Planetary Camera and Spectrograph (PCS) Review

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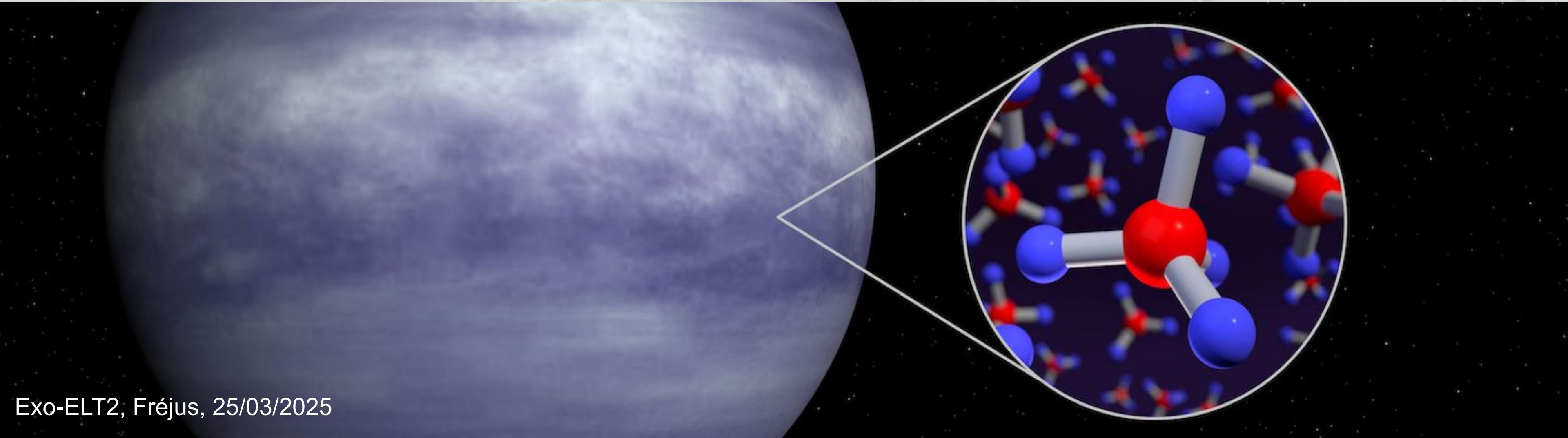


Exo-ELT2, Fréjus, 25/03/2025

PCS in the ELT instrumentation plan

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* ~ 3200 *R* ~ 7100 *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				
	IFU (SCAO)							
	Multi object (TBC)	*R* ~ 10 000						
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	*R* ~ 5000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5000–20 000	0.8–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

ESO website



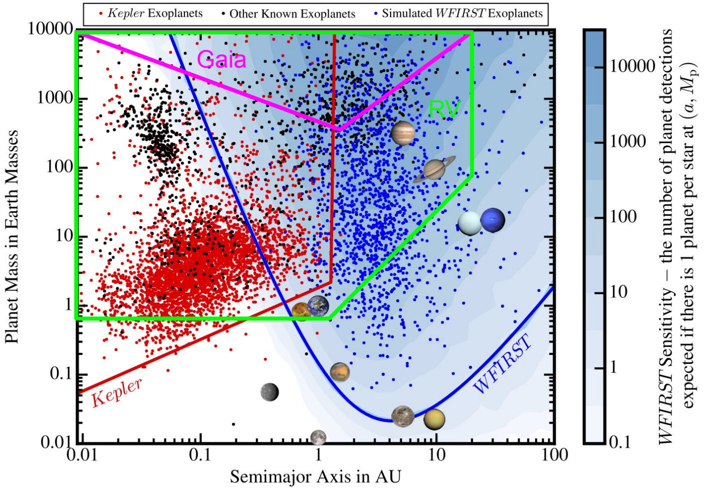

Next ELT instrument to be launched

R ~5, ~10 000, ~100 000
λ ~ 0.6 - 1.8 μm
Phase A > 2028

Exoplanet field by PCS 1st light in ~2040

- **Kepler, TESS, PLATO:** nearly complete statistical census of small transiting exoplanets has been recorded
- **HARPS/NIRPS, SPIRou, CARMENES, ESPRESSO, …:** census of most nearby small exoplanets on longer period
- **JWST & ARIEL:** spectra of some (d>10pc) giants and mini-Neptunes (maybe some rocky planets?)
- **Gaia astrometry:** huge potential from excess noise estimations to identify interesting systems
- **Gaia + Roman/CGI:** precise orbits of giant planets observable by PCS
- **ELT 1st gen instruments (METIS, MICADO, HARMONI):**
  - Measured thermal continuum emission from warm protoplanets and their circumplanetary disks
  - Determined the occurrence rate of long period gas giant planets (SFR, beyond ice-line)
  - Characterized warm giant exoplanets through high-res spectroscopy
  - Detected a few rocky exoplanets around very nearby FGK stars

Adapted from Penny et al. (2019)



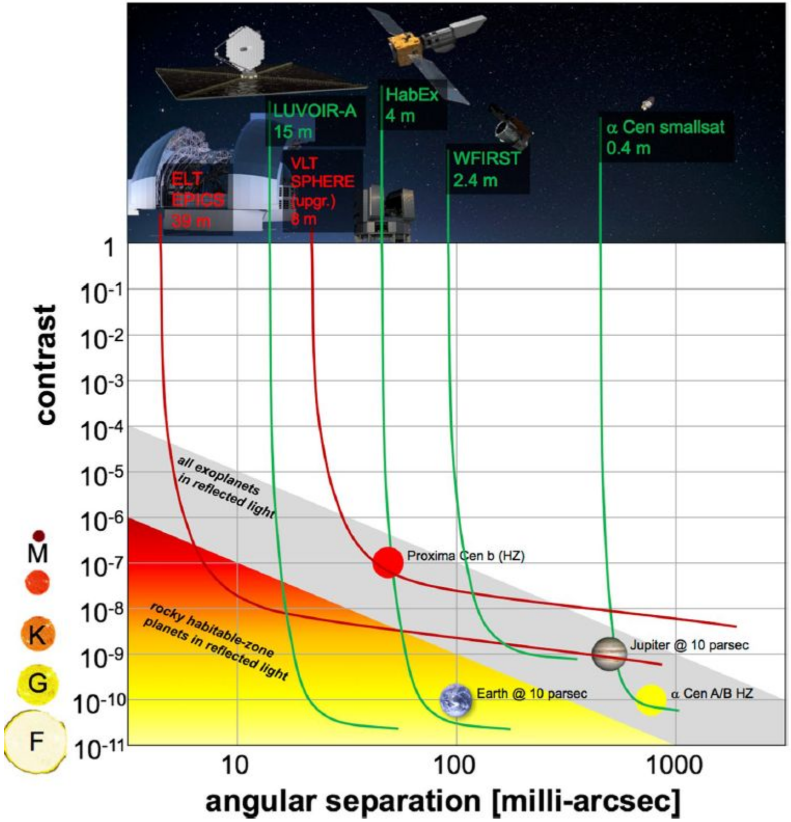
PCS science goals

Unrivaled contrast sensitivity for sub-100 mas angular separations

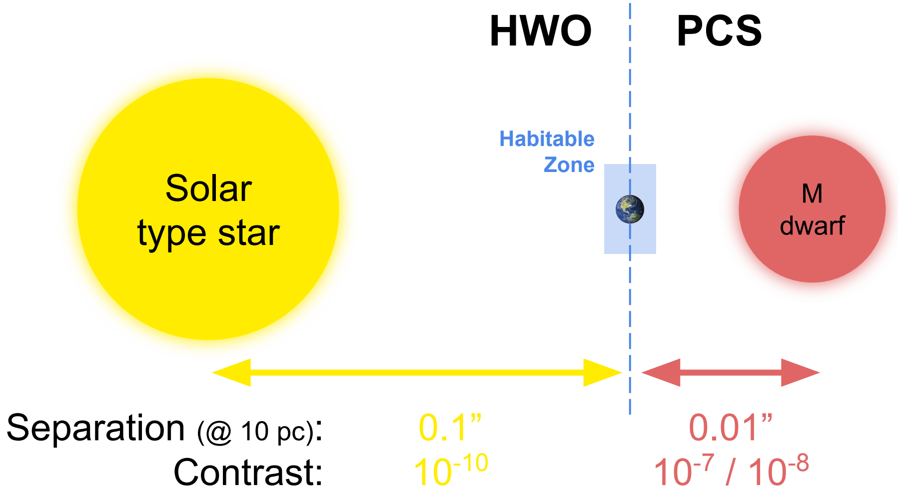
- **Rocky planets:** detection, orbit determination and inclination, habitability - presence of (liquid) H_2O, biosignatures (O_2, CH_4), variation in atmospheric composition, connection to dust/debris
- **Constraining planet formation:** Hα (656 nm) imaging at very high contrast and small IWA to observe small exoplanets in transitional disks. Synergy with ELT 1st light instruments (NIR and MIR)
- **Mature sub-Neptune & giant planet characterization:** orbits, compositions, formation
- **Young giant exoplanets:** high S/N enables studies of precise photometric variability
- **Circumstellar disks and dust:** imaging at ~5 mas resolution with 15 mas IWA. Synergies with ALMA (similar spatial resolution at mm wavelengths)

Contrast and angular separation

Snellen et al. (2022)



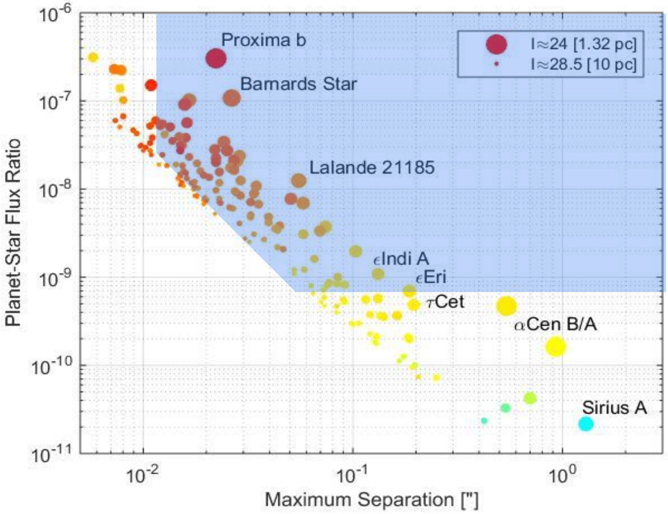
- ❑ Unique combination of angular resolution and contrast
- ❑ Major complementarity with HWO, projected to be launched in the early 2040s



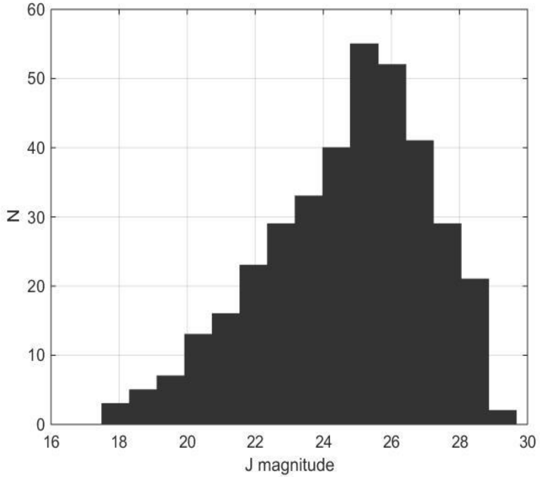
Detection and characterization of Earth analogs

Detection of Earth analogs around nearby stars

Synthetic exo-Earth population imaged in reflected light



Brightness of nearby known exoplanets (all sizes)



Kasper et al. (2021)

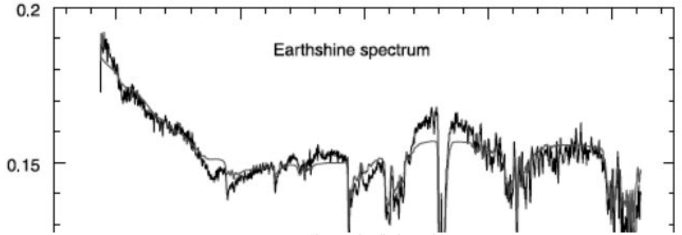
- ❏ Terrestrial planets more abundant around the abundant M-stars (~80%)
- ❏ Contrast ≤ 10^{-8} at 15 mas (~4 λ/D at 700 nm) and ≤ 10^{-9} at 100 mas
- ❏ Good sensitivity - Detect exoplanets with I- and J-magnitudes ≥ 26

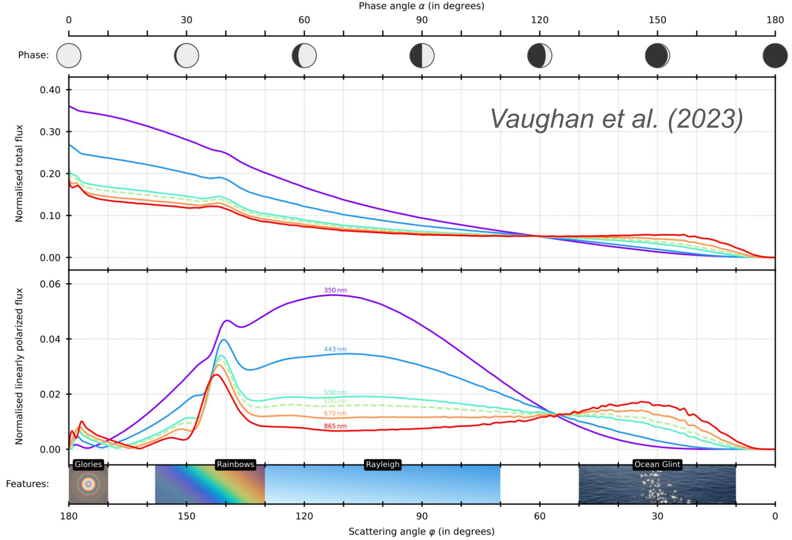
Detection and characterization of Earth analogs

Characterization of telluric planets down to Earth size

- Potentially habitable planets
  - In habitable zone: T and surface P suitable for liquid water
  - Found by radial velocity, transits
- “Habitable” planets
  - Presence of liquid water on surface → “ocean glint” (need polarization)
  - Water vapor possible to detect
- (Possibly) planets with life
  - Presence of biomarkers (O_2, O_3, red-edge, CH_4)
  - Biomarker != Life !!!!!
- PCS anticipated as a **follow-up instrument**

Woolf et al. (2002)





Spectral bandpass requirements

From Astro2020 Decadal Survey

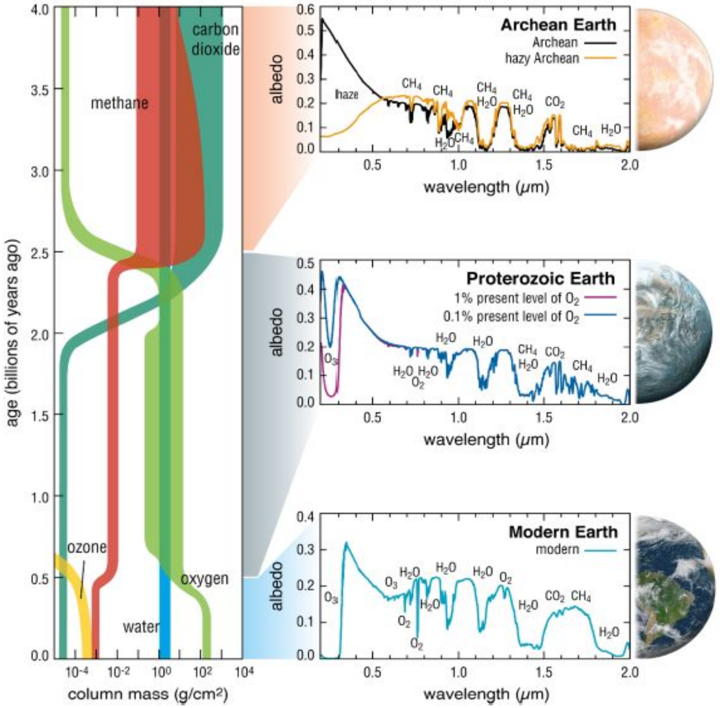
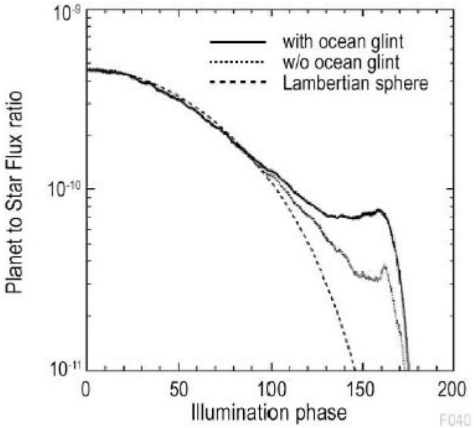


Table 3-2. *Desired spectral features for habitability assessment.*

Habitability Markers		
Molecules/Feature	UV-VIS wavelengths (0.2–1.0 μm)	NIR wavelengths (1.0–2.0 μm)
H_2O	0.65, 0.72, 0.82, 0.94	1.12, 1.4, 1.85
H_2	0.64–0.66, 0.8–0.85	
CO_2		1.05, 1.21, 1.44, 1.59
CH_4	0.6, 0.79, 0.89, 1.0	1.1, 1.4, 1.7
S_8	0.2–0.5	
H_2S	< 0.3	
SO_2	< 0.3	
Ocean glint	0.8–0.9	1.0–1.05, 1.3
Rayleigh scattering	≲ 0.5	

From Luvoir final report



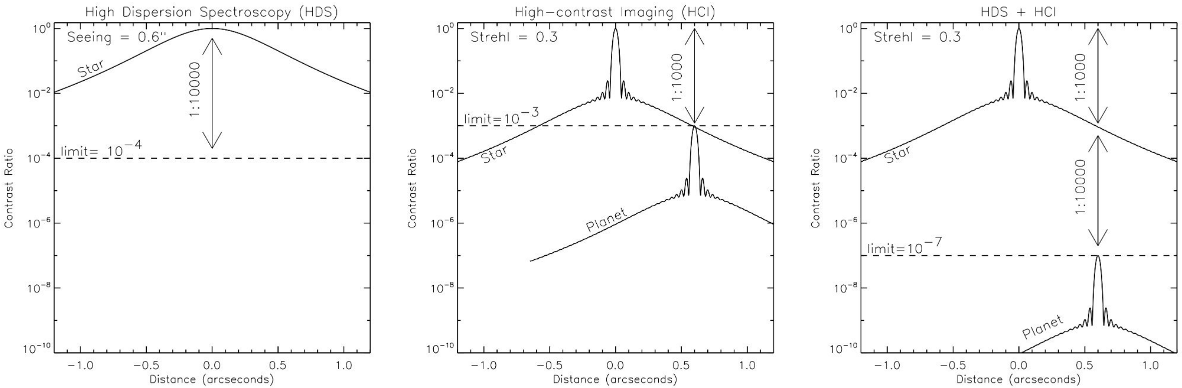
+ O_2 at 760 and 1270 nm
+ $H\alpha$ at 656 nm

Minimum requirement:
600 – 1800 nm

High-level technological requirements

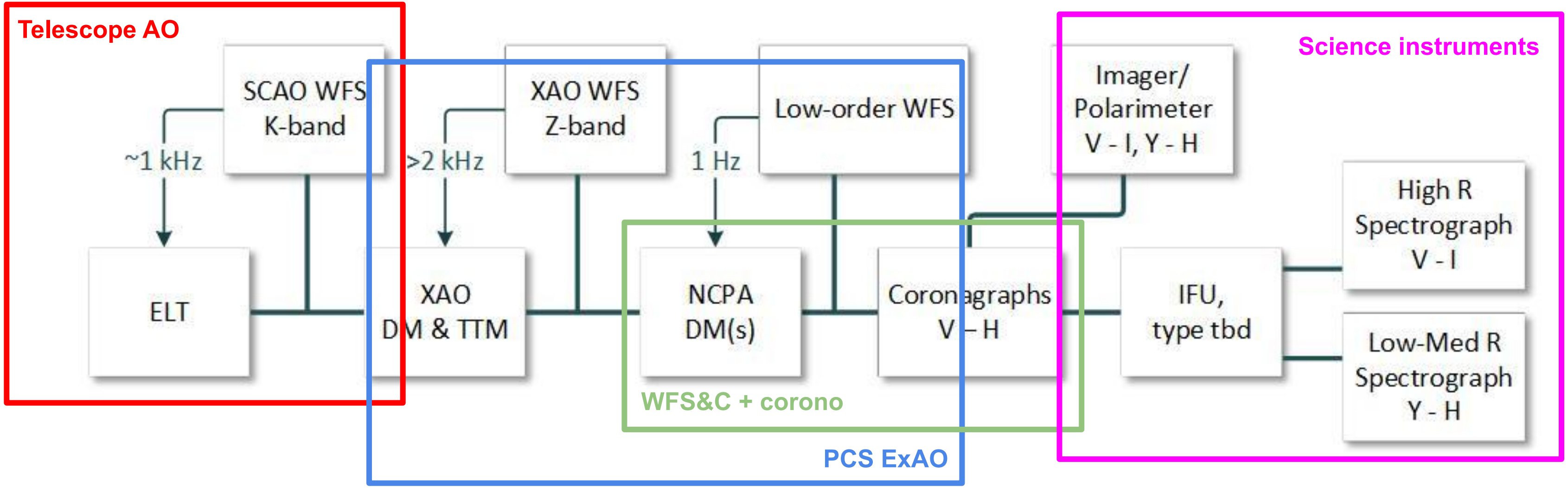
ExAO and high-dispersion spectroscopy at the core of PCS!

Snellen et al. (2015)



- PCS concept = High-Contrast Imaging + High Dispersion Spectroscopy
- 10^{-4} contrast gain by HDS demonstrated on-sky (e.g., Birkby et al. 2017, Hoeijmakers et al. 2018, Spring et al. 2022)
- 10^{-4} - 10^{-5} raw PSF contrast required to reach 10^{-8}-10^{-9} contrast (need XAO + coronagraph)
- PSF residual halo is dominating noise source ➡ exposure time proportional to contrast, optimize ExAO

PCS draft concept as seen by ESO



Kasper et al. (2021)

R&D activities towards PCS

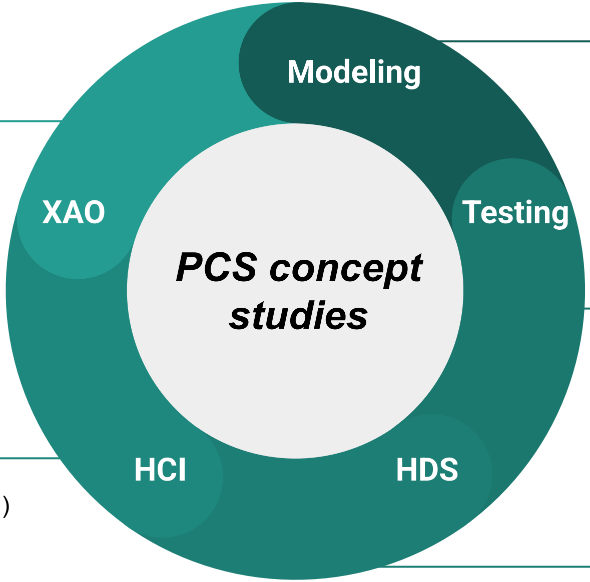
A dynamic landscape in R&D

Extreme Adaptive Optics

High-order DM >10 000 actuators
Wavefront sensing (PyWFS, ZeWFS, etc.)
Cascade AO w/ predictive control - PO4AO
SAXO+
E2E modeling
RTC
etc.

High-contrast imaging

QSS PSF contrast: $<10^{-5}$ (HDS), $<10^{-7}$ (imager)
Coronagraphy
WFC (NCPAs) and WFS (DH)
ELT special requirements (LWE, segment phasing, …)
Super-polished optics
etc.



Planet yield & science prep.

Instrument E2E modeling
1D/3D Exoplanet atmospheres
Disks and planet-disk interactions
Spectra for reflected light or thermal emission
GCM models
etc.

On-sky & lab. platforms

HiRISE - SAXO+ (2027)
VIPA - PAPYRUS - RISTRETTO
GHOST - THD2 - SPEED, etc.
etc.

Fiber-fed spectroscopy

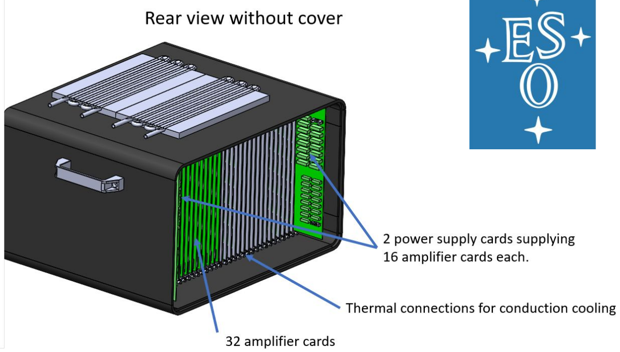
HiRISE - RISTRETTO
Compact spectrographs (VIPA)
Integrated optics?
Coupling of PSF into fibers or slicer?
Dispersion by grating or VPHG?

Funding support from PEPR ORIGINS (axe 1 & 5)
⇨ Infratech EXOSHARE (expected 2026, if selected)

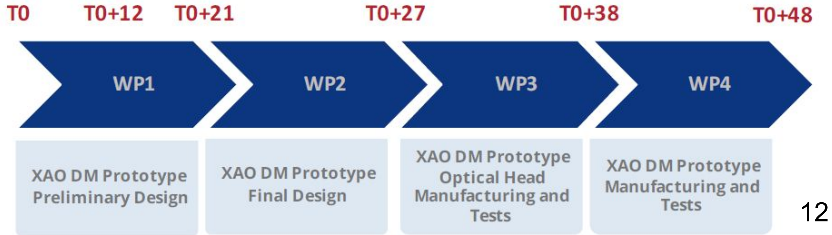
R&D activities towards PCS: HODM

High-order DM development

- Development with ALPAO
  - Many actuators: > 13000, >128 across pupil
  - High speed: small stroke settling < 300 us
  - ±3μm Stroke @ 0.2 nm resolution
  - Integrated drive electronics
- Started in March 2024
  - Initial Phase: Parallel dev. of 2 Concepts
  - Best / Least risky: Scaling up of existing technology
- Integrated drive electronics
  - Thermal management
  - Reduce number of connections

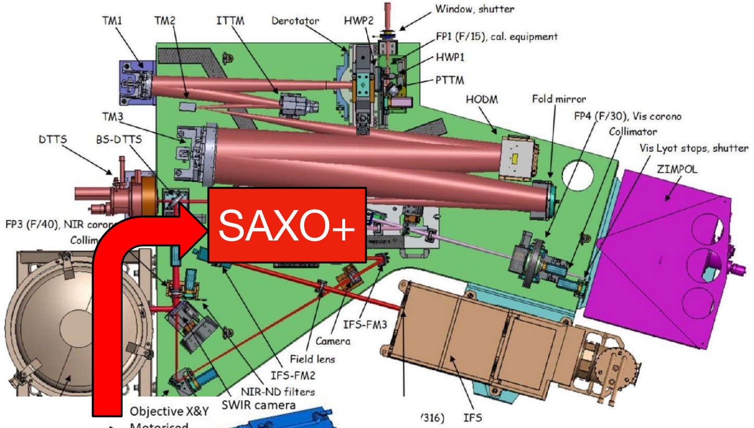


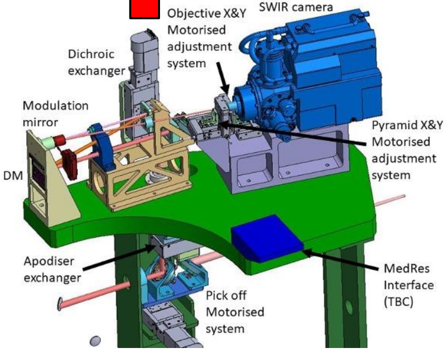
On the way to PDR
End of WP1 ~ mid 2025



R&D activities towards PCS: a few examples

Second-stage extreme adaptive optics

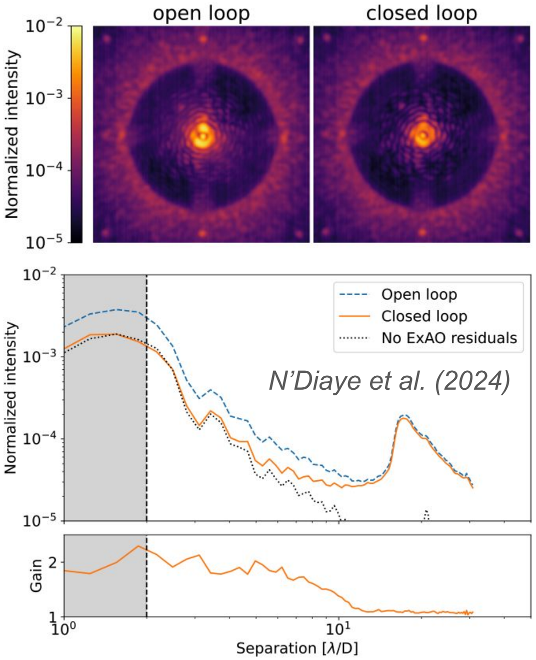




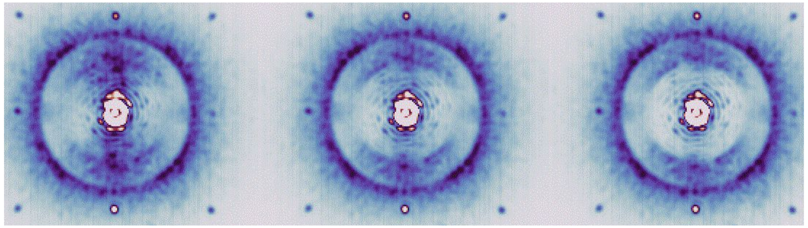
Boccaletti et al. (2020)

- 3 kHz PyWFS in NIR
- Versatile COSMIC RTC
- Various control laws to be tested
- First light: 2027

- GHOST testbed at ESO
- Narrow- or broad-band
- SPHERE-like 1st stage AO with SLM
- Pyramid or Zernike WFS
- COSMIC RTC
- Control with integrator or PO4AO (ML)



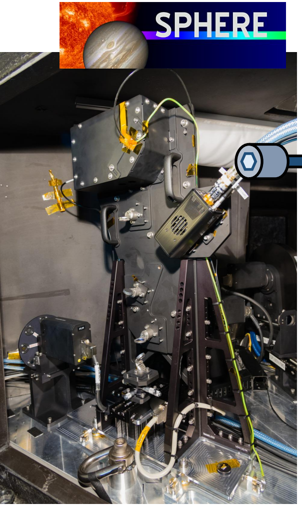
N'Diaye et al. (2024)



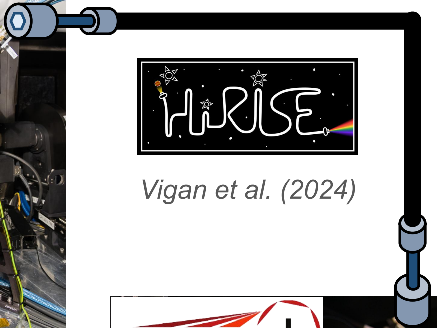
Nousiainen et al. (2024)

R&D activities towards PCS: a few examples

High-contrast imaging + high-dispersion spectroscopy

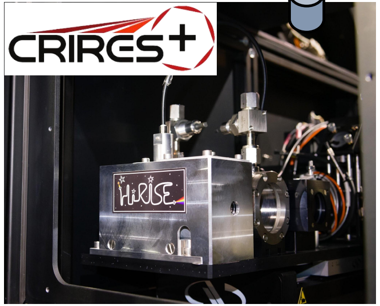


80m fiber bundle



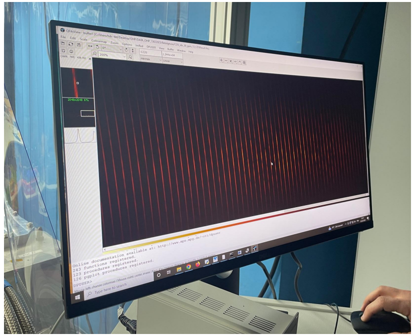
HiRISE

Vigan et al. (2024)



- Giant exoplanets in emission
- H band
- R = 140 000
- On-sky since 2023

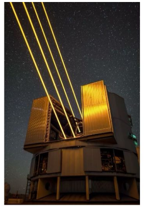
VIPA compact spectrograph (Carlotti et al.)



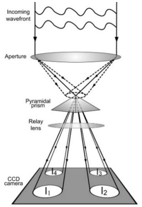
- Compact spectrograph
- H and K band
- R = 80 000
- High-transmission: 50%
- Tested on sky
  - Palomar
  - Papyrus

RISTRETTO (Lovis et al. 2017)

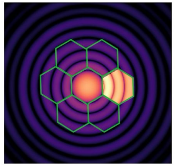
- Planets in reflected light
- ExAO in the visible
- Few spaxels IFU
- Still in development phase



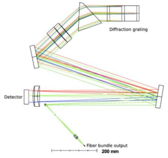
VLT-UTx
8-m primary mirror



XAO system based on near-IR Pyramid wavefront sensor

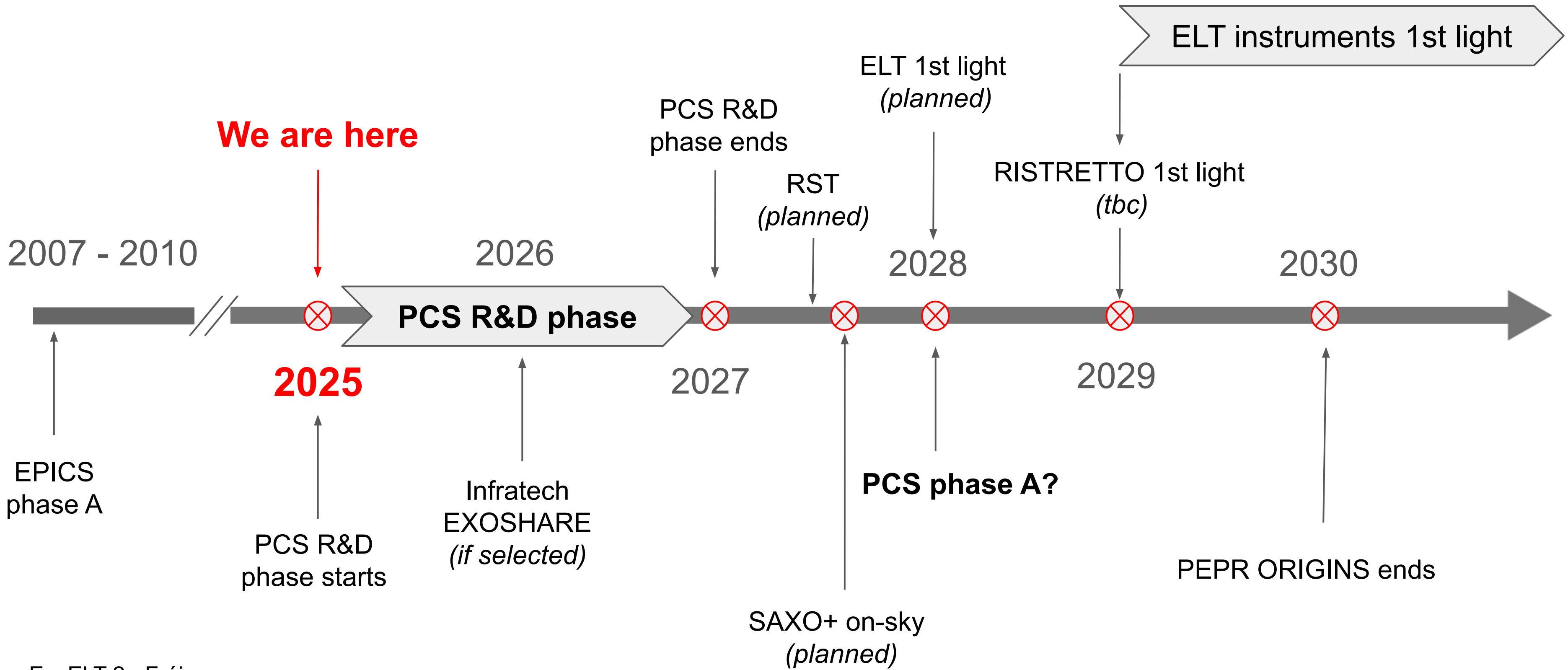


7-spaxel coronagraphic IFU & single-mode fibers



Visible high-resolution spectrograph

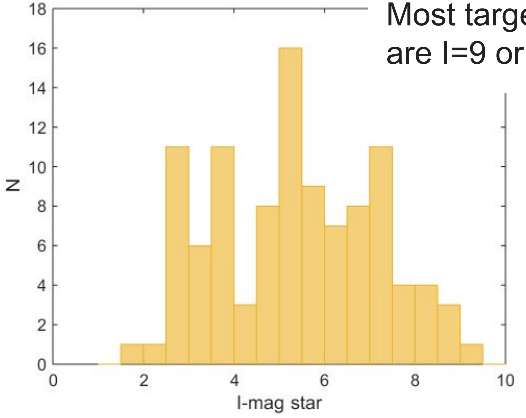
Projects Timeline



Exoplanet yield simulations

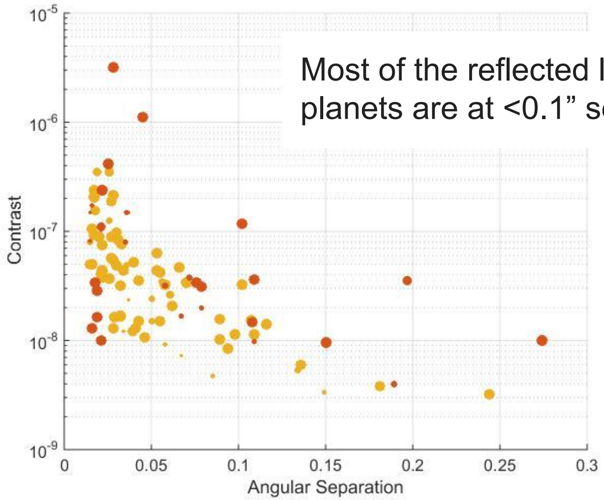
Initial yield simulations

- Simulations by Jens Kammerer & Markus Kasper
- PCS sensitivity model
  - XAO + HDS, coro residuals simulated
  - R~100 000, 700-800 nm, doppler-shifted CCF
  - 20 hours observation
  - Instrument transmission (10%)



Most target stars are I=9 or brighter!

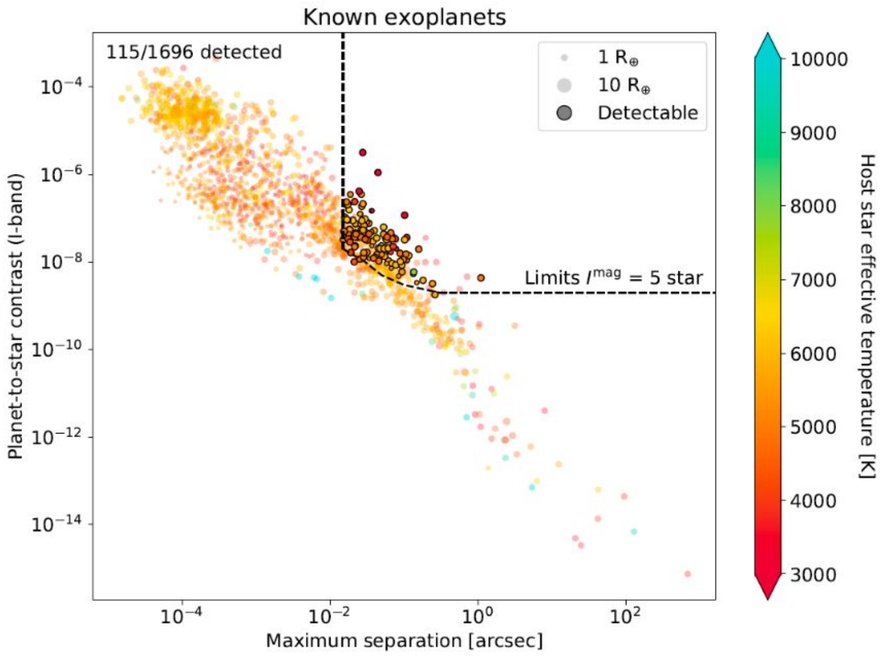
- Two types of targets:
  - Known exoplanets
    - https://exoplanetarchive.ipac.caltech.edu/
    - ~1700 potential targets for PCS
  - Synthetic populations
    - Based on Kepler occurrence rates
    - Geometric albedo = 0.3
    - Randomly oriented circular orbits

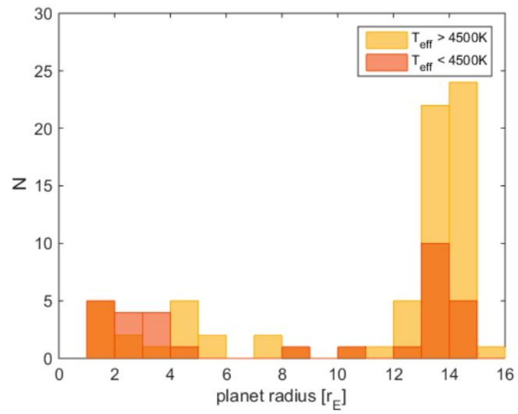


Most of the reflected light planets are at <0.1” separation

Exoplanet yield simulations

PCS observable exoplanets, known systems





Detectable known exoplanets:

- **~10 Earths**
- **>20 Neptunes**
- **>70 Jupiters**

Estimations to be refined

Kasper & Kammerer

PCS R&D phase: working group set up by ESO

PCS R&D preparatory phase (2025 - 2027)

- ➢ **This is NOT a phase A!**
- ➢ Revise PCS science case and Top-Level Requirement
- ➢ XAO wavefront sensing and control
- ➢ XAO DM development
- ➢ XAO end-2-End simulations
- ➢ Concept studies for:
  - Coronagraph(s)
  - WF sensing & control: NCPA, dark hole
  - PCS science instruments: imager / spectrograph(s), Vis / NIR, polarimetry
- ➢ System concept, science yield
  - Straw-man instrument concept: integrating AO, coronagraph & science instruments
  - Science yield prediction: data simulation, data reduction, observing program simulations

Lead
Markus Kasper

Participants:
MPIA, Leiden, Geneva, Porto/Lisboa, Durham, Oxford, INSU, ETH, INAF, CNRS, Caltech, U. Michigan, IFA/Subaru

PCS R&D phase: WP structure

WP1 – Science case and TLR (G. Chauvin, S. Desidera, B. Charnay)

WP2 – Corono and WFC concept (S. Haffert, A. Potier)

WP3 – Science instr. concept (M. Tecza, F. Pedichini)

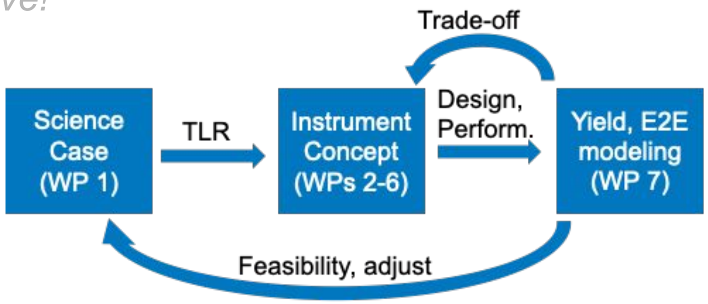
WP4 – XAO concept (M. Langlois, C. Correia)

WP5 – XAO DM development (S. Stroebele) → ESO prerogative!

WP6 – System concept (E. Diolati, E. Stadler)

WP7 – Science yield (O. Carrion-Gonzalez, A. Vigan)

Strong French community!



Conclusions

Getting ready for ELT-PCS

- ➢ PCS anticipated to characterize nearby Exoplanet down to Earth-size including biosignatures
- ➢ PCS R&D preparatory phase 2025 - 2027 (MoU under finalization) ➪ **Self-funded activities!**
- ➢ PCS white paper expected at the end of this period (~2027)
- ➢ PCS expected to enter phase-A >2028
- ➢ R&D programme period can be seen as a pre-phase A
  - XAO-DM development
  - optimize XAO (WFS, predictive control of cascade AO)
  - Science, instruments, and HCI (coronagraphy, wavefront shaping)

Ultimate goal is to present strong case for PCS to ESO in 2028

Participation still possible, please contact WP resp.