Getting ready for ELT-PCS
R&D incl. on-sky experiments with SPHERE SAXO+

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SAXO+ team (PI A. Boccaletti) and many more

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		
	Single slit	*R* ~ 20 000						
MORFEO	AO Module SCAO – MCAO		0.8–2.45	2010	2015			
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		
	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* ~ 5 000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5 000–20 000	0.8–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

1 milliarcsecond (mas) = 0.001″

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

PCS

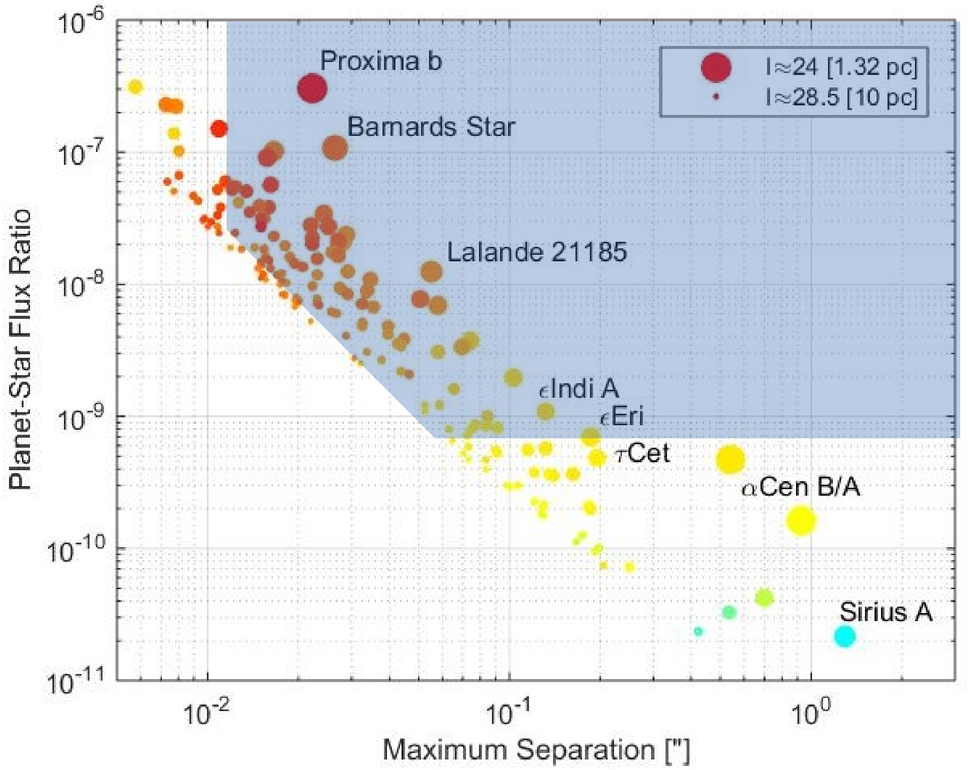
R ~ 3000 - 100.000

λ ~ 0.6 – 1.8

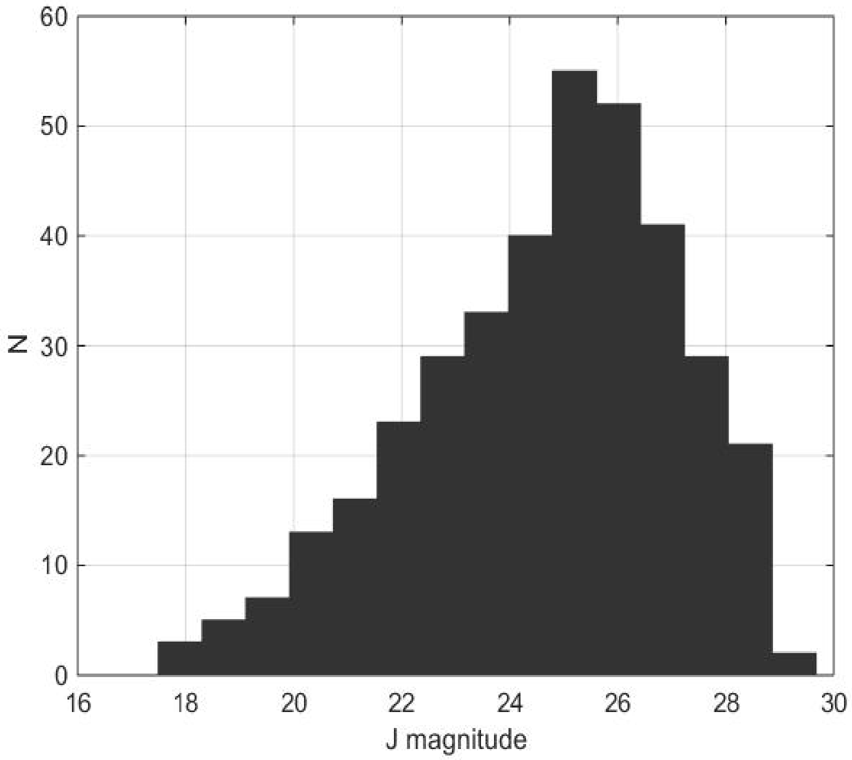
Phase-A > 2026

Characterization of nearby Exoplanets down to Earth-size: contrast and sensitivity

Synthetic Exo-Earth population imaged in reflected light



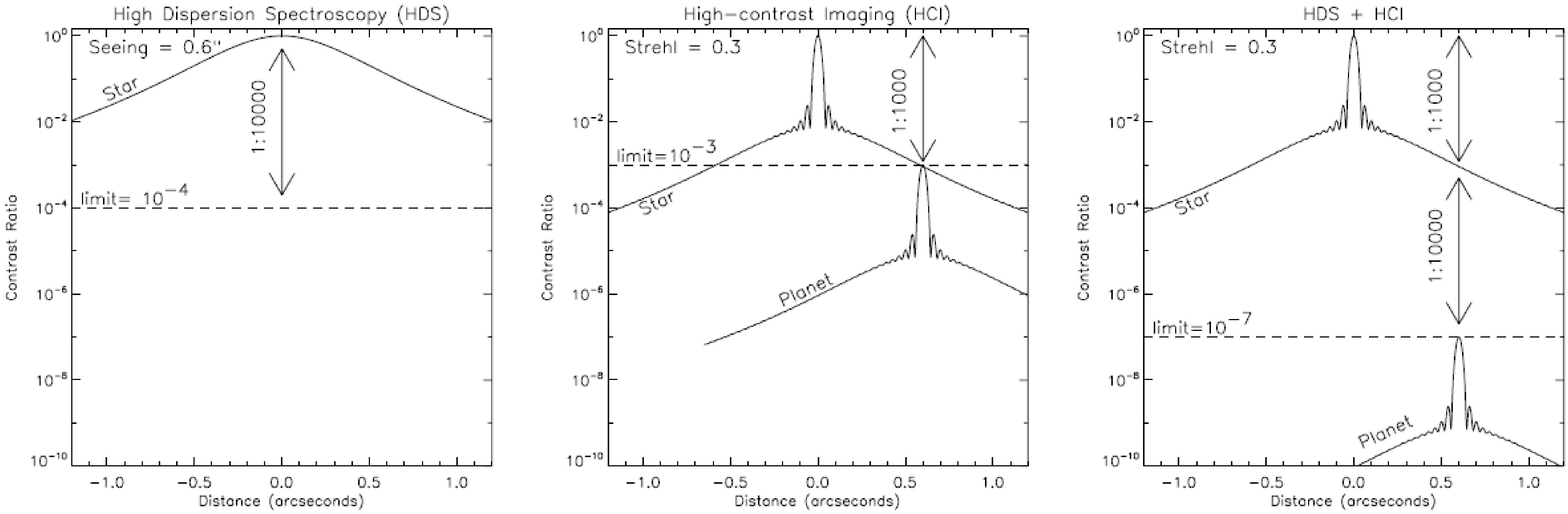
Brightness of nearby known Exoplanets (all sizes)



Terrestrial Planets more abundant around the abundant M-stars (~80%)

- high contrast and small inner working angle ($\lesssim 10^{-8}$ at few tens of mas)
- good sensitivity (I,J $\gtrsim$ 26)

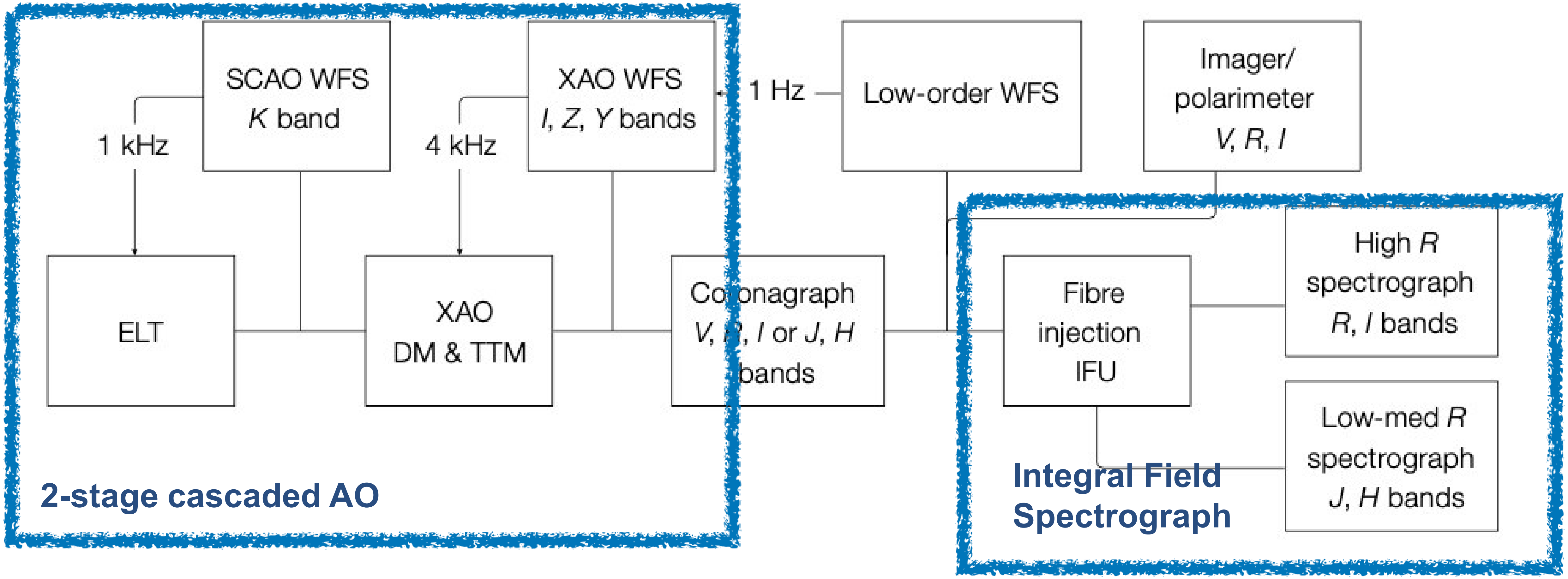
PCS Concept
High Contrast Imaging + High Dispersion Spectroscopy



Snellen et al. 2015

- 10^{-4} contrast gain by HDS already demonstrated on-sky (e.g. Birkby, de Kok, Brogi et al. AJ 2017)
- R ~ 100.000 is needed to observe molecules in planet atmosphere or doppler shifted star spectrum
- 10^{-4} - 10^{-5} raw PSF contrast required from XAO + coronagraph to reach 10^{-8} - 10^{-9} contrast

PCS concept, AO + science instruments



Plenty of R&D needed

- IFU: Integrated Optics, coupling of PSF into optical fibers
- Wavefront Control
  - Non-common path aberrations (focal plane WFS, low-order WFS, …)
  - Special requirements ELT (LWE, segment phasing, …)
  - Detector technology (MKIDs, SAPHIRA, …)
- Coronagraphy
- XAO
  - Deformable Mirrors with > 10.000 Actuators
  - Wavefront sensing
  - Cascaded AO with Predictive Control
- …

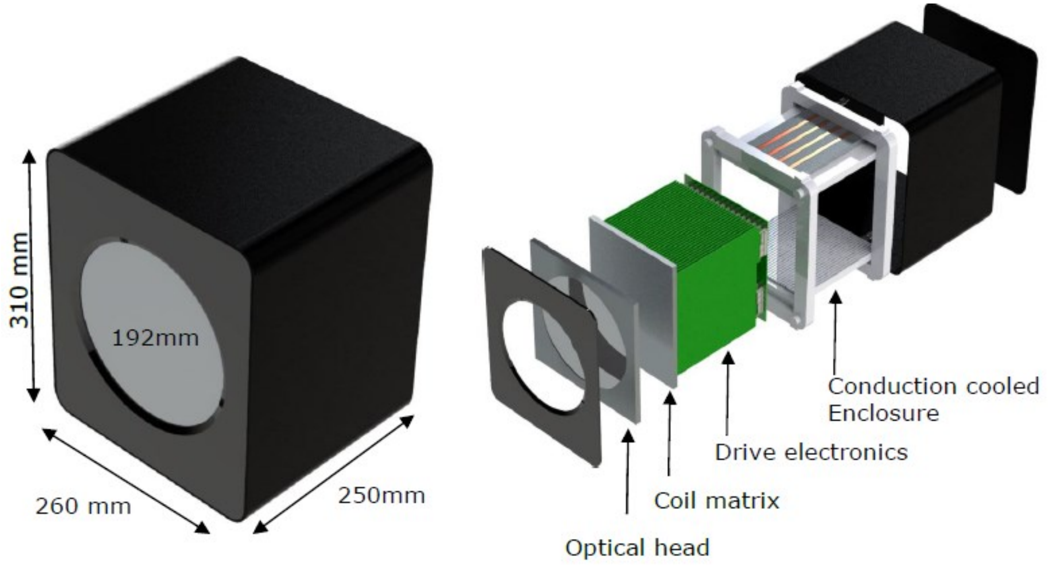
XAO DM R&D: Scale 1 prototype (led by S. Stroebele, ESO)

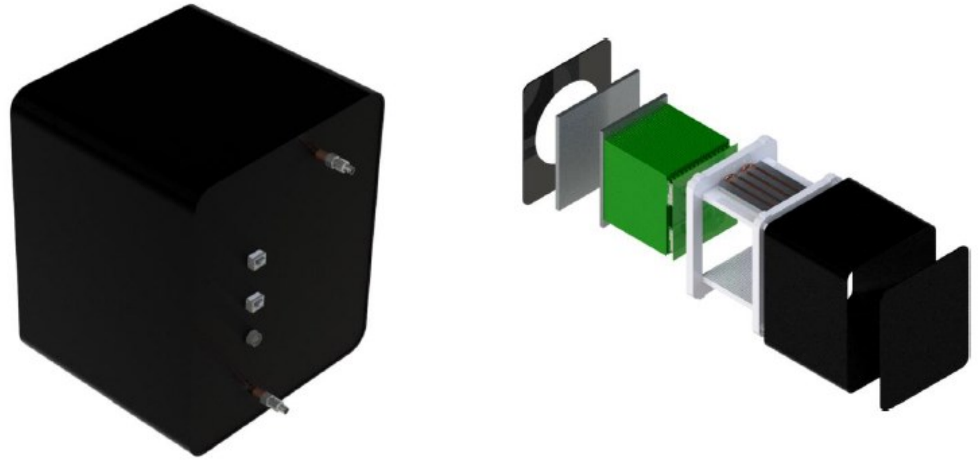
- Development with ALPAO
  - Many actuators: > 13000, >128 across pupil
  - High speed: small stroke settling < 300 us
  - Sub-nm resolution

T0	T0+12	T0+21	T0+27	T0+38	T0+48

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

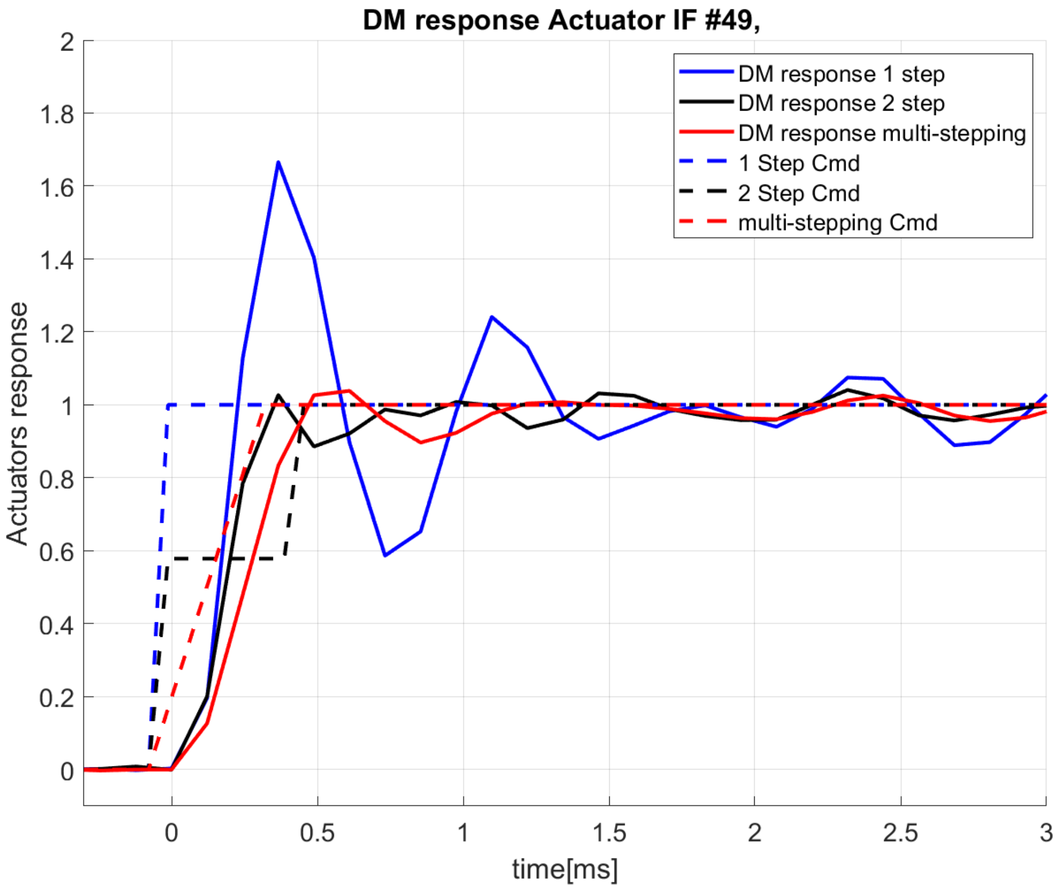
T0: March 2023, WP1 funded, looking for funding for WPs 2-4

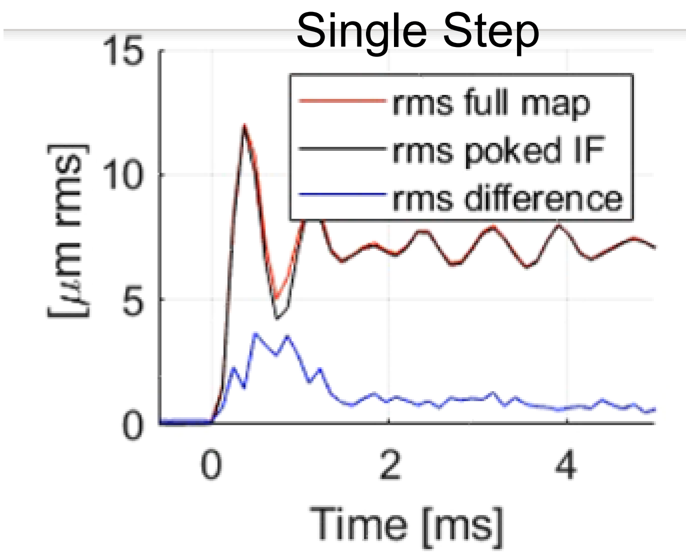


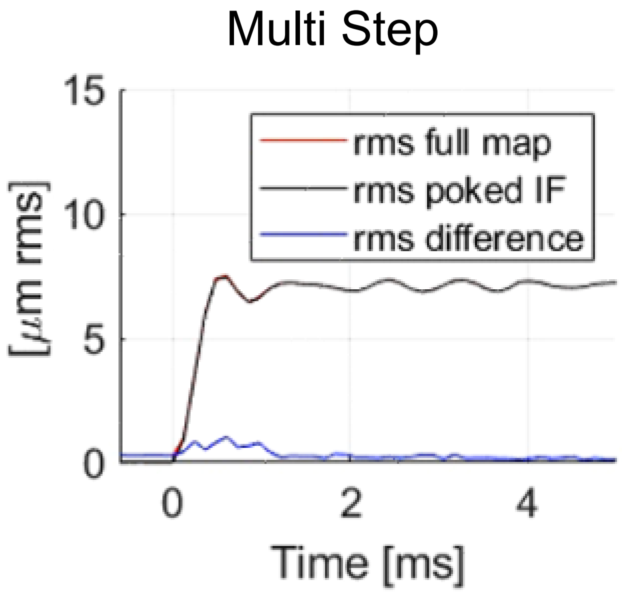


XAO DM R&D: Suppress DM ringing by input shaper

- Multi-stepping of 6 equal steps
  → ramp (ALPAO default)



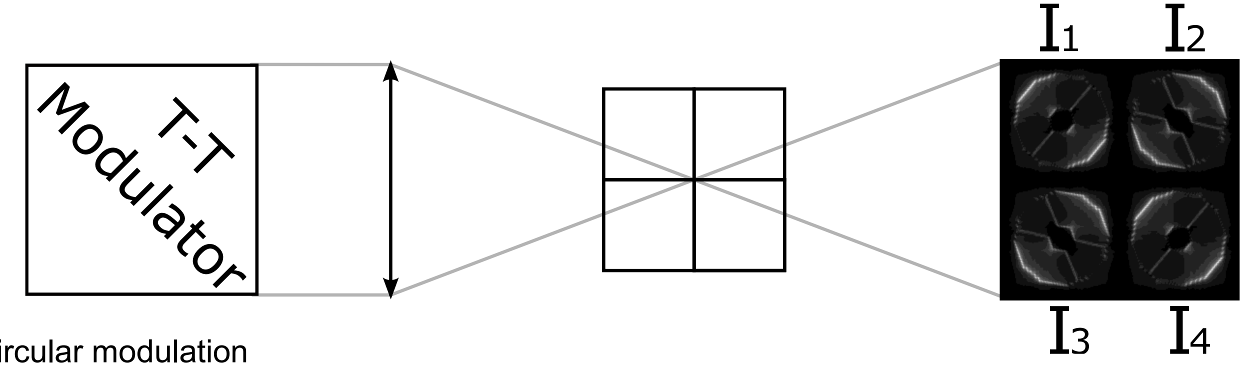




Stroebele et al. SPIE proc. 2022

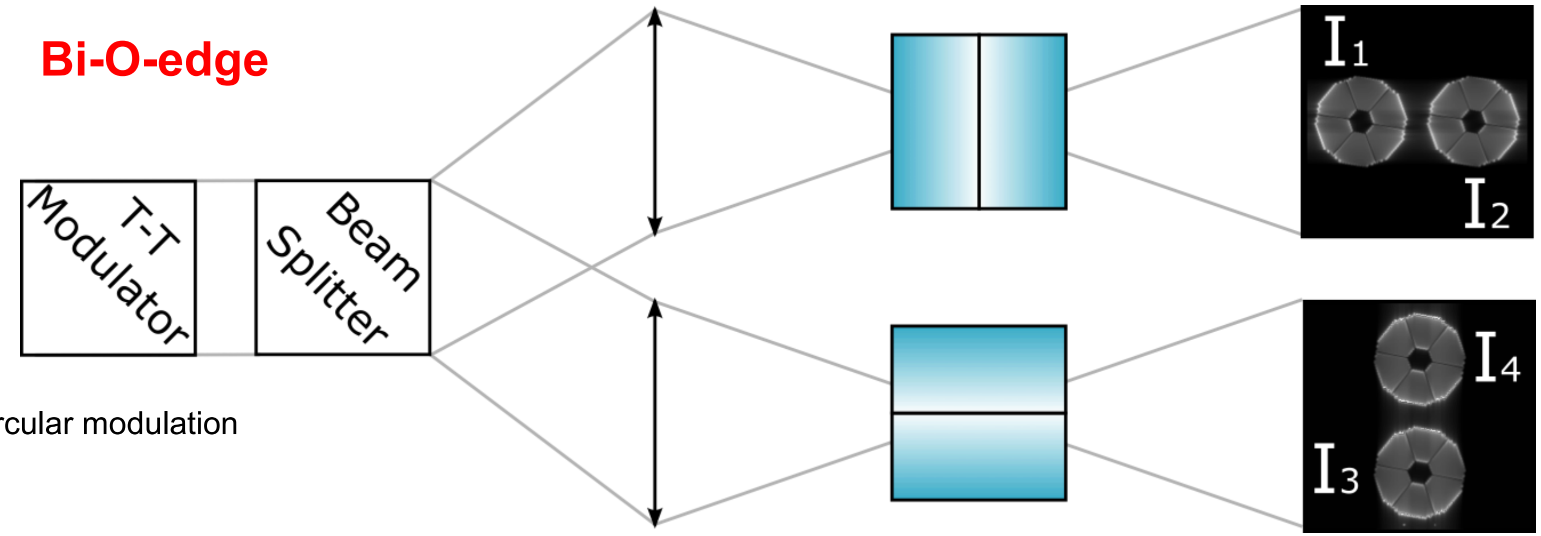
XAO WFS R&D: the Bi-Orthogonal-Edge sensor

Pyramid



Circular modulation

Bi-O-edge



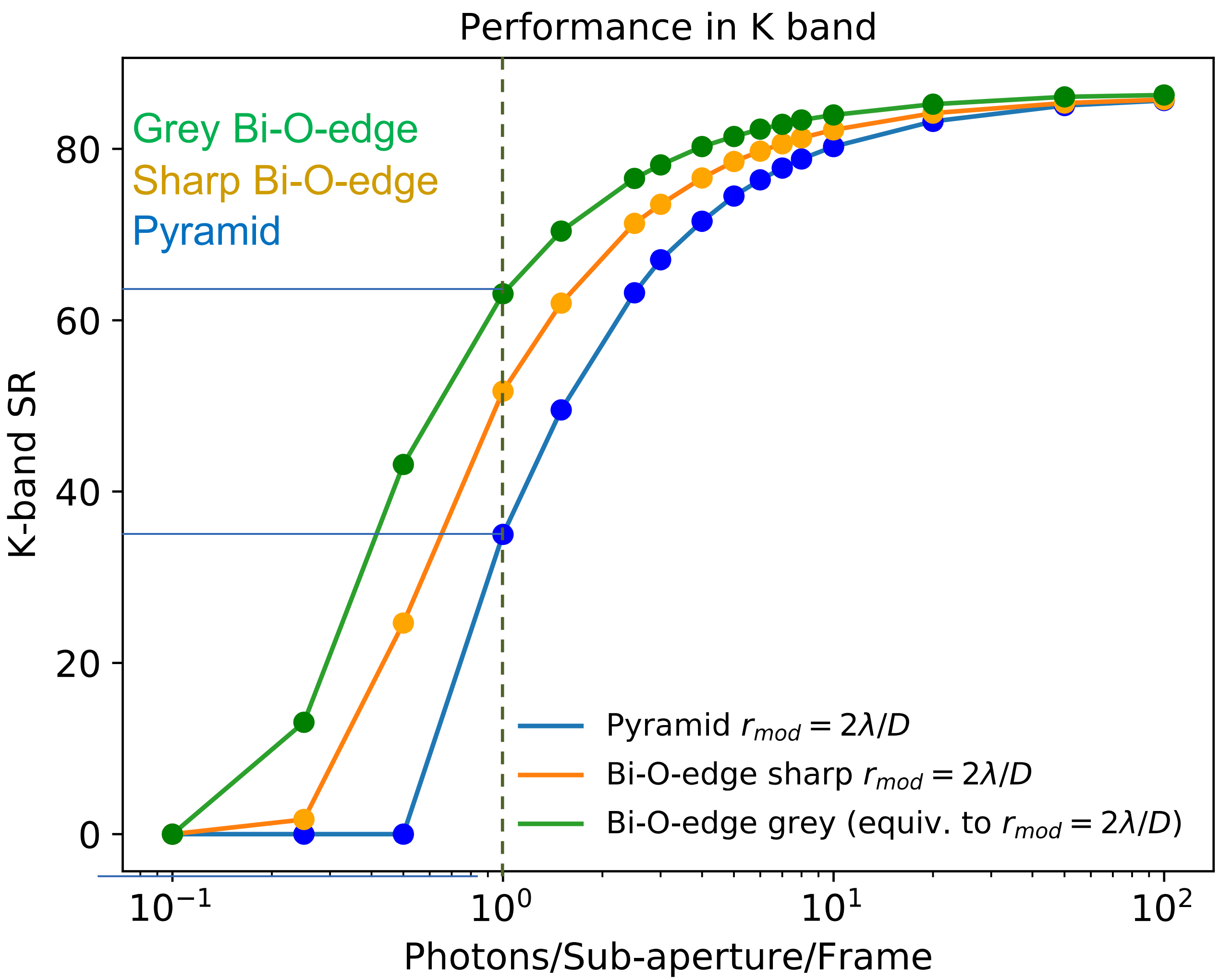
Circular modulation

Bi-O-Edge up to 4x more sensitive (guide star magnitude +1.5 mag) than Pyramid WFS

Verinaud et al.
submitted to A&A

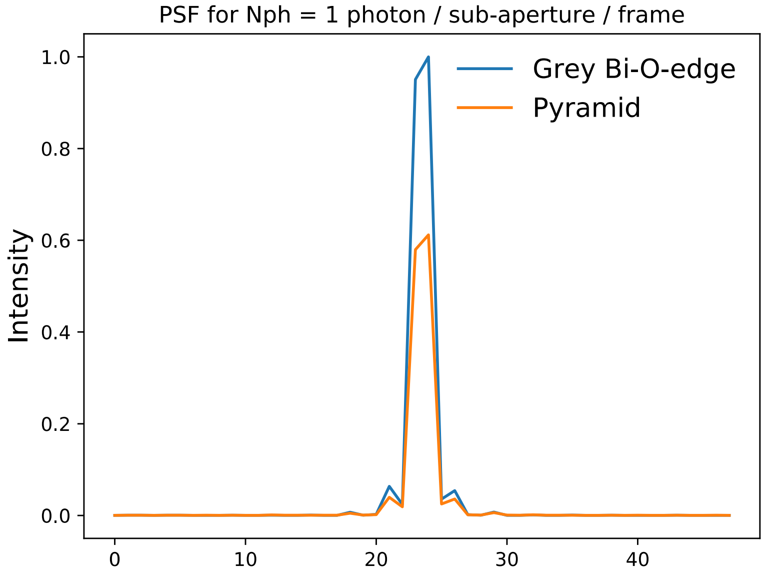
XAO WFS R&D: Bi-O-Edge numerical simulation

ELT SCAO simulation confirms predicted sensitivity gain



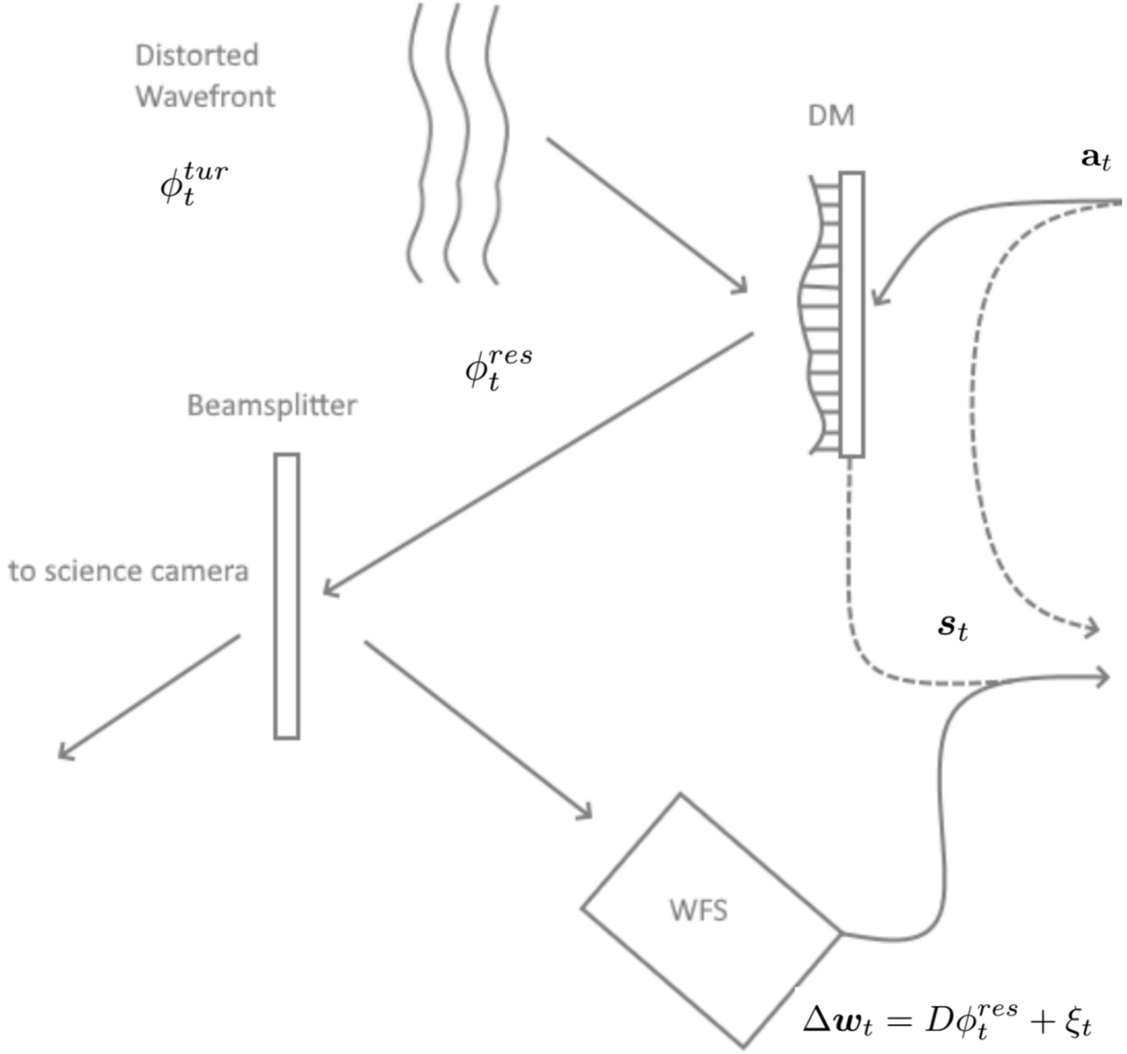
For N=1 photon / subap / frame:

Grey Bi-O-edge: SR = 62%
Pyramid: SR = 36%



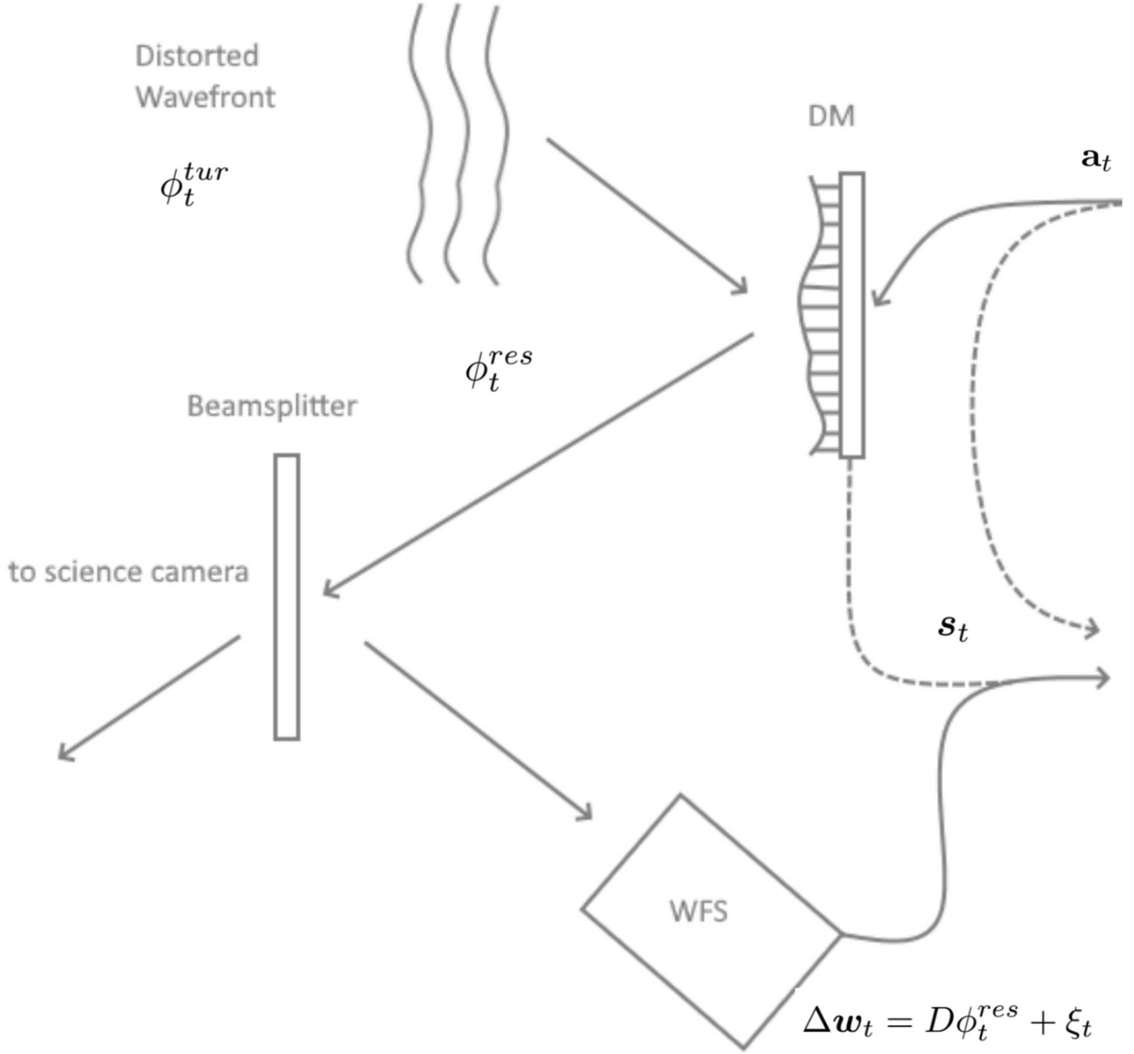
Verinaud et al. submitted to A&A

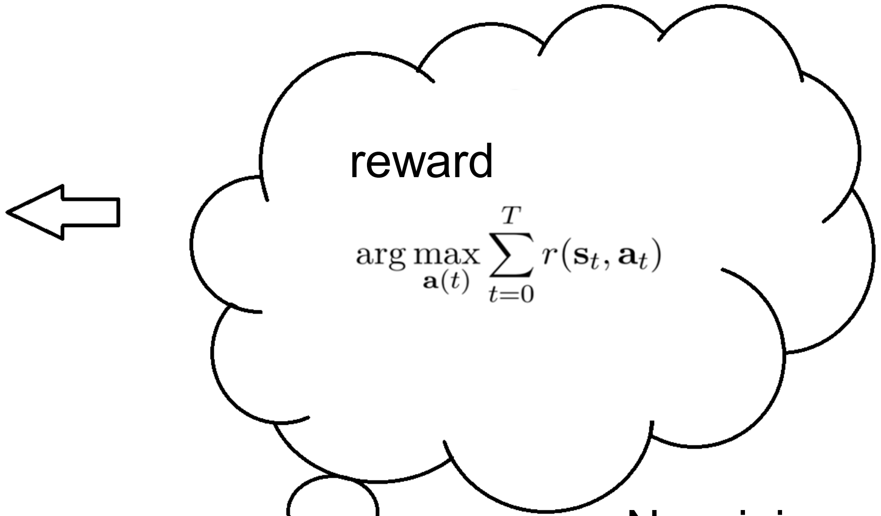
Predictive AO Control R&D with Machine Learning



Classical AO control:
$\Delta a = R\Delta w$
$a_t = la_{t-1} + g\Delta a$

Reinforcement Learning for AO





Nousiainen et al., A&A, 2022

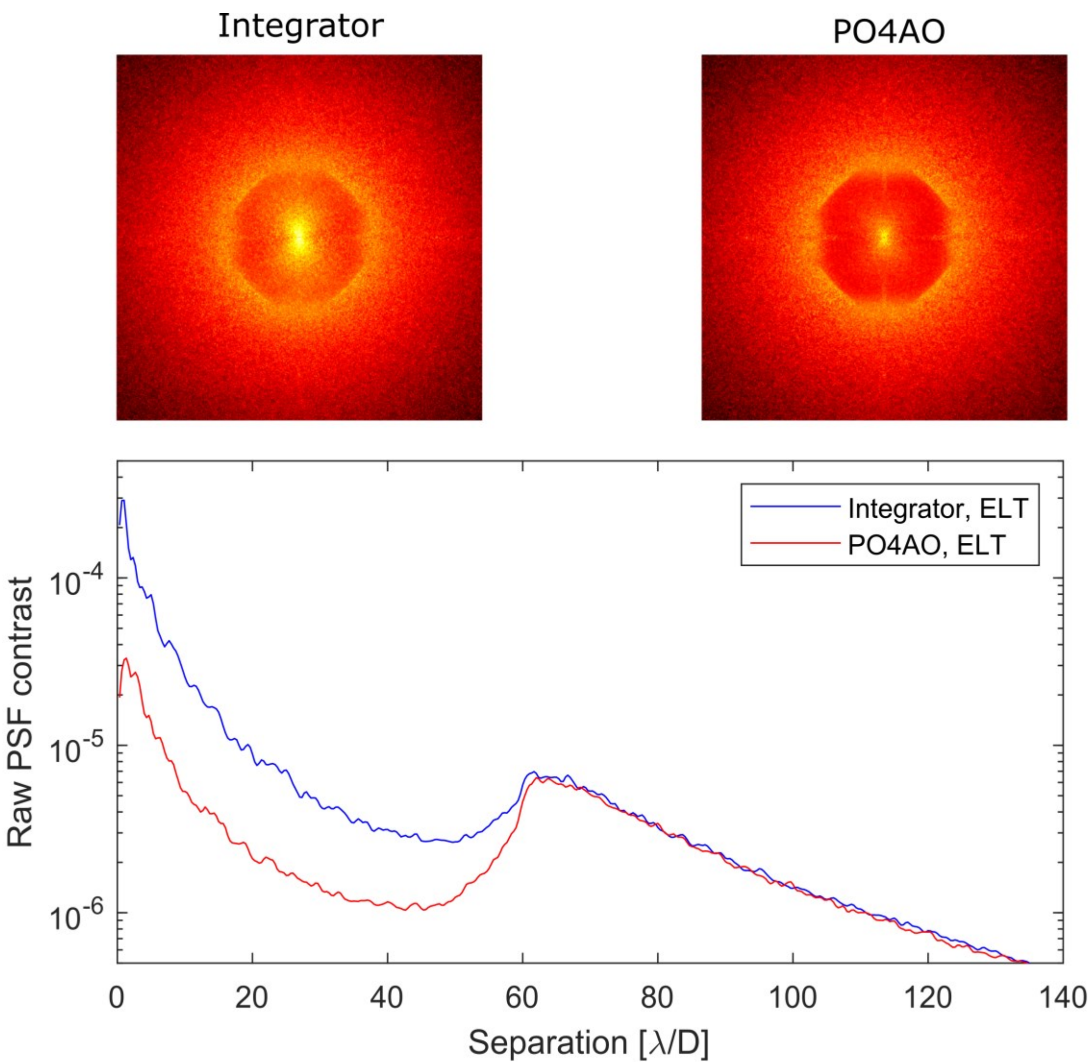
PO4AO: Policy Optimization for AO

Policy (recon and control, CNN): $\pi_\theta(a_t|s_t)$
Dynamics Model (CNN): $p_\omega(s_{t+1}|s_t, a_t)$

Iterate over episodes:
1. Run policy, collect data
2. Improve dyn. model (supervised learning)
3. Improve policy using improved dyn.model

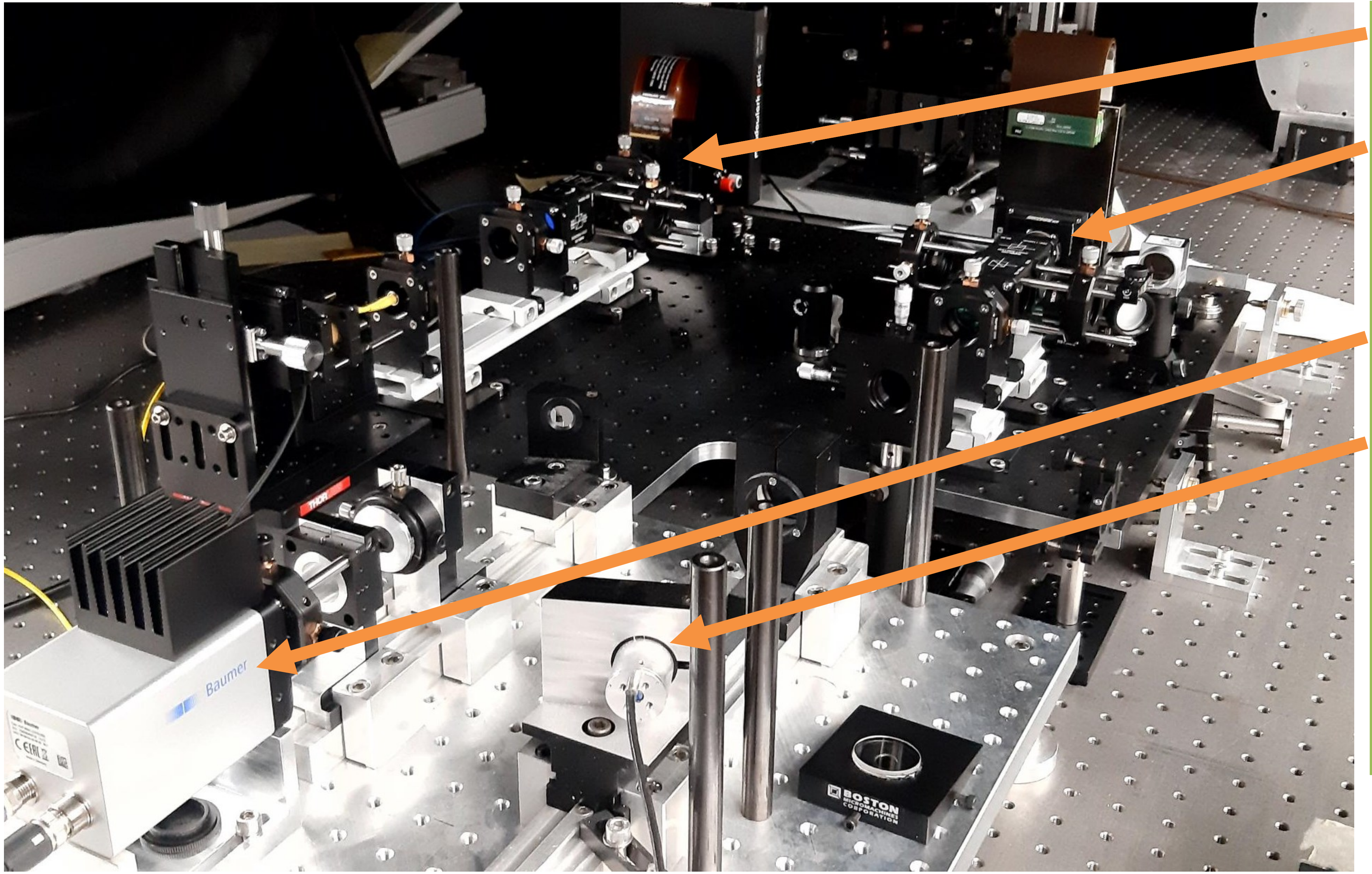
PO4AO simulations

- PO4AO is fast (inference time < 1 ms on ELT)
- Training in parallel to observations, upload of new policy after each episode (typically some seconds)
- PO4AO follows environmental changes
- **Factor 3-5 contrast improvement**
- Features: Self-calibrating, predictive, robust to noise, can correct unexpected errors (?)



Nousiainen et al., Optics Express, 2021
Nousiainen et al., A&A, 2022

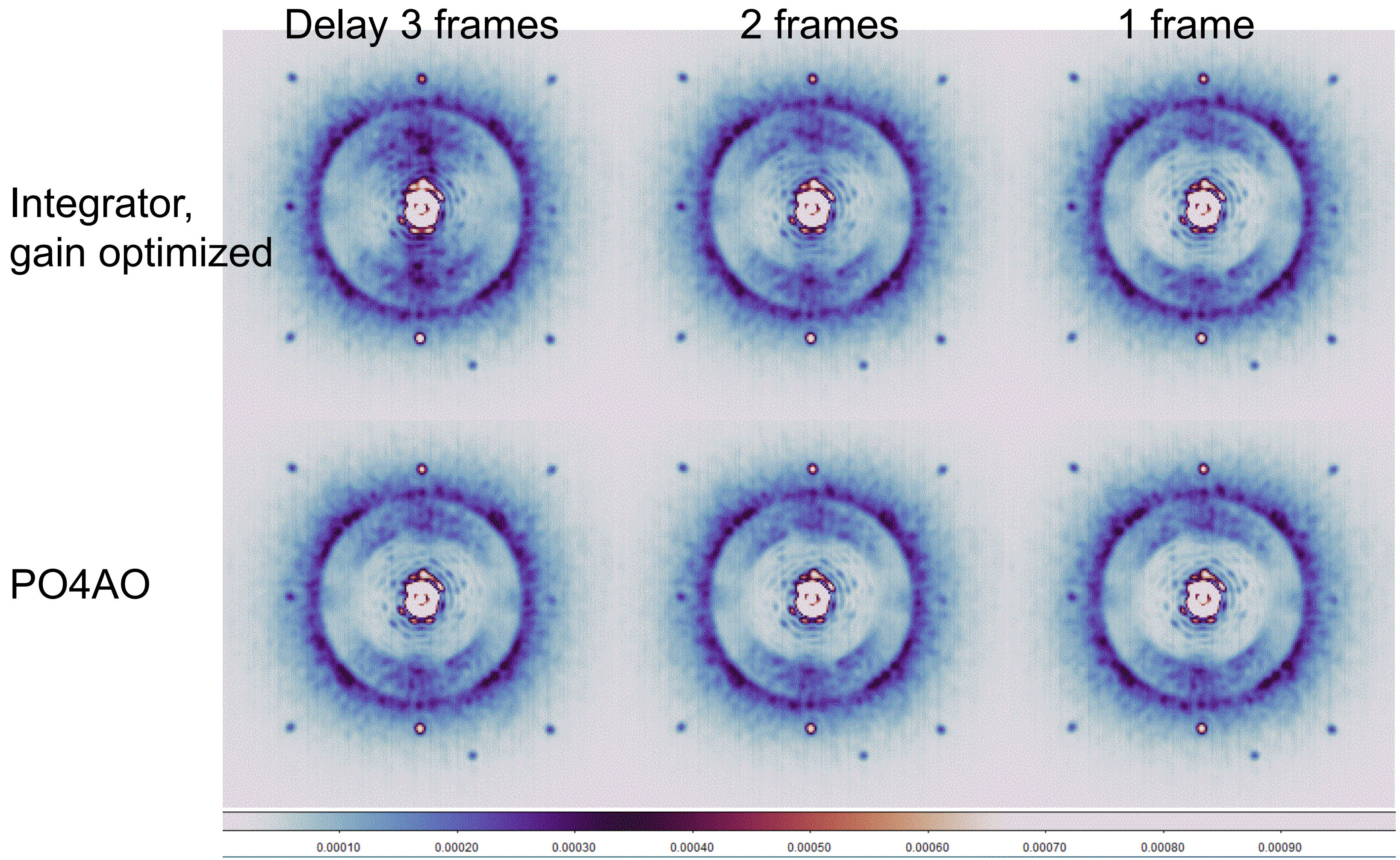
Lab facility: GHOST bench at ESO

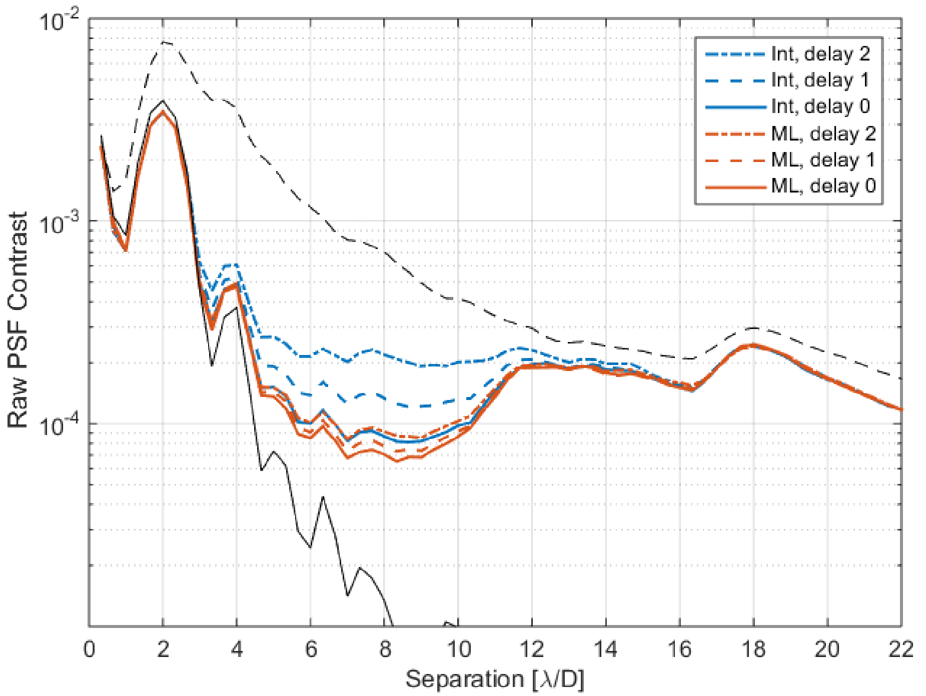


- SLM Meadowlark injects turbulence at 420Hz
- BMC 492-1.5 DM (ETH loan)
  - 300 um pitch
  - 100% actuator yield
- PWS (Arcetri design)
  - 10 GigE camera (Sony IMX426 CMOS)
  - PI modulation mirror SL-325
- GPU server implementing
  - COSMIC platform (ANU/LESIA, since August 2022)
  - Python code (B. Engler)

Engler et al., SPIE 2022

PO4AO, GHOST Bench Experiments





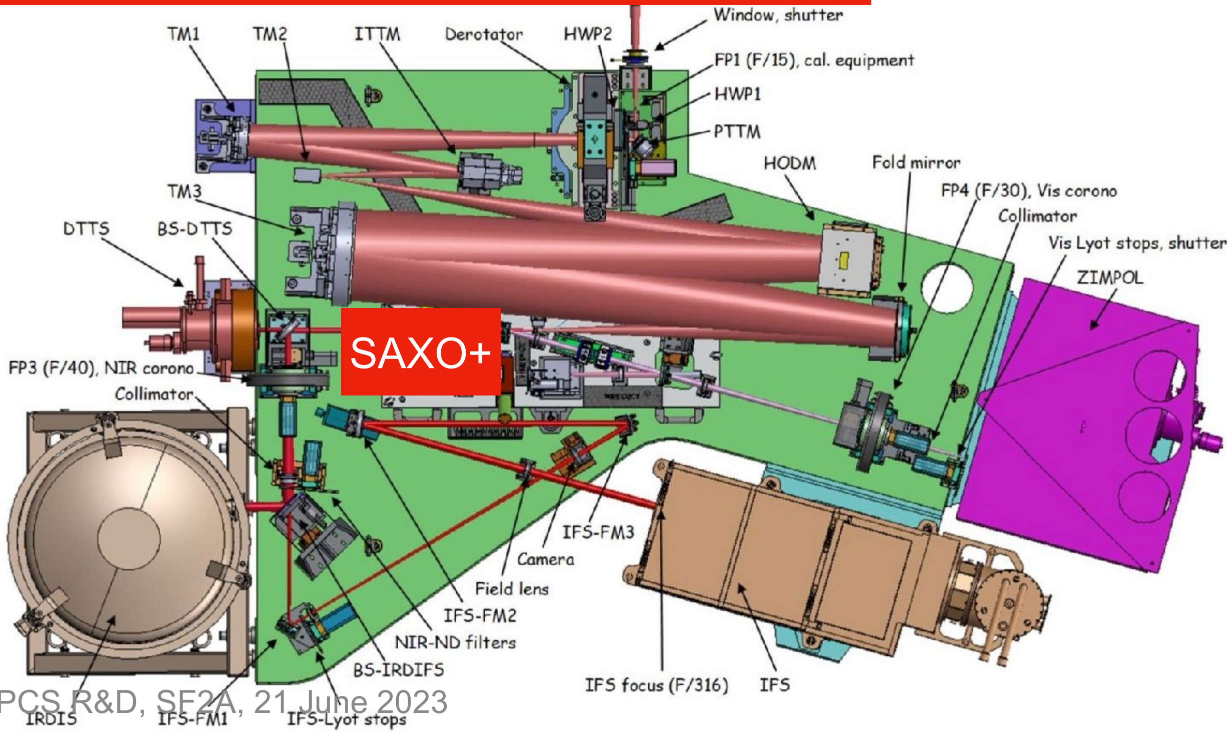
Nousiainen et al. JATIS in prep.

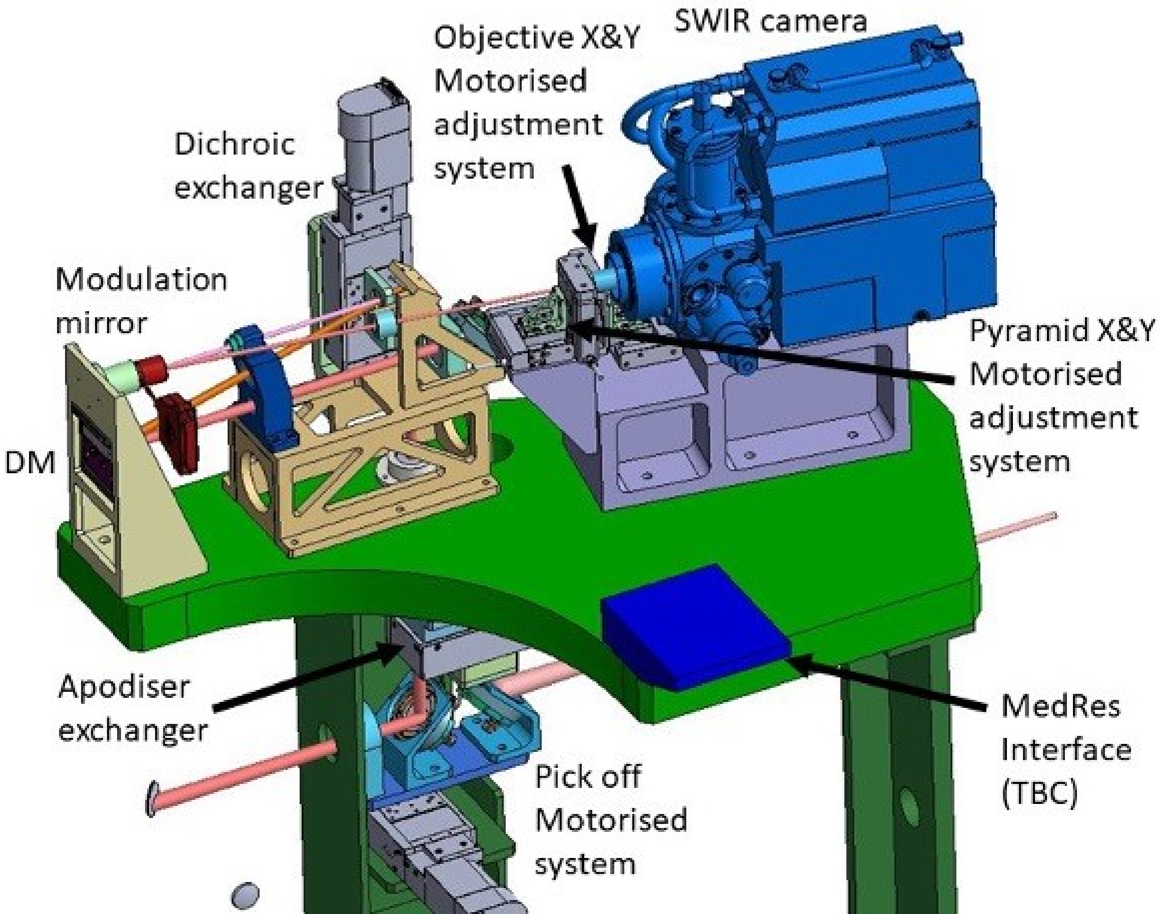
SAXO+ in a nutshell

Requirements :

- Improve contrast to 1e-5 at few λ/D
  => faster AO : 3 kHz
- Gain sensitivity for red stars
  => wavefront sensor in the IR
- Test control approaches for PCS
  => versatile RTC architecture

- SAXO+ optics on top of the main beam (Diolaiti/Stadler et al.)
- IR Pyramid WFS + modulation + CRED 1 + 2nd DM (~28x28)
- Real Time Computer (COSMIC, Gratadour et al.)
- Predictive control (iterative, data driven ML)





SPHERE+ cols and partners

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Raphaël Galicher	CNRS / LESIA
Arthur Vigan	CNRS / LAM
Mickaël Bonnefoy	CNRS / IPAG
Maud Langlois	CNRS / CRAL
Mamadou N'Diaye	CNRS / Lagrange
Caroline Kulcsar	LCF

SAXO+ Schedule

Phase	Duration	Milestones	Dates	
-	-	Kick-off meeting	T0	October 2022
Consolidation phase	18 months	consolidation review + Cost and funding review	T0+18	
Design phase	12 months	FDR. procurement starts	T0+30	
MAIT phase	12 months	PAE	T0+42	
AIV phase	6 months	Commissioning report	T0+48	April - October 2026

- On-sky experience of XAO ctrl and the XAO/HDS concept also pursued through
  - RISTRETTO – XAO/HDS in the optical (Lovis et al.)
  - HIRISE – XAO/HDS in the NIR (Vigan et al.)
  - PAPYRUS (Sauvage et al.) and SCExAO (Guyon et al.)

Summary

- ELT-PCS is designed to characterize nearby Exoplanet down to Earth-size including biosignatures
- ELT PCS is expected to enter phase-A around 2026
- A comprehensive R&D programme is carried out by ESO and its partners and focuses on optimized XAO
  - XAO-DM development
  - Optimized Bi-O-Edge WFS
  - Predictive control of cascaded AO with Machine Learning
- R&D is carried out through simulations, lab experiments and on-sky demonstrations with SAXO+