30-m telescopes

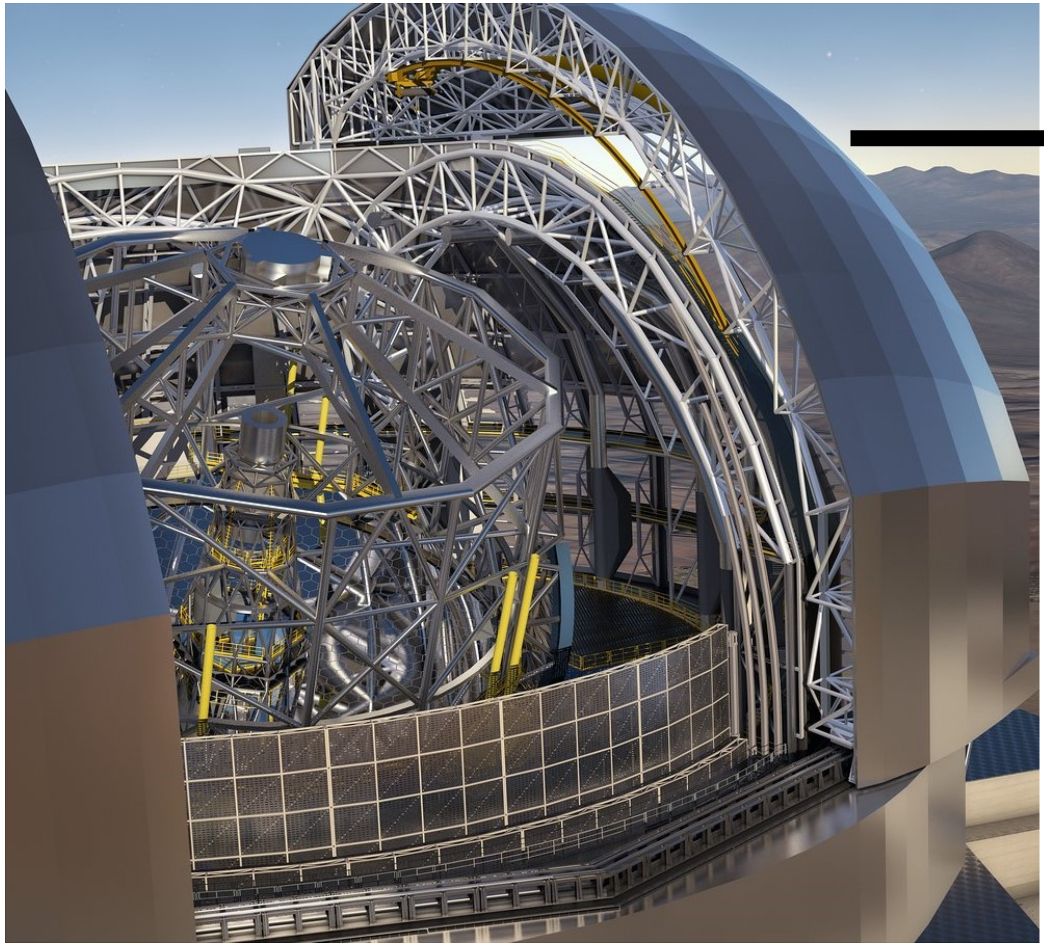
Markus Kasper (ESO)

Overview of the talk

- Why big telescopes?
- Extremely Large Telescopes
- ELT 2st gen instrumentation
- 2nd generation, PCS

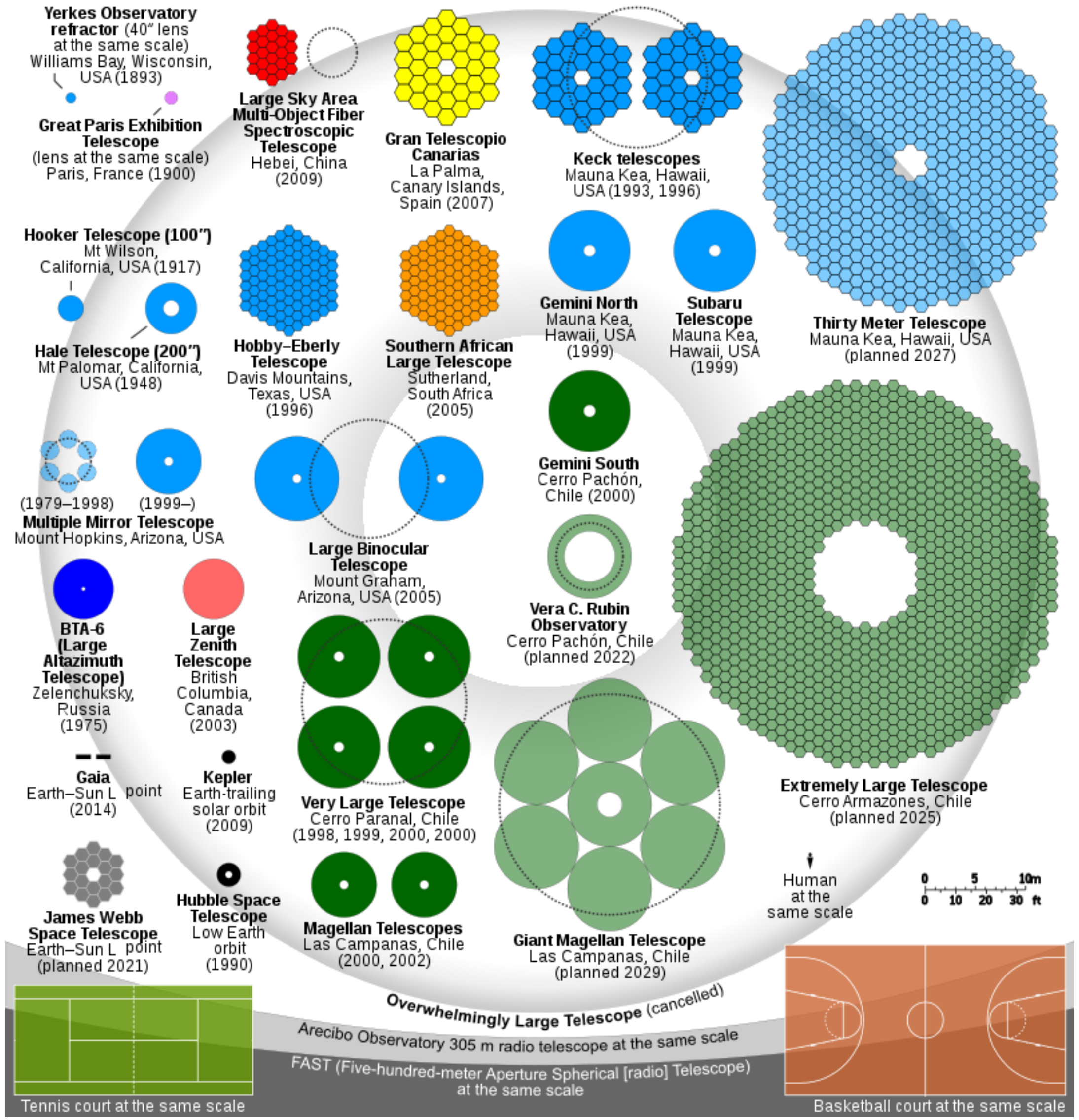
Disclaimer: This is a Euro-centric presentation, US 30-m telescopes are progressing on similar time-scale with similar instruments

The Extremely Large Telescope



https://xkcd.com/1294/

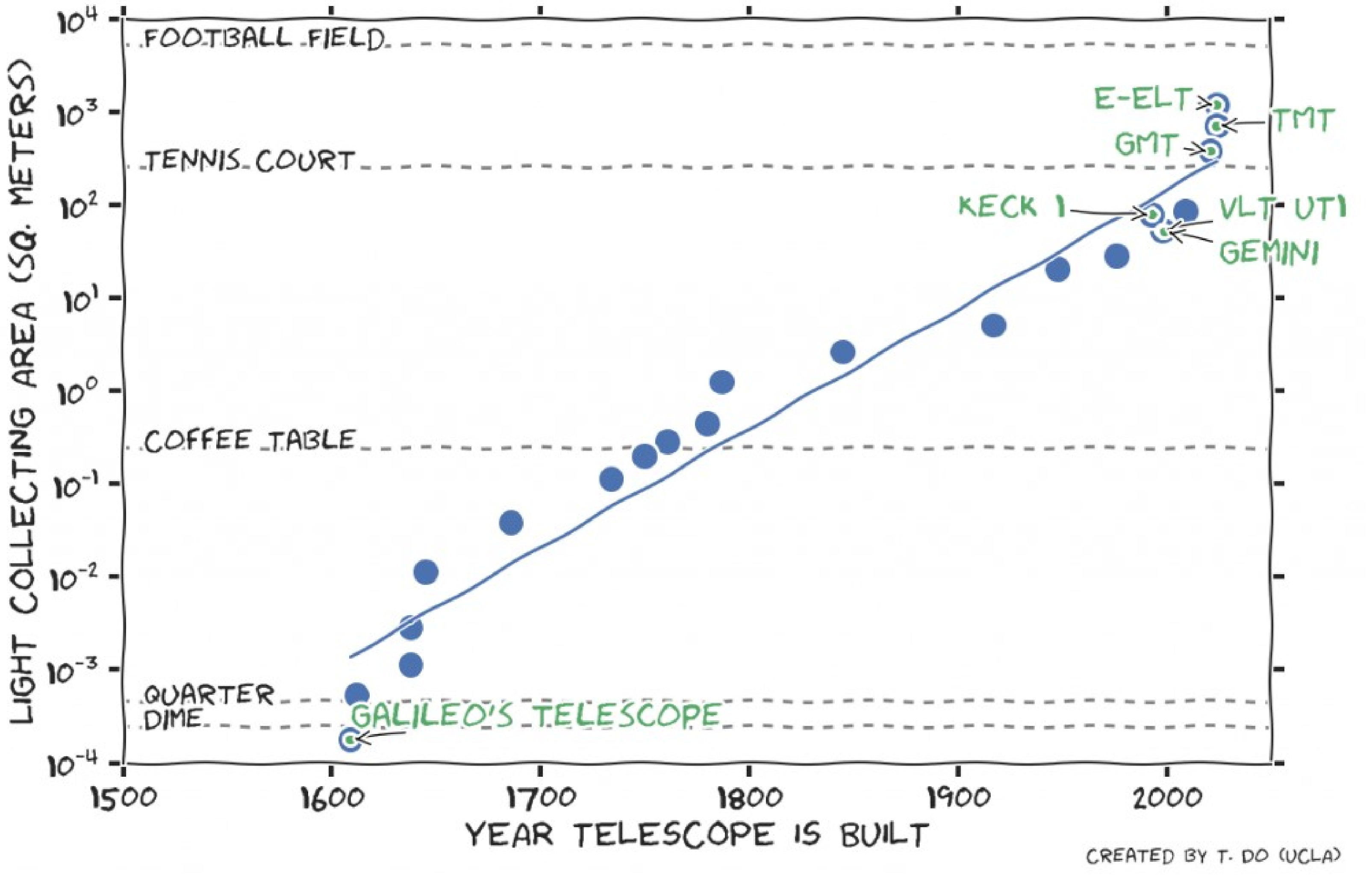
Why build an extremely large telescope?



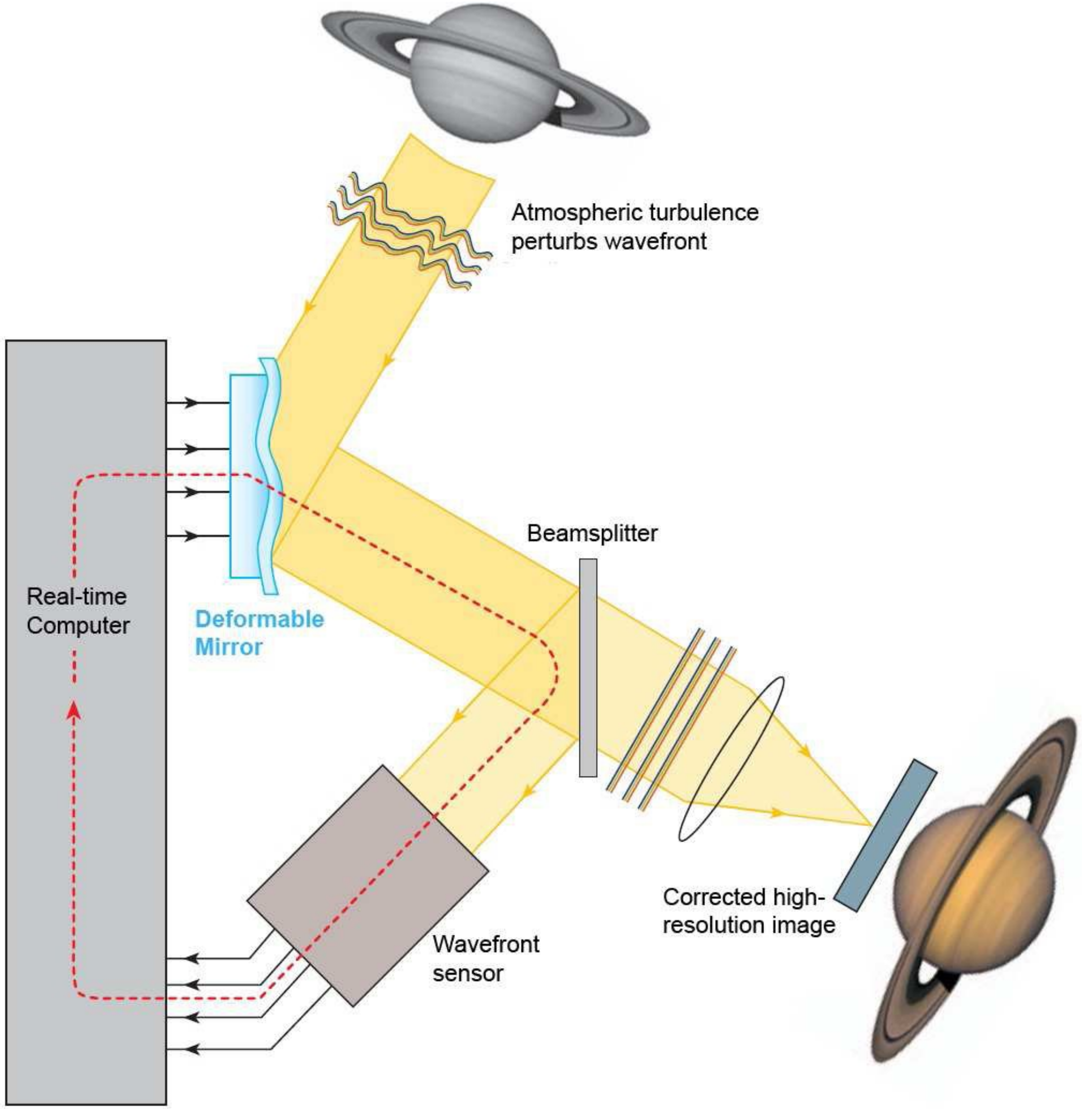
- Astronomers today have access to a huge number of telescopes
- On the ground and in space
- Not just for visible light, but X-ray, radio ….
- But there are always limits to the possible observations and no limits to curiosity ……or to the innovation of engineers!
- Larger aperture telescopes > fainter objects, smaller details

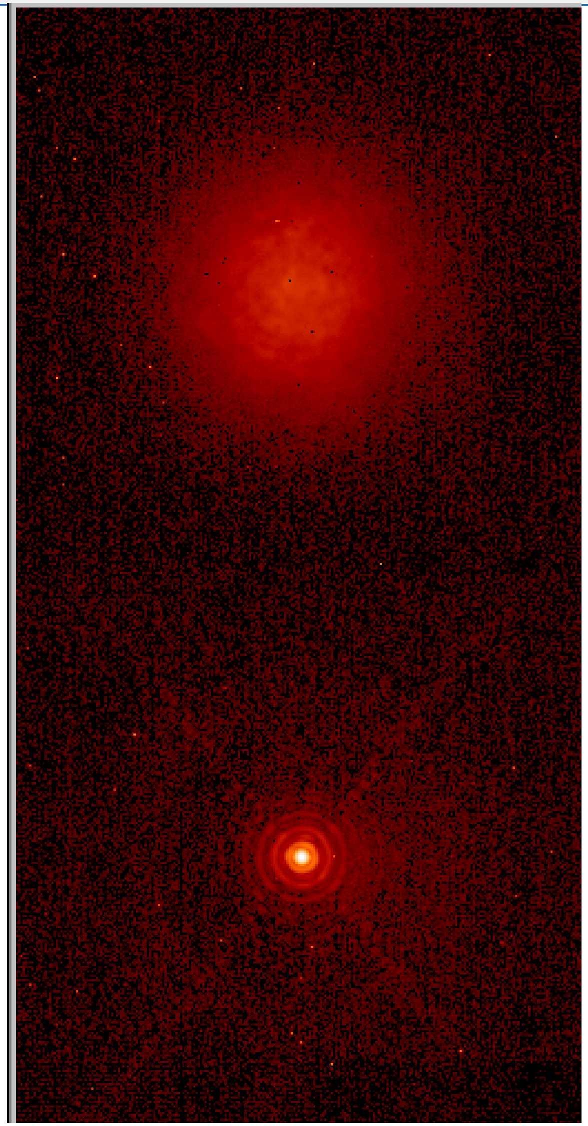
Why build larger (aperture) telescopes?

- 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





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
  - collects more flux ($\propto D^2$)
  - concentrates it (with AO) onto a smaller patch on the sky ($\propto 1/D^2$)
- Consider diffraction limited point source (Airy pattern area)
  - Collected flux $\propto D^2$
  - Sky noise stays constant (flux increase is compensated by patch size decrease)

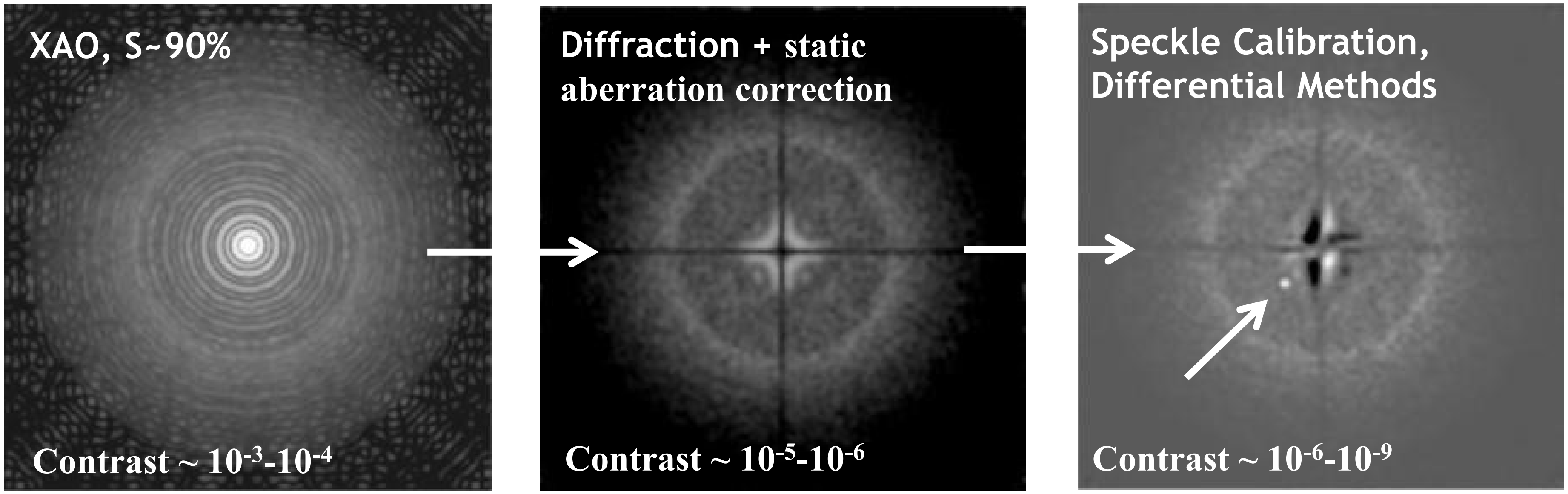
$$SNR \propto D^2 \times \sqrt{t} \quad \Rightarrow \quad t_{SNR} \propto D^{-4}$$

A 40-m telescope can do an observation $5^4 = 625$ times faster than an 8-m, NIR magnitude limits increase from ~23 mag to ~26.5 mag

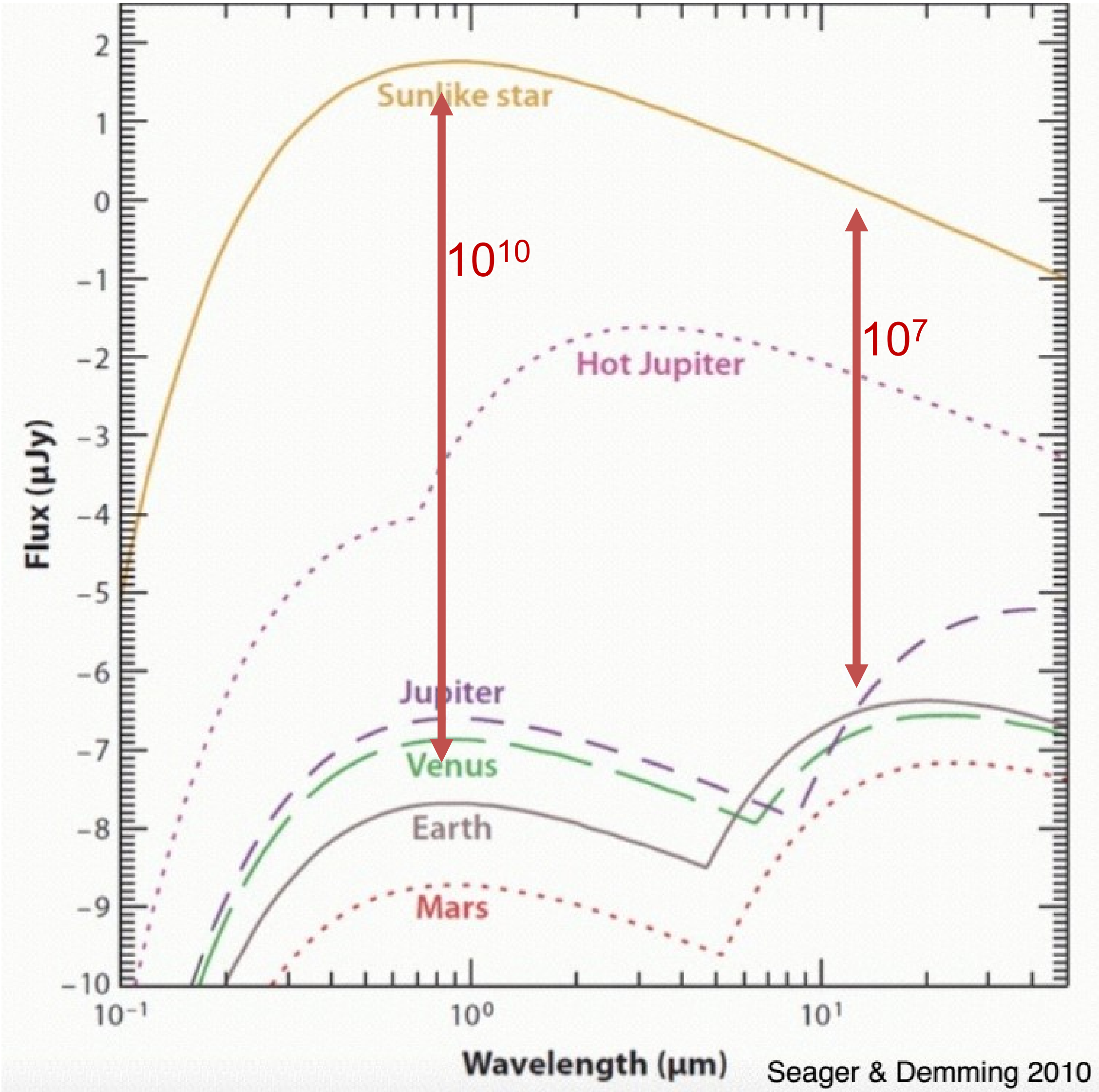
How to achieve high imaging contrasts

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



Different wavelengths show different things



Seager & Demming 2010

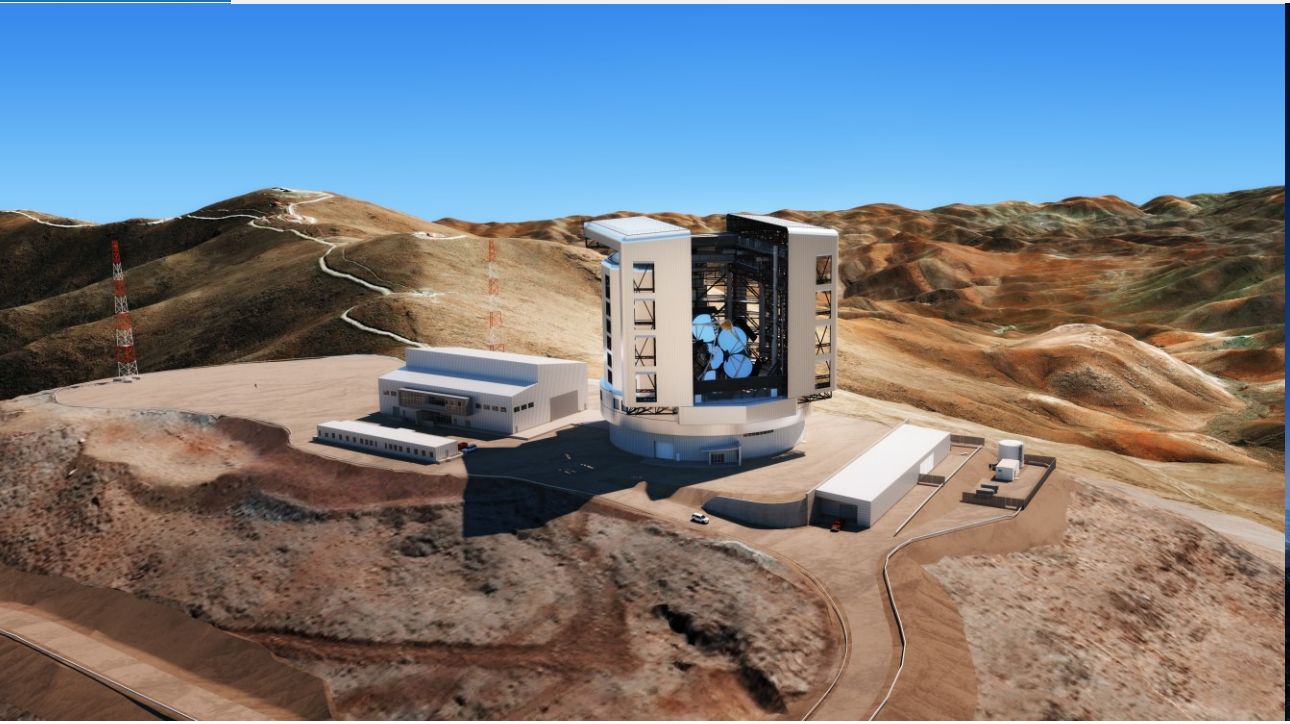
Mid IR / N-band: Planet glows
$c \approx r_s^2 T_s / (r_p^2 T_p)$

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/

EXTREMELY LARGE TELESCOPES

Extremely Large Telescope Projects

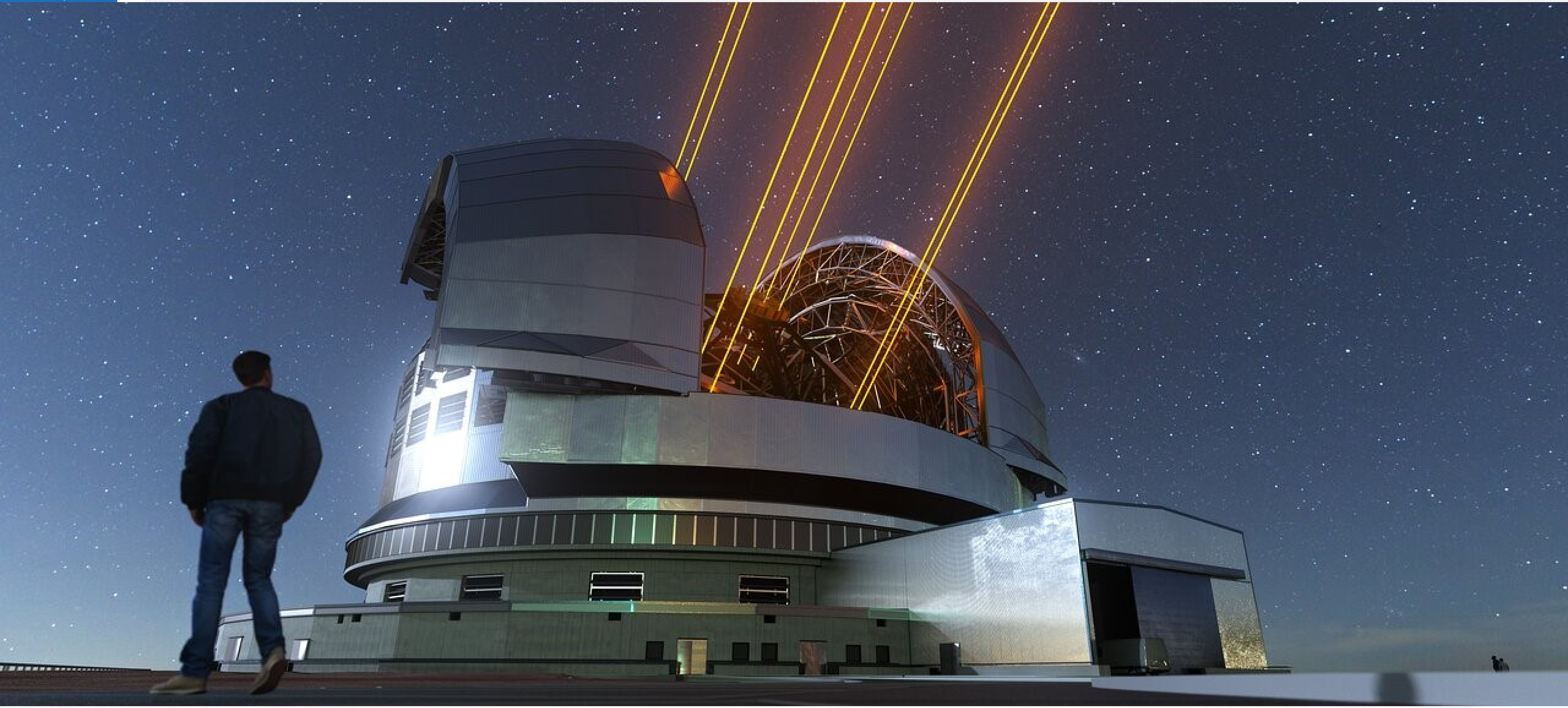


The 25-m Giant Magellan Telescope (www.gmto.org)

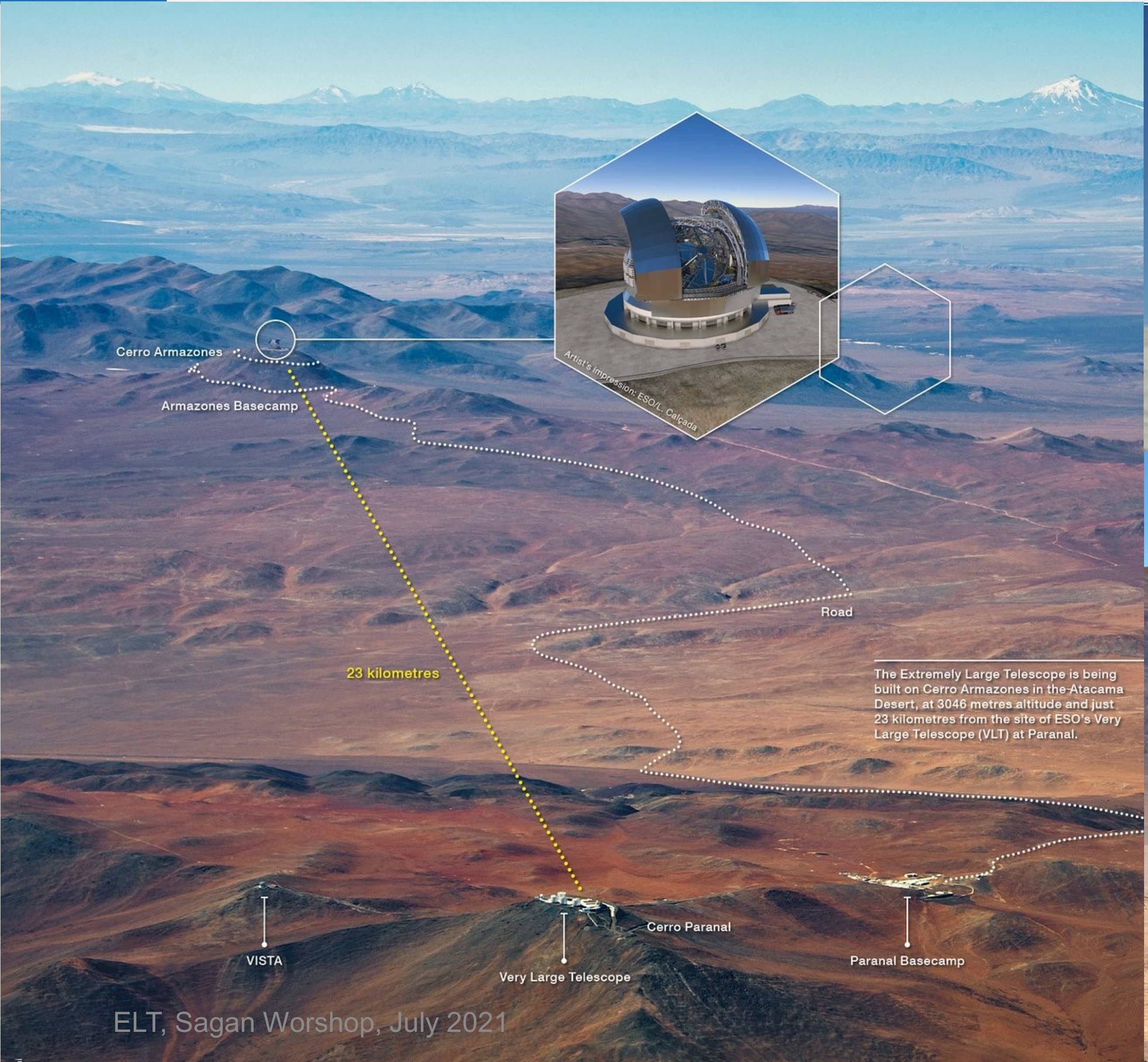
The Thirty Meter Telescope (www.tmt.org)

- 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

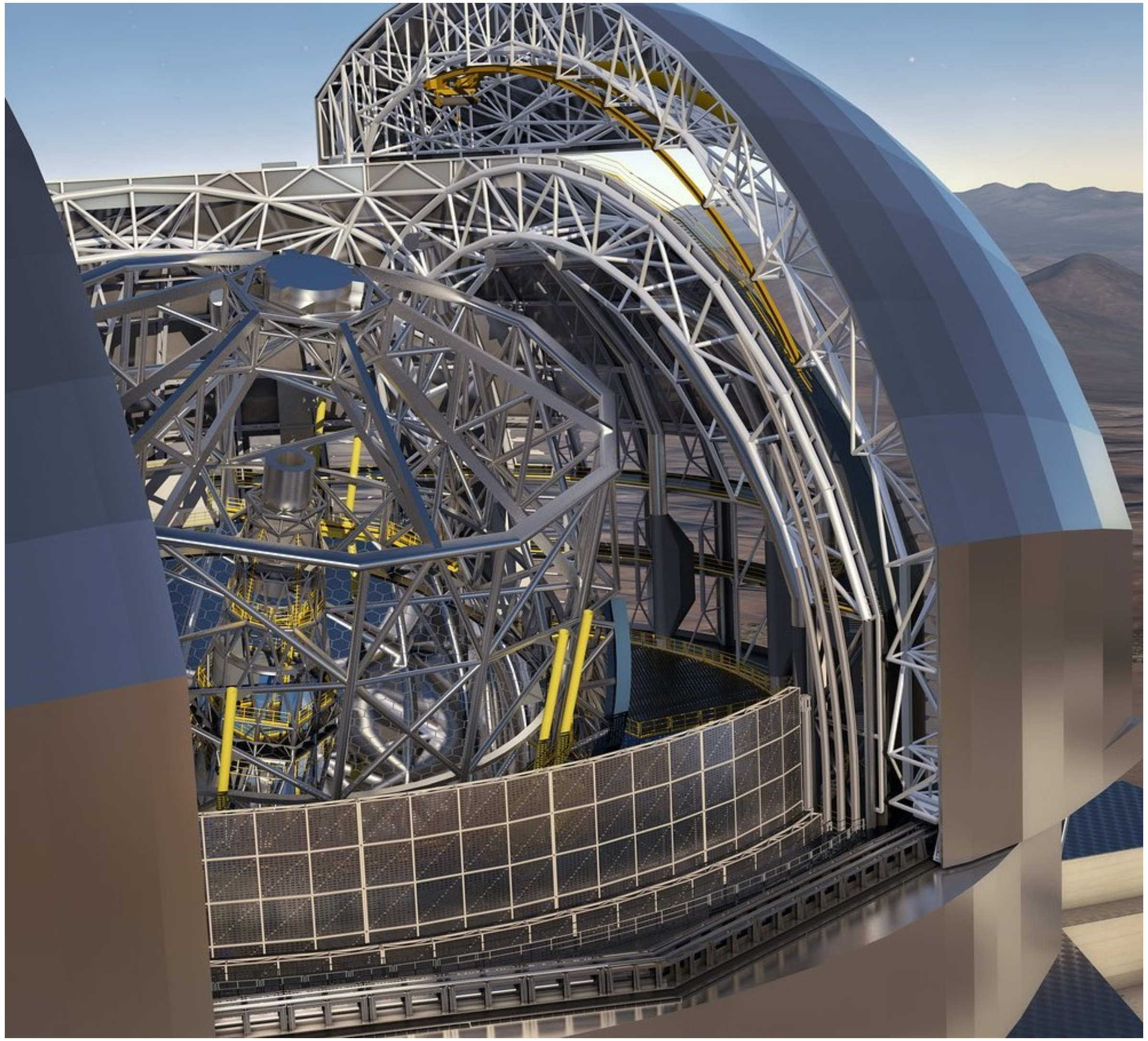


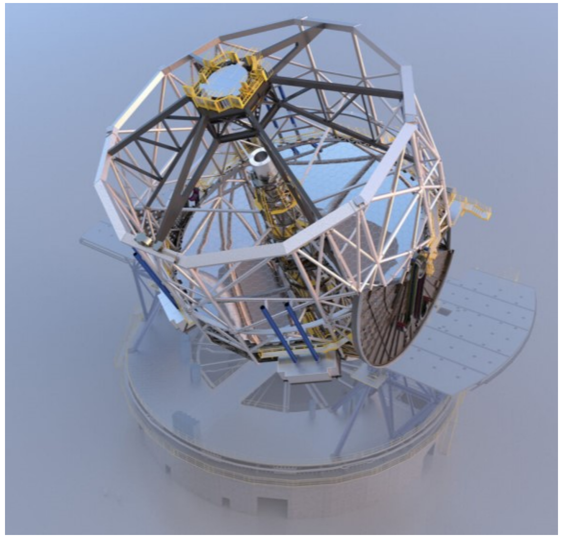
The site today

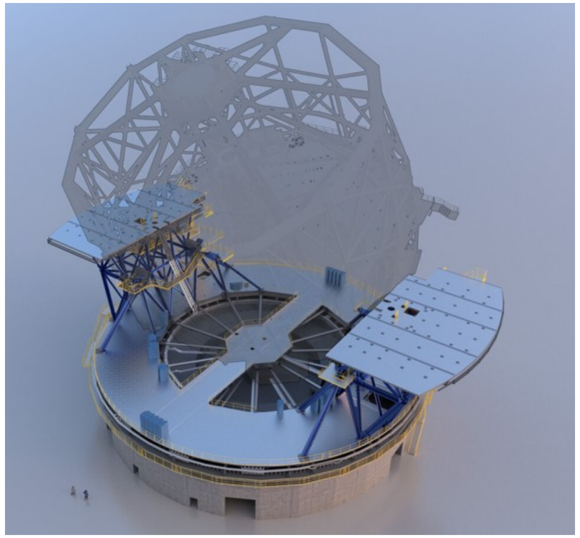
ELT DOME

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

Telescope structure

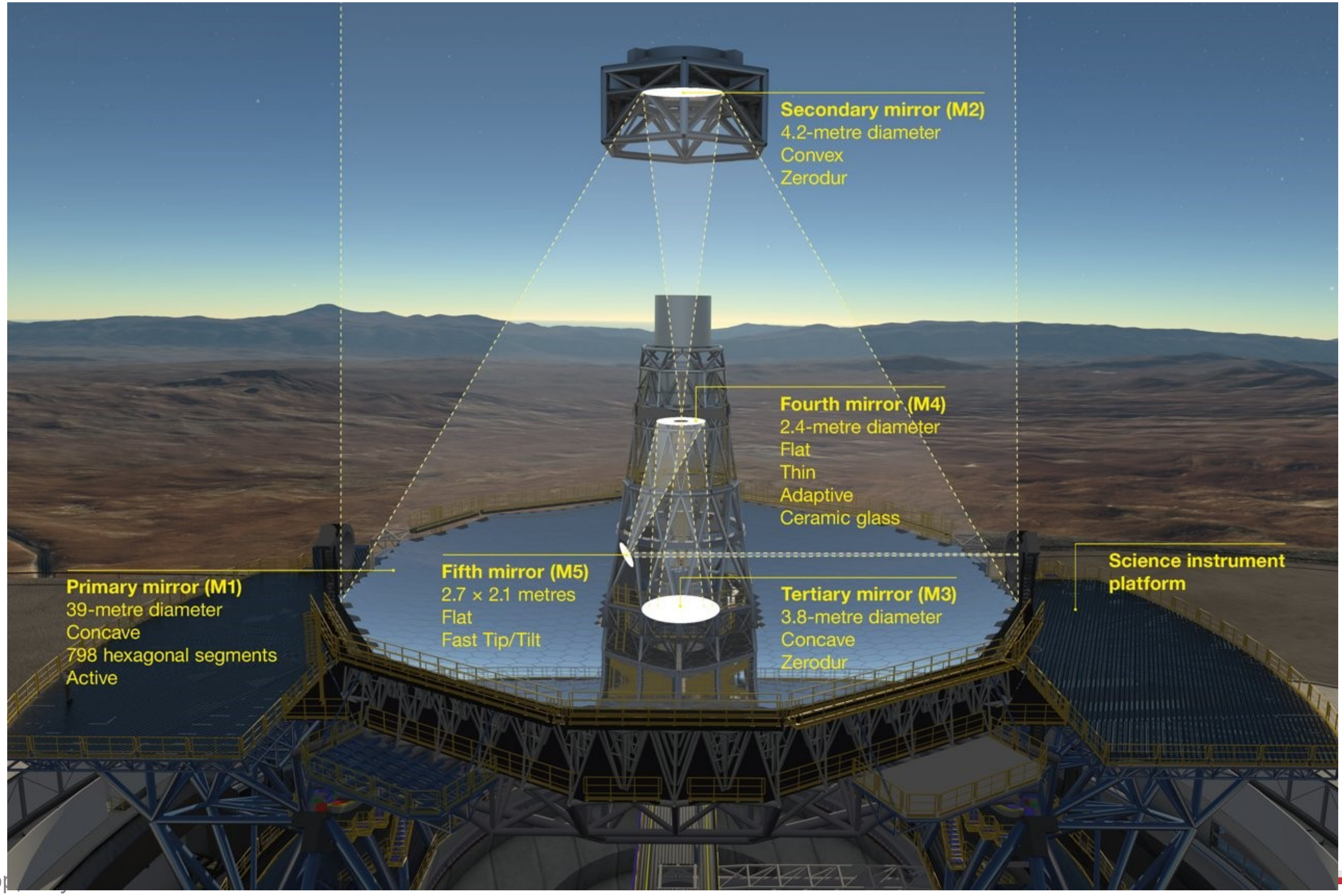






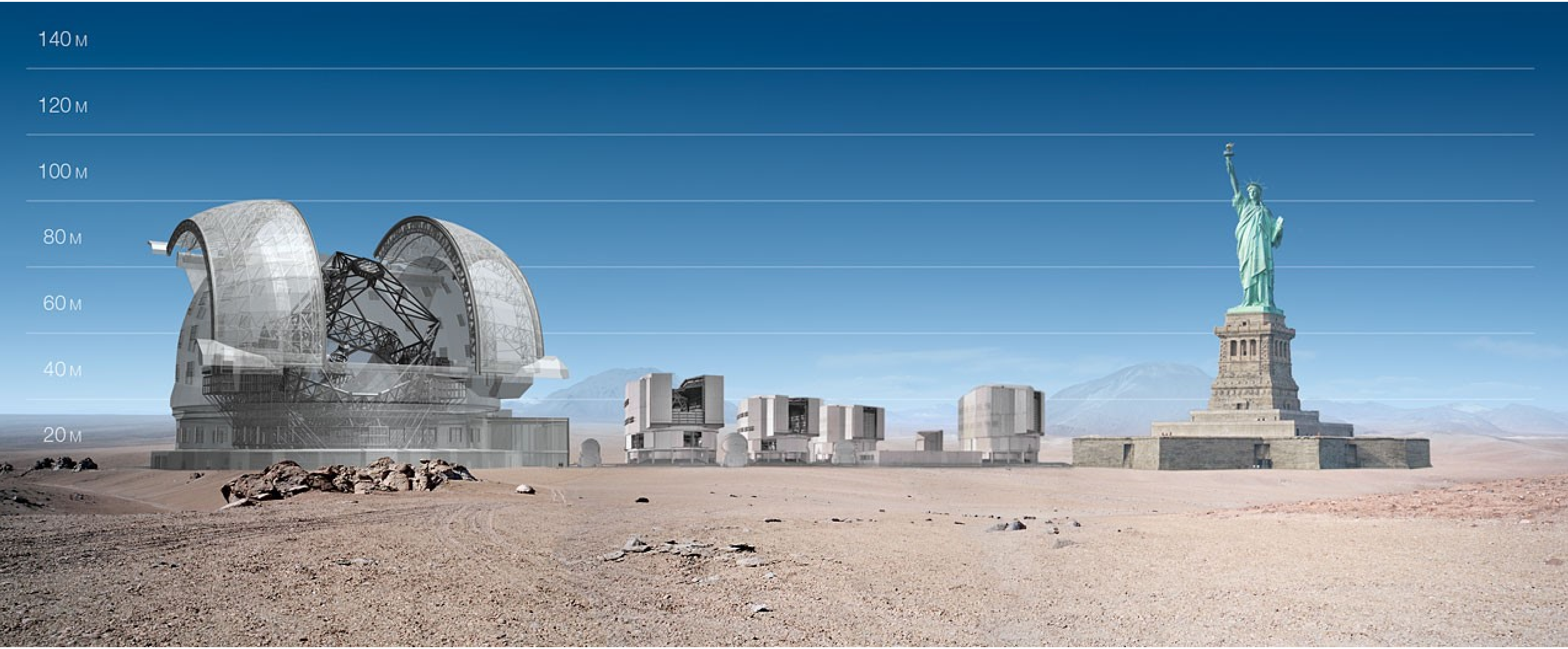
- Telescope rotates on oil bearings (largest 50m dia.)
- ~3700 tons incl mirrors and instruments
- Instrument (Nasmyth) platforms are 27-m above ground, 15m x 30m (or ~2 tennis courts !)

ELT optics

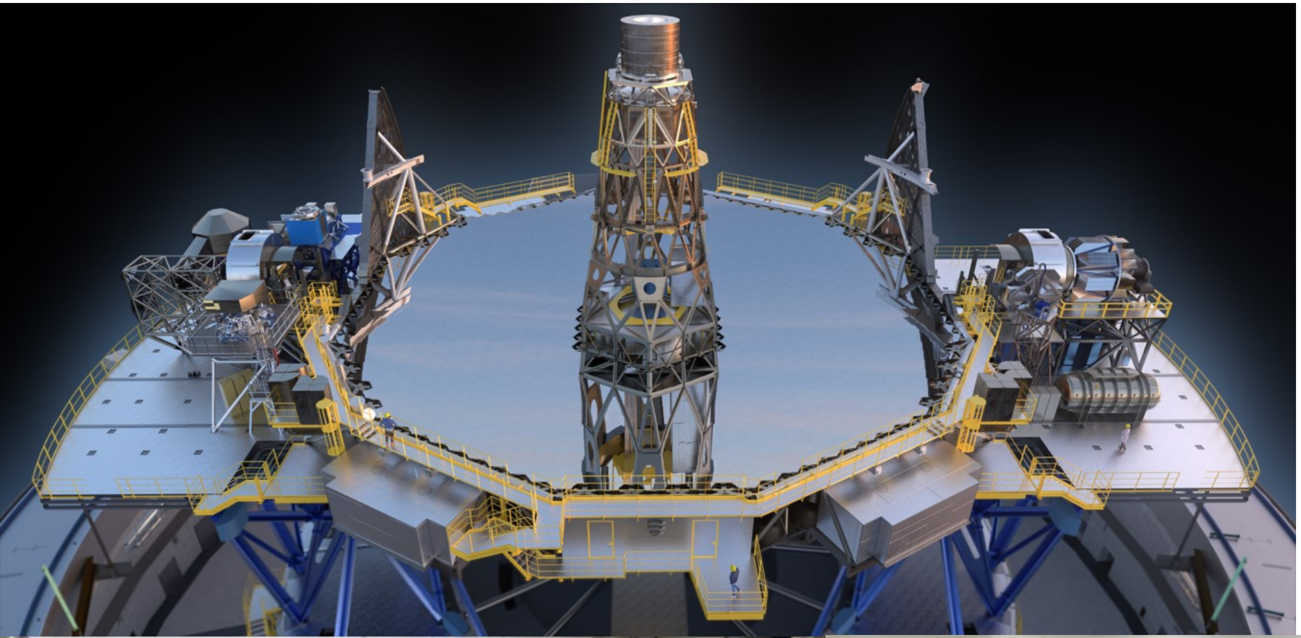


Secondary mirror (M2)
4.2-metre diameter
Convex
Zerodur
Fourth mirror (M4)
2.4-metre diameter
Flat
Thin
Adaptive
Ceramic glass
Science instrument platform
Primary mirror (M1)
39-metre diameter
Concave
798 hexagonal segments
Active
Fifth mirror (M5)
2.7 × 2.1 metres
Flat
Fast Tip/Tilt
Tertiary mirror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

Scale



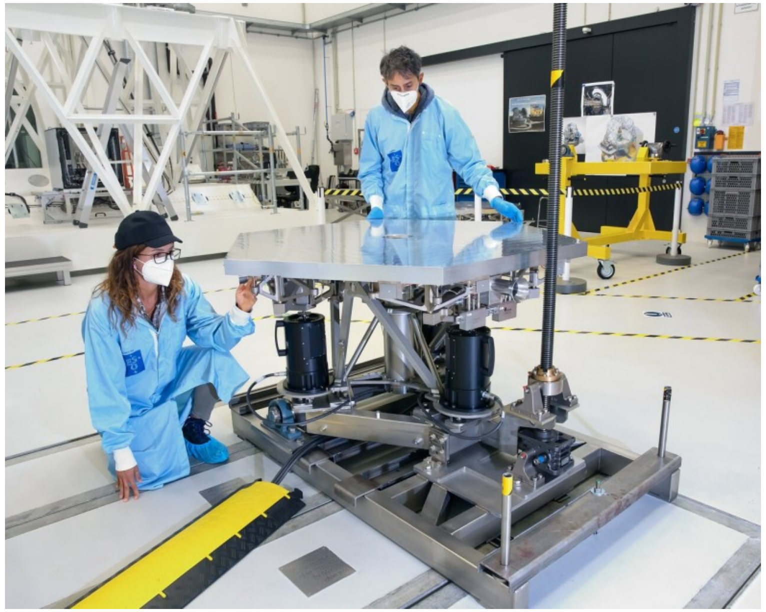
M1

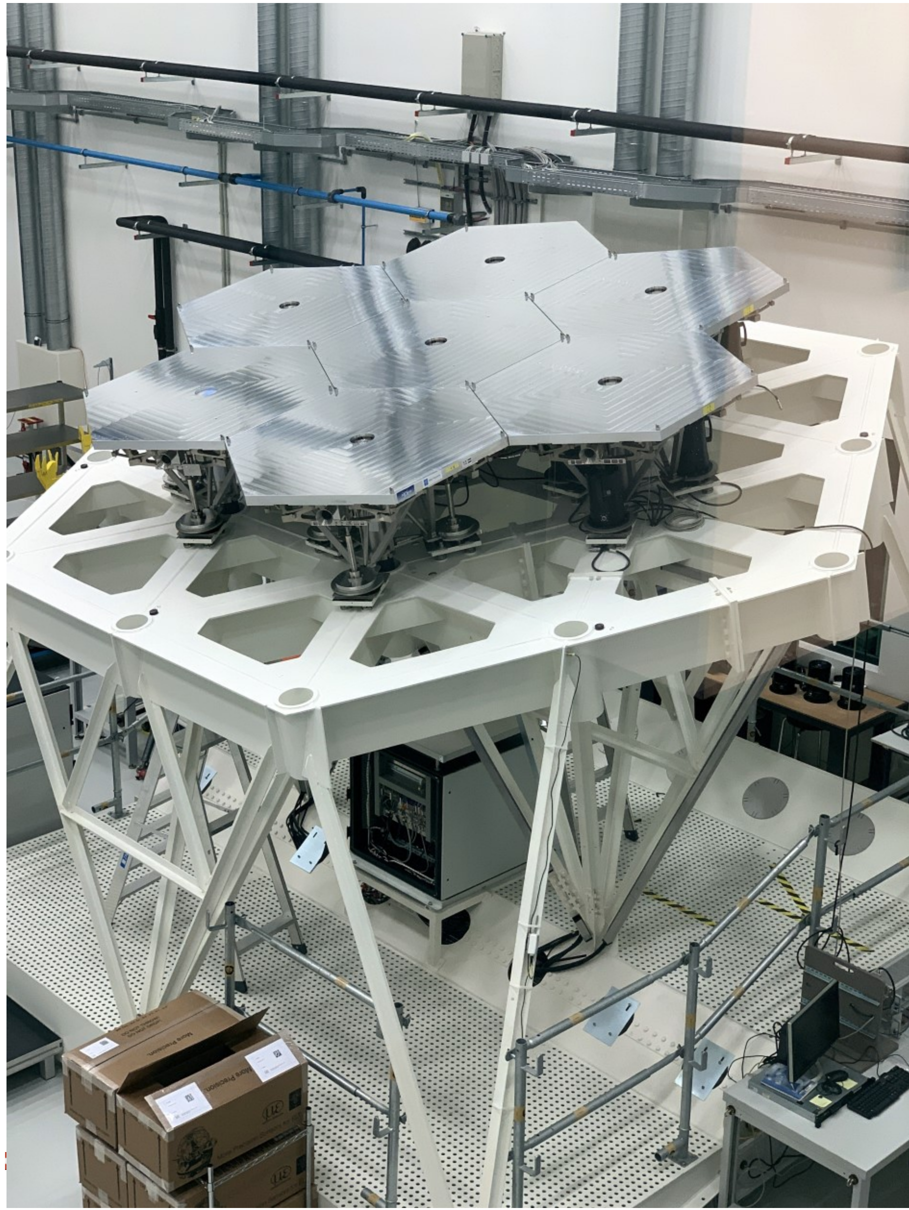


- M1 consists of 798 hexagonal segments 1.4m in ‘diameter’
- Circular mirror “blanks” are made in Germany by Schott and cut and polished in France by SAFRAN-REOSC then mounted on their support structure

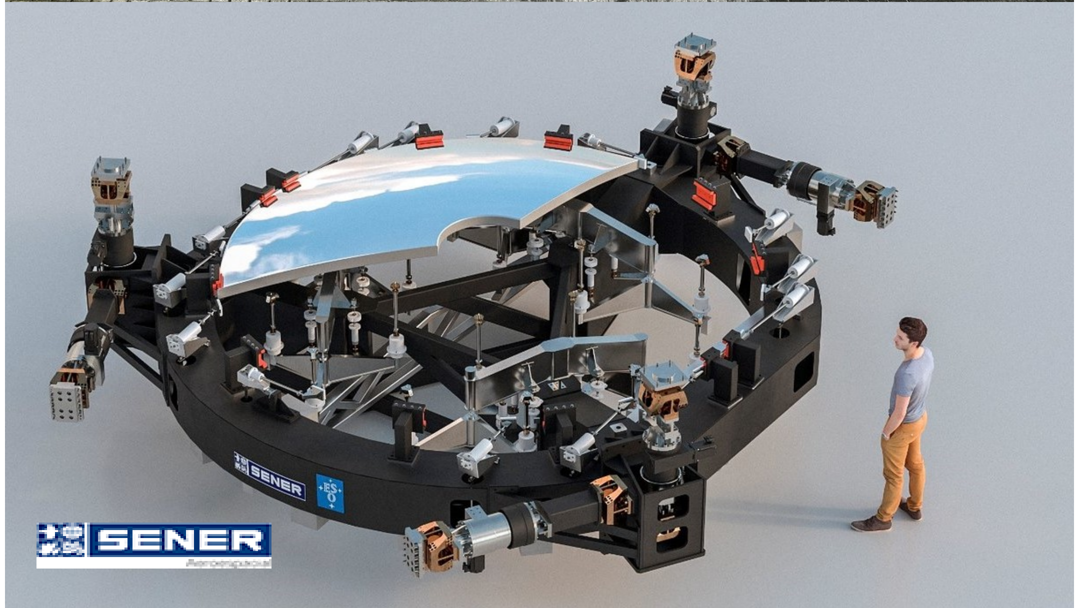
M1 – the ELT primary mirror

- 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





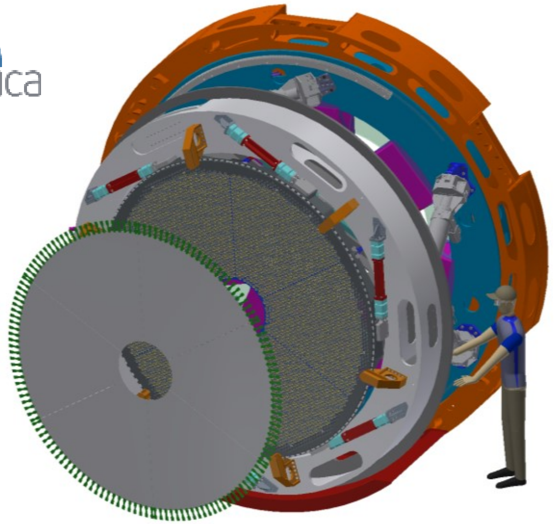
M2 and M3



- Casting of the 4-m mirrors in 2017 at Schott, Germany
- 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 in France at SAFRAN-REOSC and mounted in a cell made in Spain by SENER

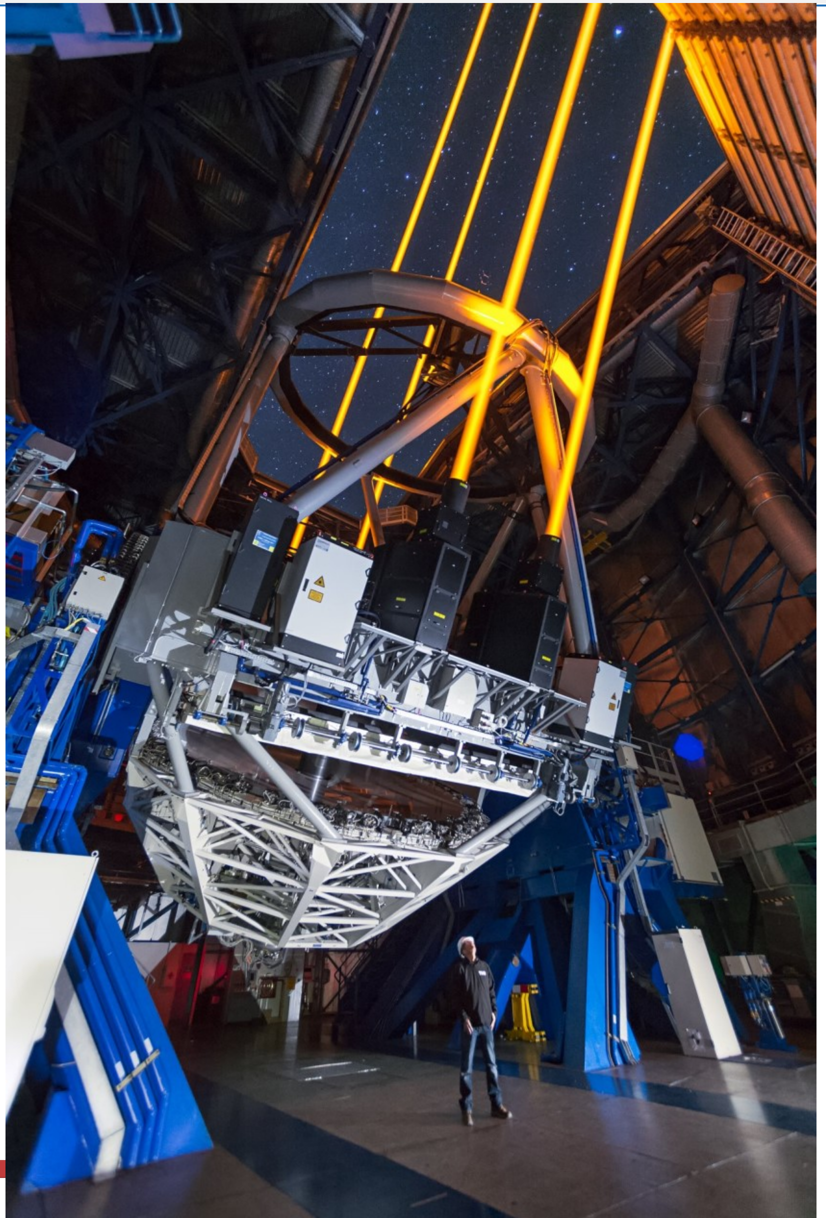
M4

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



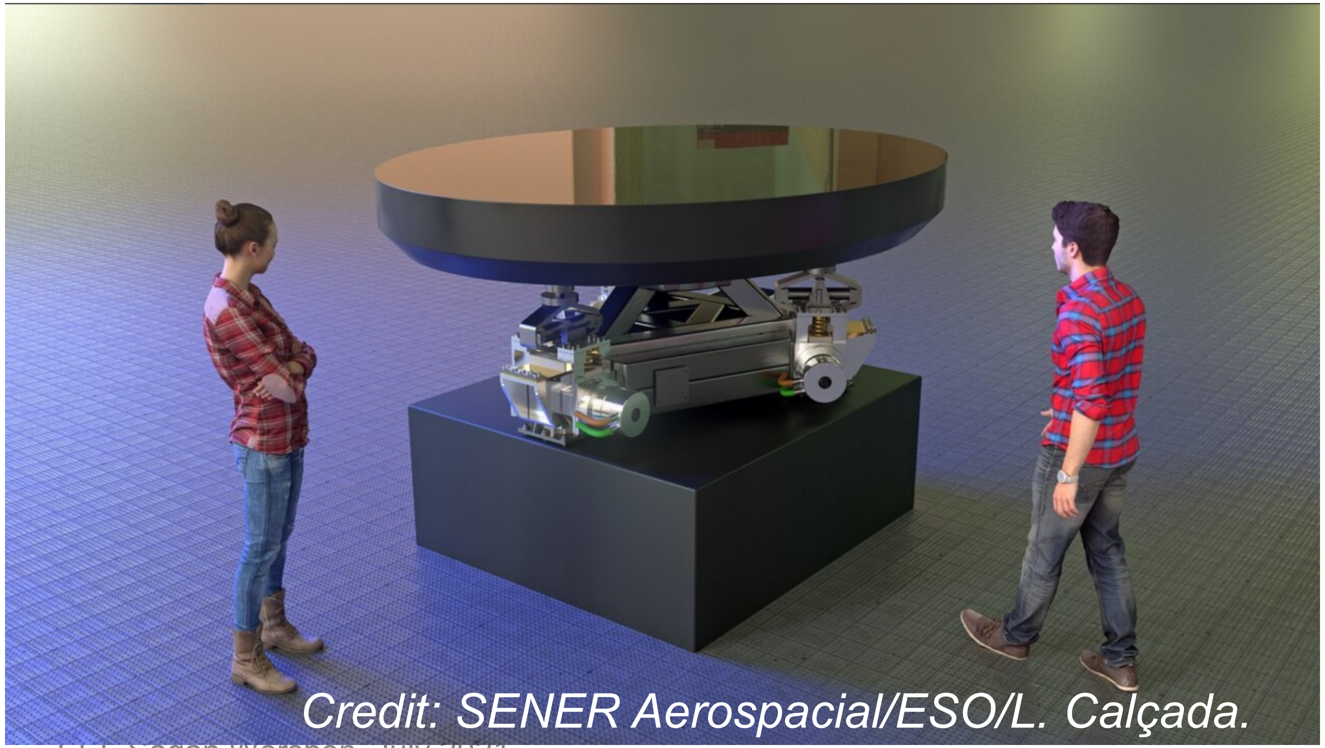
Laser guide stars

- AO needs bright “guide” star near the astronomical target. Using “natural” guide stars, we can only observe a few percent of the sky
- Artificial guide stars created by laser are used when real stars are not available

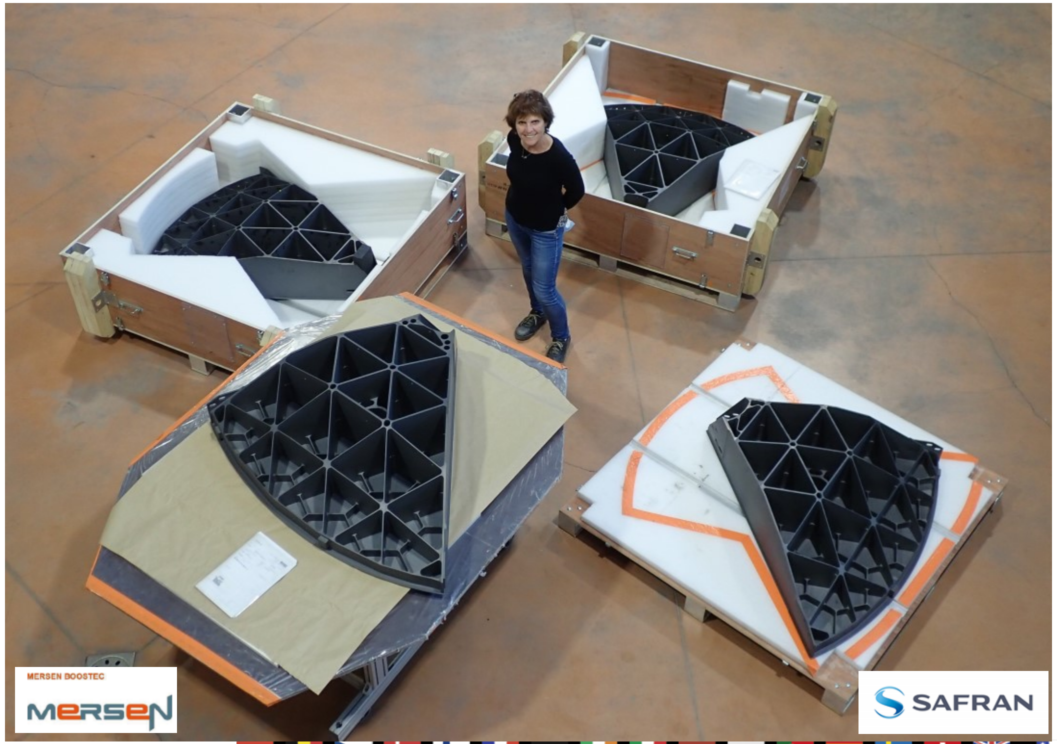


M5

- M5 also helps correct for the atmospheric turbulence “tip-tilt” (image stablisation)
- It is a 2.7m x 2.2m Silicon carbide mirror (Safran-Reosc and Mersen Boostec) mounted on a cell by Sener Aerospatiale

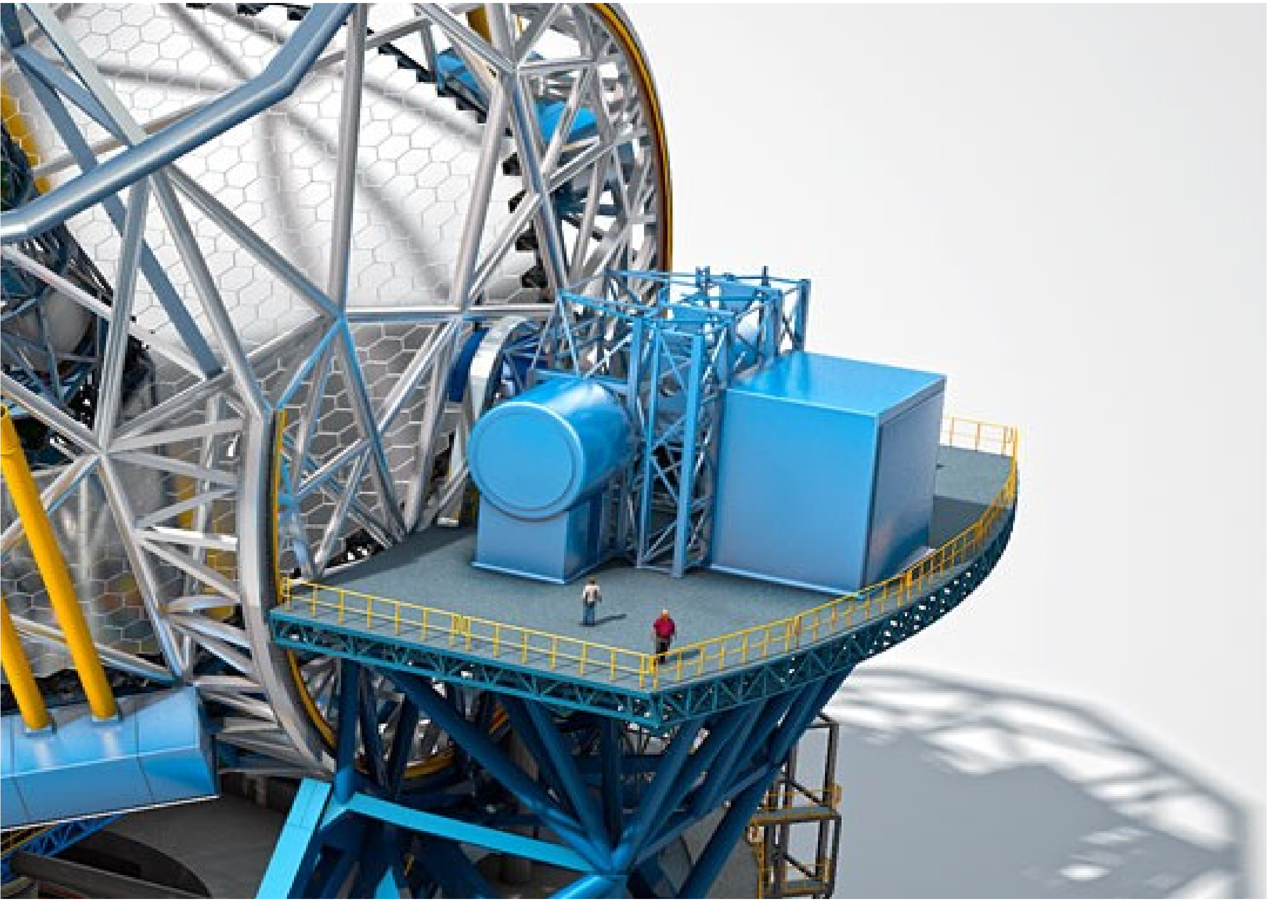


Credit: SENER Aerospacial/ESO/L. Calçada.



ELT INSTRUMENTS

The ELT Nasmyth platform



James Nasmyth
(1808-1890)

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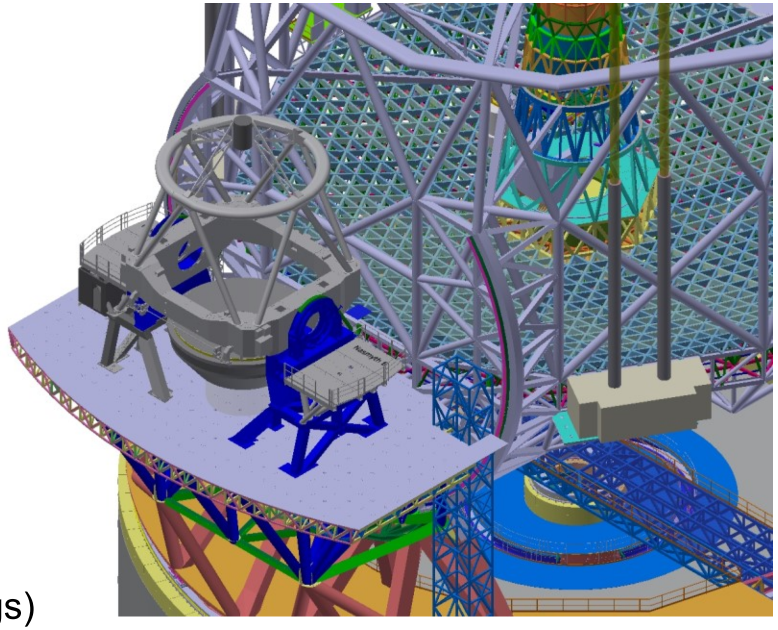


A VLT on the ELT
Nasmyth platform
(credit: ESO/Rob Ridings)

Big telescope → big instruments

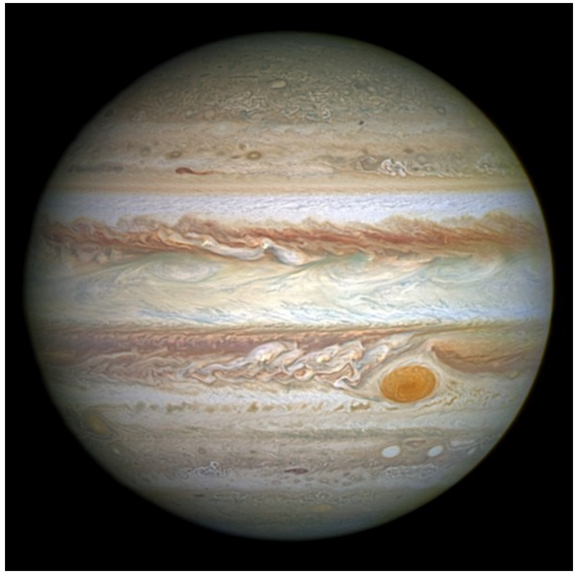
$$x = f\theta$$

- 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

METIS Kick-off 2015

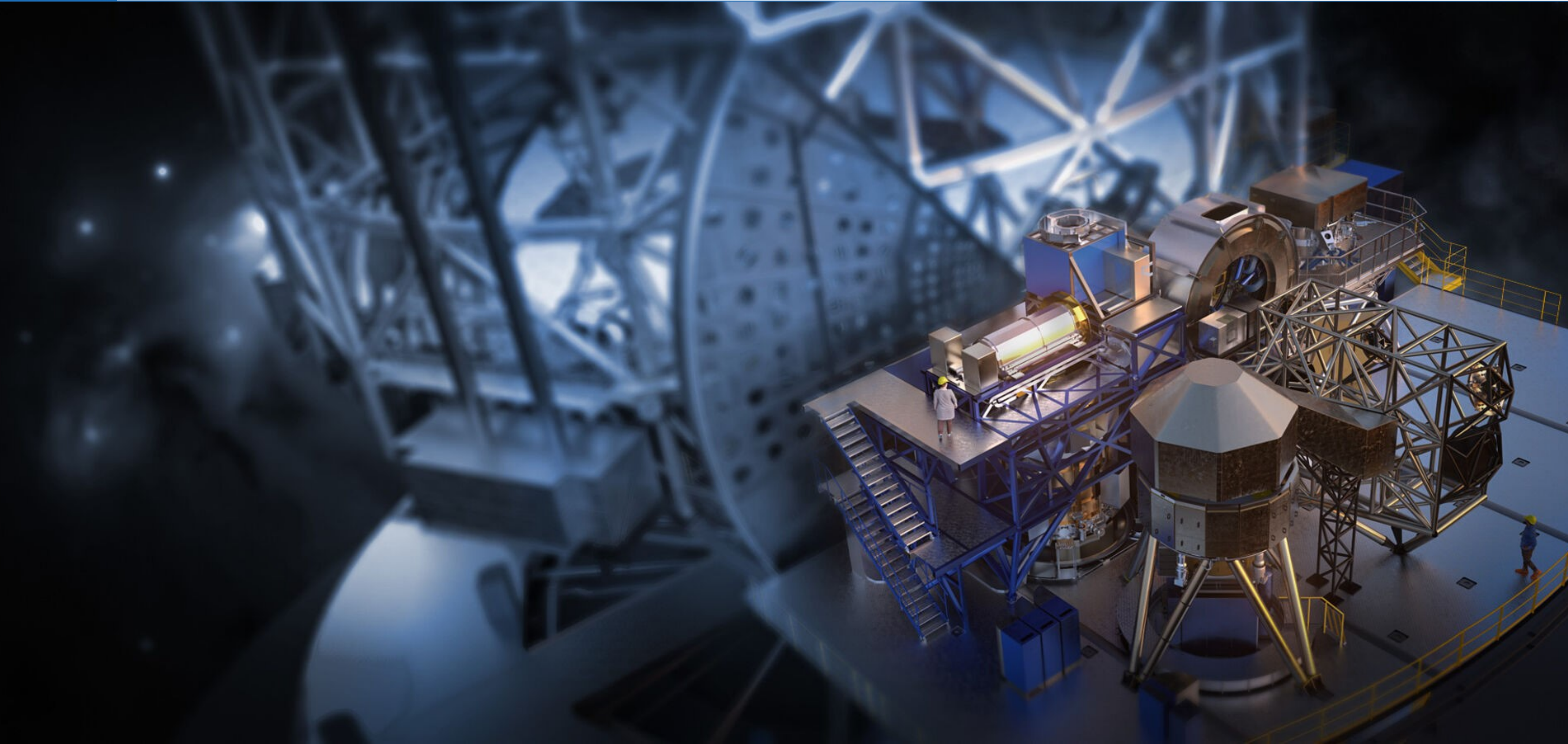
MICADO Kick-off 2015

MAORY Kick-off 2016

- ESO instruments are either built at ESO or by teams from ESO community institutes and universities.
- ESO often participates in these teams if not leading
- ESO always follows the development with a dedicated team of engineers and scientists

HARMONI Preliminary Design Review 2017

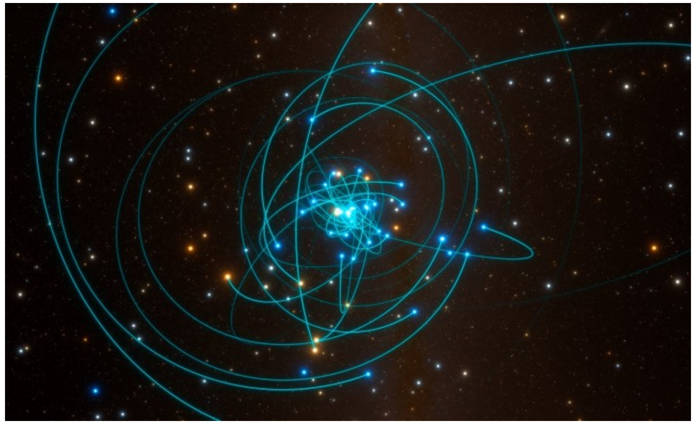
The ELT Nasmyth platform, view of ~2028



ELT 1st gen Instruments: MICADO & MAORY

- MICADO camera (~2027, SCAO)
- E.g. precision measurements of the positions: can observe stars orbiting the black hole at the centre of the Milky Way

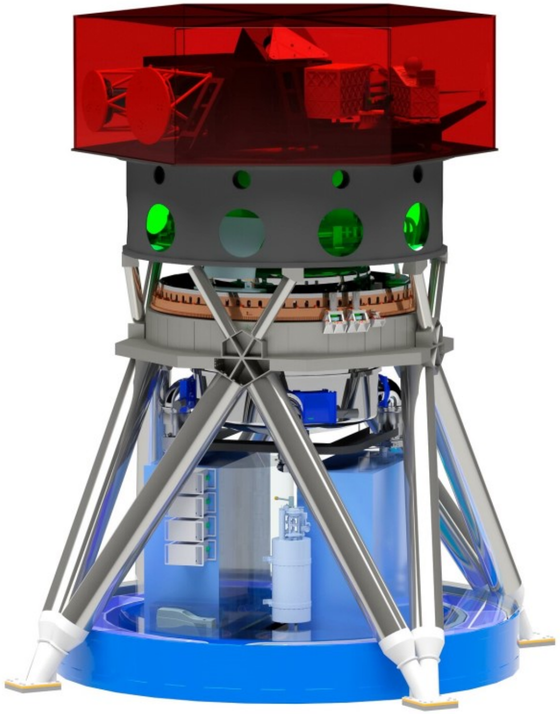
- MAORY multi-conjugate AO using laser guide stars (~2028)
- Provides MICADO with sharp images over a large FOV (~1 arcminute)

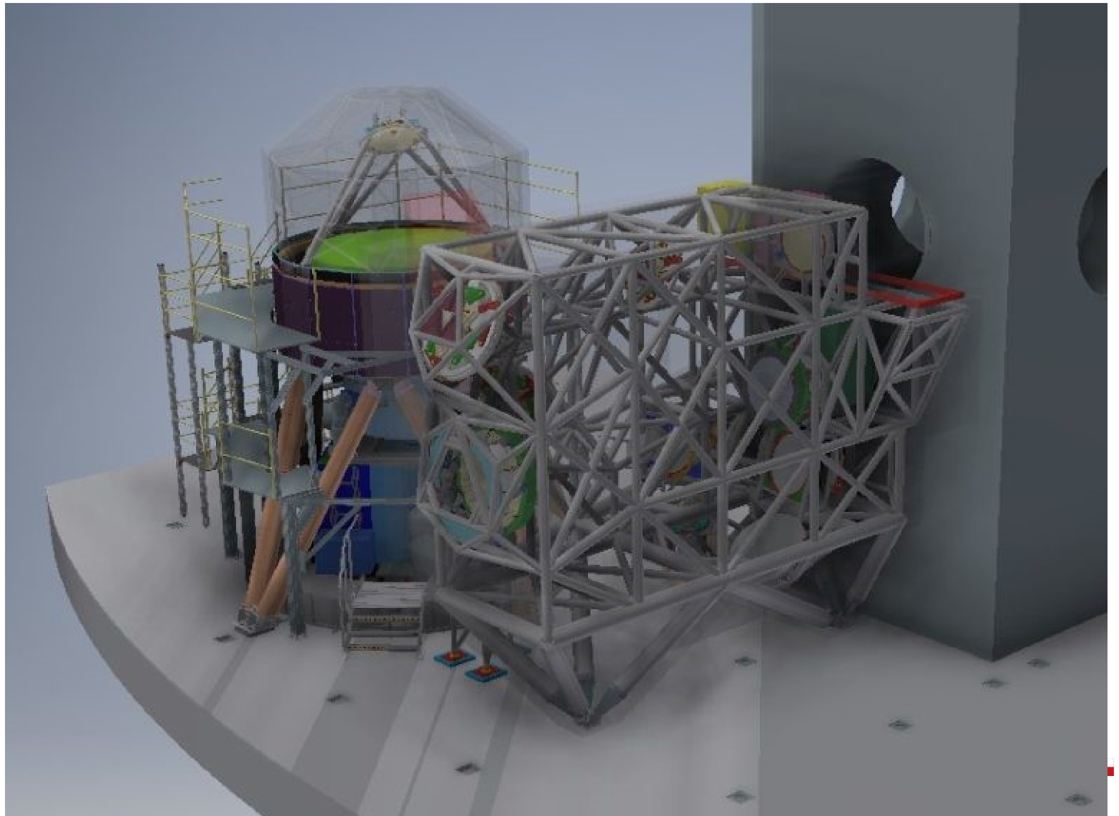


Reinhard Genzel

Andrea Ghez

2021





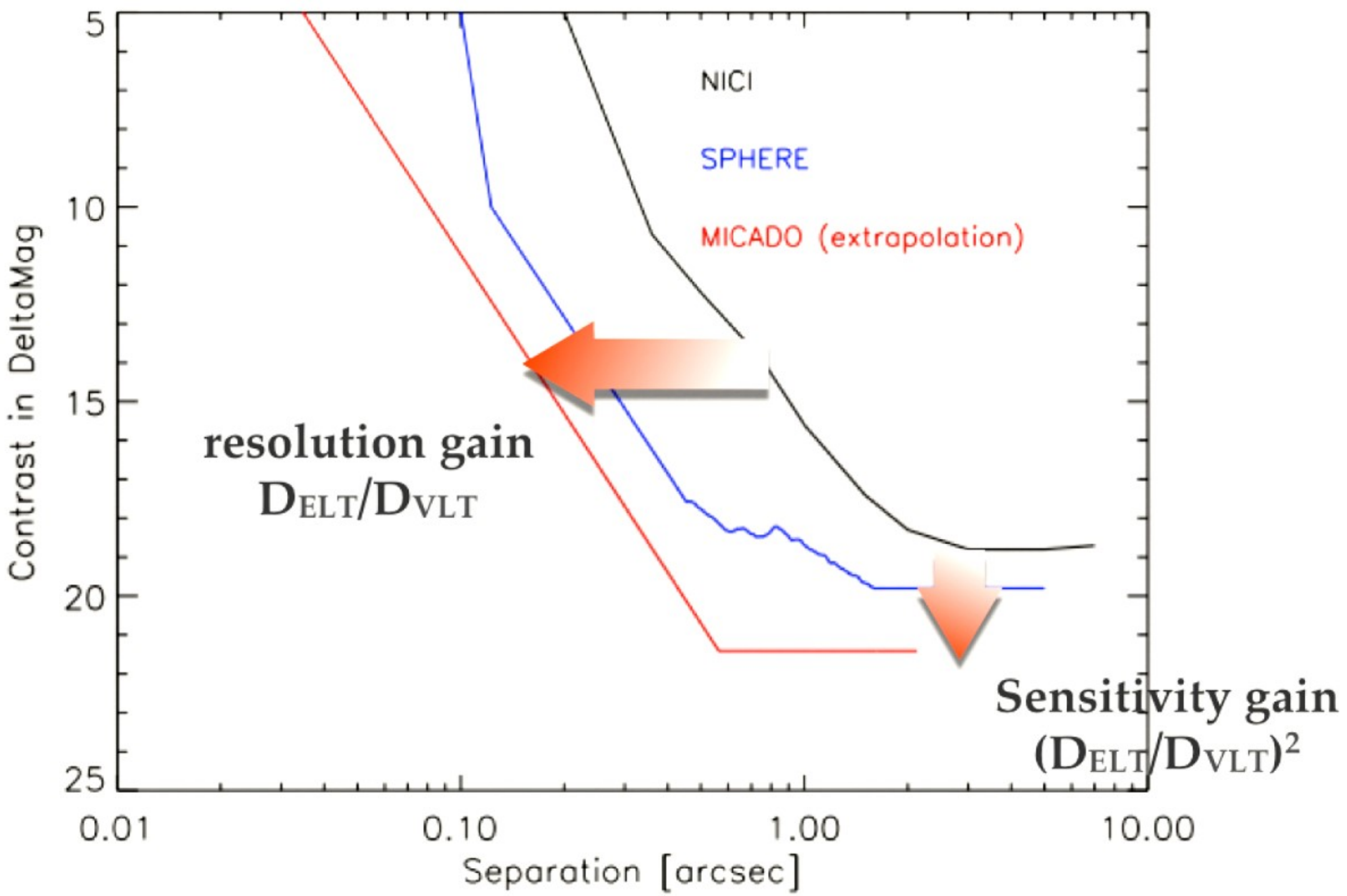
MICADO required capabilities

- ❑ 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

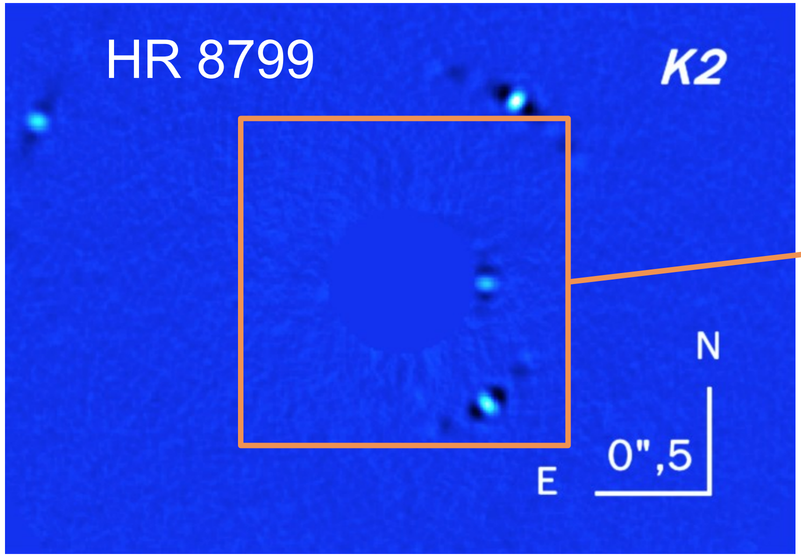
MICADO Coronagraphic Imaging

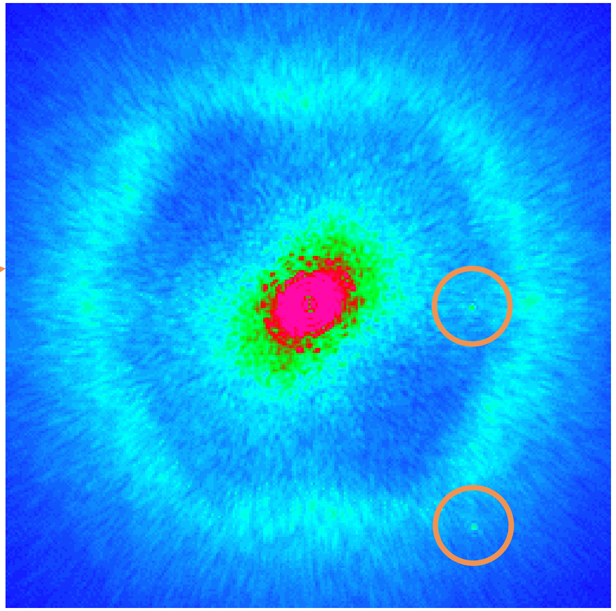
- Primary aim: exploit smaller inner working angle
  - Exoplanets at small orbital separations (a few AU) around nearby (<20pc) stars.
  - Exoplanets at larger separations (>10 AU) around young stars (complementary to SPHERE)
  - Circumstellar disks.
  - AGN

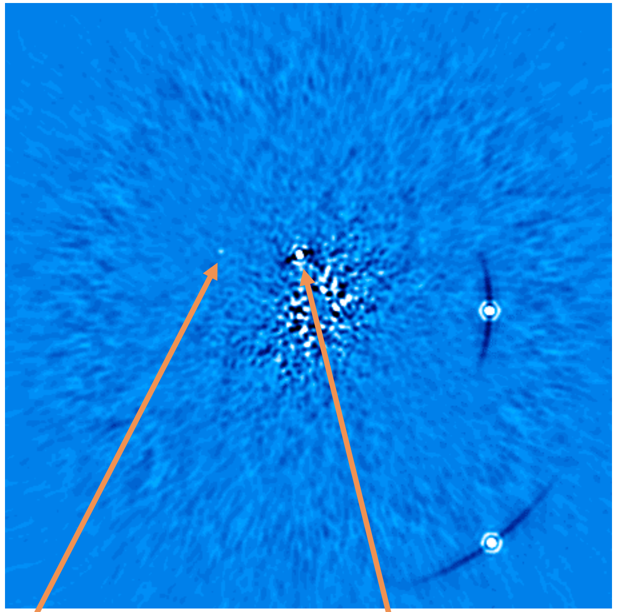


MICADO Coronagraphy simulations

SPHERE (2hr, Zurlo et al. 2016)

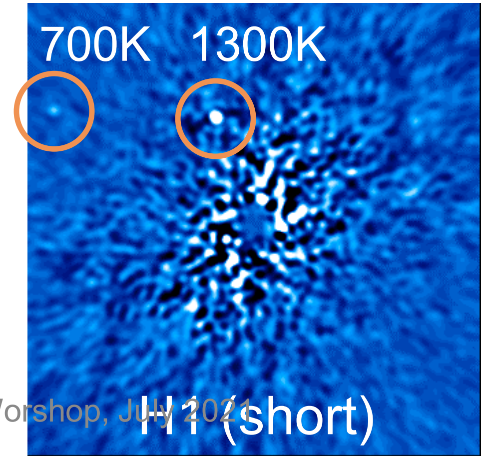


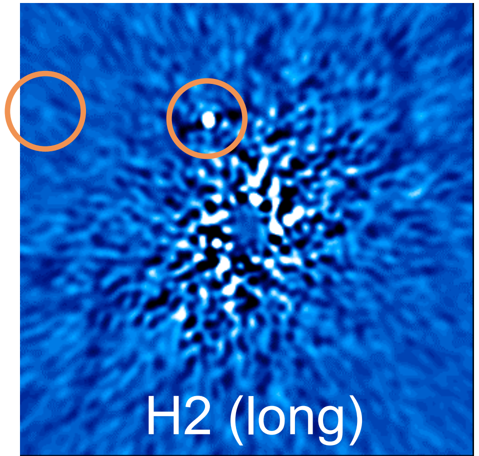




added exoplanet at 10 AU, 700 K, log(g)=4

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

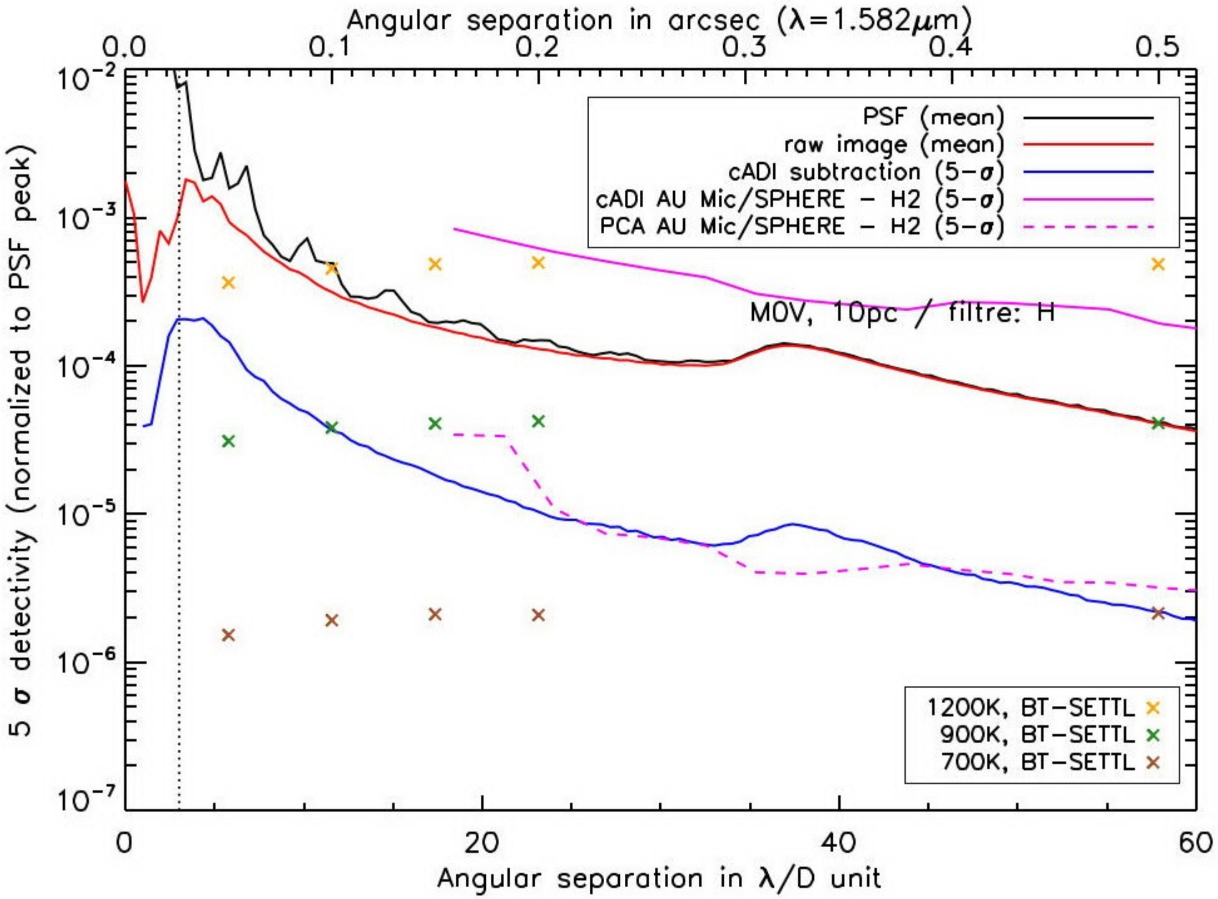


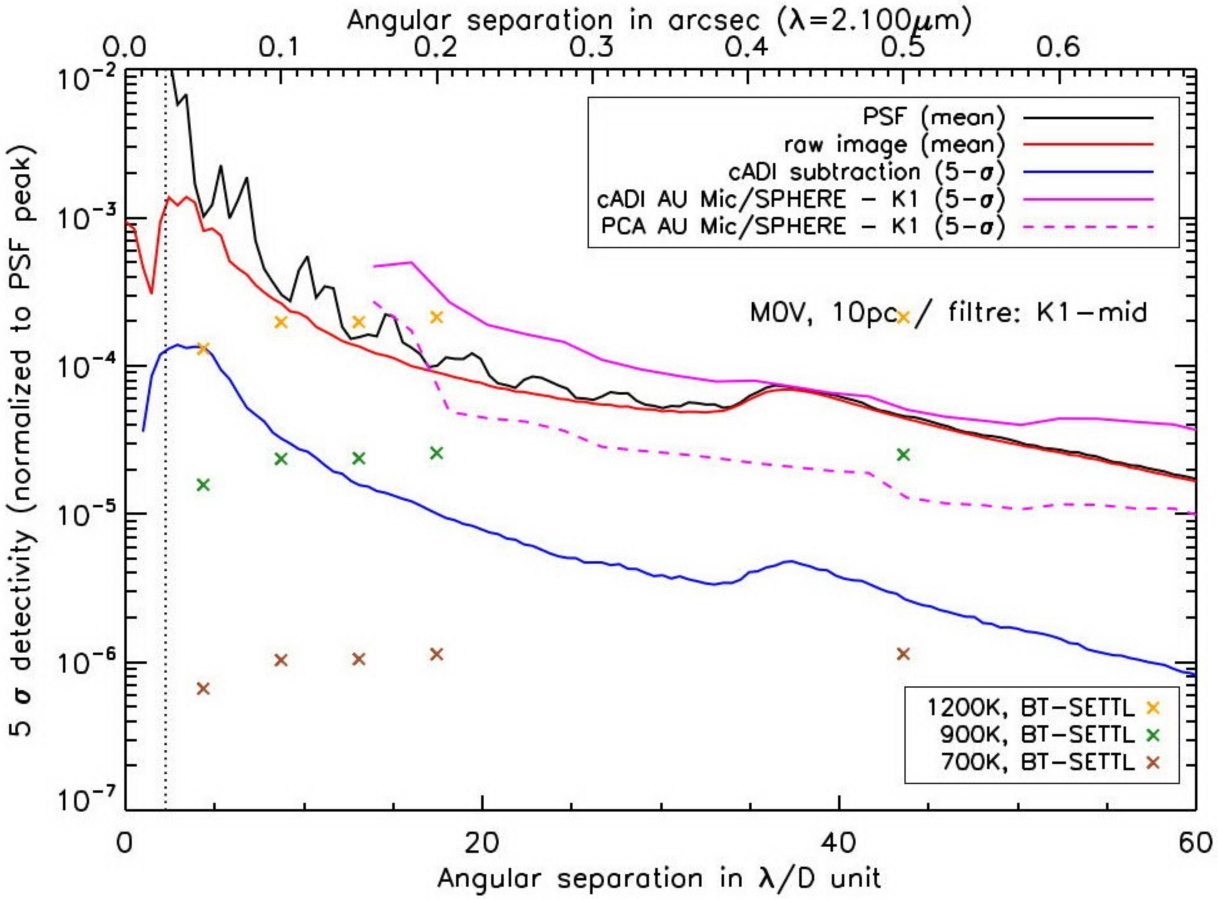


Probing a regime where we expect to have masses & radial velocities from GAIA

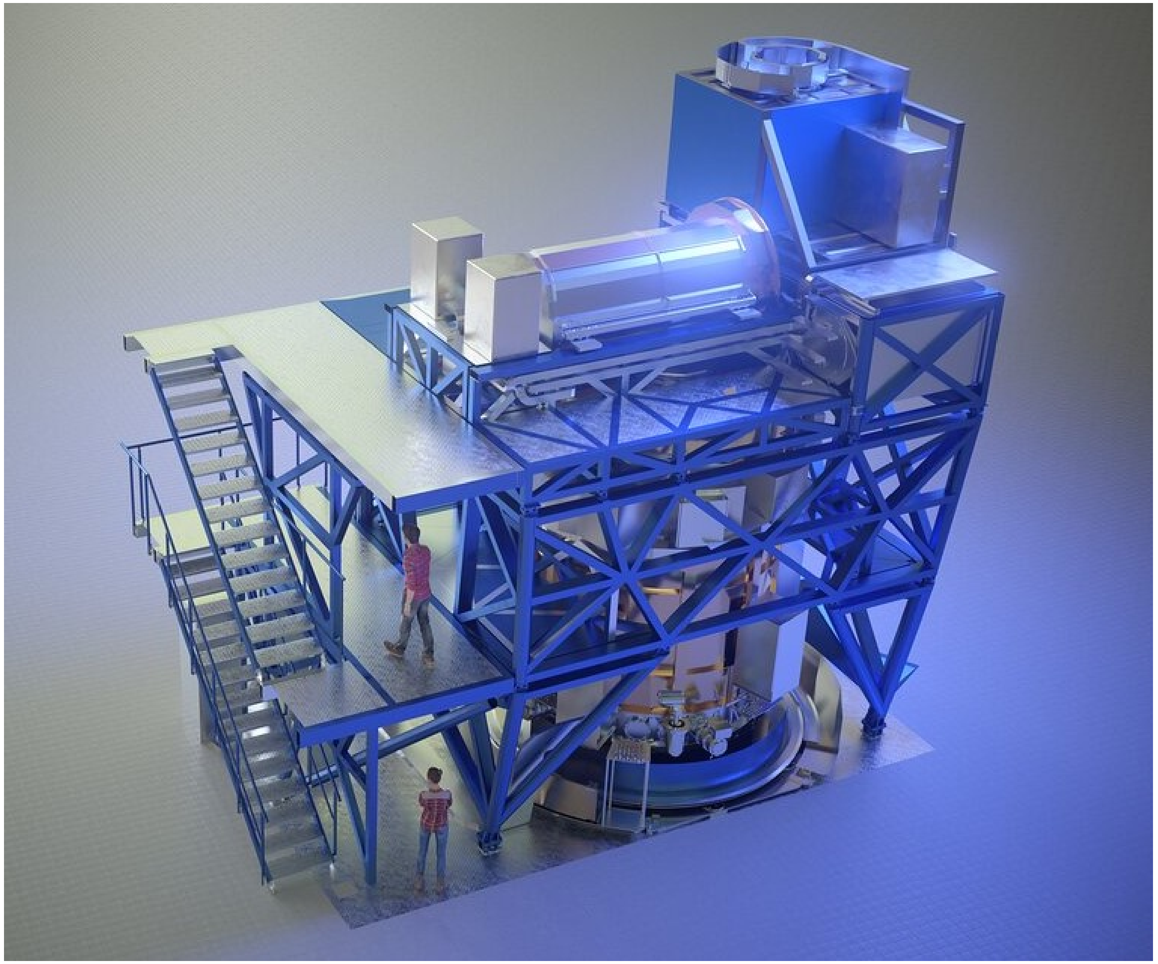
MICADO contrast sensitivity

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





ELT 1st gen Instruments: HARMONI (~2027)



visible and infrared 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

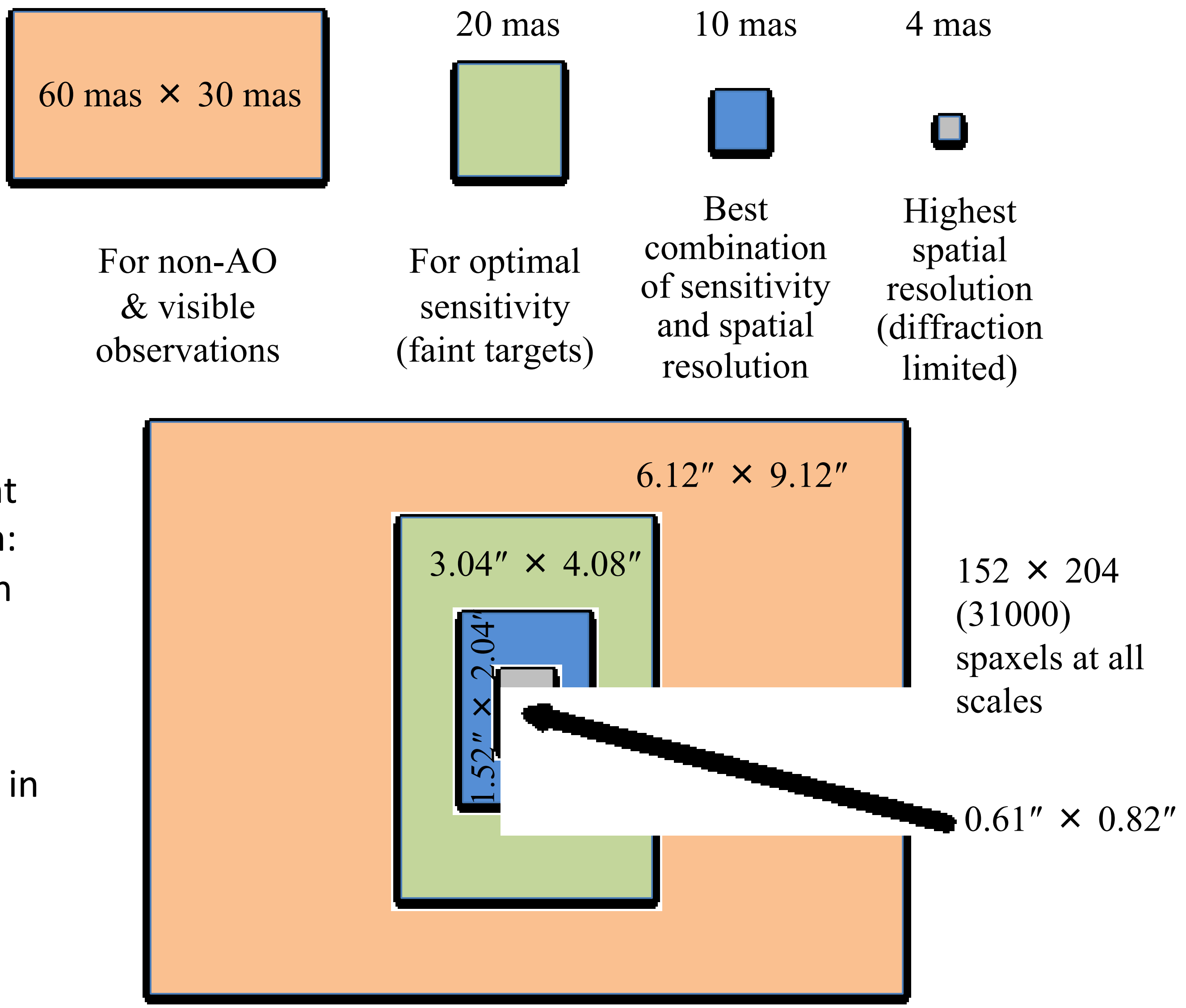
HARMONI field of views

- Four spaxel scales
- 31000 spaxels
- 9.12″ × 6.12″ to 0.63″ × 0.84″ FoV
- Shape suited for “nodding-on-IFU”
- Half FoV at visible wavelengths

Equivalent slit length: 16 arcmin

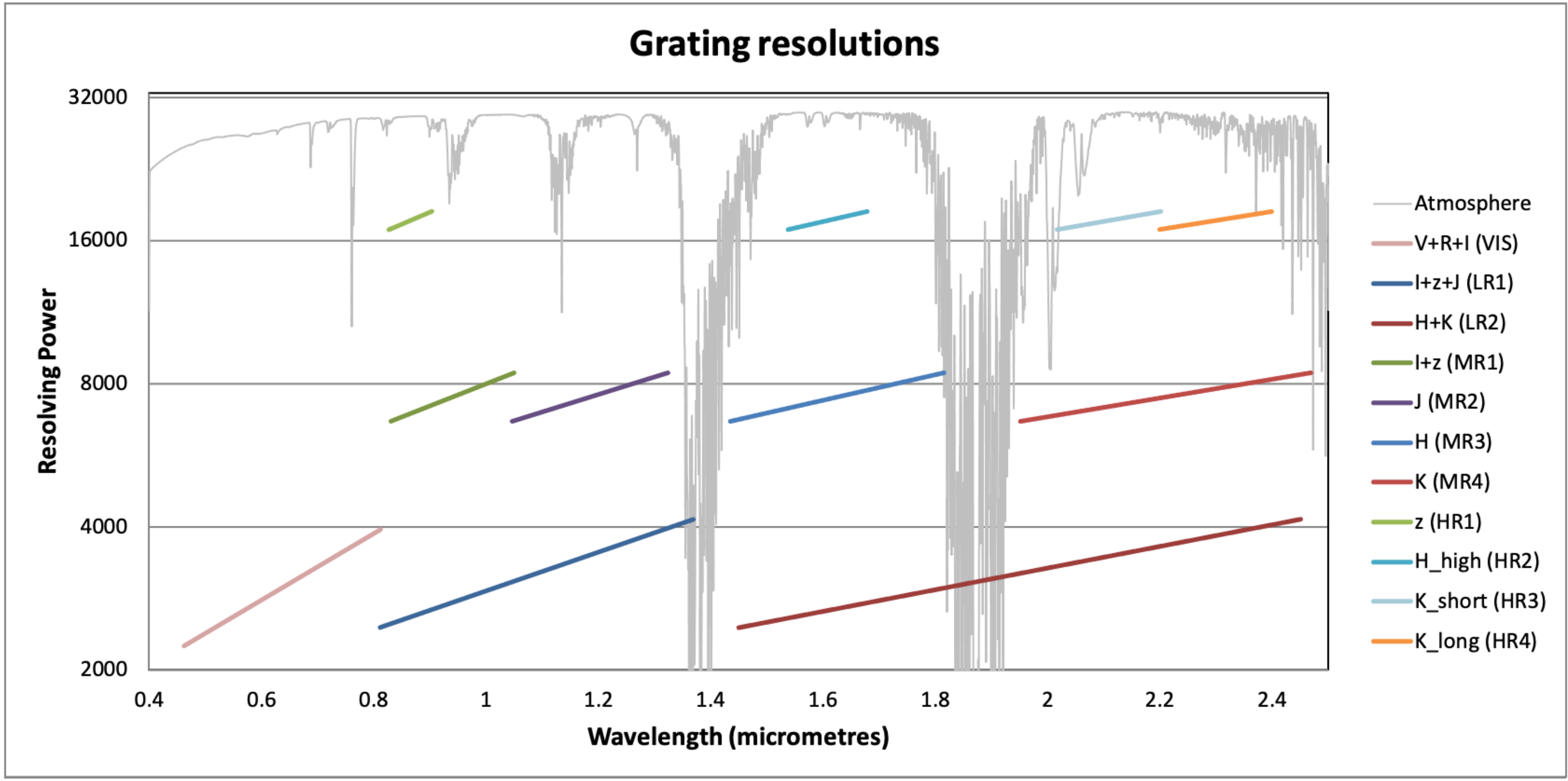
or

3.2 metres in ELT focal plane



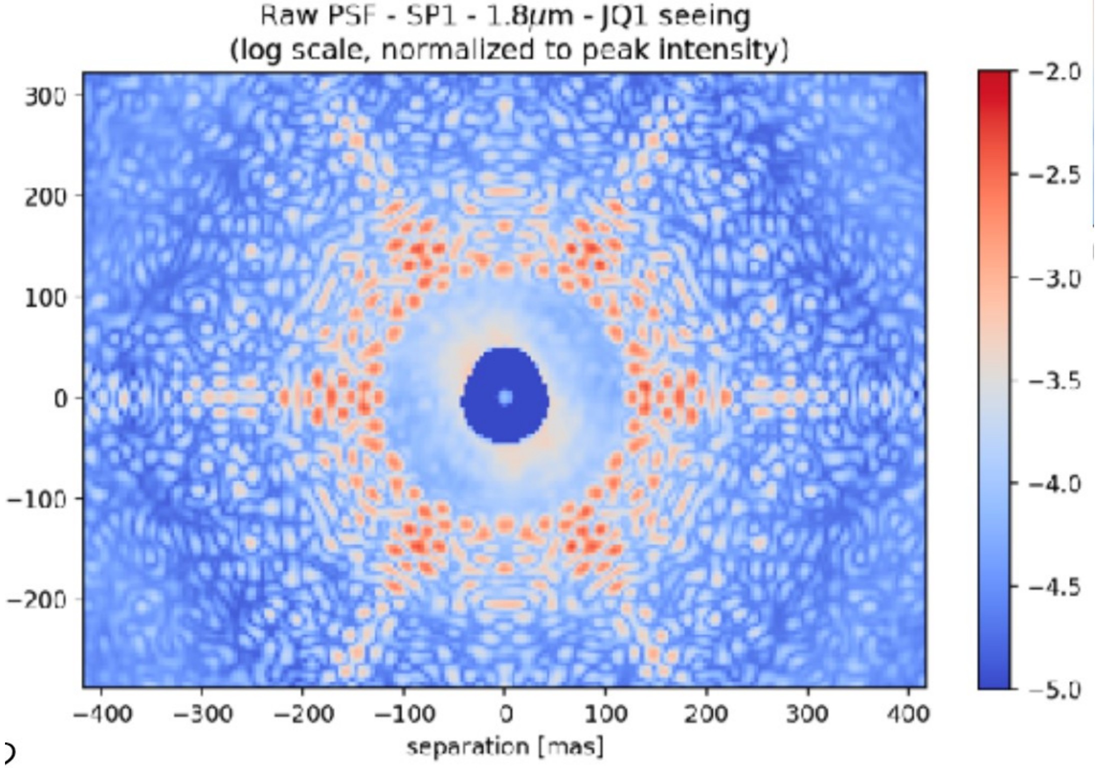
HARMONI Spectral layout

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



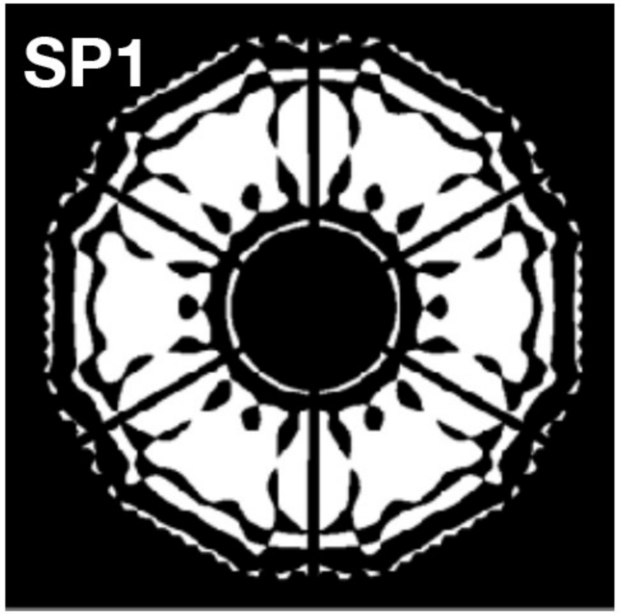
HARMONI High Contrast capability

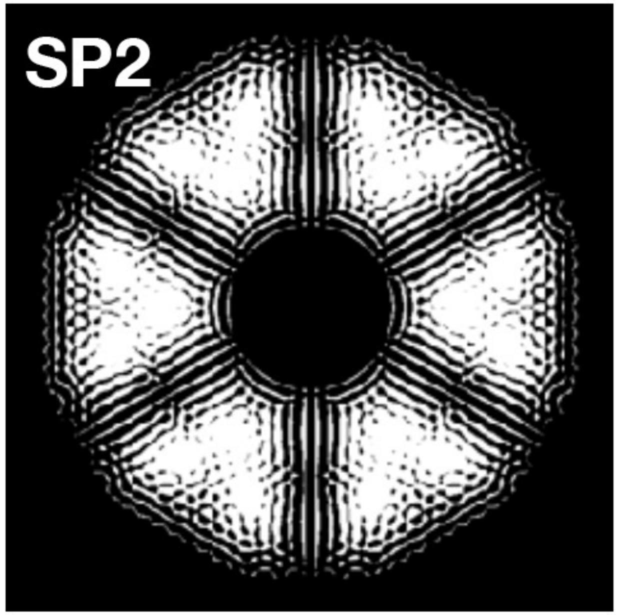
- SCAO operating mode, 4 mas spaxels and pupil tracking (ADI-like post processing)
- Wavelength range (1450 – 2450 nm) (goal 1250 – 2450 nm)
- Performance goal: 1e-6 (after post-processing) at 100 mas
- No coronagraph! 2 Pupil Plane apodisers and 3 focal plane masks (with T = 10^{-4})

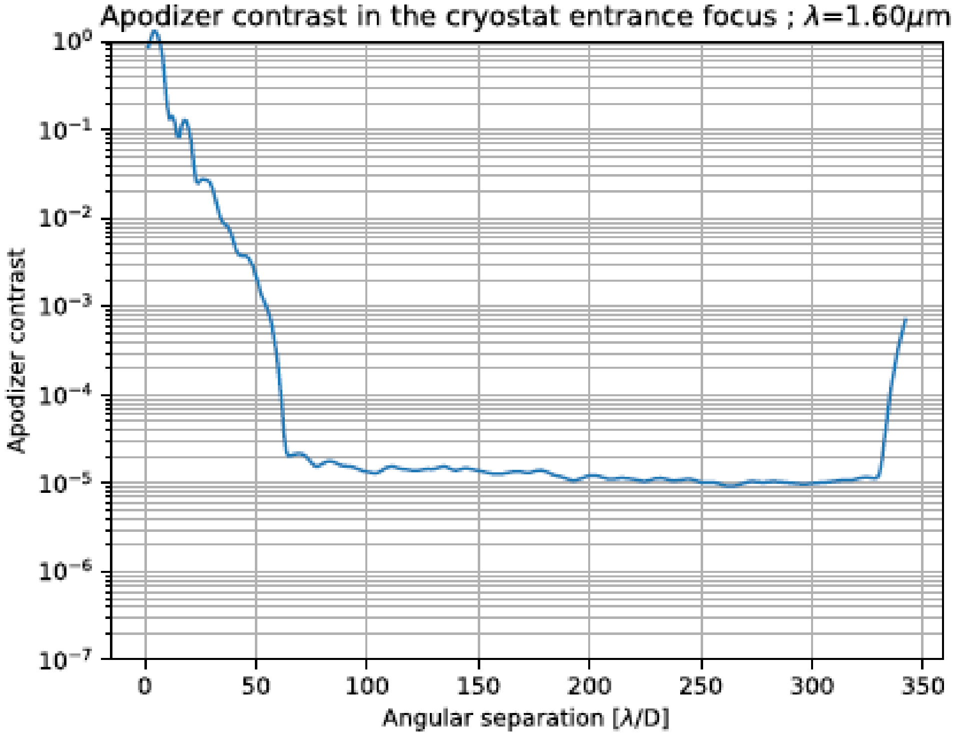


HARMONI apodisers and performance

Apodiser	Inner Working Angle		Outer Working Angle	
	H band	K band	H band	K band
SP1 (5 - 12 λ/D)	48 mas	66 mas	88 mas	120 mas
SP2 (7 – 40 λ/D)	67 mas	92 mas	300 mas	407 mas



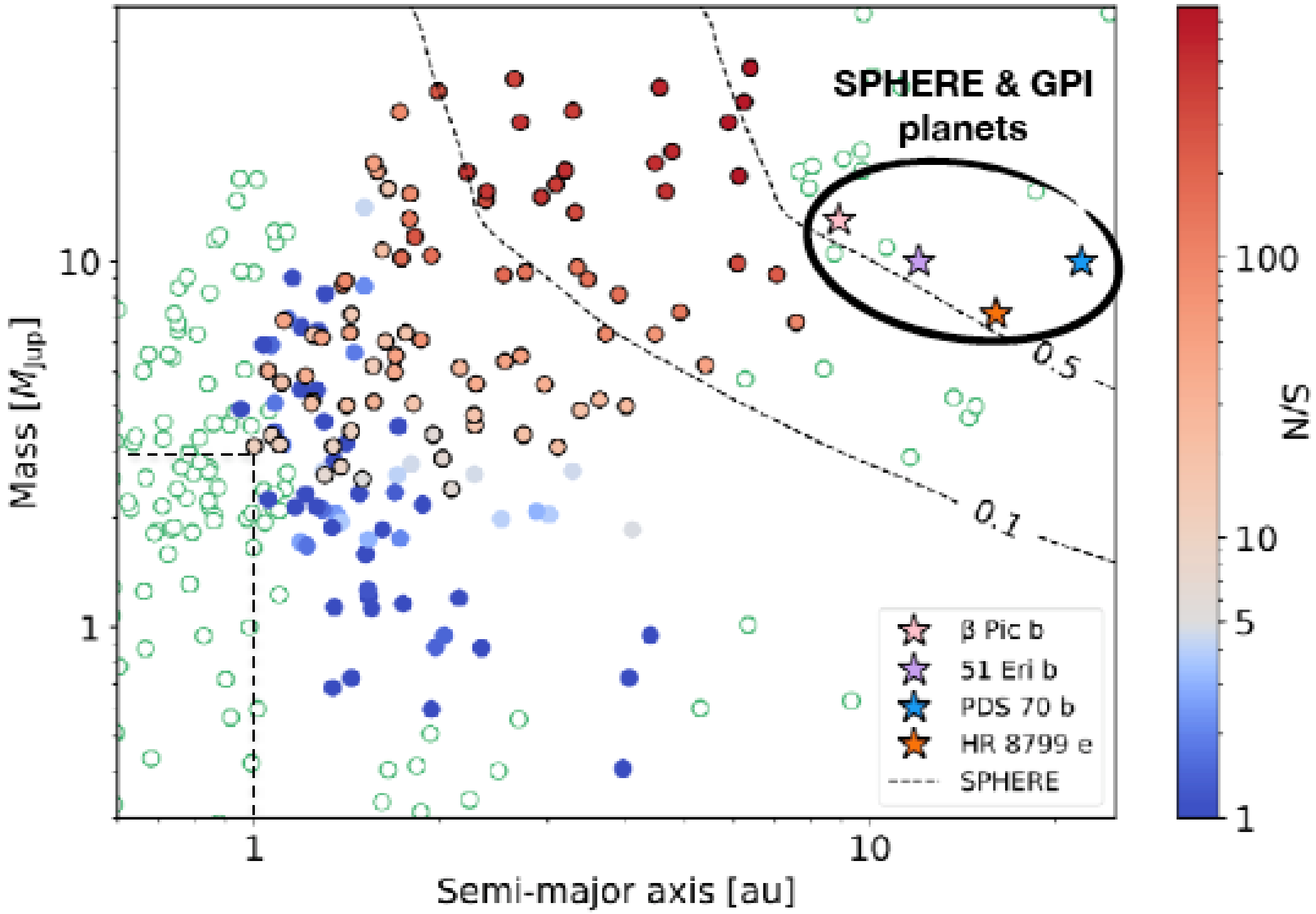




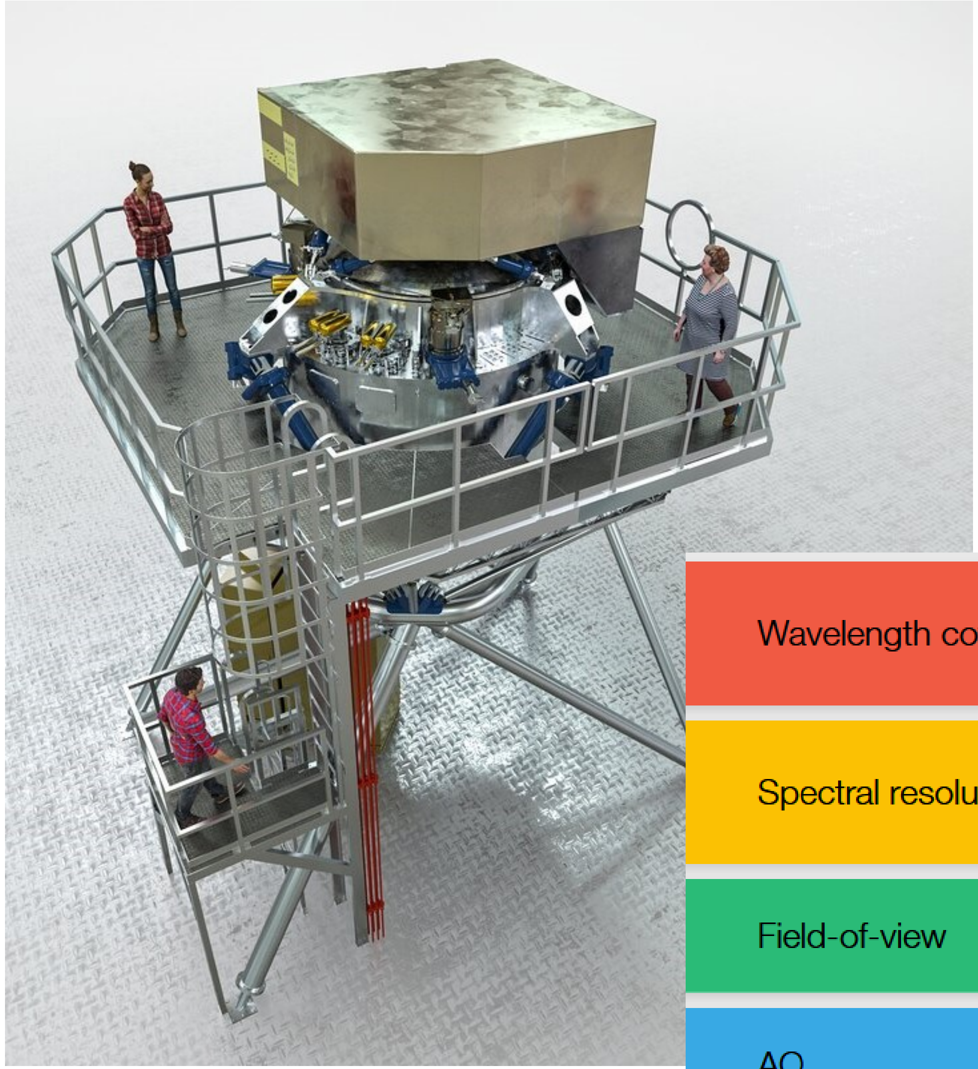
HARMONI Recent Simulation results

- 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!



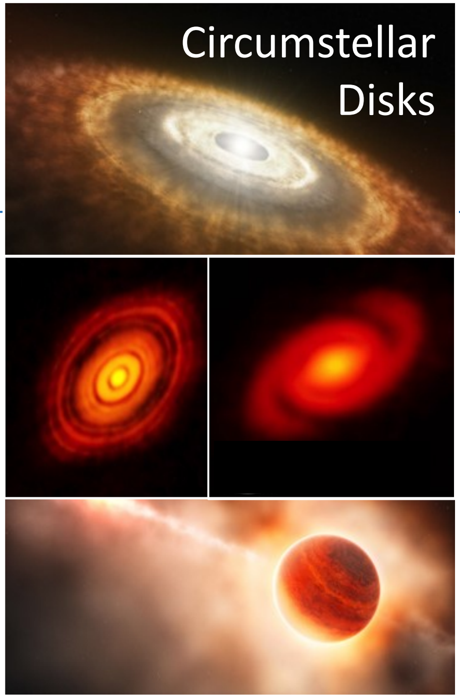
ELT 1st gen Instruments: METIS (~2027)

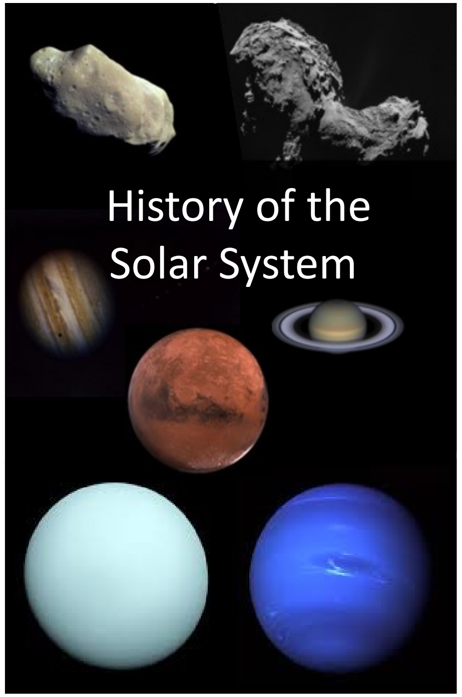


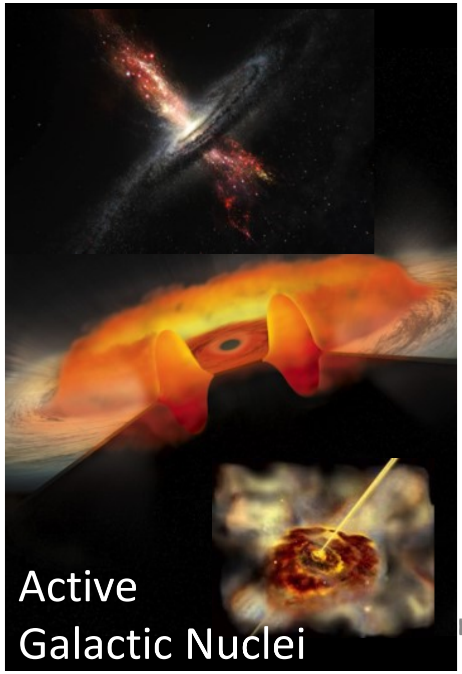
Near- to mid-IR imager and spectrograph

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 Science Case Overview



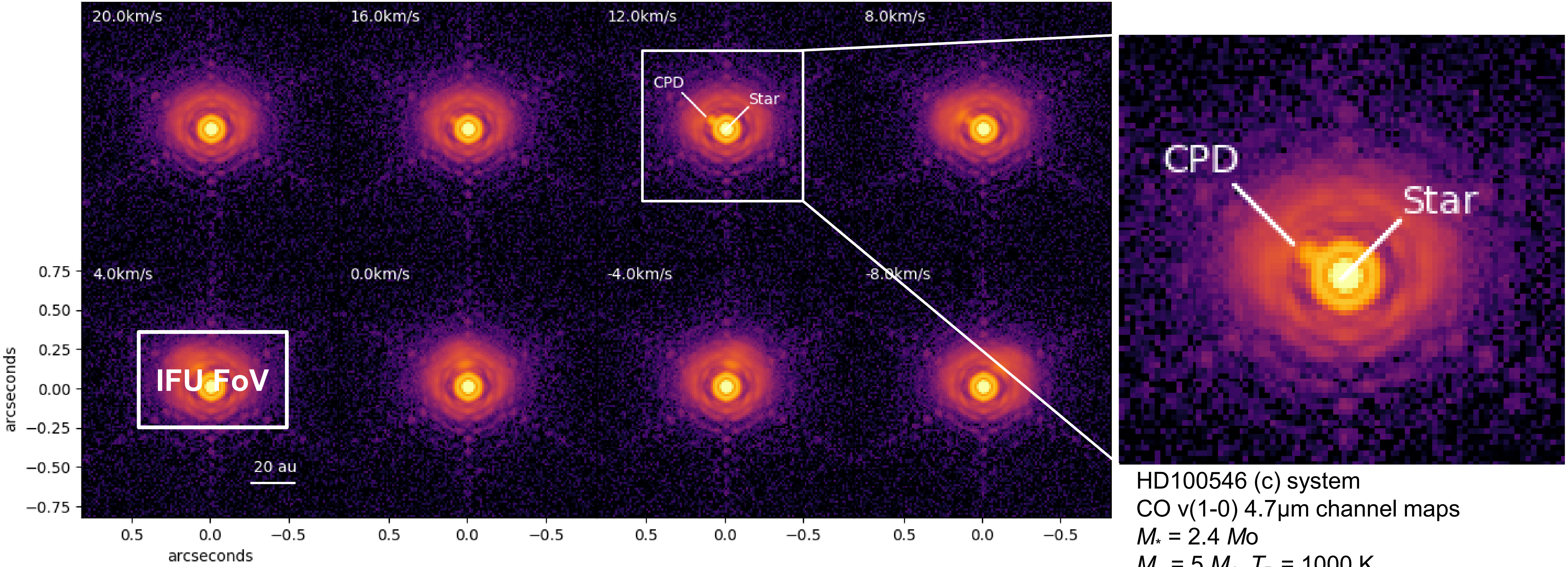




METIS: Proto-planetary Disks and Planet Formation

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

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

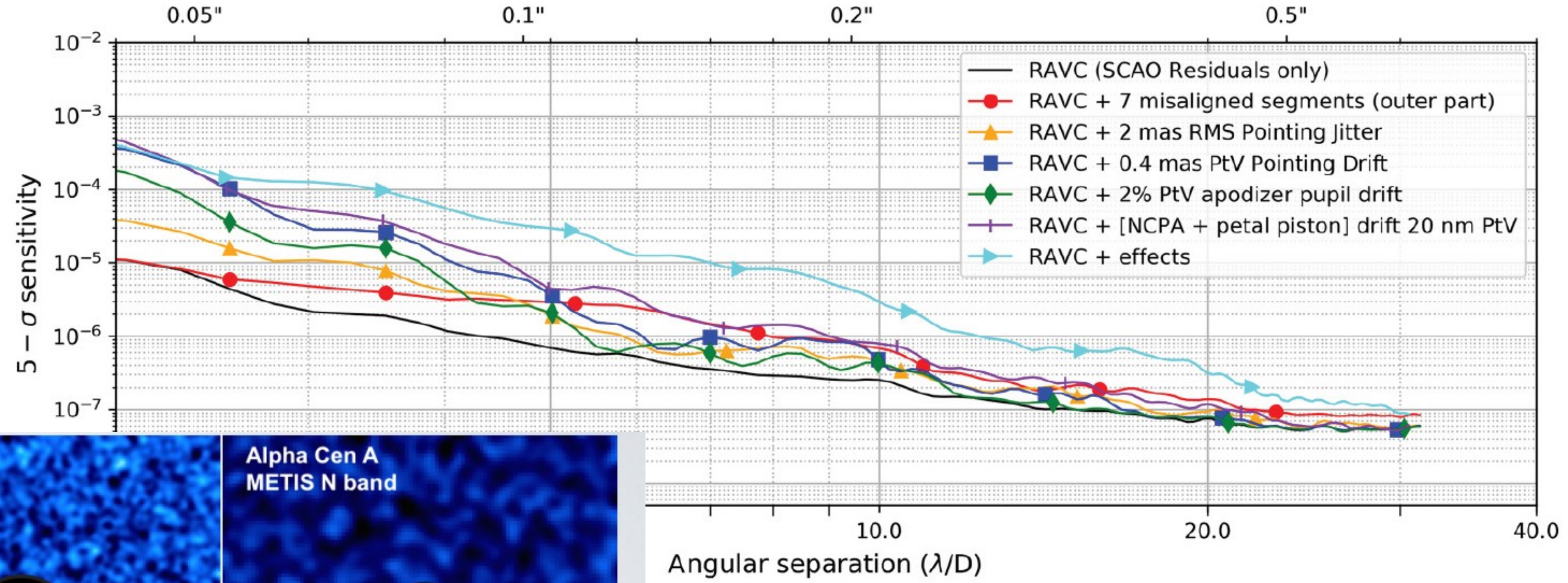


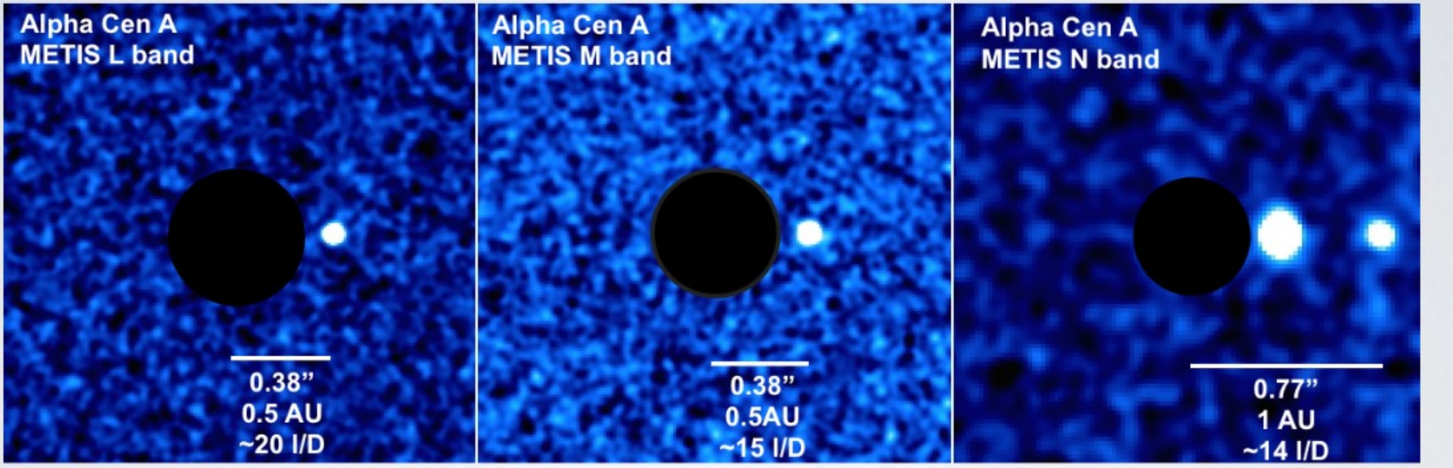
Simulated METIS observations of the same model

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

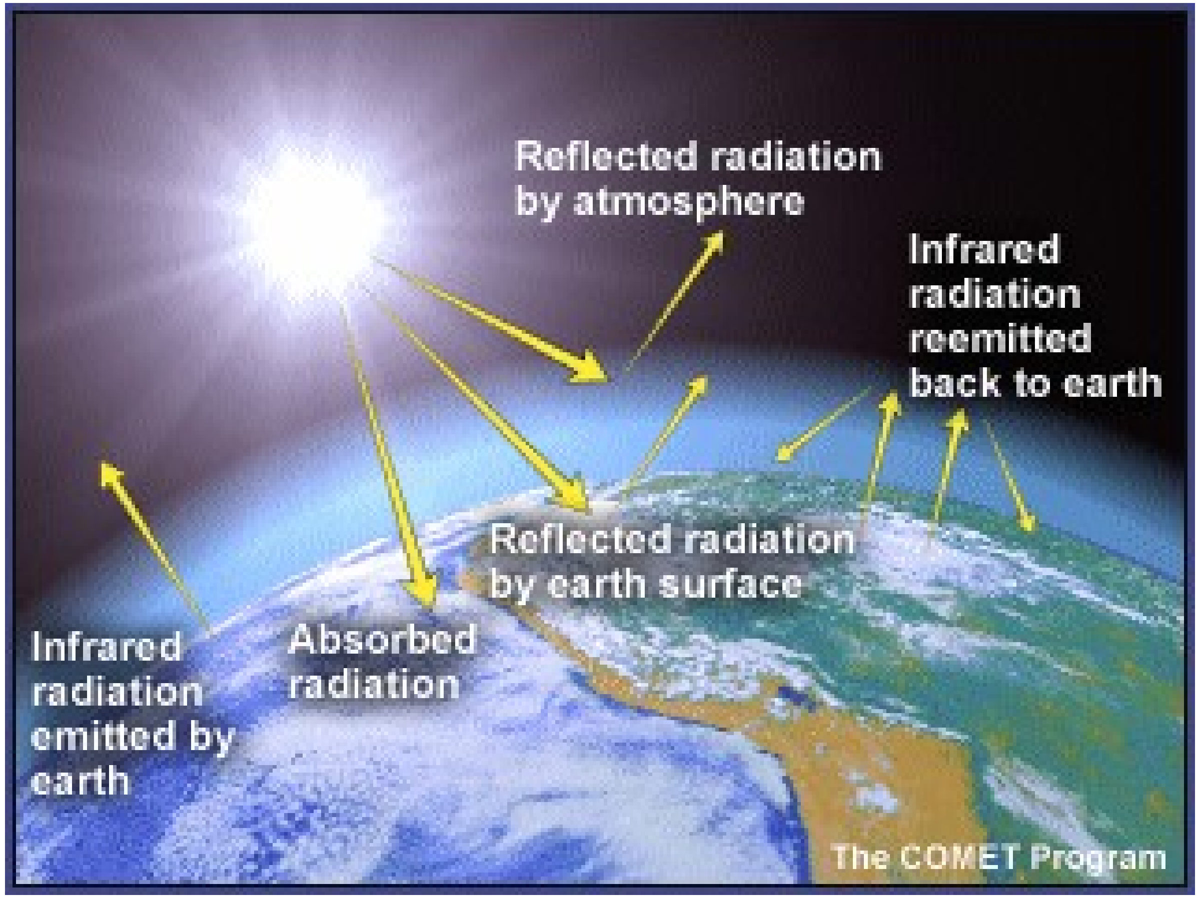
METIS contrast

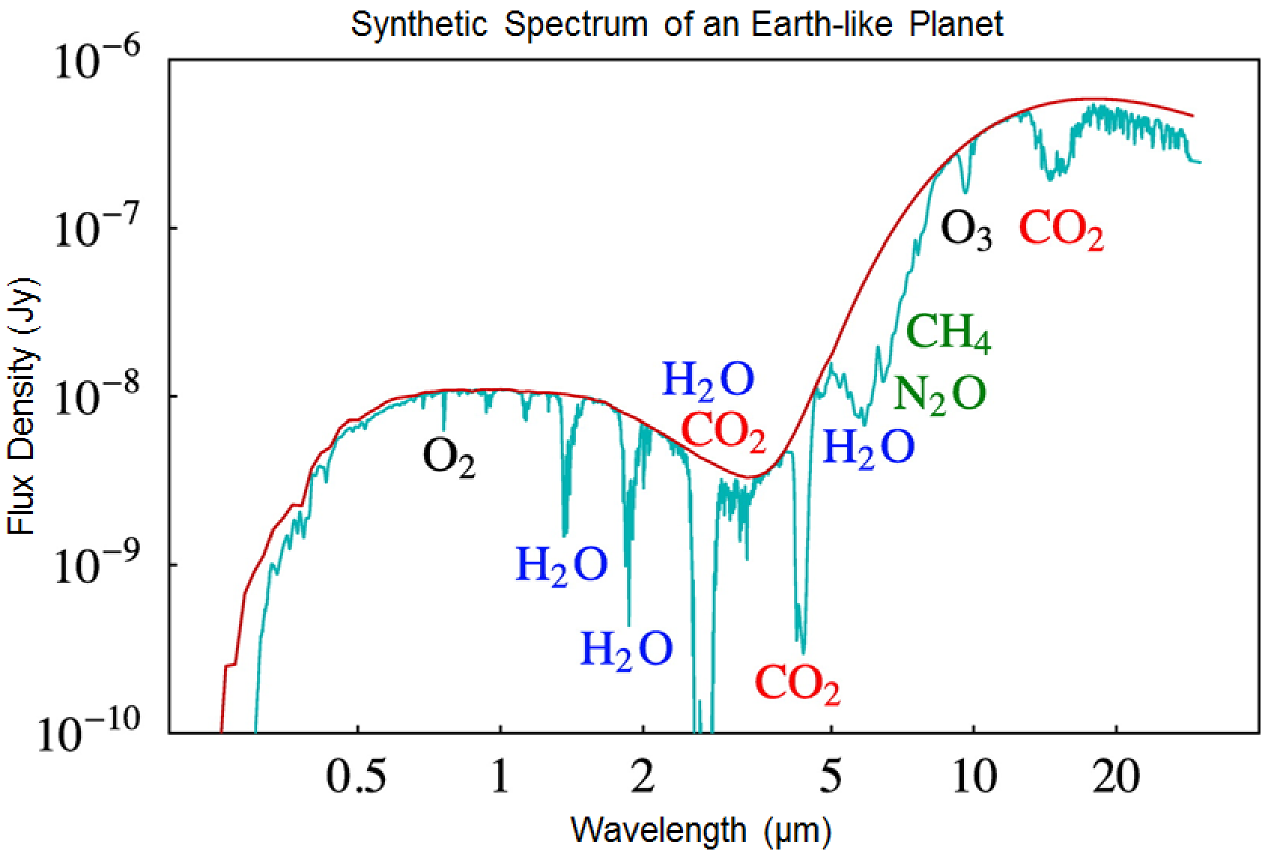
- MidIR contrast with ring apodized Vortex coronagraph (Carlomagno et al. proc. SPIE 2020)





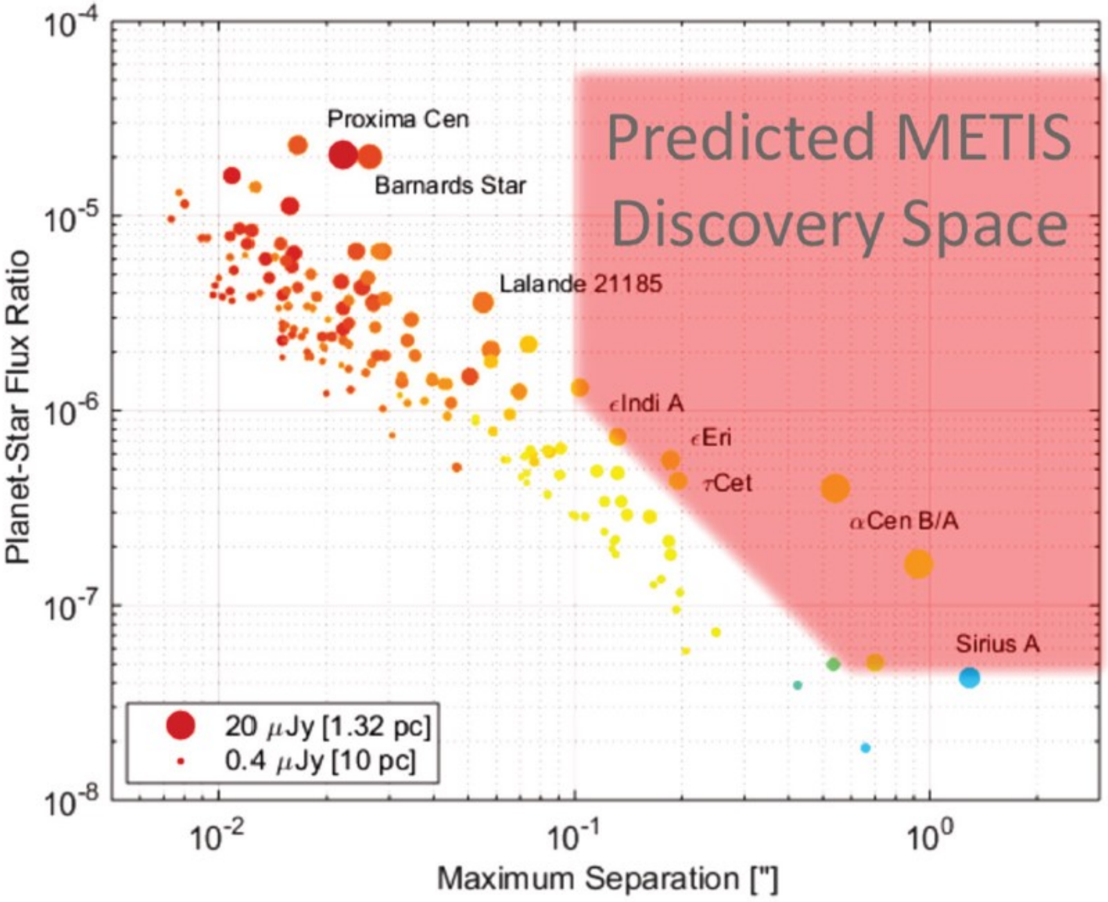
Thermal + Reflected Light: Complementary Information

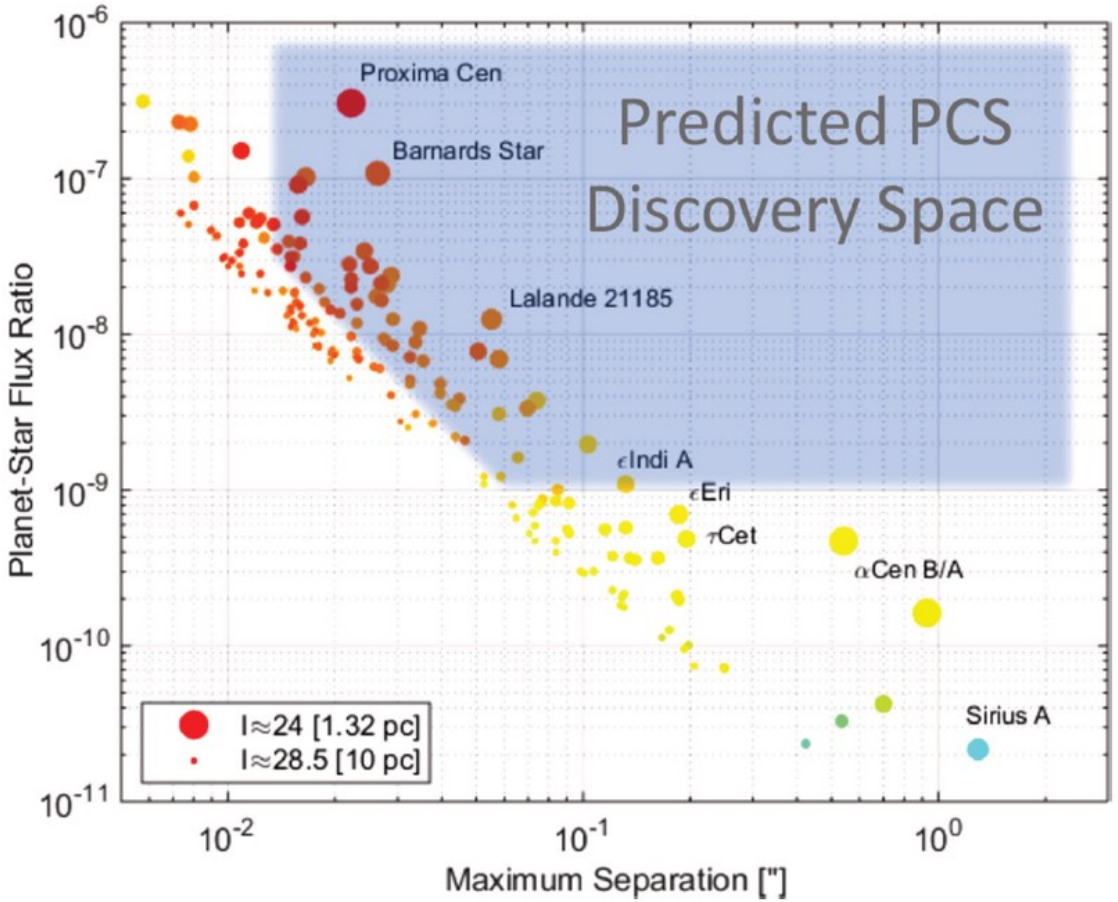




Ji, Meyer, et al. 2019; cf. Morley et al. (2016)

Nearby Exoearths with METIS and ELT PCS (~2033)

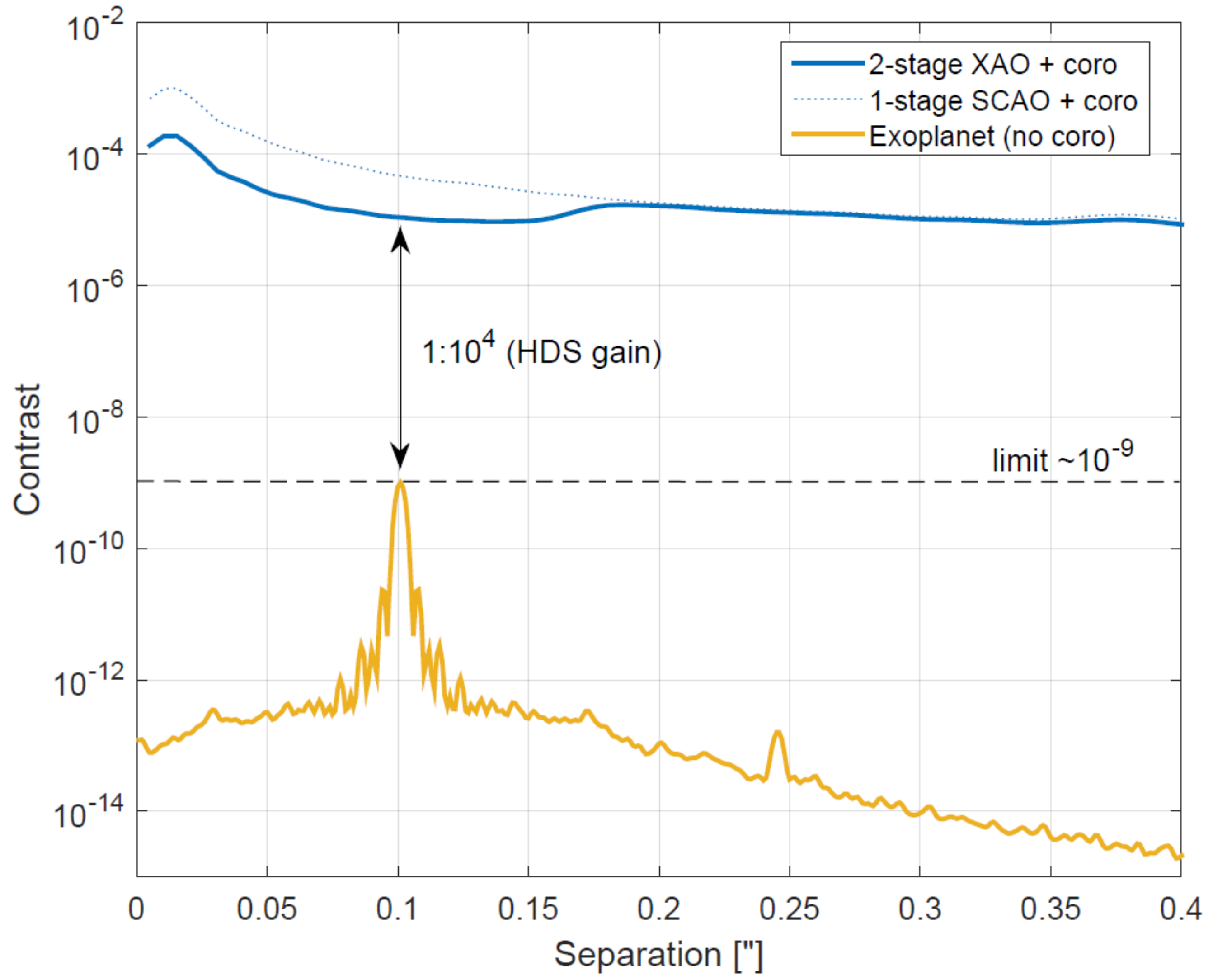




METIS: solar-type stars, contrast ~10^{-6} @ 100 mas, 10^{-7} @ 500 mas

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