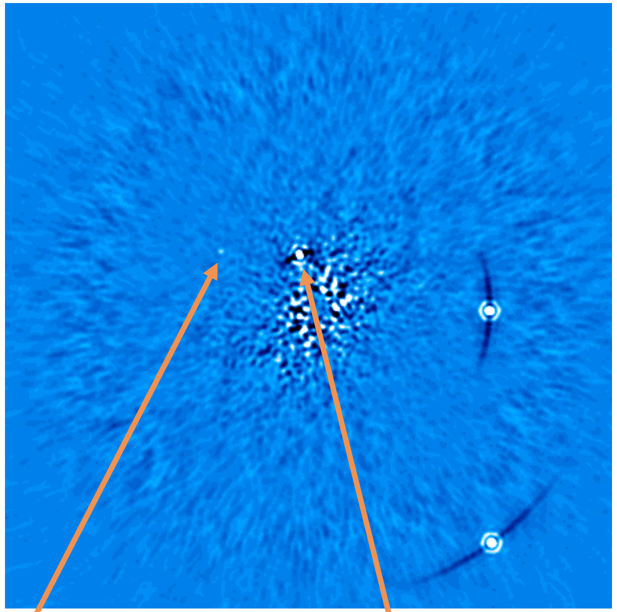
Wavelength	0.8–2.4 µm
Field-of-view	50.5" x 50.5" (4 mas pixels); 18" x 18" (1.5 mas pixels)
Filters	IYJHK broad band + medium and narrow band filters
Relative astrometry	50 µas (10 µas goal)
Contrast requirement	1×10^{-4} at 100 mas; 1×10^{-5} at 500 mas
Spectral resolution	< 20,000
Simultaneous spectral range	1.45–2.46 µm; 0.84–1.48 µm

MICADO Coronagraphy simulations

SPHERE (2hr, Zurlo et al. 2016)

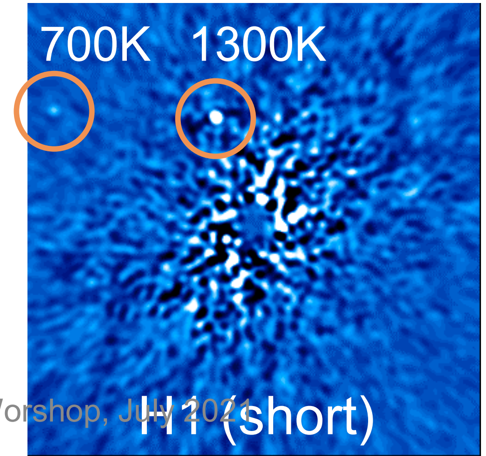


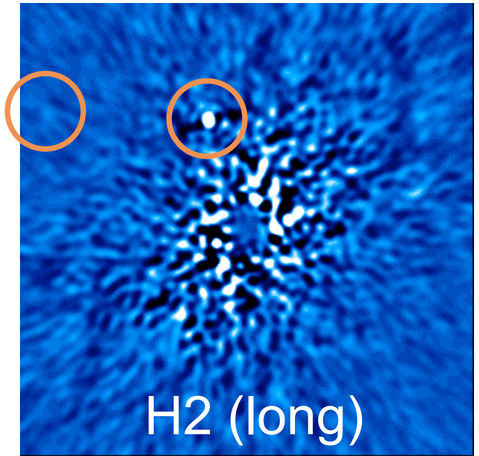




added exoplanet at 10 AU, 700 K, log(g)=4

added exoplanet at 5 AU, 1300 K, log(g)=4

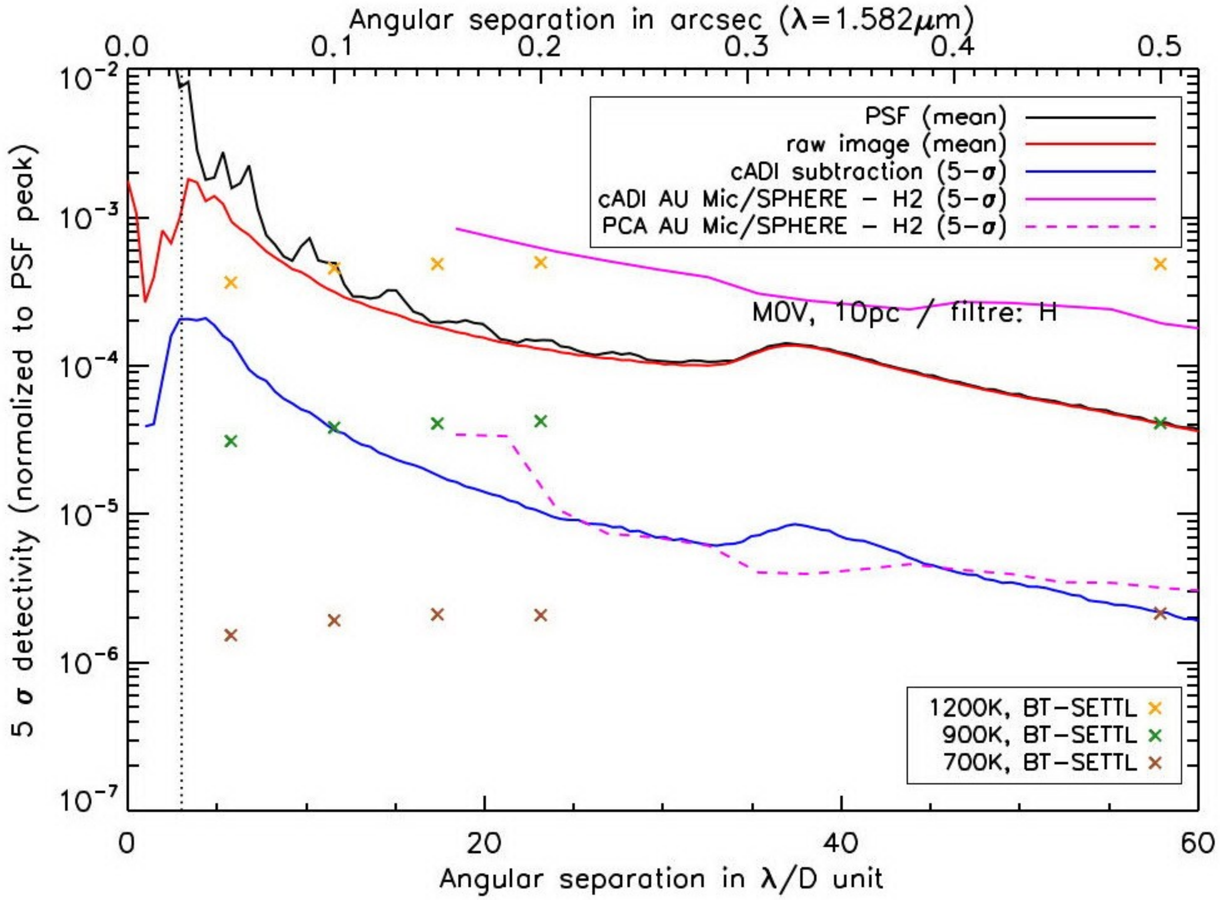


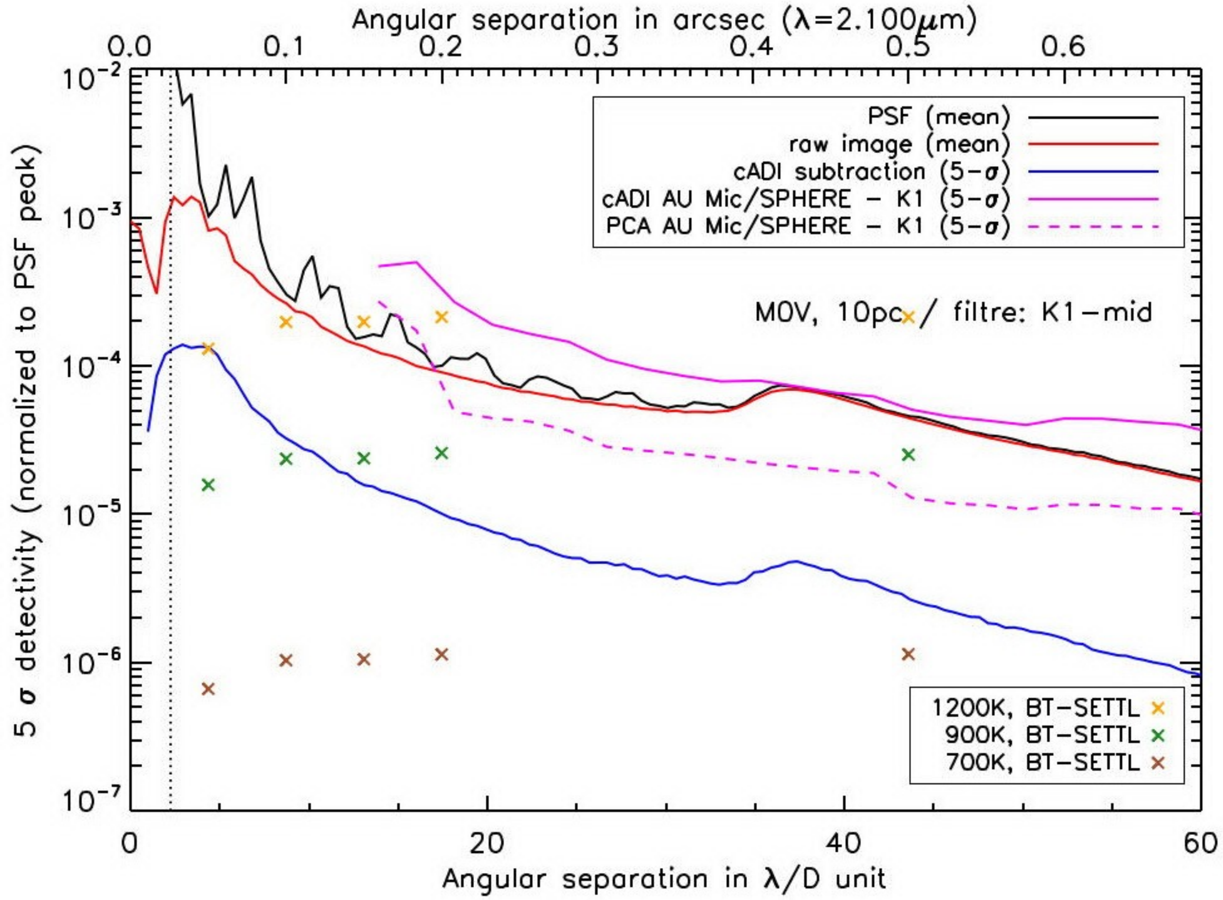


Probing a regime where we expect to have masses & radial velocities from GAIA

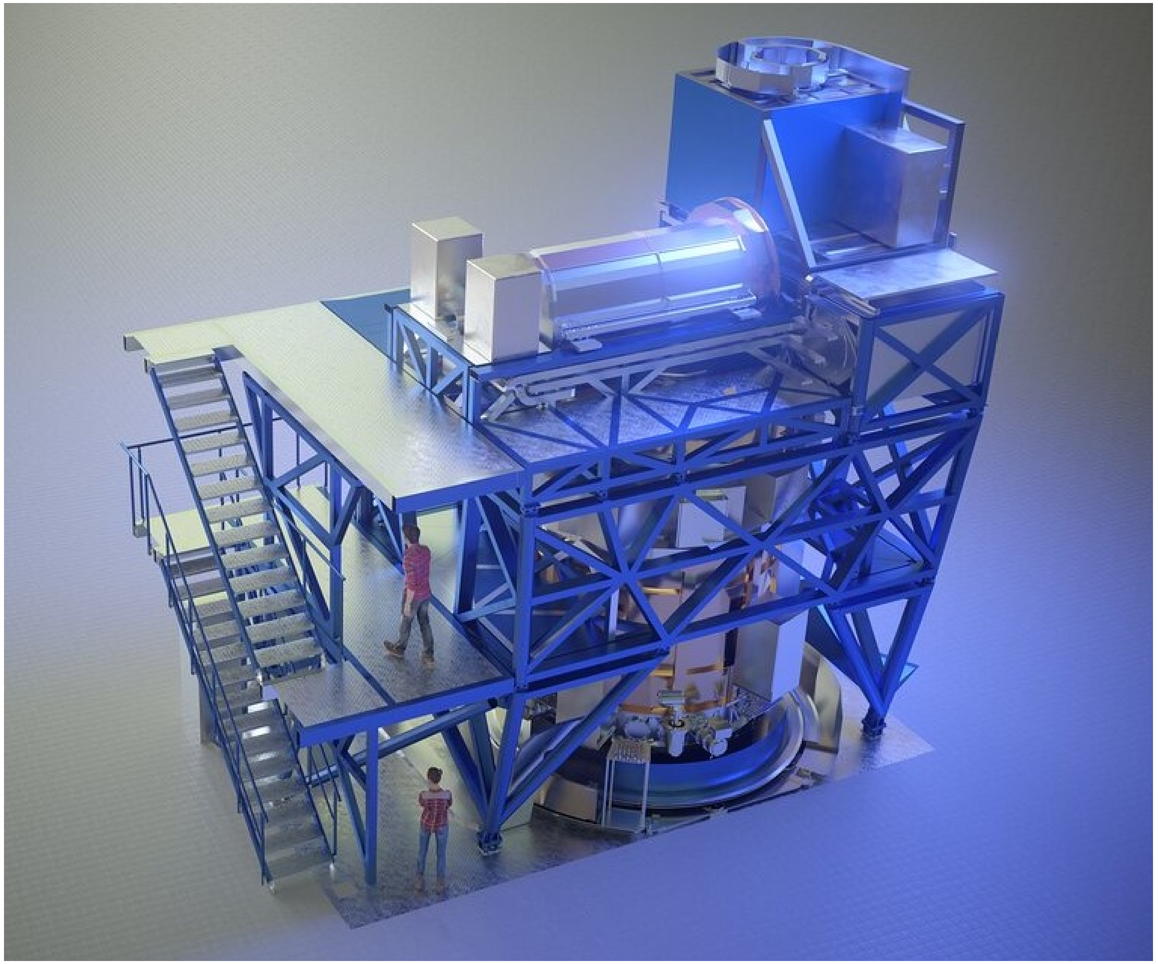
MICADO contrast sensitivity

Comparison to SPHERE from MICADO PDR report - see also Perrot et al. 2018 (SPIE)





ELT 1st gen Instruments: HARMONI (~2027)



Optical and NIR integral field spectrograph with AO

Wavelength	0.47—2.45 µm
Spectral resolution	~3,500, 7,500, and 18,000 in the NIR and ~3,500 in the VIS bands
Simultaneous spectral range	at least one band at a time R~7,500 (i, z, J, H, K), two at R~3,500
Field(s)-of-view	four, corresponding to different spaxel scales
AO	LTAO and SCAO

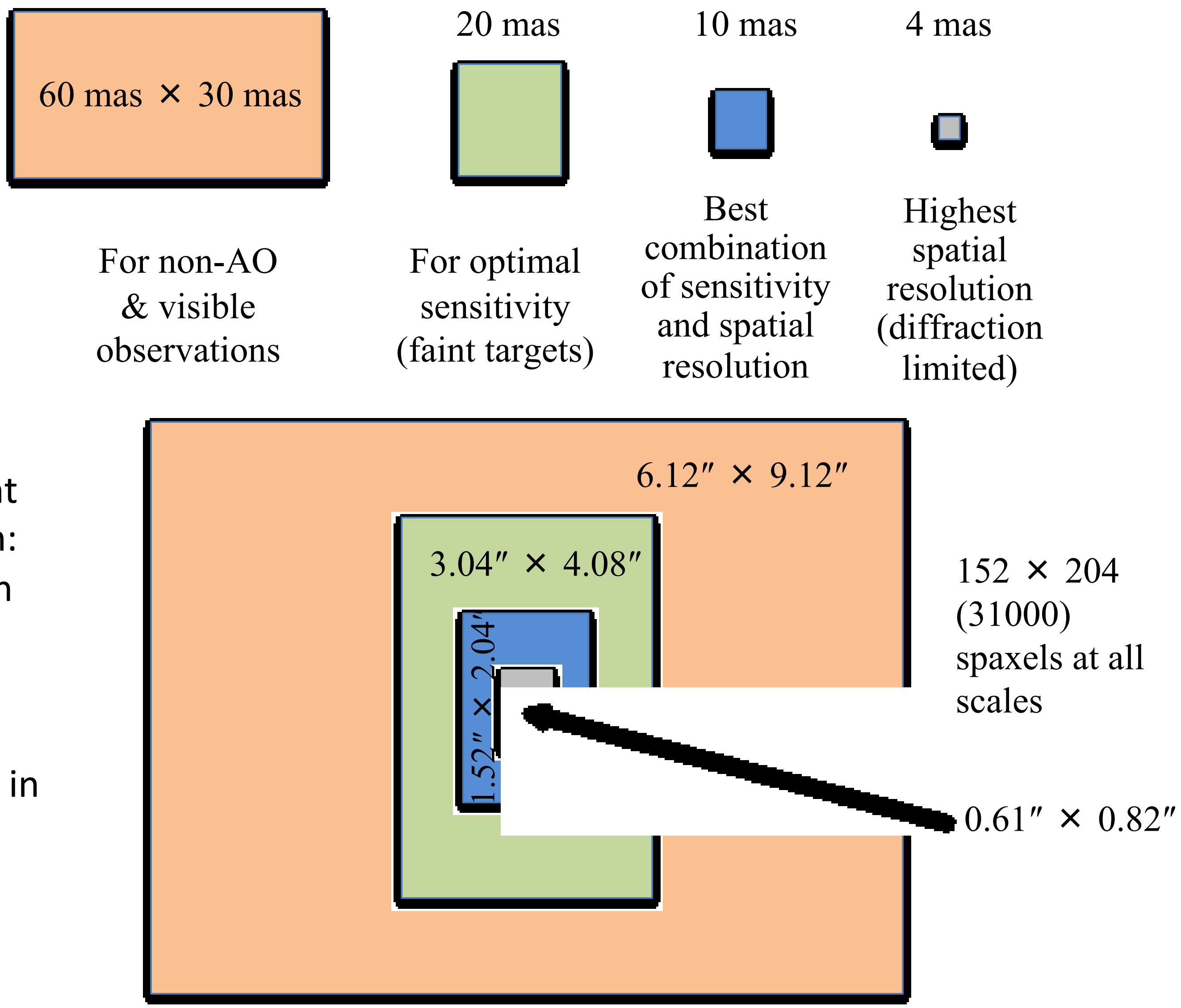
HARMONI field of views

- 4 spaxel scales
- 31000 spaxels ~200x150
- 9.12″ × 6.12″ to 0.63″ × 0.84″ FoV
- Half FoV at visible wavelengths

Equivalent slit length: 16 arcmin

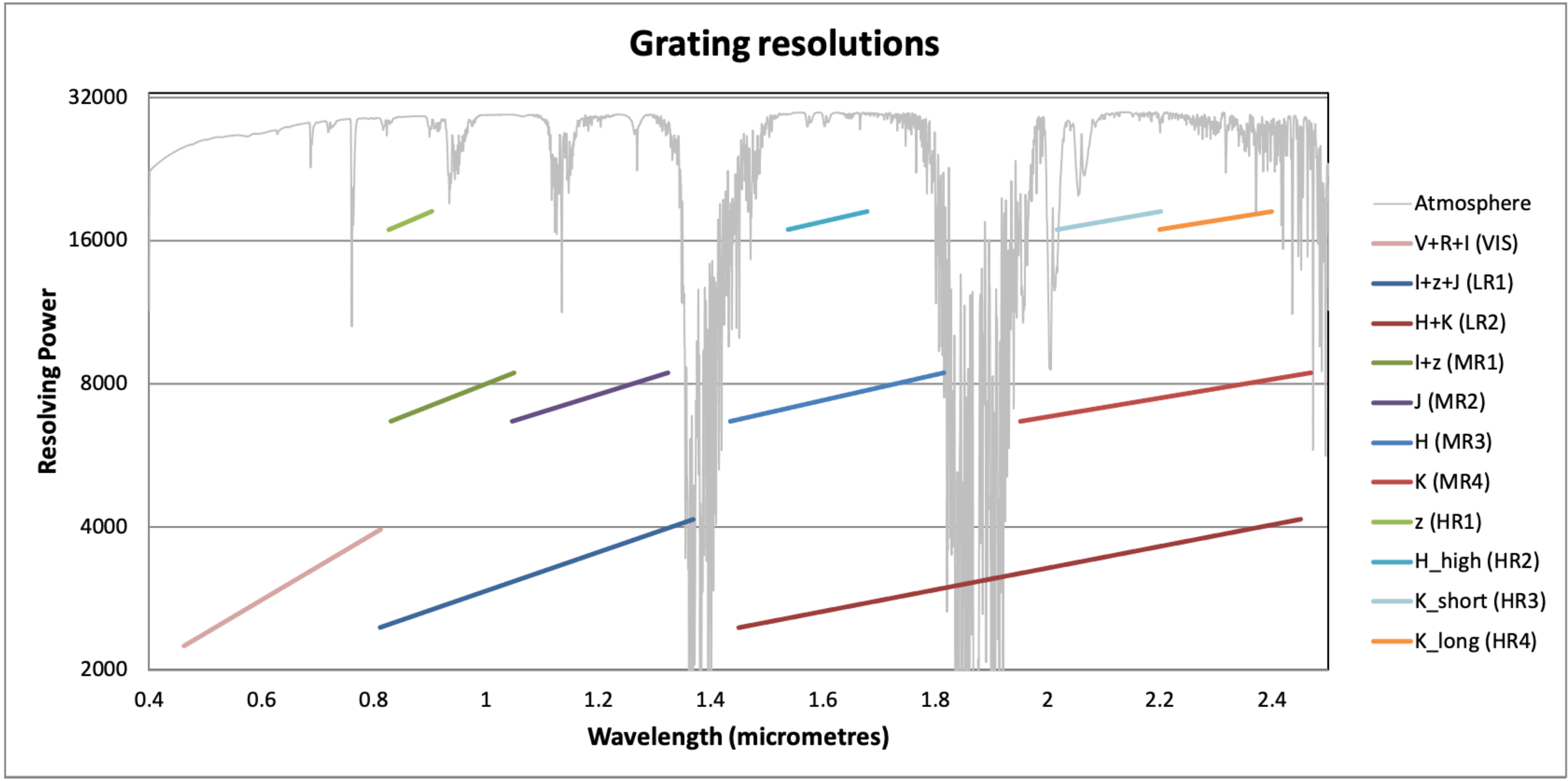
or

3.2 metres in ELT focal plane



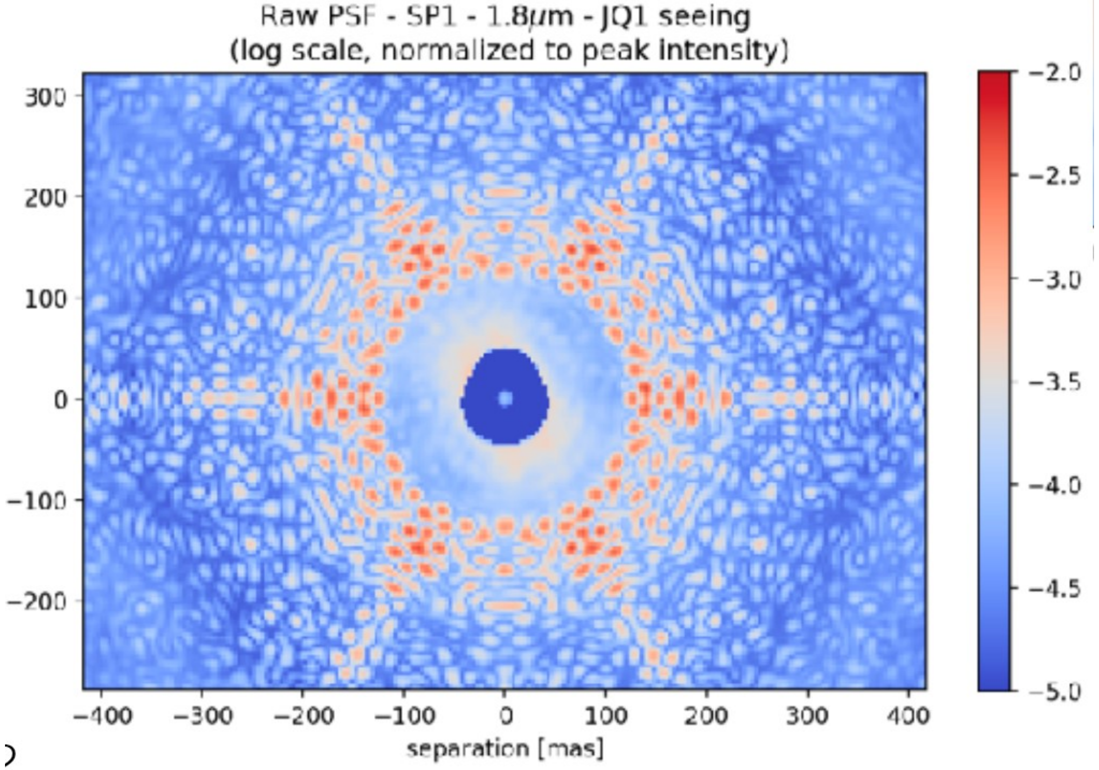
HARMONI Spectral layout

- 3 spectral resolving powers
- All gratings VPHGs in 1st order for maximal efficiency
- VIS and NIR cameras + all reflective design up to disperser



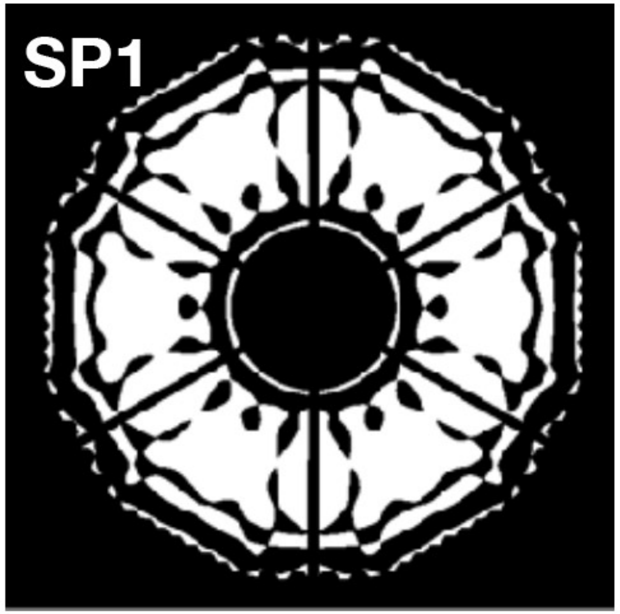
HARMONI High Contrast capability

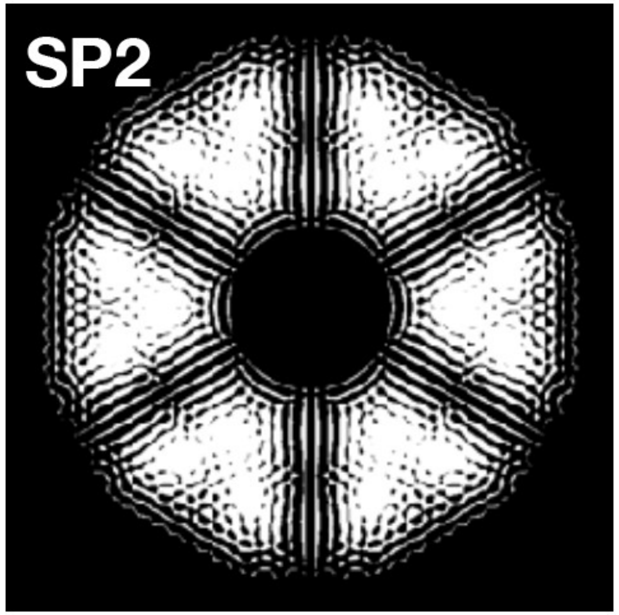
- SCAO operating mode, 4 mas spaxels and pupil tracking (ADI-like post processing)
- Wavelength range (1450 – 2450 nm) (goal 1250 – 2450 nm)
- No coronagraph! 2 Pupil Plane apodisers and 3 focal plane masks (with $T = 10^{-4}$)
- Performance goal: 10^{-6} (after post-processing) at 100 mas

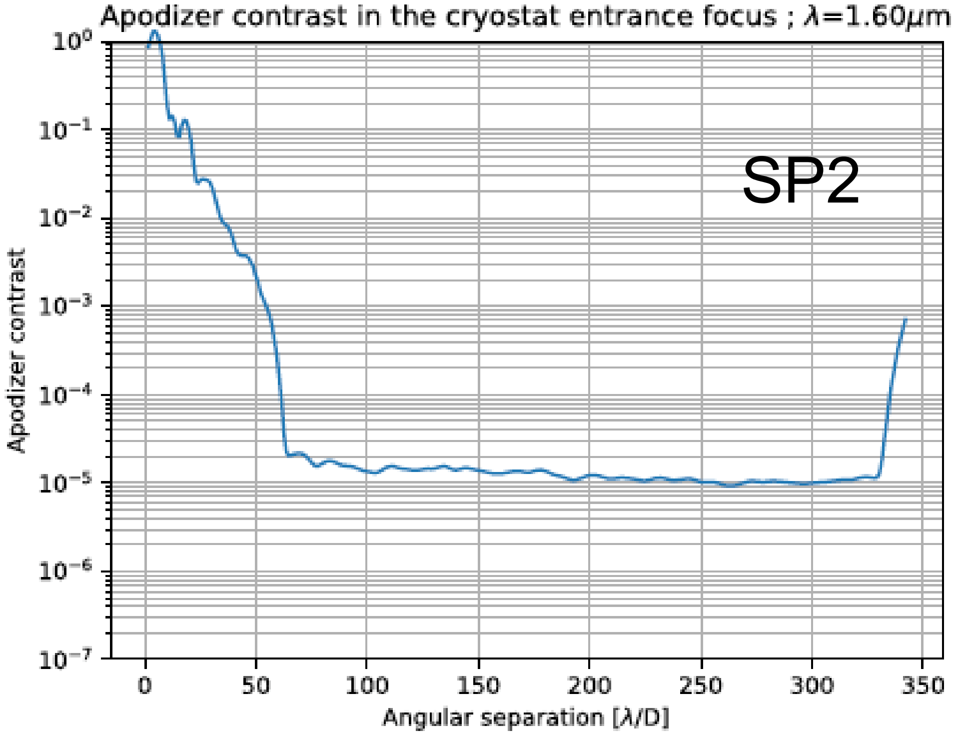


HARMONI apodisers and performance

Apodiser	Inner Working Angle		Outer Working Angle	
	H band	K band	H band	K band
SP1 (5 - 12 λ/D)	43 mas	60 mas	100 mas	140 mas
SP2 (7 – 40 λ/D)	60 mas	80 mas	340 mas	460 mas





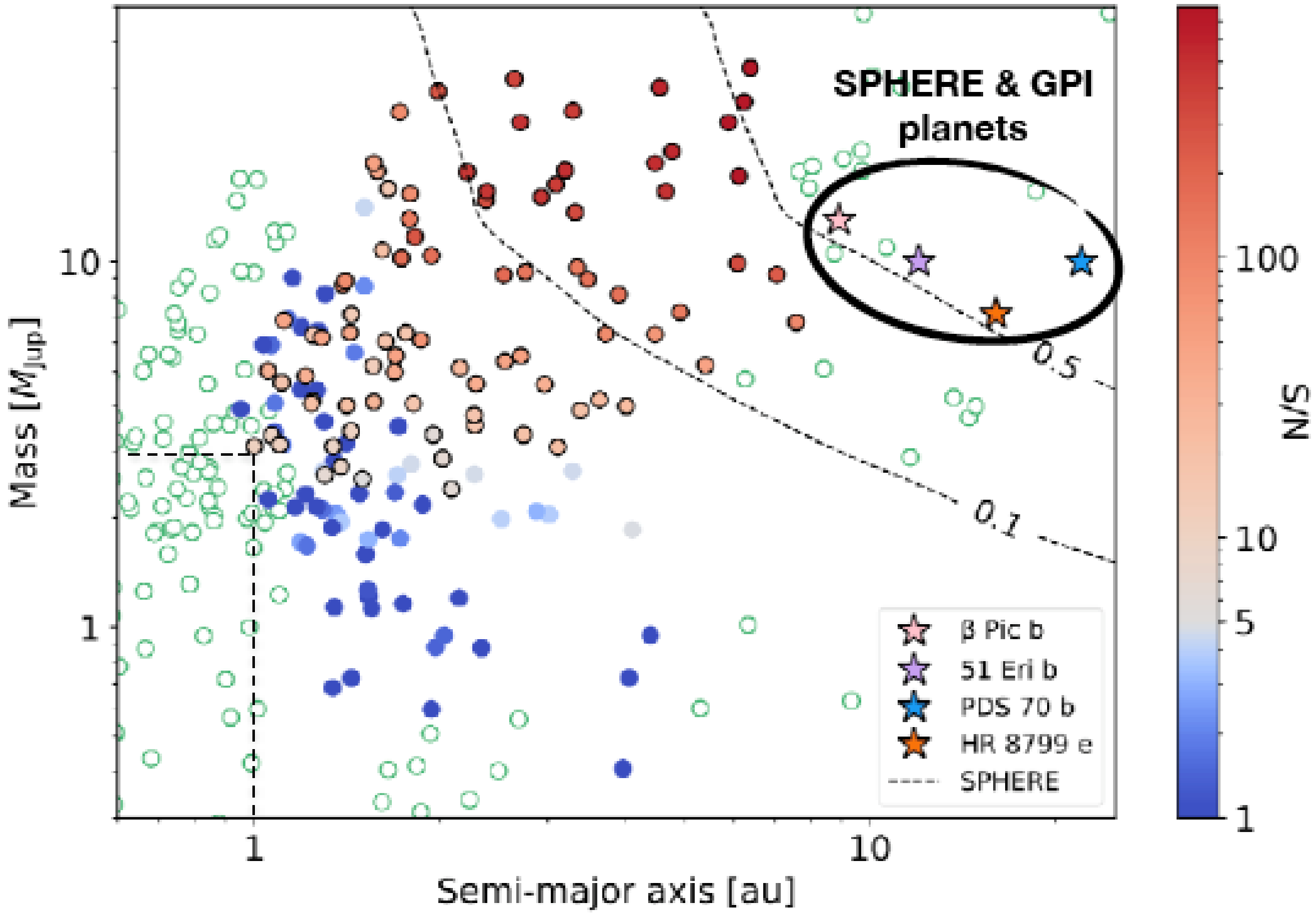


HARMONI Recent Simulation results

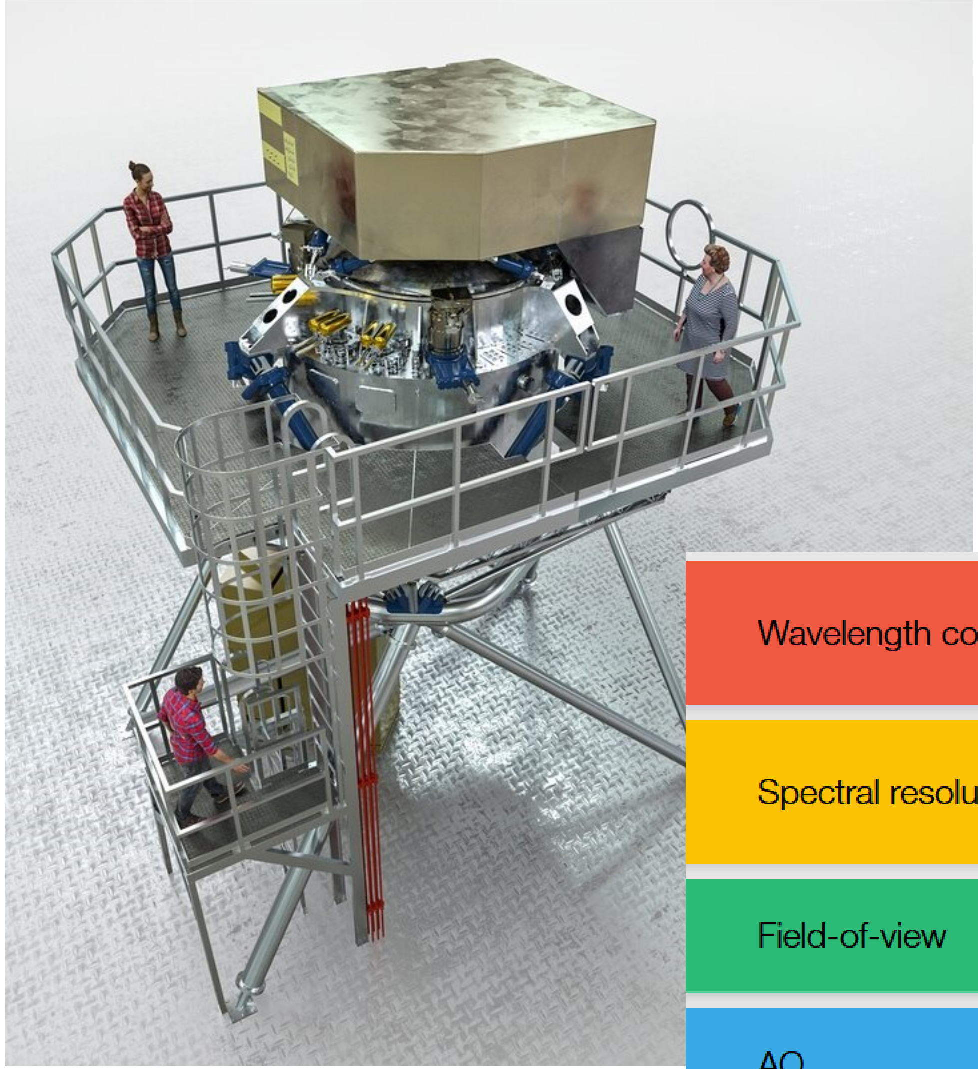
Houllé et al., A&A, 2021

- estimate detection limit of young giant planets with HARMONI using molecular mapping & ADI
- detect planets down to ~3 Mjup at 1AU for 30pc, 20Myr stars.
- contrast limit 15-16 Δmag (~10^{-6})

Detection of 2-3 M_{Jup} as close as 1AU!



ELT 1st gen Instruments: METIS (~2027)



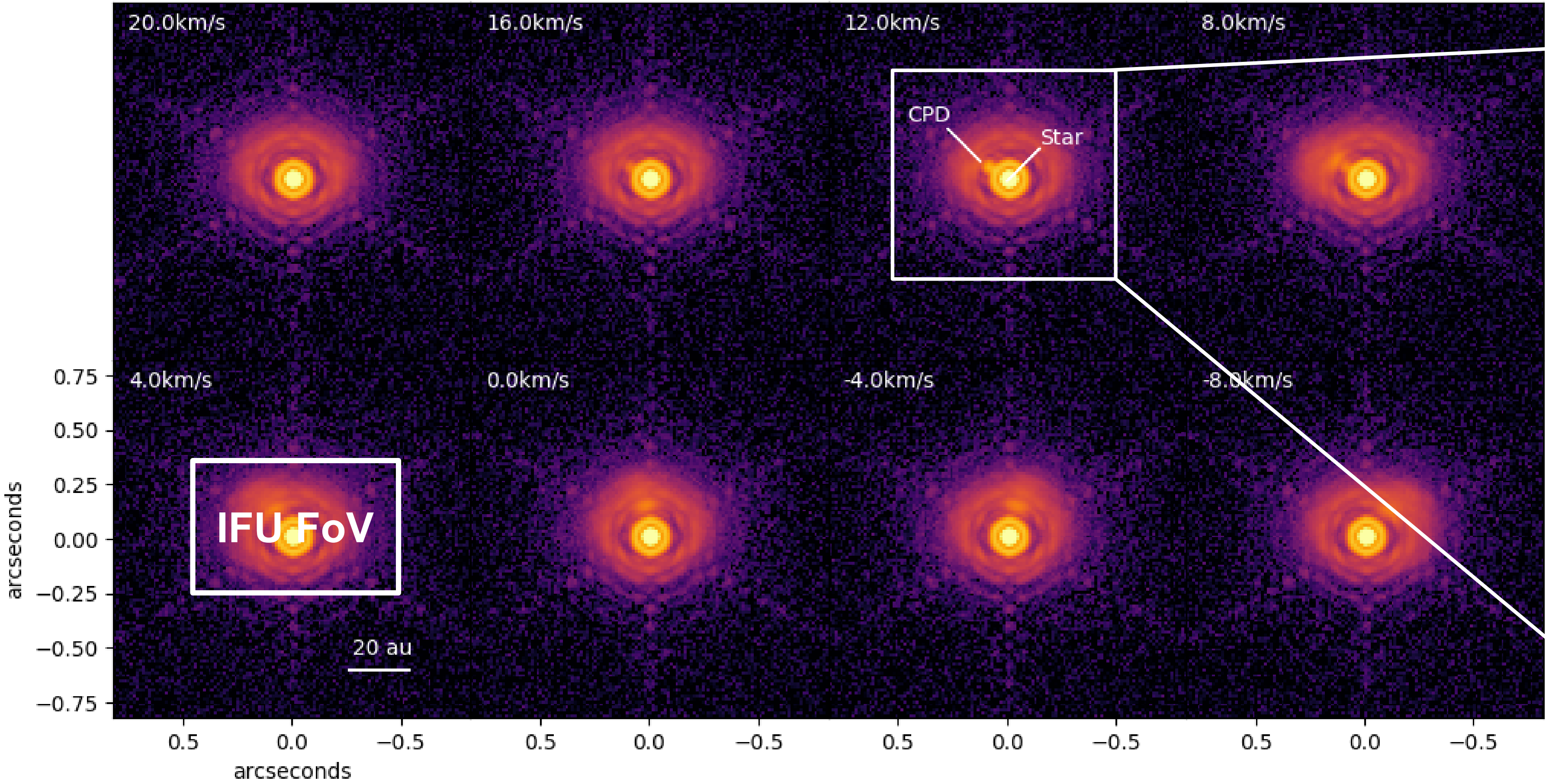
Near- to mid-IR imager and spectrograph

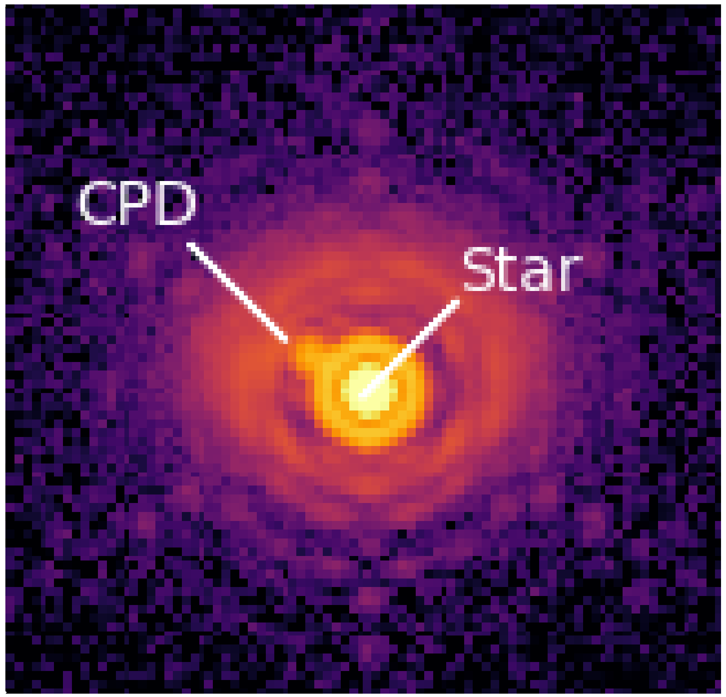
Wavelength coverage	3 – 13 µm (imaging); the imager includes low-resolution slit spectroscopy and coronography 3 – 5 µm IFU spectroscopy
Spectral resolution	Low-resolution, long-slit R~400 (N-band), R~1500 (L-band), R~1900 (M-band) High-resolution, IFU R~100,000 (L,M bands)
Field-of-view	~10'' (imager), <1'' (high resolution IFU spectroscopy)
AO	all observing modes work at the diffraction limit with a single conjugate AO system

METIS: Proto-planetary Disks and Planet Formation

Radiative transfer simulations of CO v(1-0) emission at 4.7 μm

Quanz et al. "METIS Science Case" (2019)



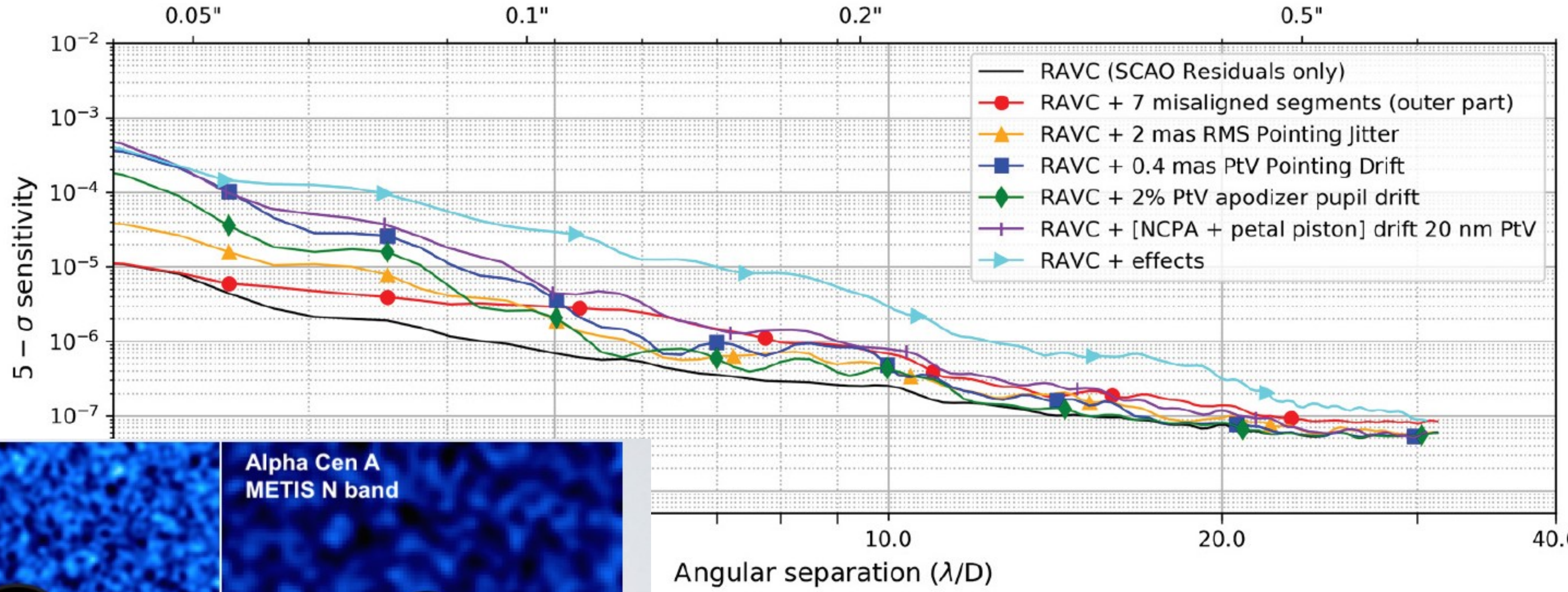


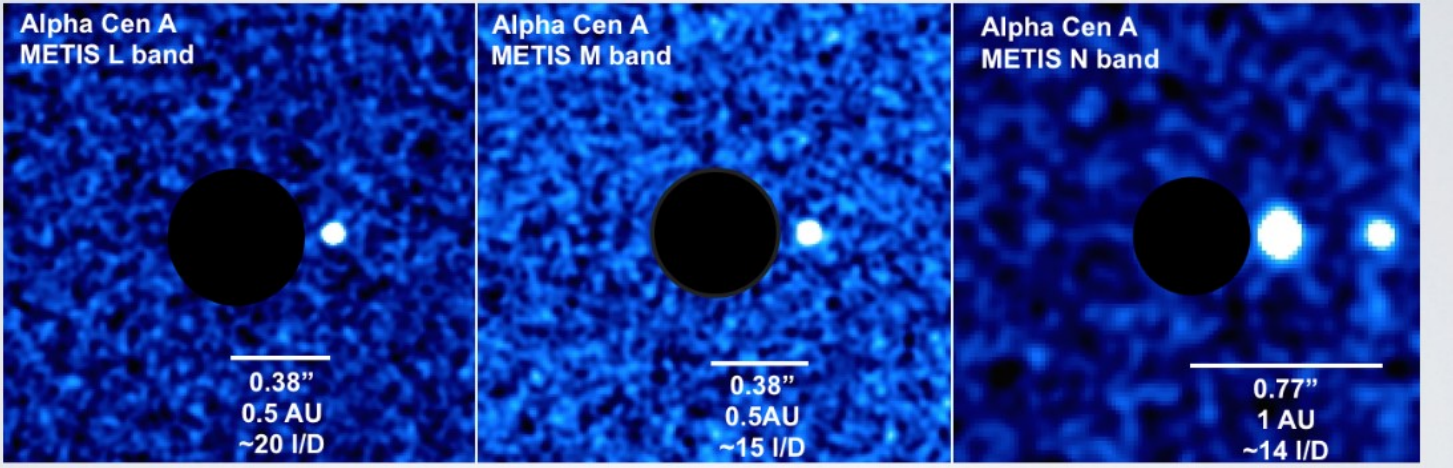
Simulated METIS observations of the same model

HD100546 (c) system
CO v(1-0) 4.7μm channel maps
$M_* = 2.4\ Mo$
$M_p = 5\ M_J$, $T_P = 1000$ K
$M_{CPD} = 5\text{x}10^{-2}\ M_J$
$t_{int} = 1$ hr

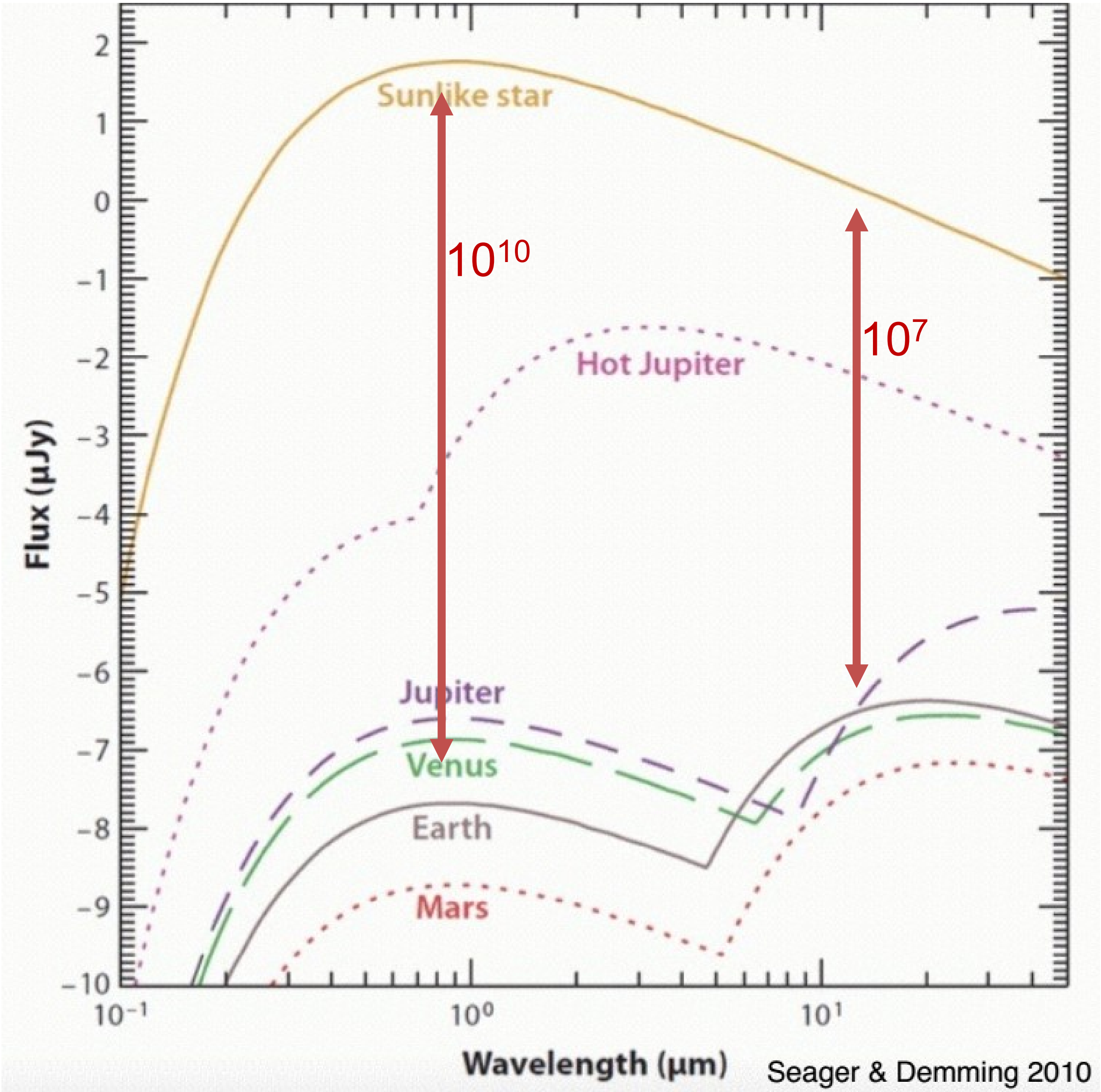
METIS contrast

- MidIR contrast with ring apodized Vortex coronagraph (Carlomagno et al. proc. SPIE 2020)





Different wavelengths show different things



Mid IR / N-band: Planet glows

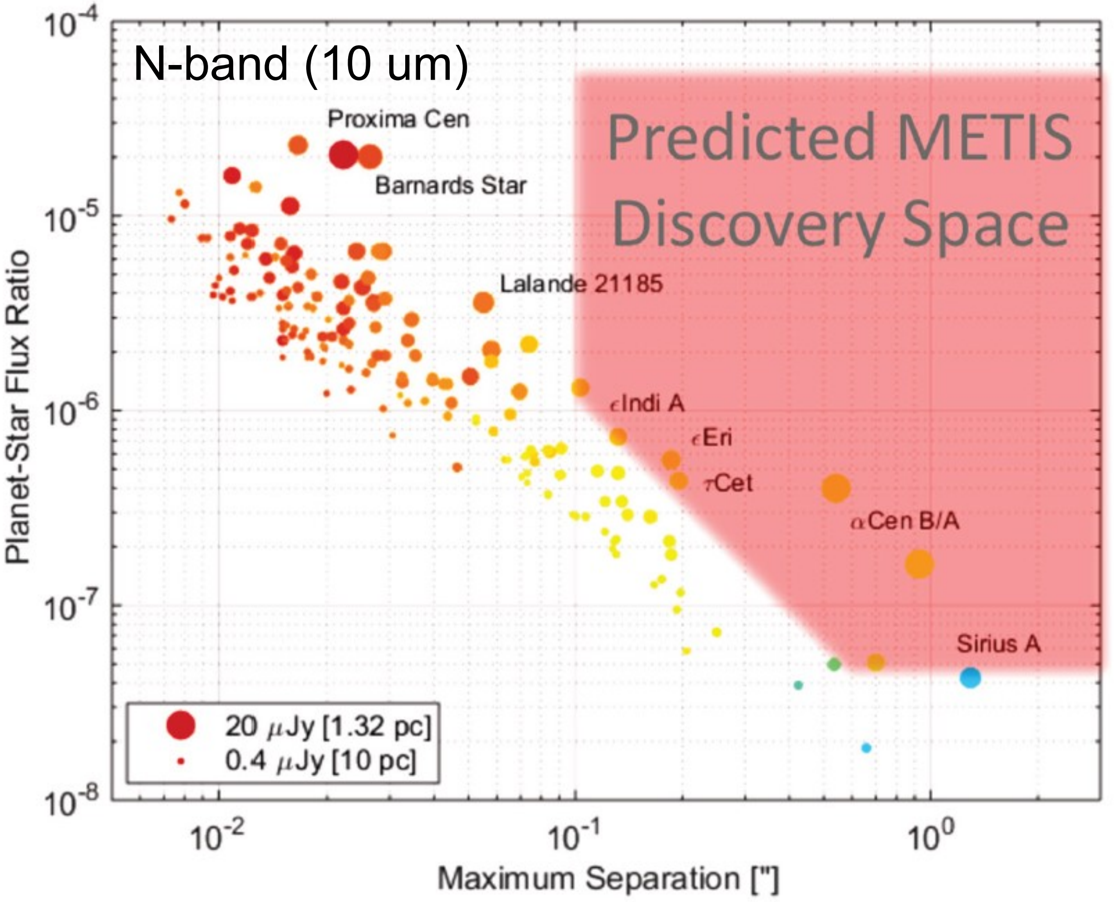
$$c \approx r_s^2 T_s / (r_p^2 T_p)$$

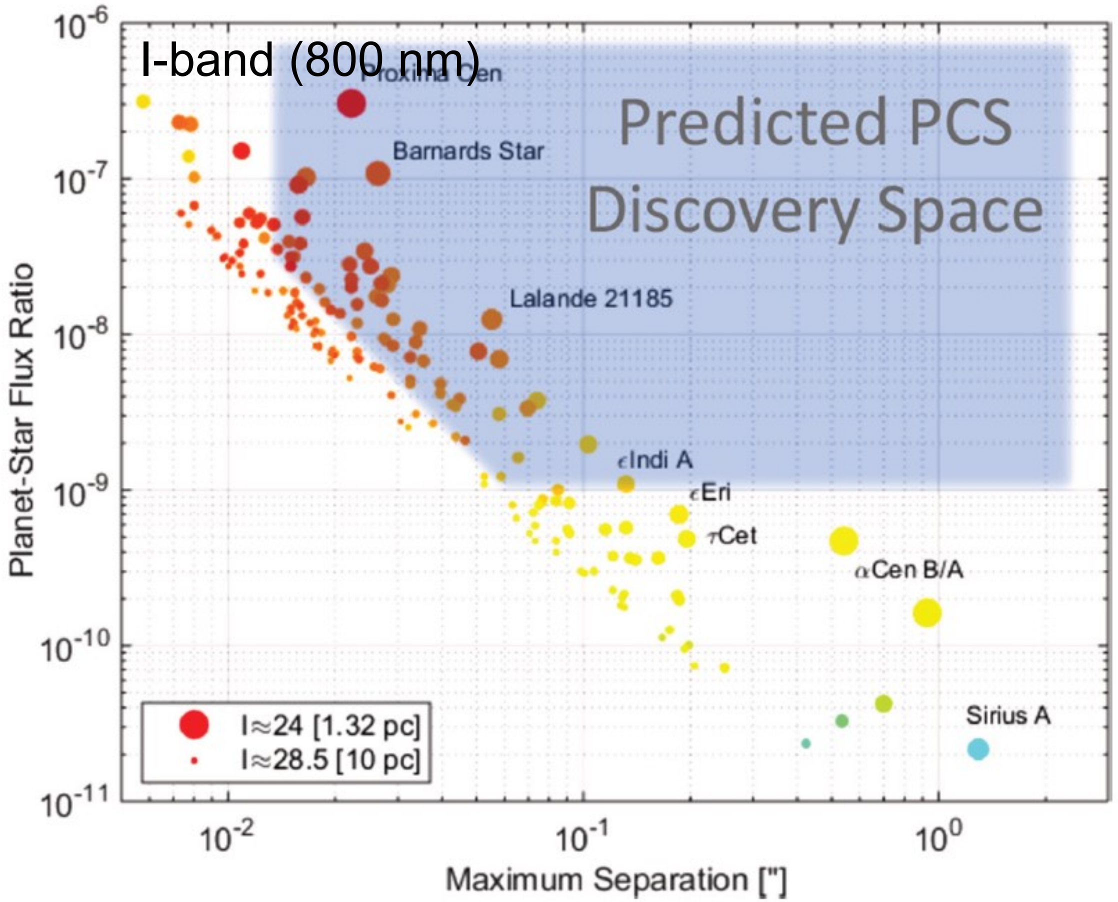
Opt/NIR: Planet reflects starlight

$$c \approx a^2 / r_p^2$$

https://www.wired.com/2014/04/the-world-looks-different-when-you-see-in-infrared/

Exoearths with METIS and ELT PCS (~2033)

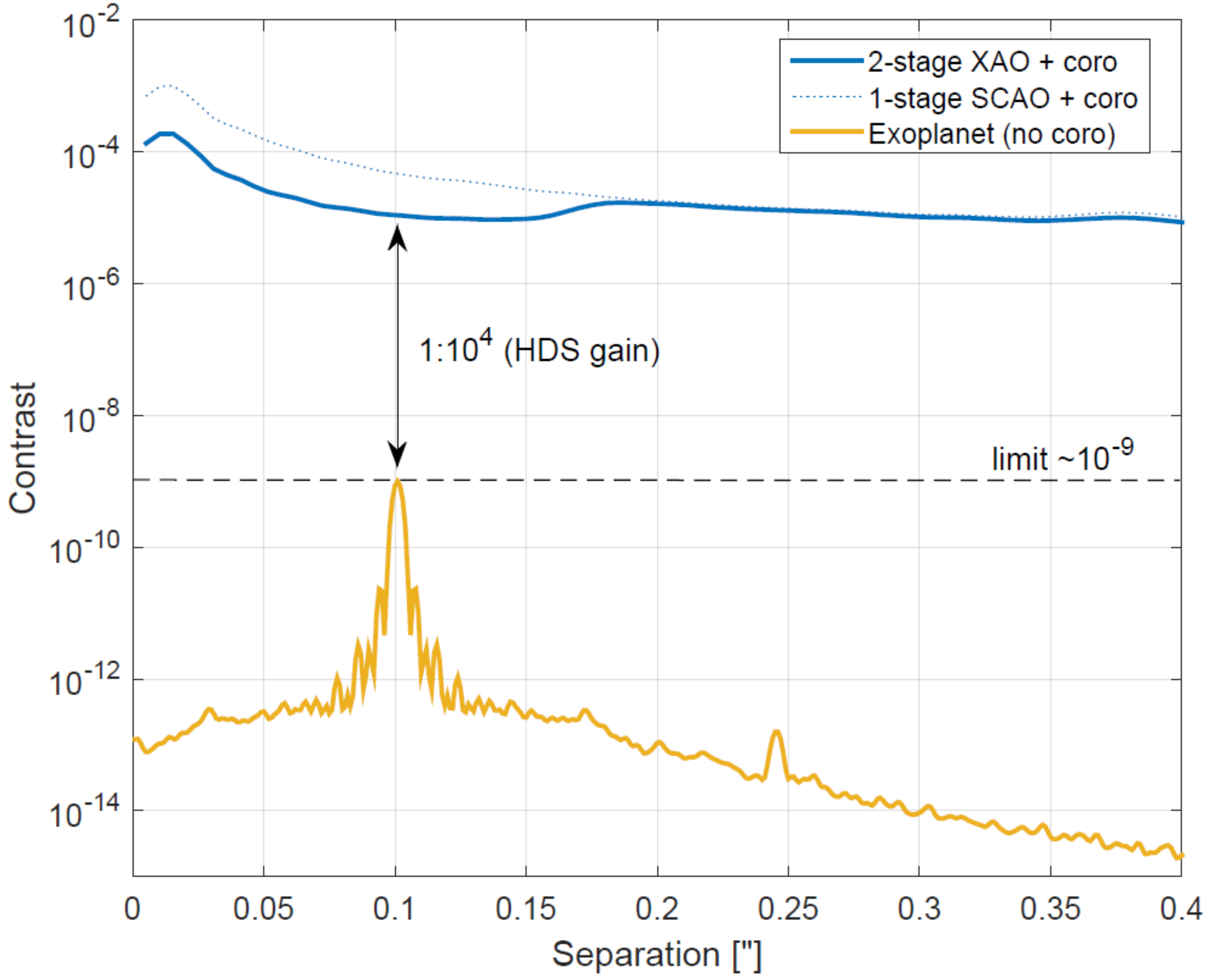




METIS: solar-type stars, contrast ~10^{-6} @ 100 mas, 10^{-7} @ 500 mas

PCS: late-type stars, contrast ~10^{-8} @ 15 mas, 10^{-9} @ 100 mas

How PCS achieves high contrast



Combine eXtreme AO with high-resolution (R~100.000) spectroscopy

(Snellen et al. 2015)

Concept validation on-sky with 8-m telescopes: HiRISE, KPIC, MagAO-X, SCExAO….

Take away

- Ground-based ELTs with AO
  - Have superb spatial resolution,
  - gain more than 3 magnitudes in sensitivity and >500x in speed over 8-m telescopes
- Instruments are extremely large as well and reach imaging contrasts between ~10^{-5} (1st gen) at 30-50 mas approaching the iceline at 100pc (MICADO and HARMONI at the ELT, ~2027)
- Terrestrial exoplanets in the HZ are within reach in the mid-IR for solar-type stars (METIS, ~2027) and in the optical/NIR for M dwarfs (PCS, ~2033)