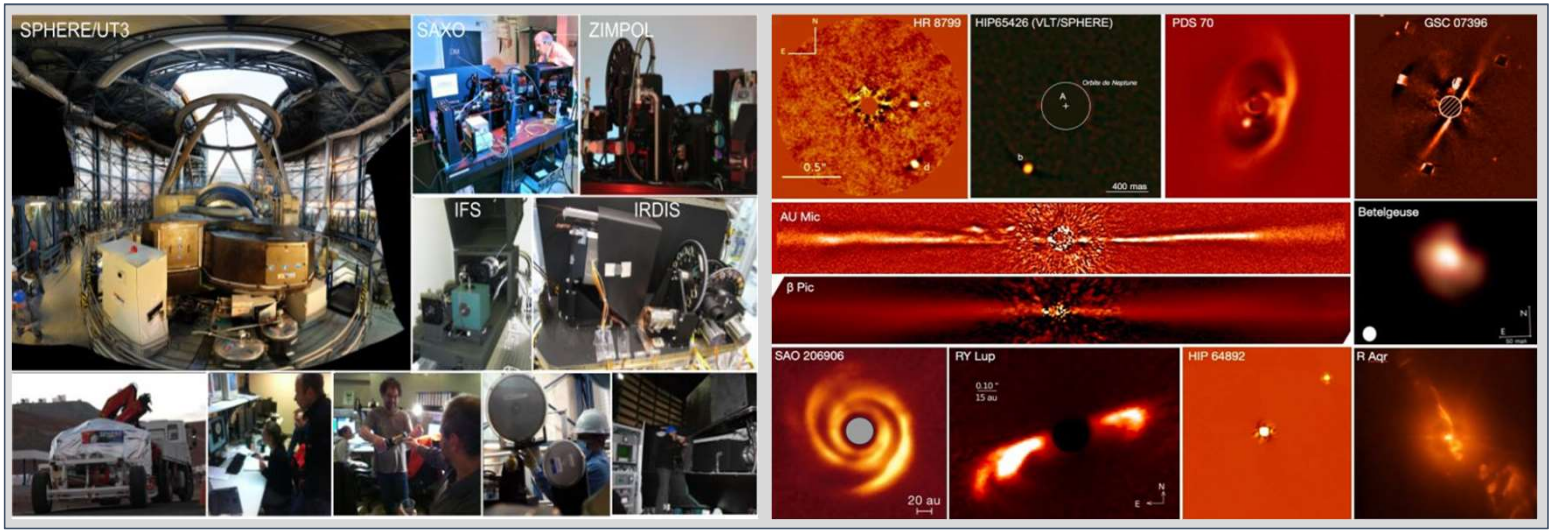
SPHERE+


SPHERE/UT3
SAXO
ZIMPOL
IFS
IRDIS
HR 8799
HIP65426 (VLT/SPHERE)
PDS 70
GSC 07396
AU Mic
β Pic
Betelgeuse
SAO 206906
RY Lup
HIP 64892
R Aqr
20 au
400 mas

CONTEXT

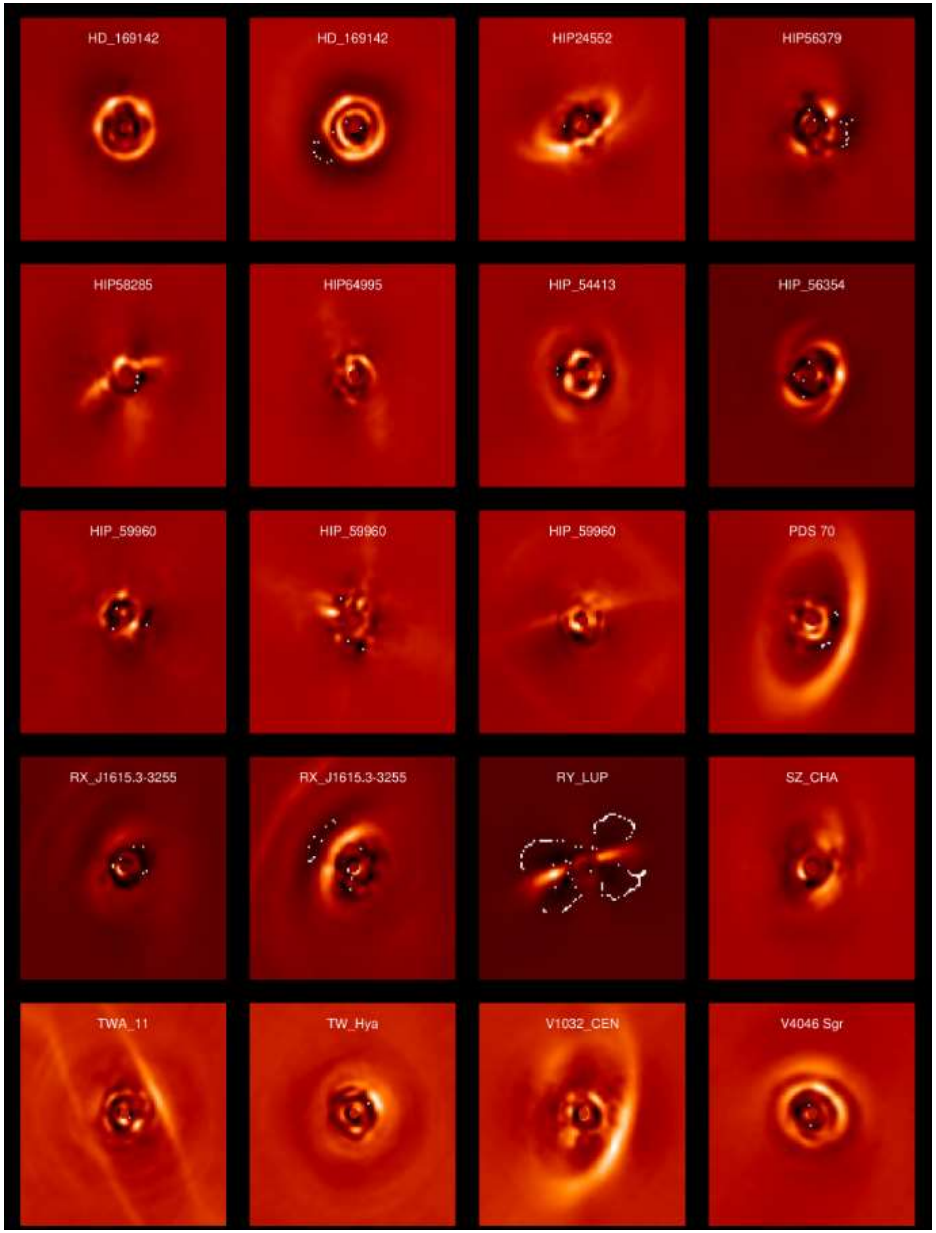
- 6 years of expertise with SPHERE
- ~116 Publications by the consortium (~ 200 in total)
- Good ideas of how to boost SPHERE performances
- VLT workshop June 2019 – first proposal
- Identification by ESO of 3 candidates for phase A implementation
- Feb 2020: White paper
- May 2020: 2 instruments selected, not SPHERE+… but identified in the roadmap towards PCS
- Summer 2020: initiate discussions with Tech Dev. Group (PCS)
- OCT 2020: Roadmap confirmed by STC, validated by DG
- MoU 1st draft Dec 2020

Lessons learned

** Six years of operation & 100+ GTO publications*

Transformational in the field of optical/nIR imaging of disks

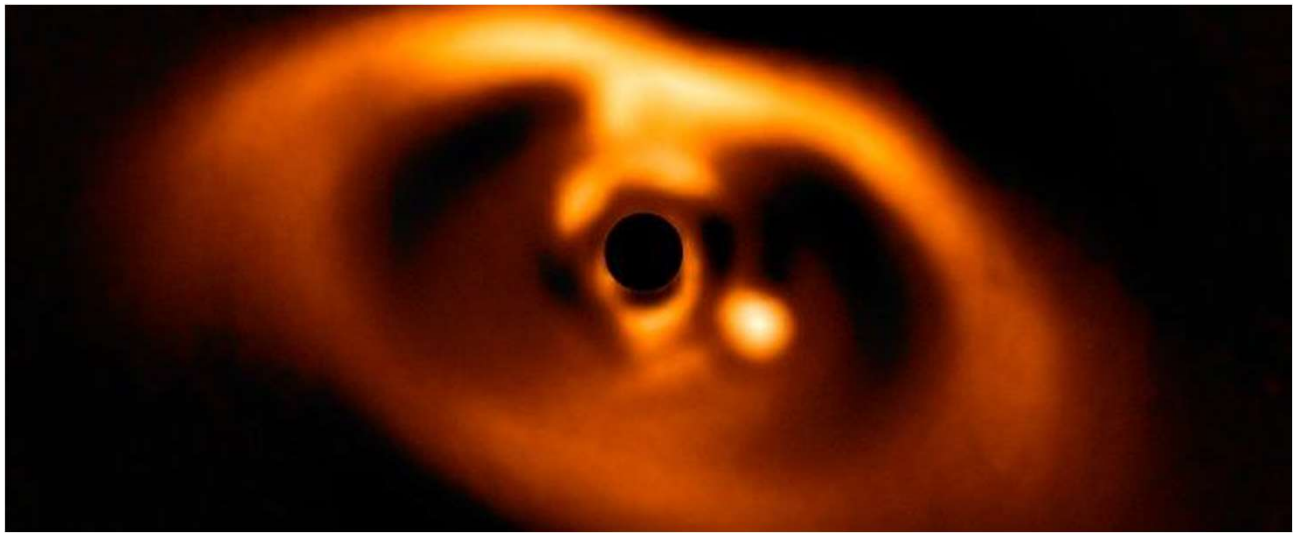
Diversity of morphologies: spirals, gaps, cavities, vortices, shadows observed in scattered-light revealing a zoo of sub-structures in some cases to possible planets in formation...
Synergies: ALMA



Lessons learned* *Six years of operation & 100+ GTO publications*

Planet(s) caught in formation

First Confirmed Image of Newborn Planet Caught with
ESO's VLT
2 July 2018 (ESO - PR 1821)



Insight on: giant planet formation, multiple planetary systems, planet/disk interactions, architectures & stability, physics of accretion, circumplanetary disks,
...
Synergies: MUSE, ALMA, Gravity…

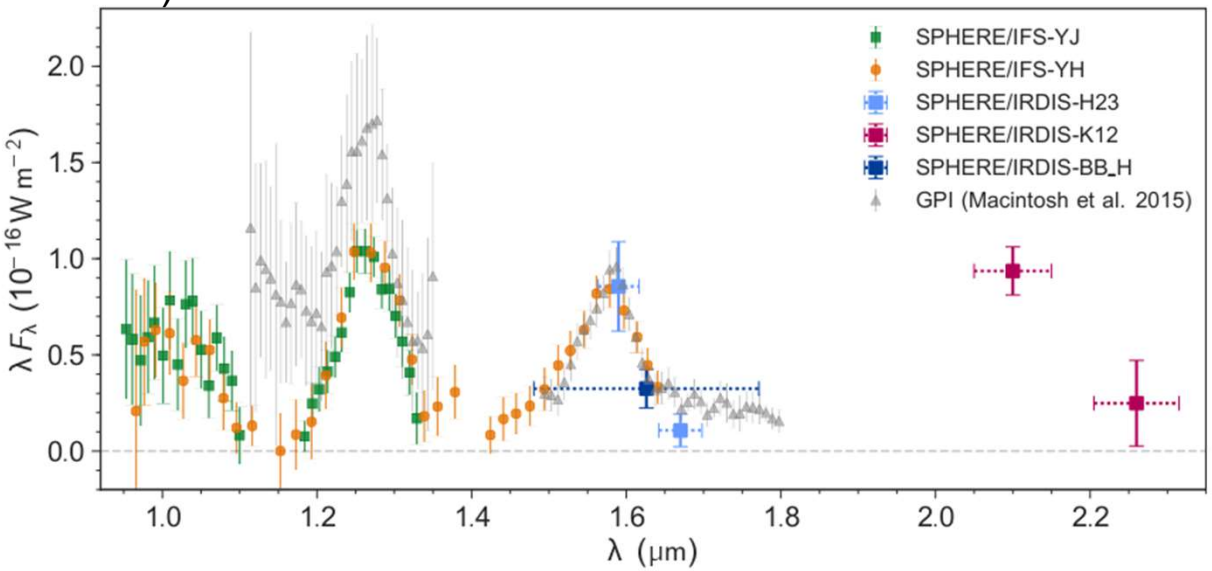
Lessons learned

** Six years of operation & 100+ GTO publications*

Physics of exoplanets - Atmospheres

Spectral and atmospheric characterization of 51 Eridani b

19 July 2017 (Astronomy & Astrophysics Highlighted papers of the year 2017)



From color-magnitude diagramme (<2014) to low-resolution spectra of young Jupiters to access effective temperature, surface gravity, clouds & metallicity...
Synergies: SINFONI/ERIS(+), Gravity (K-band), CRIRES+, JWST (NIRSpec, MIRI…)

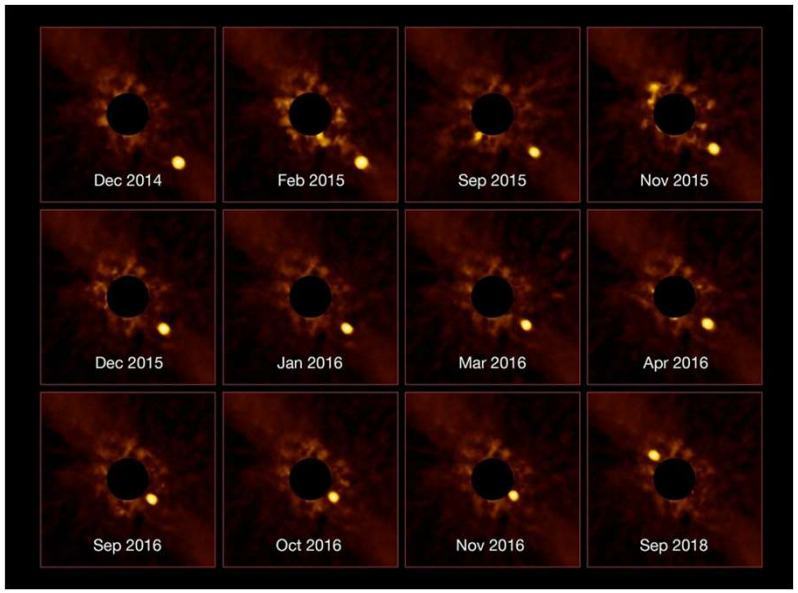
Lessons learned

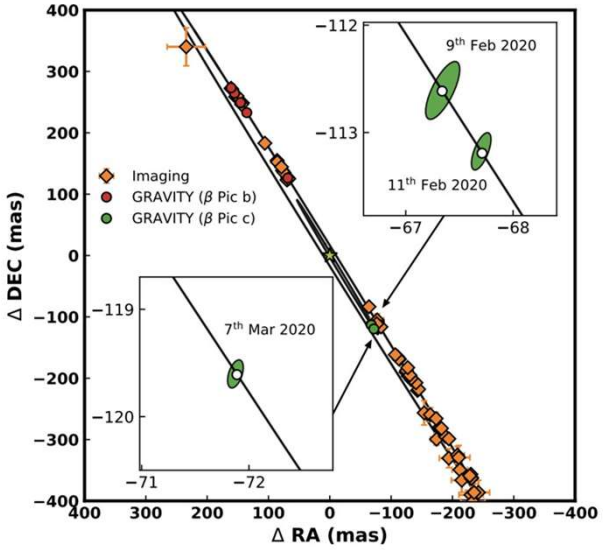
** Six years of operation & 100+ GTO publications*

Physics of exoplanets - Architectures/Orbits

Stunning Exoplanet Time-lapse of β Pictoris b

12 November 2018 (ESO Picture of the week)





Accessing mas-astrometry for monitoring of exoplanetary orbits, (also shadows & disk features,)

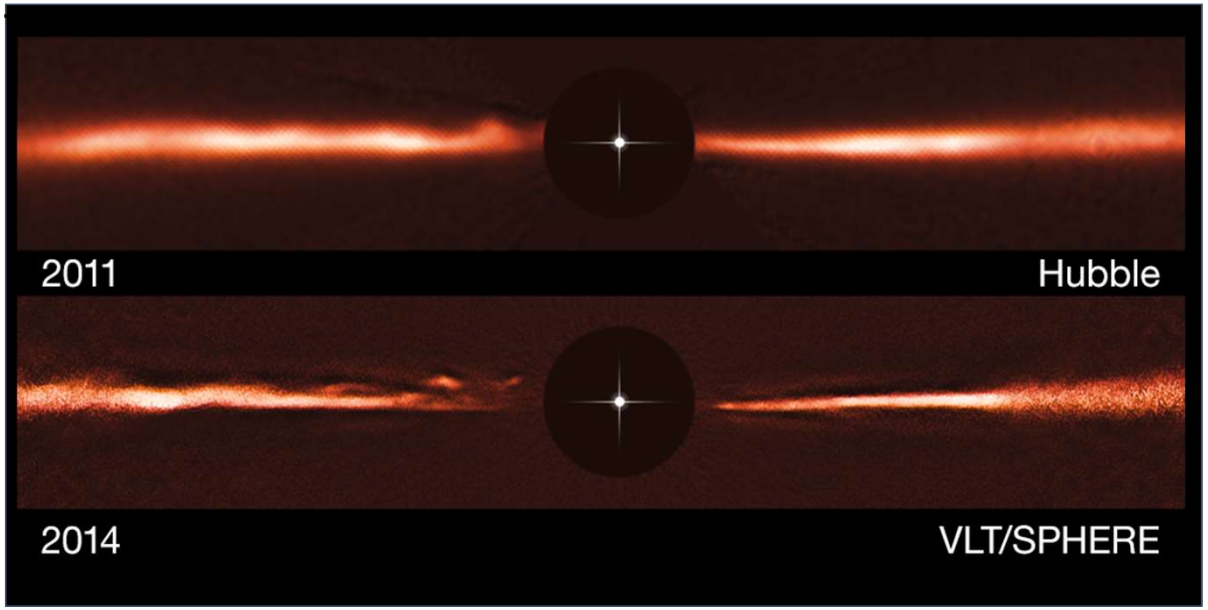
Synergies: Gravity (K-band)

Lessons learned

** Six years of operation & 100+ GTO publications*

Debris disks morphology and mineralogy

Mysterious Ripples Found Racing Through Planet-forming Disc



Accessing mas-astrometry for monitoring of exoplanetary orbits, (also shadows & disk features,)
Synergies: ALMA, JWST

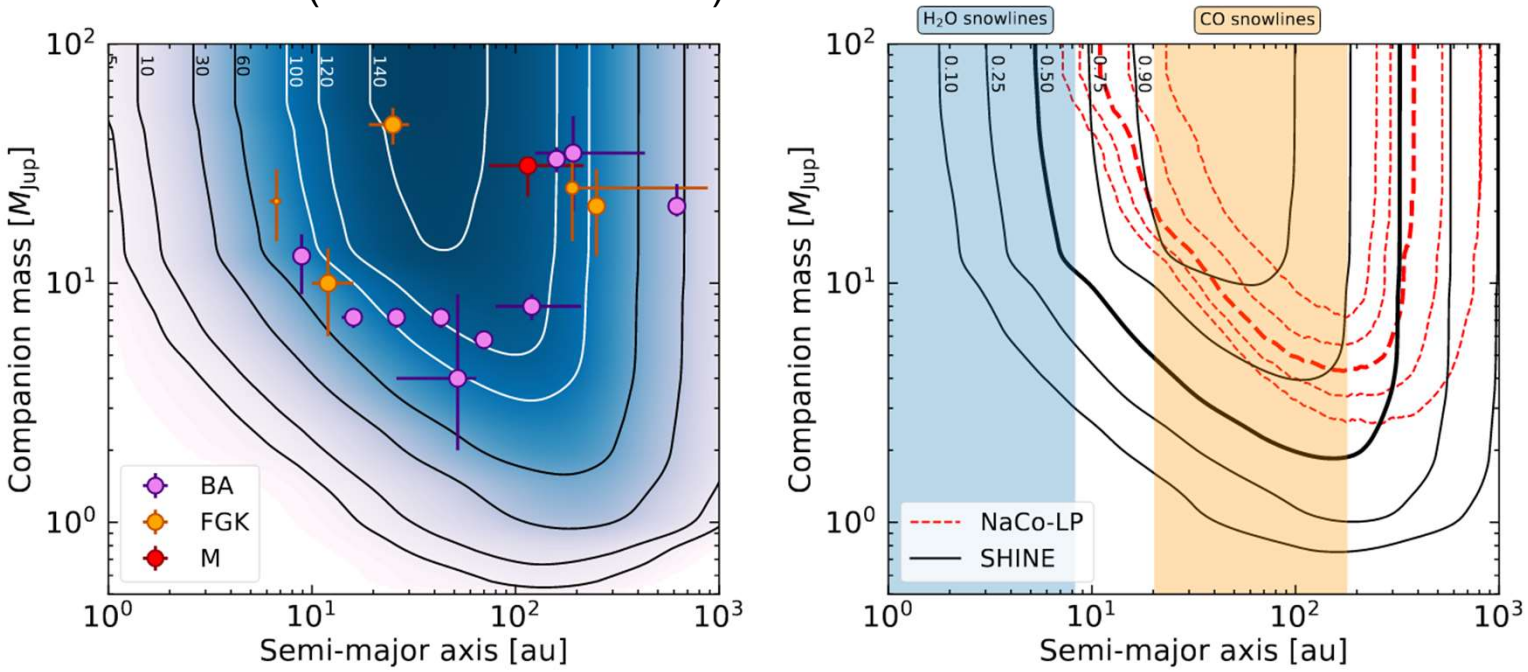
Lessons learned

** Six years of operation & 100+ GTO publications*

Exoplanet Demographics

The population of young giant exoplanets below 300 au

9 March 2021 (INSU/INAF/MPIA PR)



Occurrence of planetary system hosting at least one giant planet (5 - 1000 ua, M > 1 M_{Jup}) around young, solar-type stars = $5.7^{+3.8}_{-2.8}$ % ; Overlap of 2 populations (planets/BDs); dependency with M_{Star}

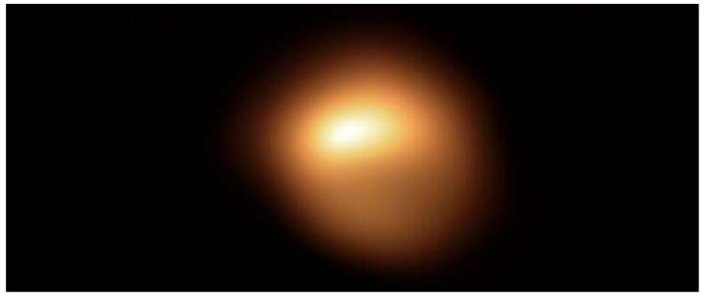
Lessons learned

** Six years of operation & 100+ GTO publications*

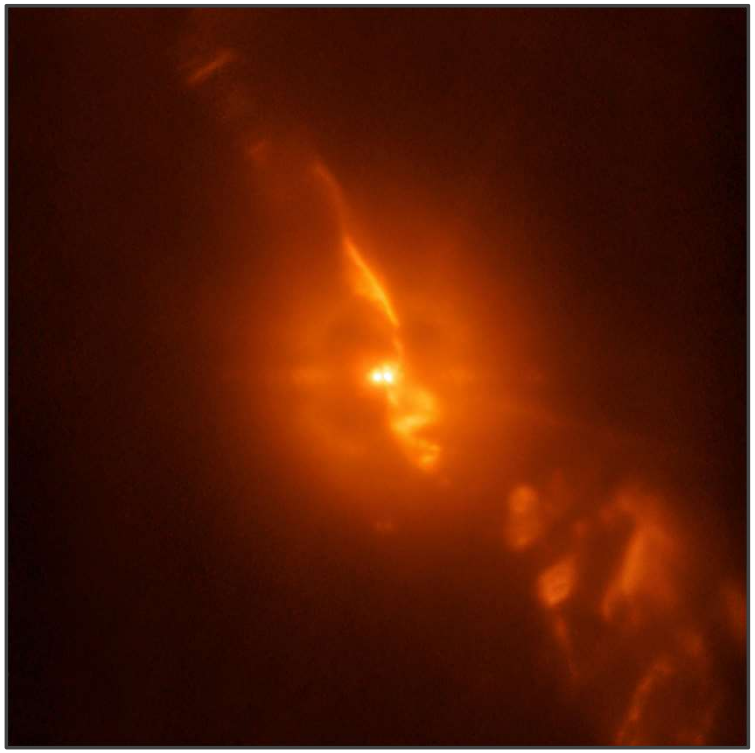
Solar systems, evolved stars, active galactic nuclei...

New SPHERE view of Vesta (ESO POTW-1836)

Telescope Sees Surface of Dim Betelgeuse (ESO PR-2003, 2109)



R Aquarii peculiar stellar relationship (ESO PR-1840)



Lessons learned

** Six years of operation & 100+ GTO publications*

Astrophysical success thanks to:

- Well identified science cases, tight specifications & trade-off analysis
- SAXO: xAO high-performances, stability, robustness in terms of operation (<3% downtime),
- Versatile instrumentation: ZIMPOL, IRDIS and IFS in terms of wavelengths, spectral resolution, field of view & observing modes (ADI, SDI, DPI, RDI),
- After 6 years, well identified limitations:
  - Saxo: xAO **correction servo-lag, low-order aberrations, low-wind effects, wind driven halo, NCPAs**...
  - CPI/IRDIS (Polar): Derotator re-coating (beamshift), IRDIS polarizing beamsplitter,
  - ZIMPOL: low-RON mode...
  - Path forward new solutions: PT/DPI mode, star-hopping, NCPA zelda, dark-hole,...

& some unexpected aspects...

- SAXO: HODM and dead-actuators, Kalman filtering (tip-tilt), NCPA not corrected...
- 4QPM not performant in current state, main use of the “classical” APLC coronograph,
- Designed for H-band, to detect CH4-atmospheres (DBI), but limited use for exoplanet discovery,
- IFS-YH, not foreseen initially, extremely useful for red L dusty exoplanets (PDS70b-like)

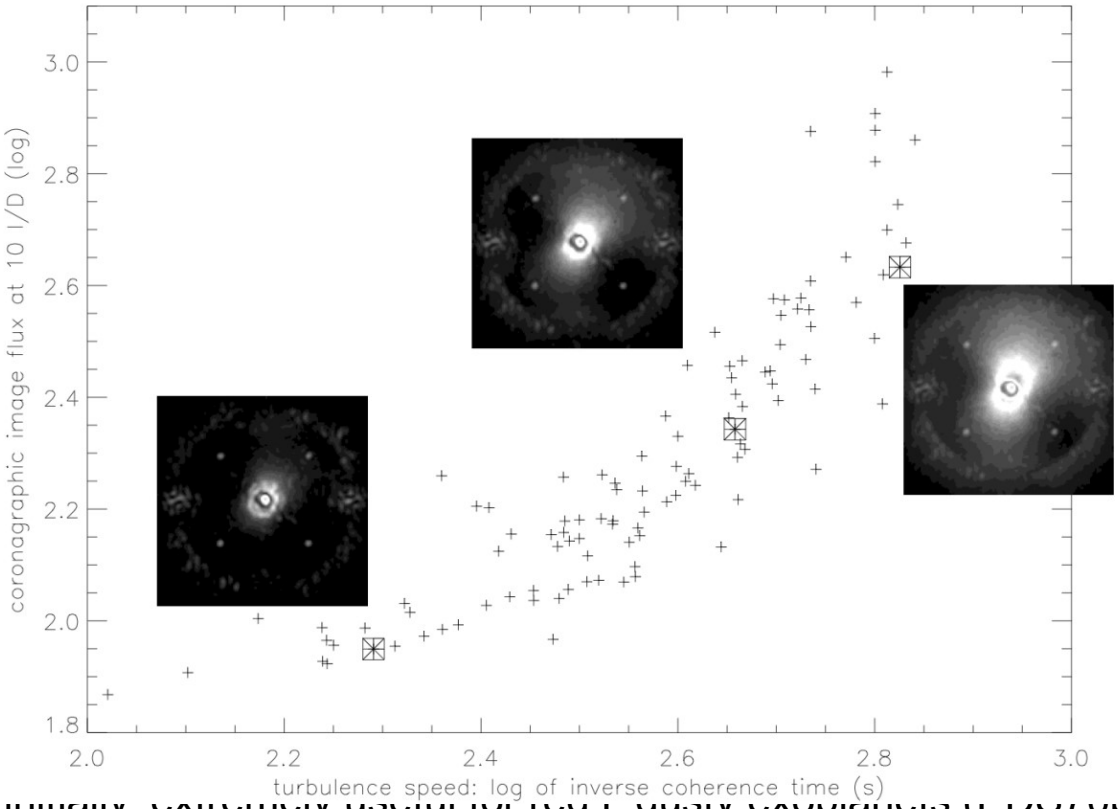
Upgrade? Do not break SPHERE, and push on the instrument strengths!

Lessons learned

** Six years of operation & 100+ GTO publications*

Astrophysical success

- Well identified scienc
- SAXO: xAO high-per
- Versatile instrumenta
  & observing modes (
- After 6 years, well id
  - Saxo: xAO **corr**
    NCPAs...
  - CPI/IRDIS (Pola
  - ZIMPOL: low-R(
  - Path forward ne



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wind driven halo,
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le,...

& some unexpected as

- SAXO: HODM and d
- 4QPM not performar
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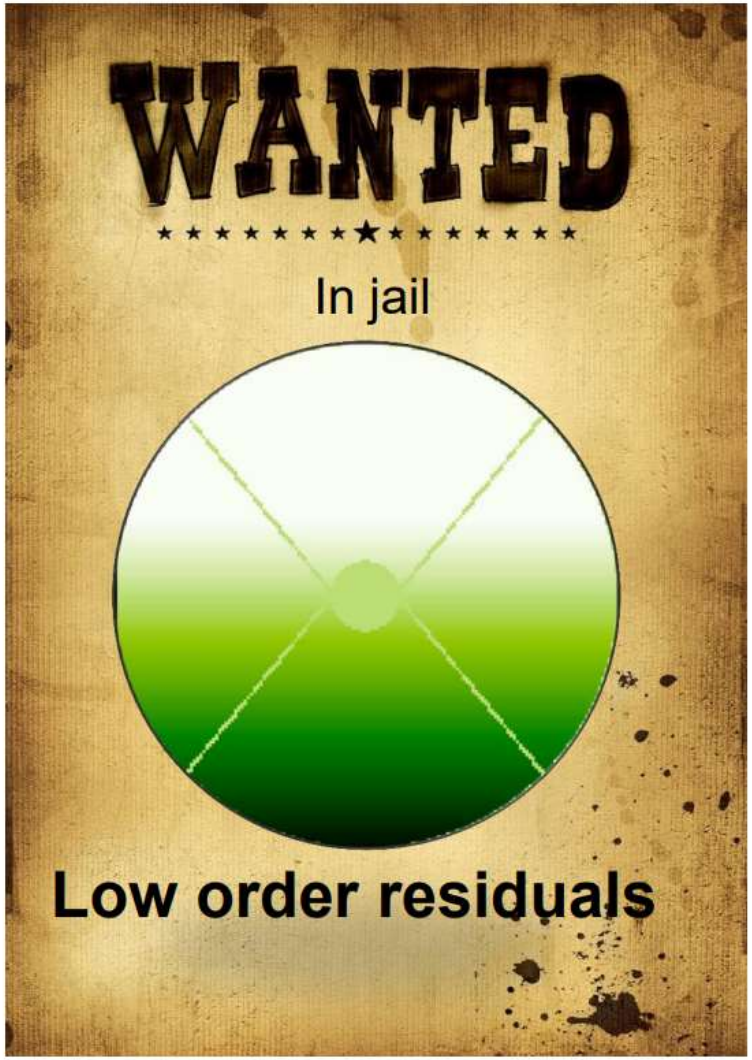
- IFS-YH, not foreseen initially, extremely useful for red L dusty exoplanets (PDS70b-like)

oh,
net discovery,

Upgrade? Do not break SPHERE, and push on the instrument strengths!

L

The contrast killers #1



Astrophysical

- Well identif
- SAXO: xAO
- Versatile in
  & observing
- After 6 yea
  - Saxo:
    NCPAs
  - CPI/IR
  - ZIMPO
  - Path fo

& some unexp

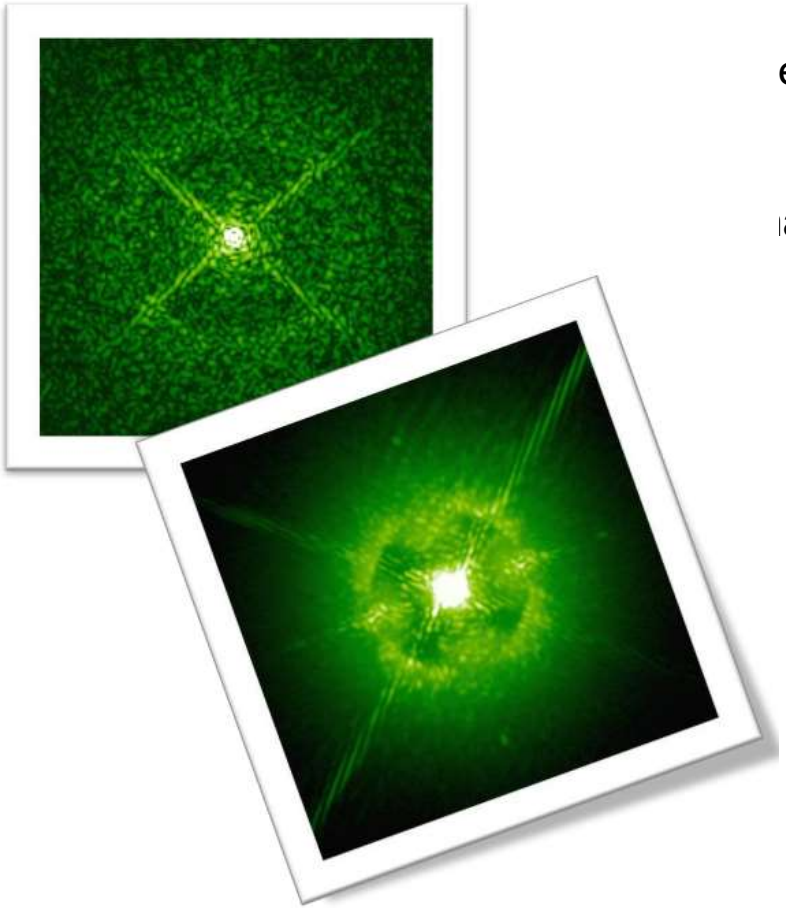
- SAXO: HO
- 4QPM not
- Designed f
- IFS-YH, no

Upgrade? Do

1- Dissection of a SPHERE image

☹☹☹

Responsible for the
"**jitter**"



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Astrophysical

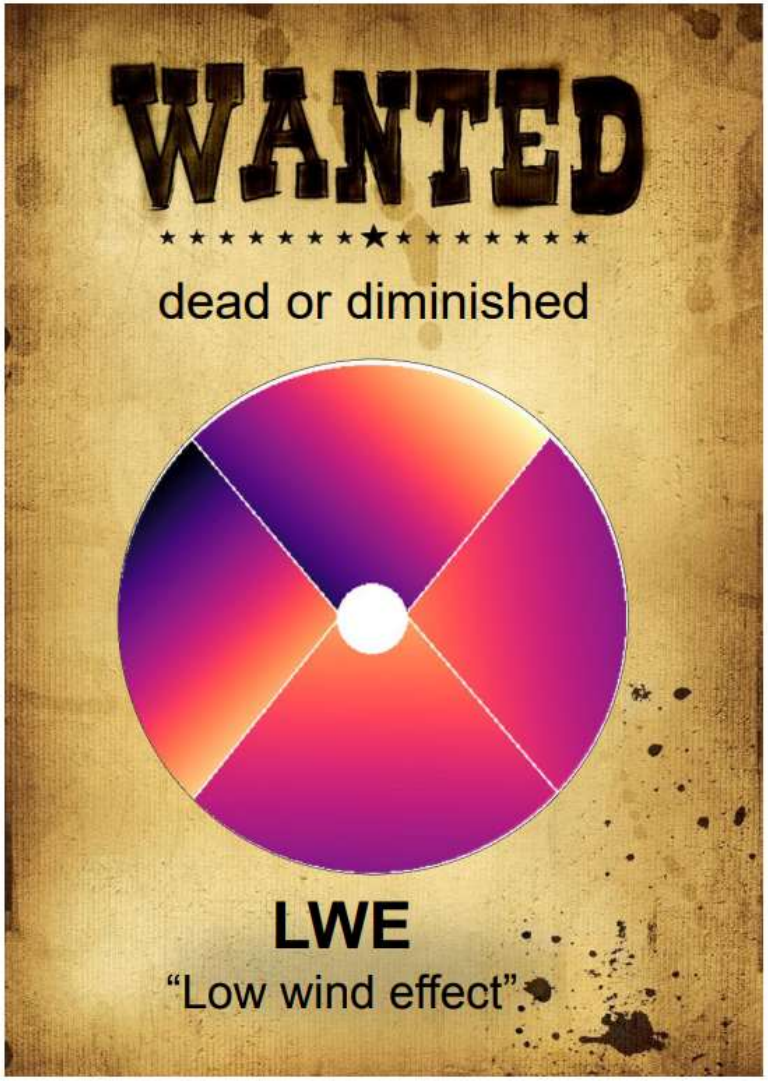
- Well identi
- SAXO: xA
- Versatile ir
  & observin
- After 6 yea
  - Saxo:
    NCPA
  - CPI/IF
  - ZIMP
  - Path f

& some unexp

- SAXO: HC
- 4QPM not
- Designed f
- IFS-YH, nc

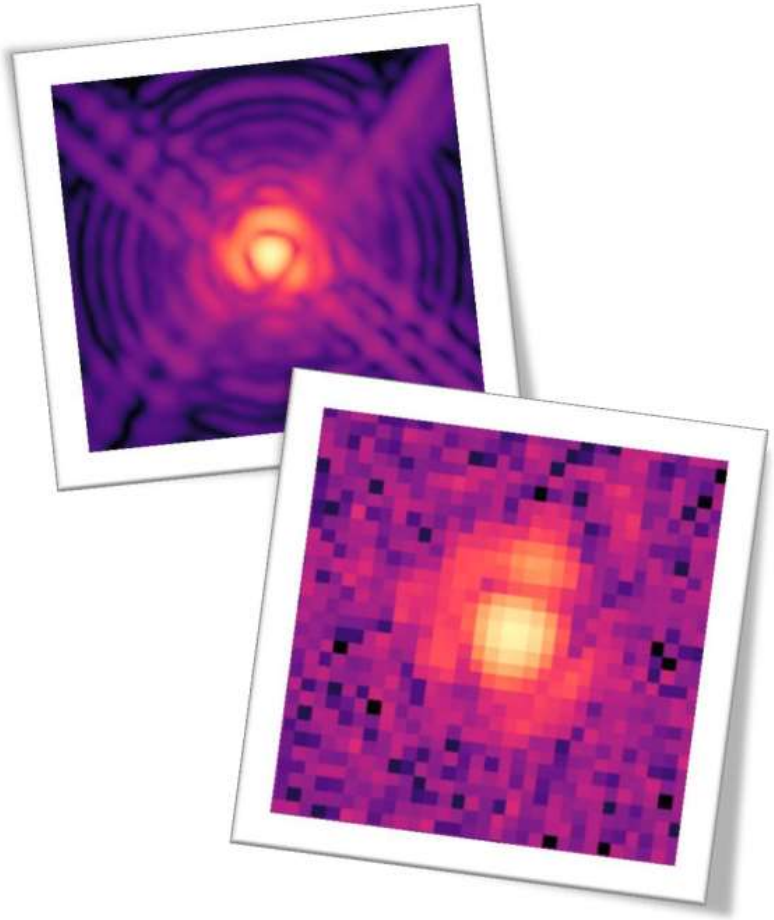
Upgrade? Do

The contrast killers #2



1- Dissection of a SPHERE image
☹☹☹

Responsible for the
"**Mickey Mouse effect**"



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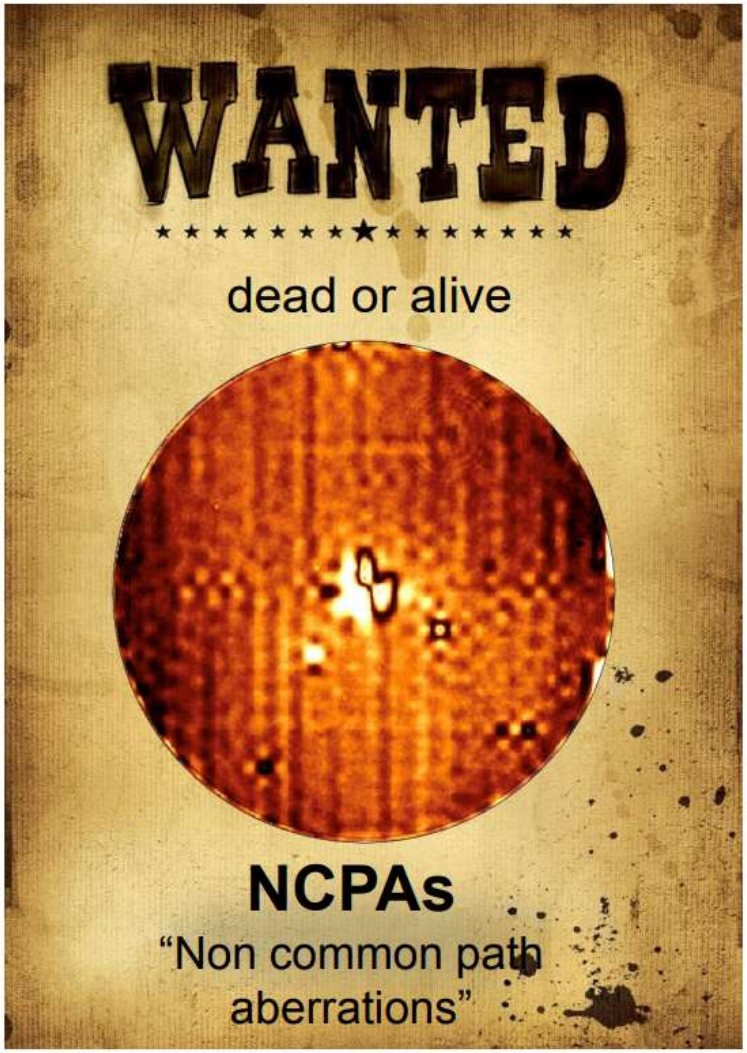
The contrast killers #3



Astrophysical

- Well identi
- SAXO: xA
- Versatile ir
  & observin
- After 6 yea
  - Saxo:
    NCPA
  - CPI/IF
  - ZIMP
  - Path f

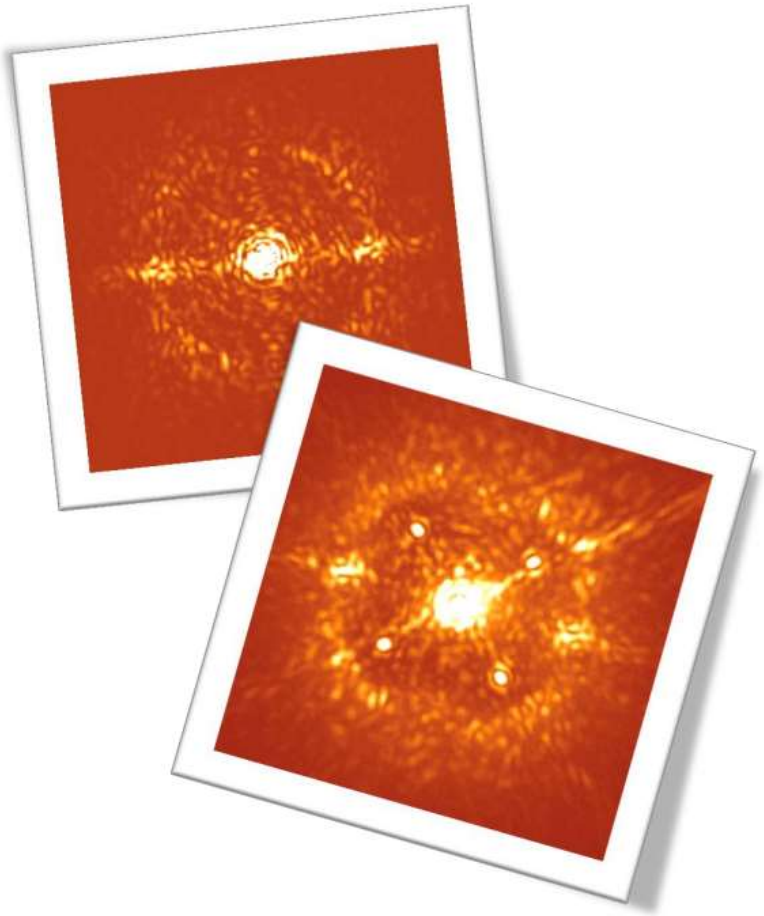
& some unexp

- SAXO: HC
- 4QPM not
- Designed f
- IFS-YH, nc

Upgrade? Do

1- Dissection of a SPHERE image
☹☹☹

Responsible for the
“**quasi-statics speckles**”



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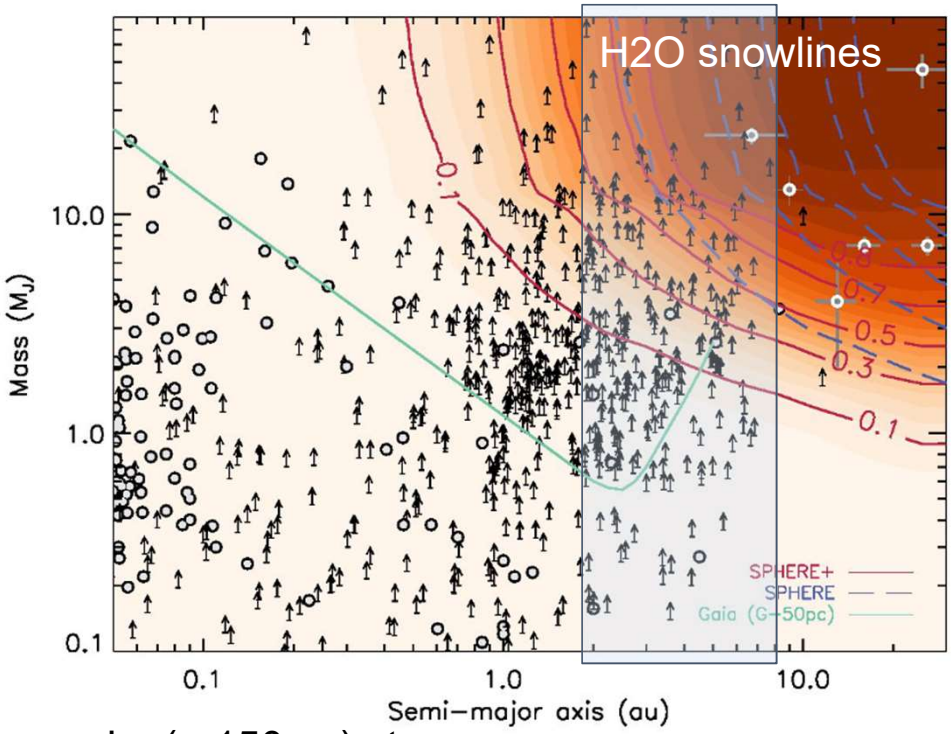
Science Cases – Main Extension

SC-Exoplanets: Demographics down to the snow line



Known exoplanets to date
exoplanets.eu

Sample: Young (< 500 Myr), nearby (< 150 pc) stars
Synergies: RV & Gaia (DR3/DR4)

Sc. Req. 1: Deeper/Closer in contrast (10-5 at 100mas, 5σ) on bright (R < 9.5) targets at H-band

Trade-off (SAXO+):
2nd stage AO (3kHz) for IR,
RTC integrated solution,
new HODM?

SCIENCE/TECHNIAL REQUIREMENTS

- **sci.req 1: Acces the bulk of the young giant planet population down to the snow line**
  - **tech.req 1: increase bandwidth of AO system**

- **sci.req 2: Observe a large number of fainter (lower mass) stars**
  - **tech.req 2: operate WFS in NIR**

- **sci.req 3: Improve the level of characterization of exoplanetary atmospheres**
  - **tech.req 3: increase resolution of spectroscopic facilities**

MAIN UPGRADES

- 2 main blocks:

PCS roadmap

- **2nd stage AO (SAXO+)**
  - Faster correction (1kHz -> 3kHz) + predictive control
    => contrast gain close to the star
  - IR WFS
    => increase coverage of red targets (protoplantes / protoplanetary disks)

Visitor instrument

- **Medium resolution IFS**
  - Boost resolution (R=50 -> R=3000-5000)
  - Small FoV

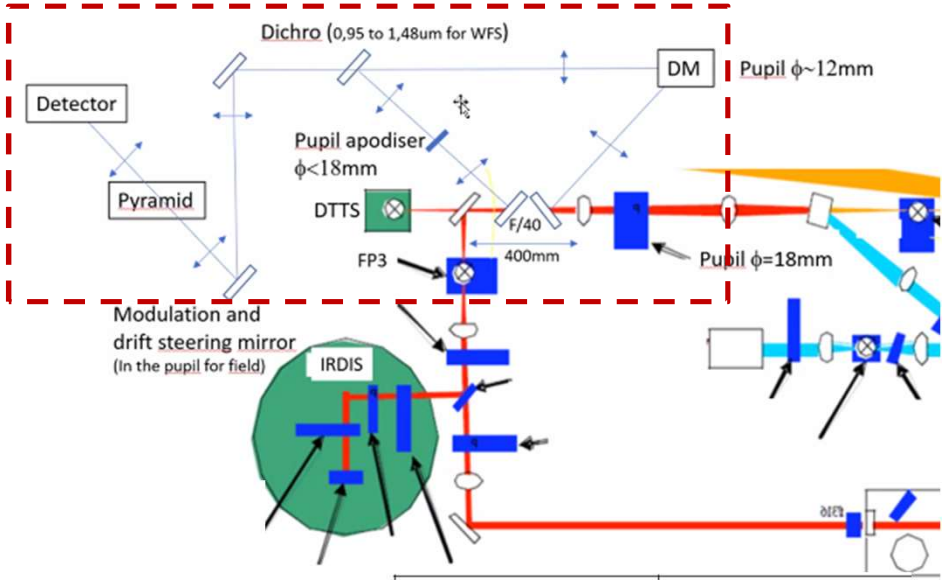
- Smaller upgrades
  - Coronagraphy, polarimetry, HIRISE…

MoU ESO-~~SPHERE~~SAXO+ (still under negotiation)

- based on STC recommendation to develop, implement, and test a second stage AO system
- proposition of collaboration between the "PCS roadmap" and SPHERE+ consortium
- common interest in terms of technology (in particular the RTC) and science goal
- **based on best effort, no commitment**. ESO provides: support for analysis, simulations, AIV at Paranal and VLT access, develop predictive control (ML based), access to GHOST (testbench at ESO), help in the review of the project
- **We provide a technological demonstrator. Need acceptance (new proposal) to open the mode if SAXO+ meets performance**

Going on-sky with MBRL? SAXO+ (2025+)

- SPHERE 2nd stage AO (CAO) within PCS R&D
  - Test new control approaches on-sky
  - Proposal, not yet approved or formalized
  - Fast (> 3kHz) PWS using CRED One (Saphira)
  - BMC 24x24 or 32x32 DM
  - Goal objective: offer to community after

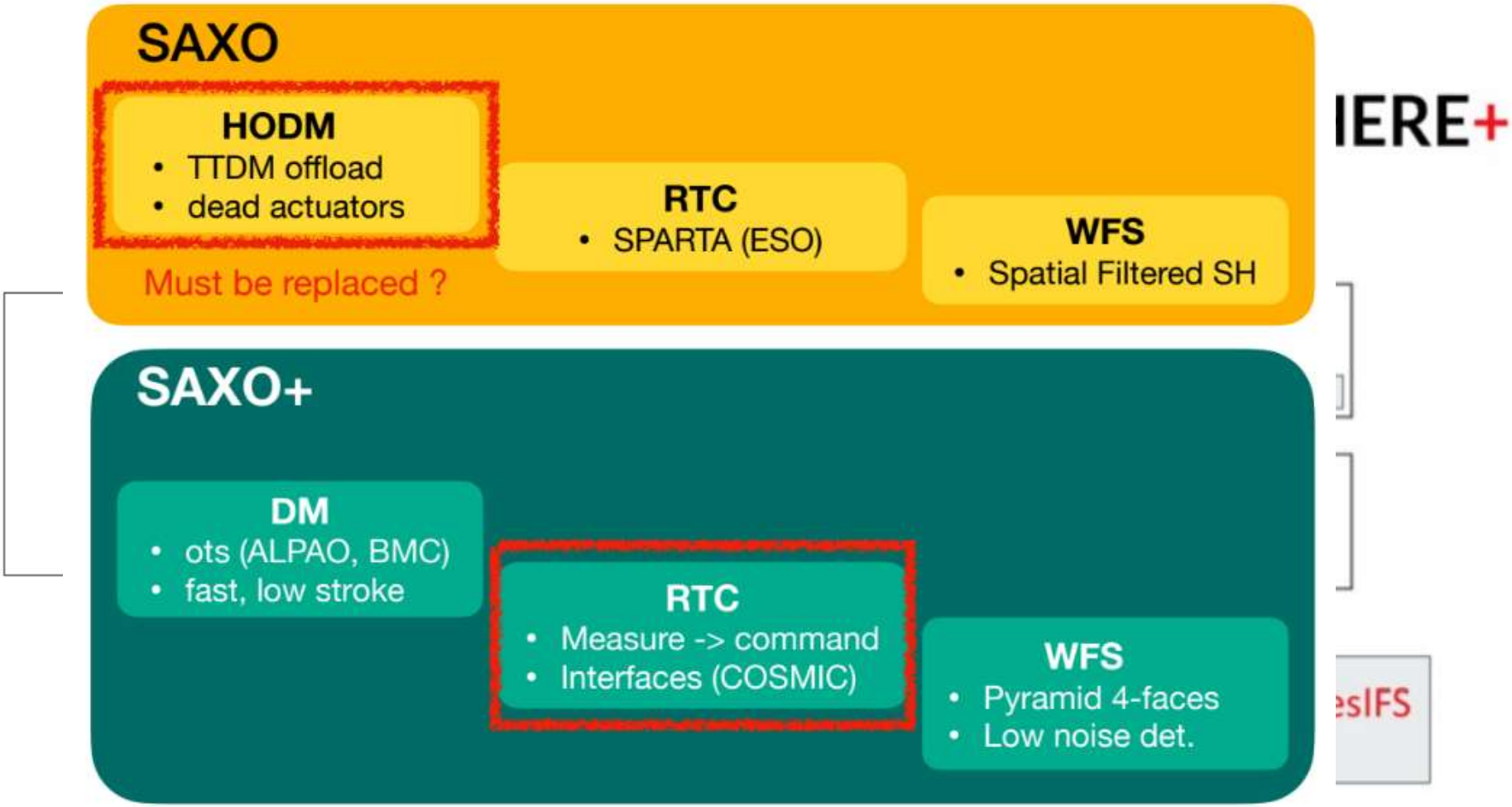


Adaptive Optics WP
AO system lead : F. Vidal (LESIA)
AO scientist : F. Cantalloube (LAM)

System analysis / global Simulation E. Gendron (LESIA)	WFS perf. T. Fusco (LAM)	ICS A. Baruffolo (OAPD)	AO Calibrations M. Langlois (CRAL)	Control algorithms : M. Tallon (CRAL) - direct approach: F. Vidal (LESIA) - iterative approach: E. Thiébaut (CRAL) - machine learning : M. Kasper (ESO)	
Science Trade off J. Milli (IPAG)	Opto Meca E. Stadler (IPAG) / E. Diolaiti (OAB)	WFS detector IR F. Wildi (Obs. Geneva)	RTC platform D. Gratadour (LESIA)	Focal plane sensing J. Mazoyer (LESIA)	AIT (LESIA)

Timeline	SAXO+
Oct 2021	concept phase
Apr 2022	
Oct 2022	
Apr 2023	procurement, AIT
Oct 2023	
Apr 2024	
Oct 2024	
Apr 2025	AIV, 1st light

IMPLEMENTATION

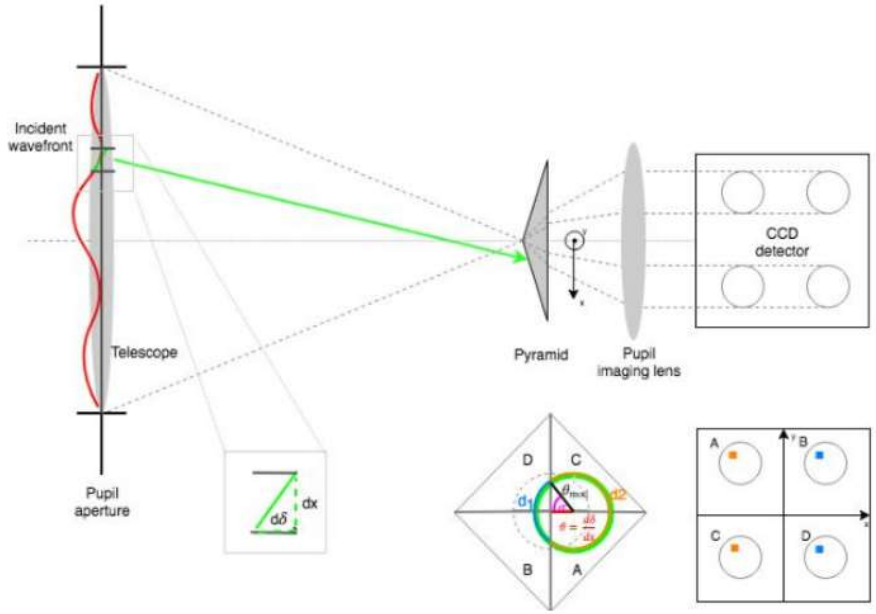


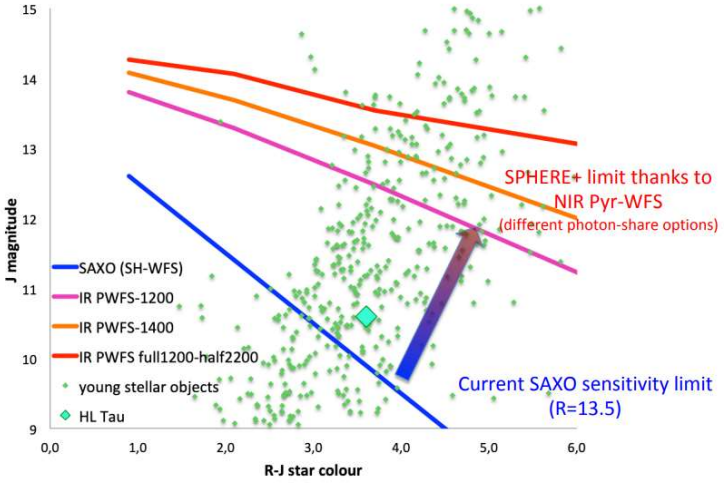
WaveFront Sensor type:

Current baseline: Pyramid WFS

+ uses less pixels than a SH.
+ better overall wavefront sensitivity w.r.t SH
+ less sensitive to aliasing (> perf at high flux)
+ lower noise propagation. (> limit mag at low flux)
+ becoming mature thanks to others instruments (FLAO, SCExAO, MICADO, HARMONI, METIS, ++, …)

- chromatic (=> double pyramid)
- small linear regime (=> modulate the PSF)
- cannot handle large NCPAs





Near IR => NIR WFS detector:

Current baseline: First light C-RED one.

++ 320x256 pixels J, H, K detector >80% QE in H,K bands
++ well suited for PYR WFS
++ high speed 3.5kHz speed @ full frame.
++ already available camera.

? cryostats modification

=> cool down the entire WFS i.e:

(Modulation mirror) + Field stop + Pyramid + Pupil imaging lens + detector.

=> modification of the C-red cryostat (???)
optical design => where to put the cold stop since no pupil is usually needed in the Pyramid WFS core…

2nd stage deformable mirror:

Current baseline: Boston micromachines 32x32/24x24 actuators
MEMS technology

++ already available
++ high control speed and high mecanical resonnance
++ well knowns DMs
++ compact…

-- limited stroke (=! versions…)
-- non linear command (electrostatic shape)
-- ...but sometimes too small aperture

DM Models	Total Actuator Count *	Actuator Count Across Aperture	Physical Stroke (µm)	Wavefront Stroke (µm)	Aperture (mm)	Pitch (µm)	Mechanical Response (small step, 10% - 90%) (µs)	Digital Update Rate: Standard (kHz)	Digital Update Rate: High Speed (kHz)	Approximate Inter Coupling
Multi-C-1.5	137	13	1.5	3.0	3.60	300	<20	2	100	15%
Multi-3.5	140	12	3.5	7.0	4.40	400	<75	2	100	13%
Multi-3.5-L	140	12	3.5	7.0	4.95	450	<75	2	100	13%
Multi-5.5	140	12	5.5	11.0	4.95	450	<100	2	100	22%
492-S-0.6	492	24	0.6	1.2	6.90	300	<20	60	n/a	15%
492-S-1.0	492	24	1.0	2.0	9.20	400	<75	60	n/a	13%
492-1.5	492	24	1.5	3.0	6.90	300	<20	45	60	15%
492-3.5	492	24	3.5	7.0	9.20	400	<75	45	60	13%
492-5.5	492	24	5.5	11.0	10.35	450	<100	45	60	22%
648-5.5	648	28	5.5	11.0	12.75	450	<100	45	60	22%
Kilo-CS-0.6	952	34	0.6	1.2	9.90	300	<20	60	n/a	15%
Kilo-CS-1.0	952	34	1.0	2.0	13.20	400	<75	60	n/a	13%
Kilo-C-1.5	952	34	1.5	3.0	9.90	300	<20	45	60	15%
Kilo-C-3.5	952	34	3.5	7.0	13.20	400	<75	45	60	13%
2K-1.5	2040	50	1.5	3.0	19.60	400	<40	30	n/a	15%
2K-3.5	2040	50	3.5	7.0	19.60	400	<75	30	n/a	13%
3K-1.5	3063	62	1.5	3.0	18.30	300	<20	16	n/a	15%
4K-3.5	4092	64	3.5	7.0	25.20	400	<75	16	n/a	13%

PROPOSED MPIA CONTRIBUTION

Task	Description	Responsible	Time	Units
AO Simulations	• Prerequisite: Existing COMPASS config for SPHERE+ (tbc LESIA) • Introduce METIS reconstructor (Zonal VDM) • Comparative case study wrt ◦ Standard performance ◦ Impact of LWE ◦ Impact of TBD	M. Feldt H. Steuer	2022-2023	1.0 FTE
Pyramid Prism	• Review procurement specs • handle contact with WZW (attempt others again if necessary) • Receive prism • handle characterization / verification of pyramid	TBD	2023	50k€ 0.5FTE
Control Electronics	TBD	L. Mohr	2024-2025	1.0 FTE
Fibre coupling study for IFU	• Study of optimal design of IFU fibre link ◦ Evaluating technologies, throughput, Field of View etc ◦ New novel concepts (printed reformatters, dithered lenslets) • Possibly: Full design of Sphere+ link • With money, could build link	R. J. Harris	2022-2023	R.J.H. gets 20% his time for own research. I would suggest 10% max goes on this