The PCS extreme AO instrument for ELT

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and the PCS R&D roadmap collaboration

PCS is the next ELT instrument to be launched

Instrument	Main specifications			Schedule				
	Field of view/slit length/ pixel scale	Spectral resolution	Wavelength coverage (μm)	Phase A	Project start	PDR	FDR	First light
MICADO	Imager (with coronagraph) 50.5″ × 50.5″ at 4 mas/pix 19″ × 19″ at 1.5 mas/pix	*I, Z, Y, J, H, K* + narrowbands	0.8–2.45	2010	2015	2019	2024	
	Single slit	*R* ~ 20 000						
MORFEO	AO Module SCAO – MCAO		0.8–2.45	2010	2015	2023		
HARMONI + LTAO	IFU 4 spaxel scales from: 0.8″ × 0.6″ at 4 mas/pix to 6.1″ × 9.1″ at 30 × 60 mas/pix (with coronagraph)	*R* ~ 3 200 *R* ~ 7 100 *R* ~ 17 000	0.47–2.45	2010	2015	2018		
METIS	Imager (with coronagraph) 10.5″ × 10.5″ at 5 mas/pix in *L, M* 13.5″ × 13.5″ at 7 mas/pix in *N*	*L, M, N* + narrowbands	3–13	2010	2015	2019	2024	
	Single slit	*R* ~ 1400 in *L* *R* ~ 1900 in *M* *R* ~ 400 in *N*						
	IFU 0.6″ × 0.9″ at 8 mas/pix (with coronagraph)	*L, M* bands *R* ~ 100 000						
ANDES	Single object	*R* ~ 100 000	0.4–1.8 simultaneously	2018	2024			
	IFU (SCAO)							
	Multi object (TBC)	*R* ~ 10 000						
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	*R* ~ 5 000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5 000–20 000	0.6–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

1 milliarcsecond (mas) = 0.001″

https://elt.eso.org/instrument/

Background: From EPICS to PCS

EPICS – First conceptual design of an ELT extreme high-contrast planet finder (XAO + coronagraphy + IFS), developed **up to Phase A** level **(2007-2010)** but not pursued further at the time.

Limited mainly by **technology readiness**:

- extreme actuator density (tens of thousands of actuators)
- real-time control requirements (multi-kHz loops)
- high-speed, low-noise NIR wavefront sensing detectors
- coronagraphic stability and post-coronagraph wavefront control at ELT scale

PCS roadmap community collaboration, started early 2025

Clear understanding of the PCS instrument’s scientific objectives

Draft instrument concept addressing these scientific objectives

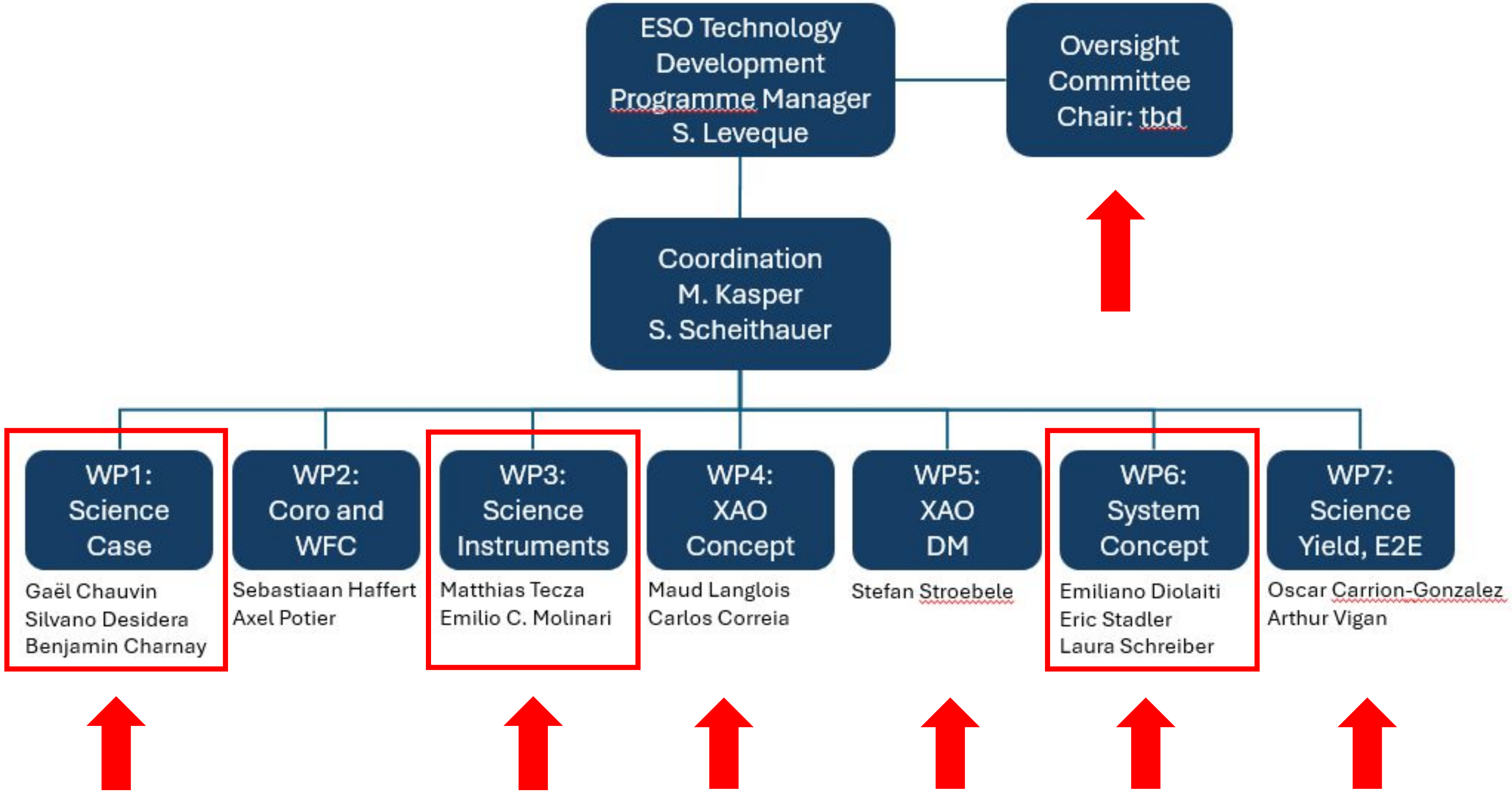
Rough estimates of important instrument budgets (volume, weight, transmission, power, cost)

Analysis of scientific capabilities of the proposed concept

Summary in a white paper early 2028

Establish training opportunities for graduate students and fellows in the field of high-contrast imaging

PCS R&D roadmap Organisation



INAF staff contributes to many WPs and co-leads 3 out to 7

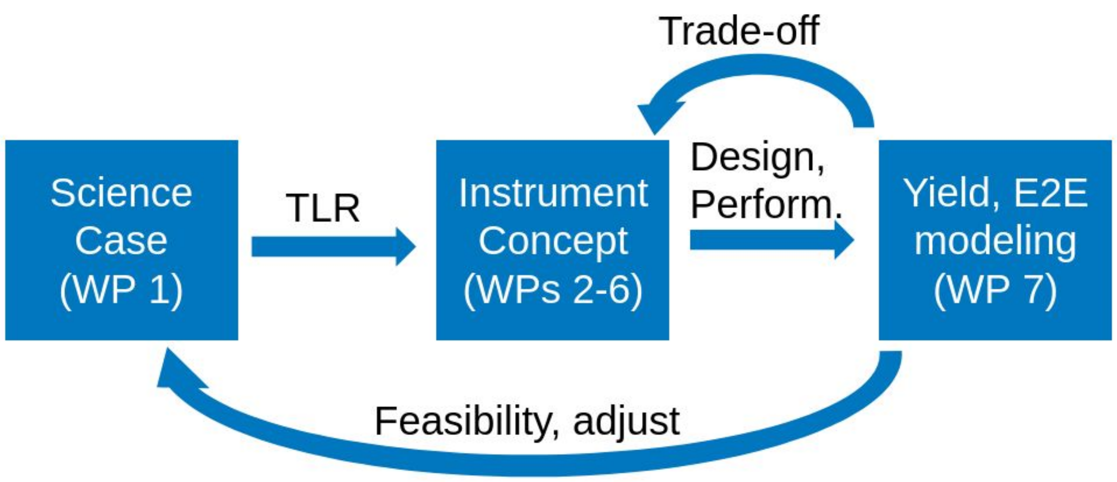
About 150 contributors from the community (SCI+TEC)

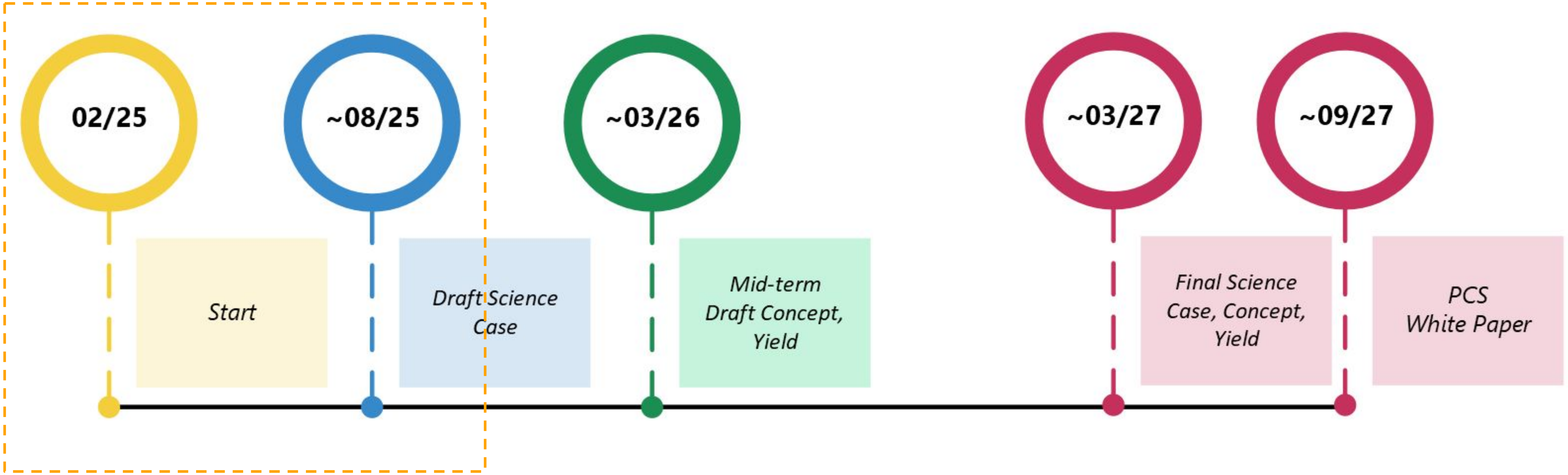
Courtesy of Markus Kasper

PCS R&D roadmap partners

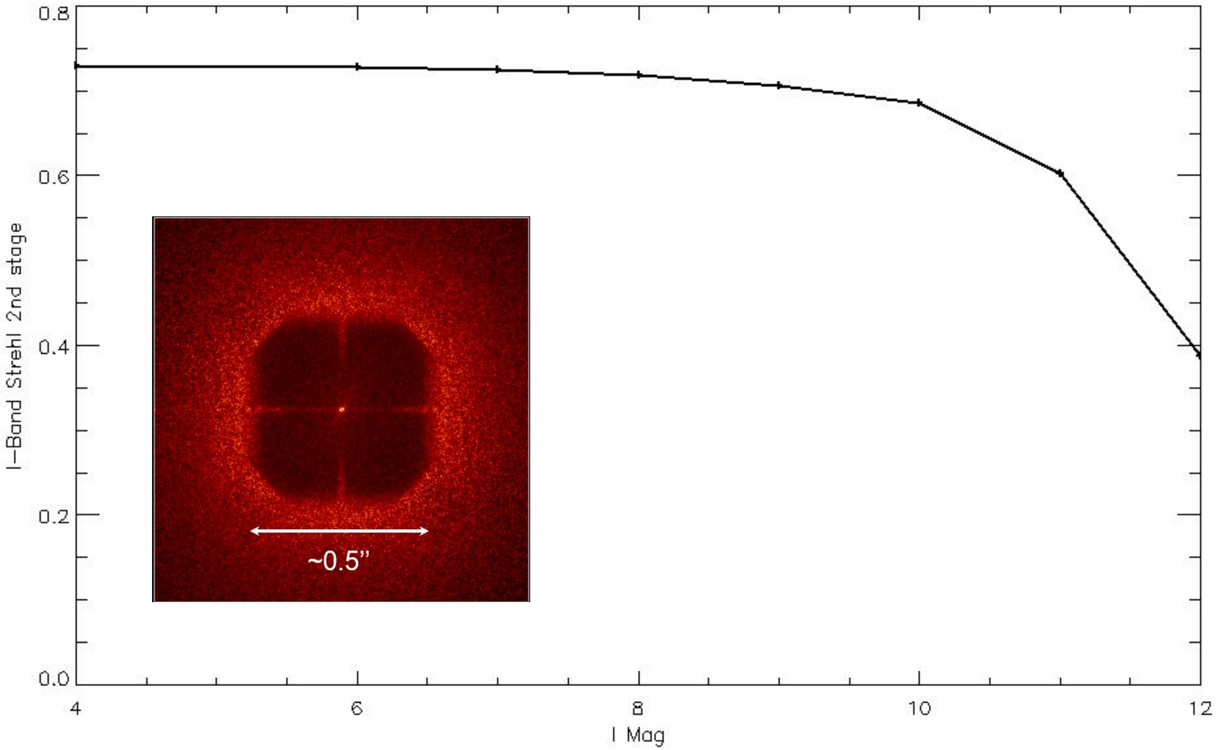
The European Organisation for Astronomical Research in the Southern Hemisphere (ESO)
The Centre National de la Recherche Scientifique (CNRS)
The Institut d'Optique Théorique et Appliquée (IOTA)
CEA
Istituto Nazionale di Astrofisica (INAF)
Università di Bologna (UniBo)
University of Geneva
Durham University
United Kingdom Astronomy Technology Centre
University of Oxford
The Instituto de Astrofísica e Ciências do Espaço (CAUP)
Universidade do Porto
NOVA
Université de Liège
University of Michigan

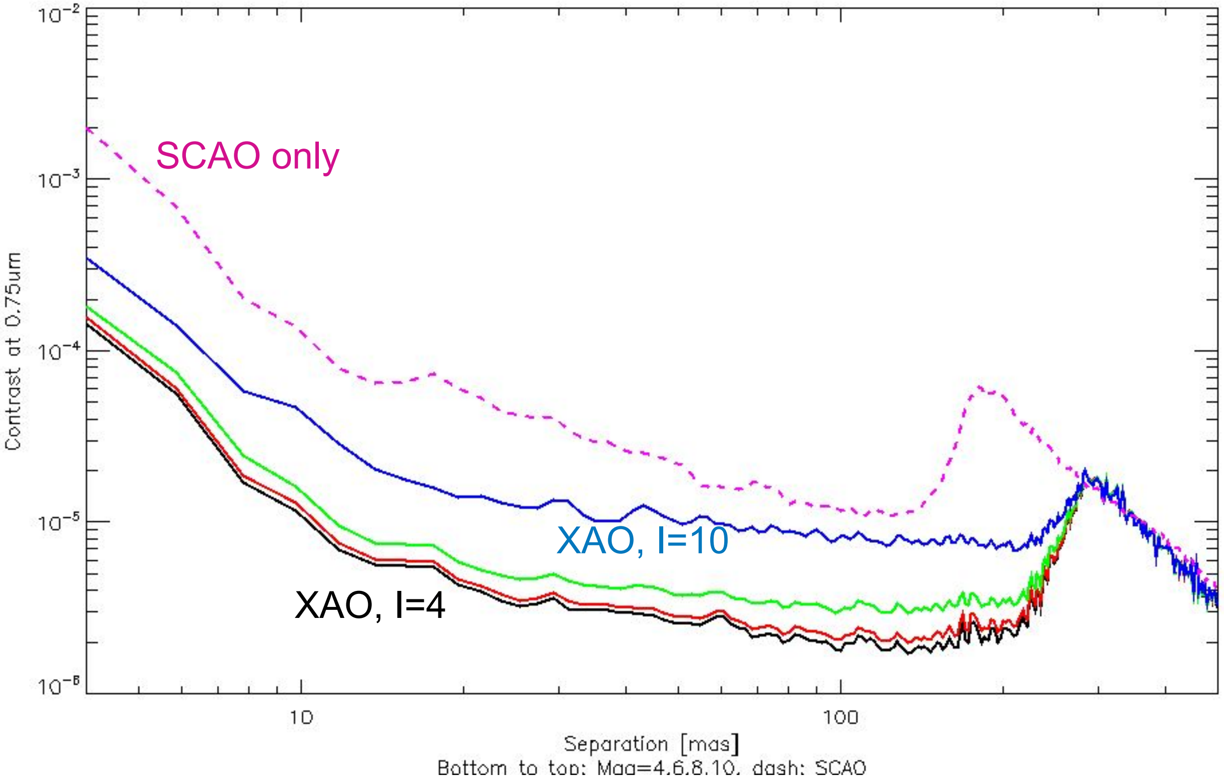
Timeline & information flow





XAO Strehl ratio and contrast

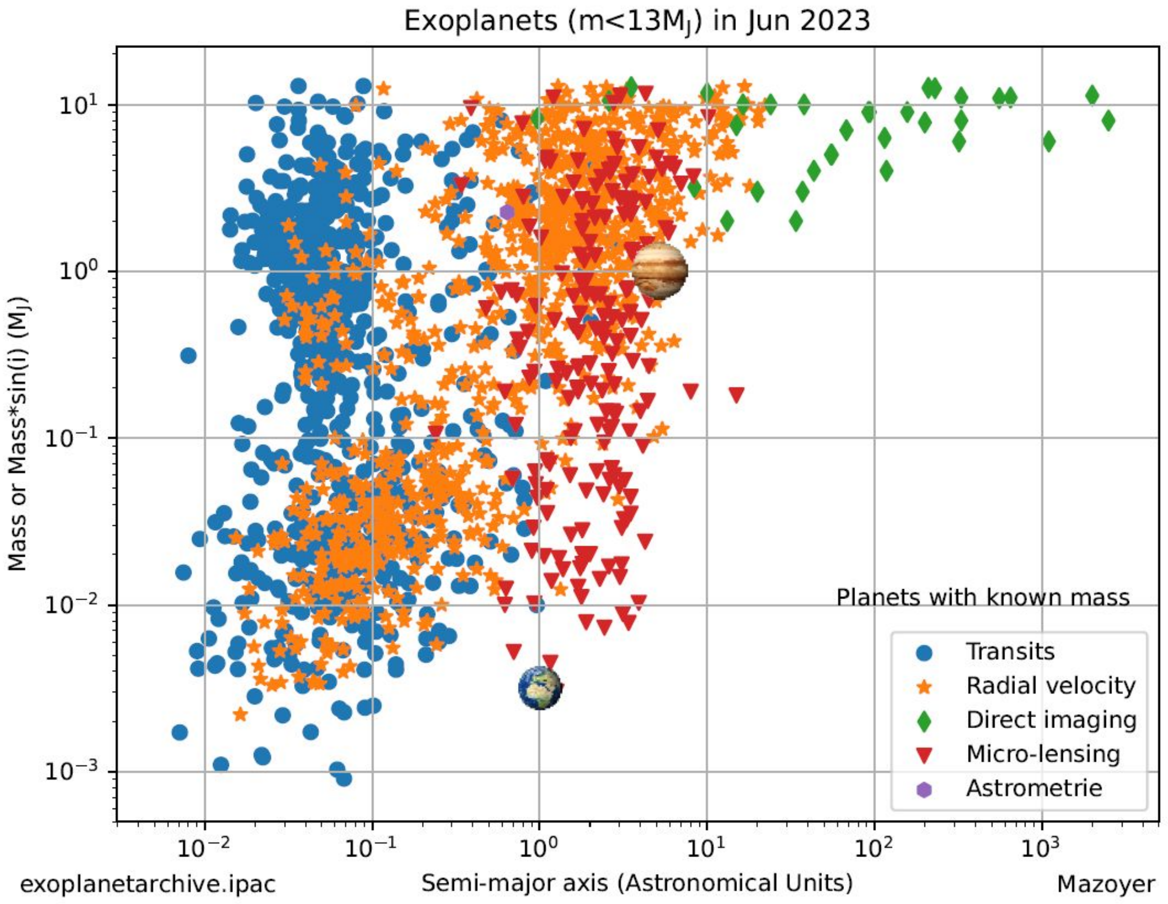


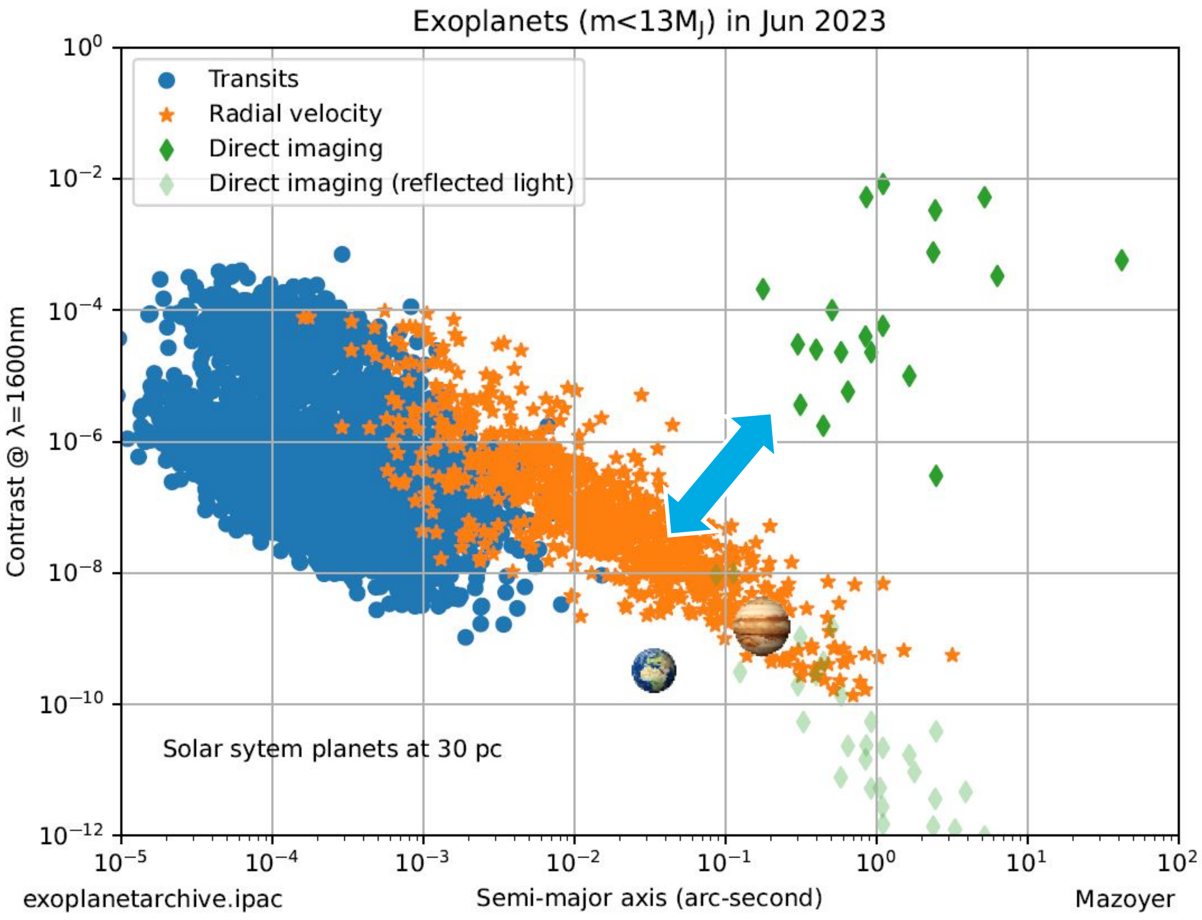


Credit: M. Le Louarn

- XAO provides factor ~15 gain in raw contrast and a **factor ~40 gain in observation "speed" over SCAO**
- Small benefit for NGS I>~12, **PCS is a "bright star instrument**

How to increase directly imaged planet yield?





By courtesy of Johan Mazoyer

Push **inner working angle and contrast** to observe Exoplanets in reflected light
Need 10^{-8} contrast at 10-50 mas separation

Preliminary SCs & TLRs document (Sept. 15th release)

State-of-the-art
Key scientific questions for PCS
Proposed program & targets
Requirements

Key science cases:

3.1 Rocky planets (coord.: Turbet, **Pino**)

3.2 Sub-Neptunes/Neptunes (coord.: Charnay, **Desidera**)

3.3 Giants (coord.: Parmentier, **Gratton**, Chauvin)

3.4 Exomoons & Exorings (coord.: **Lazzoni**, Limbach, Haffert)

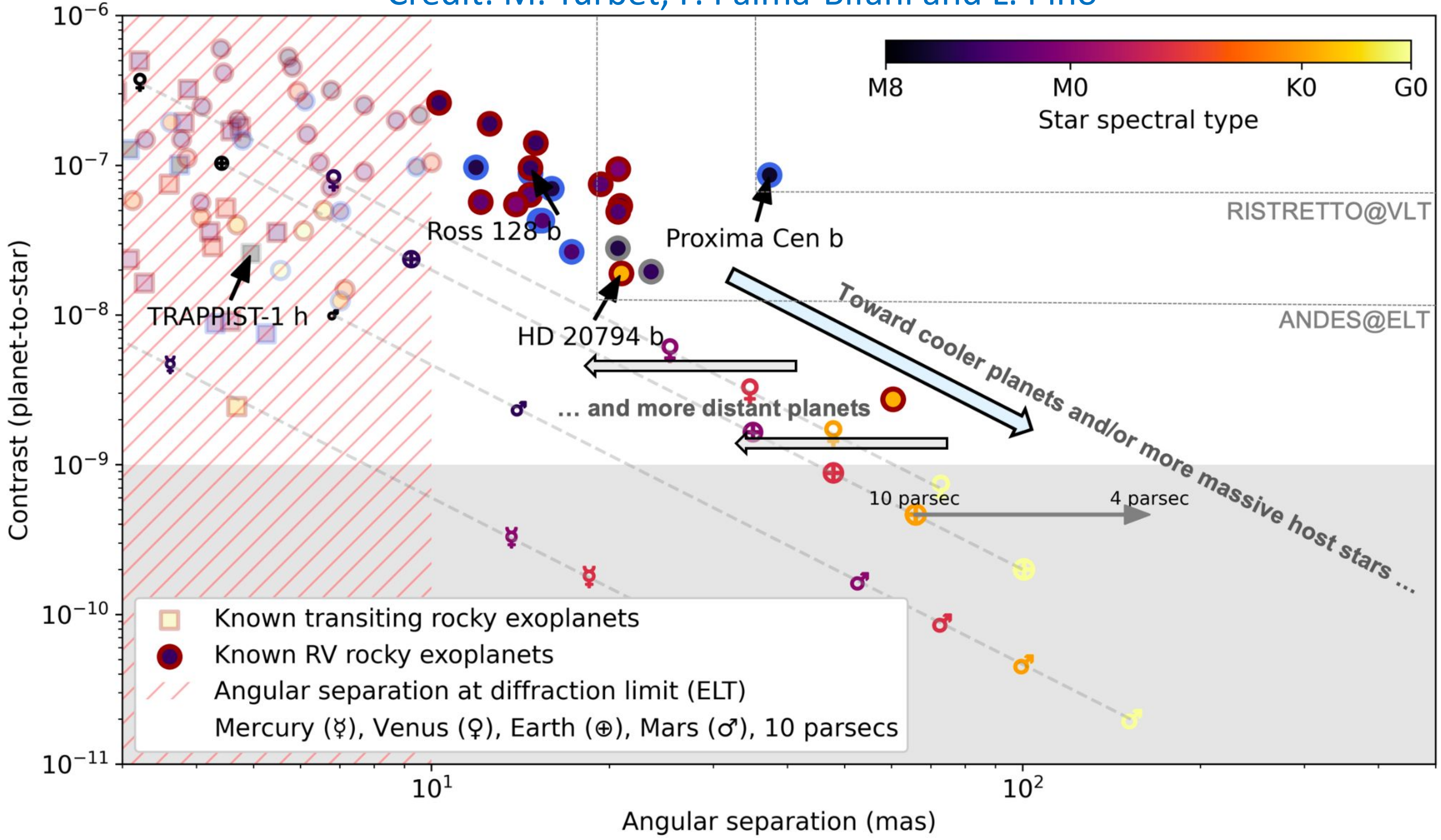
3.5 Protoplanets (coord.: Bonnefoy, Lichtenberg, **Fedele**)

3.6 Planet-forming disks (coord.: **Rigliaco**, **Fedele**, Toci)

3.7 Debris disks & exo-zodii (coord.: **Roccatagliata**, di Folco)

Rocky Planets in reflected light with PCS

Credit: M. Turbet, P. Palma-Bifani and L. Pino



<u>Proposed program and strategy</u>

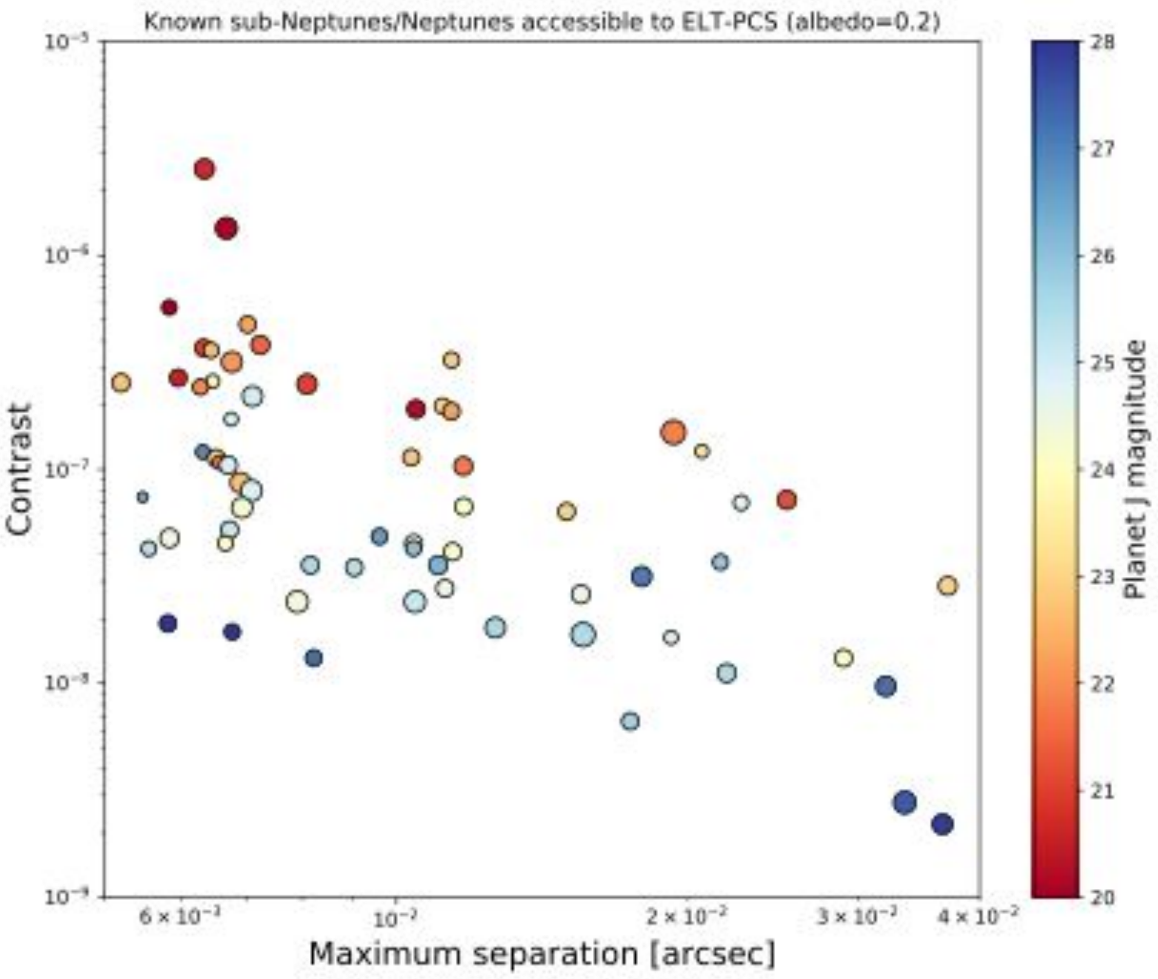
Tier 1: direct detection
constrain orbits (inclination, true mass), estimate albedo

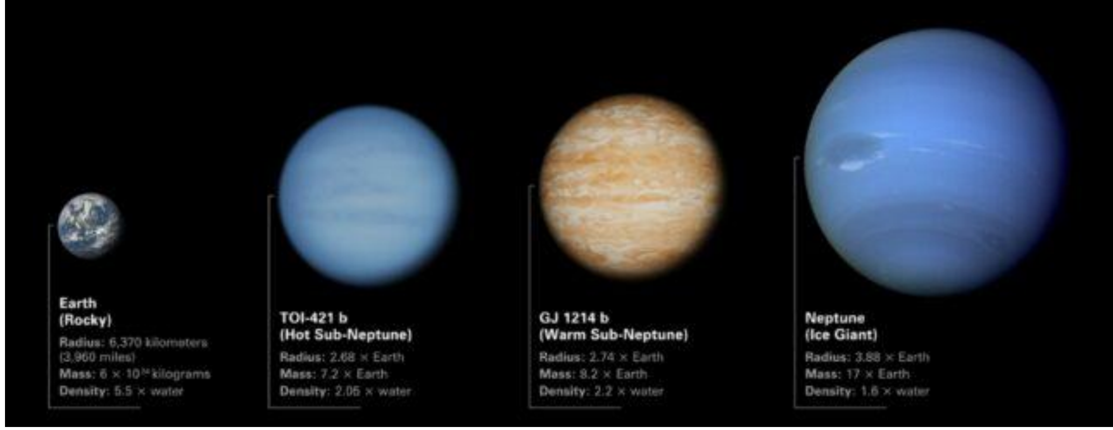
Tier 2: spectral characterization
variations of albedo and detection of atmospheric molecules (e.g. O_2, CH_4, H_2O; CO)

Tier 3: phase angle variations
ocean glint, atmospheric stratification

Tier 4: polarimetry
Breaking degeneracies

Sub-Neptunes and Neptunes





Lower hanging fruits, most common type of exoplanet

<u>2 tiers strategy</u>

- Spectroscopic survey of ~40 sub-Neptunes/Neptunes orbits, metallicity, C/O, albedo, abundances (H_2O, CH_4 and CO)
- Detailed characterisation of best 10-20 targets abundances of minor species (e.g. CO_2, NH_3, H_2S), rotation rate, the tidal evolution and aerosol optical properties, map cloud/haze and search for ocean glint (for potential water worlds)

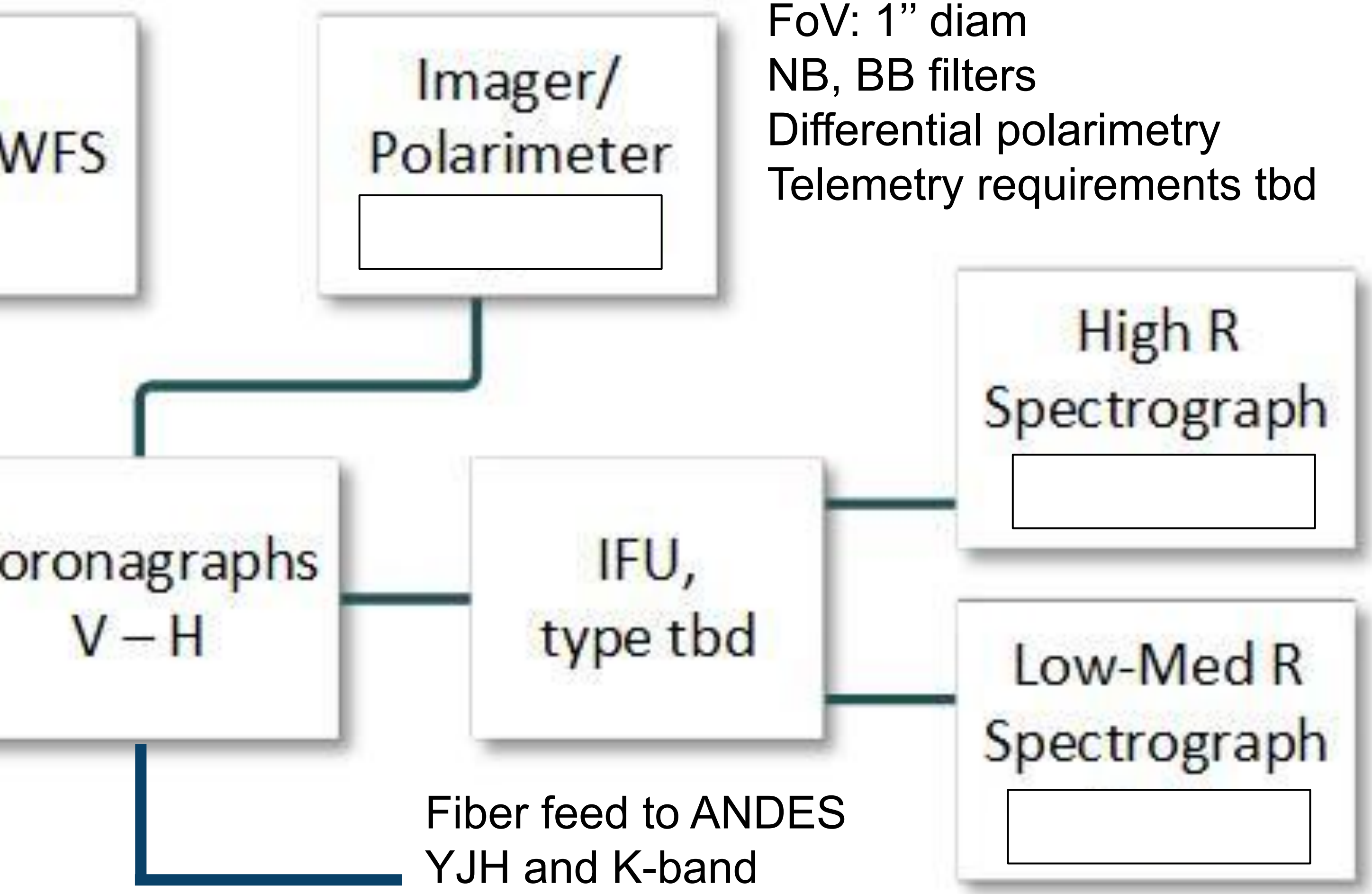
Few known **transiting planets** may be within detection limits (most promising AU Mic c)
Very relevant to break degeneracies (radius known) and to observe the same planet with different techniques

TLR

Type	Value	Remark
Modes	HCI, +HRS, +MRS, +Pol	
FoV radius	>50-100 mas (up to 500 mas off-axis) IFU	Exoplanets in reflected light (discovery mode) Young giants, Exomoons/ring
	>500-1000 mas Imager	Disks, outflows (continuous FoV)
	Diff. lim	Spectral characterization, Doppler Imaging
Wavelength coverage	R-K	H-alpha – CO
Spectral resolution	~100k (optical) ~100k (NIR) ~10k (NIR) ~100	CC, spectral analysis Characterization, Doppler Imaging Molecular Mapping Imaging, Polarimetry
Contrast	10^{-8} @ 10 mas 10^{-9} @ 30 mas	2.5 λ/D at 750 nm 7.5 λ/D at 750 nm

Maximize instrument flux transmission !

Possible instrumentation setup (ongoing work)



R-K
FoV: 1'' diam
NB, BB filters
Differential polarimetry
Telemetry requirements tbd

FoV: r=50 mas (~200 λ/D-sized spaxels)
R ~ 100k
Bandpass: 100 nm
Wavelength range: 600-950 nm

FoV: r=100 mas (~200 λ/D-sized spaxels)
R ~ 10-20 k
Bandpass: 400 nm (cover full J,H, or K band)
Wavelength range: 1100-2400 nm

Fiber feed to ANDES
YJH and K-band
spectrographs

Link to ANDES: concept

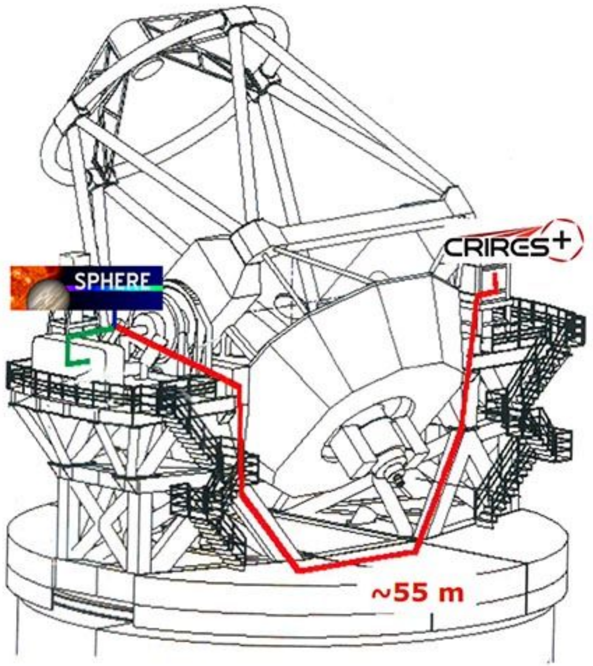
PCS foresees high spectral resolution spectroscopy, to be coupled with the high spatial resolution provided by the AO system.

Possibility to exploit some of the channels of the ANDES spectrograph through fiber link

Concept already working at VLT (HiRISE fiber fed between the SPHERE AO module and the CRIRES spectrograph)

First priority: YJH bands spectrograph
Second priority: K band spectrograph
Specialized IFU for detection of rocky planets should be internal to PCS

Current situation: discussion started, no obvious showstoppers identified.
Will be investigated after ANDES PDR

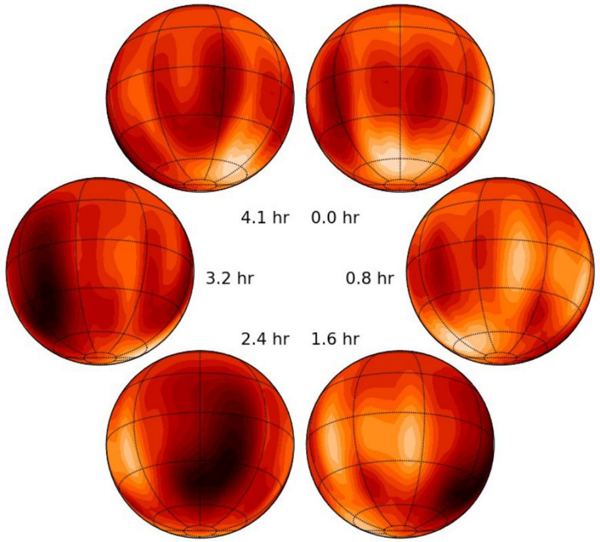


Link to ANDES: science goals

ANDES + PCS foresee as a dedicated mode for **exoplanet characterization**

Atmospheric characterization at high spectral resolution

Doppler imaging: **mapping the clouds** configuration



Crossfield et al. 2014 and 2024

Search for exomoons though RV monitoring of spatially resolved planets

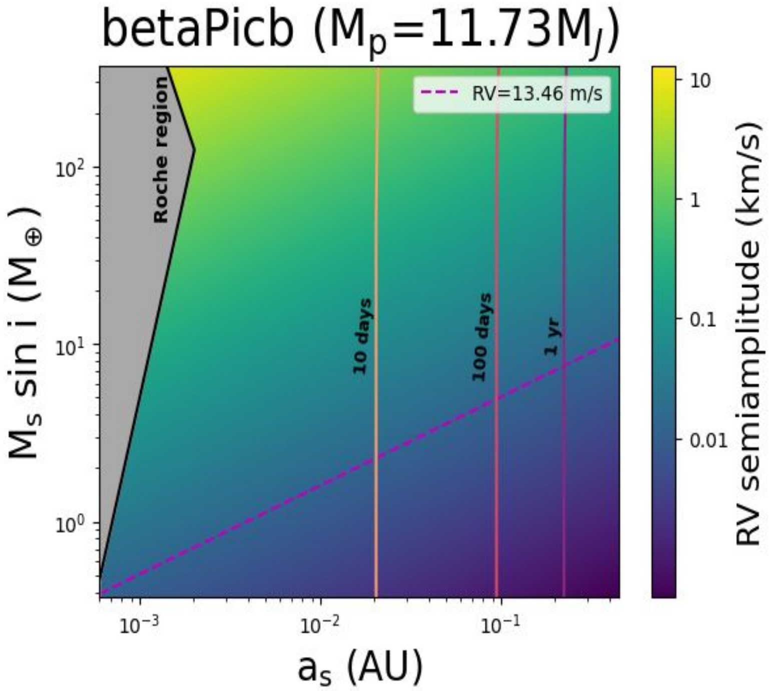
Ongoing with CRIRES and HiRISE at VLT, KPIC at Keck
Sensitivity to “binary planets”. Promising results emerging

Major improvement expected with ANDES and even more with PCS+ANDES

Simulations based on ANDES SCAO non-coronagraphic PSF (thanks to E. Pinna & ANDES team)

Detectability of Earth-mass satellites around β Pic b close to Roche limit

Giovannini+ in prep.

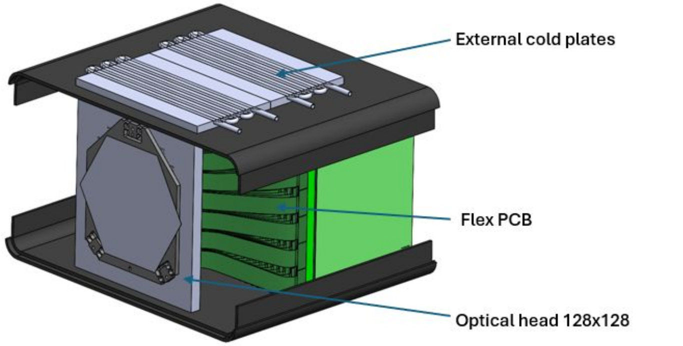


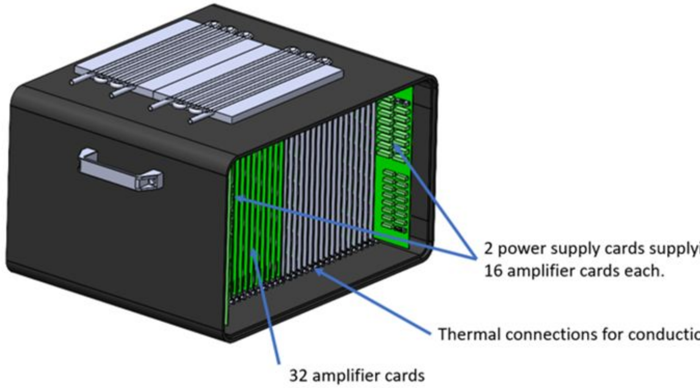
XAO DM development (S. Stroebele, M. Schweitzer)

XAO DM prototype manufacturing

Development with Bertin-ALPAO

- Many actuators: > 13000, >128 across
- High speed: small stroke settling < 300 us
- ±3µm Stroke @ 0.2 nm resolution
- Integrated drive electronics





03/2026

WP1	WP2	WP3	WP4
XAO DM Prototype Preliminary Design	XAO DM Prototype Final Design	XAO DM Prototype Optical Head Manufacturing and Tests	XAO DM Prototype Manufacturing and Tests

06/2028

SAXO+ on sky

On-sky demonstration of 2 stages AO

Upgrade on the AO system of SPHERE at VLT

- 2° stage correction AO
- NIR Pyramid Wavefront sensor 50X50 sub-apertures
- Up to 2.7 KHz (goal 3KHz) correction frequency
- Wavelength range (common path) 0.95 – 2.32 μm
- Wavelength range (WFS path) 0.95 – 1.1 μm/ 0.95 – 1.45 μm
- DM with 28X28 actuators across the pupil diameter
- Guide star up to mag H 11.7+ (mag R 16.8)

SPHERE / SAXO+ as the key stepping stone for PCS – Operational experience and ongoing upgrades provide the main technological and methodological foundation for PCS (wavefront control, calibration, stability, validation on-sky). **Main objective of the SAXO+ Project** (as approved by ESO) **to carry out a PCS R&D demonstration on-sky**

Three key ingredients expected in 1st half 2028

White paper summarizing R&D effort

SAXO+ on sky

XAO DM prototype manufacturing

Following step: move to PCS project start

Summary

PCS R&D Roadmap Science Activities

- On-going activities, iterations on proposed instrument configurations
- Highly significant and transversal italian participation (co-leadership for all science goals). No formal italian WG at this stage but dedicated mailing list already set-up: pcs-sci-it@inaf.it
- Instrument specifications driven by exoplanet and disk science. Open to additional goals after first definition of the instrument characteristics and expected performance
- Specific scientific interest for a fiber link to ANDES
- Strong synergies in the scientific preparation with ANDES, HWO, and LIFE
- Good perspectives for the following phase of actual instrument design and building (starting 2028/29)