Direct characterization of young giant exoplanets at high spectral resolution

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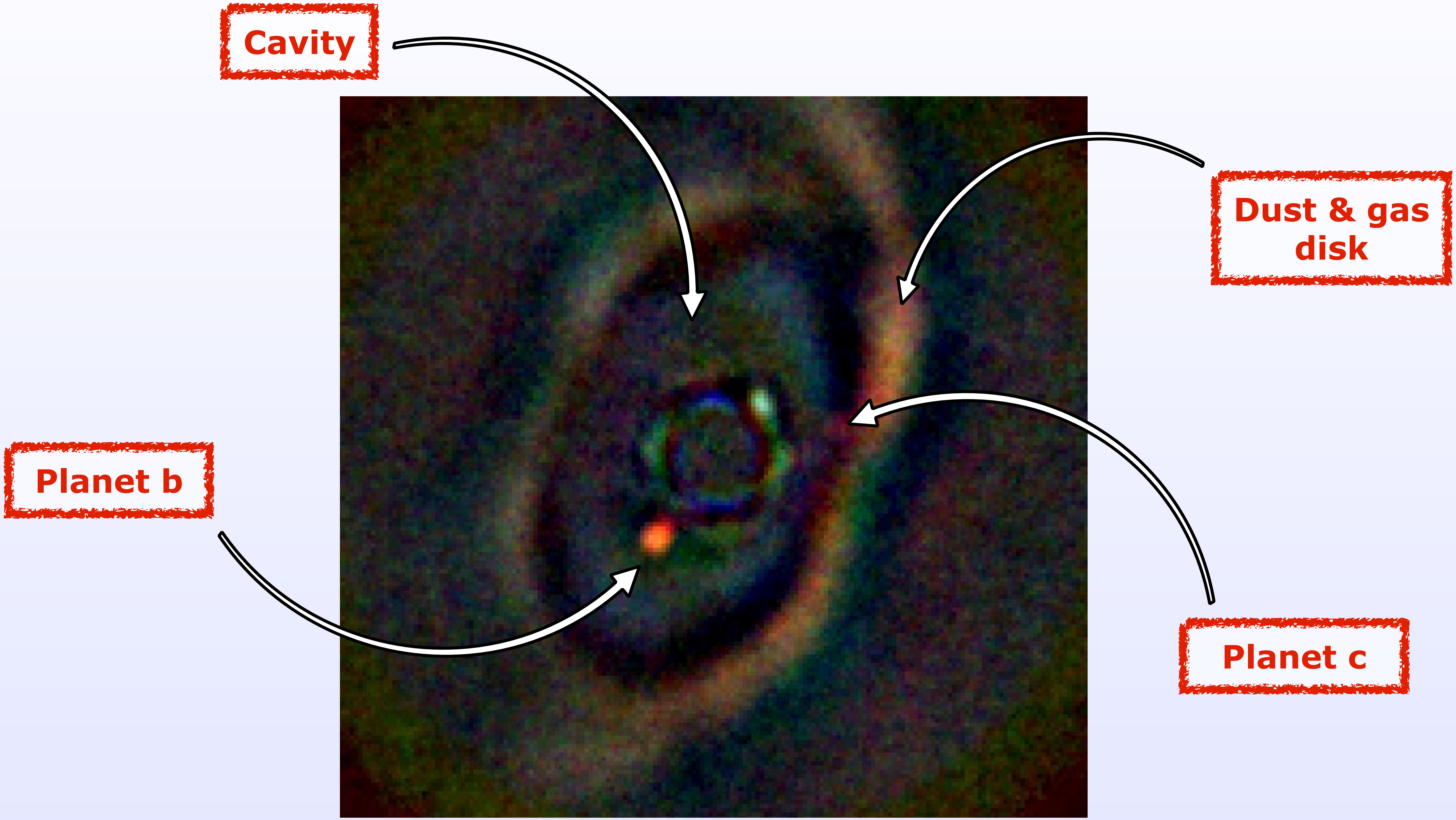
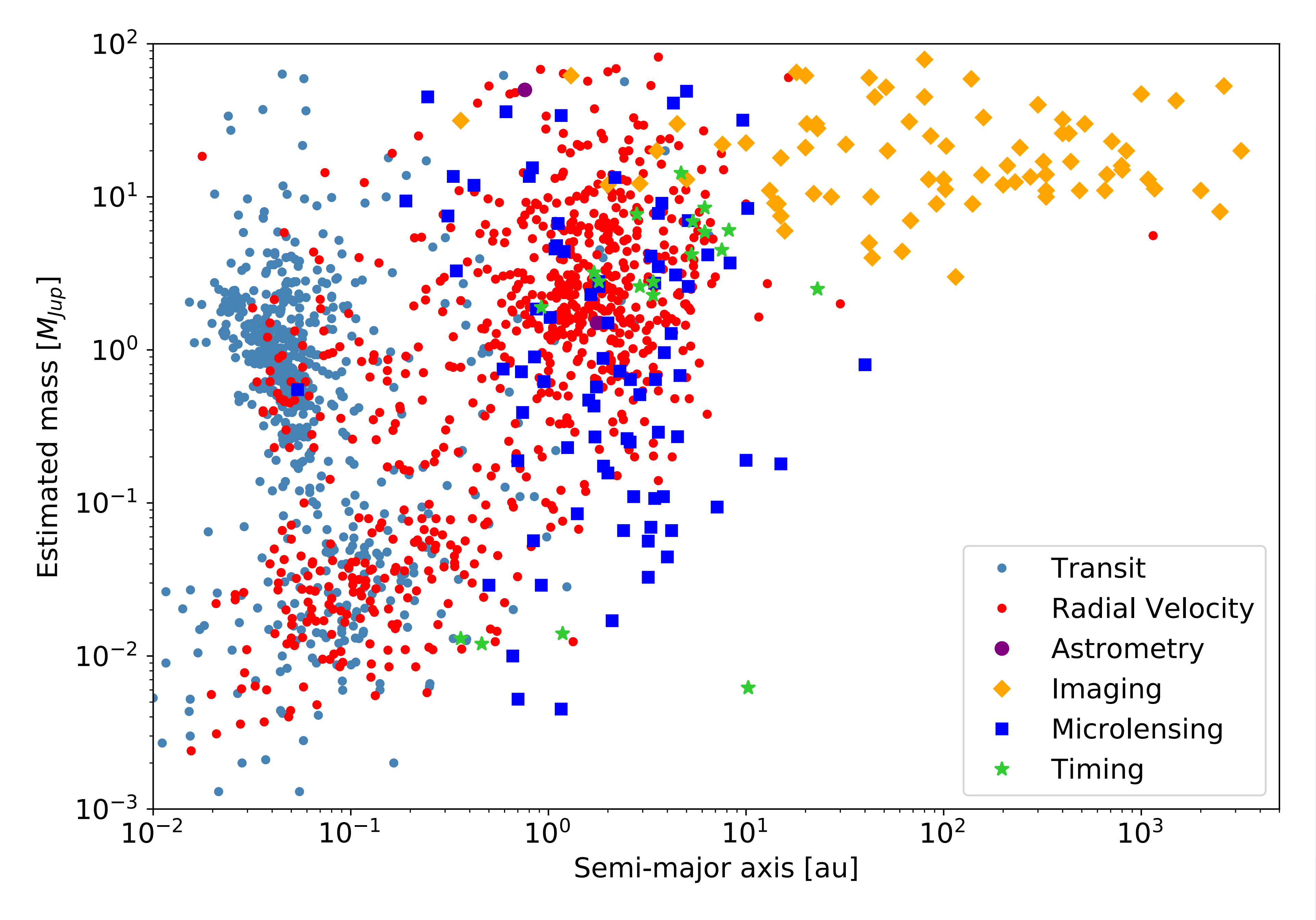
Direct imaging of exoplanetary systems



PDS 70 - Keppler et al. (2018)

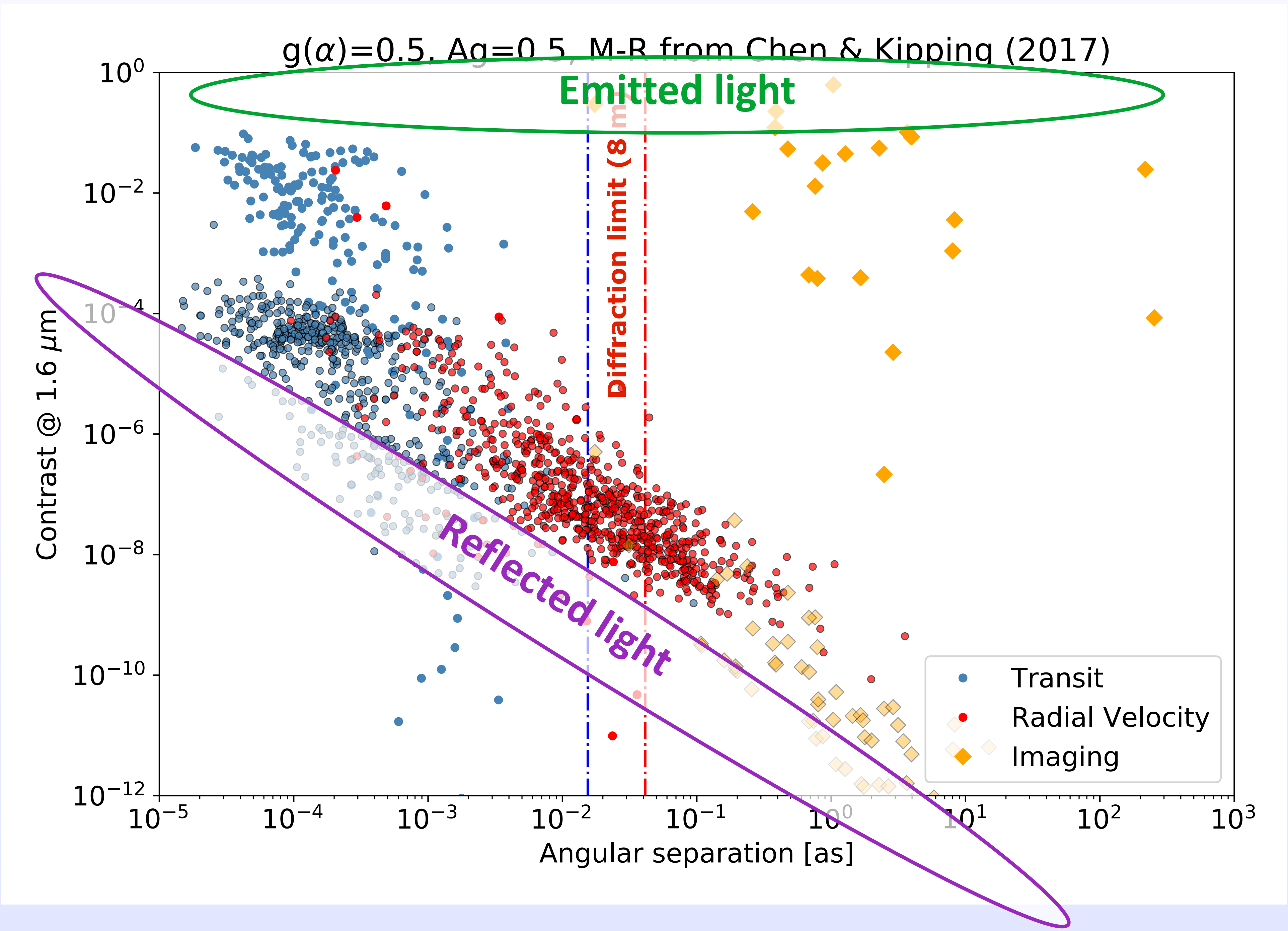
Direct imaging: the challenge

Physical units

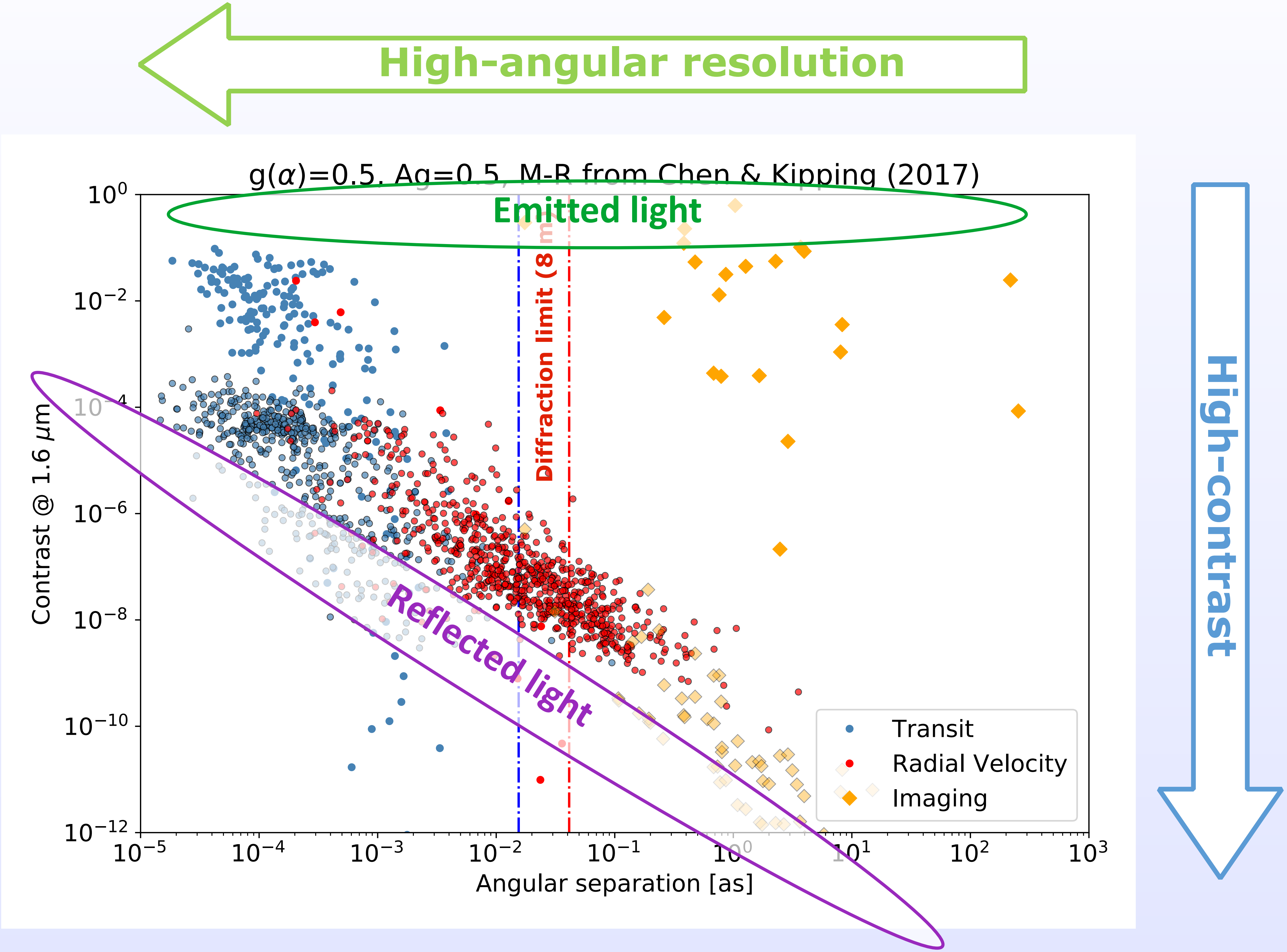


Direct imaging: the challenge

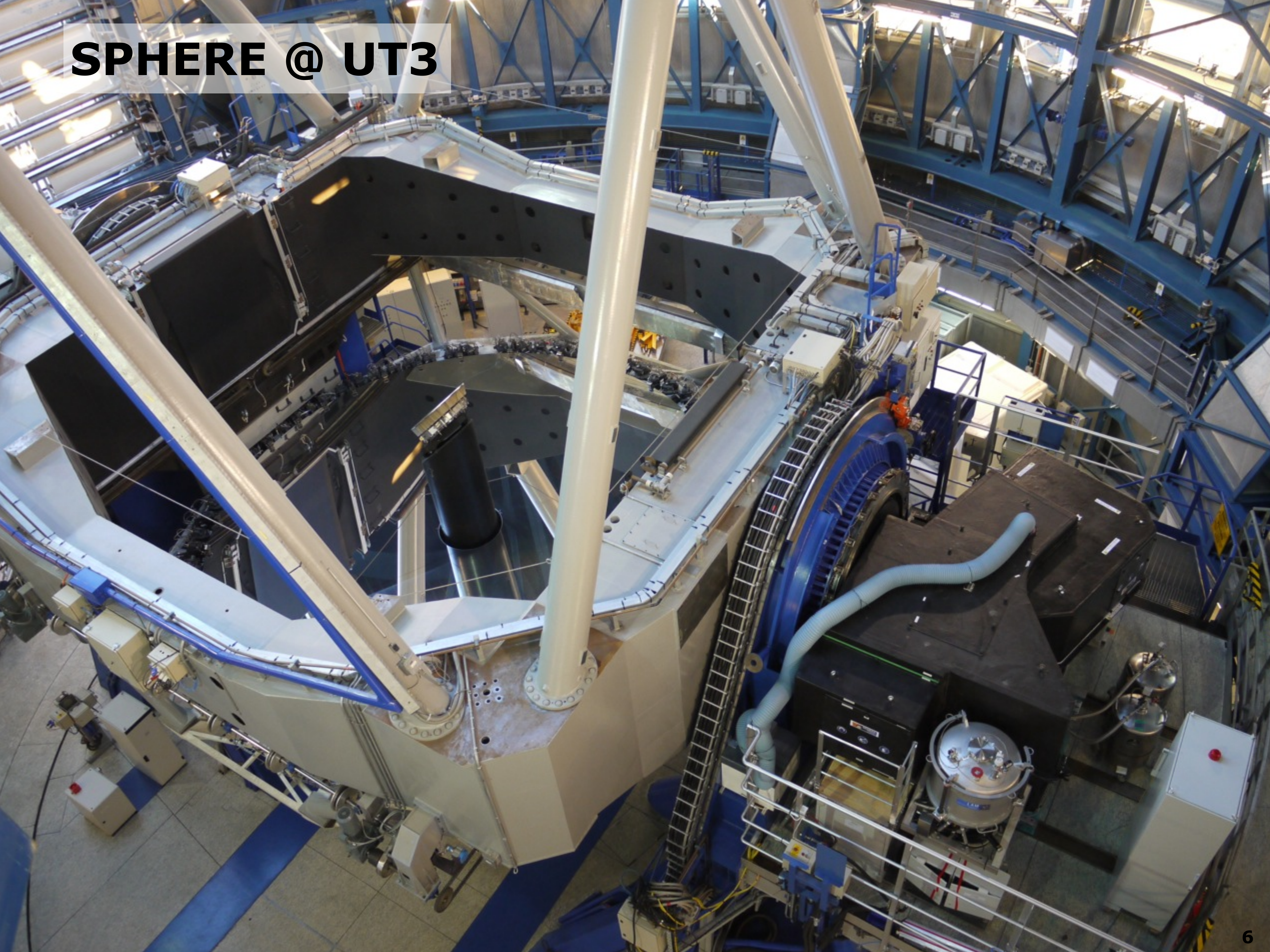
Observables



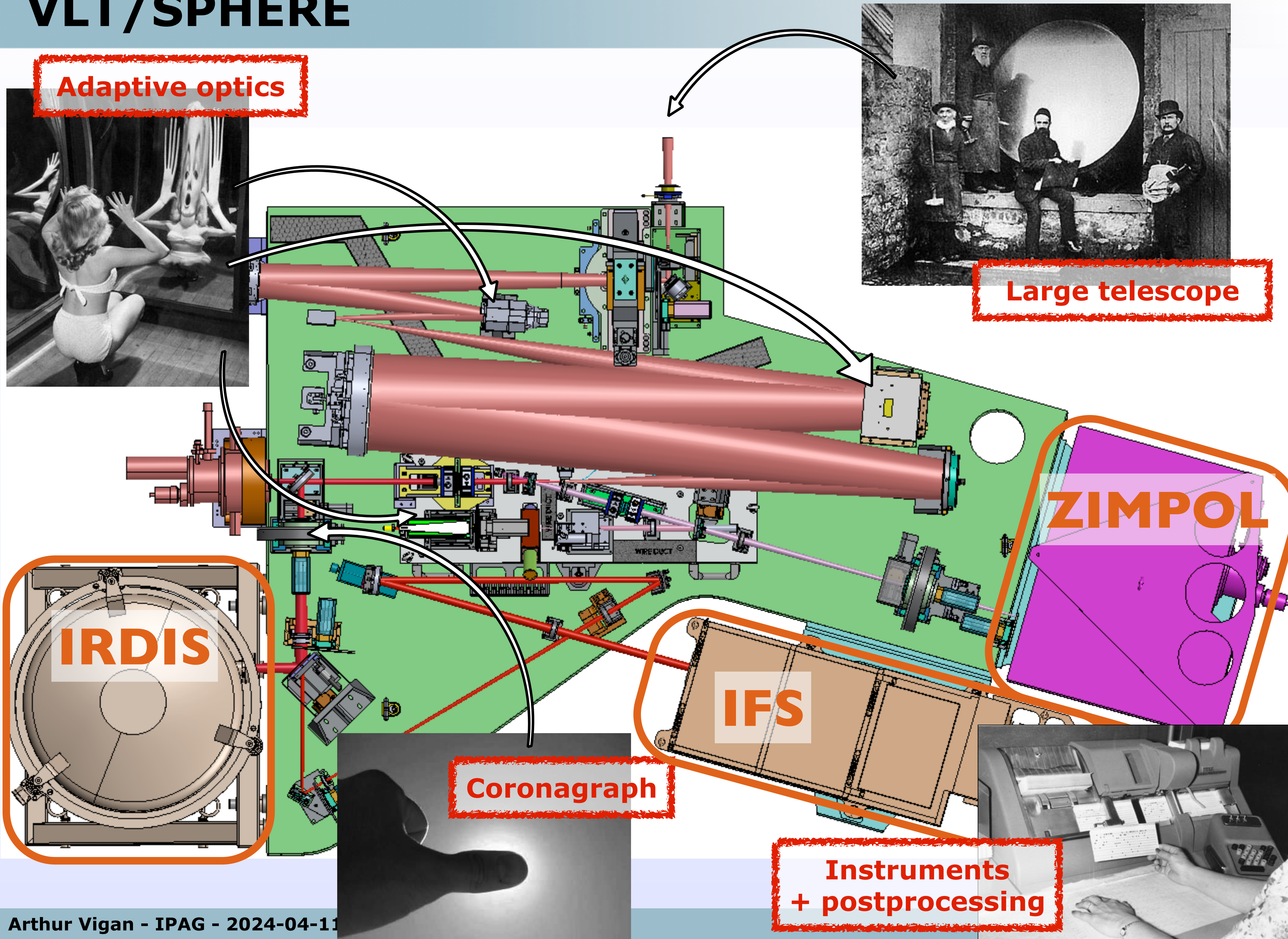
Direct imaging: the challenge



SPHERE @ UT3



VLT/SPHERE



Adaptive optics
Large telescope
ZIMPOL
IRDIS
IFS
Coronagraph
Instruments
+ postprocessing

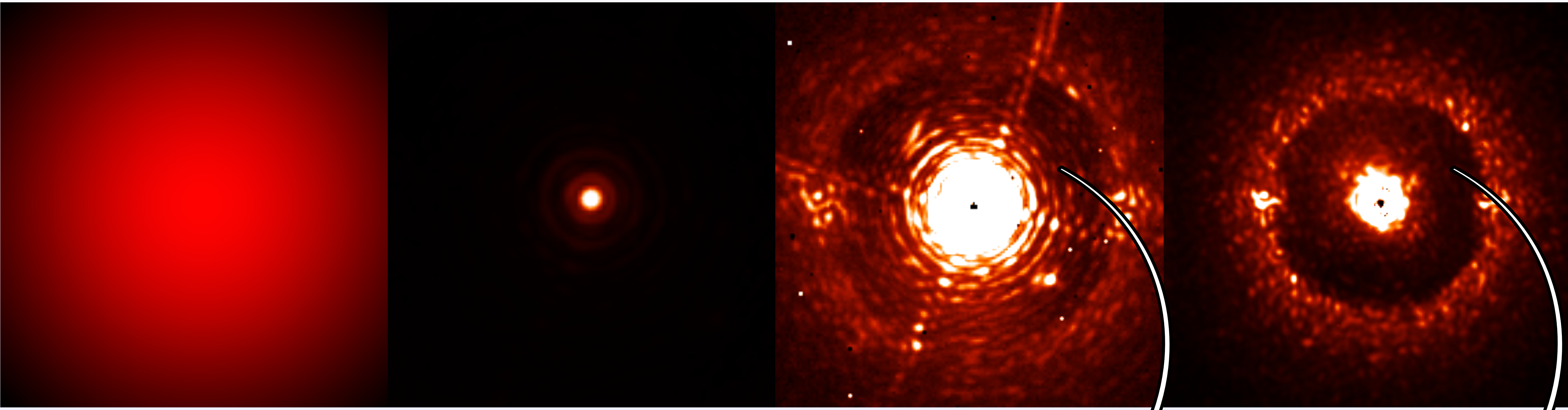
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



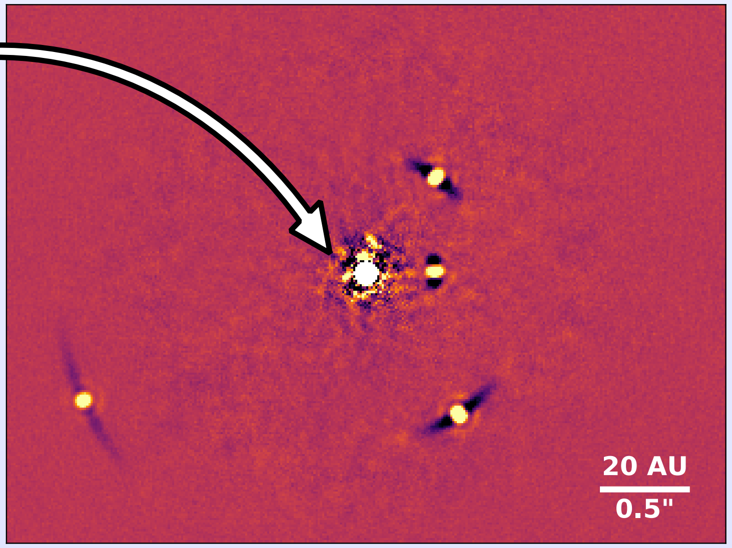
Diffraction limited within 20 λ/D

10^{-4}-10^{-5} contrast in dark zone

post-processing

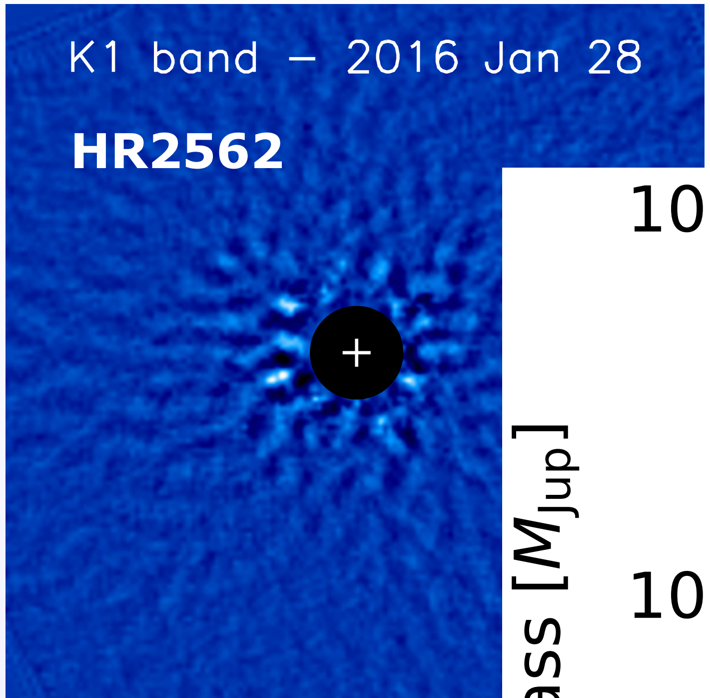
~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

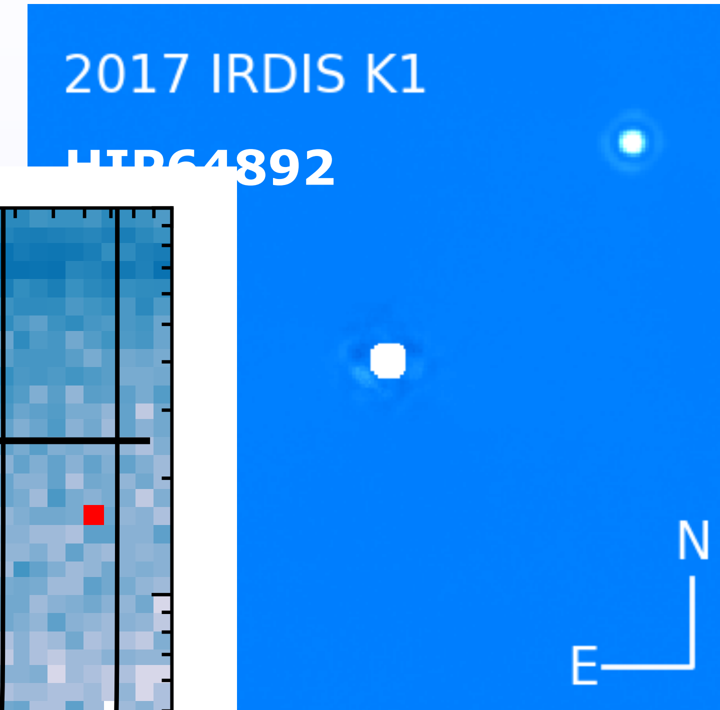


Populations analysis

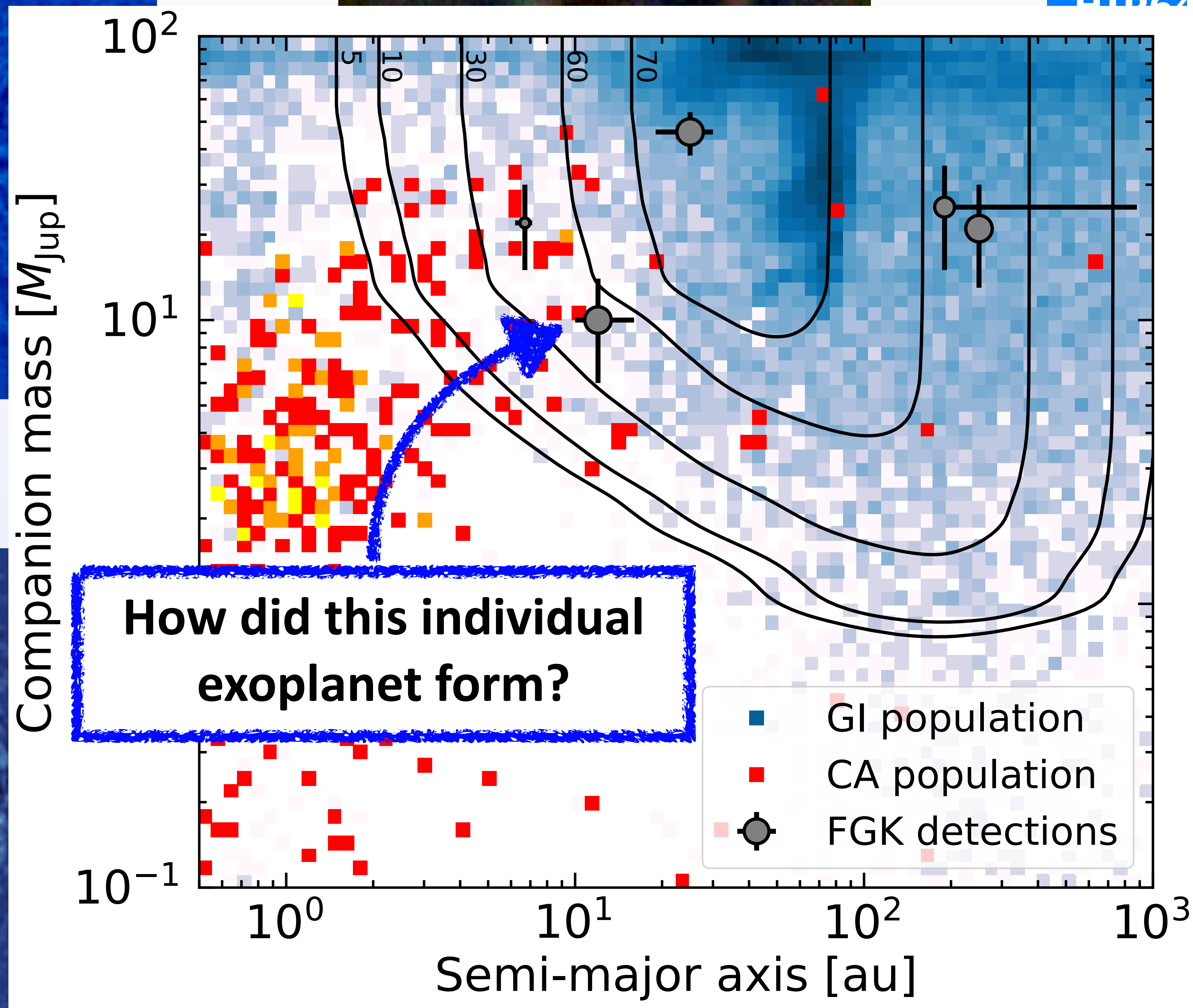
Nielsen et al. (2019)
Vigan et al. (2021)

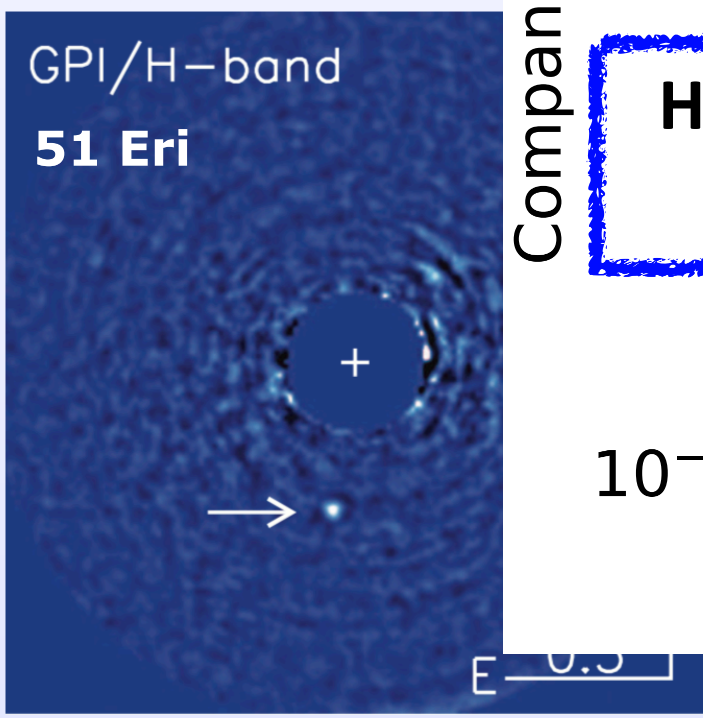


Konopacky et al. 2016

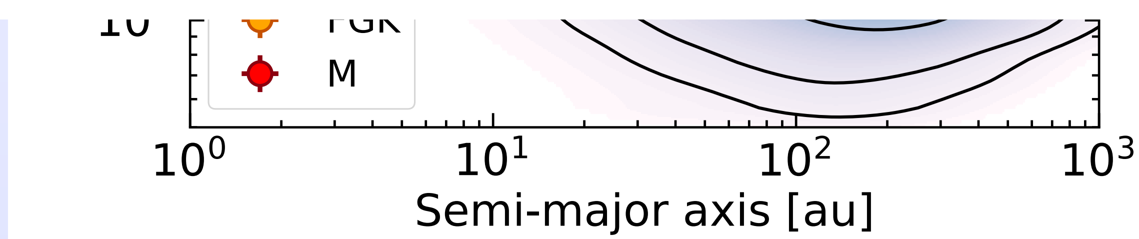


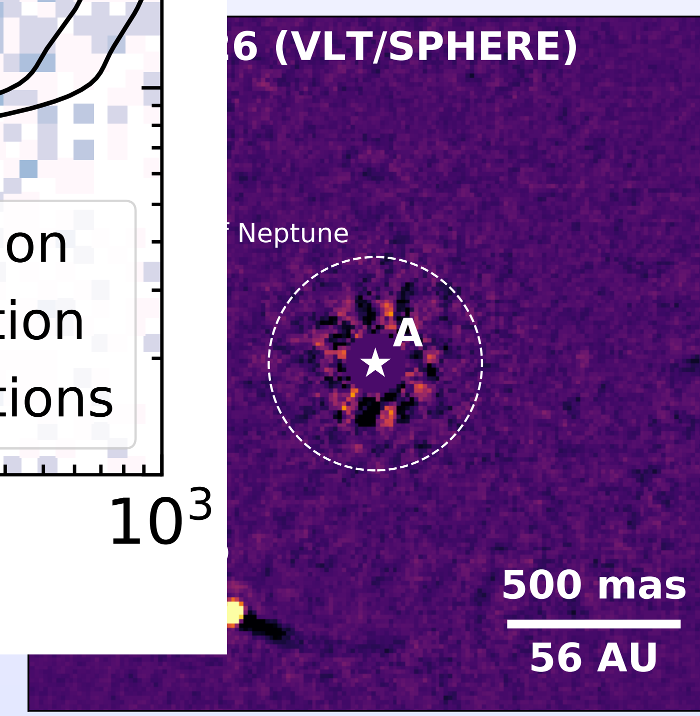
et al. 2018





Macintosh et al. 2015





Chauvin et al. 2017

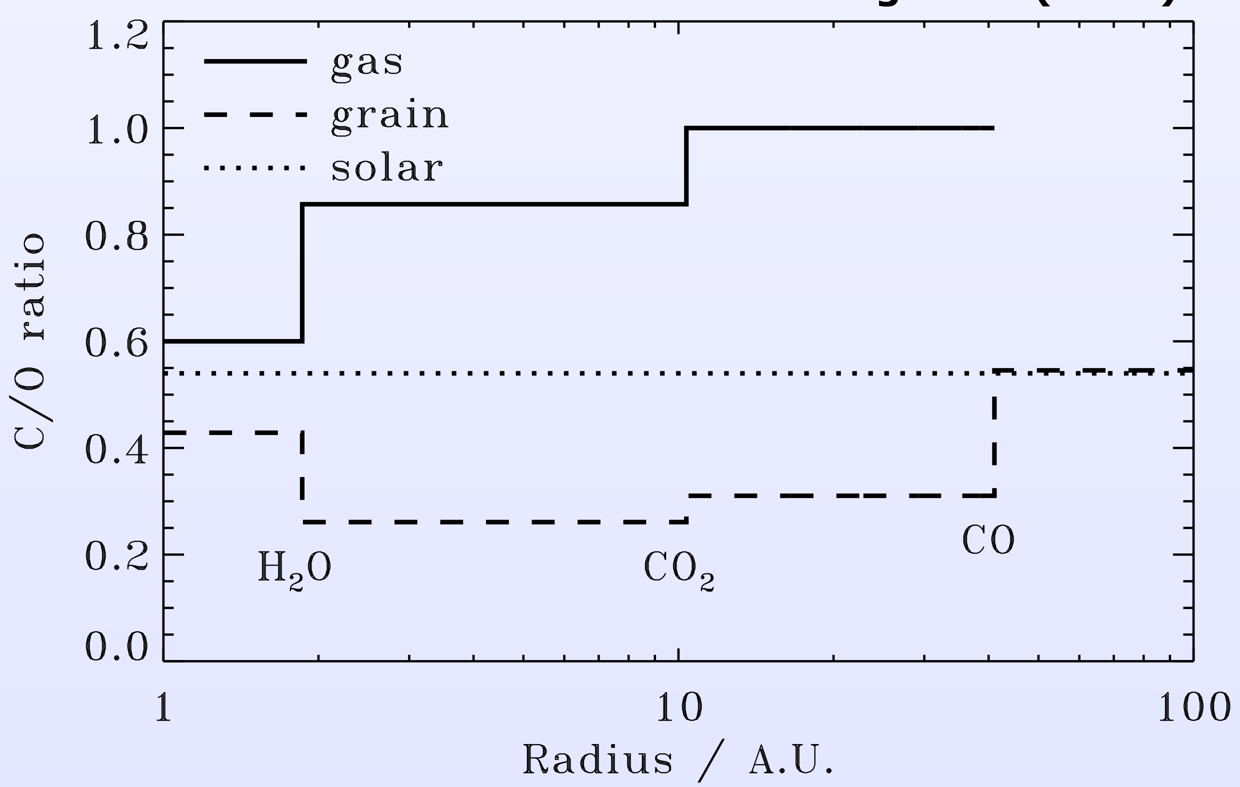
How to study the formation of a given planet?

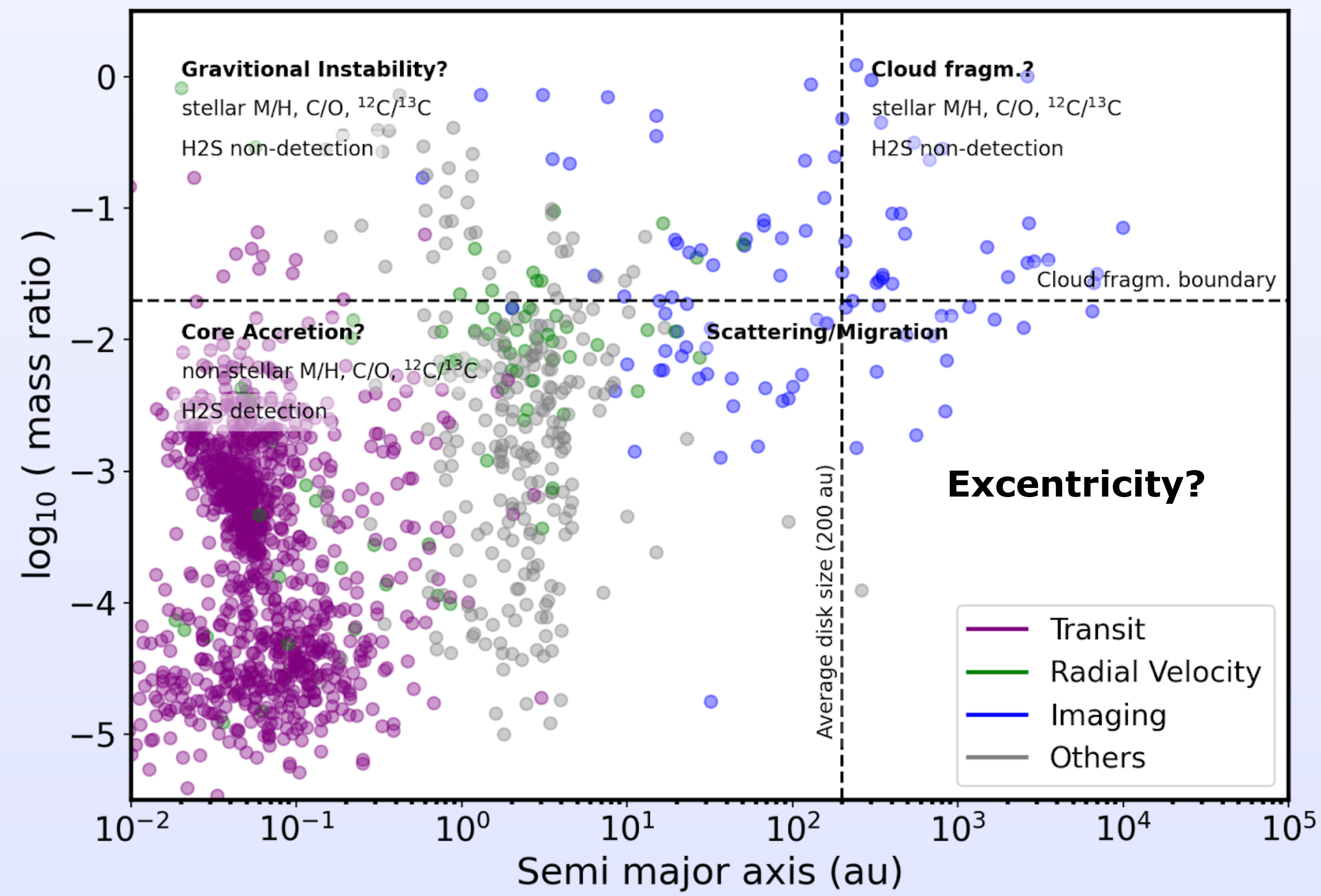
Atmospheric composition is a key to determine the formation

Parameters possibly linked to the formation location or the formation process

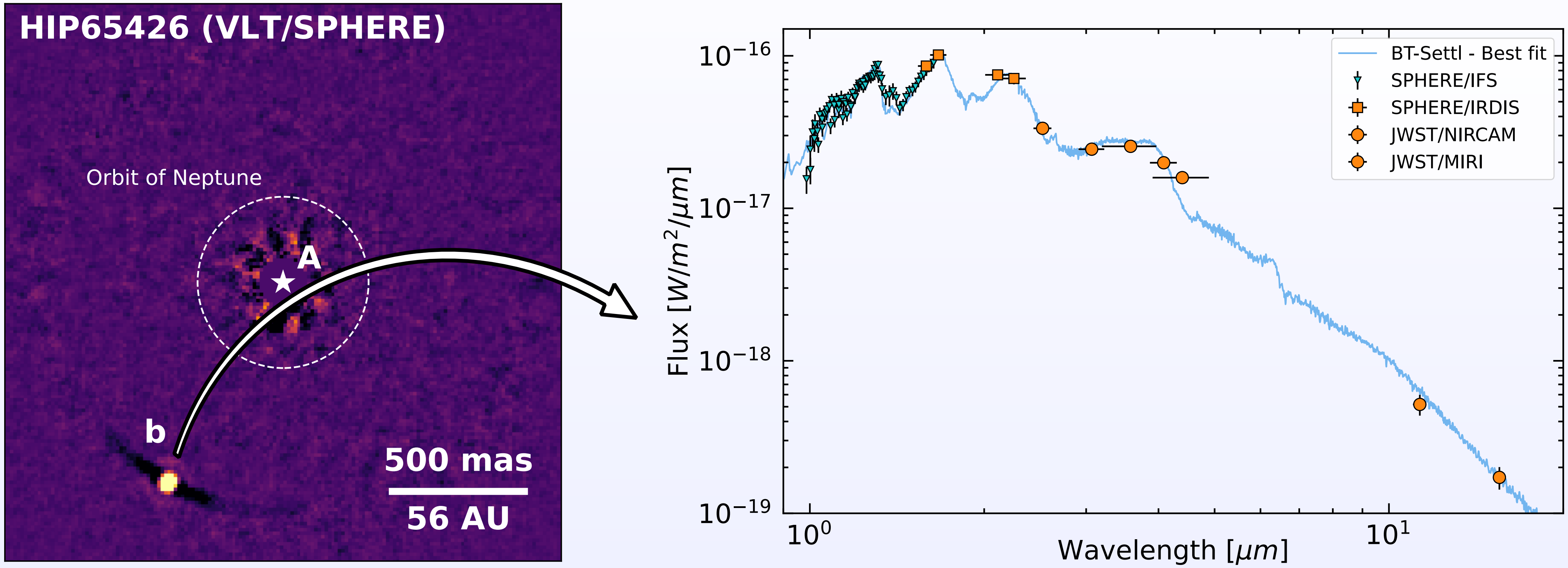
- Abundance ratios: C/O, [M/H], ...
- Isotopic ratios: D/H, $^{12}CO/^{13}CO$, ...

Öberg et al. (2011)





Detections with high-contrast instruments



Chauvin et al. 2017

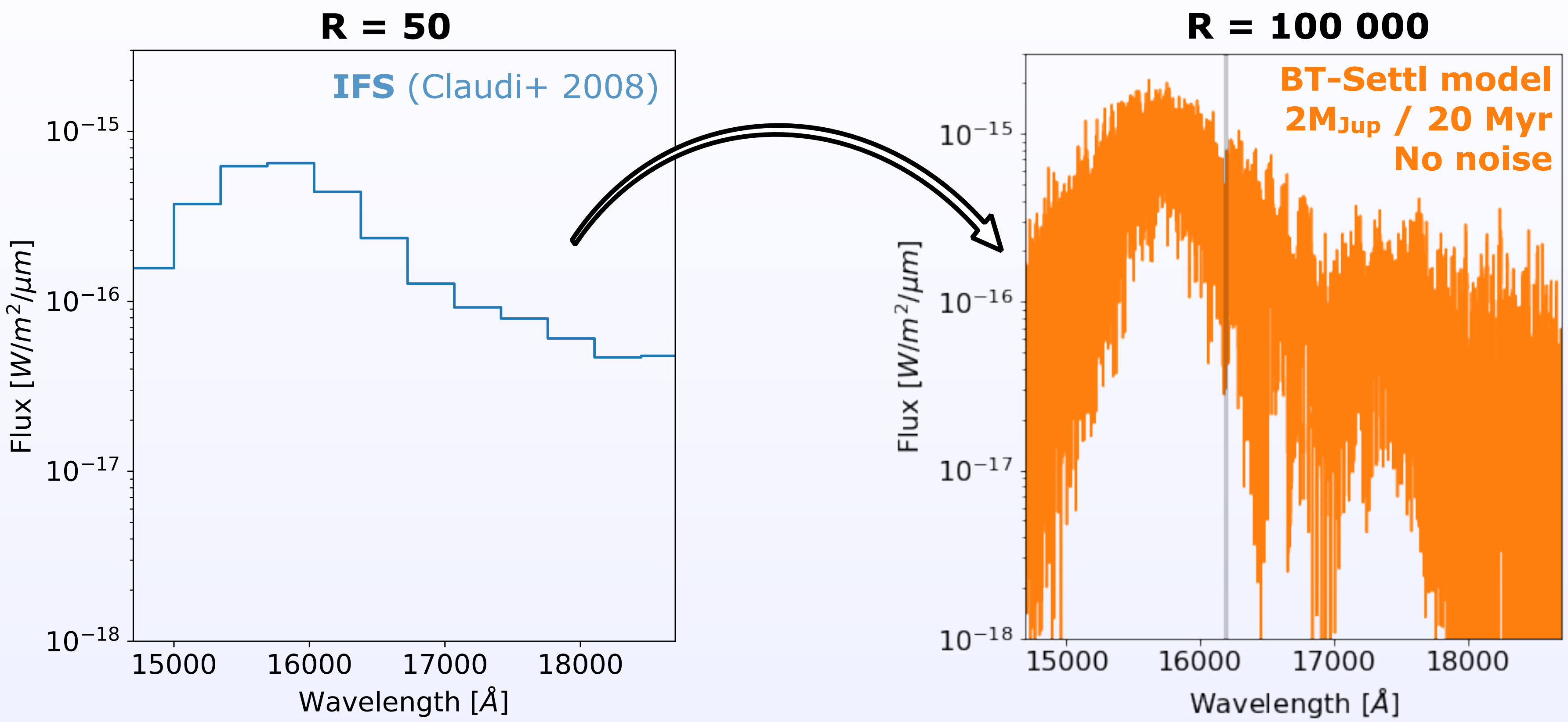
Very low resolution spectroscopy

Enough for first order characterisation!

Resolution	*Parameters*
R=50	Teff, clouds
R=500	+log(g), ~FeH, ~C/O

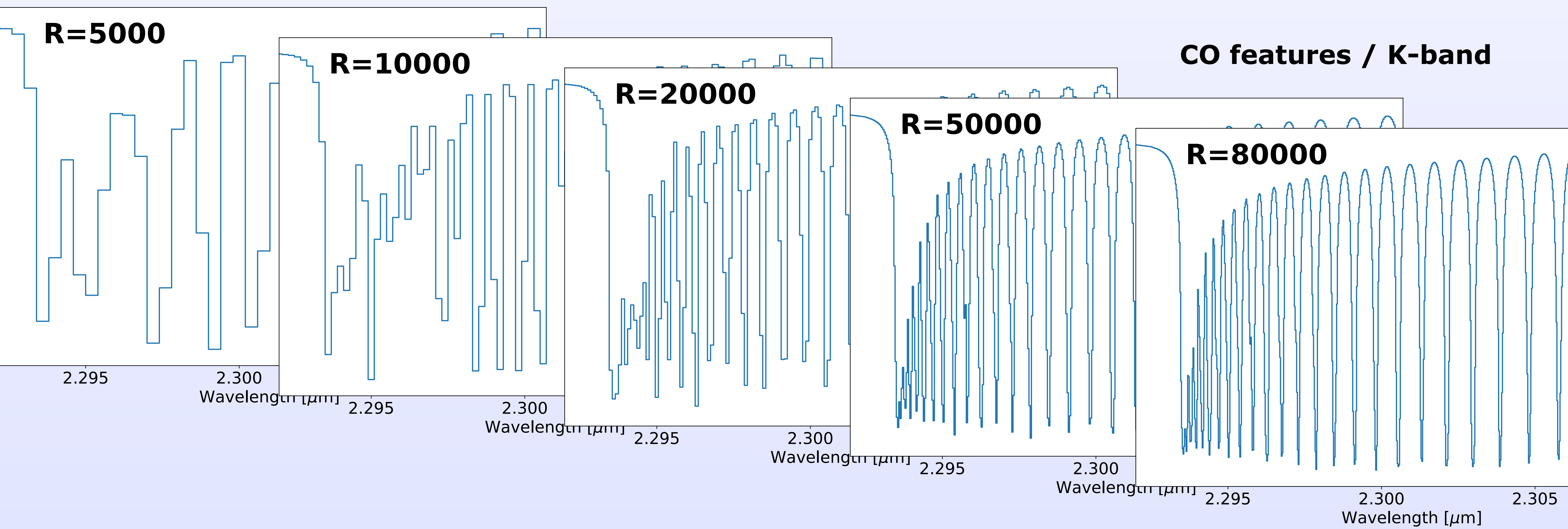
Need for high spectral resolution!

Spectral content

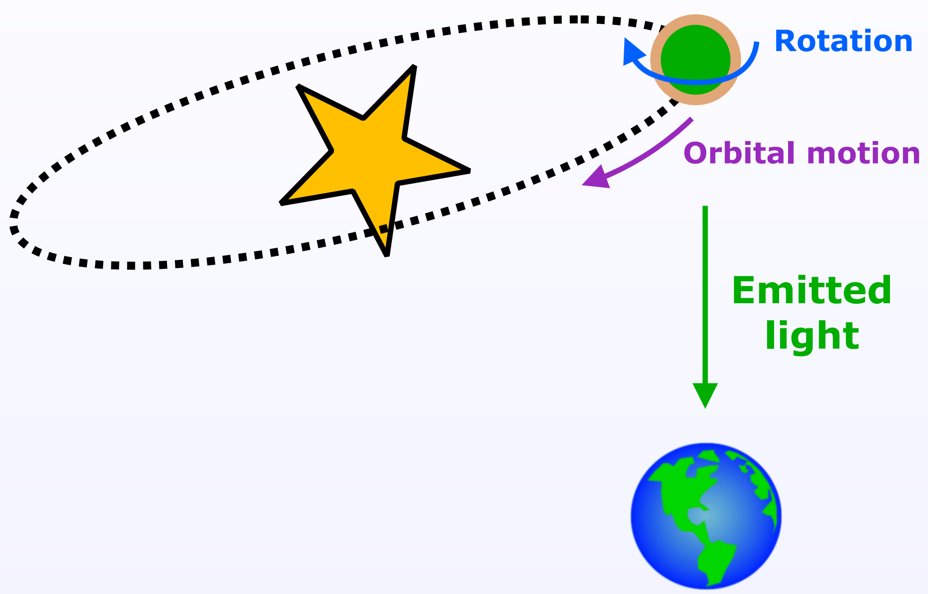


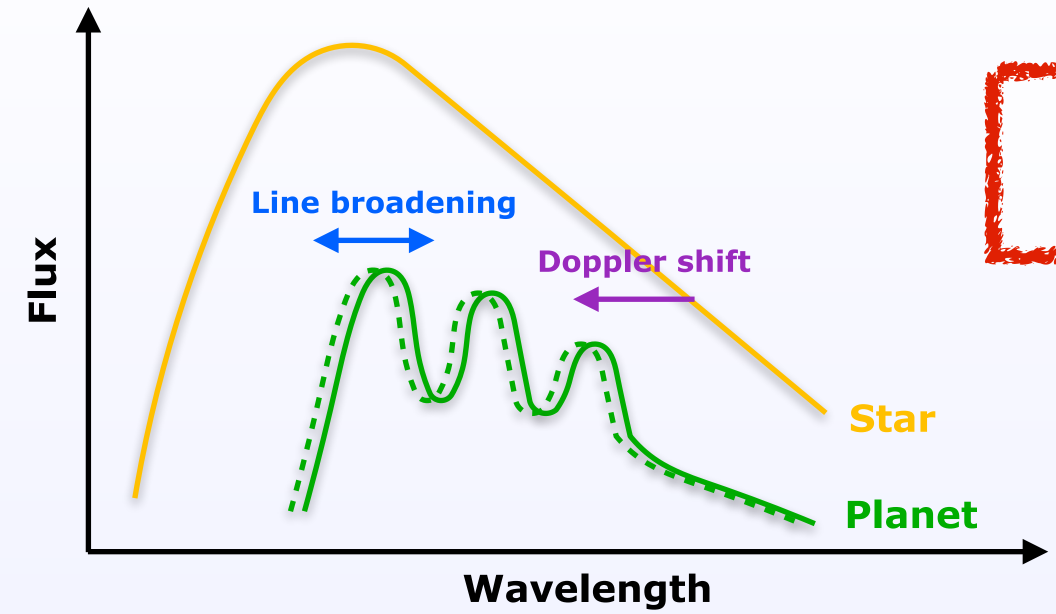
Requires
R ≫ 10 000

CO features / K-band



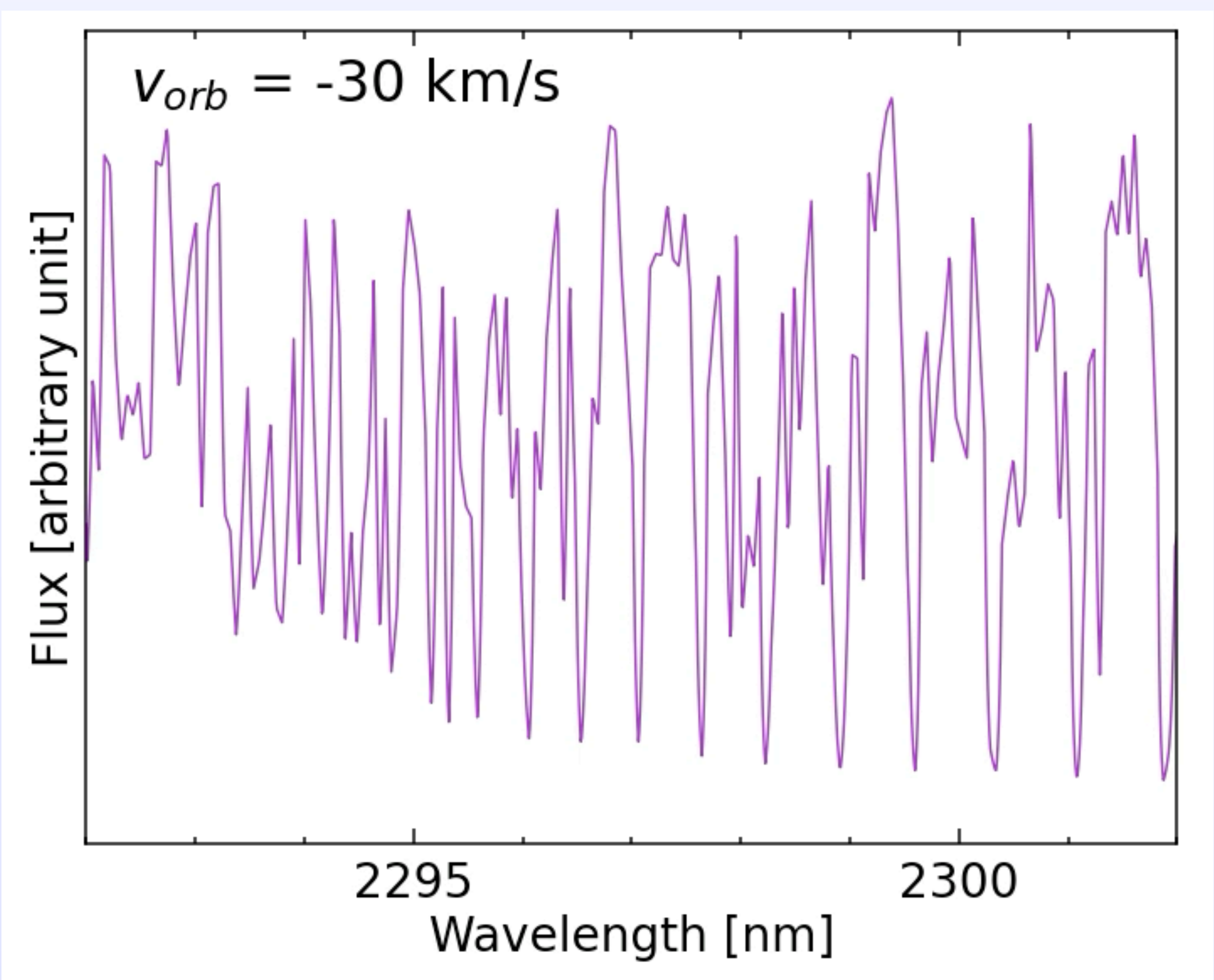
Orbital and rotational information



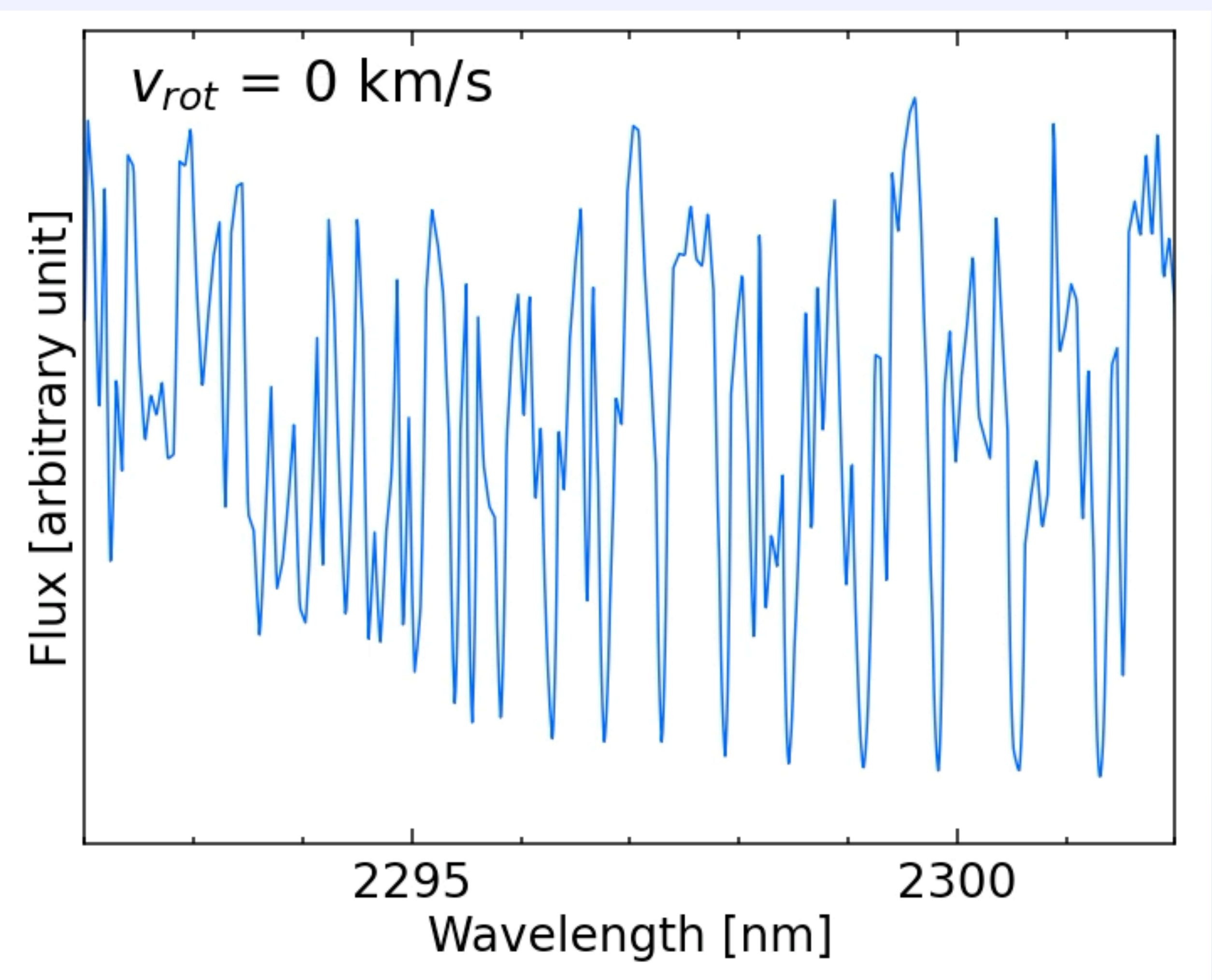


Requires $R \gg 30\,000$

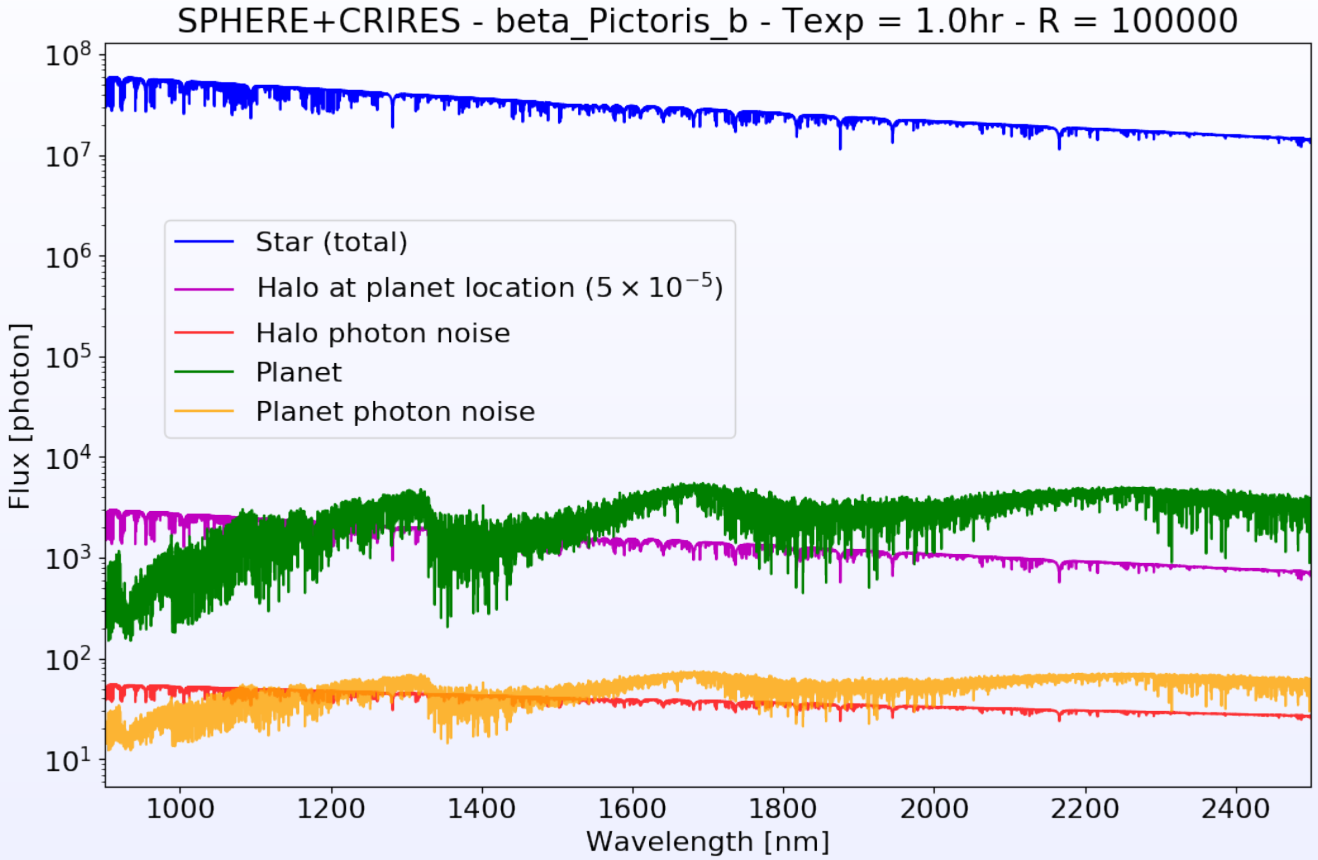
Effect of orbital motion

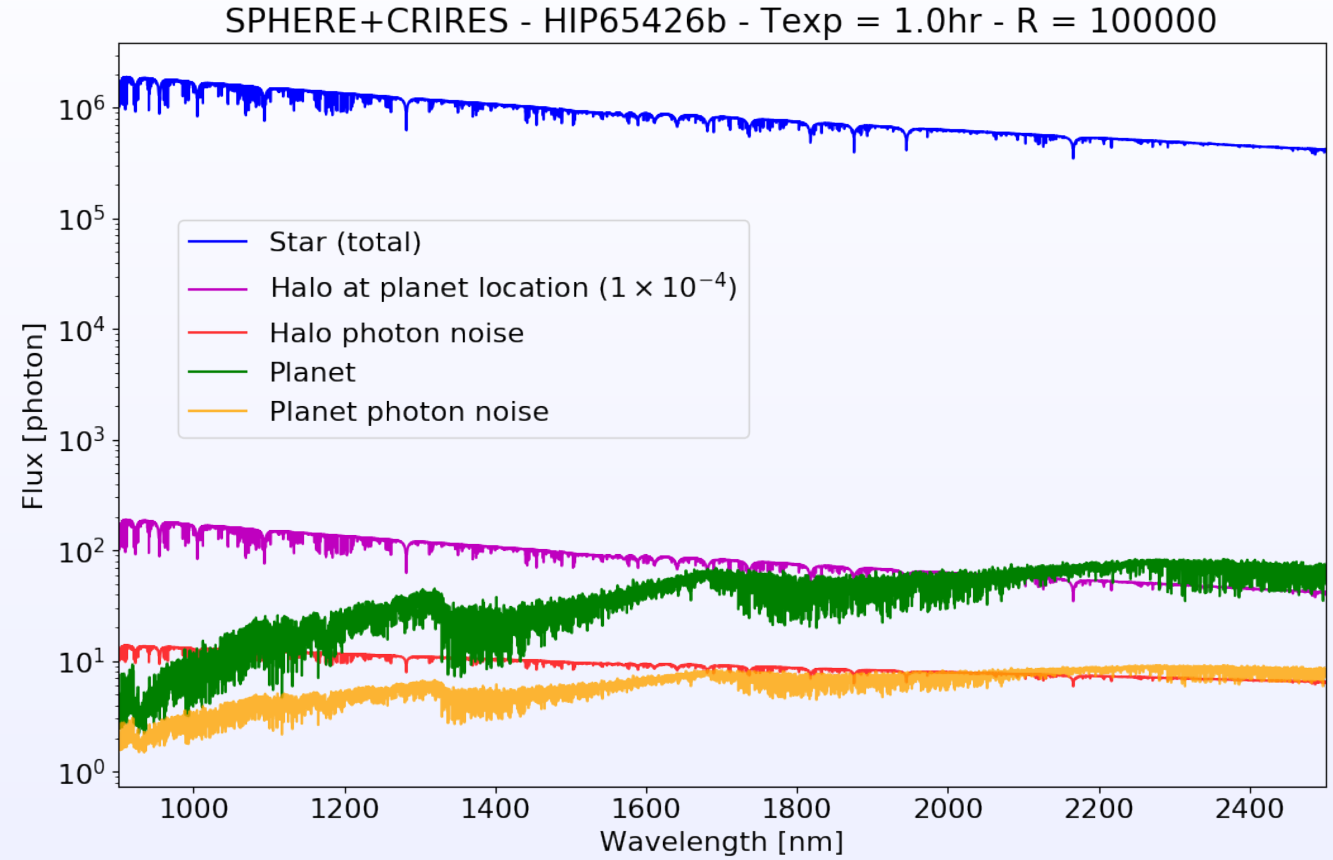


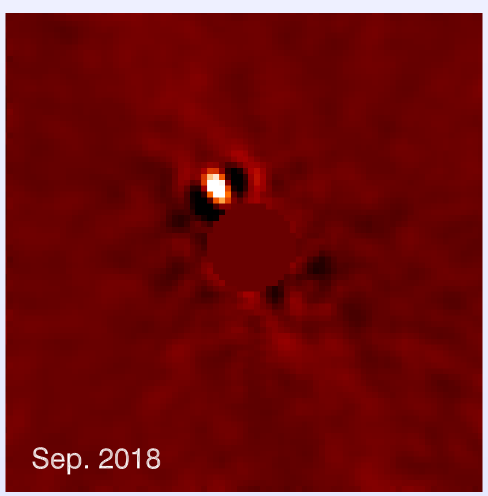
Effect of rotation



A few numbers...

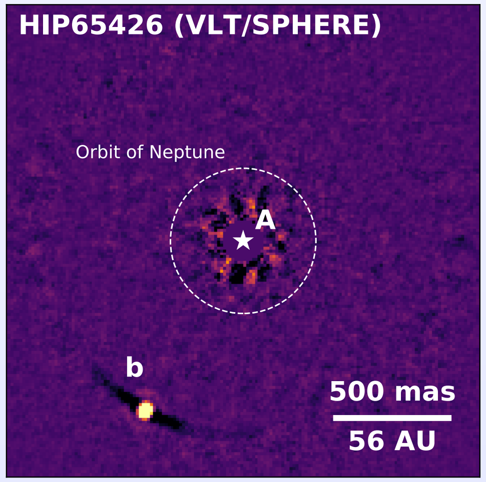






>1000 photon/channel

SNR > 100



>10 photon/channel

SNR > 10

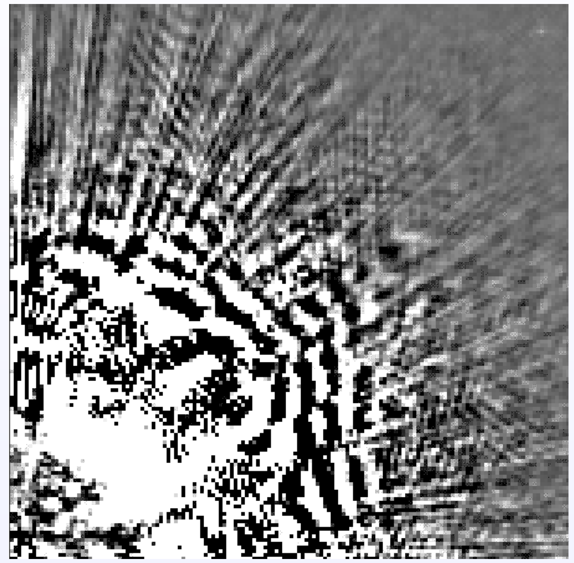
It's hard!!

Boost in detection

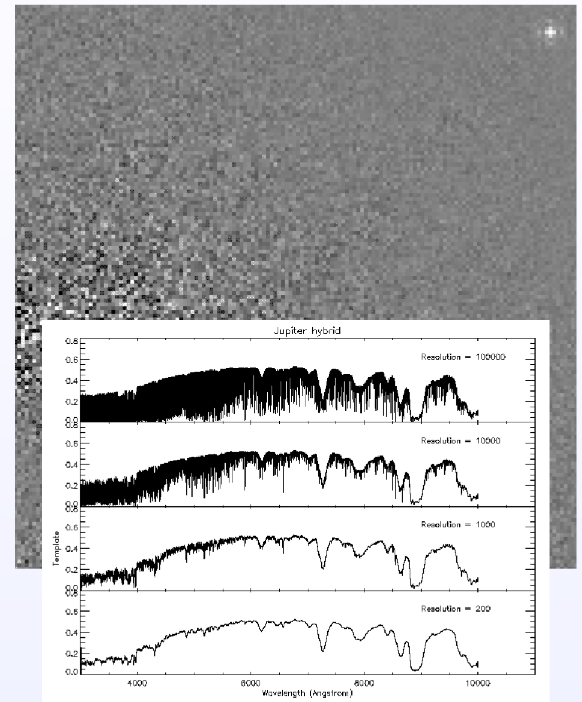
HST/ACS simulation

Sparks & Ford (2002)

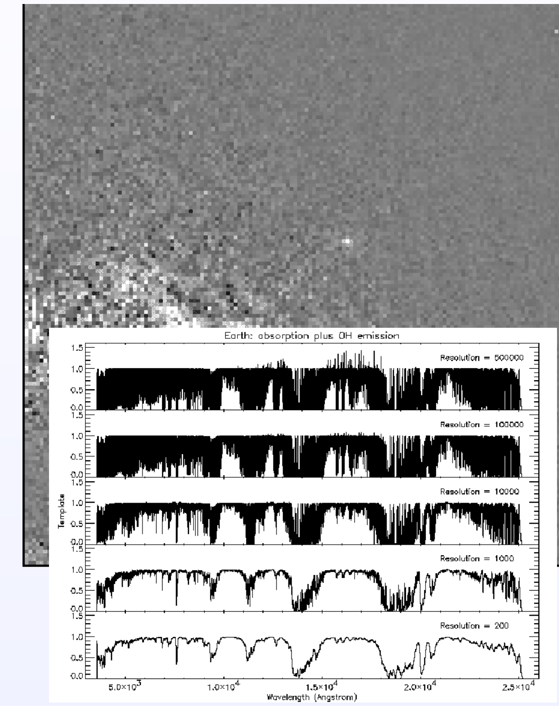
Roll-subtraction (=ADI)

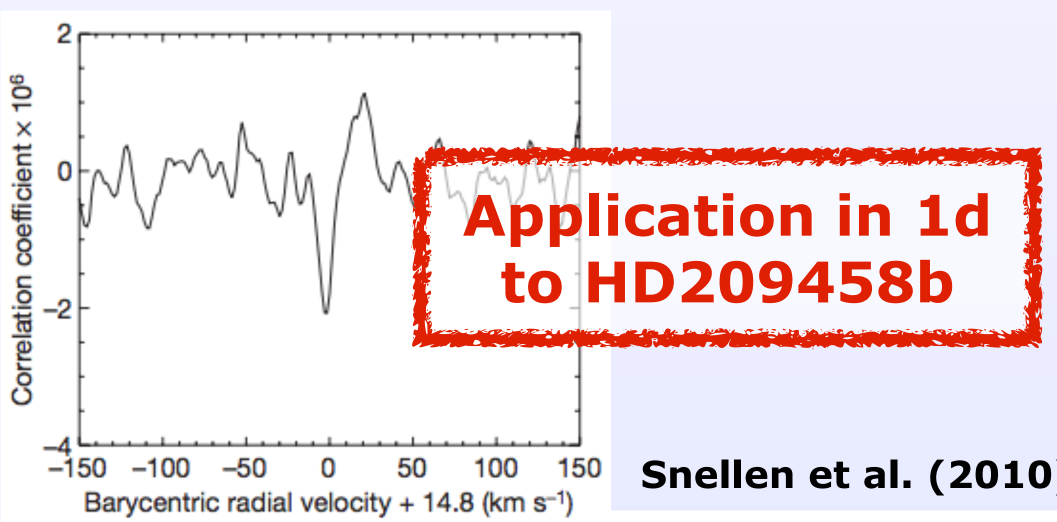


Jupiter template CCF

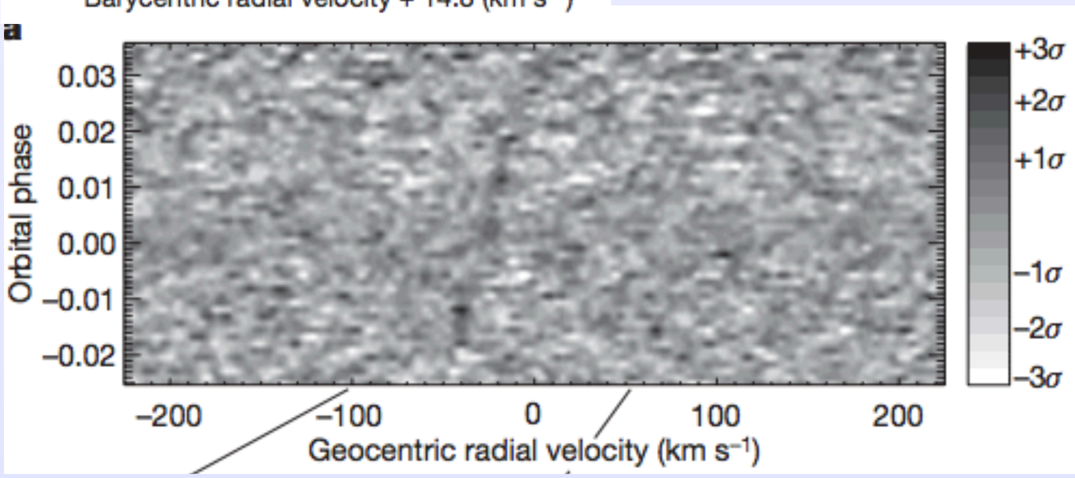


Bright Earth template CCF

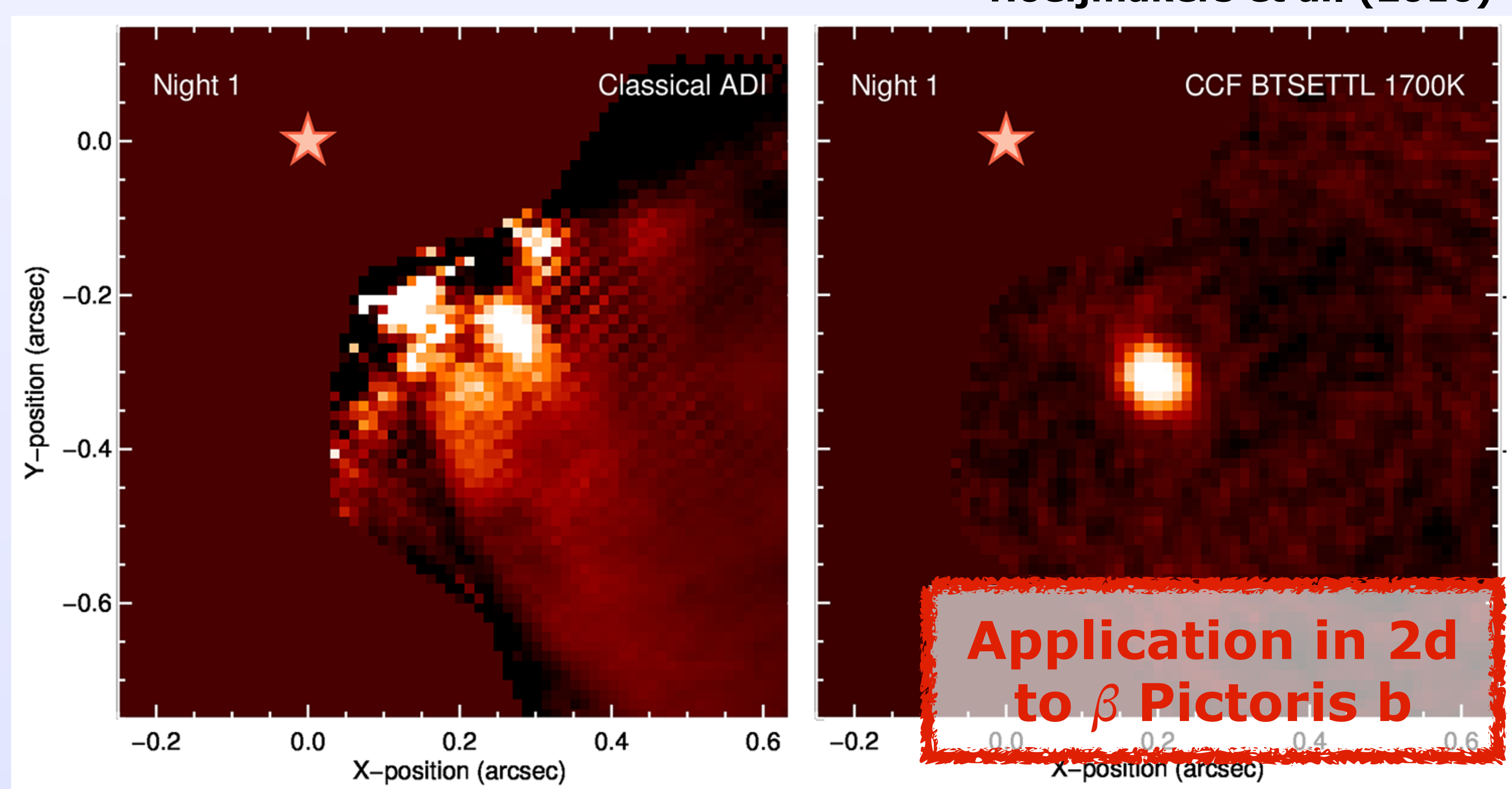




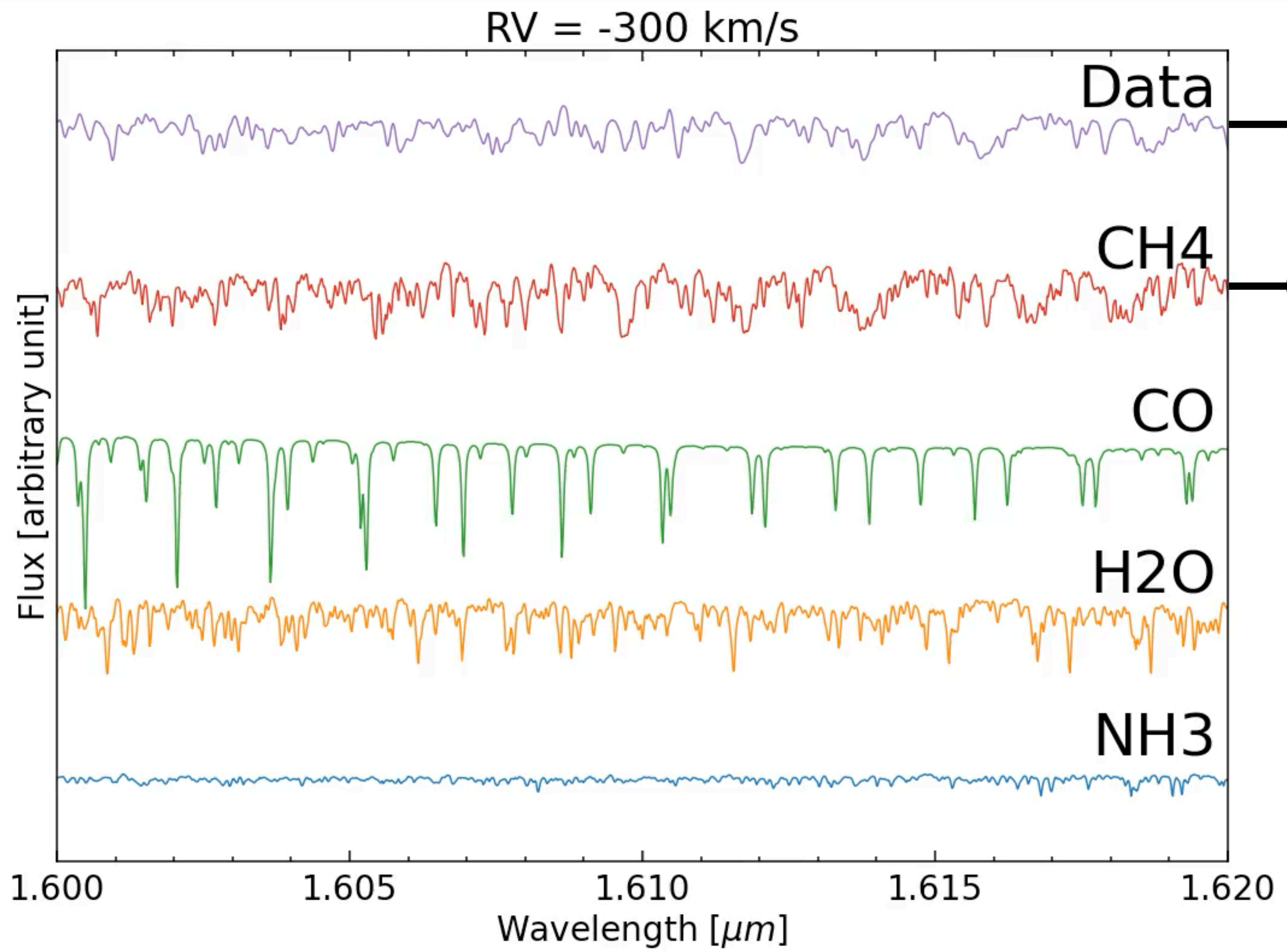
Snellen et al. (2010)



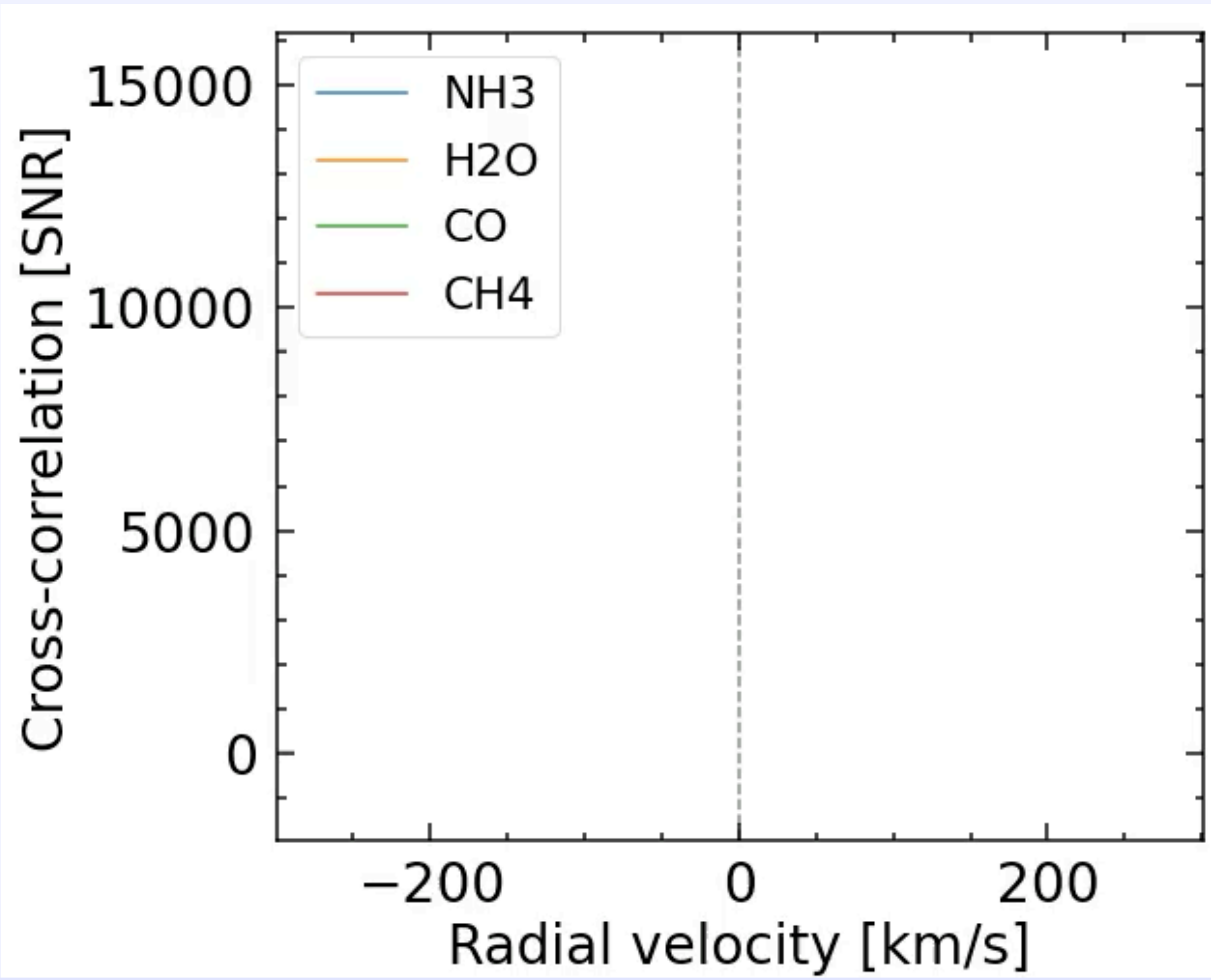
Hoeijmakers et al. (2016)



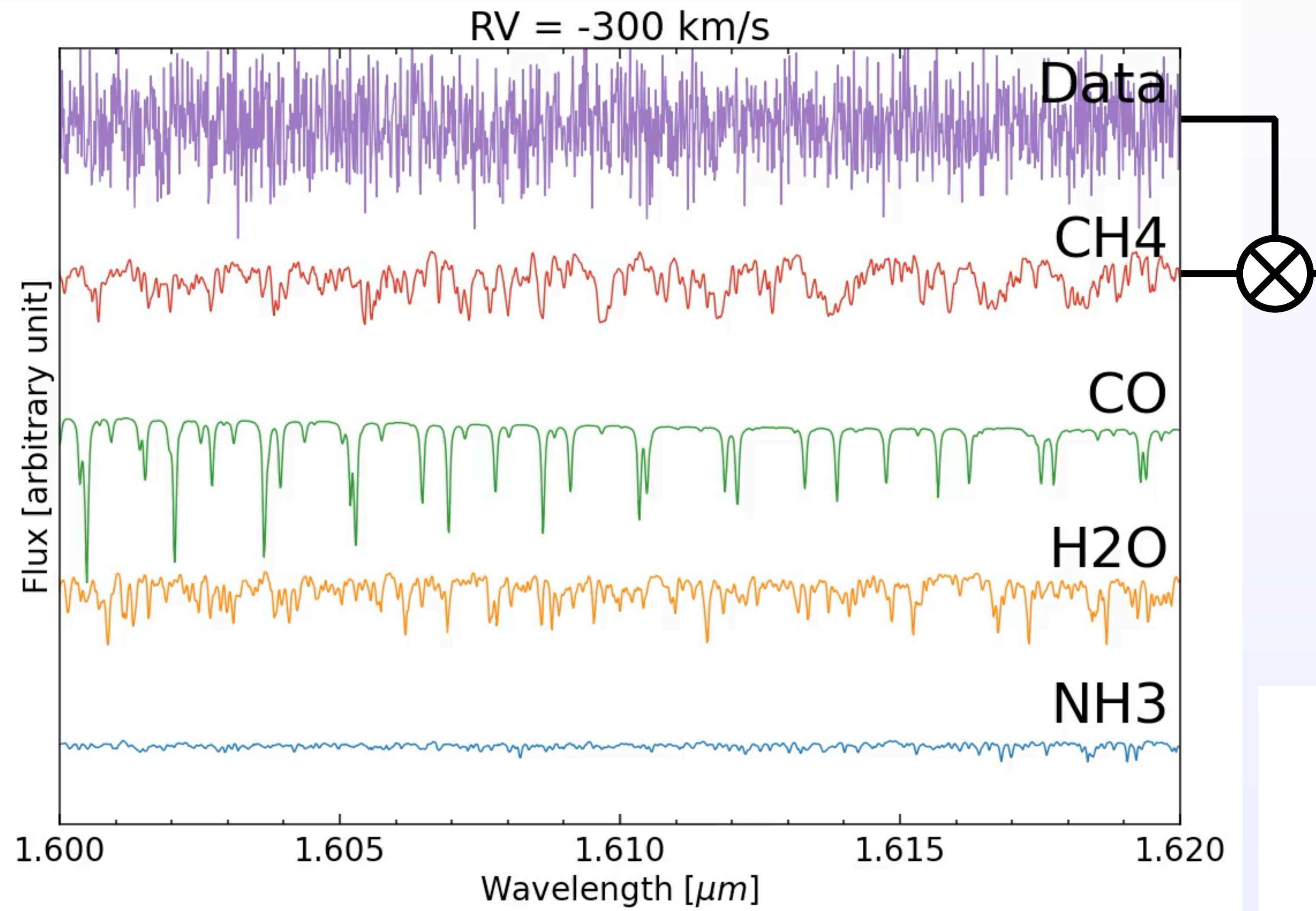
Boost in detection



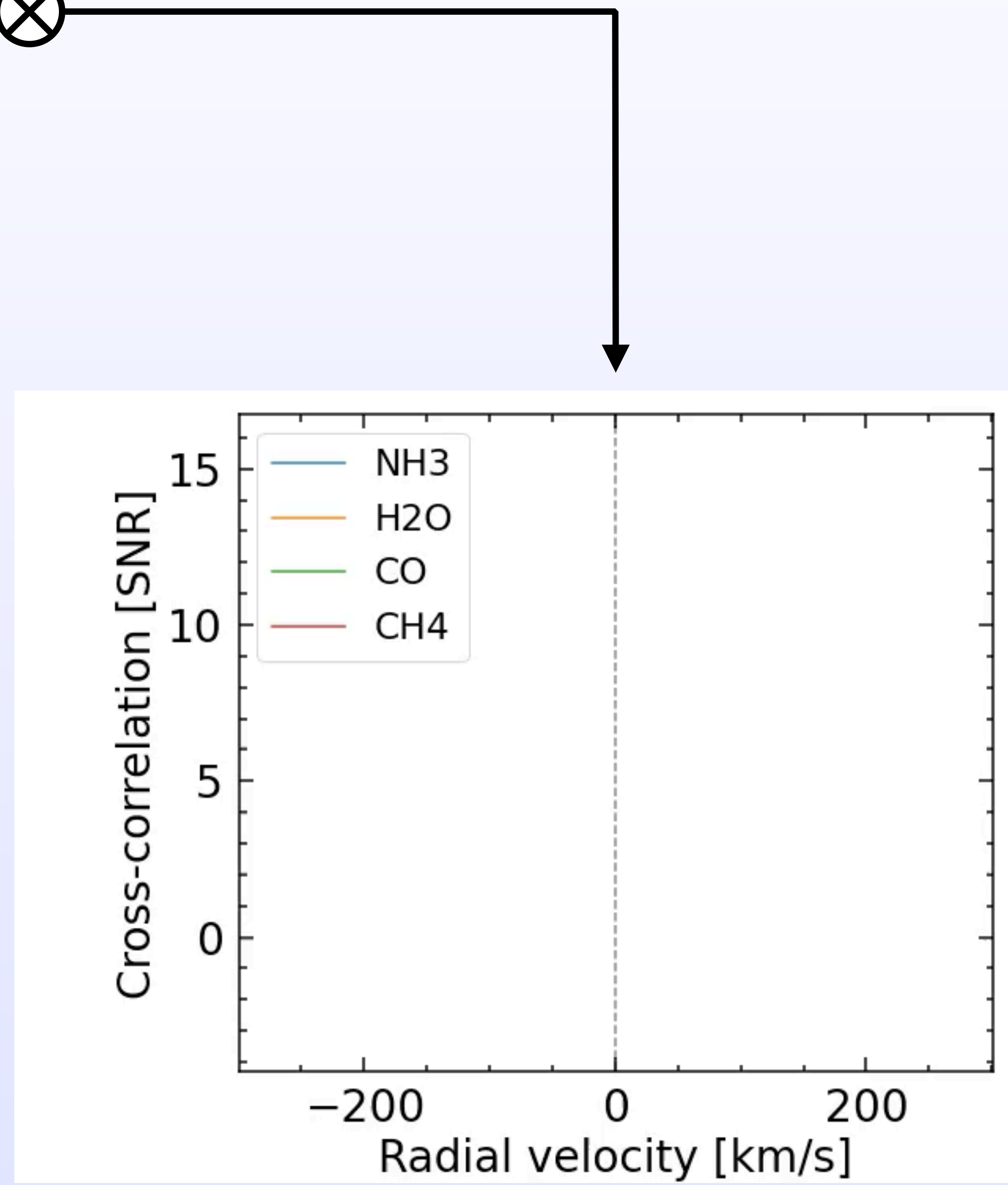
Cross-correlation boosts the signal!



Boost in detection



Cross-correlation boosts the signal!

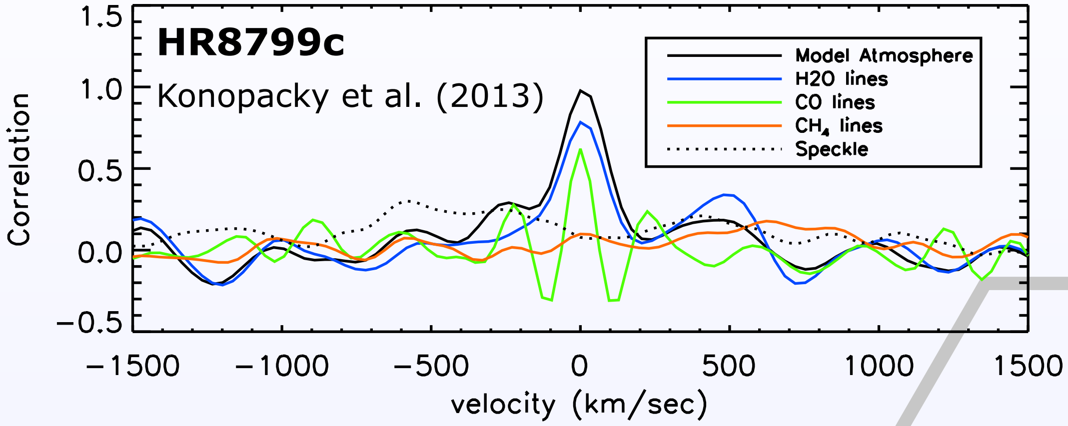


$$S/N = \frac{S_{\mathrm{planet}}}{\sqrt{S_{\mathrm{star}} + \sigma^2_{\mathrm{bg}} + \sigma^2_{\mathrm{RN}} + \sigma^2_{\mathrm{dark}}}} \sqrt{N_{\mathrm{lines}}}$$

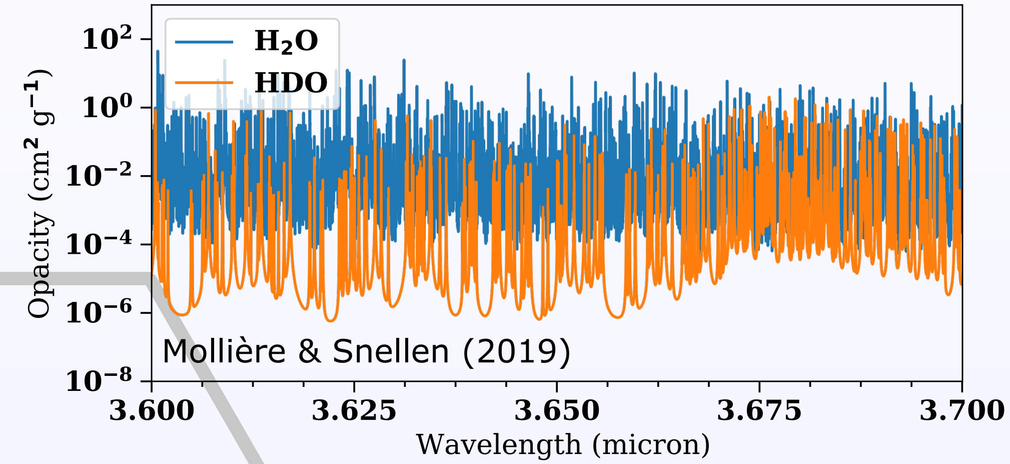
Snellen et al. (2015)

Exoplanet science at high resolution

Molecules detection

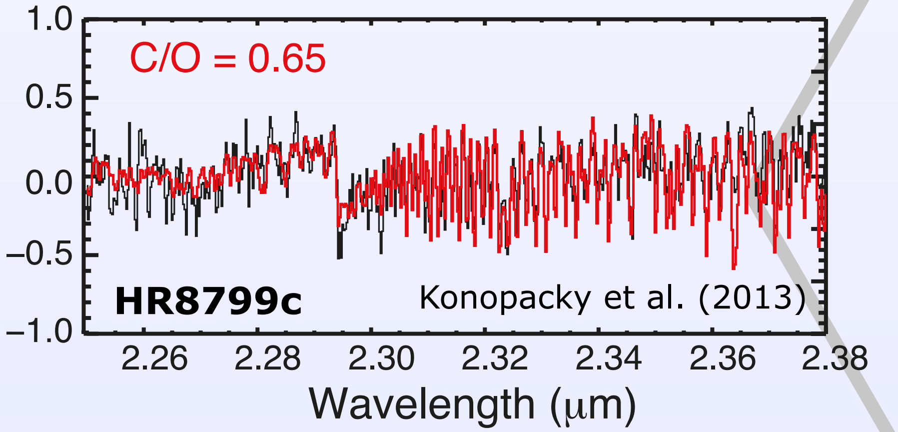


Isotopologues detection

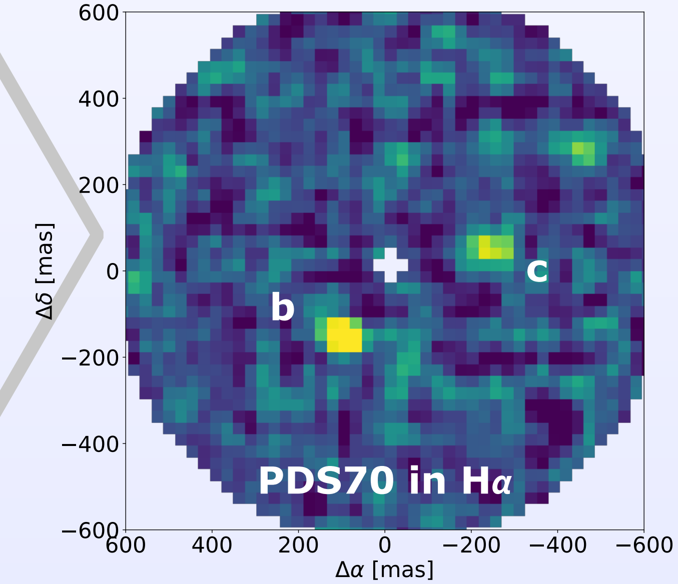


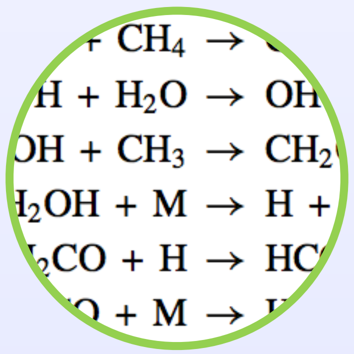
Formation, migration & evolution

Abundances determination



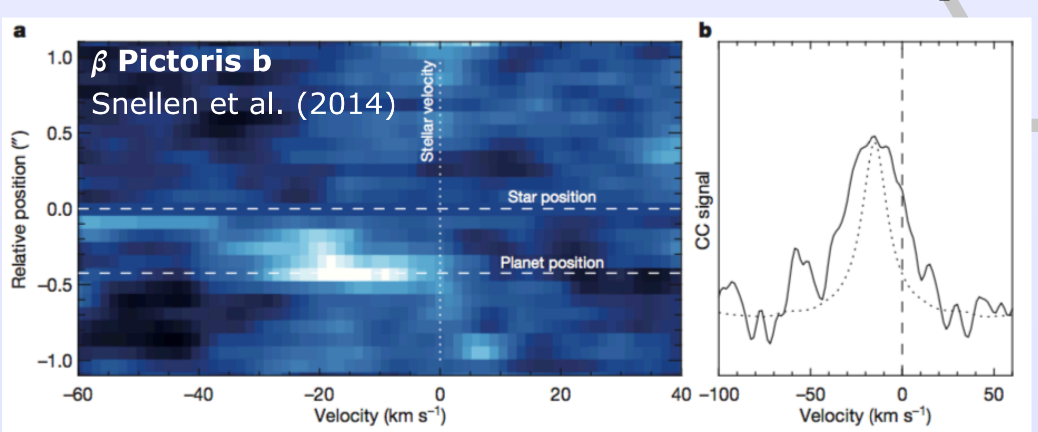
Accretion lines



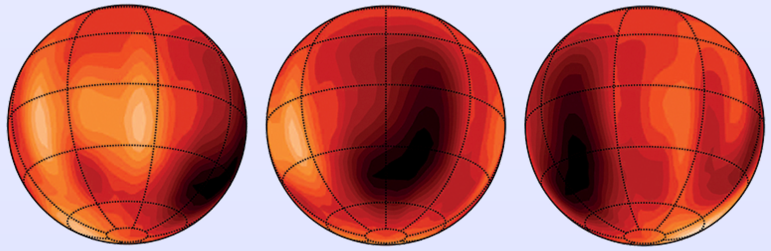


Atmospheric chemistry & dynamics

Orbital and rotational velocity

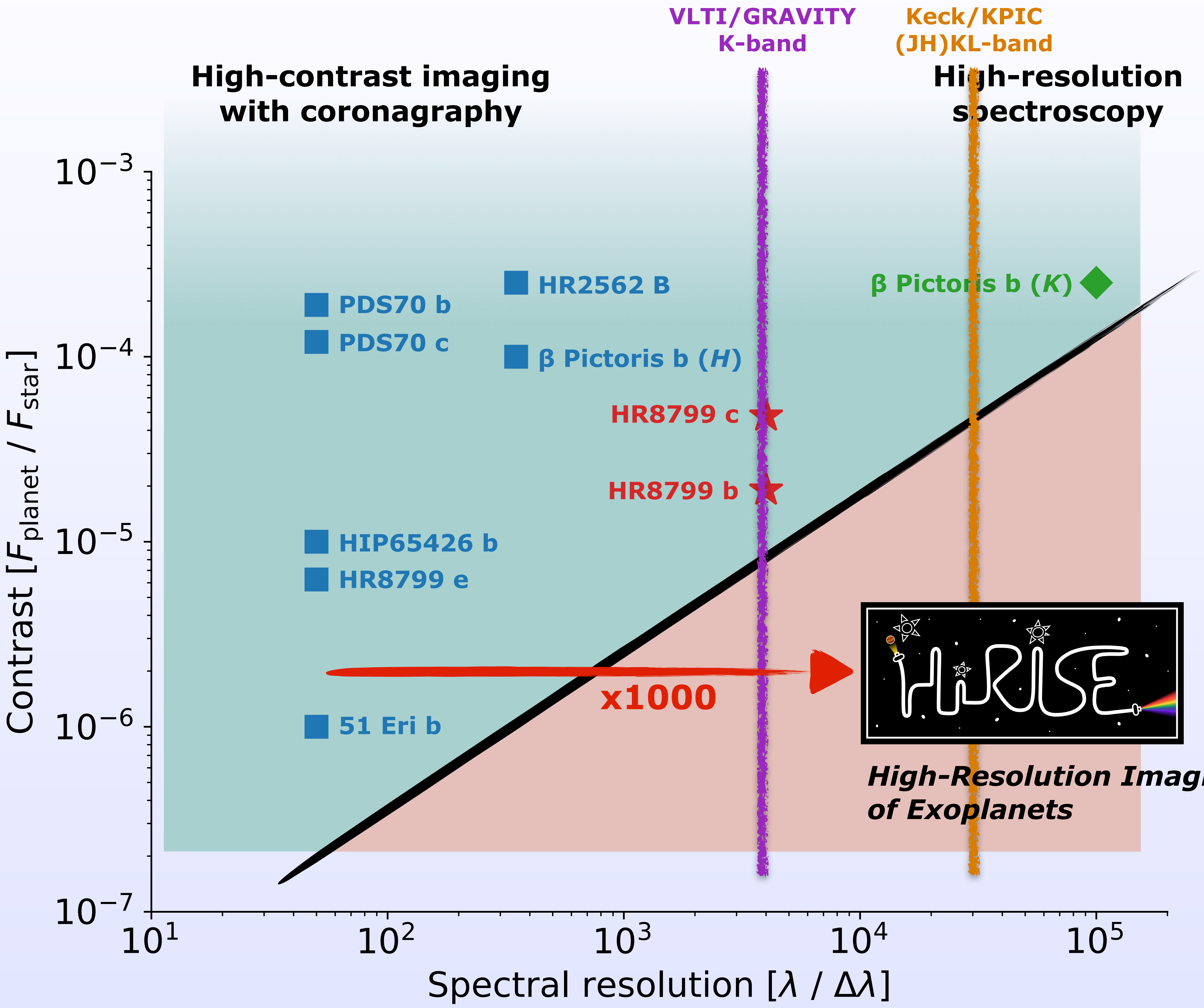


Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR



Characterisation

15-20 companions already known at

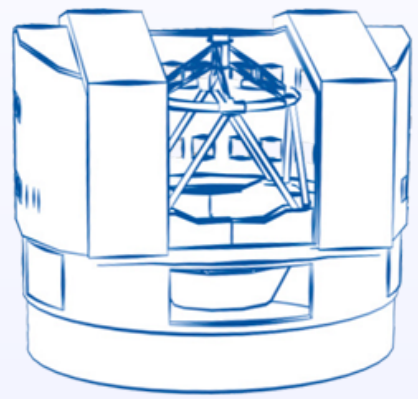
- **separation < 1"**
- **contrast < 10^{-4}**

Companions detected by other means

- **Imaging**
- **ESA/Gaia**
- **RV?**

A unique window of opportunity

VLT/UT3



High-contrast exoplanet imager

SPHERE

High-resolution spectrograph

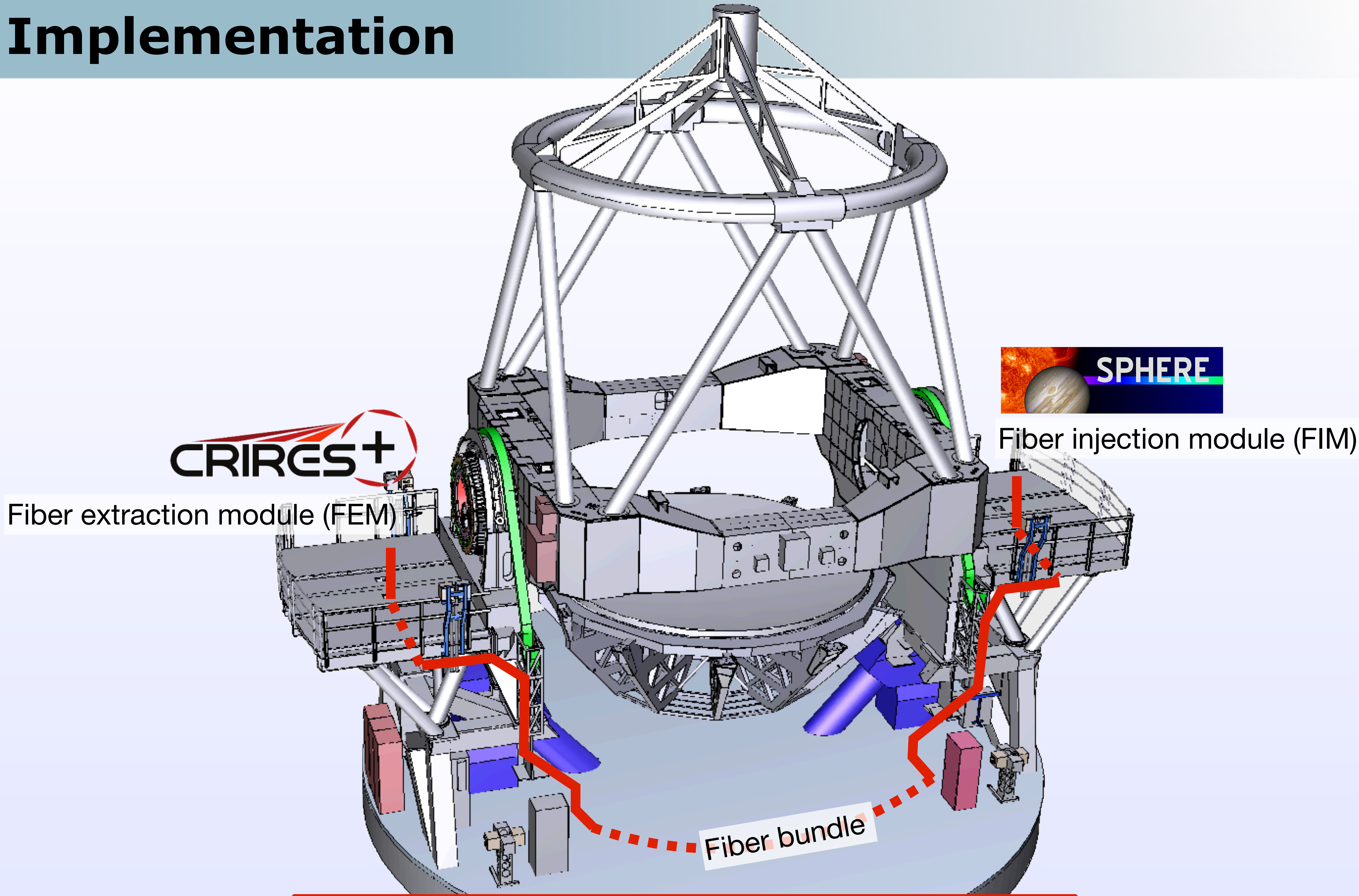
CRIRES+

SPHERE		CRIRES+
✔	**Extreme adaptive optics**	✘
✔	**Coronagraphy**	✘
Y J H K	**Spectral coverage**	Y J H K L M
50 - 350	**Spectral resolution**	50 000 - 100 000

Fiber coupling

HiRISE

Implementation



Is it really worth it?

Performance and trade-off study

Scientific requirements

The instrument must:

sci.req.1 Enable direct characterization of companions in less than 1 night

sci.req.2 More efficient than CRIRES standalone for the same science case

sci.req.3 Provide access to H band and, if possible, to K band

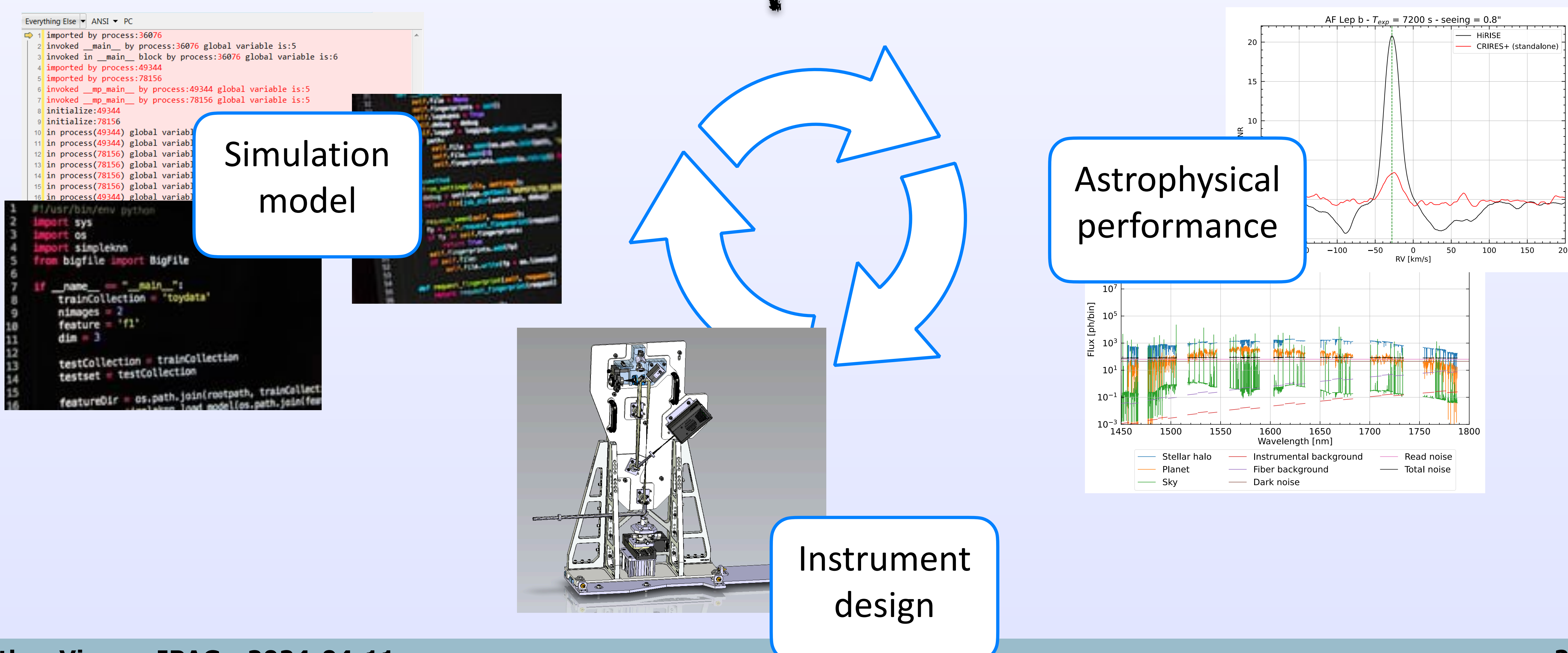
Technical requirements

The instrument must:

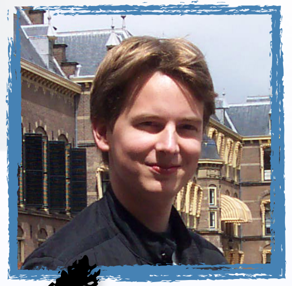
tech.req.1 Have no impact on regular operations of SPHERE, CRIRES, or UT3

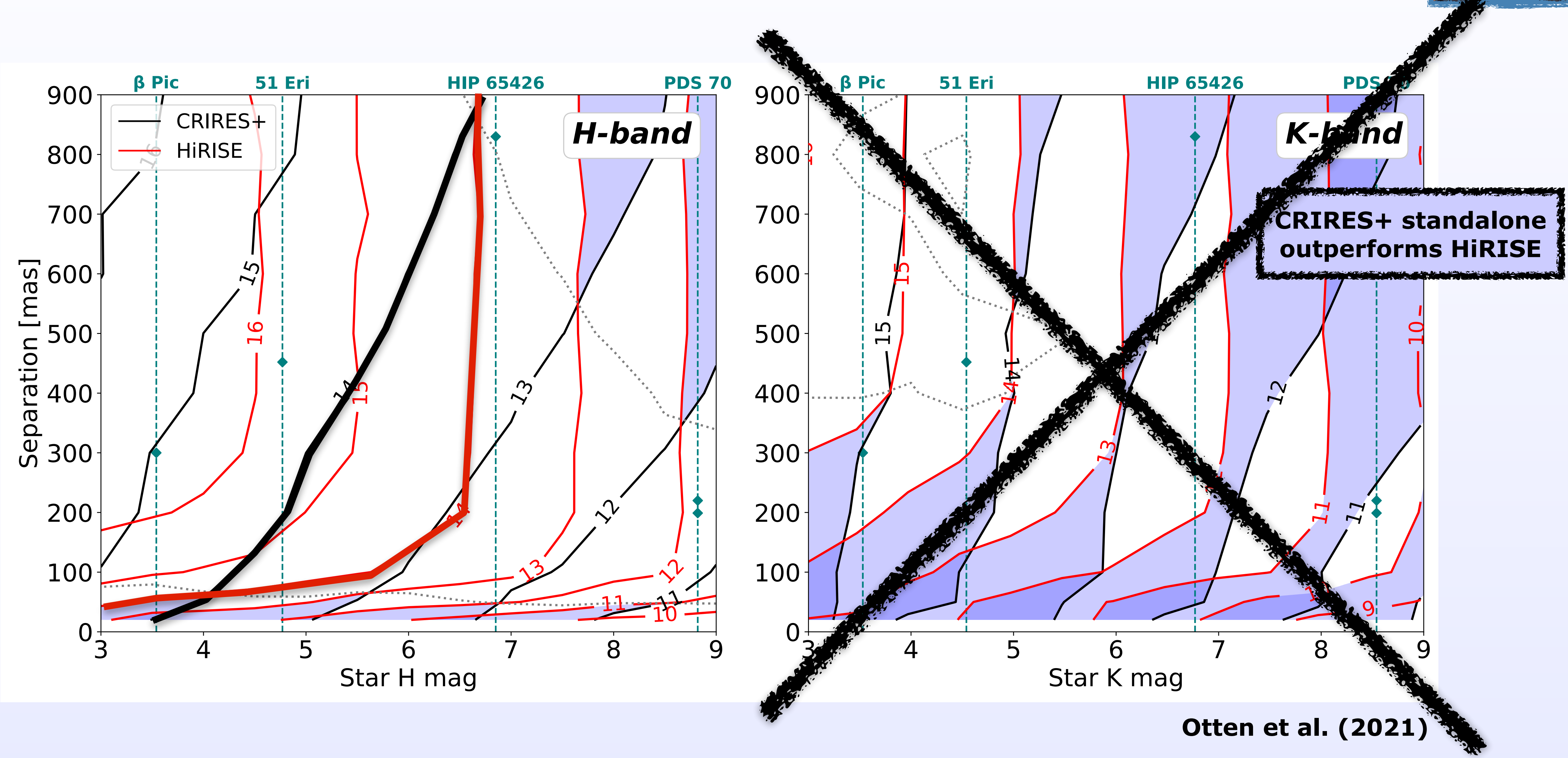
tech.req.2 Induce no modification of hardware used in regular operations

tech.req.3 Be compatible with ESO and VLT standards



Performance analysis

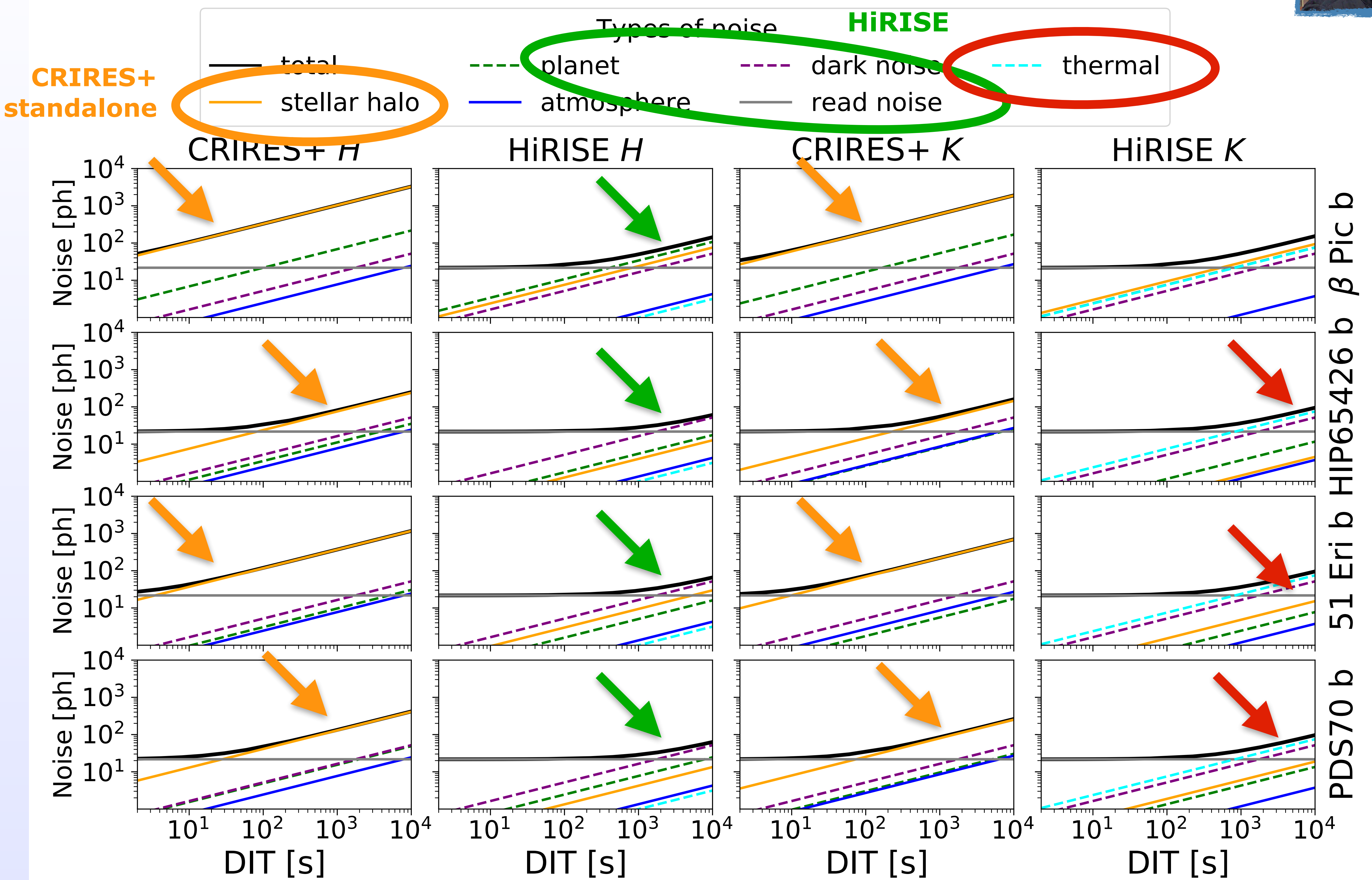




Otten et al. (2021)

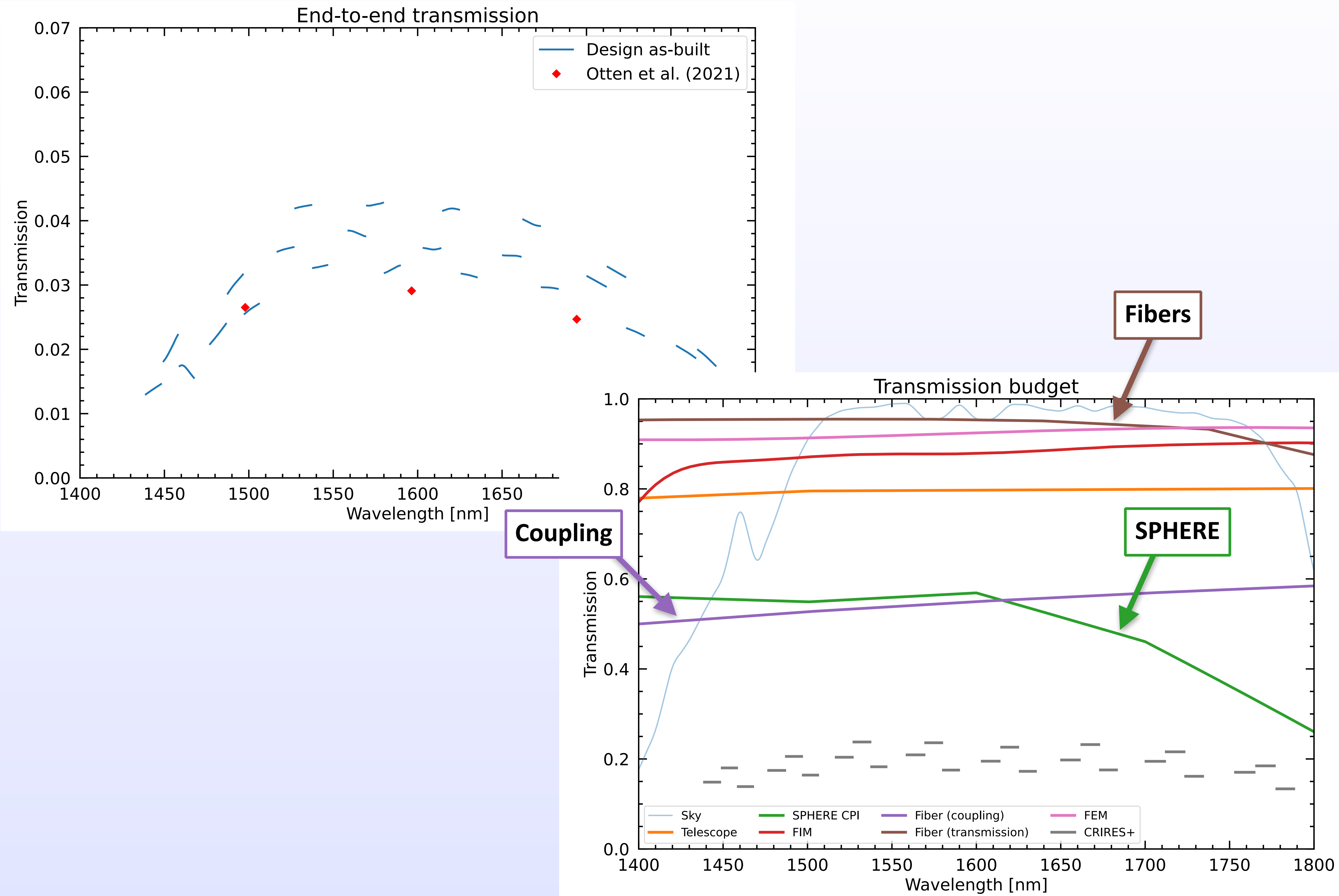
It is worth it in the H band!

Performance analysis

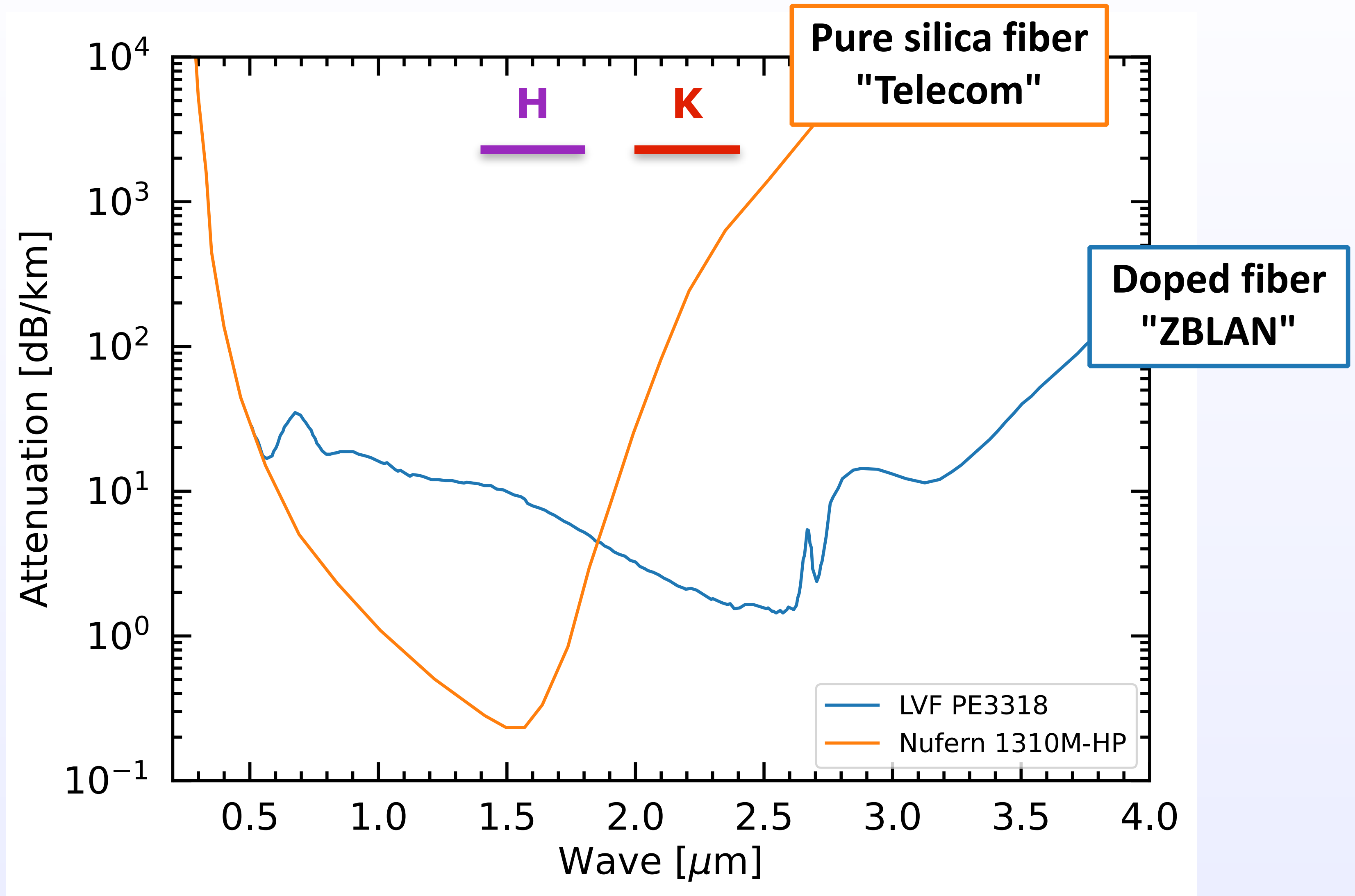


Otten et al. (2021)

Transmission budget



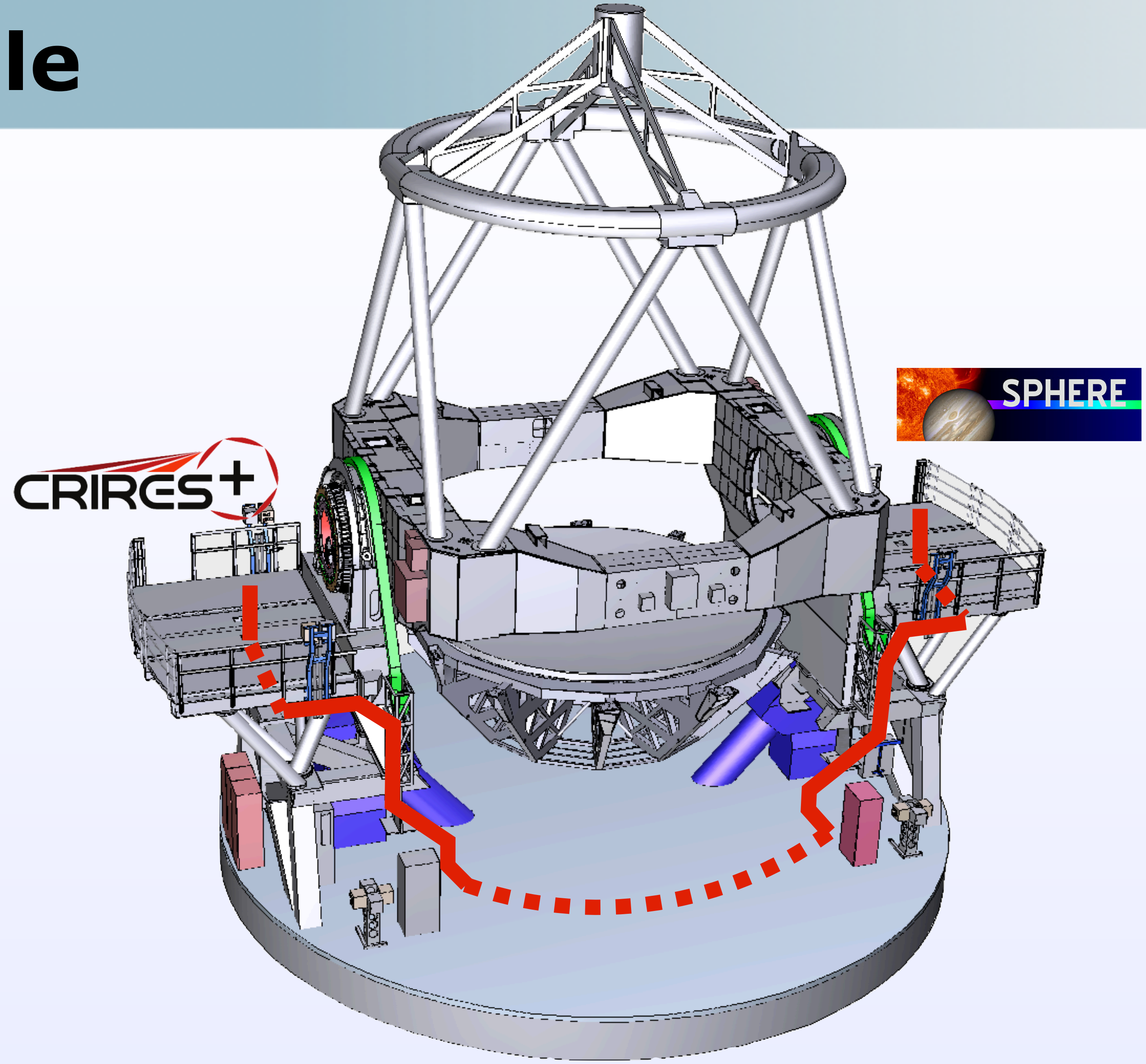
Choice of optical fiber

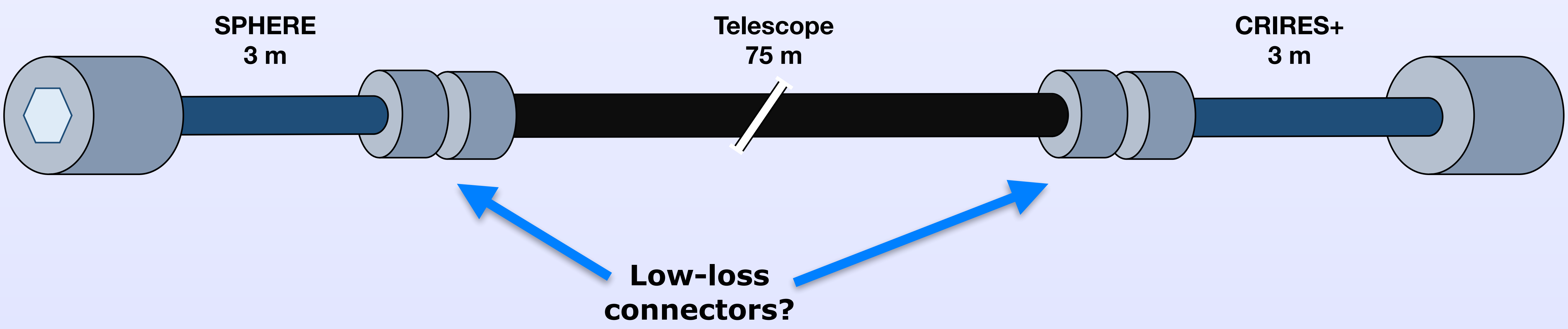


	Advantages	Drawbacks
ZBLAN	**Transmission in K band**	**(Supposedly) fragile** **Very expensive (~100 €/m)** **Transmission in H band**
Telecom	**Transmission in H band** **Extremely cheap (~1 €/m)**	**Transmission in K band**

Final choice: Telecom fiber

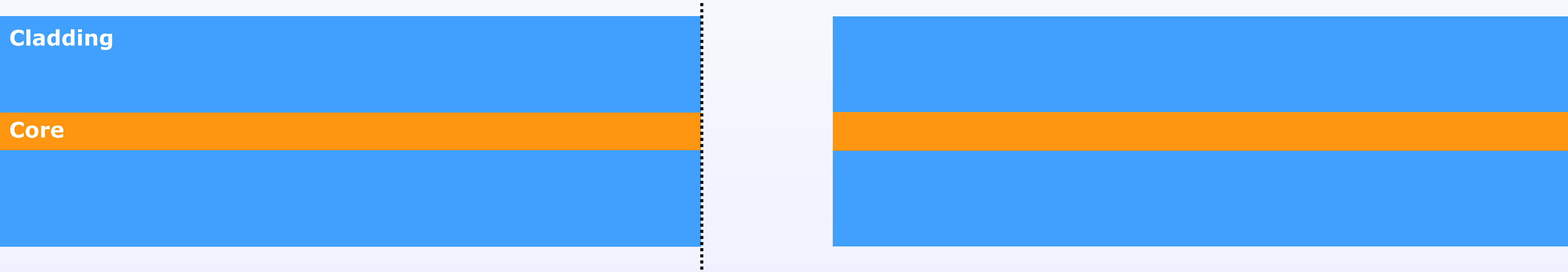
Fiber bundle

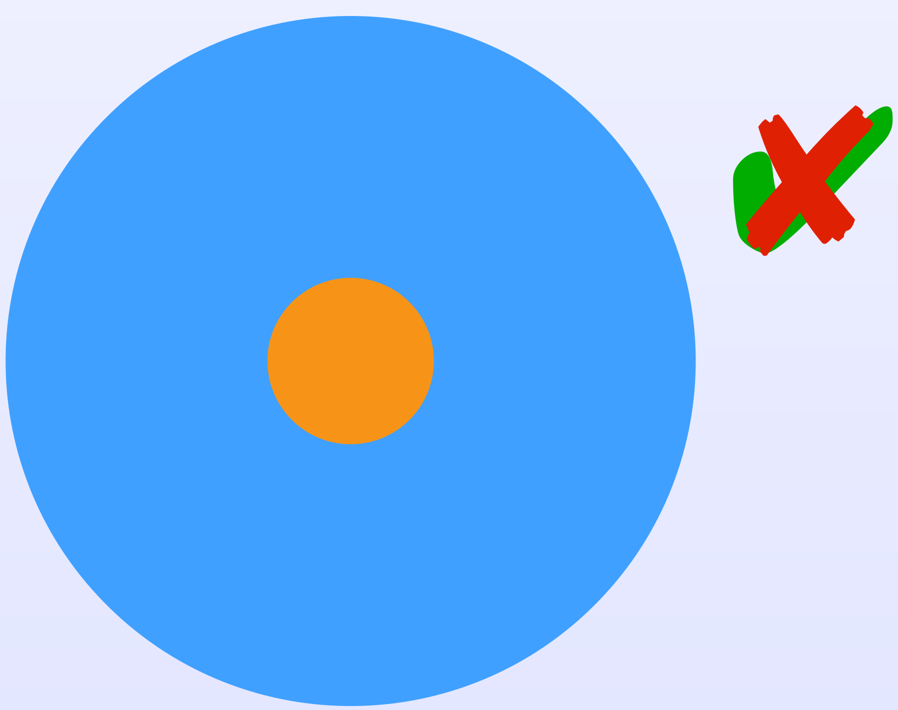


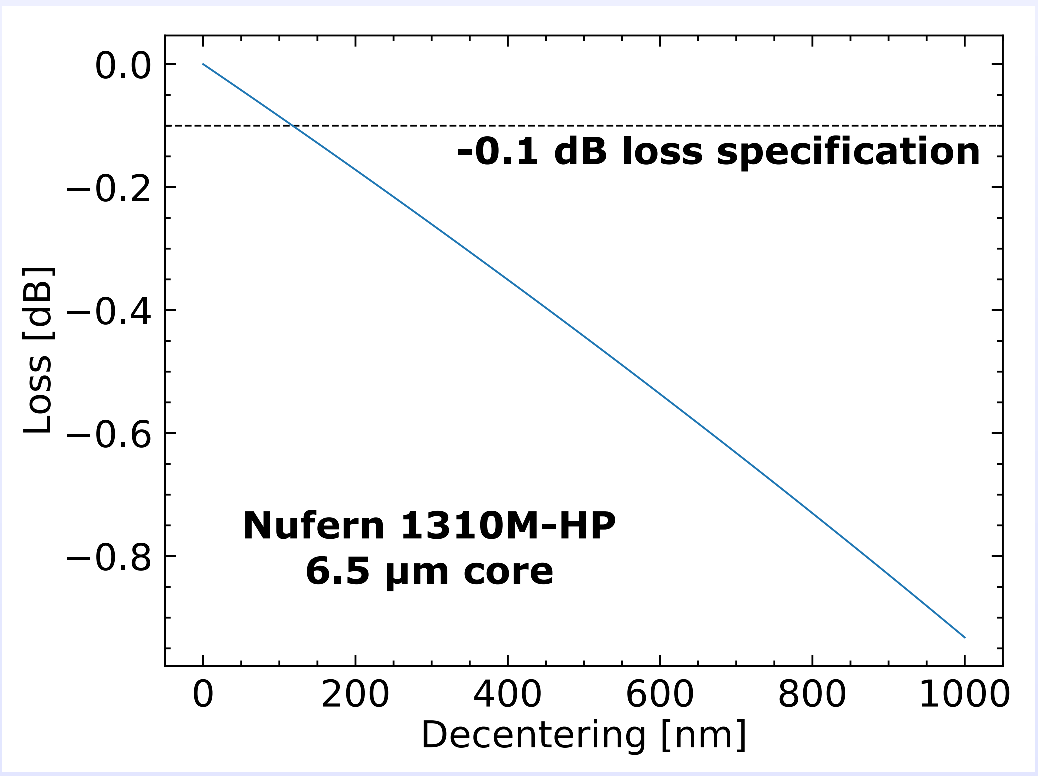


Low-loss connectors

Problem: single-mode fibres have very small cores! Typically **4-8 µm**





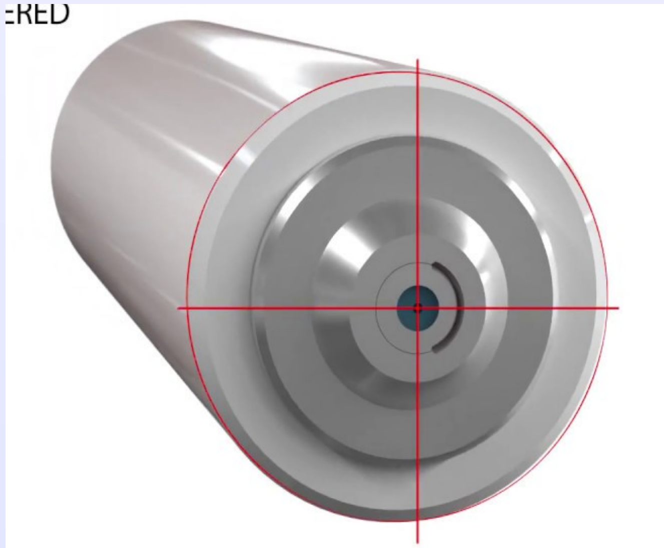


Low-loss connectors

- Rugged connectors with repeatable connection exist...

- ... but they need properly aligned fibres in the first place
- Only solution on the market: Diamond SA, Active Core Alignment → very (very) expensive

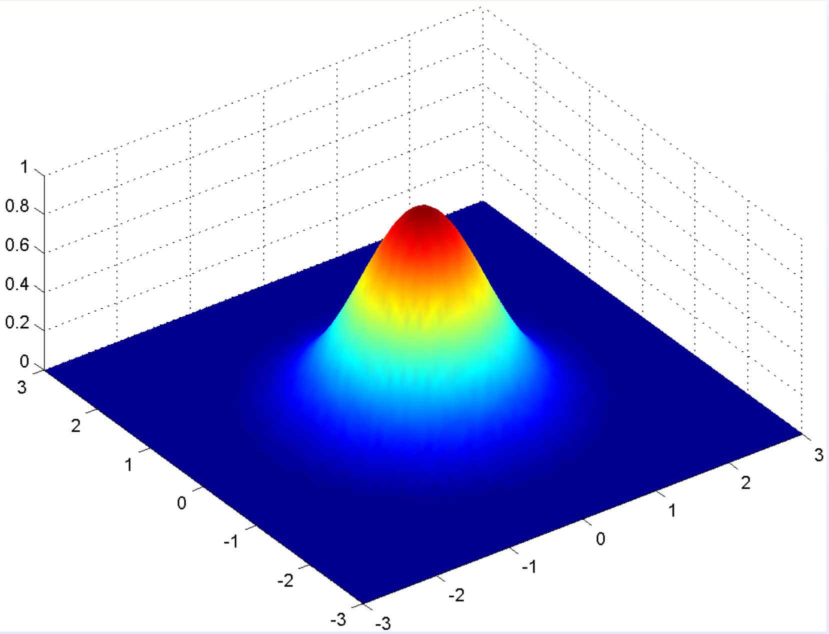


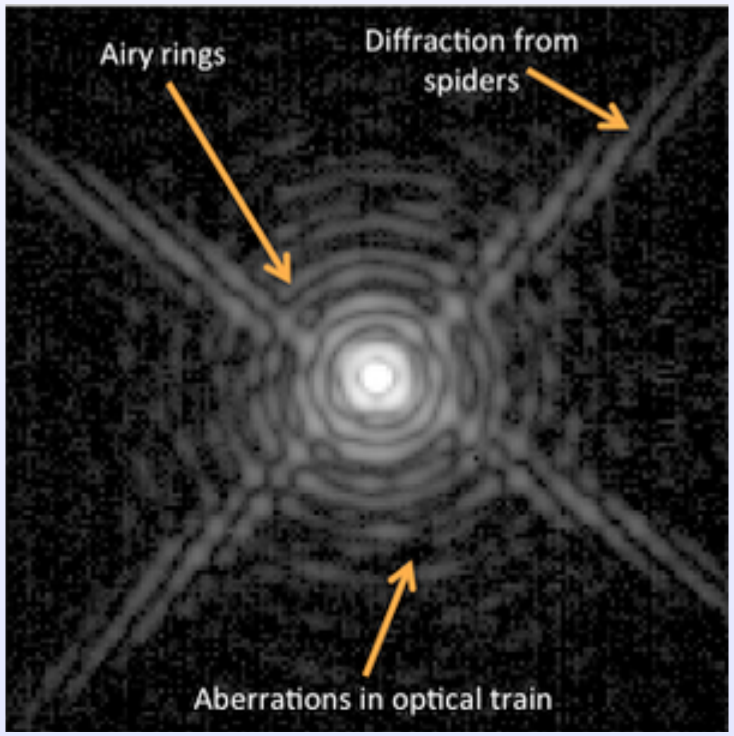
**Final choice:
No connectors**

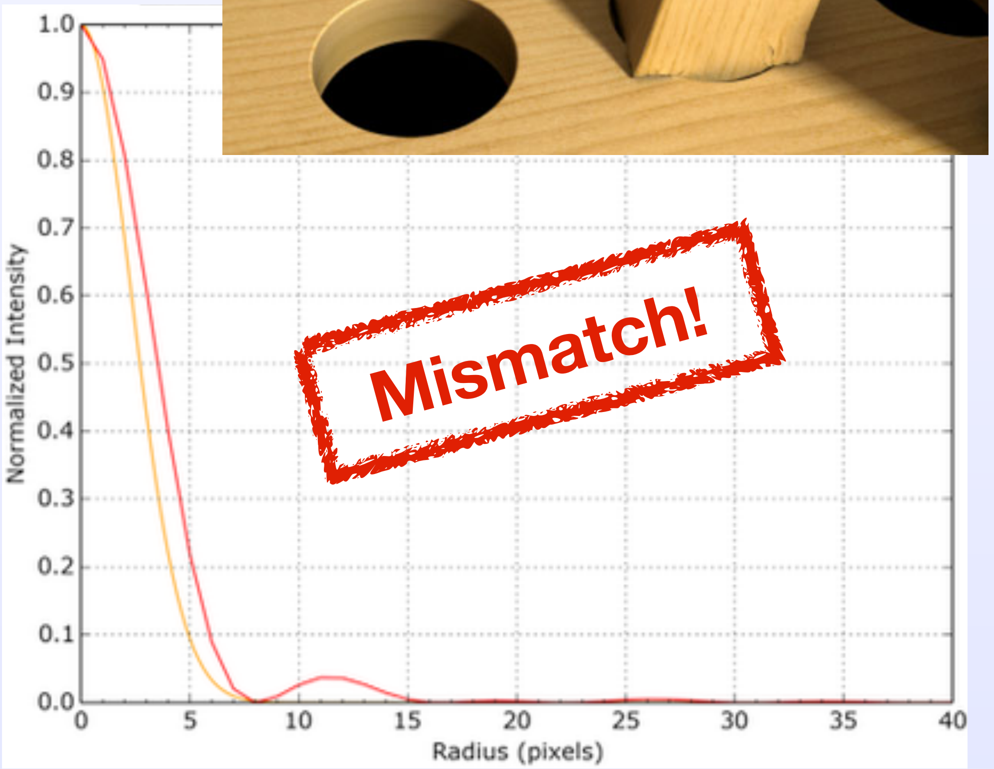
Single-mode fiber coupling

How much stellar/planetary light can you inject into an SMF?

- Single-mode fiber:
  - EM_{00} mode is quasi-Gaussian
- Telescope PSF:
  - Obstructed pupil + spiders
  - Complicated pattern

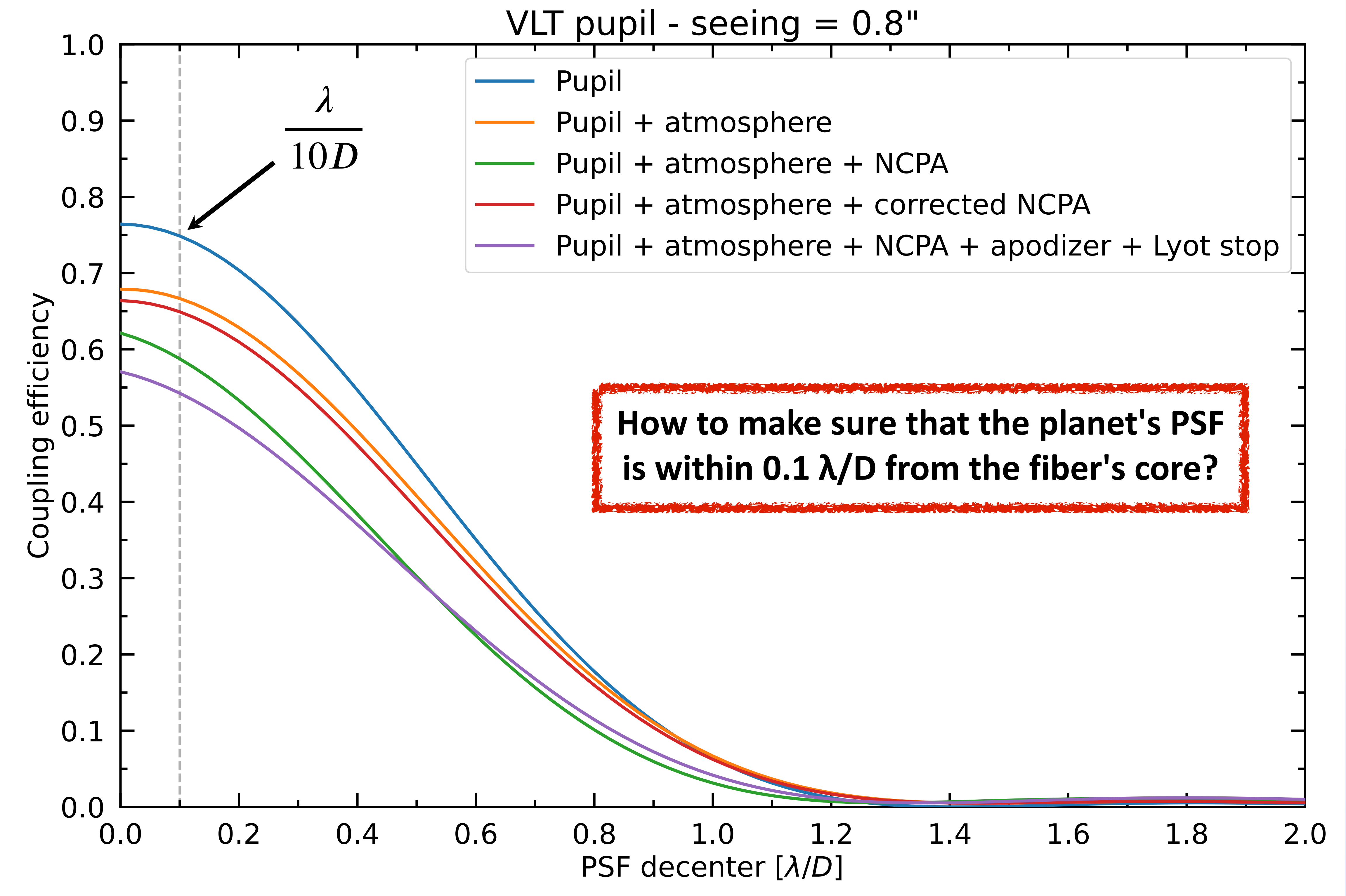






Jovanovic et al. (2017)

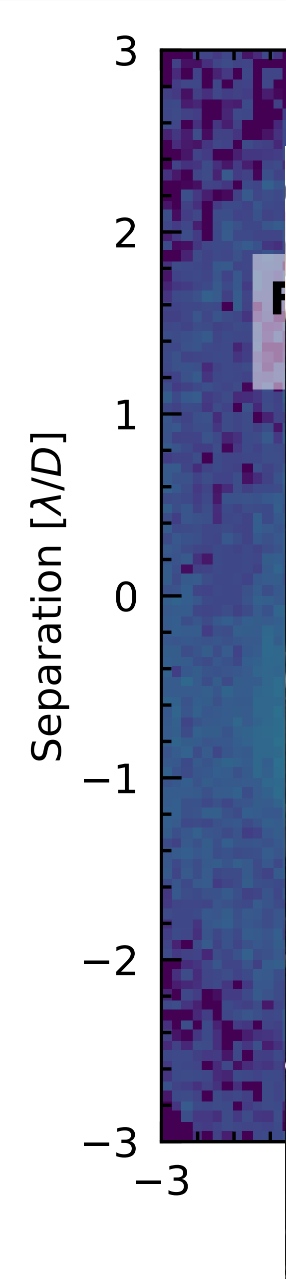
Coupling vs. PSF centering

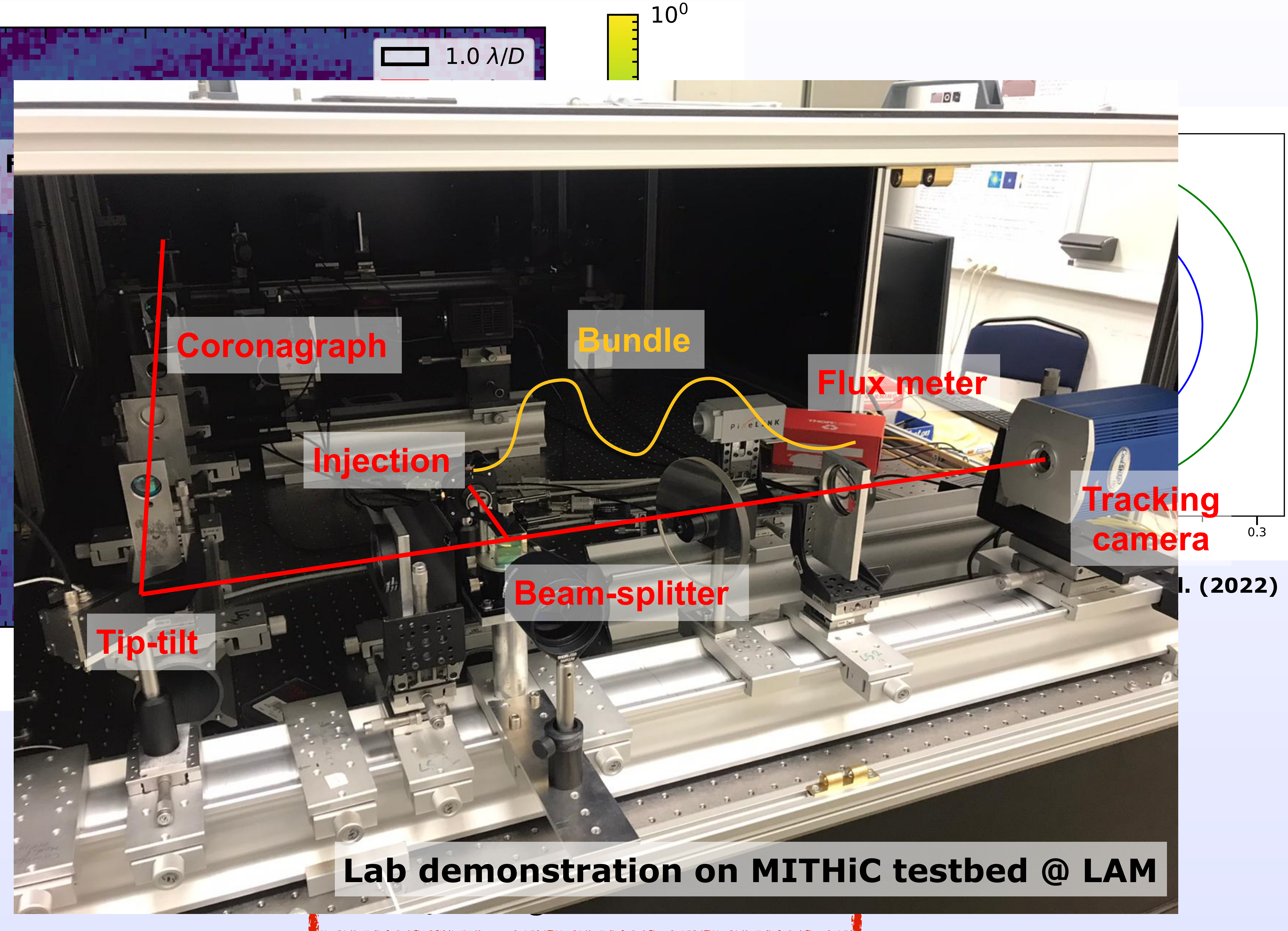


How to make sure that the planet's PSF is within 0.1 λ/D from the fiber's core?

PSF centering: an operational challenge

Coupling

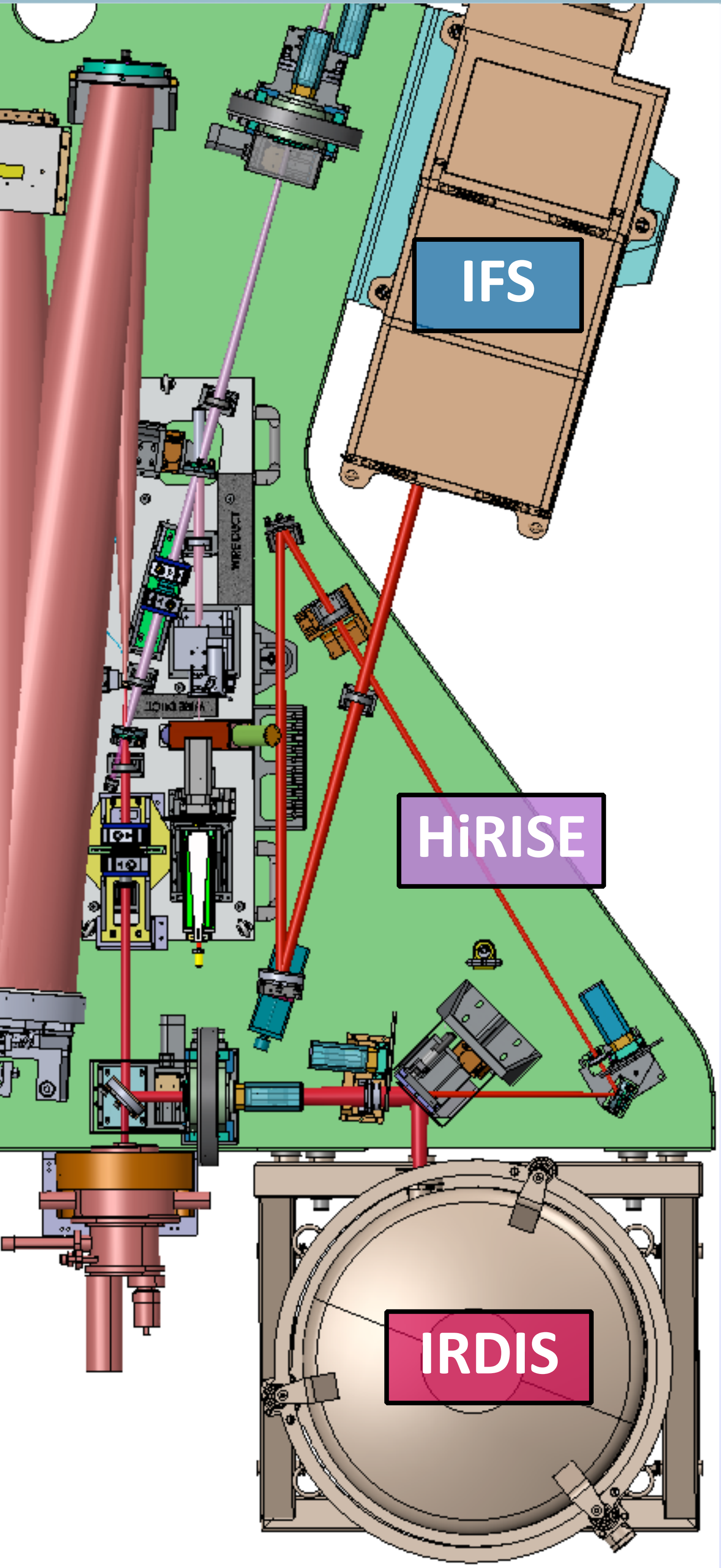


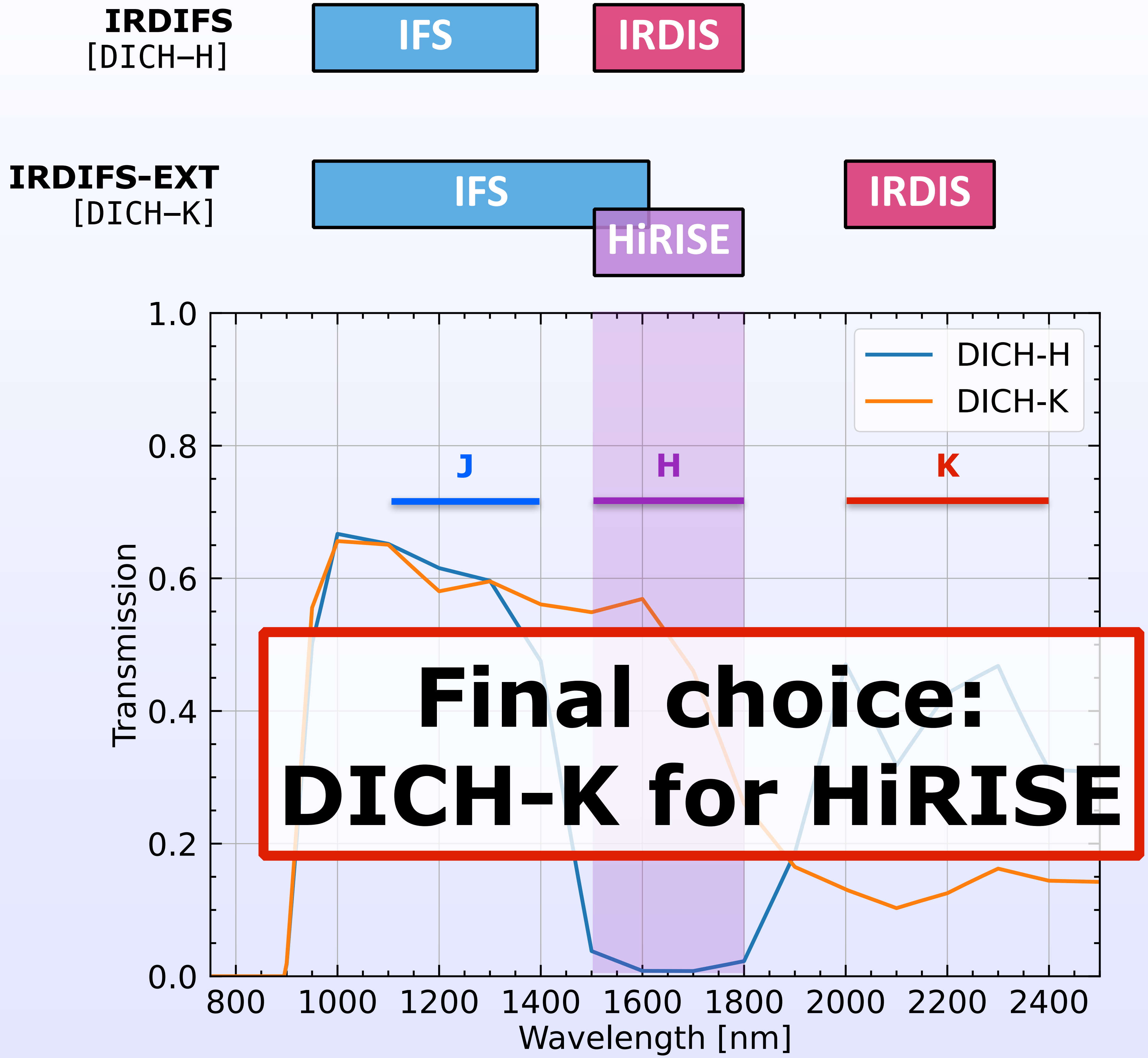


l. (2022)

Photon sharing in SPHERE

SPHERE



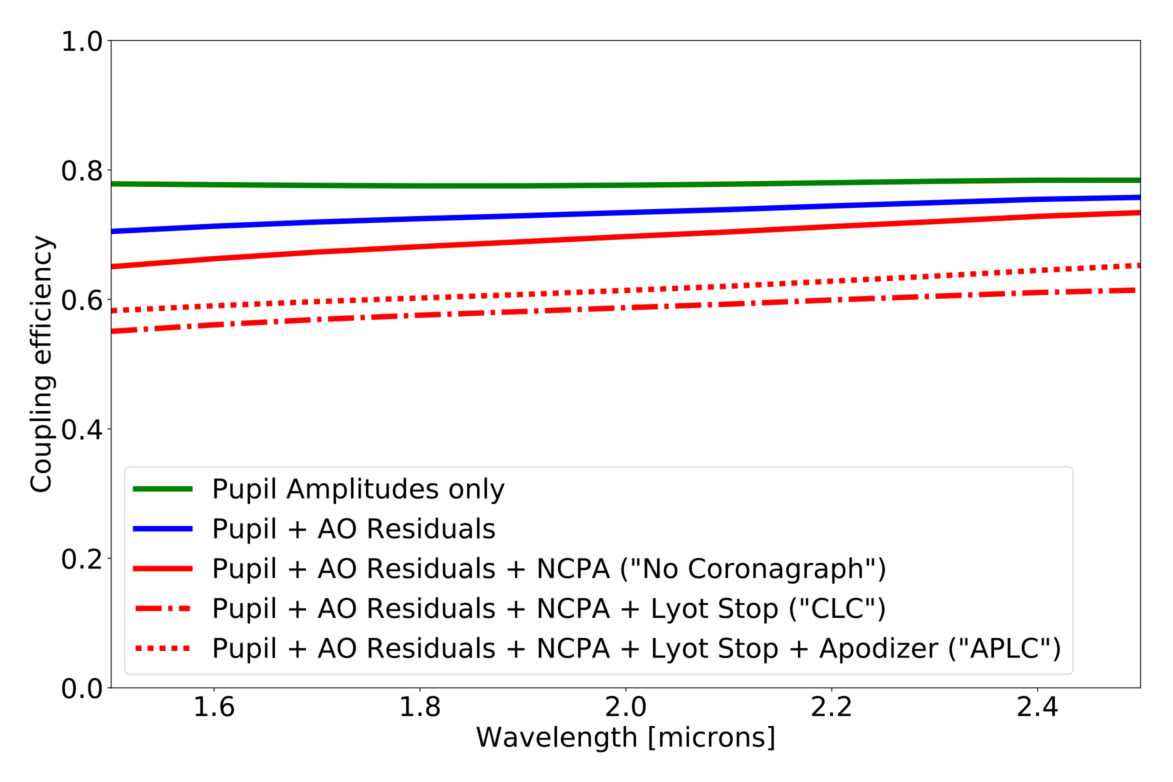


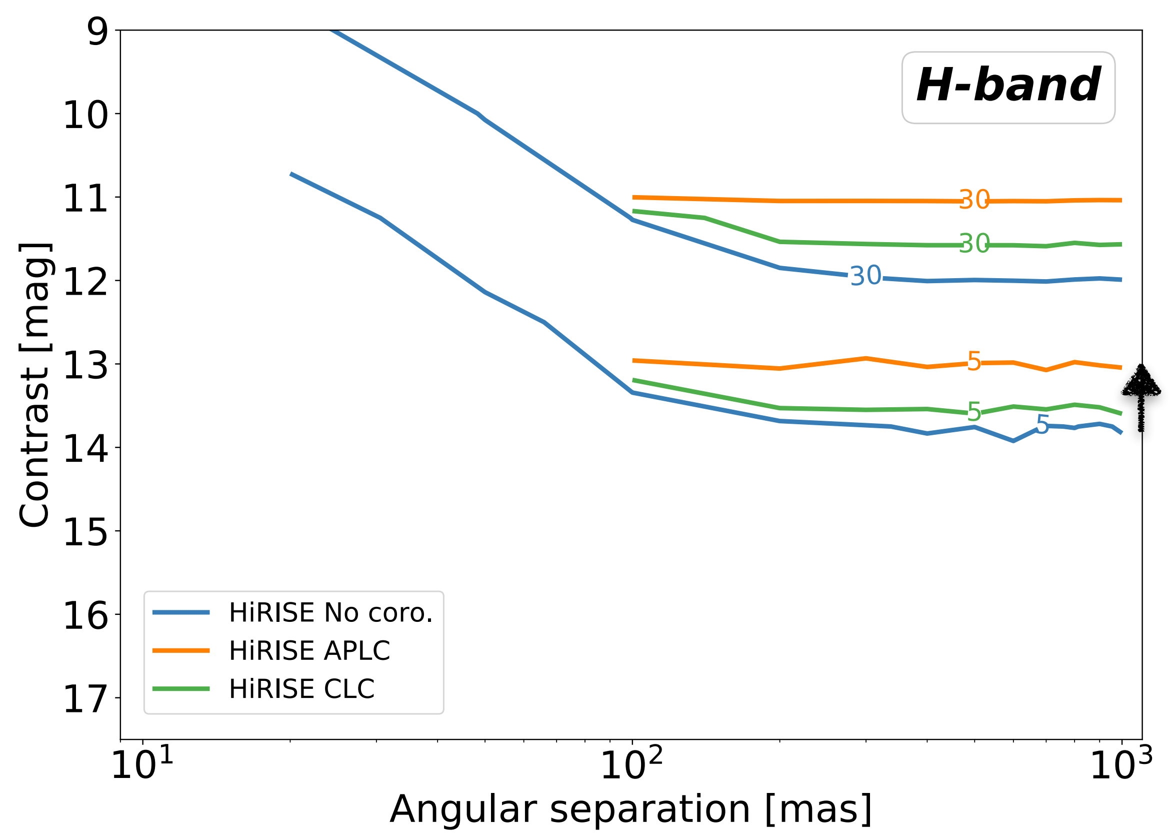
Final choice: DICH-K for HiRISE

To have or not to have [a coronagraph]?

SPHERE

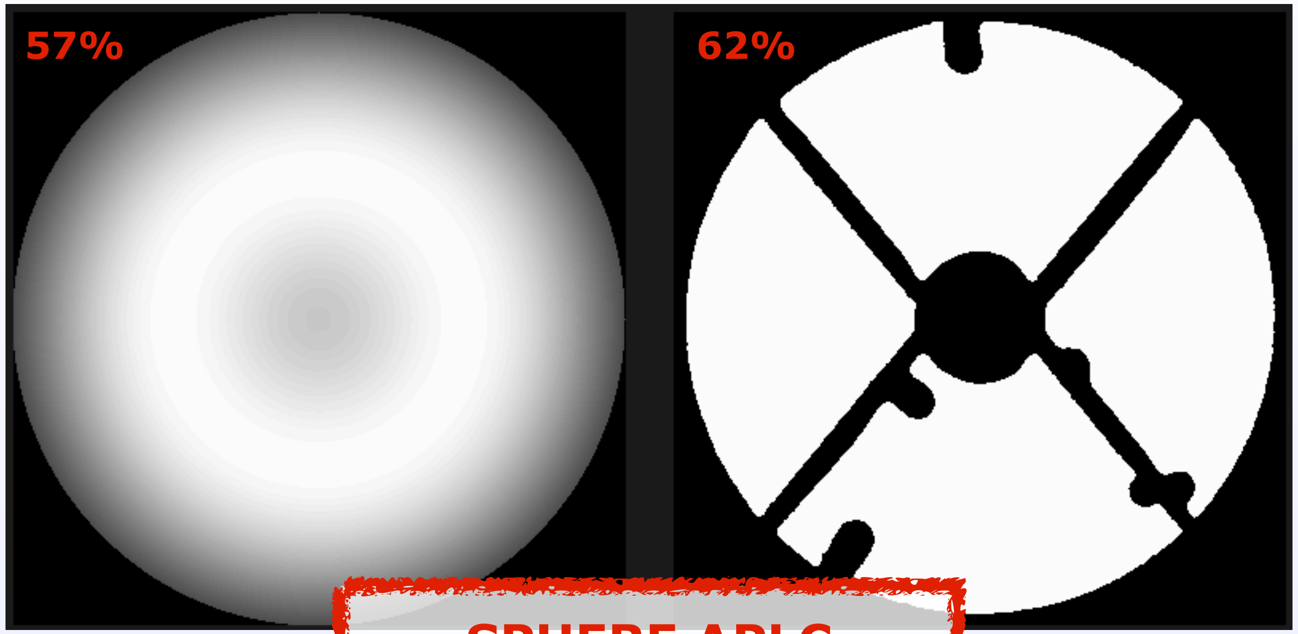
Coupling efficiency





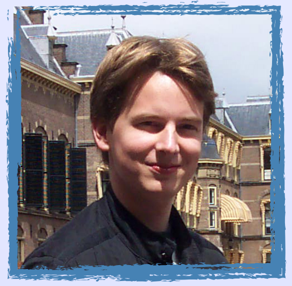
1 mag loss

Transmission

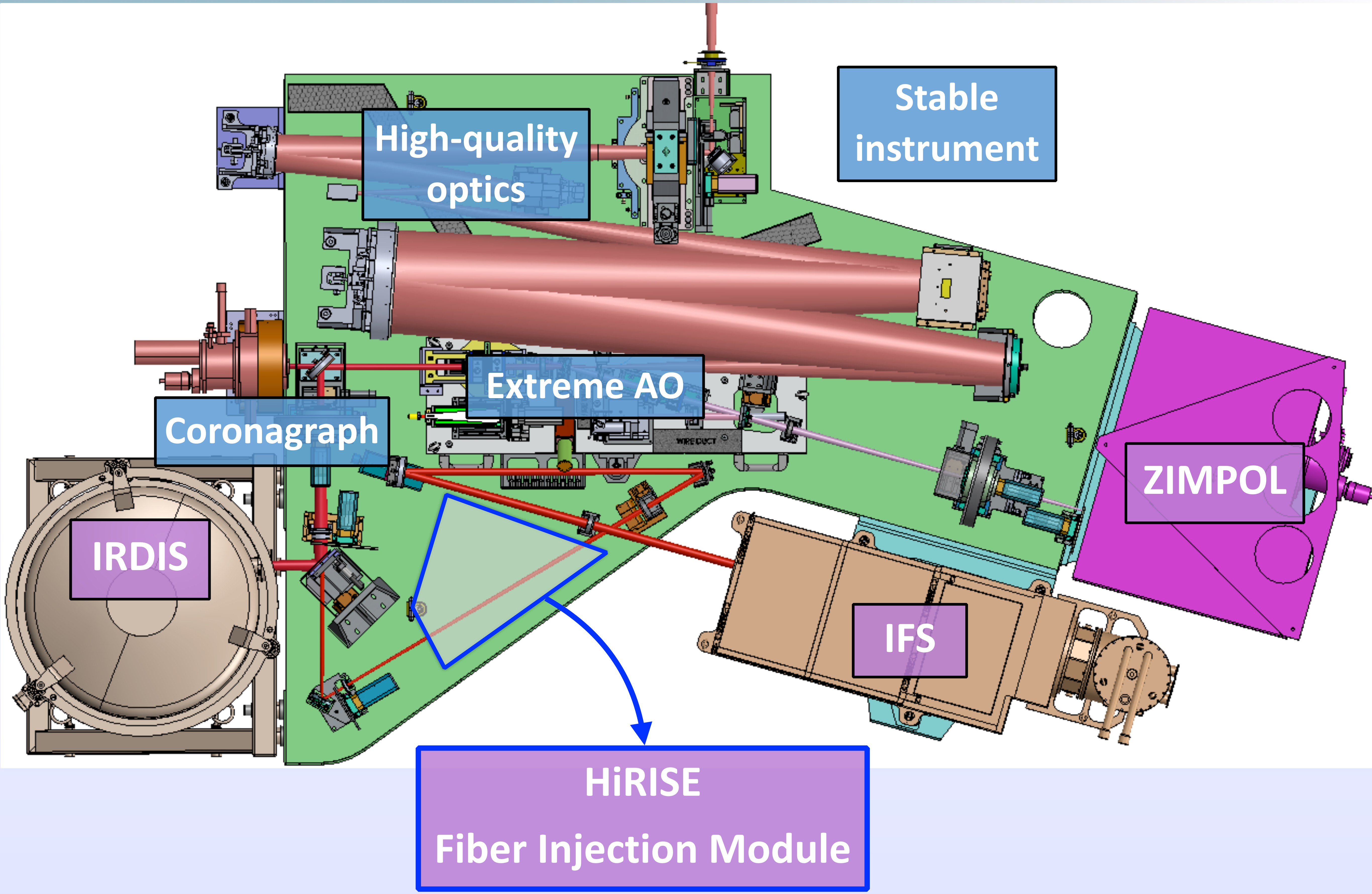


SPHERE APLC <40% of the total flux is transmitted!!

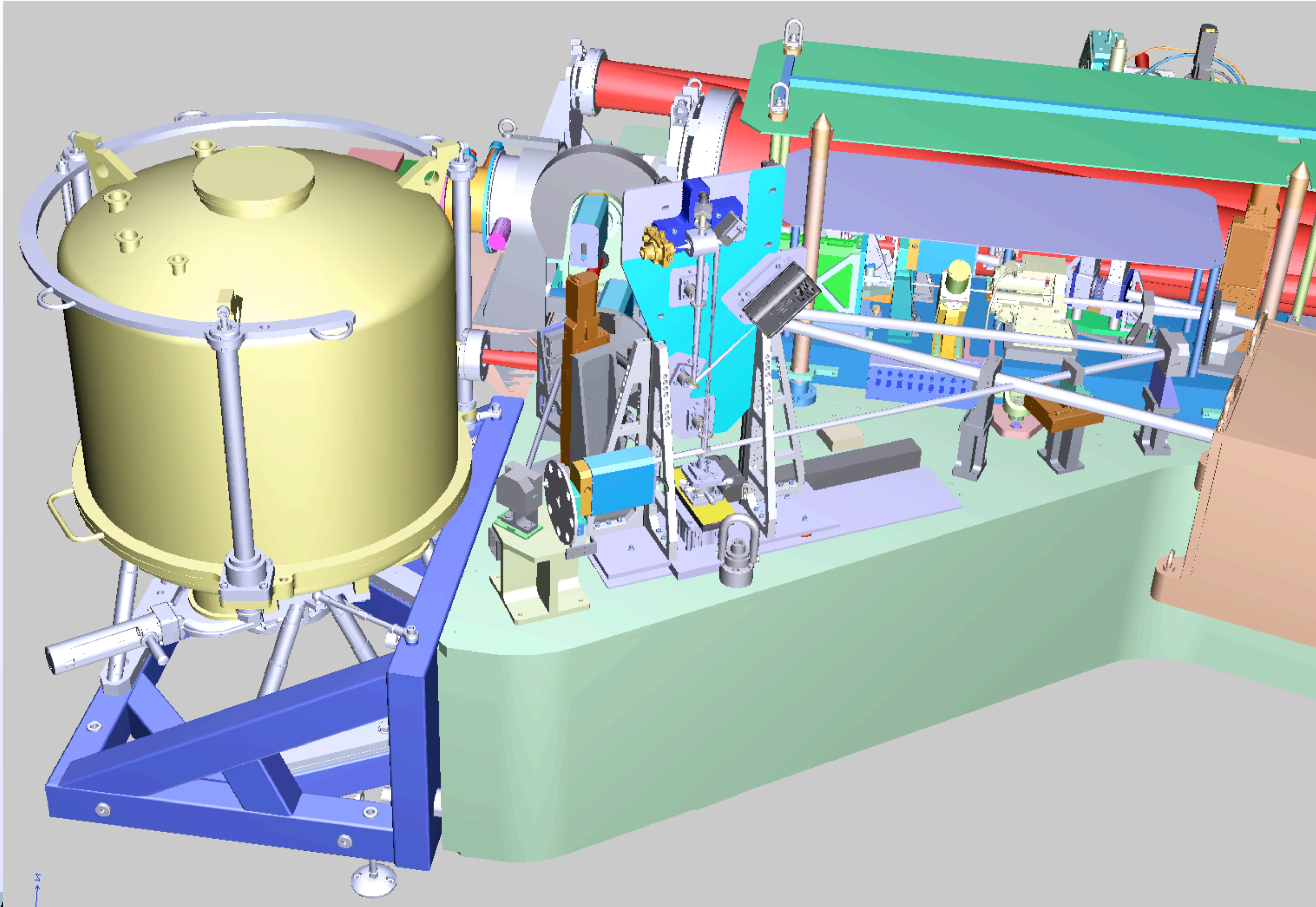
Final choice: No coronagraph

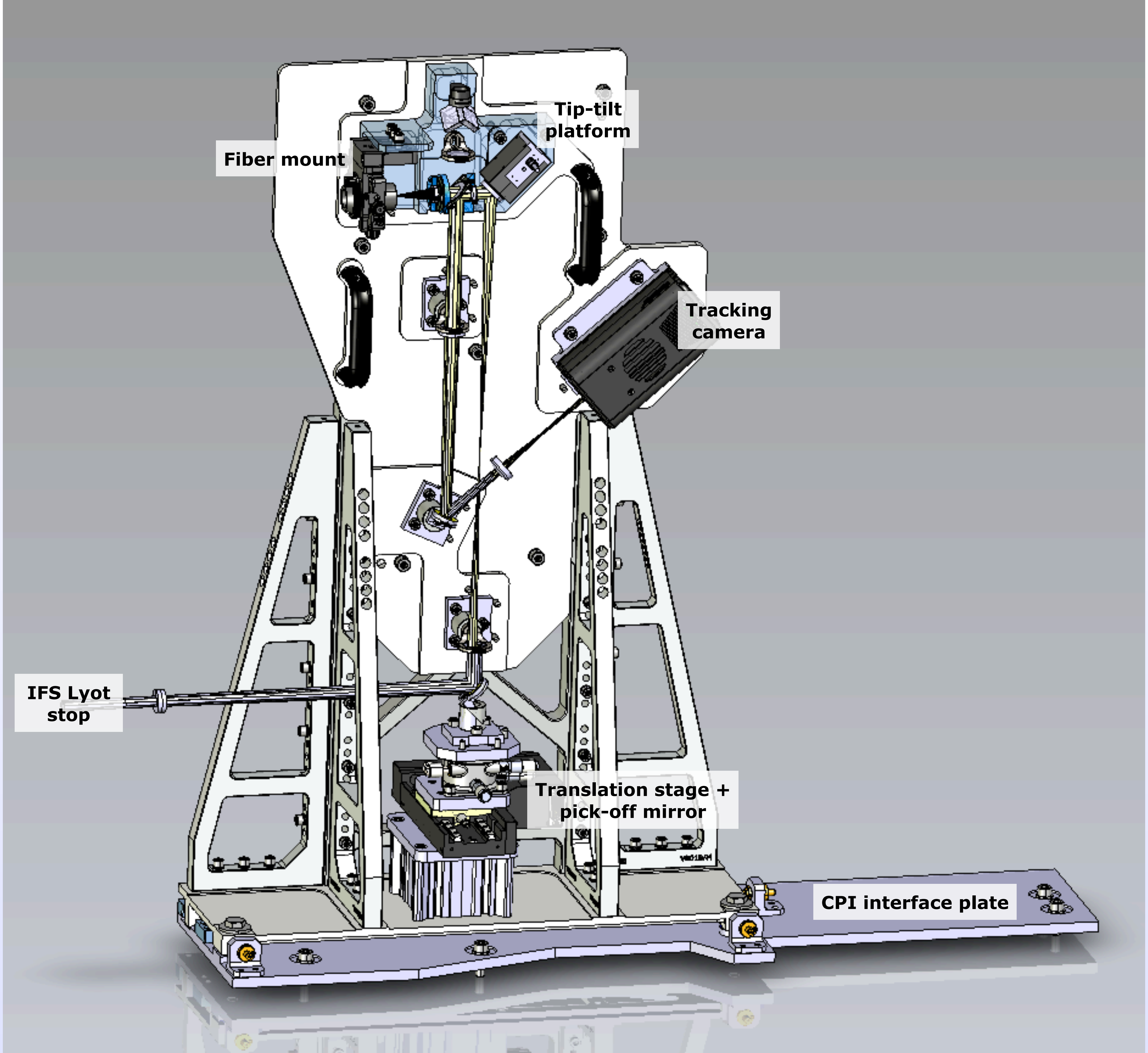


Fiber injection module

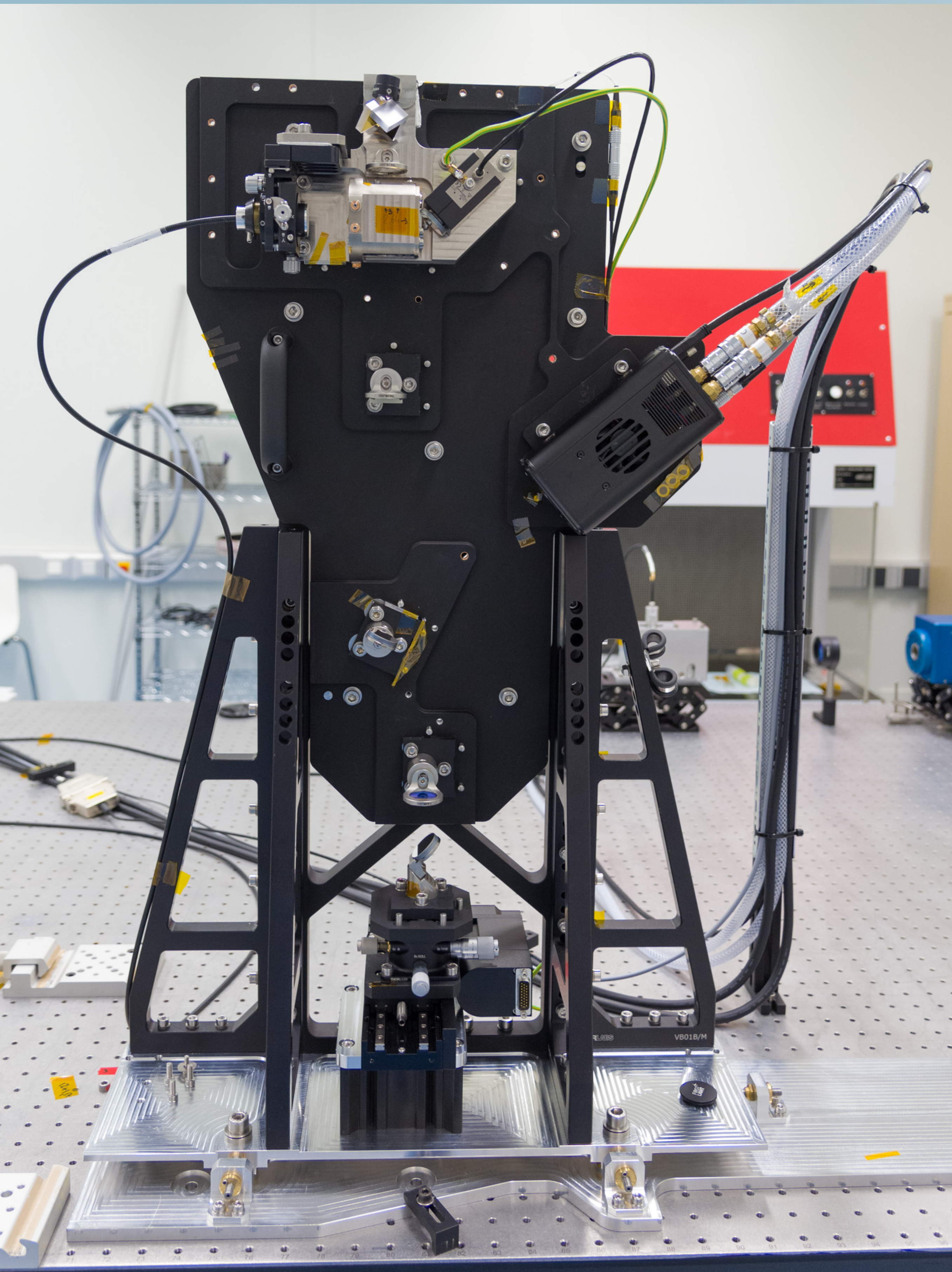


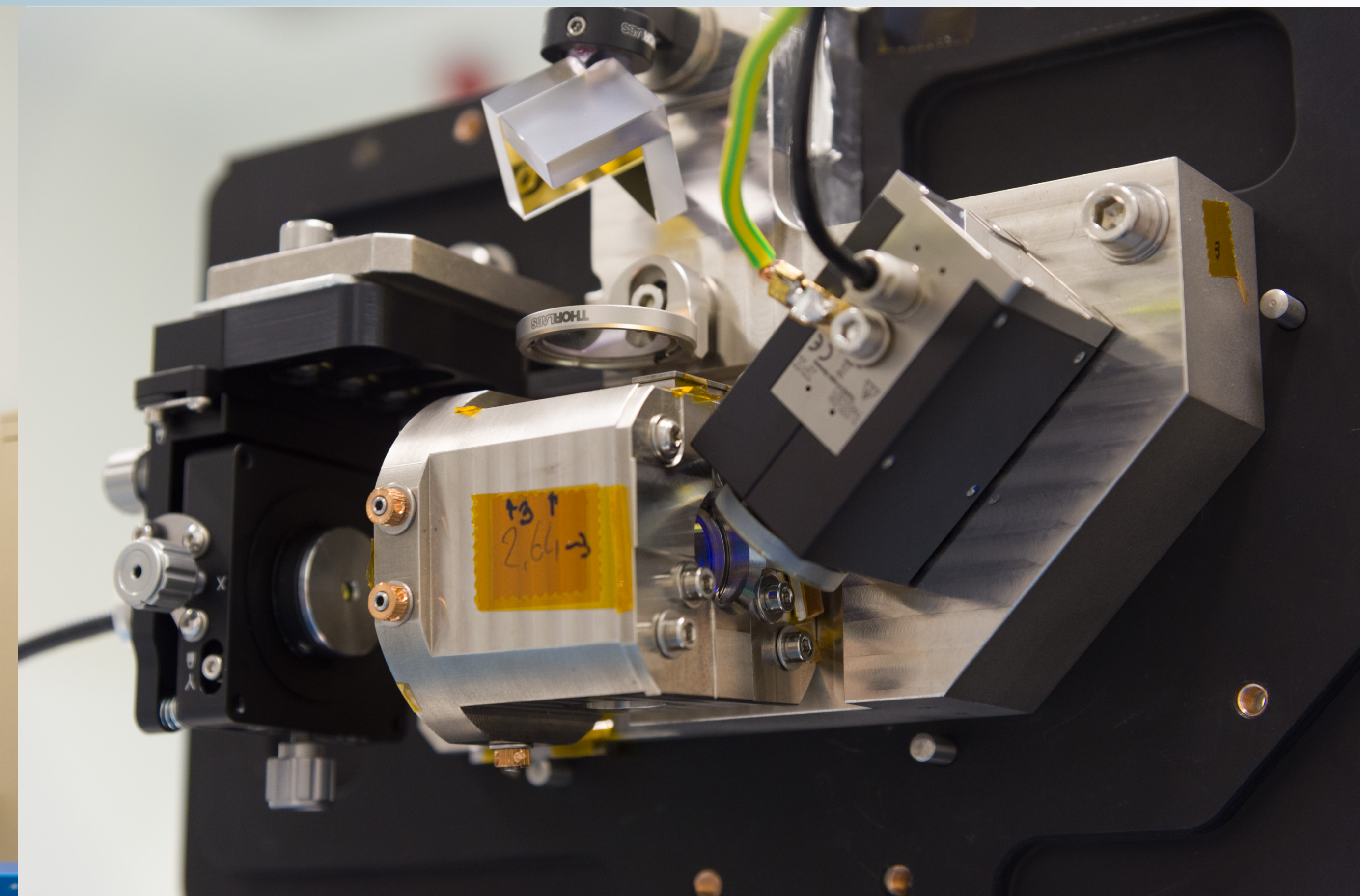
Fiber injection module

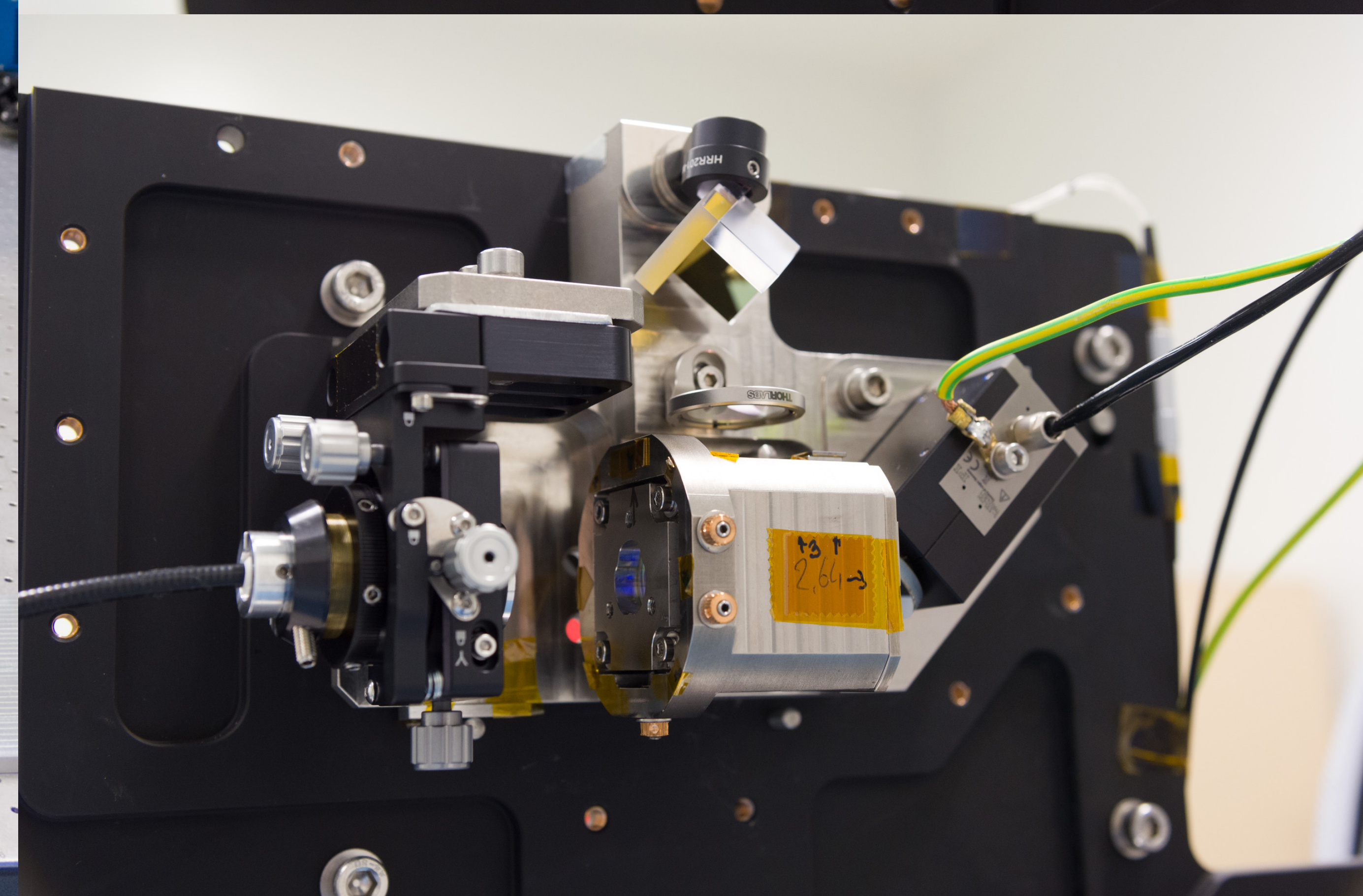



Tip-tilt platform
Fiber mount
Tracking camera
IFS Lyot stop
Translation stage + pick-off mirror
CPI interface plate

Fiber injection module

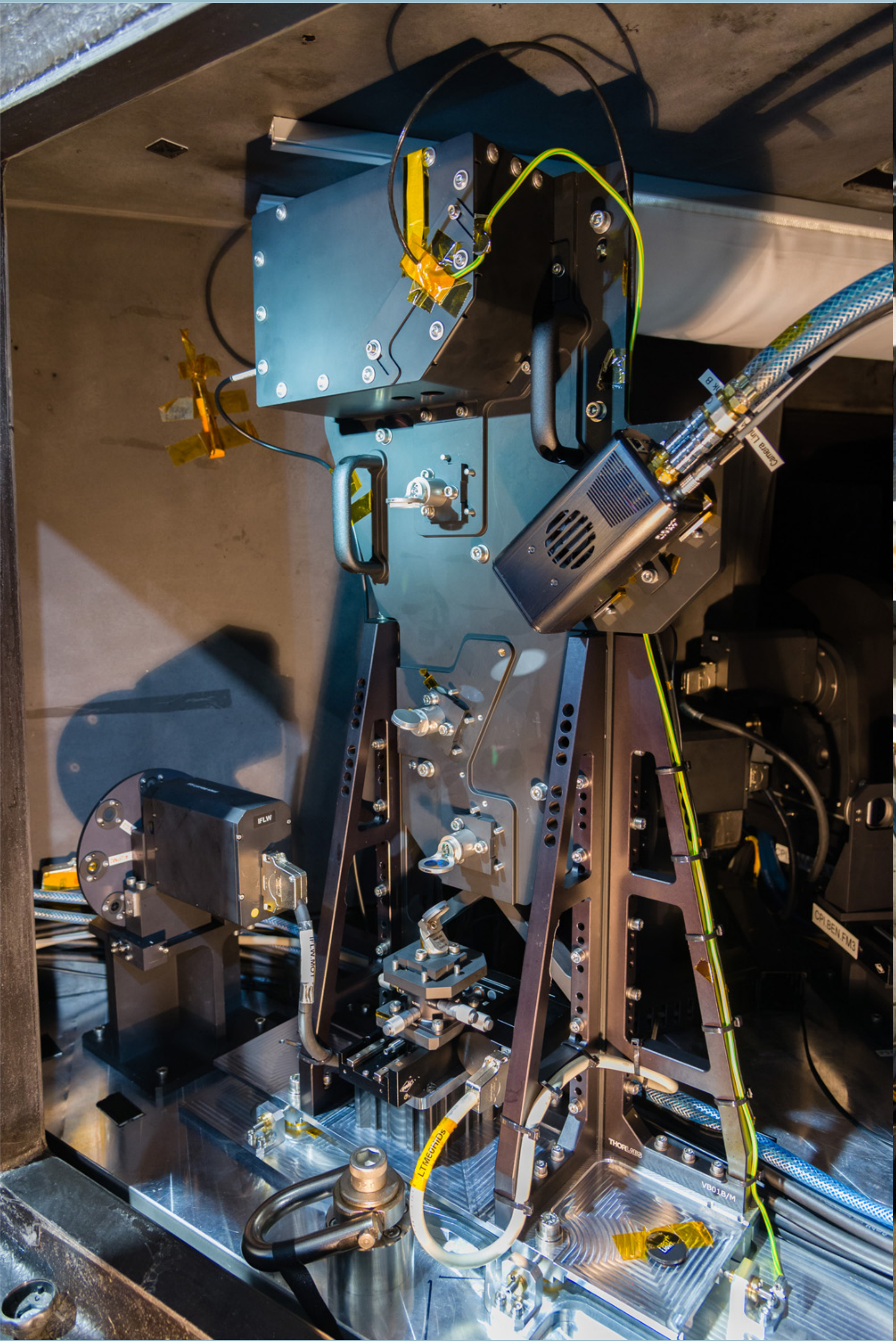


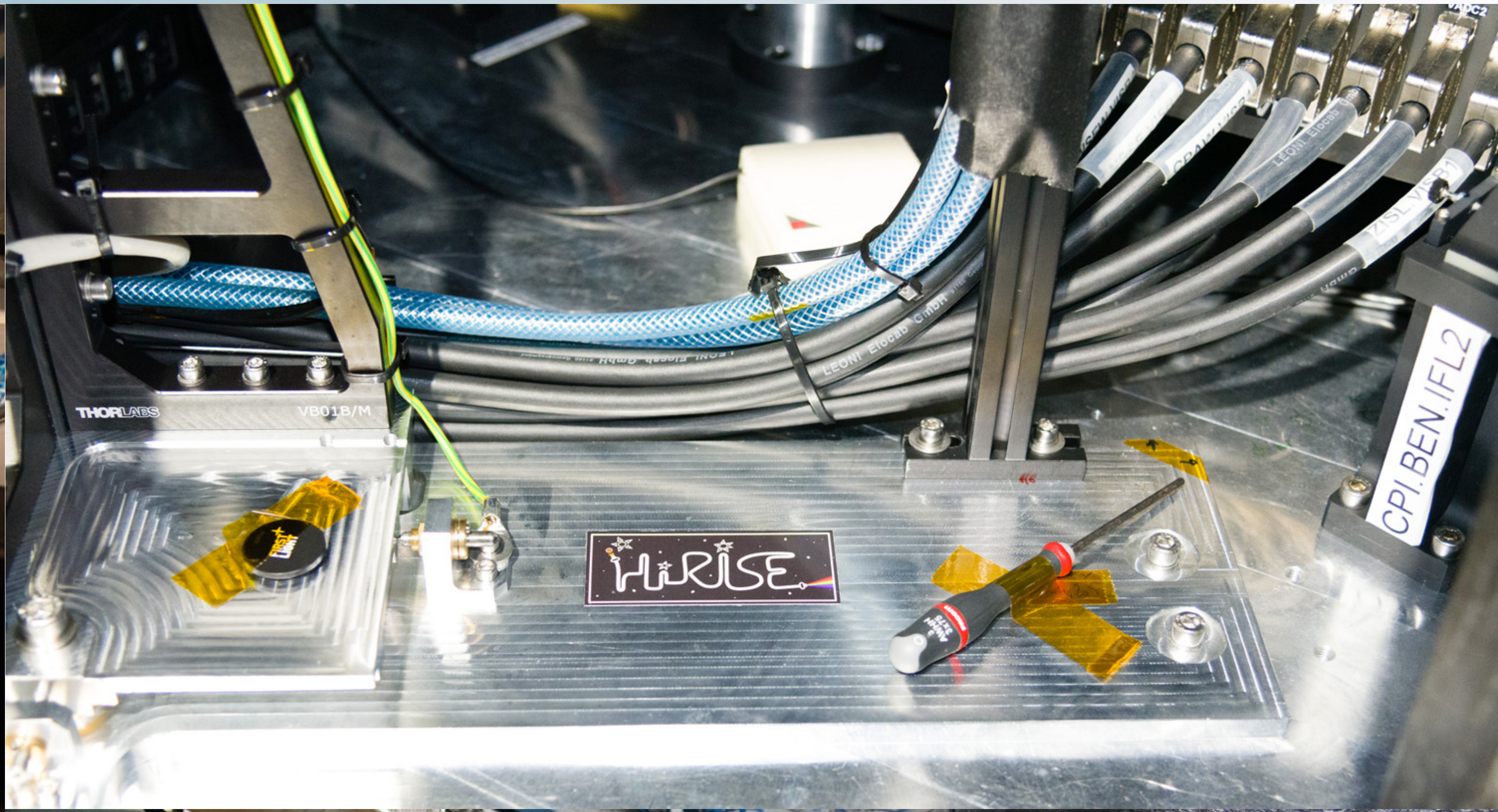


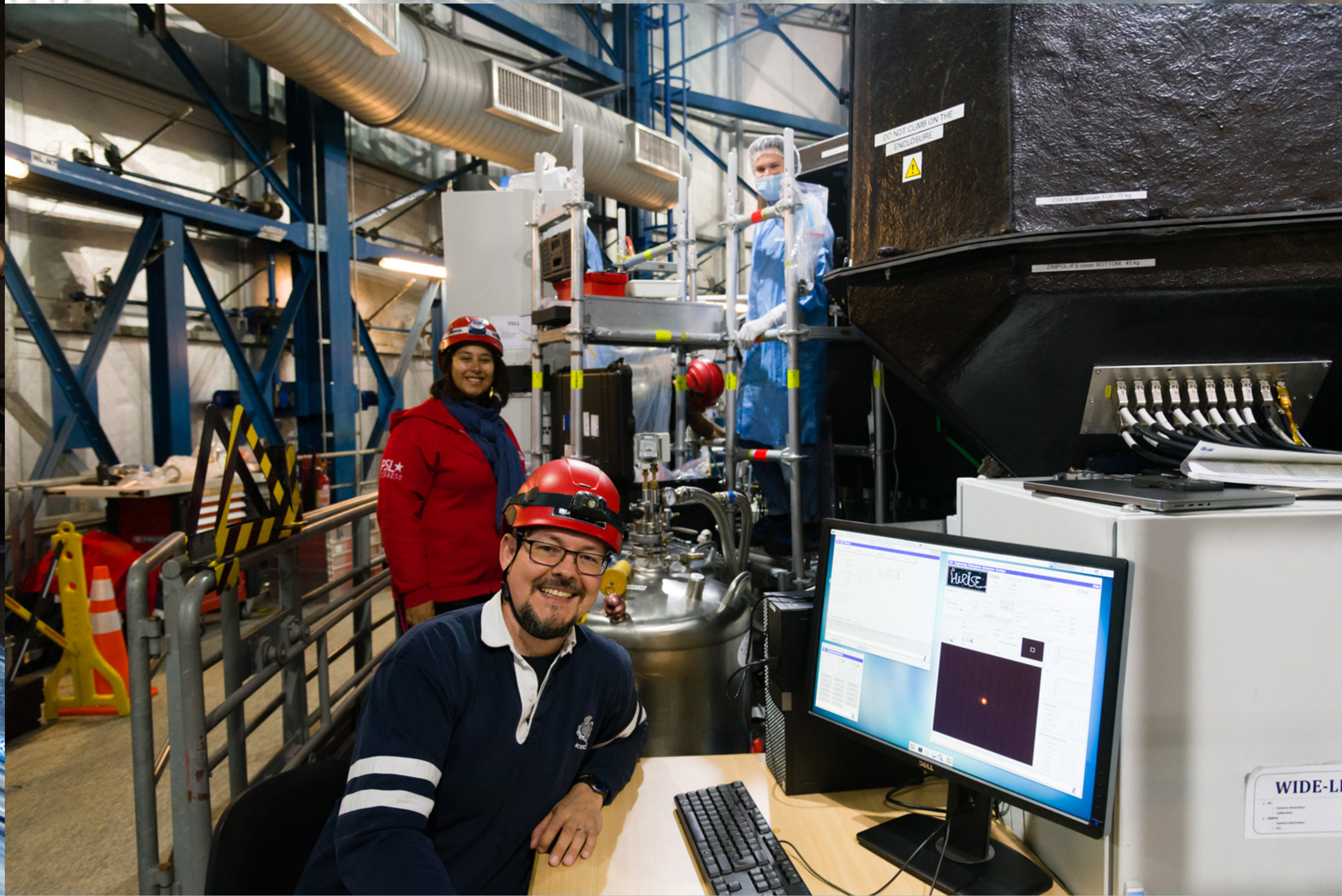


Fiber injection module

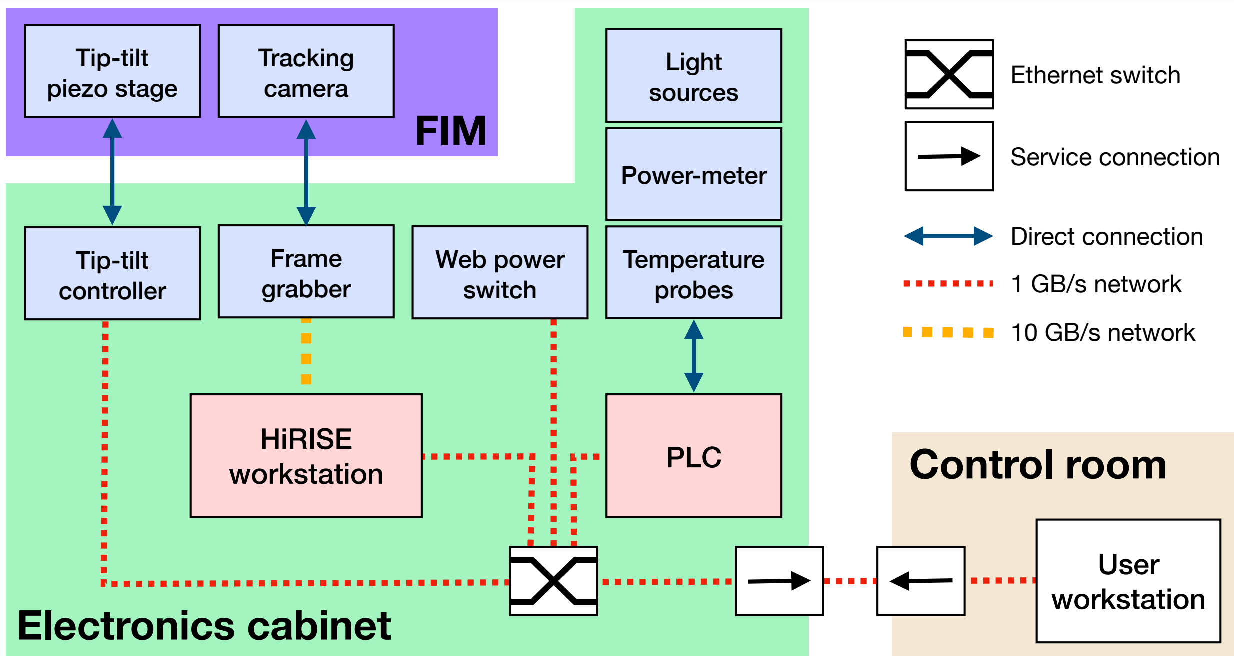
Fiber injection module

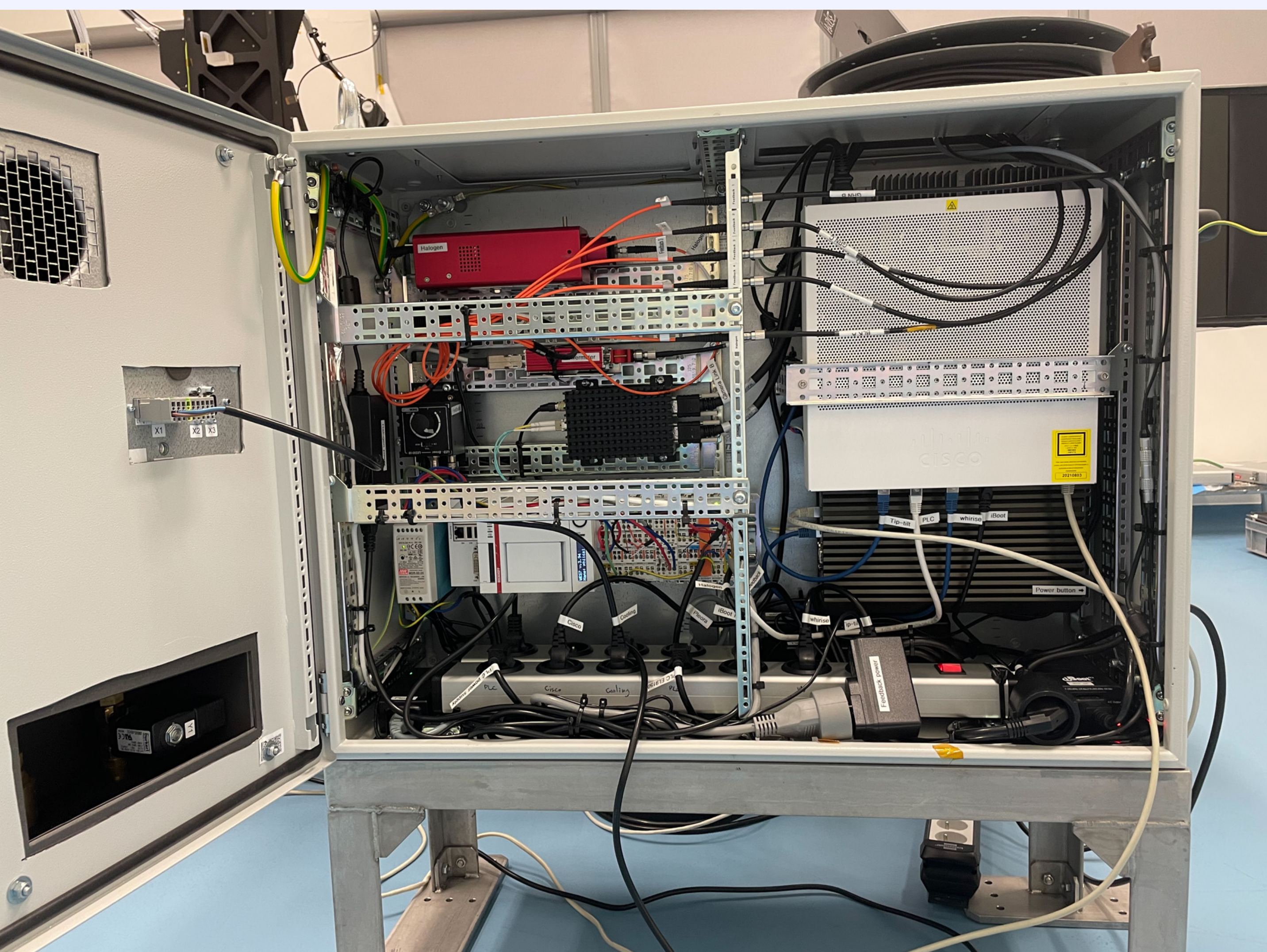




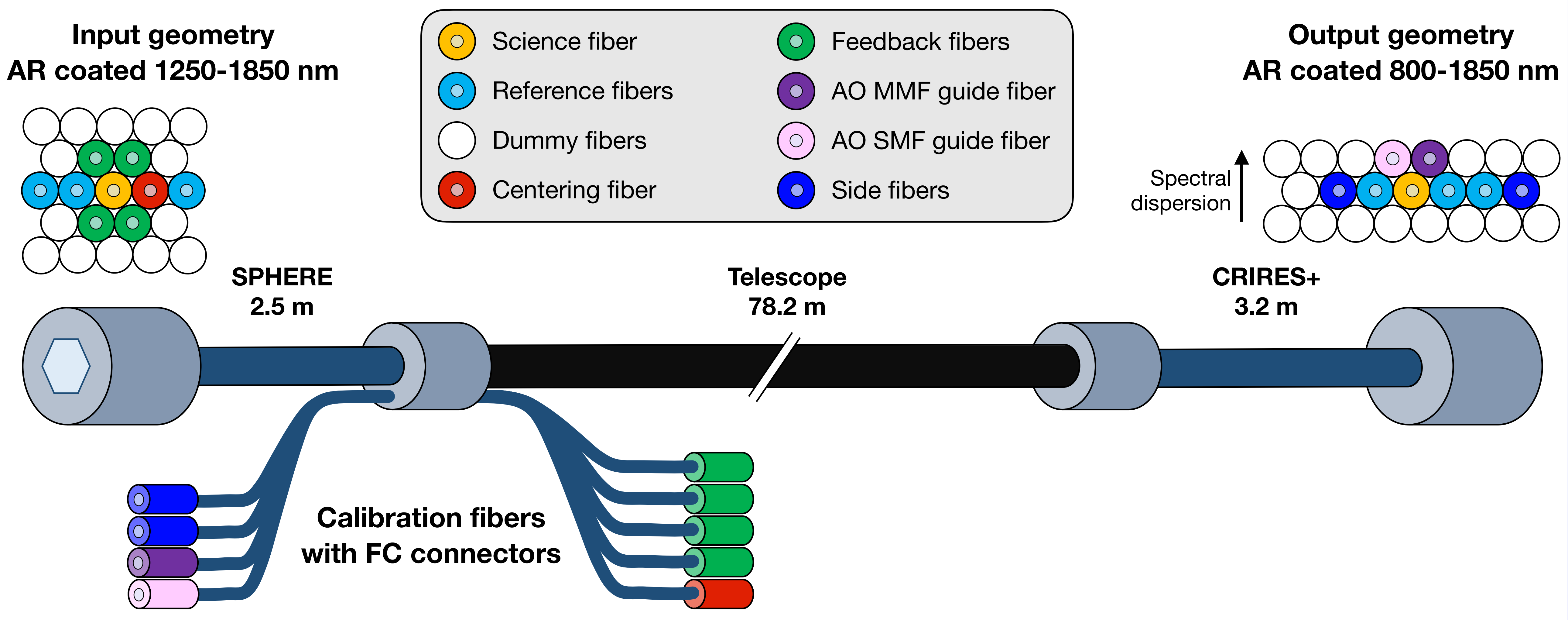


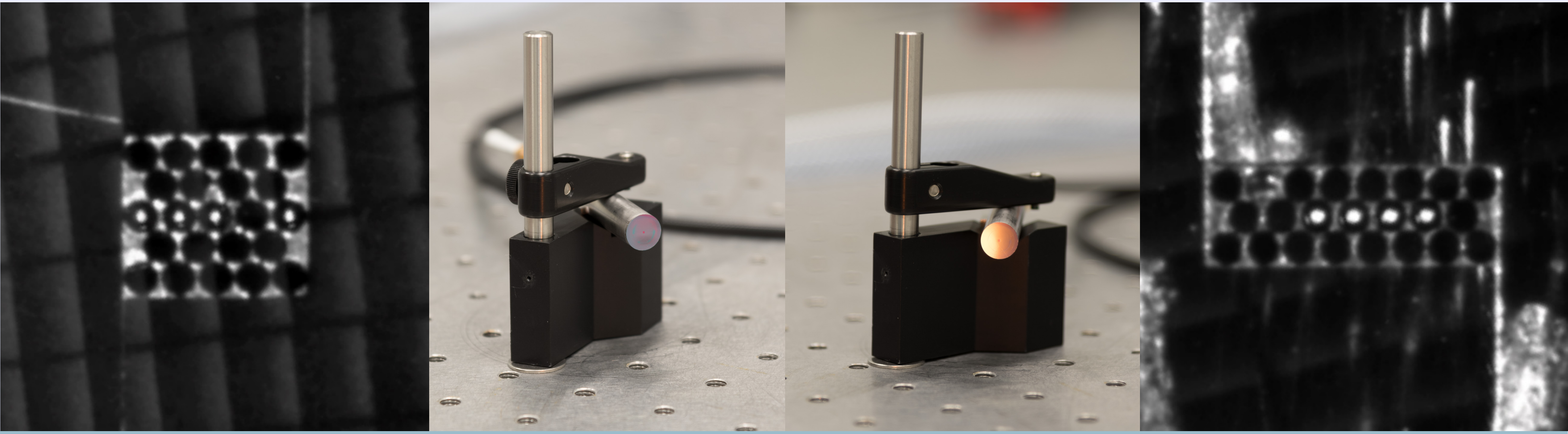
Electronics cabinet



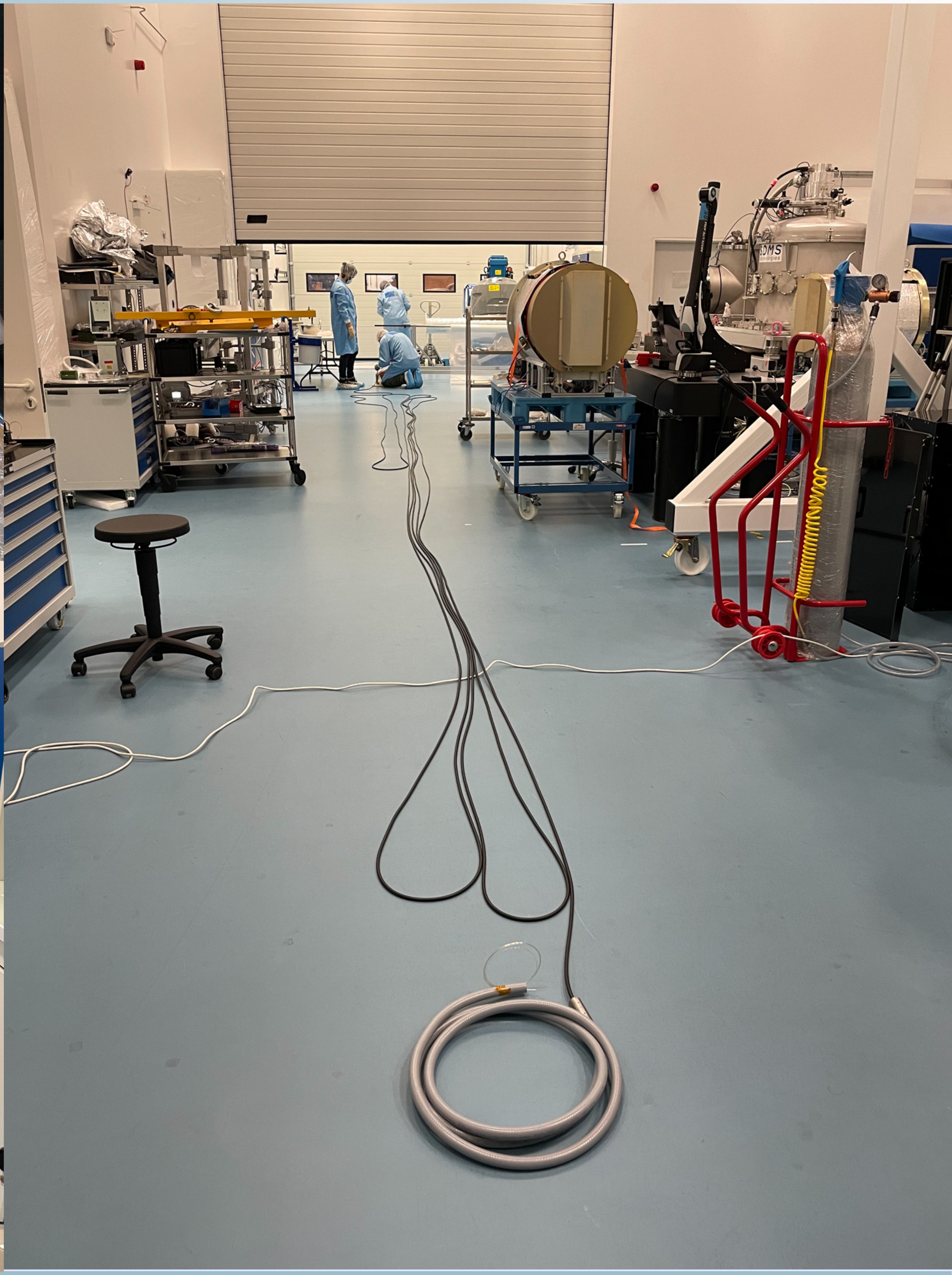


A complex fiber bundle



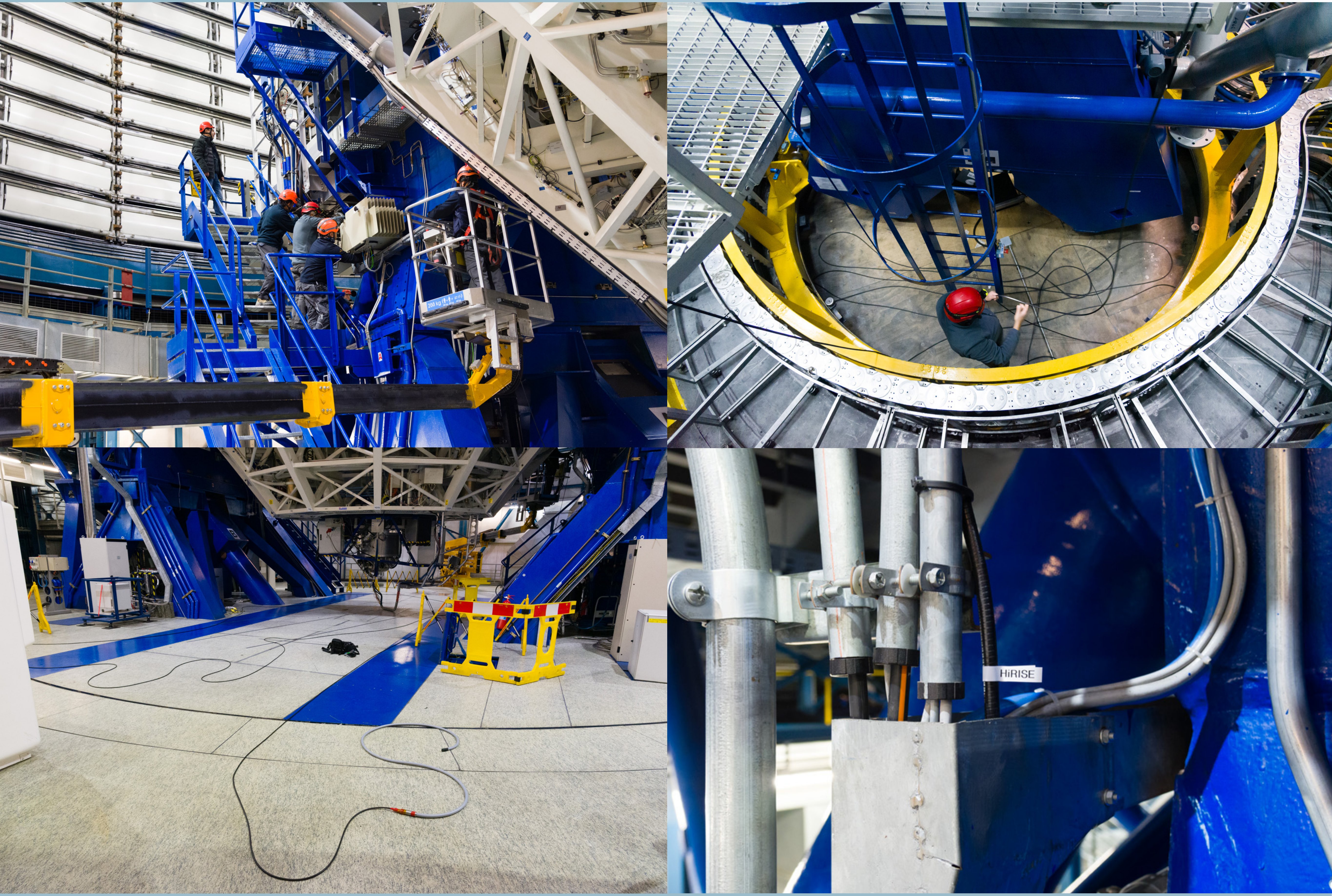


A complex fiber bundle

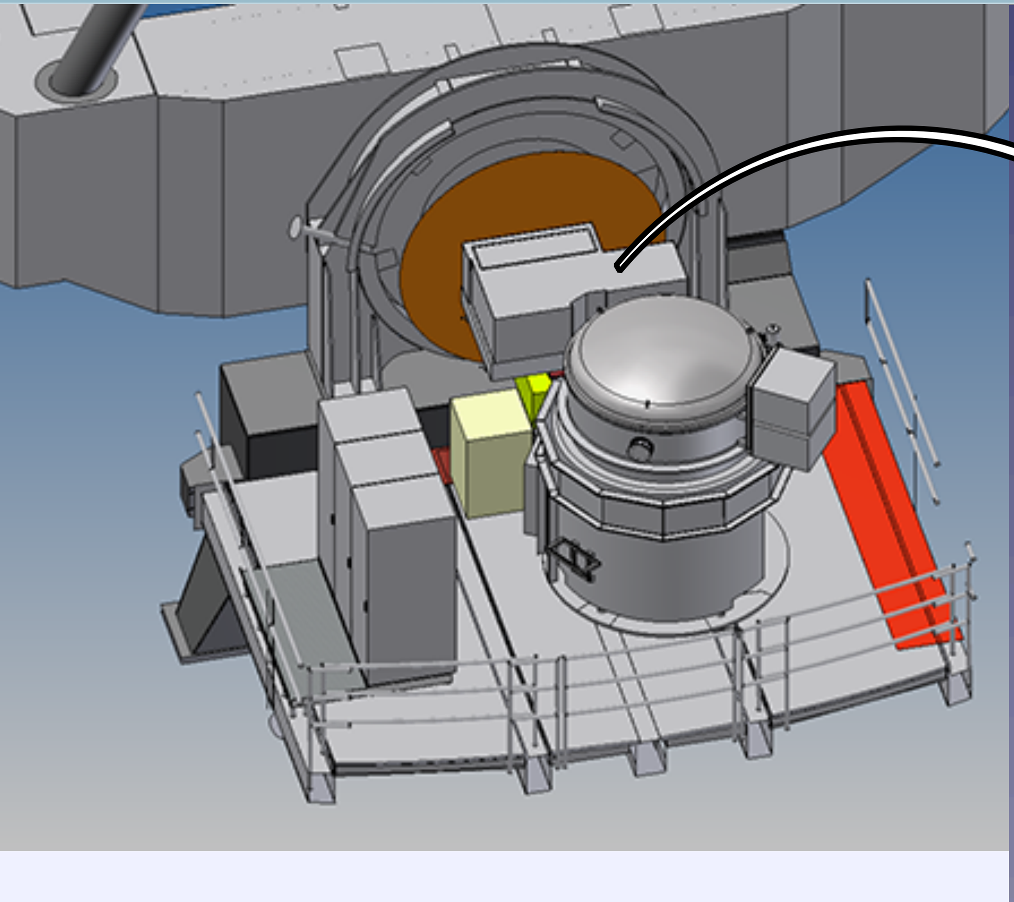


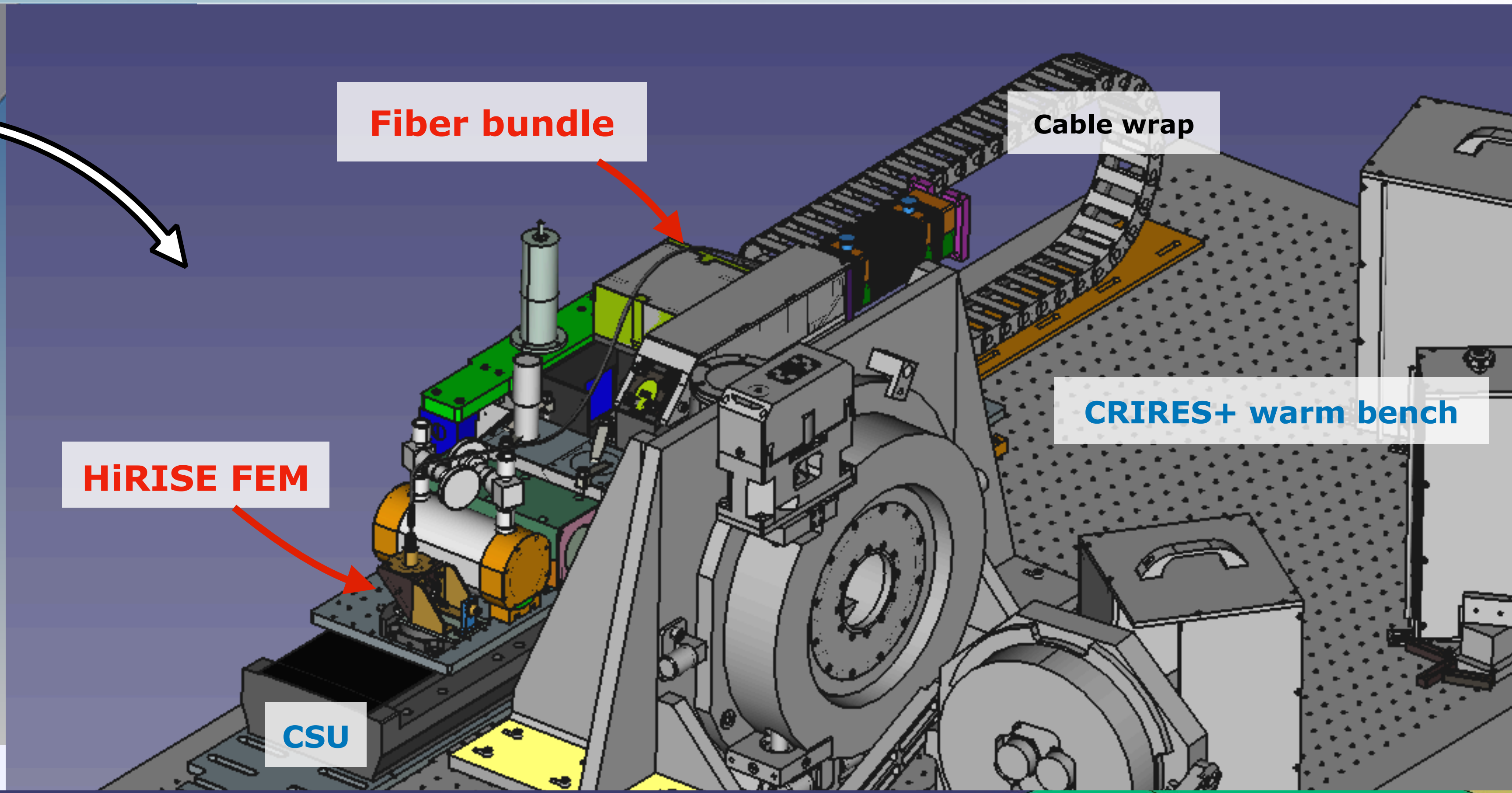
A complex fiber bundle

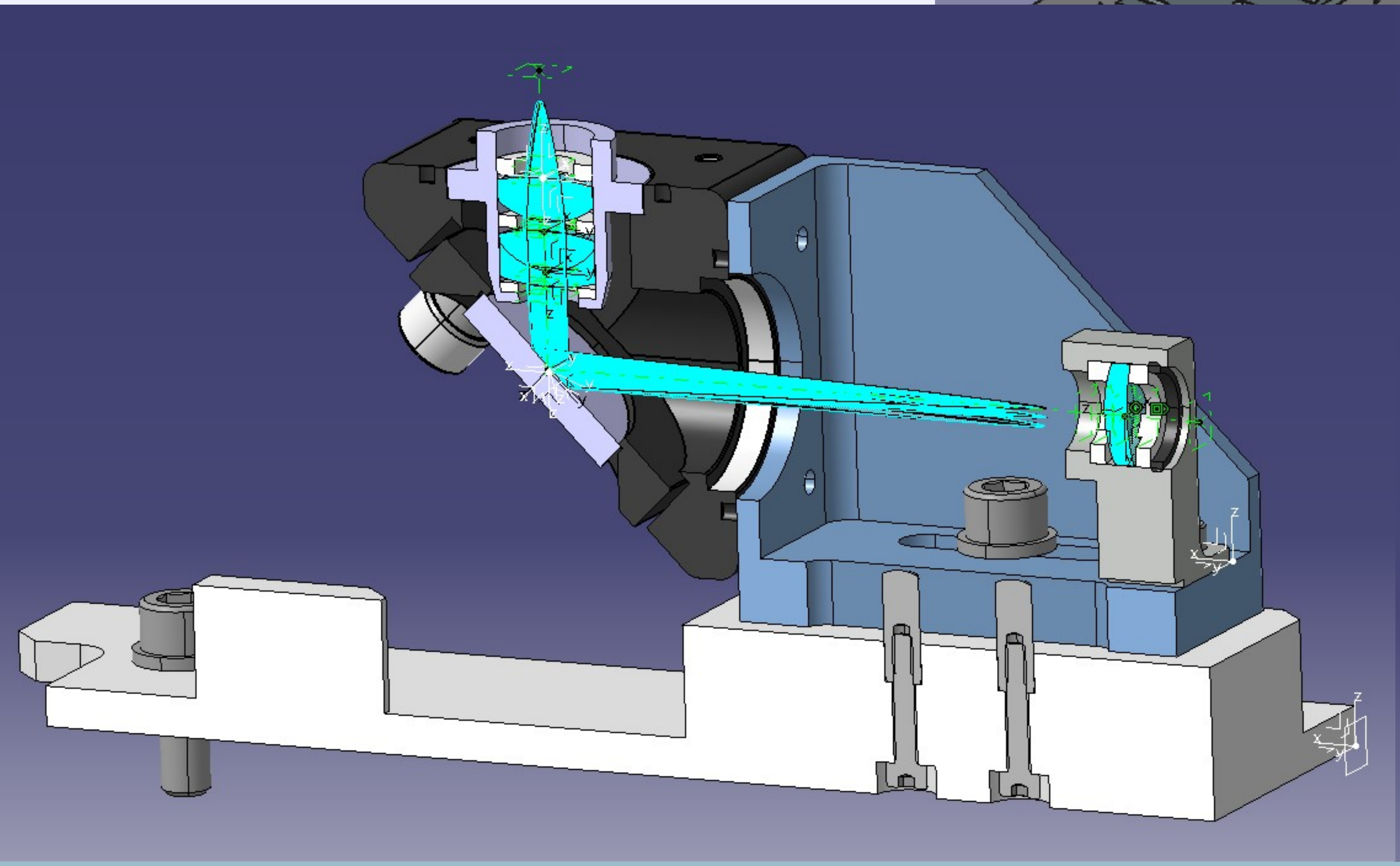
A complex fiber bundle

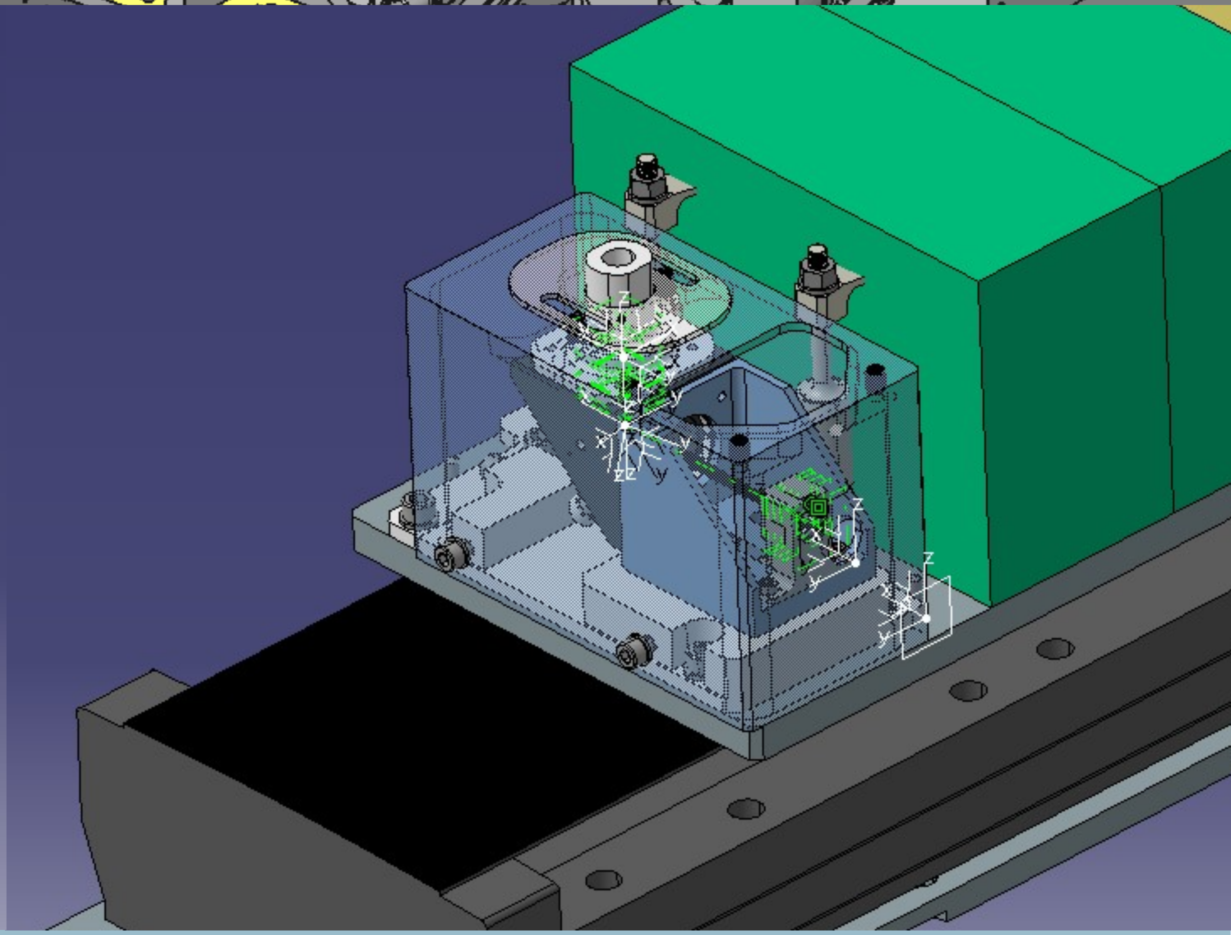


Fiber extraction module

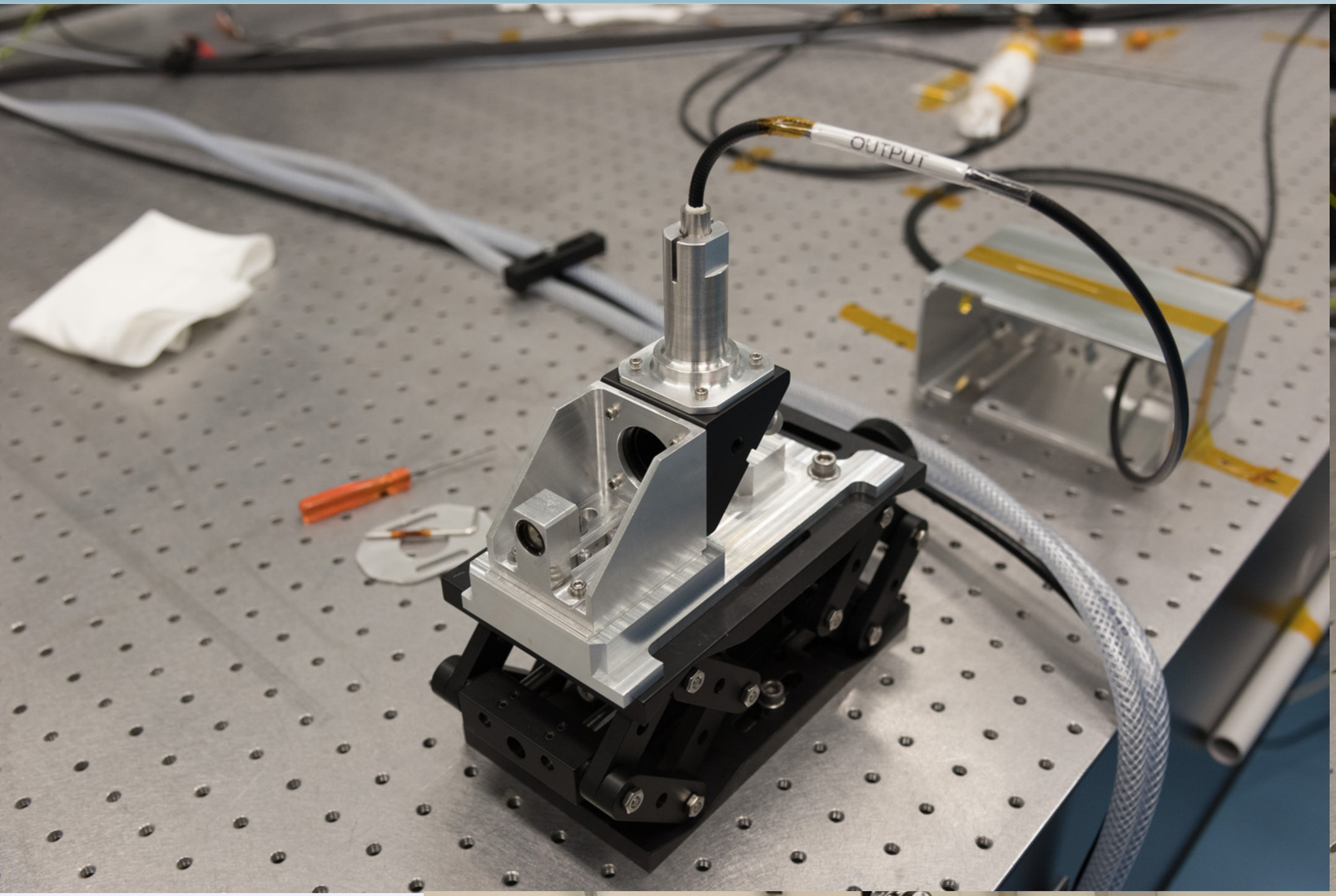


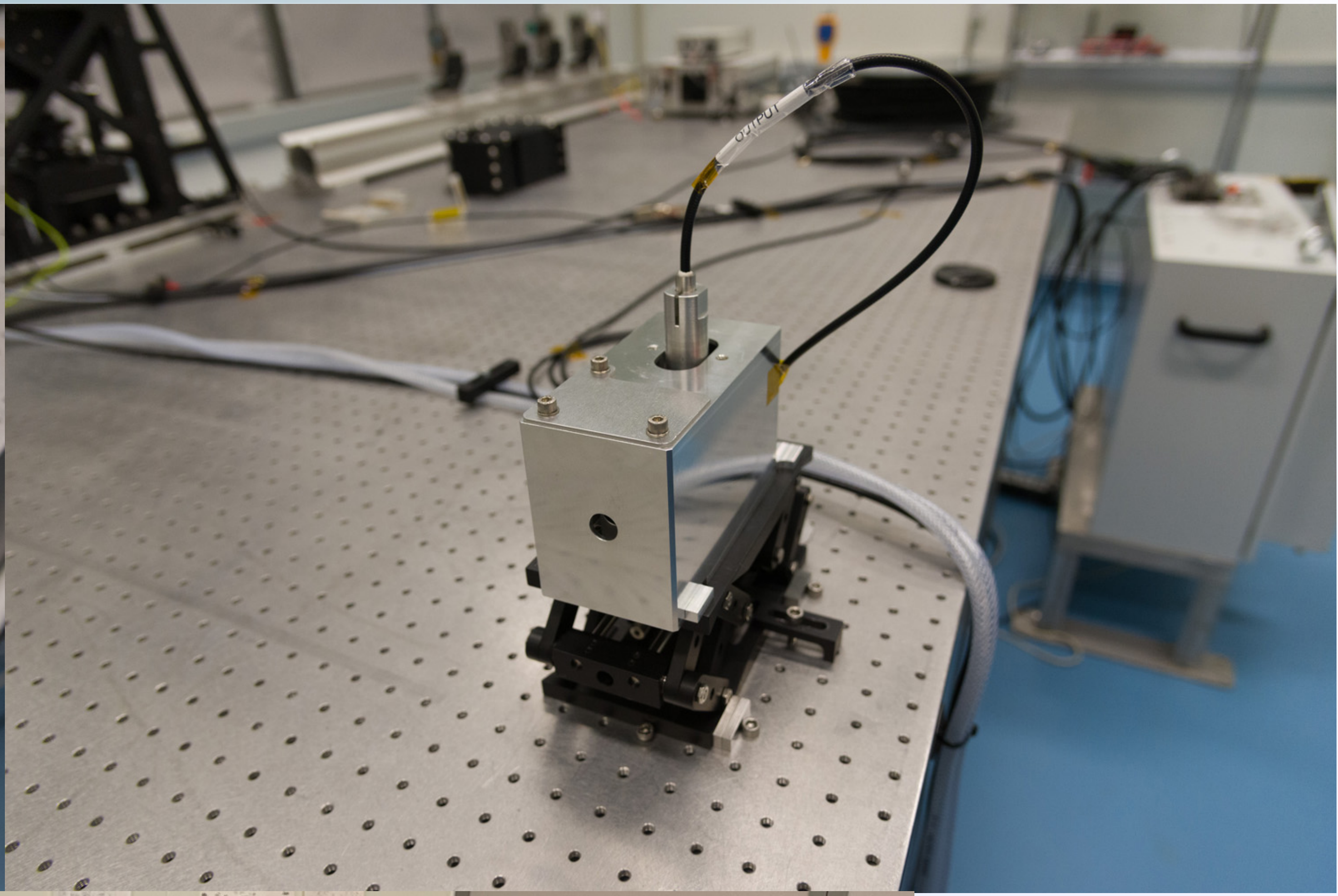


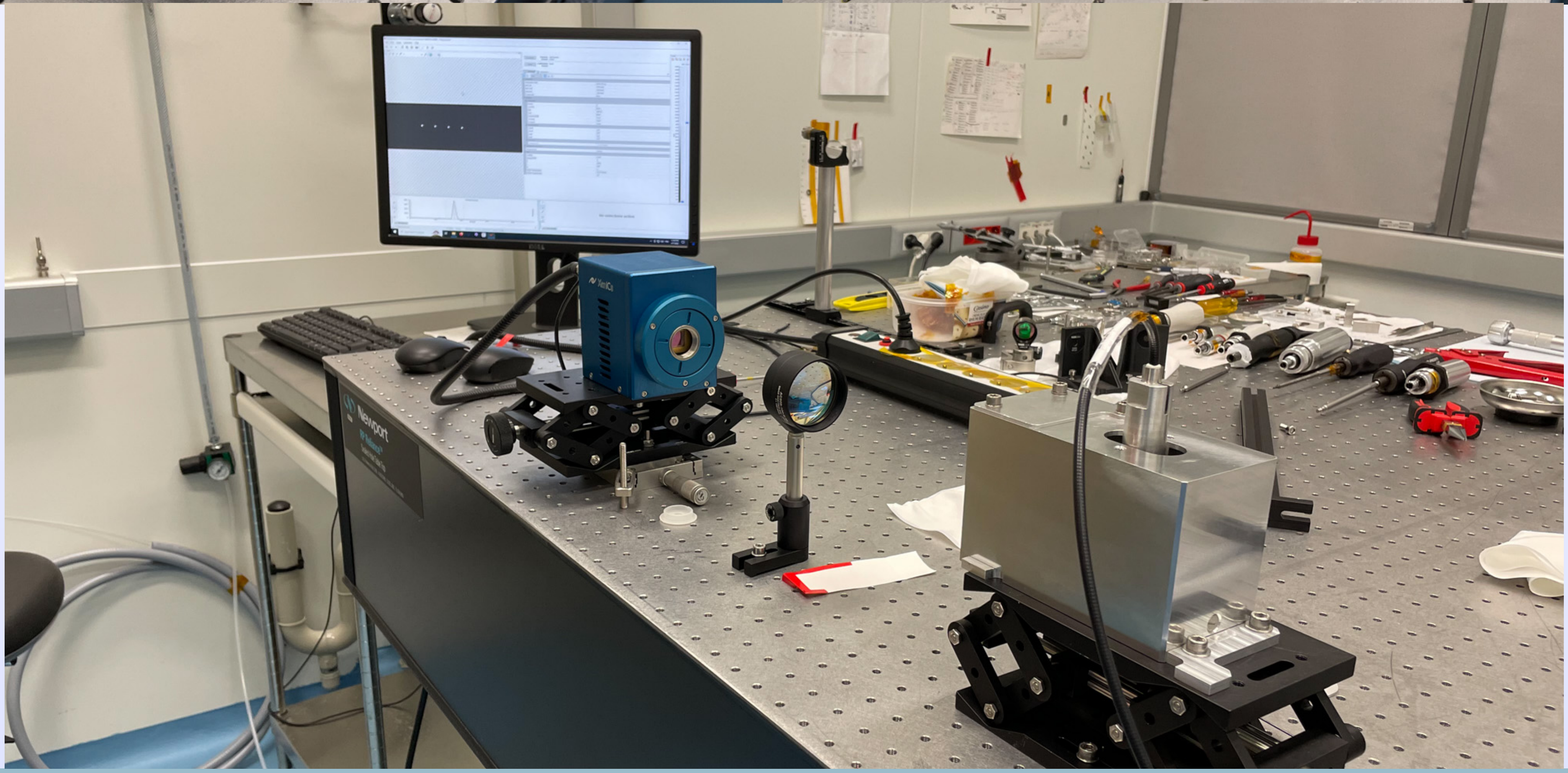




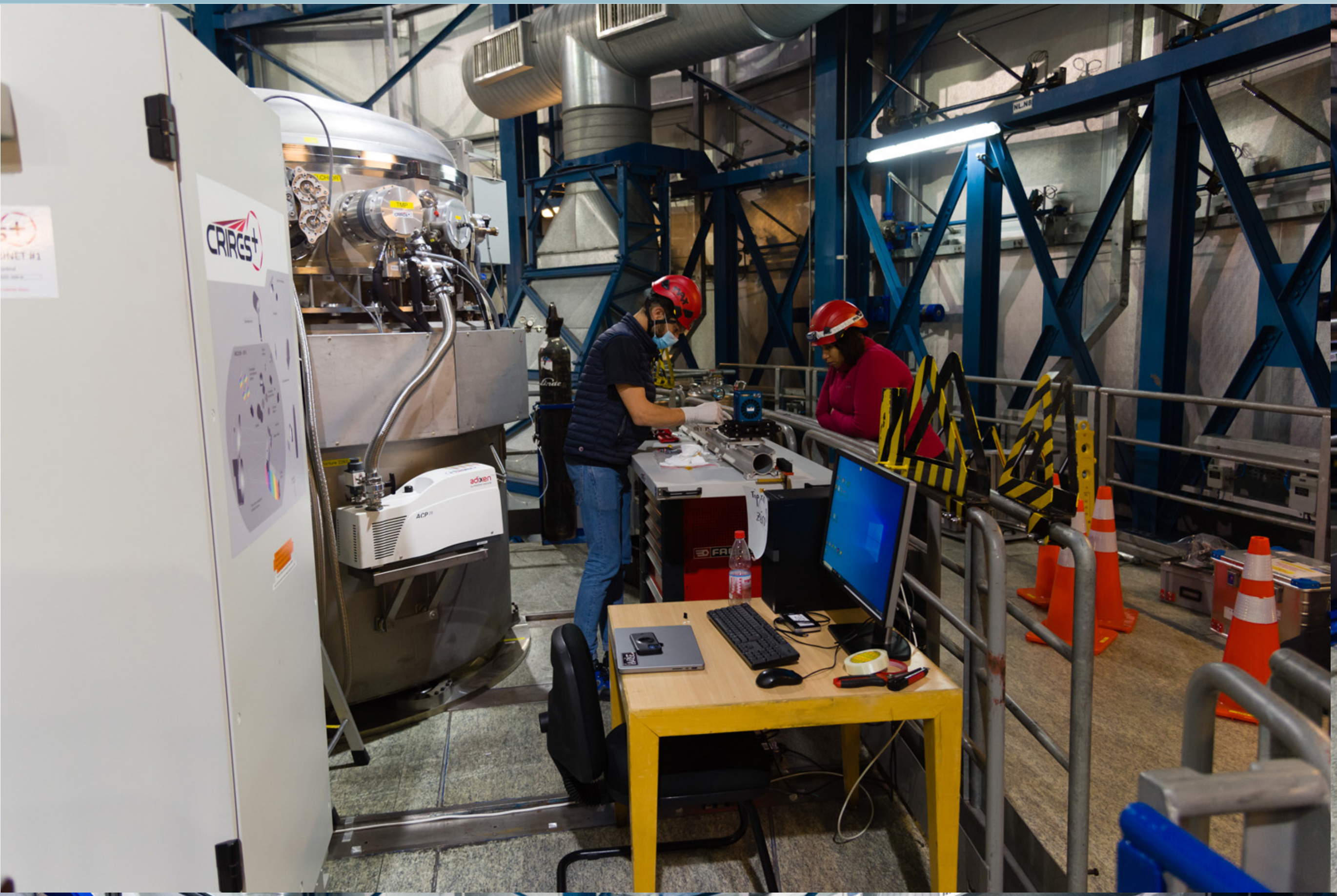
Fiber extraction module

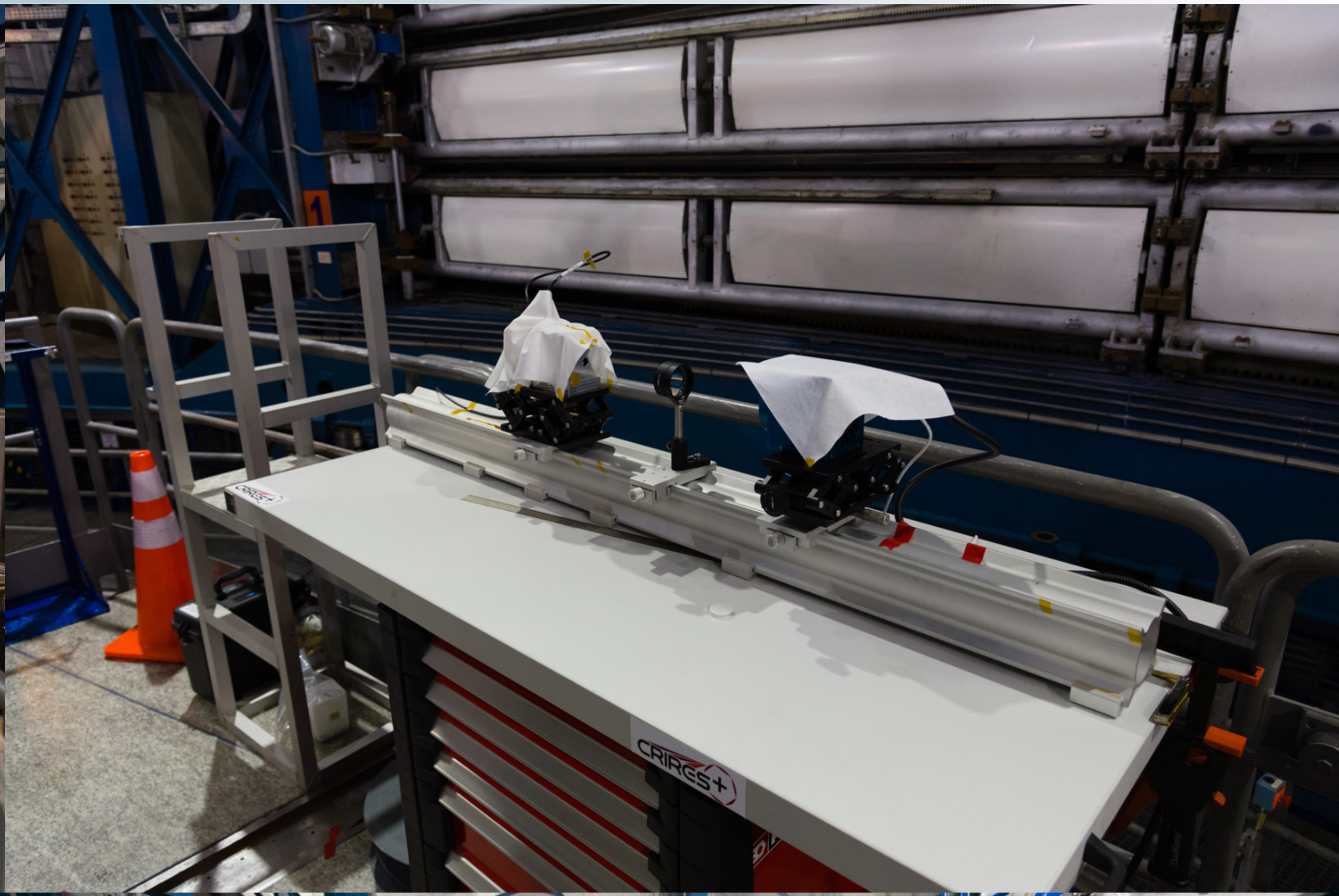




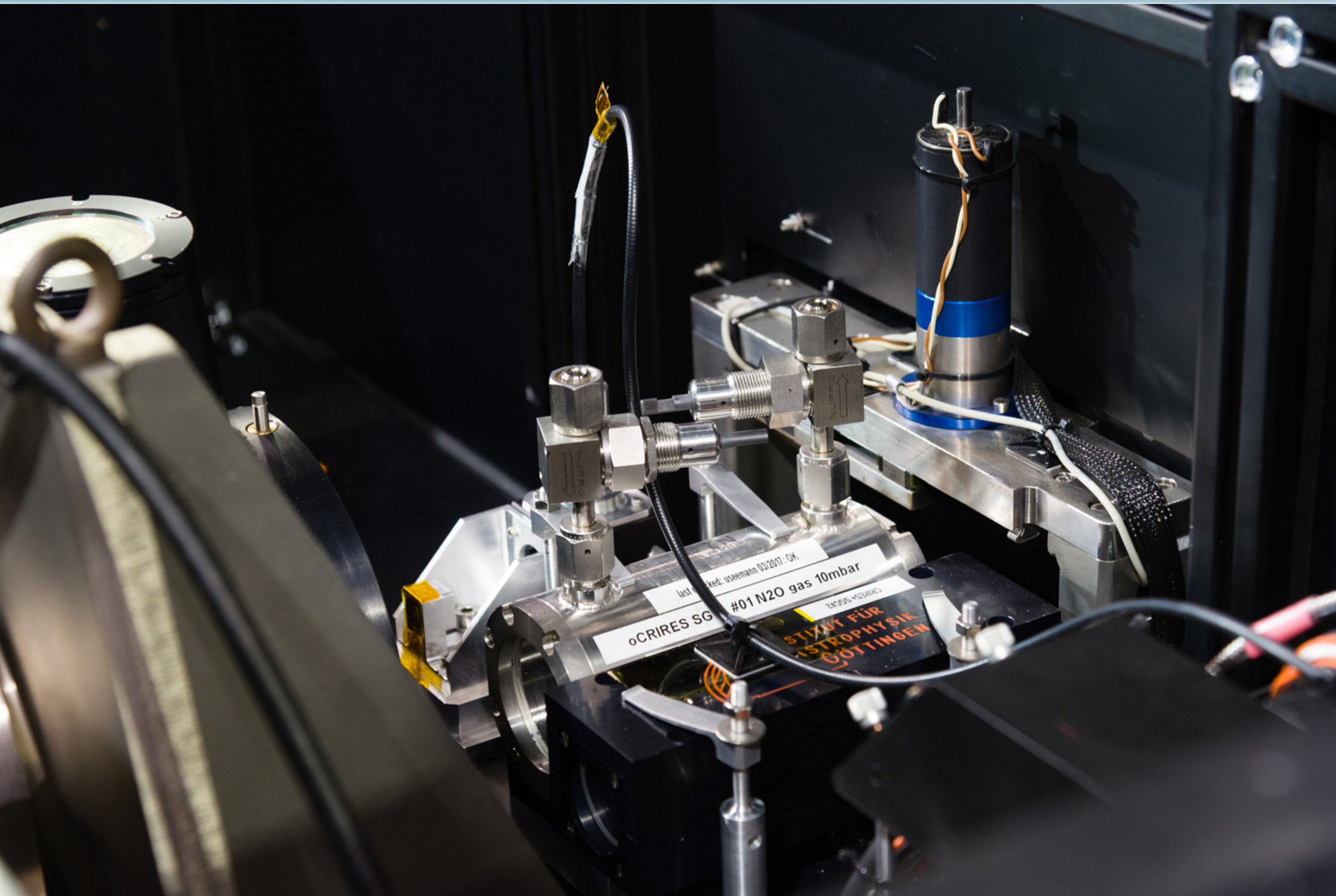


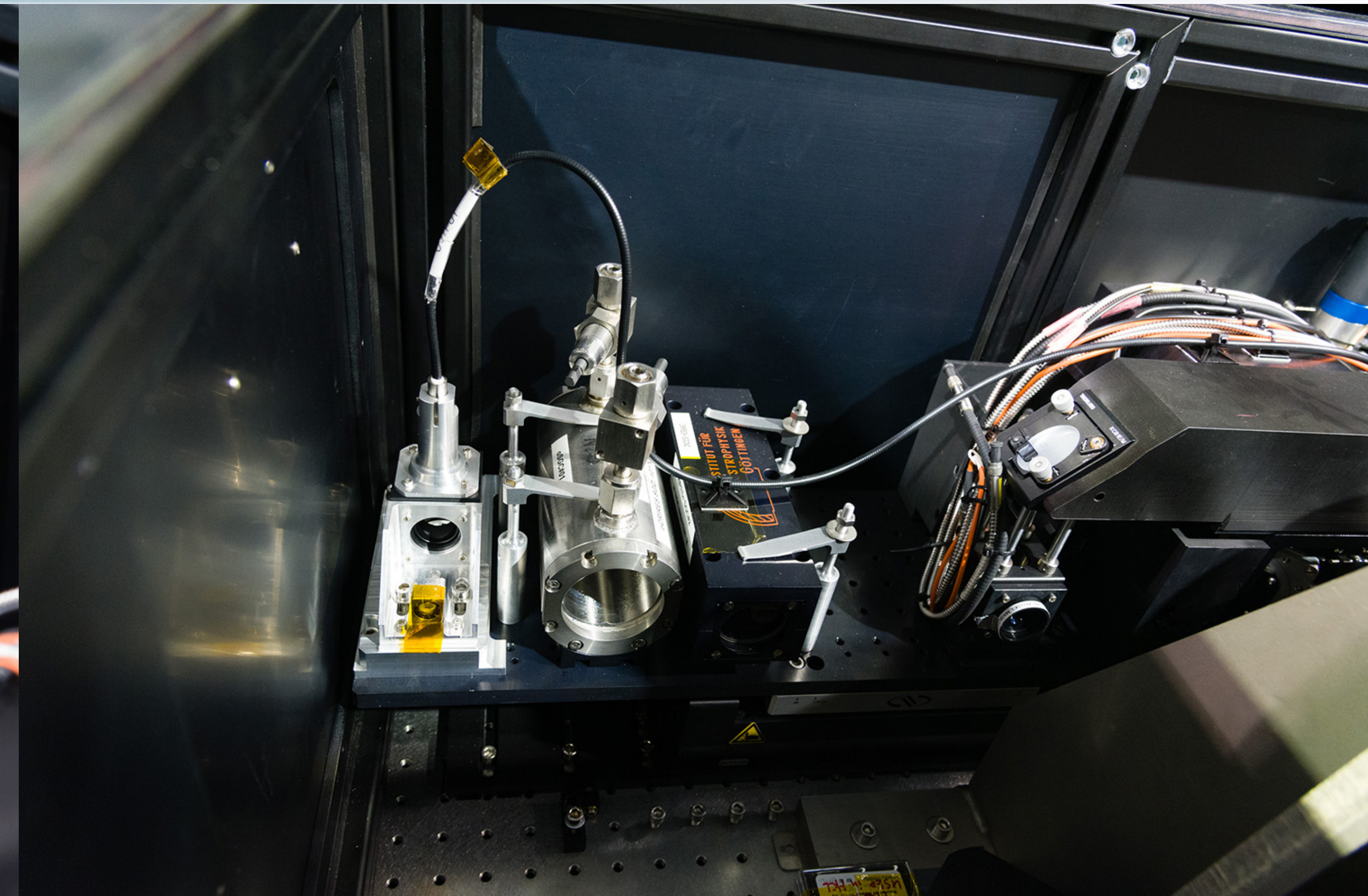
Fiber extraction module

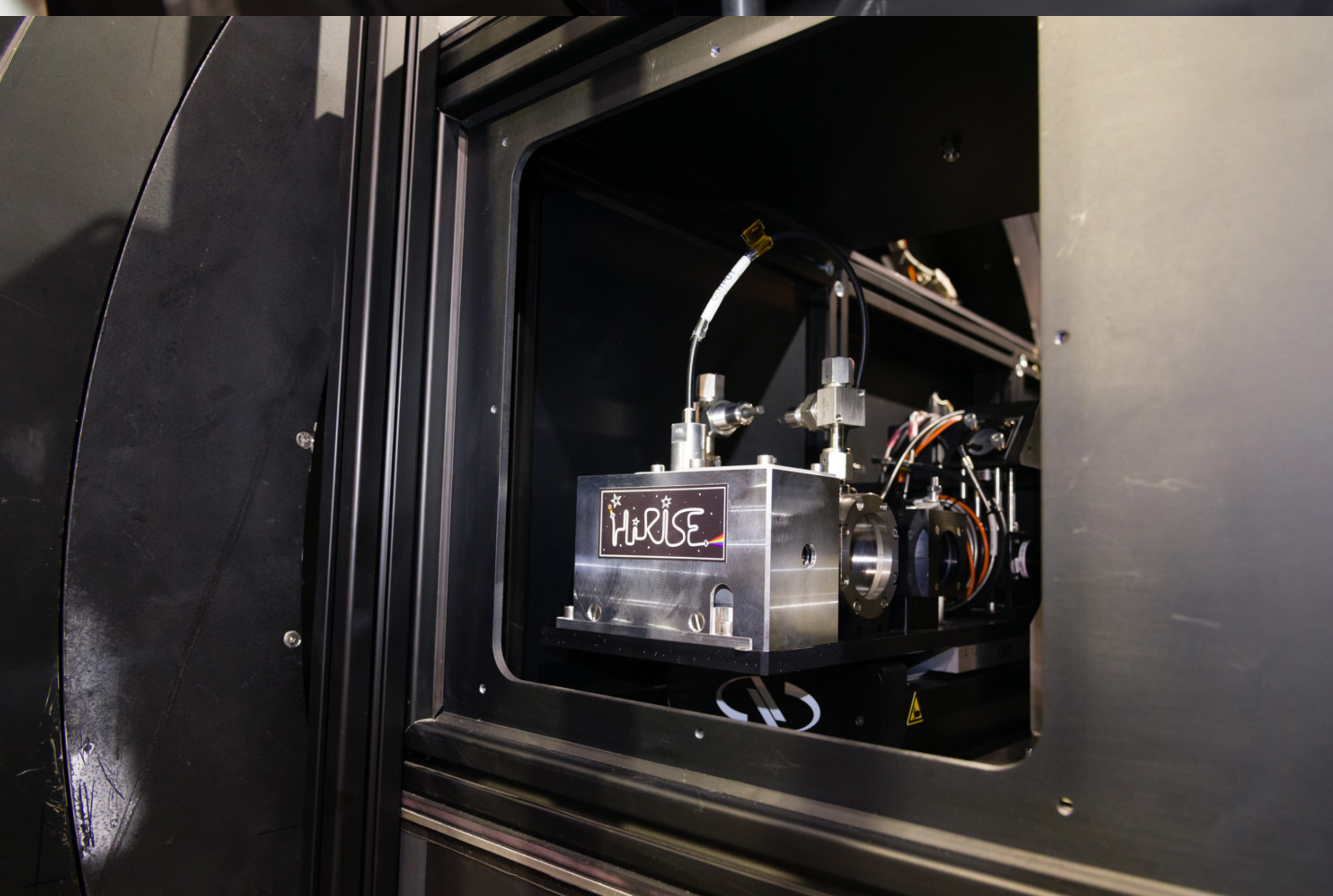


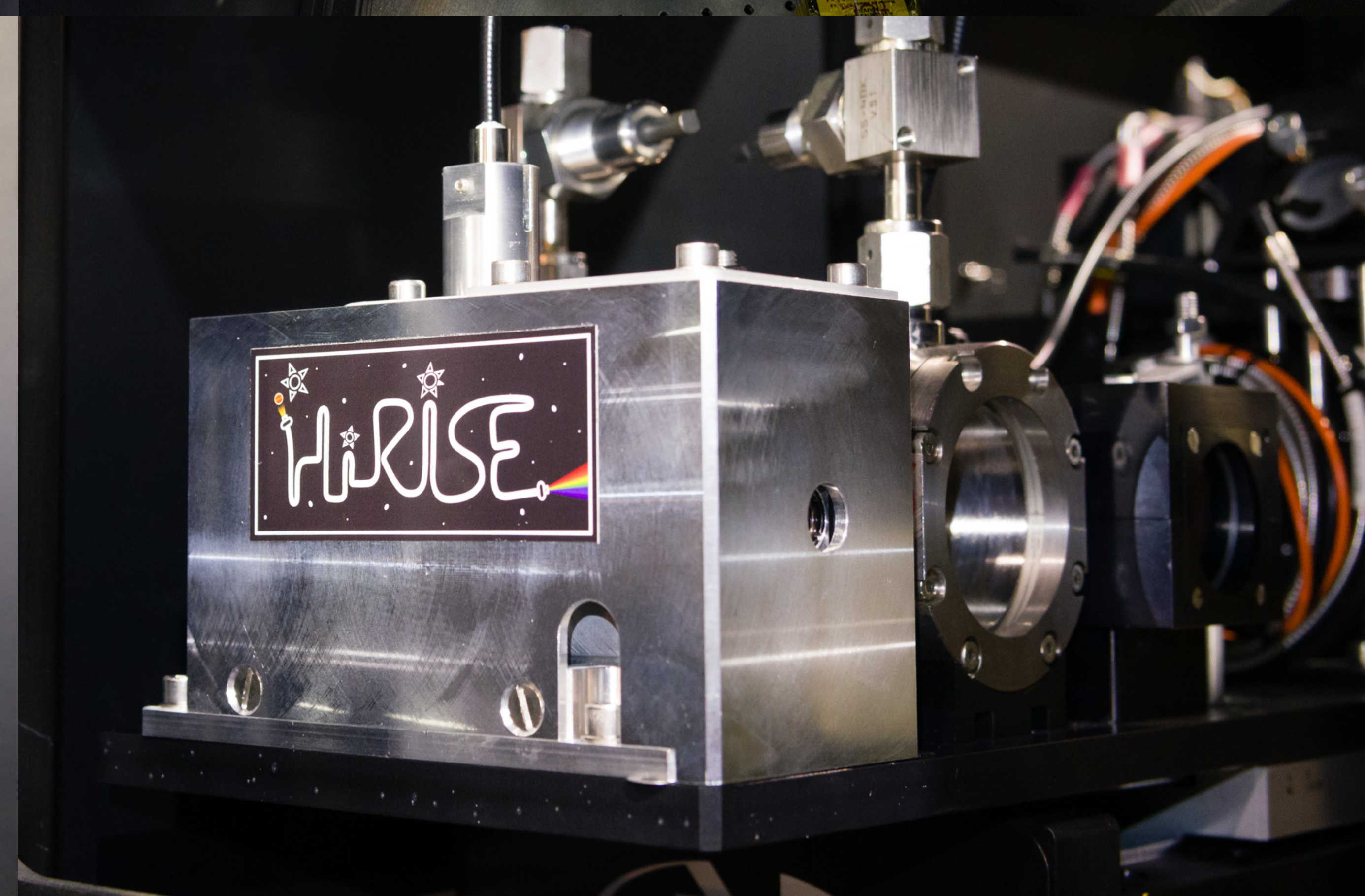


Fiber extraction module

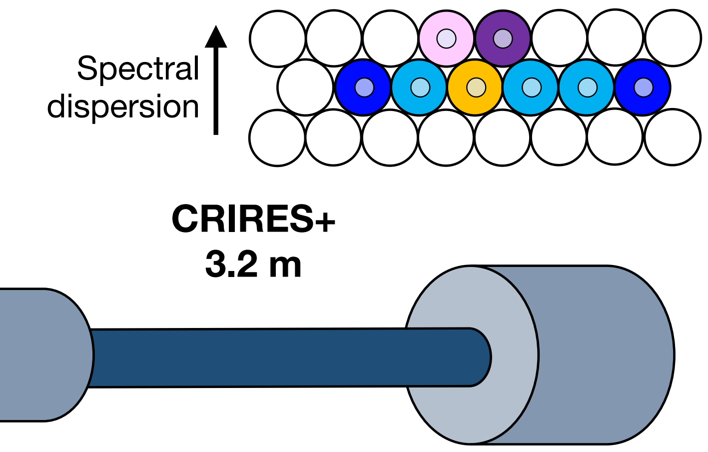


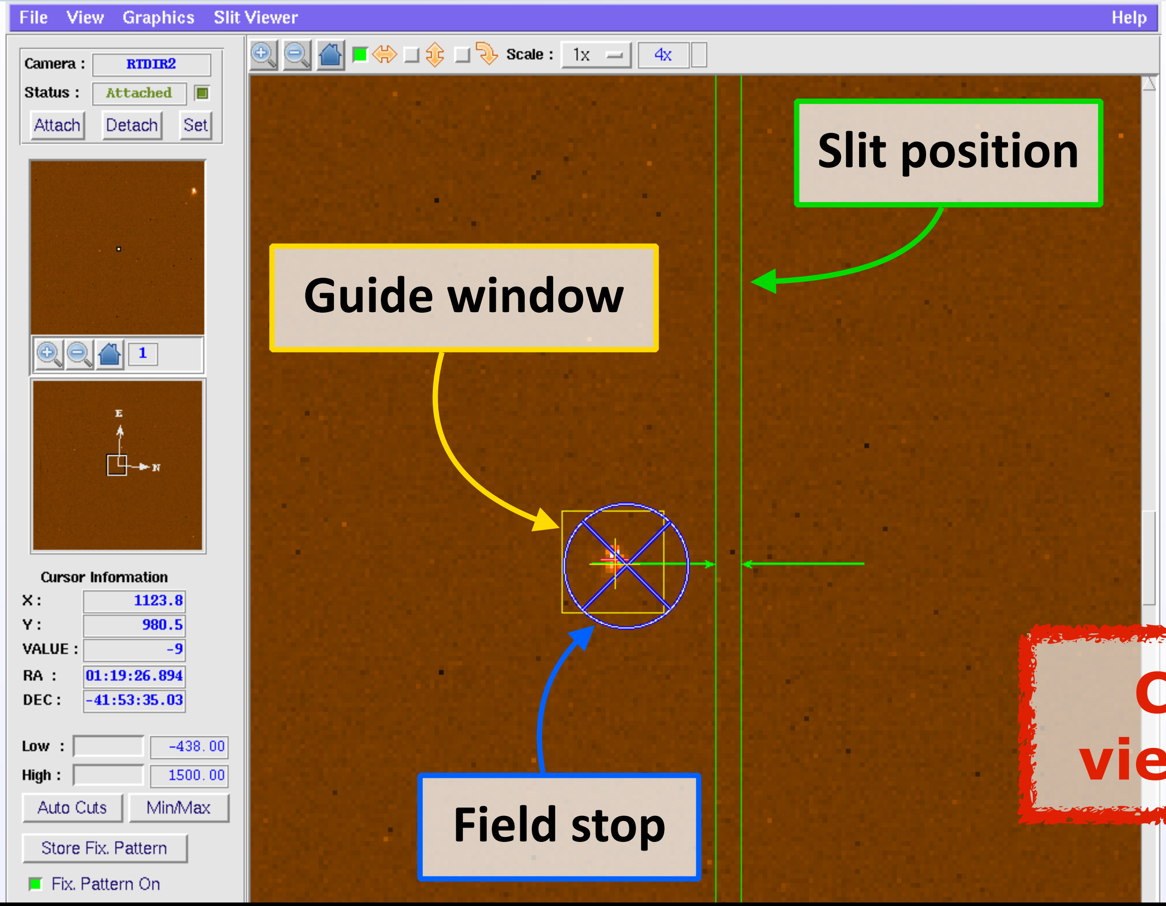


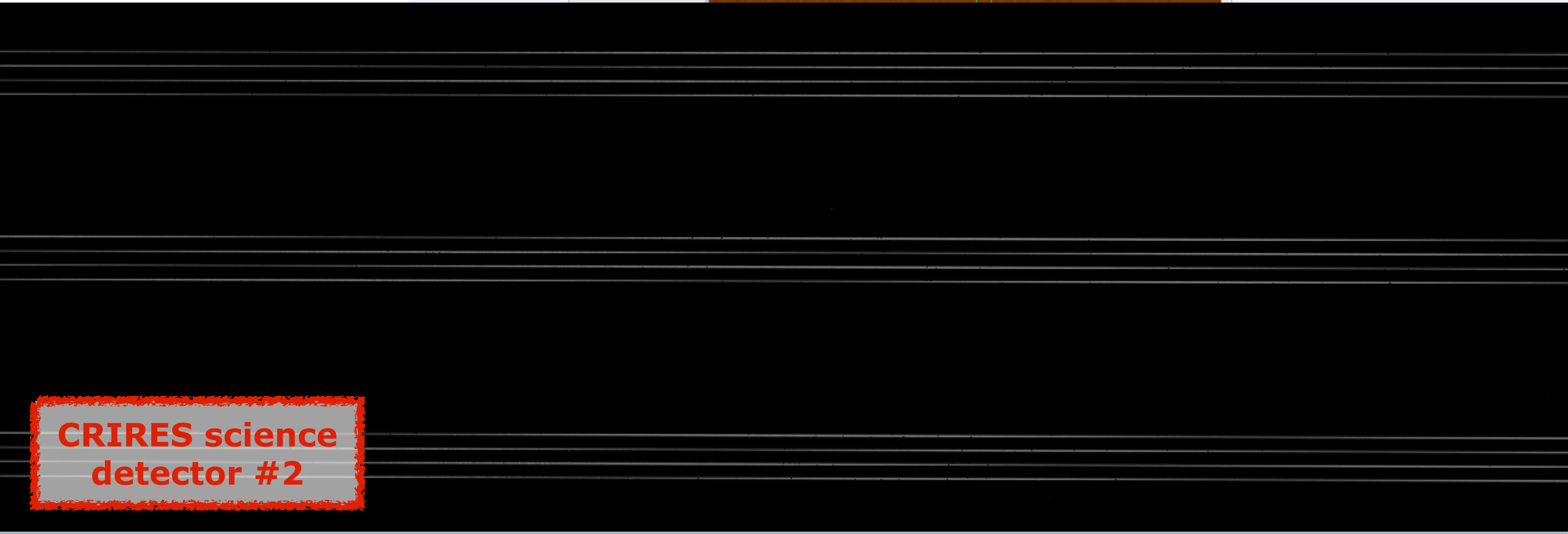




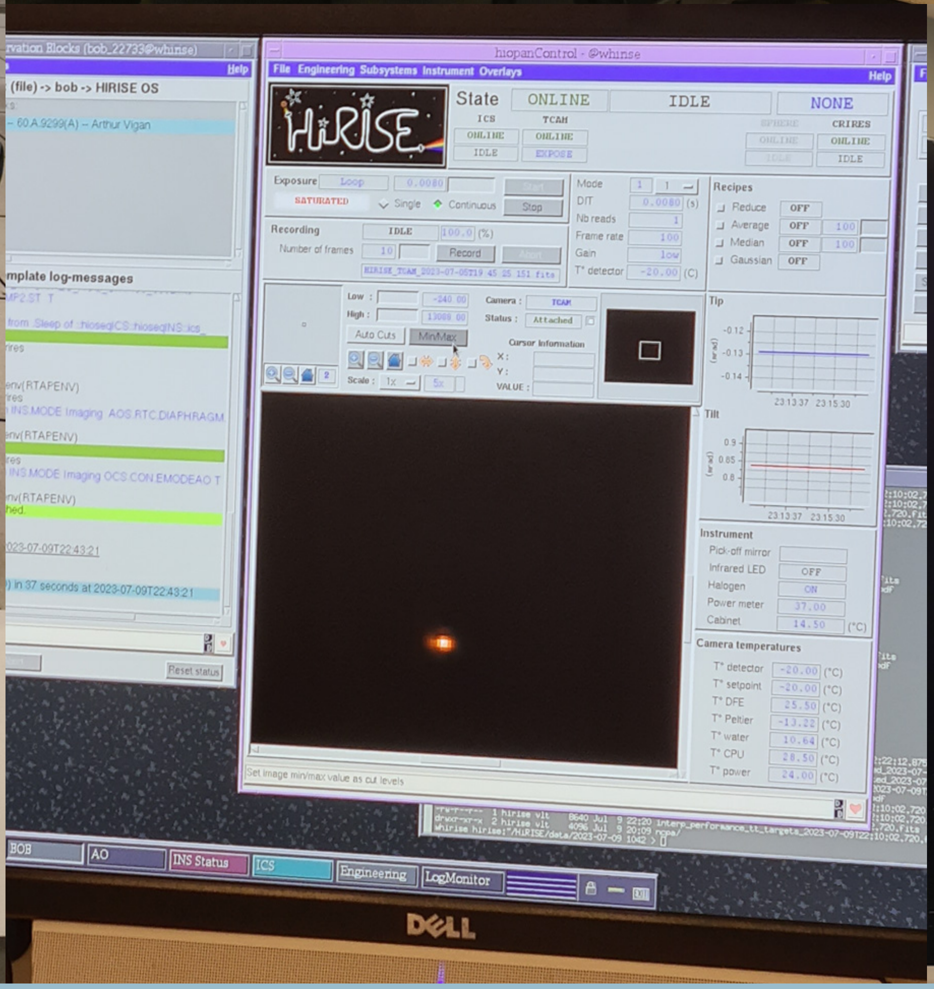
Light into the CRIRES: the moment of truth 😱

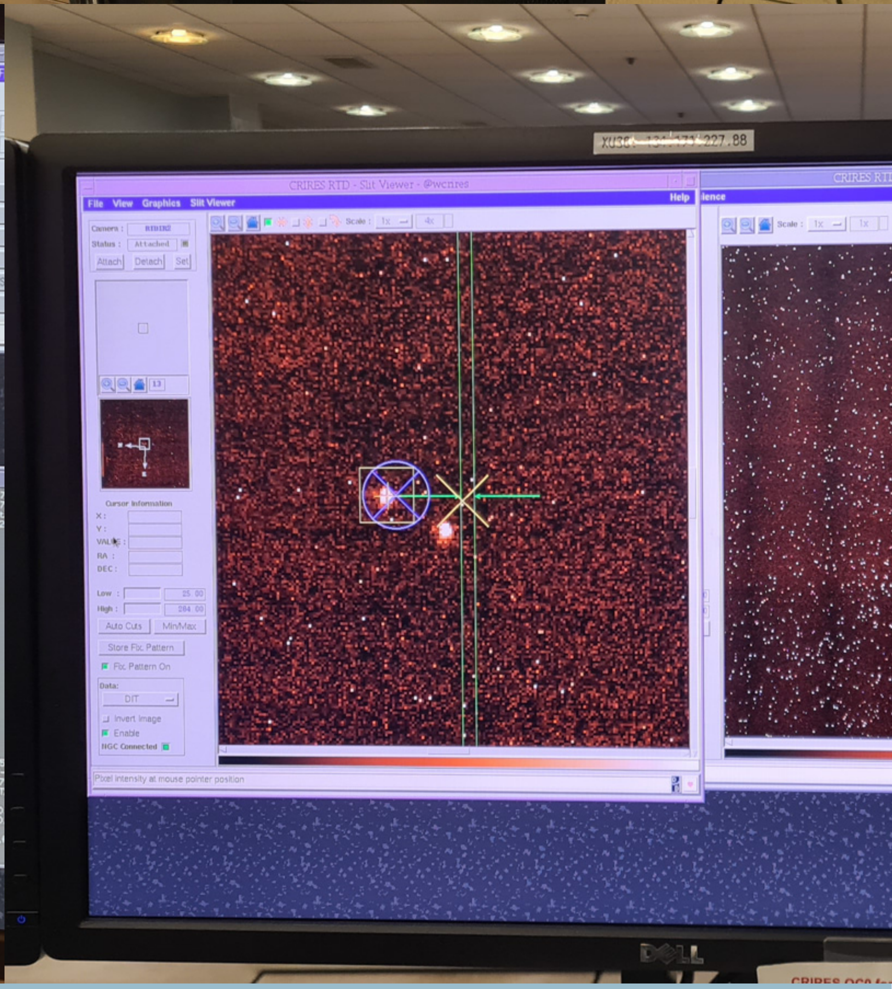






First light!

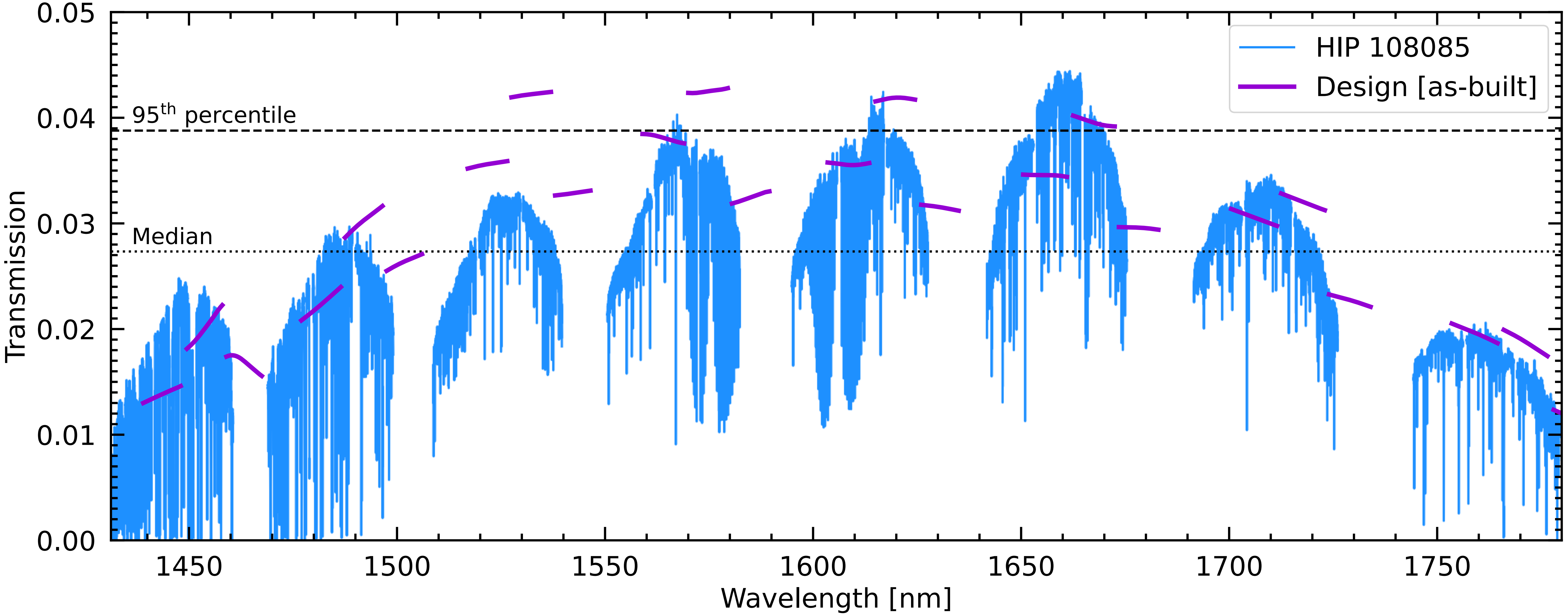





First light!

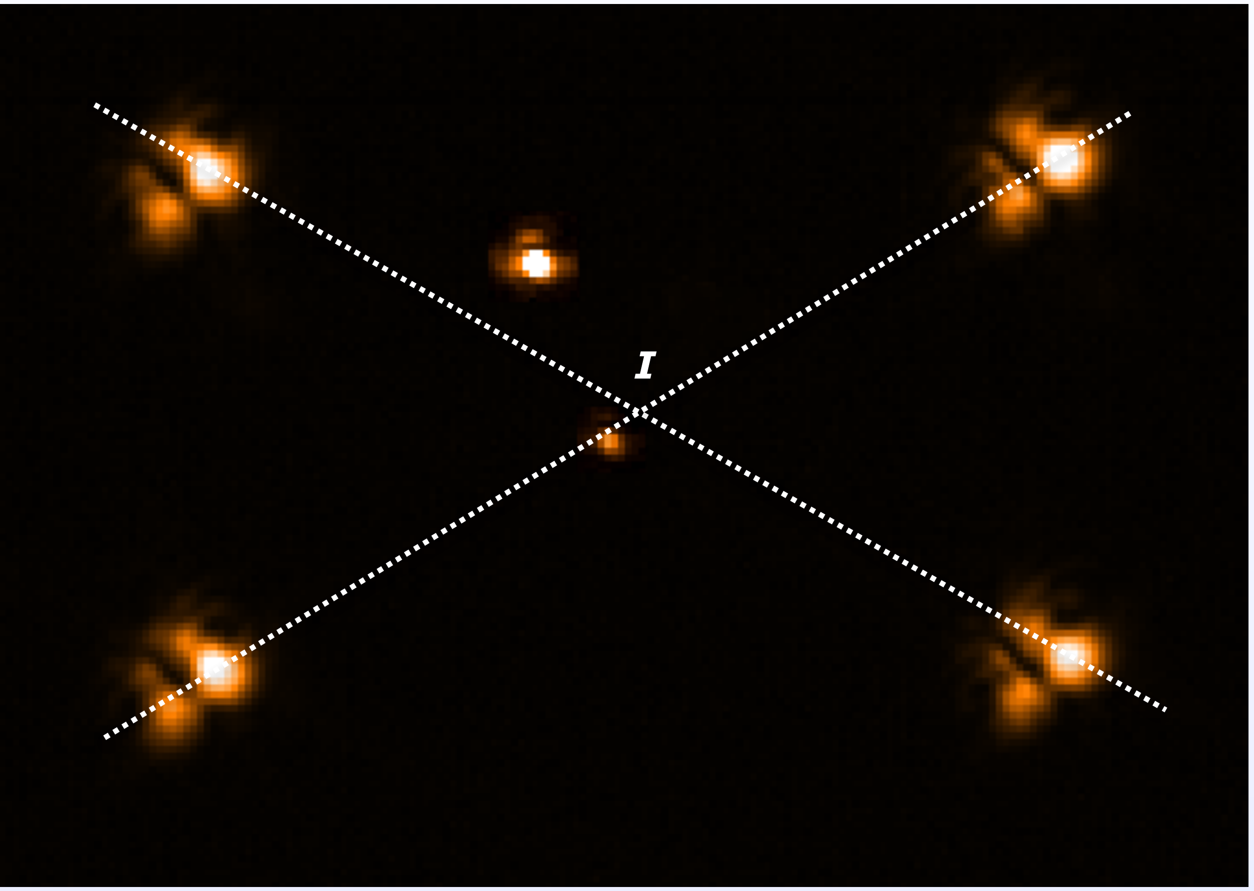
Commissioning results: transmission

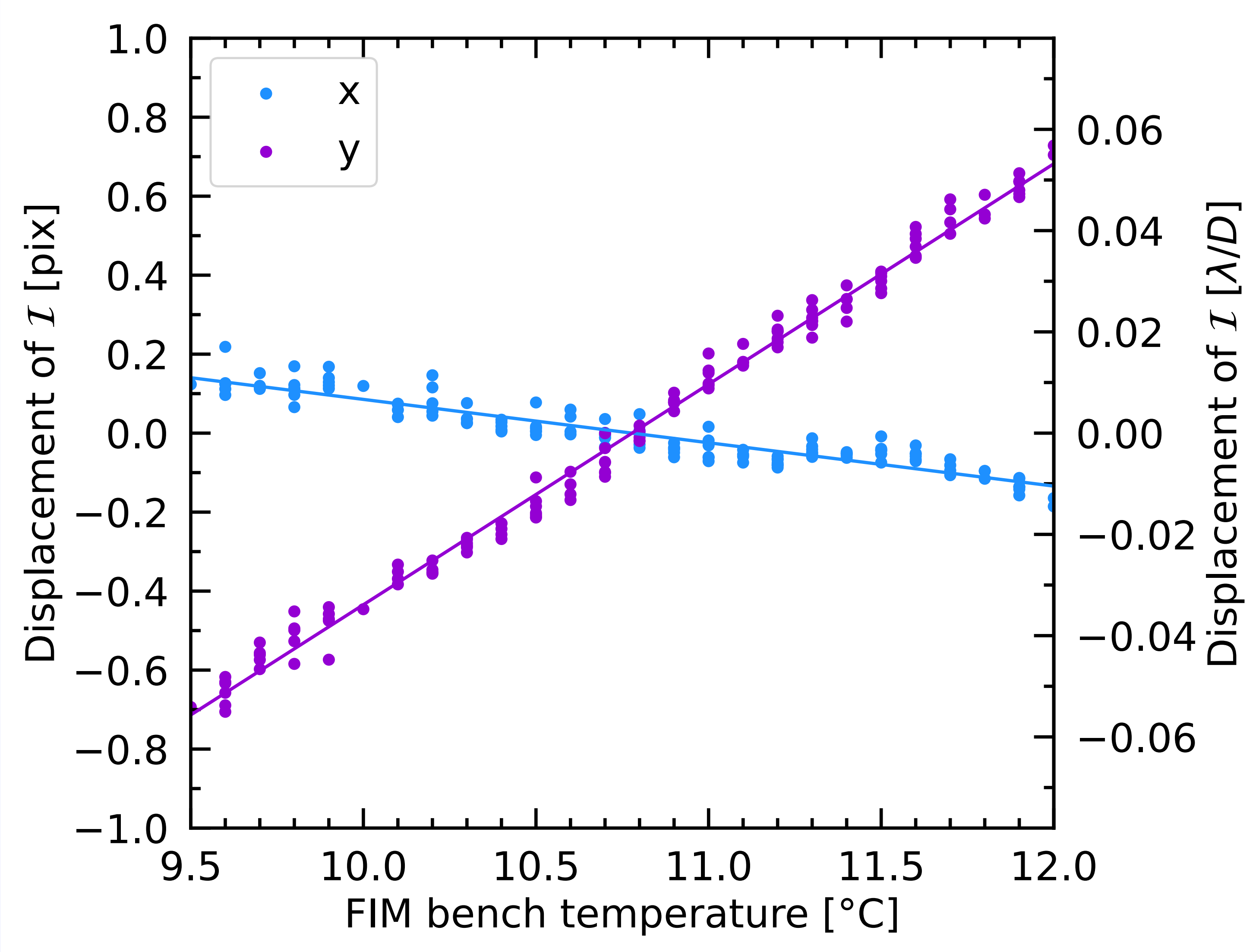
Median conditions
Bright star



End-to-end transmission exactly within specifications

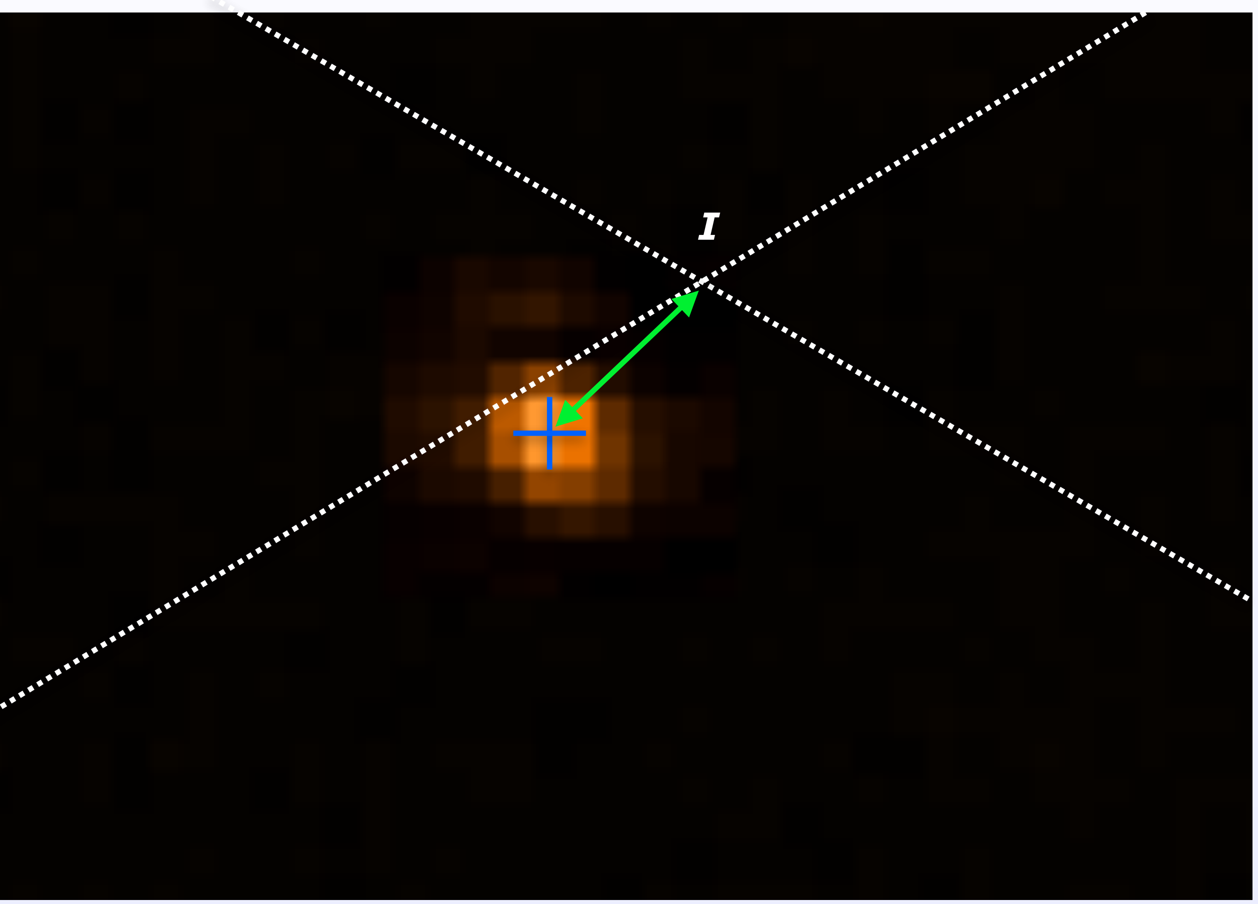
Commissioning: stability

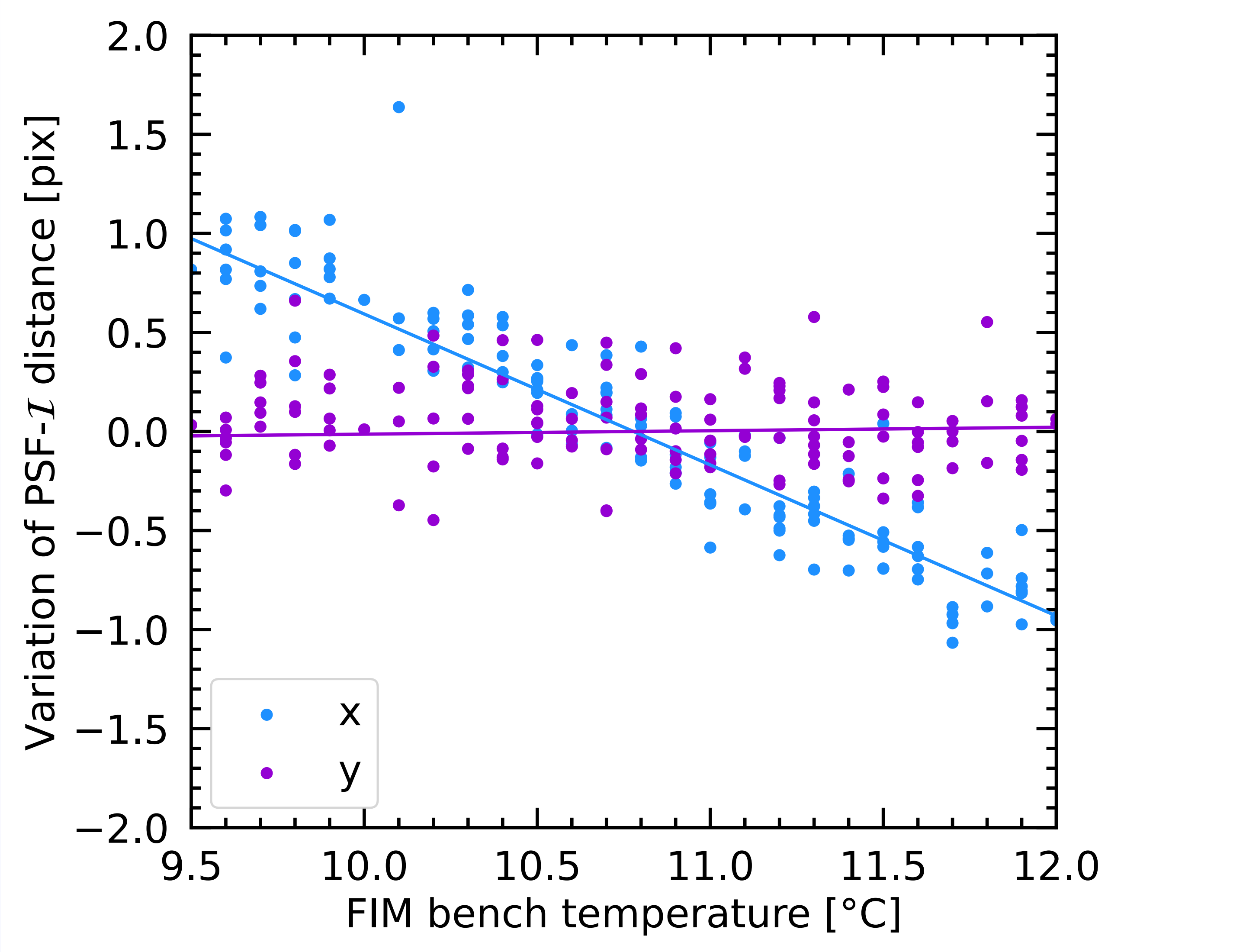




The science PSF moves a lot with temperature

Commissioning: stability

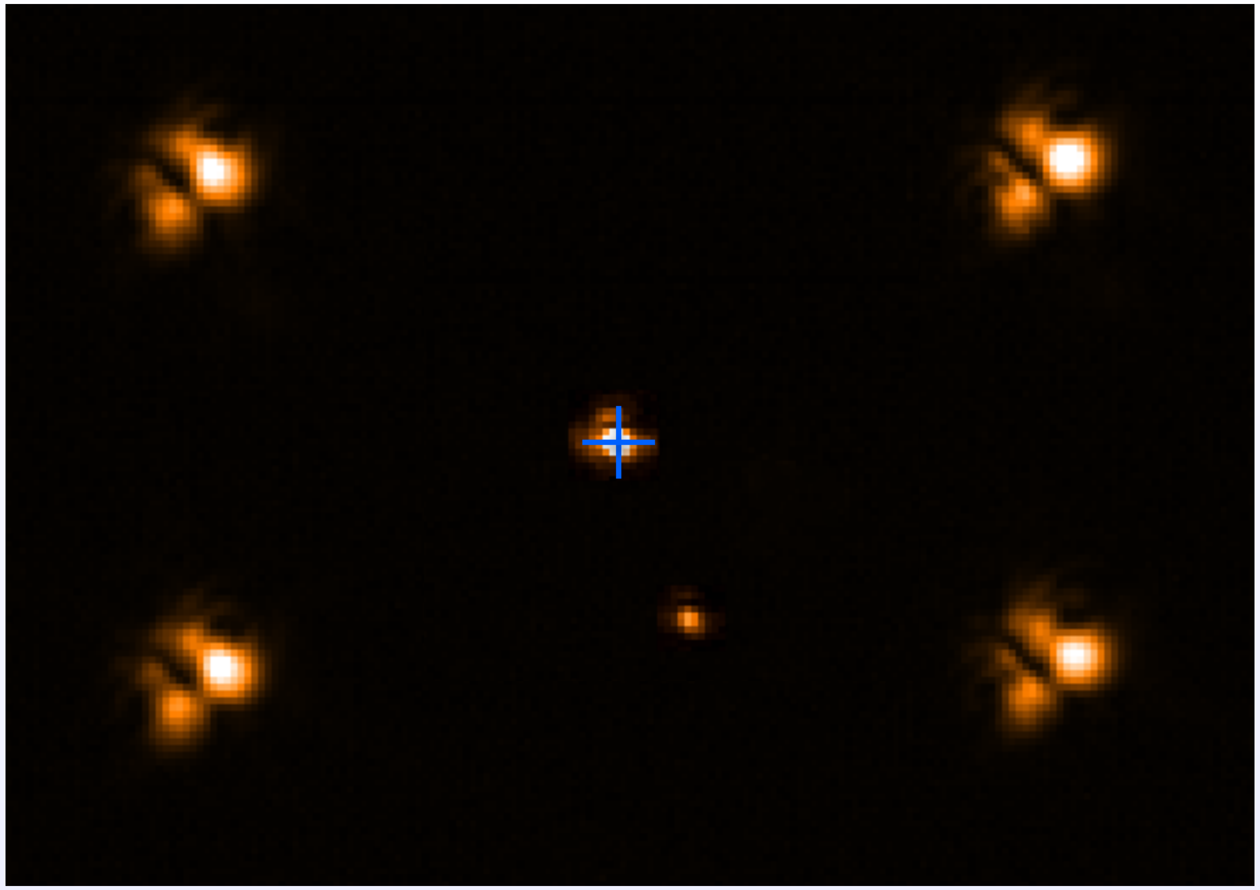


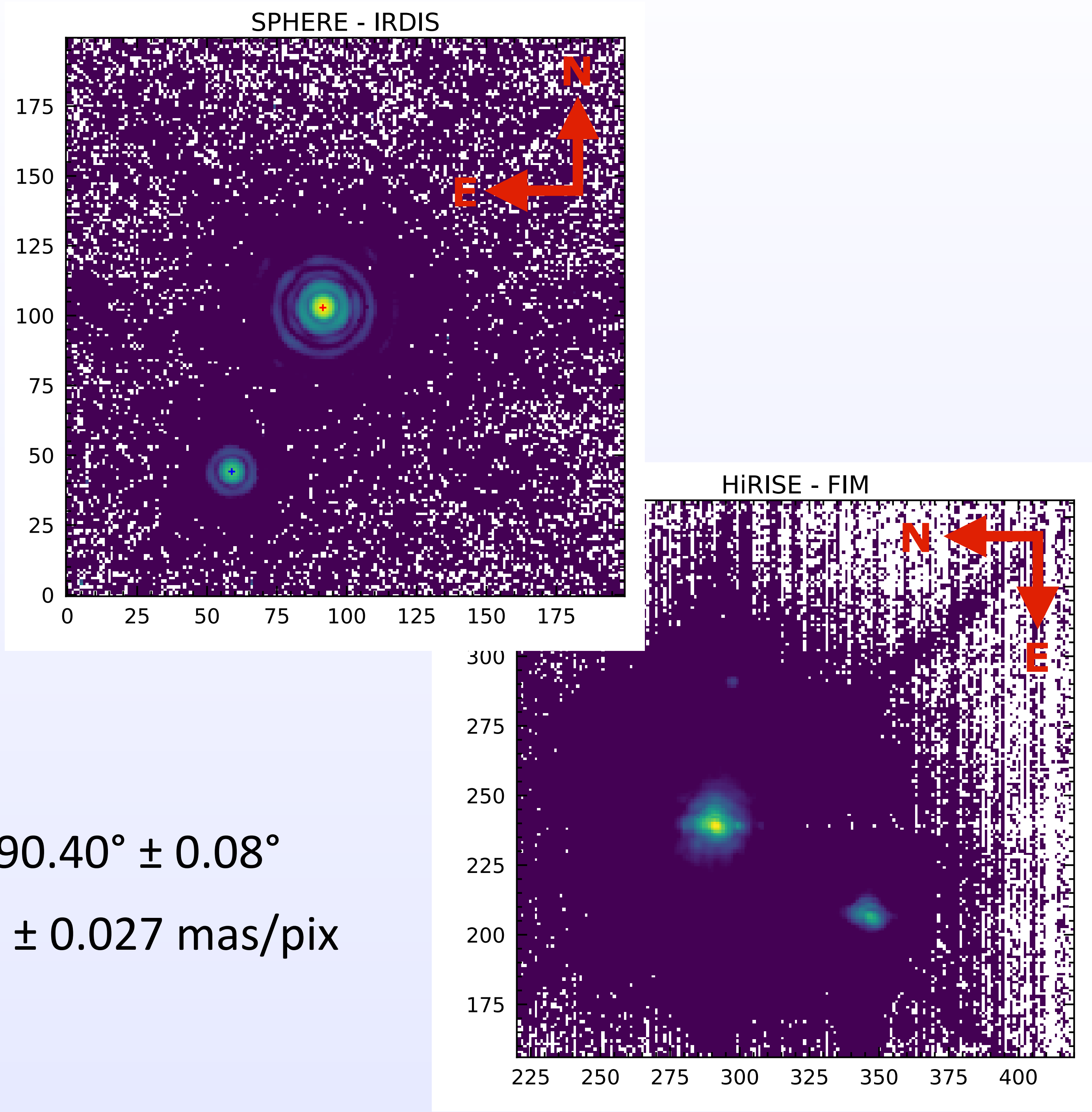


The science PSF moves a lot with temperature

Motion compensation is NOT straightforward

Commissioning: astrometry

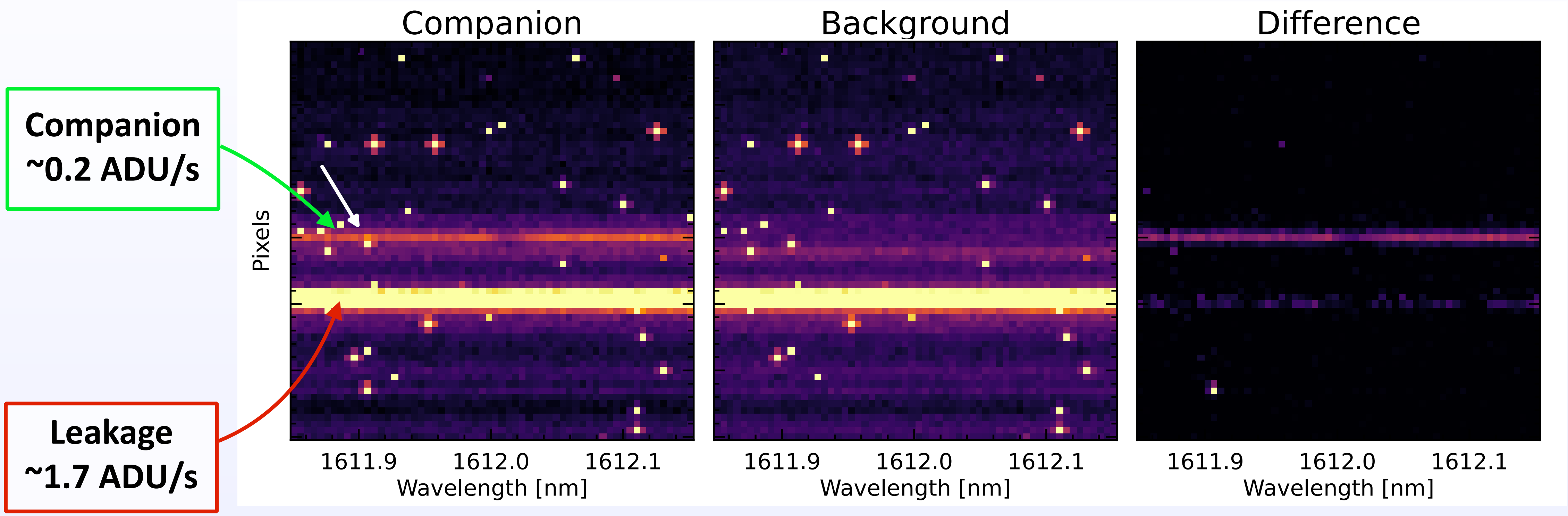




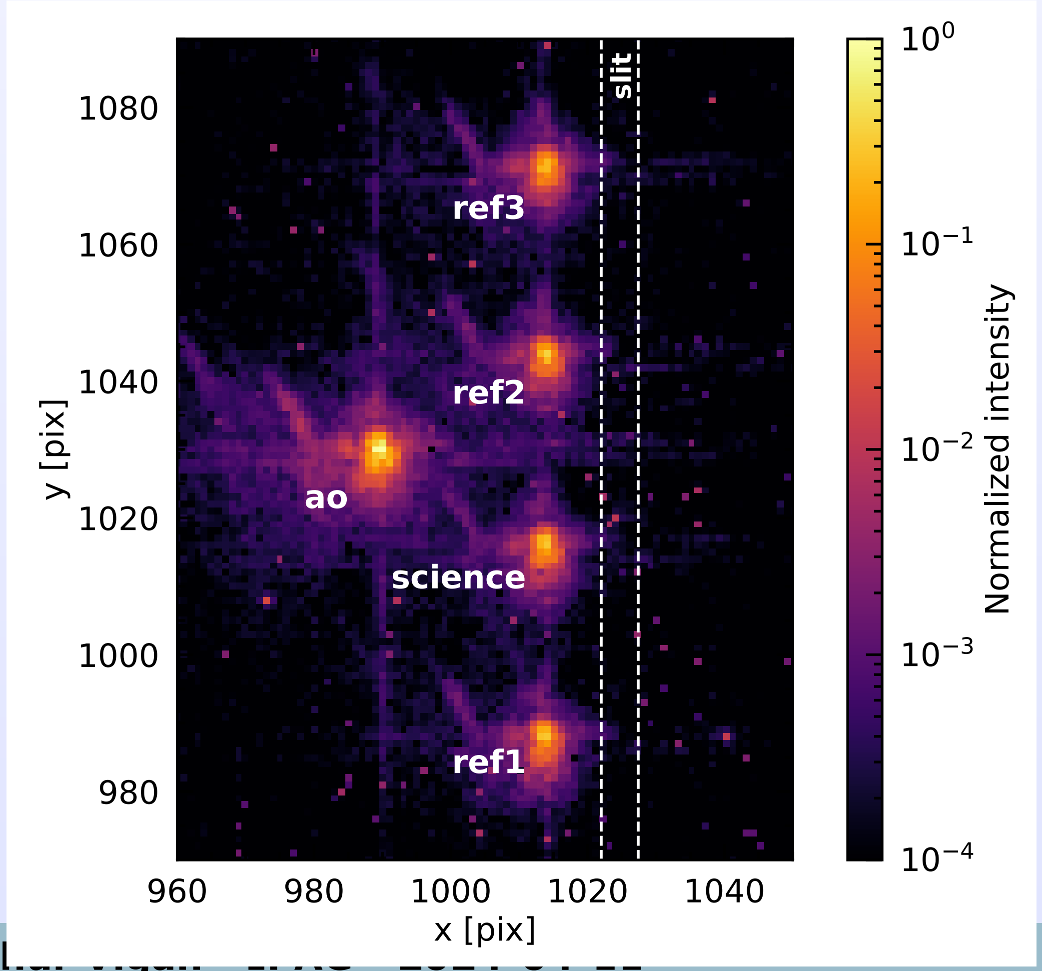
- North correction = 90.40° ± 0.08°
- Pixel scale = 12.805 ± 0.027 mas/pix

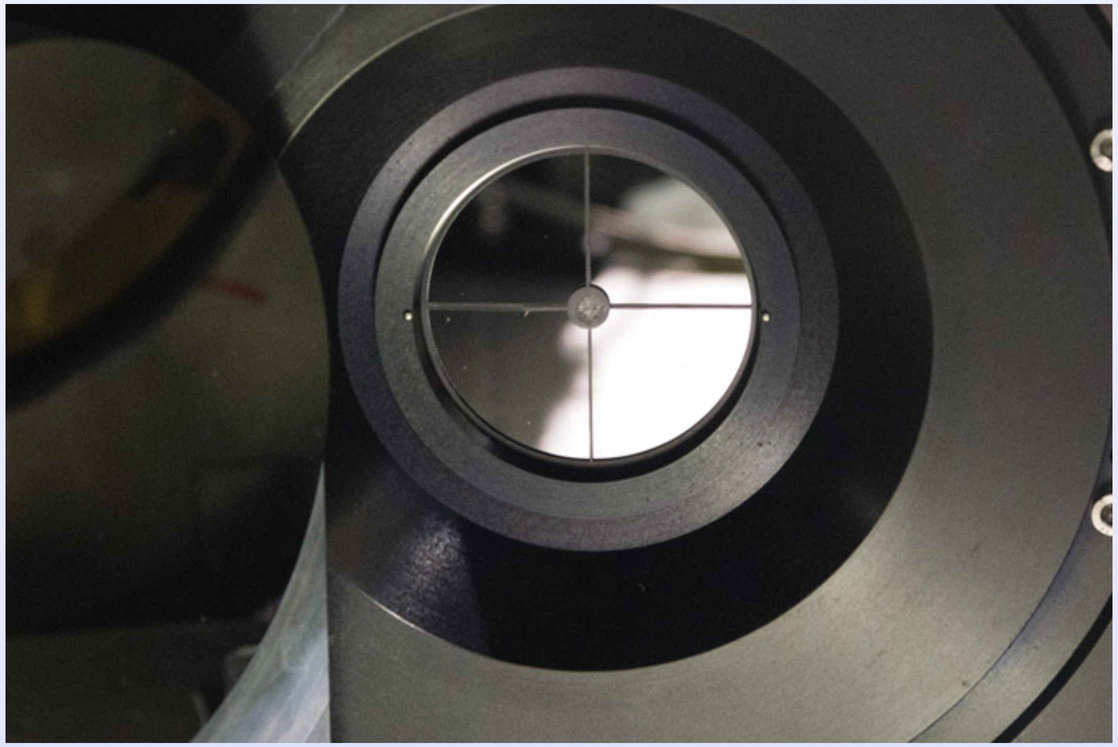
Cross-calibration strategy with SPHERE/IRDIS

Commissioning: AO guide fiber leakage

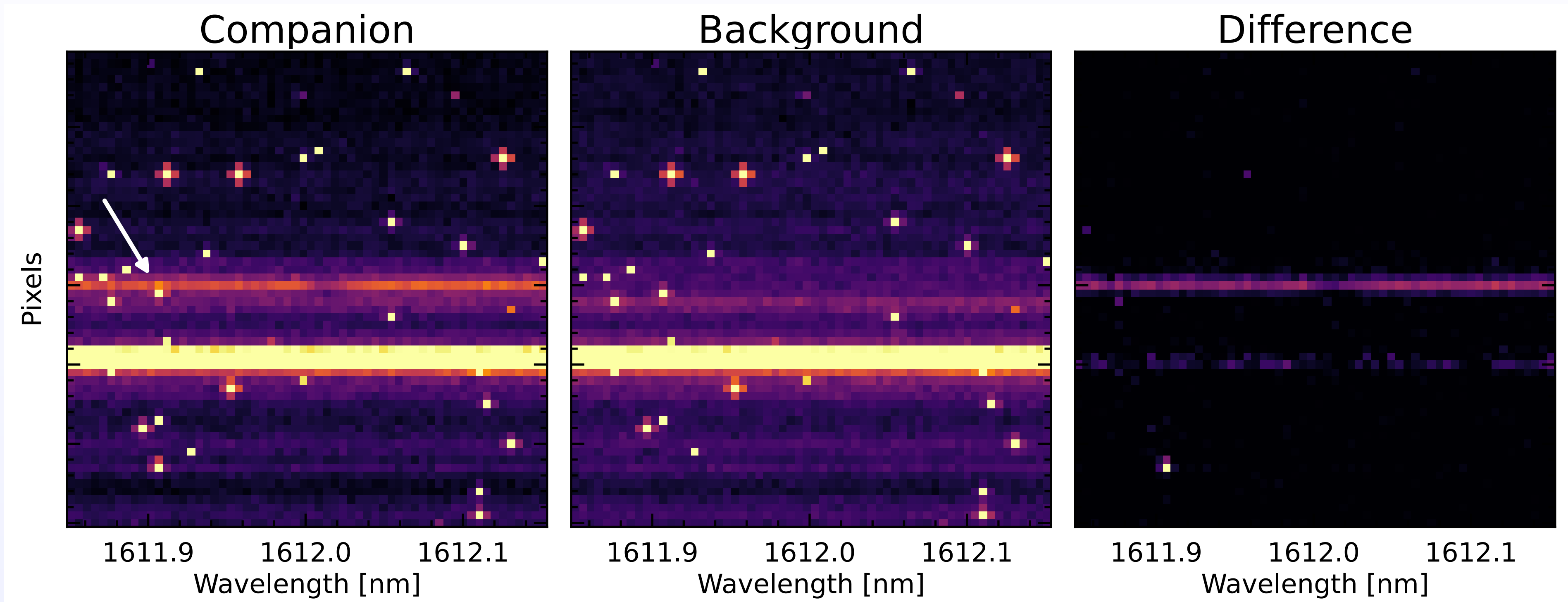


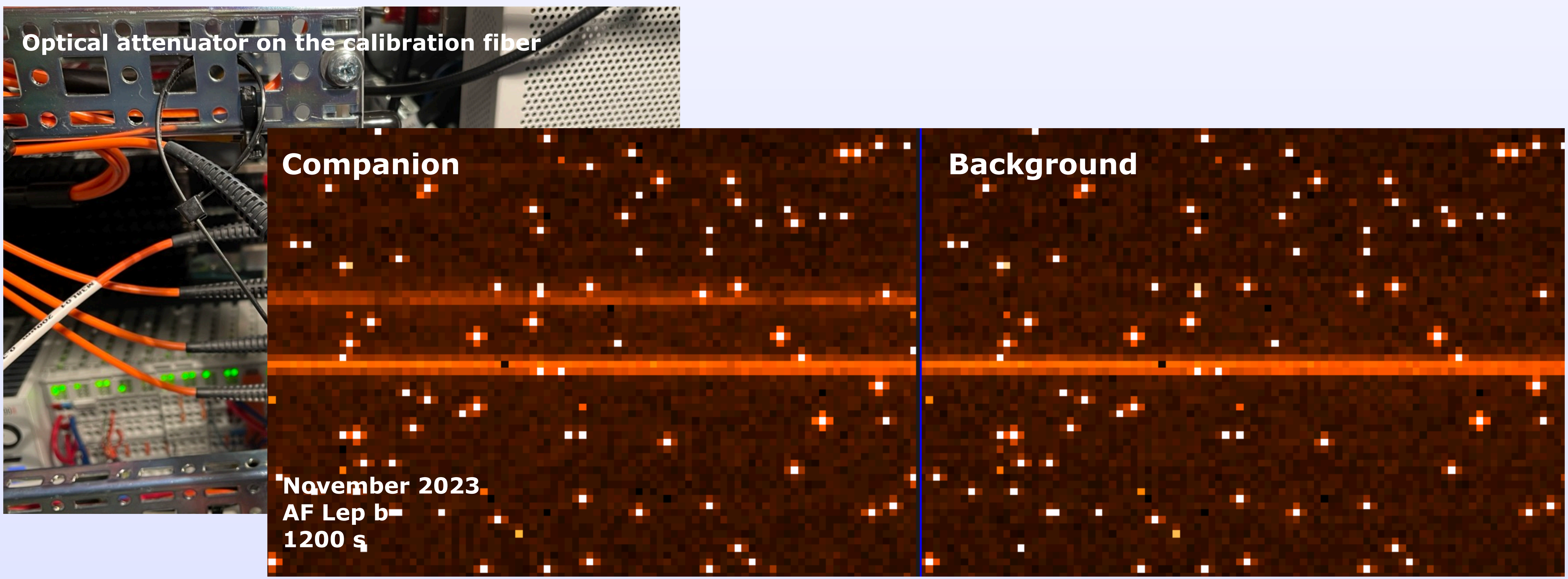
MACAO guide fiber leaks inside the slit





Commissioning: AO guide fiber leakage

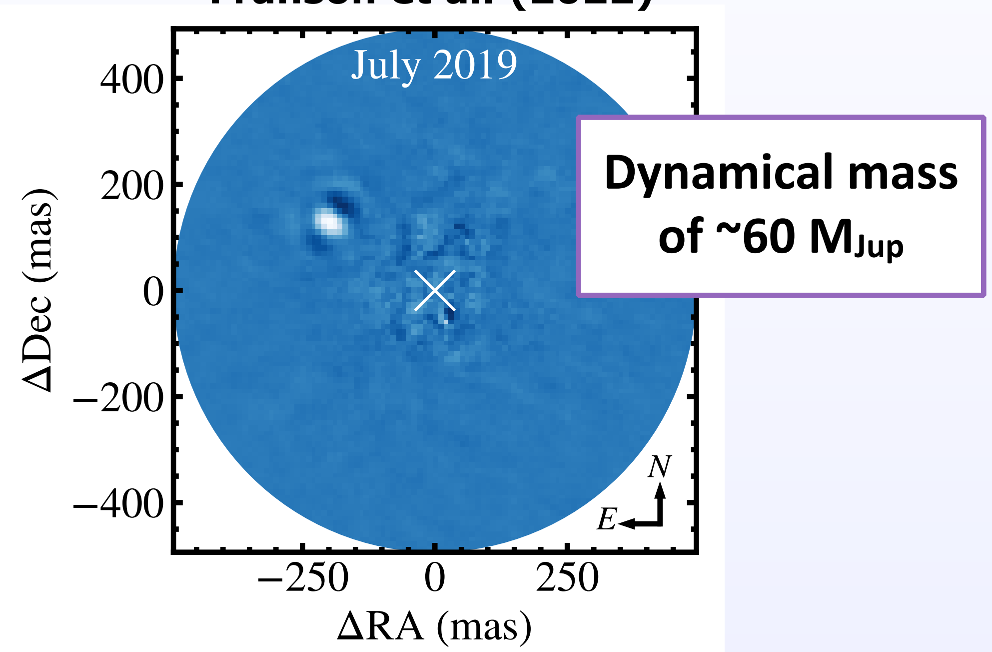


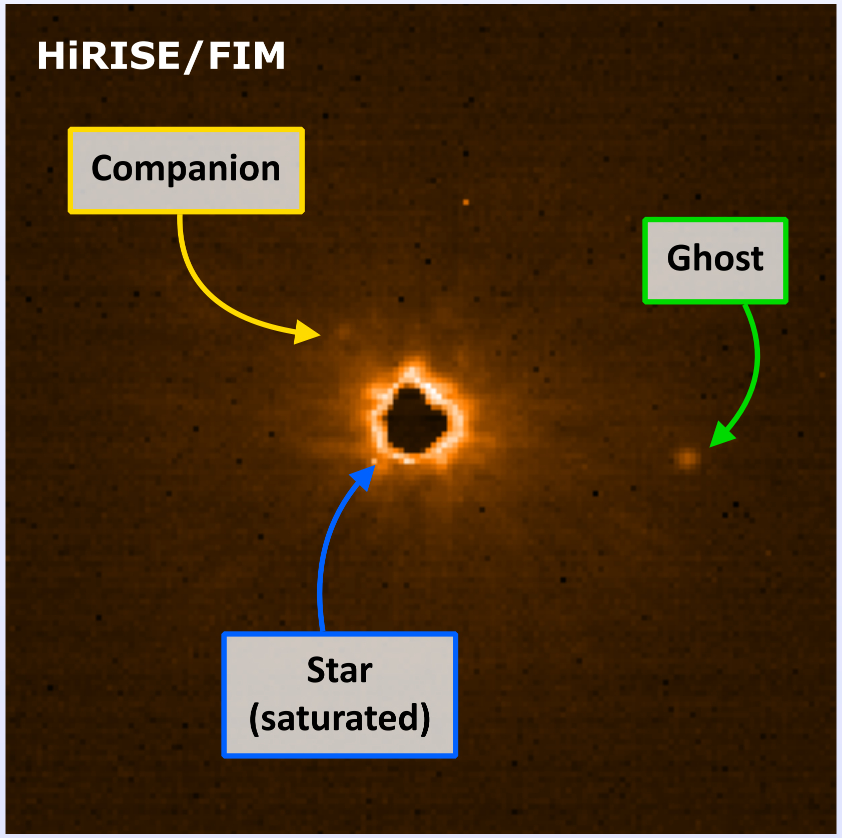


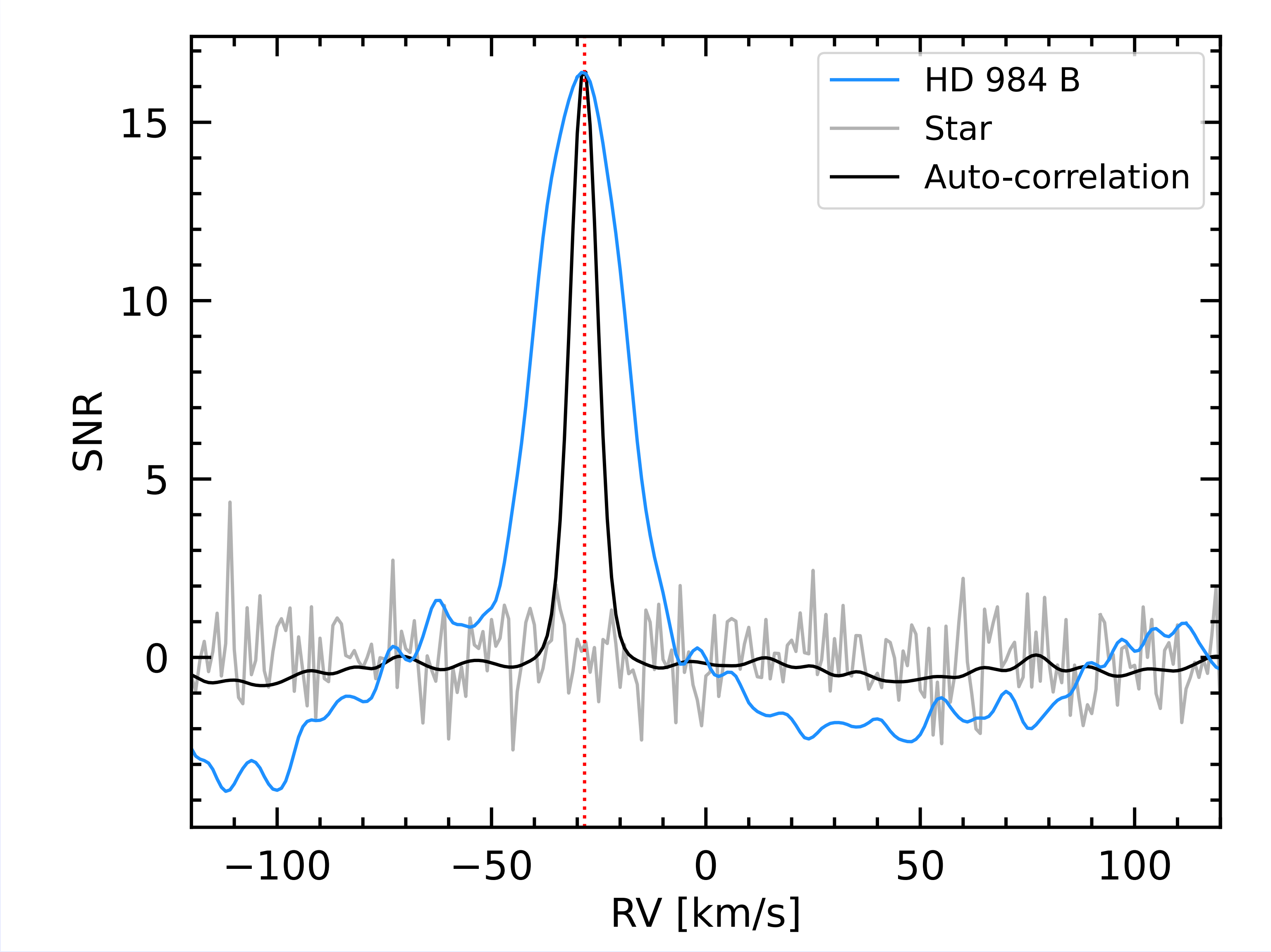
Commissioning: a first detection of HD984 B

Discovery: **Meshkat et al. (2015)**

Franson et al. (2022)





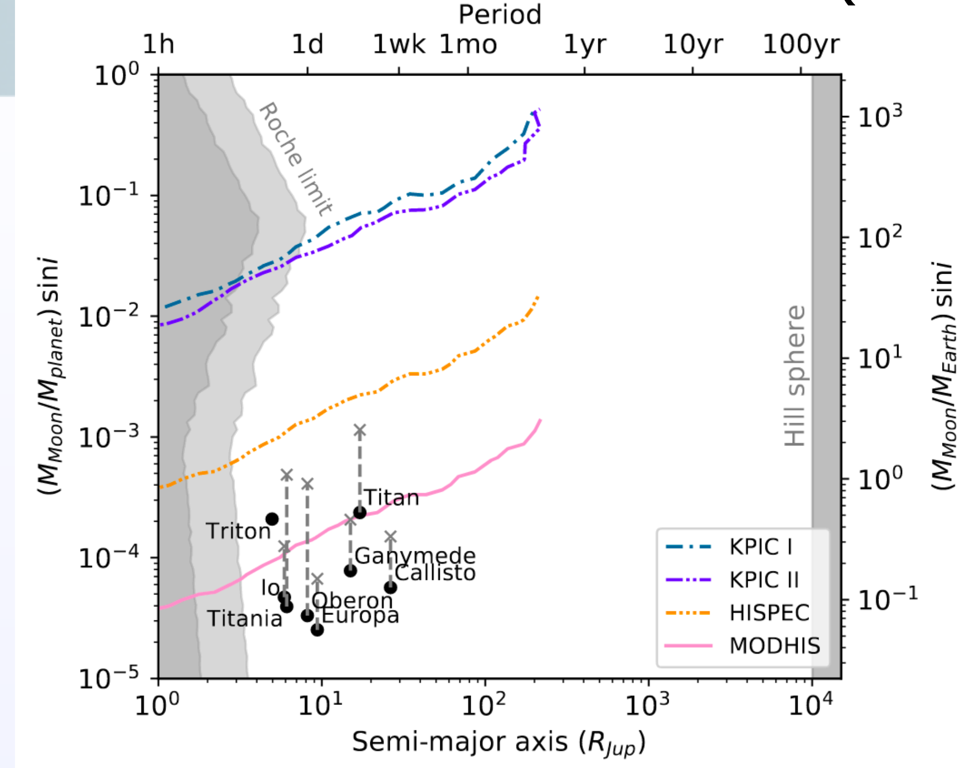


- Least-square CCF analysis
- BT-Settl model at T_{eff} = 2700K
- v_{orb} sin i = -31 km/s, v_{rot} sin i = 13 km/s
- Value in agreement wit KPIC data (Costes et al. in prep.)

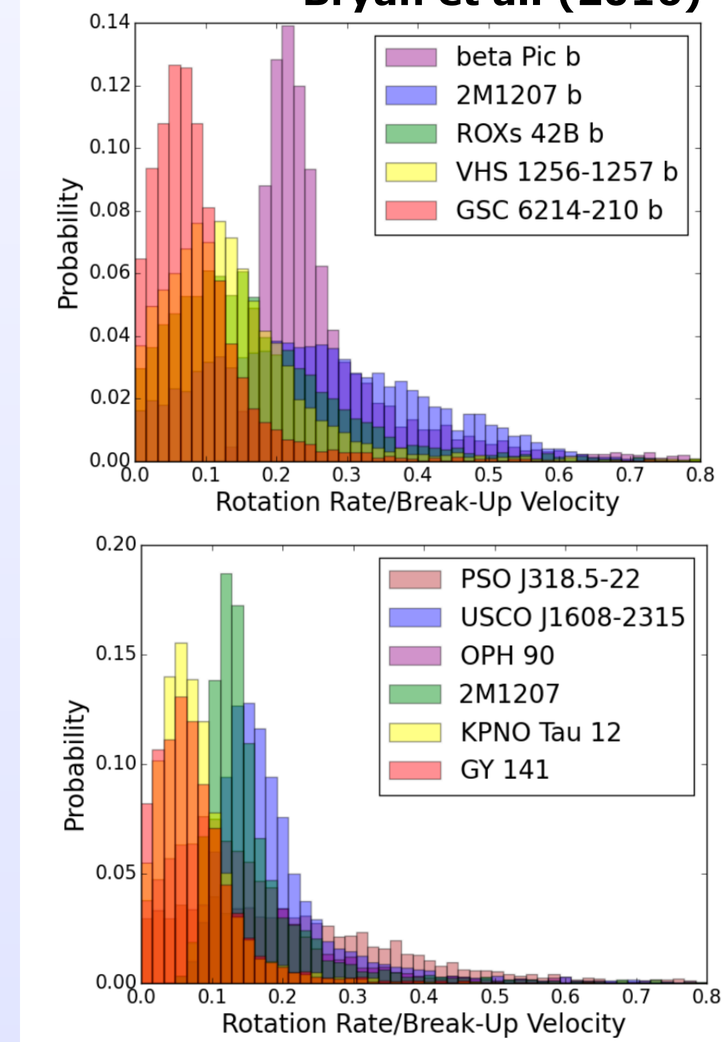
The HiRISE survey

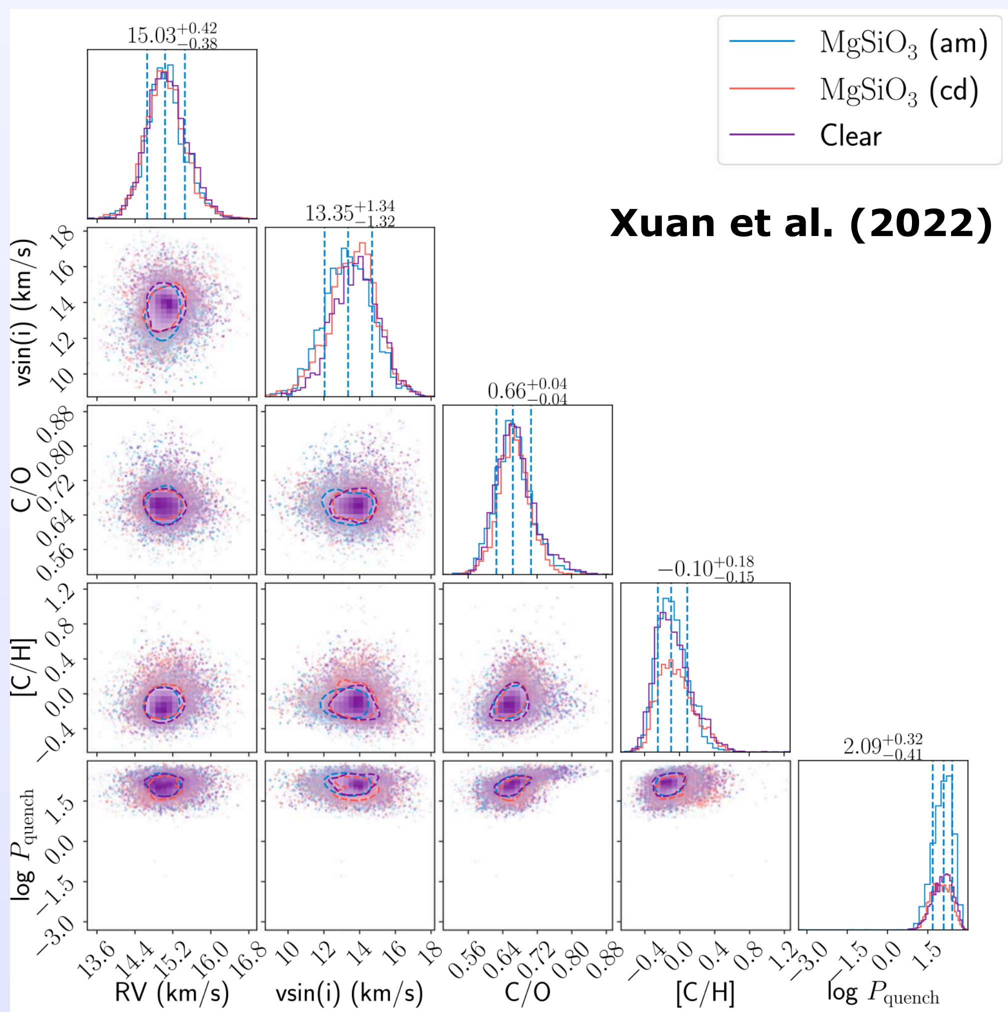
- Goal: survey all companions accessible to HiRISE in a "reasonable" amount of time
- Rotational periods
  - ➙ comparison with field object
- Detailed characterization
  - ➙ forward modelling
  - ➙ retrieval
- Isotopologues
  - ^{13}CO Zhang et al.
- Exo-moons / binary planets

Ruffio et al. (2023)



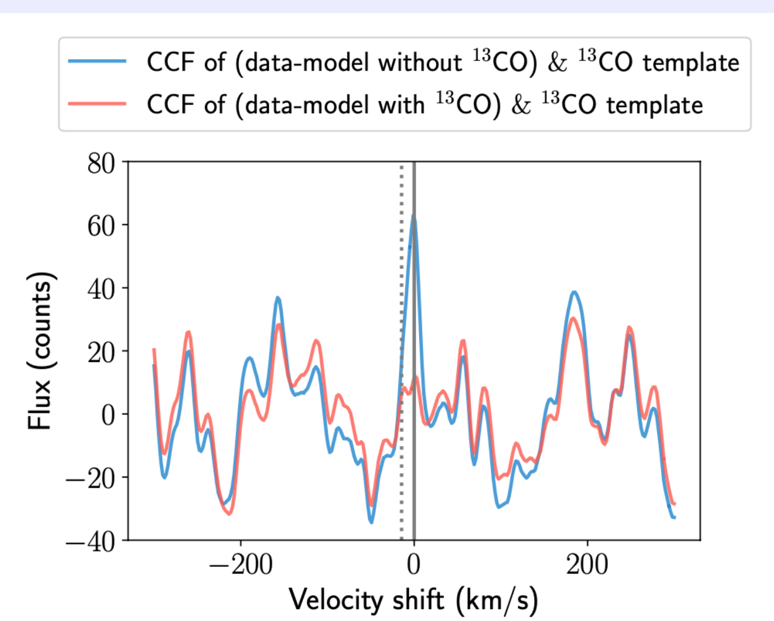
Bryan et al. (2016)





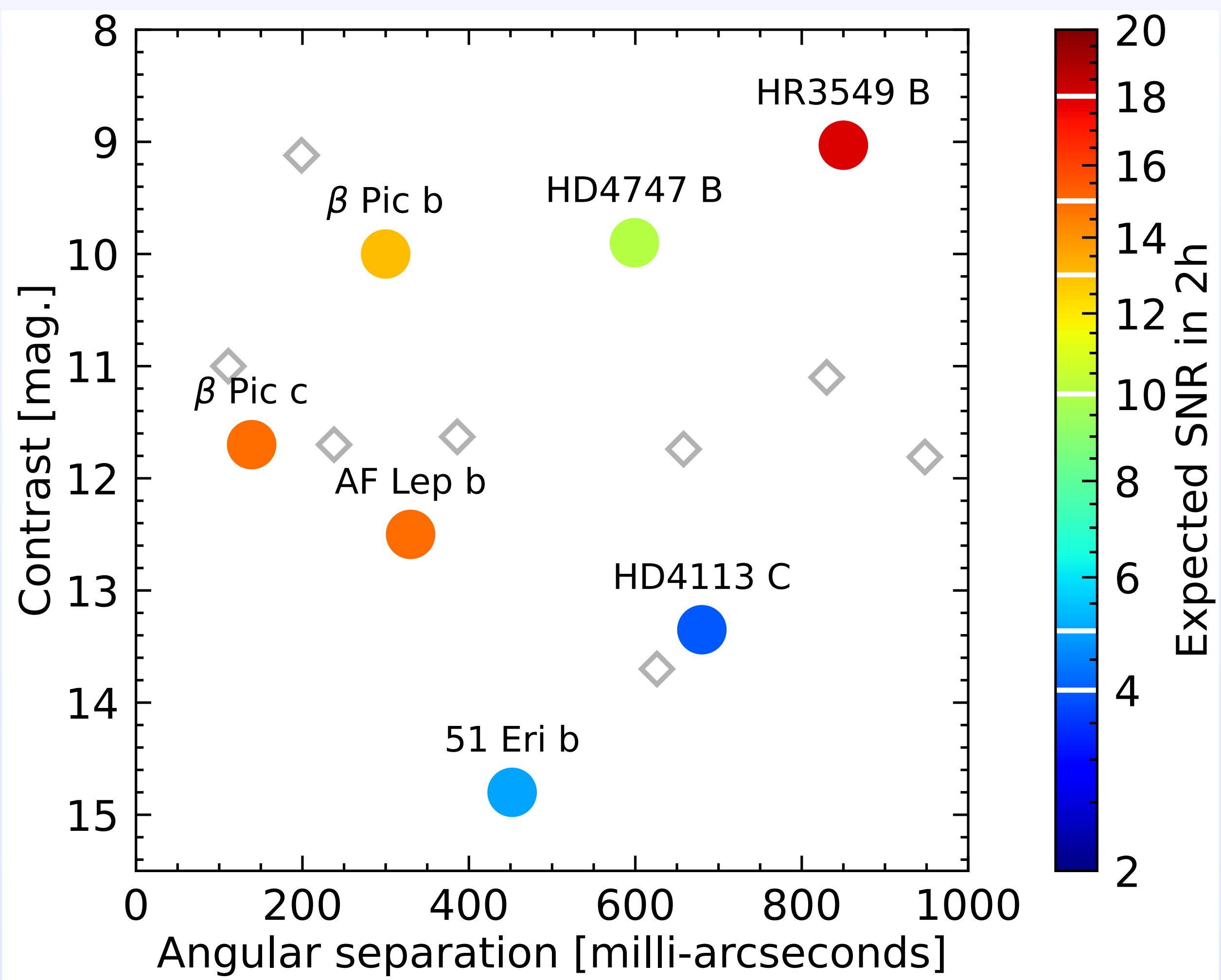
Xuan et al. (2022)

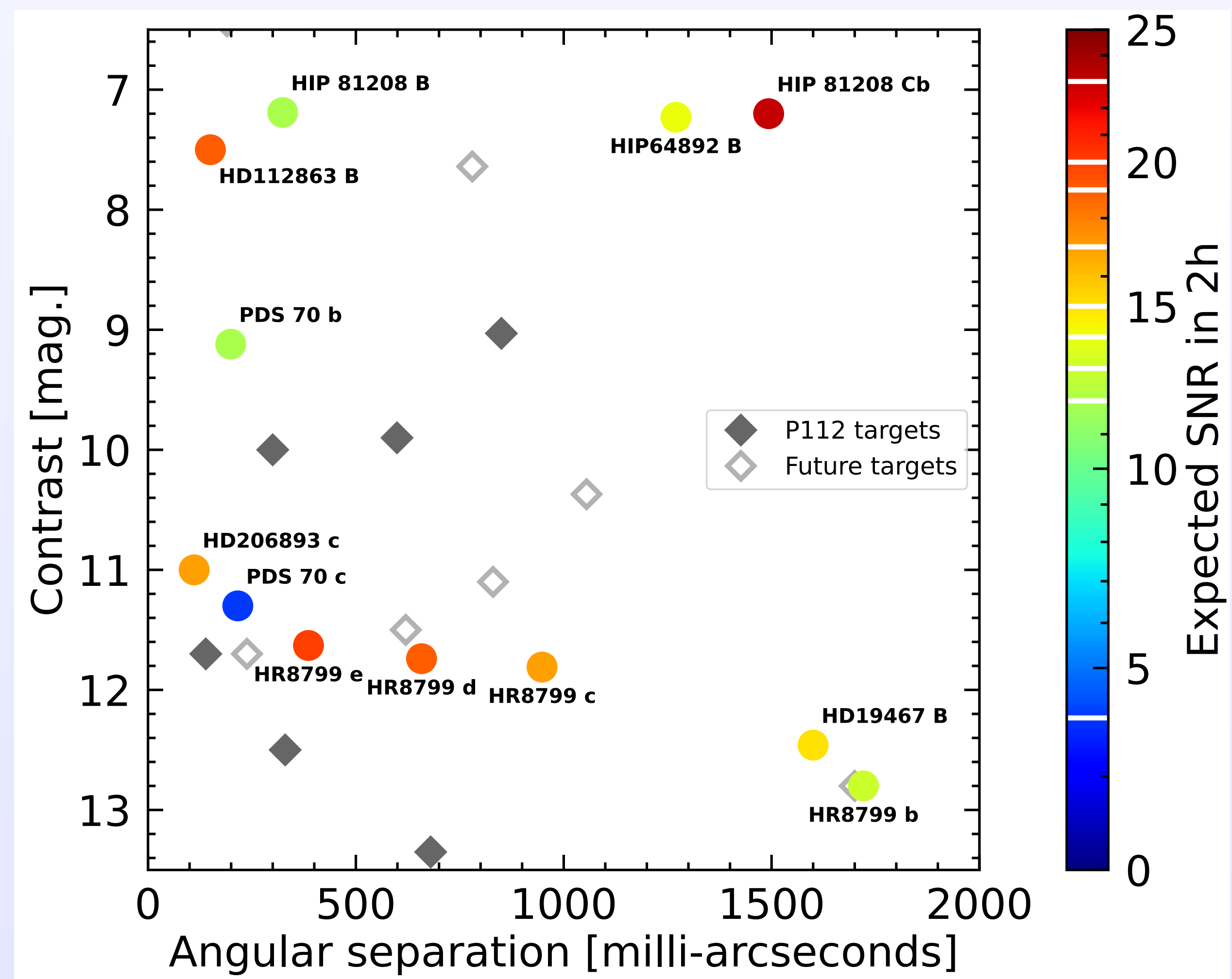
Xuan et al. (2024)



On-going observing programmes

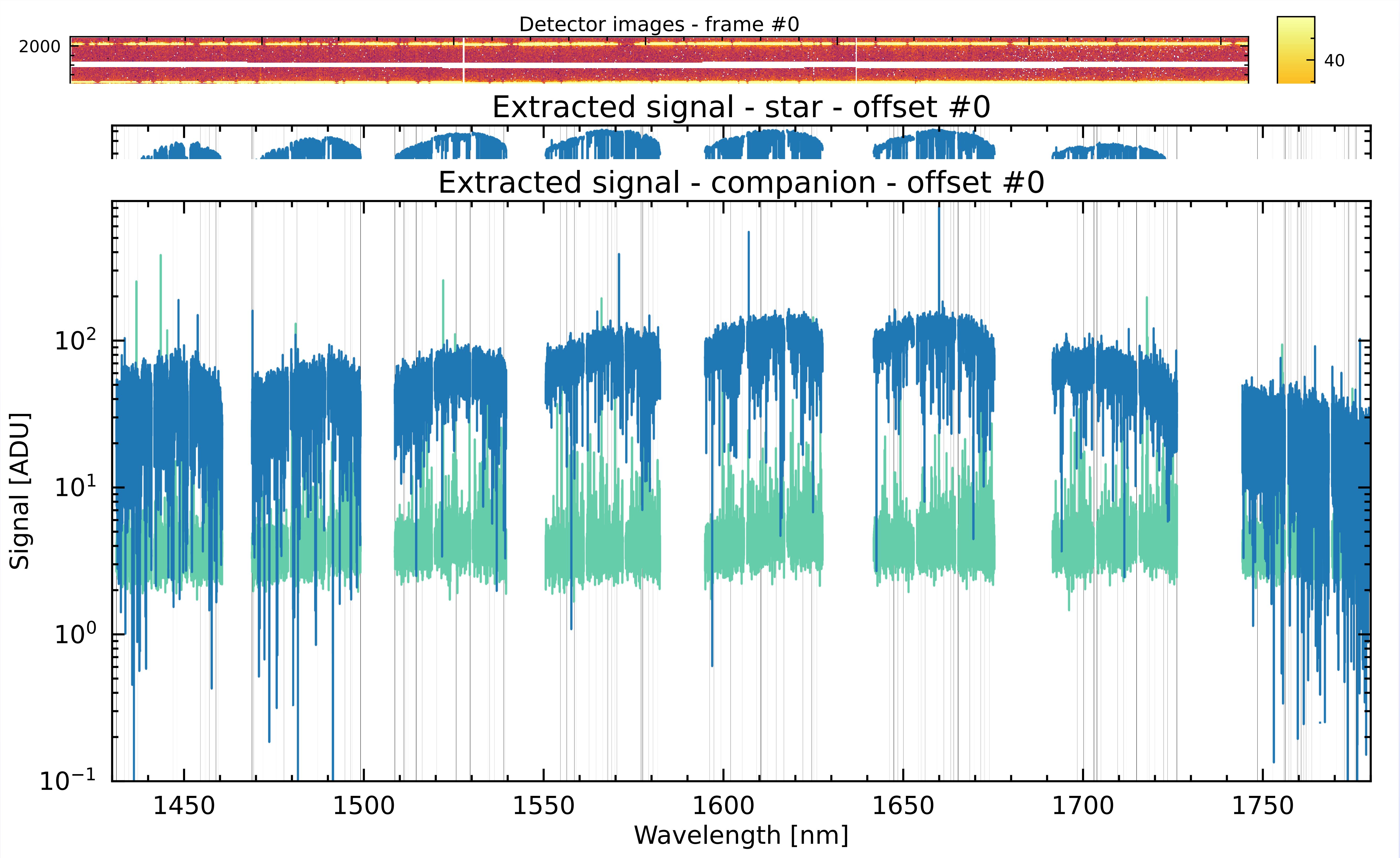
- Visitor instrument have **no GTO**!!
- Normal programmes:
  - P112: **accepted & executed**, 3 nights
  - P113: **accepted**, 4 nights (April & August 2024)
  - P114: 5 nights requested



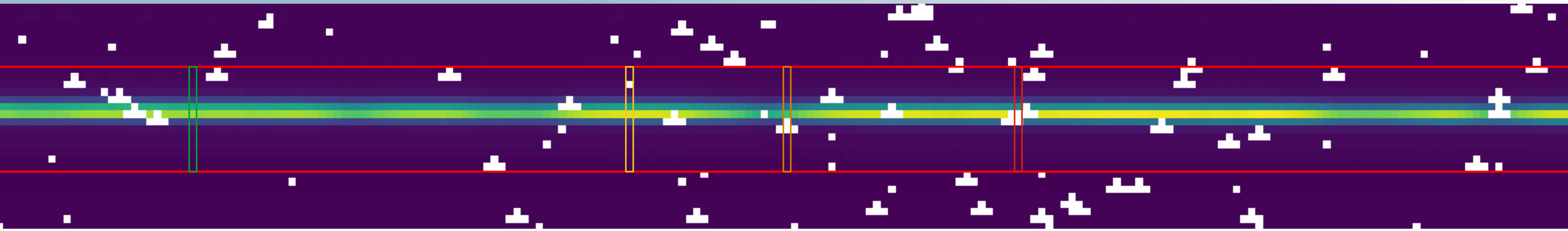


Data reduction pipeline

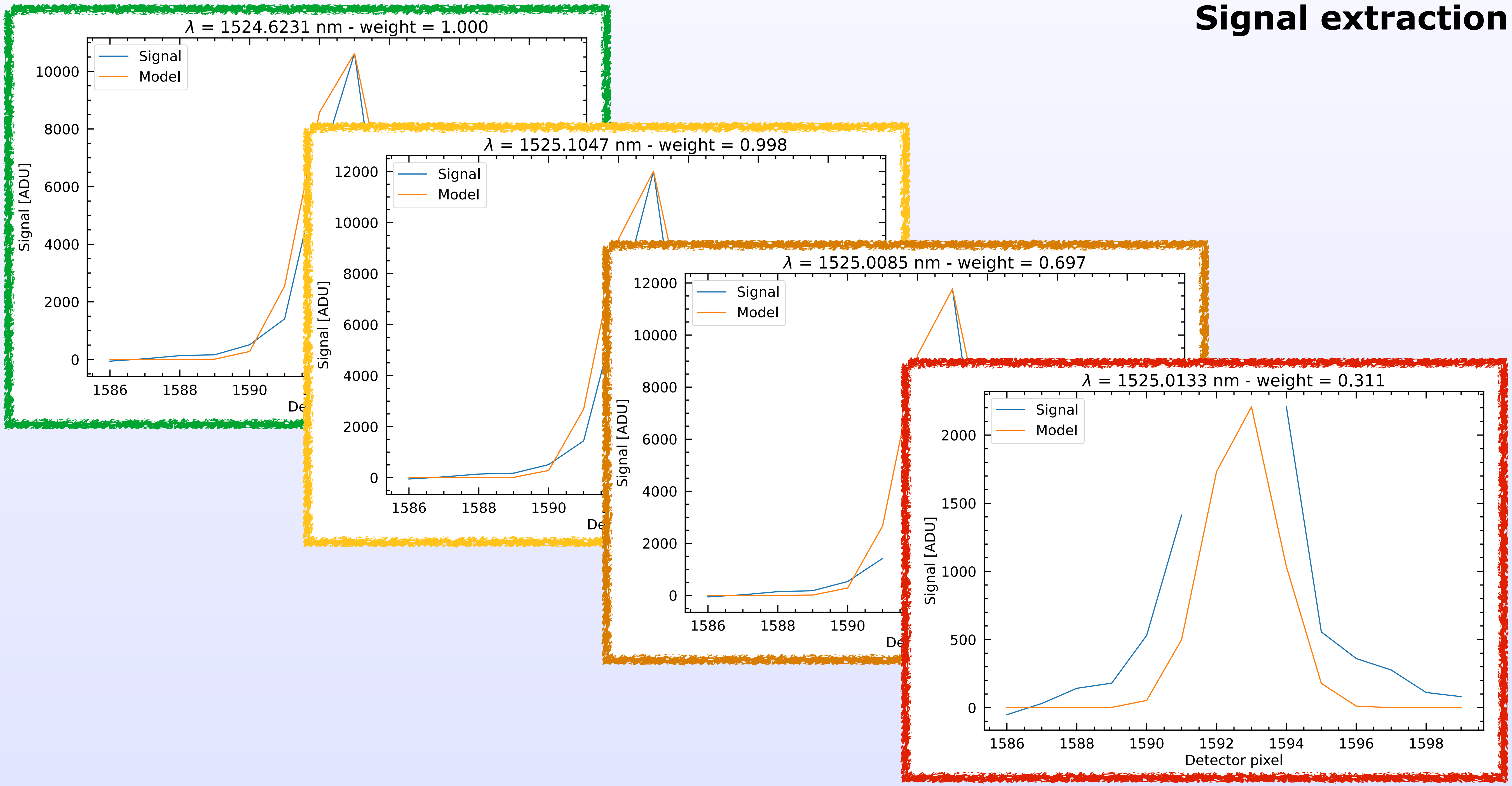
- Dedicated HiRISE pipeline: mix of official CRIRES pipeline & python



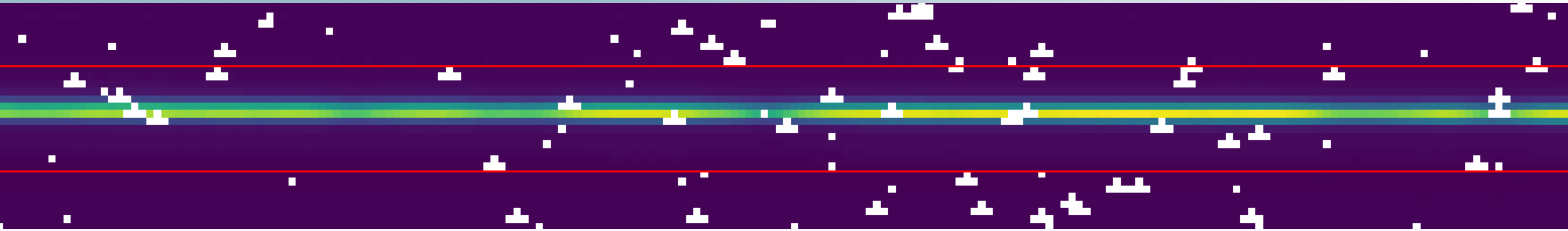
Data reduction pipeline: current limitations



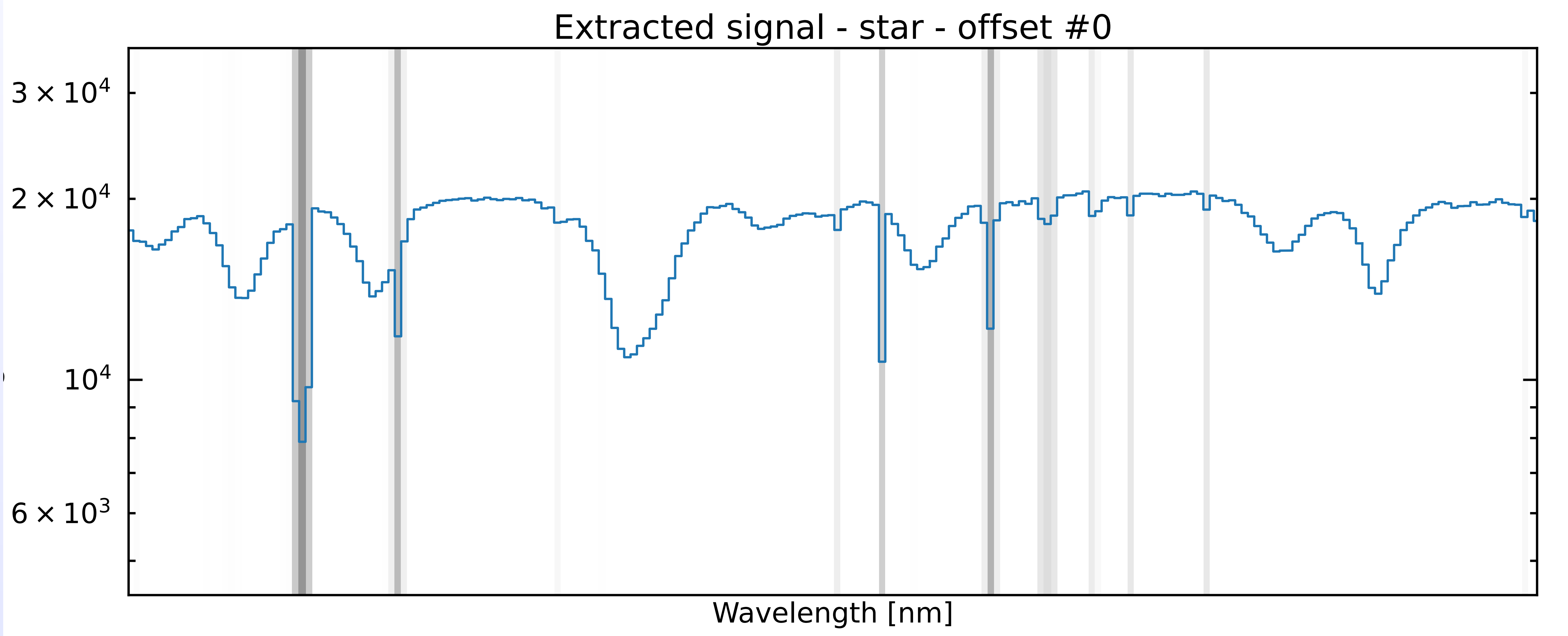
Signal extraction



Data reduction pipeline: current limitations



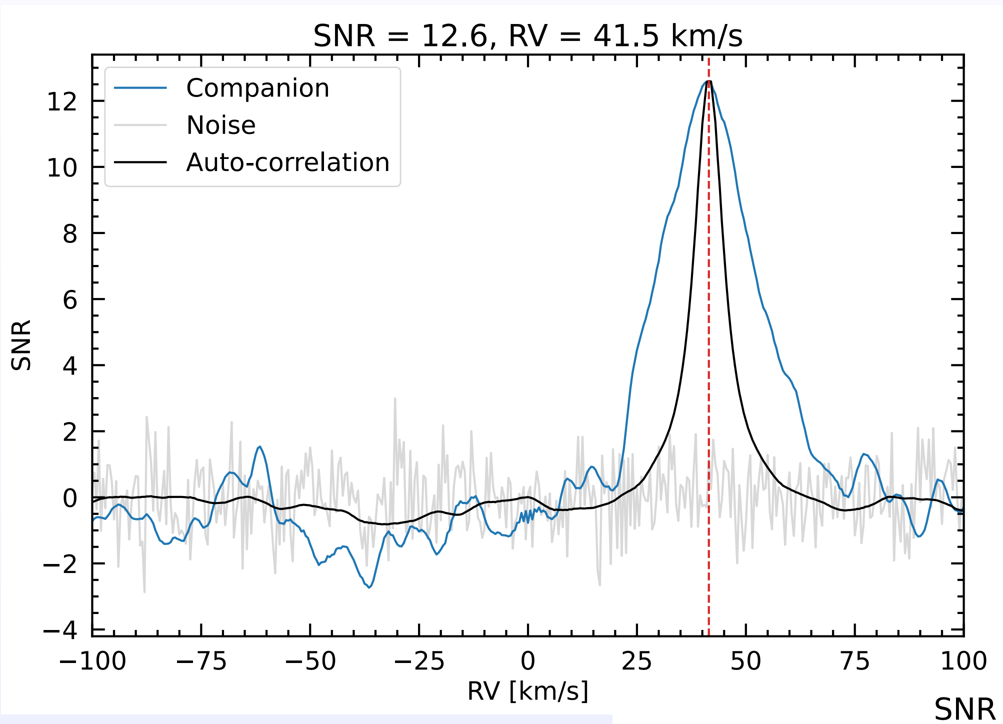
Signal extraction

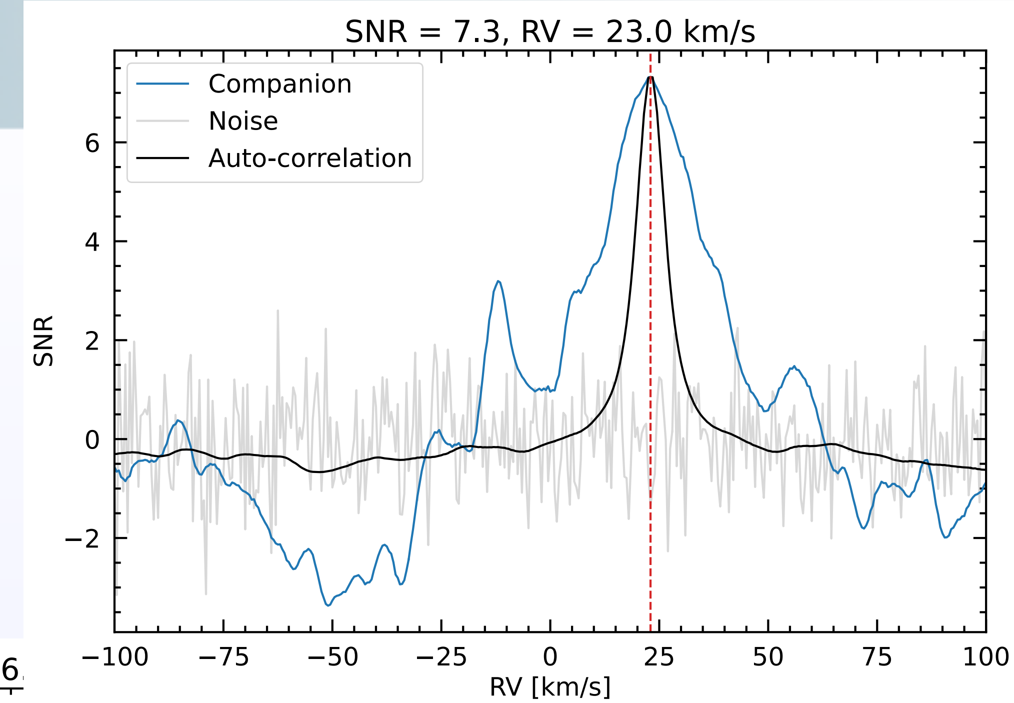


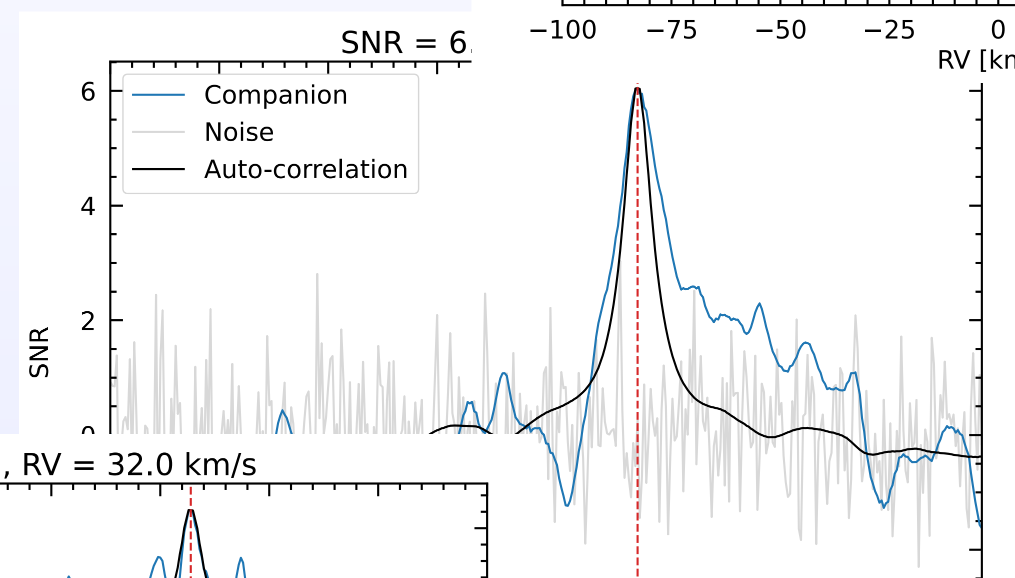
Bad pixels are really bad

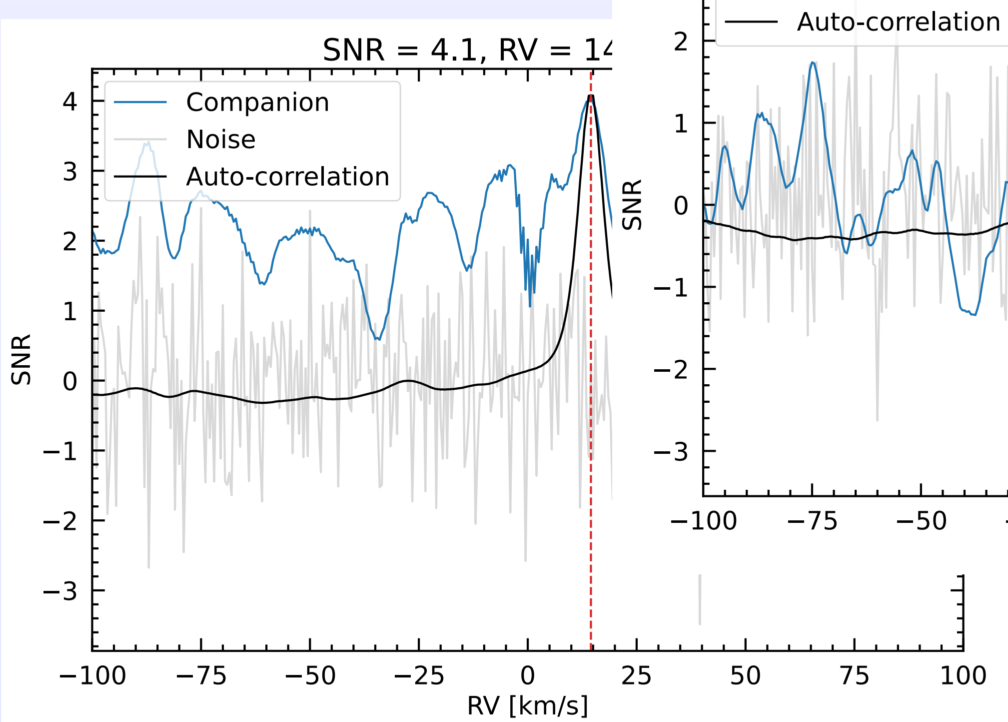
First results

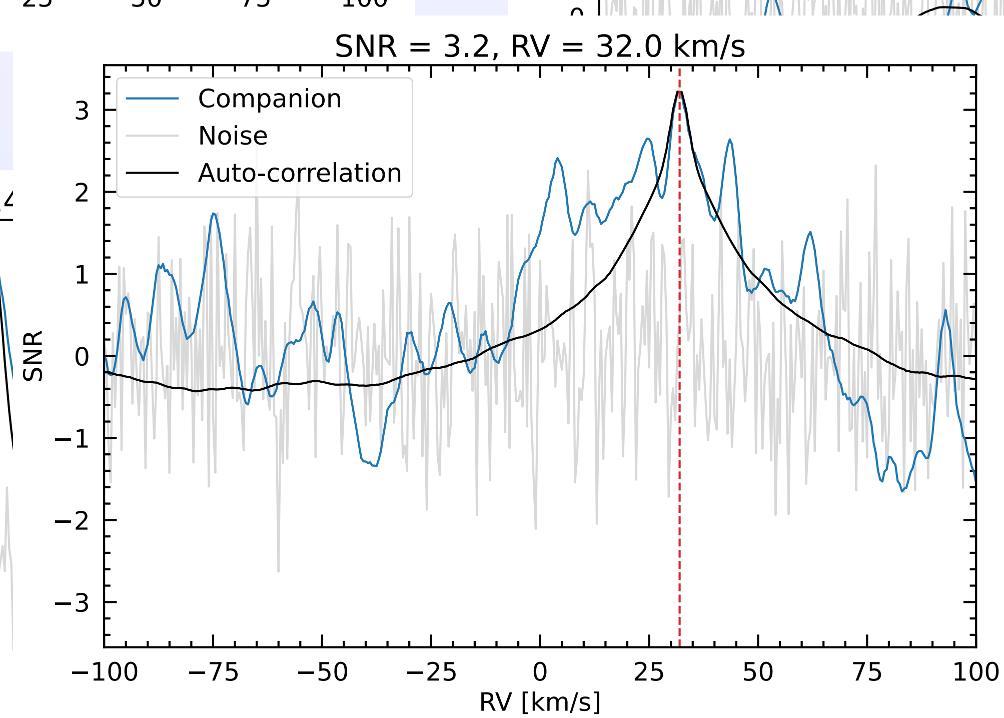
- November 2023: HD4747 B, HD4113 C, 51 Eri b, HR3549 B, AF Lep b and β Pic c

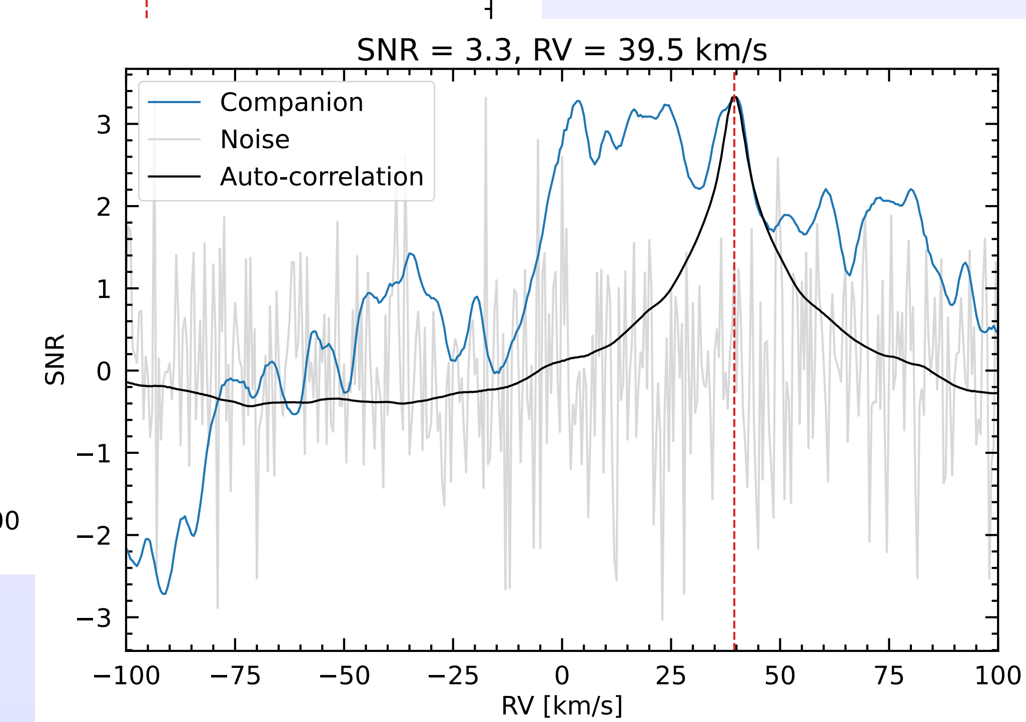






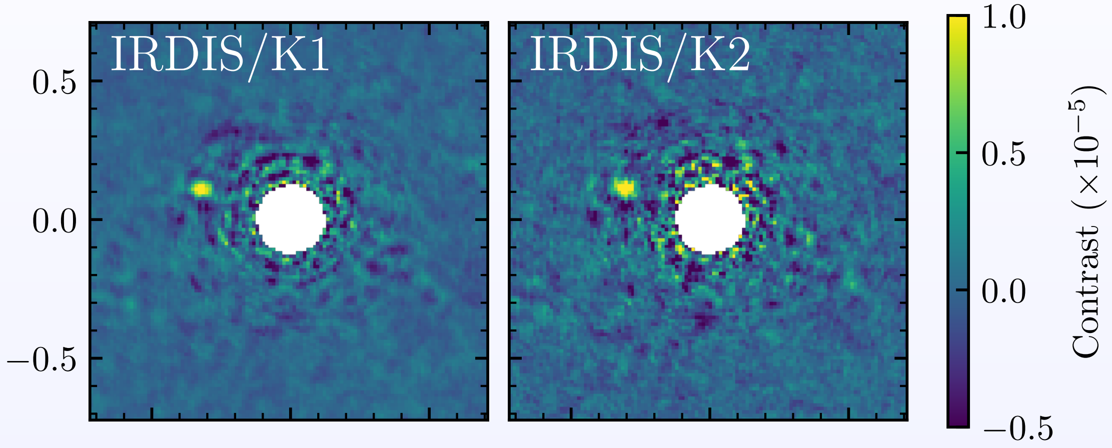


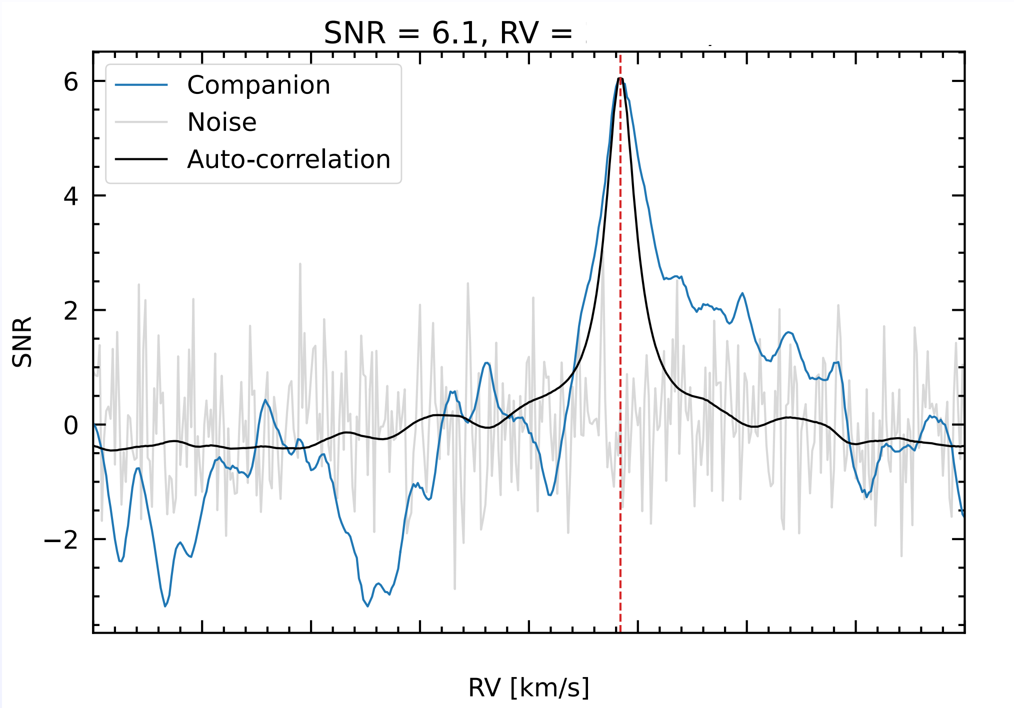


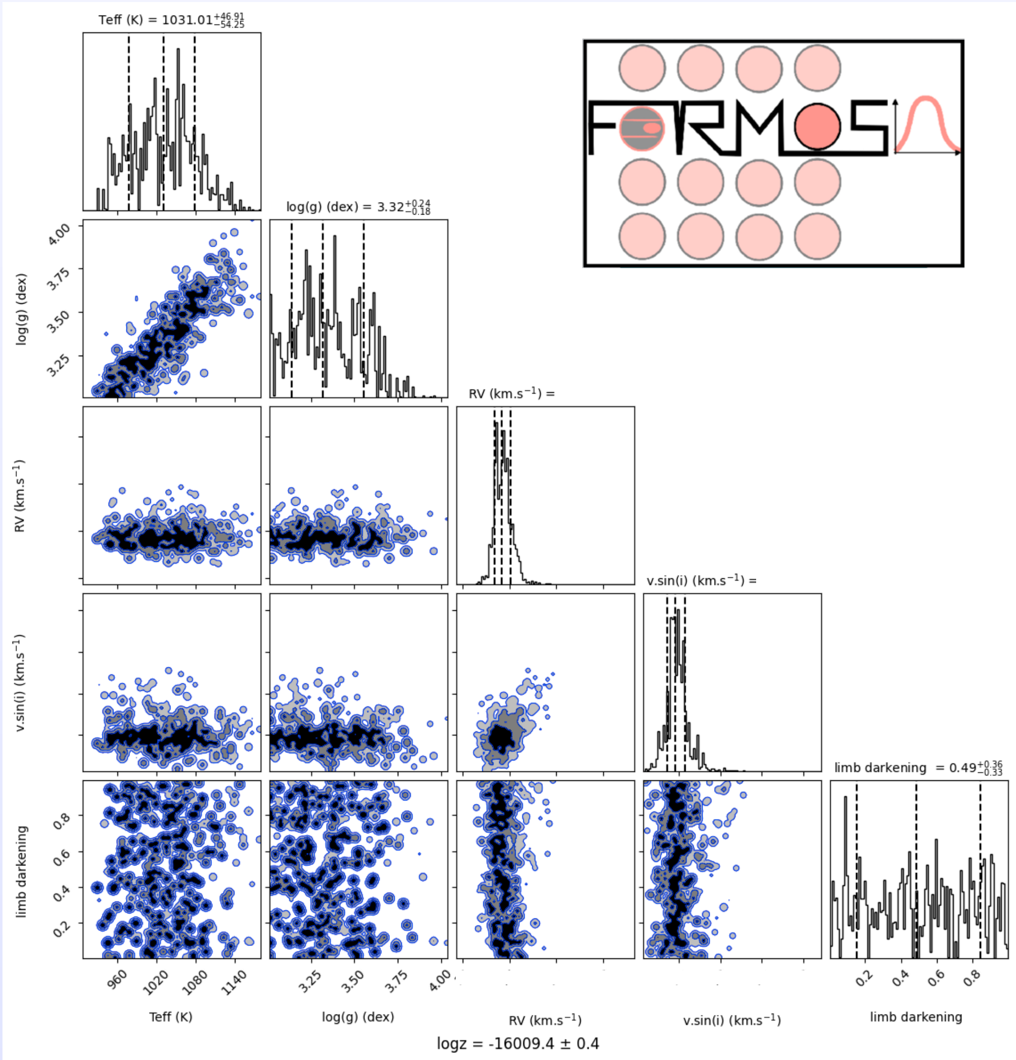


AF Lep b: a young super Jupiter

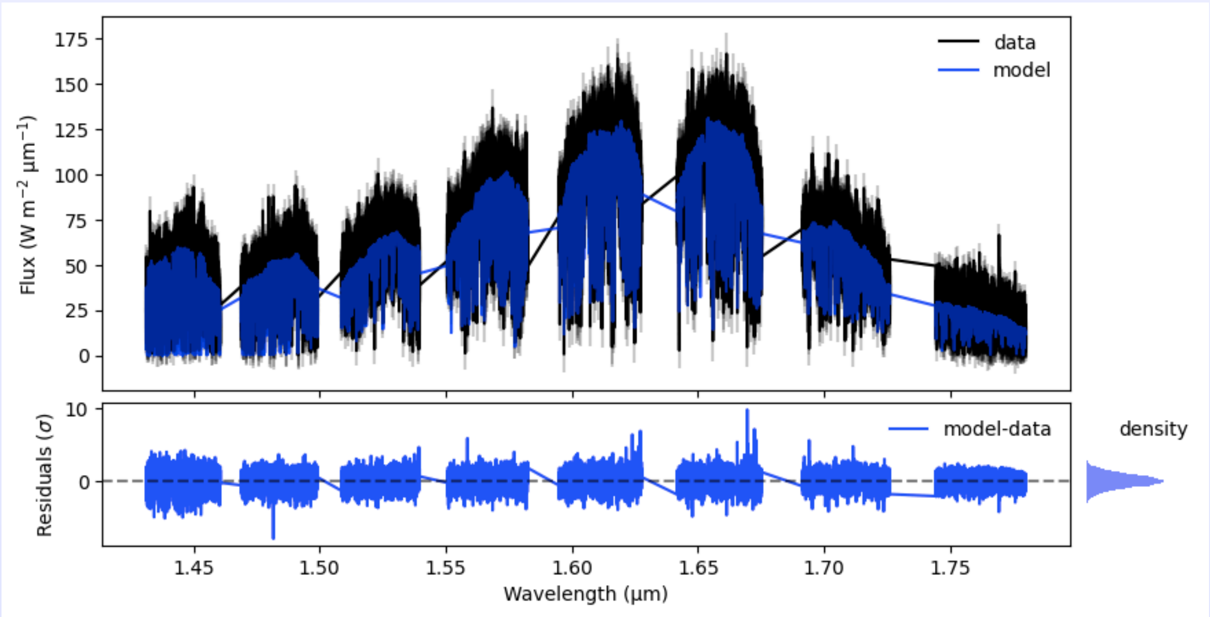
Discovery: **De Rosa et al. (2023), Mesa et al. (2023)**



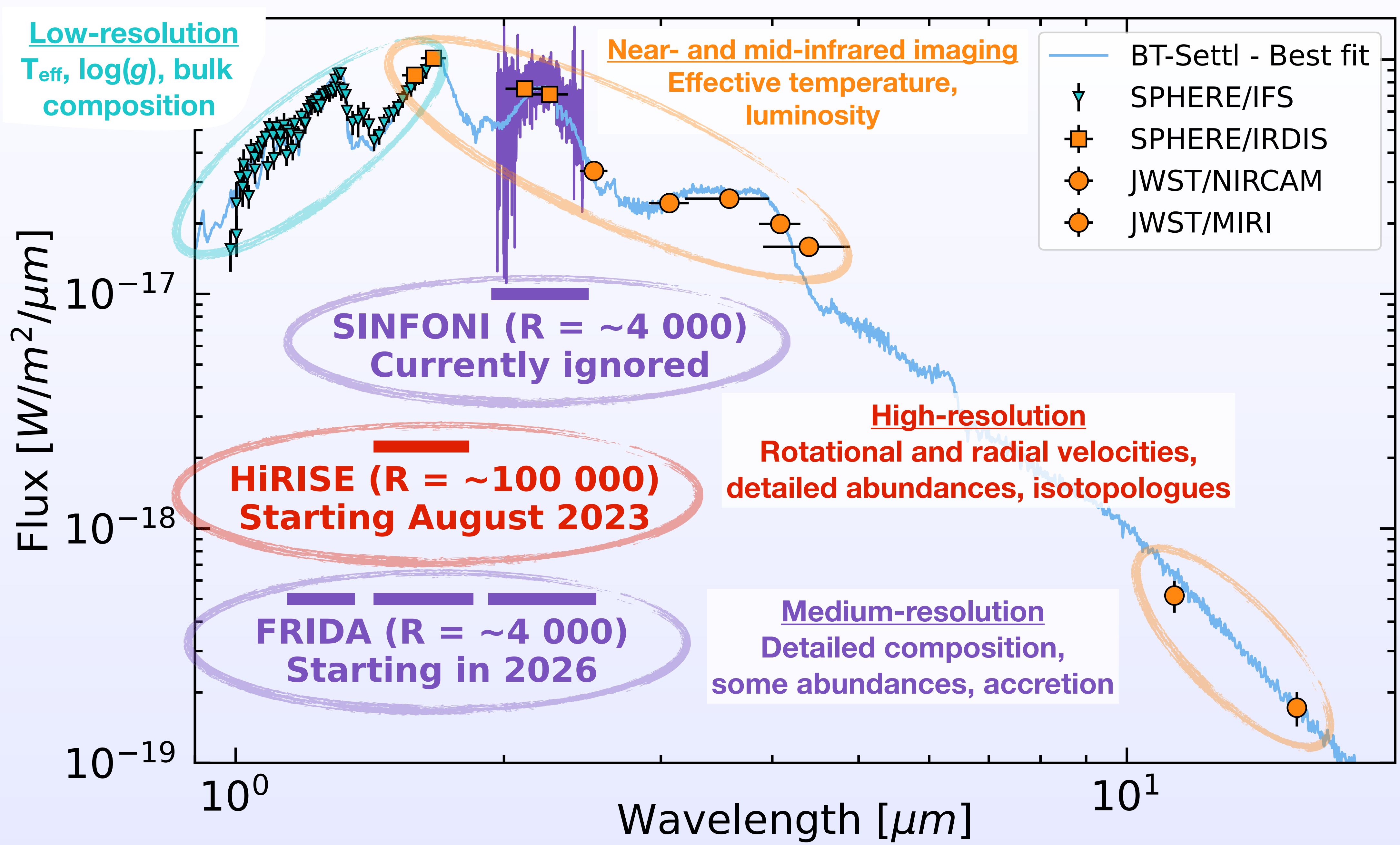


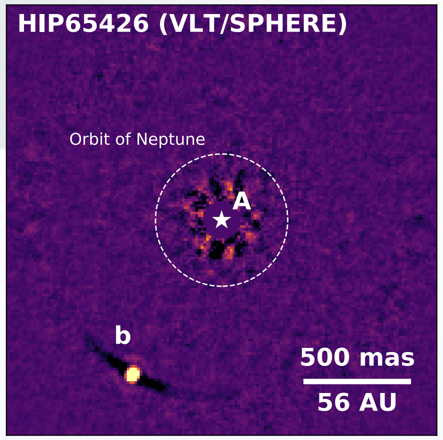


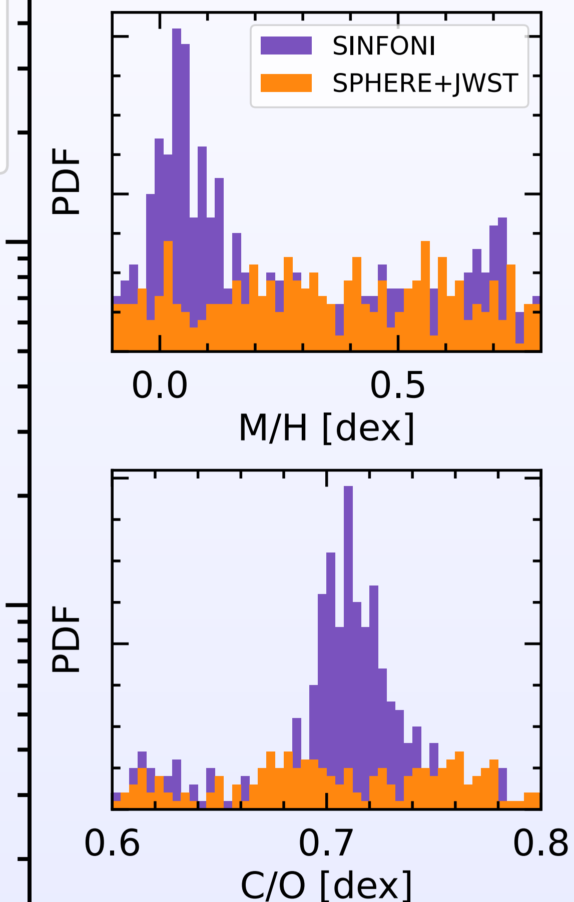
- Observed in November 2023
- Analysis work on-going
- Lead by Allan Denis (PhD)



The problem, illustrated on HIP65426b







How to merge these highly heterogeneous data in a consistant framework?

MIRAGES

R = 50
SHINE

R = 50
ExoGRAVITY

R = 50
BEAST

R = 500
SHINE

R = 500
ExoGRAVITY

R = 5 000
SINFONI

R = 5 000
X-SHYNE

R = 5 000
JWST ERS

R = 5 000
MUSE

R = 5 000
MUSE

R = 30 000
KPIC

R = 80 000
CRIRES

And certainly more to come!

Multi-Resolution Analysis of Giant Exoplanets

Objective 1
Produce the most comprehensive understanding of the physical and chemical properties governing the spectral properties of young EGP

Objective 2
Develop an ambitious data analysis fusion strategy incorporating the most advanced development in exoplanetary atmosphere modelling

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

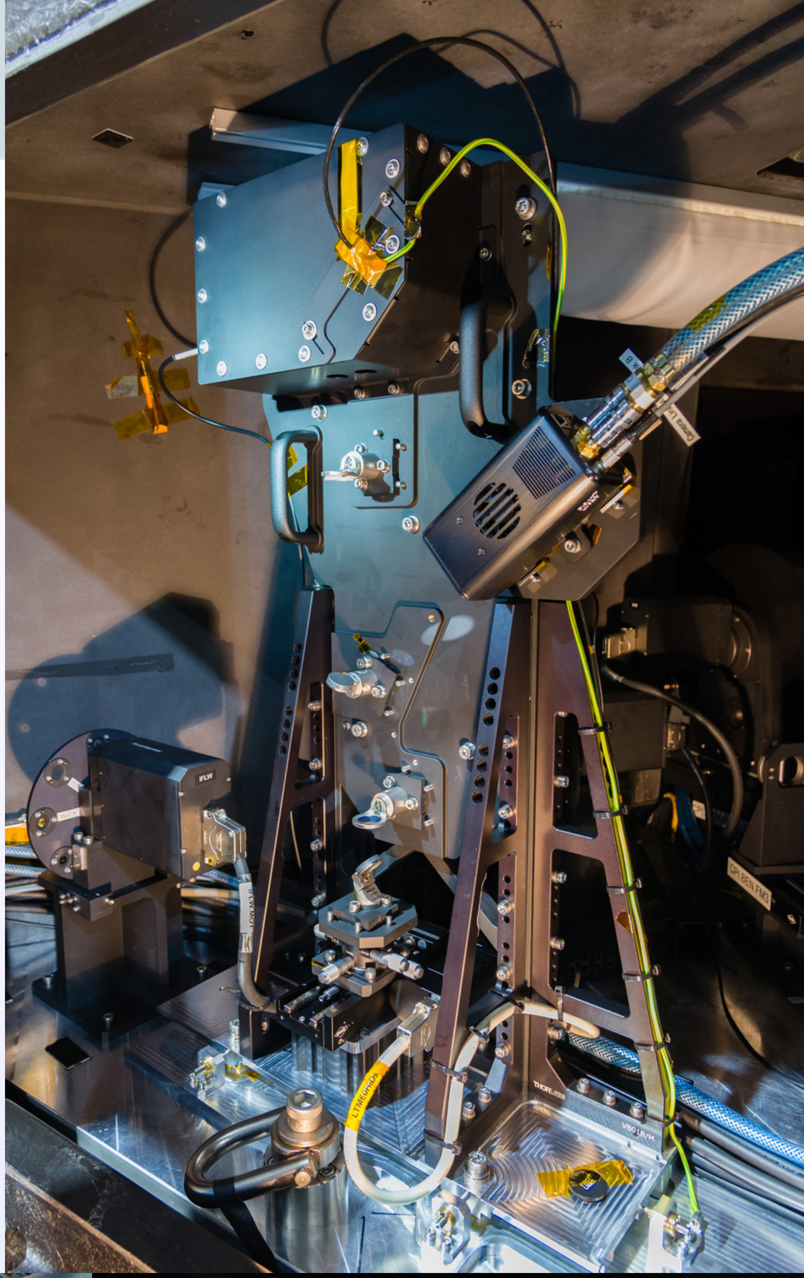
LAGRANGE

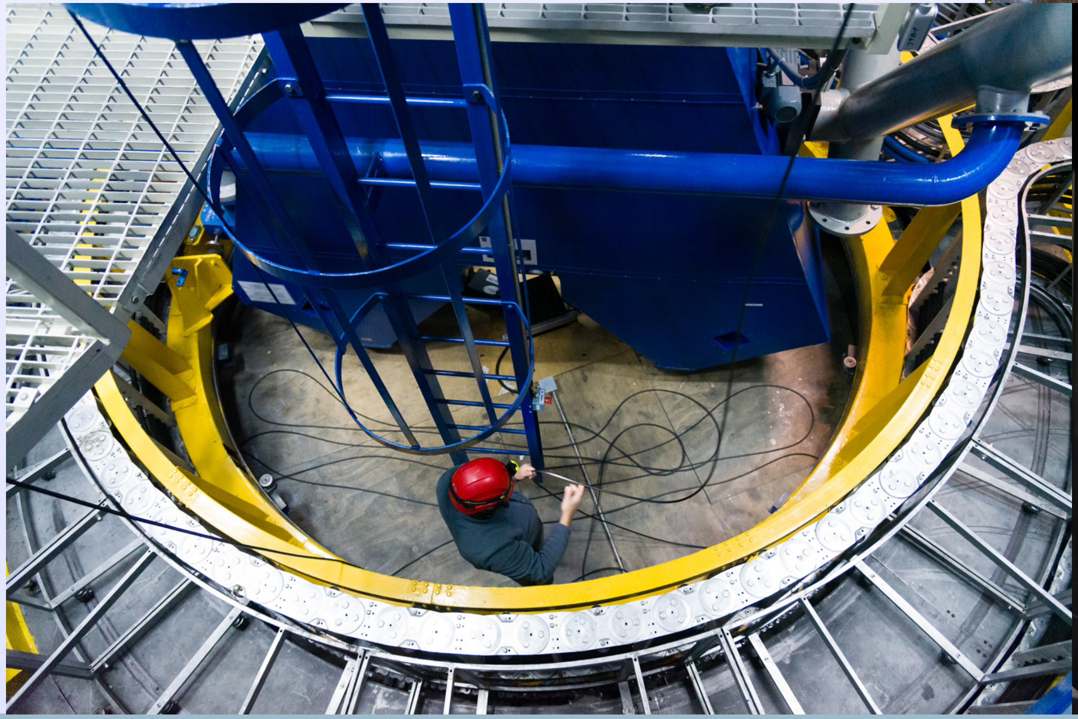
IPAG Institut de Planétologie et d'Astrophysique de Grenoble

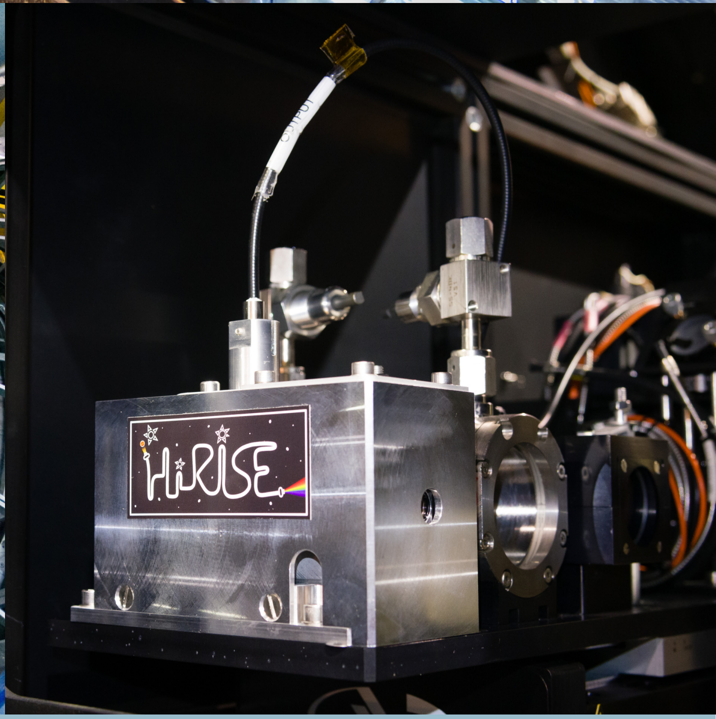
LESIA

Conclusions & prospects

1. **High-spectral resolution of directly-imaged exoplanets**
   - Unique opportunity on VLT/UT3!
   - Coupling between SPHERE and CRIRES+ in H band
   - Visitor instrument on the VLT
   - First light in July 2023
2. **HiRISE survey**
   - New opportunities for understanding of exoplanets
   - Started in November 2023
   - First results already in the pipeline





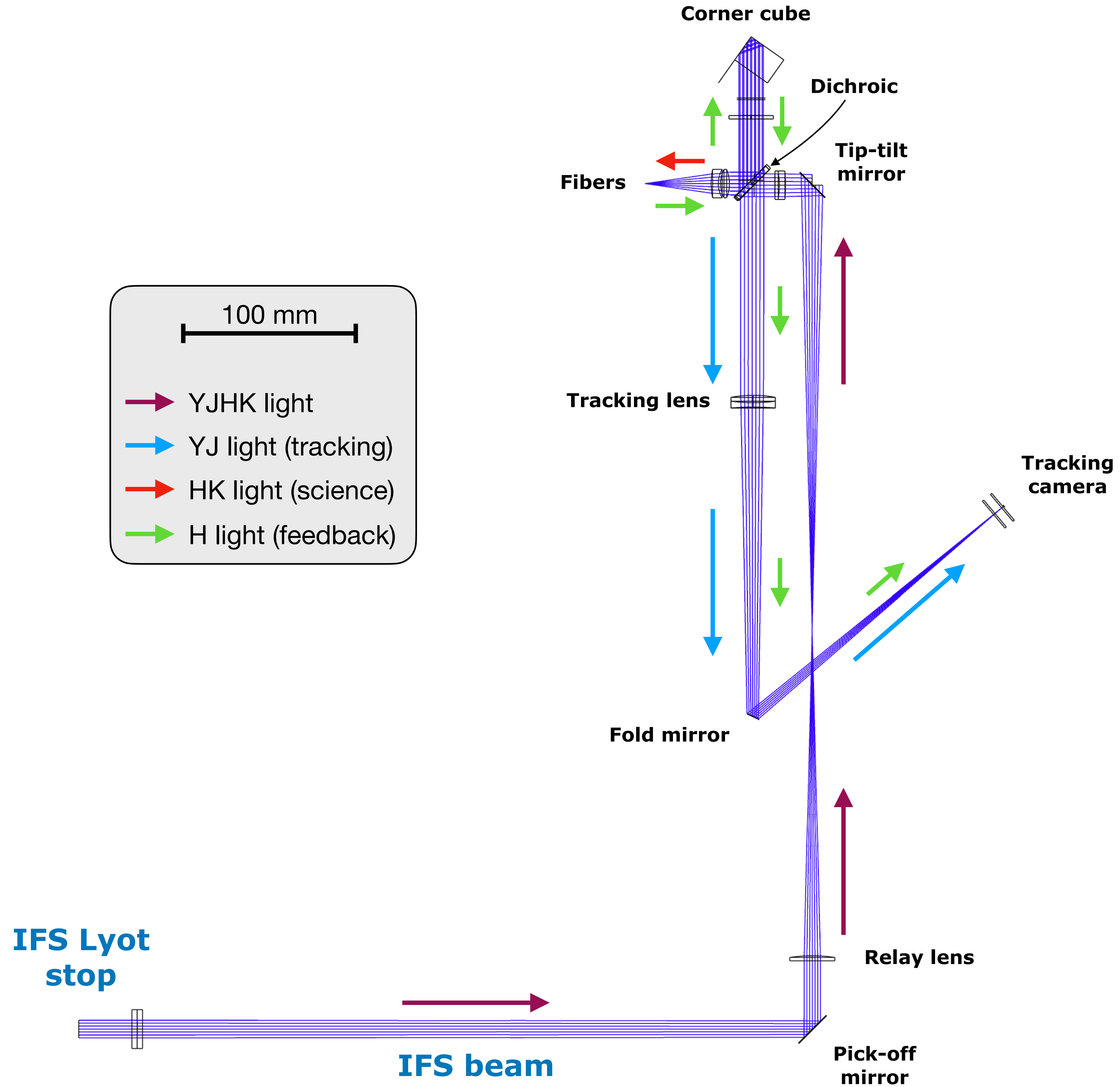


HiRISE core team

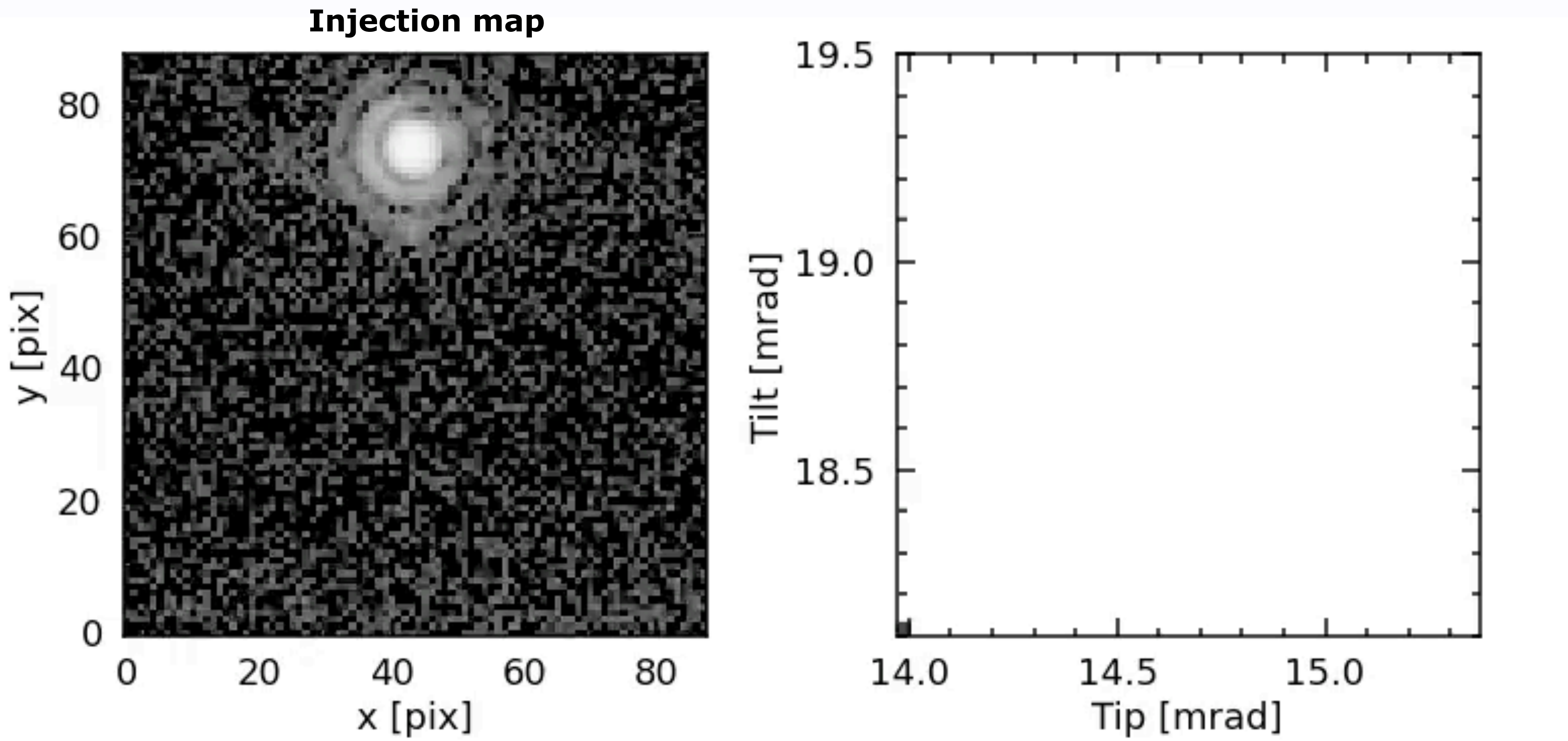
+Graham Murray
+Gérard Zins
+Jérôme Paufique
+Ulf Seemann
+Heiko Anwand-Heerwart
+Mark Phillips


HiRISE
DELL

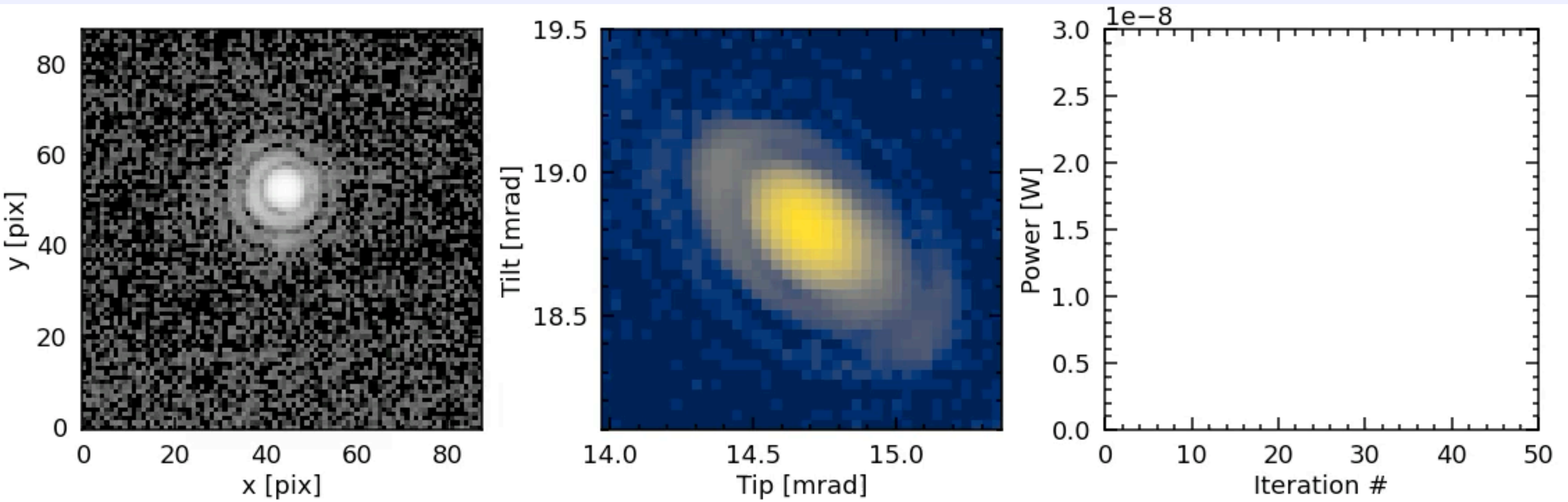
FIM optical design and photon sharing



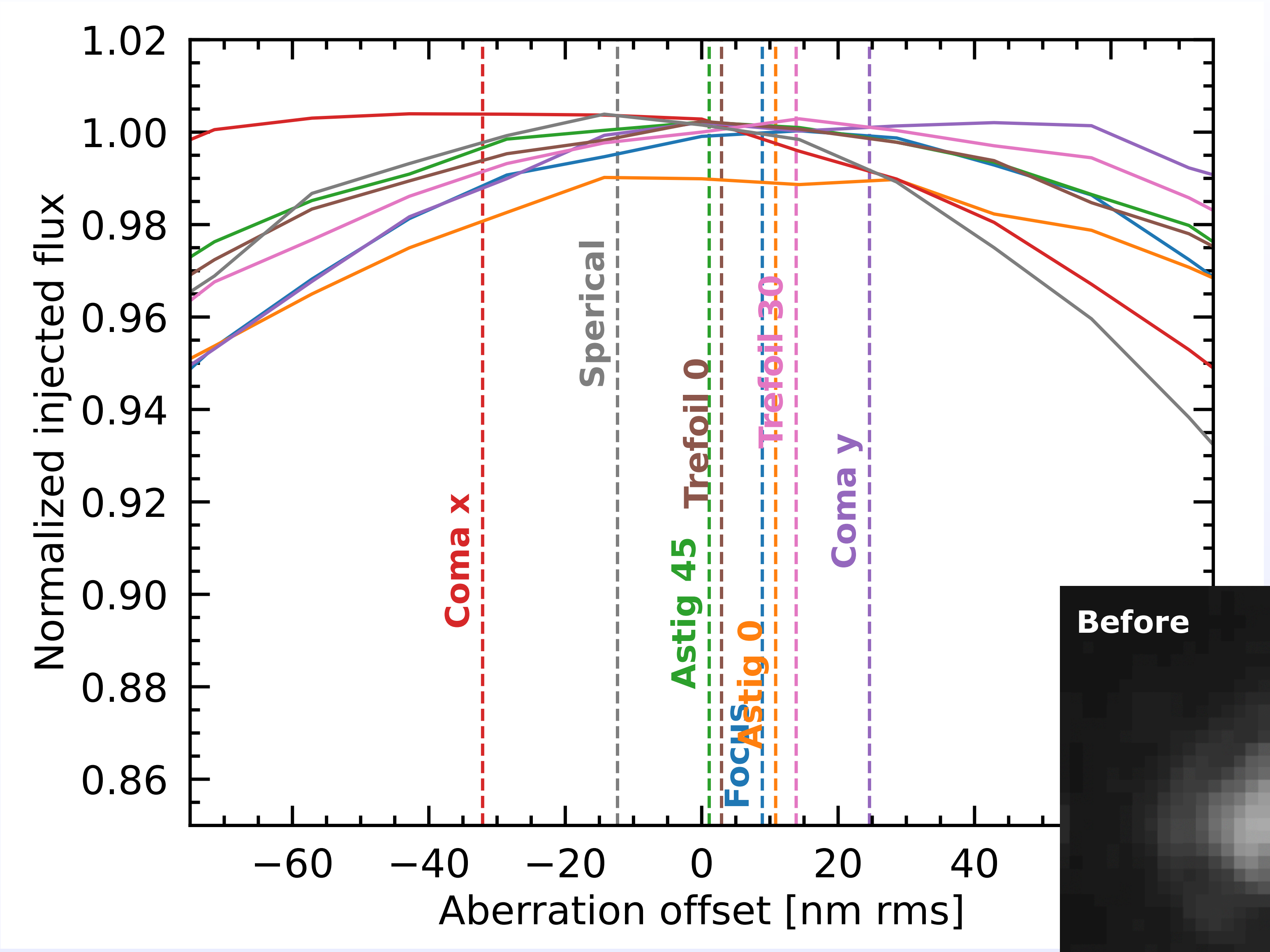
Fiber injection on MITHiC



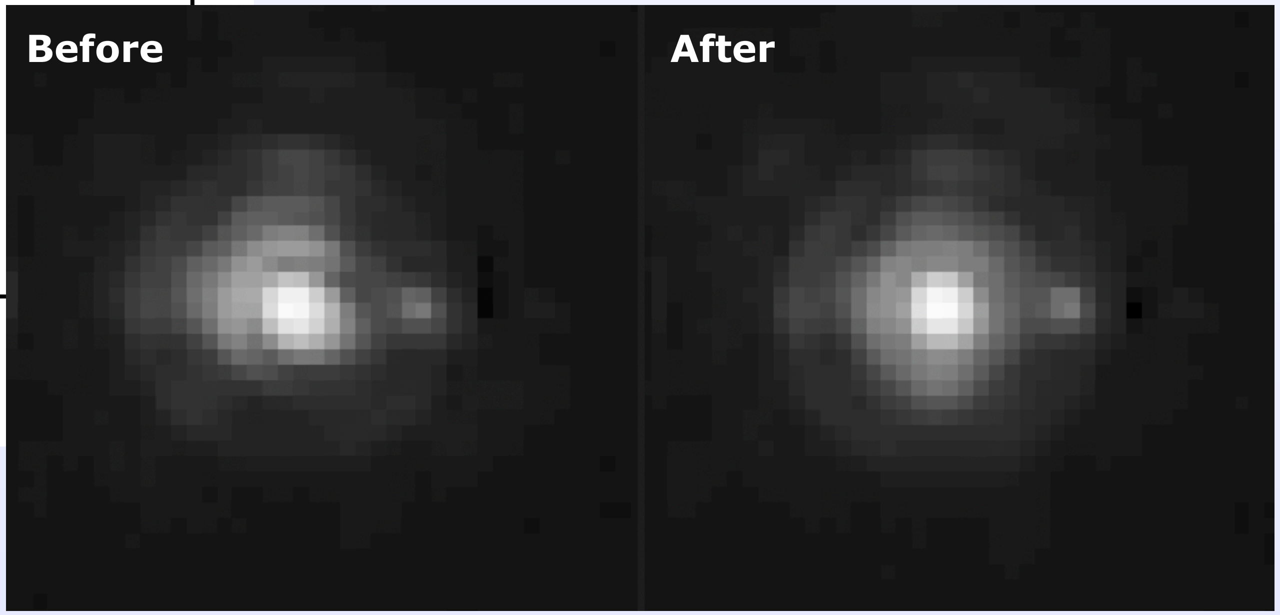
Injection optimisation



Commissioning: NCPA



Optimisation on FIM camera



Level of NCPA is acceptable and no major gain expected from compensation

Operations: daytime calibrations

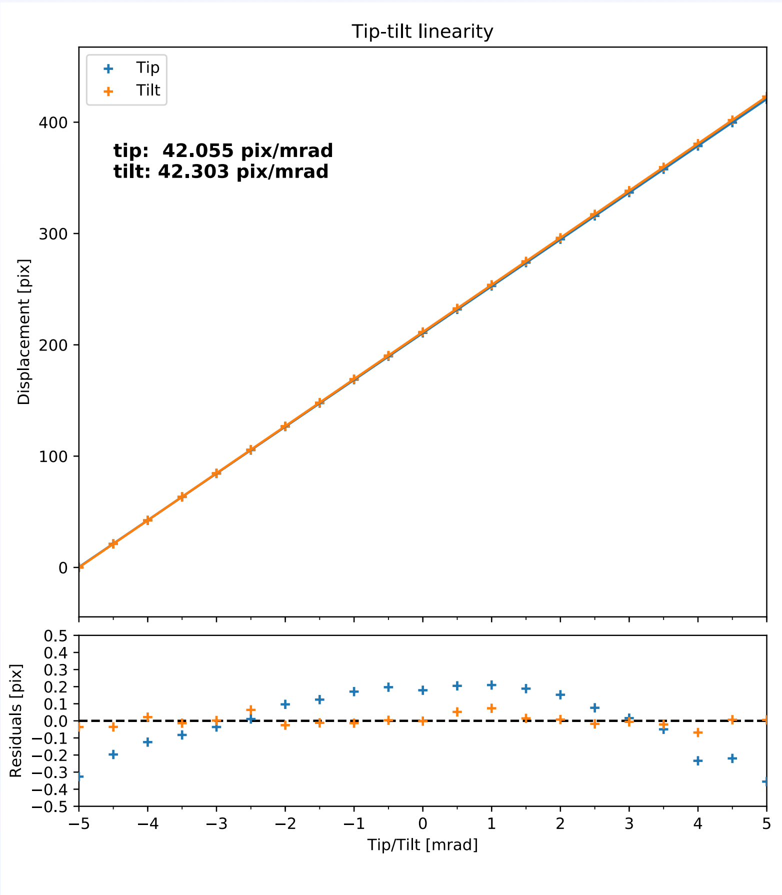
Daytime

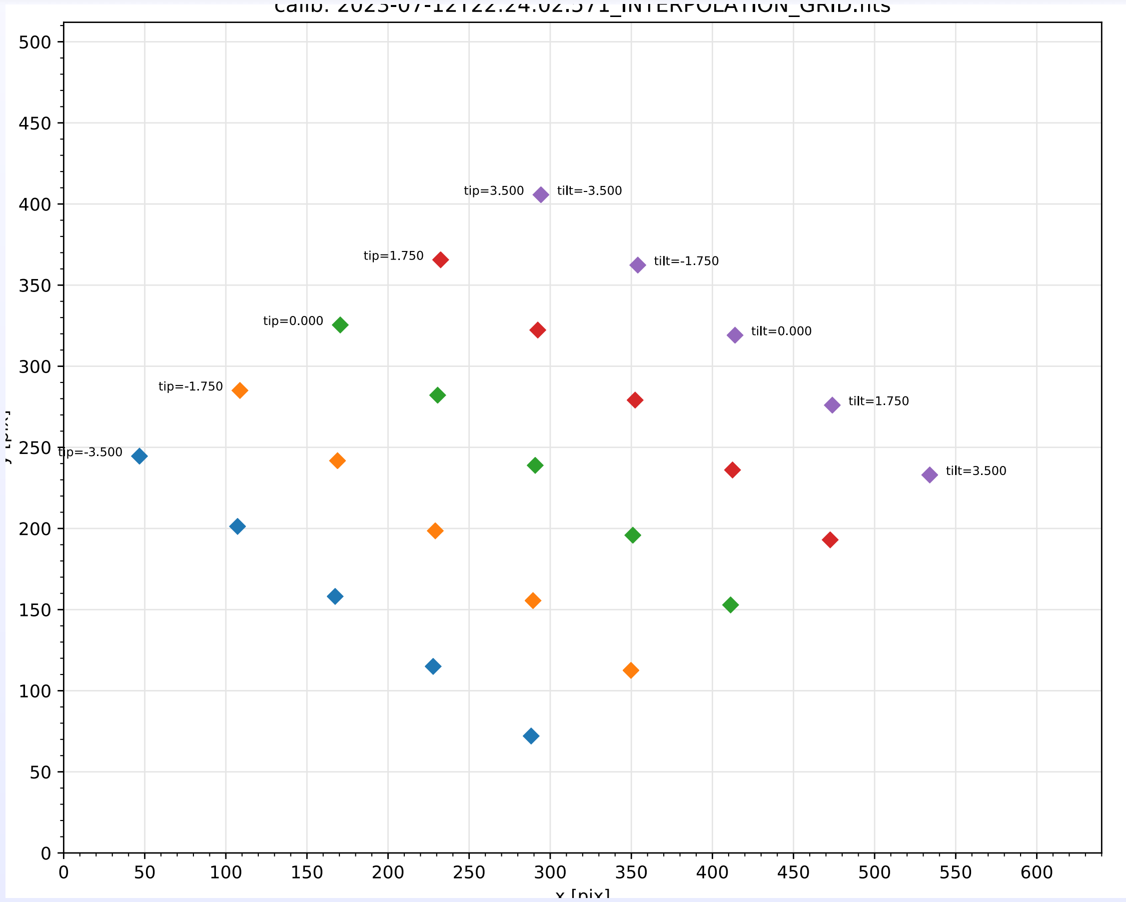
Tip-tilt mirror linearity

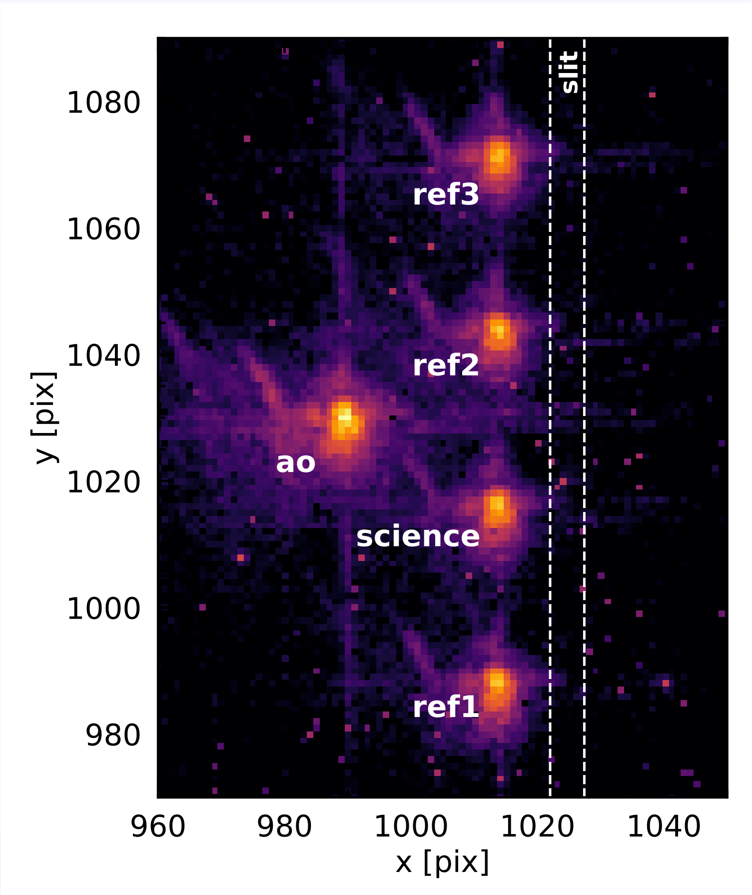
Tip-tilt mirror interpolation matrix

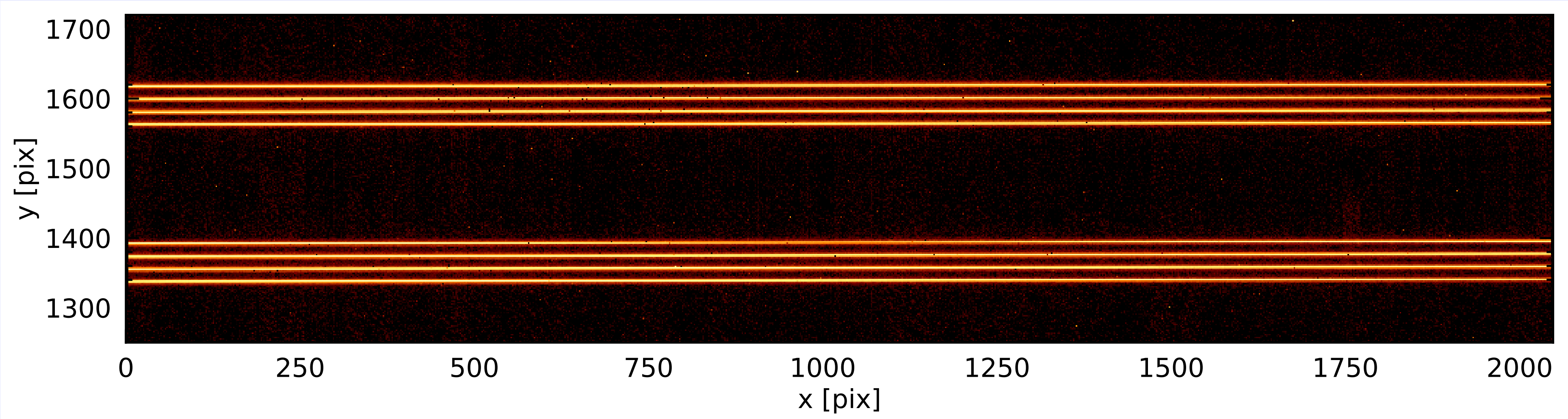
Fibers location on slit viewer

Fibers trace on science detector









Operations: target acquisition

Daytime

Tip-tilt mirror linearity

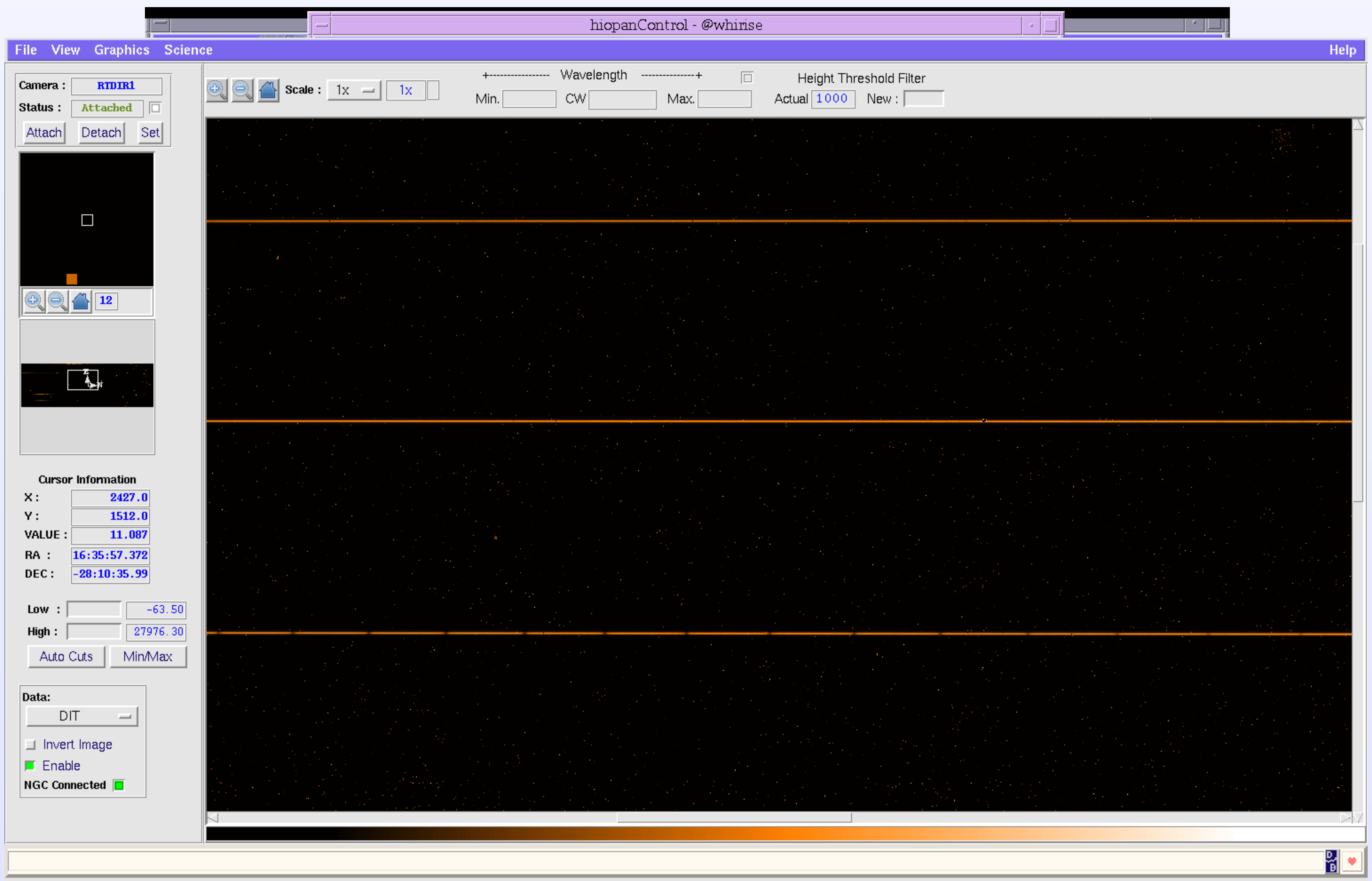
Tip-tilt mirror interpolation matrix

Fibers location on slit viewer

Fibers trace on science detector

Nighttime

SPHERE acquisition → FIM setup → Switch to internal source → Injection map on C fiber → Switch to S fiber → Injection optimisation + offset → Switch to sky → Science data acquisition



A European opportunity in the South

Existing instruments on 8-10 m telescopes with ExAO:

- ***Keck*/KPIC:** D. Mawet, Caltech ***[on-sky since 2020!]***
- ***Subaru*/REACH: T.** Kotani, NAOJ ***[on-sky since 2020!]***
- ***VLT*/HiRISE:** A. Vigan, CNRS/LAM