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SAXO+: Enhancing SPHERE high-contrast capabilities

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SAXO+: Enhancing SPHERE high-contrast capabilities

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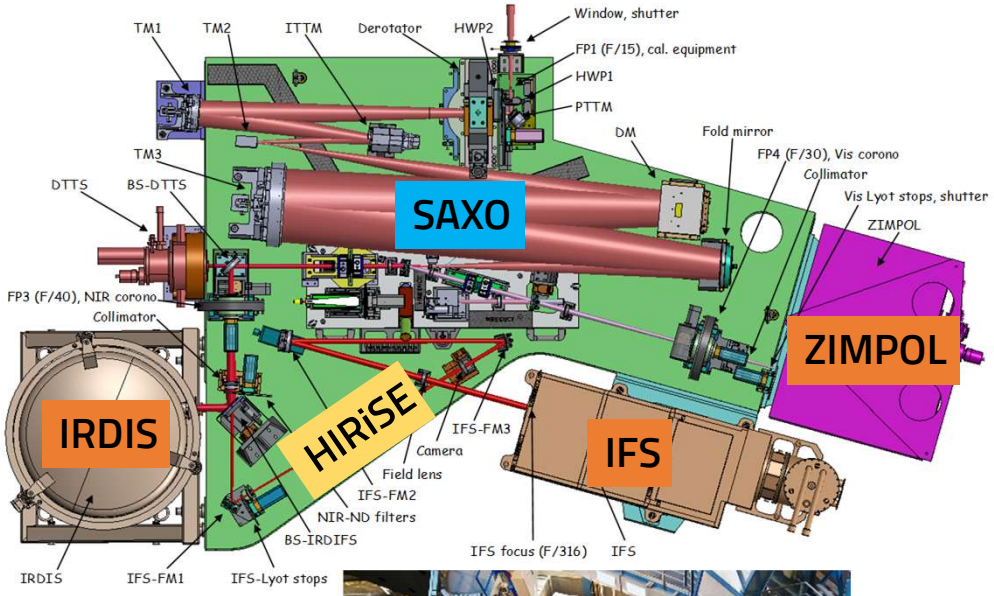
[n] Aix Marseille Univ, CNRS, CNES, LAM

The SPHERE instrument

- SPHERE: **S**pectro-**P**olarimetric **H**igh contrast imager for **E**xoplanets **RE**search
- eXtreme Adaptive Optics (XAO) system and coronagraphic facility @VLT UT3
- Science instruments: ZIMPOL, IRDIS and IFS (+HIRiSE upgrade)
- Imaging, low-resolution spectroscopy, and polarimetry for discovery and characterization of extra-solar planetary systems
- Strehl ratio > 75% in H-band in good conditions
- More than 10 years of operations, 500+ publications



SAXO+: pushing the limits of the XAO correction

- **Deeper/closer → contrast improvement**
  - Study young Jupiters close to the star (down to ~3 au)
  - Increase the frequency of the XAO system up to ~3 KHz
  - Improve the correction of non-common path aberrations and coronagraphic rejection

- **Fainter → sensitivity improvement**
  - Discovering and characterising planet-forming disks around fainter and redder stars
  - Wavefront sensing in the near-infrared benefits from first stage correction
  - Implement a more sensitive wavefront sensor in combination with a very low noise camera

SAXO+ Memorandum of Understanding / 1

- SAXO+ was proposed as part of the "**SPHERE+ upgrade"** white paper in the framework of the **VLT 2030 instrumentation programme**
  - While the whole SPHERE+ upgrade was not recommended for construction, ESO's STC recommended the implementation of SAXO+ as part of the **PCS R&D roadmap activity** within ESO's Technology Development Programme

- Technical goals of SAXO+
  - Coronagraphic raw PSF intensity contrast in H-band of $5\text{x}10^{-5}$ at 125 mas separation (3 λ/D) in average atmospheric seeing conditions of 0.7 arcsec and $\tau 0$ = 3 ms at 500 nm with a bright ($J < 8$) guide star
  - Robust operation with improved contrast compared to SPHERE alone in mediocre atmospheric seeing conditions
  - Demonstration of Cascaded Adaptive Optics, with flexibility of Real-Time Computer to apply different control laws

SAXO+ Memorandum of Understanding / 2

- Use after commissioning
  - 10 nights for technical tests
  - Up to 5 nights per semester for at least 3 years after installation for technical tests
  - Upon request by the SAXO+ Consortium, if SAXO+ provides compelling science benefits compared to the current SPHERE, ESO intends offering SAXO+ as a new SPHERE mode to the scientific community following its standard processes (starting with LSP-STC recommendation) and under the condition it can be operated by PAO
    - Amendment of current MoU
    - Granting of Guarantee Observing Time (GTO) to compensate for the investments of the SAXO+ Consortium in hardware

Thanks to Andrea Merlo (INAF DS) for reviewing the MoU

SAXO+ in pills

- Second-stage adaptive optics correction
- Adaptive deformable mirror with 28x28 actuators across the pupil diameter
- Up to 2.76 kHz (goal 3 kHz) correction frequency
- Near-infrared pyramid wavefront sensor 50x50 sub-apertures
- Common path wavelength range 0.95 – 2.32 µm
- Wavefront sensor path wavelength range 0.95 – 1.1 µm / 0.95 – 1.45 µm
- Guide star up to mag H 11.7+

Reference science cases

Name	SpT	G (mag)	J (mag)	H (mag)	K (mag)	Comments
Bright-1	AF	5.5	5.2	5.1	5.0	SHINE-AF, BEAST-ScoCen
Bright-2	AF	7.6	7.2	7.1	7.0	SHINE-AF (ScoCen)
Bright-3	GK	9.6	7.8	7.4	7.2	SHINE-GK (YNGs)
Red-1	early-M	11.9	8.5	7.9	7.7	SHINE-M (YNGs)
Red-2	K	12.8	10.1	9.5	9.4	DESTINYS
Red-3	early-M	14.5	10.1	9.4	9.2	Disk surveys
Red-4	late-M	15.3	11.4	10.6	10.2	ALMA samples
Red-5	late-M	16.8	12.5	11.7	11.3	Disk survey

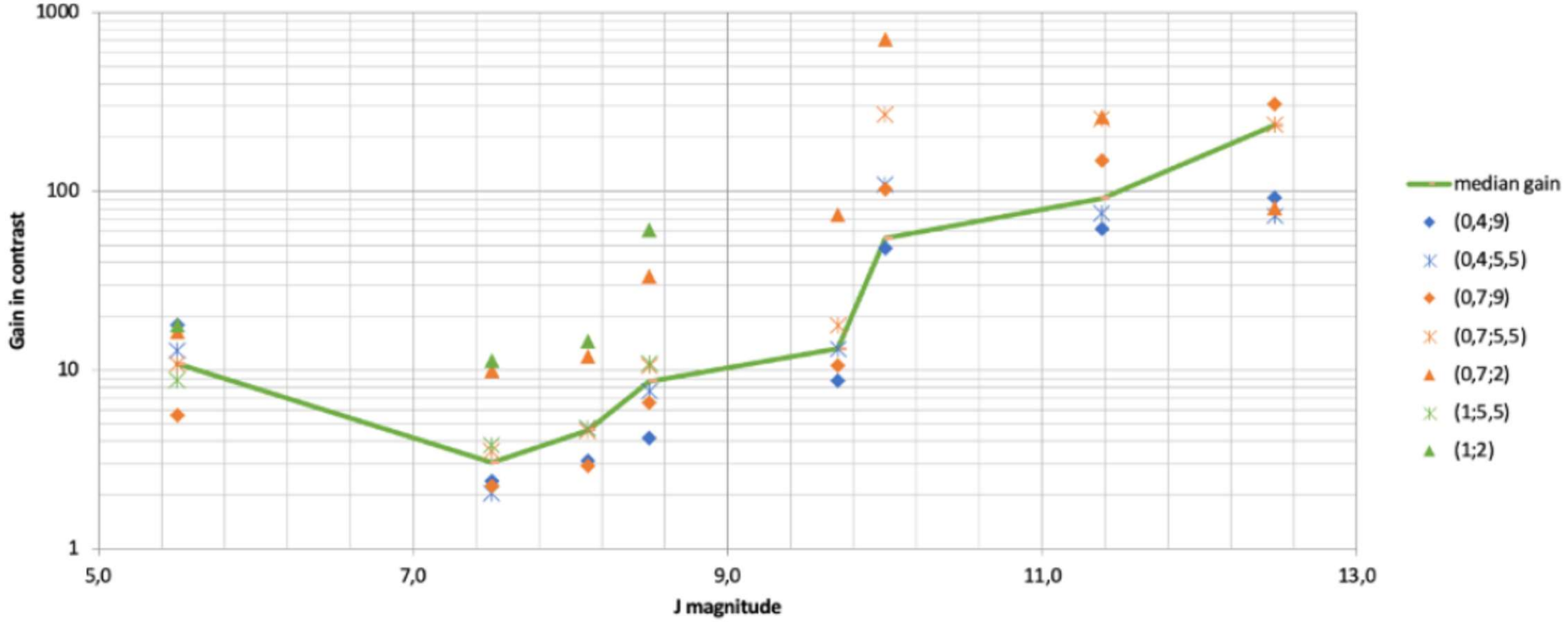
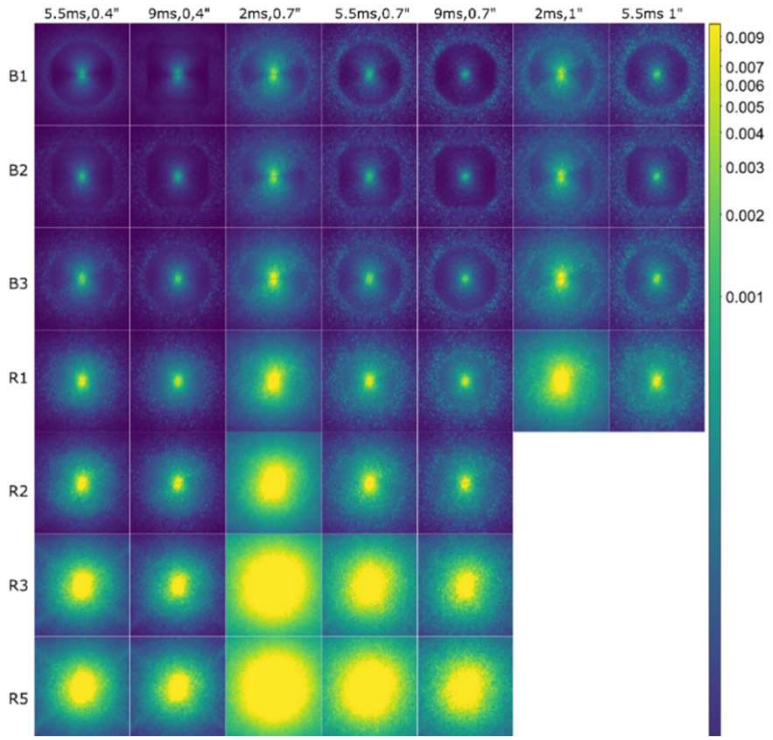


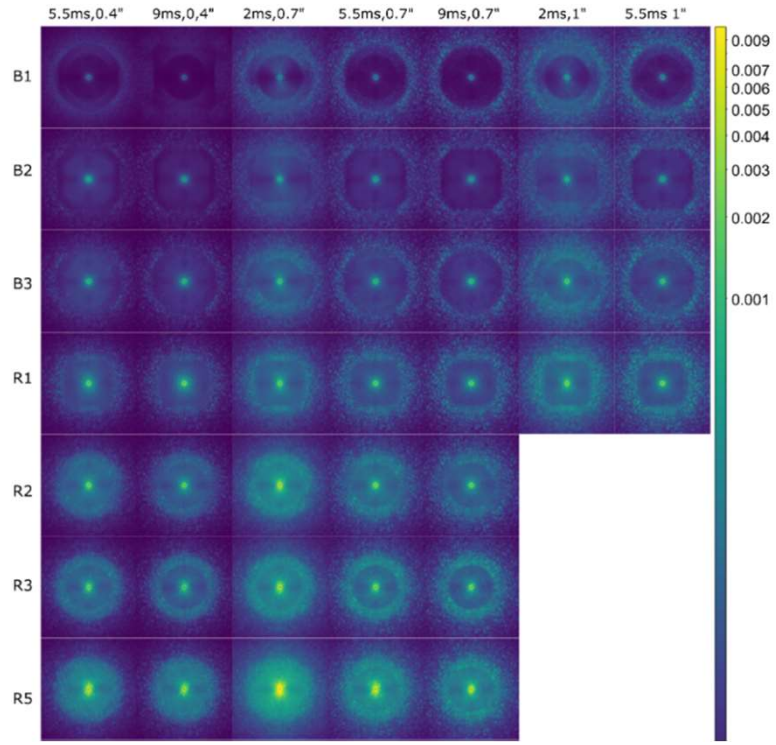
Figure 4: *Raw contrast gain of SAXO+ vs. SAXO averaged in 4 to 6 λ/D, for various science cases (B1: G=5/J=5, B2: G=7.6/J=7.2, B3: G=9.6/J=7.8, R1: G=11.9/J=8.5, R2: G=12.8/J=10.1, R2: G=14.5/J=10.1, R4: G=15.3/J=11.4, R5: G=16.8/J=12.5). The color/symbol code stands for the seeing (") and* τ_0 (ms).

Point Spread Function: SAXO vs. SAXO+

SAXO

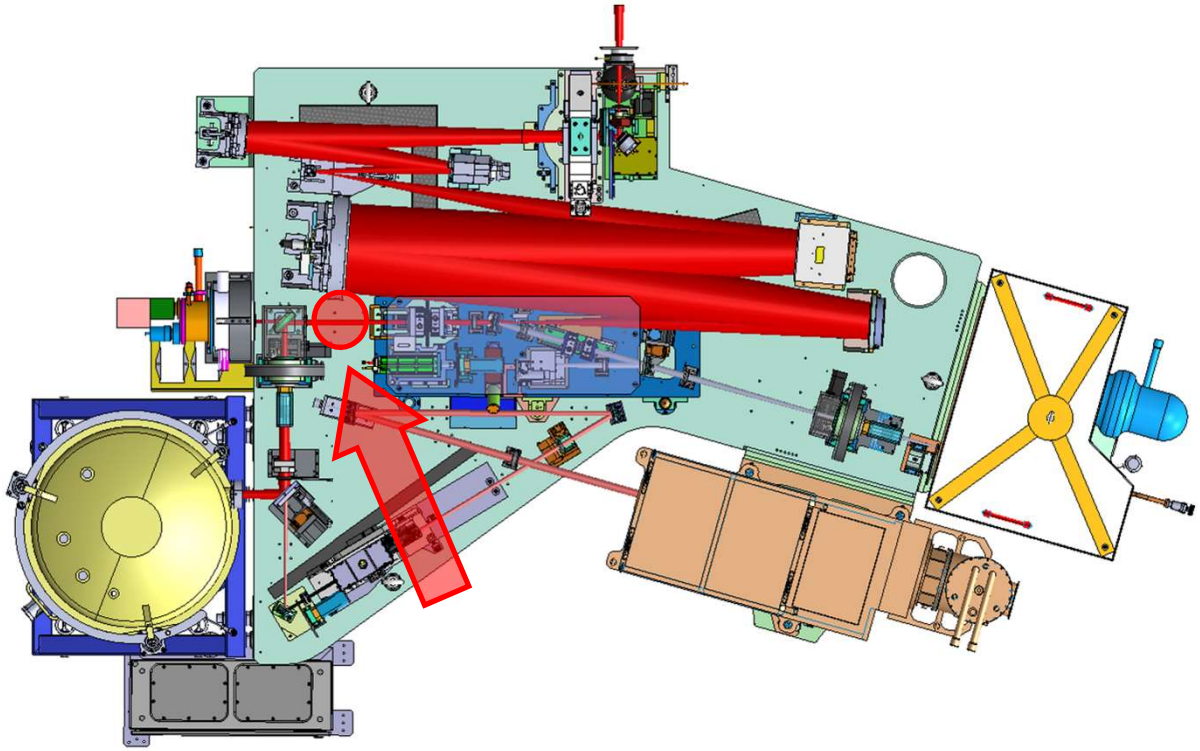


SAXO+



Non-invasive solution

- SAXO+ must preserve all current SPHERE functions and interfaces
- Implemented on a mezzanine with deployable pick-off mirrors
- Cascade control with few interactions with first correction stage
- Independent Real-Time Computer



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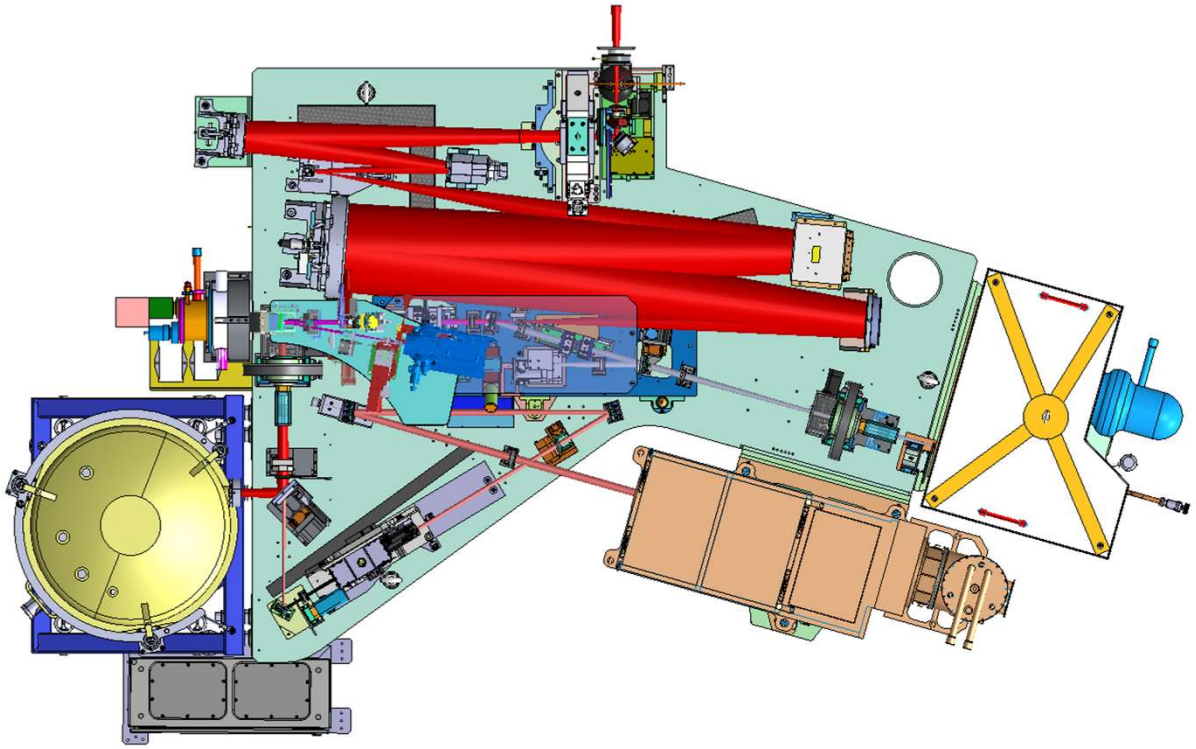
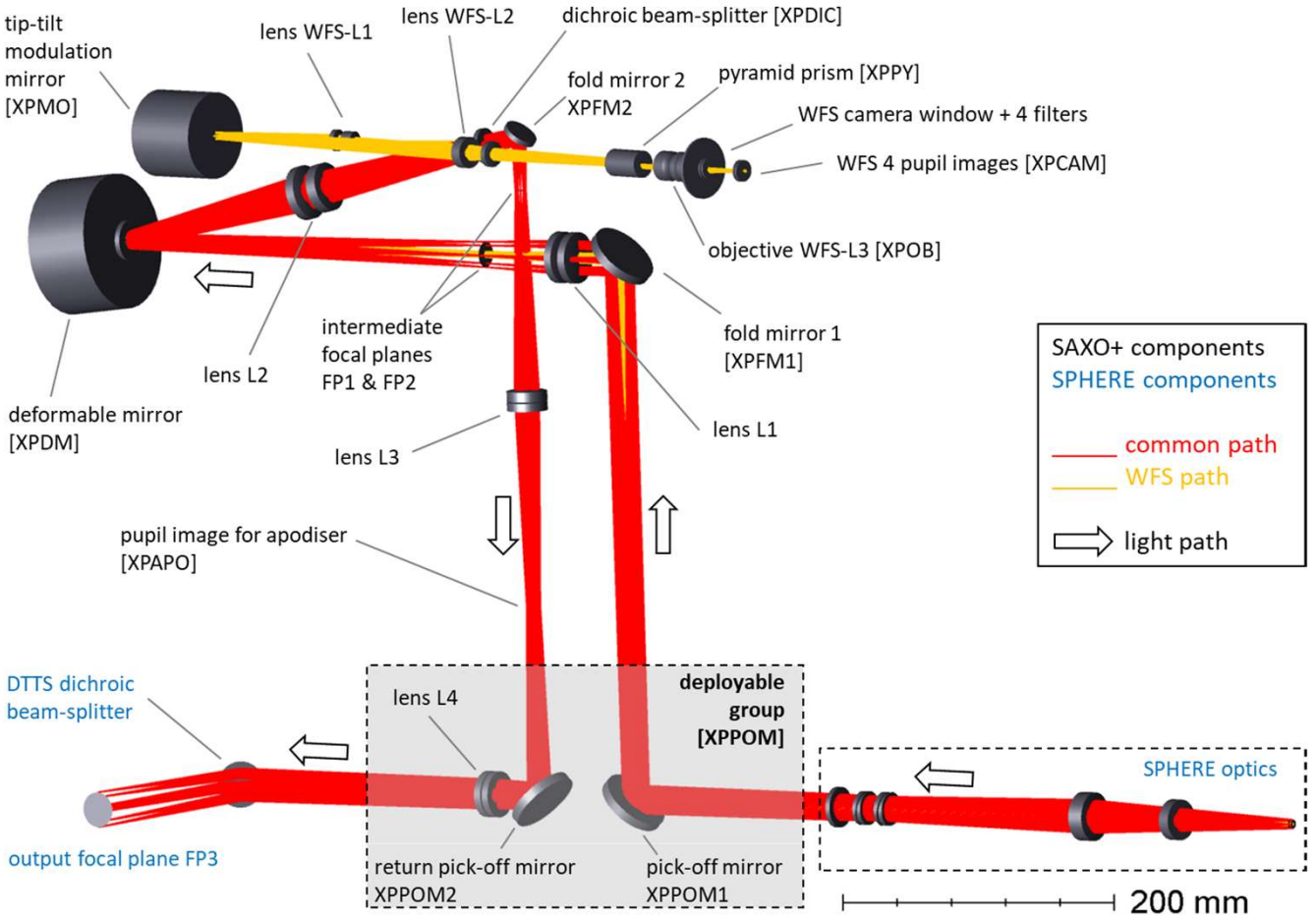
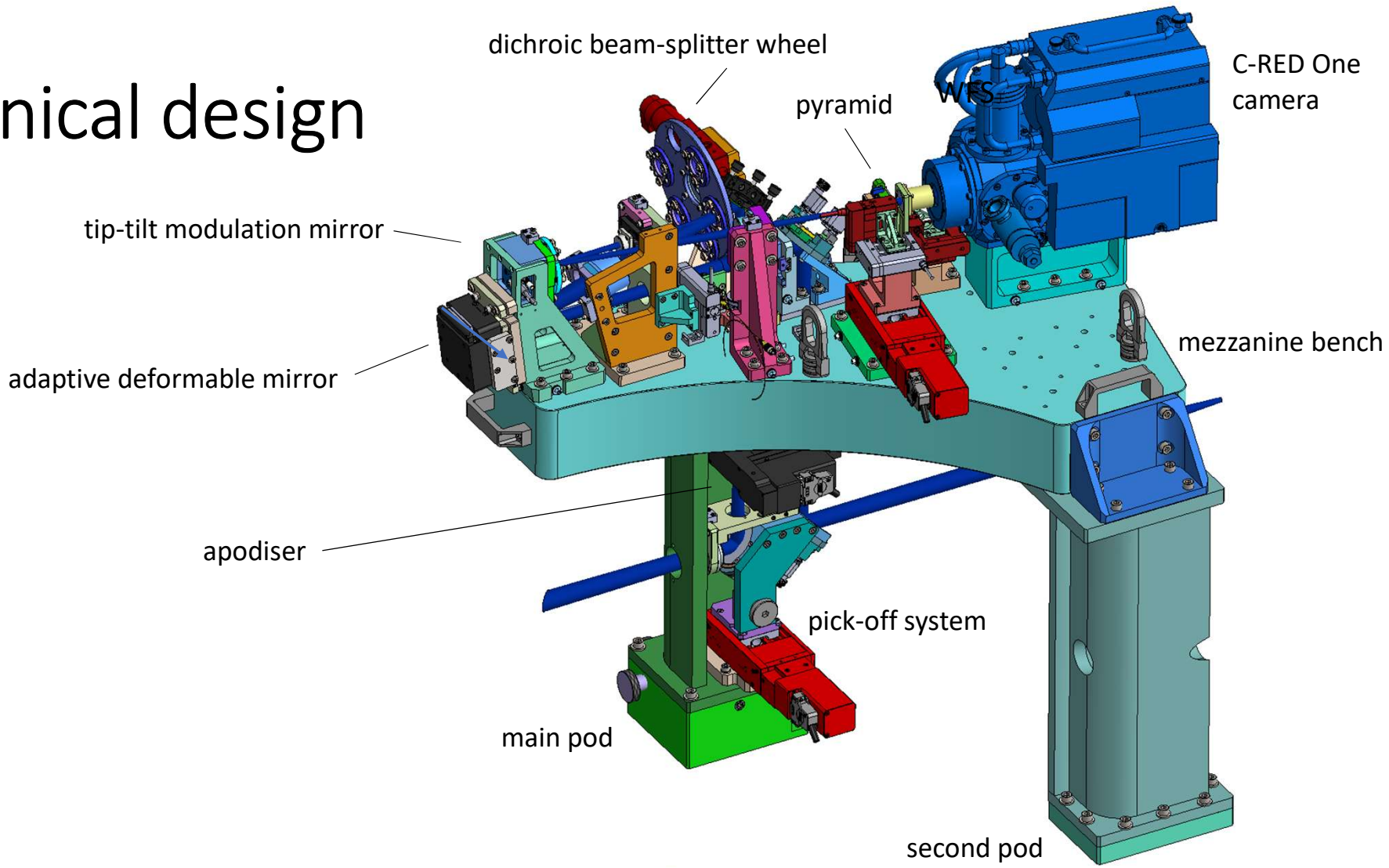


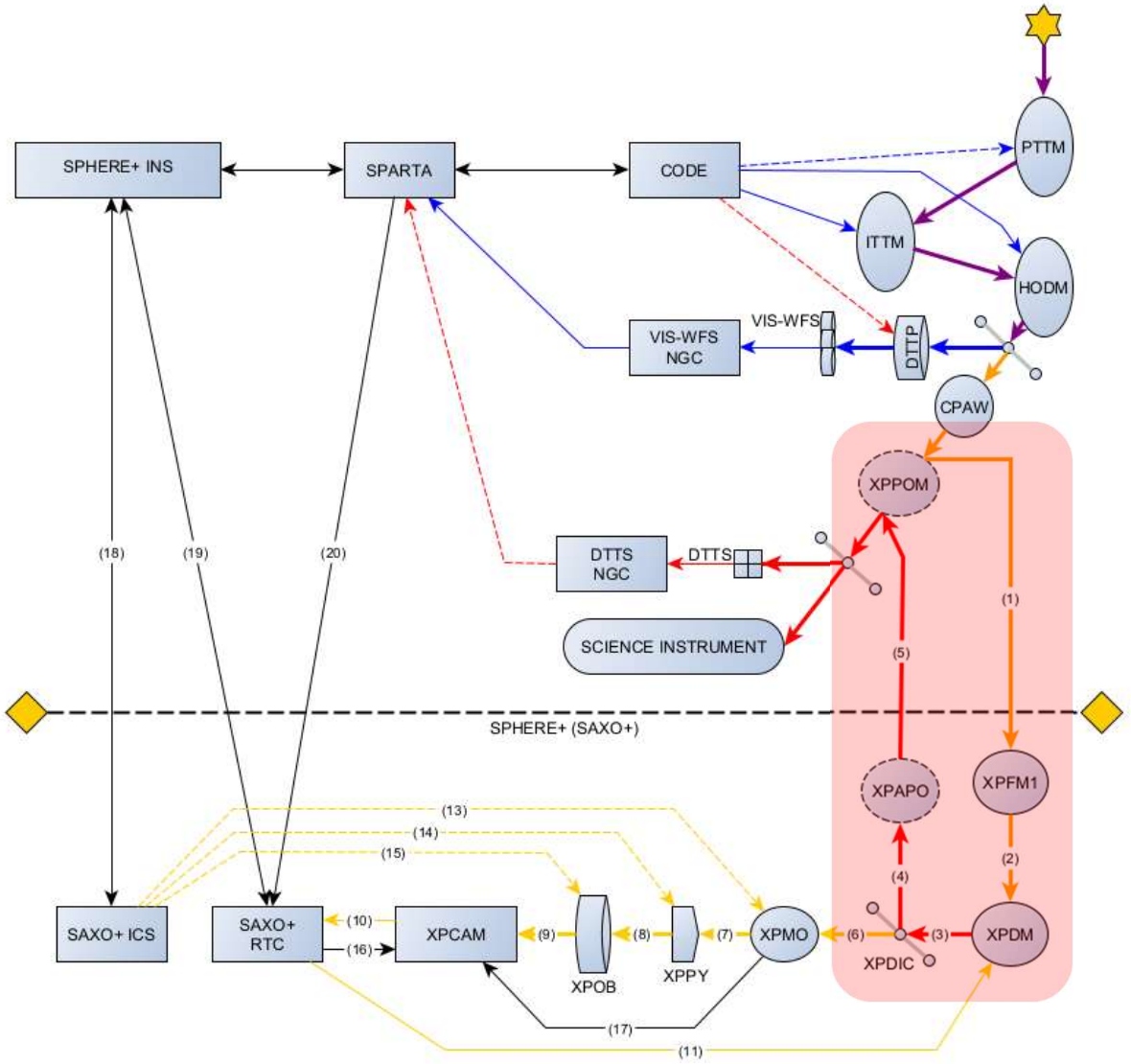
Optical design



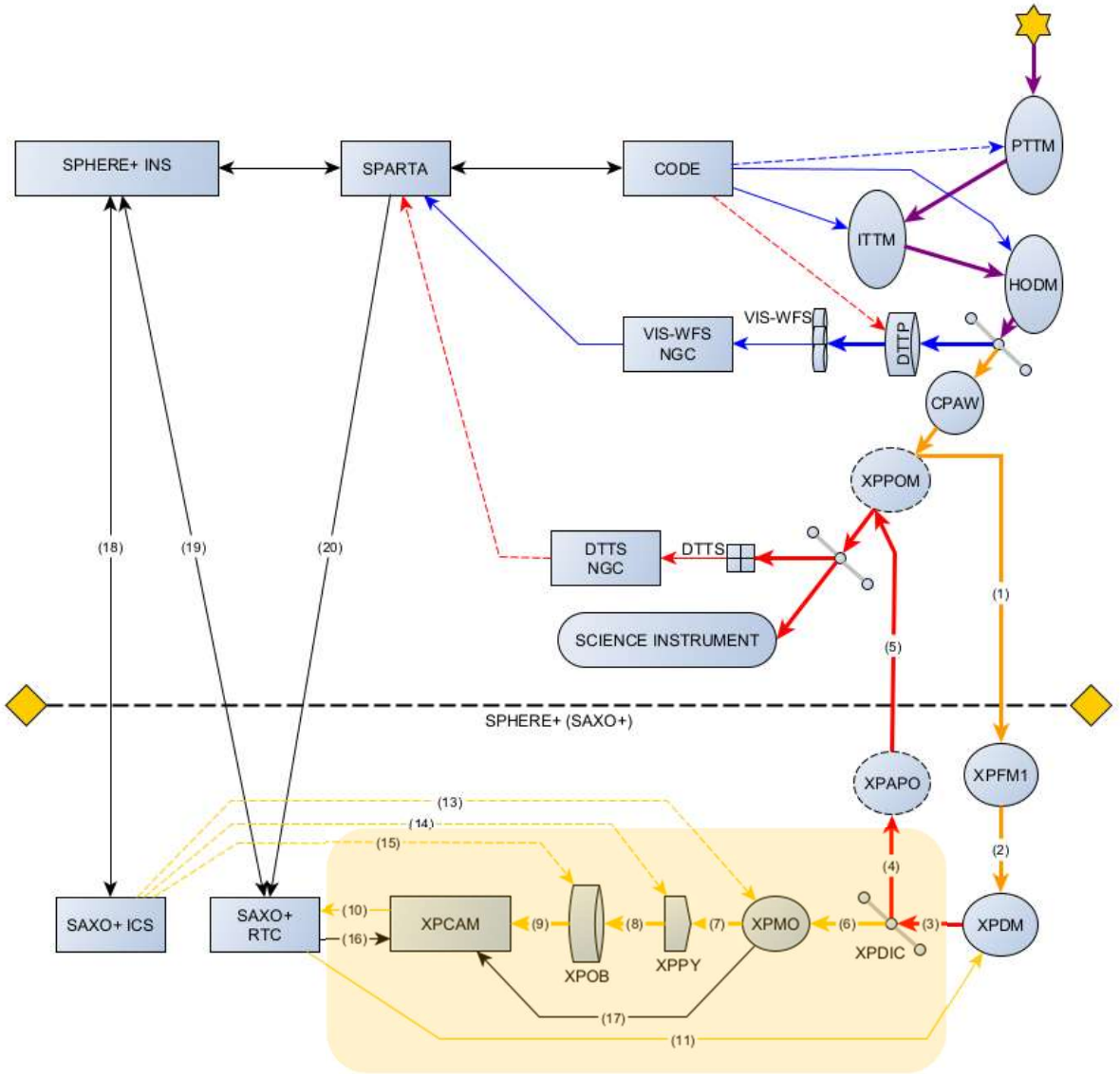
Mechanical design



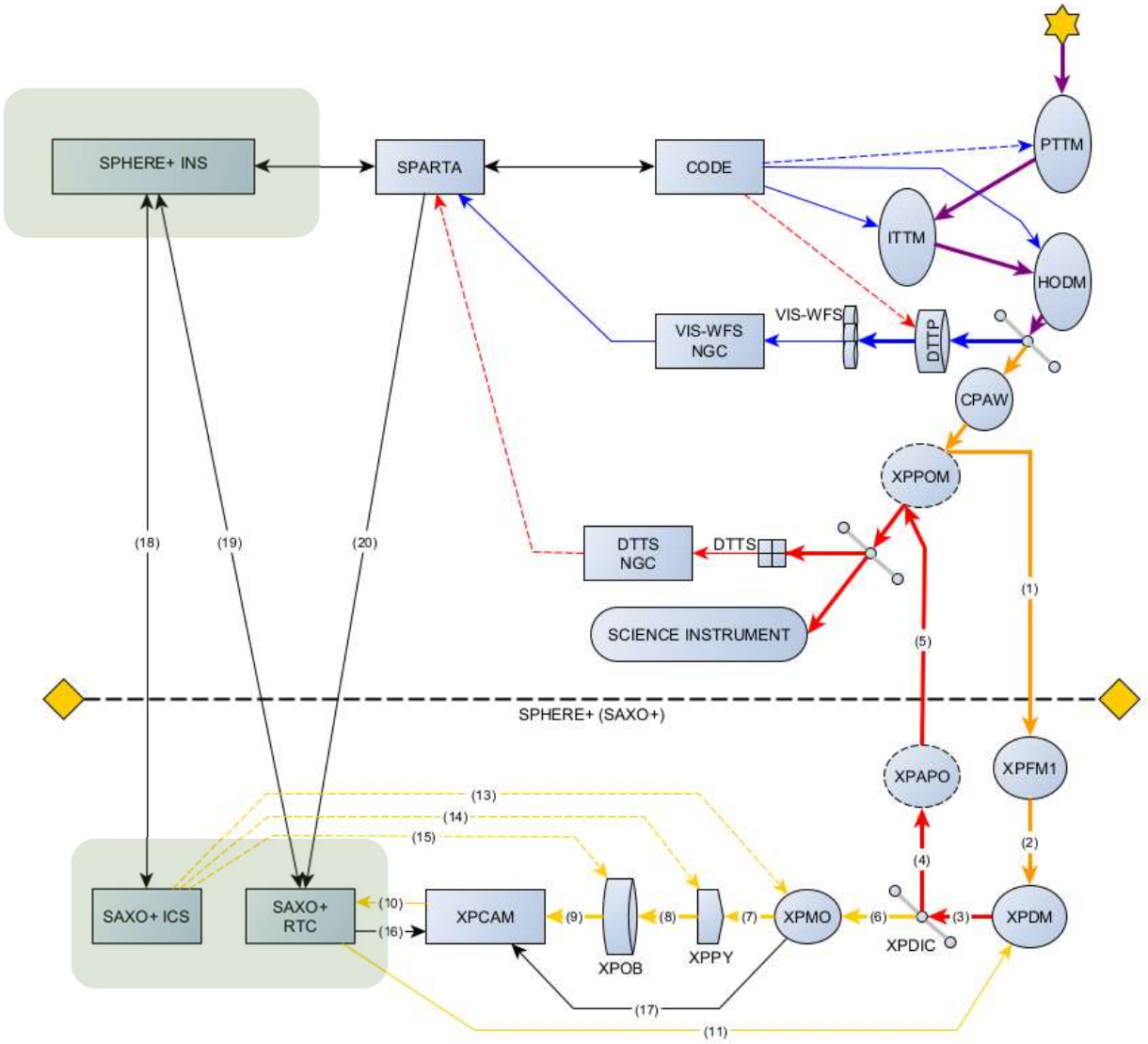
Control architecture



Control architecture



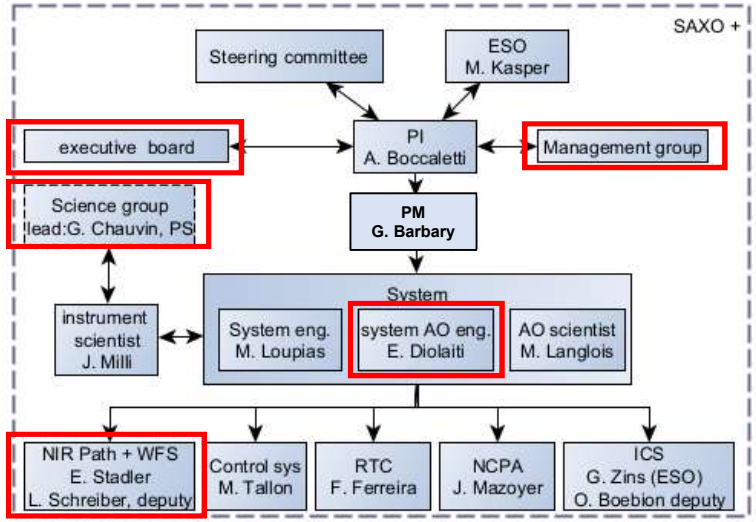
Control architecture

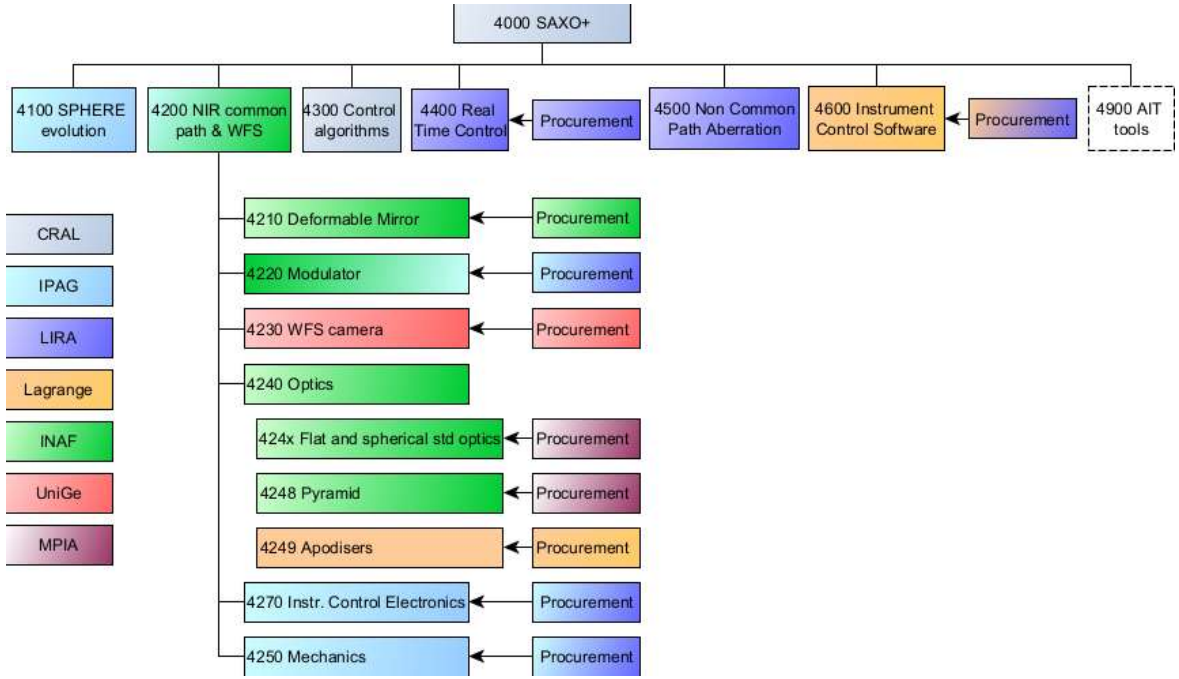


6 adaptive optics control schemes under development including classical PID, predictive control and machine-learning based

INAF contribution

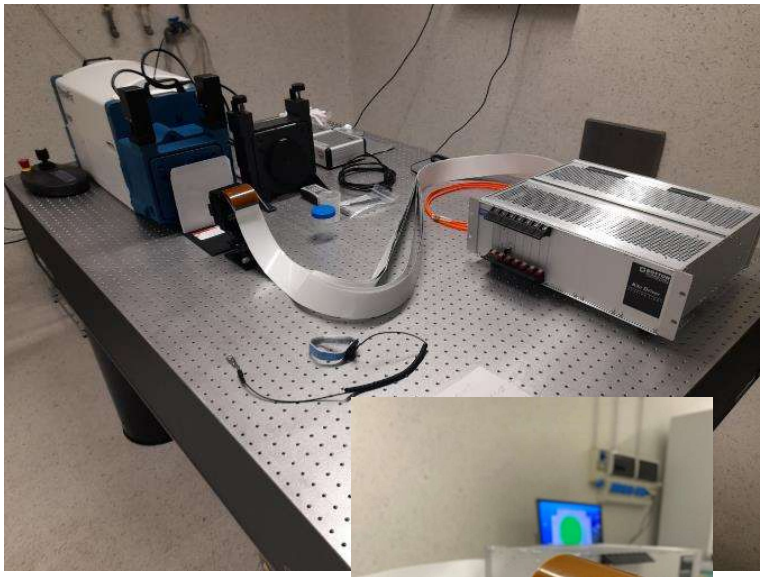
System AO engineer, WP leader deputy, Co-I, contribution to several work packages, sub-system level AIT, contribution to procurement of hardware components



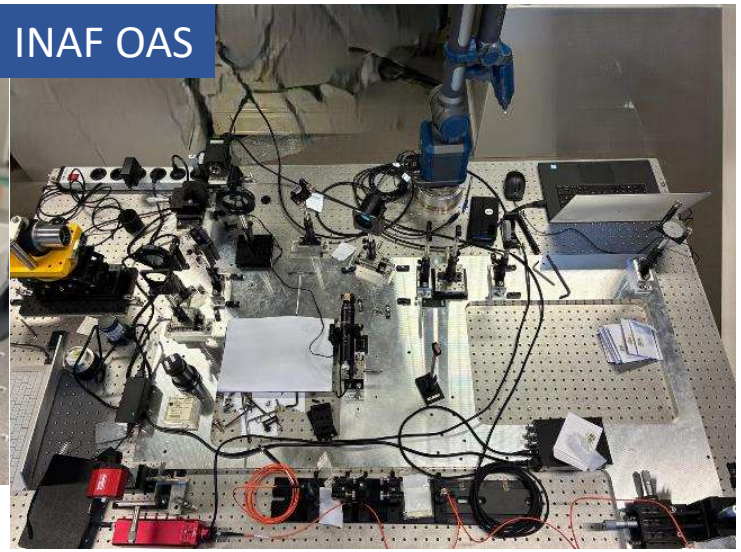


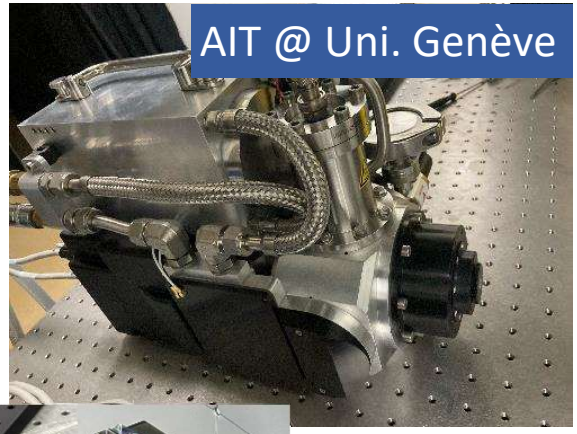
INAF contribution

- Adaptive deformable mirror procurement
- Support equipment for SAXO+ AIT
- Funded by PNRR STILES project



AIT @ INAF OAS

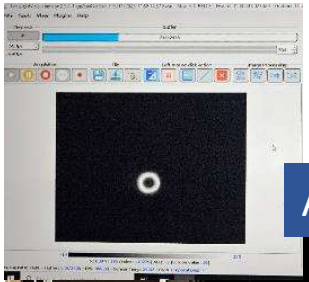




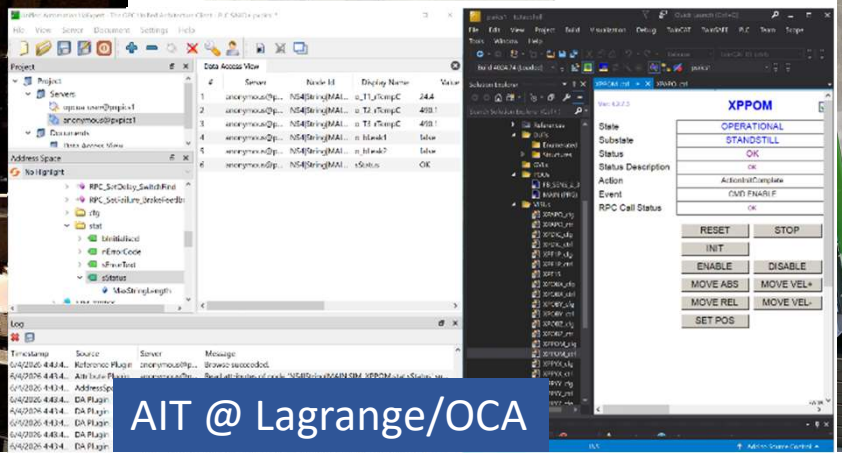
AIT @ Uni. Genève

AIT @ CRAL

AIT @ MPIA



AIT @ IPAG

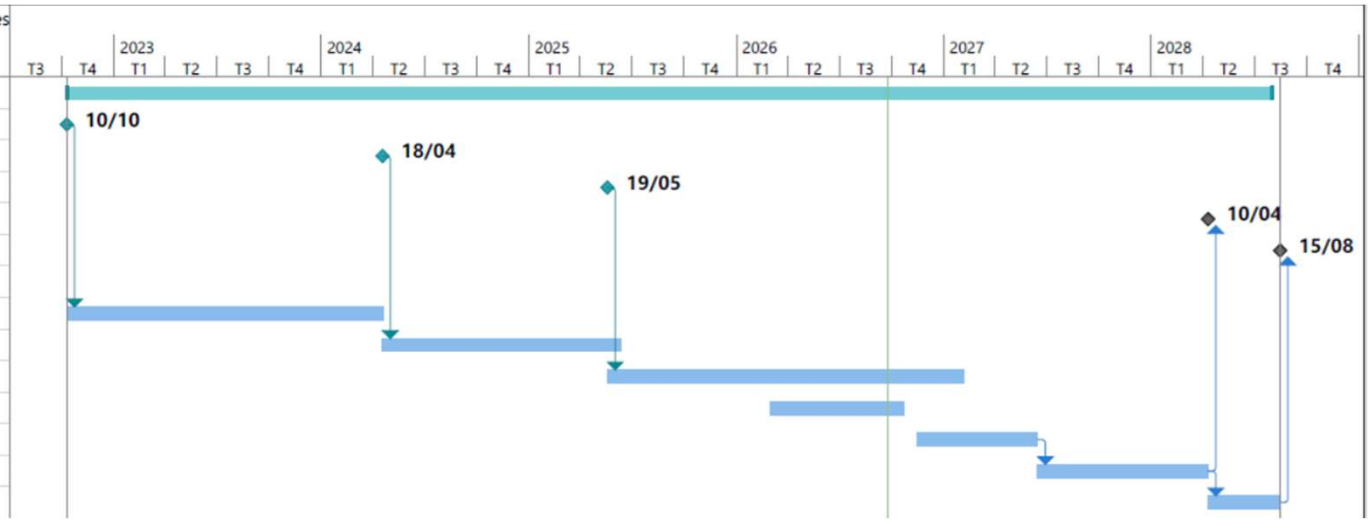


AIT @ Lagrange/OCA

AIT @ LIRA

Schedule

Task Name	Durée	Début	Fin	Prédéces
SAXOplus	1646,86	Lun 10/10/22	Lun 31/07/28	
kick-off	0 jr	Lun 10/10/22	Lun 10/10/22	
consolidation review	0 jr	Jeu 18/04/24	Jeu 18/04/24	
FDR	0 jr	Lun 19/05/25	Lun 19/05/25	
PAE Closure	0 jr	Lun 10/04/28	Lun 10/04/28	13
End of commissioning	0 jr	Mar 15/08/28	Mar 15/08/28	14
A: architecture, simulation	456 jrs	Lun 10/10/22	Ven 19/04/24	2
B/C: detailed design	320 jrs	Jeu 18/04/24	Jeu 12/06/25	3
D1: procurement	450 jrs	Lun 19/05/25	Jeu 04/02/27	4
D2-A: Mechanics & ICE integ.	170 jrs	Lun 02/03/26	Jeu 22/10/26	
D2-B: NIR CP & WFS integ.	165 jrs	Lun 16/11/26	Mar 15/06/27	
D3: system AIT	245 jrs	Mar 15/06/27	Lun 10/04/28	12
D+: shipping AIV, commissioni	104 jrs	Lun 10/04/28	Mar 15/08/28	13



- AIT at INAF OAS Nov 2026 – Jun 2027
- AIT at CRAL Jun 2027 – Apr 2028
- AIV at ESO Paranal May 2028 – Jul 2028
- Commissioning Jul 2028 – Aug 2028

Beyond Commissioning

- Visitor Instrument proposal
  - Proposal submitted by SAXO+ Consortium to ESO in Sep 2026, reviewed Dec 2026
    - Proposed observation program consists of 10 nights and two main scientific objectives: exoplanets (5 nights), planet-forming disks (5 nights)
  - If visitor instrument proposal is successful, observing proposals could be submitted to OPC in Sep 2027
  - Observations could start in P119/P120 (2028 →)

- SAXO+ as SPHERE mode could start in P121 (2030)
  - To be confirmed, pending fulfilment of conditions set out in the MoU

Acknolwedgements

The SAXO+ instrument is designed and being built by a consortium consisting of LIRA, CRAL, INAF, IPAG, Lagrange, Institut d'Optique, University of Geneva, MPIA, and LAM, in collaboration with ESO. The SAXO+ project is funded by the Fondation Charles Defforey-Institut de France, CNRS/INSU, the Programme et Equipements Prioritaires de Recherche PEPR Origins (ANR-22-EXOR-0002, ANR-22-EXOR-0003, ANR-22-EXOR-0017) within the Plan France 2030 of the French government operated by the National Research Agency (ANR), the NextGenerationEU funds within the National Recovery and Resilience Plan (PNRR), Mission 4 – Education and Research, Component 2 - From Research to Business (M4C2), Investment Line 3.1 - Strengthening and creating Research Infrastructures, Project IR0000034 – "STILES - Strengthening the Italian Leadership in ELT and SKA", CUP C33C22000640006, PlanetS, MPIA, LabEx FOCUS ANR-11-LABX-0013