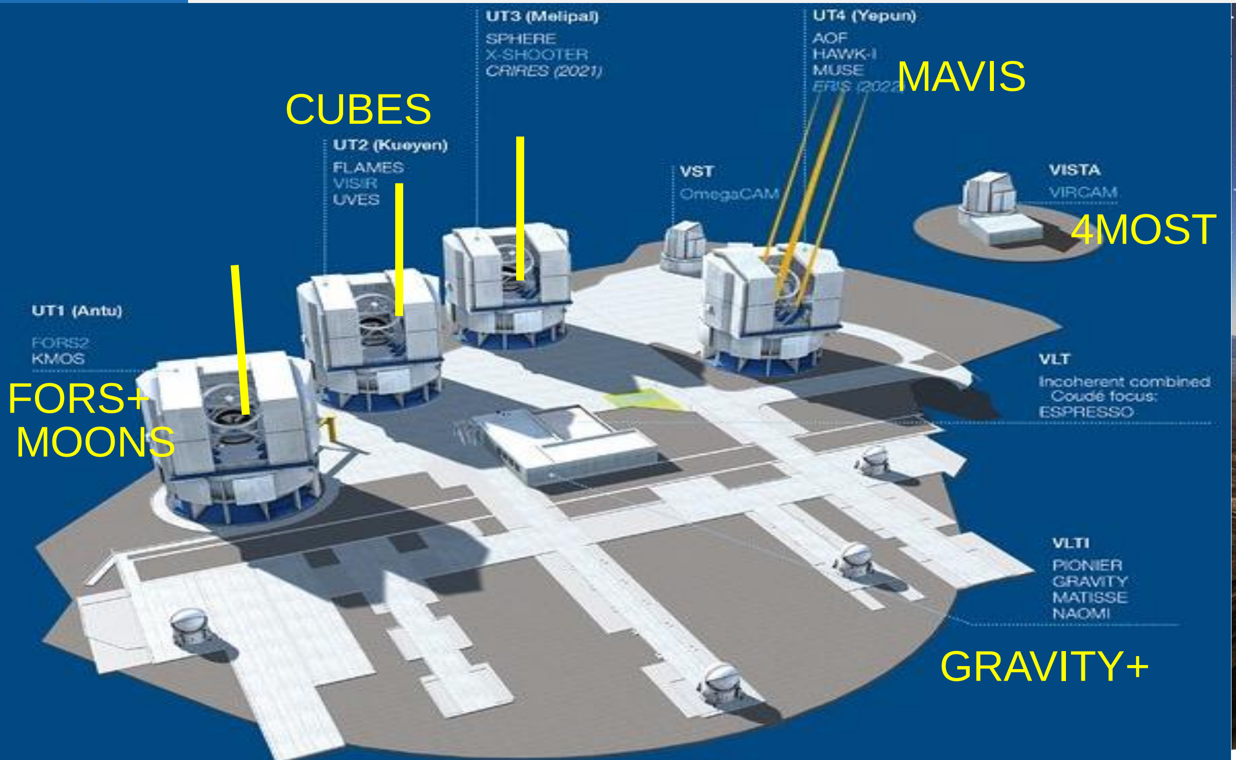
ESO R&D Development Programme and future plans

Norbert Hubin,
European Southern Observatory

ESO context & infrastructure

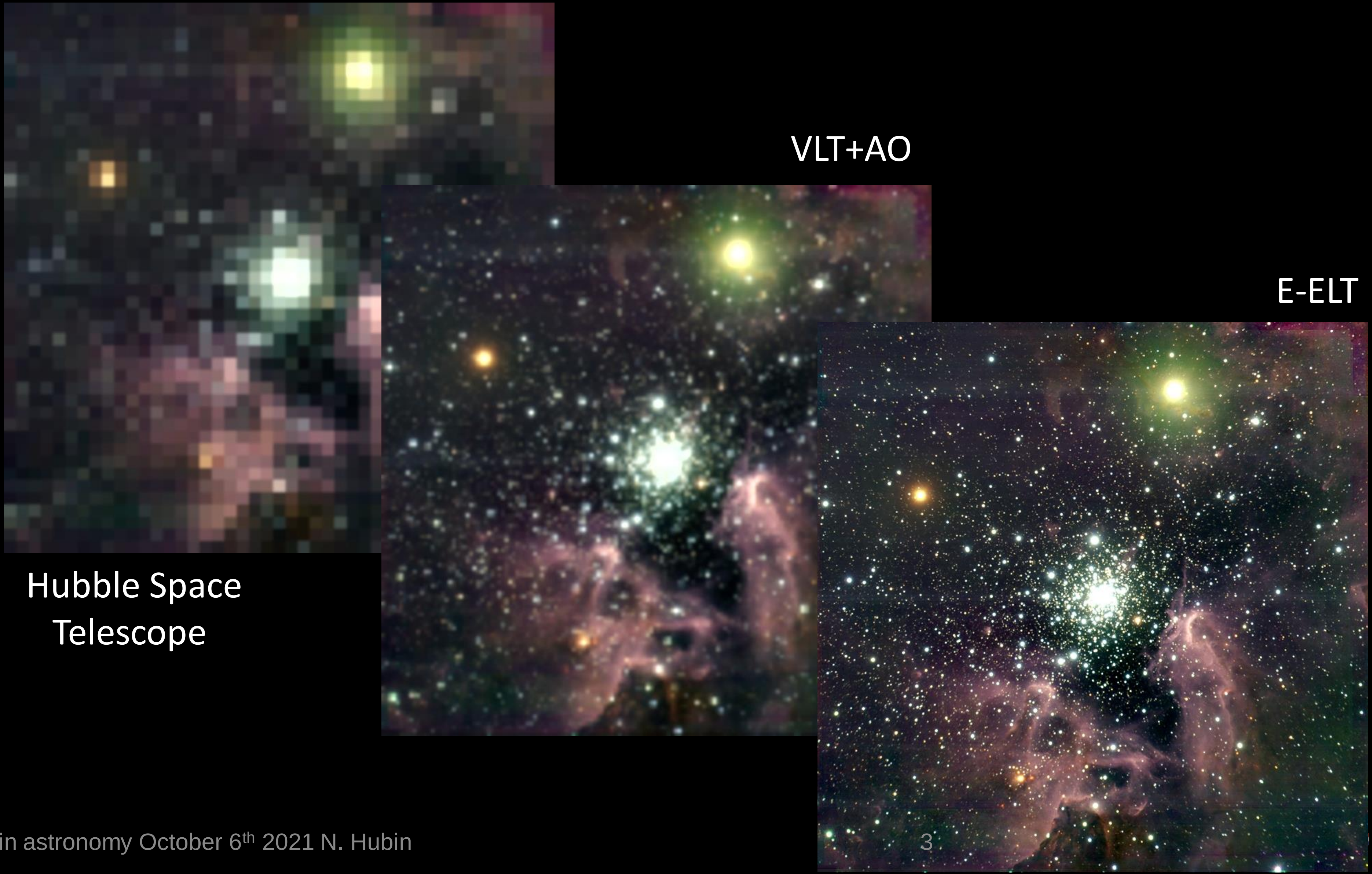


Very Large Telescope & VLT Interferometer in operation

- 4x 8-m & 4x1.8m telescopes + interferometric mode
- 2 survey 2 & 4m class telescopes
- Continuous renewal of instruments and improved capabilities ***requiring new technologies***

- 39m diameter, primary mirror, 798 high precision segments re-aligned to ~0.0001 mm in real-time
- Science: exo-earths, deep universe, resolved populations, open window to the unknowns
- Timeline 2014-2027; ESO capital cost: 1300MEUR
- Large effort to build 1st and 2nd generation instruments ***requiring new technologies***

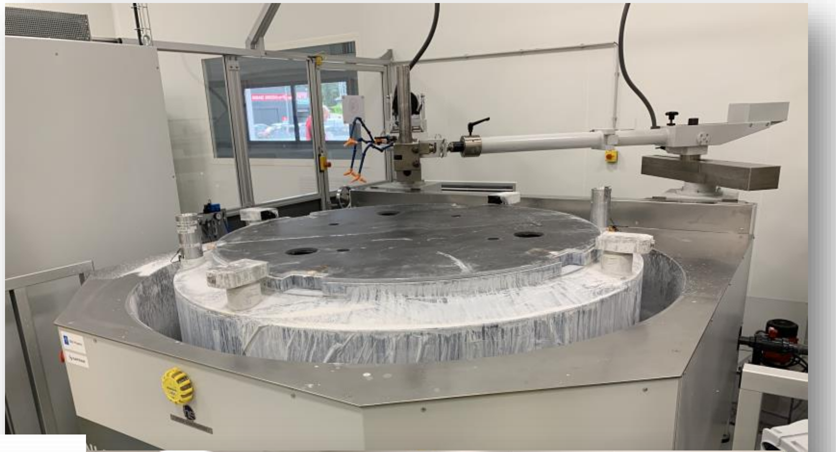
Spectacular Resolution thanks to Adaptive Optics @ VLT and ELT



Technology development approach

- Innovative technologies for telescope subsystems are developed within the construction project: Phase A-B-C largely in collaboration with industry➔ few example provided in the next slides
- In few cases, pathfinder projects on smaller telescopes were used to prepare for larger telescope needs: i.e VLT to ELT
- Some innovative technologies with TRL 5-6+ are also developed within instrument construction in collaboration with institutes few example also provided in the next slides
- Low TRL technologies are covered by a dedicated Technology development programme

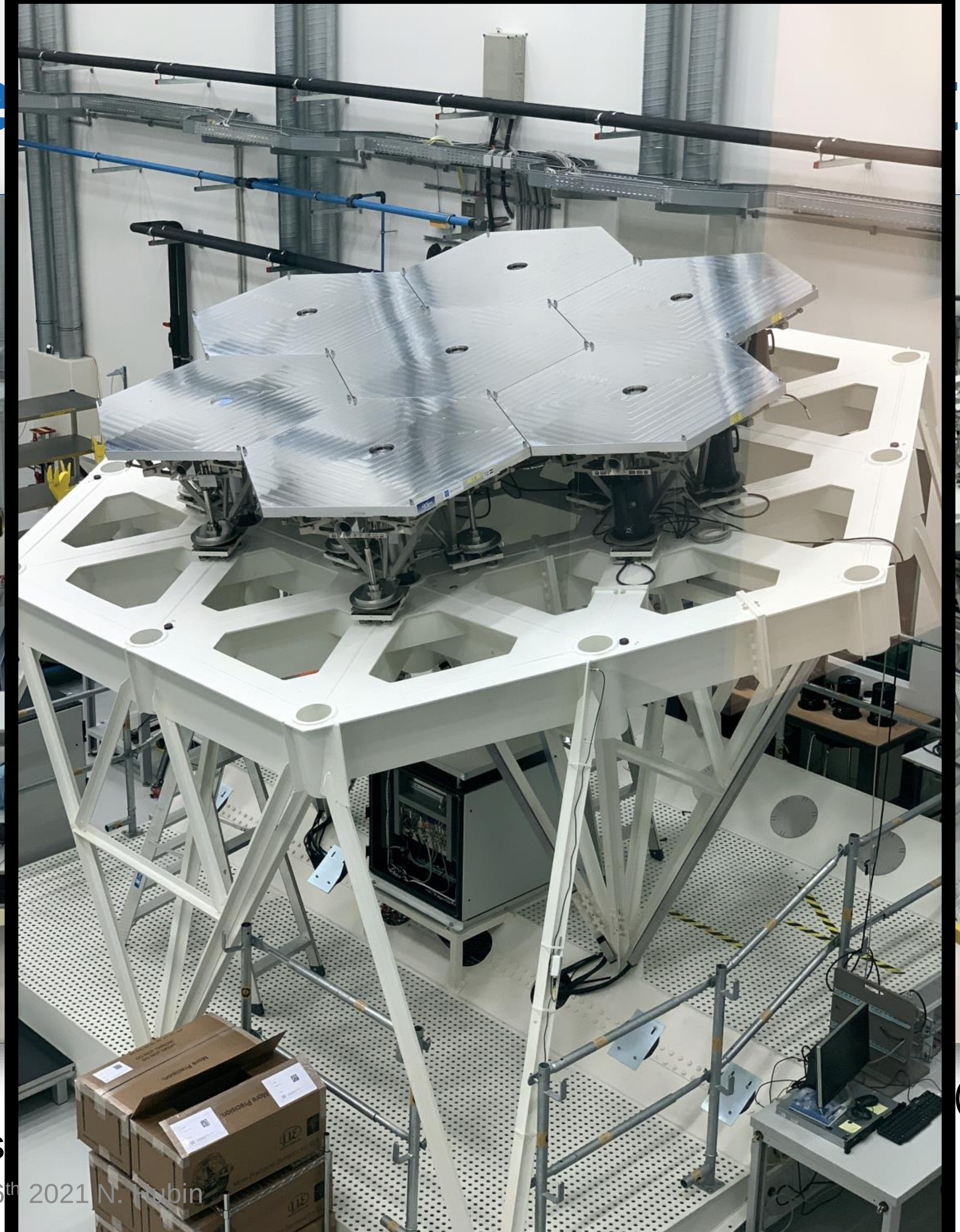
M1 Segment Manufacturing in industry

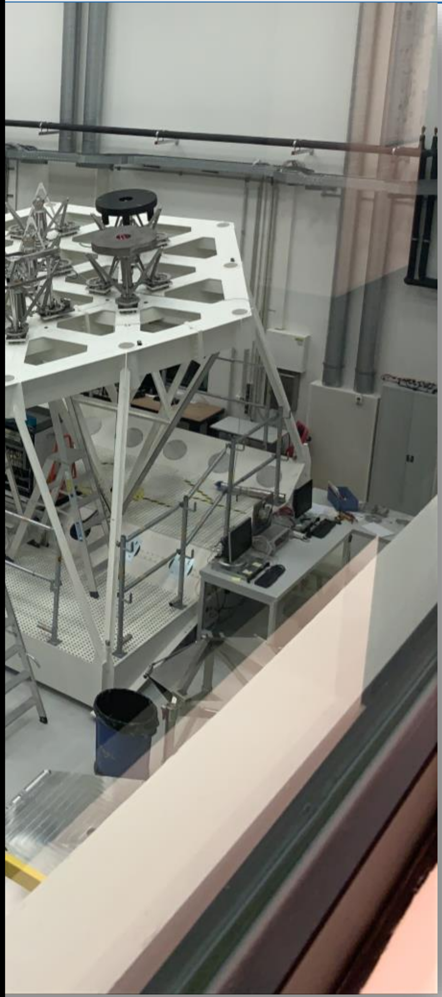


M1 Segment polishing: Eleven (out of 13) manufacturing processes are qualified.

Left: production metrology (profilometer and WFS). Middle: bonding station. Right: grinding shop

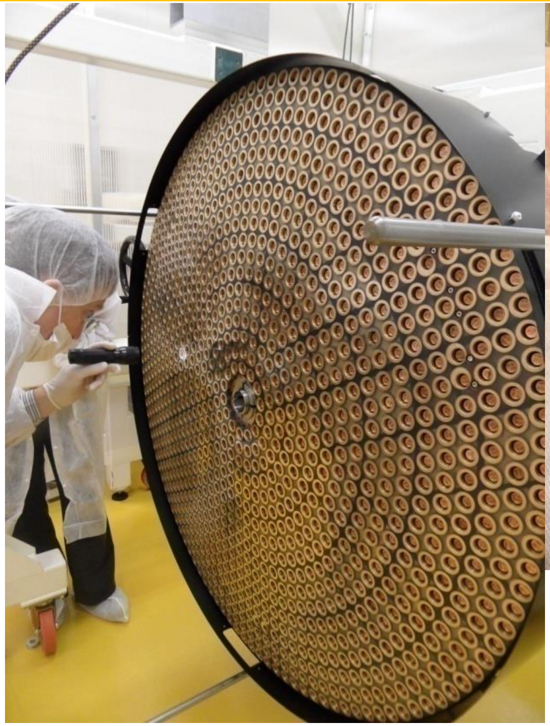
M1 Se… Rig at ESO

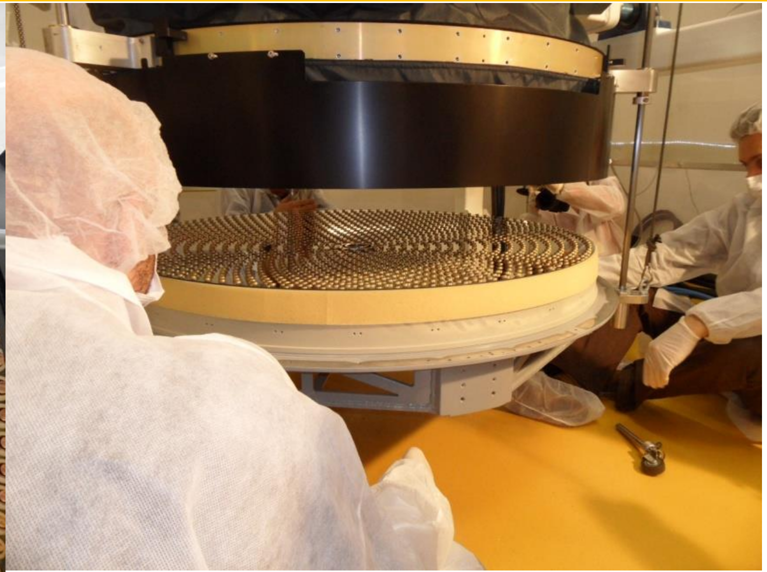




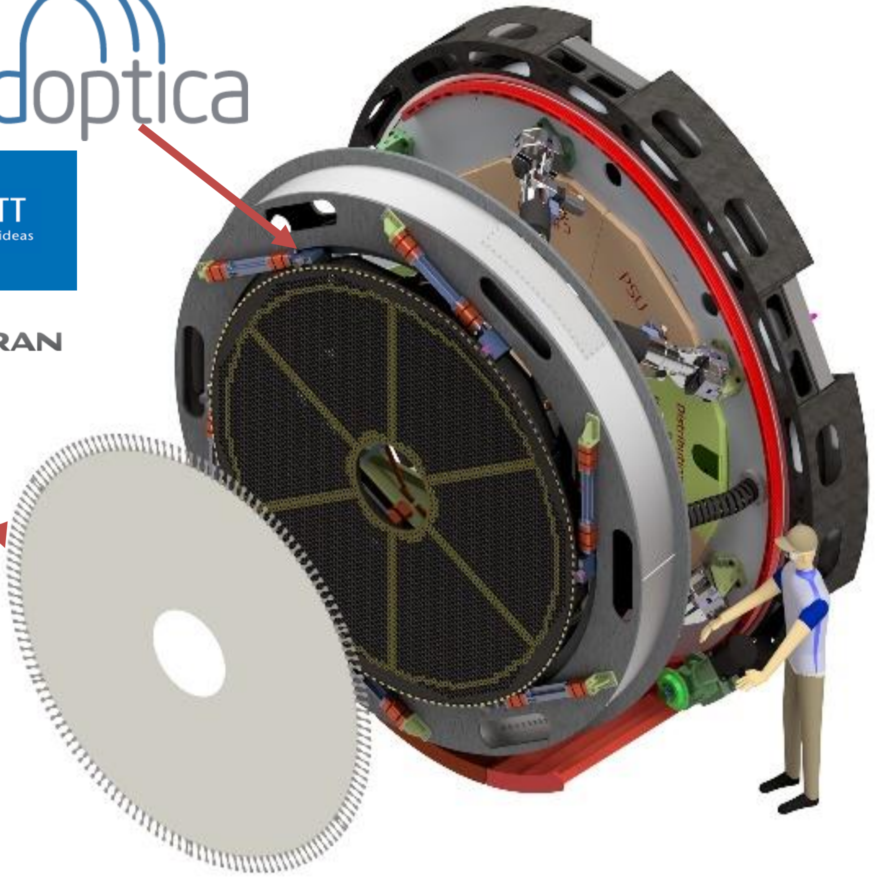
M1 test activities at ESO: … (front), testing of the assembly and integration procedures

From VLT 1.1 m Deformable mirror to ELT M4 Adaptive Mirror





VLT 1.1m deformable mirror, thin (1.95mm) ZERODUR® shells, 1180 actuators



Adaptive Optics deformable mirror integrated inside the ELT: 2.4m diameter, segmented (6 petals) thin (1.95mm) ZERODUR® shells, >5300 actuators

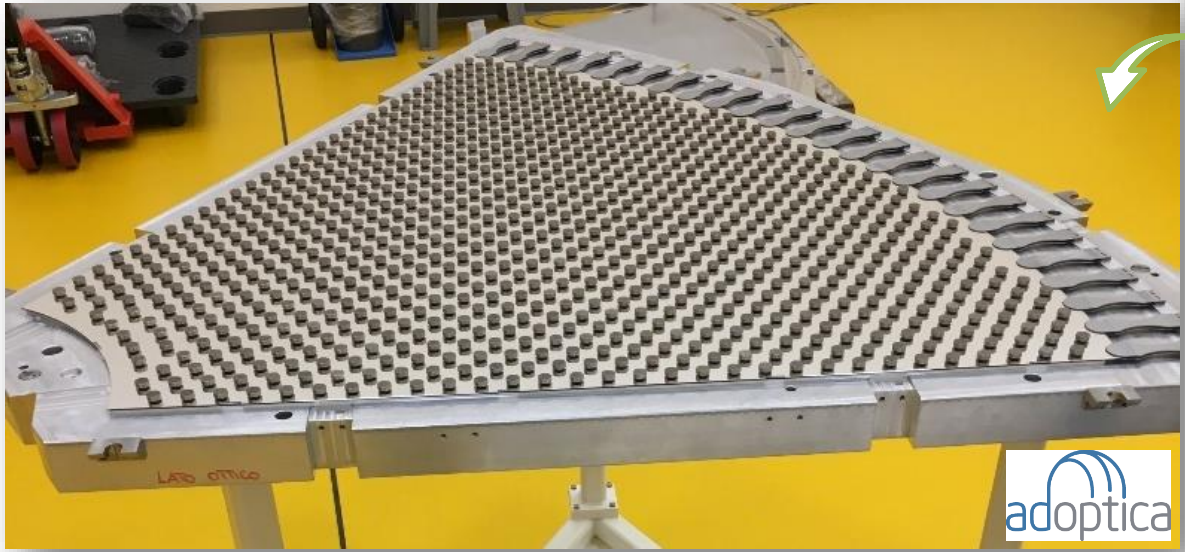
M4 Thin Shells made in Europe

- Four shells (1.95mm thick) delivered by Safran Reosc to AdOptica
- Two more by 2nd Quarter 2021
- Six more (spares) by 2023

Inspection of **M4 blanks** after manufacturing by Schott

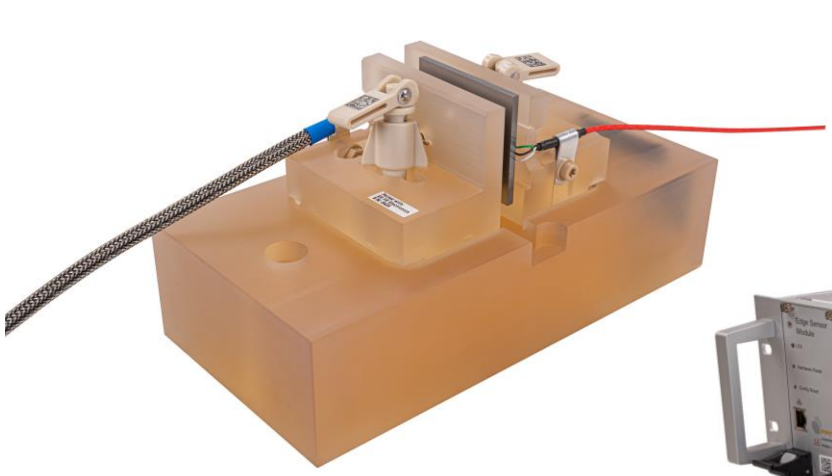
M4 Shells: Inspection after manufacturing by Safran Reosc (polishing/thinning/cutting)

Delivery of the 1st two Shells to AdOptica (Sep’2018)



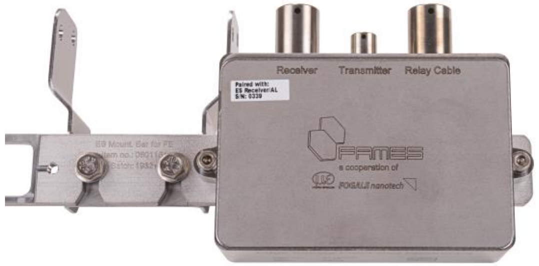
First finished Shell; back surface coated, equipped with glued magnets and lateral support (Oct’2020)

M1 Edge Sensor



FAMES

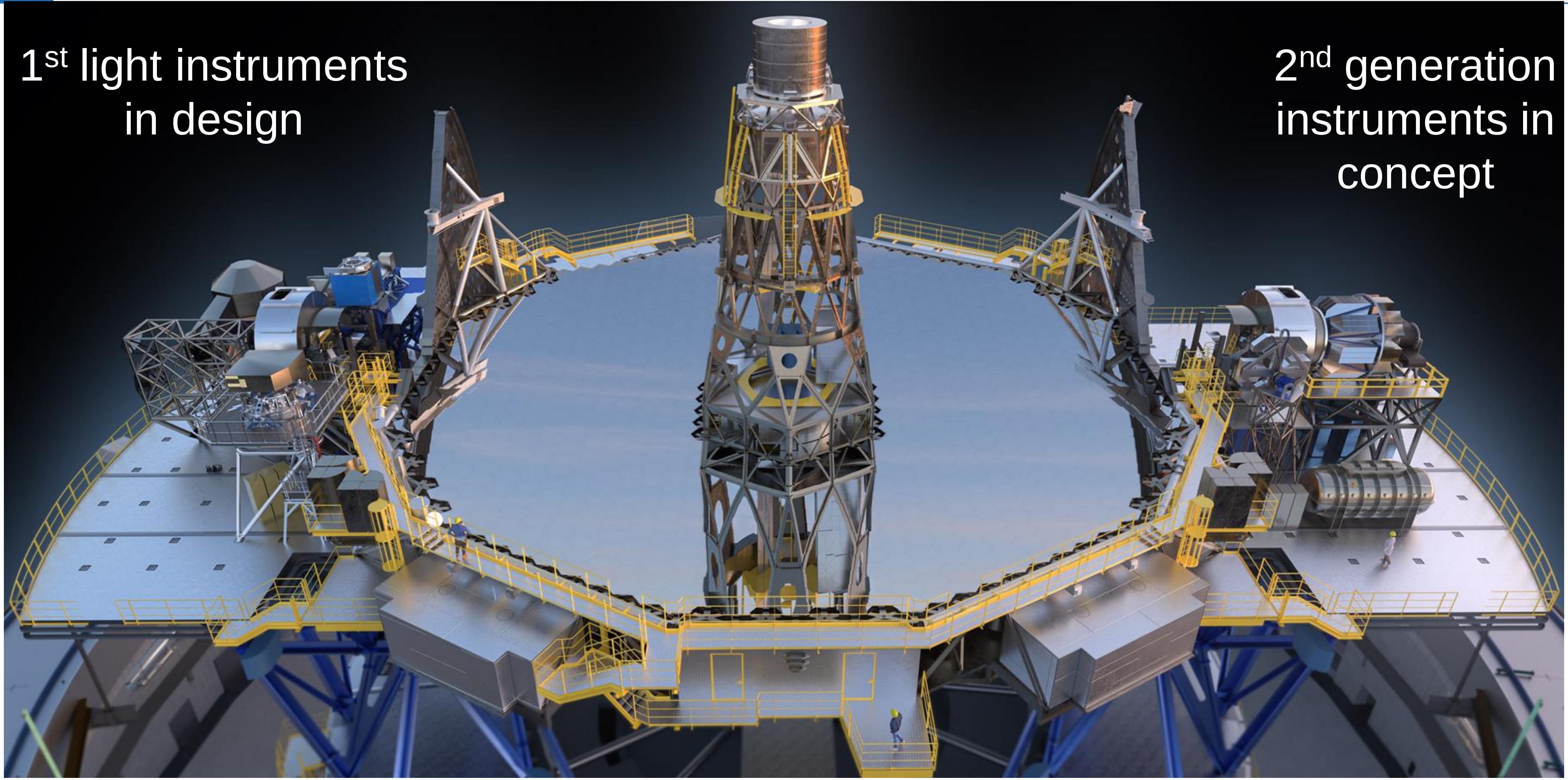
FOGALE nanotech



M1 Edge Sensors and electronics

42 Validation models delivered

ELT M1 & Instrument platform overview



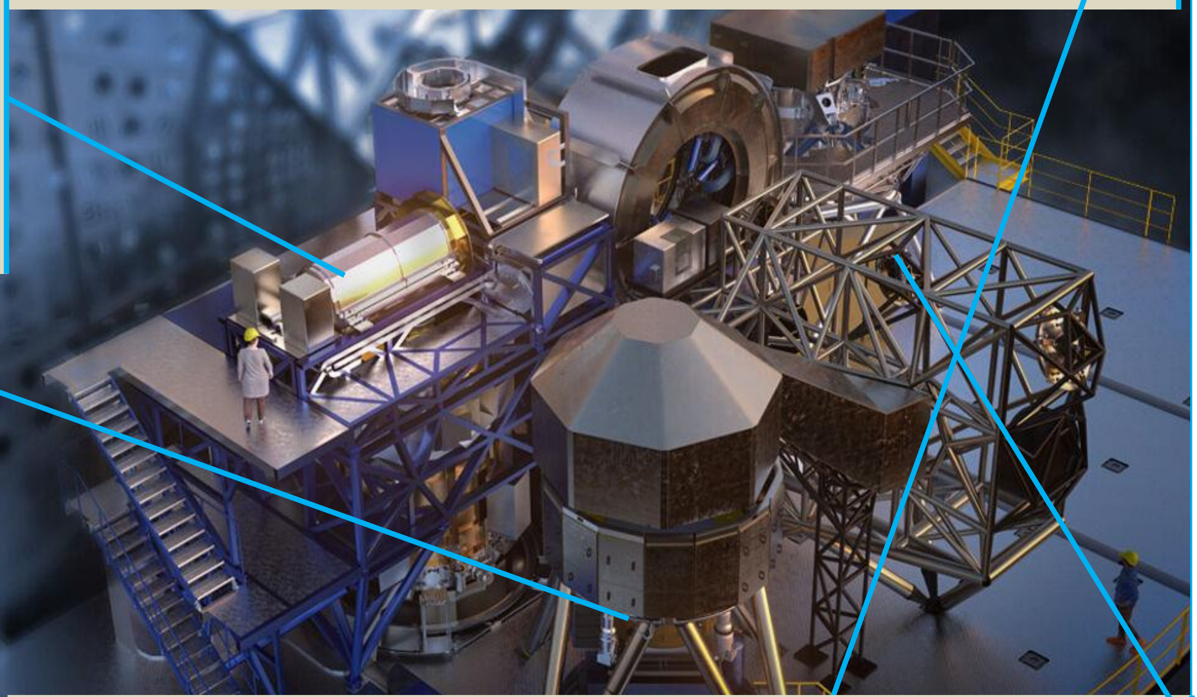
ELT First set of Instruments & Technologies

METIS: Mid infrared instrument:

- *Geosnap IR detector with digital interface*
- *400-500 mm free form cryogenic optics (40-70K)*
- *Reliable low dissipation cryogenic mechanisms (400mm)*
- *Low vibration cooling systems*

HARMONI: Near IR AO assisted 3D spectrograph

- *Reliable low dissipation cryogenic mechanisms (400mm)*
- *Low noise fast readout wavefront sensors*
- *IR and visible gratings*



MICADO: Near IR Adaptive Optics assisted instrument:

- *3-4 m accurate rotating platform*
- *Low vibration cooling systems*
- *High accuracy free form cryogenic optics 500 mm*
- *IR/Visible 500 mm dichroic*

MAORY: Multi-Conjugate AO system

- *1 m class deformable mirrors*
- *600-800 mm class dichroic (600nm cutoff)*
- *Low noise fast readout wavefront sensors*

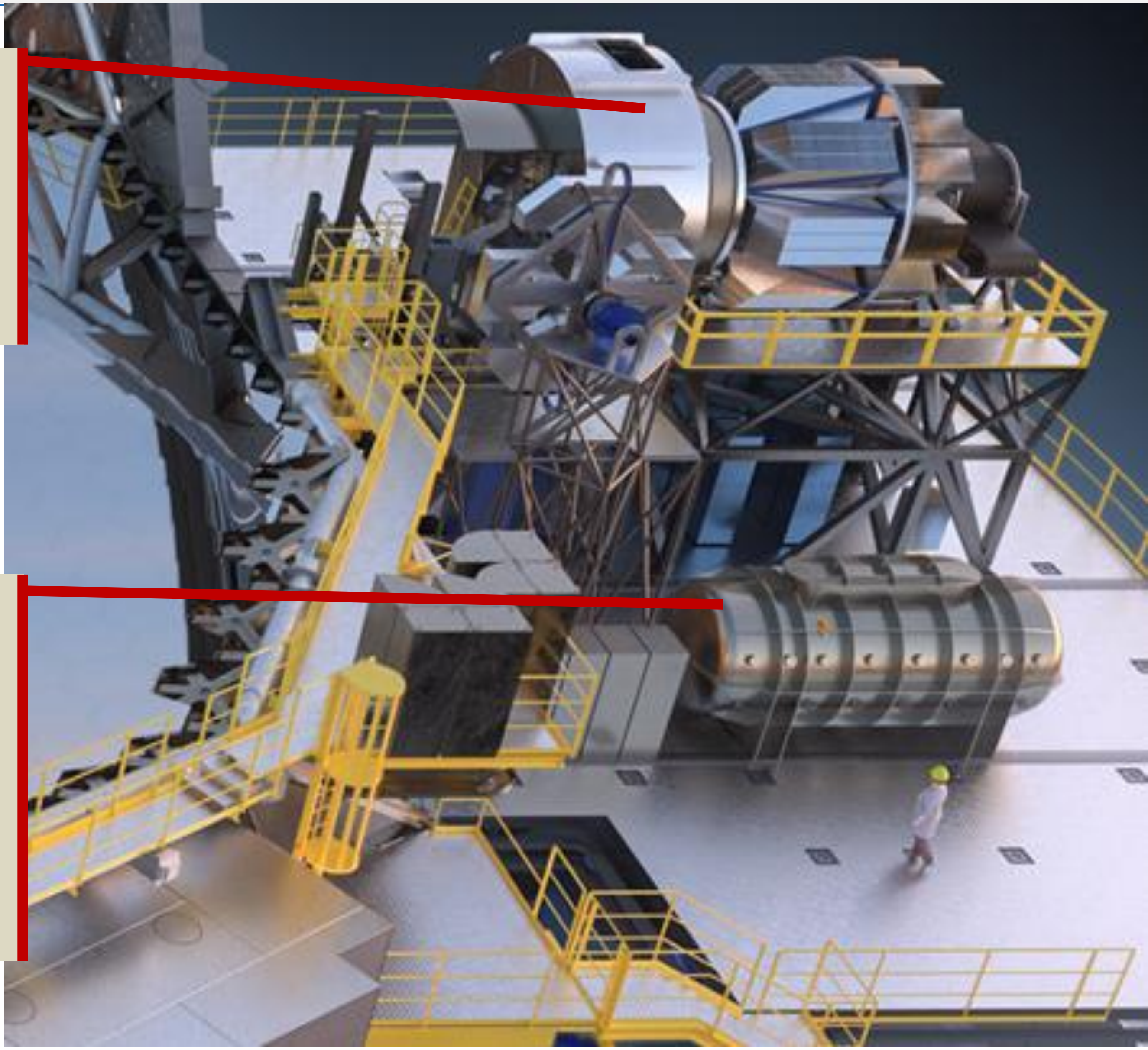
2nd generation ELT instruments and technologies

MOSAIC: Multi Object AO assisted spectrograph
Technologies to be developed

- *Large format VPHs (~300mm) for medium resolution spectroscopy (5,000-20,000) in optical and near-IR*
- *Curved detectors (CCD) 4Kx4K*
- *Coating with high performance from 0.35 to~2microns*

HIRES: HIgh REsolution Spectrograph:
Technologies to be developed

- *High-efficiency gratings for high resolution spectroscopy R > 100,000*
- *Robust & high-efficiency fibres for K-band (2.0 < λ < 2.4 microns)*
- *Coating with high performance from 0.35 to ~2microns*
- *Ultra stable calibration source: Laser Frequency Comb*

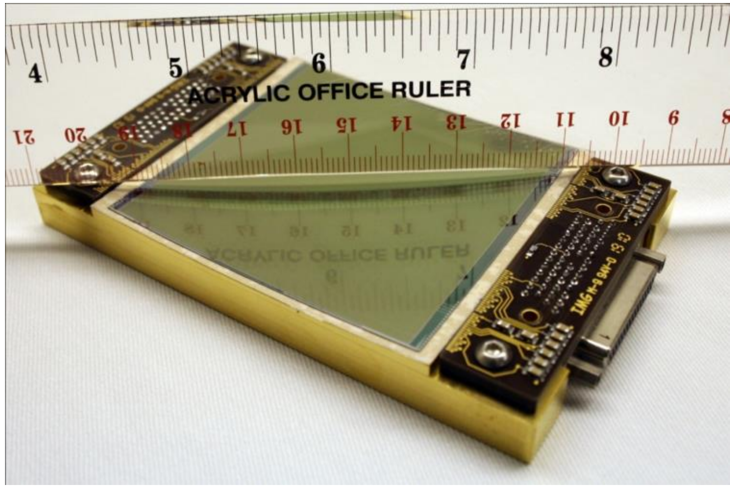


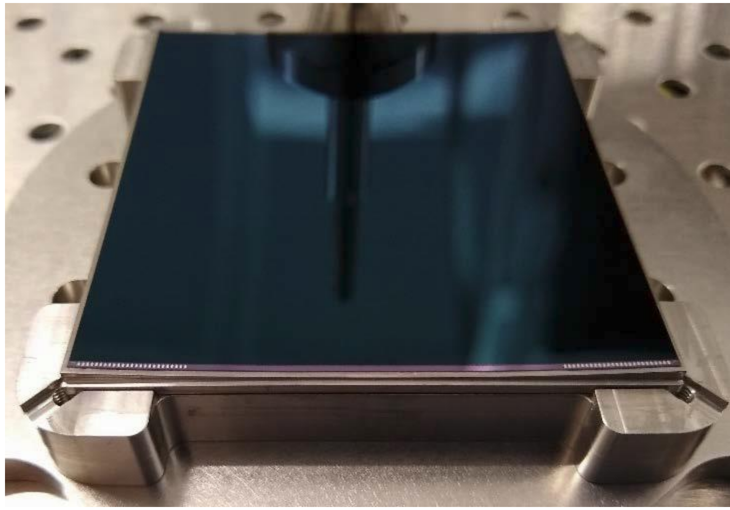
Needs for transmission gratings

Instrument	Ws	Wh	Type	Lines/mm	Angle of Incidence	Diff Order	Size	Size	Needed
CUBES	0.3	0.352	T	3107	36.07	1	170	220	1
	0.346	0.405	T	3600	35.82	1	170	220	1
BLUE MUSE	0.35	0.58	T or TG	1000	13.9	1	200	100	25
MAVIS	0.37	0.732	TG	750	12	1	40	40	1
	0.51	1.009	TG	550	12	1	40	40	1
	0.425	0.555	TG	1830	26.6	1	40	40	1
	0.63	0.887	TG	1000	22.24	1	40	40	1
VLT HRMOS (ESO concept)	0.36	0.374	T	4400	54	1	300	520	4
HARMONI	0.462	0.809	T	457	5.49	1	160	160	2
	0.81	1.369	T	284	12	1	164	156	4
	1.45	2.45	T	159	12	1	164	156	4
	0.83	1.05	T	664	21.4	1	164	160	4
	1.046	1.324	T	526	21.4	1	164	160	4
	1.435	1.815	T	384	21.4	1	164	160	4
	1.951	2.469	T	282	21.4	1	164	160	4
	0.827	0.903	T	1414	41.2	1	164	196	4
	1.538	1.678	T	760	41.2	1	164	196	4
	2.017	2.201	T	580	41.2	1	164	196	4
	2.199	2.4	T	532	41.2	1	164	196	4
FORSup	0.524	0.64	TG	484	17	1	105	112	1
	0.695	0.849	TG	480	18.23	1	105	112	1
	0.33	0.62	TG	660	6.08	1	105	104	1

Curved detectors development

- Curved detector allows compact/lighten and simpler instrument optics
- Idea proposed in 2009-12 as part of R&D at ESO:
  - 1st 4K prototype by ITL USA with 500 mm curvature radius cryogenically cooled
- ESA in close contact with ESO launches study prototype in 2018 with e2V➔ second prototype
- ESA-ESO agreement in 2020 contract to Teledyne/E2V in 2021 to confirm curved CCD detector feasibility with: Imaging tests, performance assessments, process improvements for shape accuracy and repeatability
- Future: Curved CMOS devices, curved IR devices?

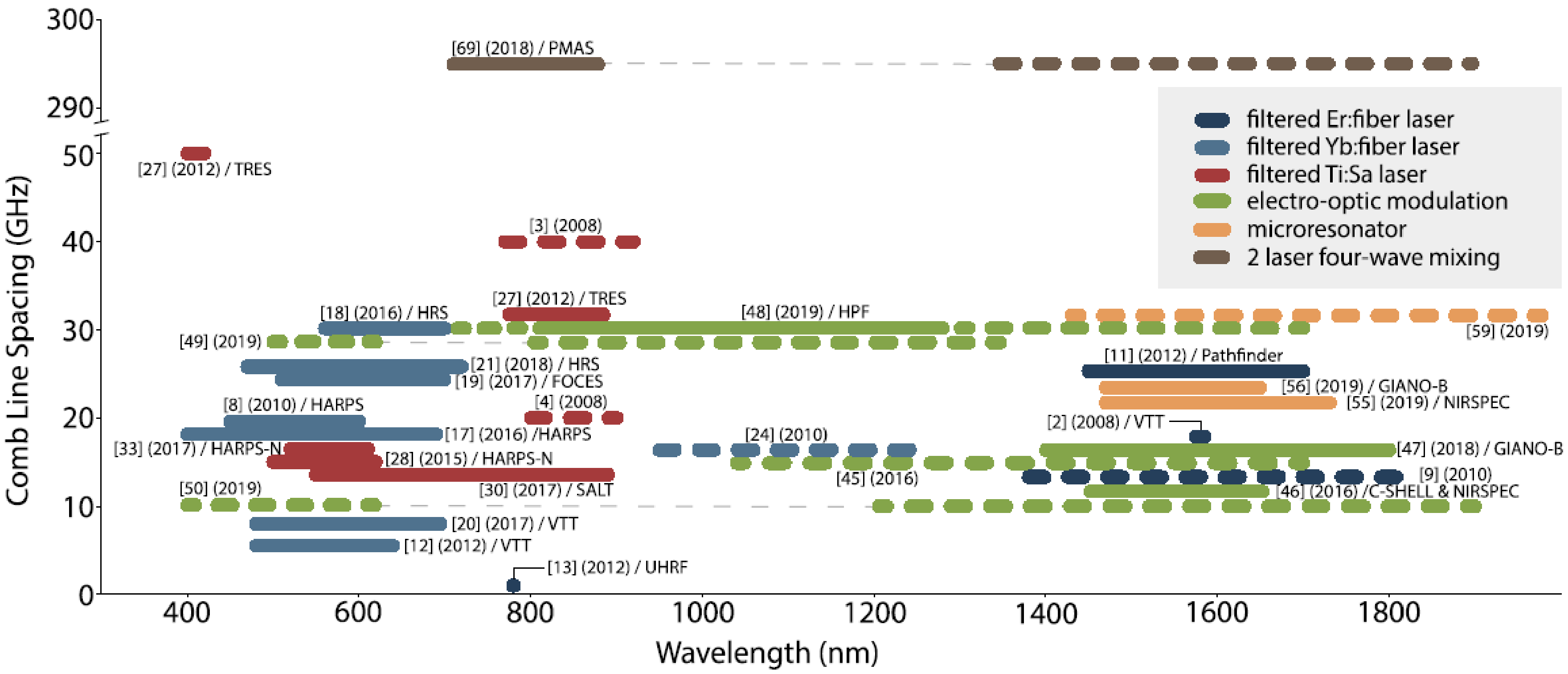




Ultra stable calibration source: Laser Frequency Comb

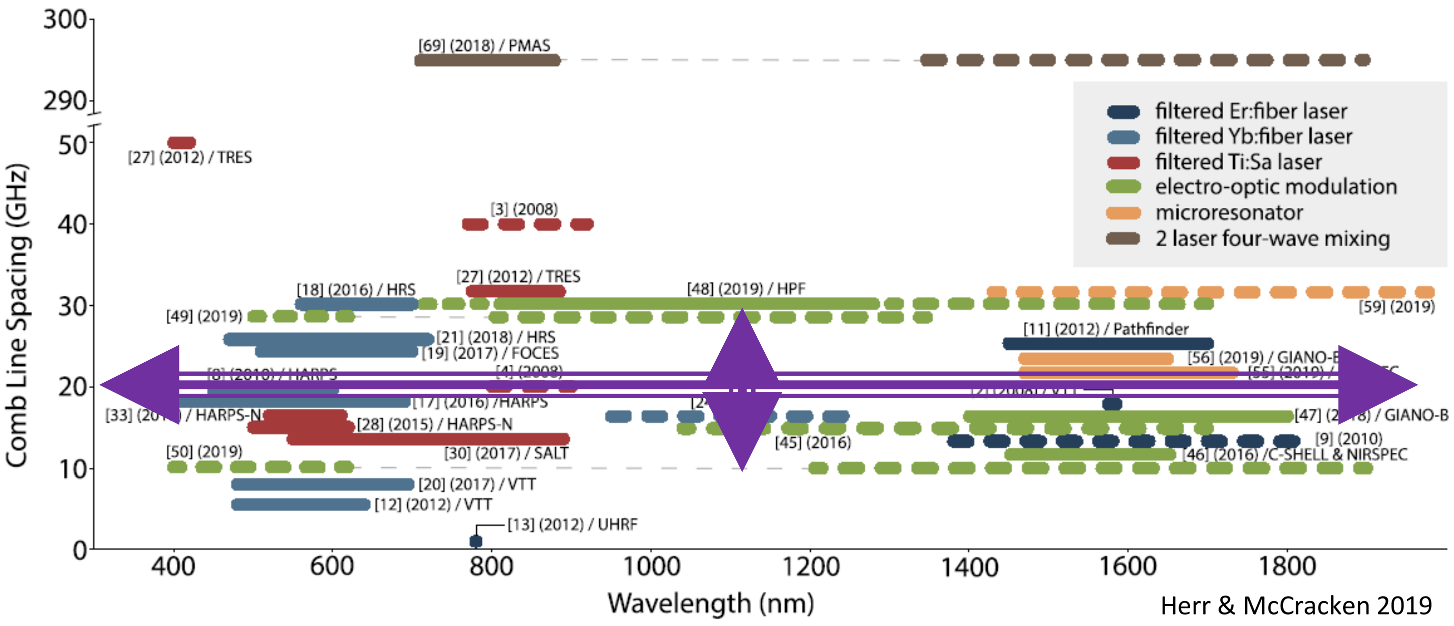
Current state of Laser Frequency Comb systems in astronomy for spectroscopy calibration:

- about 20 Astrocombs @ Observatories / 10 permanent / 2 @ ESO
- VIS (400-700nm) or NIR (1400-1800nm); Typical bandwidth 150 – 400nm



Ideal Future of LFC systems
(based on need of existing and future instruments)

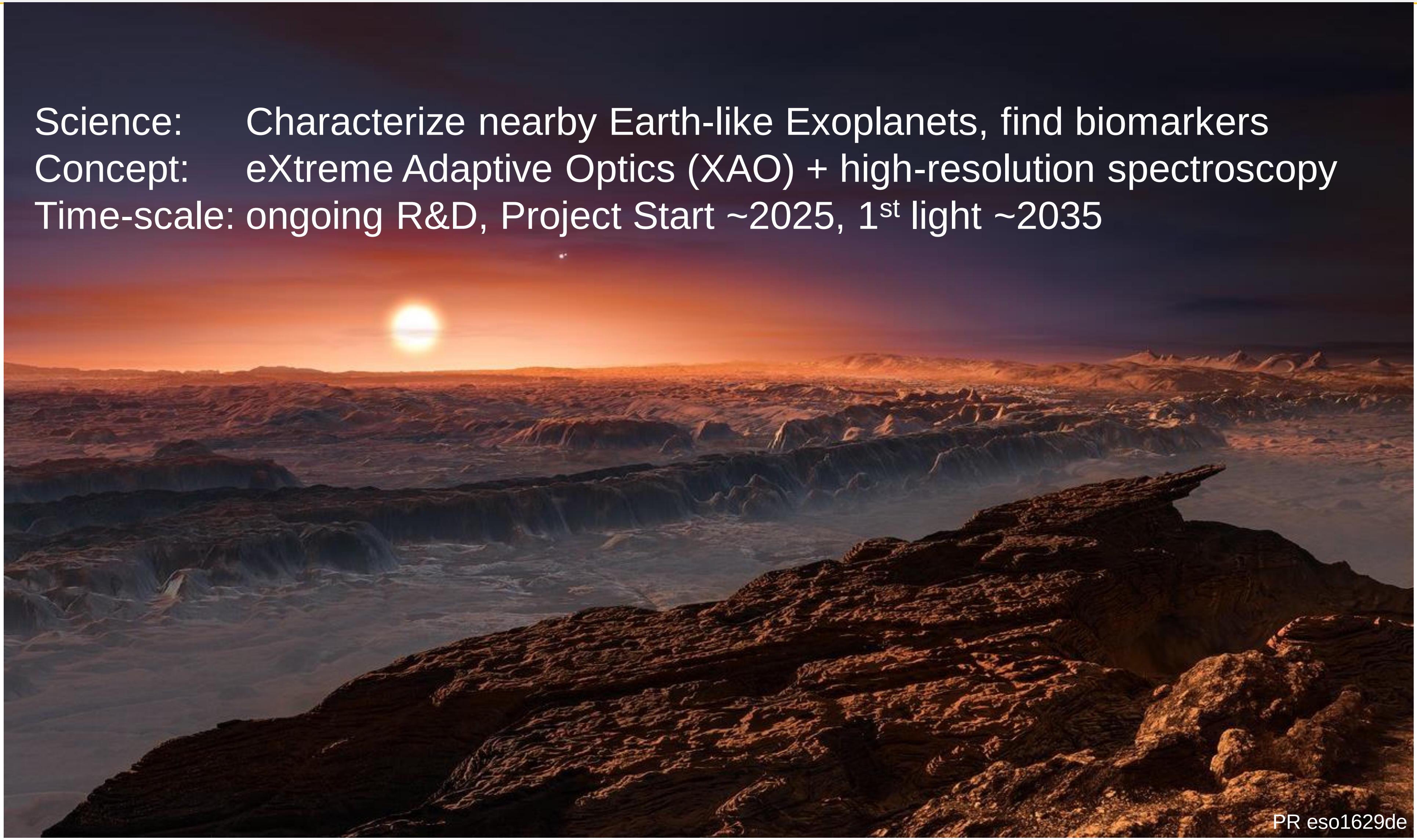
- Extend capabilities to UV (<380nm) to NIR (2400nm), maybe even MIR (5400nm)
- Tunable line spacing (allows to shift spectral lines on detector and to adapt to various spectral resolutions)
- extends wavelength coverage to UV (<380nm) without photo-degradation



Herr & McCracken 2019

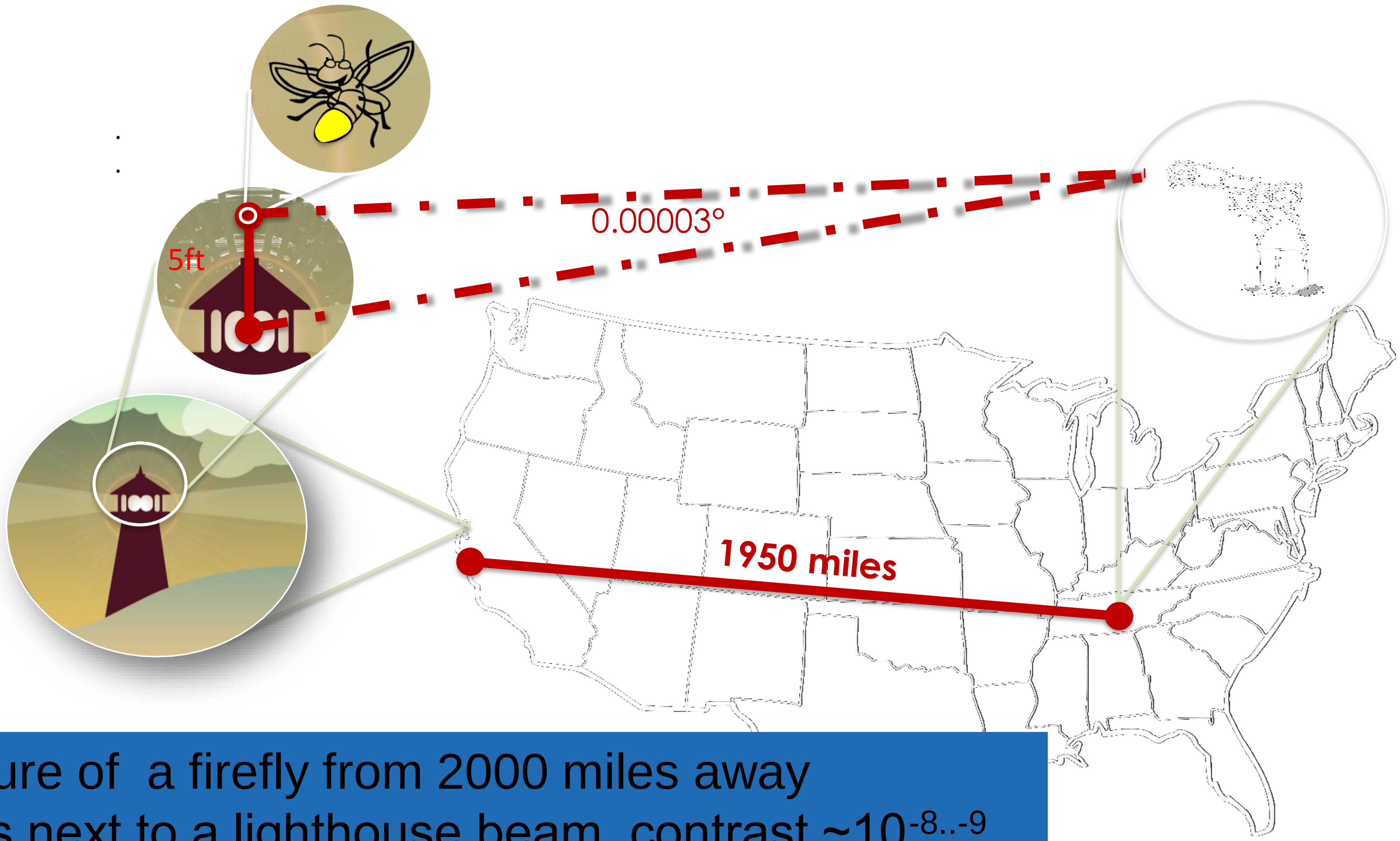
ELT – Planetary Camera and Spectrograph (PCS)

Science: Characterize nearby Earth-like Exoplanets, find biomarkers
Concept: eXtreme Adaptive Optics (XAO) + high-resolution spectroscopy
Time-scale: ongoing R&D, Project Start ~2025, 1st light ~2035



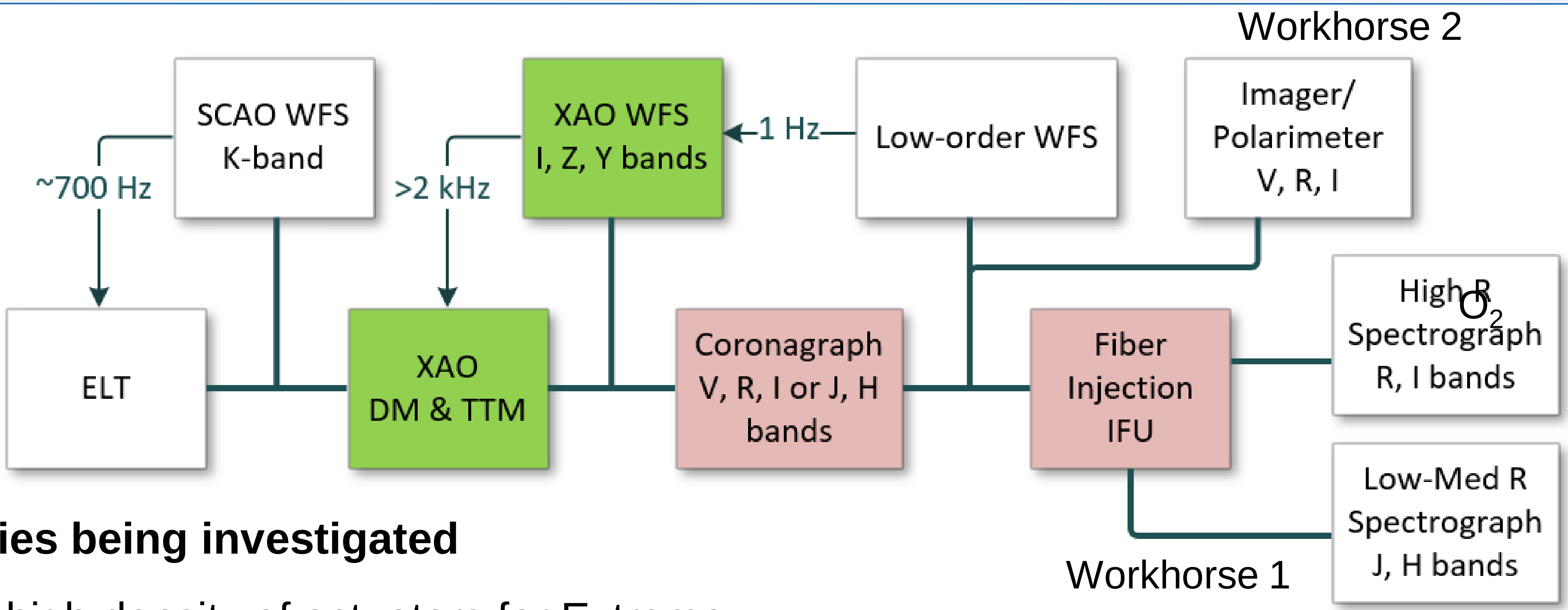
PR eso1629de

Exoearths are VERY faint and difficult to observe



Take a picture of a firefly from 2000 miles away
…which sits next to a lighthouse beam, contrast ~$10^{-8..-9}$

Nearby Exo-earths with ELT PCS (>2030)



Technologies being investigated

- Deformable mirrors with high density of actuators for Extreme Adaptive Optics 128x128 actuators; 3kHz frequency
- Fiber injection in Integral Field spectrograph
- Real Time Computer with Machine learning algorithms
- Possibly curved near-IR detectors

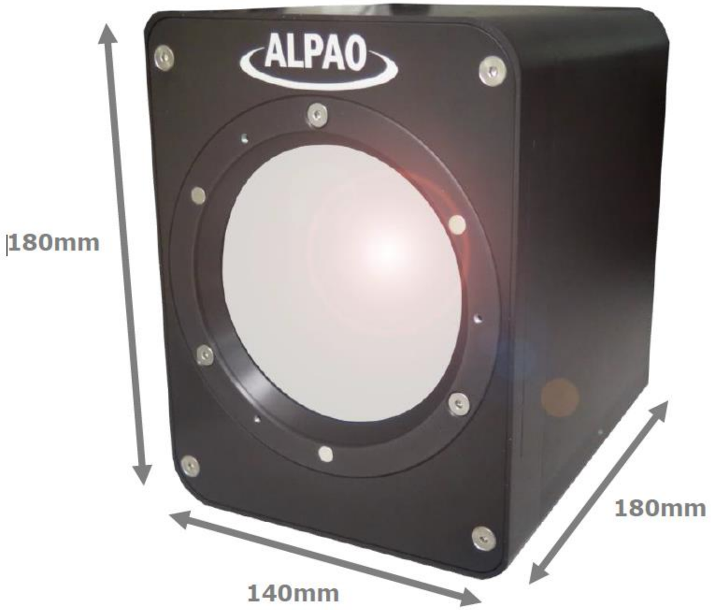
Green: R&D (partially) underway

Red: Additional R&D proposed

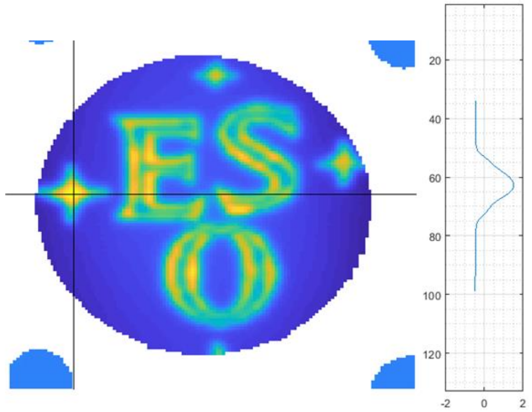
XAO Deformable Mirror: Key requirements

- Application is eXtreme AO for High Contrast Imaging (PCS)
  - Actuator count: 10800 to 20000
  - DM diameter: 150mm to 450mm
  - Small stroke settling time: 50nm to ±10% within <150µs, goal <100µs
  - Stroke: > 3µm
  - Resolution: 0.1nm goal 0.06nm! ~15Bit
  - Hysteresis: <5%
  - Few non-functioning actuators can be tolerated

So far developed: ALPAO DM3228-15



3228 actuators in the clear aperture
6 nm rms best flat



Large CMOS development

- **Motivation: Guarantee long-term access to scientific-quality detectors in the visible wavelengths for astronomy**.
- CCDs are state-of-the-art visible detectors used in all ESO visible instruments.
  - CCD production is decreasing in favor of CMOS in public market. Only 1.5 suppliers worldwide are still producing large-format CCDs, and cost continuously increases.
  - Availability not guaranteed beyond ~1 decade, (ELT).
- CMOS detectors provide: New readout schemes / operation modes, lower prod. Cost / pixel. Some established design houses and larger variety of manufacturers.
  - However, commercial CMOS specifications do not (yet) reach our requirements, and investment and development will be required to get there.
- Join forces for instance very interesting ESA's ELFIS development program with Caeleste.
  - 10 years of development so far (multiple iterations)
  - several MEuro so far, more needed to get a production sensor
  - We could build on this development for our sensor in partnership with ESA at fractional cost?

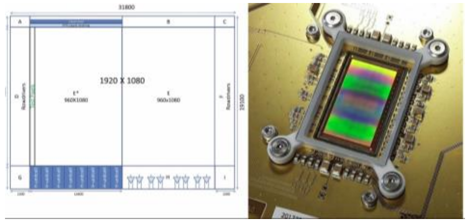
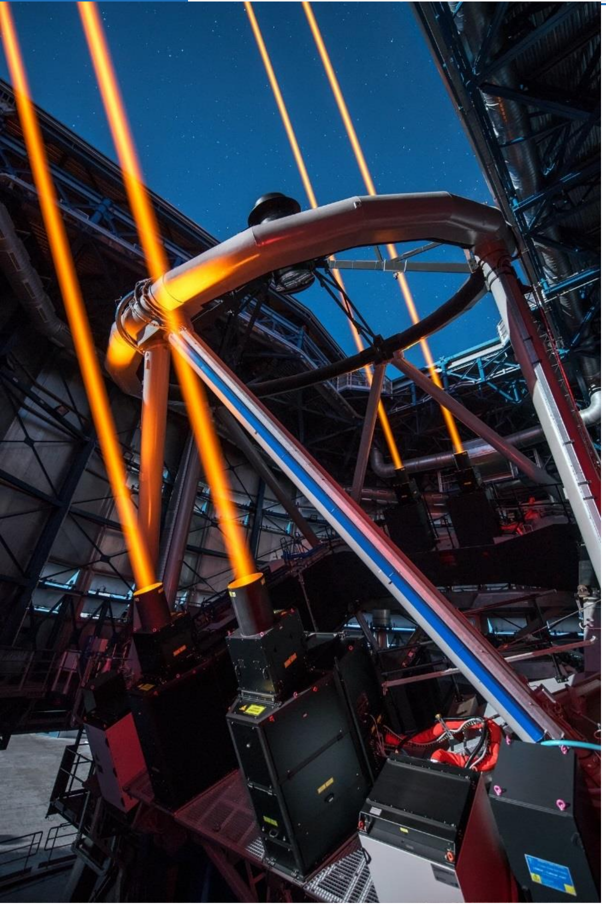


Fig 1:ELFIS building block and sensor

Laser Guide Star development effort



22W Sodium (589nm)
Laser @ VLT

- Laser Guide star concept essential for high sky coverage AO
- 22W Sodium (589nm) Laser standard product for observatories
- ESO-TOPTICA-MPB achieved 63W laser (world record) which are of great interest for satellite communication (collaboration with ESA) and for astronomy with high degrees of AO correction
- New AO concepts will be enabled by these high-power laser
- Full sky coverage AO…

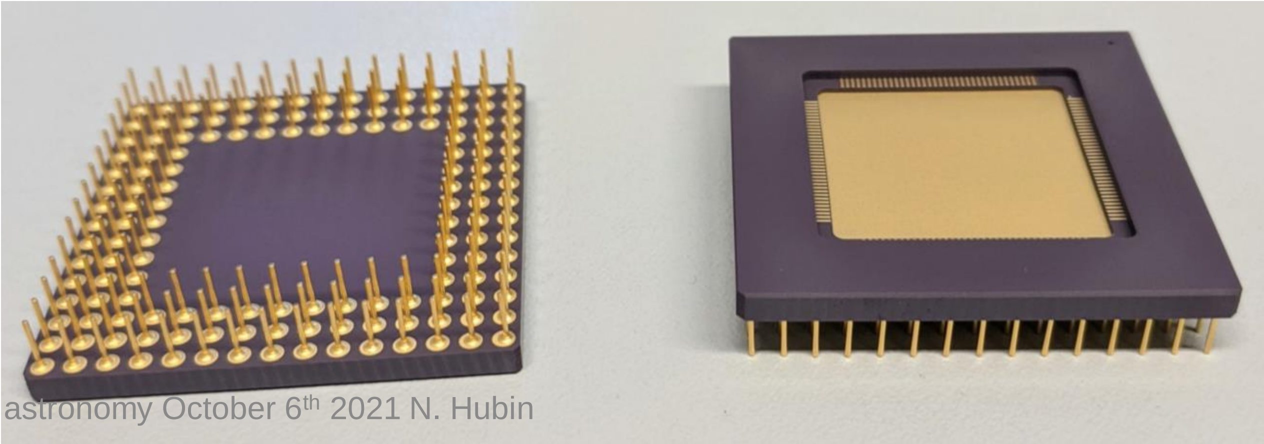
63W Sodium (589nm)
Laser @ VLT

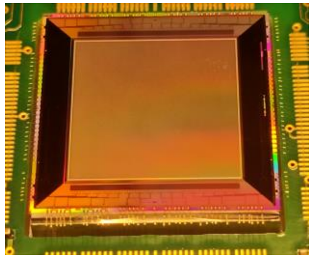
eAPD IR detector development

Based upon successful 320x256 pixels Saphira Detector from Leonardo (UK) used in GRAVITY

- 512 x 512 eAPD, 2k fps, developed for fast (pyramid) AO as well as low-noise scientific read-out
- Possibility to be used in ELT- PCS, step towards even larger eAPD arrays
- Large 512x512 SAPHIRA for ESO complementary to 1Kx1K for University of Hawaii IfA (NASA)
  - 1Kx1K: 16 outputs, low glow, long integration times, complement with large format conventional HawaiiXRG arrays, low trap assisted tunneling
  - 512x512: 64 outputs for high speed (8.7Mpix/s/output, DCS frame rate 1KHz), low glow, intermediate reference pixel subtraction for low noise, optimized for adaptive optics and pyramid WFS

Pick up on the opportunity of the 1kx1k funded by NASA and UH to explore further this technology? 2Kx2K?





512x512
LEONARDO

Conclusions

Several key technologies are needed to build state of the art instruments for ground-based astronomy:

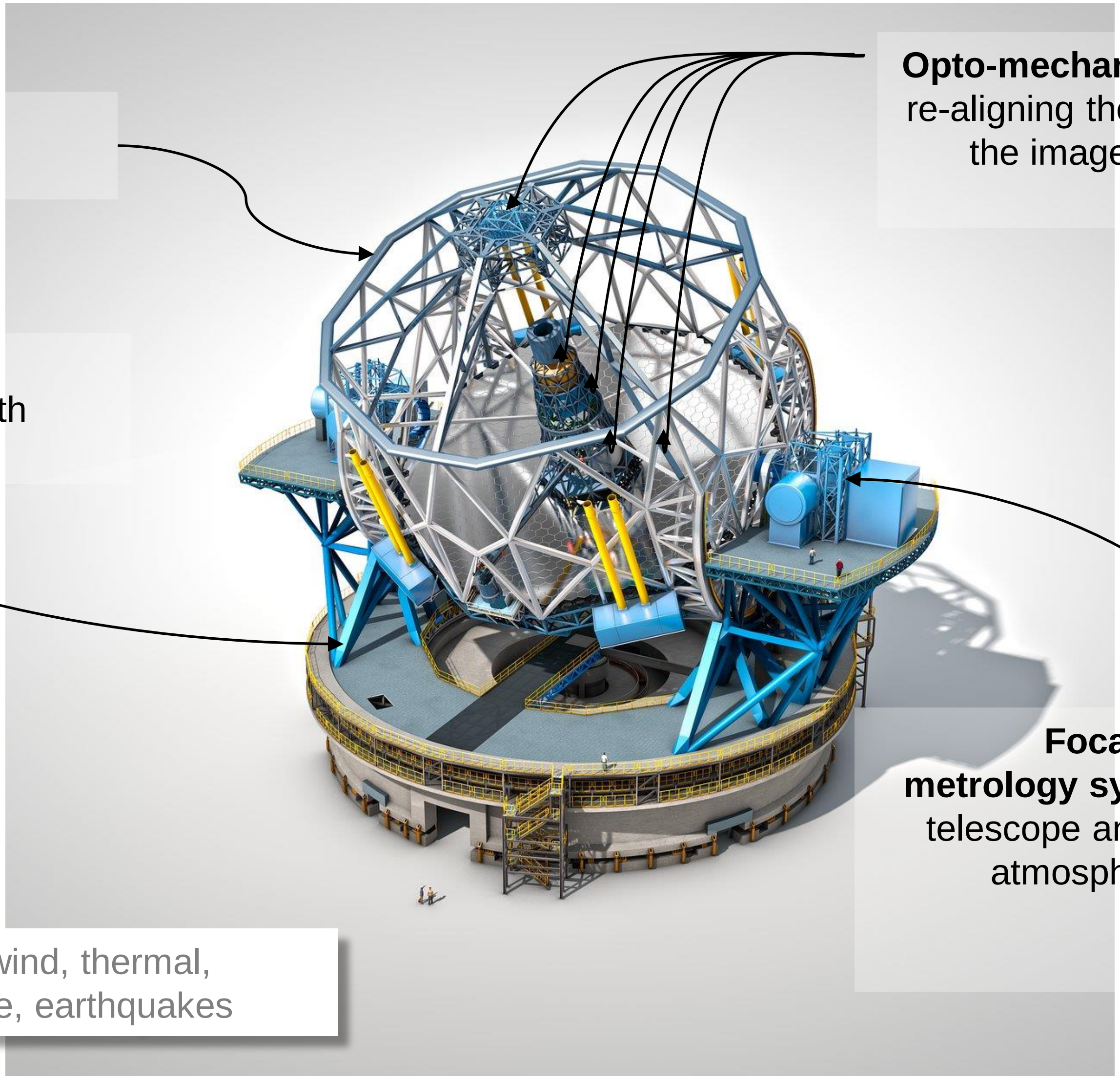
- CMOS and new IR detectors for AO or IR imaging applications incl. Kinetic Inductance detectors
- Curved visible and IR detectors to compact/simplify instrument designs
- High accuracy calibration sources: Laser Frequency Comb-ultra stable Fabry Perot
- High stability deformable mirrors with 10-20k actuators at high speed
- Laser sources and new LGS AO concept improving sky coverage
- Machine learning techniques with high-power Real Time Computer
- Robust & high-efficiency fibres for K-band ($2.0 < \lambda < 2.4$)
- Secure transmission grating availability
- Not developed in this presentation but definitly promising: astrophotonics for instance for integrated spectrograph, tip-tilt sensing, heterodyne interferometry…

SPARE SLIDES

How does it work ?

Main Structure holds the opto-mechanical units

Alt-Az mount points and tracks to compensate for target motion (earth rotation)



Opto-mechanical units are jointly capable of re-aligning themselves, refocusing, stabilizing the image, and compensating for external perturbations

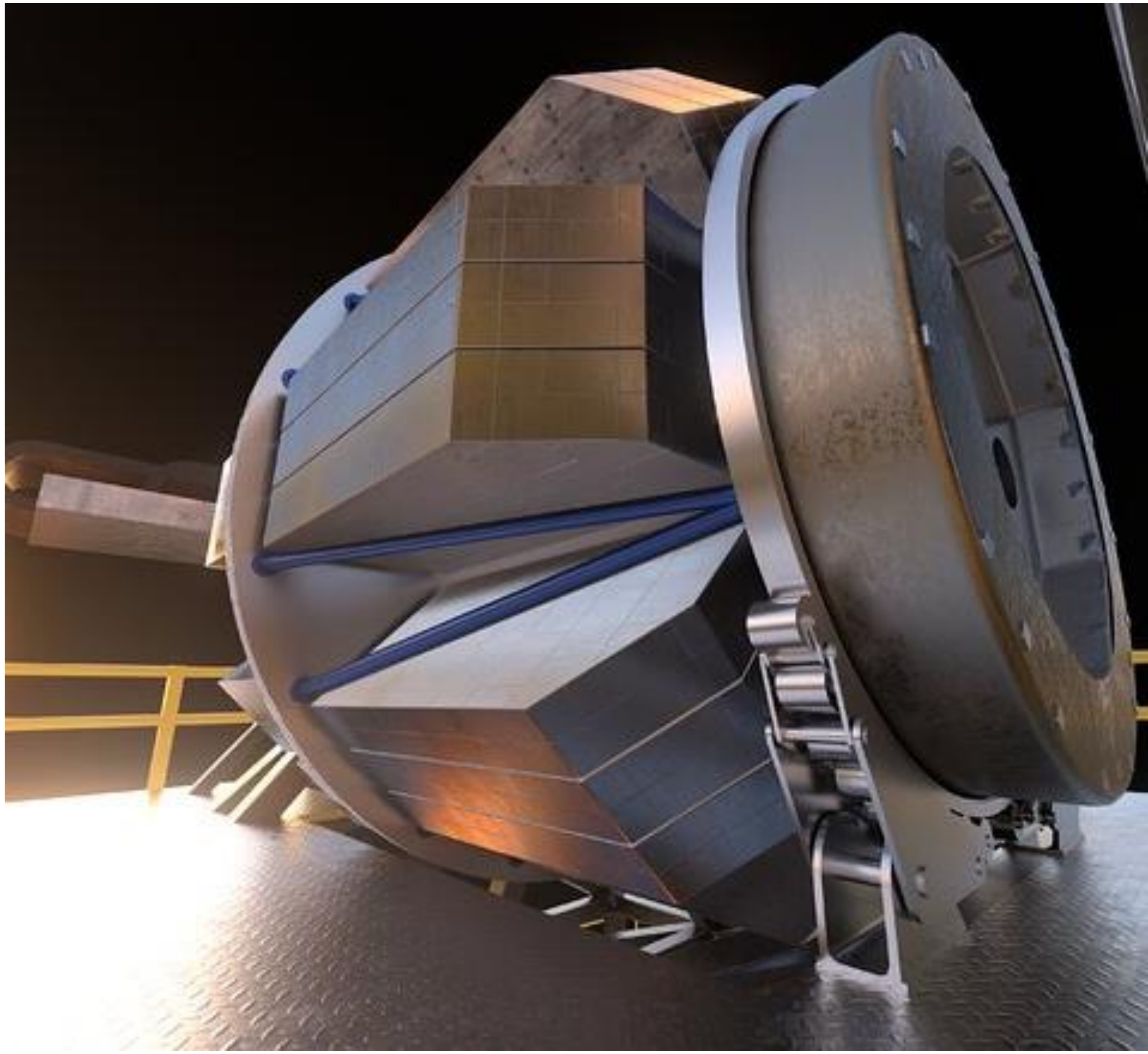
Focal plane (on-sky) and embedded **metrology systems** measure the state of the telescope and of external perturbations (e.g. atmosphere); control system derives the commands sent to the units

Hosts **Scientific Instruments**

Environment: gravity, wind, thermal, atmospheric turbulence, earthquakes

MOSAIC

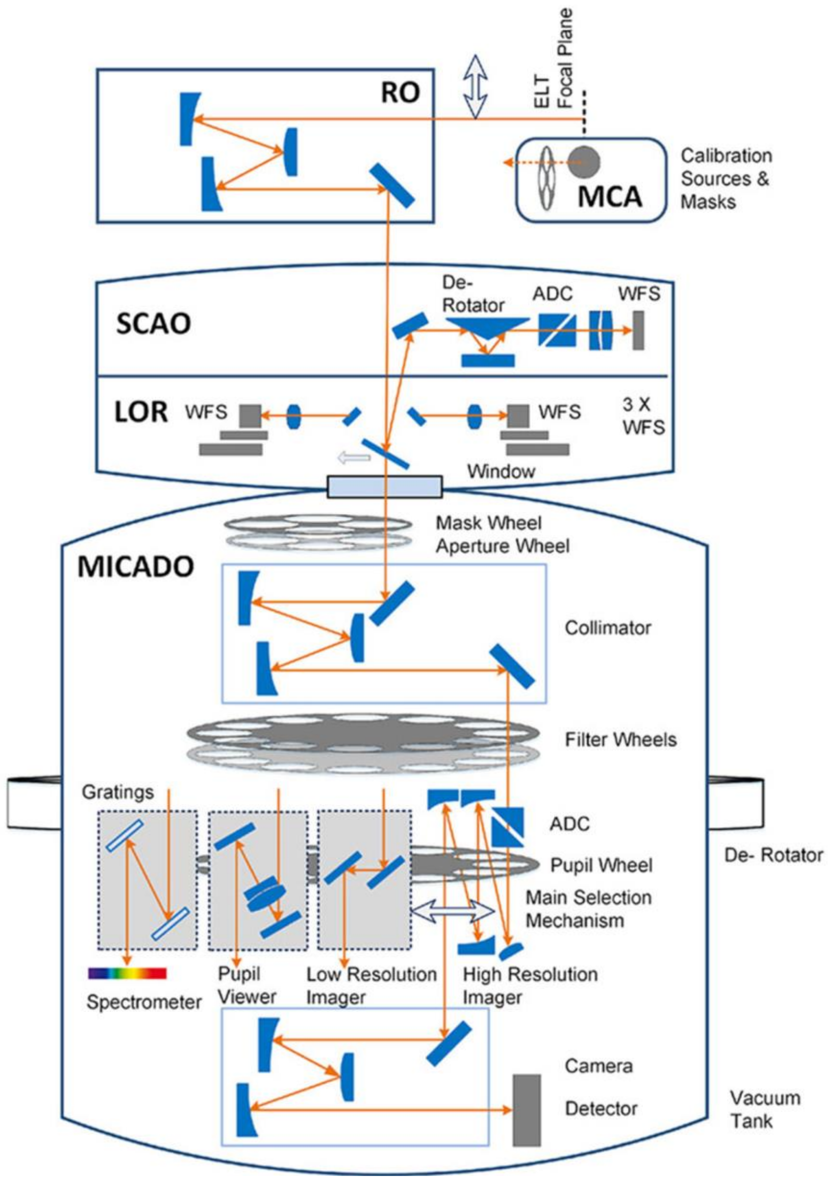
- MOSAIC will conduct the first exhaustive inventory of matter in the early Universe. This will lift the veil on how matter is distributed in and between galaxies, resulting in a tremendous leap forward in our understanding of how present-day galaxies formed and evolved.



MOSAIC

- High multiplex mode in the visible (HMM-VIS): Simultaneous integrated-light observations of almost 200 objects, with the possibility of using both medium and high spectral resolving power (R~5000 and R~20,000).
- High multiplex mode in the near-infrared (HMM-NIR): Simultaneous integrated-light observations of 80 objects (goal: 100) each of them with dedicated sky fibres to subtract the strong sky background present in the near-infrared. This mode will cover simultaneously the wavelength range 0.8–1.8 µm with the possibility to observe in medium and high spectral resolving power.
- High-definition mode (HDM): Simultaneous observations of eight integral field units (IFUs) (goal: 10 IFUs) deployed within a ~40 arcmin patrol field. Each IFU will cover a 2.5 arcsec hexagon with ~200 milliarcseconds spaxels, sharing the same spectrograph as for the HMM-NIR, with same wavelength coverage and spectral resolving power

MICADO


ELT
Focal Plane
RO
MCA
Calibration
Sources &
Masks
SCAO
De-
Rotator
ADC
WFS
LOR
WFS
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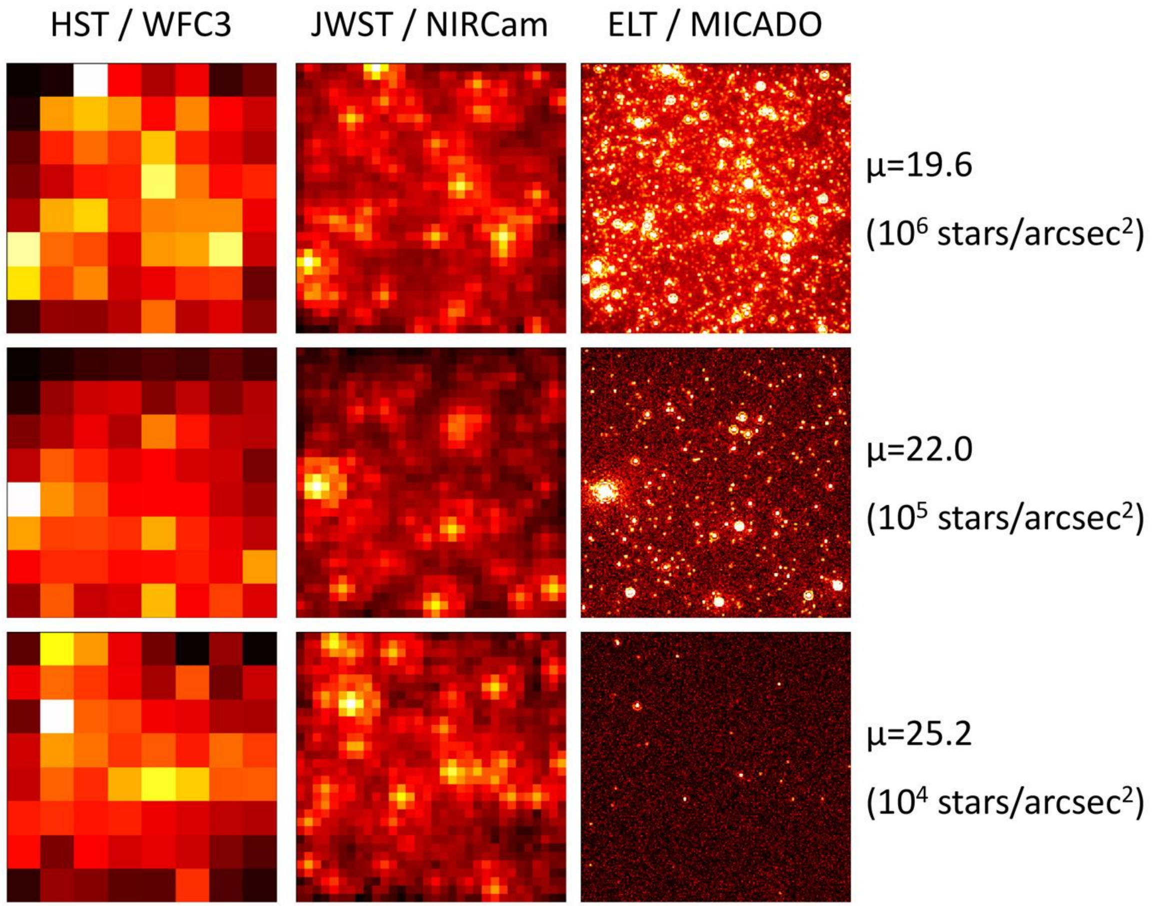
3 X
WFS
Window
Mask Wheel
Aperture Wheel
MICADO
Collimator
Filter Wheels
Gratings
ADC
Pupil Wheel
Main Selection
Mechanism
De- Rotator
Spectrometer
Pupil
Viewer
Low Resolution
Imager
High Resolution
Imager
Camera
Detector
Vacuum
Tank

MICADO

- 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: $1x10^{-4}$ at 100 mas; $1x10^{-5}$ at 500 mas
- Spectral resolution: < 20,000
- Simultaneous spectral range: 1.45–2.46 µm; 0.84–1.48 µm
- Slit width/length: 16 mas/3arcsec



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Mid-infrared ELT Imager and Spectrograph: METIS

- **How do stars and planets form? How many Earth-sized planets exist around the nearest stars? What lurks at the centre of the Milky Way and galaxies further afield? These are just some of the questions the METIS instrument on the ELT will tackle.**
- Imaging at L/M (3–5 μm) band. The imager will include medium resolution (R ~ 1,000) slit spectroscopy as well as coronagraphy for high contrast imaging;
- Imaging at N (7.5–13.5 μm) band. The N-band imager will include low resolution (R ~ few hundred) slit spectroscopy as well as
- coronagraphy for high contrast imaging;
- High resolution (R ~ 100,000) IFU spectroscopy at L/M band,
- To achieve diffraction-limited performance, METIS will use adaptive-optics to compensate for atmospheric turbulence.

HIgh REsolution Spectrograph: HIRES

- The high-resolution ELT instrument HIRES will allow astronomers to study astronomical objects that require highly sensitive observations. It will be used to search for signs of life in Earth-like exoplanets, find the first stars born in the Universe, test for possible variations of the fundamental constants of physics, and measure the acceleration of the Universe's expansion.
- The HIRES baseline design is that of a modular fibre-fed cross dispersed echelle spectrograph which has two ultra-stable spectral arms, visual and near-infrared, providing a simultaneous spectral range of 0.4 -1.8 µm at a spectral resolving power of R~100,000 for a single object. HIRES will also include an IFU mode fed by a single-conjugate adaptive optics (SCAO) module to correct for the blurring effect of turbulence in the atmosphere.

HARMONI

- HARMONI: Integral Field Unit (IFU) with image slicer to divide a single contiguous field of view into many spatial pixels (called spaxels). The signal from each spaxel will be fed into a spectrograph that generates a spectrum for each one of them. Four spaxel scales (from 4 mas to 60 mas) that result in different fields of view

- Spectral resolution (3000, 7000, 18000) available in all spatial scales covering wavelengths between 0.47 μm and 2.45 μm. Two different AO systems that will correct for atmospheric turbulence: single-conjugate adaptive optics (SCAO) that uses a bright (R≤16) reference star to provide high Strehl image quality over a small fraction of the sky, and laser tomography adaptive optics (LTAO) that combines laser guide stars with fainter natural stars to deliver diffraction-limited image quality in the JHK bands over a large fraction of the sky.