The SCAO module for ANDES, the high resolution spectrograph for the ELT

ANDES

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ANDES PM, INAF-OATs

Broad context

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

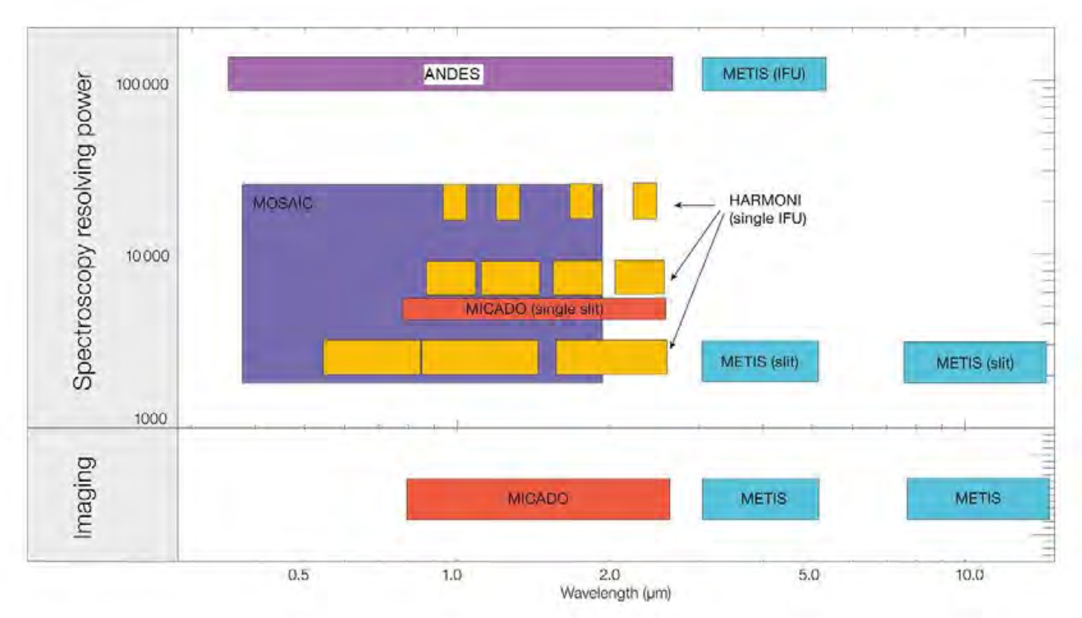
- Flagship science cases: the detection of life signatures in Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration (both require high resolution spectroscopy)

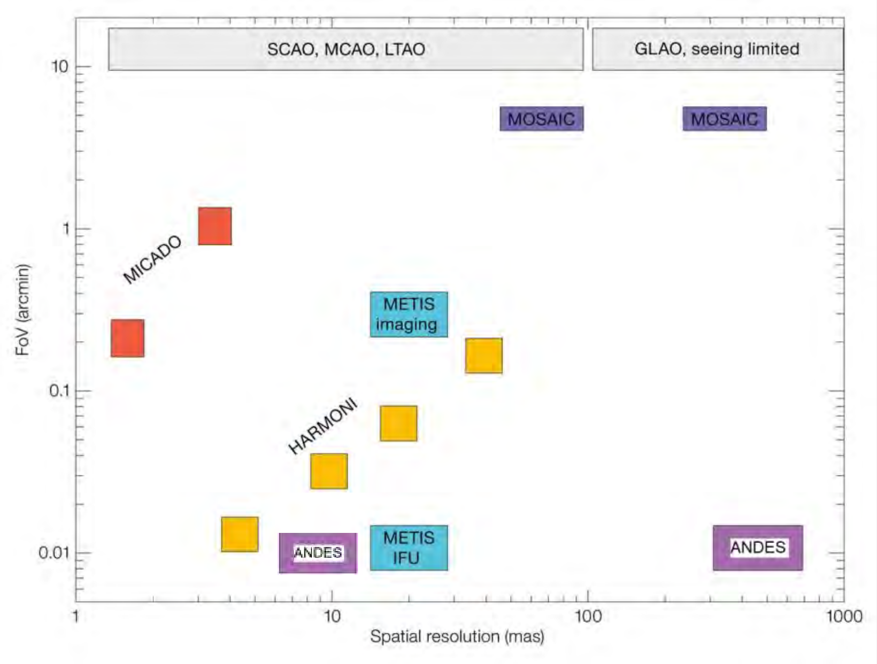
High resolution spectroscopy

- Interdisciplinary (from Exoplanets to Stars, to Cosmology and Fundamental Physics)
- Successful ESO tradition (UVES, FLAMES, CRIRES, X-shooter, HARPS, ESPRESSO)
- More than 30% of ESO publications can be attributed to its high-resolution spectrographs.

ANDES parameters 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 (0.37-2.4 μm goal)
- Spectral resolution ~100,000 (also 150,000 possible)
- Interchangeable, observing modes: seeing limited & SCAO+IFU module
- Sensitivity: 1h, 10σ, AB = 21.7

ANDES history

- ESO commissioned two phase-A studies for high-resolution spectrographs, CODEX and SIMPLE, in the framework of “ESO instrumentation roadmap for ELT construction proposal” (successfully completed in 2010)

- HIRES initiative: merging of CODEX and SIMPLE with a preparation of community white paper (2013)

- HIRES Phase A study: started 2016, successfully concluded beginning 2018

- the “waiting-for-approval phase”: new partners (USA and Canada) joined the (existing) consortium, modified baseline design adopted, new organisation of consortium developed, preparation of agreements

- ESO Council approves HIRES Construction (December 2021)

- New name adopted: ANDES (ArmazoNes high Dispersion Echelle Spectrograph)

- Start of the construction phase with SAR (System Architecture Review) completed on 18th of October 2023

A subset of ANDES science cases

- ❑ Exoplanets (characterisation of Exoplanets Atmospheres: detection of signatures of life)
- ❑ Protoplanetary Disks (dynamics, chemistry and physical conditions of the inner regions)

- ▪ Stellar Astrophysics (abundances of solar type and cooler dwarfs in galactic disk bulge, halo and nearby dwarfs: tracing chemical enrichment of Pop III stars in nearby universe)
- ▪ Stellar Populations (metal enrichment and dynamics of extragalactic star clusters and resolved stellar populations)

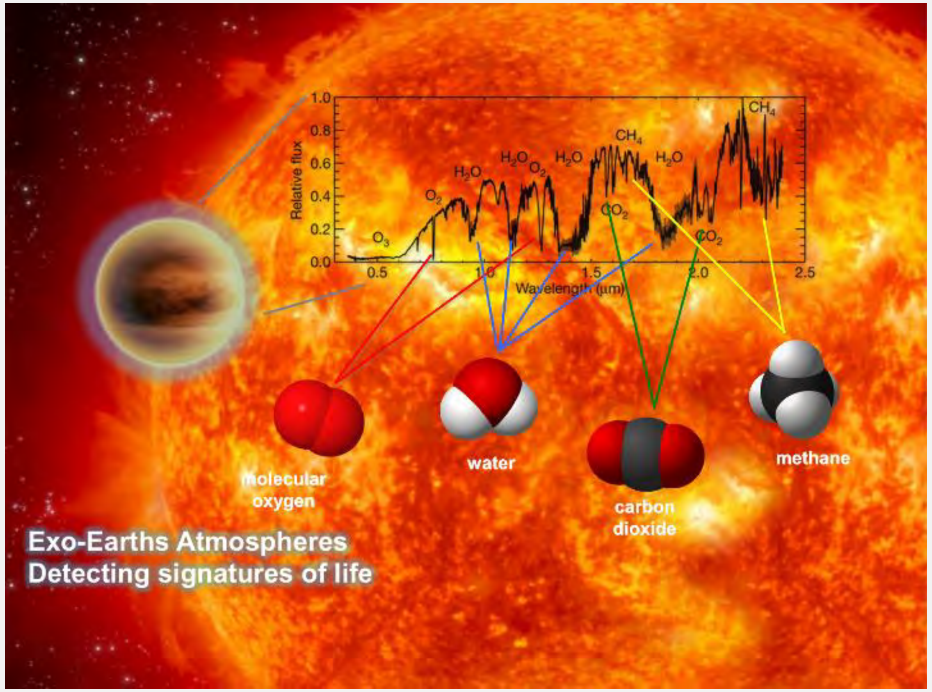
- ➢ Intergalactic Medium (Signatures of reionization and early enrichment of ISM & IGM observed in high-z quasar spectra)
- ➢ Galaxy Evolution (massive early type galaxies during epochs of formation and assembly)
- ➢ Supermassive Black Holes (the low mass end)

- ❖ Fundamental Physics (variation of fundamental constants - α, Sandage Test)

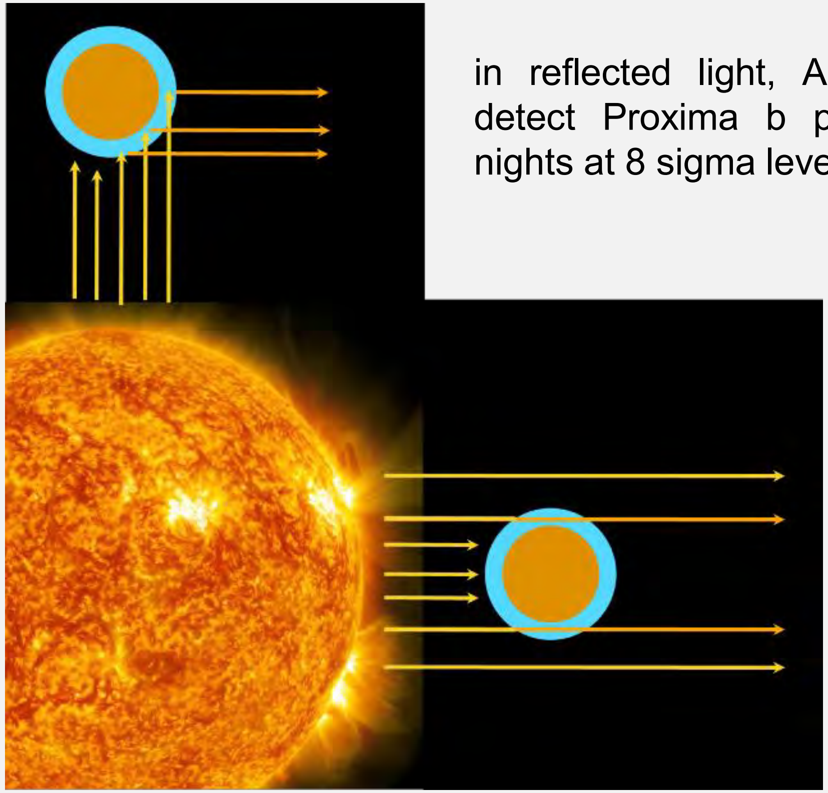
Community White Paper: Maiolino et al. 2013, ArXiV:1310.3163

ANDES key scientific objectives I

❖ Exoplanets and Circumstellar disks (characterisation of exoplanets atmospheres, detection of signatures of life and dynamics, chemistry and physical conditions of disks)



ANDES Science Team WG1



in reflected light, ANDES can detect Proxima b planet in 7 nights at 8 sigma level

in transmitted light, ANDES can detect Trappist 1 & 2
H_20 (1.3-1.7 µm) in 2 transits,
H_20 (0.9-1.1 µm) in 4 transits
CO2 in 4 transits
O2 in 25 transits

…

ANDES SCAO specifications

Name	Text
[R-AND-101]	**Strehl ratio** Under median conditions as specified in AD5 (p.8) and zenith angles <30° the ANDES SCAO module shall deliver on on-axis guide stars with mAB(I)<12 diffraction-limited images in H-band (1.65µm) with a Strehl ratio >40% (goal: >50%). *Note, see [R-AND-69] for a conversion to the photon flux at the instrument*
[R-AND-102]	**Contrast (TLR-A.16)** Under median seeing conditions as specified in AD5 (p. 8) using an AO reference star m(IAB)<=14, the IFU mode of the instrument shall deliver a raw contrast of 100 (TBC) at a distance of 30mas and 1000 (TBC) at a distance of 90mas at 1600nm and a contrast of 100 (TBC) at a distance of 30mas and 600 (TBC) at a distance of 90mas at 1000nm. As a goal, under best seeing conditions (JQ1 as specified in AD5 p.8) with an AO reference star m(IAB)<=15, the IFU mode of the instrument shall deliver a contrast of 1000 at a distance of 30mas and 10000 at a distance of 90mas at 1600nm and a contrast of 1000 at a distance of 30mas and 5000 at a distance of 90mas at 1000nm. The instrument shall deliver the required contrast performance at zenith distance of 30 degrees. For angles different from 30 degrees, variation in performance should be consistent with the natural variation in seeing with zenith distance. *Note, see [R-AND-69] for a conversion to the photon flux at the instrument.*
[R-AND-104]	**Magnitude range** SCAO wavefront sensing shall be possible with stars in the range m(IAB)=6-15 mag. *Note, see [R-AND-69] for a conversion to the photon flux at the instrument.*

Therefore, taking into account these driving requirements, the SCAO WFS is a pyramid WFS with tip/tilt modulation equipped with ADC, optical pupil derotator (k-mirror) and two translation stages to provide the field patrolling. The pyramid WFS has been selected as the one providing the highest performance for high contrast applications.

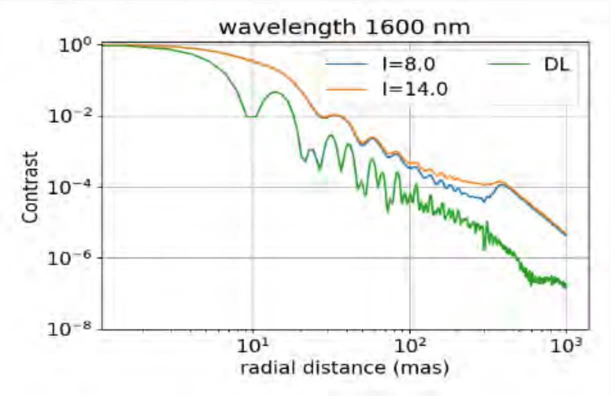
SCAO Performance – contrast estimation

The WG1 wish is: contrast 1.0E-3 for I=8 @14mas 1600nm

3 scenarios considered

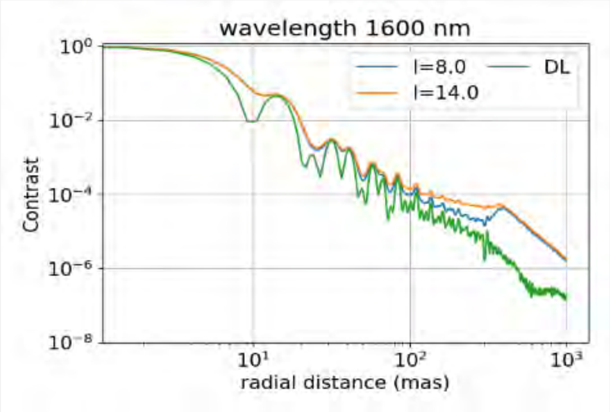
Expected contrast profiles, DL means Diffraction Limit.

1. **High piston**
   Phase A design: no correction of M4 petal piston
   (differential piston error 200nm RMS)



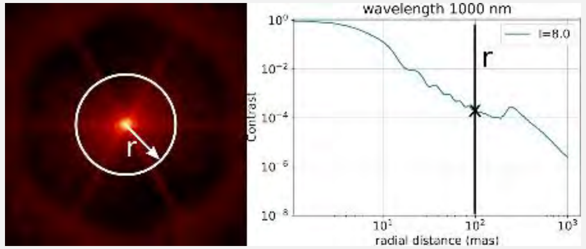
I=8→ SR=0.22
I=14 → SR=0.20

2. **Low piston**
   Phase A + phasing sensor
   (25nm residual piston error)



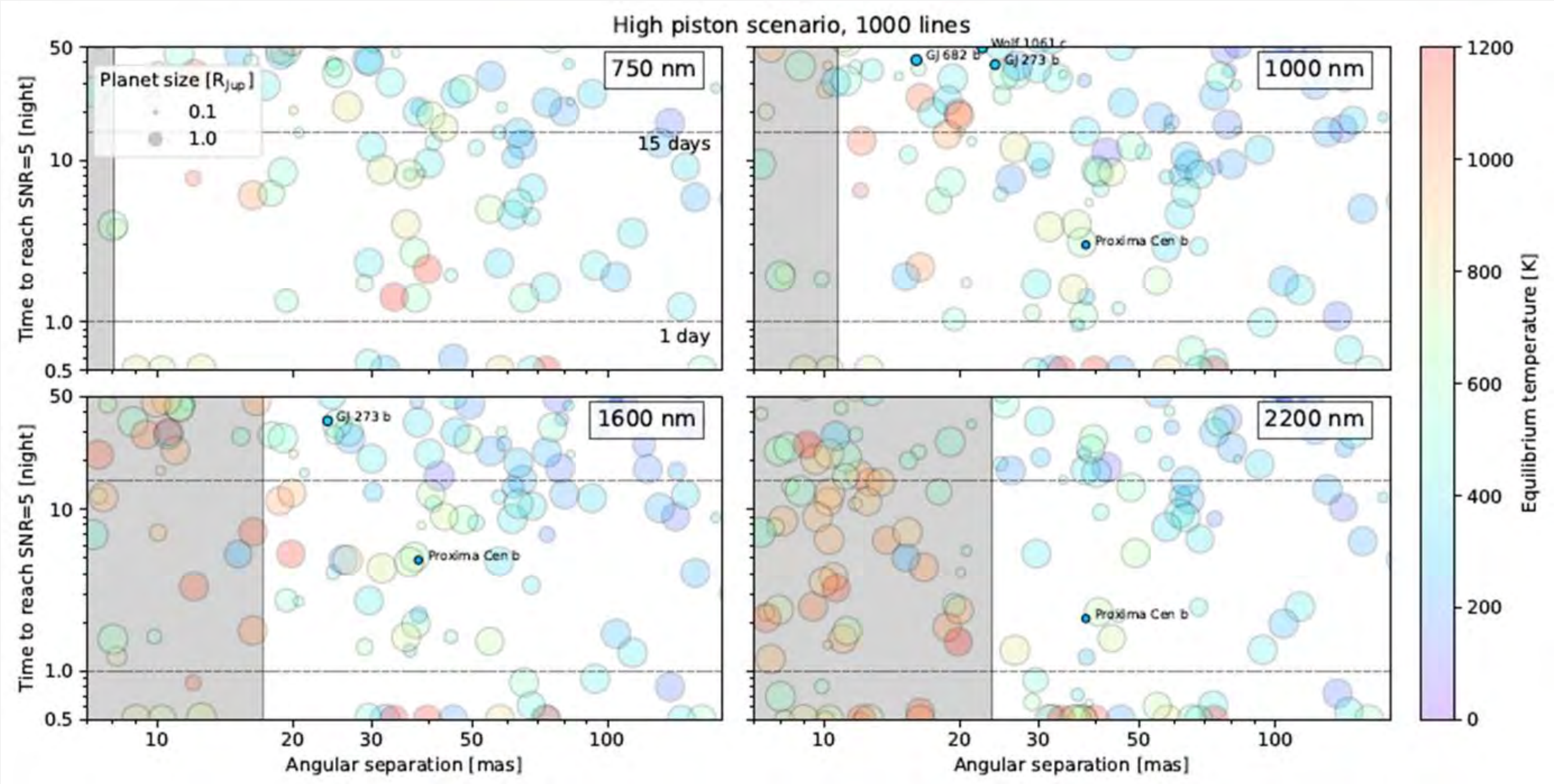
I=8→ SR=0.59
I=14 → SR=0.54

3. **Low piston + Lyot coronograph**
   (work ongoing by OCA team)



One point on the curve on the right corresponds to the average of the flux in all the pixels sitting on the white circle on the left picture

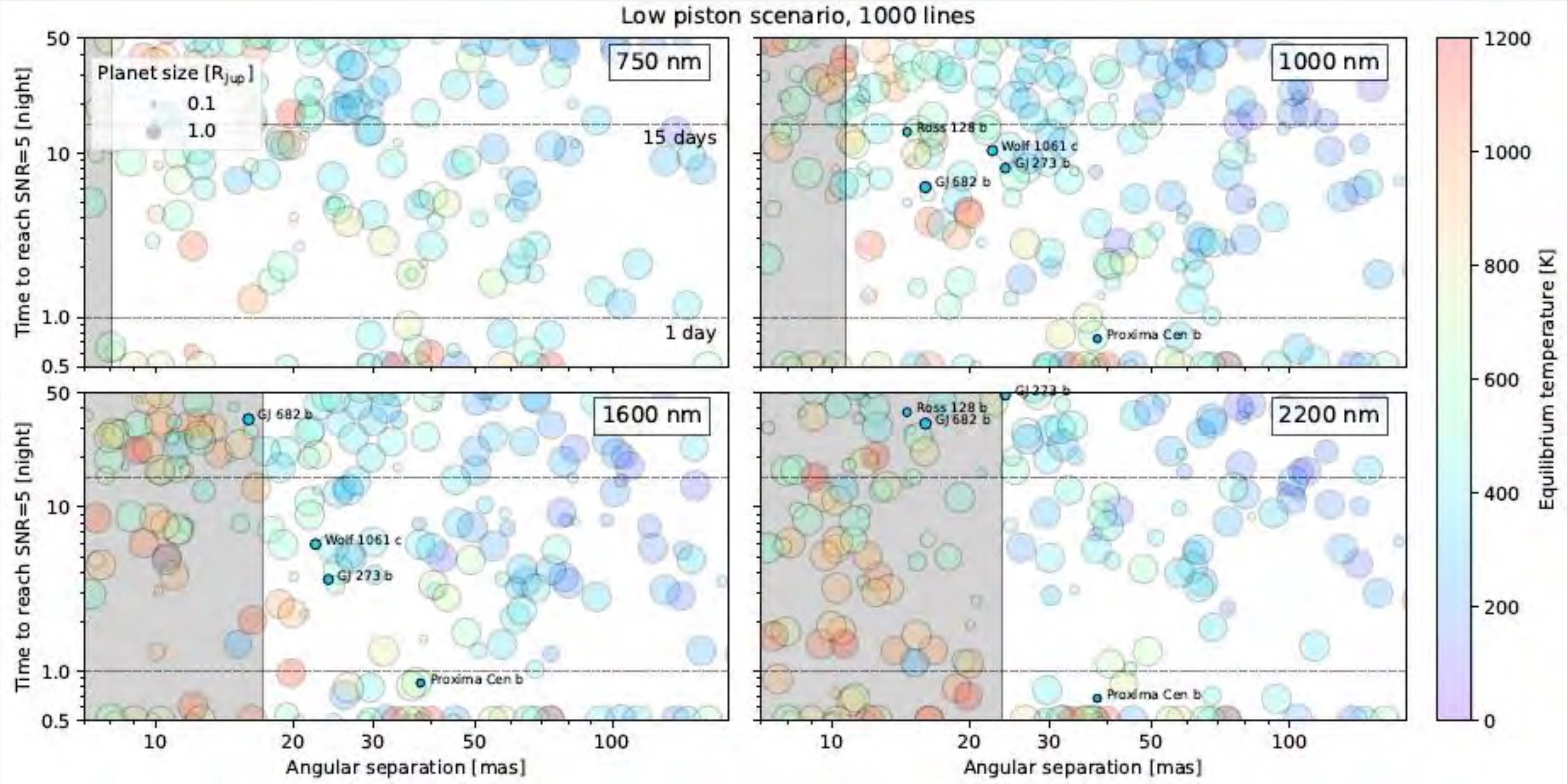
ANDES Key scientific objectives I



(labels mark exoplanets in our rocky-HZ ‘golden sample’)

(Palle et al. in prep)

ANDES Key scientific objectives I

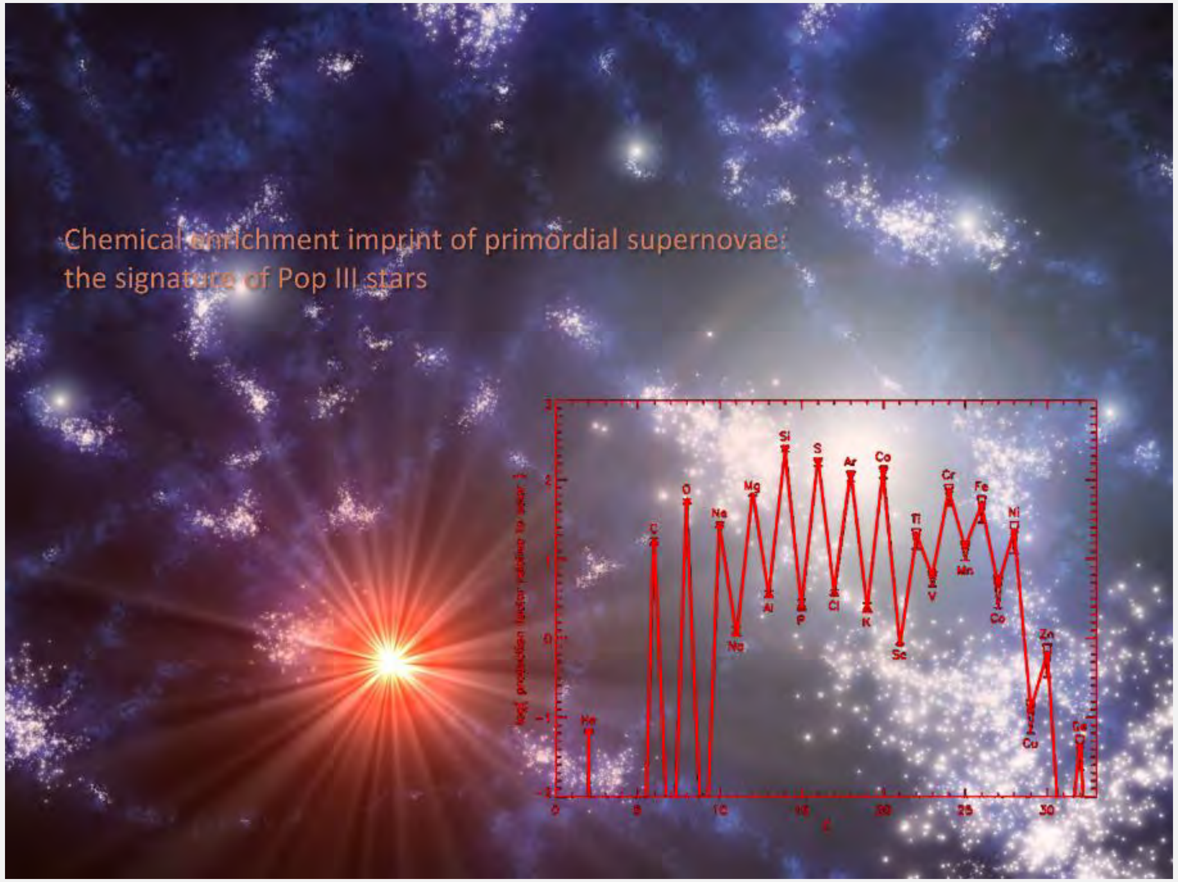


(labels mark exoplanets in our rocky-HZ 'golden sample')

(Palle et al. in prep)

ANDES key scientific objectives II

❖ Stars and Stellar Populations (abundances of solar type and cooler dwarfs in our and nearby galaxies, tracing chemical enrichment of Pop III stars in nearby universe, early chemical enrichment)

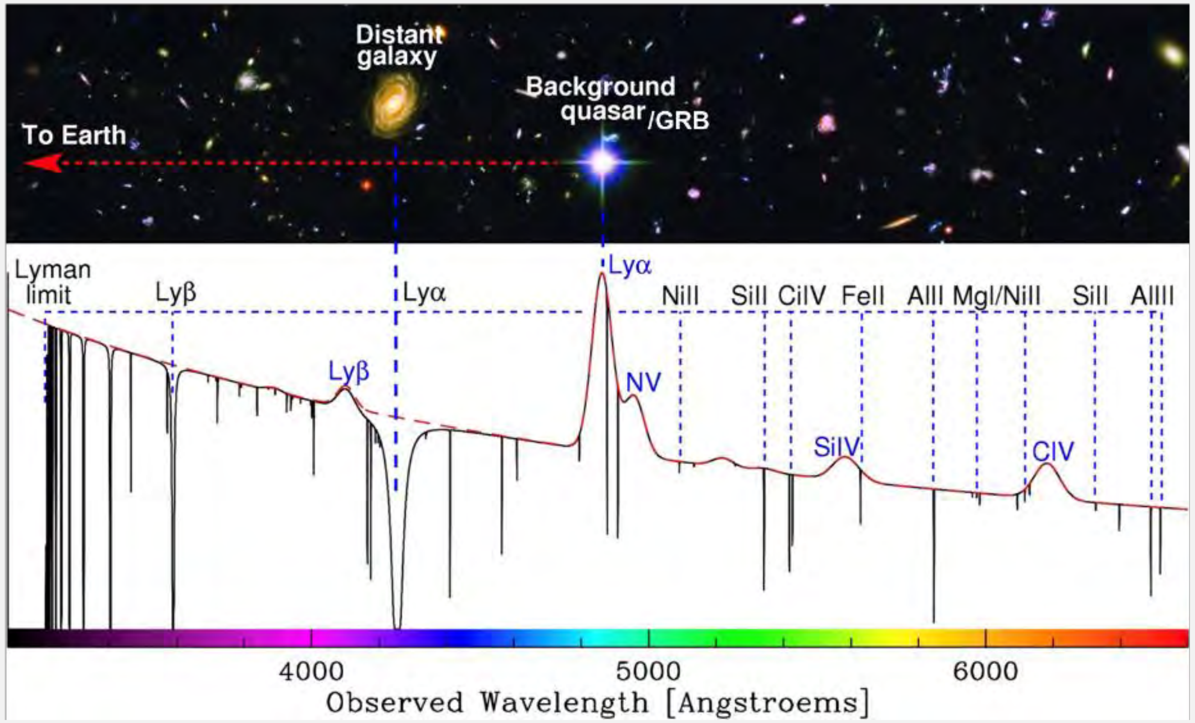


ANDES Science Team WG2

ANDES key scientific objectives III

❖ Galaxies (formation and evolution) and Intergalactic Medium (signatures of reionization and early enrichment of IGM observed in high-z quasar spectra, evolution of massive early type galaxies during epochs of formation and assembly)

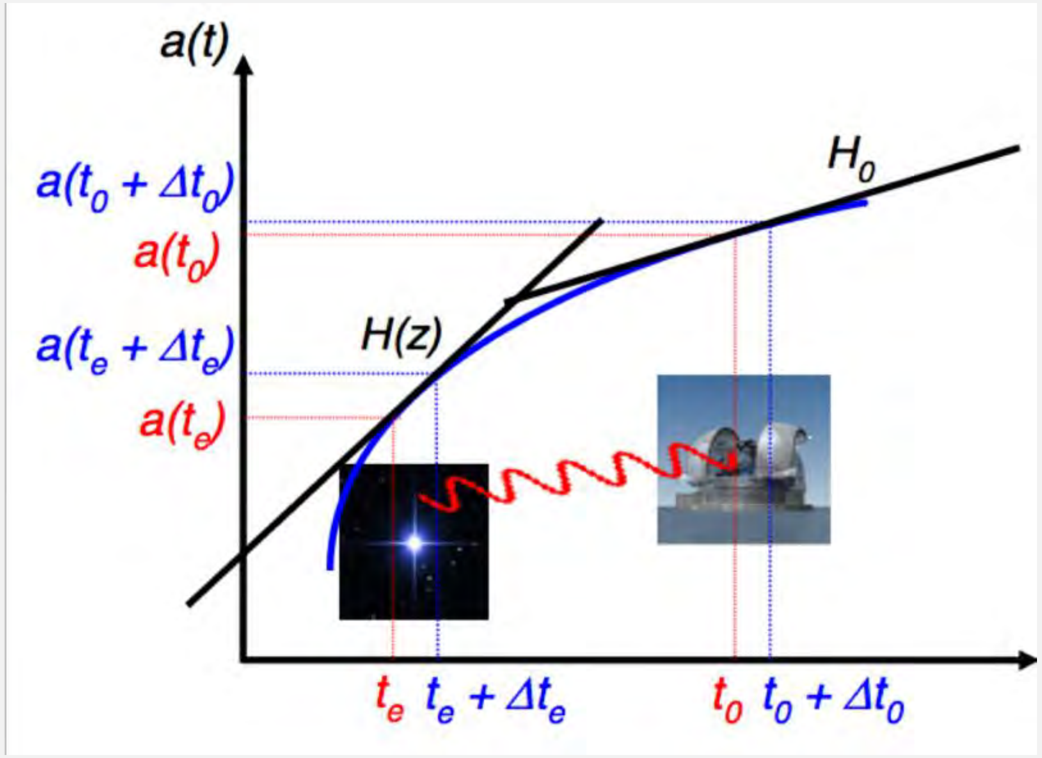
The Inter-Galactic Medium:
tracing the chemical enrichment of the universe (e.g. Pop III SNe)
High spectral resolution (R>50-100x10^3) and broad spec. cov. (opt+NIR)

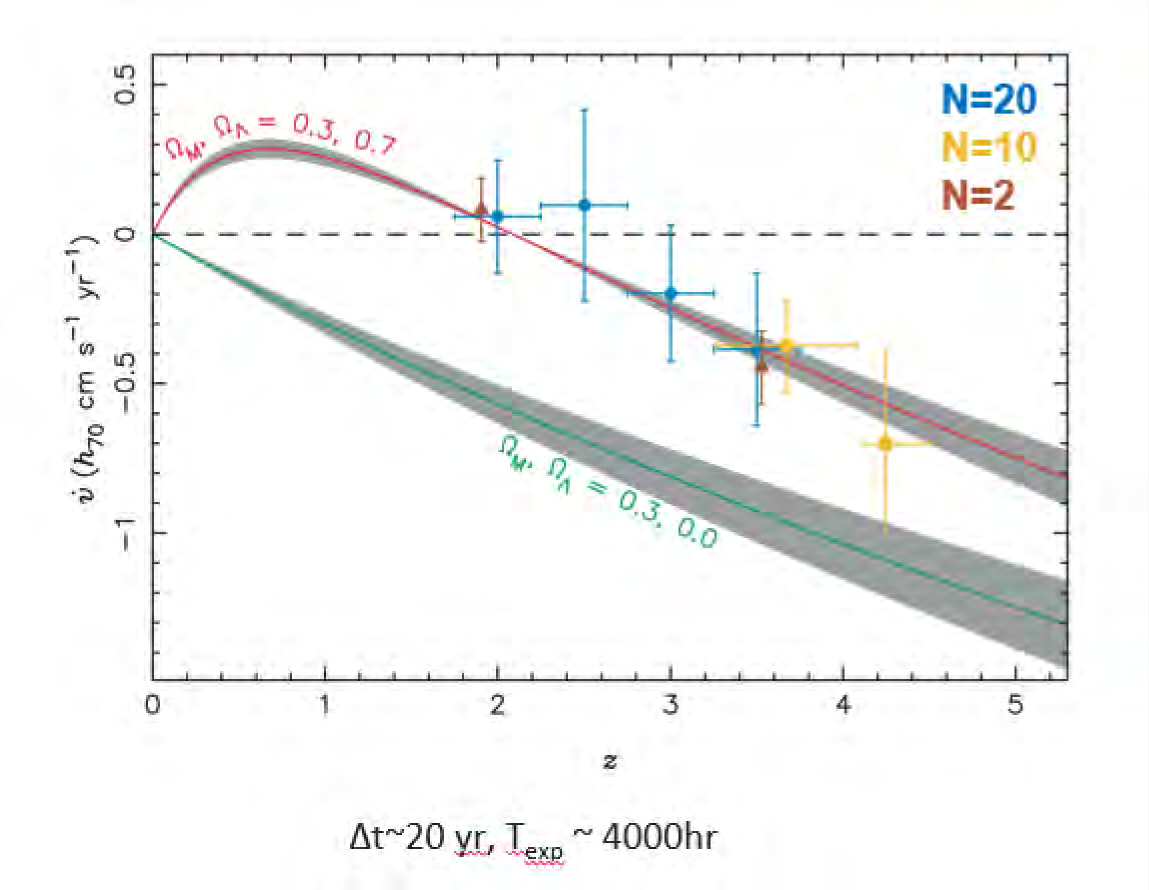


ANDES Science Team WG3

ANDES key scientific objectives IV

- Cosmology and Fundamental Physics (variation of fundamental constants, Sandage Test)





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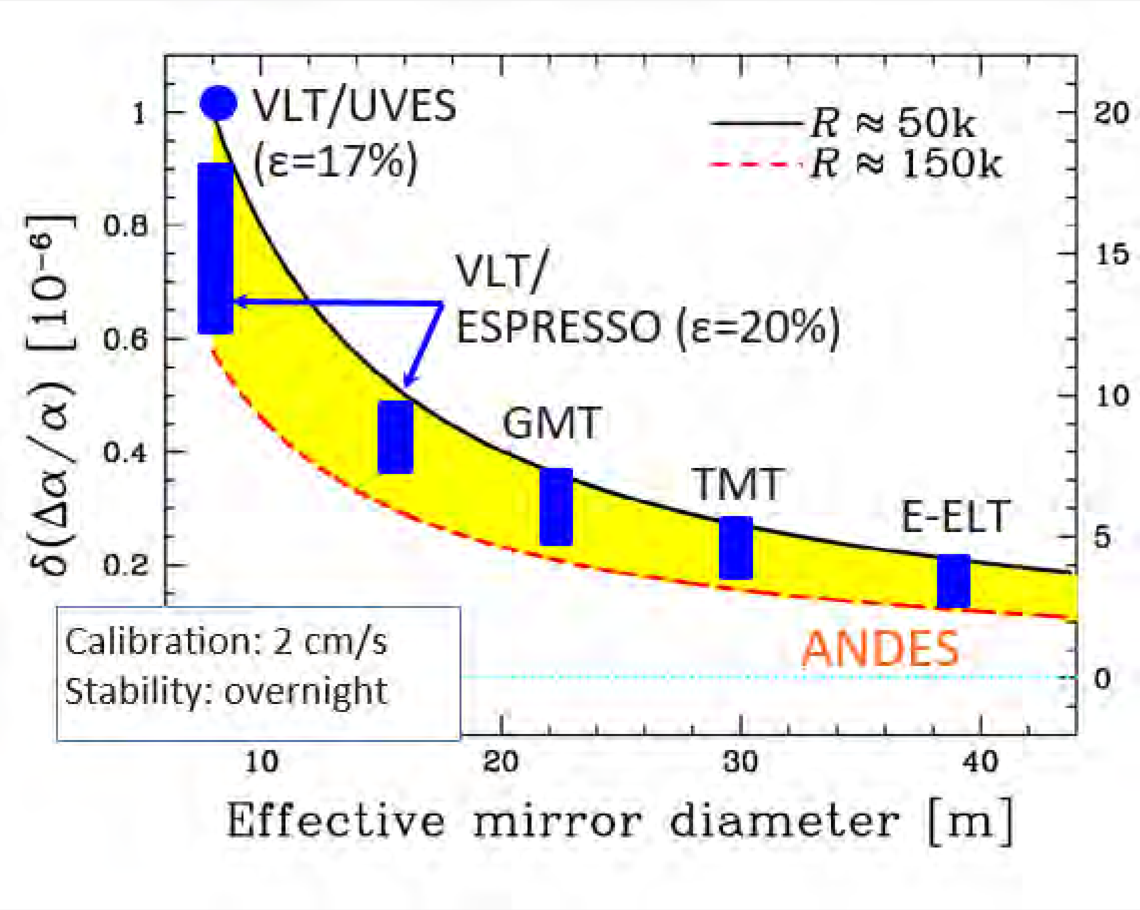
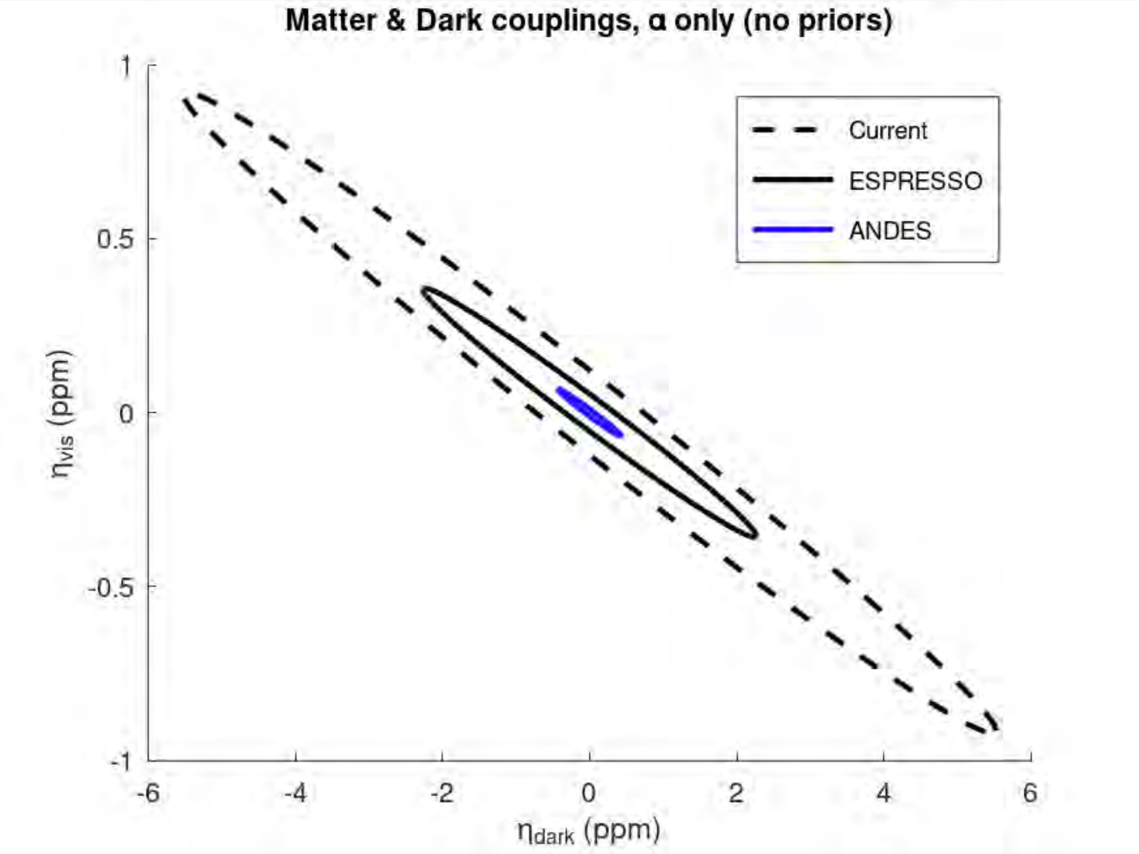
ANDES key scientific objectives IV

Fundamental Physics: variation of the fundamental constants





Martins 2016, 2017

More science cases, see *“Community White Paper: Maiolino et al. 2013, ArXiV:1310.3163”*

ANDES Science Prioritisation

- ❖ Priority 1: Exoplanet atmospheres via transmission spectroscopy (potential detection of bio-signatures)

  TLR 1: R > 100,000, 0.5-1.8 μm; drive the ANDES baseline design
  - ➢ Enables: reionization of Universe; characterization of Cool stars
  - ➢ Doable: detection and investigation of near pristine gas; 3D reconstruction of the CGM; Extragalactic transients
- ❖ Priority 2: Variation of the fundamental constants of Physics

  TLR 2: blue extension to 0.37 μm

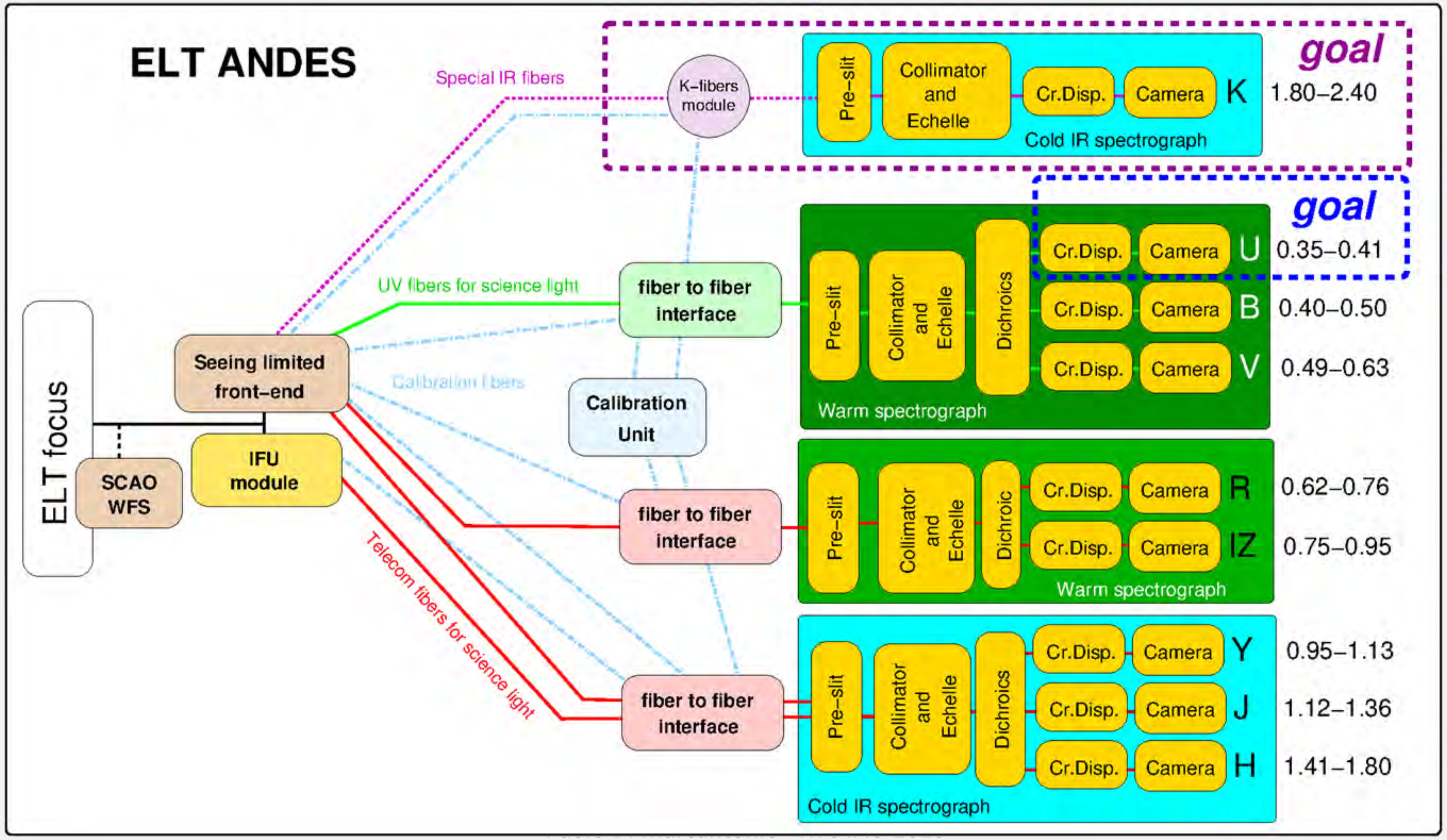
  Enables: Cosmic variation of the CMB temperature, Determination of the deuterium abundance; investigation and characterization of primitive stars
- ❖ Priority 3: Exoplanet atmospheres via reflection spectroscopy (potential detection of bio-signatures)

  TLR 3: SCAO+IFU
  - ➢ Enables: Planet formation in protoplanetary disks; characterization of stellar atmospheres; Search of low mass Black Holes
  - ➢ Doable: characterization of the physics of protoplanetary disks
- ❖ Priority 4: Redshift drift (Sandage test)

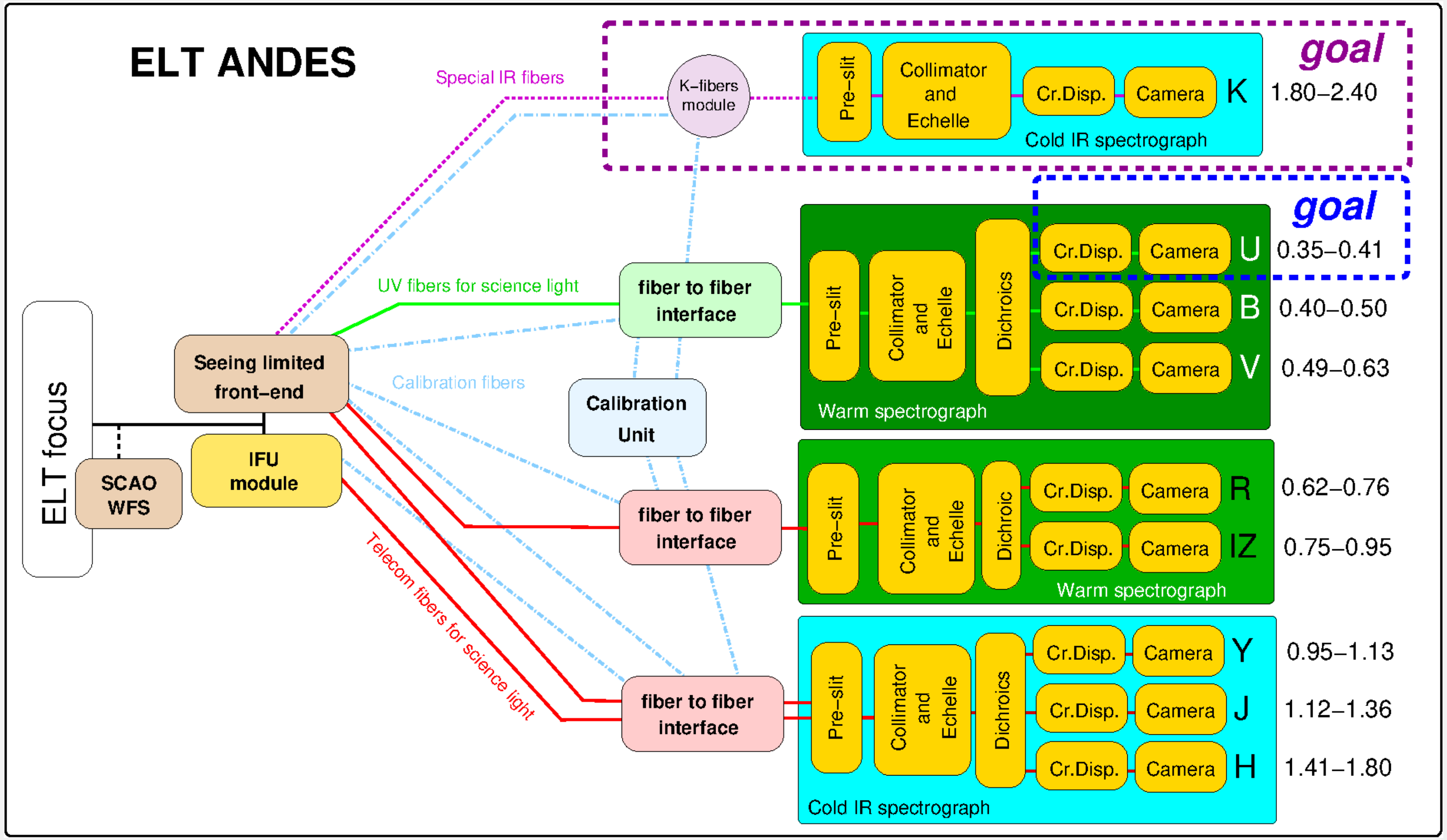
  TLR 4: λ accuracy 2 cm/s, stability 2 cm/s
  - ➢ Enables: Mass determination of exoplanets (Earth-like objects)
  - ➢ Doable: Radial velocity search for exoplanets around M-dwarf stars

ANDES concept

Combination of ANDES science cases requires R~100,000, 0.35<λ<2.4μm, many different observing modes, and several other challenging TLRs which lead to a fiber-fed, modular instrument:

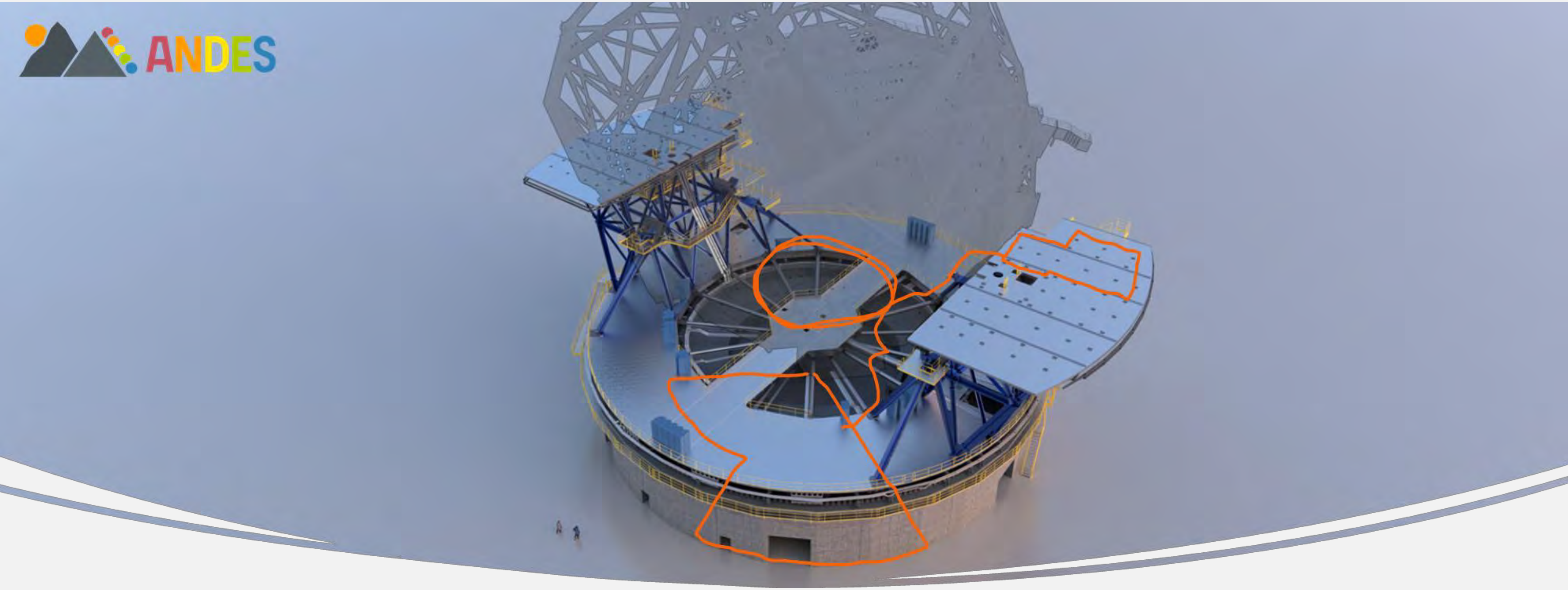


ANDES architecture



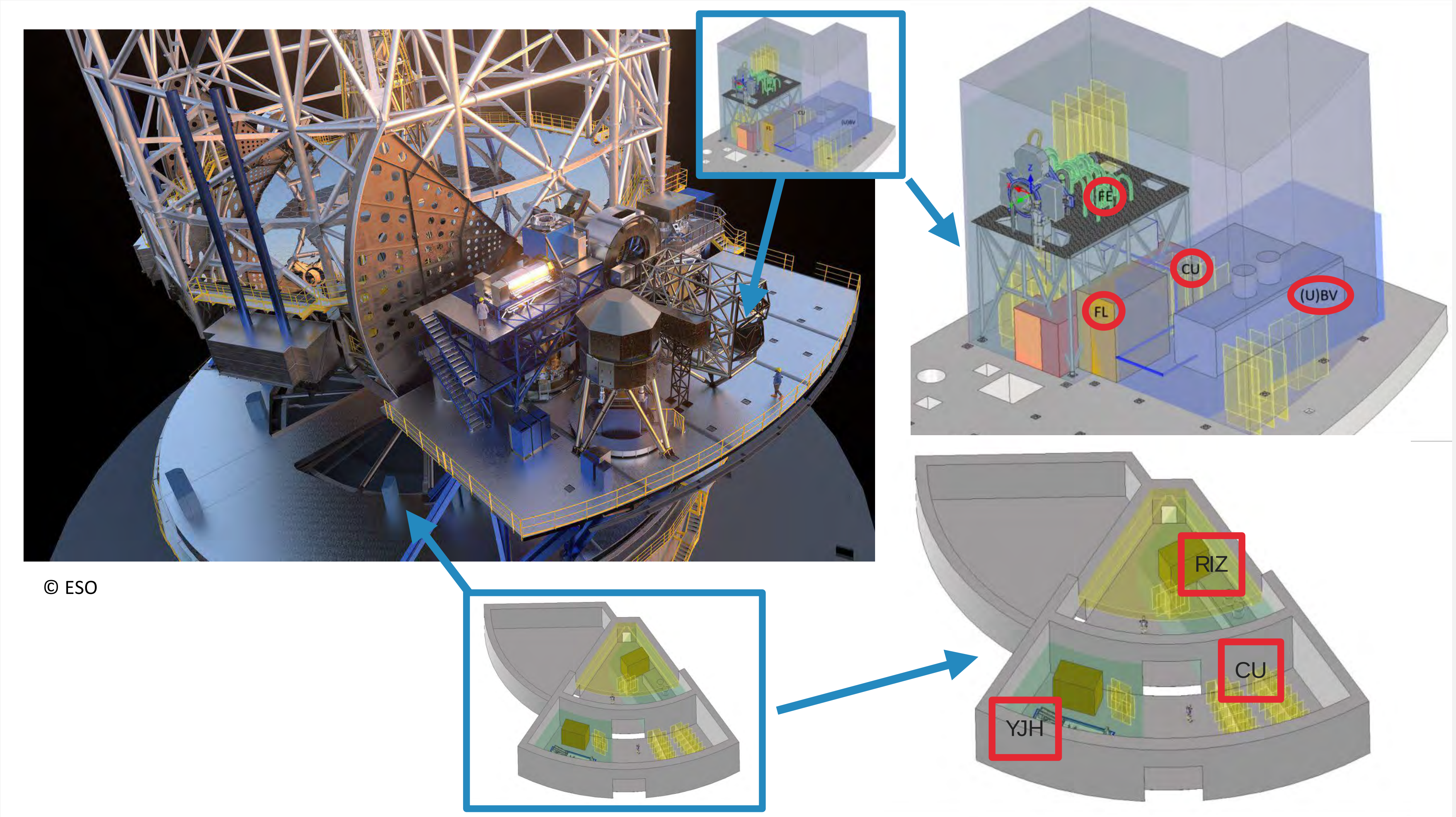
- Front End (FE)
- Fiber Link (FL)
- SCAO module
- Calibration Unit (CU)
- (U)BV Spectrograph
- RIZ Spectrograph
- YJH Spectrograph
- (K Spectrograph)
- Software

ANDES concept: deployment



Background image © ESO

ANDES concept: deployment



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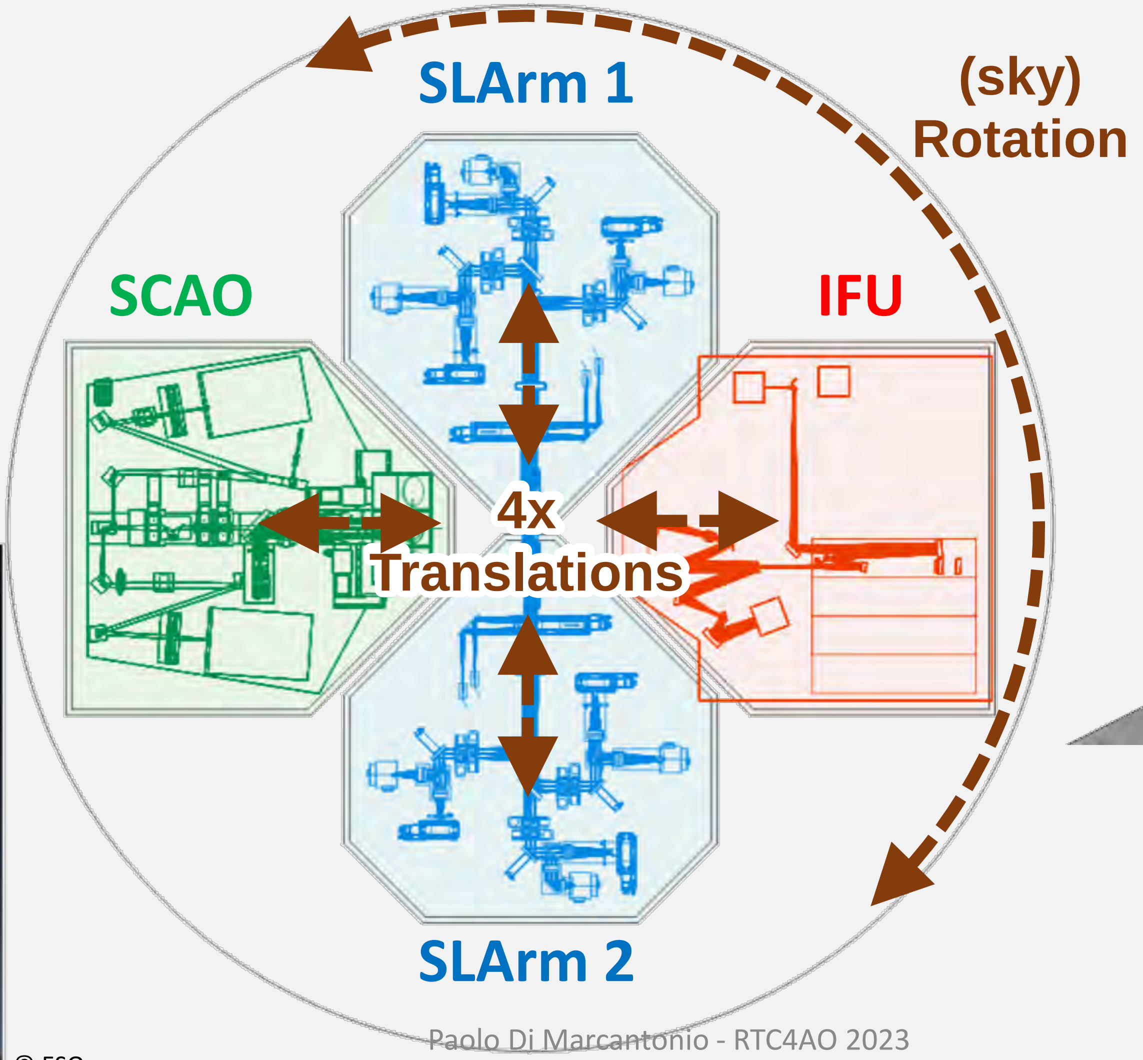
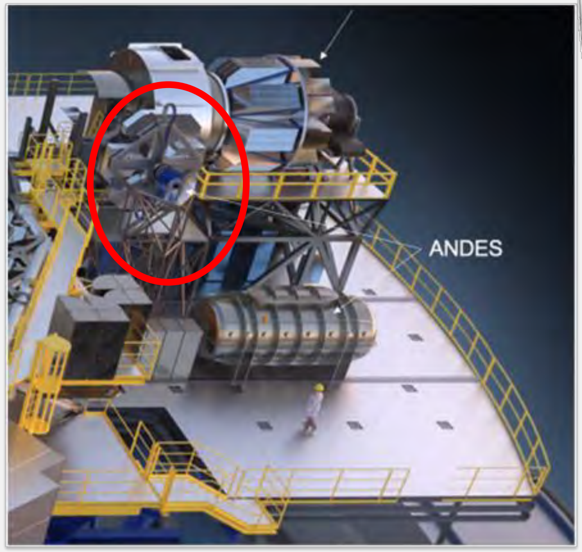
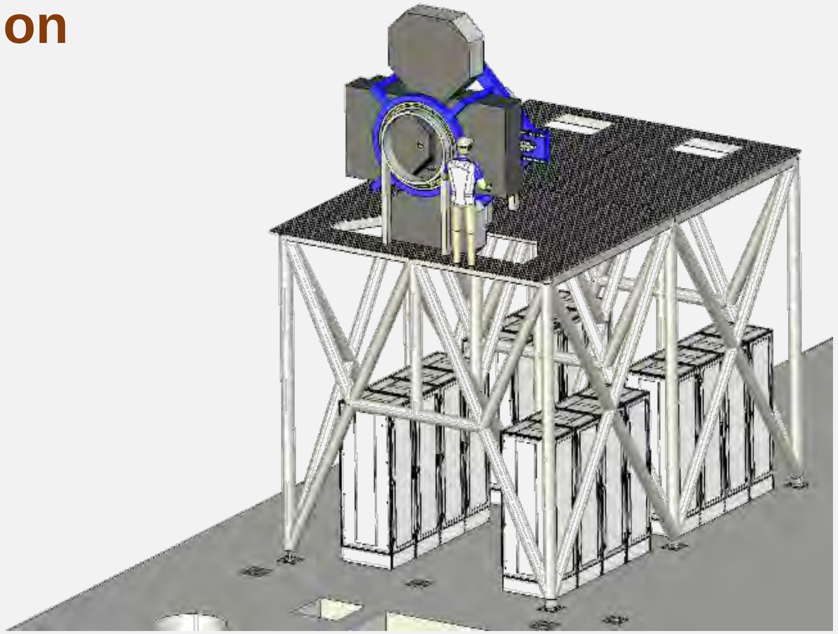
ANDES

Front-end: old design

❖ **Front End structure preliminary design:** *Arms management*







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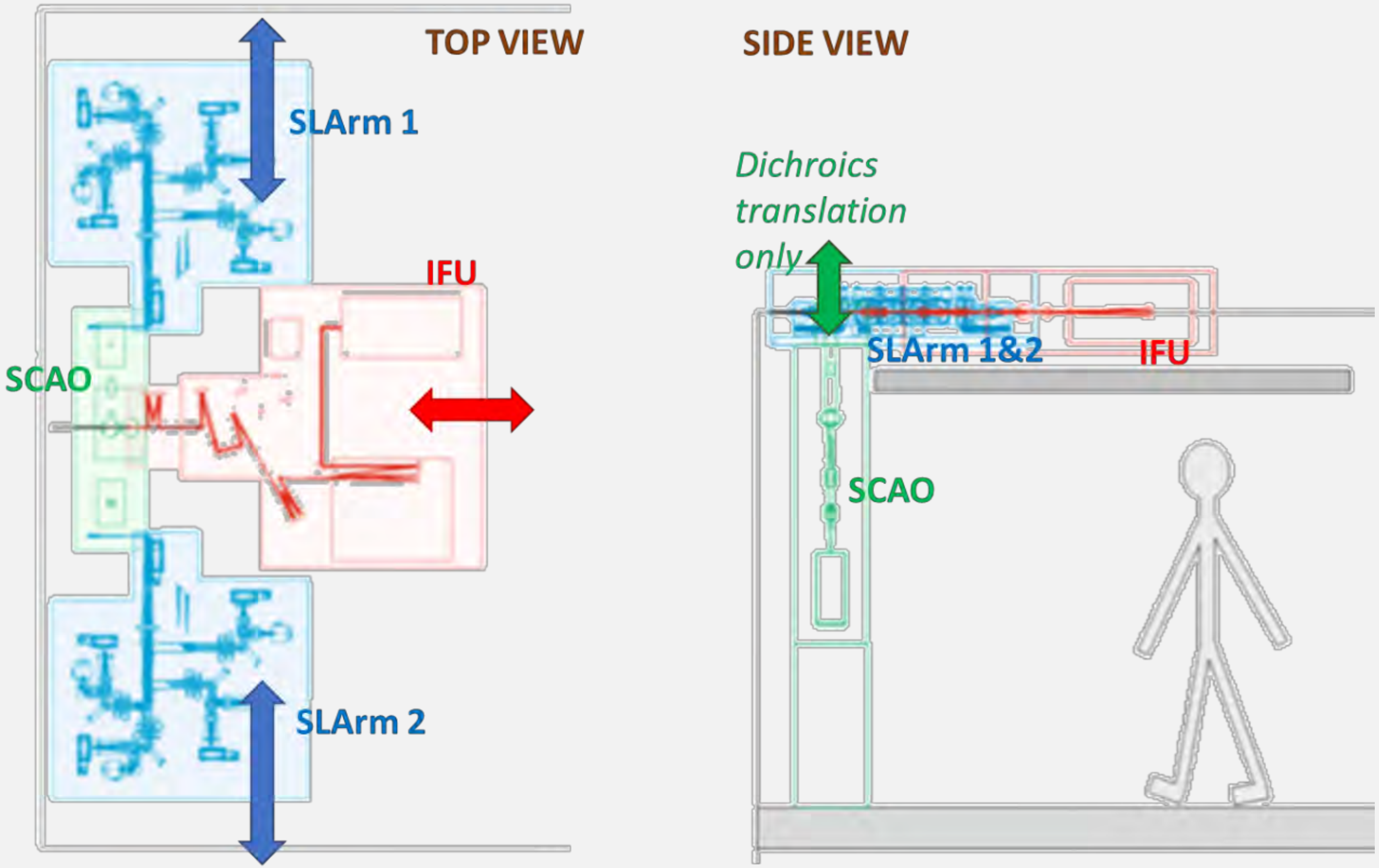
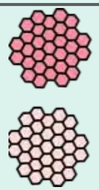
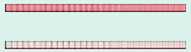
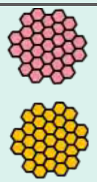
Front-end: new design

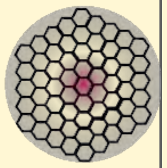
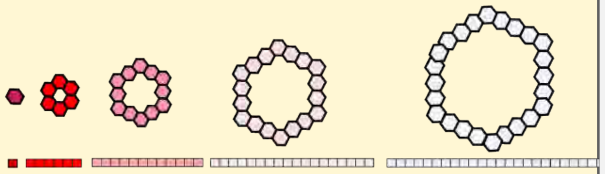


Science operations

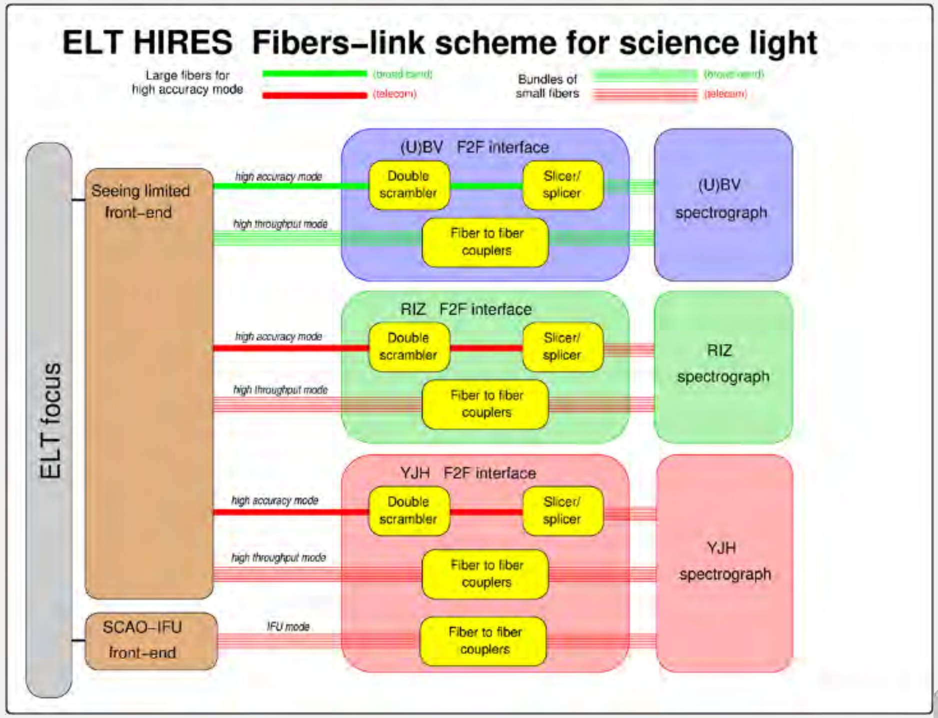
Seeing Limited Observing Mode

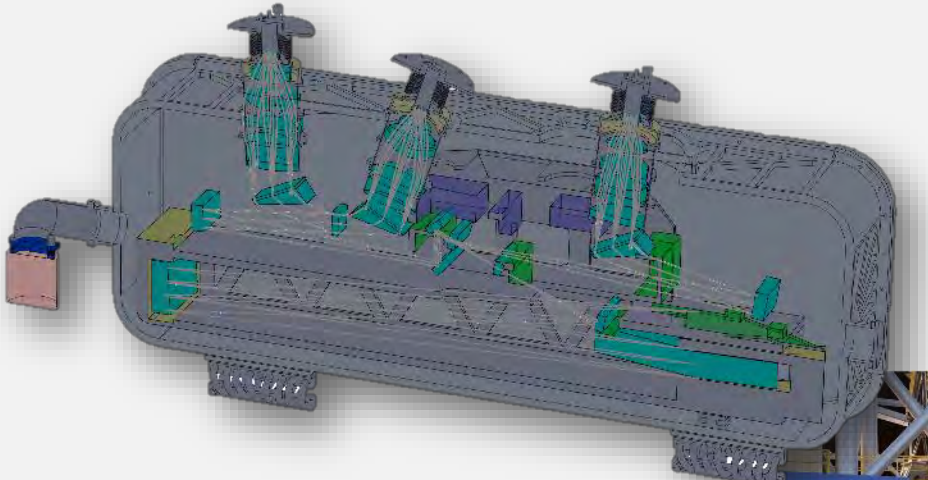
observing mode	FE	FL	along the spectrograph slit
SL_UNI [U]BV+RIZ+YJH two identical apertures simultaneously illuminated by target and sky, or target and wavelength calibration. If needed, beam-switching of the two apertures can be performed.	input light on two, individual large fibres	2 bundles of small fibres, uniformly illuminated after scrambler & slicer to maximize spectral fidelity	2 segments of uniformly illuminated fibres
SL_UNI_TS Target + Sky			
SL_UNI_TC Target + Wavelength Calibration			

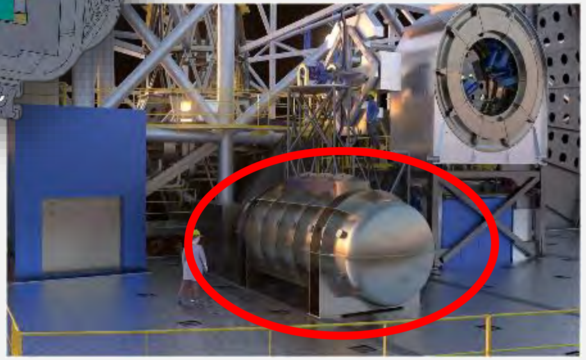
IFU+SCAO Observing mode

Observing mode	FE	FL	along the spectrograph slit
IFU_SCAO YJH IFU of maximum 61 spaxels. 4 spaxel scales in the 5-100 mas range are foreseen. Off-axis guiding out to 3 arcsec is also possible.	input PSF on microlenses array and fibre bundle. 	fibre bundle after fiber2fiber couplers. 	4 segments (S1, S2, S3, S4), one per each hexagonal annulus around the central spaxel, + the central spaxel (S). 

Other ANDES subsystems







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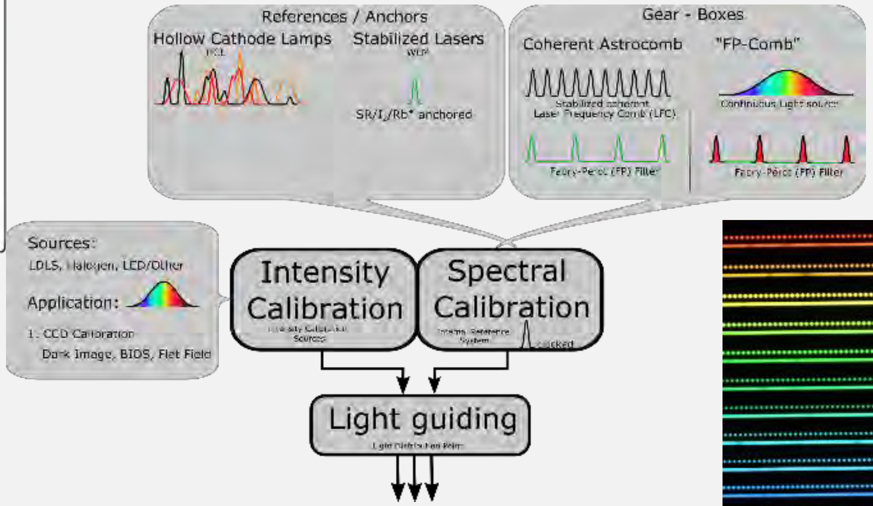
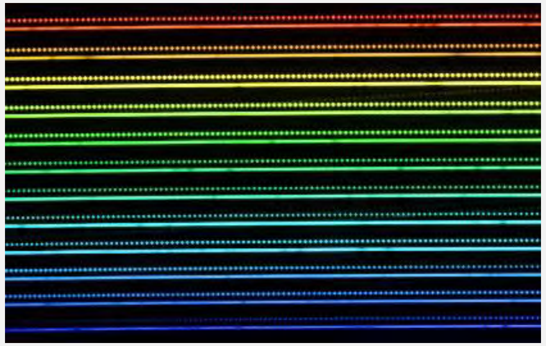


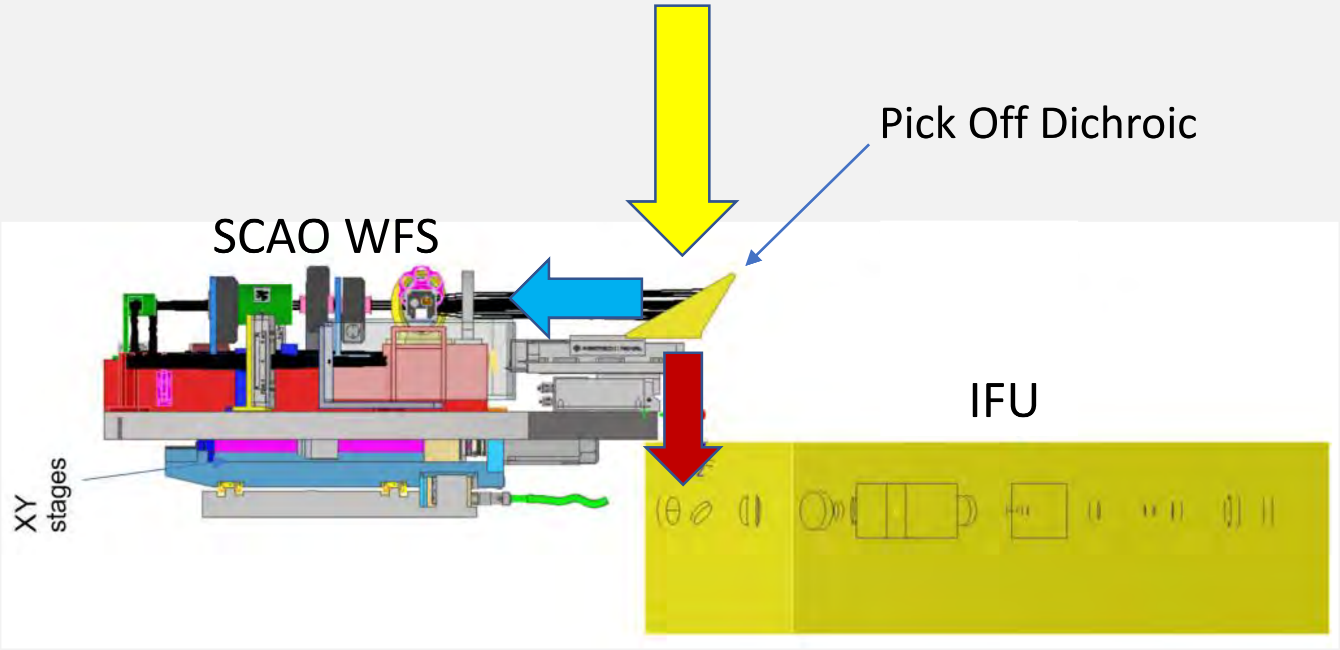


SCAO subsystem

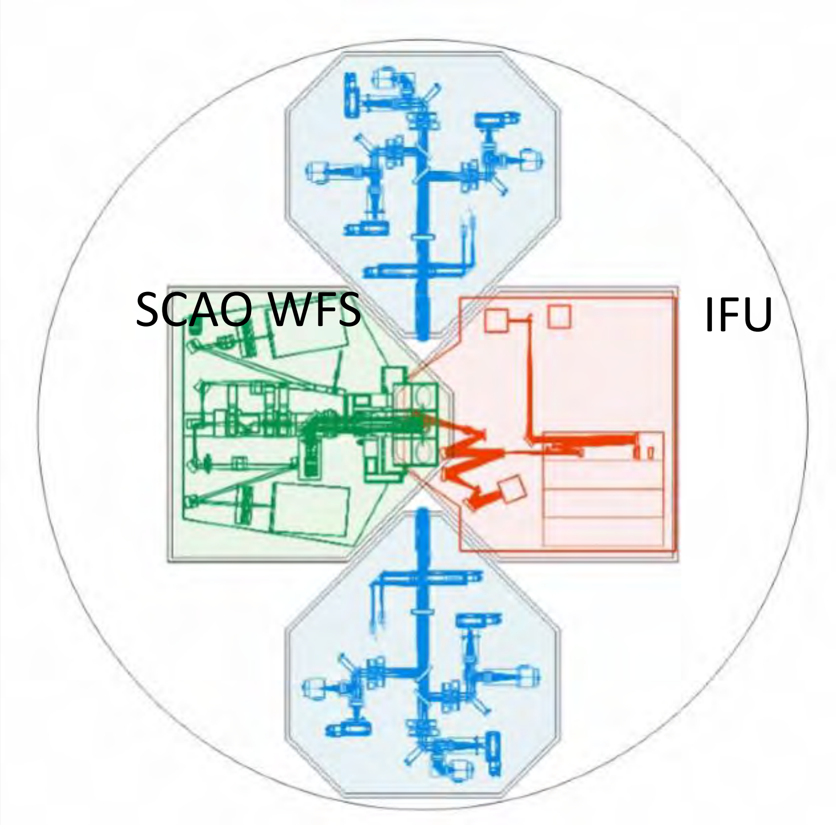
The SCAO subsystem is aimed to provide the adaptive optics correction to the IFU feeding the YJH spectrograph and, in the case of its implementation, to the IFU feeding the K-band spectrograph. The possibility to feed the RIZ spectrograph is currently under evaluation.

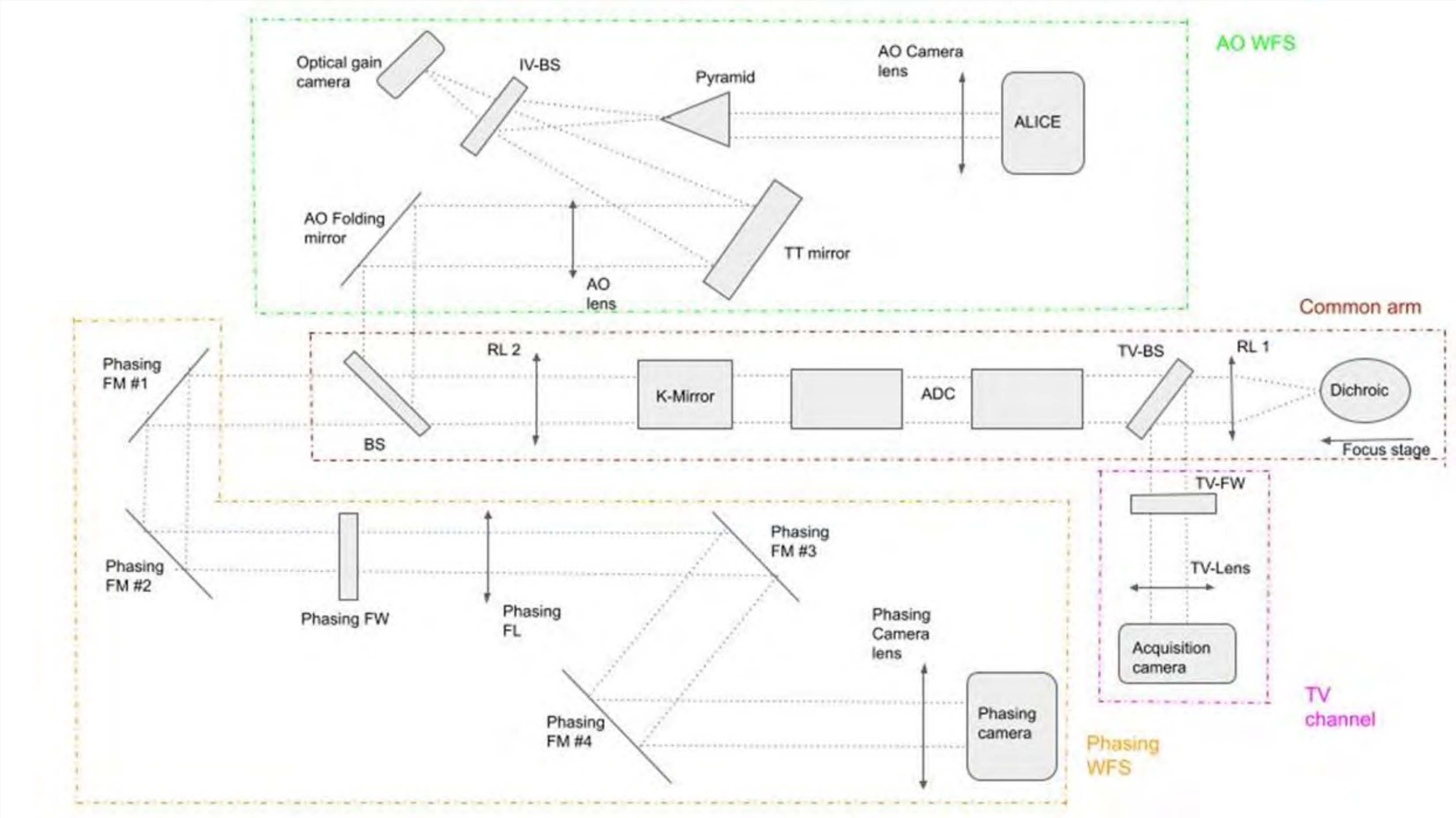
The main elements involved in the SCAO subsystem are:

- Wavefront Sensors: AO WFS and phasing WFS
- Real Time Computer (RTC)
- Deformable Mirror (DM): the ELT M4 - not part of the SCAO itself.

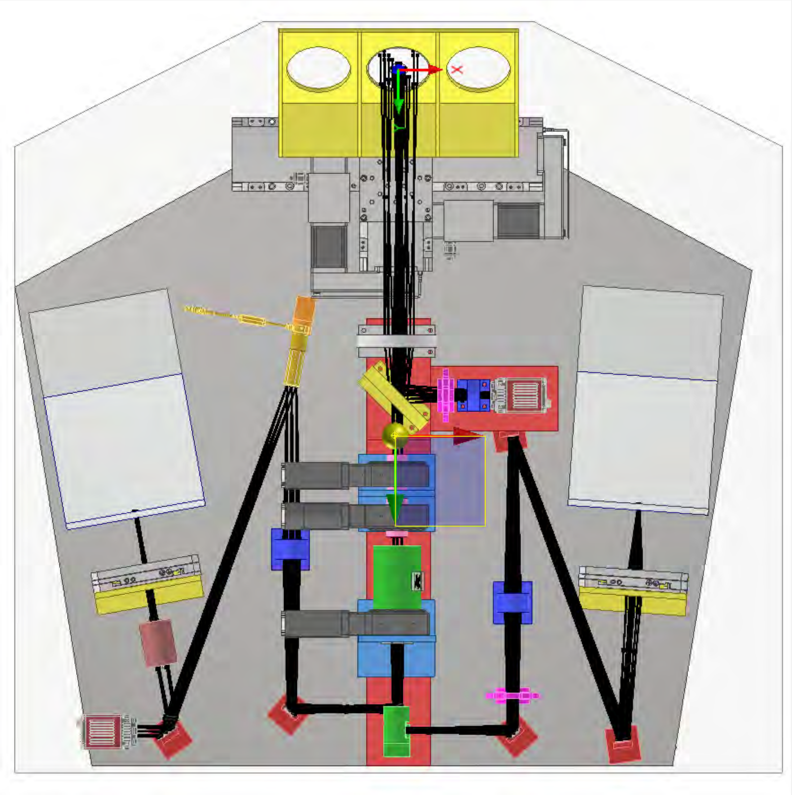


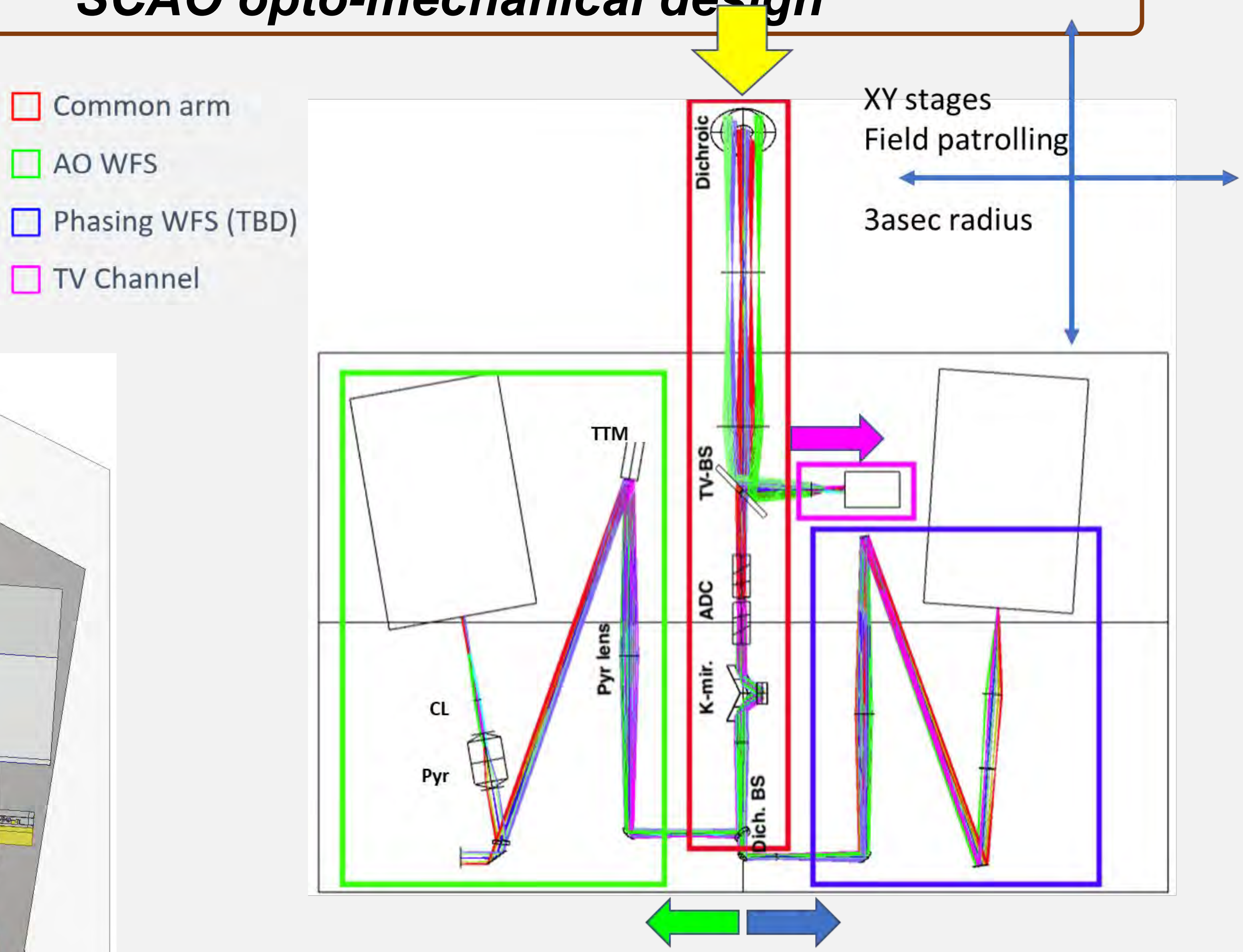
SCAO functional scheme





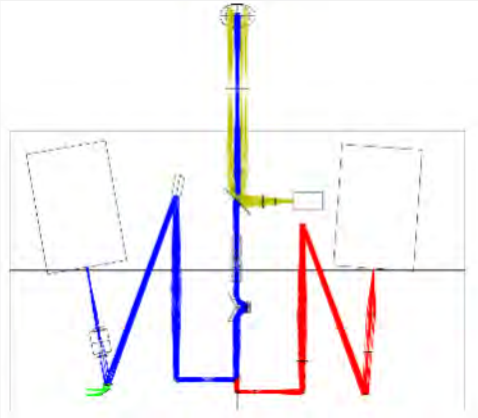
SCAO opto-mechanical design

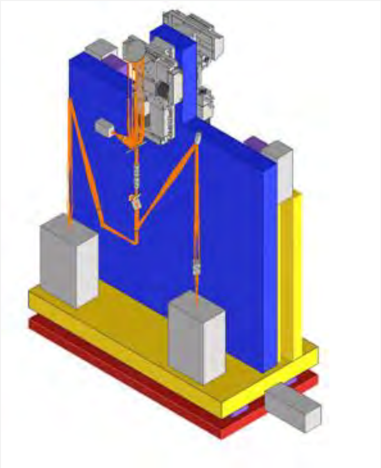




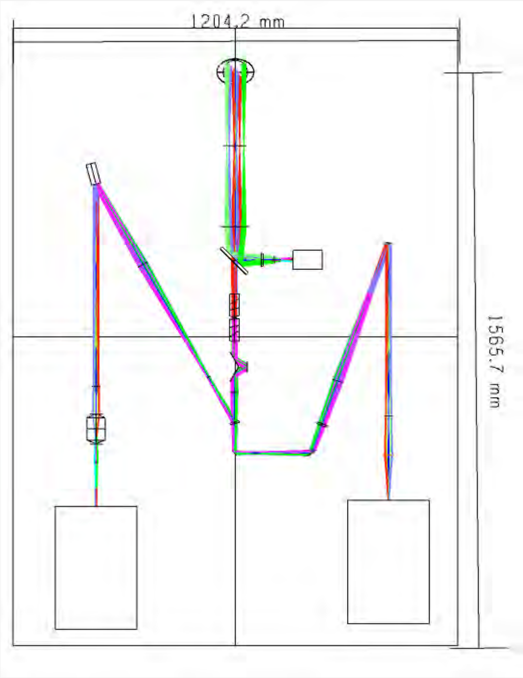
SCAO in the fix FE

Rotating FE



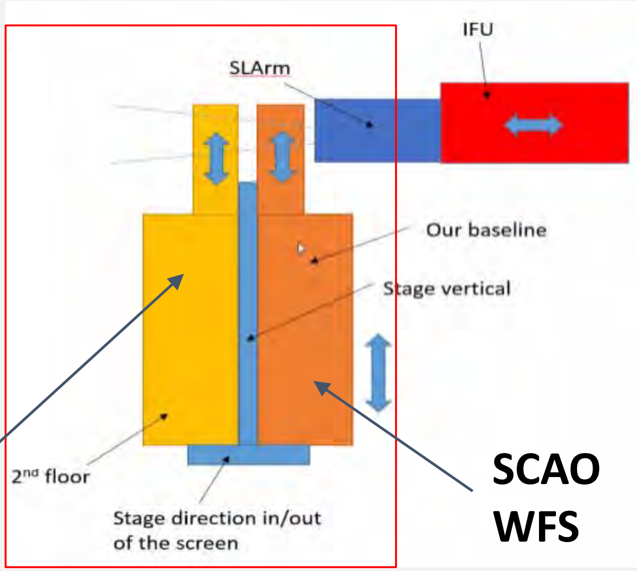


Fix FE
unfolded scheme



Fixed FE benefits for SCAO

- Gravity invariant:
  - Simplified requirements and test for devices (stages)
  - Simplified interfaces (proximity electronics, cabling, etc)
  - Improved stability
- Improved mass budget
- Improved volume budget



SCAO-IFU technical source (telescope simulator)

Volume and mass on fix FE allows for technical source for SCAO+IFU non-spectral calibration (yellow box)

RTC specifications

A preliminary design to control the ANDES SCAO module foresees the adoption of HEART, the Herzberg Extensible Adaptive Real-time Toolkit. Under study possible customization to fit the HEART Soft Real-time into the ESO RTC toolkit.

→ See talk of J. Dunn: *HEART On-Sky Results and Soft-Realtime Functionality*

I/O functional requirements	AN-AO-03-00_9 RTC	The ANDES HRTC shall offload persistent TBD Zernike correction to the M1 control system as per TBD ICD
I/O functional requirements	AN-AO-03-00_9 RTC	The SRTC shall communicate with the ICS as per TBD ICD
HRTC functional requirements	AN-AO-03-00_9 RTC	The ANDES HRTC and SRTC shall implement the AO operation algorithms described in "AO Algorithm Description Document"
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall have the capability to start/pause/stop the real-time processing pipeline
HRTC functional requirements	AN-AO-03-00_9 RTC	The ANDES RTC shall calibrate the WFS detector pixels by subtracting a background frame and dividing by a flat field frame, both of which are determined during calibration
HRTC functional requirements	AN-AO-03-00_9 RTC	Calibrated pixels shall be scaled by dividing them by the average intensity per pixel. This average can be computed from the previous frame
HRTC functional requirements	AN-AO-03-00_9 RTC	Valid pixels are selected based on a valid pixel mask provided by the SRTC.
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall compute slopes from selected pixels, unless direct pixel reconstruction is selected.
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall compute modal coefficients from slopes using a reconstructor provided by the SRTC. The HRTC should provide the option of feeding the reconstructor directly with selected pixels (direct pixel reconstruction).
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall scale the modal coefficient error vector by dividing it by an optical gain vector provided by the SRTC
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall subtract a reference vector from the scaled modal coefficient errors. The reference vector is provided by the SRTC (TBC)
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall apply a temporal filter to each modal coefficient. The temporal filter is a IIR filter with up to 10 taps (one per mode, up to 20 coefficients each) and is provided by the SRTC.
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall apply an integrator to the filtered modal coefficients
HRTC functional requirements	AN-AO-03-00_9 RTC	The HRTC shall be able to add a disturbance vector provided by the SRTC to the integrated coefficients

work ongoing

- WFS type: modulated pyramid WFS
- WFS camera: ALICE 240x240 pixels
- WFS on chip binning: 2x2, 3x3, 4x4 (TBC)
- WFS signal: pixel map / slopes
- AO loop frame rate: 500Hz
- Deformable Mirror: ELT-M4/M5

Project organisation: the Consortium

The ANDES Consortium is composed by 24 institutes from 13 countries.

- **Brazil:** Federal Univ. of Rio Grande do Norte
- **Canada:** Univ. De Montreal, Herzberg Astrophysics Victoria
- **Denmark:** Univ. Copenhagen, Univ. Aarhus, Danish Tech. Univ.
- **France:** LAM Marseille, LAGRANGE Nice, IPAG Grenoble, IRAP/OMP Toulouse, LUPM Montpellier
- **Germany:** AIP Potsdam, Univ. Göttingen, Landessternwarte Heidelberg, MPIA Heidelberg, Thüringer Landesternwarte Tautenburg, Univ. Hamburg
- **Italy**: INAF Istituto Nazionale di AstroFisica (Lead) (Arcetri, Bologna, Brera, Padova, Trieste)
- **Poland:** Nicolaus Copernicus Univ. in Toruń
- **Portugal:** Instituto de Astrofísica e Ciências do Espaço, CAUP and FCiências
- **Spain:** Inst. Astrofísica de Canarias (IAC), Inst. Astrofísica de Andalucía (IAA - CSIC), Centro de Astrobiología (CSIC-INTA) Madrid
- **Sweden:** Uppsala Univ., Lunds Univ., Stockholm Univ.
- **Switzerland:** Univ. de Genève, Univ. Bern
- **United Kingdom:** Univ. of Cambridge, UK Astronomy Technology Centre, Heriot-Watt Univ.
- **USA:** Univ. of Michigan

Project organisation: members

ANDES, the high resolution spectrograph for the ELT: science case, baseline design and path to construction

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Over 230 (scientific and technical) people contributing to ANDES, see author list of recent SPIE paper (Marconi et al. 2022, SPIE)

Schedule

Project timeline			
Project phases	**Milestones**	**Duration**	**Name**
Phase B	KM.1	T0	Kick-off (KO)
	KM.2	T0 + 9 months	System architecture completion (SAR)
	KM.3	T0 + 22 months	Preliminary design completion (PDR)
		T0 + 26 months	Funding review (FR)
Phase C	KM.4	T0 + 48 months	Final design completion (FDR)
Phase D	KM.5	T0 + 80 months	Integration readiness completion (IRR)
	KM.6	T0 + 88 months	Test readiness completion (TRR)
	KM.7	T0 + 108 months	Preliminary acceptance Europe completion (PAE)
Phase E	KM.8	T0 + 120 months	Provisional acceptance Chile completion (PAC)
Phase F	KM.9	PAC + 2 years	Final acceptance completion (FAC)

Challenges

ANDES is a challenging instrument in several aspects: it is actually a *multi-instrument* composed by several modules (subsystems) where each one is an instrument by itself already exceeding dimensions of current largest spectrographs of such kind, worldwide.

At the project management level main challenges are represented by its *large consortium*, the needs of *huge efforts and funds' investments* for its construction within a not negligible time frame to reach on-sky operations.

In order to master ANDES complexity, a modular approach has been adopted both at project and system level: 9 major subsystems have been identified with their own project managers and system engineers which are responsible for their respective subsystems and, at the same time, are also part and support the project manager and system engineer at the system level.

ANDES

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Max Planck Institute for Astronomy Heidelberg

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