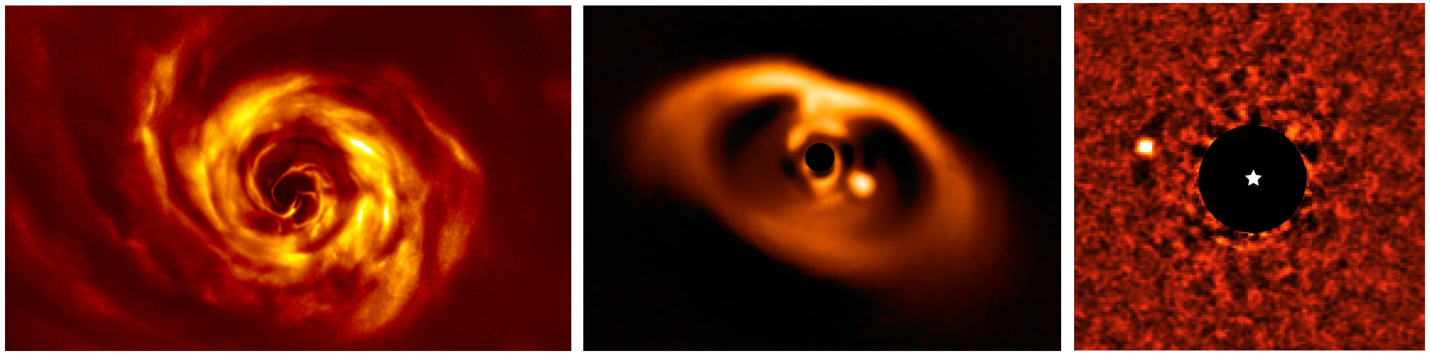
SPHERE+
Spectro Polarimetric High contrast Exoplanet REsearch uPgrade

SAXO+: a technology demonstrator and science precursor for PCS

from very young to young exoplanetary systems ...



Anthony Boccaletti (LIRA, Obs. Paris)

on behalf of the SAXO+ consortium

G. Chauvin, M. Langlois, E. Diolaiti, M. Loupias, G. Barbary, M. Feldt, M. Tallon, F. Ferreira, E. Stadler, S. Rochat, O. Boebion, M. N'Diaye, G. Zins, F. Wildi, J. Milli, J. Mazoyer, L. Schreiber, C. Kulcsar, C. Bechet, H.F. Raynaud, I. Bernardino., M. Lombini, F. Cortecchia, R. Gratton, M. Kasper, C. Goulas, F. Vidal, P. Delorme, M. Bonnefoy, D. Segransan, R. Galicher, A. Vigan

INAF ISTITUTO NAZIONALE DI ASTROFISICA
ESO
IPAG Institut de Planétologie et d'Astrophysique de Grenoble
Max-Planck-Institut für Astronomie Heidelberg / Max Planck Institute for Astronomy Heidelberg
CRAL CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON
INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech
PlanetS National Centre of Competence in Research
LIRA Observatoire de Paris | PSL
LAGRANGE
LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

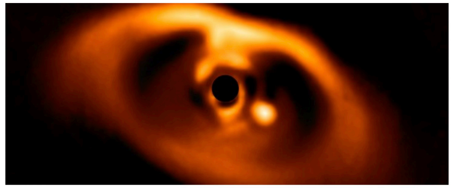
SPHERE+ motivations

eso1821 — Science Release

First Confirmed Image of Newborn Planet Caught with ESO's VLT

Spectrum reveals cloudy atmosphere

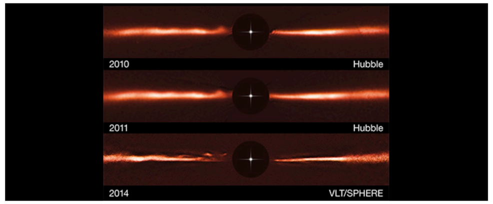
2 July 2018 Mueller et al. 2018



Mysterious Ripples Found Racing Through Planet-forming Disc

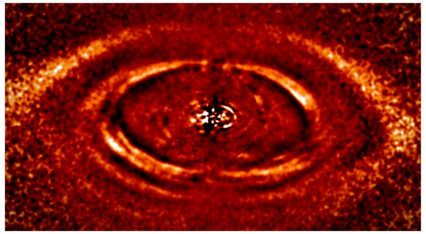
Unique structures spotted around nearby star

7 October 2015

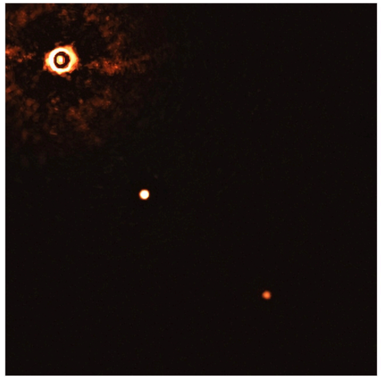


Boccaletti et al. 2015

Boulevard of broken rings Perrot et al. 2016



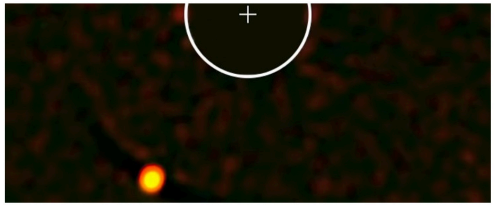
First ever image of a multi-planet system around a Sun-like star Bohn et al. 2020



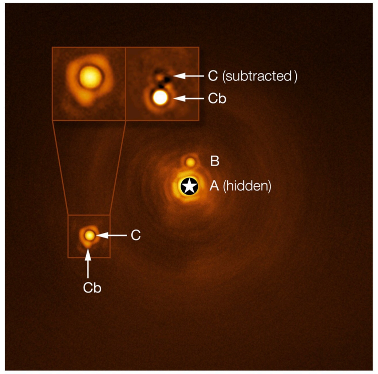
Announcement

ESO's SPHERE Unveils its First Exoplanet

6 July 2017 Chauvin et al. 2017



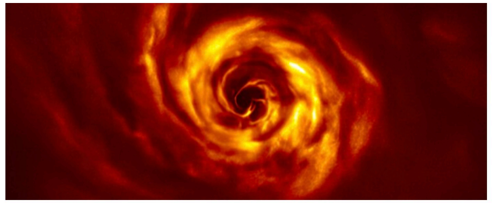
New planetary-mass object found in quadruple system Chomez et al. 2023



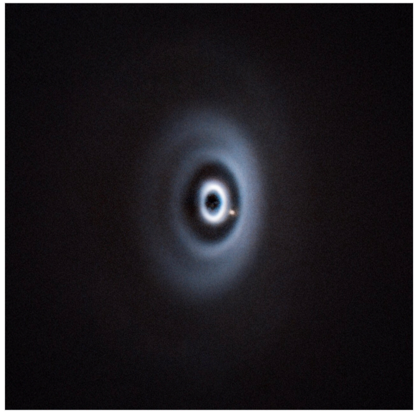
ESO Telescope Sees Signs of Planet Birth

The Twist Marks the Spot

20 May 2020 Boccaletti et al. 2020

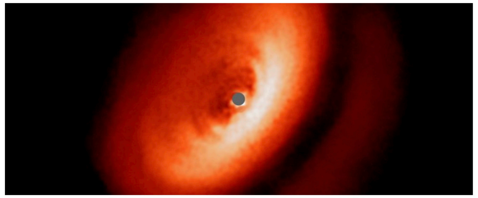


A very hungry planet Van Capelleveen al. 2025

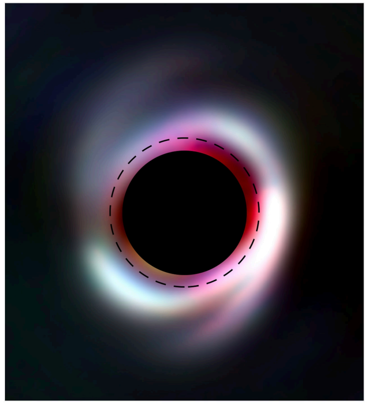


SPHERE Reveals Fascinating Zoo of Discs Around Young Stars

11 April 2018 Avenhaus et al. 2018

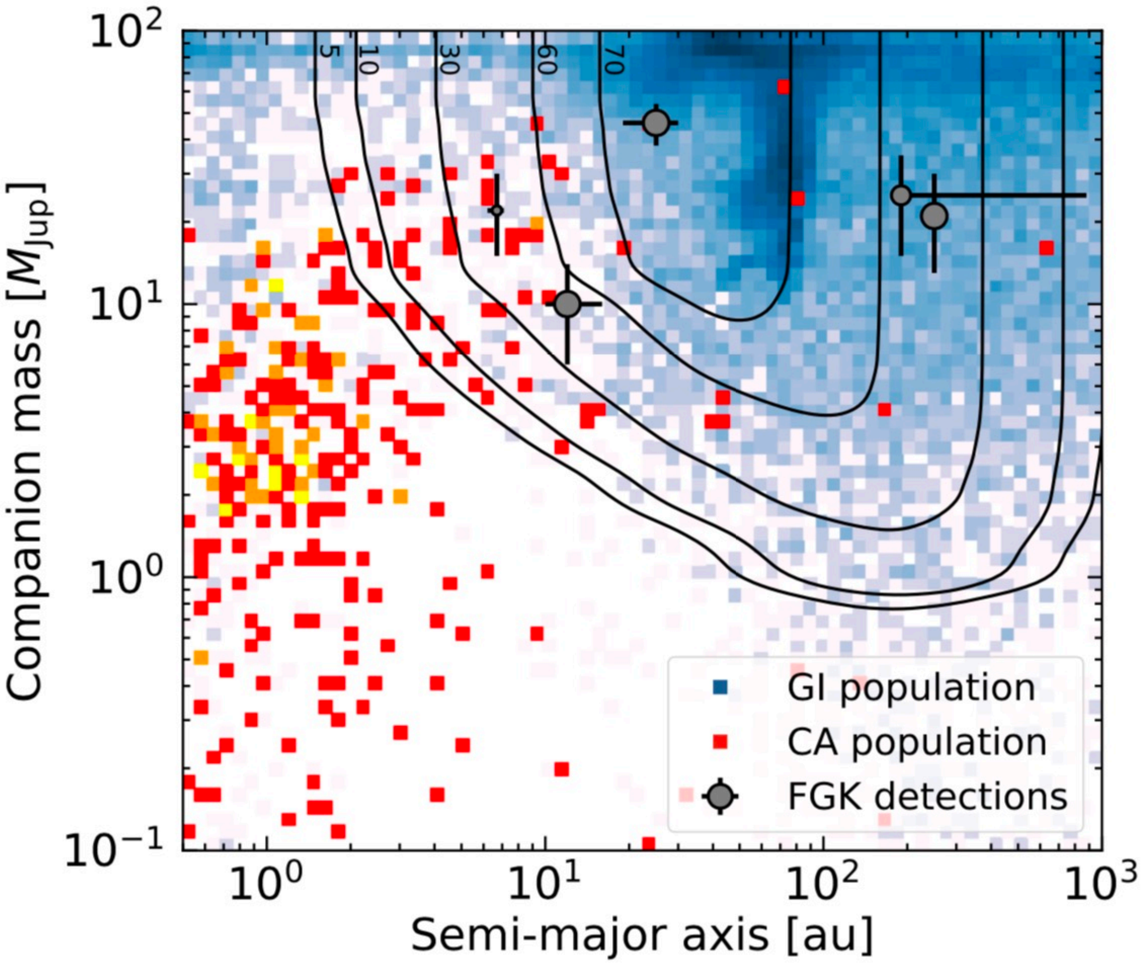


SPHERE reveals spiral disc around nearby star



Wagner et al. 2015

SPHERE contrast limits translate to:
> few Mass of Jupiter
> few tens of AU



Vigan et al. 2020, Desidera et al. 2021, Langlois et al. 2021, Chomez et al. 2025

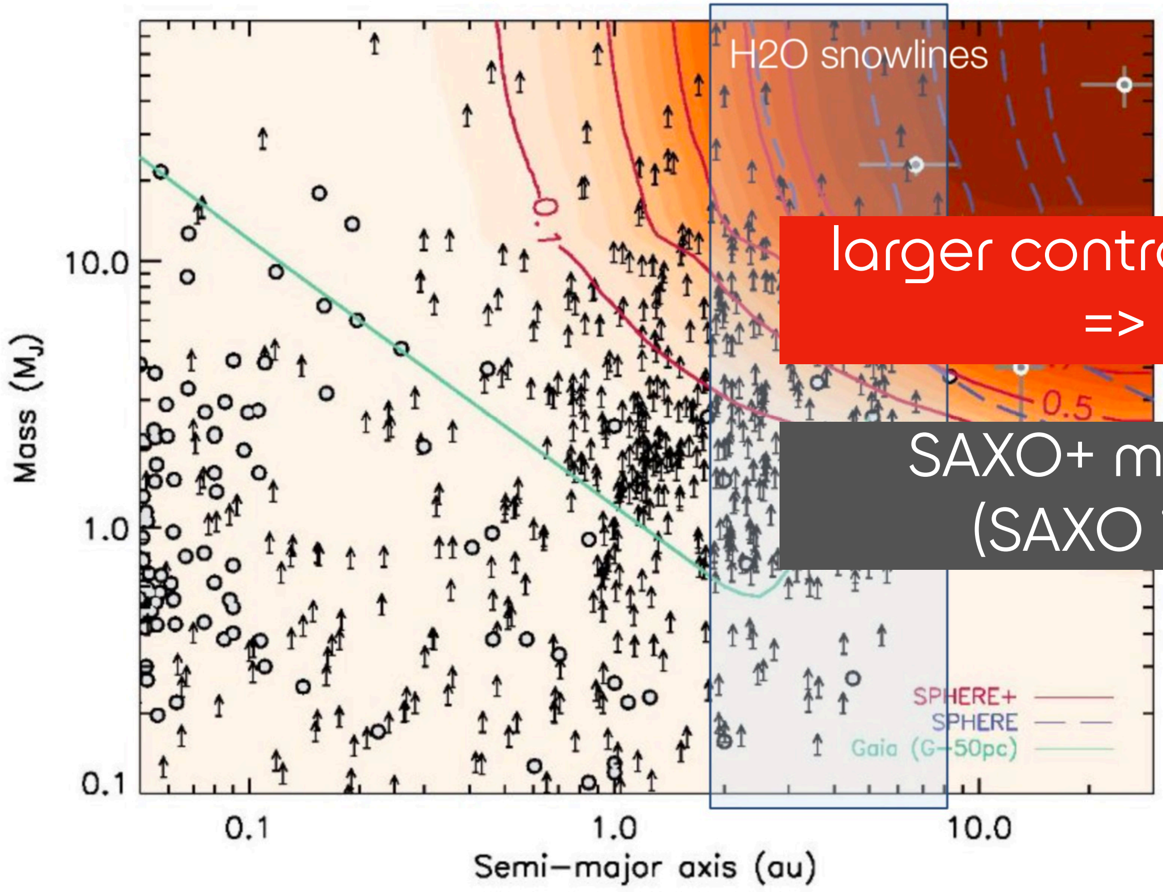
SAXO+ science drivers

Synergy: RV, Gaia

SPHERE+
Spectro Polarimetric High contrast Exoplanet REsearch uPgrade

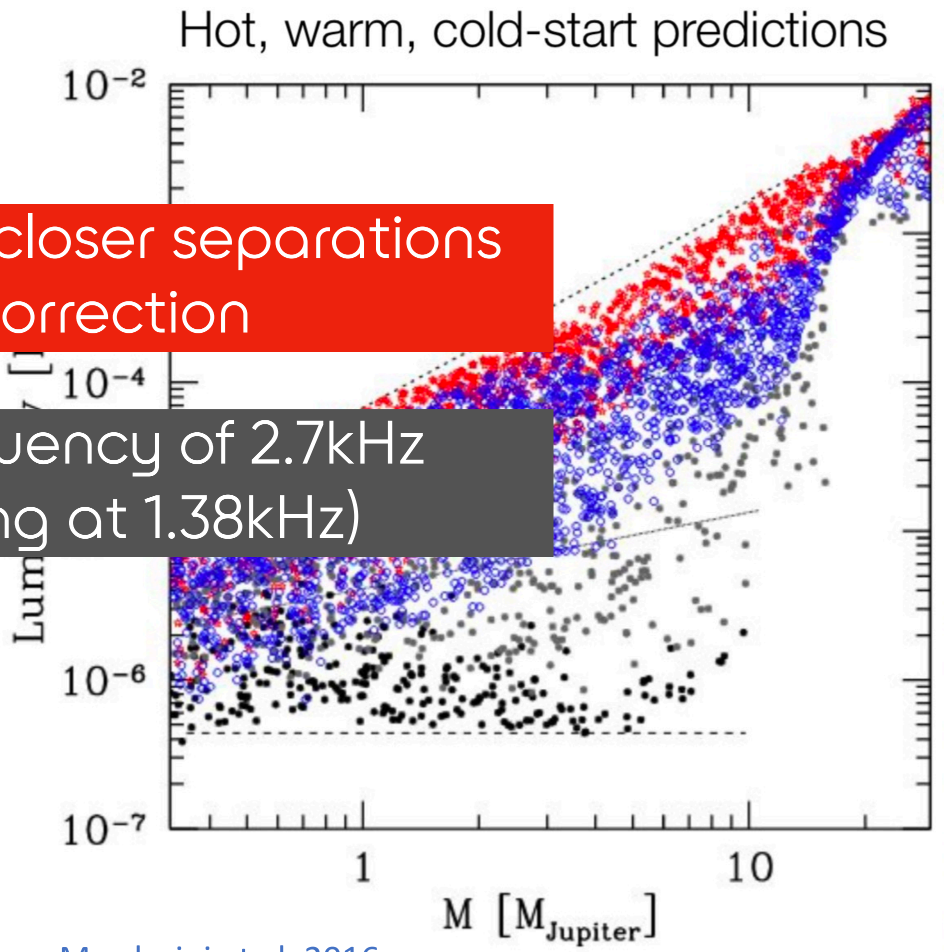
1. DEEPER/CLOSER: to access the bulk of RV/Gaia giant planet population

1.1 Demographics down to the snowline



sample: young (<500Myr), nearby (<150pc) stars

1.2 Mass luminosity relation for young Jupiters



Mordasini et al. 2016

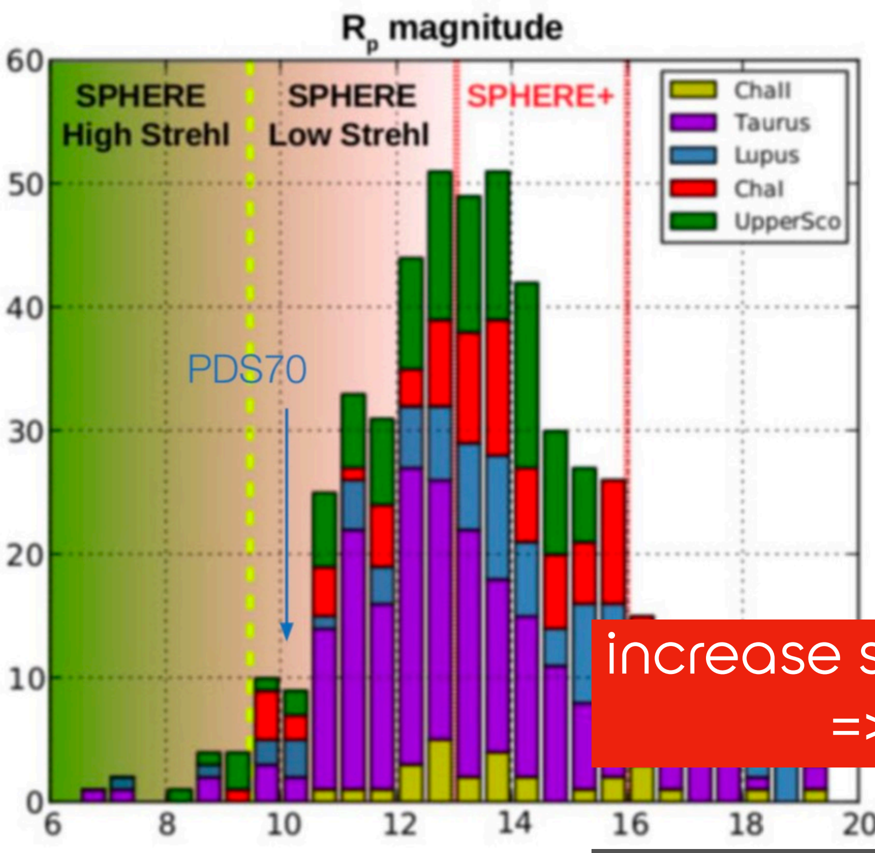
larger contrasts at closer separations
=> faster correction

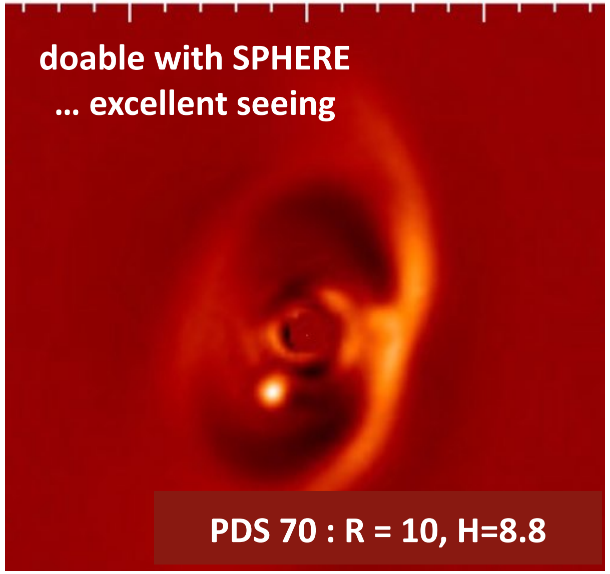
SAXO+ max frequency of 2.7kHz
(SAXO is running at 1.38kHz)

SAXO+ science drivers

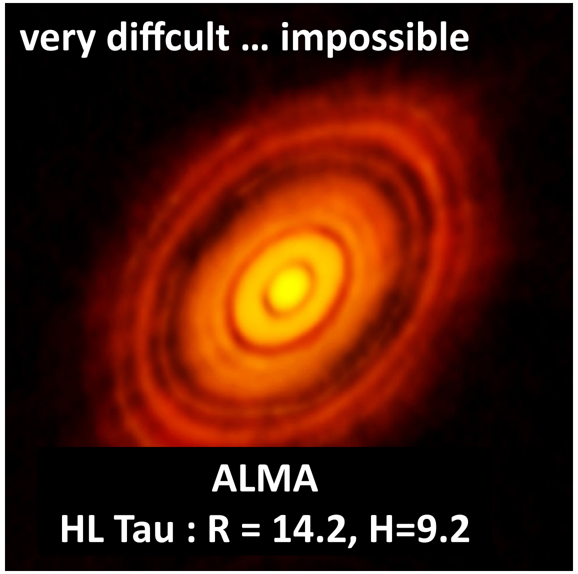
Synergy: ALMA, JWST

2. FAINTER/REDDER: architecture of young planetary systems

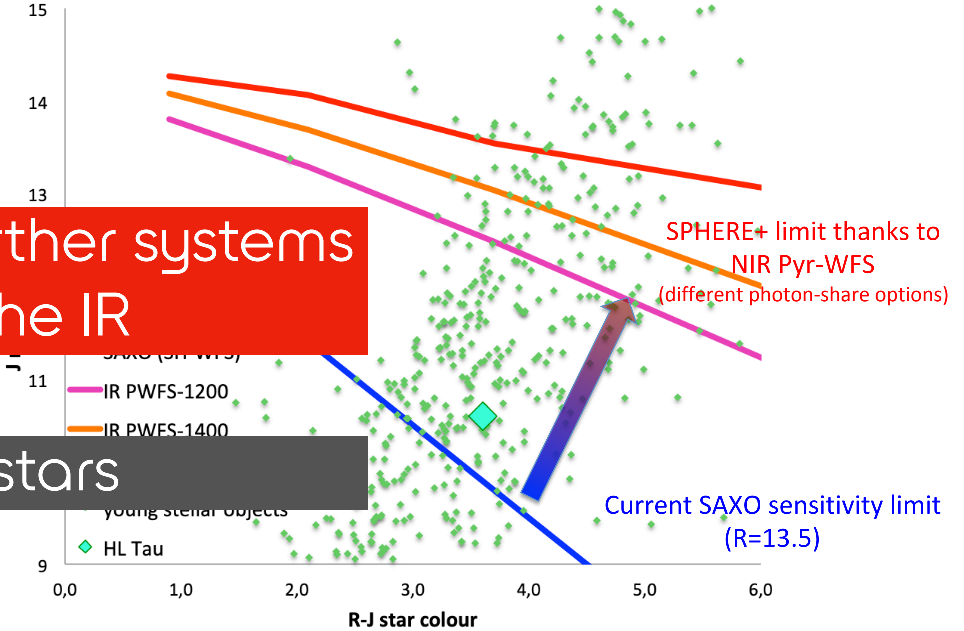




Mueller et al. 2018



ALMA part. et al. 2014



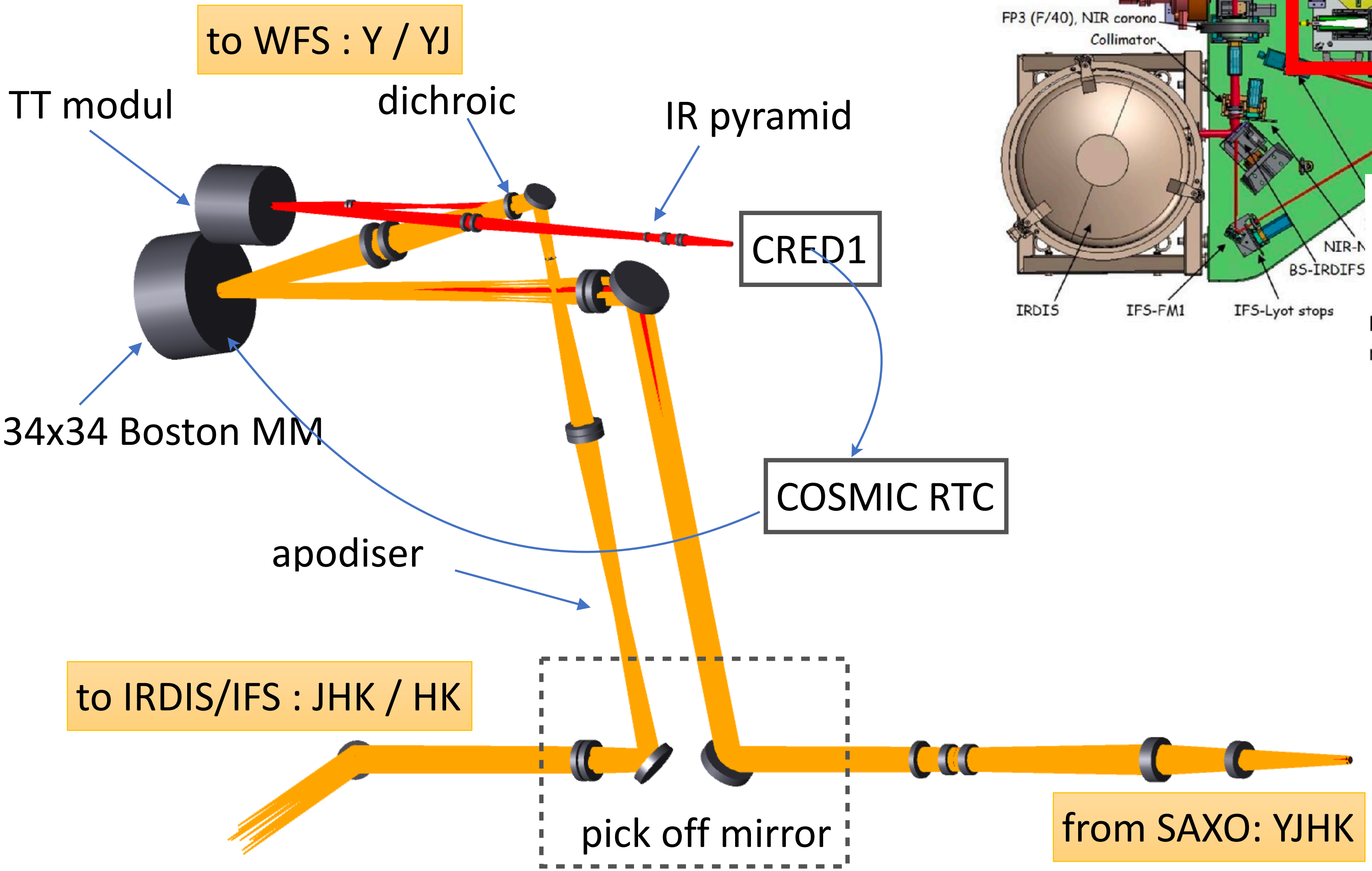
increase statistics to younger/farther systems
=> improve sensitivity in the IR

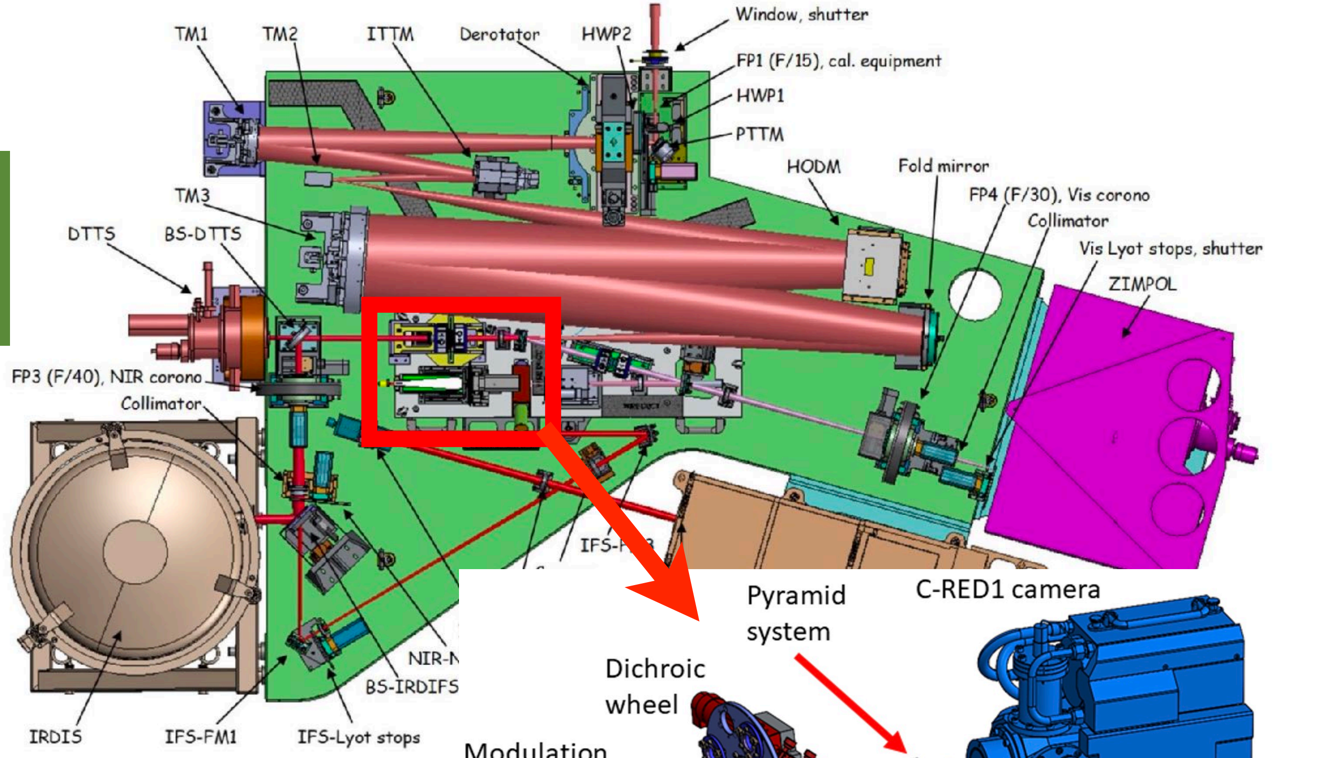
sample: faint members of SF

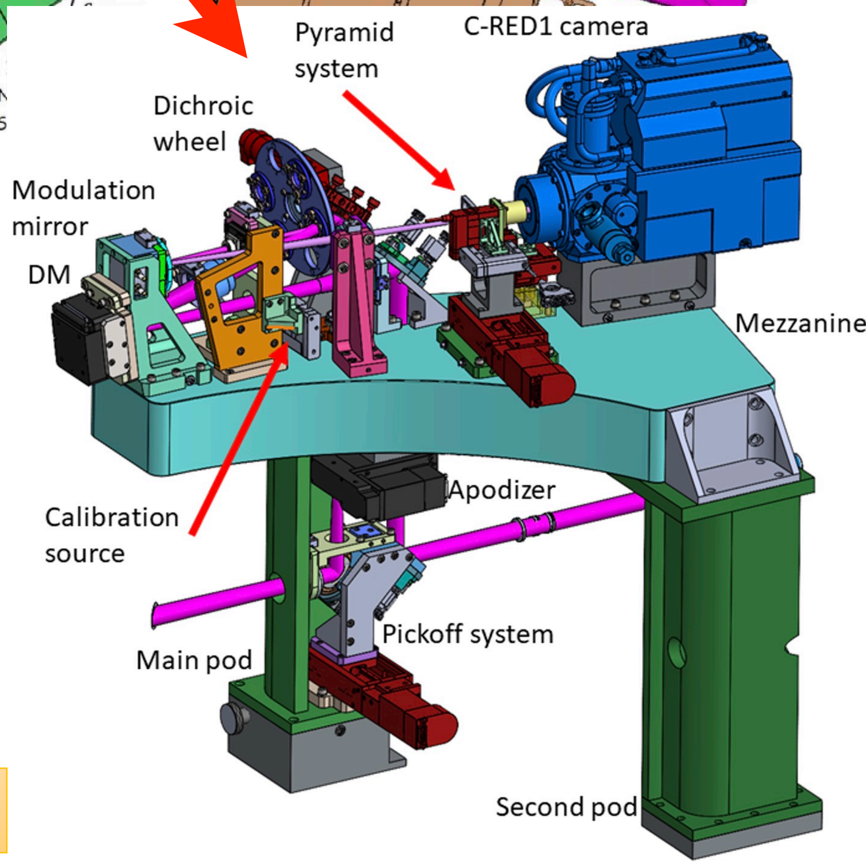
SAXO+ will observe J<12 stars

SAXO+ concept

Technical goals (in preparation for PCS):
- demonstrate the gain in contrast with a cascaded AO system
- compare several control algorithms in same conditions
- Improve NCPA correction at low freq. (FP-WFS)







Frequency optimisation 1st vs. 2nd stages

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PAOLA simulations

max frequency on 1st/2nd stage

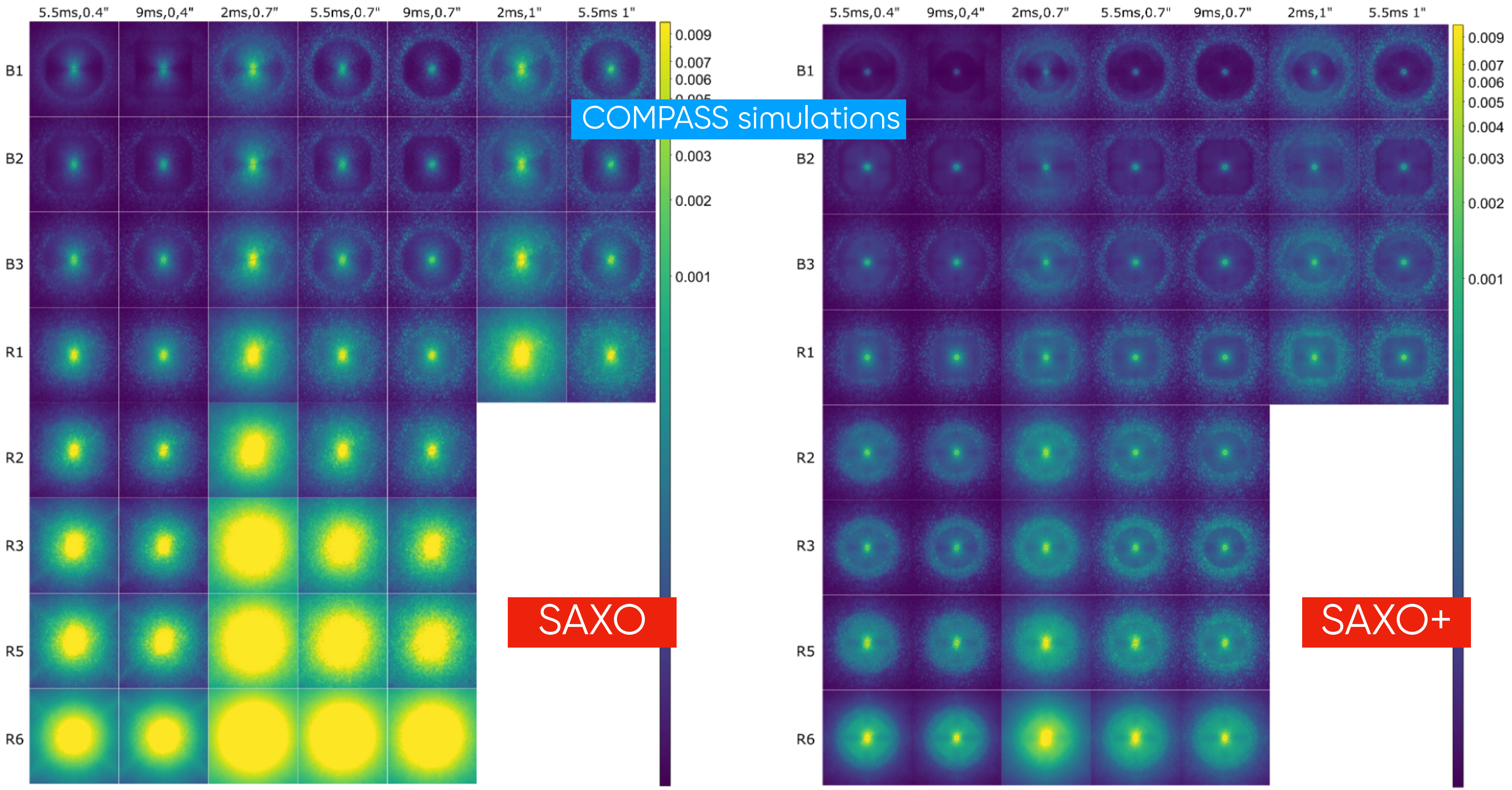
very low frequency on the 1st stage

2 simulation approaches

- **semi-analytical PAOLA** : error budget, 2nd stage frequency optimisation
- **E2E COMPASS** : optimisation combined to semi-analytical + global parametric exploration
- SAXO/SAXO+ parameters: frequencies and gains 1st/2nd stage, modulation amplitude …

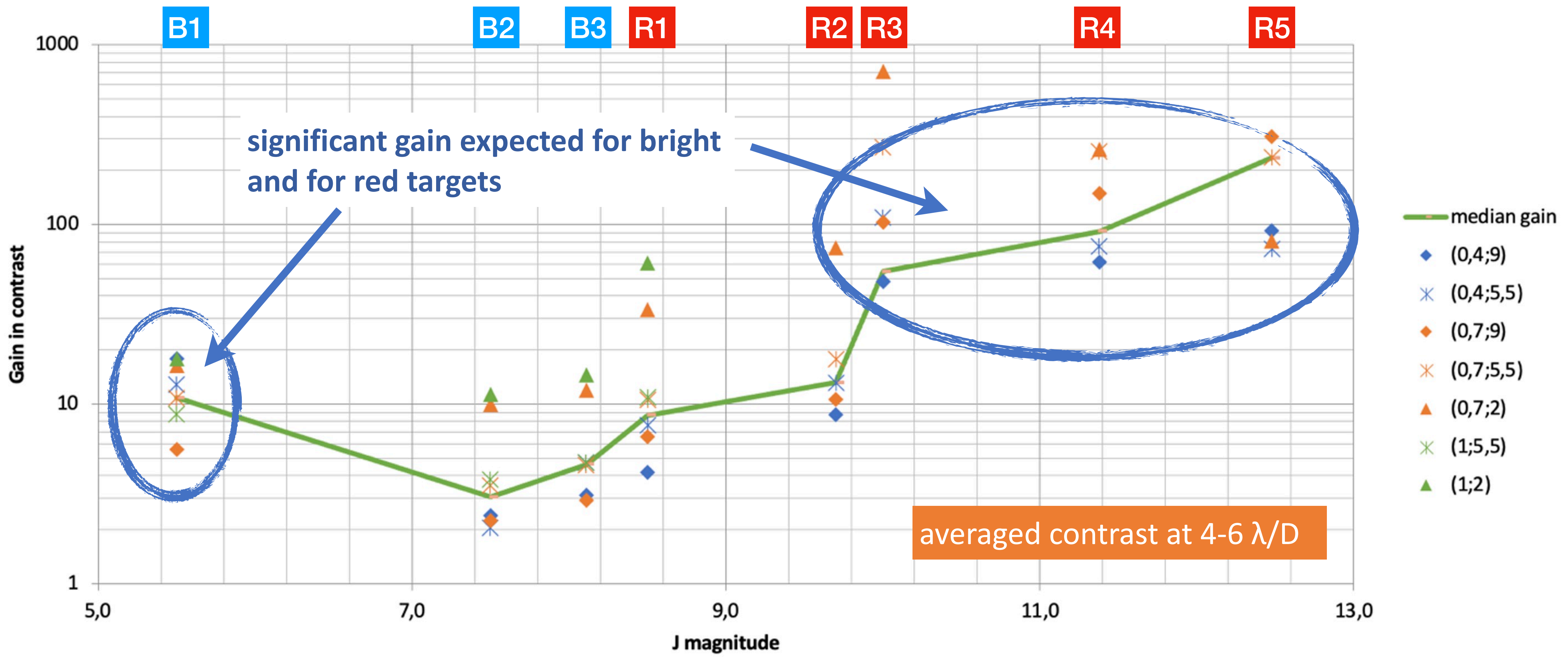
Science Case	Seeing = 0.4"			Seeing = 0.7"			Seeing = 1.0"		
	τ_0=2ms	τ_0=5.5ms	τ_0=9ms	τ_0=2ms	τ_0 =5.5ms	τ_0 = 9ms	τ_0=2ms	τ_0=5.5ms	τ_0=9ms
Bright-1 G=5, J=5	1380, 3000	1380, 3000	1380, 3000	1380, 3000	1380, 3000	1380, 3000	1380, 3000	1380, 3000	1380, 3000
Bright-2 G=7.6, J=7.2	1380, 3000	1380, 3000	1380, 2000	1380, 3000	1380, 2500	1380, 2000	1380, 3000	1380, 2500	1380, 1750
Bright-3 G=9.6, J=7.8	600, 3000	600, 2250	600, 1500	600, 3000	600, 2000	600, 1500	600, 3000	600, 2000	600, 1500
Red-1 G=11.9, J=8.5	300, 3000	300, 2000	300, 1500	300, 3000	300, 2000	300, 1500	300, 3000	300, 1750	300, 1250
Red-2 G=12.8, J=10.1	150, 2000	150, 1250	150, 750	150, 2000	150, 1250	150, 750	150, 2000	150, 1000	150, 750
Red-3 G=14.5, J=10.1	50, 2000	50, 1250	50, 750	50, 2000	50, 1250	50, 750	50, 2000	50, 1000	50, 750
Red-4 G=15.3, J=11.4	25, 1000	25, 500	25, 450	25, 1000	25, 500	25, 450	25, 1000	25, 500	25, 450
Red-5 G=16.8, J=12.5	10, 500	10, 300	10, 300	10, 500	10, 300	10, 300	10, 500	10, 300	10, 300

Coronagraphic images SAXO/SAXO+



Gain in contrast SAXO/SAXO+

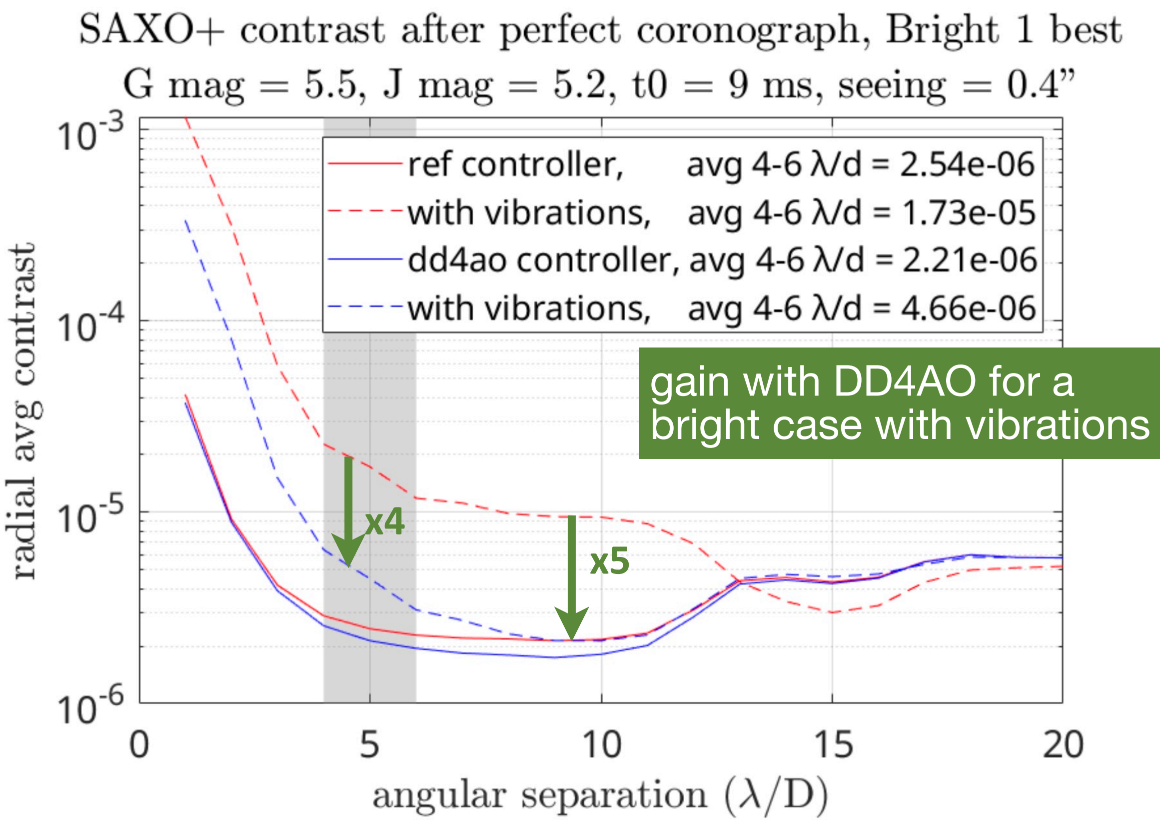
COMPASS E2E simulations



Control algorithms

- Baseline: two integrators in “cascade” (standalone)
  - REF – reference controller **=> scalar gains on 1st stage (SPARTA) - Optimized Modal Gains on 2nd Stage (COSMIC)**
- Other controllers (1st stage integrator + …)
  - *Linear + machine learning*, standalone or standalone+
    - LQGSPH / LQGSPH+ – Linear Quadratic Gaussian for SPHERE (IOGS)
    - DD4AO / DD4AO+ – Data driven for AO (Obs. Geneva)
    - TAO1 / TAO1+ – Themis AO number 1 (CRAL)
  - *Nonlinear + neural networks*, standalone
    - PO4AO – Policy Optimization for AO (ESO)
    - DSRL – Dual-stage Supervised & Reinforcement Learning (LIRA)

- Gain
  - important gain with vibrations
  - reduce DM stroke
  - tolerance in the tuning of the first stage
  - standalone+ (feedforward of the HODM commands) provides very limited gain

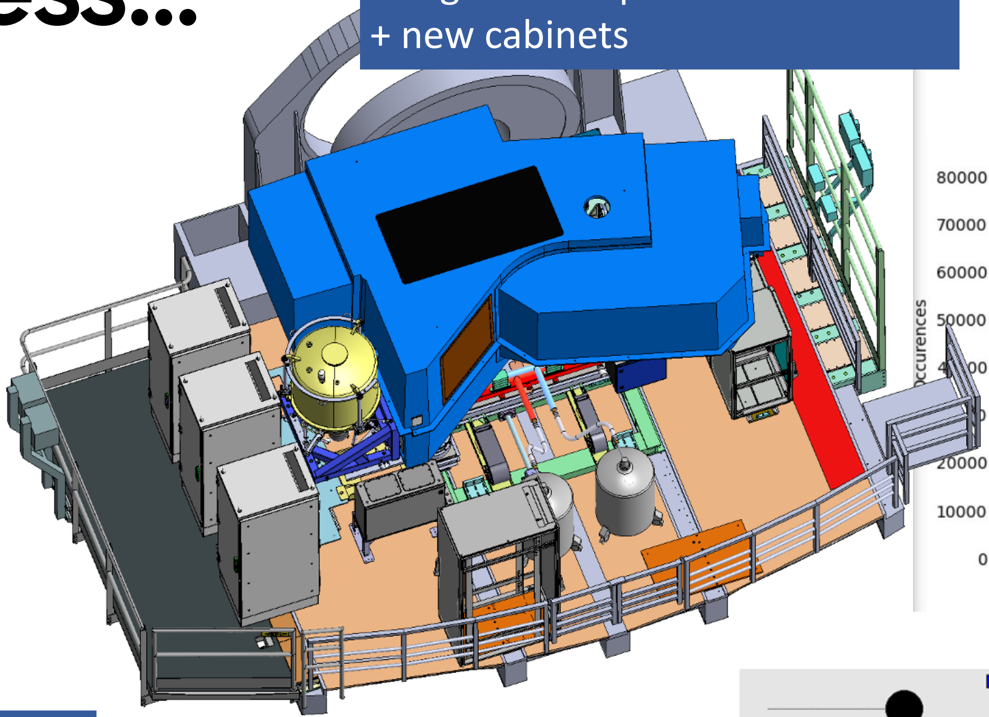


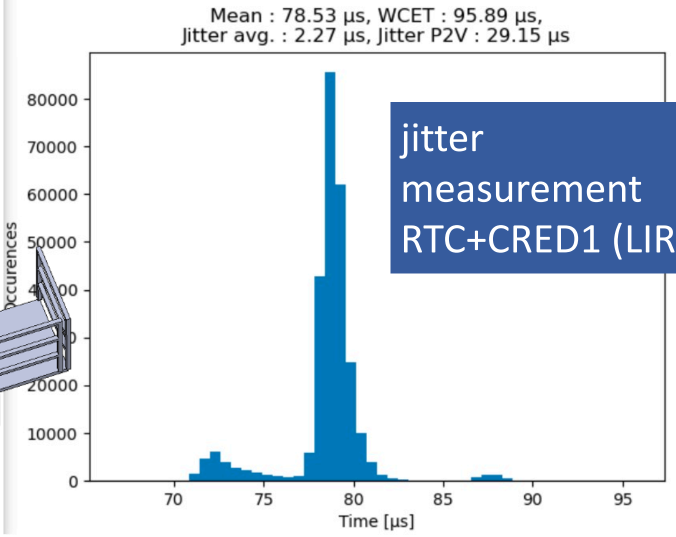
Activities in progress...

SPHERE+

mezzanine breadboard (IPAG)

design for the platform extension
+ new cabinets

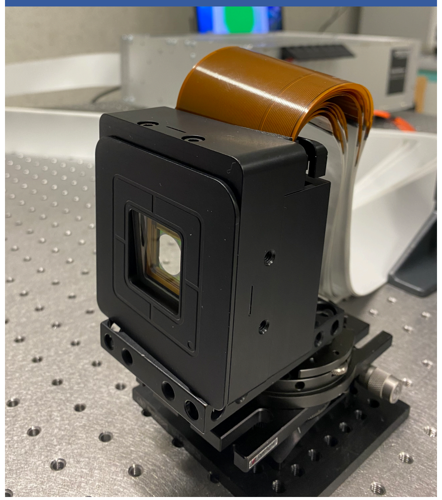


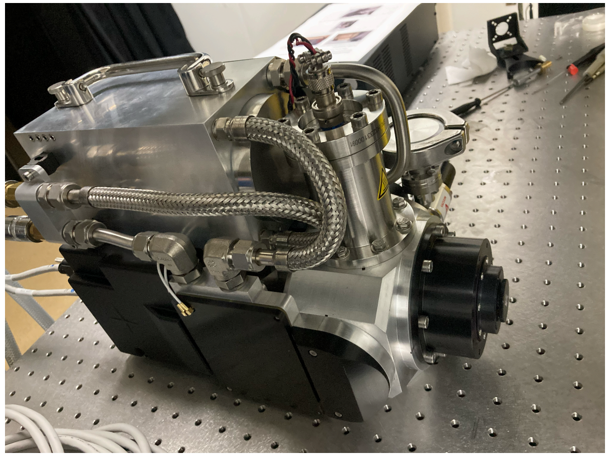


jitter
measurement
RTC+CRED1 (LIRA)

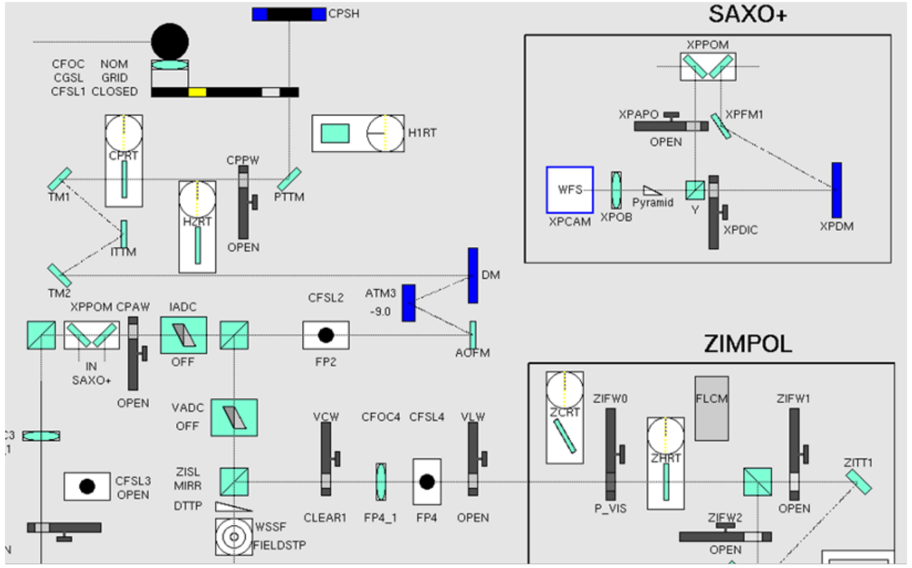
Gimbal mount of Pick off
mirror (IPAG)

34x34 BMM testing
(INAF)



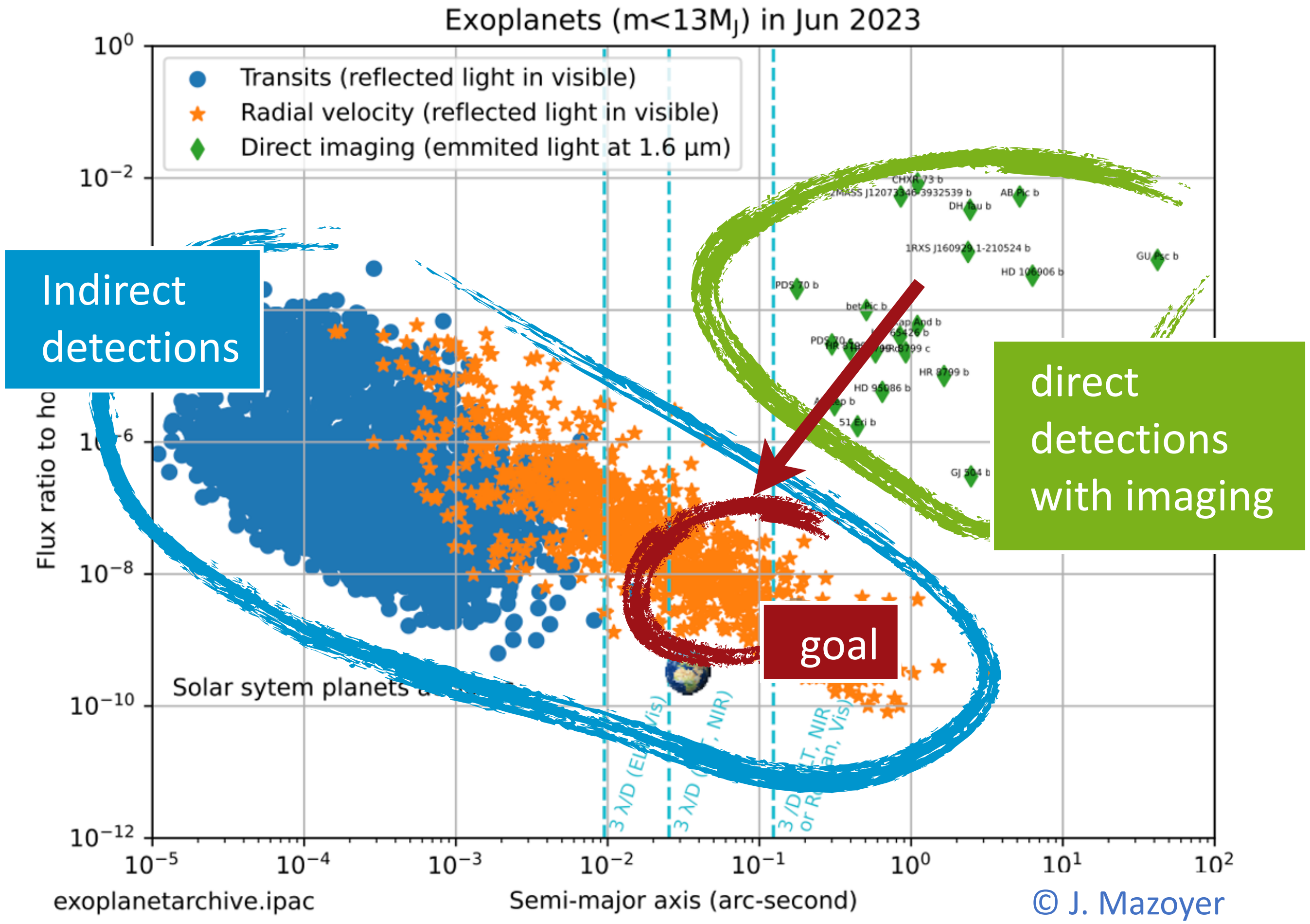


CRED1 WFS camera (U. Geneva,
Lagrange, LIRA)



synoptic SPHERE panel (Lagrange)

PCS @ ELT



Gain :
1-2 orders of mag in separation
2-3 orders of mag in contrast

- **Rocky planets**: detection, orbit determination, habitability - presence of (liquid) H_2O, biosignatures (O_2, CH_4)
- **Sub-Neptunes – Giant Planets**: characterization in reflected light, orbits, compositions
- **Planet formation**: Hα imaging, accreting Exoplanets in transitional disks
- **Young Giant** Exoplanets: photometric variability, Doppler imaging
- **Exomoons**: detection by RV, transits, imaging
- **Circumstellar disks**: ~5 mas resolution with 15 mas inner working angle

PCS R&D roadmap

started on Sep. 2024

ESO Technology Development Programme Manager
S. Leveque

Oversight Committee
Chair: tbd

Coordination
M. Kasper
S. Scheithauer

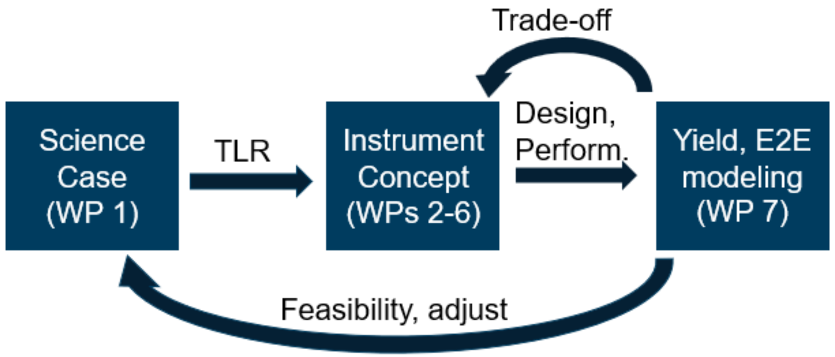
- **WP1: Science Case** — Gaël Chauvin, Silvano Desidera, Benjamin Charnay
- **WP2: Coro and WFC** — Sebastiaan Haffert, Axel Potier
- **WP3: Science Instruments** — Matthias Tecza, Emilio C. Molinari
- **WP4: XAO Concept** — Maud Langlois, Carlos Correia
- **WP5: XAO DM** — Stefan Stroebele
- **WP6: System Concept** — Emiliano Diolaiti, Eric Stadler, Laura Schreiber
- **WP7: Science Yield, E2E** — Oscar Carrion-Gonzalez, Arthur Vigan

+ INSU representatives:
M. Bonnefoy (IPAG)
P. Martinez (Lagrange)
A. Vigan (LAM)
A. Boccaletti (LIRA)

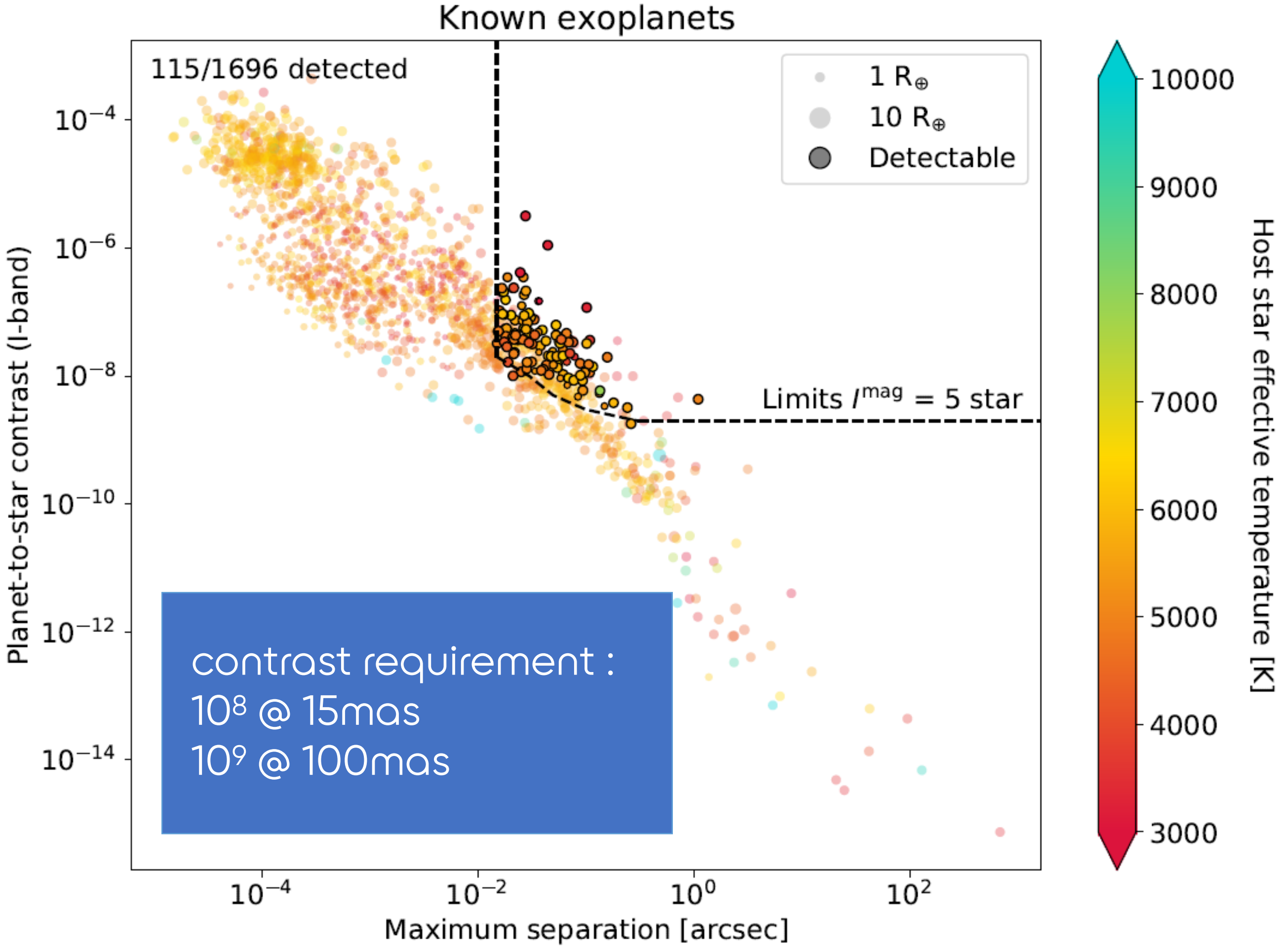
scientific animation / organisation ?

+ >140 contributors from the community !
Best effort, everyone can join

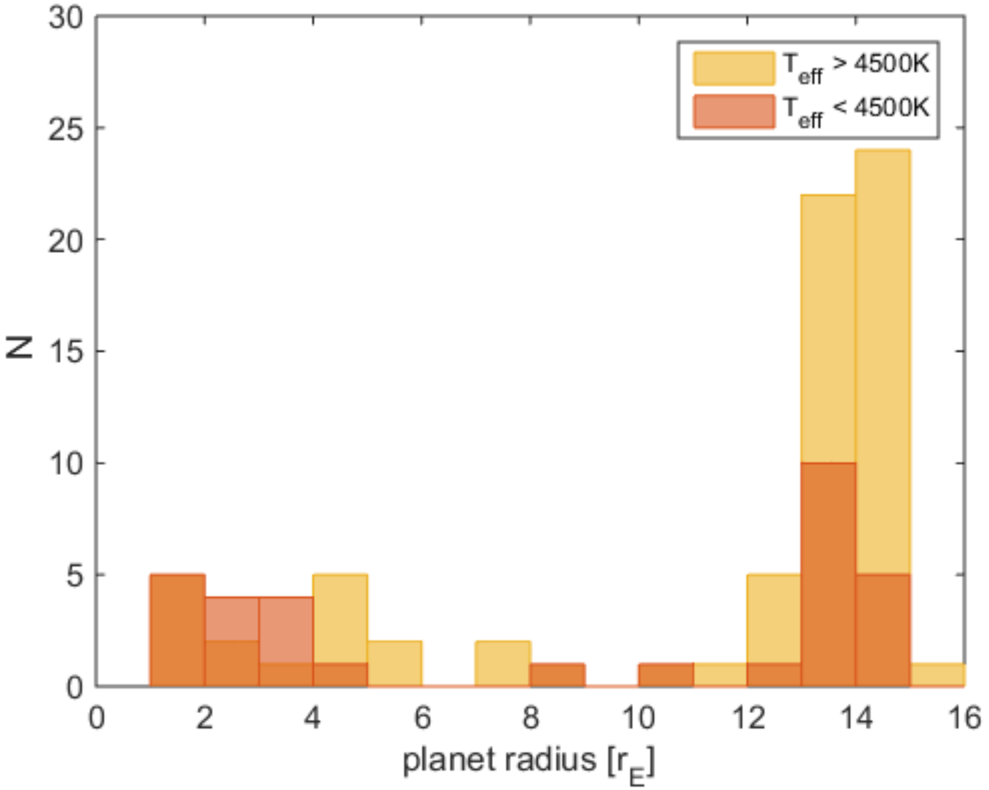
Interested ? ==> mkasper@eso.org



PCS detection performances



contrast requirement :
10^8 @ 15mas
10^9 @ 100mas



Exoplanet yield (already known planets) :

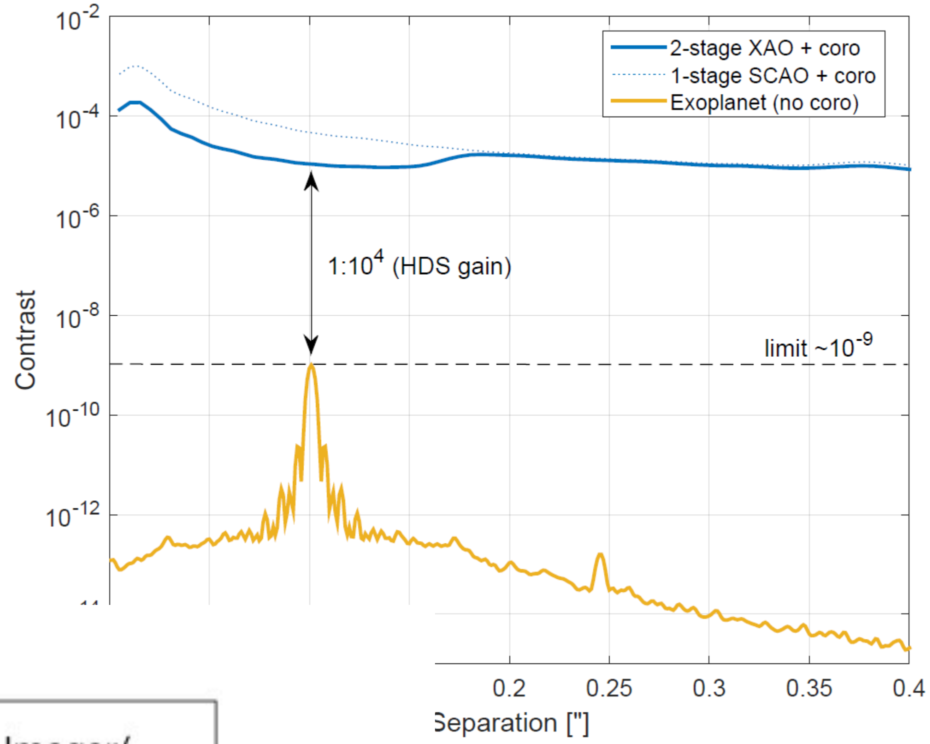
- ~ 10 Earth/Super Earths
- > 20 Sub Neptunes
- > 70 jovians

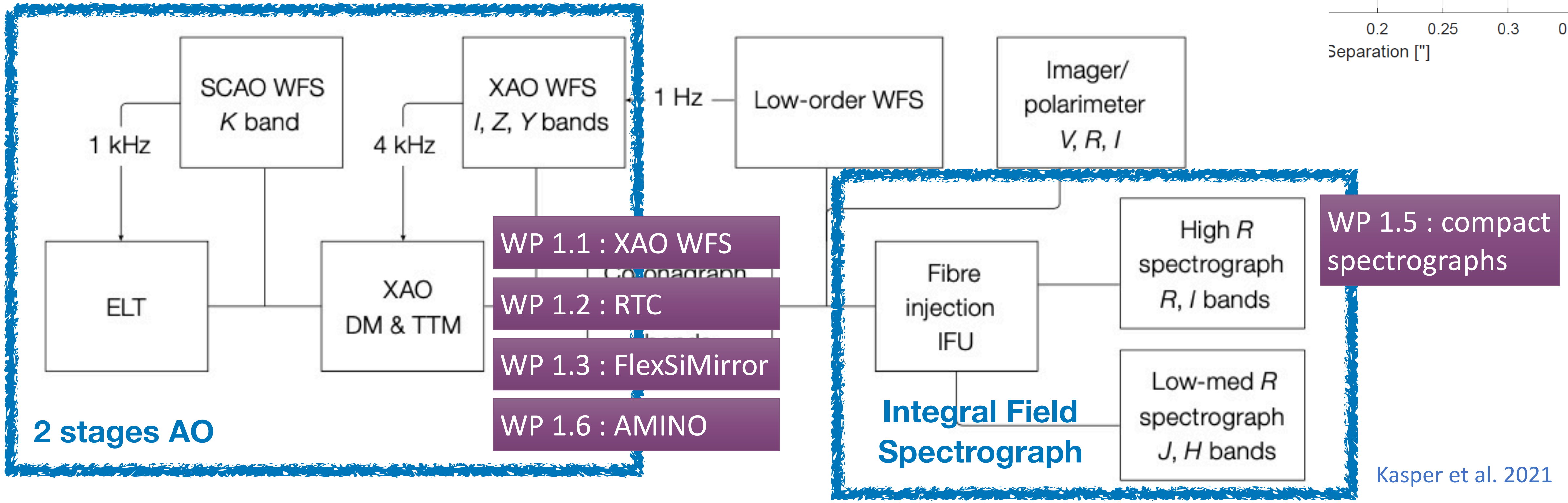
Simulation by Jens Kammerer

PCS design concept

- telescope size 8m => 39m : AO system complexity increases
- need to tackle "temporal delay error"

PCS will implement 3 solutions :
- faster AO : 1 to 4 kHz
- include prediction in the wavefront control (ML, RL)
- focal plane wavefront control (dark hole)





Kasper et al. 2021

Summary and next steps

- **SAXO+** will demonstrate key techniques/strategies for **PCS** on a routine basis
  - **cascaded AO** in extreme AO regime with visible SH + IR Pyr
  - optimized control algorithms (comparison vs. conditions)
  - focal plane wavefront control
- Procurement is ongoing. optics delivery is on critical path (delivery June/July 2026)
- First tests of opto-electro-mecanic @INAF-Bologna, **July 2026 => ~6 months**
- AO tests @CNRS-CRAL in **2027 => ~12 months**
- aim to be **on-sky by early 2028** (phased with PCS R&D roadmap and possible start of PCS phase A)
- **Demonstration phase on-sky** (part of the PCS roadmap) : commissionning 20 nights + 5n/semester for 3 years
- **Exploitation phase** if **SAXO+** meets performance. in open time (add. work, templates, pipeline, ETC, …)
- **PCS R&D roadmap is ongoing**
  - Timely for the french community to be involved
  - Crucial to determine future contributions when a phase A will start (~2030)