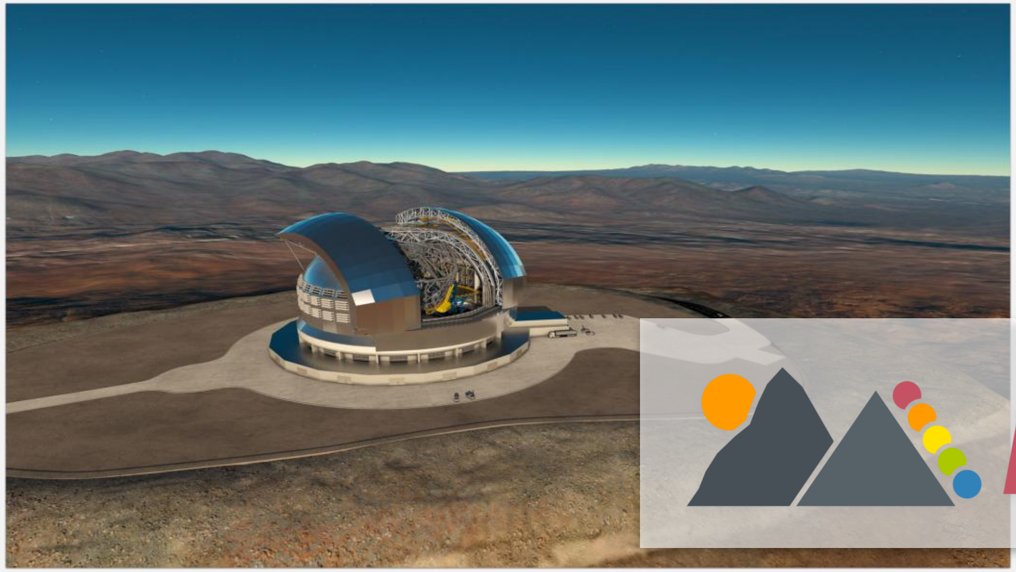
CUBES and ANDES

-

ground-based technological enablers for the HWO



ANDES

HABITABLE WORLDS OBSERVATORY

ANDES: broad context

European Extremely Large Telescope (ELT) will be the largest ground-based telescope at visible and infrared wavelengths

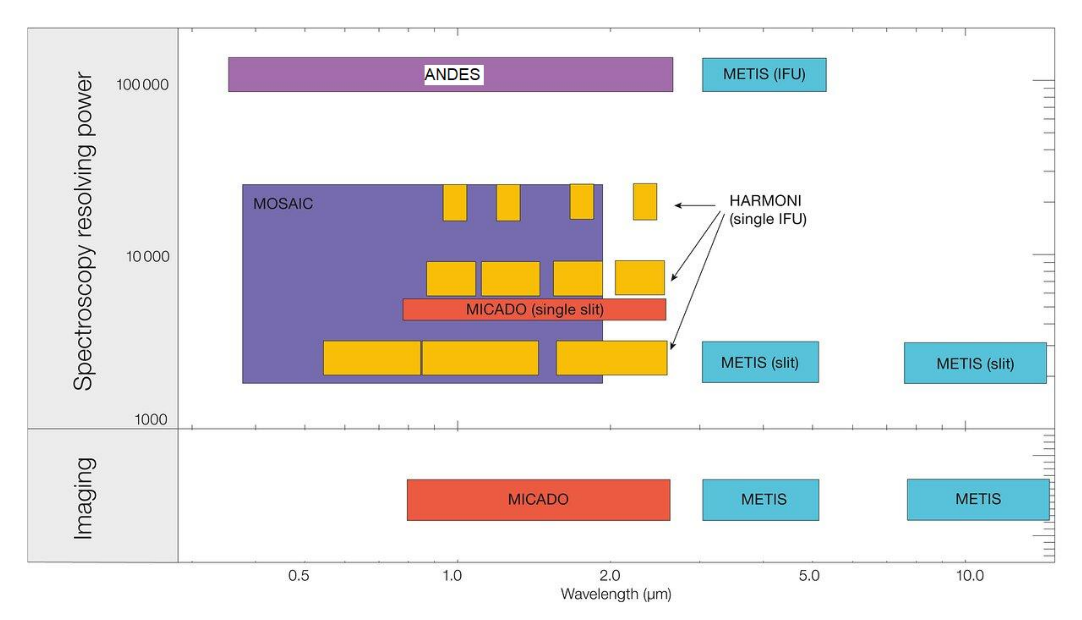
- Flagship science cases: the detection of life signatures in Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration (both require high resolution spectroscopy)

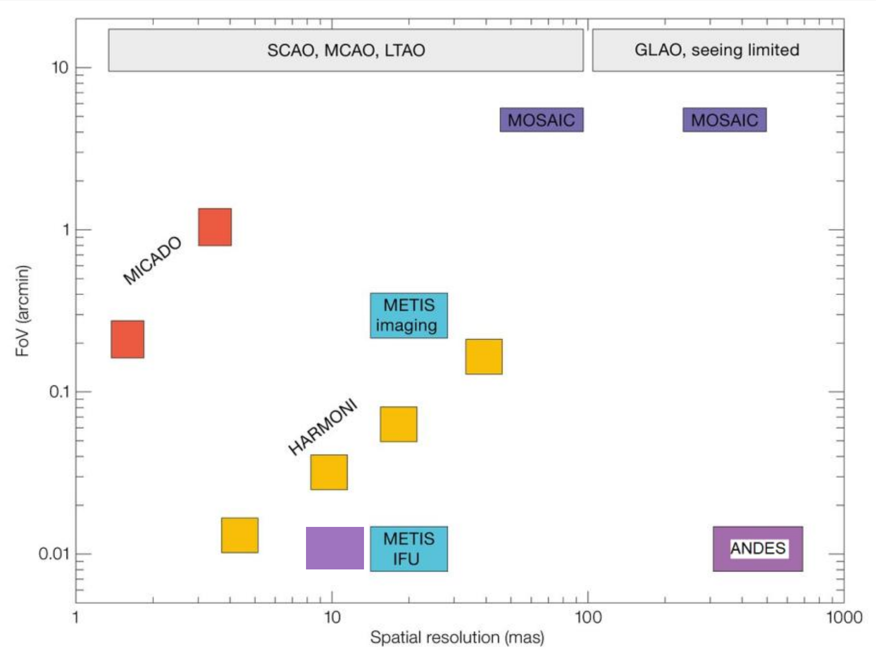
High resolution spectroscopy

- Interdisciplinary (from Exoplanets to Stars, to Cosmology and Fundamental Physics)
- Successful ESO tradition (UVES, FLAMES, CRIRES, X-shooter, HARPS, ESPRESSO)

ANDES: the parameter space

ANDES (ArmazoNes high Dispersion Echelle Spectrograph) is the high-resolution, high-precision, modular, fiber fed, optical-infrared spectrograph for the ESO/ELT (European Southern Observatory/Extremely Large Telescope) thought to study astronomical objects that require highly sensitive observations.





- Simultaneous spectral range 0.4-1.8 μm (0.35-2.4 μm goal)
- Spectral resolution ~100,000
- Interchangeable, observing modes: seeing limited & SCAO+IFU module
- Sensitivity: 1h, 10σ, AB = 21.7

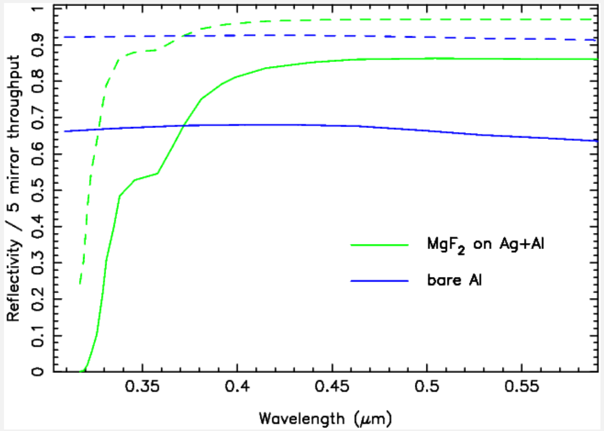
CUBES: broad context

Cassegrain U-Band Efficient Spectrograph: the ultimate UV instrument for VLT.

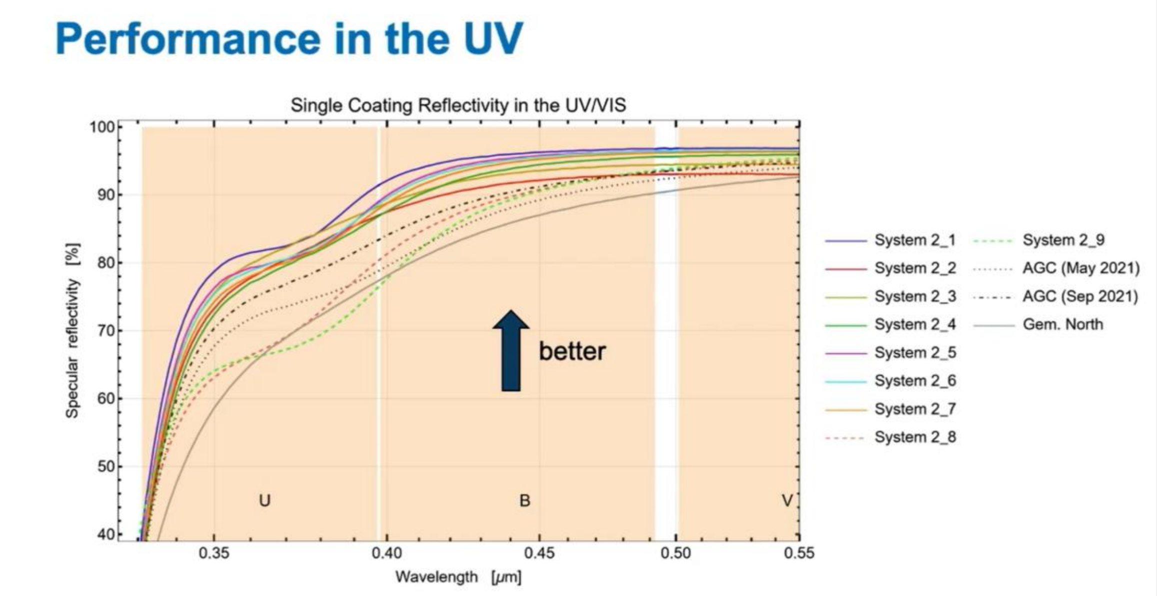
- High-res spectroscopy of the near-UV regime provides access to key lines of stellar spectra
- The near-UV range is also critical in extragalactic observations (V. D’Odorico talk)

Unique discovery space
Competitive for observations at λ < 400 nm well into the 2030s (Evans et al. 2016)

ELT Performance



https://www.eso.org/sci/facilities/eelt/science/drm/tech_data/telescope/



Ronald Holzlöhner, *Optimization of Protected Silver Coating Recipes for E-ELT Telescope Mirrors (Conference Presentation), SPIE 2024*

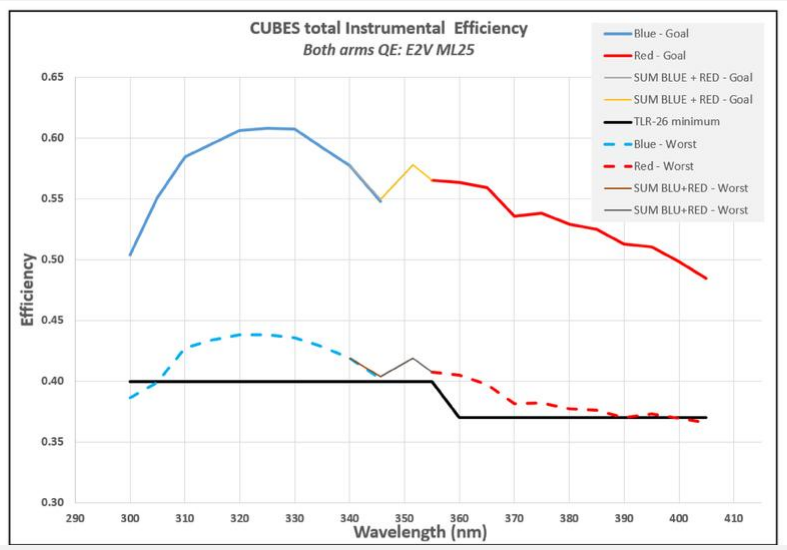
CUBES: the parameter space

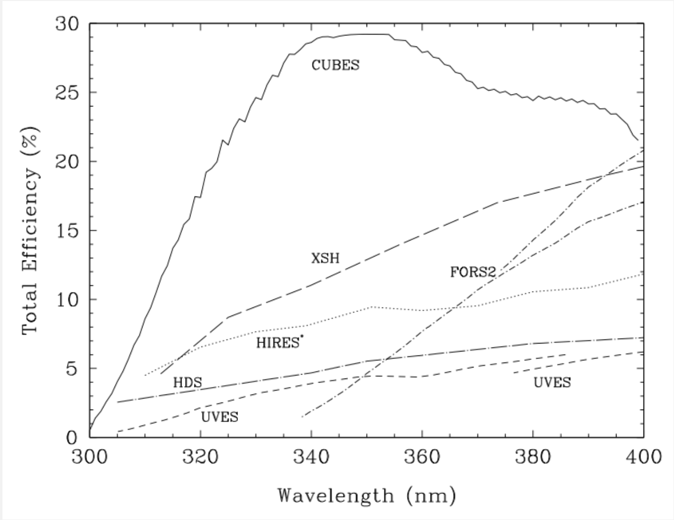
- **Spectral range**: CUBES shall provide a spectrum of the target over the entire wavelength range of 305–400 nm in a single exposure (goal: 300 – 420 nm)

- **Efficiency**: The efficiency of the spectrograph, from slit to detector (included), shall be > 40% for 305–360 nm (goal > 45%, with > 50% at 313 nm), and > 37% (goal 40%) between 360 and 400 nm

- **Resolution**: R ~ 24000 (HR mode) and R ~ 7000 (LR mode)

- **Signal-to-noise ratio**: In a one hour exposure the spectrograph shall be able to obtain, for an A0-type star of U = 17.5 mag (goal U 18 mag), a SNR = 20 at 313 nm for a 0.007 nm wavelength pixel (at an airmass of 1.16).





ANDES and CUBES: INAF context

INAF is the technological lead of both instruments (ANDES – PI: **A Marconi**, CUBES – PI: **S. Covino**)

Agreement No. 99240/ESO/21/108794/ADE

for the

Design, development, manufacturing, assembly, integration, installation on site and commissioning of the Cassegrain U-Band Efficient Spectrograph (CUBES) on one of the VLT UT telescopes

BETWEEN

the **European Organisation for Astronomical Research in the Southern Hemisphere**, hereinafter referred to as **ESO,** having its Headquarters at Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany, represented by its Director General, Xavier Barcons,

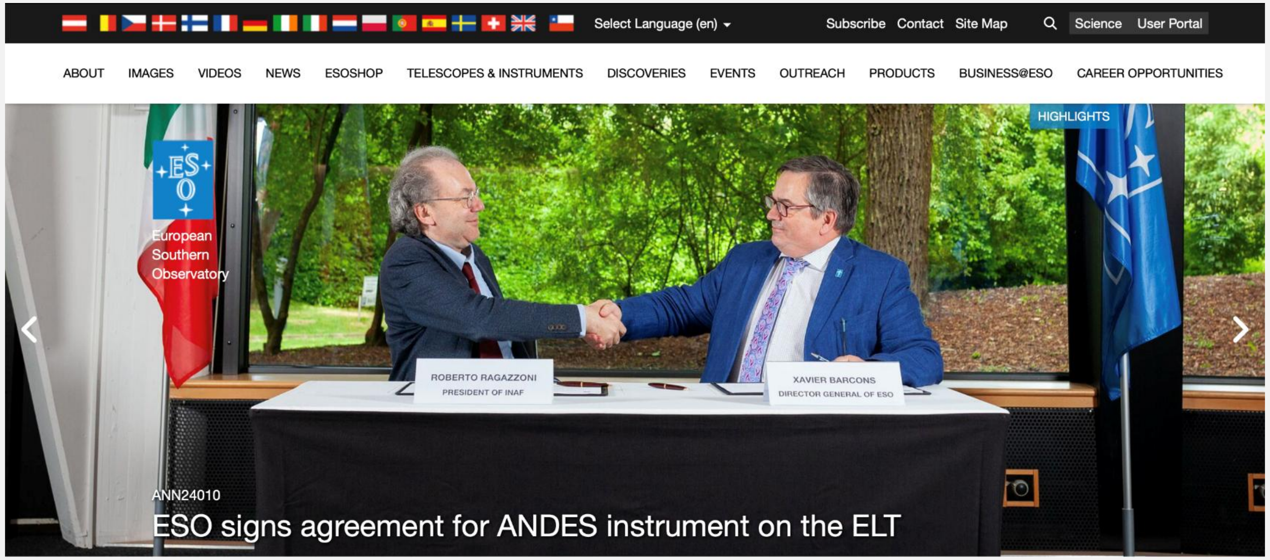
on the one hand,

AND

Istituto Nazionale di Astrofisica (INAF), having its Headquarters at Viale del parco Mellini 84, I-00136, Roma, Italy, hereafter referred to as the "**Institute**", represented by its President, Prof. Marco Tavani, in the name and on behalf of the "VLT UV Spectrograph Consortium", consisting of the Members listed below,

on the other hand.

CUBES, 15 February 2022



ANDES, 5 June 2024

ANDES – CUBES – HWO: technological synergies

ANDES

Organization

The HWO Technology Plan is organized along three ***tracks***:

Each track is further divided into ***lanes*** associated with specific technology components or capabilities

Coronagraph System Technologies

- Starlight Suppression
- Deformable Mirrors
- Sensing & Control
- Low-noise / Noiseless Detectors
- Spectroscopy
- Near-UV Capability
- Post-Processing

Ultra-stable Telescope System Technologies

- Ultra-stable Mirrors
- Ultra-stable Structures
- Thermal Control System
- Sensing & Control
- Low-Disturbance Systems
- Deployable Systems

High-sensitivity UV/VIS Instrumentation Technologies

- Far-UV Mirror Coatings
- Near-UV / VIS Detectors
- Far-UV Detectors
- Multi-object Selection / Integral Field Unit
- UV Gratings & Filters

credits: *Matthew R. Bolcar (GSFC) & Feng Zhao (JPL)*
HWO Chief Technologists

Technological challenges

Common technological challenges: **UV Efficiency, Stability**, **Contrast**,

CUBES: UV Spectroscopy

- Reflective coatings and specialized materials
- Compact optics for the Cassegrain focus

ANDES: high precision and stability

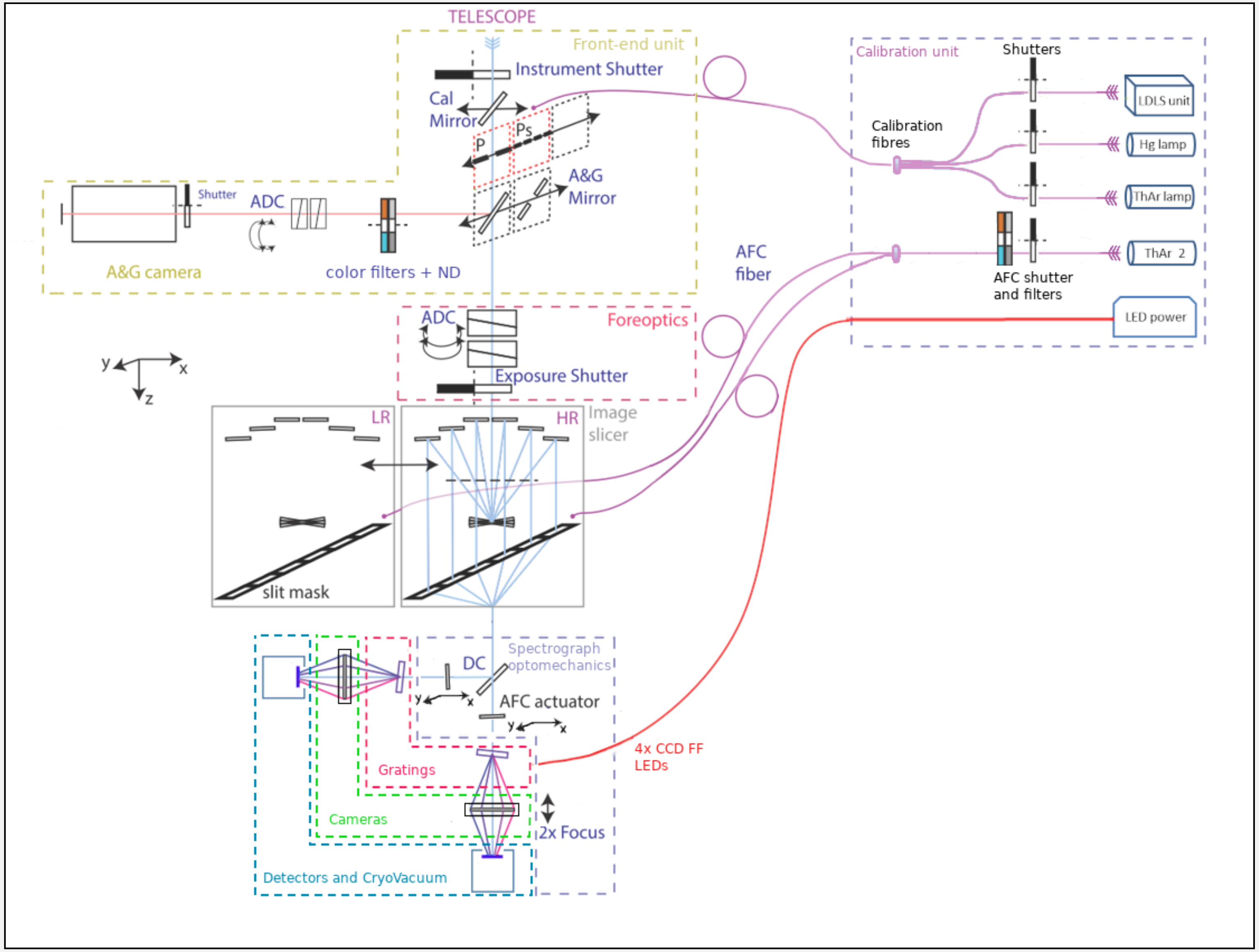
- Thermal stabilization at the mK level
- Absolute calibration (e.g., laser frequency combs)
- Engineering challenges

HWO: Advanced Space Technologies

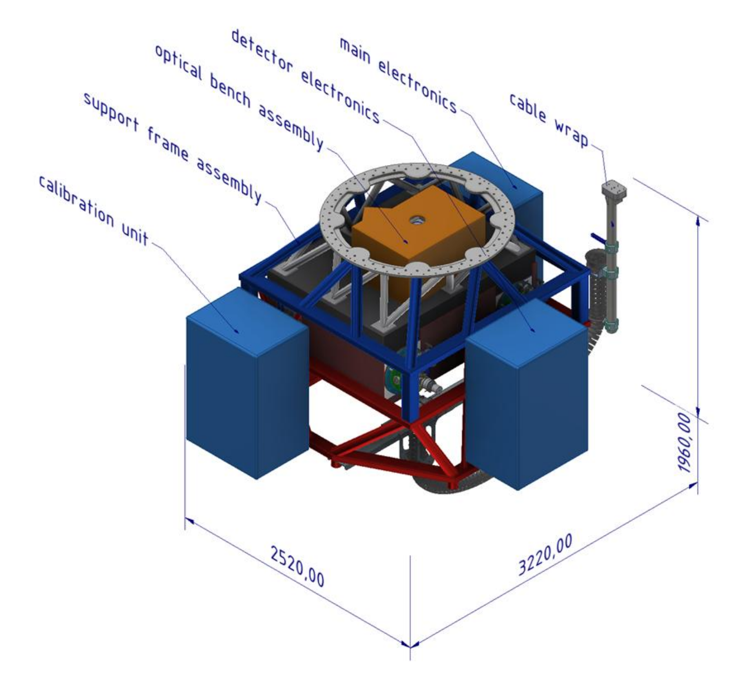
- High-contrast coronagraphs
- Ultra-stable optics and precision metrology

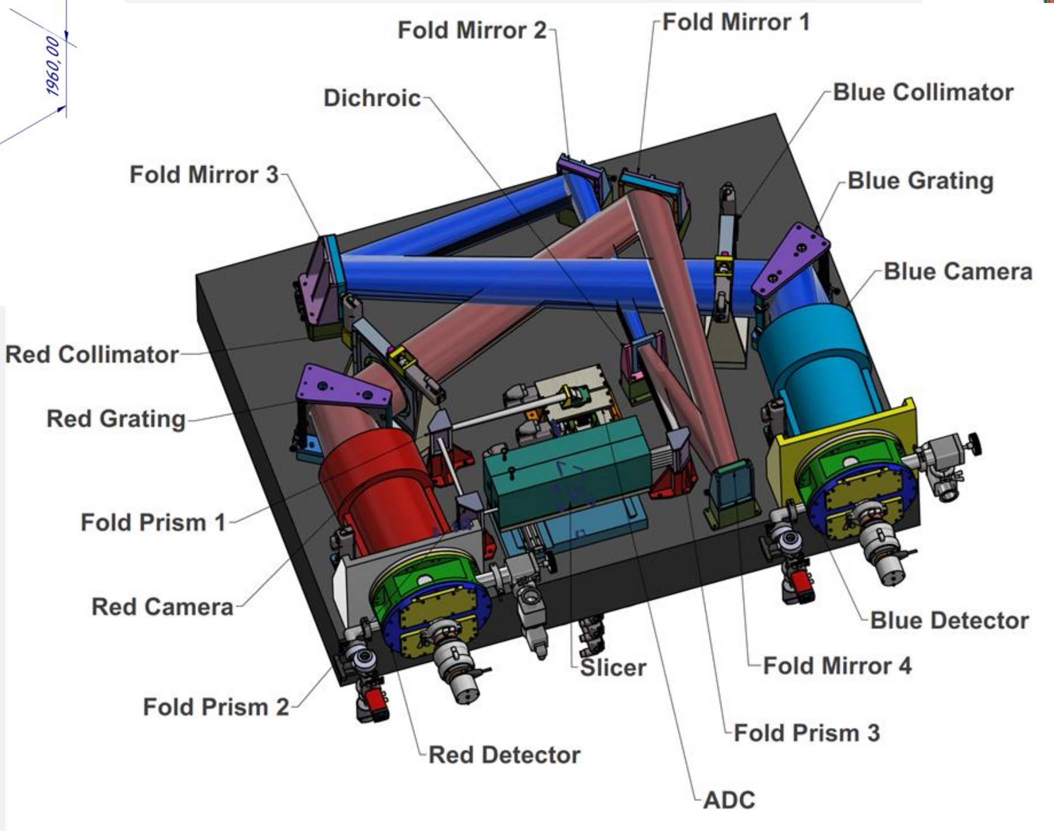
CUBES

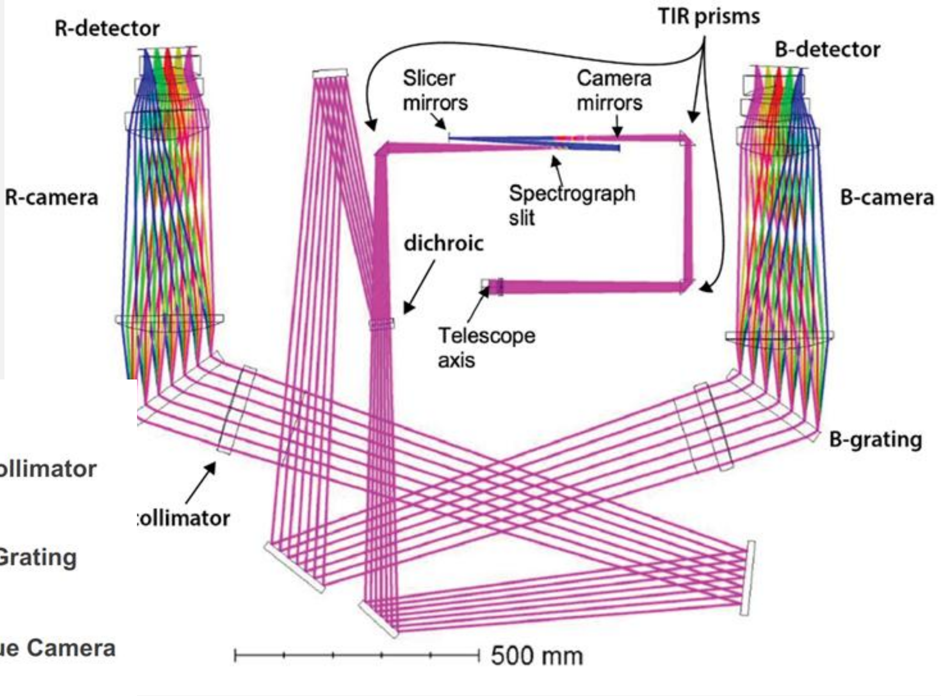
CUBES: functional overview



CUBES: system







CUBES: grating specifications

Table 1: Specification of the CUBES UV-gratings.

Type of grating	binary transmission grating	
	grating #1	grating #2
Line density	3600 lines/mm	3112 lines/mm
corresponding grating period	278nm	312nm
Operating wavelength range	300 – 352 nm	346 – 405 nm
Angle of incidence	36.07°	35.89°
Grating size (substrate)	180mm x 220mm	
Clear aperture	167mm x 197mm	
Diffraction efficiency	90%, polarization and wavelength averaged	
Polarization independency	best effort, not finally specified	
Wavefront quality and substrate wedge	<100nm rms	
A/R coating on non-grating side	R<1% within relevant spectral range for each grating	

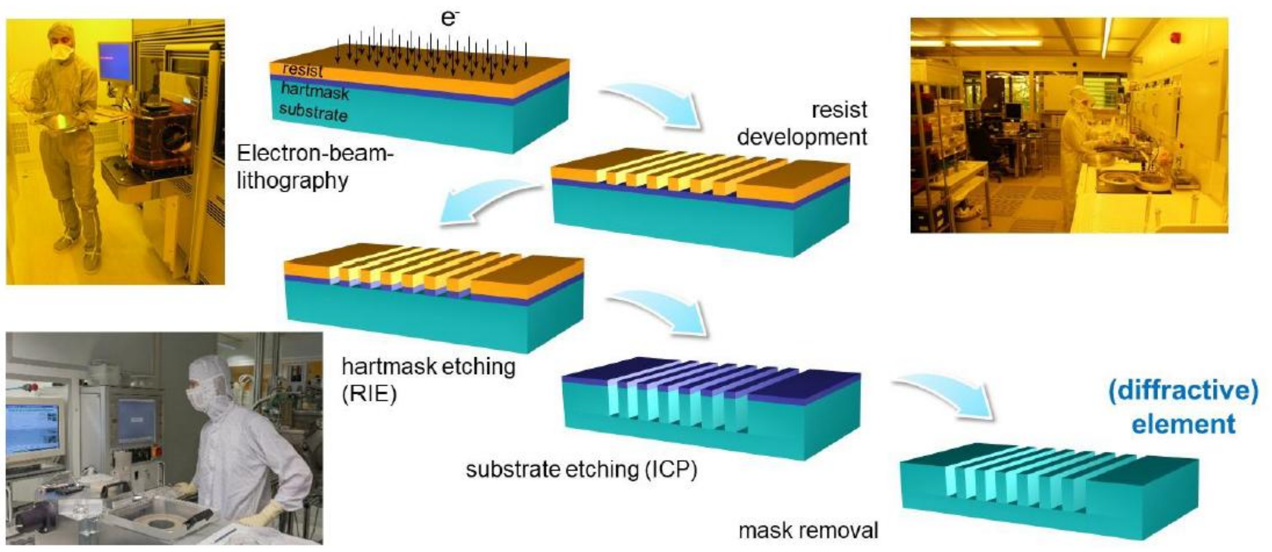
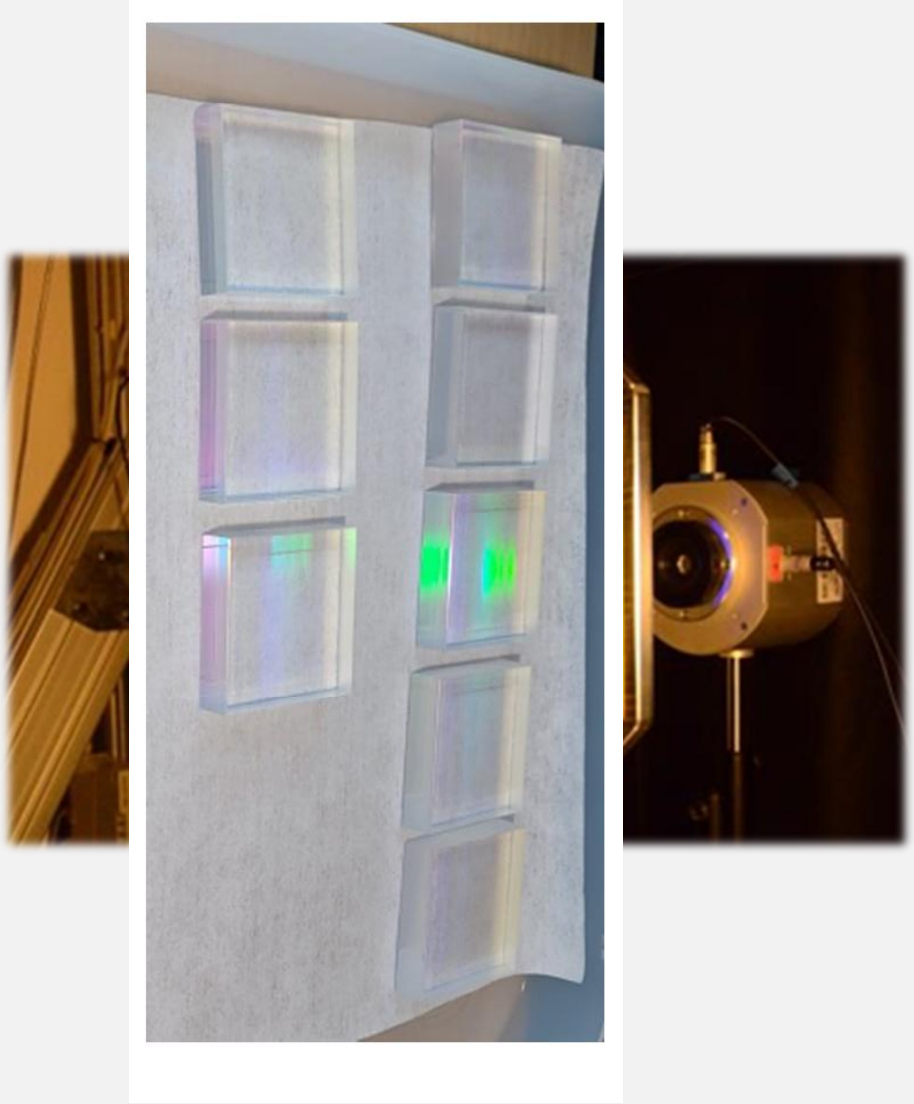
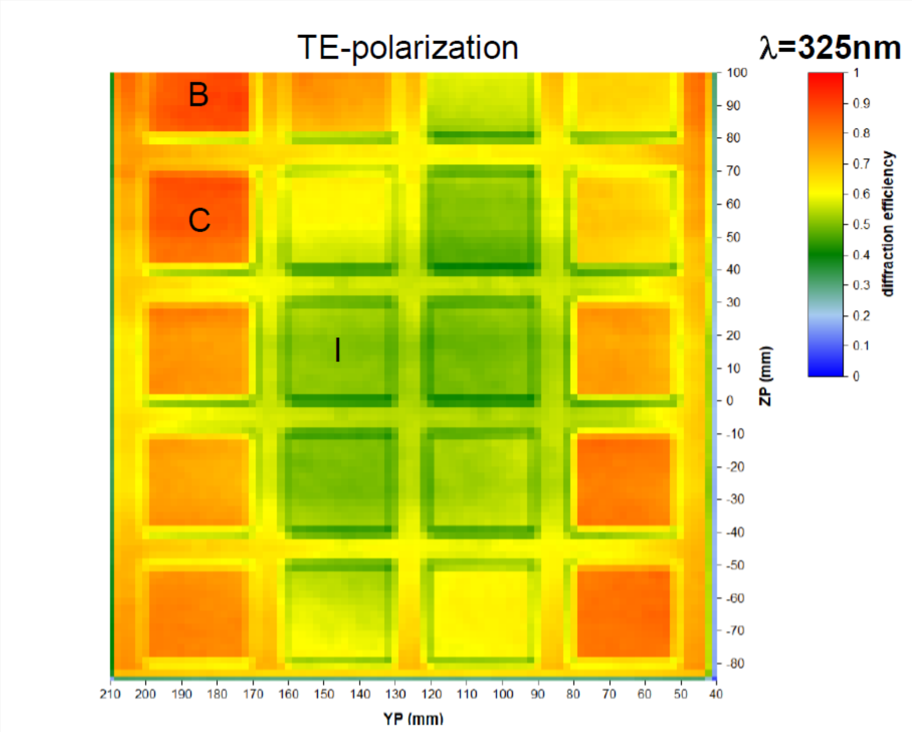


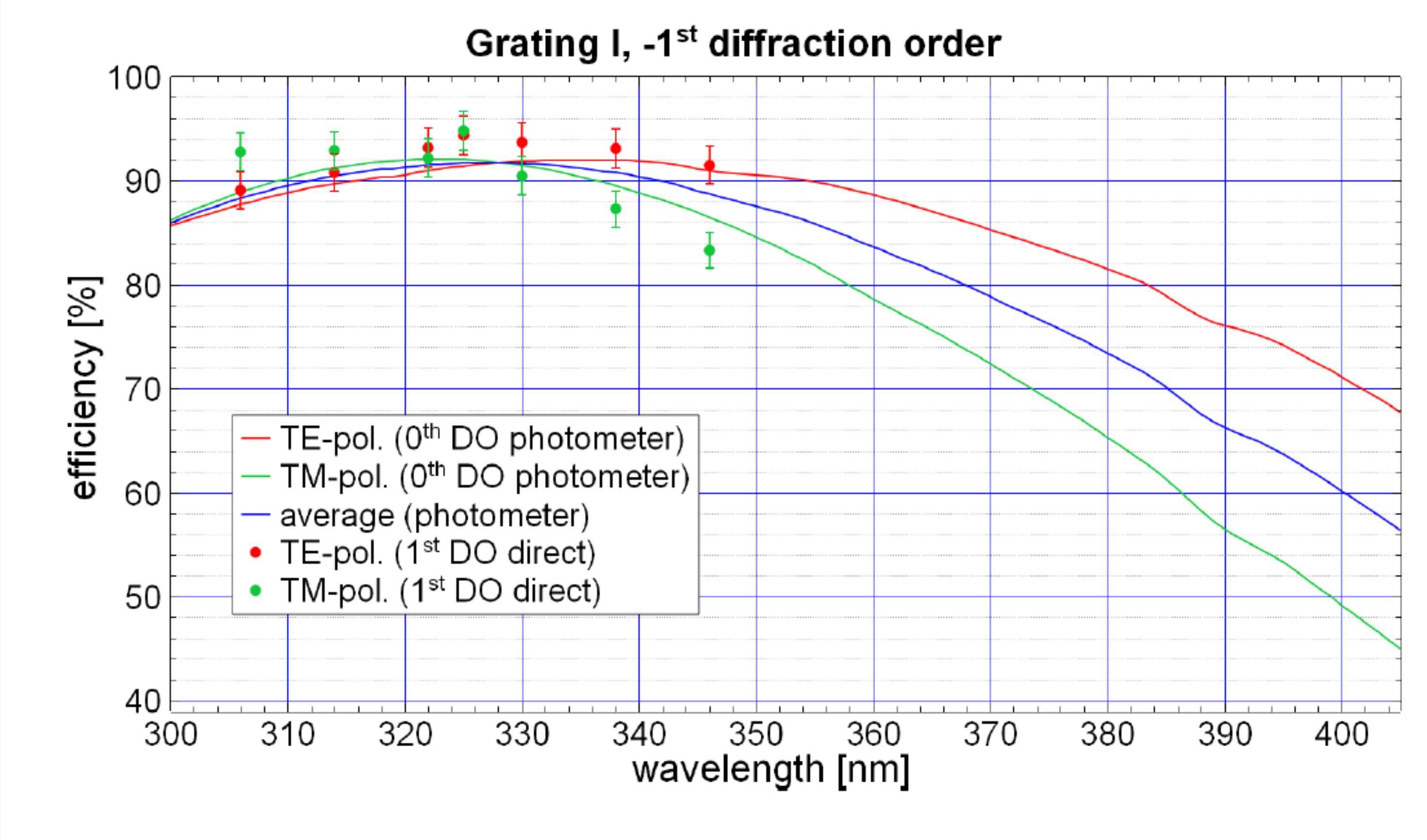
Figure 3. Manufacturing process flow for the realization of the binary CUBES-grating in a fused silica substrate.



Zeitner et al., Proc. of SPIE Vol. 12188 121884Y-3

CUBES: grating efficiency





CUBES: image slicer

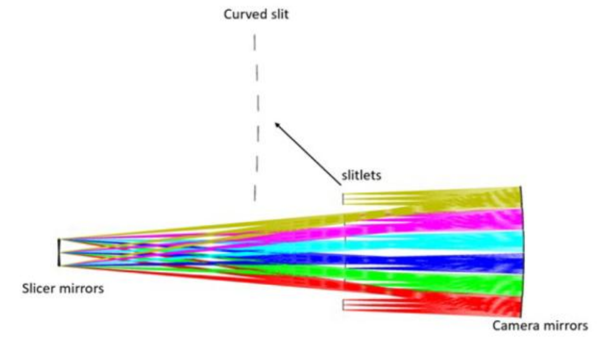


Figure 3: Optical design of the HR image slicer.

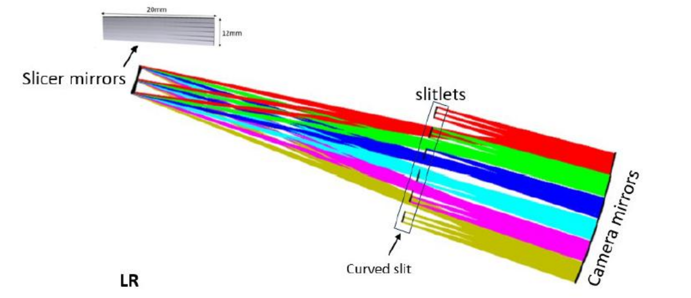
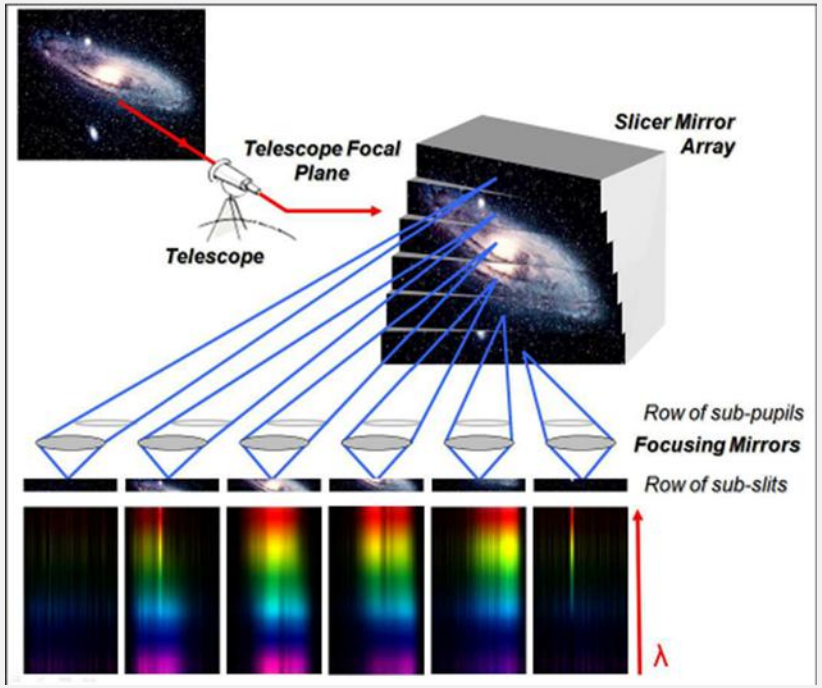


Figure 4: Optical design of the LR image slicer.

Roughness of slicer mirrors	< 1nm RMS
Coating for slicer mirrors	Dielectric coating (preference) or metallic coating optimised within 300 to 405nm with a minimum reflectivity of 97.5% per mirror and a goal of 99%.
Number of camera mirrors	6
Curvature of camera mirrors	Spherical
Size of camera mirrors	10mm x 16mm
Substrate for the camera mirrors	Fused Silica
Coating for the camera mirrors	Dielectric coating within 300 to 405nm with a minimum reflectivity of 97.5% per mirror and a goal of 99%.
Baseplate substrate	Fused Silica or a material with a similar CTE.
Specification for efficiency for the whole image slicer	Minimum efficiency of 95% with a goal of 98% within 300 to 405nm.
Output Focal-ratio (at image slicer image focal	For all configurations, the output focal-ratio



A. Calcines, *Design of the VLT-CUBES image slicers: Field re-formatters to provide two spectral resolutions, ExA, Volume 55, pages 267–280, (2023)*

CUBES: Italian contribution in optics

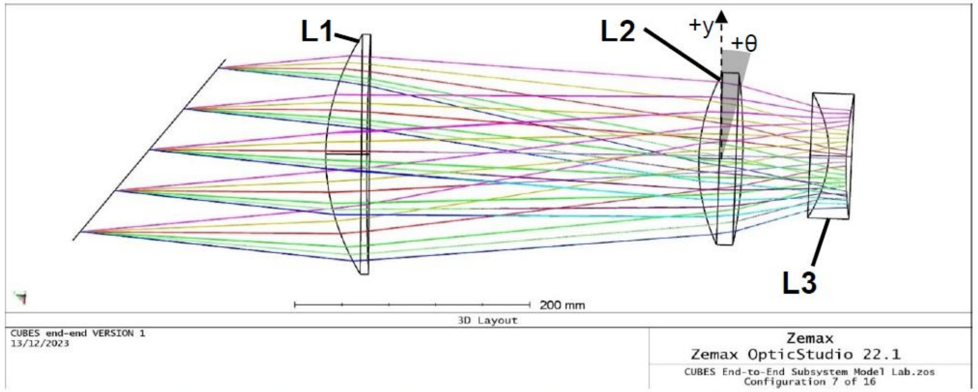


Figure 1: Layout of the 3 camera lenses in the barrel.

TOMELLERI S.R.L.
Quality and innovation

TOMELLERI ASTRONOMY AND RESEARCH	**CUBES** Collimator and Camera Lenses Ottiche per lo spettrografo CUBES	Doc: Tech. Proposal Date: 7 Feb. 2025 Page: 5 of 43

1. Executive summary

This technical proposal highlights the main driving factors and critical areas identified. Primary design drivers include optical throughput, image quality, and thermal and mechanical stability. High efficiency in the U-band has been achieved by selecting high transmission materials and optimizing anti-reflection coatings. The image quality is ensured through accurate lens manufacturing, alignment, and stable mounting. Thermal and mechanical stability are maintained by optimized camera barrels, stable lens mount interfaces, and using high stiffness materials and designs.

Main critical areas:

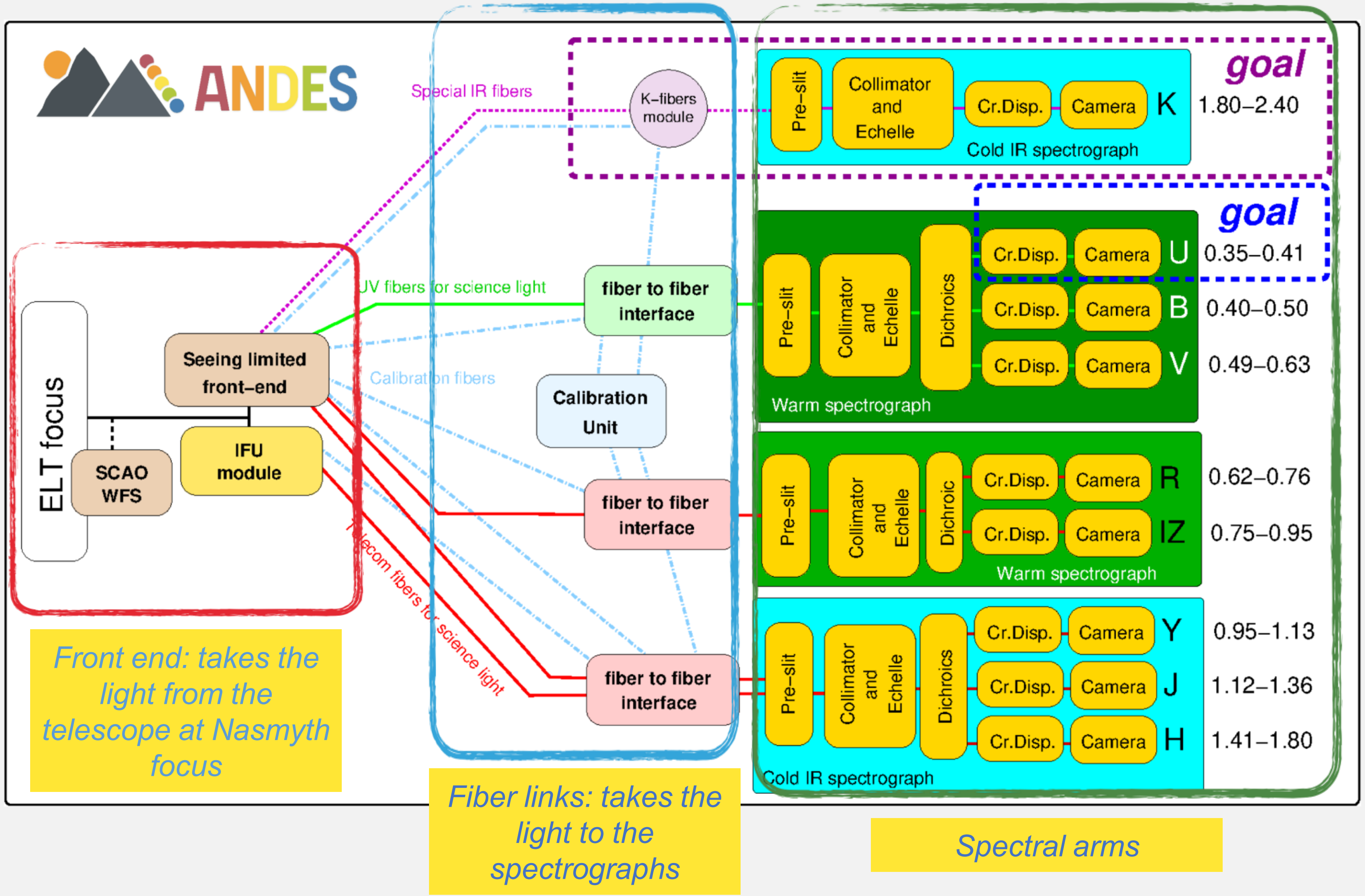
1. **Large Aspherical Lenses:** Advanced manufacturing techniques and state-of-the-art optical metrology are required to meet the challenging specifications.
2. **UV AR Coatings:** Low-absorption materials and high-energy deposition processes are used to achieve the required performance.
3. **Asymmetric Optical Design:** Innovative alignment procedures are necessary due to the lack of a common optical axis.

A&G and fore-optics

GESTIONESIL
SOCIETÀ ITALIANA LAVORAZIONE OTTICA

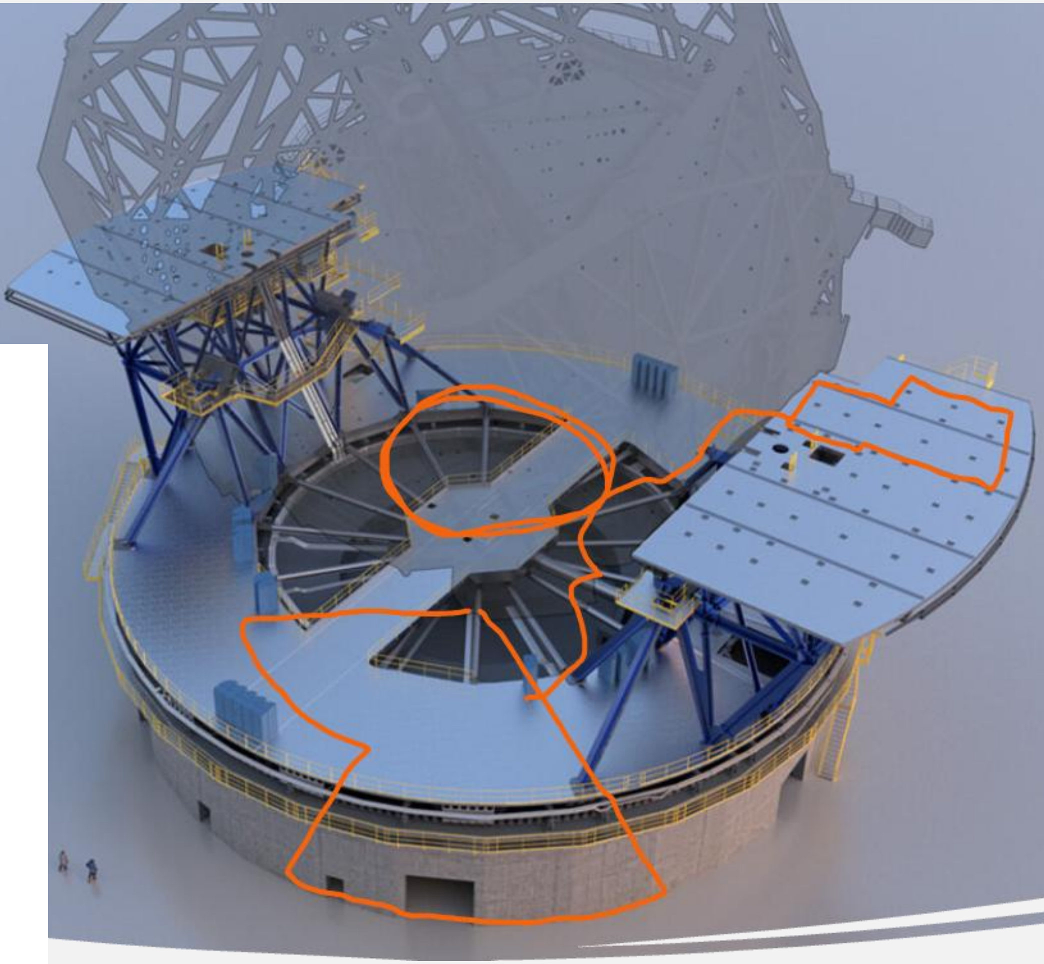
ANDES

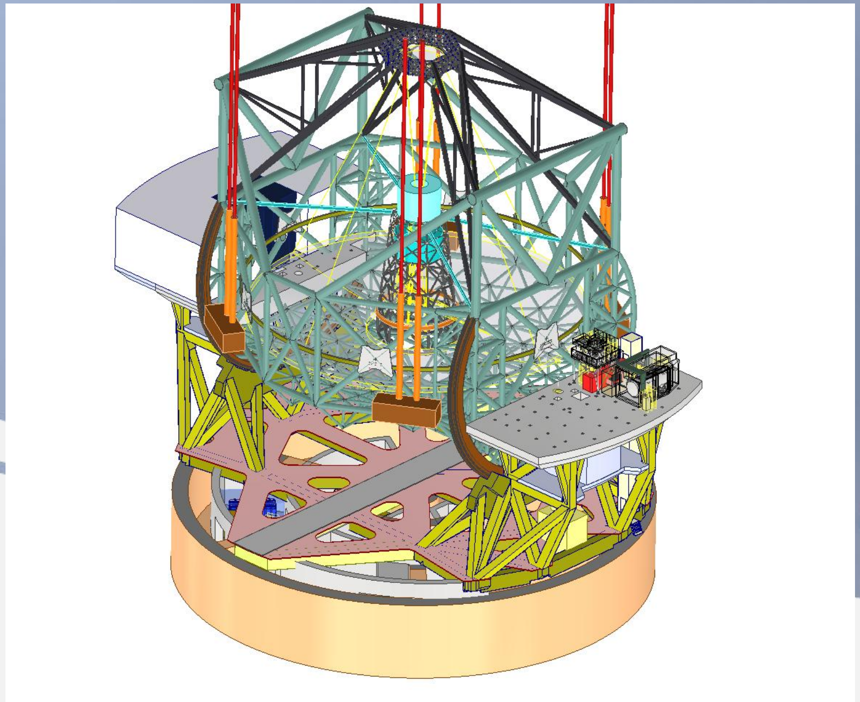
ANDES: functional overview



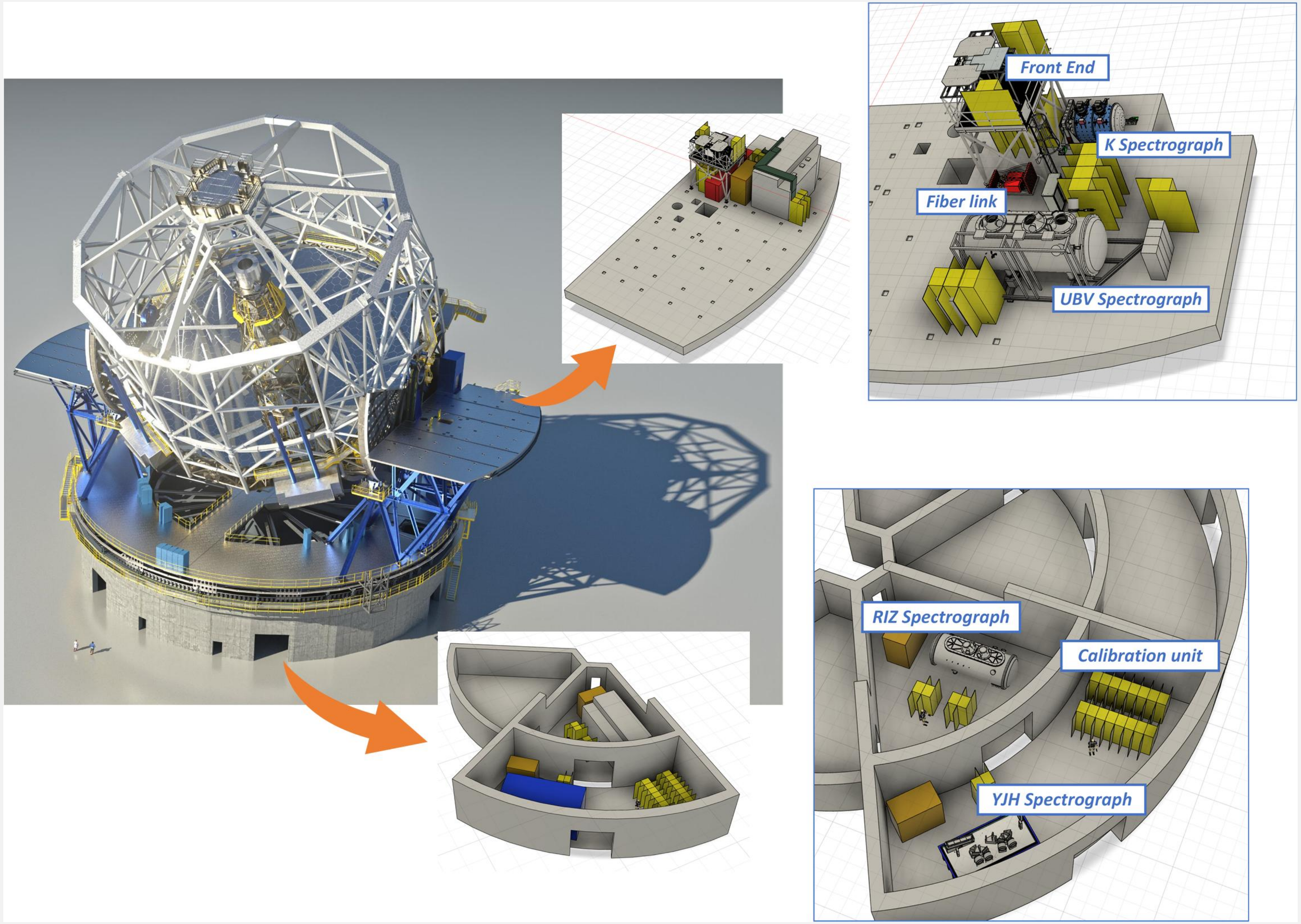
- Modular fiber-fed cross dispersed echelle spectrograph
- Simultaneous range 0.4-1.8 µm (ultra-stable BV+RIZ+YJH) Goal 0.37-2.4 µm (with U and K); Resolution ~100,000
- Several interchangeable, observing modes: Seeing limited & SCAO+IFU

ANDES: deployment @ELT

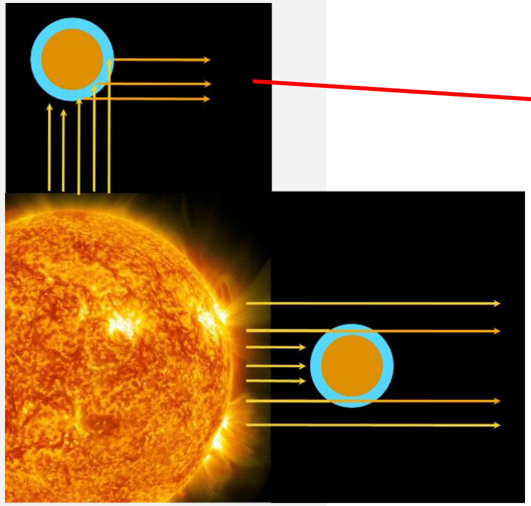


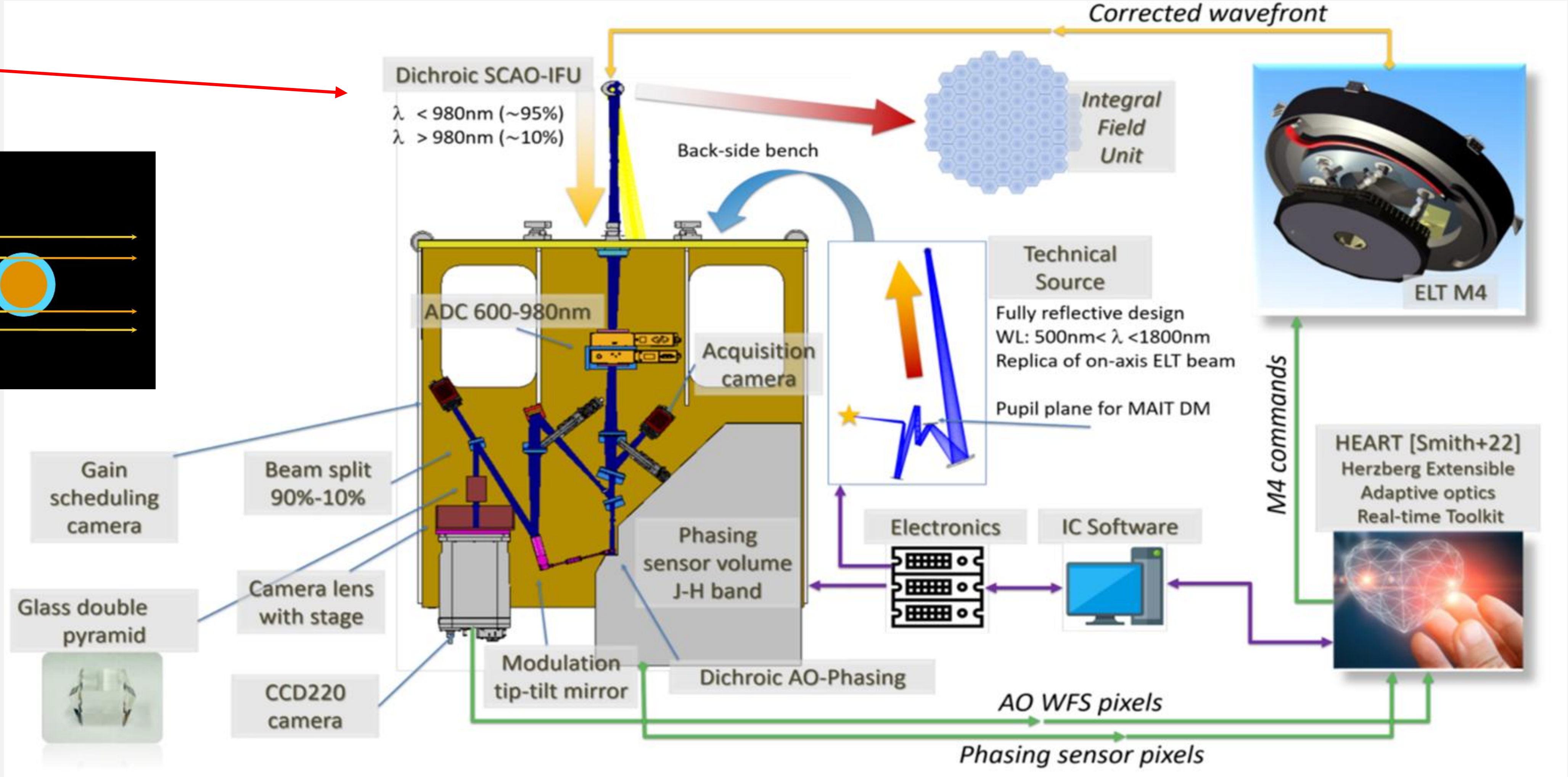


ANDES: design



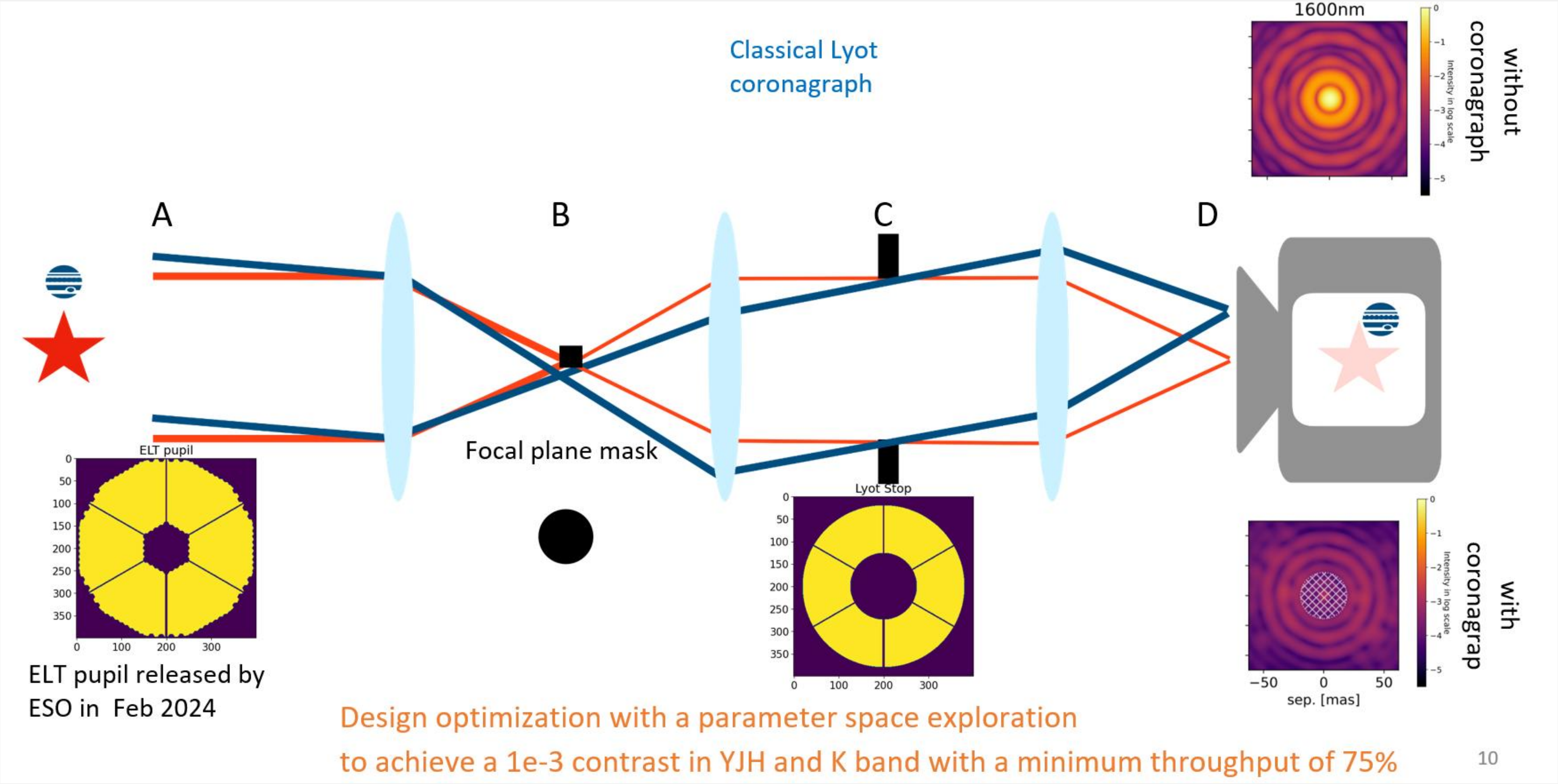
ANDES: SCAO





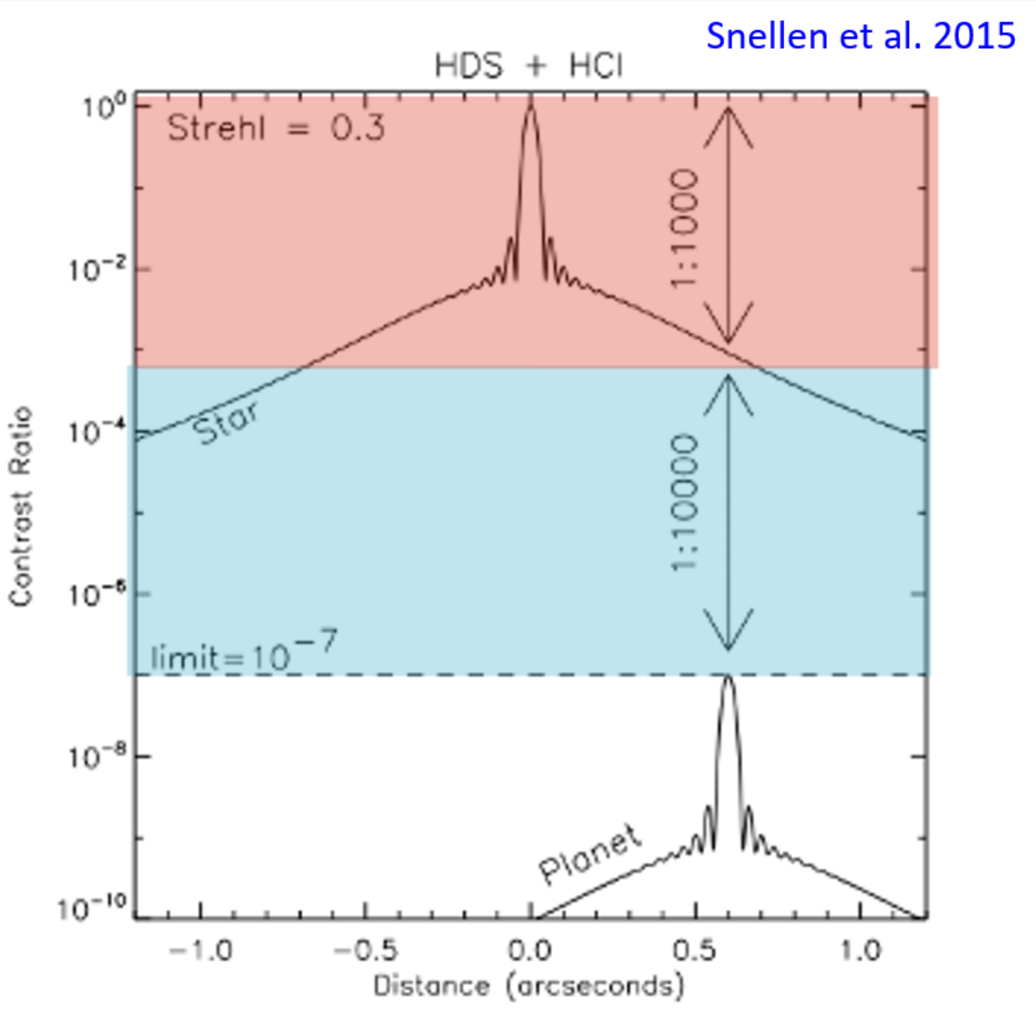
Corrected wavefront
Dichroic SCAO-IFU
λ < 980nm (~95%)
λ > 980nm (~10%)
Back-side bench
Integral Field Unit
ELT M4
Technical Source
Fully reflective design
WL: 500nm< λ <1800nm
Replica of on-axis ELT beam
Pupil plane for MAIT DM
ADC 600-980nm
Acquisition camera
M4 commands
HEART [Smith+22]
Herzberg Extensible Adaptive optics Real-time Toolkit
Gain scheduling camera
Beam split 90%-10%
Phasing sensor volume J-H band
Electronics
IC Software
Glass double pyramid
Camera lens with stage
Modulation tip-tilt mirror
Dichroic AO-Phasing
CCD220 camera
AO WFS pixels
Phasing sensor pixels

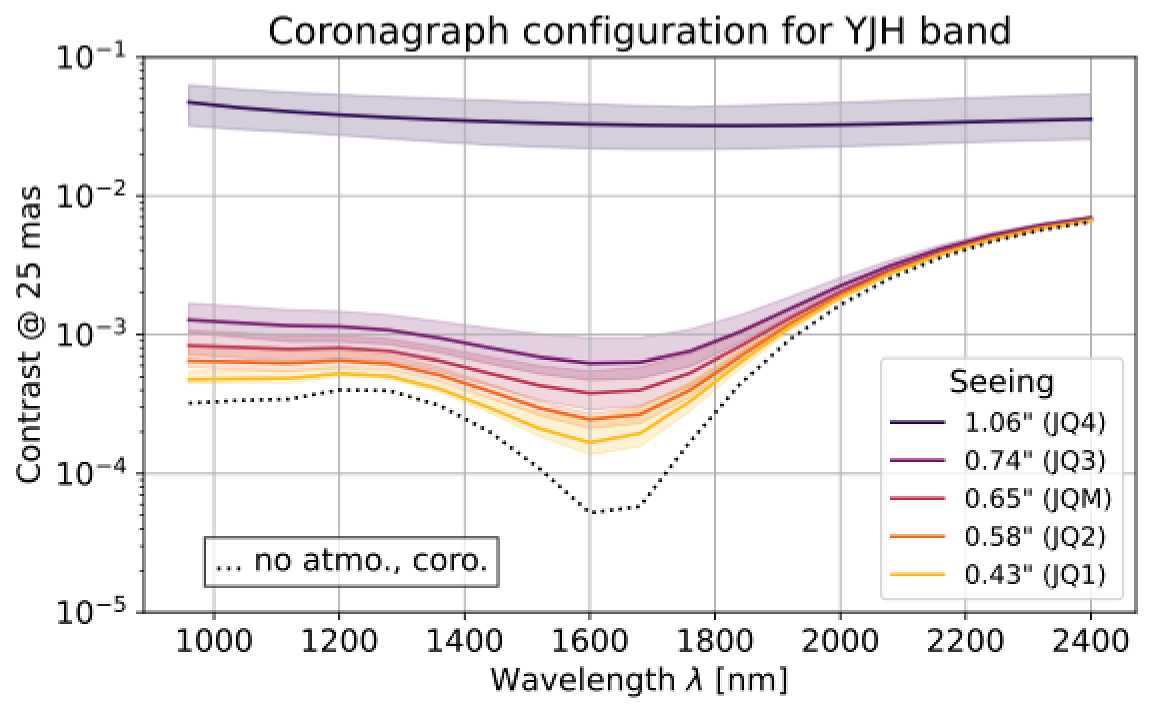
ANDES: coronagraph



credits: A. Chiavassa et al., OCA-LAGRANGE

ANDES: coronagraph

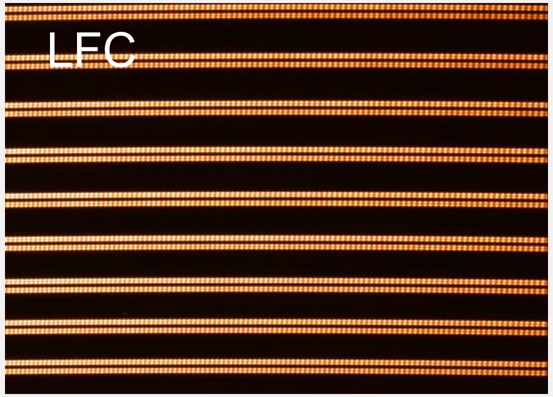




Except for the JQ4 conditions in purple, the top plot shows that the image contrast is better than $2x10^{-3}$ in all conditions and better than 10^{-3} in JQM (median conditions) from Y to K bands (980 to 2420nm).

ANDES: calibration

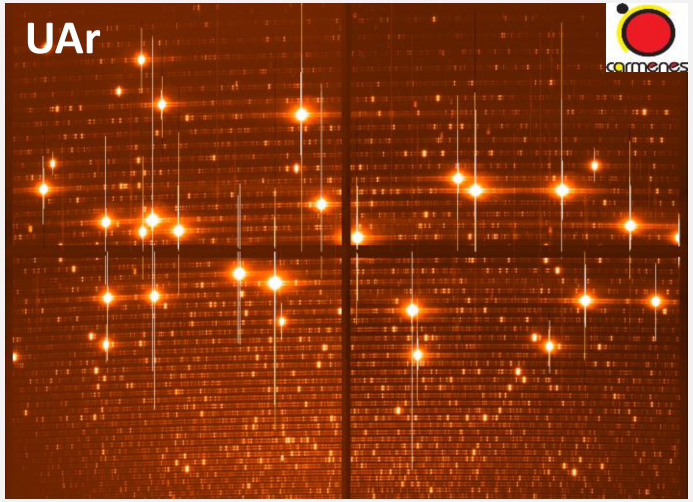
- ➢ Critical for achieving sub-m/s radial velocity precision
- ➢ Provide a stable and dense grid of reference lines across the full spectral range
- ➢ Enable absolute wavelength calibration with unprecedented accuracy



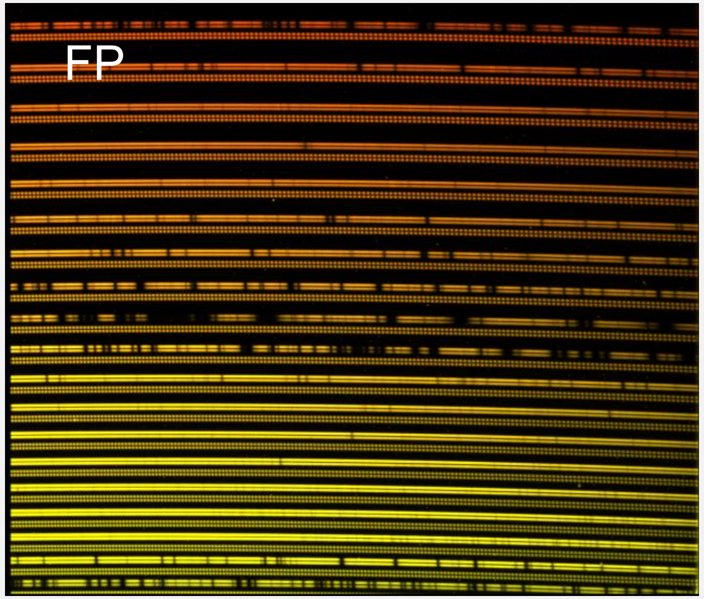
Key Features:

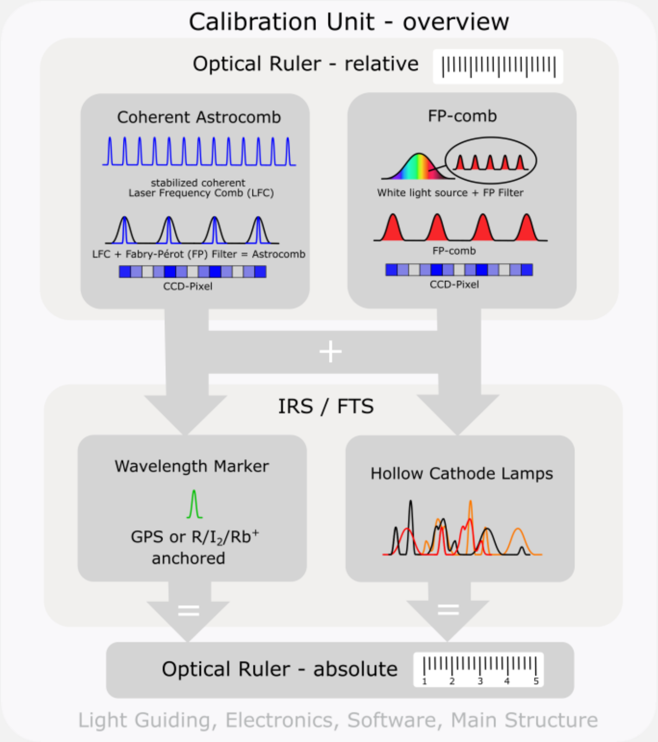
- Line spacing matched to spectral resolution
- Broad spectral coverage
- Long-term frequency stability traceable to atomic clocks

1000 nm



550 nm





ANDES: thermal stability

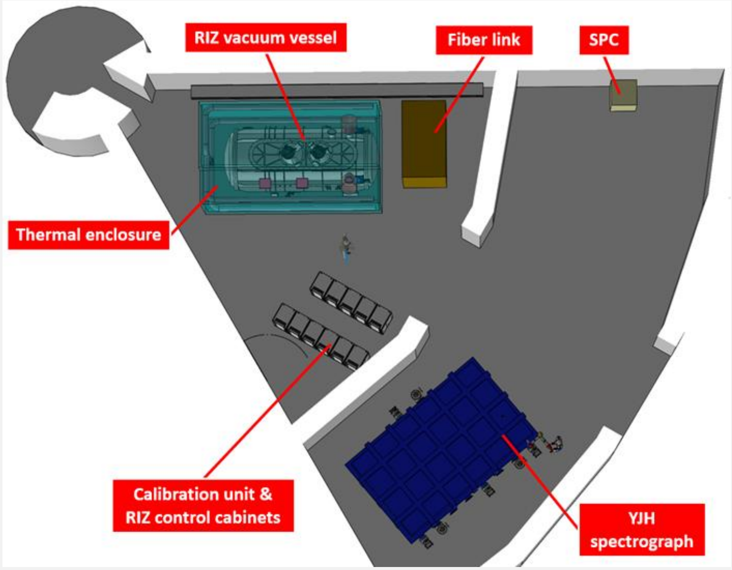
Spectrographs are extremely sensitive to thermal drifts. Even sub-micron expansion or contraction can affect radial velocity precision. Achieving milli-kelvin control is crucial for sub-m/s stability.

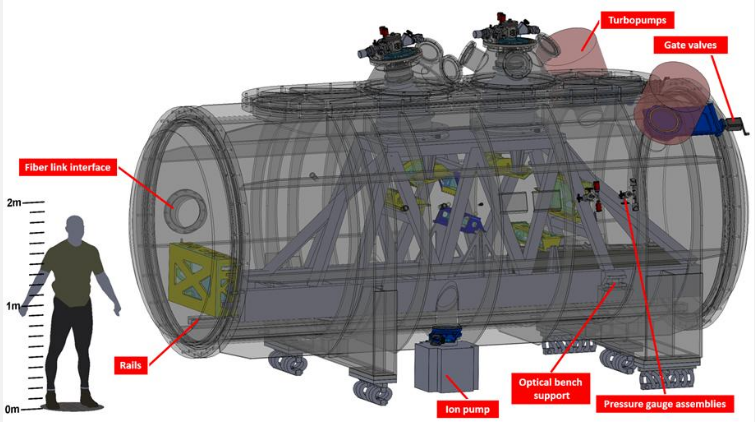
Engineering Solutions:

- Active thermal control systems with multiple feedback loops
- Isolation from ambient temperature fluctuations using vacuum chambers and multi-layer insulation temperature-stabilized enclosures for optical benches and detectors

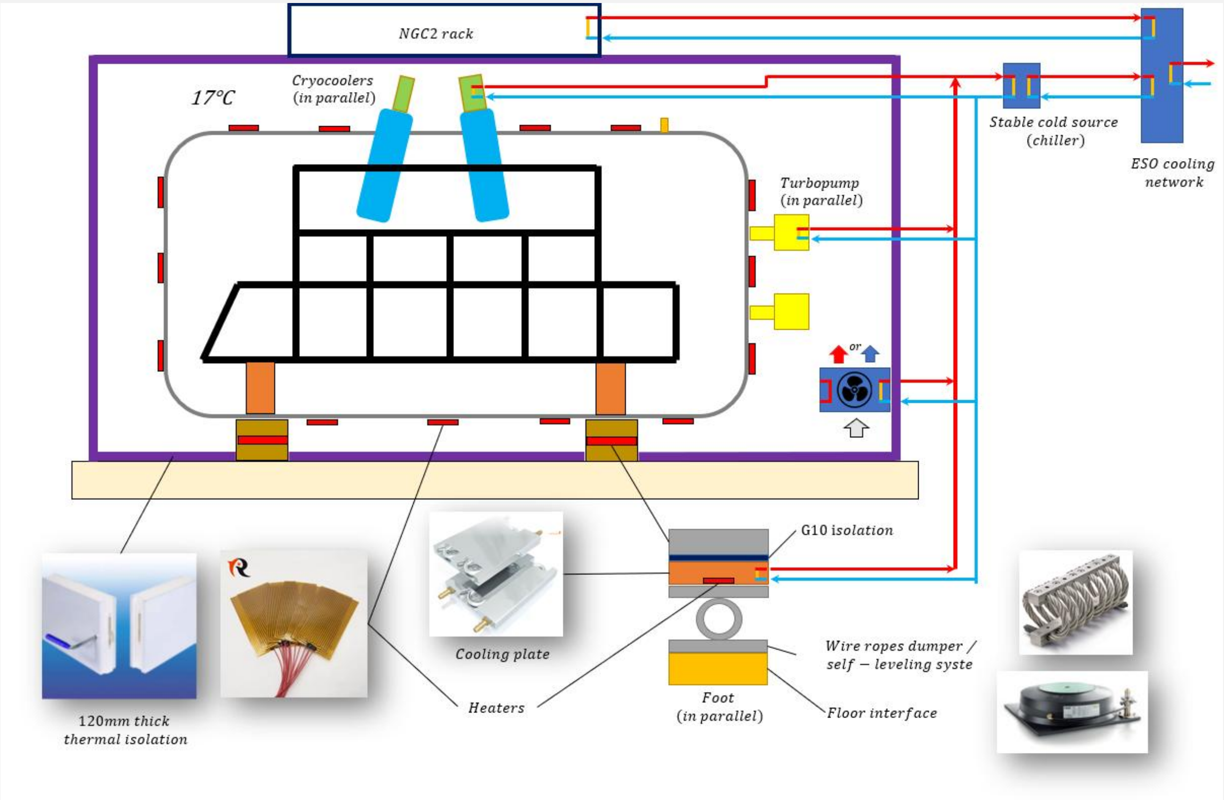
Key Technologies:

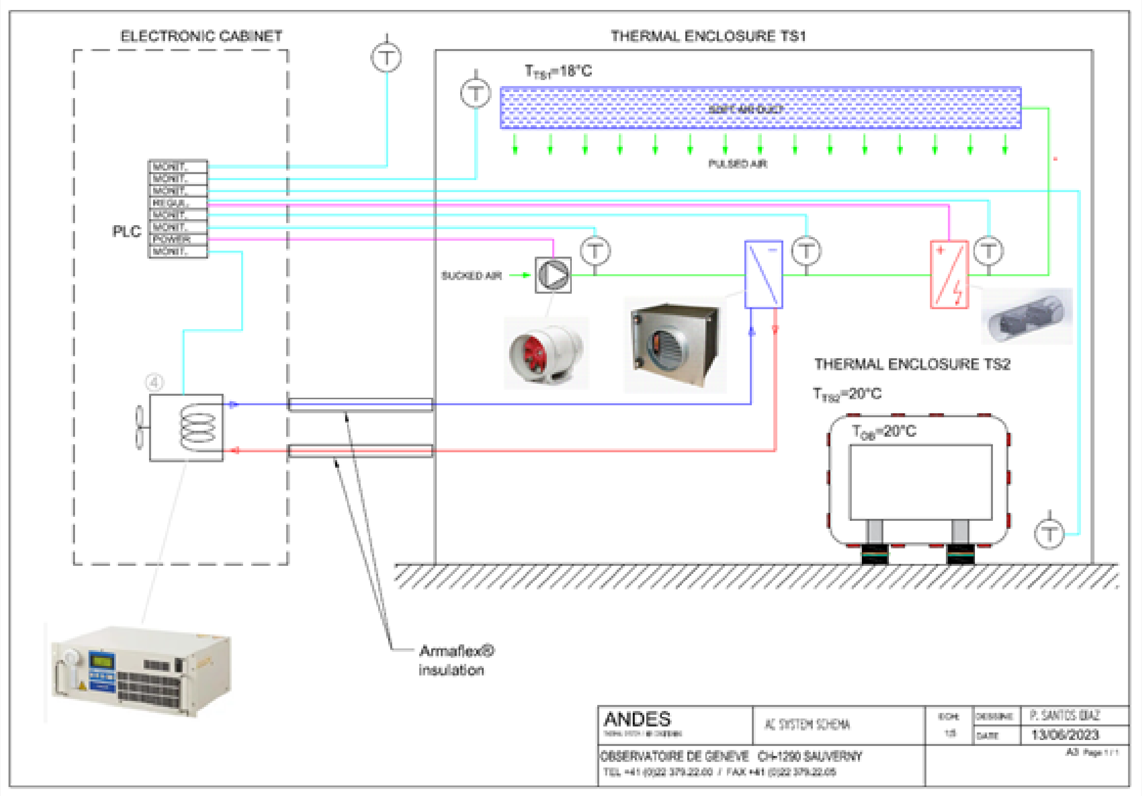
- Precision temperature sensors with <1 mK resolution
- Low-noise PID controllers with real-time monitoring
- Radiative and conductive thermal shielding for critical components



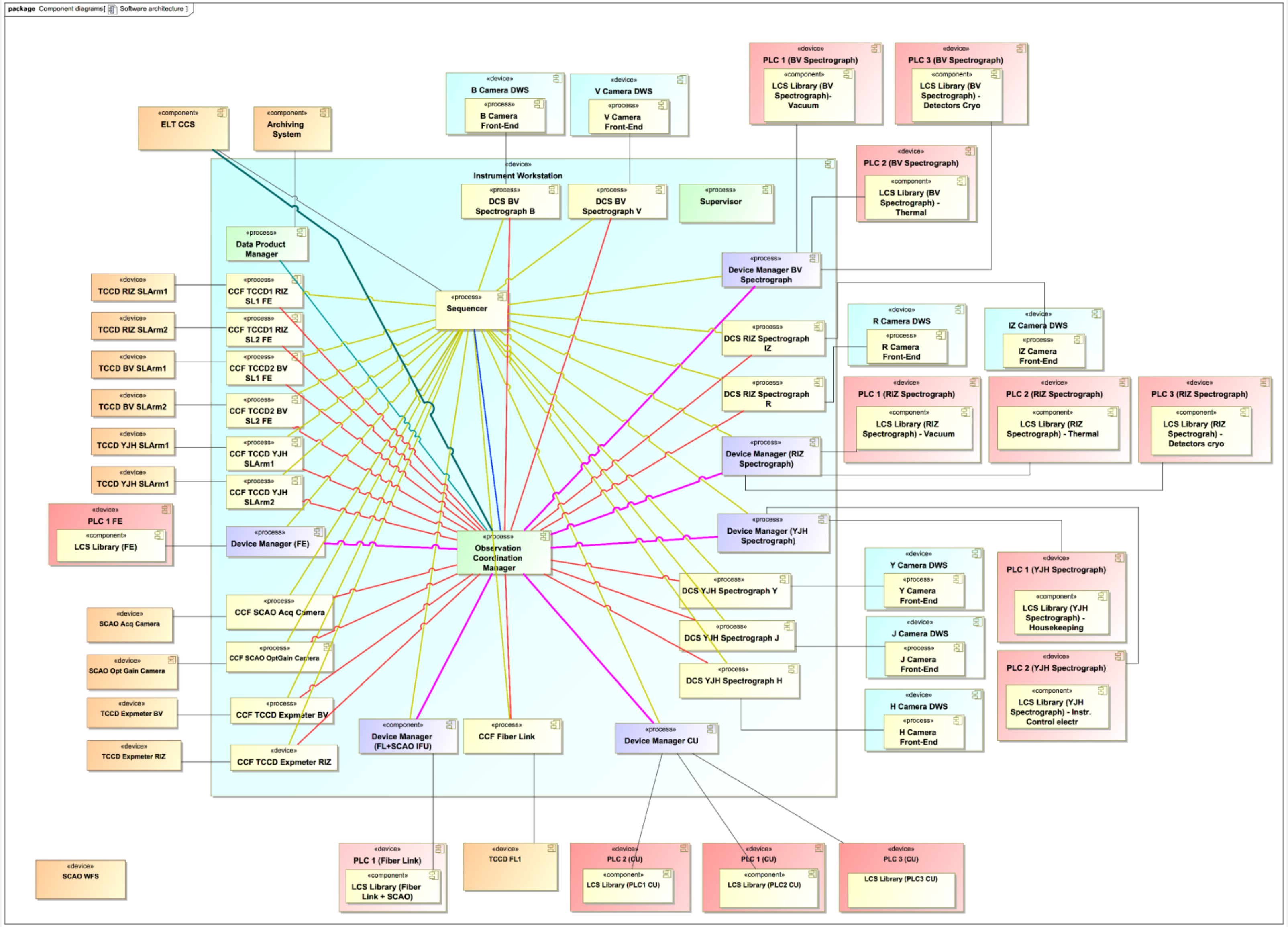


ANDES: VCS control system





ANDES: mastering complex systems

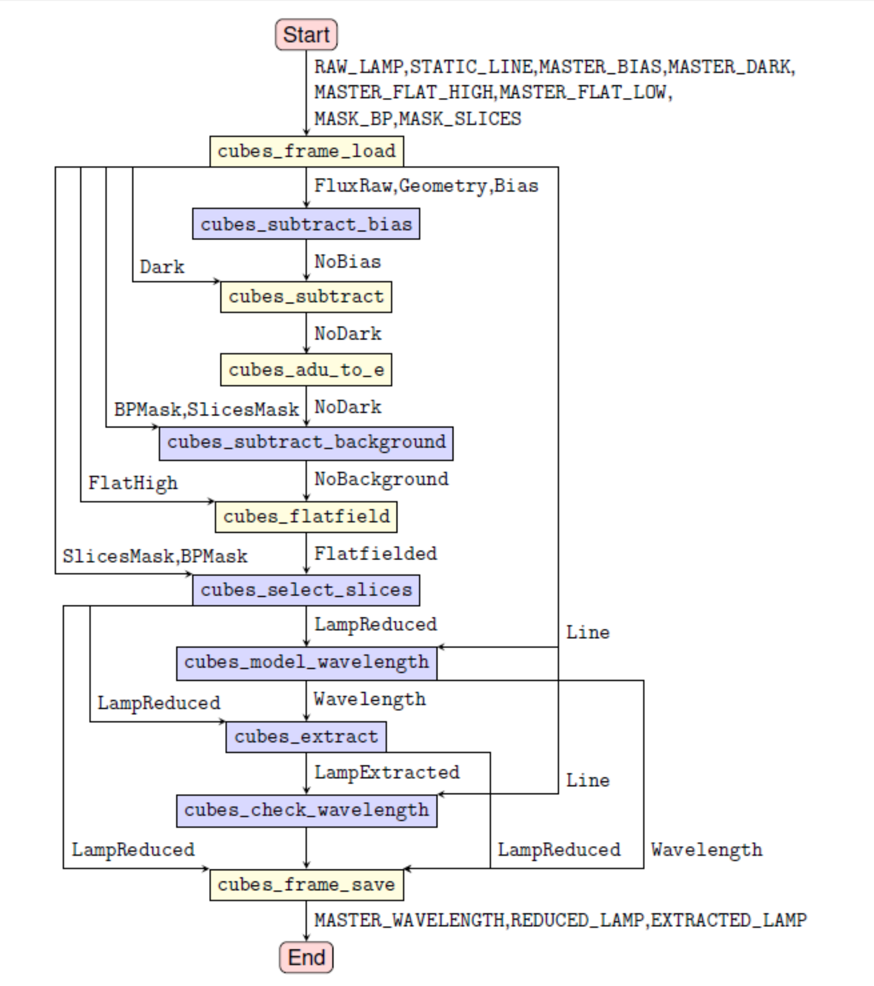


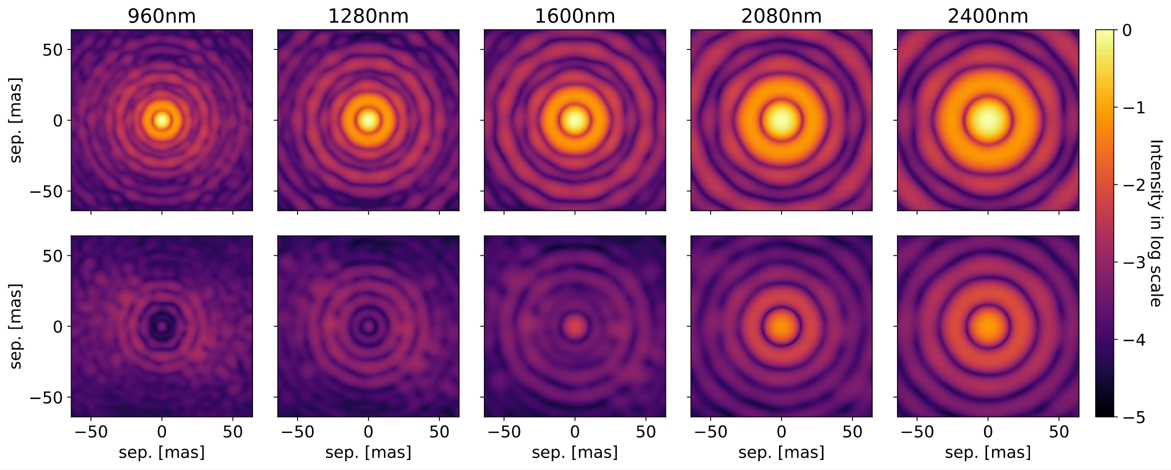
TETIS
TEchnologies for Telescopes and Instrument control Software

develop synergies for networking the knowledge and skills acquired by the participating groups, and **supporting the level of excellence** achieved @INAF

DRS and simulations

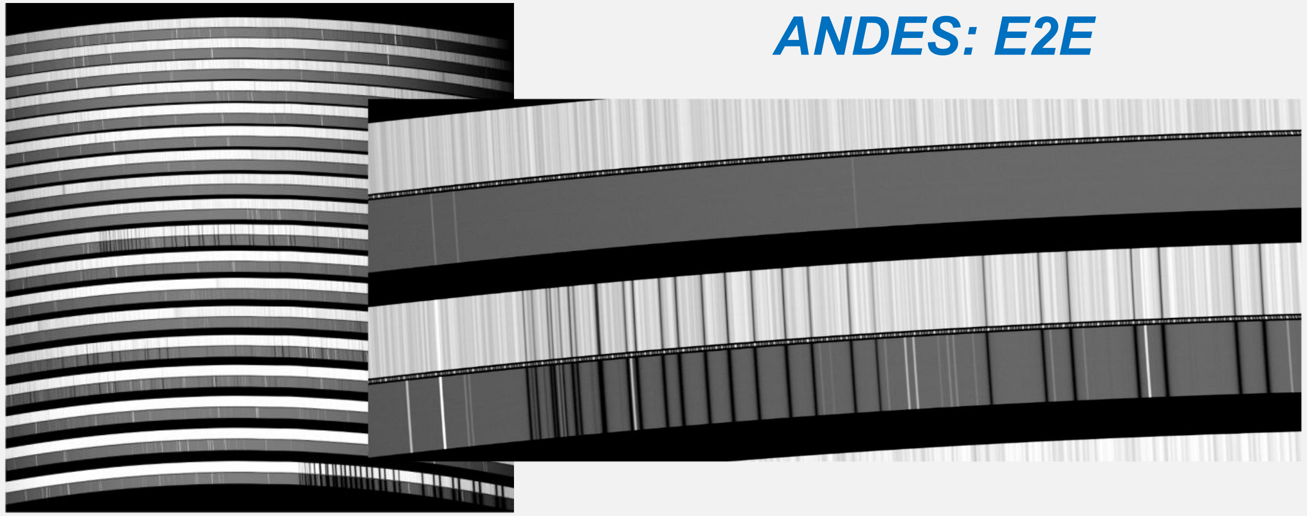
CUBES: DRS



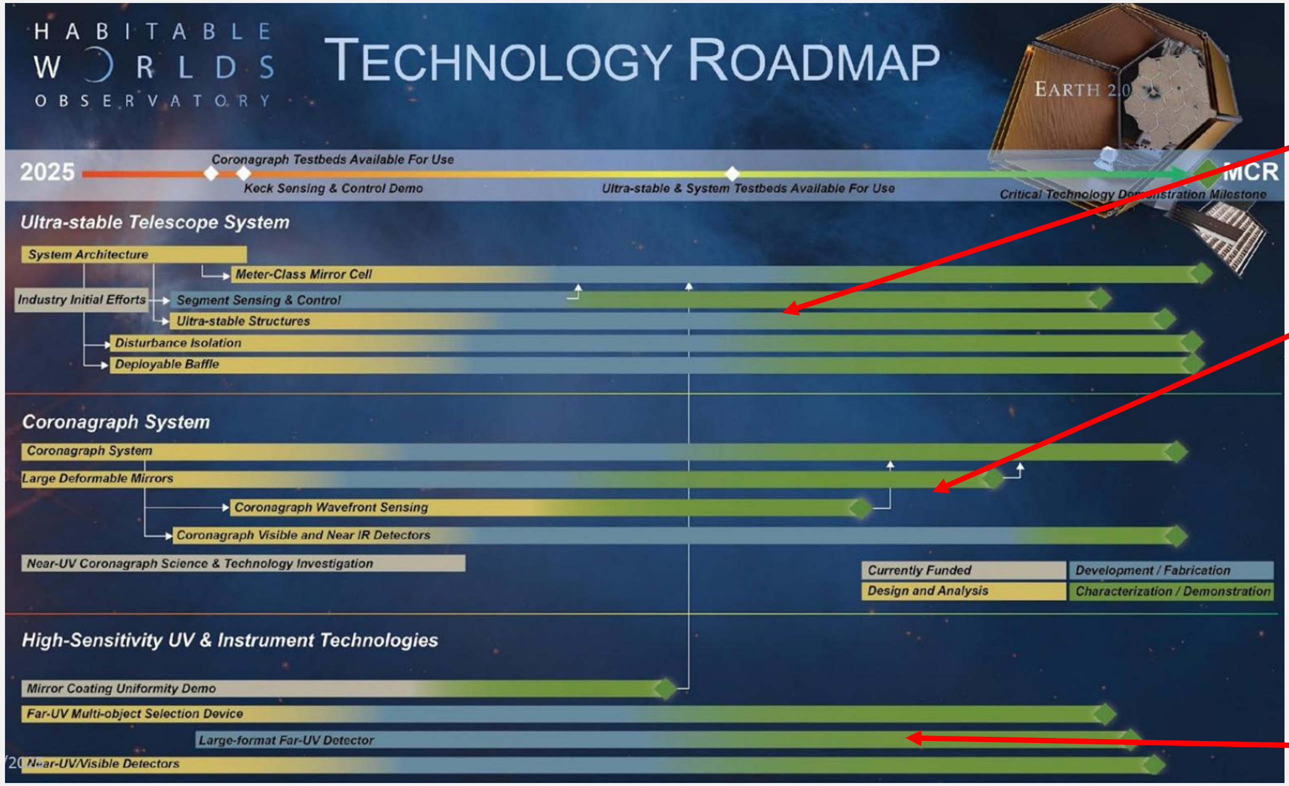


Simulated images of an on-axis point source in median observing conditions after SCAO correction.

ANDES: E2E



Conclusion



credits: *Matthew R. Bolcar (GSFC) & Feng Zhao (JPL)*
HWO Chief Technologists